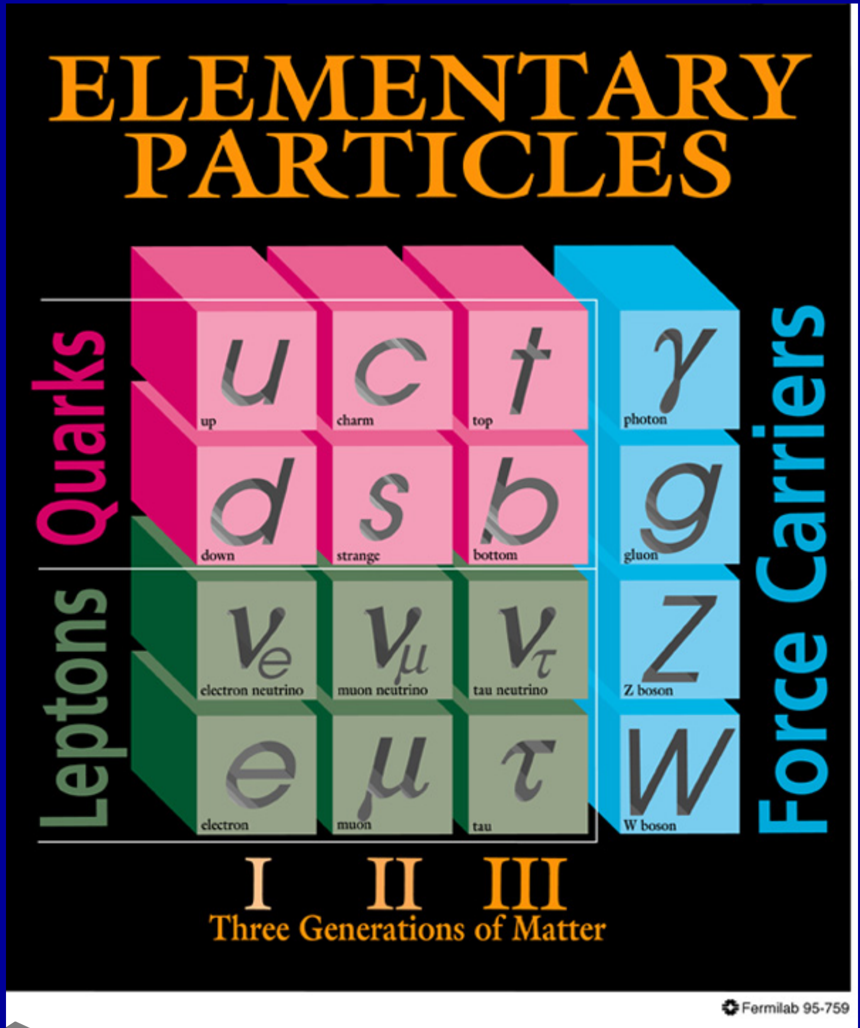
LHC: the first results
and worrying expectations

Dmitri Kazakov

The Standard Model

SU(3) SU(2) U(1)

Particles



H

The Higgs boson

Forces

Electromagnetic

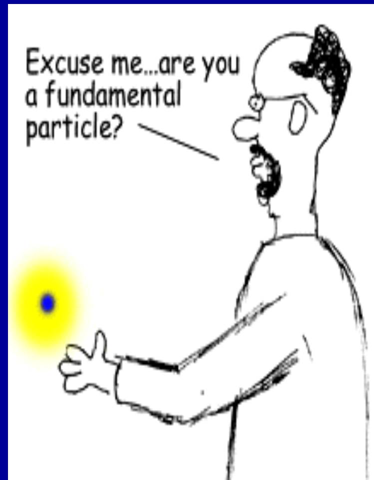
Strong

Weak

Gravity

The SM and Beyond

The problems of the SM:



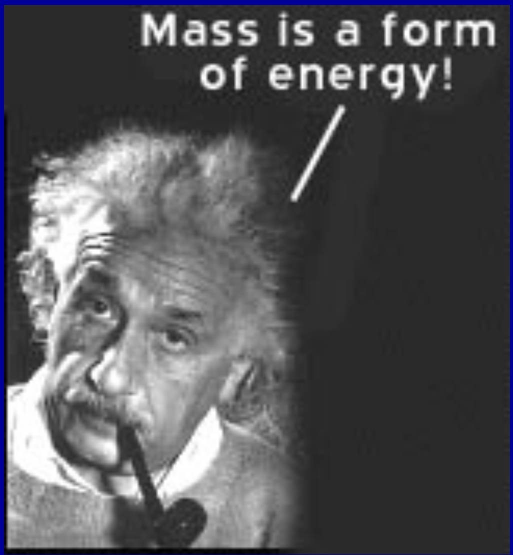
- Inconsistency at high energies due to Landau poles
- Large number of free parameters
- Still unclear mechanism of EW... breaking
- CP-violation is not und...
- The origin of the m... unclear
- Flavour mixing and ...er of generations is arbitrary
- Formal unification of ...rong and electroweak interactions

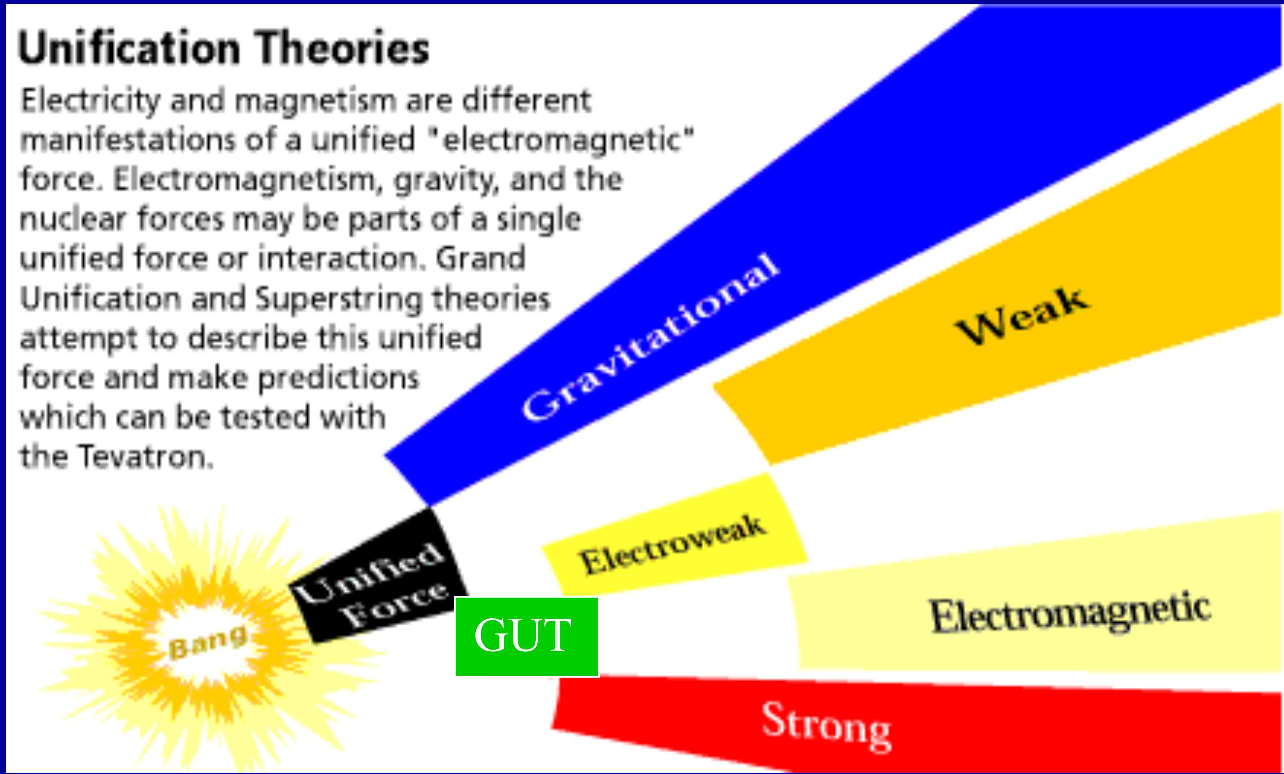
Where is the Dark matter?

The way beyond the SM:

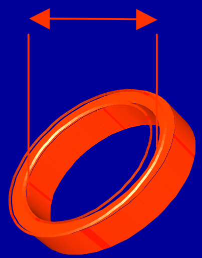
- The SAME fields with NEW interactions and NEW fields ⇨ GUT, SUSY, String, ED
- NEW fields with NEW interactions ⇨ Compositeness, Technicolour, preons

Unification Paradigm





$10^{-34}\,m$

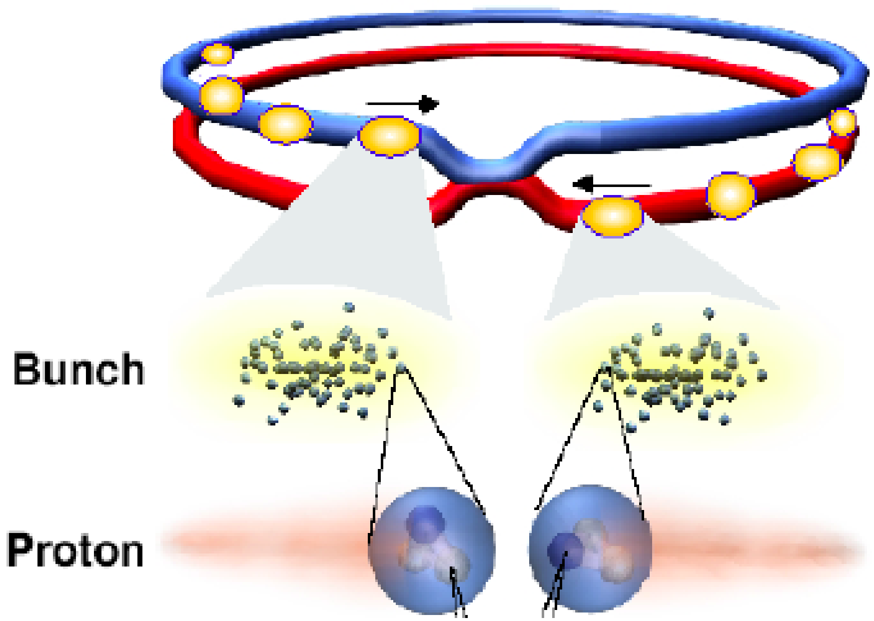


D=10

- 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:

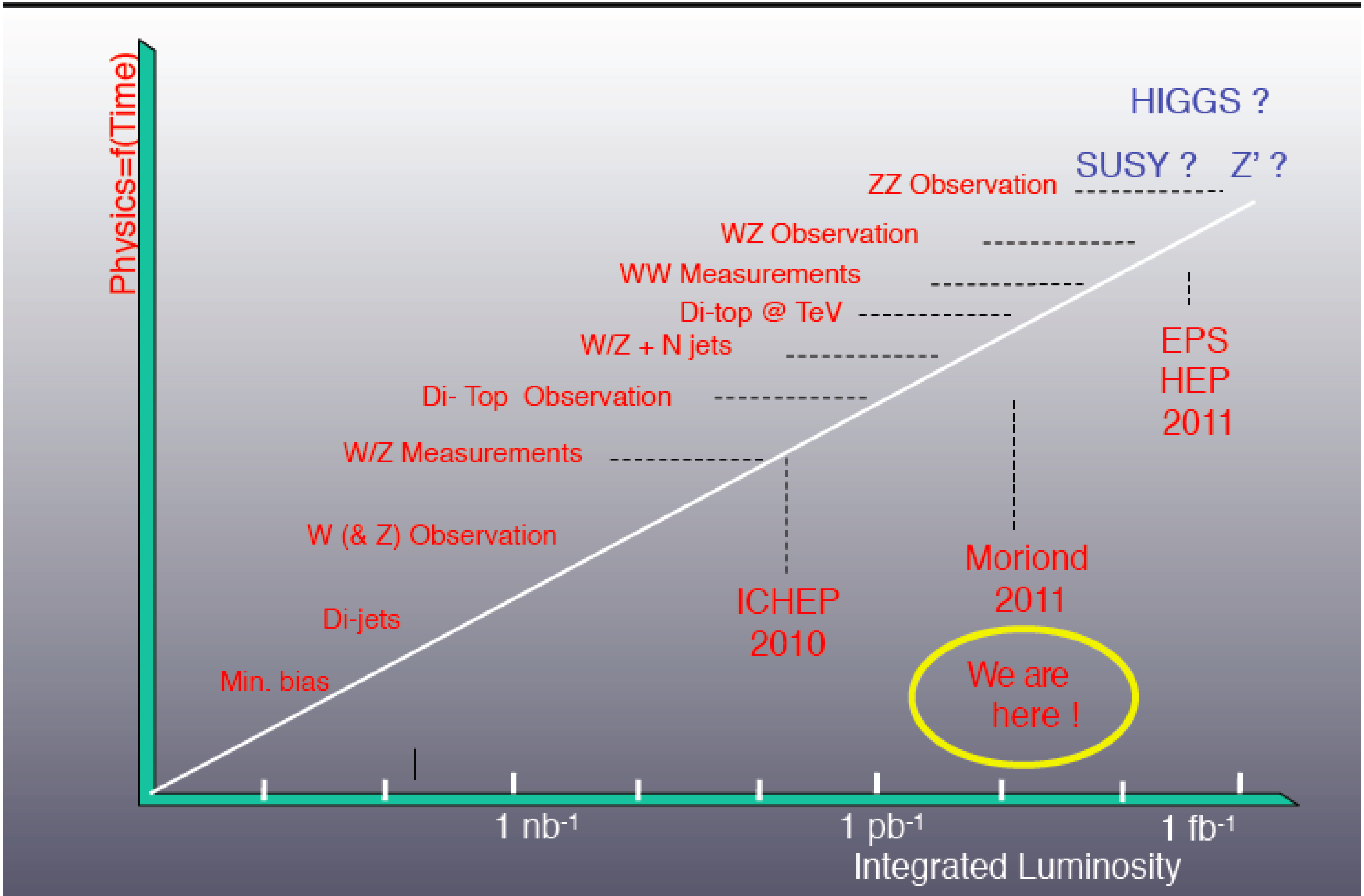
- N_i = bunch intensity
- n_b = number of bunches
- σ = colliding beam size

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

Units for the luminosity:

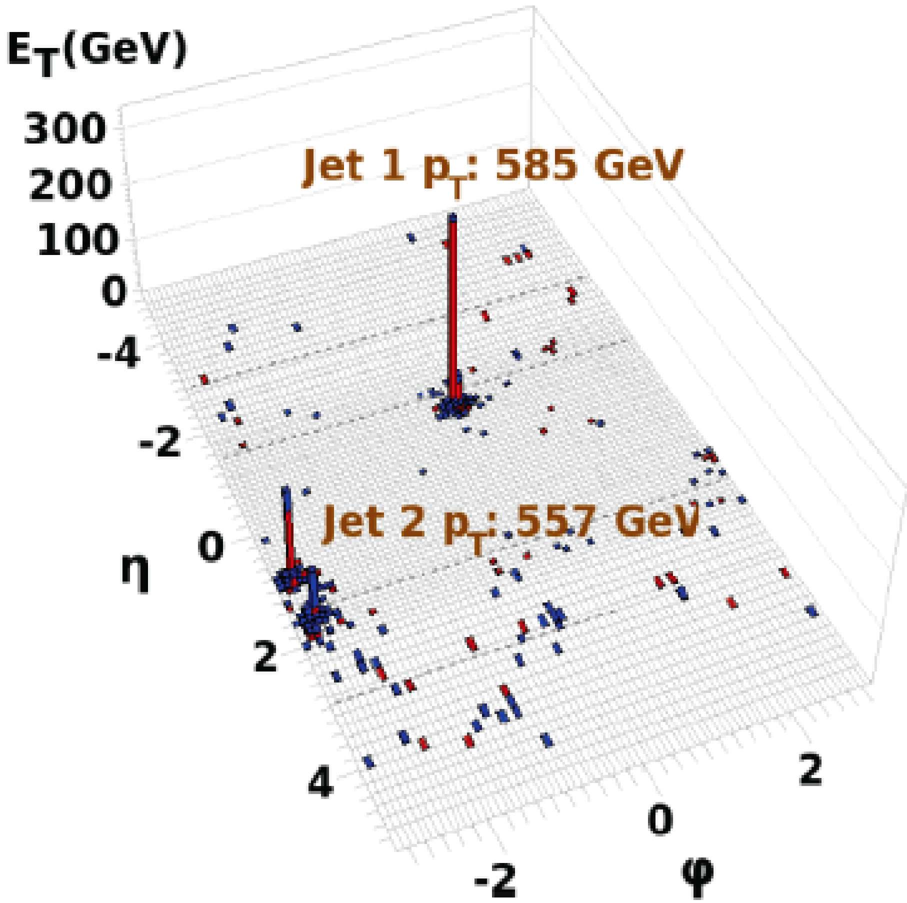
- *Peak luminosity given in event rate per unit of area* $cm^{-2}s^{-1}$: ***2010 goal = $10^{32}cm^{-2}s^{-1}$***
- *Integral luminosity (prop. to number of collisions)* fb^{-1} : ***2011 goal = 1 fb^{-1}***

