SEARCH FOR NEW PHYSICS AT LARGE HADRON COLLIDER

(Hope not last hadron collider)

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And CMS Physics TDR, v.2

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OUTLINE

- 1. Introduction
- 2. Search for standard Higgs boson
- 3. Search for supersymmetry(MSSM model)
- 4. Search for new physics beyond the SM and the MSSM
- 5. Conclusions

1.Introduction

LHC(Large Hadron Collider)
Start: 2008
Two proton beams with total energy
$E = 14$ TeV
Low luminosity stage with $L_{low} = 10^{33}$ $cm^{-2}s^{-1}$

Remember: Nev = sigma Lt

with total luminosity $L_t = 10$ fb^{-1} per year   Remember: 1 fb = 10^{-39} cm^2s^{-1}

Two big detectors:
CMS(Compact Muon Solenoid)
ATLAS(A Toroidal LHC Apparatus)

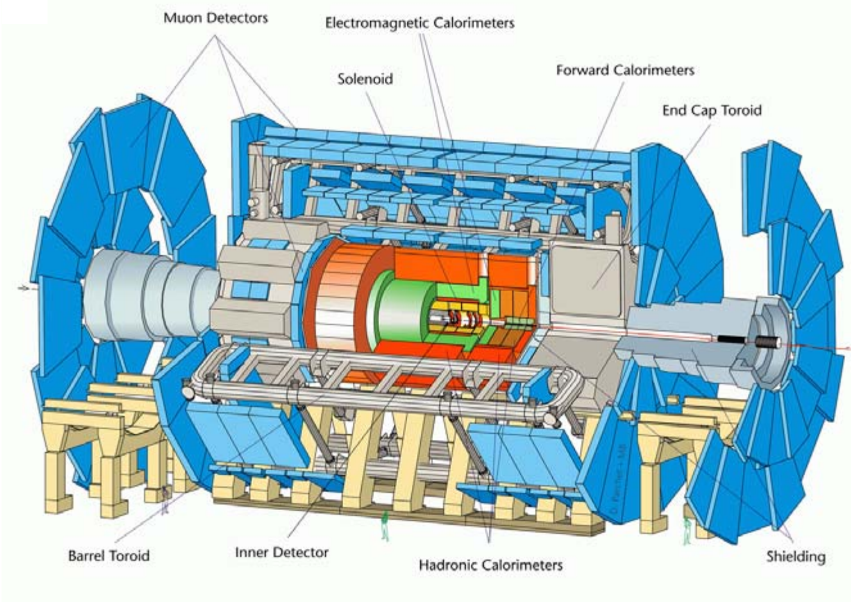
In this talk we review

1. The search for Standard Higgs boson
2. The search for supersymmetry
3. The search for new physics beyond SM and MSSM

ATLAS and CMS Experiments

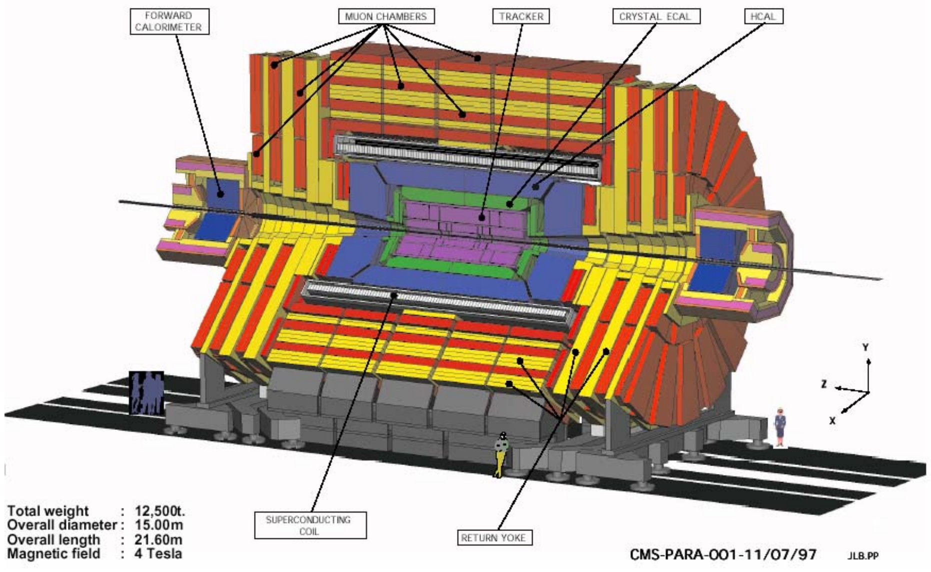
Large general-purpose particle physics detectors

A Large Toroidal LHC ApparatuS



Total weight	**7000 t**
Overall diameter	**25 m**
Barrel toroid length	**26 m**
End-cap end-wall chamber span	**46 m**
Magnetic field	**2 Tesla**

Compact Muon Solenoid



Total weight	**12 500 t**
Overall diameter	**15.00 m**
Overall length	**21.6 m**
Magnetic field	**4 Tesla**

Detector subsystems are designed to measure:
energy and momentum of γ ,e, μ, jets, missing E_T up to a few TeV

Higgs boson search

- The existence of the Higgs boson is the direct consequence of the renormalizability of electroweak interactions and vice versa
So the discovery of the Higgs boson last nondiscovered ingredient of Standard Model will be the triumph of the renormalizability approach which severely restricts the form of possible interactions and fixes Lagrangian up to several arbitrary terms with D =<4

2. Standard Higgs boson search

In $SU(3)\otimes SU(2)\otimes U(1)$ Standard Model

$H(X)=(H_1(x),H_2(x))$ Higgs field is SU(2)$_L$ doublet

In unitare gauge $H(x)=(0,\frac{v}{\sqrt{2}}+\frac{H(x)}{\sqrt{2}})$, v=242GeV

The most important interactions are:

$$\frac{2M_W^2}{v}HW_\mu^+W+\frac{M_Z^2}{v}Z_\mu Z^\mu-\frac{m_t}{v}H\bar{t}t-\frac{m_\tau}{v}\bar{\tau}\tau$$

Experimental bounds on the Higgs boson mass

$m_H \geq 114.4 GeV$ LEP2 bound

<190 GeV (rad.cor.LEP1)

