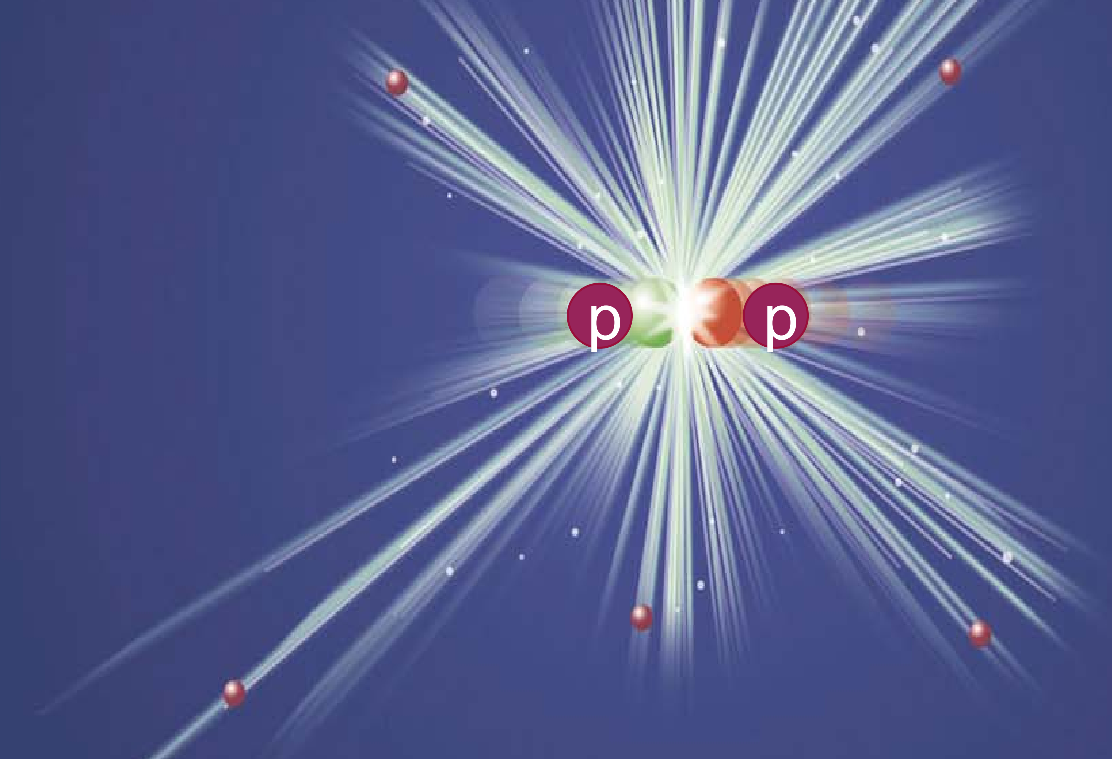
# LHC: the first results and worrying expectations




Dmitri Kazakov

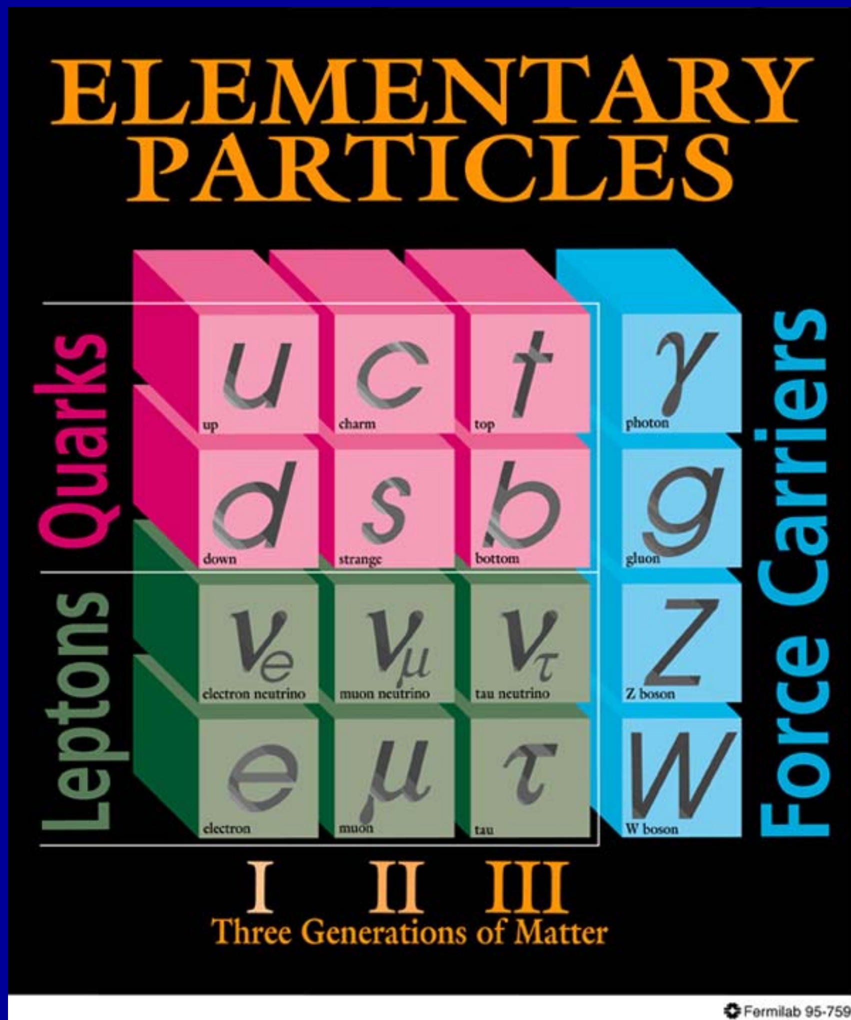
# The Standard Model

SU(3)

SU(2)

U(1)

Particles





The Higgs boson

Forces

Electromagnetic

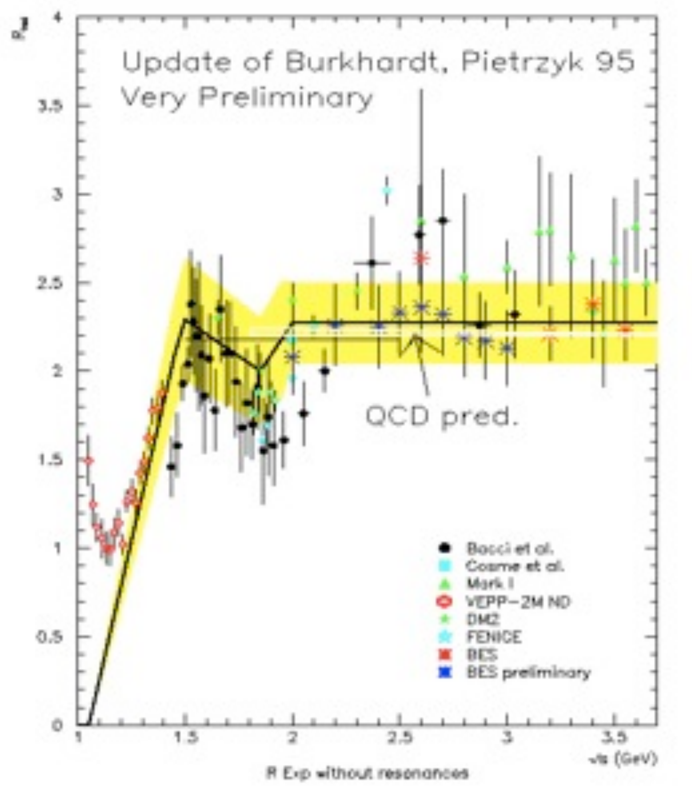
Strong

Weak

Gravity

# How well do we know the SM?

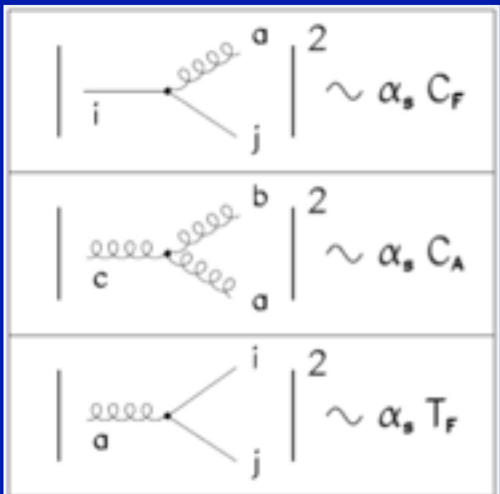
# The Number of Colours




- The x-section of electron-positron annihilation into hadrons is proportional to the number of quark colours. The fit to experimental data at various colliders at different energies gives

$$N_c = 3.06 \pm 0.10$$

# The Group Structure of the SM




$$\sum_{a=1}^{N_A} (T^a T^{\dagger a})_{ij} = \delta_{ij} C_F \quad , \quad \sum_{i,j=1}^{N_F} T^a_{ij} T^{\dagger b}_{ji} = \delta^{ab} T_F \quad , \quad \sum_{a,b=1}^{N_A} f^{abc} f^{*abd} = \delta^{cd} C_A$$

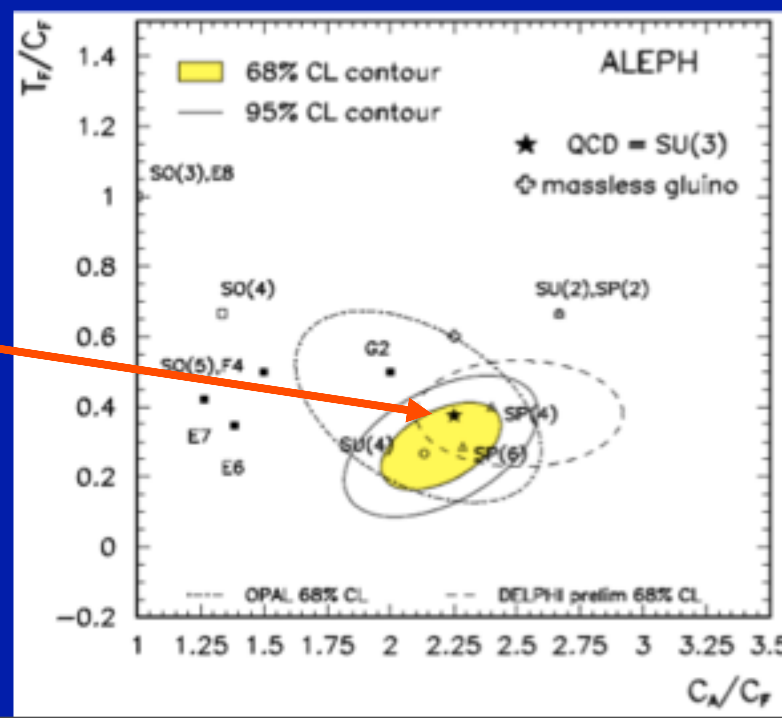
Algebra $[T^a, T^b] = i f^{abc} T^c$

Casimir Operators

For SU(N)

$$C_A = N_C \quad , \quad C_F = \frac{N_C^2 - 1}{2N_C} \quad , \quad T_F = 1/2$$

QCD analysis definitely singles out the SU(3) group as the symmetry group of strong interactions



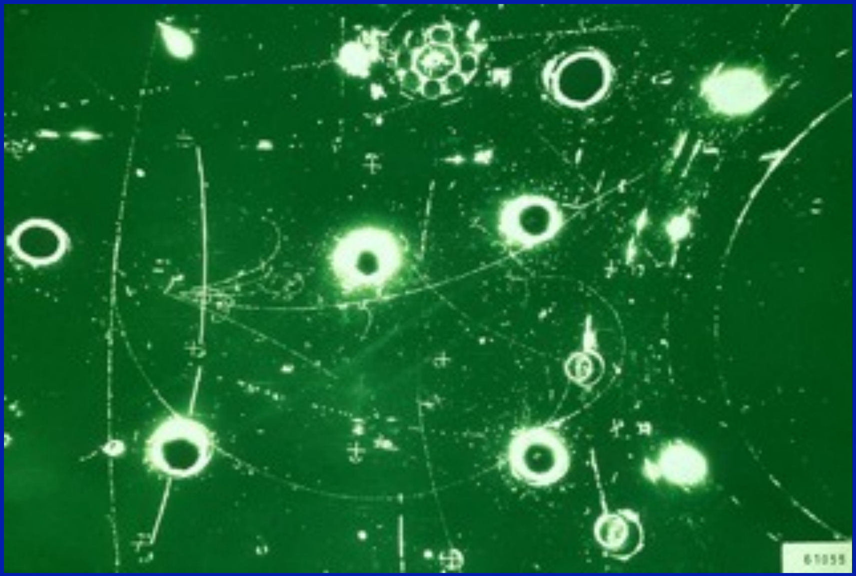
# Electro-weak sector of the SM

SU(2) x U(1) versus O(3)

3 gauge bosons 1 gauge boson 3 gauge bosons

After spontaneous symmetry breaking one has

| | | |
|---|---|---|
| 3 massive gauge bosons ($W^+$ , $W^-$ , $Z^0$) and 1 massless (γ) | ⟺ | 2 massive gauge bosons ($W^+$ , $W^-$ ) and 1 massless (γ) |



- Discovery of neutral currents was a crucial test of the gauge model of weak interactions at CERN in 1973

- The heavy photon gives the neutral current without flavour violation

# Quantum Numbers of Matter

- Quarks

| | $SU(3)_c$ | $SU(2)_L$ | $U_Y(1)$ |
|---|---|---|---|
| $Q_L = \begin{pmatrix} up \\ down \end{pmatrix}_L$ | 3 | 2 | $1/3$ |
| $U_R = up_R$ | 3 | 1 | $4/3$ |
| $D_R = down_R$ | 3 | 1 | $-2/3$ |

triplets

doublets

singlets

V-A currents in weak interactions

- Leptons

| | | | |
|---|---|---|---|
| $L_L = \begin{pmatrix} \nu \\ e \end{pmatrix}_L$ | 1 | 2 | $-1$ |
| $N_R = \nu_R$ ? | 1 | 1 | 0 |
| $E_R = e_R$ | 1 | 1 | $-2$ |

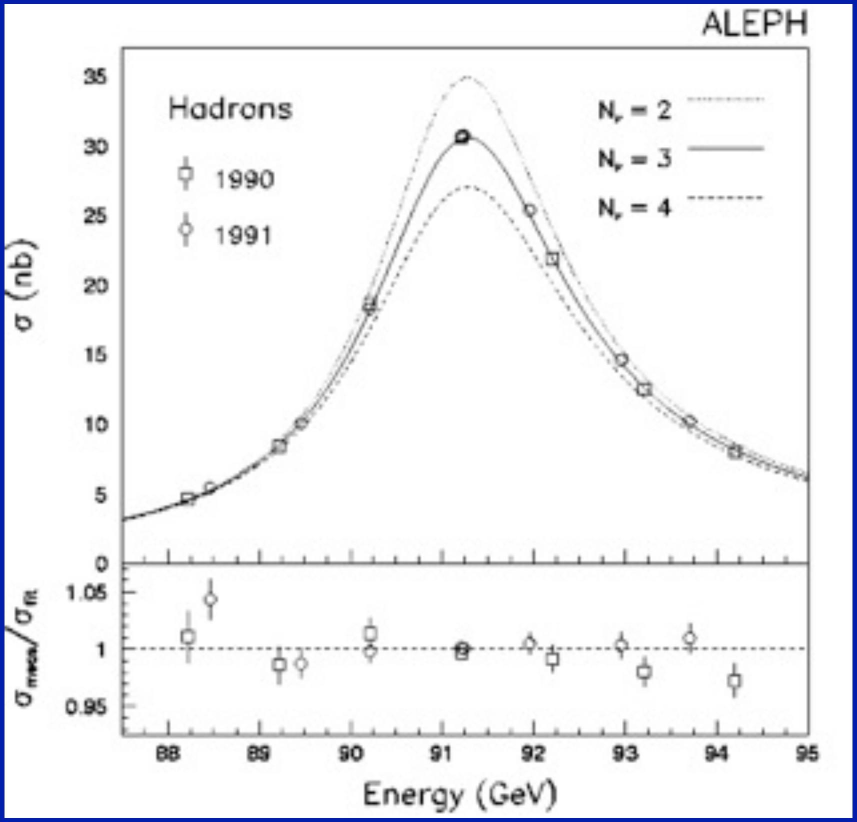
$\frac{1}{2}$, $-\frac{1}{2}$ ↔ $T_3$

0, 0 ↔ $T_3$

Electric charge

$$Q = T_3 + Y/2$$

# The Number of Families




- Z-line shape obtained at LEP depends on the number of flavours and gives the number of (light) neutrinos or (generations) of the Standard Model

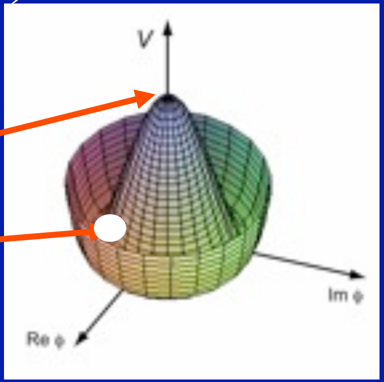
$$N_g = 2.982 \pm 0.013$$

# Spontaneous Symmetry Breaking

$$SU_c(3) \otimes SU_L(2) \otimes U_Y(1) \rightarrow SU_c(3) \otimes U_{EM}(1)$$

Introduce a scalar field with quantum numbers: (1,2,1) $H = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix}$

With potential $V = -m^2 H^\dagger H + \frac{\lambda}{2}(H^\dagger H)^2$




Unstable maximum

Stable minimum

At the minimum

v.e.v.  scalar

$$H = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix} = \begin{pmatrix} H^+ \\ v + \frac{S + iP}{\sqrt{2}} \end{pmatrix} = \exp(i\frac{\vec{\xi}\vec{\sigma}}{2})\begin{pmatrix} 0 \\ v + \frac{S}{\sqrt{2}} \end{pmatrix}$$

pseudoscalar

Gauge transformation

Higgs boson

$$H \rightarrow H' = \exp(i\frac{\vec{\alpha}\vec{\sigma}}{2})H \xrightarrow{(\vec{\alpha} = -\vec{\xi})} H' = \begin{pmatrix} 0 \\ v + \frac{h}{\sqrt{2}} \end{pmatrix}$$

# The Higgs Boson and Fermion Masses

$$H = \begin{pmatrix} 0 \\ v + \frac{h}{\sqrt{2}} \end{pmatrix} \Rightarrow V = -m^2 H^\dagger H + \frac{\lambda}{2}(H^\dagger H)^2$$

$$\Rightarrow V = -\frac{\lambda v^4}{2} + \lambda v^2 h^2 + \frac{\lambda v}{\sqrt{2}} h^3 + \frac{\lambda}{8} h^4 \qquad v^2 = m^2/\lambda$$

$$m_h = \sqrt{2}m = \sqrt{2\lambda}\,v$$

$$L_{Yukawa} = y^E_{\alpha\beta}\bar{L}_\alpha E_\beta H + y^D_{\alpha\beta}\bar{Q}_\alpha D_\beta H + y^U_{\alpha\beta}\bar{Q}_\alpha U_\beta \tilde{H}$$

α, β =1,2,3 - generation index

Dirac fermion mass

$$M^u_i = Diag(y^u_{\alpha\beta})v, \quad M^d_i = Diag(y^d_{\alpha\beta})v, \quad M^l_i = Diag(y^l_{\alpha\beta})v$$

$$y^N_{\alpha\beta}\bar{L}_\alpha N_\beta \tilde{H} \rightarrow M^\nu_i = Diag(y^N_{\alpha\beta})v$$

Dirac neutrino mass

# Quark/Lepton Mixing

- The mass matrix is non-diagonal in generation space
- It can be diagonalized by field rotation Q -> Q'= V Q

$$\bar{U} M_U U -> \bar{U}' V_U^{+} M_U V_U U' = \bar{U}' M_U^{Diag} U'$$

$$\bar{D} M_D D -> \bar{D}' V_D^{+} M_D V_D D' = \bar{D}' M_D^{Diag} D'$$

- Neutral Current: $\bar{U} Z_\mu U -> \bar{U}' V_U^{+} Z_\mu V_U U' = \bar{U}' Z_\mu U' \;\; V_U^{+} V_U = \bar{U}' Z_\mu U'$

- Charged Current $\bar{U} W_\mu D -> \bar{U}' V_U^{+} W_\mu V_D D = \bar{U}' W_\mu V_U^{+} V_D D'$

Cabibbo-Kobayashi-Maskawa mixing matrix $K = V_U^{+} V_D$

The (only) source of flavour mixing in the SM

Unitarity: $K^{+} K = 1$

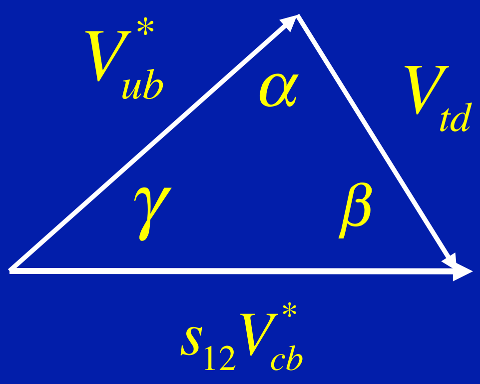
# CKM Matrix and Unitarity Triangle

$$K = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

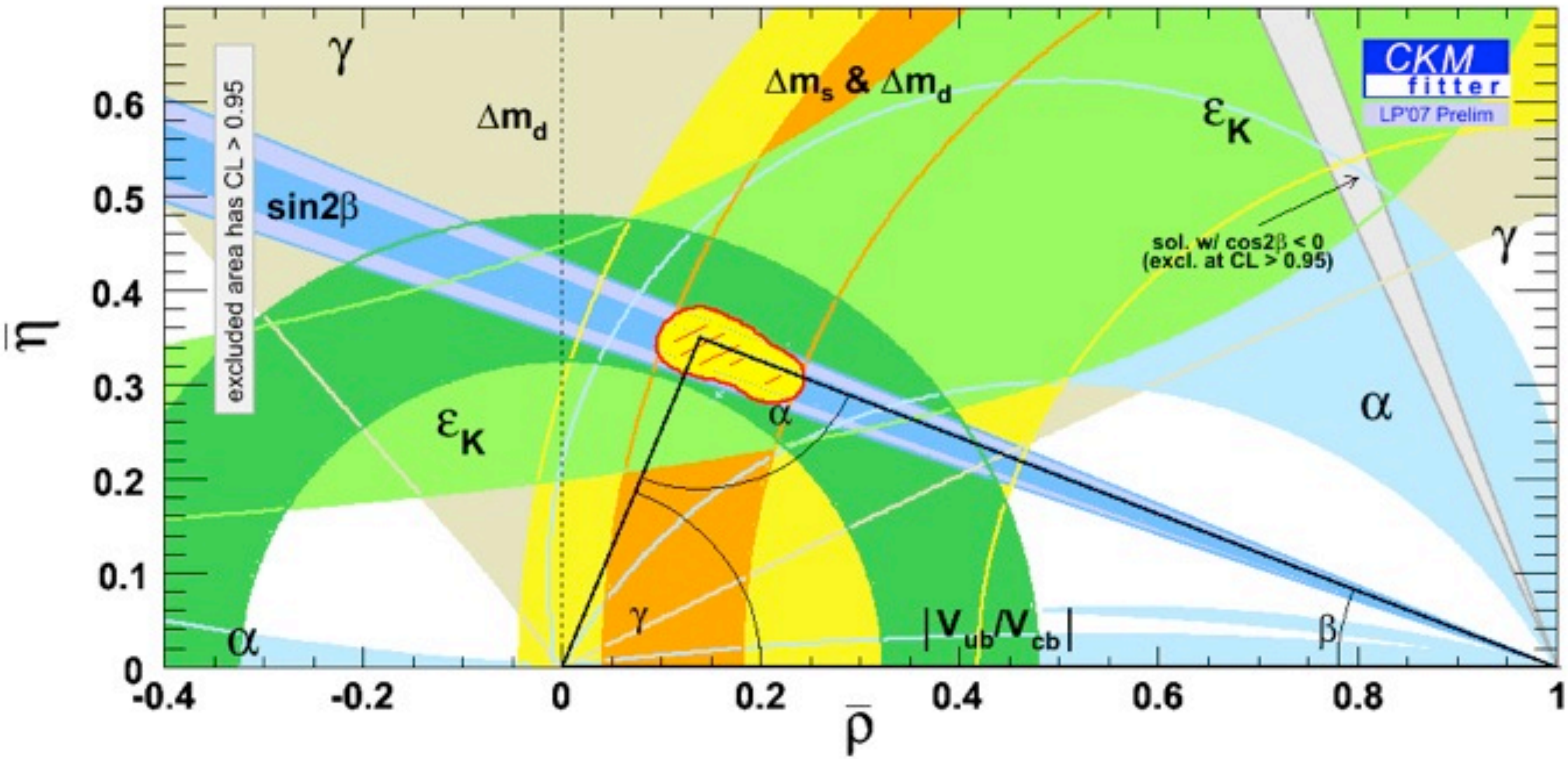
Two important properties

1. CP-violation due to a complex phase $\delta$ !
2. Unitarity triangle

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$
$$\Rightarrow \quad V_{ub}^* + V_{td} = s_{12}V_{cb}^*$$



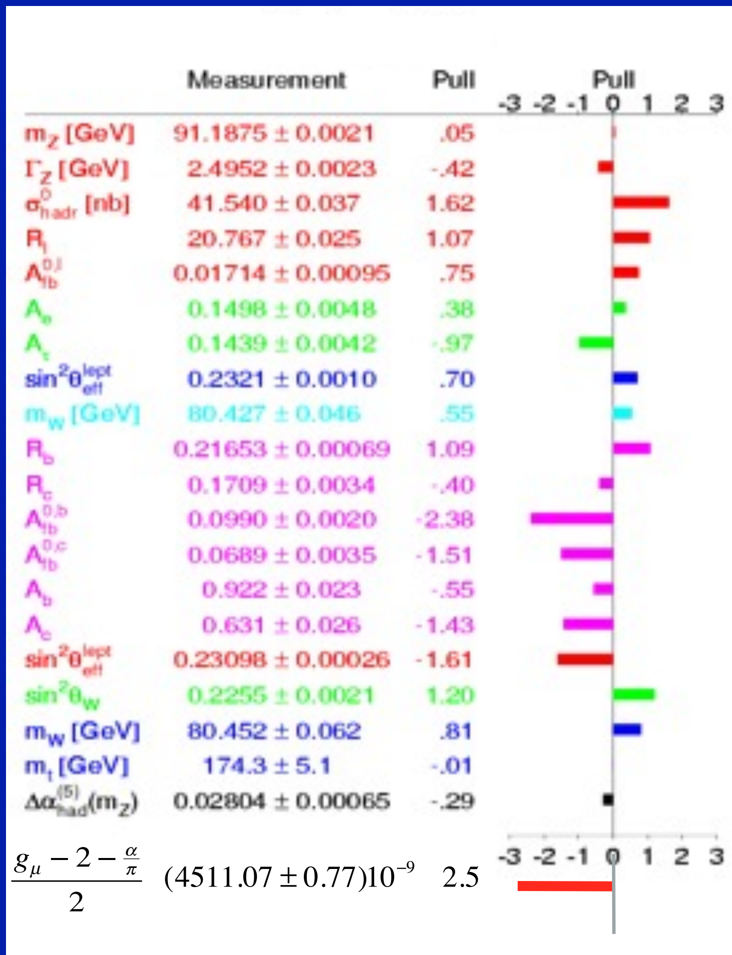
# The Unitarity Triangle: all constraints