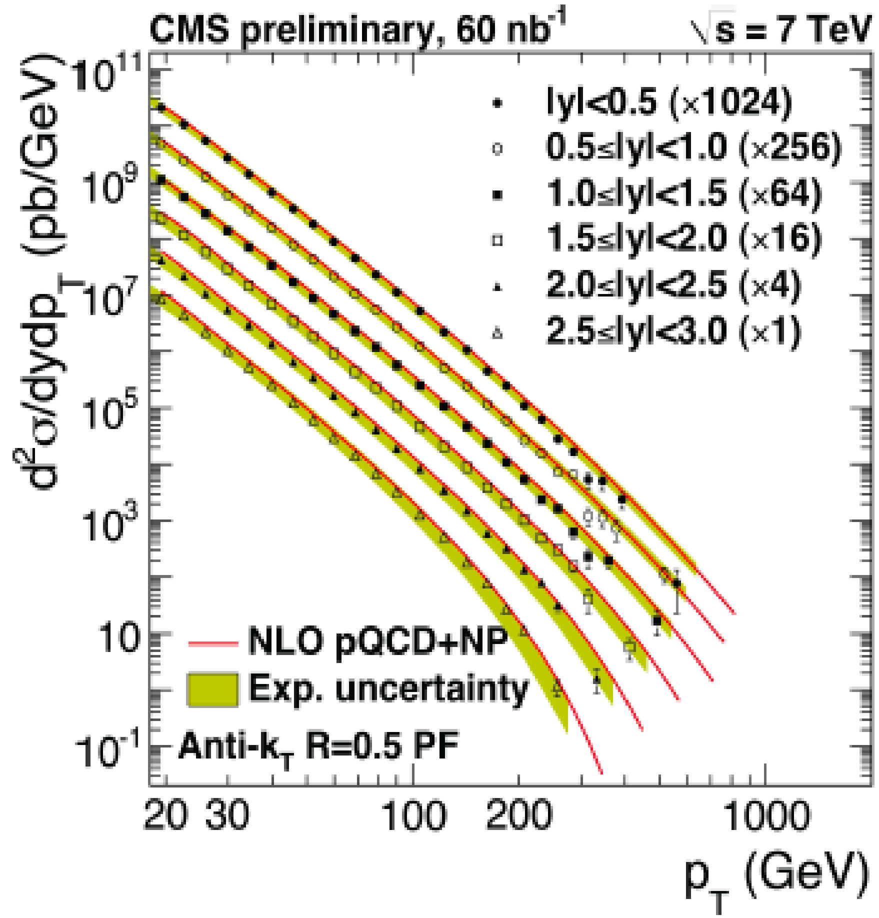
CMS Physics Objectives through 2011



Inclusive Jet Production

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





Two-Particle Angular Correlations

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

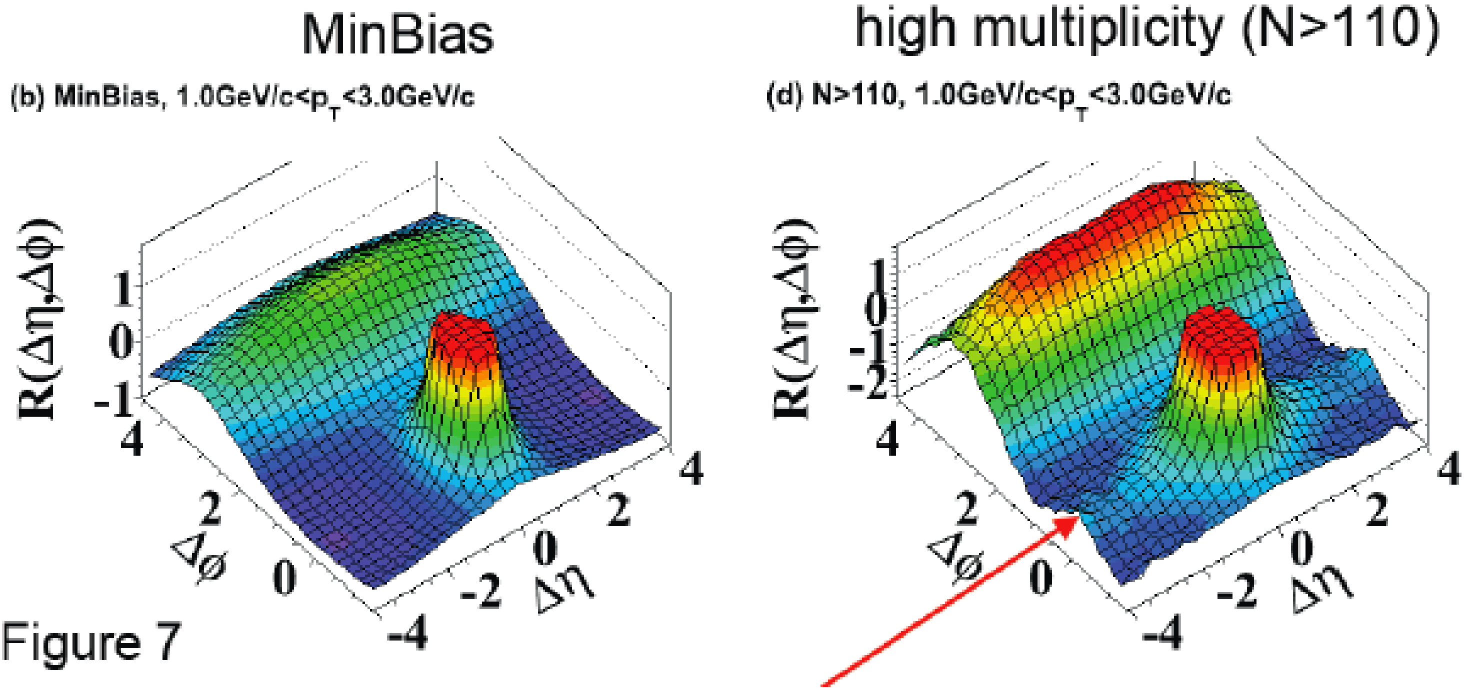
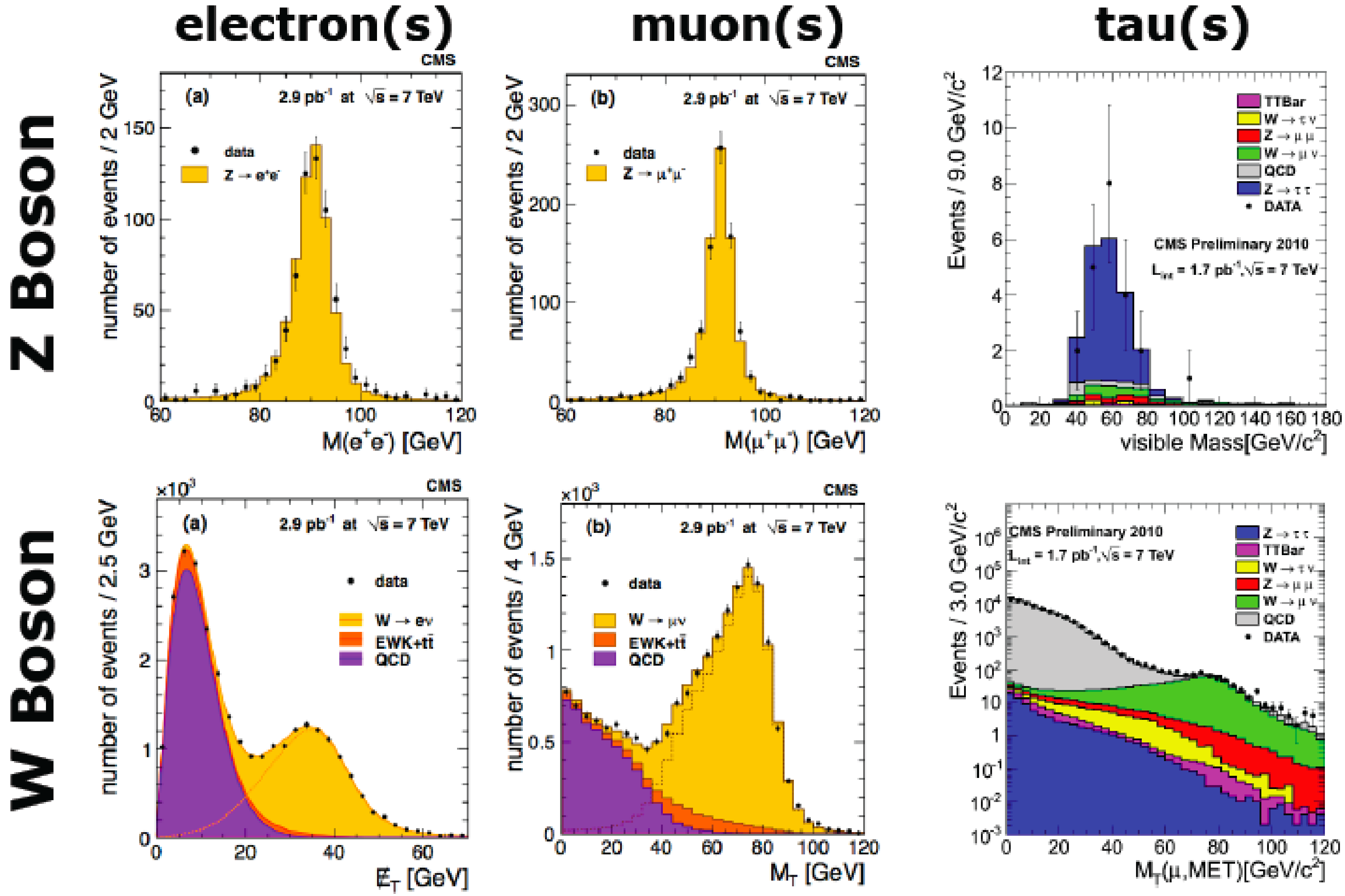


Figure 7

No conclusive explanation yet , sizeable impact on scientific community!

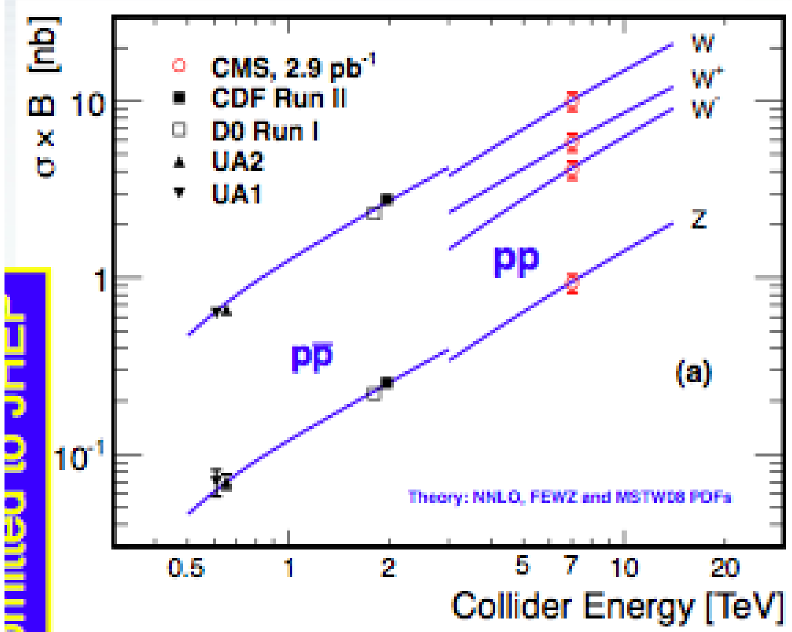
W & Z Boson Production

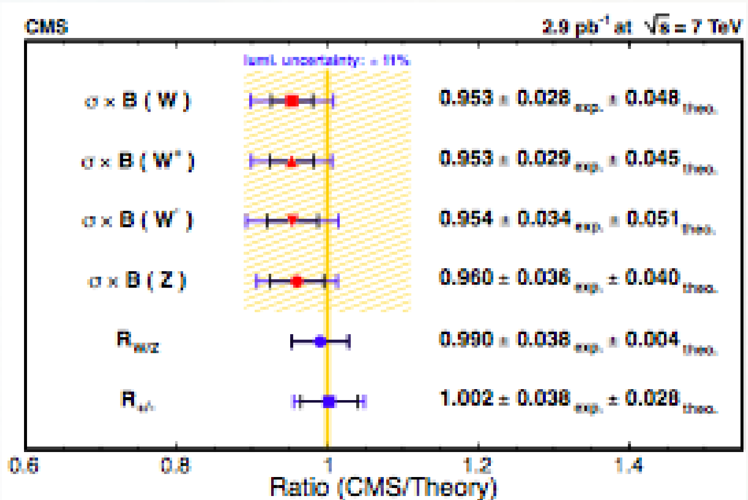


Electro-Weak Physics

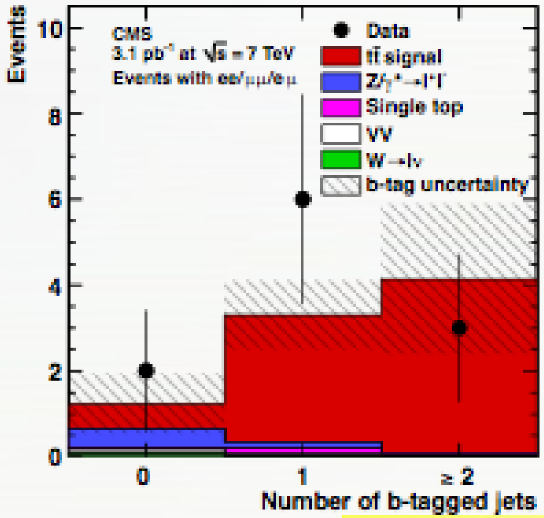
- Measurement of the W/Z and top cross section

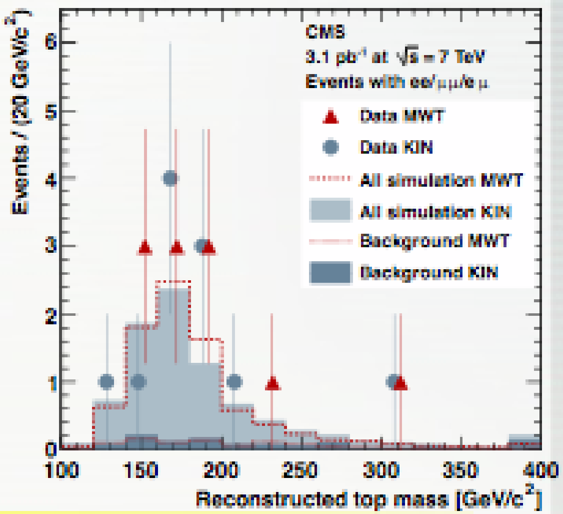
arXiv:1012.2466, submitted to JHEP



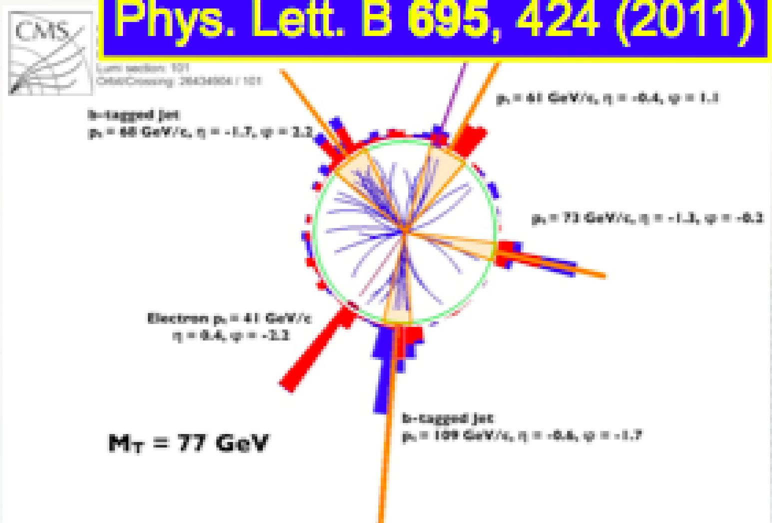


$$\sigma(pp \to t\bar{t}) = 194 \pm 72(\text{stat.}) \pm 24(\text{syst.}) \pm 21(\text{lumi.})\ \text{pb}$$

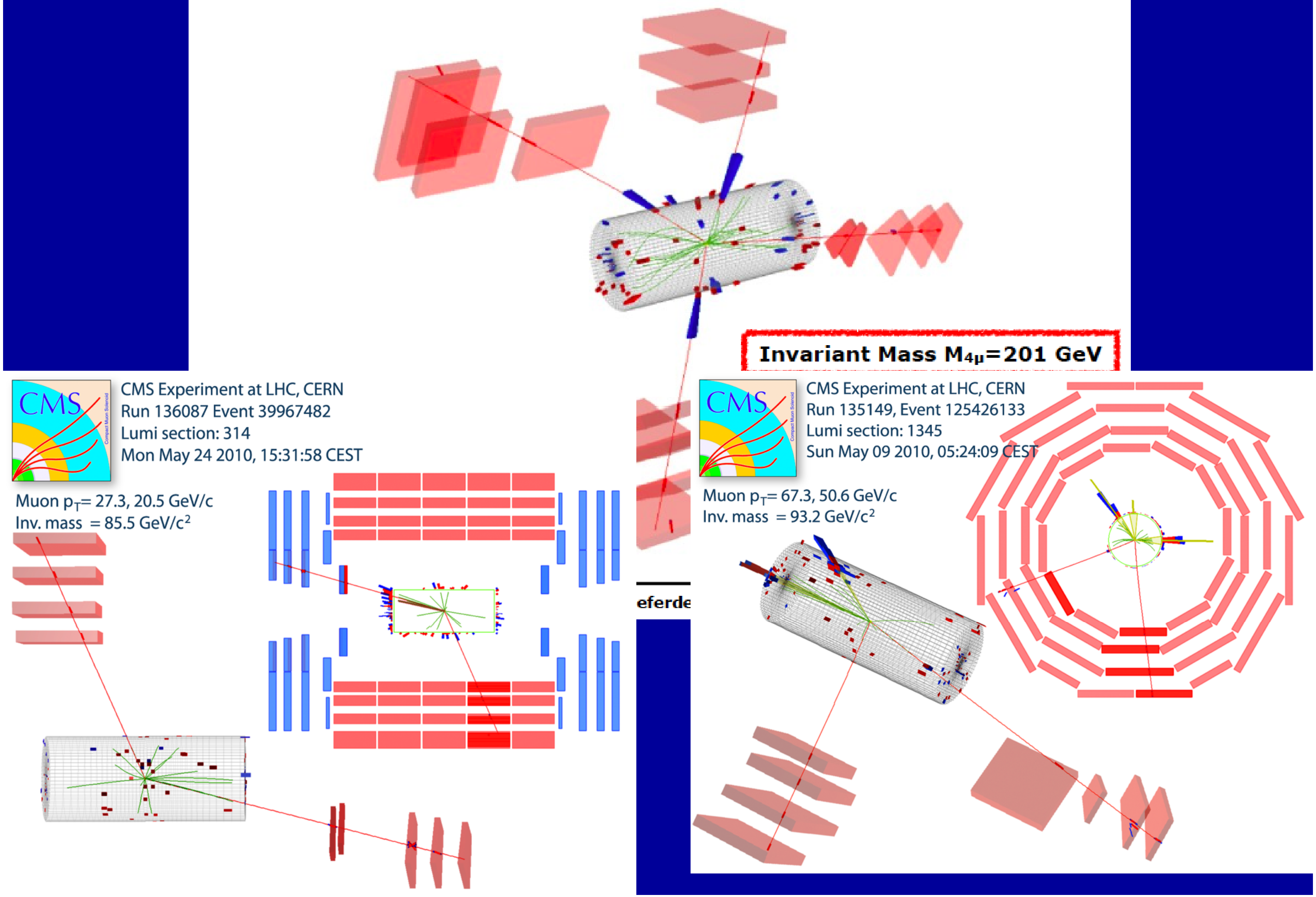




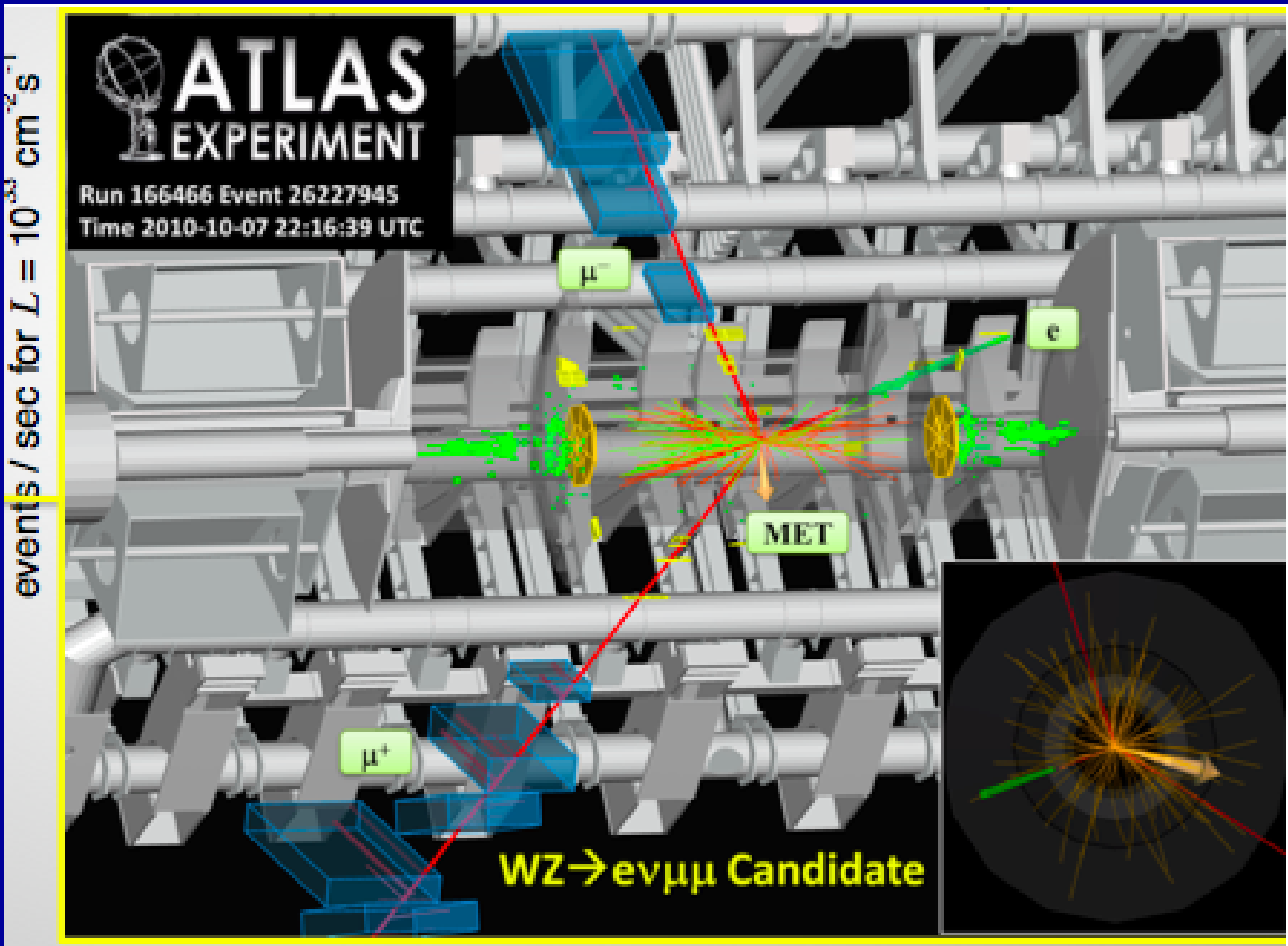
Phys. Lett. B 695, 424 (2011)