Higgs boson decays

The most important Higgs boson decays are:

$$H \to \gamma\gamma$$

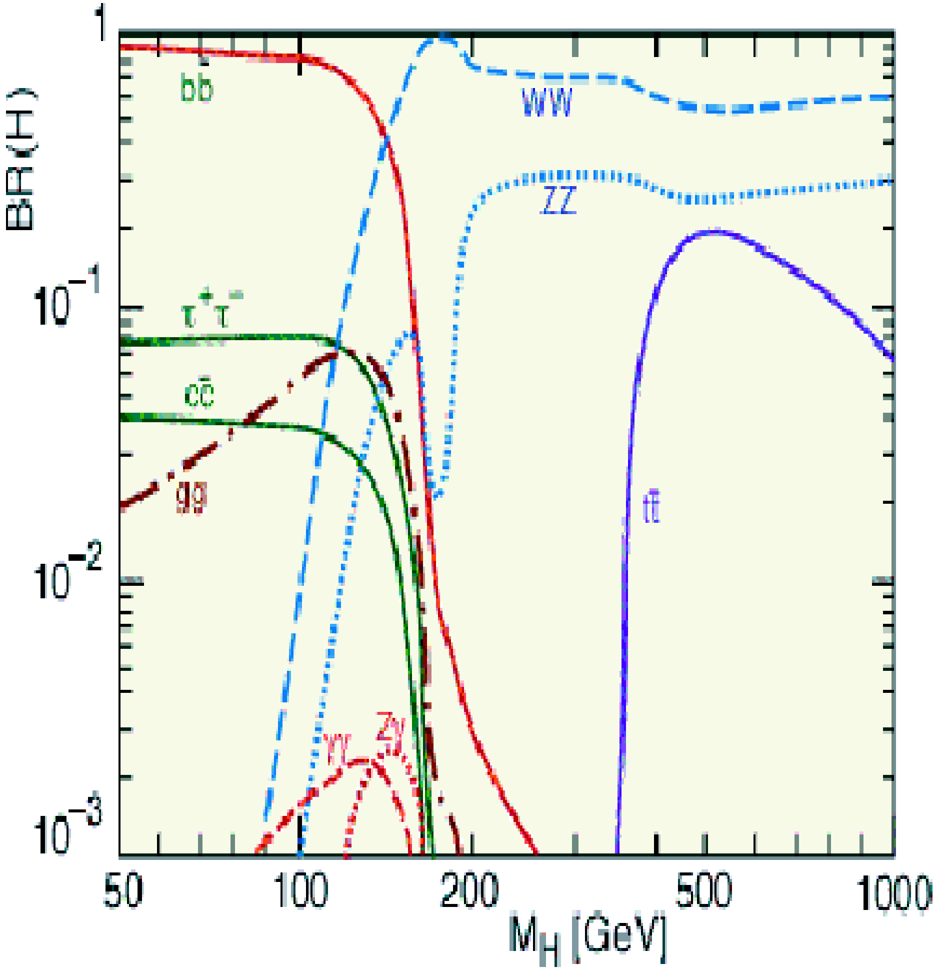
$$H \to ZZ^{*}/ZZ \to l^{+}l^{-}l'^{+}l'^{-}$$

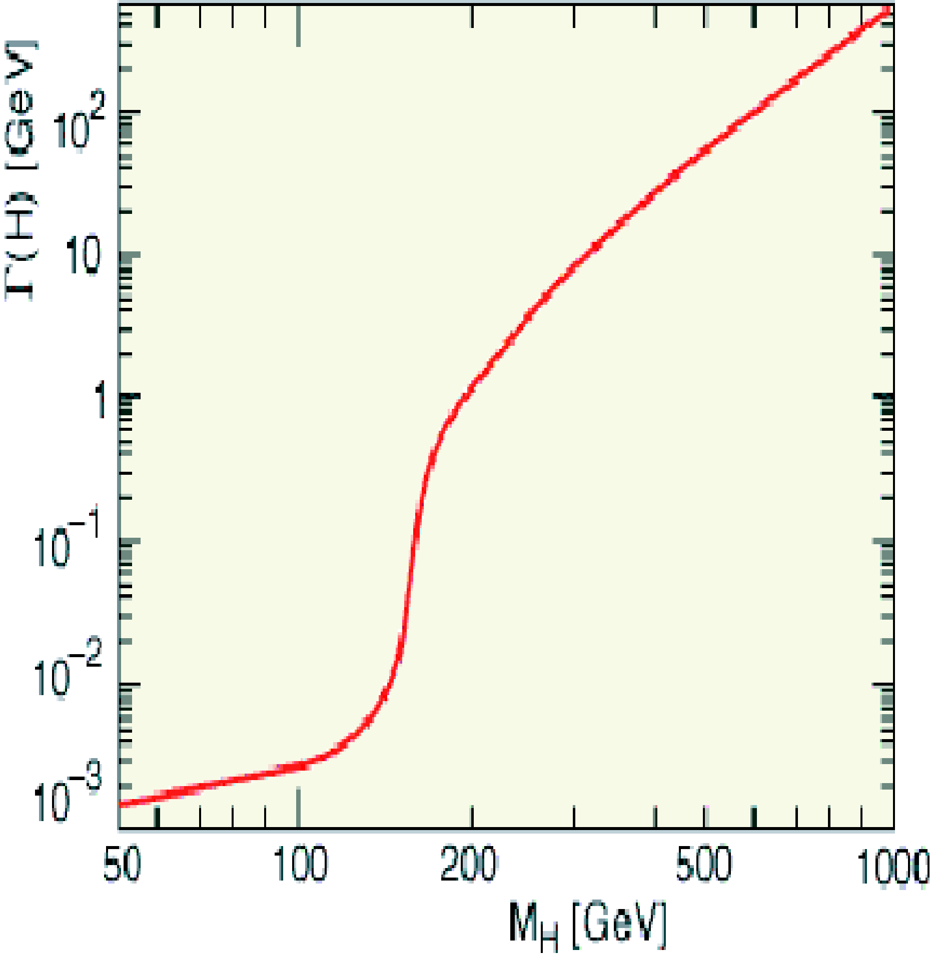
$$H \to WW^{*}/WW \to l^{+}\upsilon l'^{-}\upsilon$$