A consistent picture across a huge array of measurements

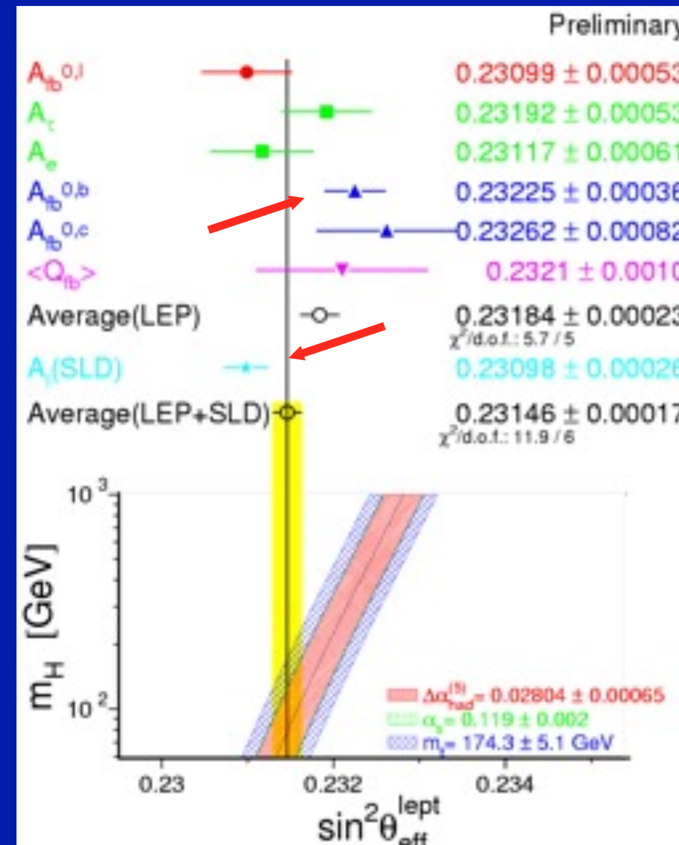
# Comparison with Experiment

Global Fit to Data




Remarkable agreement of ALL the data with the SM predictions - precision tests of radiative corrections and the SM

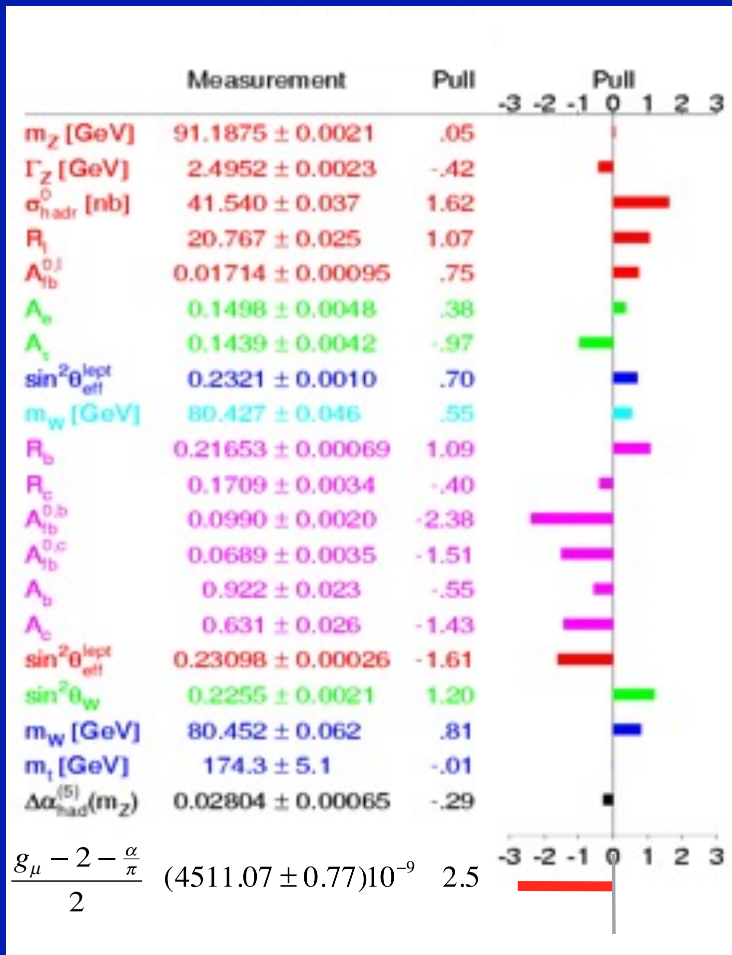
Higgs Mass Constraint




Though the values of sin $\vartheta$w extracted from different experiments are in good agreement, two most precise measurements from hadron and lepton asymmetries disagree by 3$\sigma$

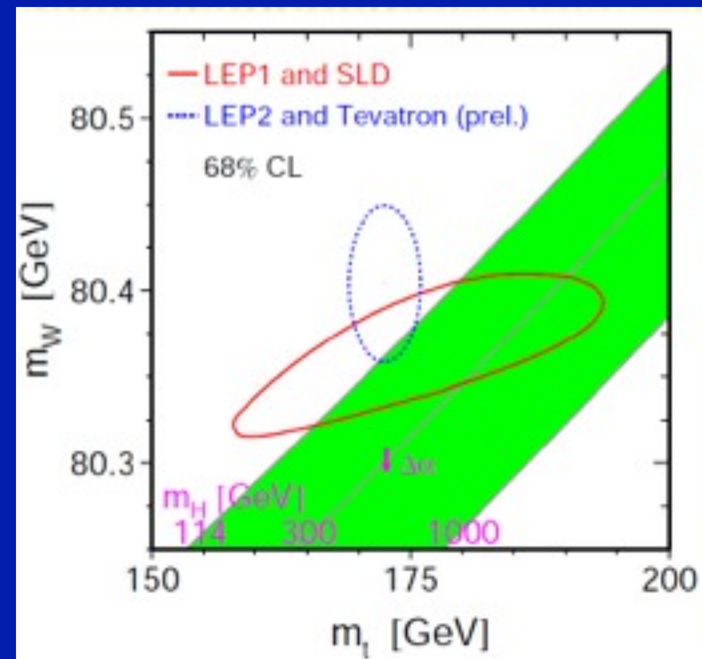
# Comparison with Experiment

Global Fit to Data



| | Measurement | Pull |
|---|---|---|
| $m_Z$ [GeV] | $91.1875 \pm 0.0021$ | .05 |
| $\Gamma_Z$ [GeV] | $2.4952 \pm 0.0023$ | -.42 |
| $\sigma^0_{hadr}$ [nb] | $41.540 \pm 0.037$ | 1.62 |
| $R_l$ | $20.767 \pm 0.025$ | 1.07 |
| $A^{0,l}_{fb}$ | $0.01714 \pm 0.00095$ | .75 |
| $A_e$ | $0.1498 \pm 0.0048$ | .38 |
| $A_\tau$ | $0.1439 \pm 0.0042$ | -.97 |
| $\sin^2\theta^{lept}_{eff}$ | $0.2321 \pm 0.0010$ | .70 |
| $m_W$ [GeV] | $80.427 \pm 0.046$ | .55 |
| $R_b$ | $0.21653 \pm 0.00069$ | 1.09 |
| $R_c$ | $0.1709 \pm 0.0034$ | -.40 |
| $A^{0,b}_{fb}$ | $0.0990 \pm 0.0020$ | -2.38 |
| $A^{0,c}_{fb}$ | $0.0689 \pm 0.0035$ | -1.51 |
| $A_b$ | $0.922 \pm 0.023$ | -.55 |
| $A_c$ | $0.631 \pm 0.026$ | -1.43 |
| $\sin^2\theta^{lept}_{eff}$ | $0.23098 \pm 0.00026$ | -1.61 |
| $\sin^2\theta_W$ | $0.2255 \pm 0.0021$ | 1.20 |
| $m_W$ [GeV] | $80.452 \pm 0.062$ | .81 |
| $m_t$ [GeV] | $174.3 \pm 5.1$ | -.01 |
| $\Delta\alpha^{(5)}_{had}(m_Z)$ | $0.02804 \pm 0.00065$ | -.29 |
| $\frac{g_\mu - 2 - \frac{\alpha}{\pi}}{2}$ | $(4511.07 \pm 0.77)10^{-9}$ | 2.5 |

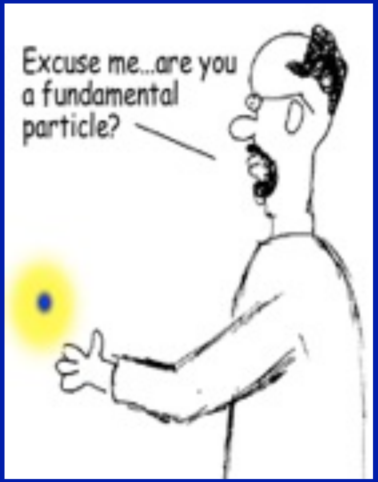
Higgs Mass Constraint




Remarkable agreement of ALL the data with the SM predictions - precision tests of radiative corrections and the SM

Radiative corrections suggest light Higgs almost in contradiction with direct search within 1σ

# The SM and Beyond




## The problems of the SM:

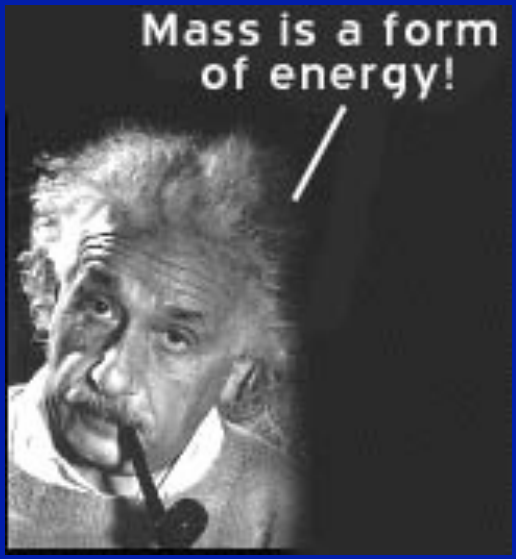
- Inconsistency at high energies due to Landau poles
- Large number of free parameters
- Still unclear mechanism of EW... y breaking
- CP-violation is not under...
- The origin of the m... clear
- Flavour mixing and ... of generations is arbitrary
- Formal unification o... ng and electroweak interactions

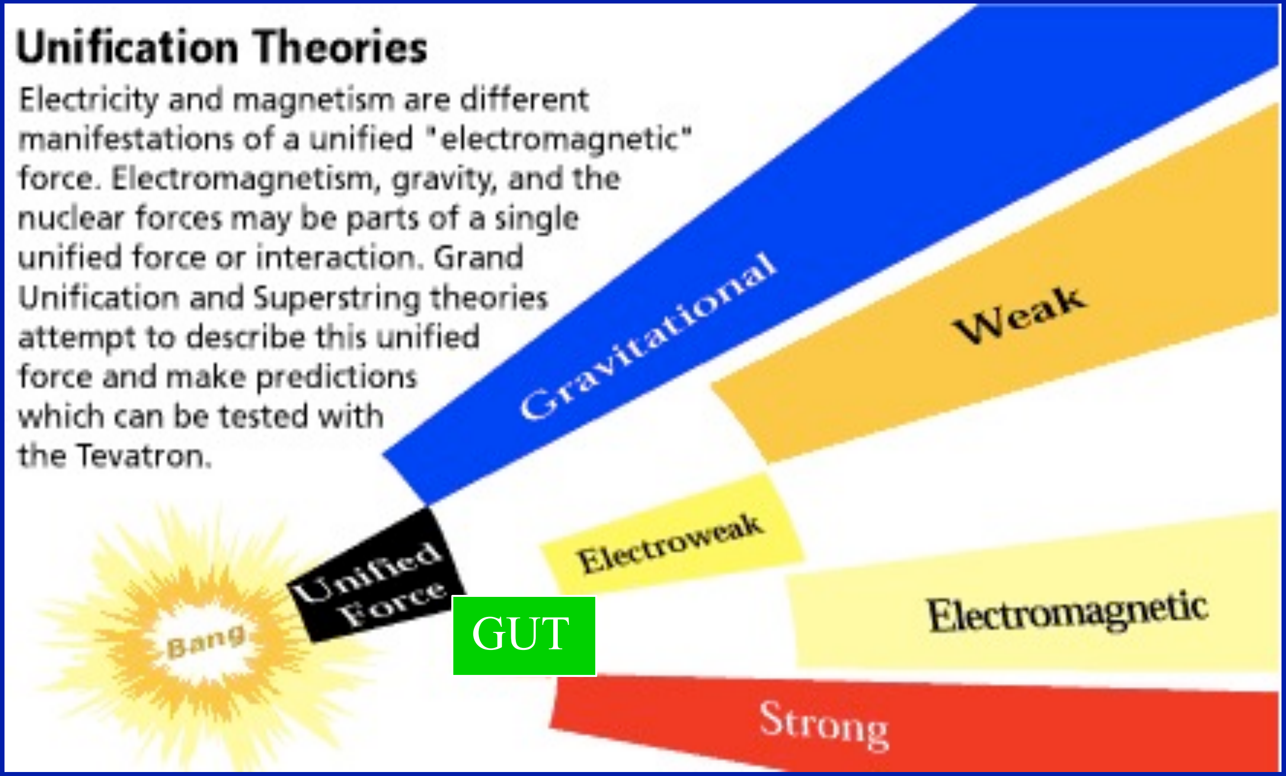
**Where is the Dark matter?**

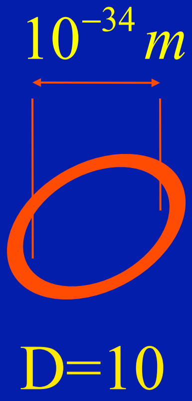
## The way beyond the SM:

- The SAME fields with NEW interactions and NEW fields ⇨ GUT, SUSY, String, ED
- NEW fields with NEW interactions ⇨ Compositeness, Technicolour, preons

# Unification Paradigm



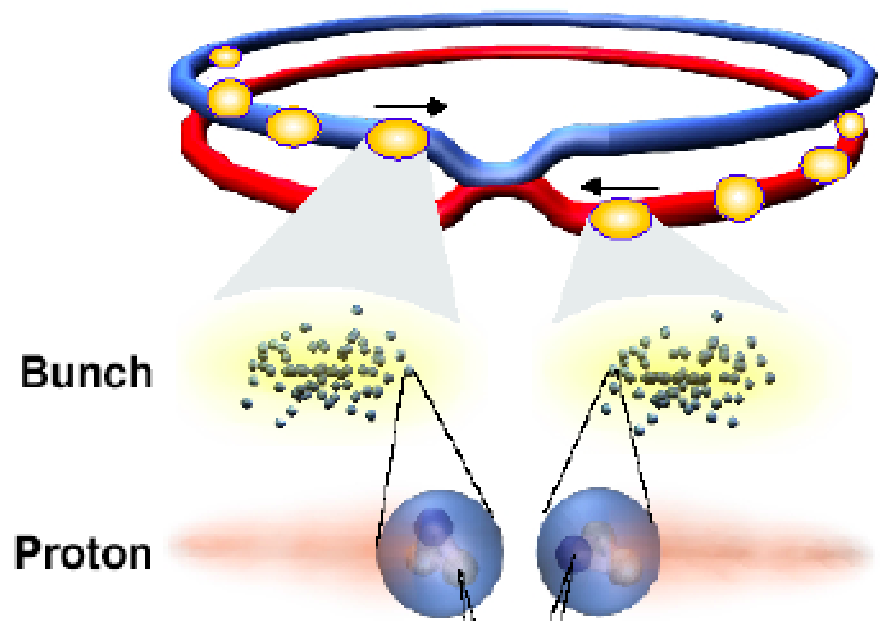




- Unification of strong, weak and electromagnetic interactions within Grand Unified Theories is the new step in unification of all forces of Nature
- Creation of a unified theory of everything based on string paradigm seems to be possible

# Introduction

*Collisions at the LHC: counter-rotating, high-intensity bunches of protons or heavy ions.*




The rate of **new particle's production** is proportional to the **luminosity**:

$$\mathcal{L} \propto \frac{N_1 N_2 n_b}{\sigma^2}$$

Key parameters:

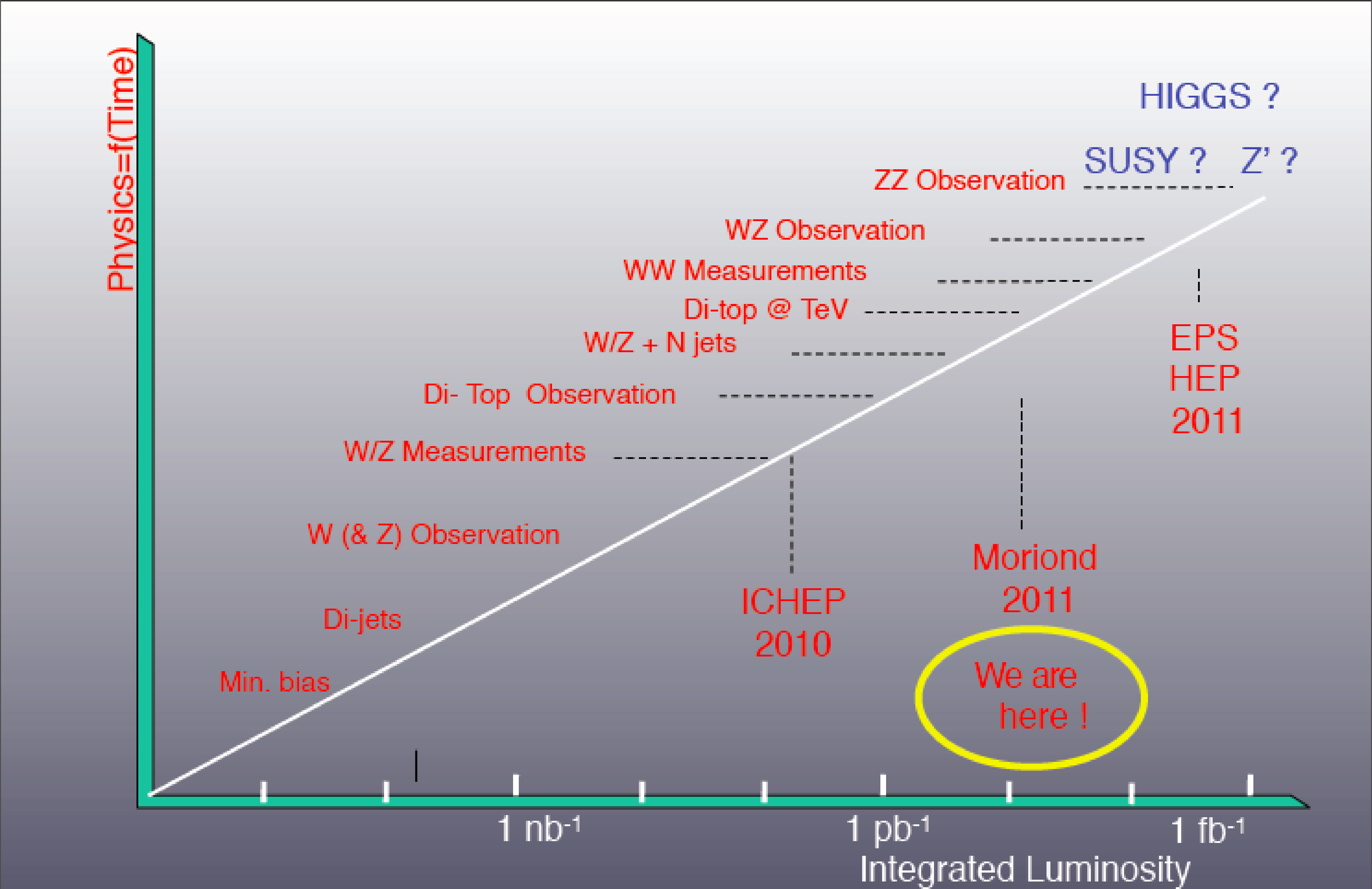
- $N_i$ = bunch intensity
- $n_b$ = number of bunches
- $\sigma$ = colliding beam size

*Nominal LHC parameters (7 TeV): **2808** bunches of **1.1x10^11** protons, **0.000016** m size.*

*Units for the luminosity:*

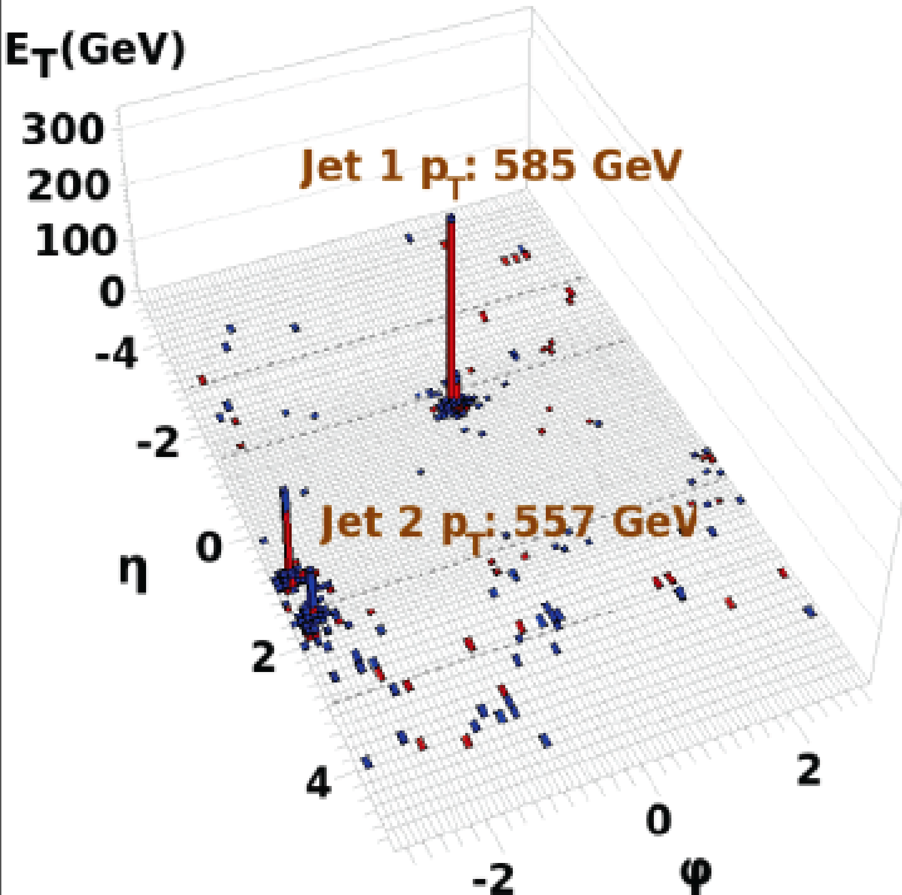
- *Peak luminosity given in event rate per unit of area* $cm^{-2}s^{-1}$: ***2010 goal = $10^{32} cm^{-2}s^{-1}$***
- *Integral luminosity (prop. to number of collisions)* $fb^{-1}$ : ***2011 goal = 1 $fb^{-1}$***

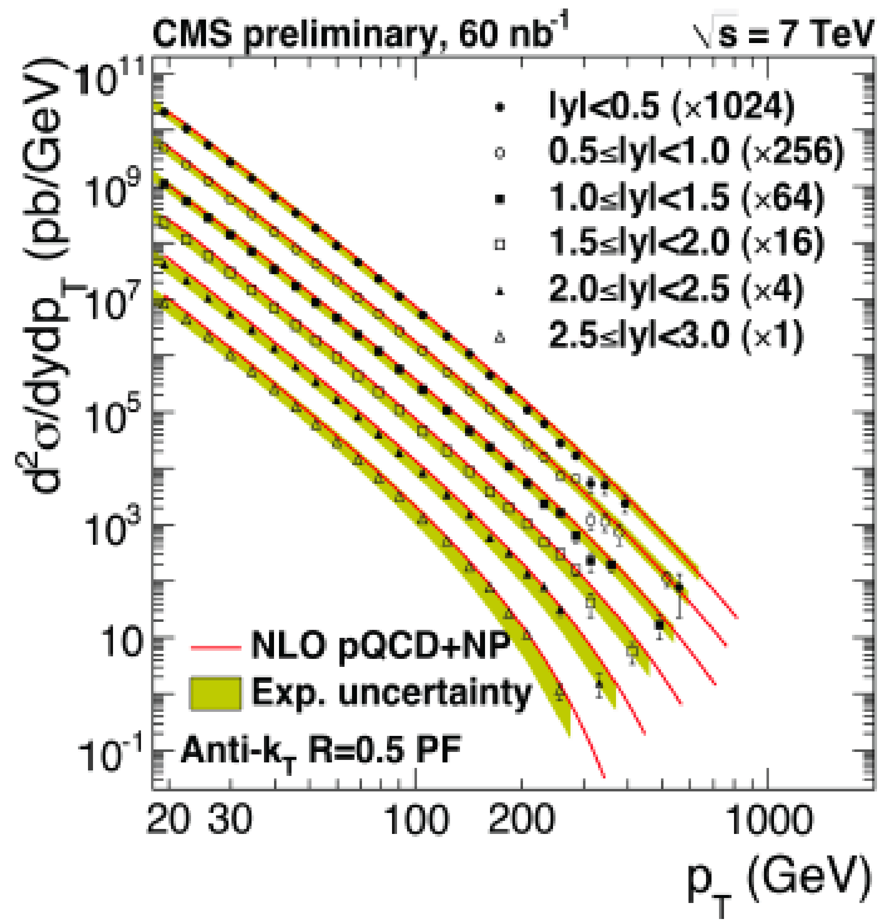
# CMS Physics Objectives through 2011



# Inclusive Jet Production

Measured Jet Production rate in good agreement within experimental and theoretical uncertainties



# Two-Particle Angular

**Published in**
J. High Energy Phys. 09 (2010) 091

First surprising result from the LHC:
Observation of Long-Range Near-Side Angular Correlations in pp Collisions