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

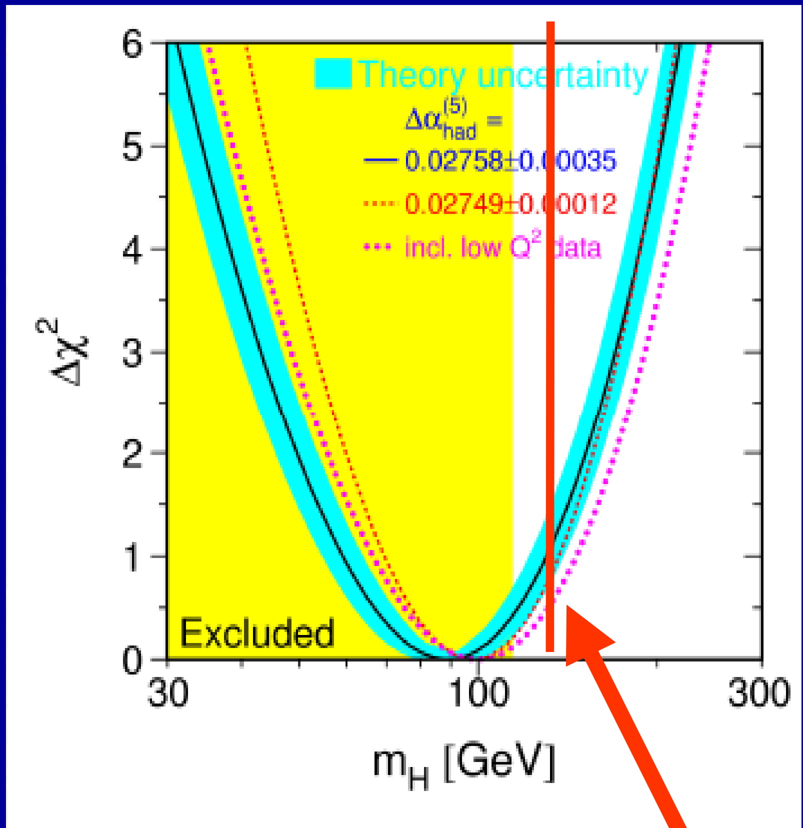


$WZ \rightarrow e\nu\mu\mu$



The Higgs Boson

SM Fit to Precision EW Data



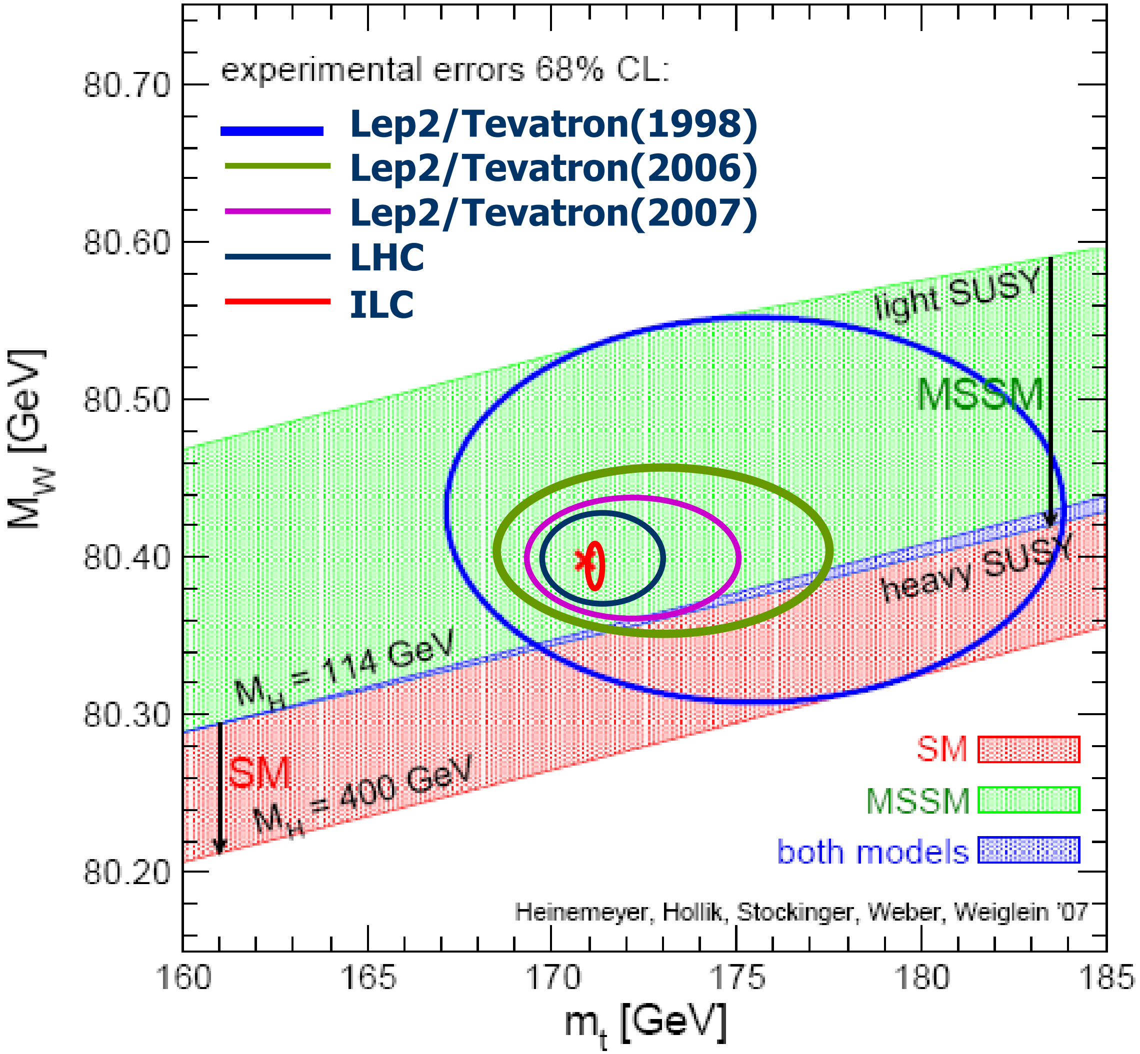
χ^2 versus M_H for SM Fit

- M_H=89 +42-30 @68%CL
- M_H < 165 GeV @95%CL

for m_{top} =172.5 GeV

If it is there we may see it soon

Measurement of M_w and m_t and Comparison with SM and MSSM



MSSM band:
scan over
SUSY masses

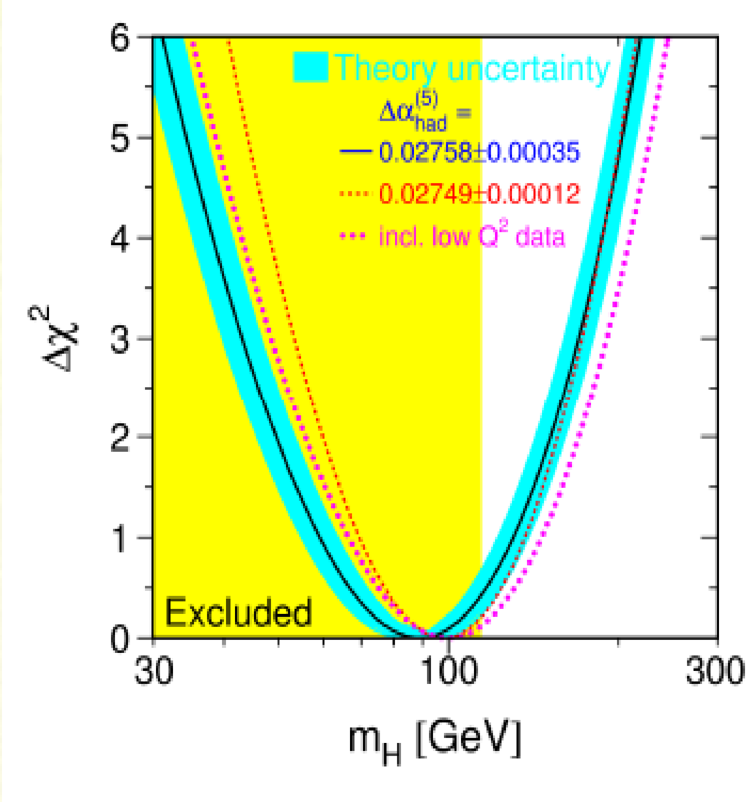
overlap:
SM is MSSM-like
MSSM is SM-like

SM band:
variation of M_H^{SM}

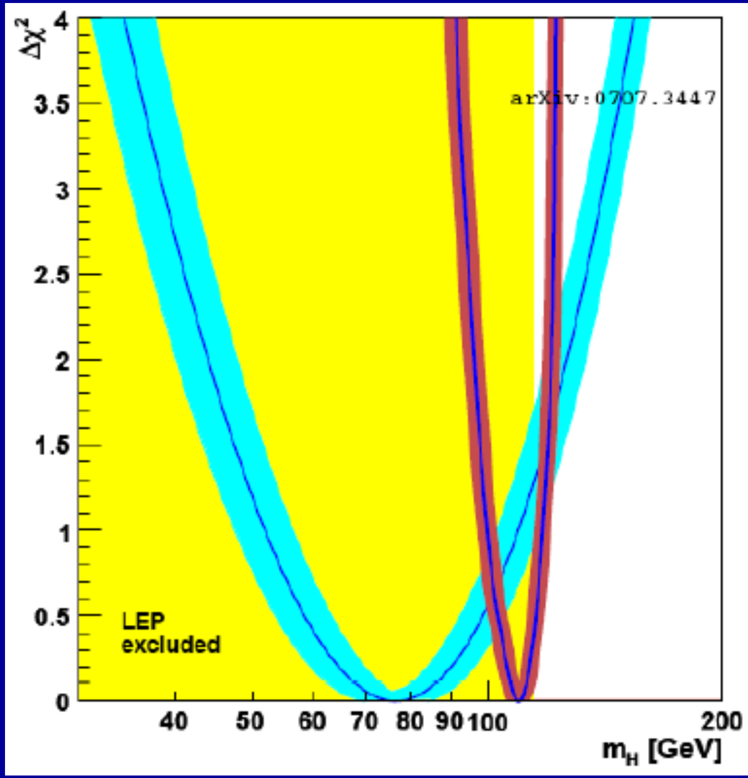
The SM versus MSSM

Fit for the Higgs Boson Mass

SM

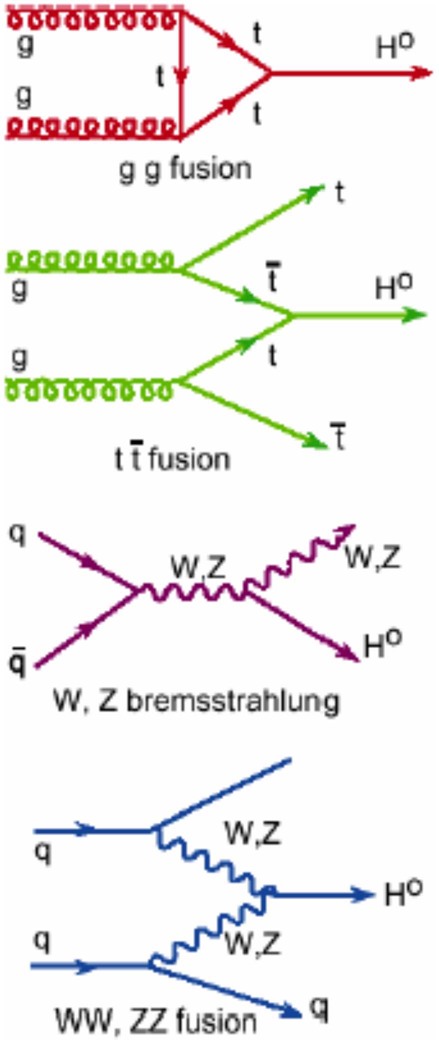


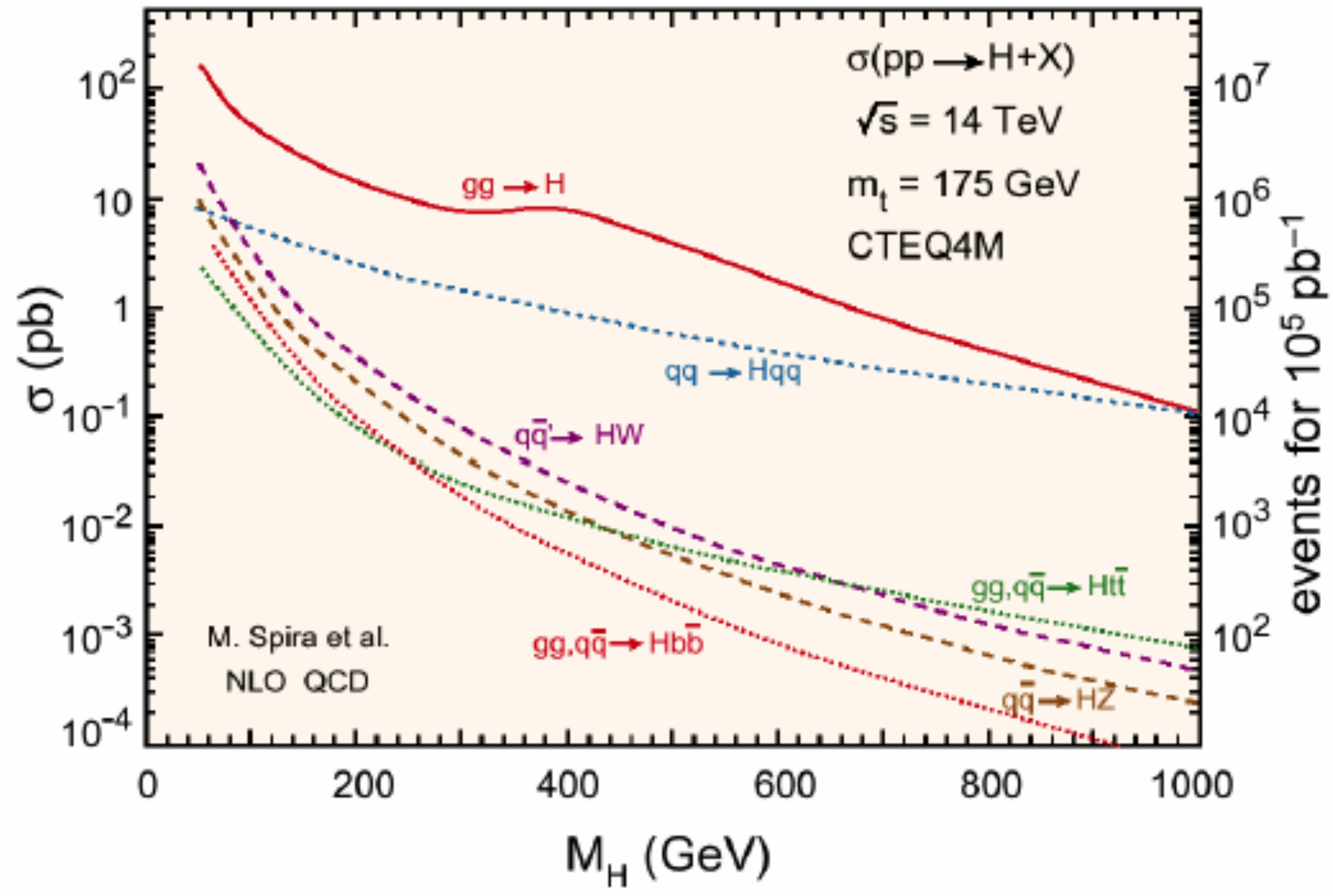
MSSM



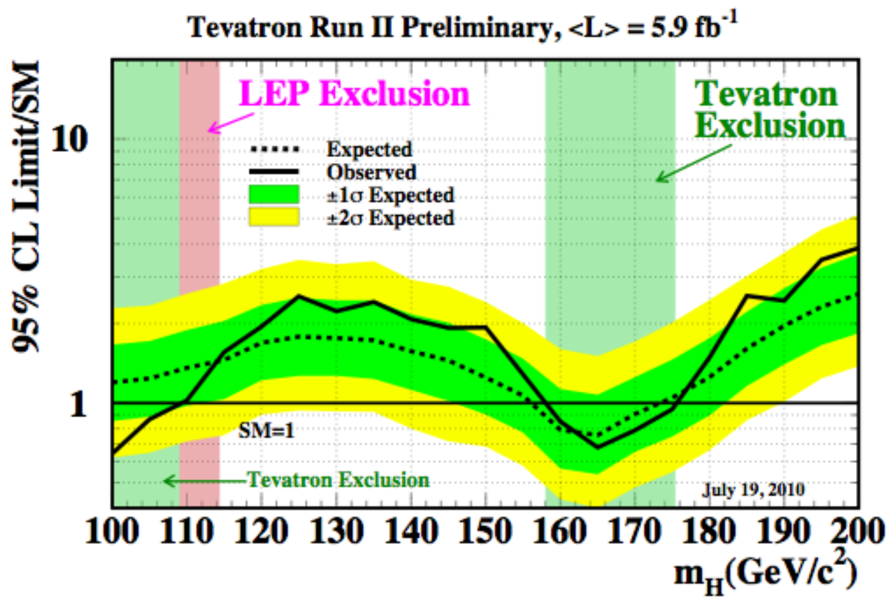
Search for Higgs Boson at LHC

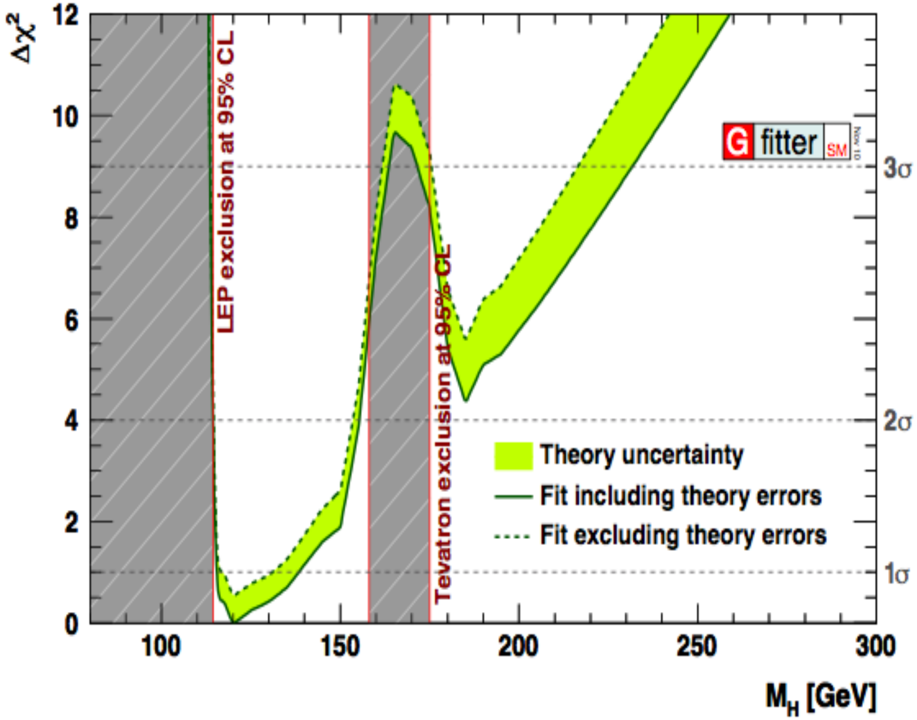
- **Production mechanisms & cross section**