$$H \to b\overline{b}$$

$$H \to \tau\overline{\tau}$$

Branching ratios and decay width of the SM Higgs boson





Higgs boson production mechanisms

1. Gluon fusion: $gg \to H$ (the main mechanism)

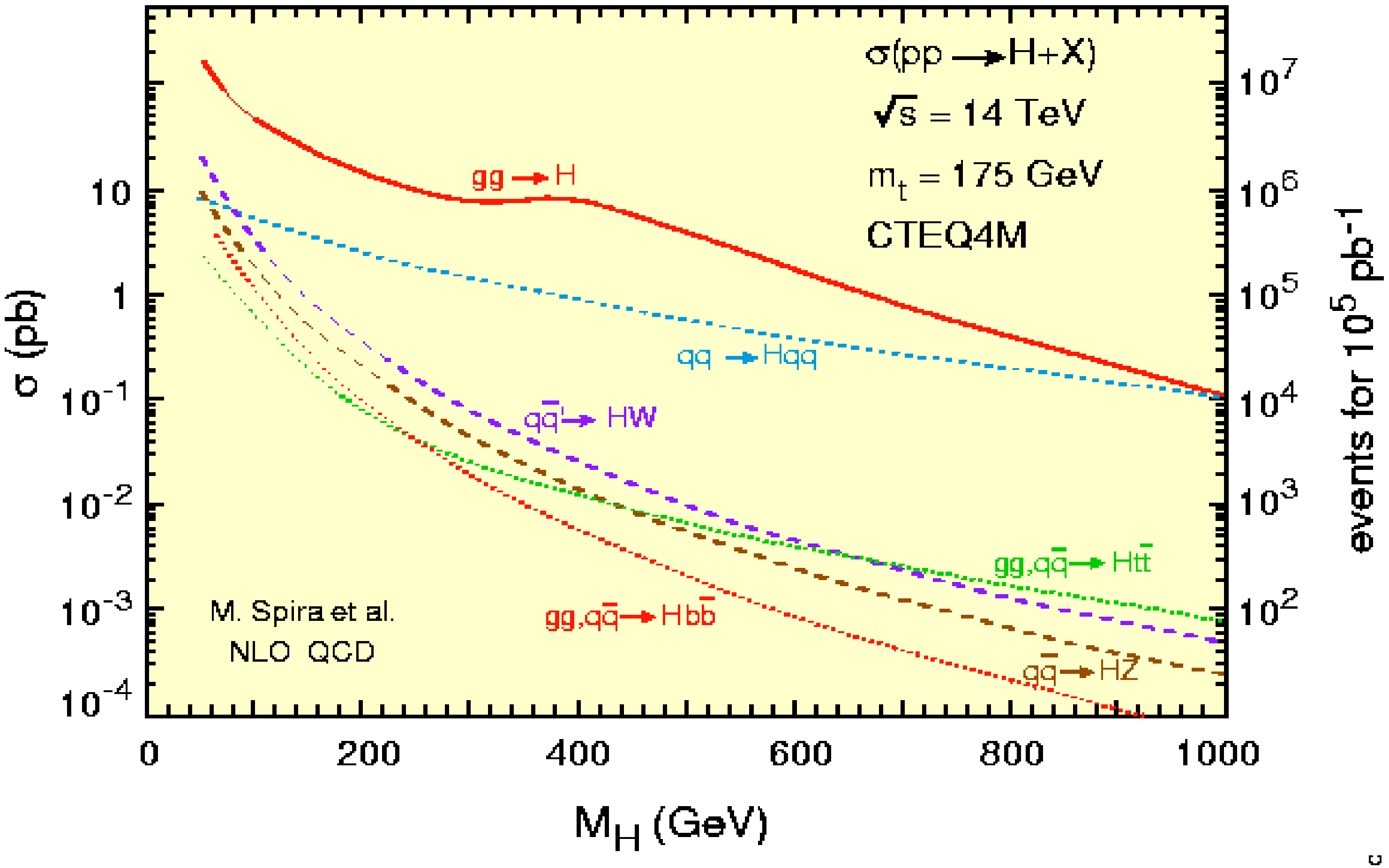
2. WW, ZZ fusion: $W^+ W^-$, ZZ → H

3. Higgs-strahlung off W, Z : qqW,Z → W +H, Z +H

4. Higgs bremsstrahlung off top quark: qq, gg →tt +H

For m_H = 120 GeV Higgs boson production cross section is around 45 pb.