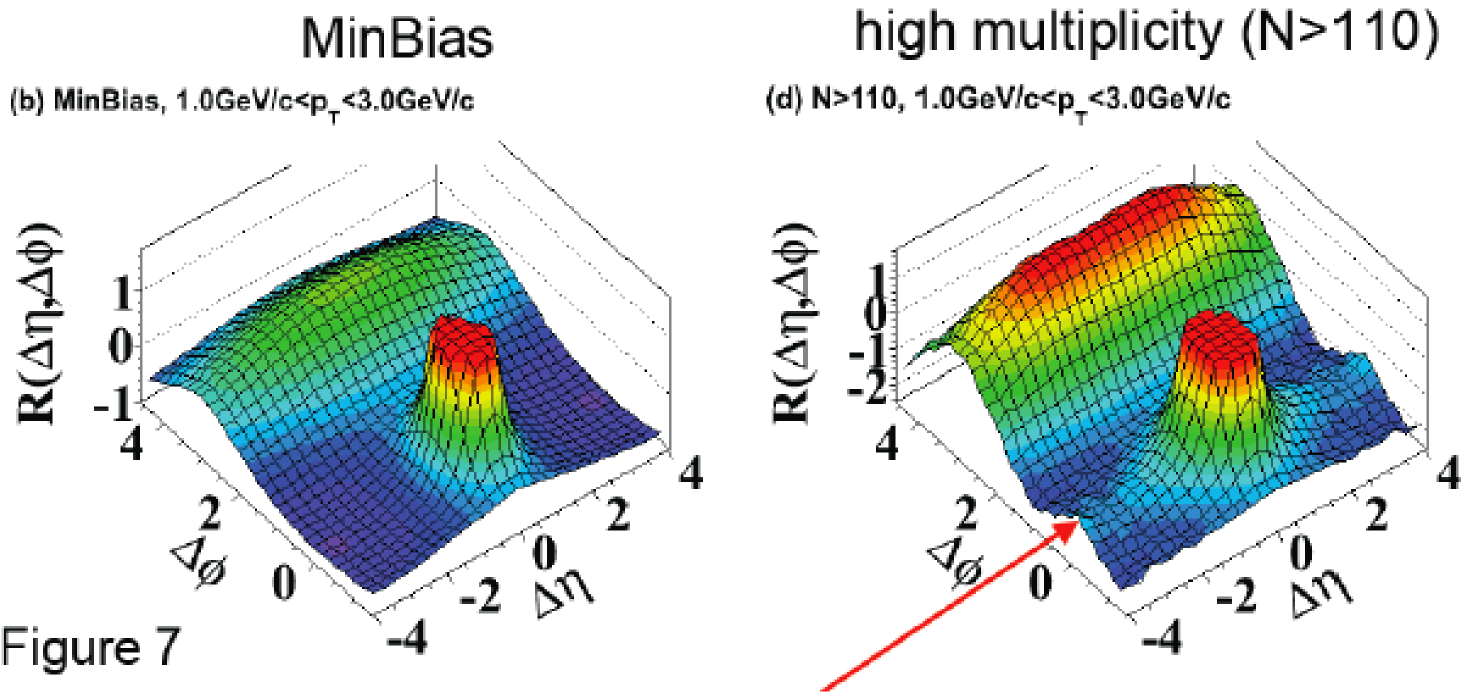


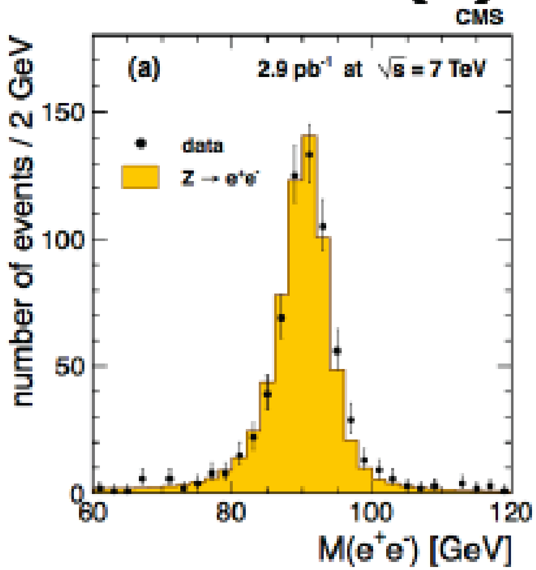

Figure 7

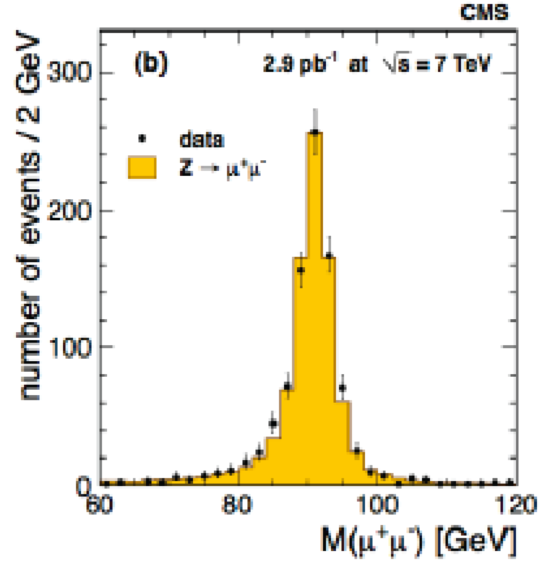
**No conclusive explanation yet , sizeable impact on scientific community!**

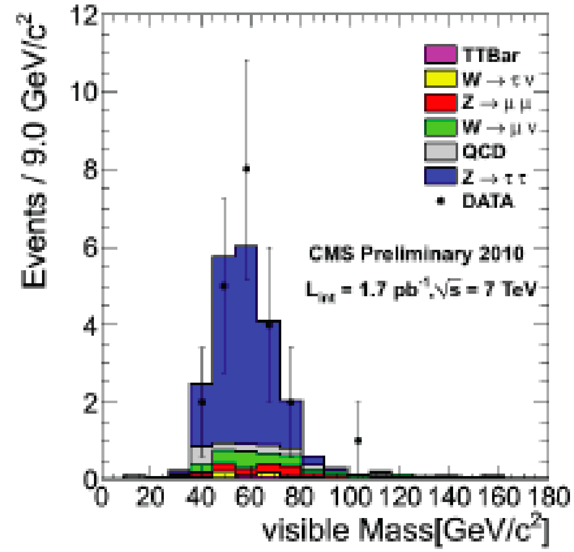
# W & Z Boson Production

**electron(s)** | **muon(s)** | **tau(s)**

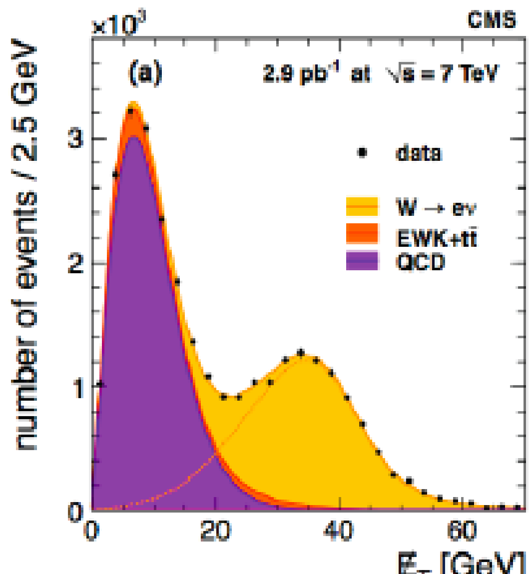
**Z Boson**

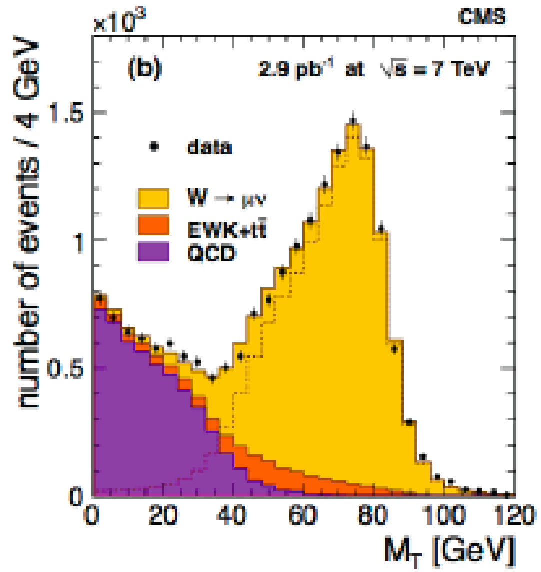


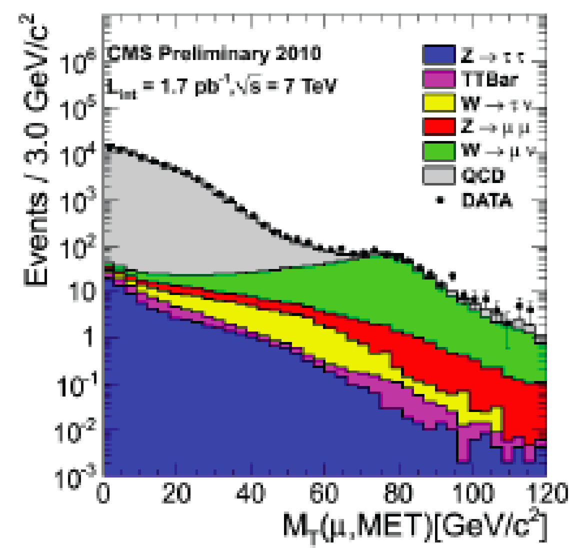




**W Boson**



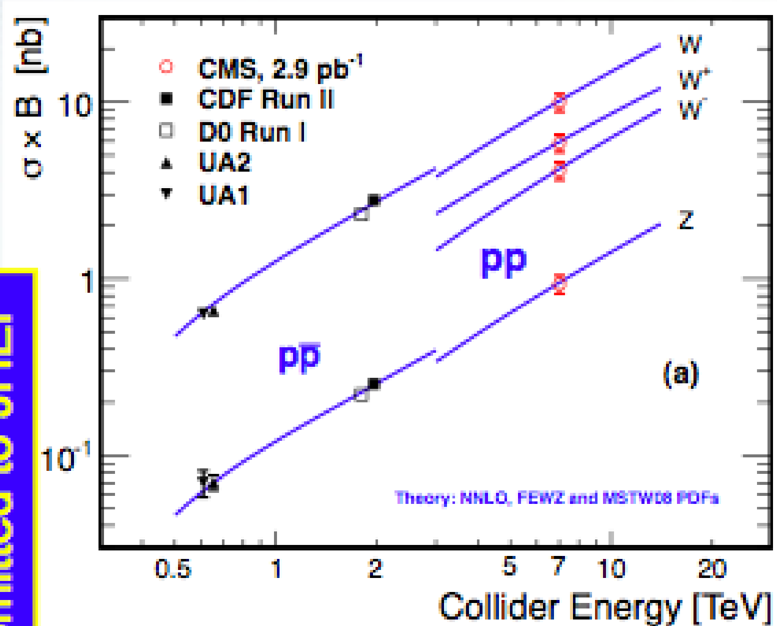



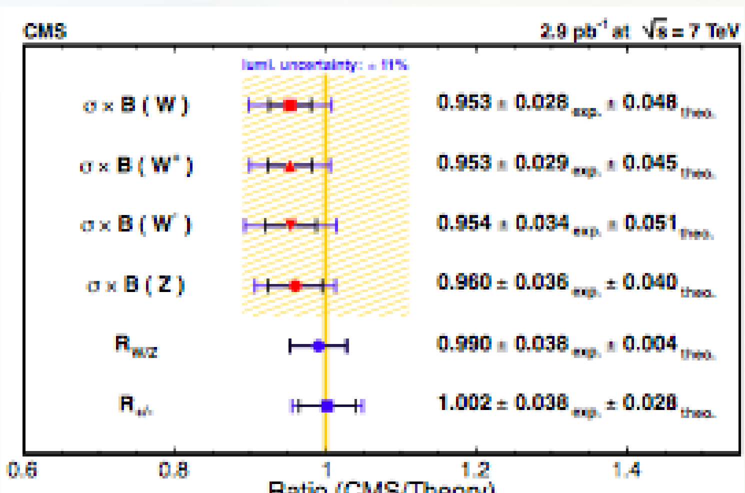



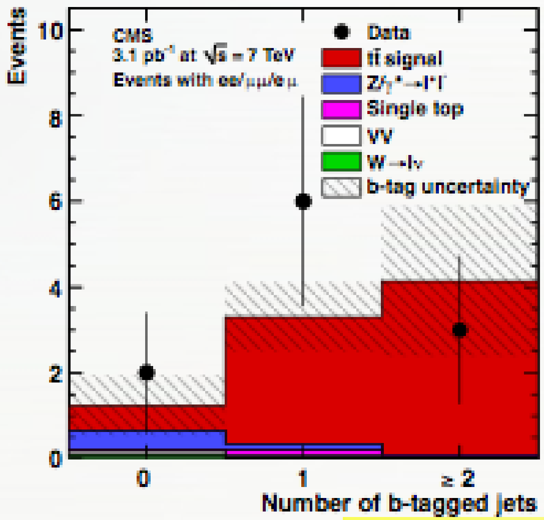
# Electro-Weak Physics

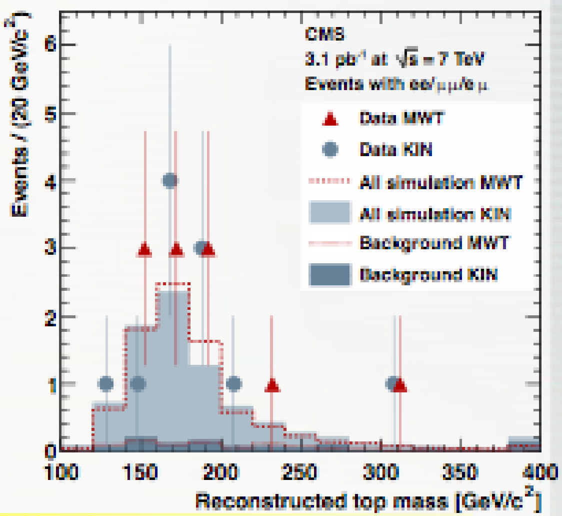
- Measurement of the W/Z and top cross section

$$\sigma(pp \to t\bar{t}) = 194 \pm 72(\text{stat.}) \pm 24(\text{syst.}) \pm 21(\text{lumi.})\ \text{pb}$$

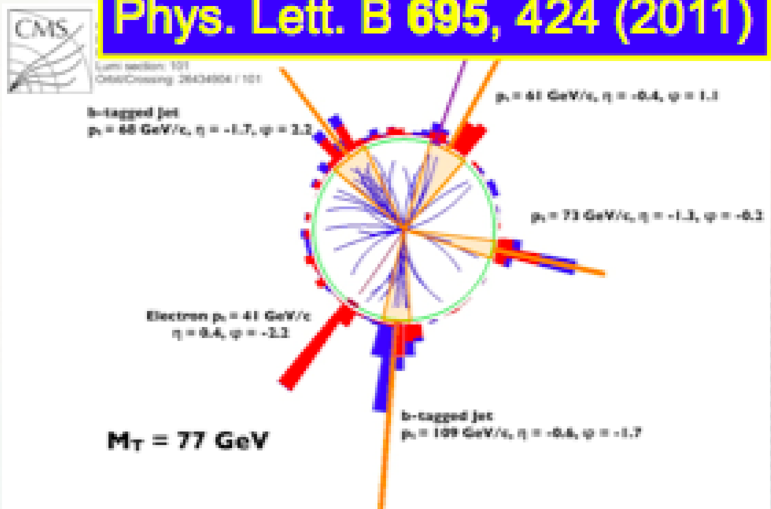


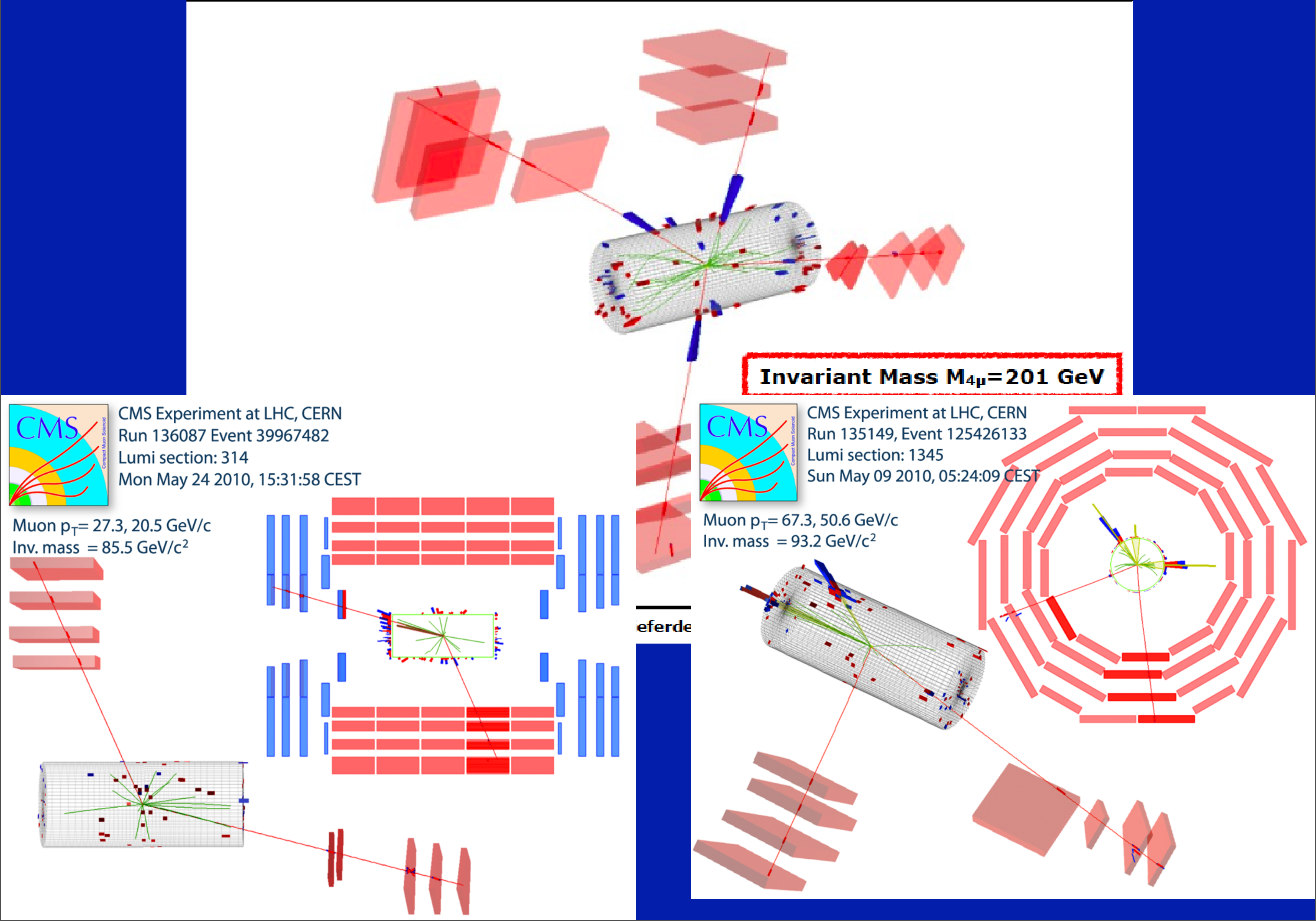




**Phys. Lett. B 695, 424 (2011)**

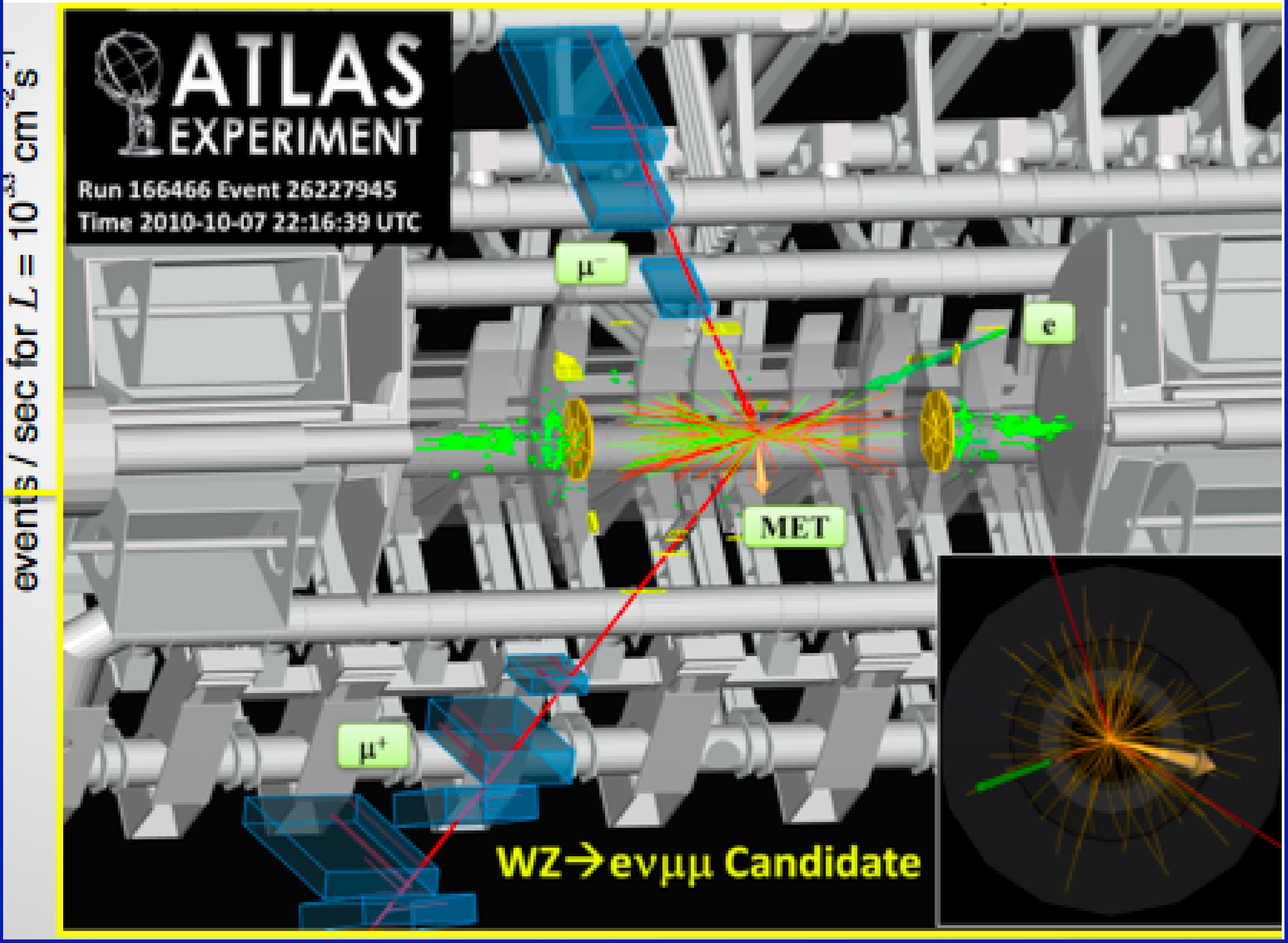



arXiv:1012.2466, submitted to JHEP

# First $(Z^0 \rightarrow \mu^+\mu^-)(Z^0 \rightarrow \mu^+\mu^-)$ Candidate



# $WZ \to e\nu\mu\mu$



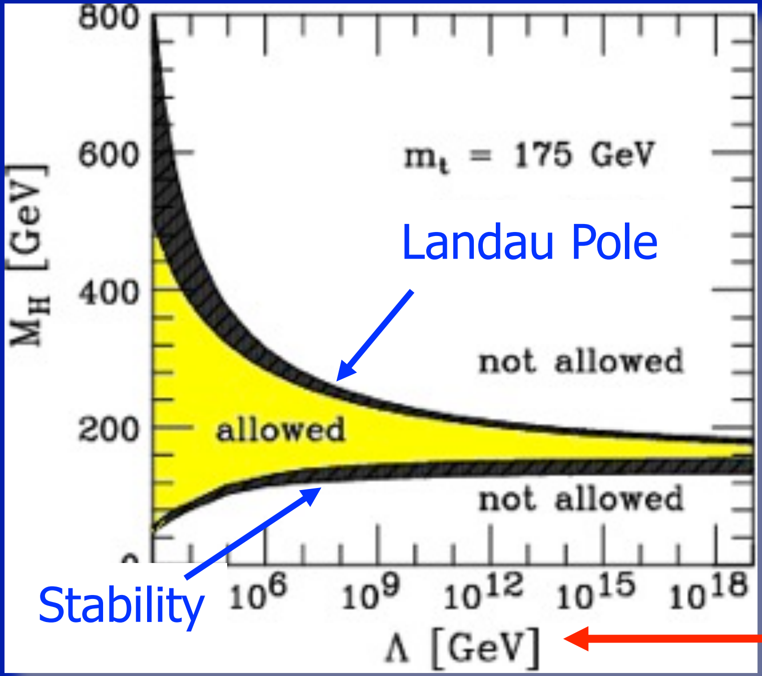
# The Higgs Boson

# The Higgs Mass Bounds

Stability bound

$$m_h > 135 + 2.1[m_t - 174] - 4.5\left[\frac{\alpha_s(M_Z) - 0.118}{0.006}\right], \qquad \Lambda = 10^{19}\ \mathrm{GeV},$$

$$m_h > 72 + 0.9[m_t - 174] - 1.0\left[\frac{\alpha_s(M_Z) - 0.118}{0.006}\right], \qquad \Lambda = 1\ \mathrm{TeV},$$



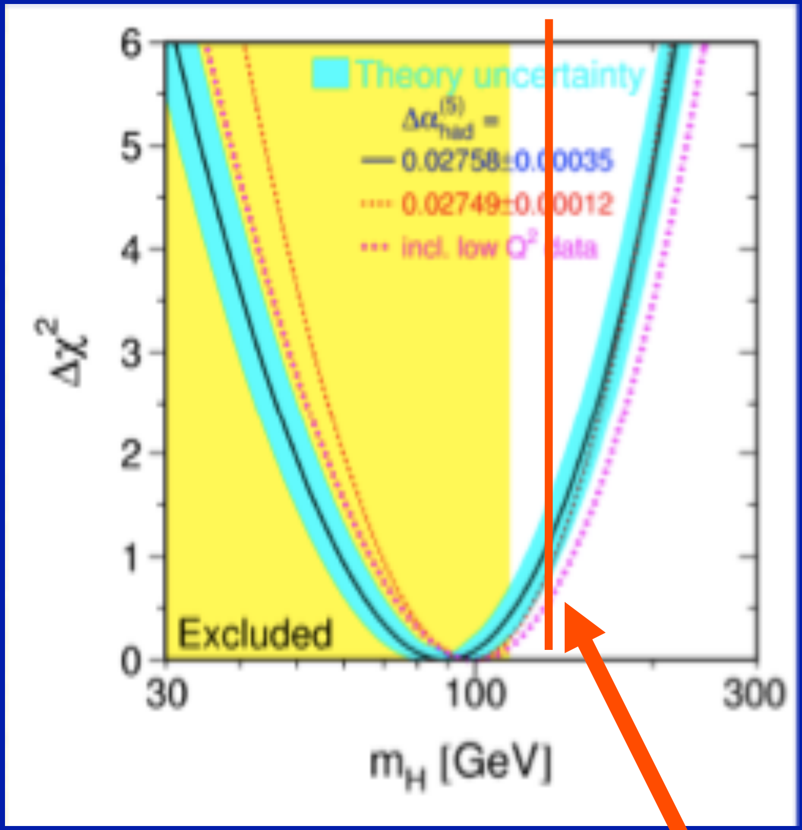

- The SM Higgs

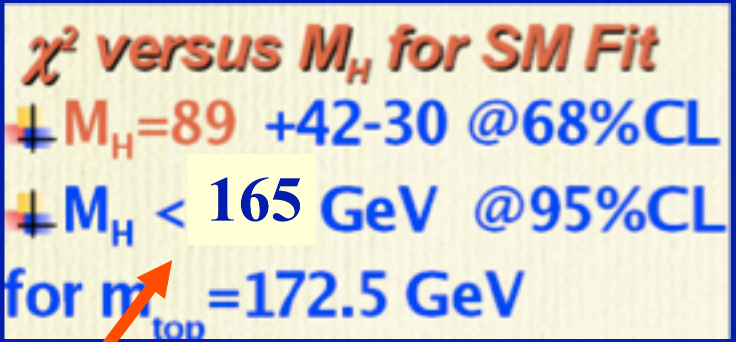
mH ≥ 134 GeV

Assuming the SM is valid up to the Plank scale

The scale up to which the SM is valid

# SM Fit to Precision EW Data

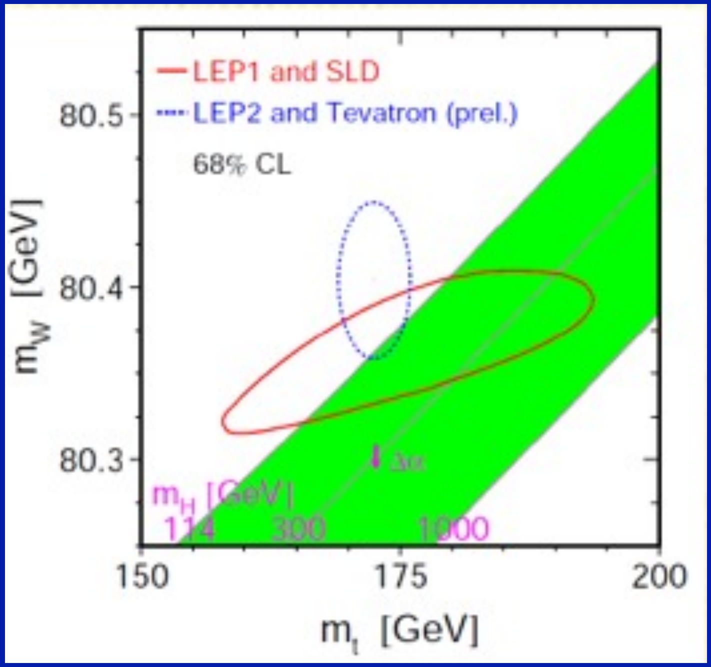


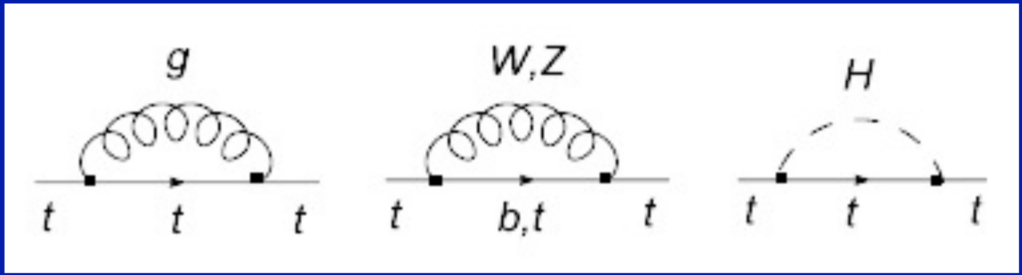

If it is there we may see it soon

# The SM Higgs Boson

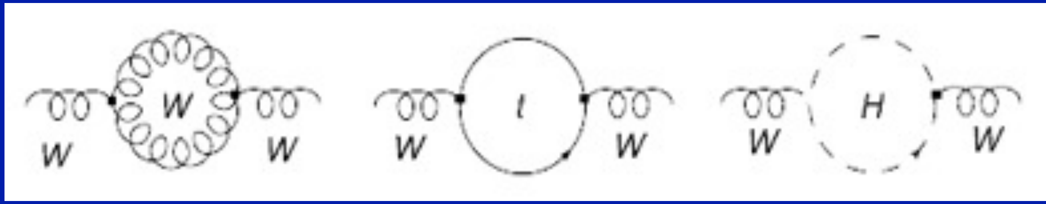
- Indirect limit from radiative corrections
- Direct limit from Higgs non observation at LEP II (CERN)
- Precision measurement of $M_W$ and $m_t$