Tevatron Higgs Searches

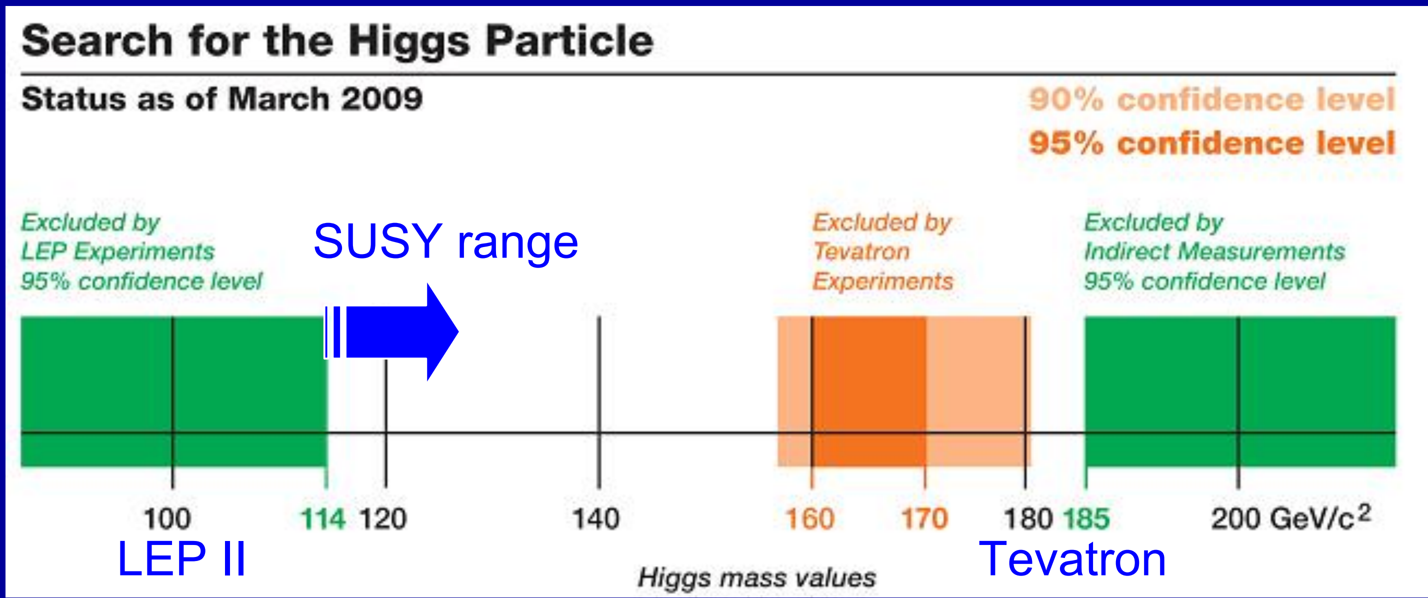




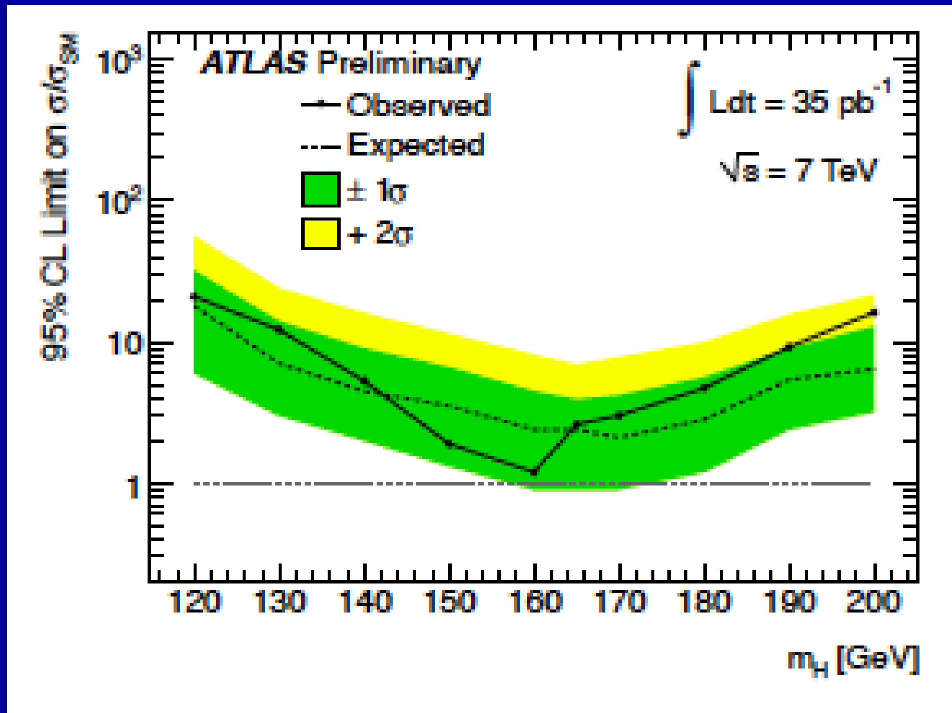
Tevatron seems to exclude the region 158< mH <175 GeV,
However large uncertainties in the calculation of the SM background does not allow to make definite statements

Modern Higgs Window

(Direct Search)

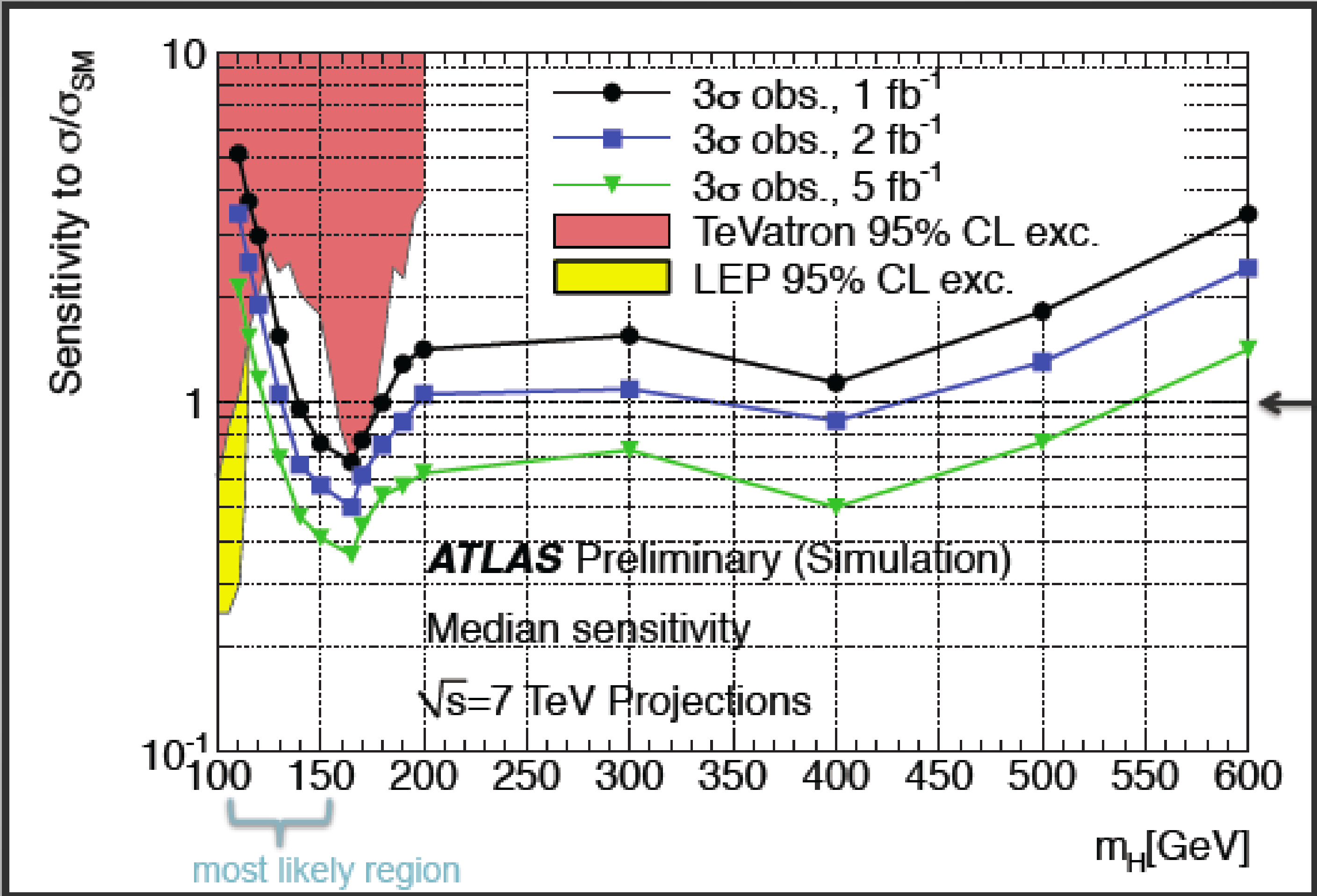


LHC Higgs Searches



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

Higgs in 2011?



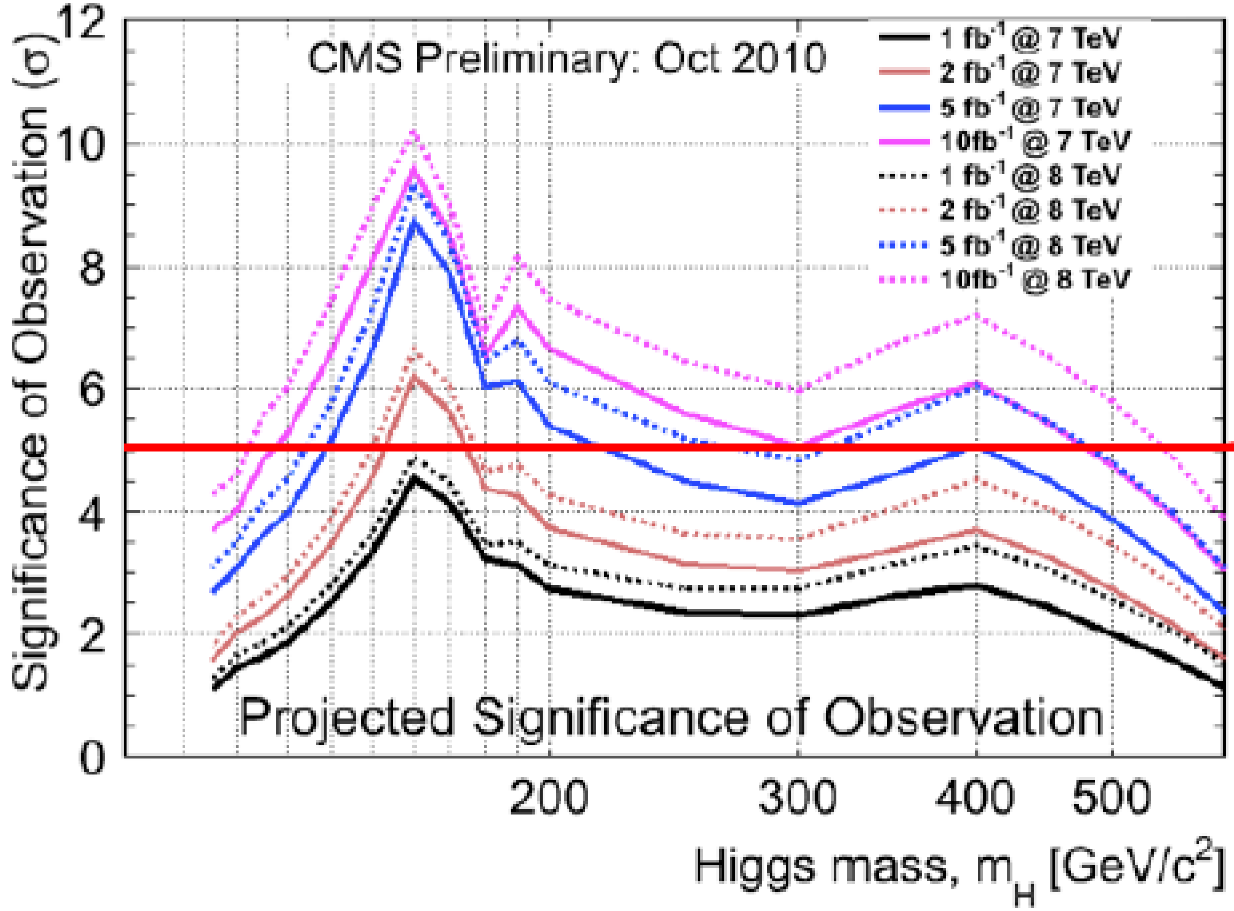
Need 5σ for disco

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



Discover

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

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

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

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

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

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

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

Superspace

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

Grassmannian parameters

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

$$\vartheta_\alpha^2 = 0, \; \bar\vartheta_{\dot\alpha}^2 = 0$$

SUSY Generators

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

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

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

Supertranslation

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

$$\theta \rightarrow \theta + \xi,$$

$$\bar\theta \rightarrow \bar\theta + \bar\xi$$

Why SUSY ?

Maxwell ED

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

Covariant derivative

Einstein GR

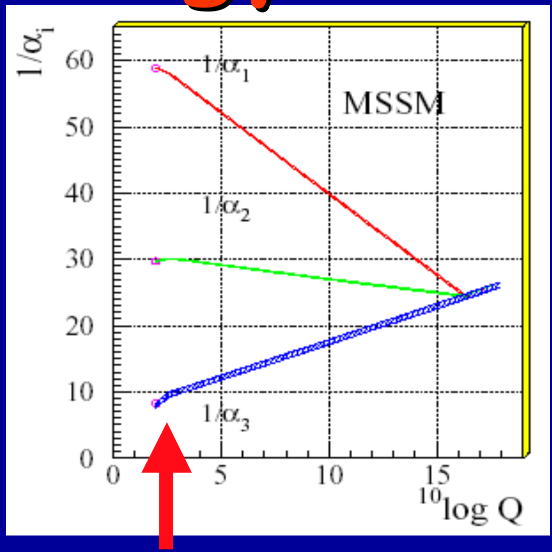
Local SUSY ⟶ Local coordinate transf ⟶ graviton

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

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 $\partial_\mu \to D_\mu = \partial_\mu + A_\mu$ → Vector field

Covariant derivative

Einstein GR

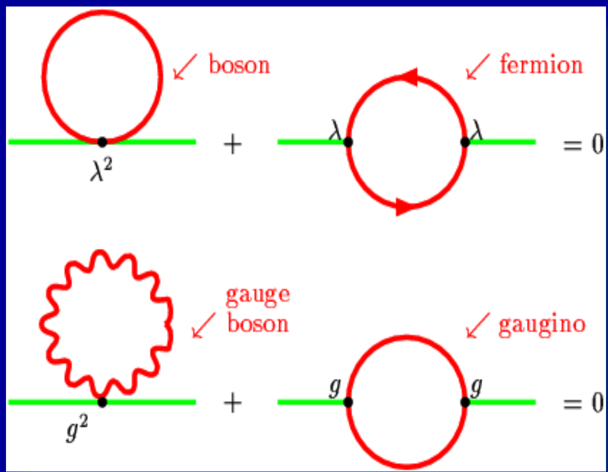
Local SUSY → Local coordinate transf → graviton

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

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

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

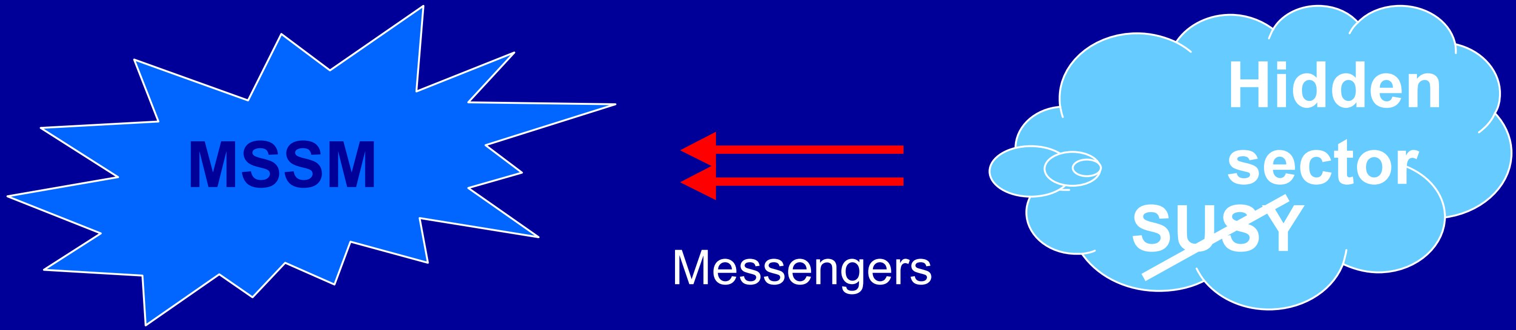
Spin 0 Spin 1/2 Spin 1/2 Spin 1 Spin 3/2 Spin 2

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

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

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

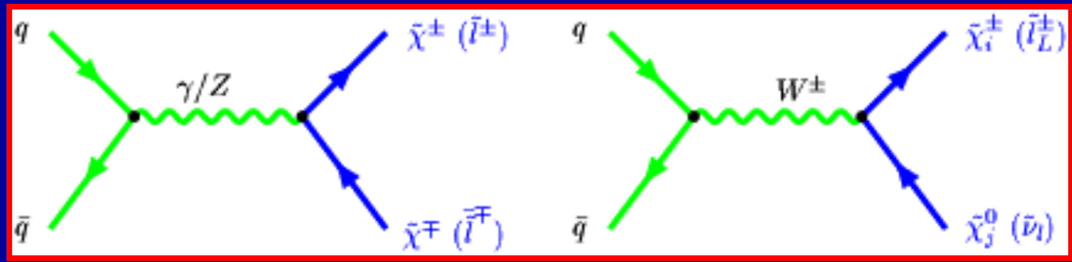
$$-L_{Soft} = A\{y_t Q_L H_2 U_R + y_b Q_L H_1 D_R + y_L L_L H_1 E_R\} + B\mu H_1 H_2 + m_0^2 \sum_i |\varphi_i|^2 + \tfrac{1}{2} M_{1/2} \sum_\alpha \tilde{\lambda}_\alpha \tilde{\lambda}_\alpha$$

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

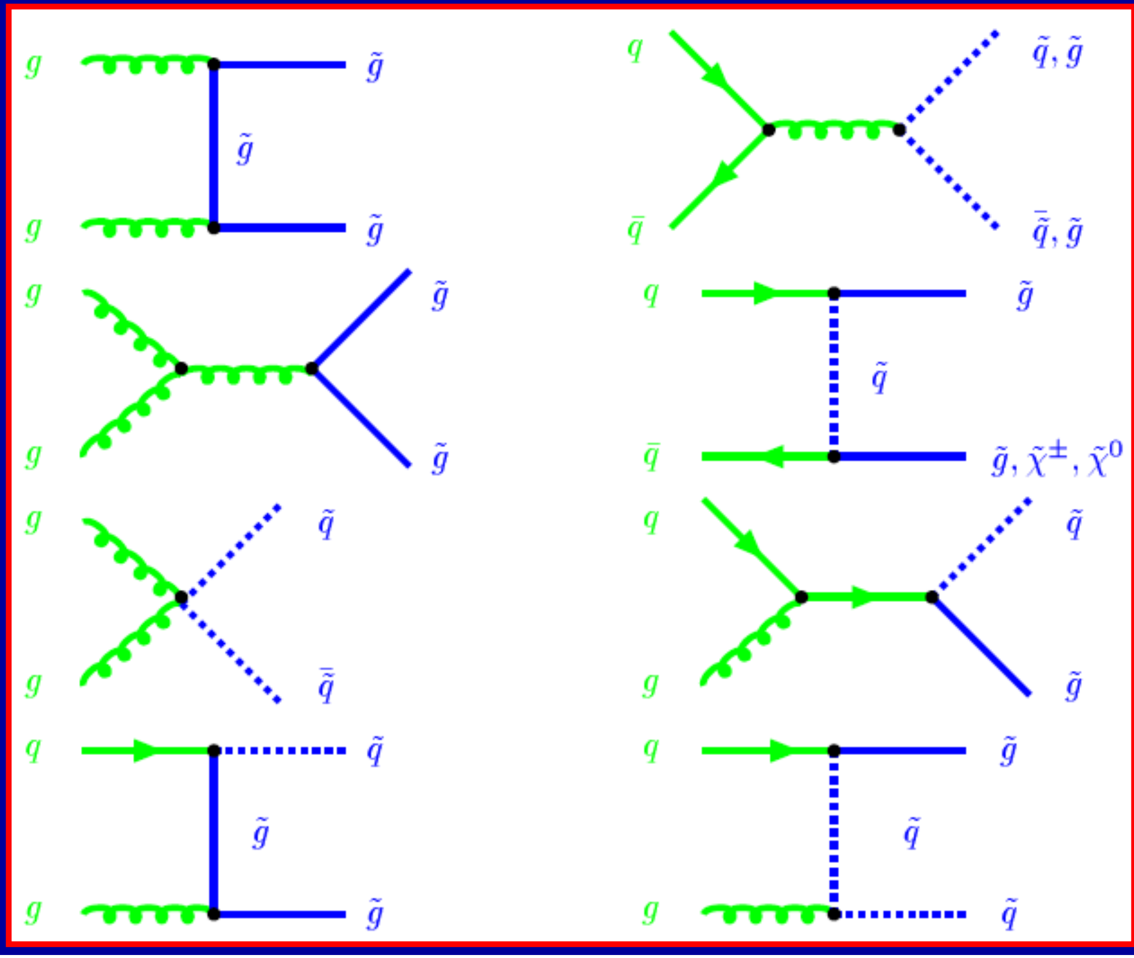
versus $m \quad \text{and} \quad \lambda$ in the SM