Higgs boson production cross section at the LHC



Recent CMS full simulation results

- 1.Inclusive production
- Discovery signatures:
- a. H → 2 photons

5 sigma discovery at $L_t = 30\ fb^{-1}$

for 110 GeV < m_H < 150 GeV

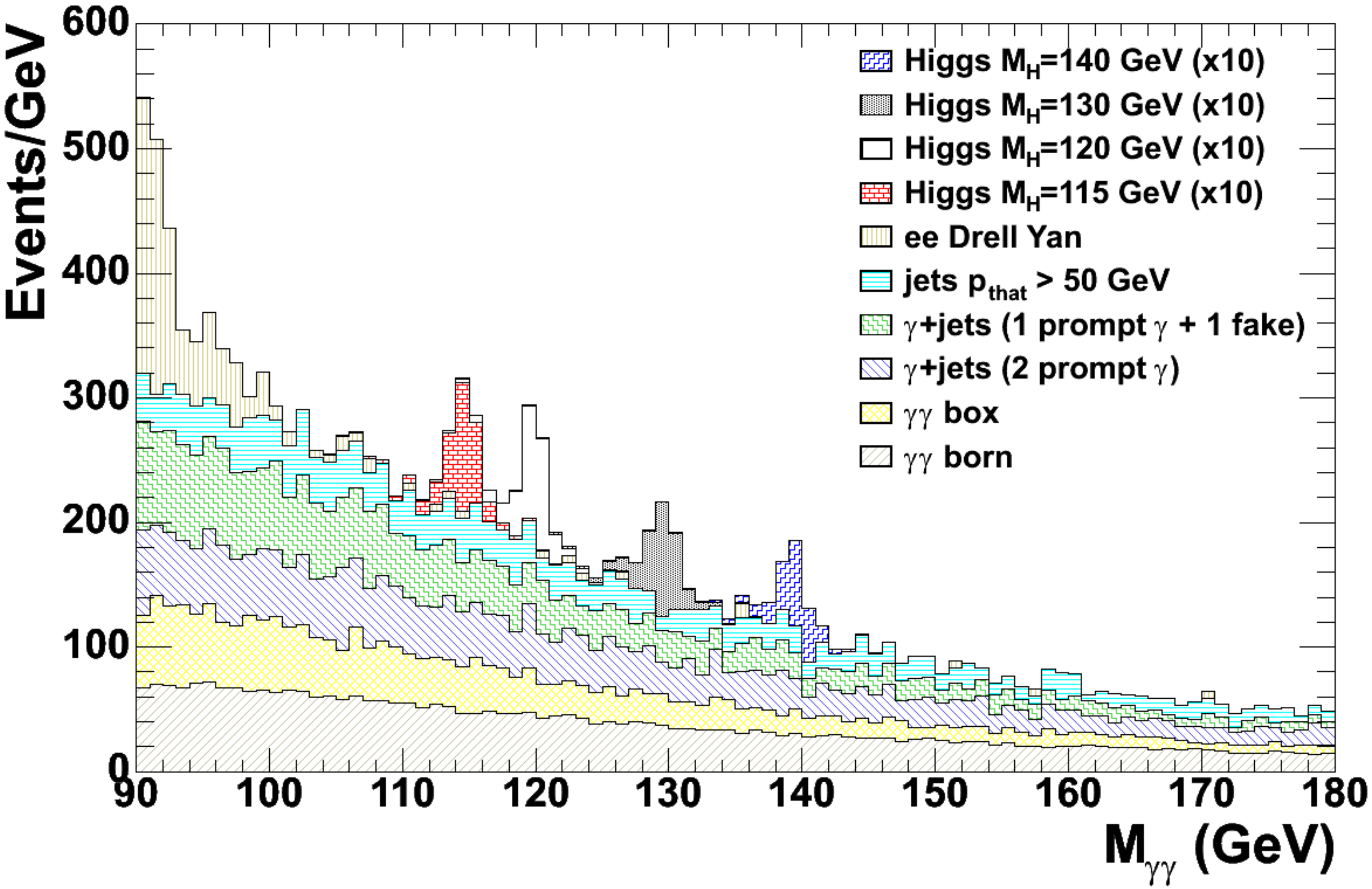
b. H → ZZ* → llll (l = e or mu)

5 sigma discovery at $L_t = 30\ fb^{-1}$

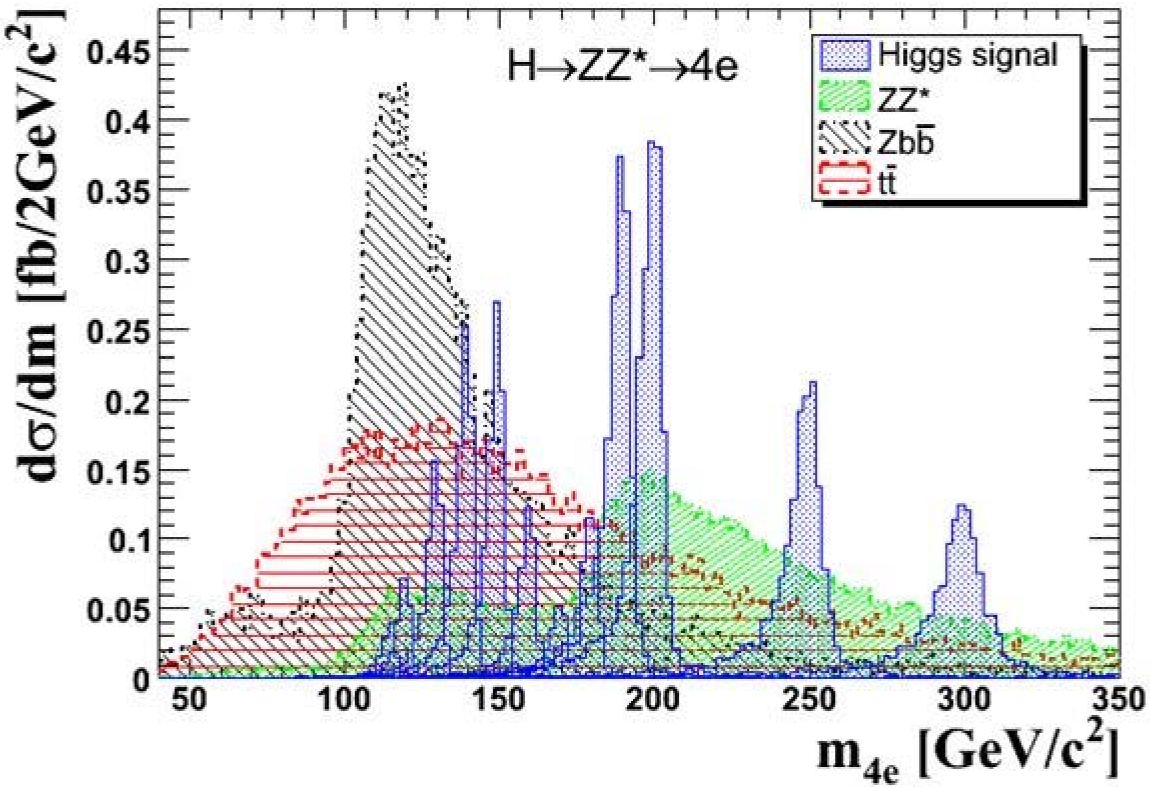
for 130 GeV < m_H < 400 GeV

Except m_H = (165 -- 175) GeV

Diphoton invariant mass spectrum



Higgs boson signal and dominant backgrounds



Recent CMS full simulation results

- Inclusive production (cont.)
- Discovery signatures:
- c. H → WW* → l nu l nu
- 5 sigma discovery at $L_t = 30\ fb^{-1}$