Radiative corrections to $M_W$ and $m_t$

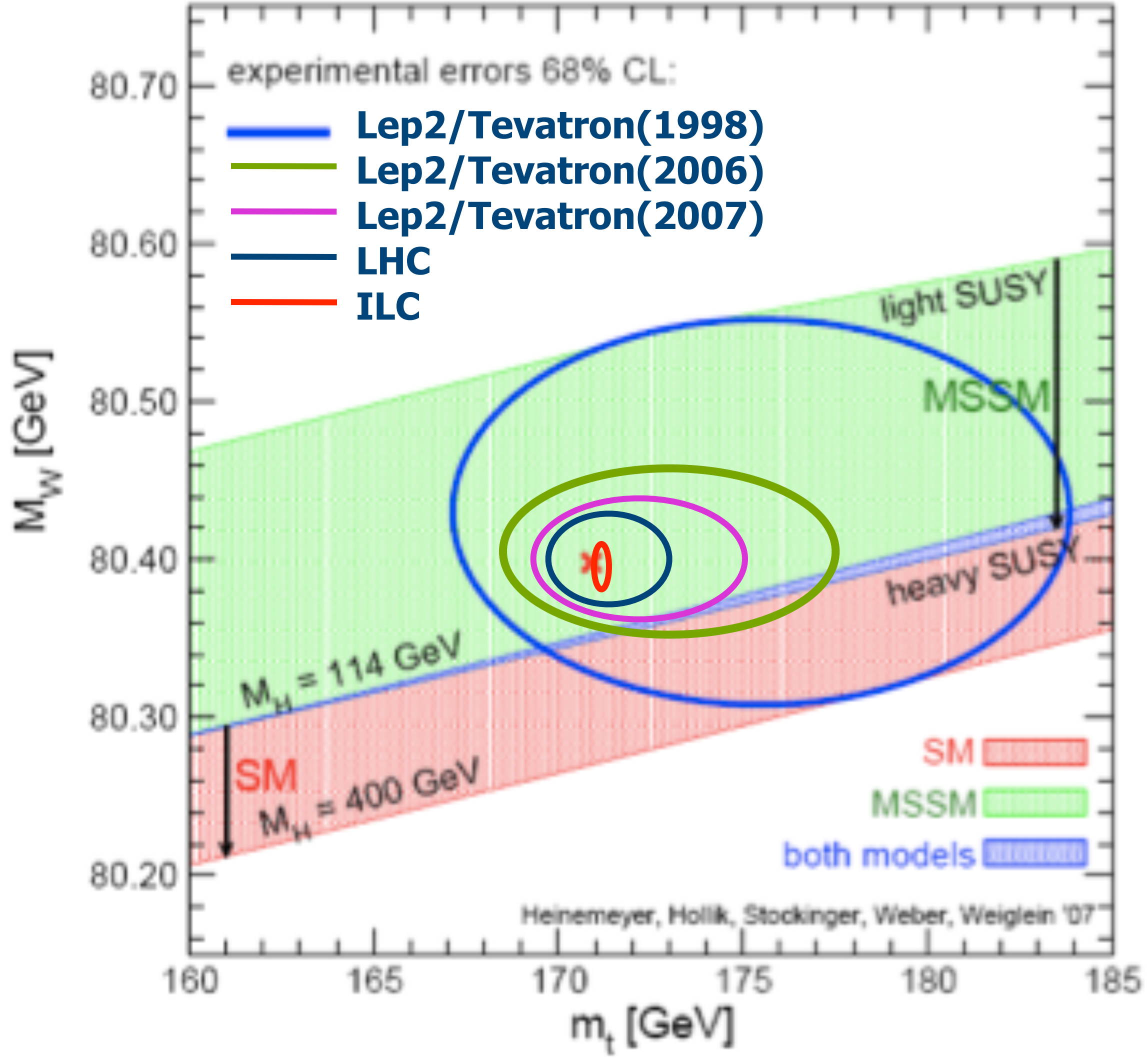



$$\sim \alpha_s m_t \qquad \sim \alpha_2 m_t \log \frac{m_Z^2}{m_t^2} \qquad \sim y_t^2 m_t \log \frac{m_H^2}{m_t^2}$$




$$\sim \alpha_2 \mathrm{M}_\mathrm{W}^2 \qquad \sim \alpha_2 \mathrm{M}_\mathrm{W}^2 \log \frac{m_t^2}{m_W^2} \qquad \sim \alpha_2 \mathrm{M}_\mathrm{W}^2 \log \frac{m_H^2}{m_W^2}$$

# Measurement of $M_w$ and $m_t$ and Comparison with SM and MSSM




MSSM band:
scan over
SUSY masses

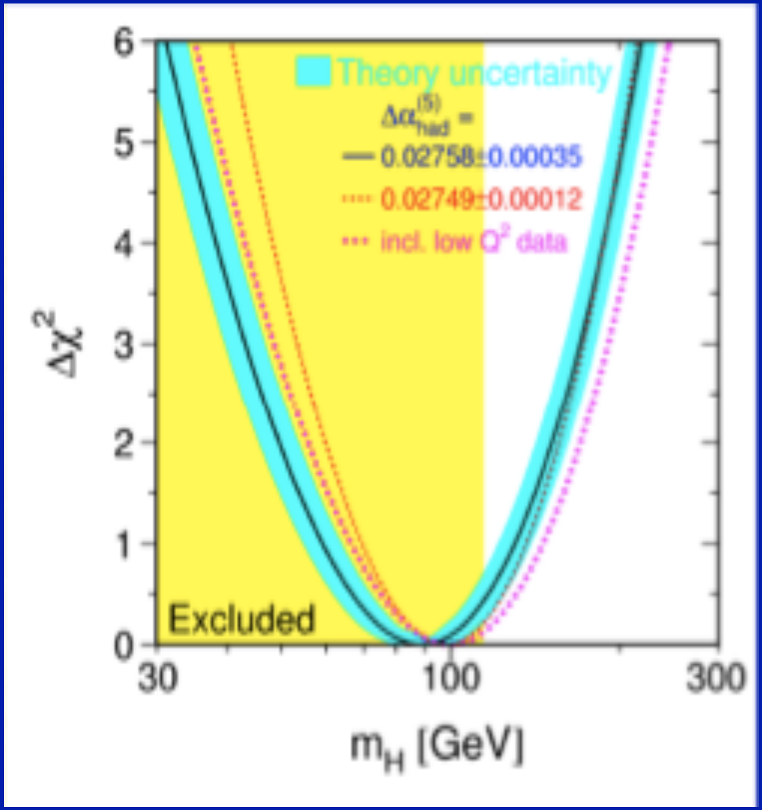
overlap:
SM is MSSM-like
MSSM is SM-like

SM band:
variation of $M_H^{SM}$

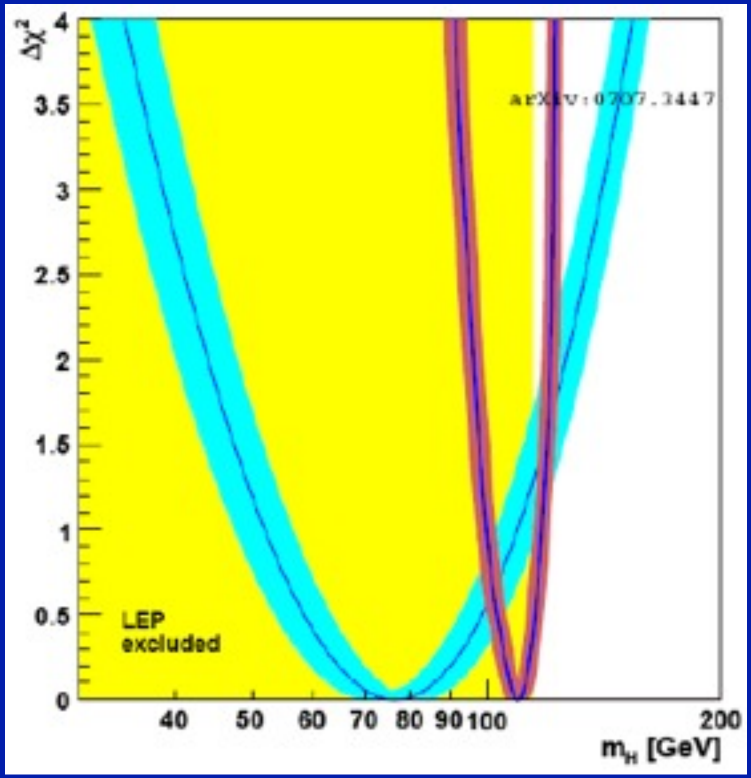
# The SM versus MSSM

## Fit for the Higgs Boson Mass

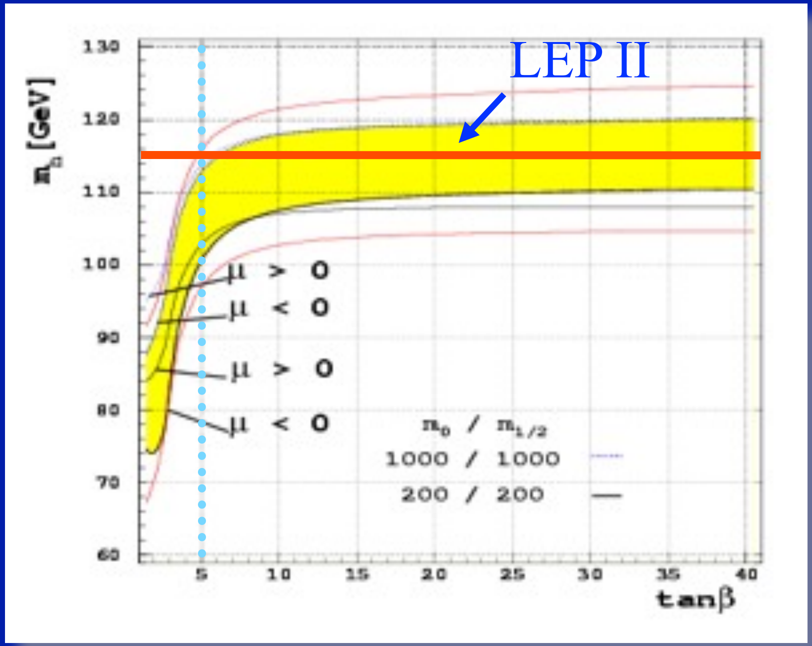
**SM**




**MSSM**



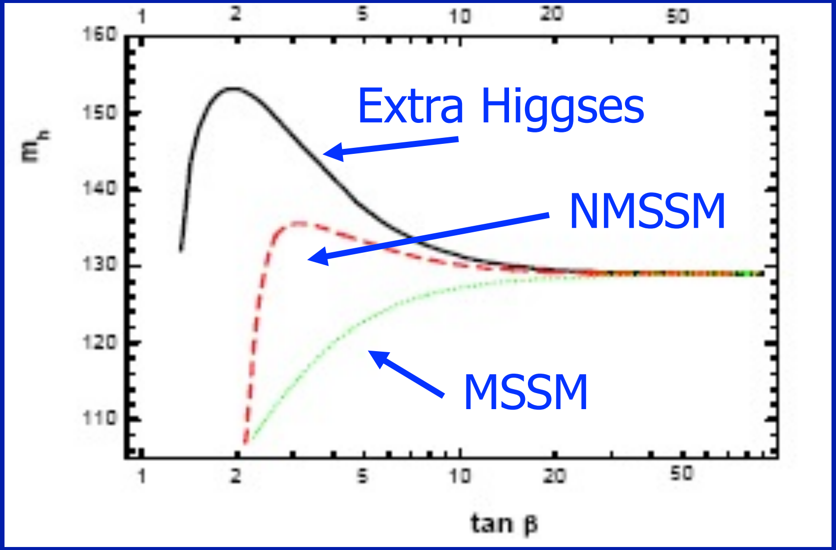
# The Higgs Mass Limit (MSSM)




- MSSM Higgs

$m_H \lesssim 130$ GeV

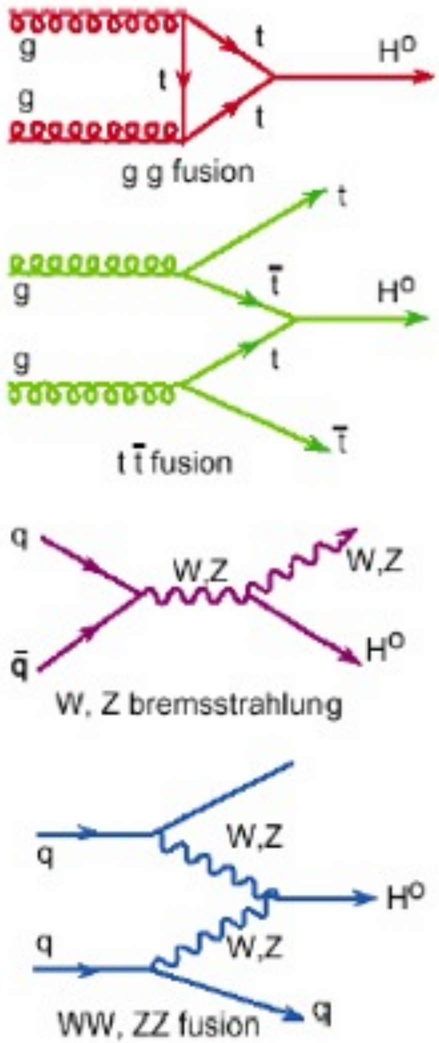
NMSSM →

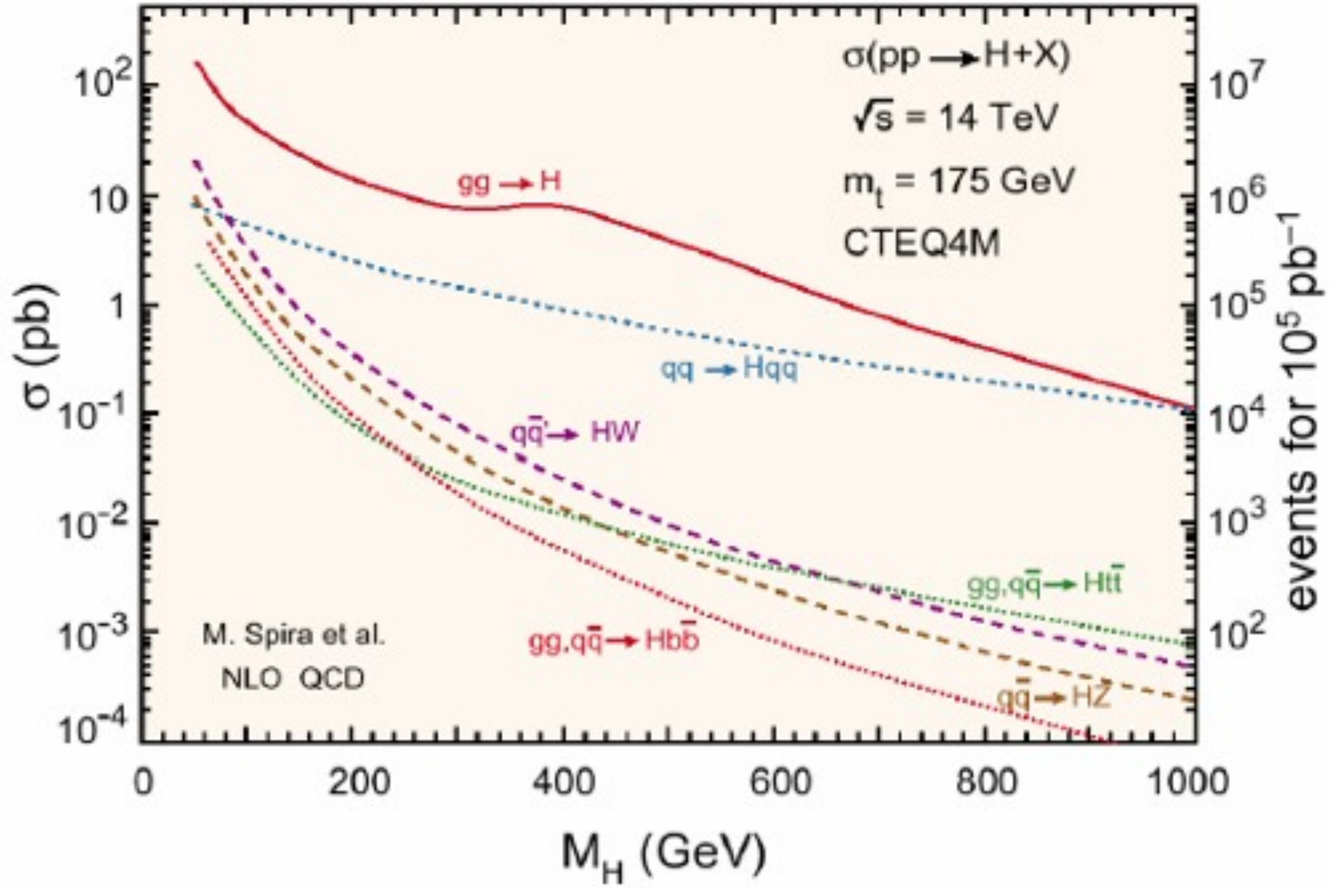



$$m_h^2 = M_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta + \ldots$$

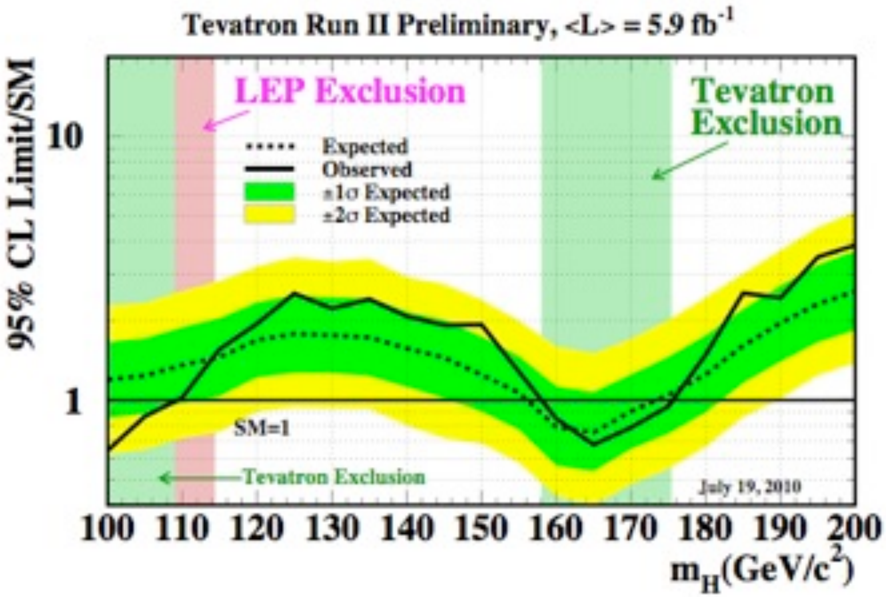
# Search for Higgs Boson at LHC

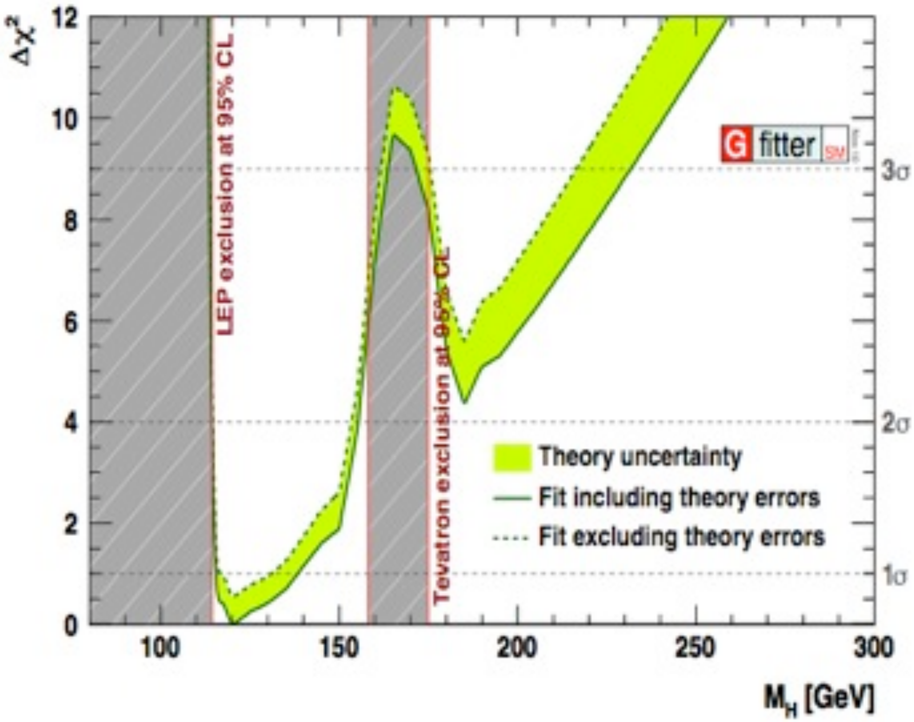
- Production mechanisms & cross section



# Tevatron Higgs Searches

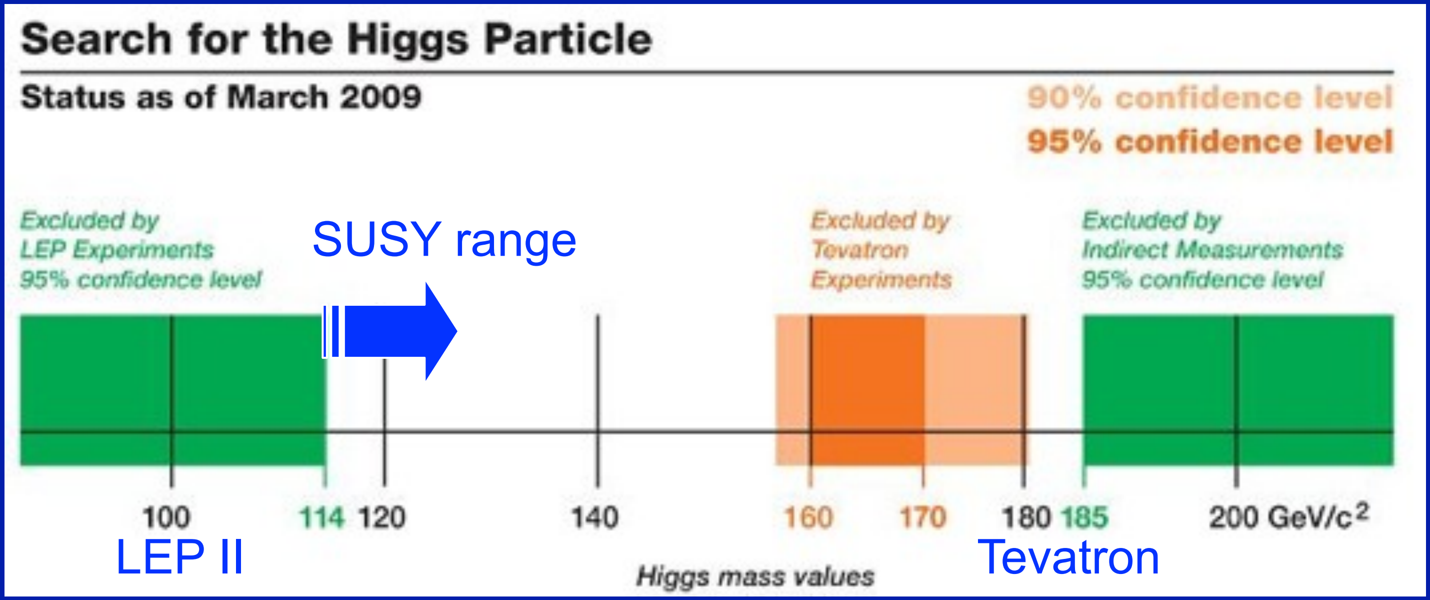


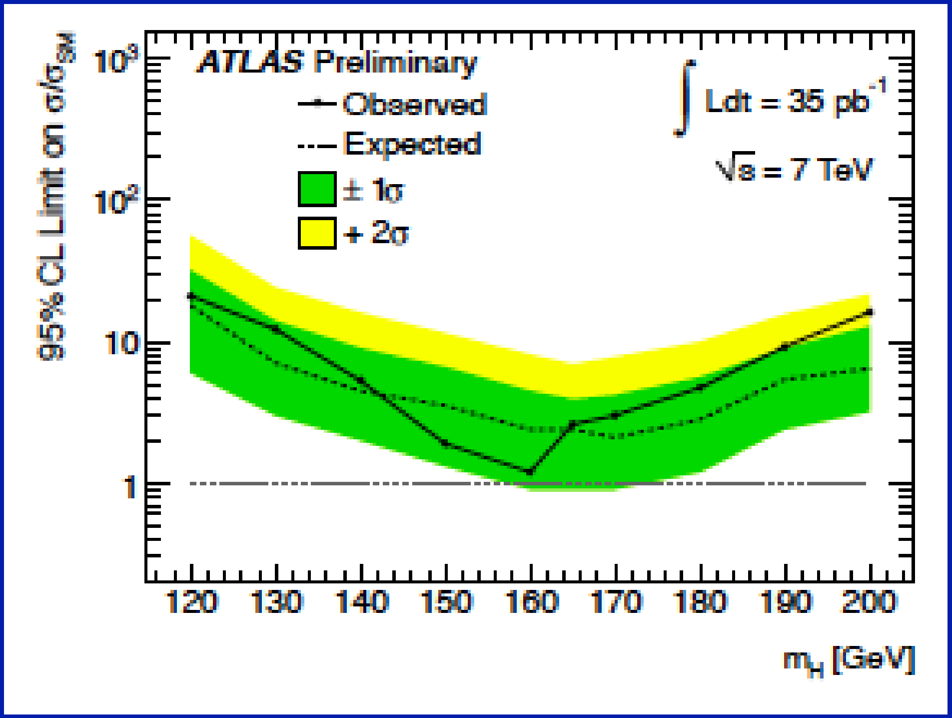

Tevatron seems to exclude the region 158< mH <175 GeV,
However large uncertainties in the calculation of the SM background does not allow to make definite statements

# Modern Higgs Window

(Direct Search)