Superpartners Production at LHC

Annihilation

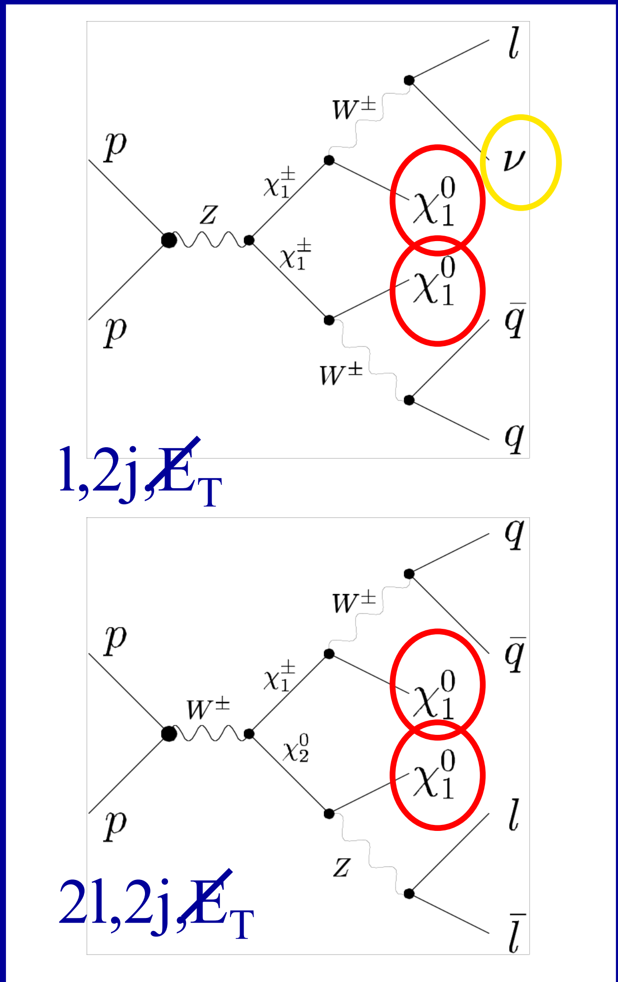


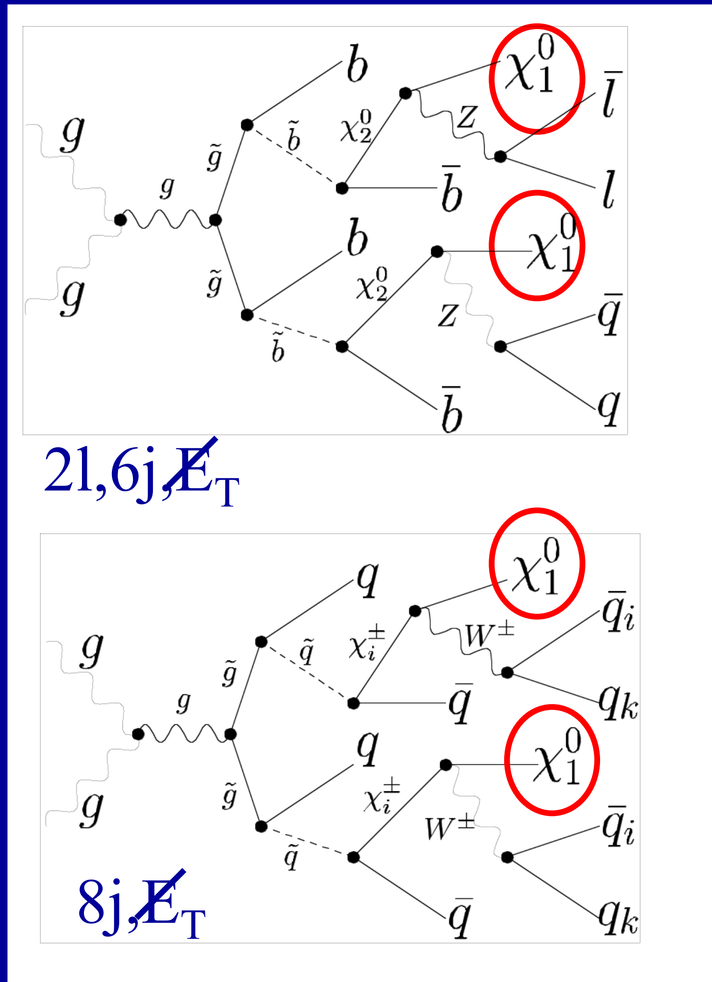
Quark- gluon Fusion



Creation and Decay of Superpartners in Cascade Processes @ LHC

weak int's



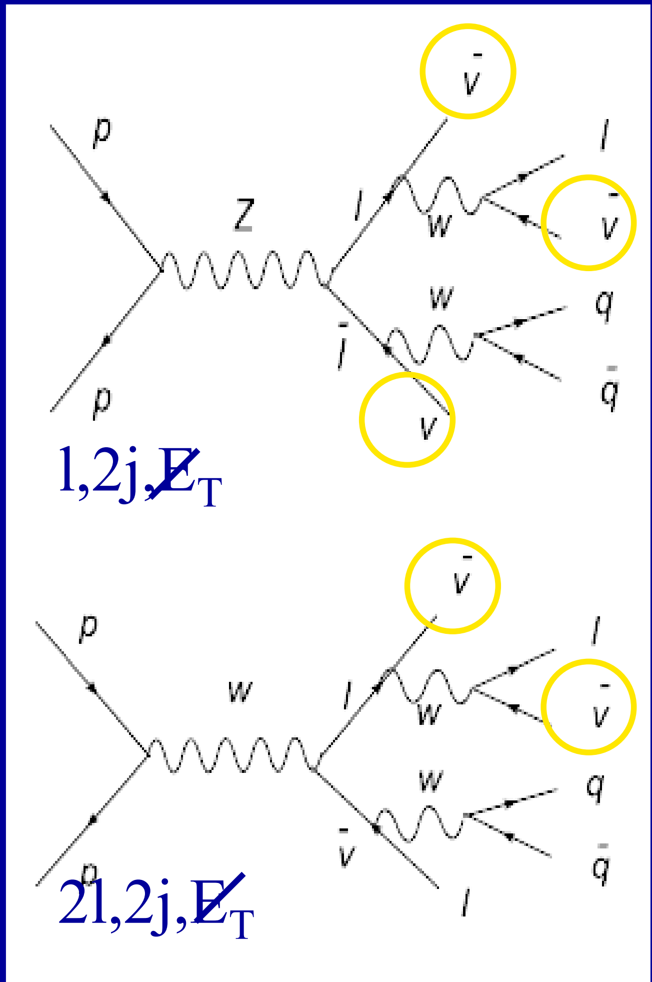


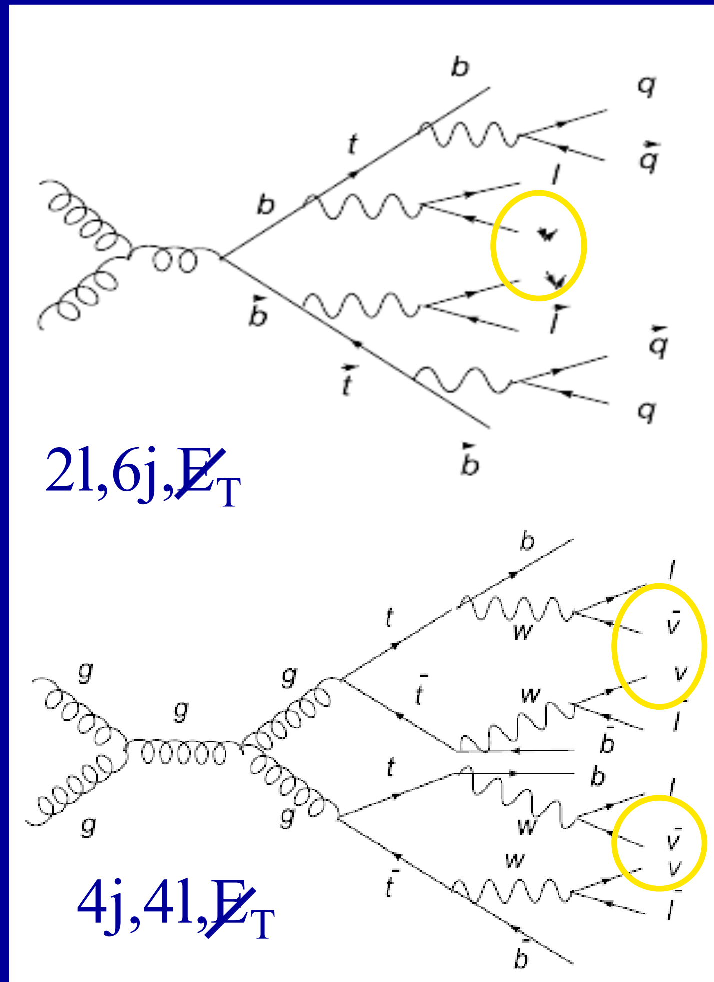
strong int's

Typical SUSY signature: Missing Energy and Transverse Momentum

Background Processes of the SM for creation of Superpartners

weak int's

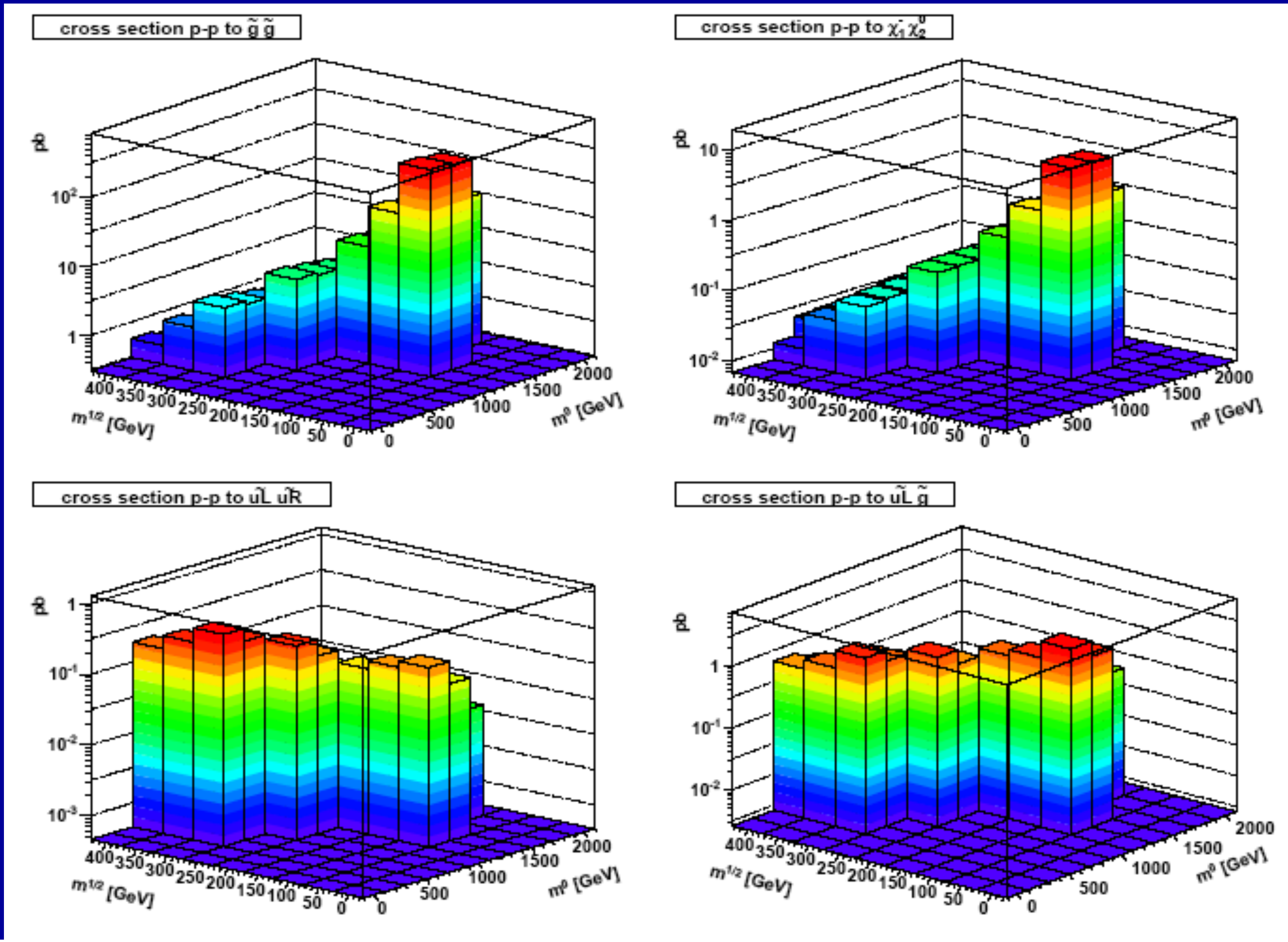




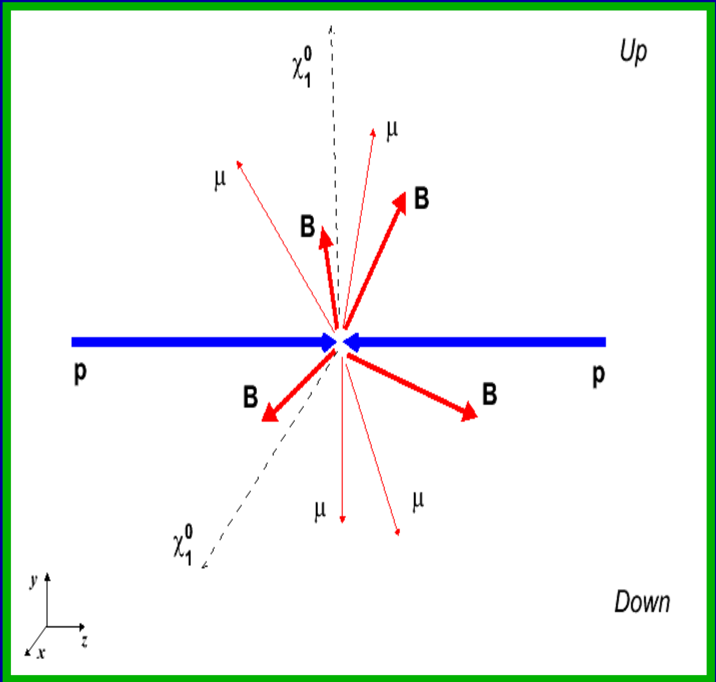
strong int's

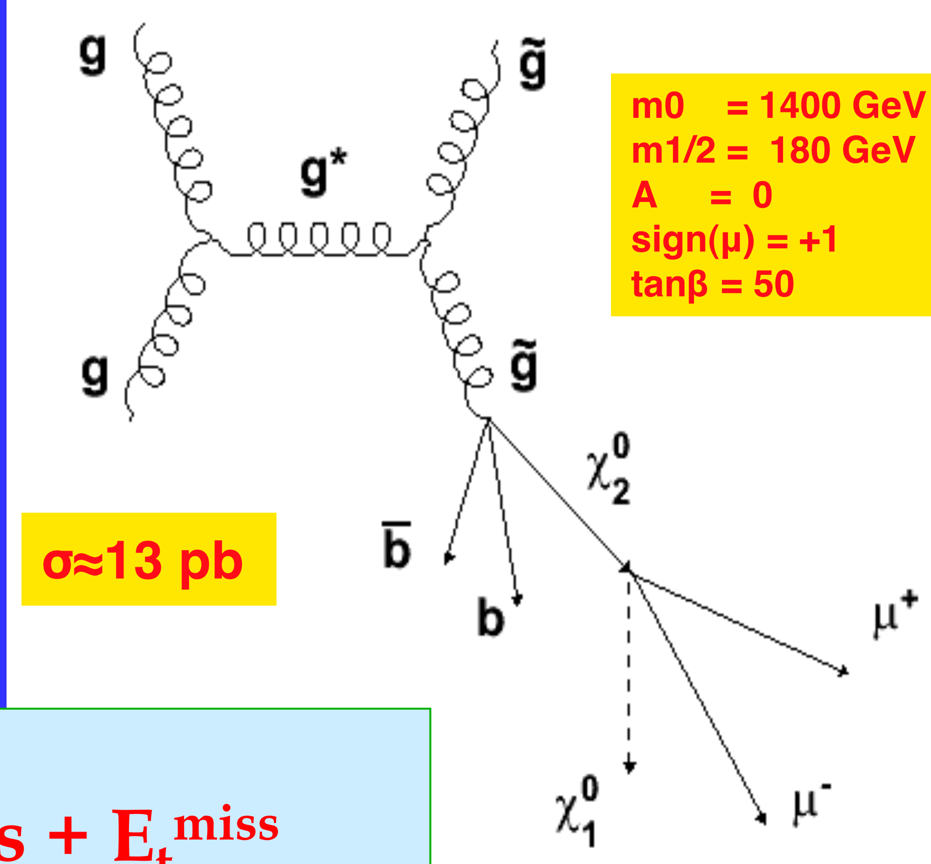
The x-sections are usually much smaller than for creation of SUSY

Cross-sections for SUSY creation @ LHC



Creation of Gluino @ LHC





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

σ≈13 pb

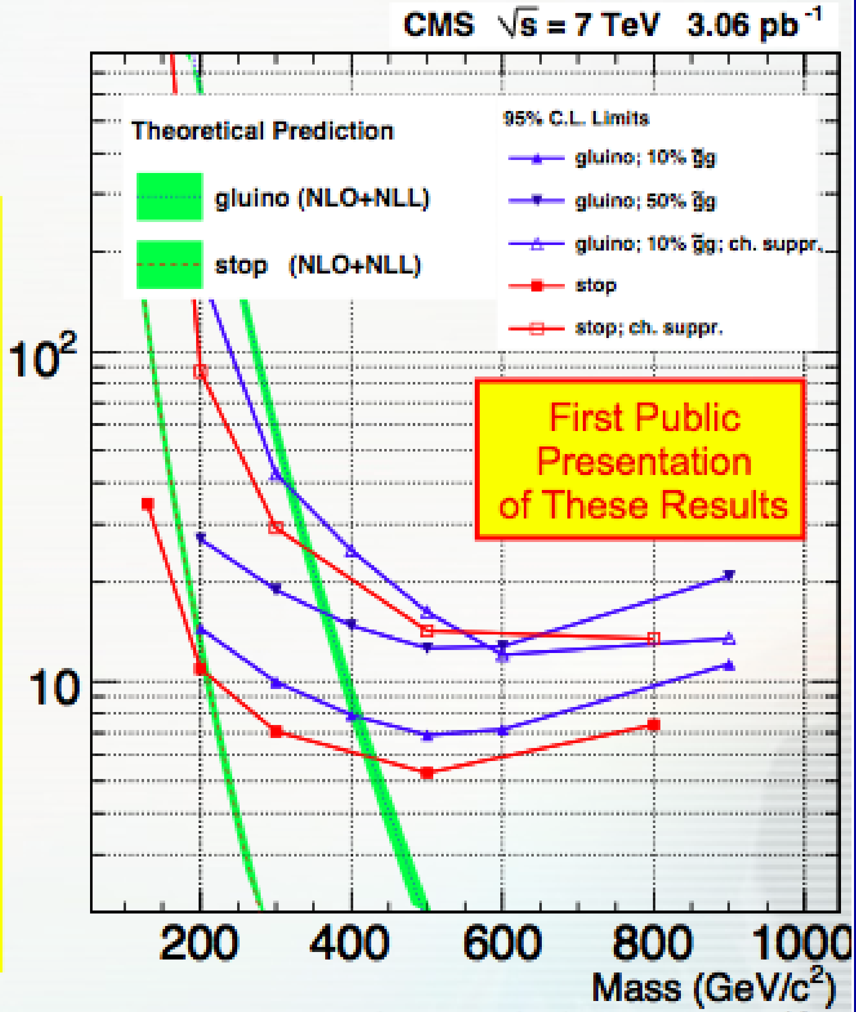
Signature:
4 b-jets + 4 muons + E_t^{miss}