for 150 GeV < m_H < 180 GeV

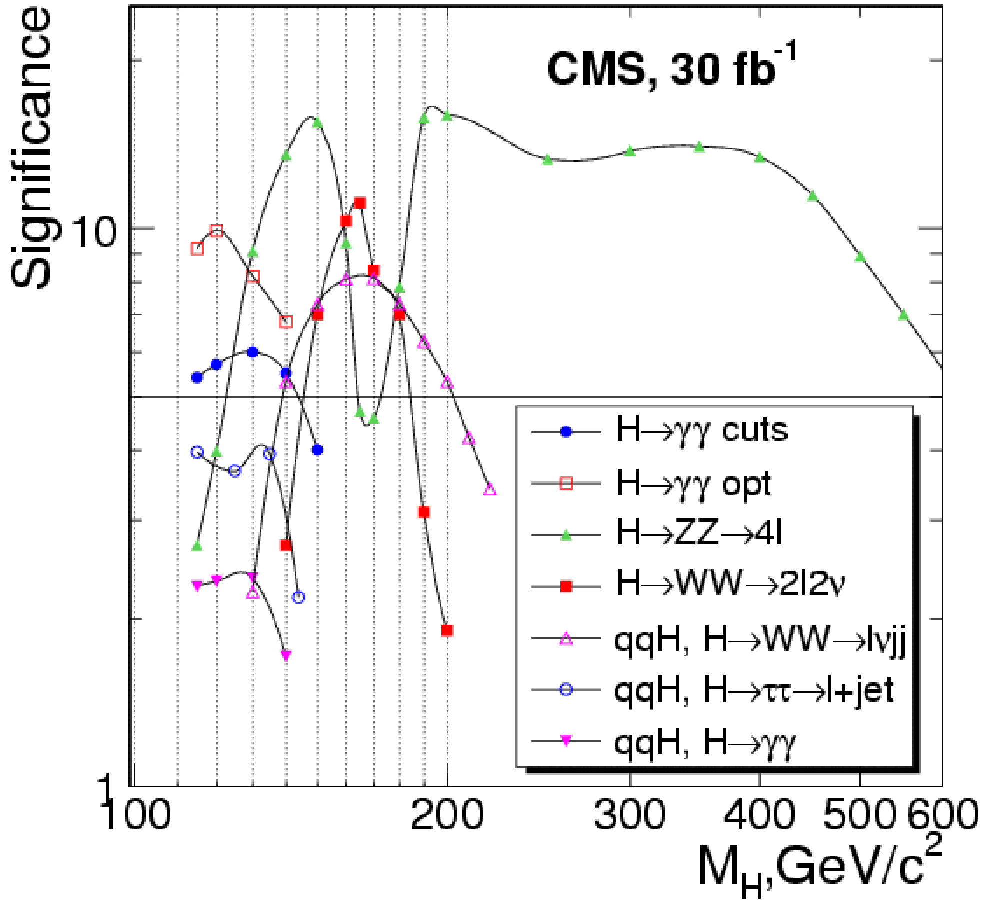
2. Vector boson Fusion production

Investigated signatures:

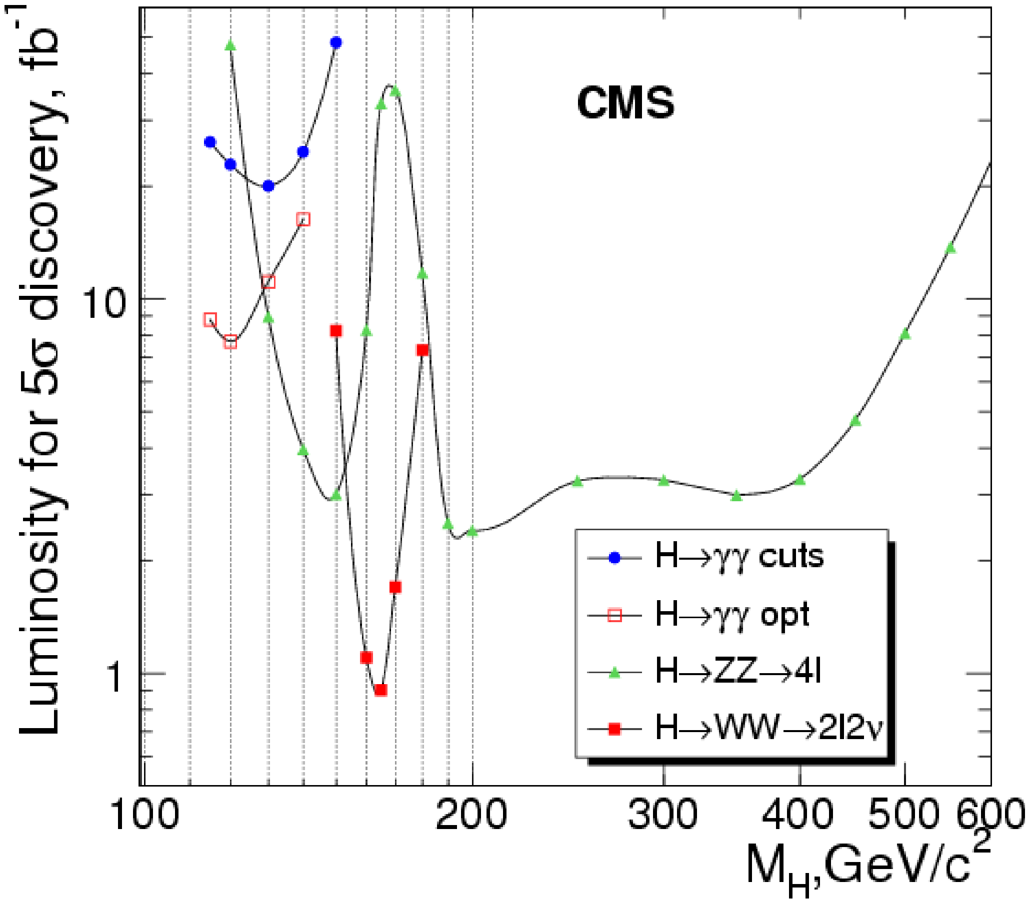
a. H → 2 photons

5 sig. discovery at $L_t = 100\ fb^{-1}$, m_H<140 GeV

CMS Higgs discovery potential



CMS Higgs discovery potential



Recent CMS full simulation results

- 2. Vector boson fusion production
- Investigated signatures:
- b. H → tau tau → l + tau-jet
- 5 sigma discovery at $L_t = 60\ fb^{-1}$

for 110 GeV $< m_H <$ 135 GeV

c. H → WW* →l nu jet jet

at $L_t = 30\ fb^{-1}$ 5 sigma discovery for

160 GeV $< m_H <$ 180 GeV

Recent CMS full simulation results

- Vector boson fusion production
- Investigated signatures
- d. H → WW* → l nu l nu
- for L_t =45 fb^{-1} 5 sigma discovery at
- 130 GeV < m_H < 200 GeV
- 3. ttH – production
- Investigated signatures:
- a. H → bb – looks hopeless , the
- ratio N_s/N_B = .009 – very small, systematics
- Is crusial

Recent CMS full simulation results

- 3. ttH-production (cont)
- Investigated signatures
- b. H → 2 photons
- For $m_H = 115 – 120$ GeV maybe 5 sigma
- discovery at $L_t = 100$ fb^{-1}
- The number of signal events is
- $N_s = (10 – 11)$, very small.