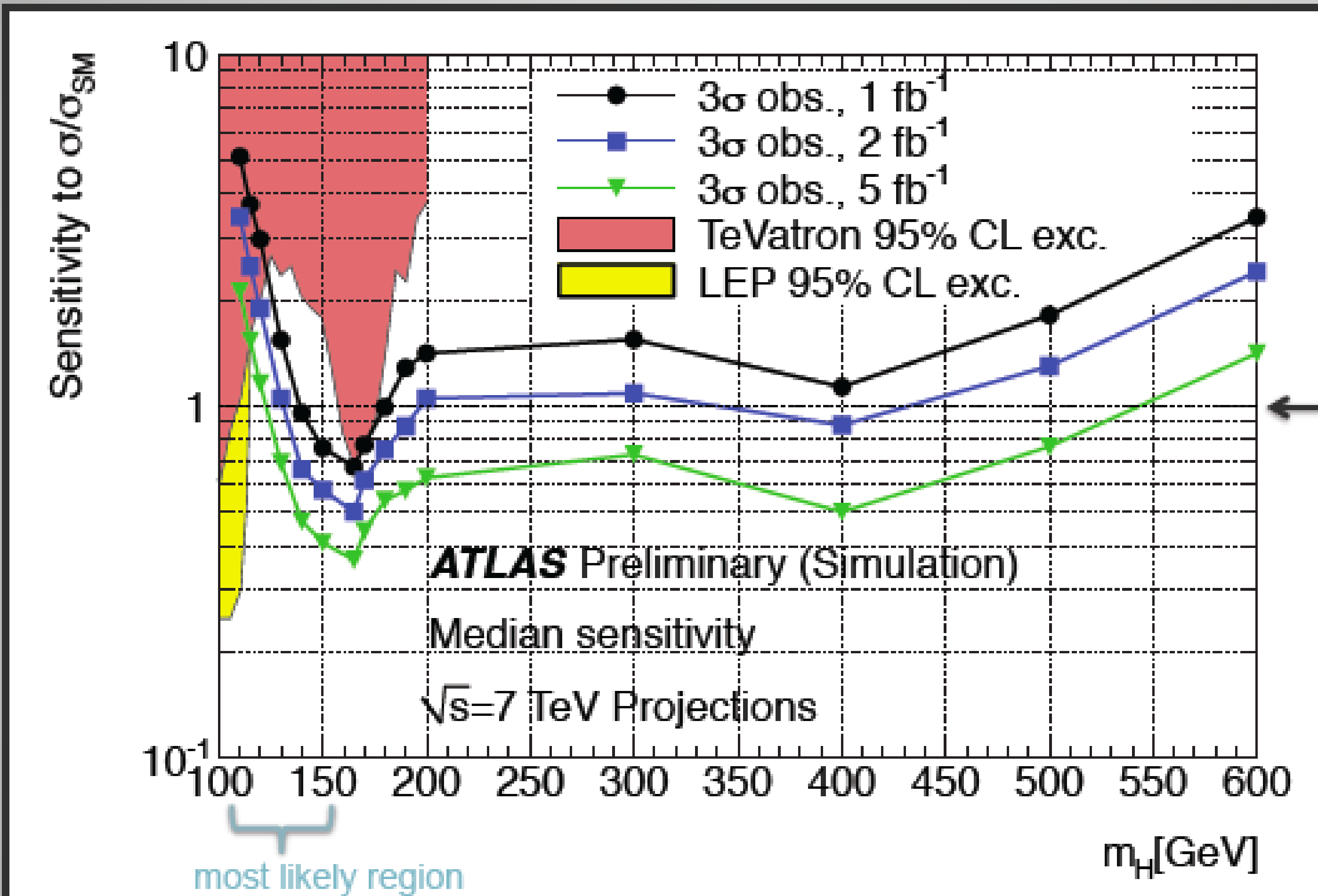


# LHC Higgs Searches




The first (negative) results from LHC at 35 pb^-1

# Higgs in 2011?



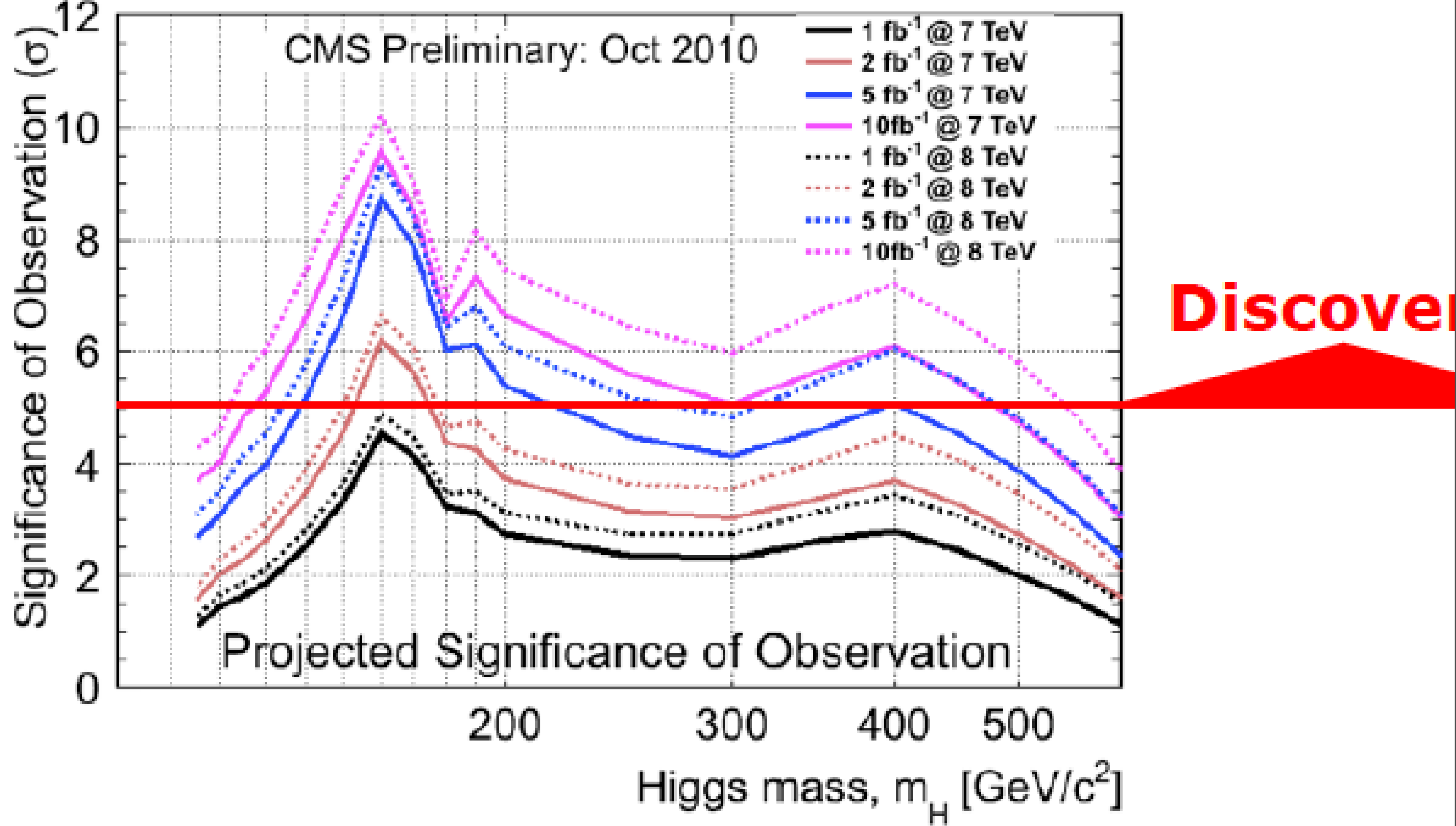

Need 5σ for *disco*

look at this lin

Improvements possible with further optimised analysis techniques

# Search for the Higgs Boson

***We don't know the mass of the Higgs Boson!***
***Evaluated the CMS discovery potential 2011 with the simulation***




**with 10fb$^{-1}$ @$\sqrt{s}$=8 TeV CMS can discover the Higgs Boson in the mass range ~115-600 GeV!**

# What if no Higgs boson is found?

Alrernative to the SM Higgs boson:

- Two-Higgs Doublet Models
- Inert Higgs Model
- Little Higgs Models
- Twin Higgs Model
- Gauge-Higgs Unification Models
- Higgsless Models

 Dynamical symmetry breaking without scalar fields

# Supersymmetry

# Superalgebra

*(Super) Algebra*

Lorentz Algebra

$$[P_\mu, P_\nu] = 0,\ [P_\mu, M_{\rho\sigma}] = i(g_{\mu\rho}P_\sigma - g_{\mu\sigma}P_\rho),$$

$$[M_{\mu\nu}, M_{\rho\sigma}] = i(g_{\nu\rho}M_{\mu\sigma} - g_{\nu\sigma}M_{\mu\rho} - g_{\mu\rho}M_{\nu\sigma} + g_{\mu\sigma}M_{\nu\rho}),$$

SUSY Algebra

$$[Q^i_\alpha, P_\mu] = [\bar{Q}^i_{\dot\alpha}, P_\mu] = 0,$$

$$[Q^i_\alpha, M_{\mu\nu}] = \tfrac{1}{2}(\sigma_{\mu\nu})^\beta_\alpha Q^i_\beta,\ [\bar{Q}^i_{\dot\alpha}, M_{\mu\nu}] = -\tfrac{1}{2}\bar{Q}^i_{\dot\beta}(\bar\sigma_{\mu\nu})^{\dot\beta}_{\dot\alpha},$$

$$\{Q^i_\alpha, \bar{Q}^j_{\dot\beta}\} = 2\delta^{ij}(\sigma^\mu)_{\alpha\dot\beta}P_\mu$$

$$\alpha, \dot\alpha, \beta, \dot\beta = 1,2;\ i, j = 1,2,\ldots,N.$$

The only possible graded Lie algebra that mixes integer and half-integer spins and changes statistics

*Superspace*

$$x_\mu \ ® \ x_\mu, \theta_\alpha, \bar\theta_{\dot\alpha}$$

Grassmannian parameters

$$\alpha, \dot\alpha = 1,2$$

$$\vartheta^2_\alpha = 0,\ \bar\vartheta^2_{\dot\alpha} = 0$$

SUSY Generators

$$Q_\alpha = \frac{\partial}{\partial\vartheta_\alpha} - i\sigma^\mu_{\alpha\dot\alpha}\bar\theta^{\dot\alpha}\partial_\mu$$

$$\bar{Q}_{\dot\alpha} = -\frac{\partial}{\partial\bar\vartheta_{\dot\alpha}} + i\theta_\alpha\sigma^\mu_{\alpha\dot\alpha}\partial_\mu$$

$$Q^2_\alpha = 0,\ \bar{Q}^2_{\dot\alpha} = 0$$

*Supertranslation*

$$x_\mu \to x_\mu + i\theta\sigma_\mu\bar\xi - i\xi\sigma_\mu\bar\theta,$$

$$\theta \to \theta + \xi,$$

$$\bar\theta \to \bar\theta + \bar\xi$$

# Why SUSY ?

Maxwell ED

Local gauge invariance $\partial_\mu \to D_\mu = \partial_\mu + A_\mu$ $\longrightarrow$ Vector field

Covariant derivative

Einstein GR

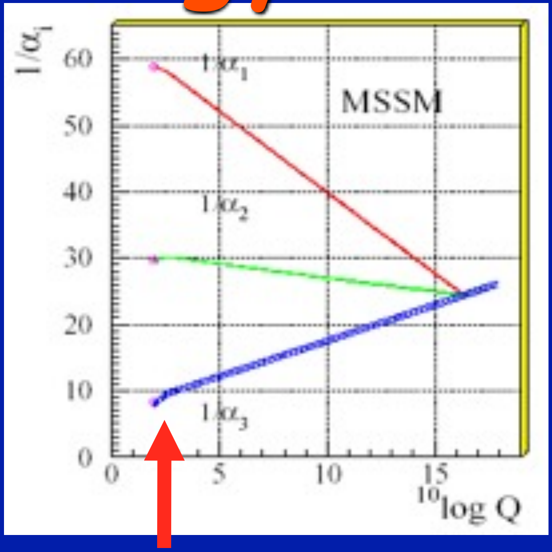
Local SUSY $\longrightarrow$ Local coordinate transf $\longrightarrow$ graviton

$$x_\mu \to x_\mu + i\theta\sigma_\mu\bar{\xi} - i\xi\sigma_\mu\bar{\theta},$$

# Why Low-energy SUSY ?

- Gauge coupling unification

$$M_{SUSY} \sim TeV$$




Change of the slope at the scale

$$M_{SUSY} \sim TeV$$

# Why SUSY ?

Maxwell ED

Local gauge invariance $\partial_\mu \to D_\mu = \partial_\mu + A_\mu$ $\longrightarrow$ Vector field

Covariant derivative

Einstein GR

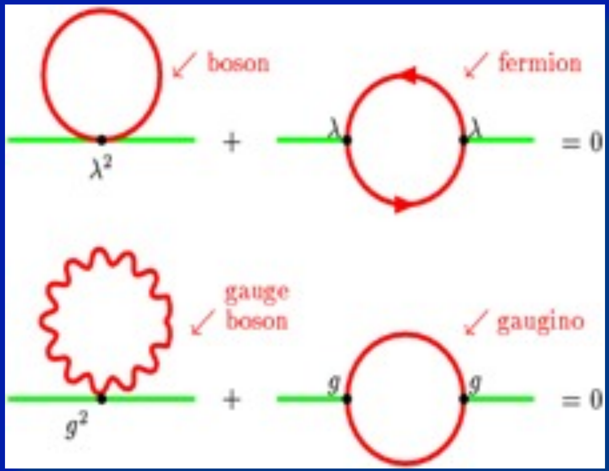
Local SUSY $\longrightarrow$ Local coordinate transf $\longrightarrow$ graviton

$$x_\mu \to x_\mu + i\theta\sigma_\mu\bar{\xi} - i\xi\sigma_\mu\bar{\theta},$$

# Why Low-energy SUSY ?

- Hierarchy problem

$$M_{SUSY} \sim TeV$$




Mass stabilization

If $gM_{SUSY} \sim M_W$

# Simplest (N=1) SUSY Multiplets

Bosons and Fermions come in pairs

$$(\varphi, \psi) \qquad (\lambda, A_\mu) \qquad (\tilde{g}, g)$$

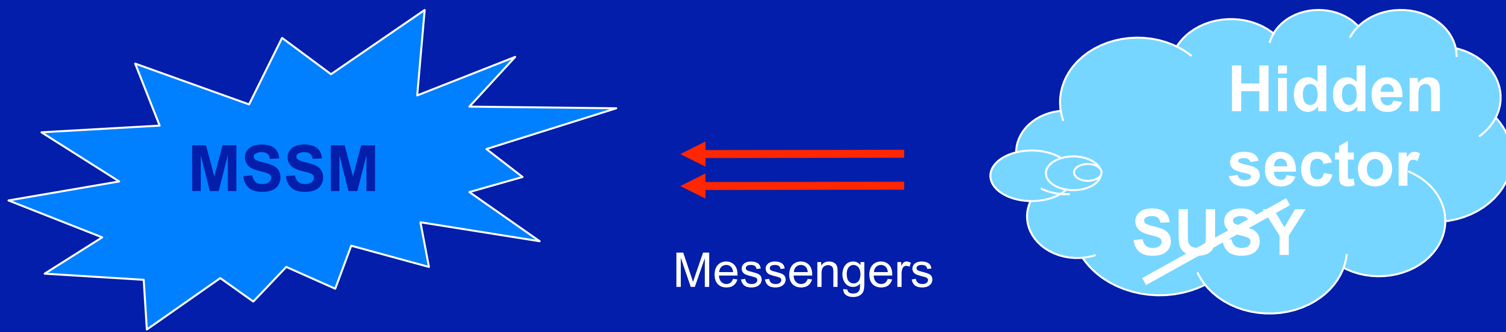
Spin 0 Spin 1/2 Spin 1/2 Spin 1 Spin 3/2 Spin 2

scalar chiral fermion majorana fermion vector gravitino graviton

# Particle Content of the MSSM

| Superfield | | Bosons | | Fermions | $SU_c(3)$ | $SU_L(2)$ | $U_Y(1)$ |
|---|---|---|---|---|---|---|---|
| *Gauge* | | | | | | | |
| $G^a$ | | gluon $g^a$ | gluino | $\tilde{g}^a$ | 8 | 1 | 0 |
| $V^k$ | | Weak $W^k(W^\pm, Z)$ | wino, zino | $\tilde{w}^k(\tilde{w}^\pm, \tilde{z})$ | 1 | 3 | 0 |
| $V'$ | | Hypercharge $B(\gamma)$ | bino | $\tilde{b}(\tilde{\gamma})$ | 1 | 1 | 0 |
| *Matter* | | | | | | | |
| $L_i$ | sleptons | $\tilde{L}_i = (\tilde{\nu}, \tilde{e})_L$ | leptons | $L_i = (\nu, e)_L$ | 1 | 2 | –1 |
| $E_i$ | sleptons | $\tilde{E}_i = \tilde{e}_R$ | leptons | $E_i = e_R$ | 1 | 1 | 2 |
| $Q_i$ | squarks | $\tilde{Q}_i = (\tilde{u}, \tilde{d})_L$ | quarks | $Q_i = (u, d)_L$ | 3 | 2 | 1/3 |
| $U_i$ | squarks | $\tilde{U}_i = \tilde{u}_R$ | quarks | $U_i = u_R^c$ | $3^*$ | 1 | –4/3 |
| $D_i$ | squarks | $\tilde{D}_i = \tilde{d}_R$ | quarks | $D_i = d_R^c$ | $3^*$ | 1 | 2/3 |
| *Higgs* | | | | | | | |
| $H_1$ | Higgses | $H_1$ | higgsinos | $\tilde{H}_1$ | 1 | 2 | –1 |
| $H_2$ | Higgses | $H_2$ | higgsinos | $\tilde{H}_2$ | 1 | 2 | 1 |

# Soft SUSY Breaking




Gravitons, gauge, gauginos, etc

Breaking via F and D terms in a hidden sector

$$-L_{Soft} = \sum_{\alpha} M_i \widetilde{\lambda}_i \widetilde{\lambda}_i + \sum_i m_{0i}^2 \, | A_i |^2 + + \sum_{ijk} \mathrm{A}_{ijk} A_i A_j A_k + \sum_{ij} \mathrm{B}_{ij} A_i A_j$$

gauginos — scalar fields

Over 100 of free parameters !

# MSSM Parameter Space

- Three gauge couplings
- Three (four) Yukawa matrices
- The Higgs mixing parameter
- Soft SUSY breaking terms

**mSUGRA** Universality hypothesis (gravity is colour and flavour blind): Soft parameters are equal at Planck (GUT) scale

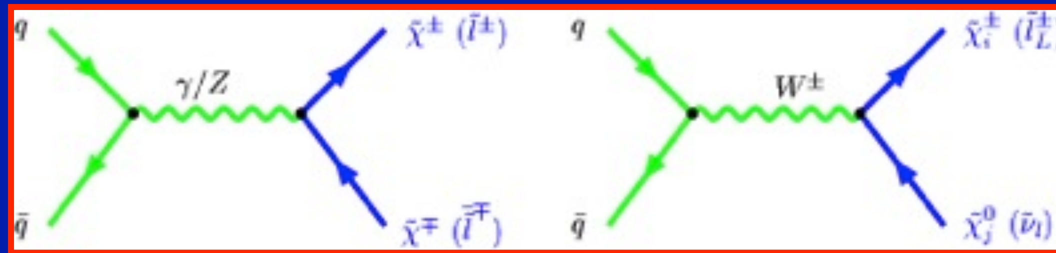
$$-L_{Soft} = A\{y_t Q_L H_2 U_R + y_b Q_L H_1 D_R + y_L L_L H_1 E_R\} + B\mu H_1 H_2 + m_0^2 \sum_i |\varphi_i|^2 + \tfrac{1}{2} M_{1/2} \sum_\alpha \widetilde{\lambda_\alpha} \widetilde{\lambda_\alpha}$$

Parameters $A,\ m_0,\ M_{1/2},\ B \leftrightarrow \tan\beta = v_2 / v_1$ and $\mu$

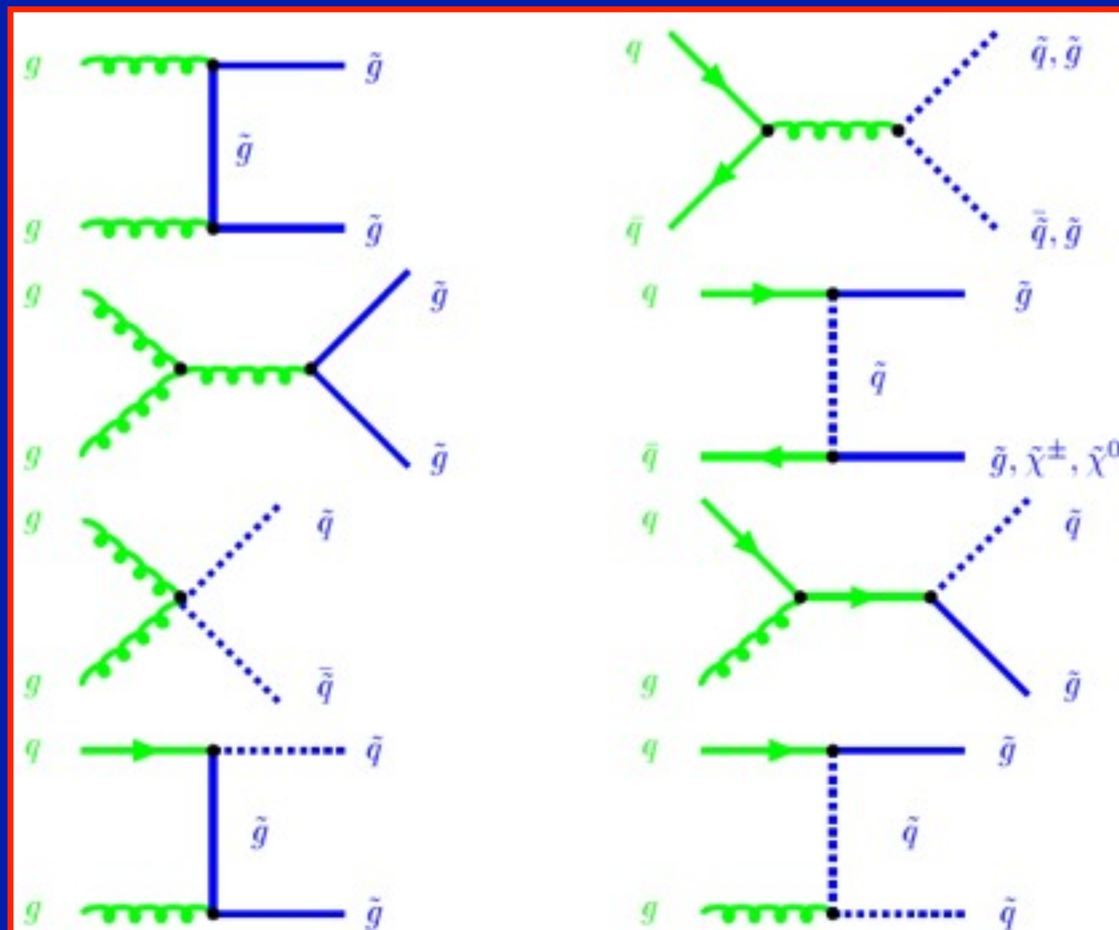
versus $m$ and $\lambda$ in the SM

# Superpartners Production at LHC

Annihilation

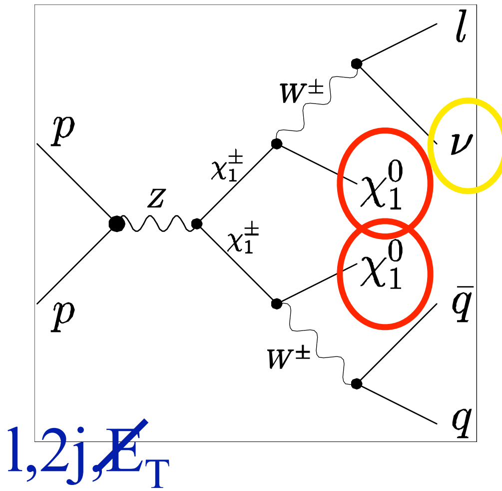


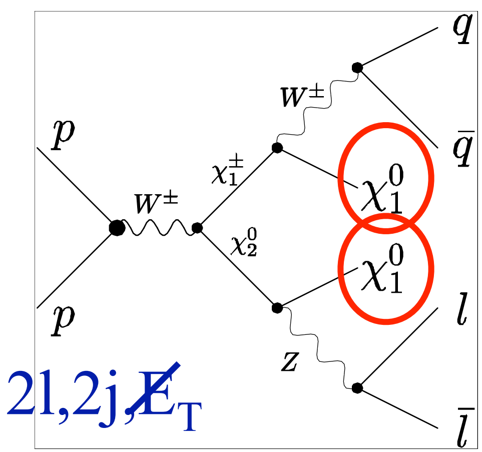

Quark- gluon Fusion

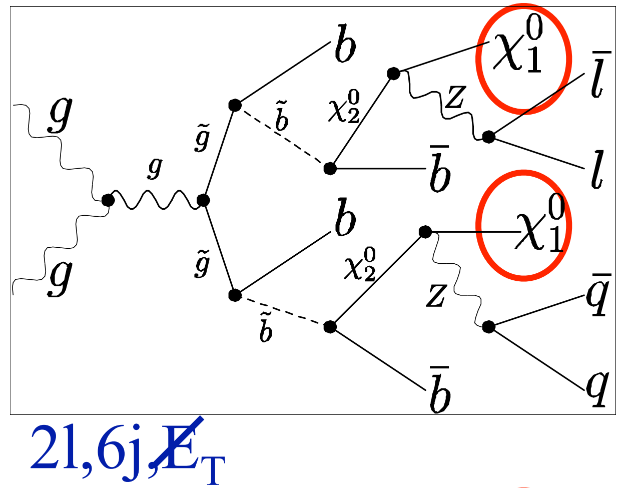


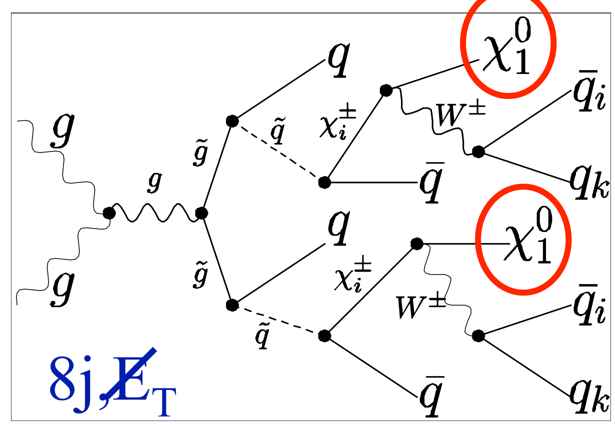
# Creation and Decay of Superpartners in Cascade Processes @ LHC