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

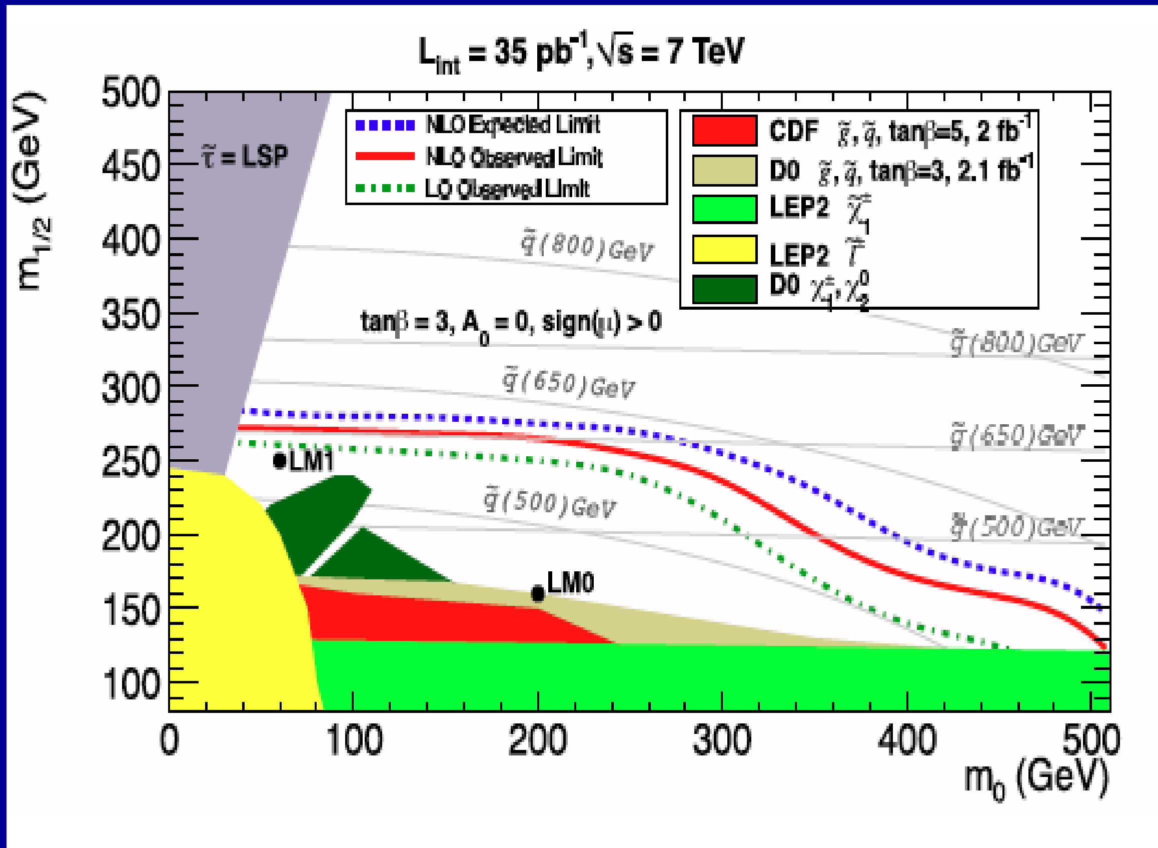
arXiv:1101.1645, submitted to JHEP



First SUSY results @ LHC

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

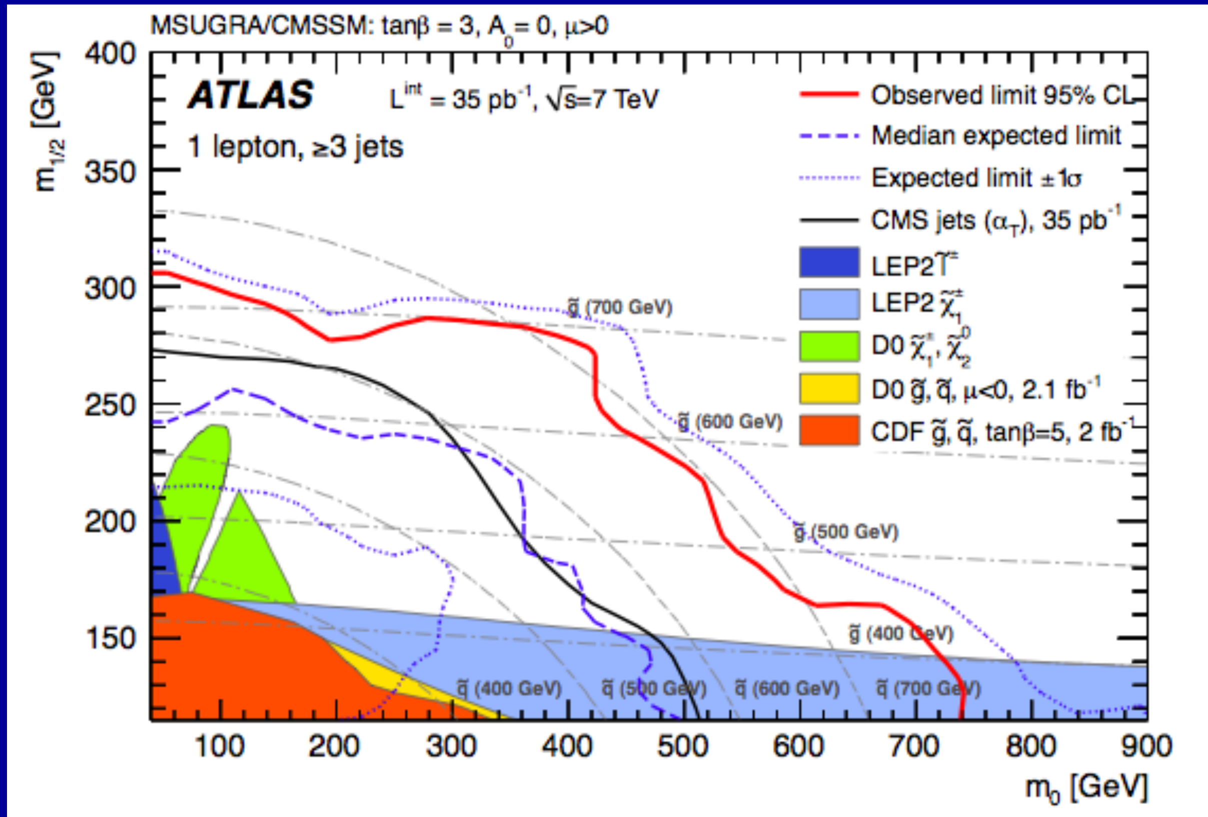
CMS



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

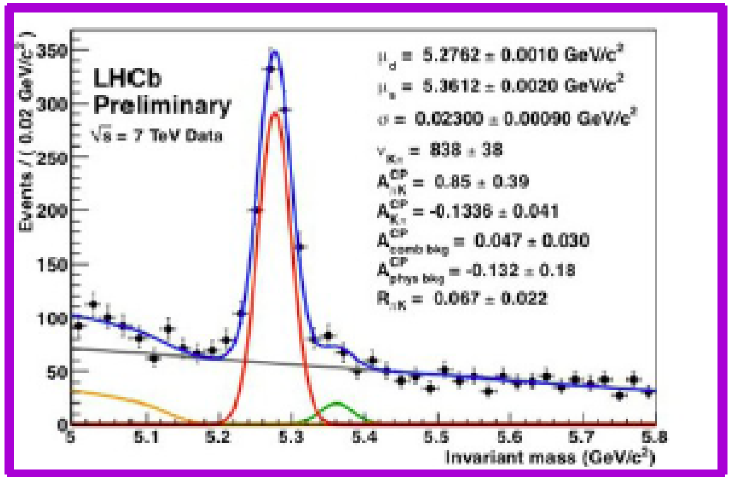
What if no SUSY is found?

- 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 ?

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



B_s^0/B_d^0 yield = (10.7±2.0)%,

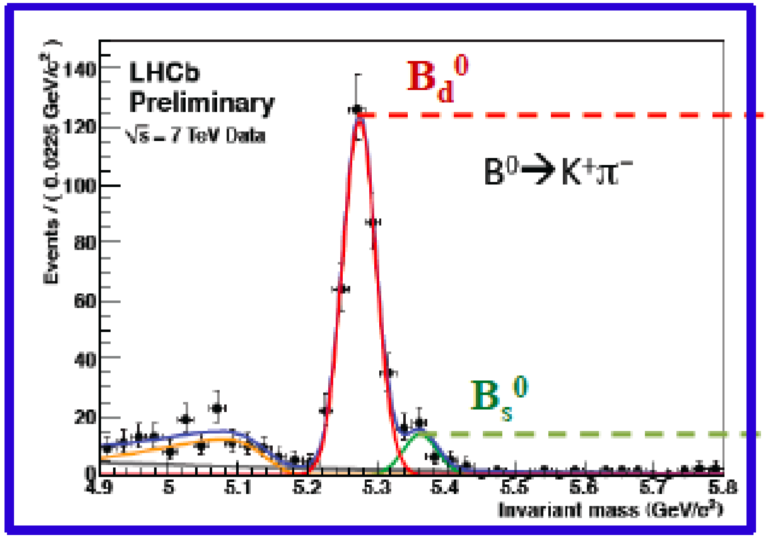
$A_{CP}(B_d^0)$=-0.134±0.041
(HFAG: -0.098±0.012)

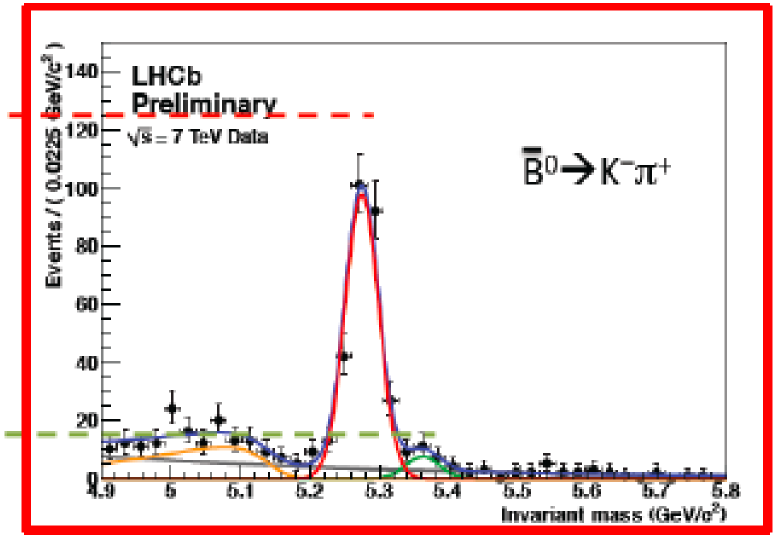
$A_{CP}(B_s^0)$=-0.43±0.17
(CDF: 0.39±0.15±0.08 in 1 fb^{-1})

CP violation →
particle and anti-particle
behave differently!

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

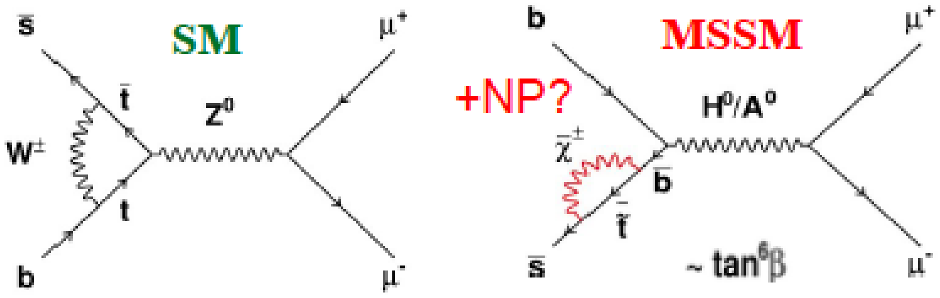
- only raw asymmetries
- not accounted for production & detector asymmetries
- ➢ this is not a physics result yet!



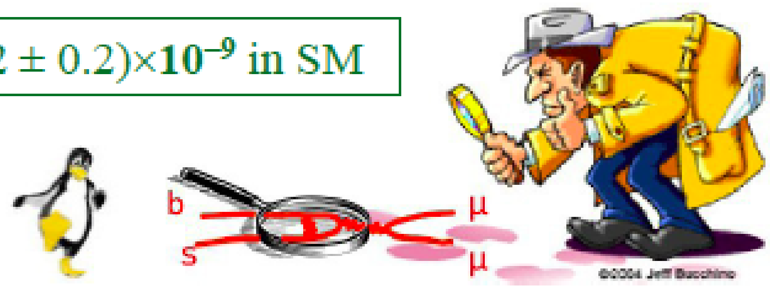


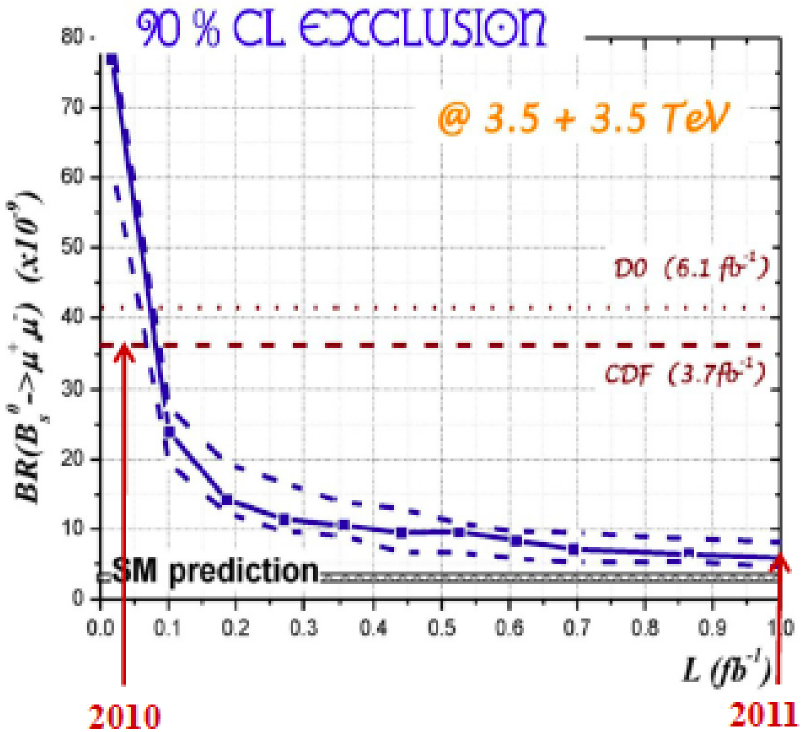
Probing New Physics in loop decays: $B_s \to \mu\,\mu$

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



BR = (3.2 ± 0.2)×**10**$^{-9}$ in SM



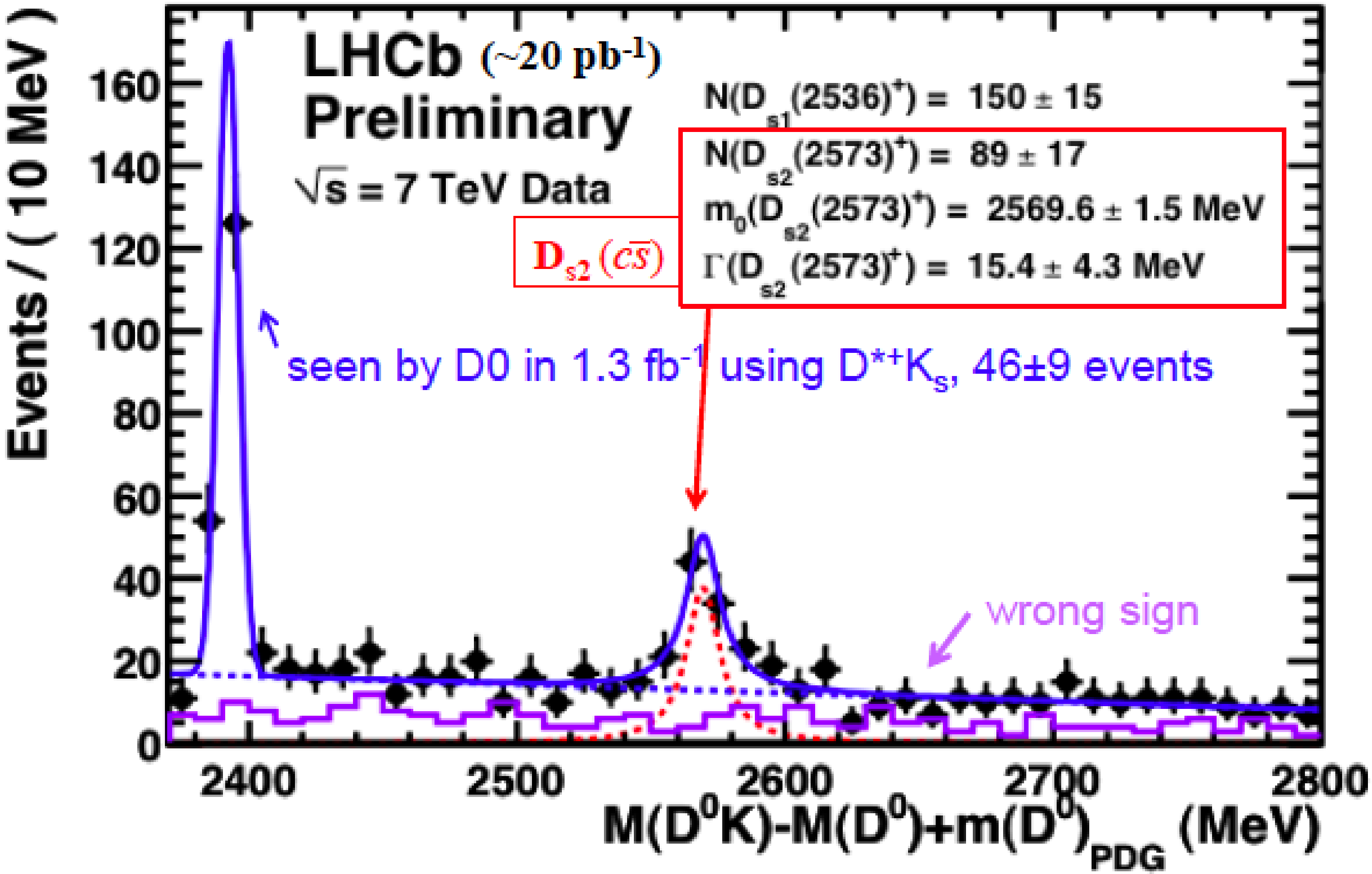


- ✓ sensitive to New Physics, can be strongly enhanced in SUSY with scalar Higgs exchange
- ✓ sensitive probe for MSSM with large tanβ:
  $B(B_S\to\mu^+\mu^-) \sim \tan\beta^{\,6} / M_A^{\,4}$

- ✓ 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

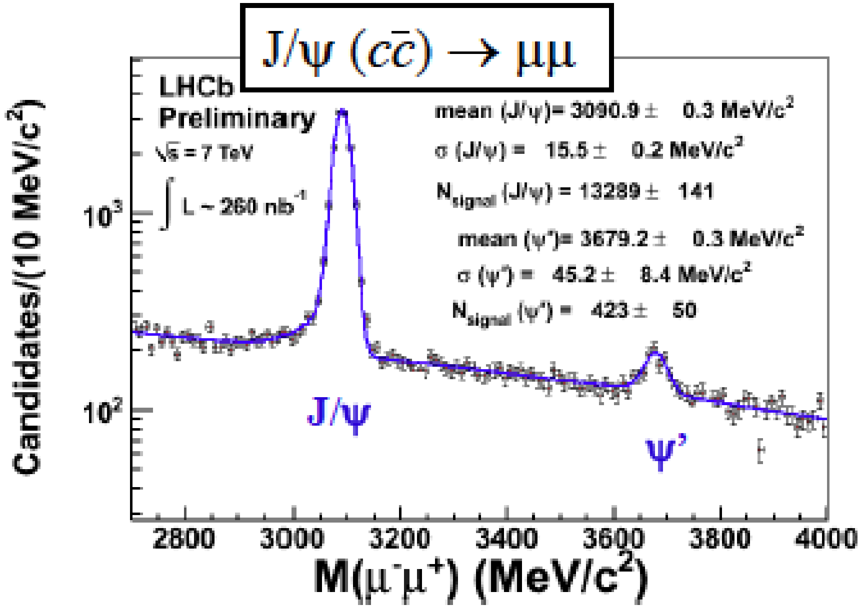
First observation of $B_s \rightarrow D_{s2}\, X\, \mu\, \nu$ with $D_{s2} \rightarrow D^0 K^+$

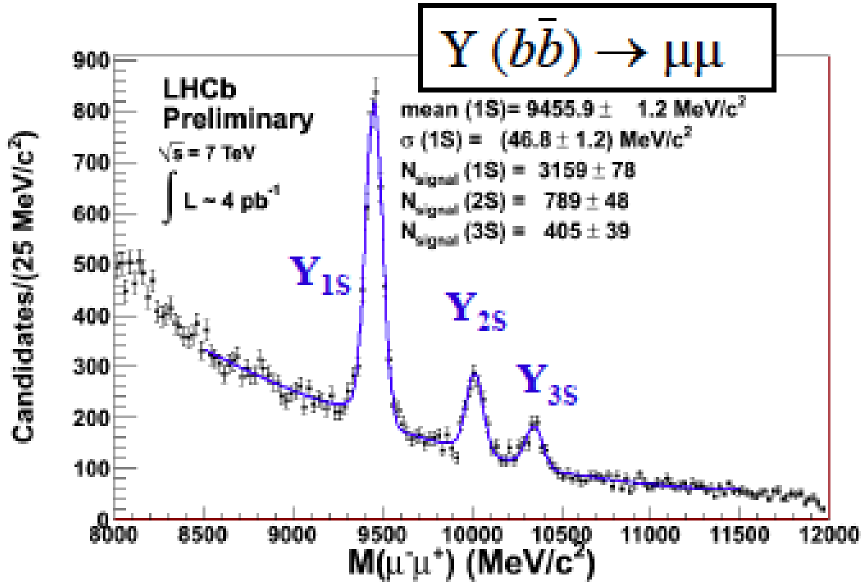


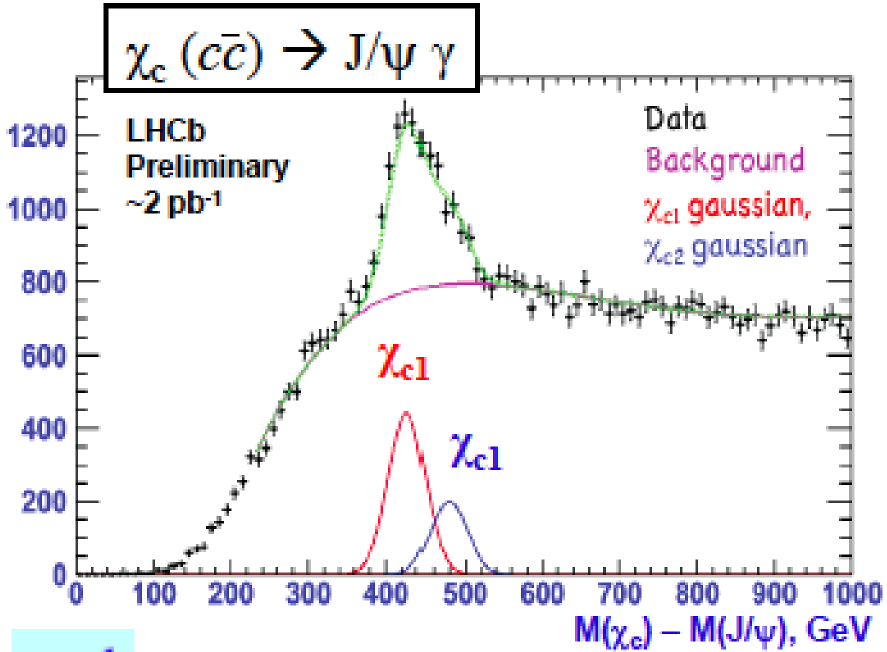
➢ **and more first observations in the pipeline… !**