Recent CMS full simulation results

- 4. WH and ZH – production mechanisms
- Investigates signatures:
- a. H → bb, hopeless , N_s/N_B is small and
- the significance is also small
- b. HW → WWW* → 3 charged leptons
- At $L_t = 100\ fb^{-1}$ 5 sigma discovery for
- 155 GeV < m_H < 178 GeV
- c. HW → WWW* → 2 same charge muons
- At $L_t = 60\ fb^{-1}$ significance S < 2 , hopeless

Recent CMS full simulation results

- 4. WH and ZH production
- Investigated signatures:
- d. H → 2 photons
- For $L_t = 100\ fb^{-1}$ 3 (only three !!!) sigma
- discovery is possible (not very exciting)

Higgs boson signatures

It should be stressed that the signature

$H \rightarrow ZZ^{*} \rightarrow 4l$ (l = e or mu)

Is the cleanest experimental signature, “golden” channel for LHC.

The main conclusion is that for $L_{tot} = 30\ fb^{-1}$ (first 2-3 years of LHC work) the Higgs boson will be discovered for

$$90\ GeV < m_H < 1\ TeV$$

Higgs boson properties

It is possible to determine the Higgs boson mass (for $m_H < 260$ GeV) with 1% accuracy. By comparison of different signatures it is possible to explore Higgs properties. For instance, the use of

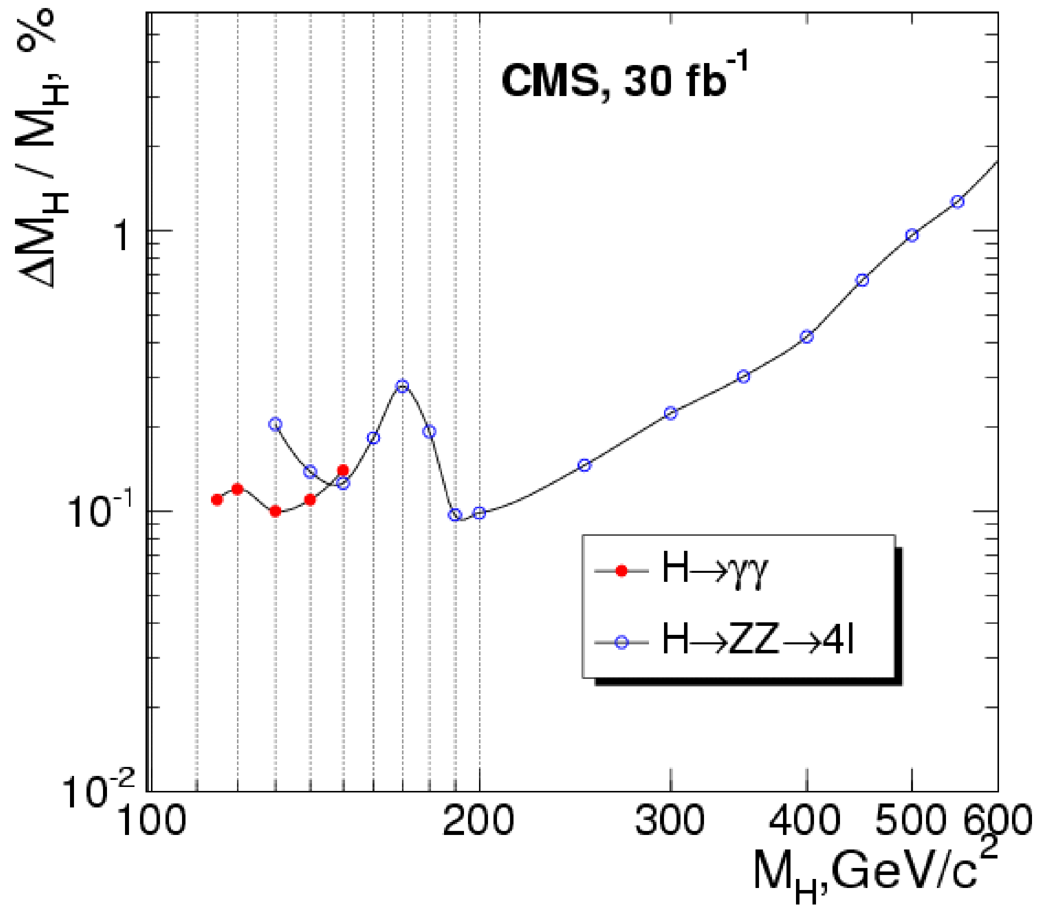
$$H \to \gamma\gamma , H \to ZZ^*$$

allows to determine

$$\frac{\Gamma(H \to \gamma\gamma)}{\Gamma(H \to ZZ^*)}$$

with an accuracy better than 20%

CMS Higgs boson mass accuracy measurment



Higgs boson (Conclusions)

The most interesting Higgs boson decay modes are:

H → gamma gamma

H → ZZ^*/ZZ → 4l

H → WW^*/WW → lvl’v’

Weak boson fusion production mechanism is also very promising for Higss boson properties investigation

3. Search for supersymmetry

- Y.A.Goldman and E.P.Likhtman
- D.V.Volkov and V.P.Akulov
- J.Wess and B.Zumino
- Why we like SUSY?
- elegant theory
- technical solution of the gauge hierarchy problem
- dark matter → LSP is natural candidate
- consistent string theories are superstring
- theories

SUSY, rules of the game

MSSM – minimal supersymmetric standard model based on $SU_c(3) \otimes SU_L(2) \otimes U(1)$ gauge group. For each known particle → superanalog superparticle (the same mass and internal quantum numbers, difference only in spin)

g (gluon, s = 1) → $\tilde{g}$ (gluino , s = ½)

quarks (s = ½) → squarks (s = 0)

leptons (s = ½) → sleptons (s = 0)

gauge bosons (photon, Z- and W-bosons) (s =1) → gaugino (s = ½)

SUSY, rules of the game

H_1, H_2 (two Higgs doublets) (s = 0) → Higgsino (s =1/2)

As a result of gaugino and higgsino mixing

In mass spectrum:

two chargino $\chi_1^{\pm}, \chi_2^{\pm}$ (s = ½)

four neutralino $\chi_1^0, \chi_2^0, \chi_3^0, \chi_4^0$ (s = ½)

R-parity conservation postulate → to get rid of dangerous terms leading to fast proton decay.