weak int's



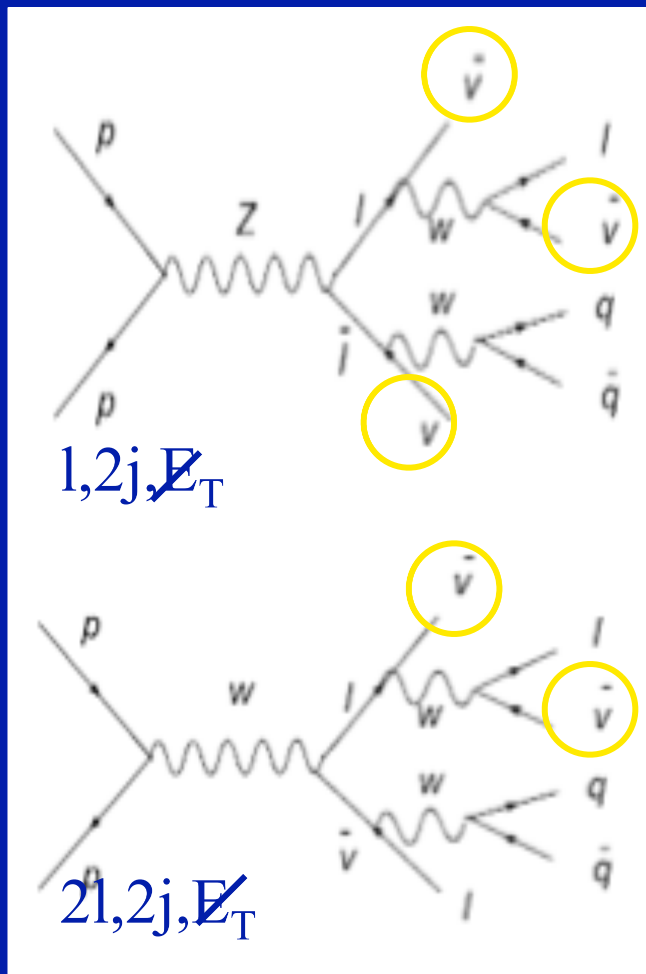



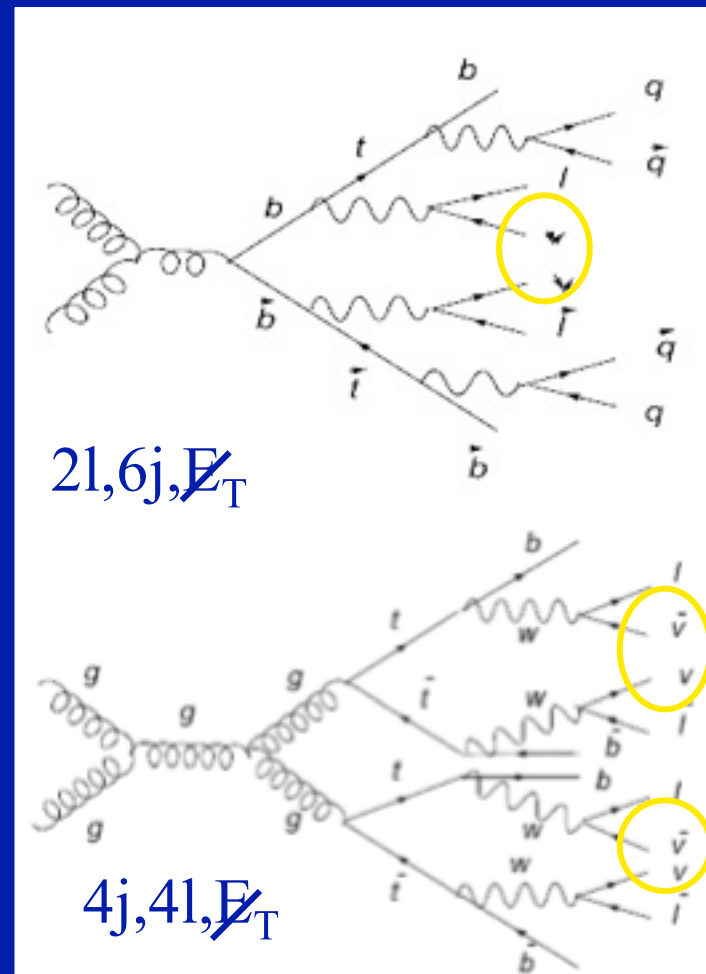

strong int's

Typical SUSY signature: Missing Energy and Transverse Momentum

# Background Processes of the SM for creation of Superpartners

weak int's

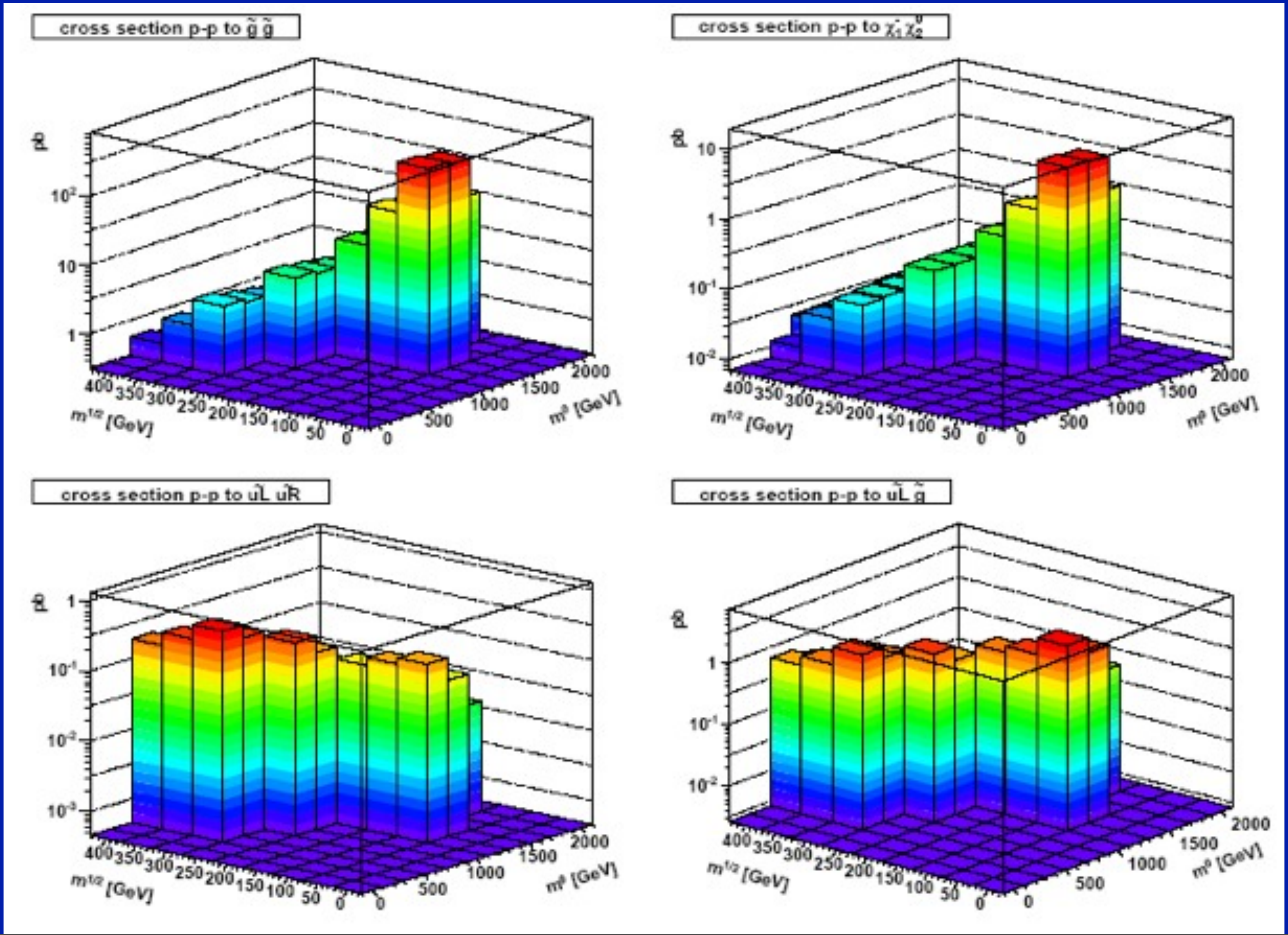


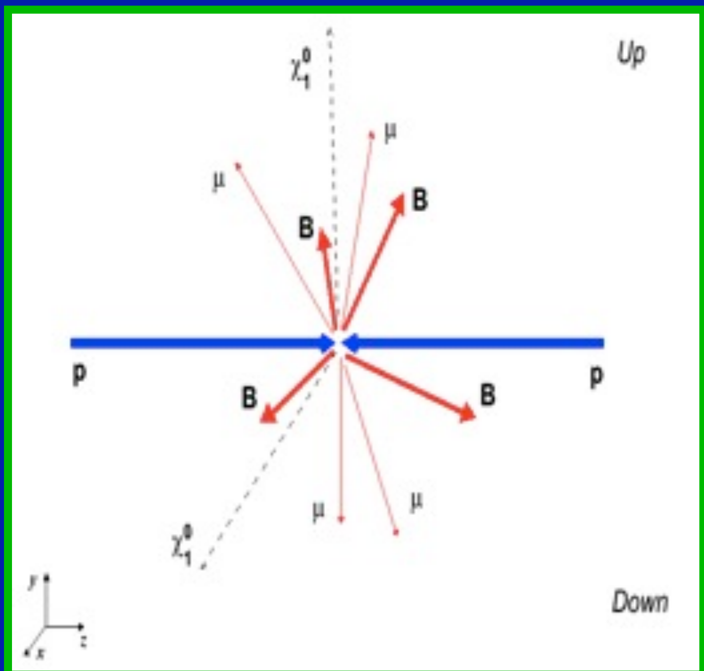

strong int's

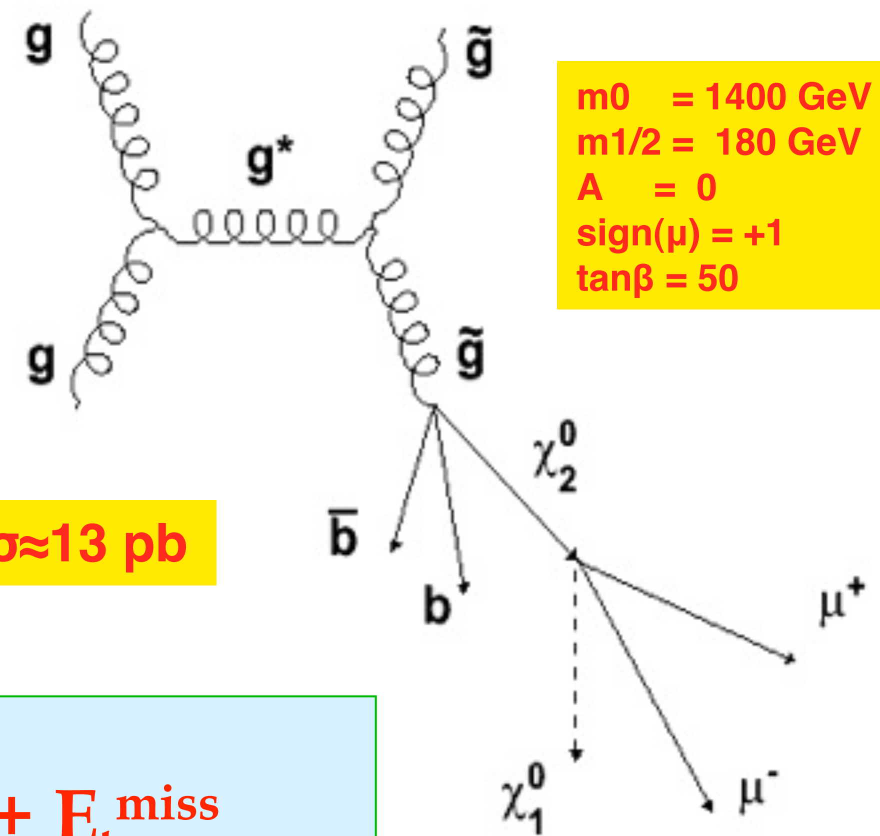
The x-sections are usually much smaller than for creation of SUSY

# Cross-sections for SUSY creation



# Creation of Gluino @ LHC




m0 = 1400 GeV
m1/2 = 180 GeV
A = 0
sign(μ) = +1
tanβ = 50

$\sigma \approx 13$ pb

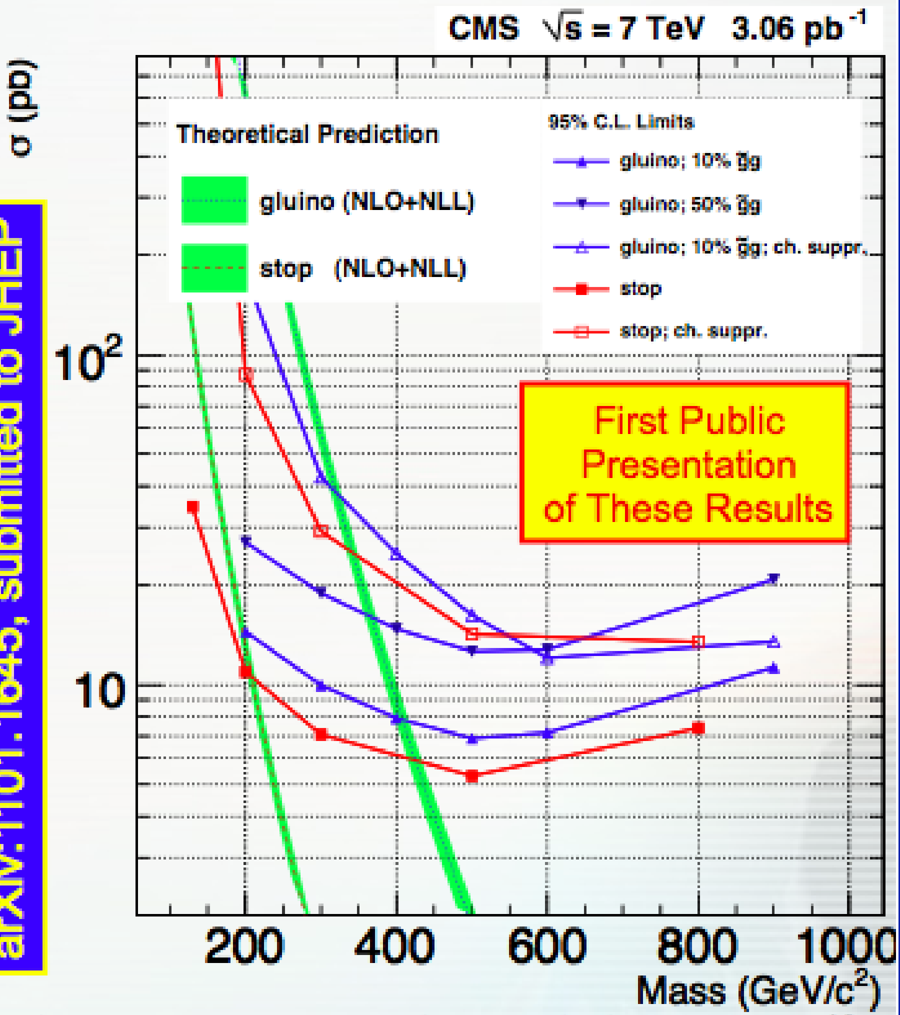
**Signature:**
4 b-jets + 4 muons + $E_t^{miss}$

Large!

# Search for Gluinos and Stops

- Tight sample is picked to have very low background (discovery optimization), optimal for low-statistics dataset
  - B = 0.025 ± 0.004 (0.074 ± 0.011) events for μ+Tr (Tr-only)
- Use tracker-only analysis for the charge suppression scenario (R-hadron emerges as a neutral object); μ+Tr for the other ones
- Set limits on the gluino mass of 357-398 GeV for the fraction f of gg hadronization between 0.5 and 0.1 (μ+Tr)
  - In the charge suppression scenario, the limit is 311 GeV (for f = 0.1)
  - These are the most restrictive limits to date
- The analogous stop limit is 202 GeV - still a bit below the Tevatron's 249 GeV limit

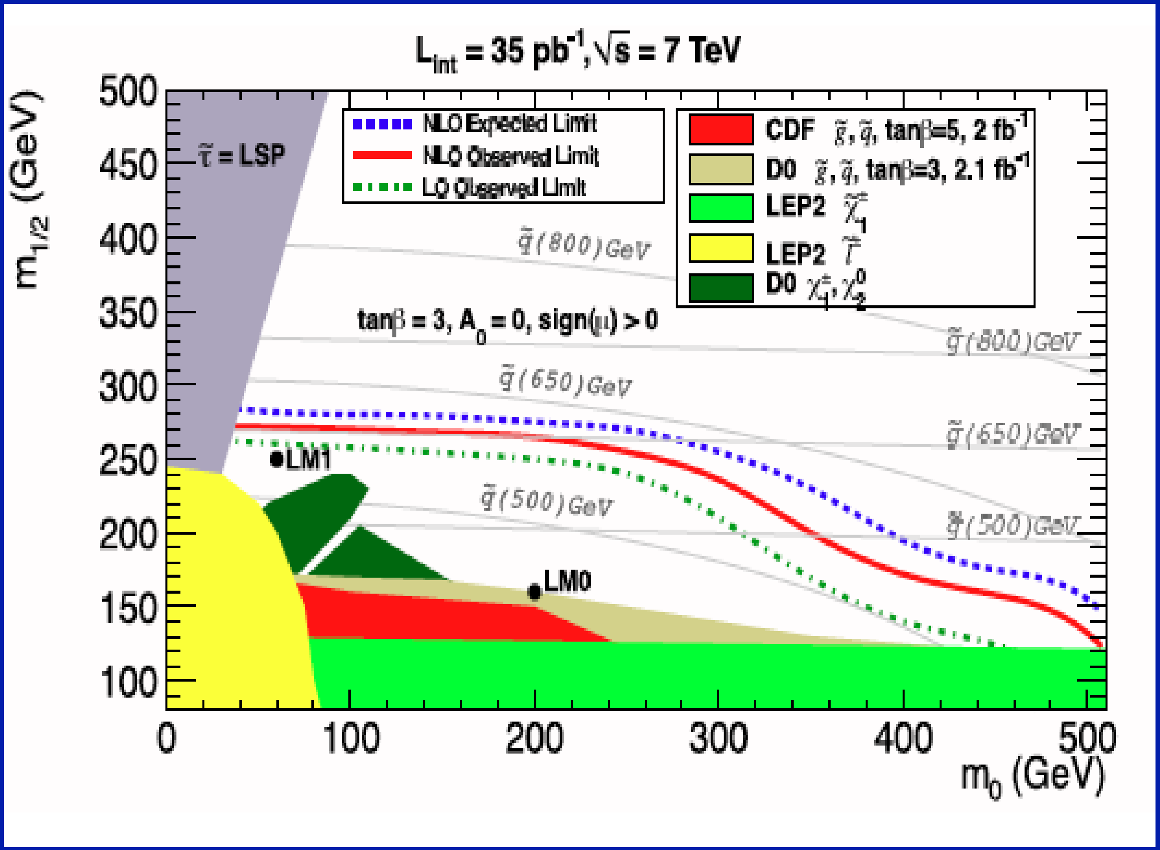
arXiv:1101.1645, submitted to JHEP



# First SUSY results @ LHC

Search for high-mass squark and gluino production in events with large missing transverse energy and two or more jets

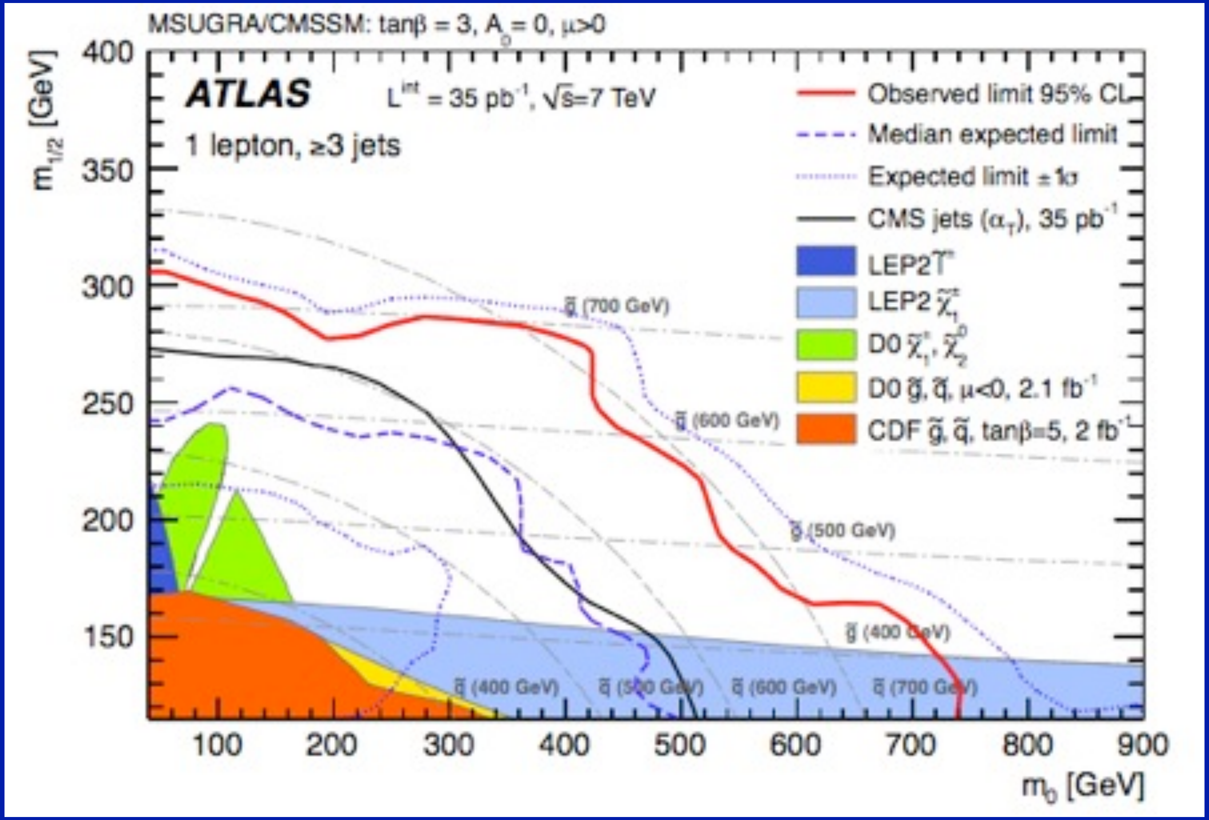
**CMS**




Expanded the excluded range established during
The last 20 years (!) by factor of two with only 35 pb^-1

# First SUSY results @ LHC

ATLAS




Search for lepton + jets + missing transverse energy with 35 pb^-1

# What if no SUSY is found?

-  Very exotic scenario is realized (doubtful)
-  Susy threashold is above few TeV

(no gauge coupling unification, hierarchy problem
needs fine-tuning)

-  Susy breaking pattern has to be changed
(most questionable part of the MSSM)

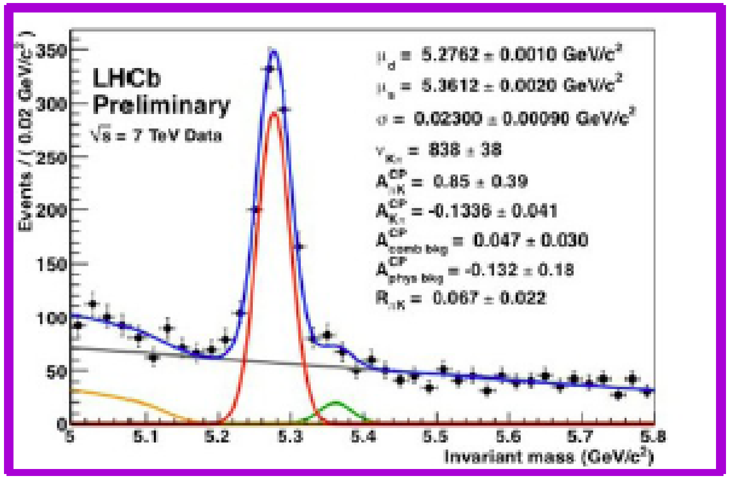
-  MSSM is not the right model (what else?)

-  Susy is not the right way (tell me what is better)

# B-physics/CP

# Evidence for CP violation in B-system in first data ?

$B_d^0 \to K\pi$ &
$B_s^0 \to K\pi$




$B_s^0/B_d^0$ yield = (10.7±2.0)%,

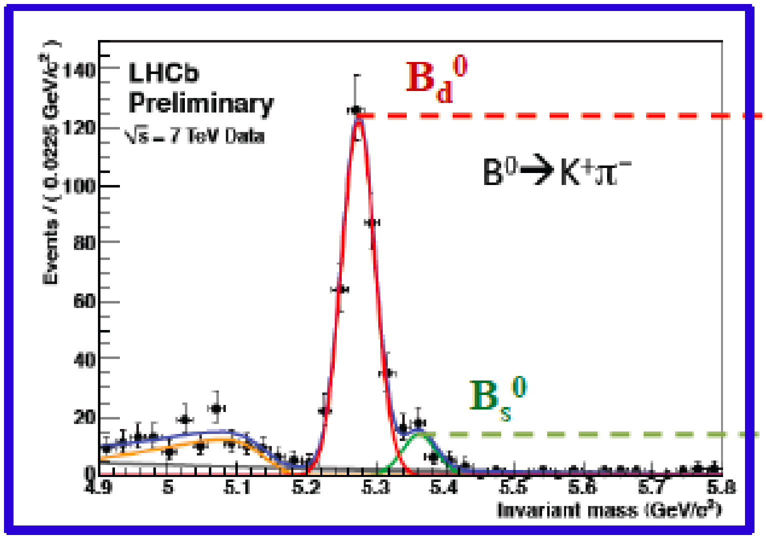
$A_{CP}(B_d^0)$=-0.134±0.041
(HFAG: -0.098±0.012)

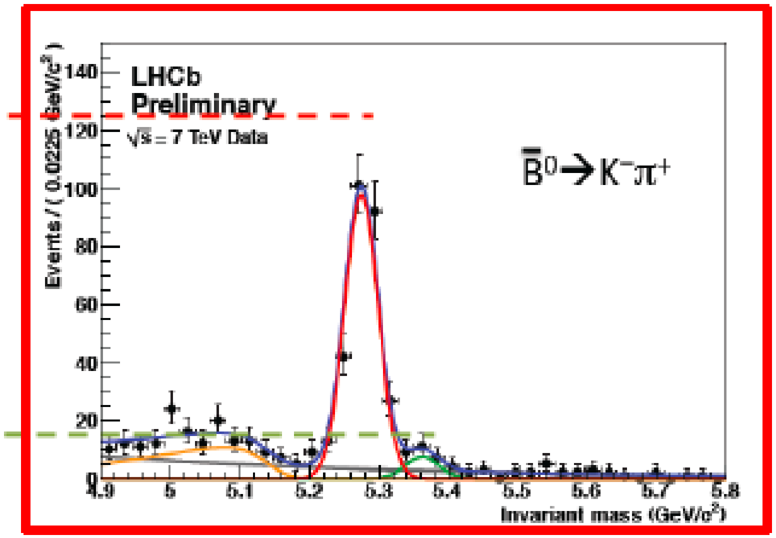
$A_{CP}(B_s^0)$=-0.43±0.17
(CDF: 0.39±0.15±0.08 in 1 $fb^{-1}$)

- only raw asymmetries
- not accounted for production & detector asymmetries
- ➢ this is not a physics result yet!

CP violation →
particle and anti-particle behave differently!