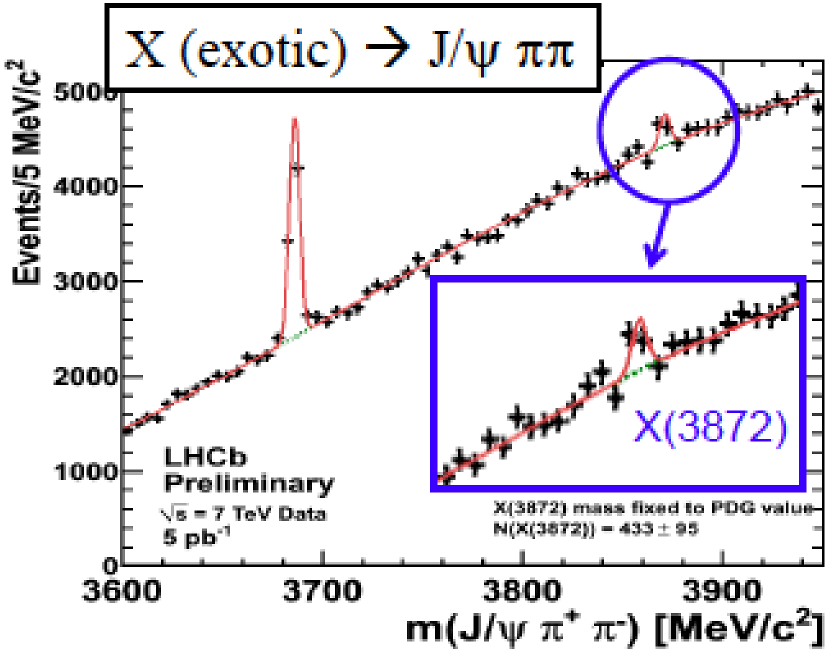
Spectroscopy

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



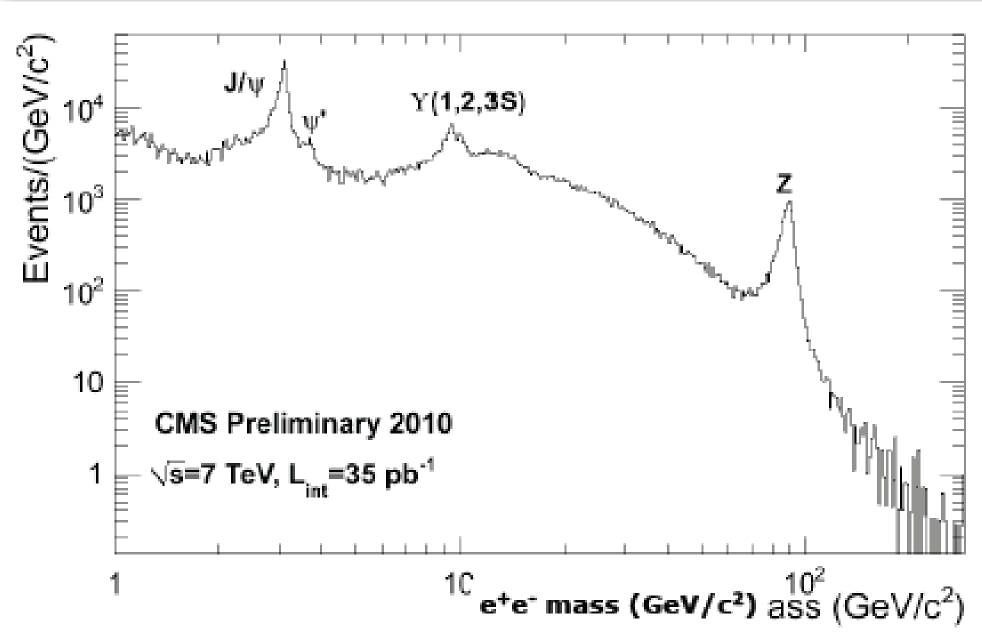




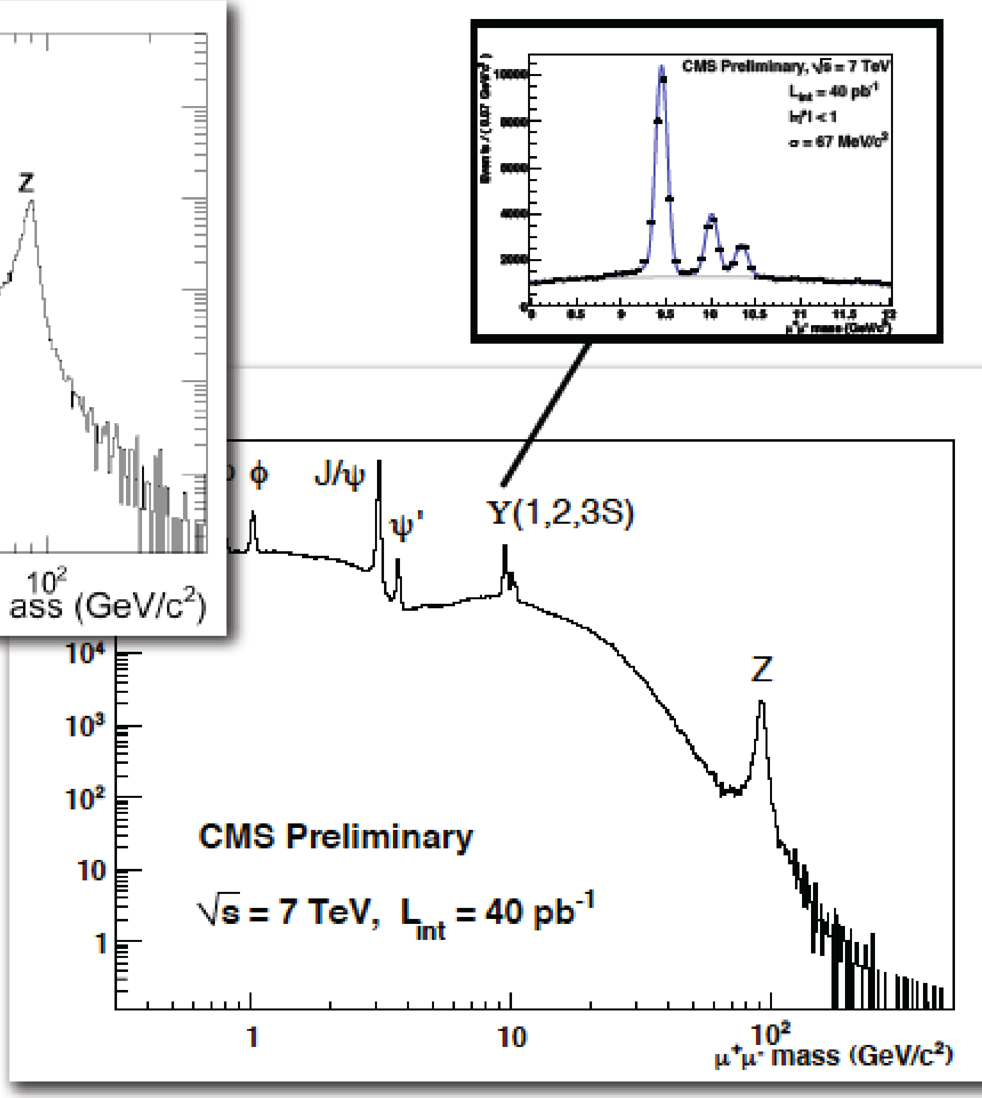


Di-Lepton Spectra

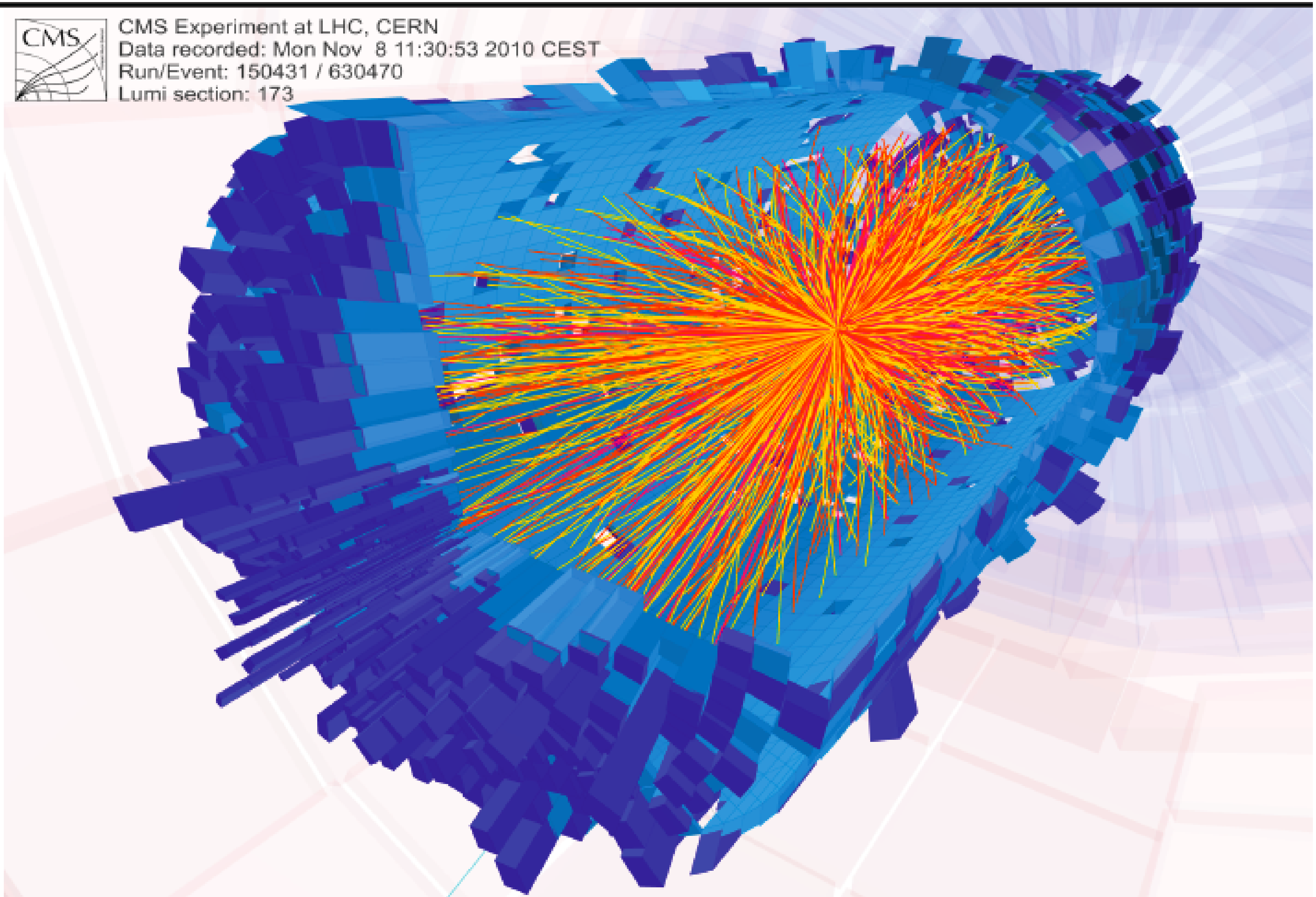
Di-Electron and Di-Muon Spectra



High-Resolution
Electron & Muon
Reconstruction over
full kinematic range



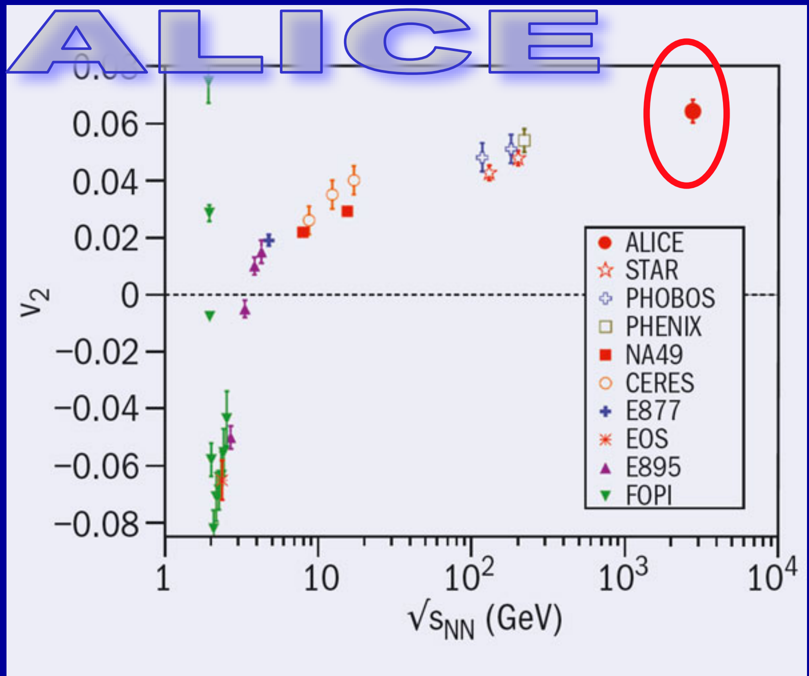
Heavy Ion (Pb-Pb) Collisions



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

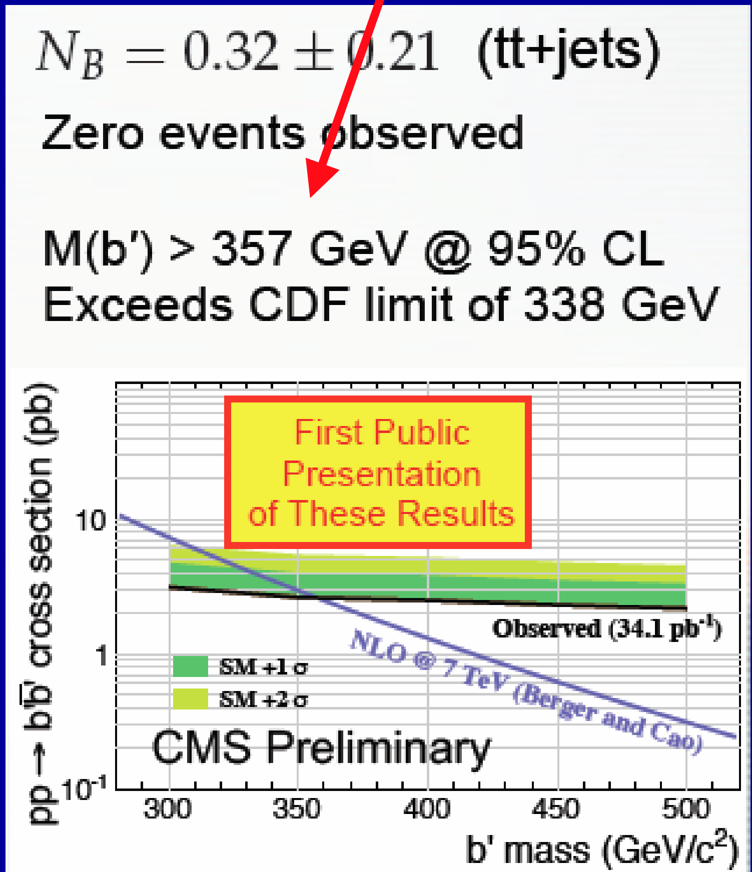
$$\eta / s = \frac{h}{4\pi k_B}$$

First obtained from AdS/CFT conjecture

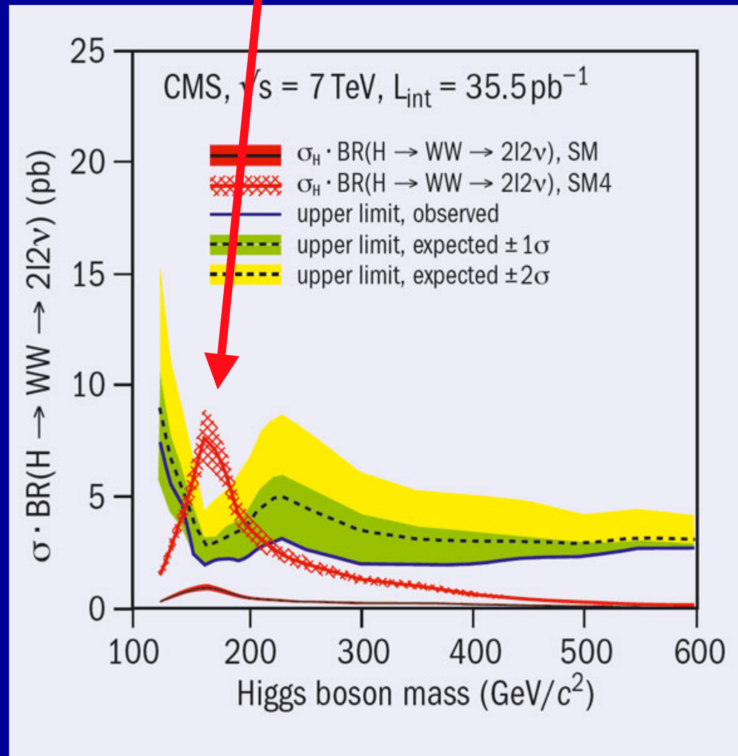
Elliptic flow v_2 at 2.76 TeV compared with lower energies

Search for 4-th generation

New quark exclusion

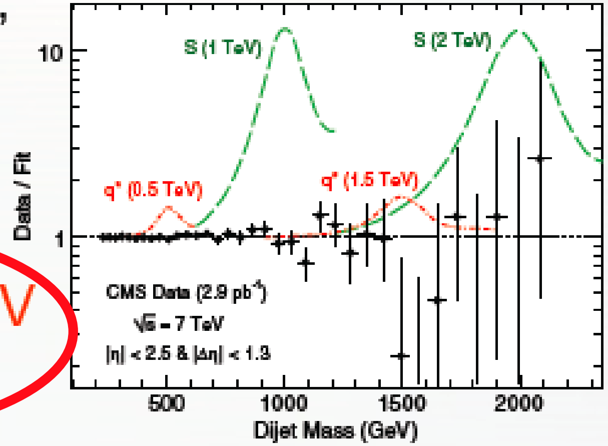


Higgs mass exclusion
144< Mh <207 Gev



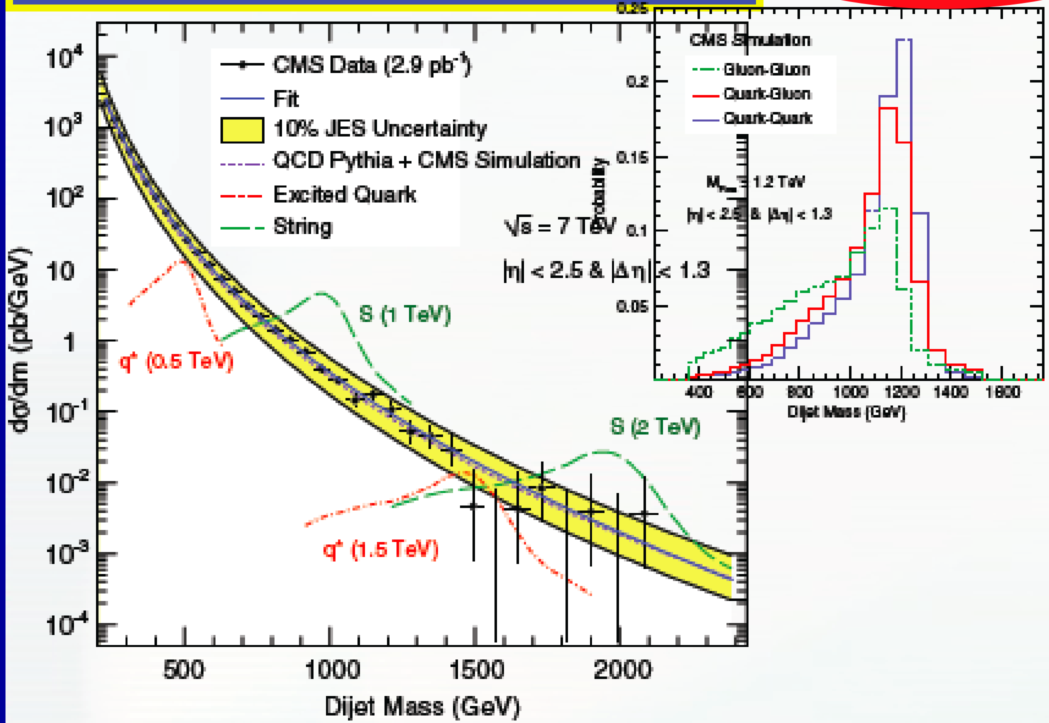
Resonances and Excitations

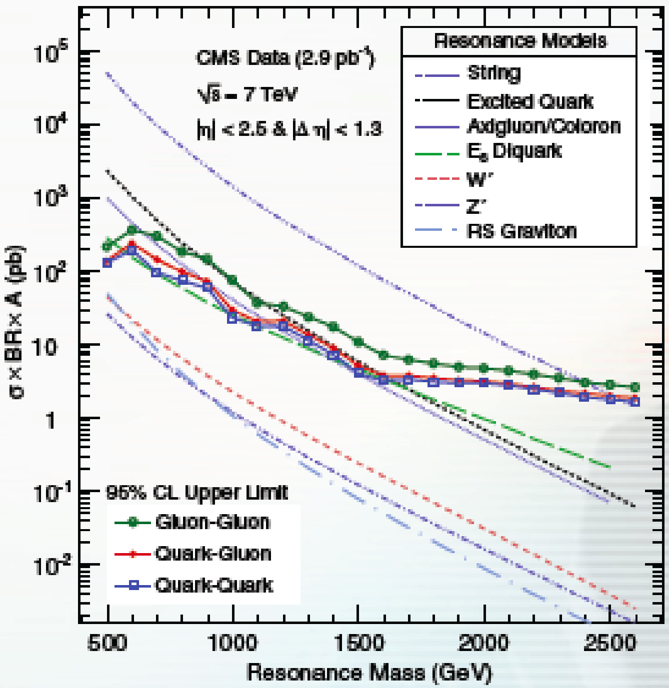
- Parameterize dijet mass spectrum with a smooth, 4-parameter fit function: $\frac{d\sigma}{dm} = \frac{P_0(1 - m/\sqrt{s})^{P_1}}{(m/\sqrt{s})^{P_2 + P_3 \ln(m/\sqrt{s})}}$, and look for bumps
- In their absence, set limits