For ordinary particles R = +1

SUSY, rules of the game

For sparticles R = -1

R-parity is conserved by construction

Two important consequences:

1. At supercolliders sparticles are pair produced
2. The lightest sparticle (LSP) is stable: χ_1^0 → dark matter candidate

- Note that SUSY models with R-parity violation are possible

MSUSGRA model

So SUSY has to be broken and in general masses of sparticles (squarks, sleptons, gluino, gaugino, Higgsino) are arbitrary that makes analysis extremely difficult

For LHC most calculations were done within so called MSUGRA model →

Squark, slepton, higgsino masses are universal at GUT scale → m_0

Gaugino masses also universal→ $m_{1/2}$

Sparticle production

- From cosmology and astrophysics → LSP is weakly interacting neutral particle. As a result LSP escapes from detection (analog of neutrino) → SUSY events are characterized by nonzero transverse missing momentum

  In real life SUSY has to be broken

1. gravity mediated SUSY breaking
2. gauge mediated SUSY breaking

Sparticle production

- At LHC sparticles can be produced via reactions:

$$gg, qq, qg \to \tilde{g}\tilde{g}, \tilde{q}\tilde{g}, \tilde{q}\tilde{q}$$

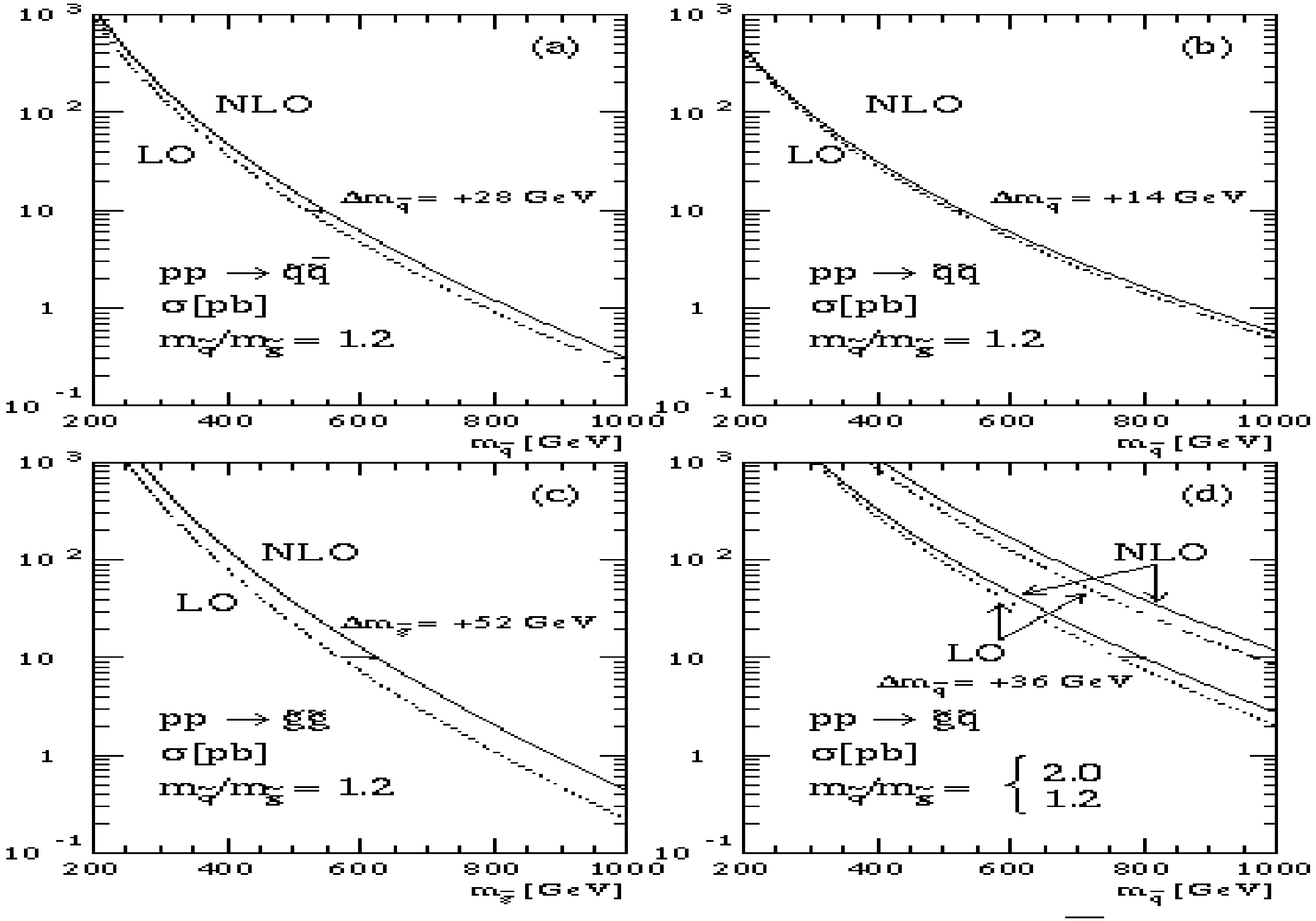
$$qq \to \chi_i^{\pm}\chi_j^{\mp}, \chi_i^{\pm}\chi_j^{0}, \chi_i^{0}\chi_j^{0}$$

$$qq, qg \to \tilde{g}\chi_i^{0}, \tilde{g}\chi_i^{\pm}, \tilde{q}\chi_i^{0}, \tilde{q}\chi_i^{\pm}$$