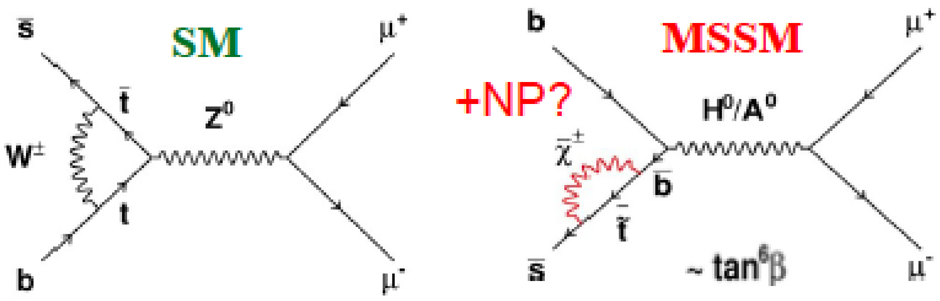
$B^0$ $\bar{B}^0$



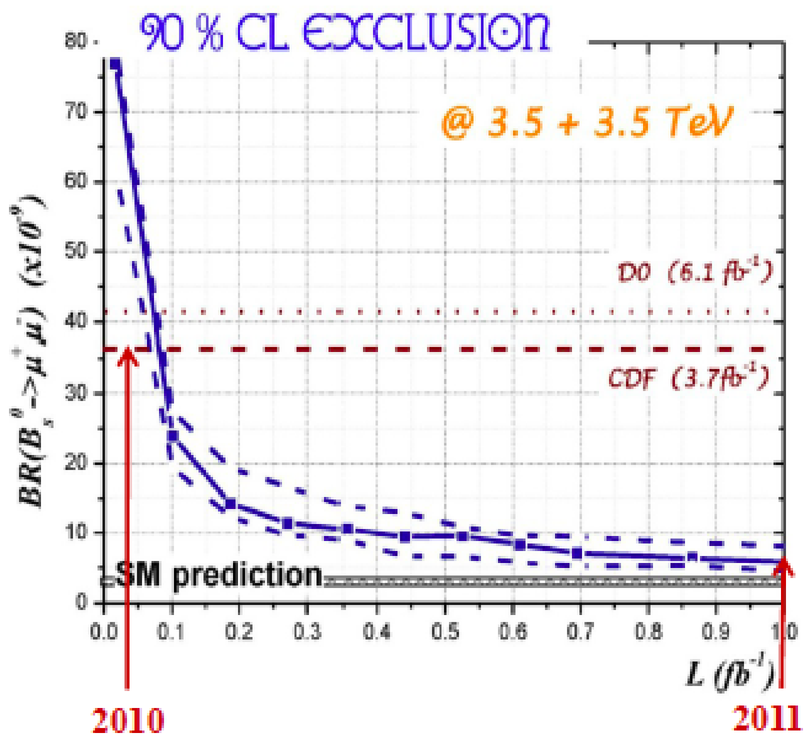



# Probing New Physics in loop decays: $B_s \to \mu\mu$

$B_s \to \mu\mu$ : the **super** rare loop decay




$BR = (3.2 \pm 0.2)\times\mathbf{10^{-9}}$ in SM

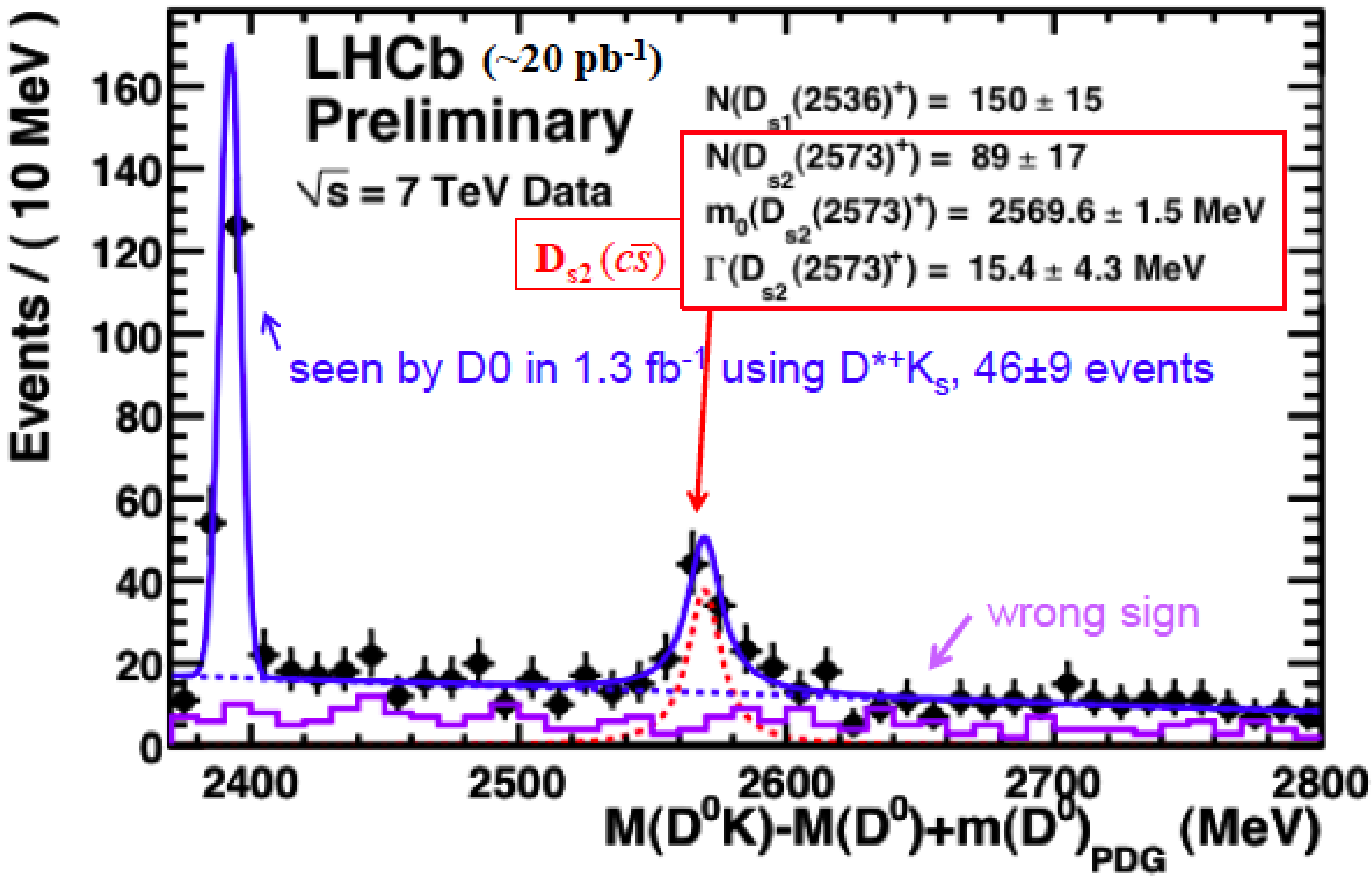




- ✓ sensitive to New Physics, can be strongly enhanced in SUSY with scalar Higgs exchange
- ✓ sensitive probe for MSSM with large tanβ: $B(B_S\to\mu^+\mu^-) \sim \tan\beta^{\,6} / M_A^{\,4}$

- ✓ analysis of 2010 data well advanced, "un-blinding" for winter conferences!
- ➢ expect competitive result with best world measurements, with this years data set
- ➢ potential to discover New Physics down to the SM predictions with next year's data

# First observation of new semileptonic $B_s^0$ decay

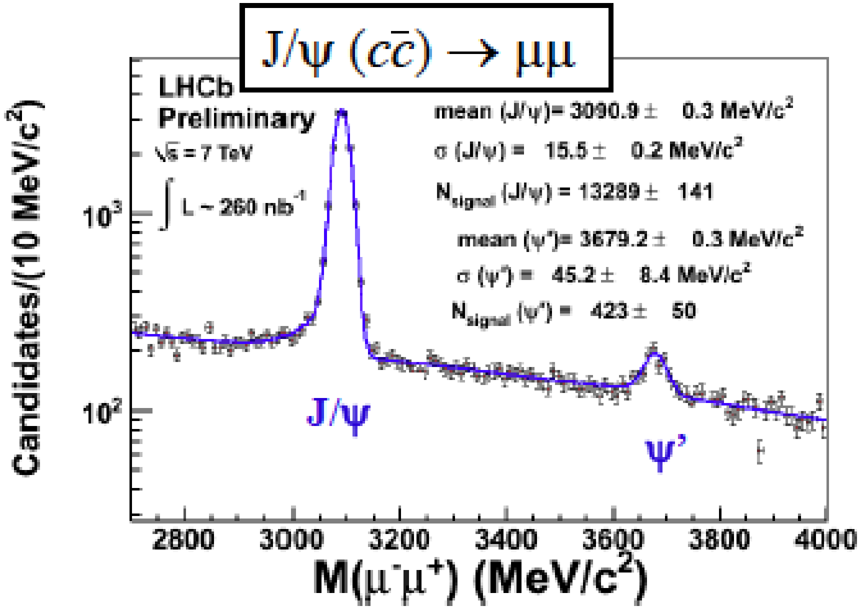
First observation of $B_s \rightarrow D_{s2} X \mu \nu$ with $D_{s2} \rightarrow D^0 K^+$

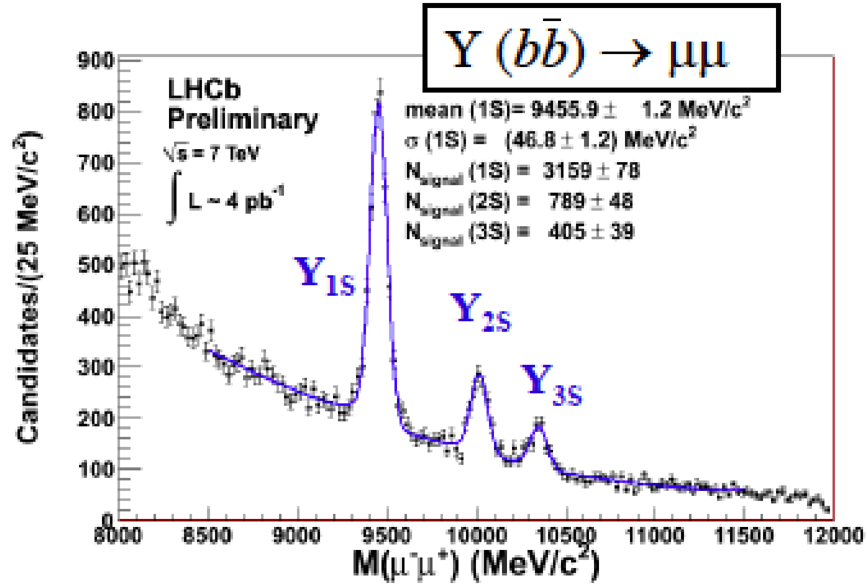


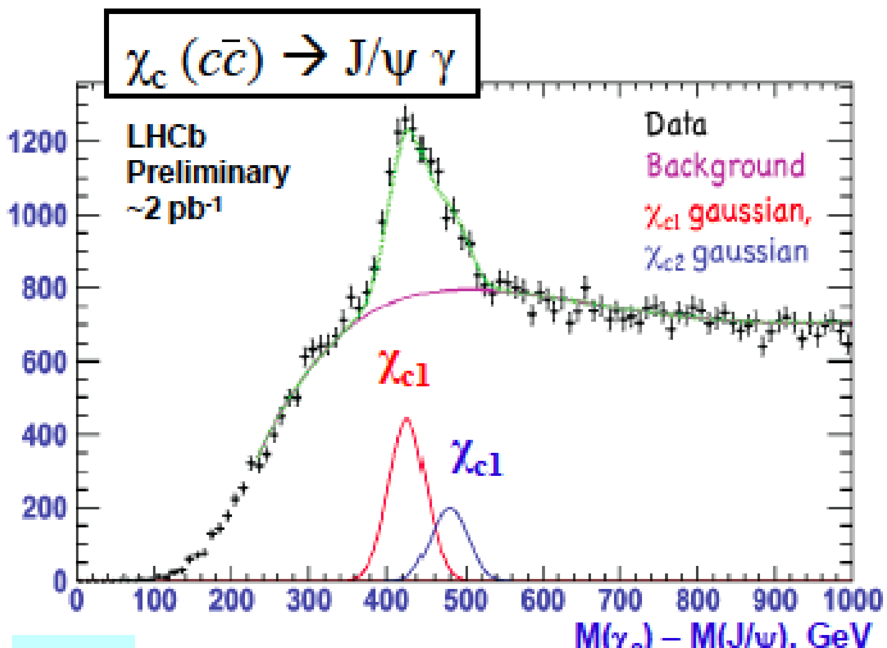

➤ and more first observations in the pipeline… !

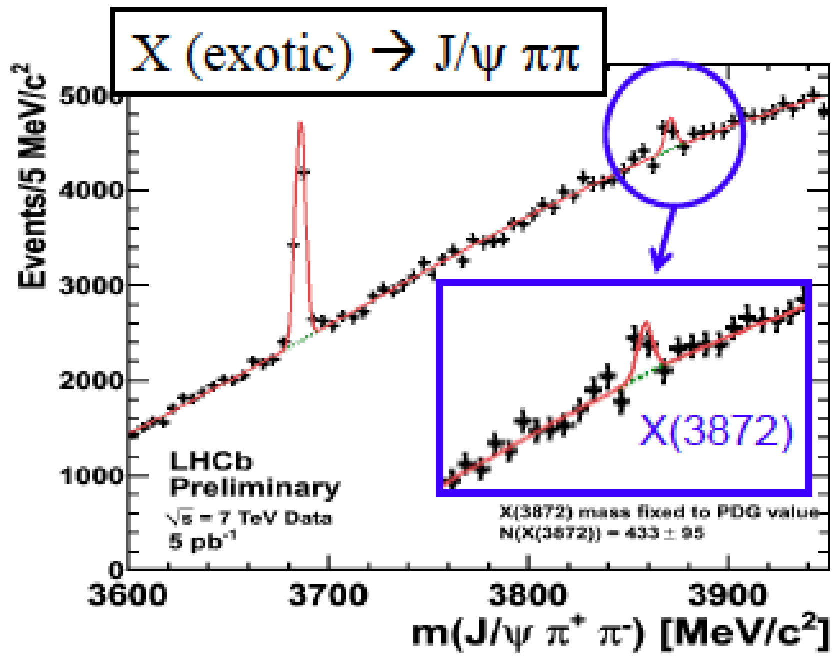
# Spectroscopy

# Spectroscopy of mesons ($q\bar{q}$)



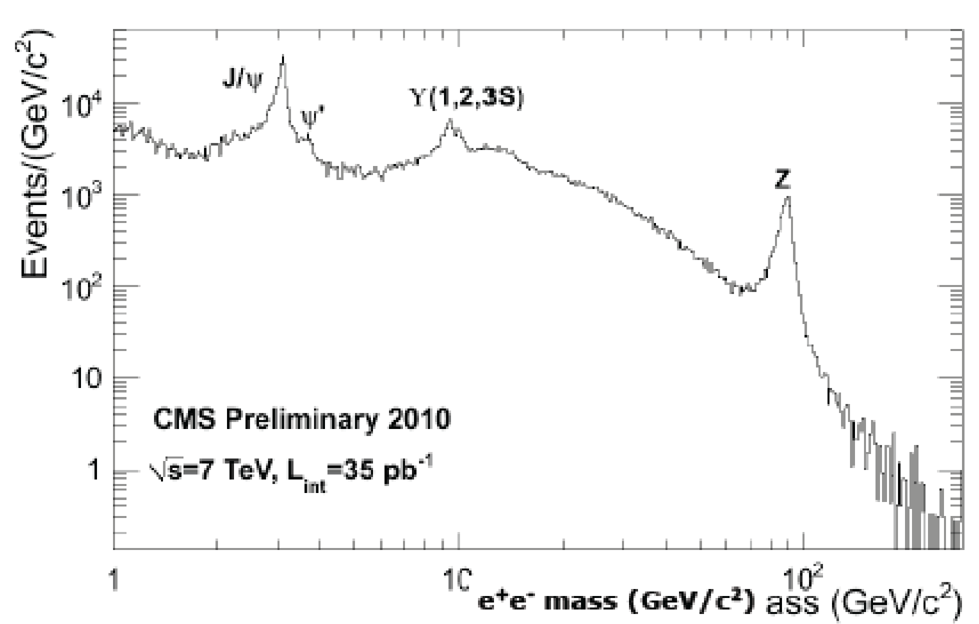



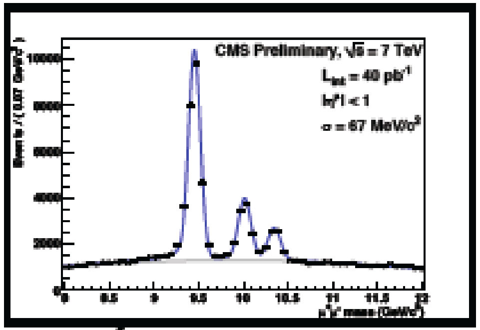



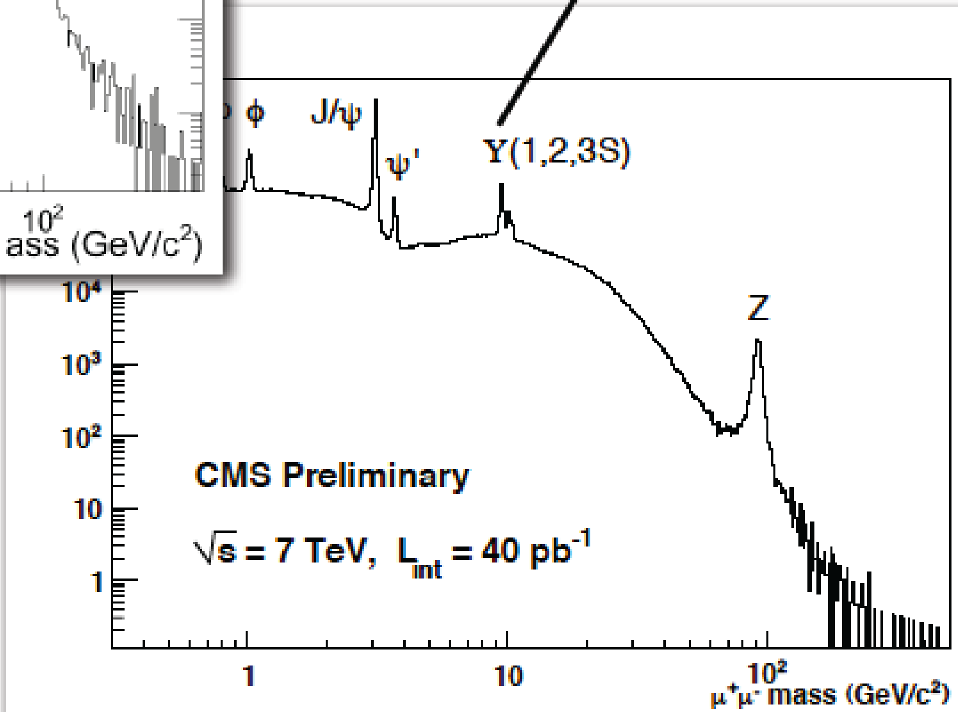



# Di-Lepton Spectra

## Di-Electron and Di-Muon Spectra

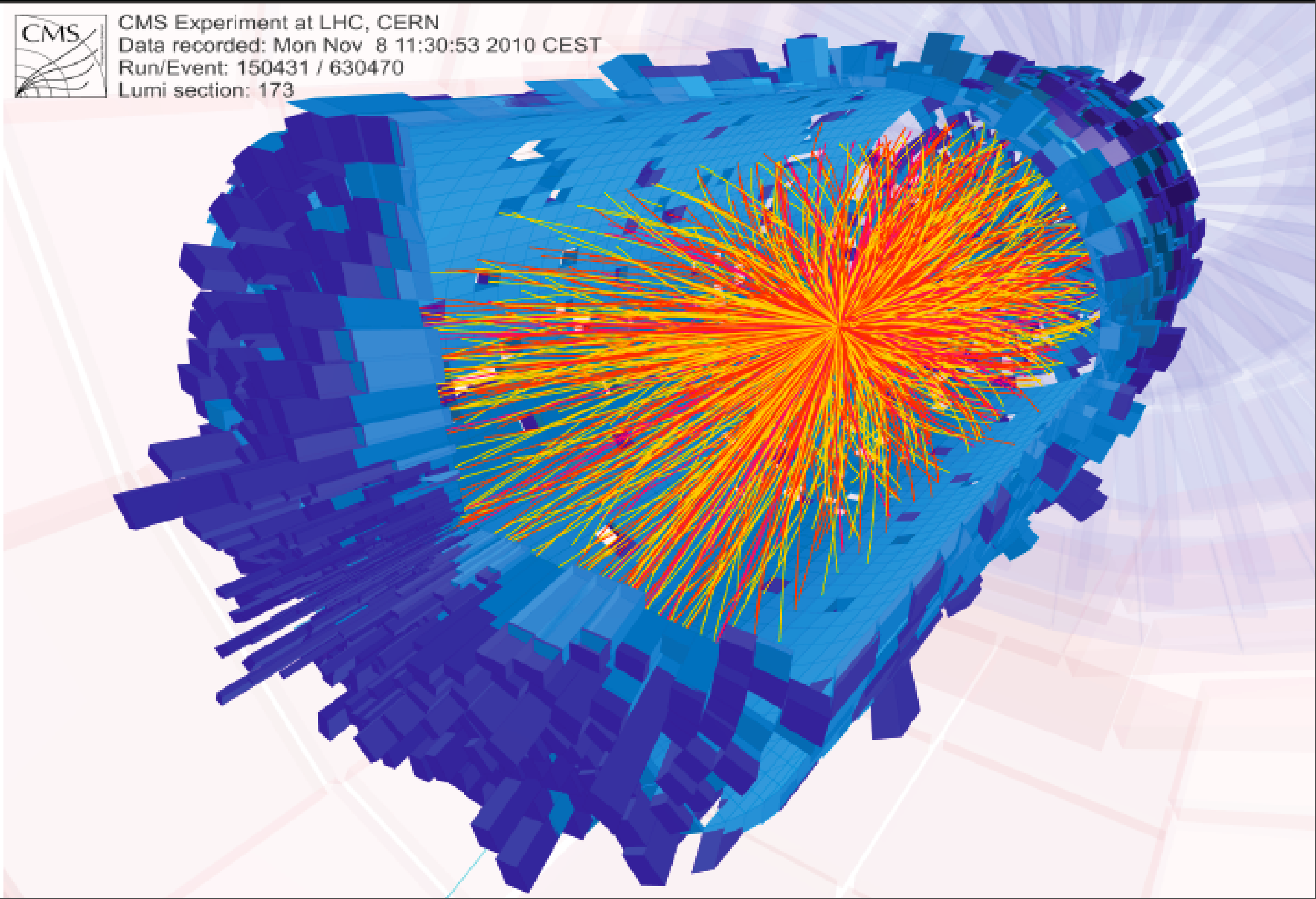



High-Resolution Electron & Muon Reconstruction over full kinematic range

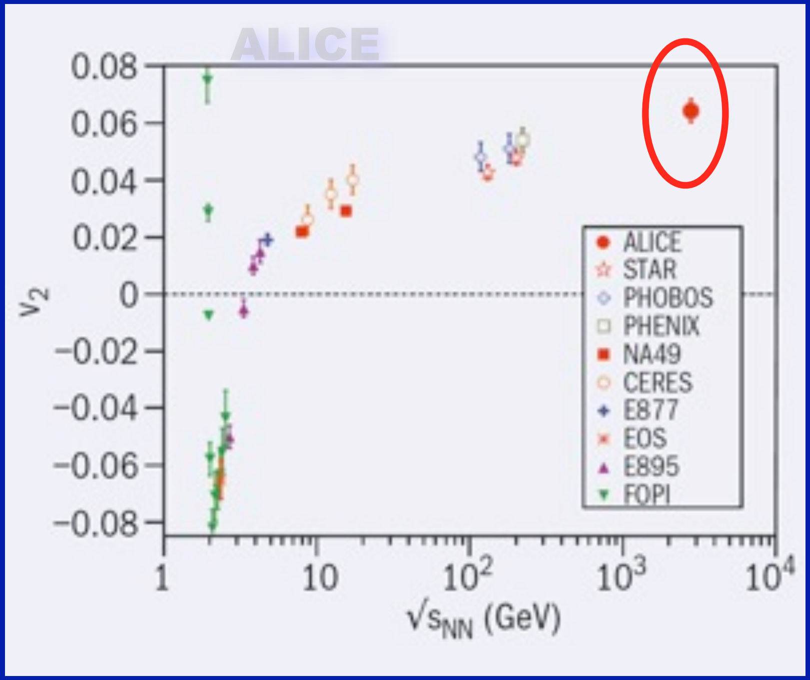
# Heavy Ion (Pb-Pb) Collisions



# Quark-Gluon Plasma @ LHC

Asimutal anisotropy in lead-lead collisions

The second Fourier coefficient of assymetry is elliptic flow $v_2$




Liquid with minimal viscosity

$$\eta / s = \frac{h}{4\pi k_B}$$

First obtained from AdS/CFT conjecture

Elliptic flow $v_2$ at 2.76 TeV compared with lower energies

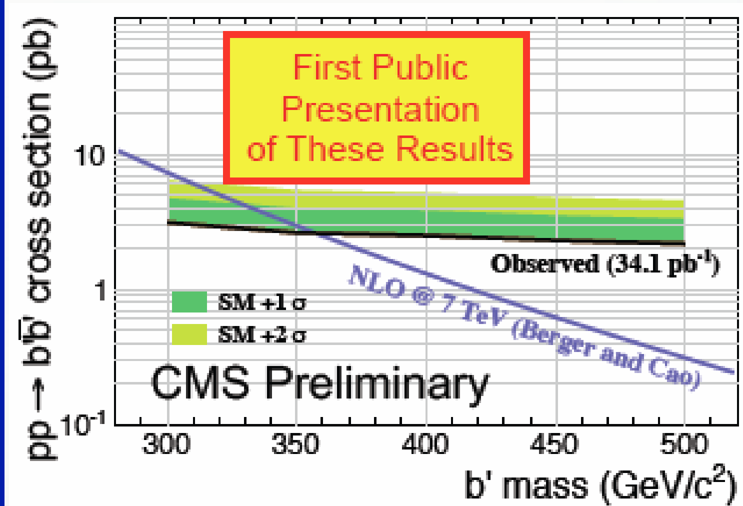
# Search for 4-th generation

New quark exclusion

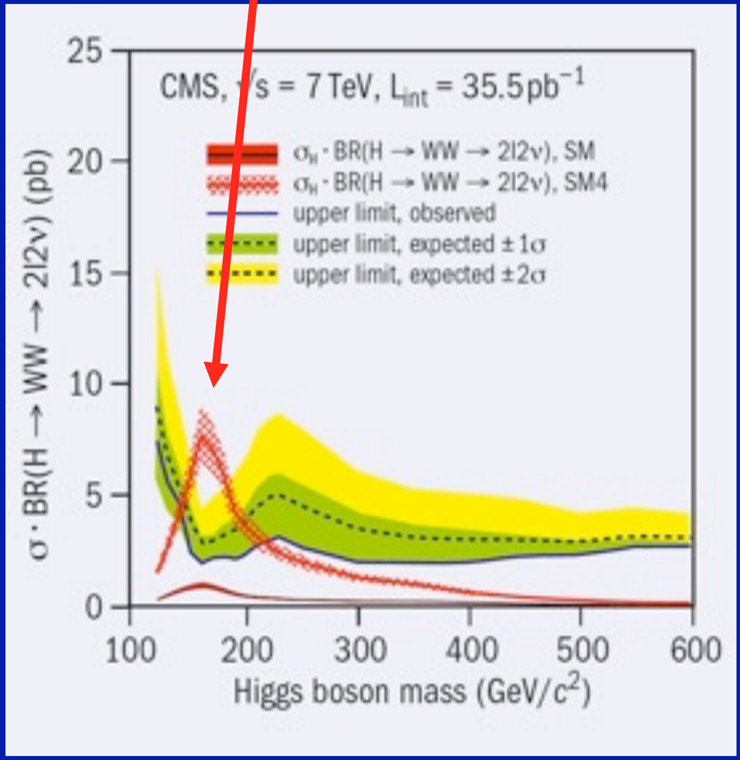
$N_B = 0.32 \pm 0.21$ (tt+jets)