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

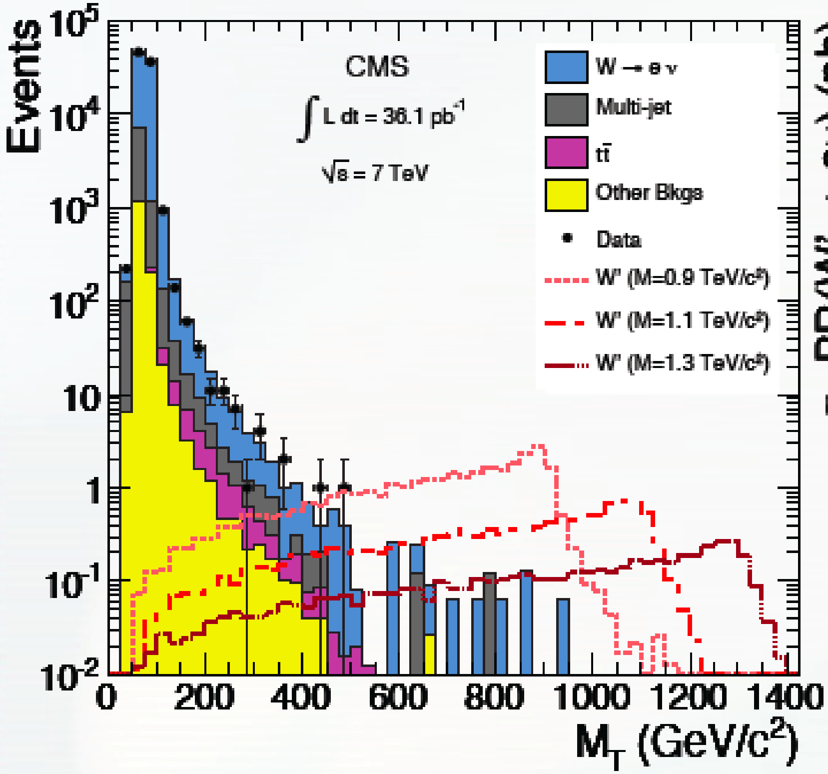
Phys. Rev. Lett. **105**, 211801 (2010)

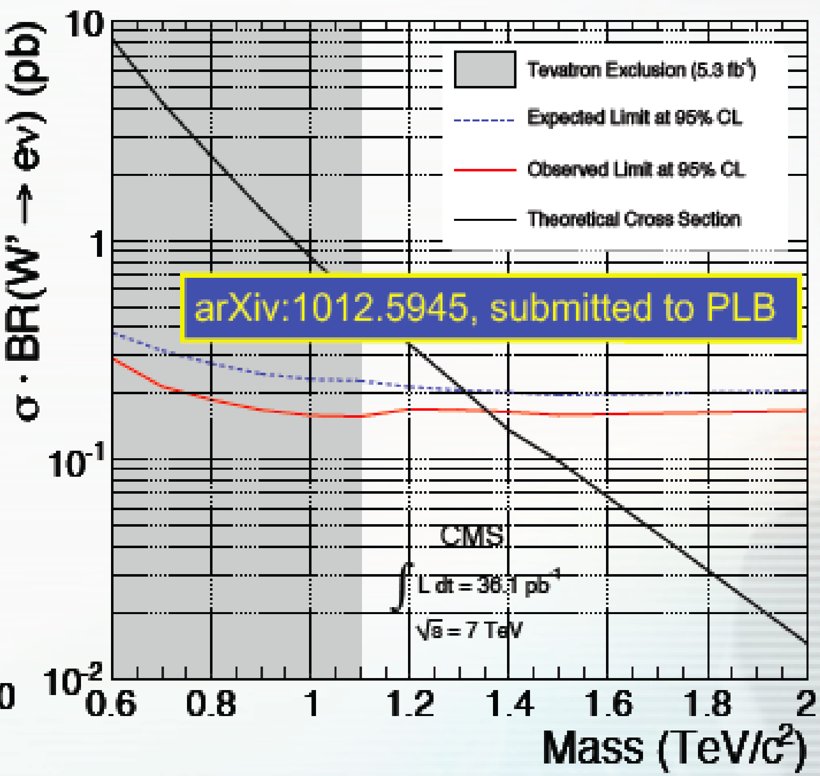




Limits on Z', W' and G_{KK}

- 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} PRL **105**, 211801 (2010)	ATLAS, 0.32 pb^{-1} PRL **105**, 161801 (2010)	CDF, 1130 pb^{-1} 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 (our estimate)
Axigluon/ Coloron	M > 1.17 TeV (M > 1.23 TeV) and not (1.42 < M < 1.53)		M > 1.25 TeV
E6 diquark	Exclude 0.50-0.58 & 0.97-1.08 & 1.45-1.60 TeV (M > 1.05 TeV)		M > 0.63 TeV

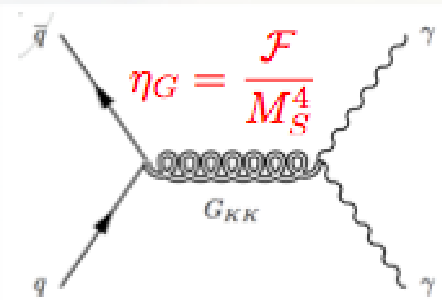
Quark Compositeness (left-handed quarks)		
CMS Centrality PRL **105**, 262001 (2010)	2.9 pb^{-1}	Λ > 4.0 (2.9) TeV actual (observed)
CMS Angular Distributions (to be submitted soon)	36 pb^{-1}	Λ > 5.6 (5.0) TeV
ATLAS (Angular Distributions) (Centrality) PLB **694**, 327 (2011)	3.1 pb^{-1}	Λ > 3.4 (3.5) TeV Λ > 2.0 (2.6) TeV
D0 (Angular Distriburions) PRL **103**, 191803 (2009)	700 pb^{-1}	Λ > 2.84-3.06 (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 $M_S \sim M_D$: $\sigma_{\rm ADD} = \sigma_{\rm SM} + A\eta_G\,\sigma_{\rm int} + B\eta_G^2\,\sigma_{\rm ED},$
  - 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

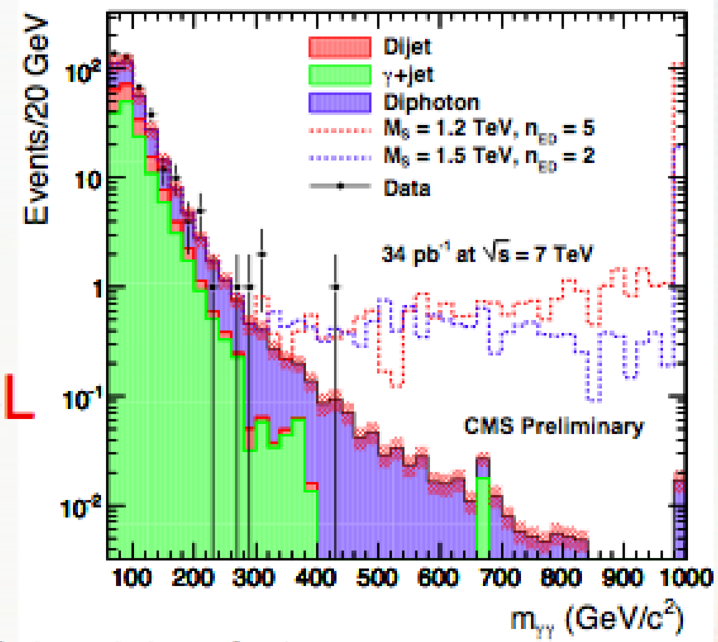
$$\mathcal{F} = \begin{cases} \log\left(\frac{M_S^2}{M^2}\right), & n = 2 \\ \frac{2}{n-2}, & n > 2 \end{cases}, \text{ (HLZ [30]);}$$
Phys. Rev. **D59** (1999) 105006

$$\mathcal{F} = \frac{2\lambda}{\pi} = \pm\frac{2}{\pi}, \text{ (Hewett [29]).}$$
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)							
	λ > 0	λ < 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

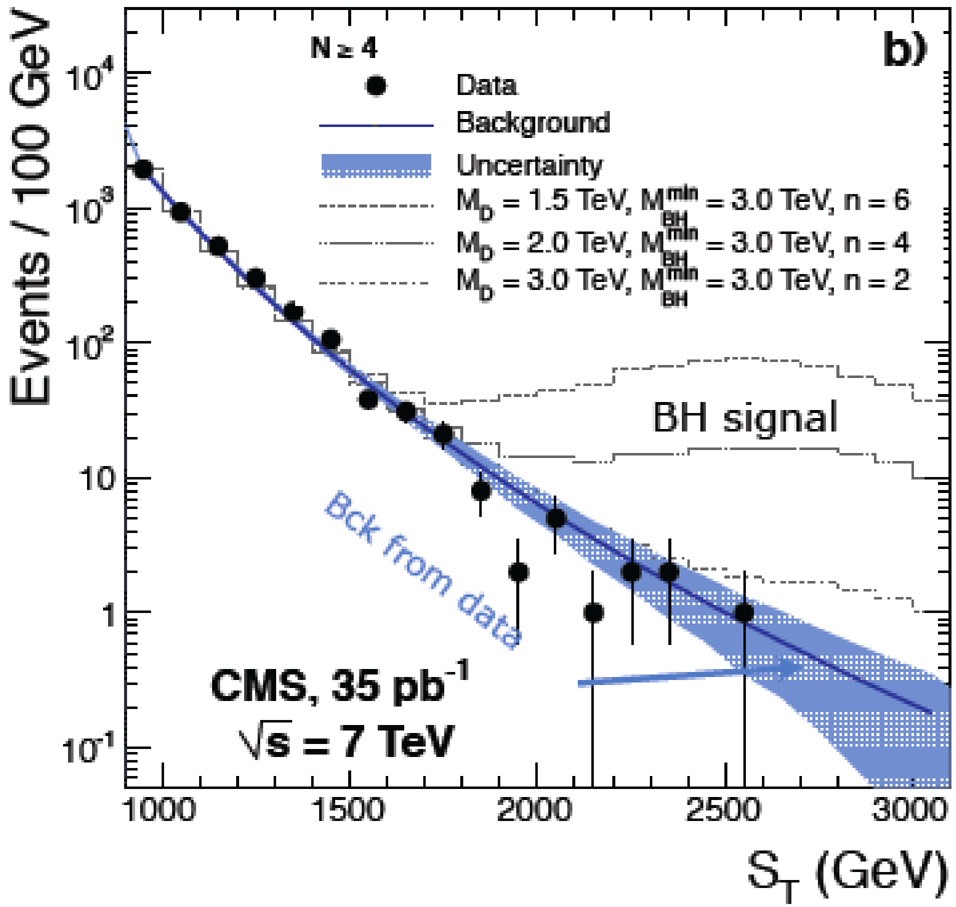
Search for Microscopic Black Holes

Submitted to PLB
arXiv:1012.3375 [hep-ex]

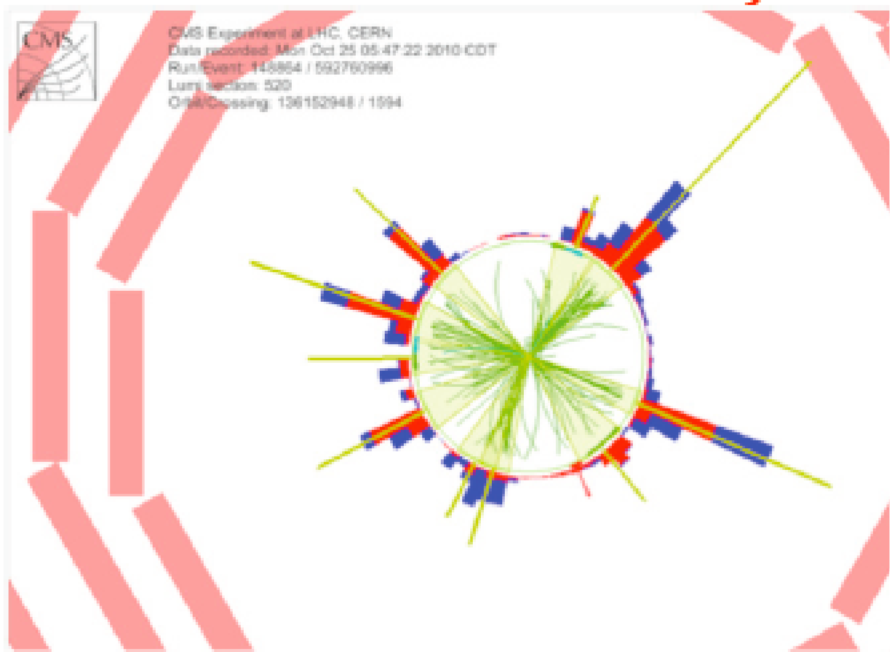
Extra dimensions?!

Decay into highly-energetic multiparticle final states

The first search for black holes at a particle accelerator



Candidate event with 10 jets

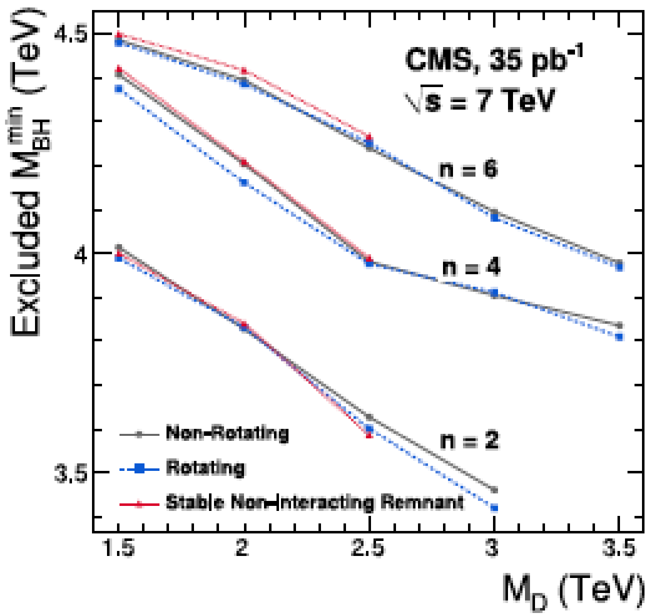


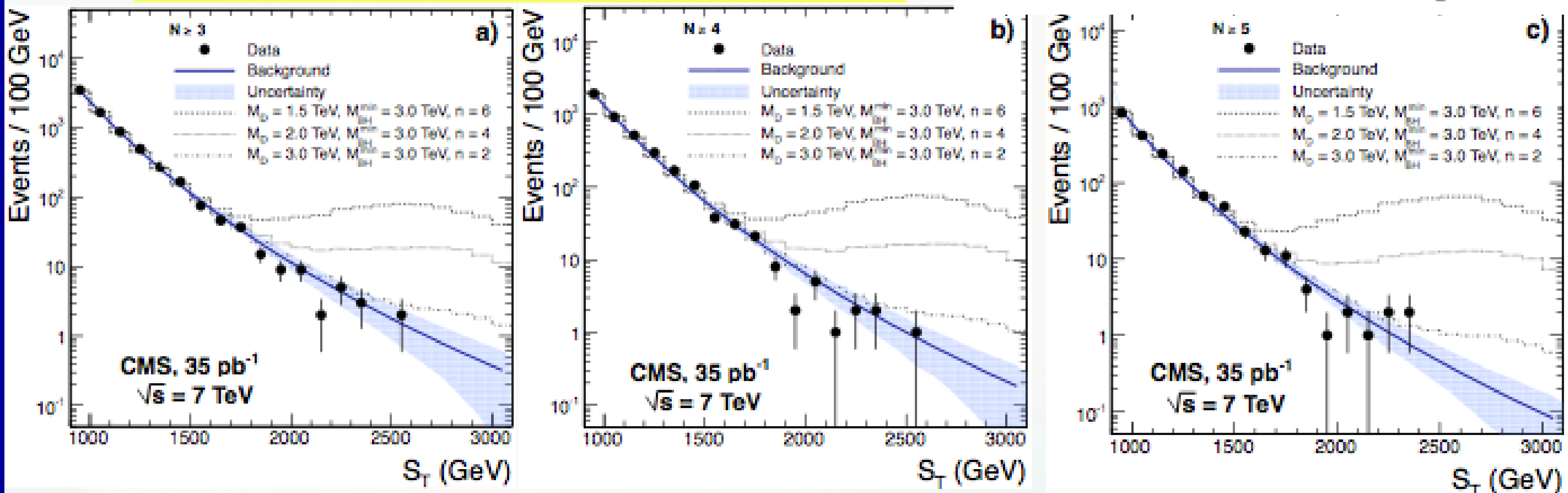
Set limits of 3.5-4.5 TeV on the minimum black hole mas

Limits on Black Holes

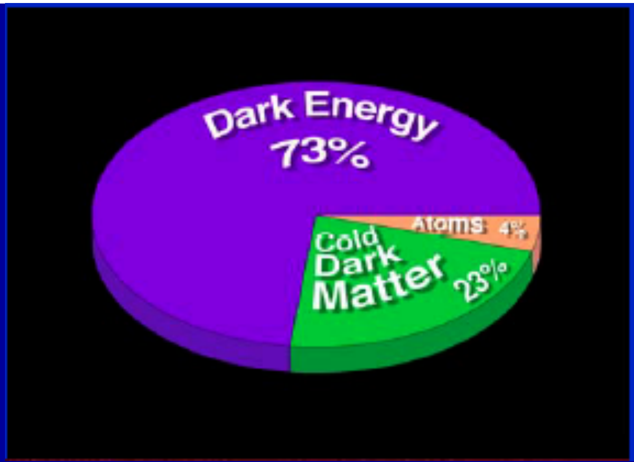
- Used the N=2 shape with its uncertainties, to fit higher multiplicities, where the signal is expected to be most prominent
- Given no excess, set limits on the minimum BH mass of 3.5-4.5 TeV in semi-classical approximation
- First direct limits at colliders

arXiv:1012.3375, submitted to PLB





The Dark Matter



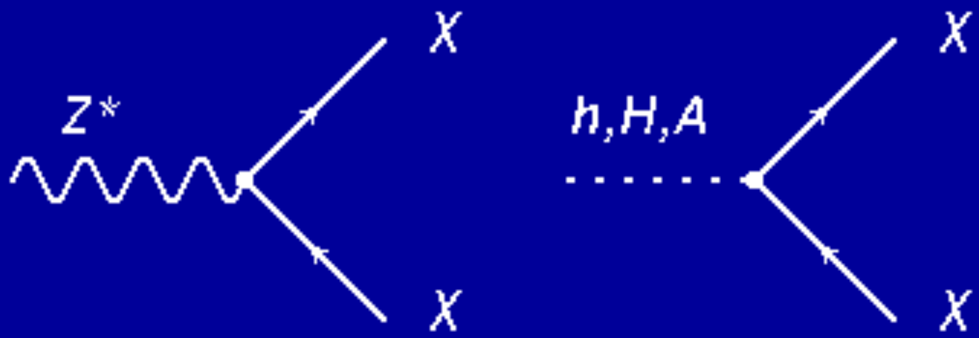
- Makes 23% of matter in the Universe

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