Zero events observed

M(b') > 357 GeV @ 95% CL
Exceeds CDF limit of 338 GeV




Higgs mass exclusion
144< Mh <207 Gev

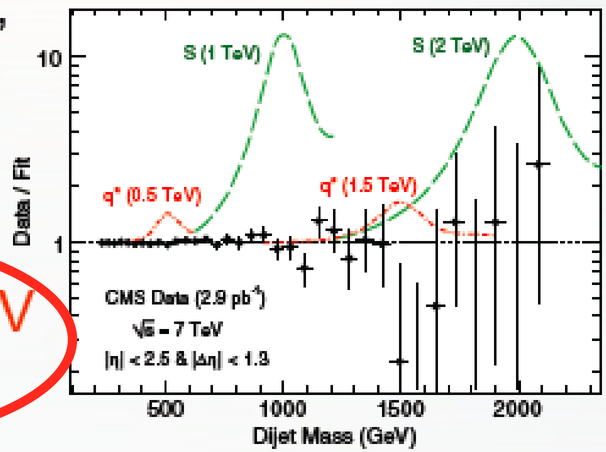


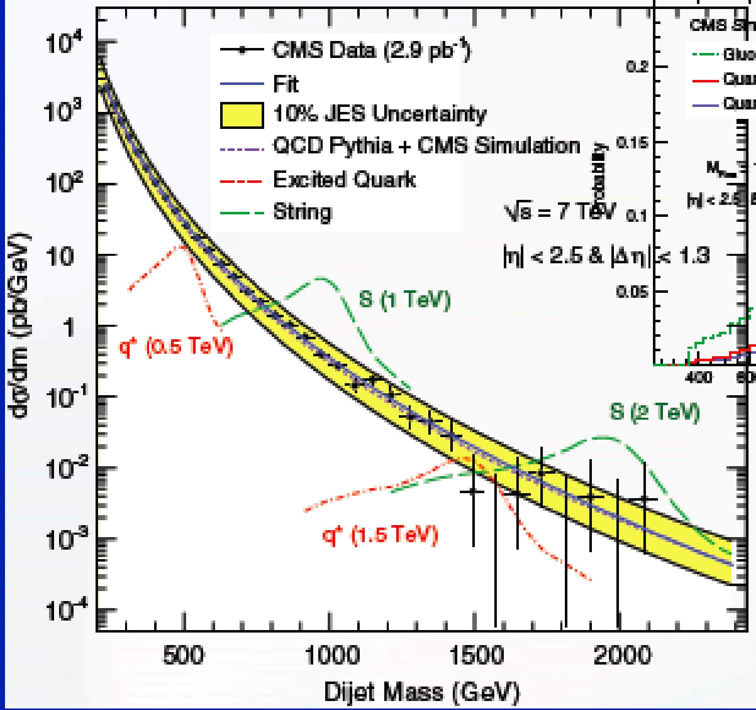
# Resonances and Excitations

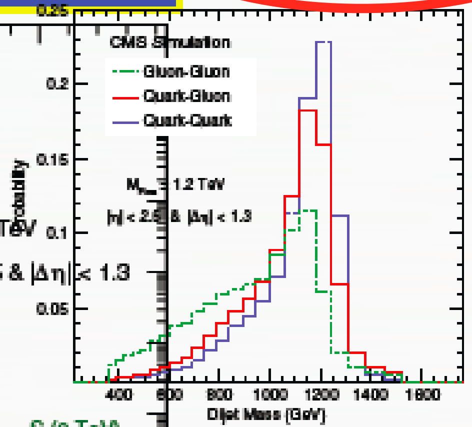
- Parameterize dijet mass spectrum with a smooth, 4-parameter fit function: $\frac{d\sigma}{dm} = \frac{P_0(1 - m/\sqrt{s})^{P_1}}{(m/\sqrt{s})^{P_2 + P_3 \ln(m/\sqrt{s})}}$, and look for bumps
- In their absence, set limits

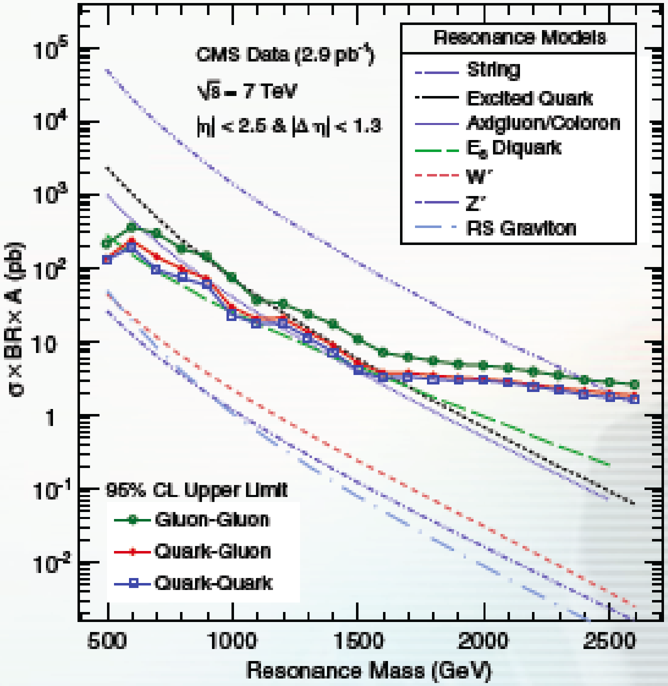
$M_{q^*} > 1.58$ TeV
$M_S > 2.5$ TeV

Phys. Rev. Lett. **105**, 211801 (2010)



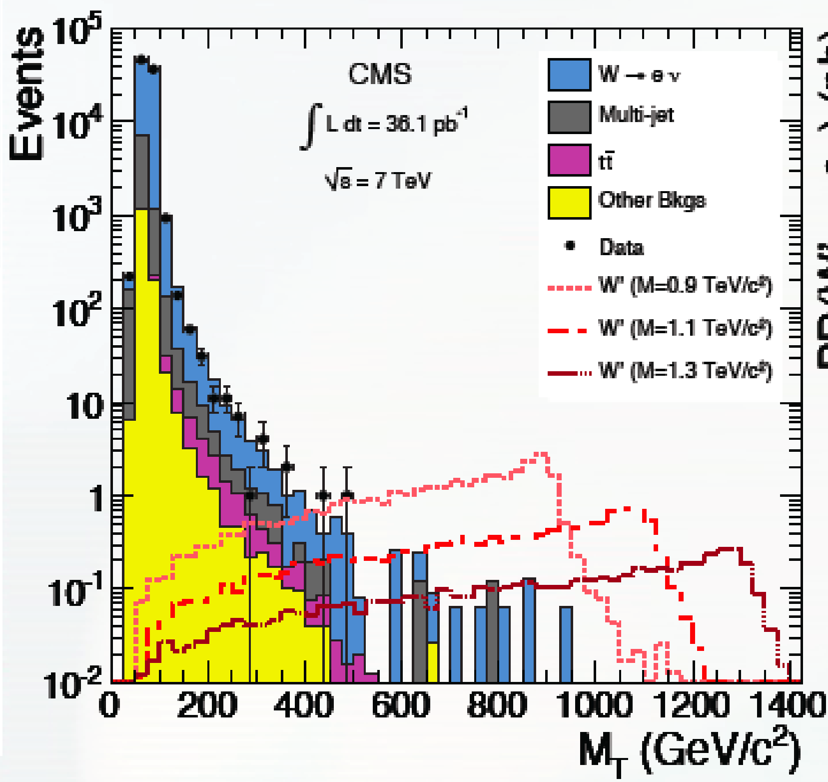



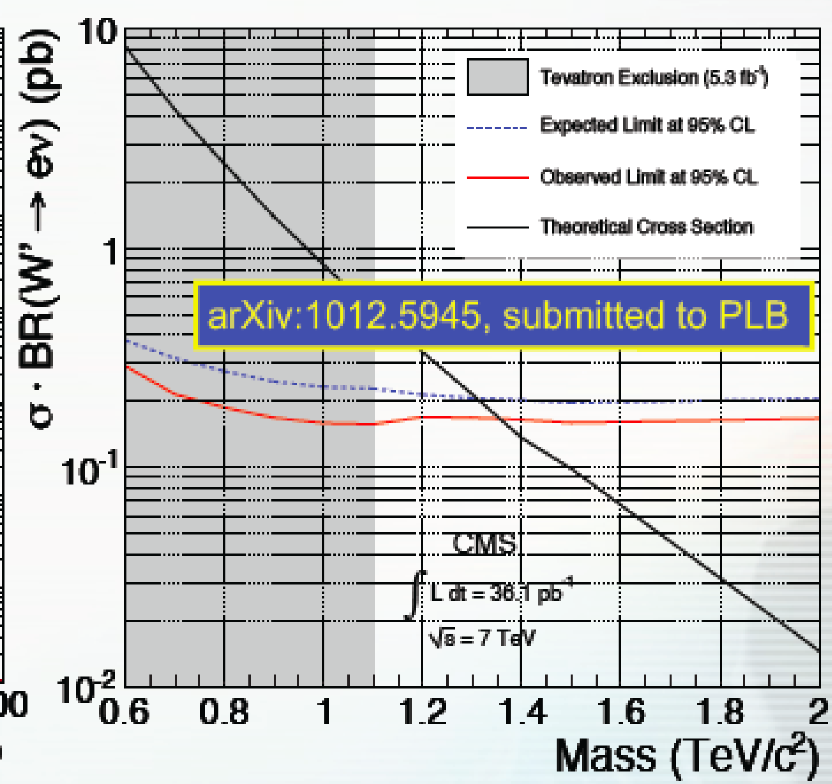



# Limits on Z',W' and $G_{KK}$

- W* and QCD backgrounds estimated via template method
- $M_T$ > 400-675 GeV for M(W′) = 0.6-2.0 TeV; 2-0 events observed
- M(W′) > 1.36 TeV (eν) - significant extension of the Tevatron limit of 1.12 TeV [CDF, arXiv:1012.5145, 5.3 fb$^{-1}$]



# Summary on Dijet Searches

| Particle | CMS, 2.9 $pb^{-1}$<br>PRL **105**, 211801 (2010) | ATLAS, 0.32 $pb^{-1}$<br>PRL **105**, 161801 (2010) | CDF, 1130 $pb^{-1}$<br>PRD **79**, 112002 (2009) |
|---|---|---|---|
| q* | M > 1.58 (1.32) TeV | M > 1.26 (1.06) TeV | M > 0.87 TeV |
| S | M > 2.50 (2.40) TeV | | M > 1.4 TeV<br>(our estimate) |
| Axigluon/ Coloron | M > 1.17 TeV (M > 1.23 TeV)<br>and not (1.42 < M < 1.53) | | M > 1.25 TeV |
| E6 diquark | Exclude 0.50-0.58 & 0.97-1.08 &<br>1.45-1.60 TeV (M > 1.05 TeV) | | M > 0.63 TeV |

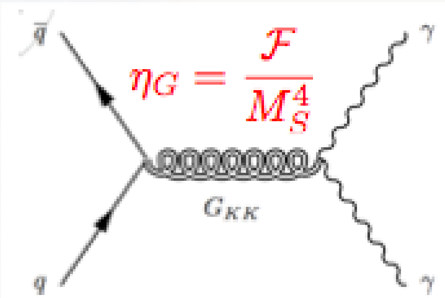
| Quark Compositeness (left-handed quarks) | | |
|---|---|---|
| CMS Centrality<br>PRL **105**, 262001 (2010) | 2.9 $pb^{-1}$ | $\Lambda$ > 4.0 (2.9) TeV<br>actual (observed) |
| CMS Angular Distributions<br>(to be submitted soon) | 36 $pb^{-1}$ | $\Lambda$ > 5.6 (5.0) TeV |
| ATLAS (Angular Distributions)<br>(Centrality) PLB **694**, 327 (2011) | 3.1 $pb^{-1}$ | $\Lambda$ > 3.4 (3.5) TeV<br>$\Lambda$ > 2.0 (2.6) TeV |
| D0 (Angular Distriburions)<br>PRL **103**, 191803 (2009) | 700 $pb^{-1}$ | $\Lambda$ > 2.84-3.06<br>(2.76-2.91) TeV |

All bounds moved but nothing is seen !

# Extra Dimensions

# Virtual Gravity Effects

- Probe models with Large Extra Dimensions (ADD) where gravity alone is allowed to propagate
  - Offers a solution to the hierarchy problem by "lowering" and apparent Planck scale $M_{Pl} \sim 10^{16}$ TeV to $M_D \sim 1$ TeV
- Non-resonant enhancement of DY and diphoton cross section due to virtual graviton exchange
- The sum over the Kaluza-Klein modes is divergent; introduce a UV cutoff $M_S \sim M_D$: $\sigma_{\text{ADD}} = \sigma_{\text{SM}} + A\eta_G\,\sigma_{\text{int}} + B\eta_G^2\,\sigma_{\text{ED}}$,
  - Complementary to, e.g., monojet searches, as probes $M_S$, not $M_D$ directly




$$\mathcal{F} = 1, \text{ (GRW [6]);}$$

*Nucl. Phys.* **B544** (1999) 3

$$\mathcal{F} = \begin{cases} \log\left(\frac{M_S^2}{M^2}\right), & n = 2 \\ \frac{2}{n-2}, & n > 2 \end{cases}, \text{ (HLZ [30]);}$$

*Phys. Rev.* **D59** (1999) 105006

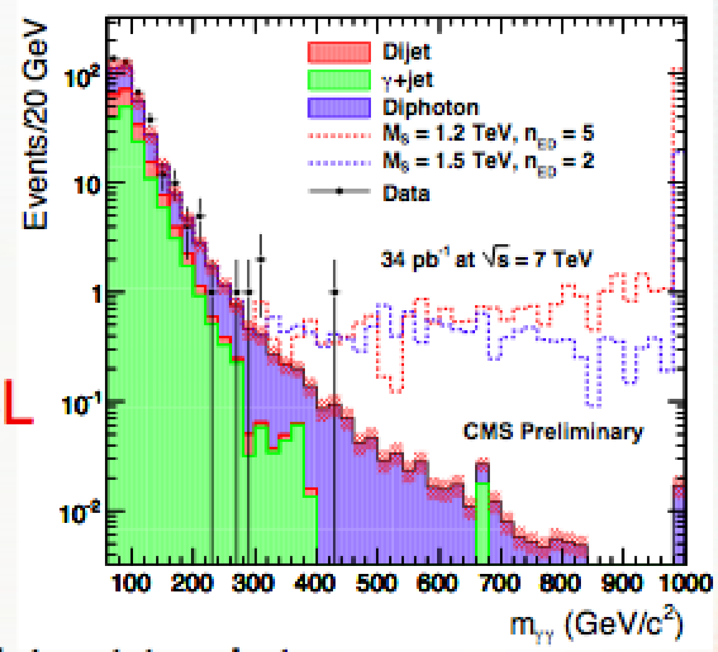
$$\mathcal{F} = \frac{2\lambda}{\pi} = \pm\frac{2}{\pi}, \text{ (Hewett [29]).}$$

*Phys. Rev. Lett.* **82** (1999) 4765

- Several conventions exist on how to truncate the sum

# Diphoton mass spectrum

- Instrumental background from jets determined from data
- Main background at high masses is irreducible diphoton production
  - Assign ~20% systematics due to the K-factor
- Optimized cuts: $M\gamma\gamma > 500$ GeV, $|\eta_\gamma| < 1.442$ (Barrel)
- B = 0.28 ± 0.06, 0 events observed
- $\sigma < 0.118$ (0.135 exp.) pb @ 95% CL
- Produce limits with and w/o perturbativity truncation
  - $\sigma(M\gamma\gamma > M_S) = 0$ conservatively
- Limits highlighted in lime are the tightest to date




| GRW | Hewett | | HLZ (limits in TeV) | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | $\lambda > 0$ | $\lambda < 0$ | n=2 | n=3 | n=4 | n=5 | n=6 | n=7 | |
| 1.93 | 1.72 | 1.70 | 1.88 | 2.29 | 1.93 | 1.74 | 1.62 | 1.53 | |
| 1.82 | | | 1.79 | 2.22 | 1.82 | 1.61 | 1.45 | 1.29 | $M < M_S$ |

# The Black Holes

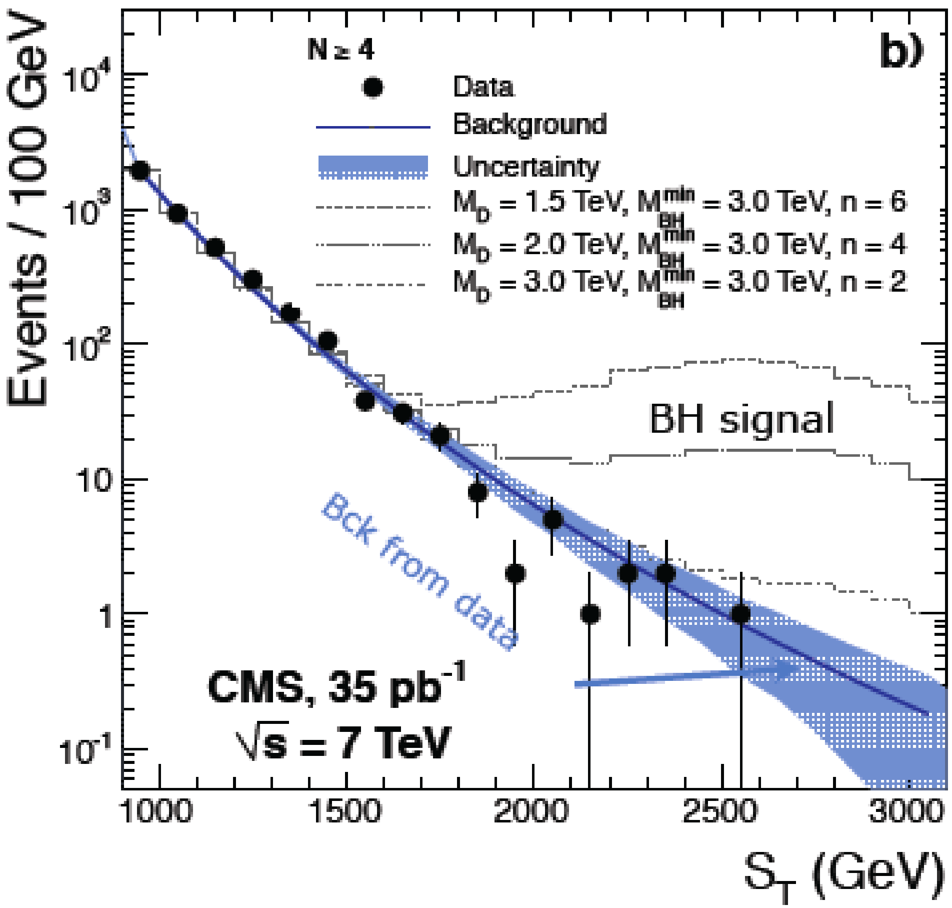
# Search for Microscopic Black Holes

**Submitted to PLB**
arXiv:1012.3375 [hep-ex]

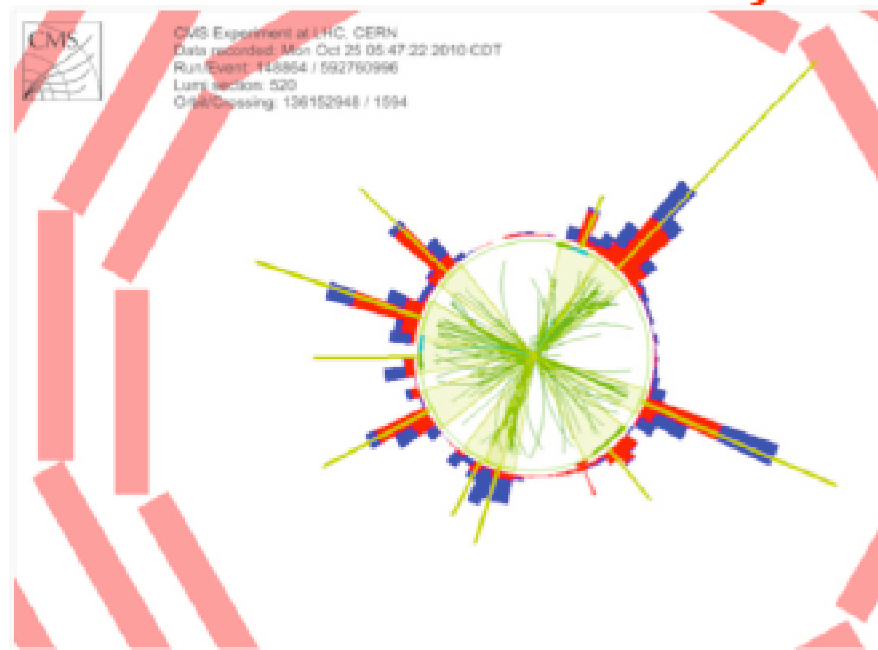
Extra dimensions?!

Decay into highly-energetic multiparticle final states

**The first search for black holes at a particle accelerator**




**Candidate event with 10 jets**

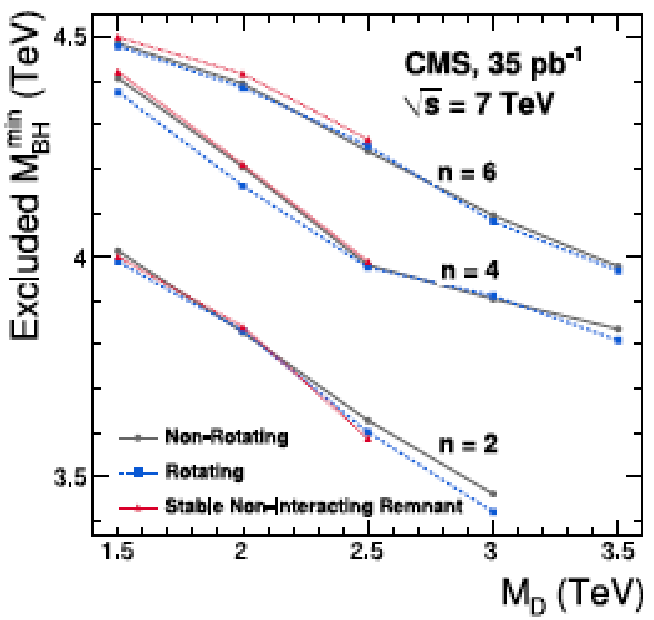


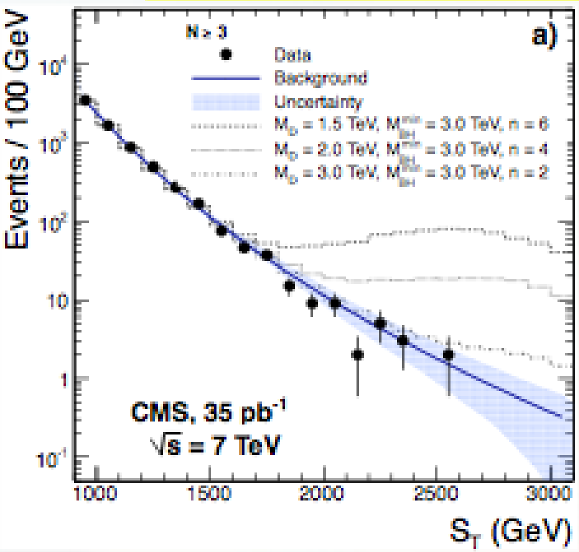

**Set limits of 3.5-4.5 TeV on the minimum black hole mas**

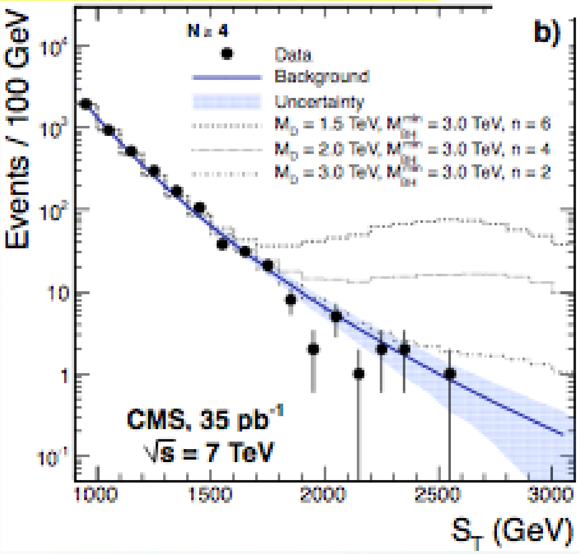
# Limits on Black Holes

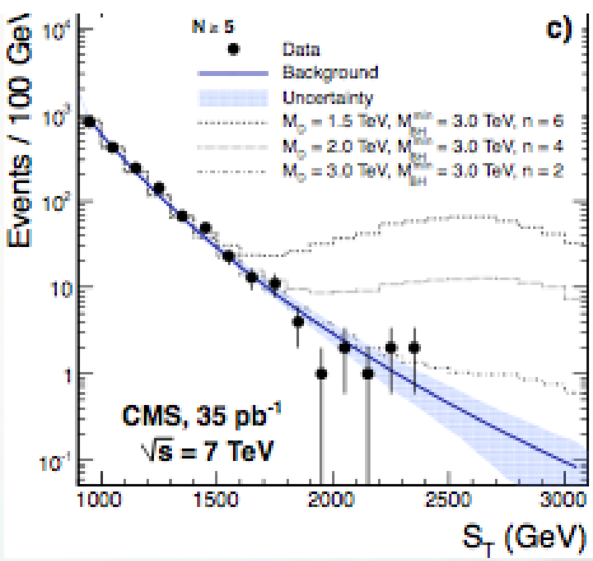
- Used the N=2 shape with its uncertainties, to fit higher multiplicities, where the signal is expected to be most prominent
- Given no excess, set limits on the minimum BH mass of 3.5-4.5 TeV in semi-classical approximation
- First direct limits at colliders

arXiv:1012.3375, submitted to PLB



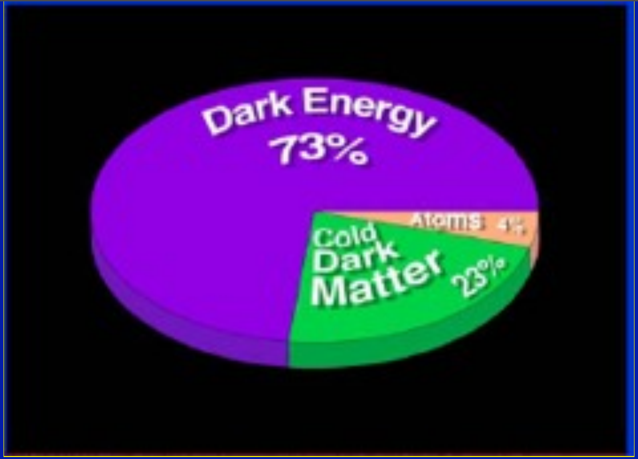



# The Dark Matter

• Makes 23% of matter in the Universe

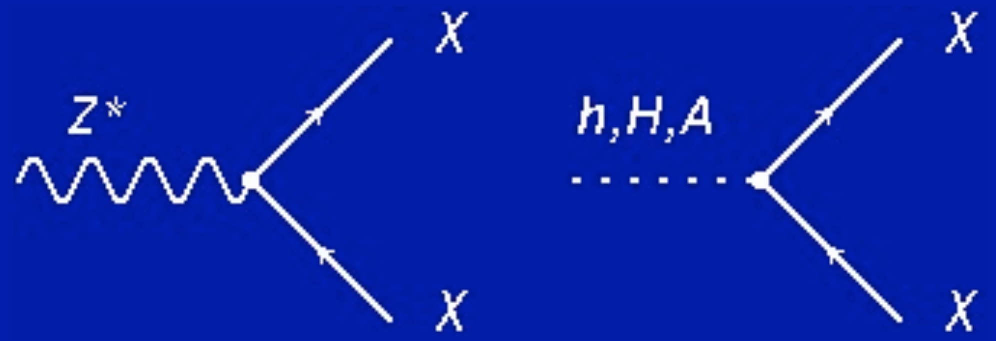



The Dark Matter is made of:

- Macro objects – Not seen
- New particles – right neutrino
  - neutralino
  - sneutrino
  - axion (axino)
  - gravitino
  - heavy photon
  - heavy pseudo-goldstone
  - light sterile higgs

# The Dark Matter @ LHC

- Not observed at accelerators yet
- Should be created at LHC if it is WIMP




Signature: missing energy and momentum

# Conclusions

-  First results of the LHC are promising
-  Big hopes for the 2011-2012 run
-  Higgs or no Higgs?
-  SUSY or no SUSY?
-  Extra D or no Extra D?
-  Deviation from the SM or not?
-  I am sure new physics is on agenda

Used presentations by A.Shopper, E.Nurse, P.Schieferdecker, G.Landsberg