$$qq \to \tilde{l}\,\tilde{\nu}, \tilde{l}\tilde{l}, \tilde{\nu}\tilde{\nu}$$

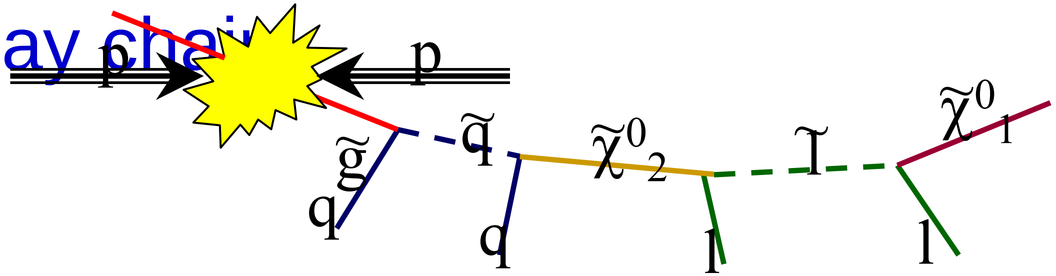
For squarks and gluino with masses O(1) TeV
squark and gluino cross sections O(1) pb

The total SUSY cross sections



LHC SUSY Searches

Typical Signature/decay chain



- Strongly interacting sparticles (squarks, gluinos) dominate production.
- Heavier than sleptons, gauginos etc. g cascade decays to LSP.
- Potentially long decay chains and large mass differences
  - **Many high p_T objects observed (leptons, jets, b-jets).**
- If R-Parity conserved LSP (lightest neutraliño in mSUGRA) stable and sparticles pair produced.
  - **Large E_T^{miss} signature (c.f. Wglν).**

SUSY Searches

- Inclusive searches to detect SUSY with first data
- Exclusive studies – performed with more data to determine model parameters e.g. masses etc from end point measurements…

Susy signatures

As a result of squark, gluino decays and chargino and neutralino decays the most interesting signatures for the search for SUSY at LHC are:

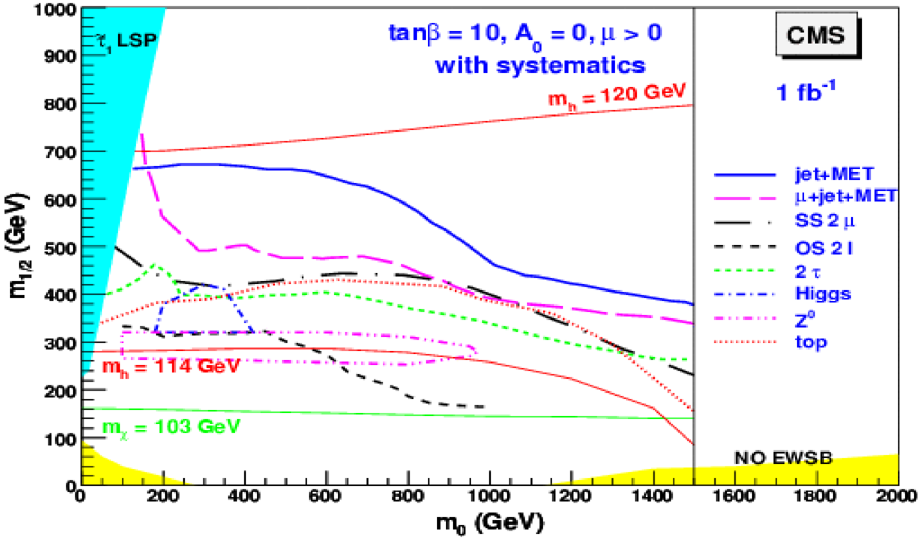
- multijets plus E_T^{miss} events
- 1l plus jets plus E_T^{miss} events
- 2l plus jets plus E_T^{miss} events
- 3l plus jets plus E_T^{miss} events
- 4l plus jets plus E_T^{miss} events

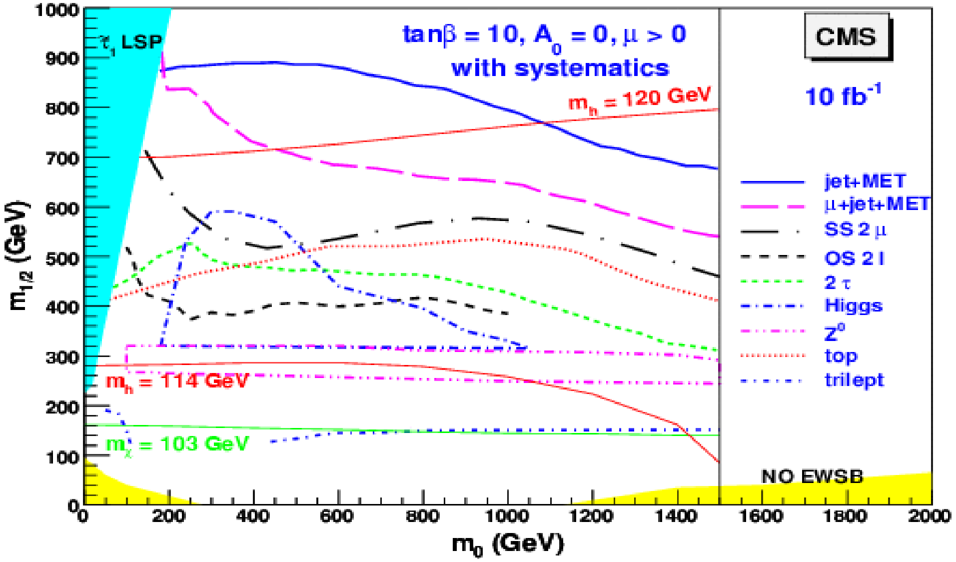
Recent CMS full simulation results

- SUSY signatures:
- 1. E^{miss}_T + n > 2 jets
- For tan(beta) =10, m_0 = 60 GeV, $m_{1/2}$=250
- GeV, sign(mu) = +1
- The 5 sigma discovery is for L_t=2 pb^{-1}

  first 4 hours of LHC work !!!
- 2. The same sign dimuons + E^{miss}_T + n>2
- Jets
- For L_t =10 fb^{-1} SUSY masses up to 1.5 TeV

CMS SUSY discovery potential

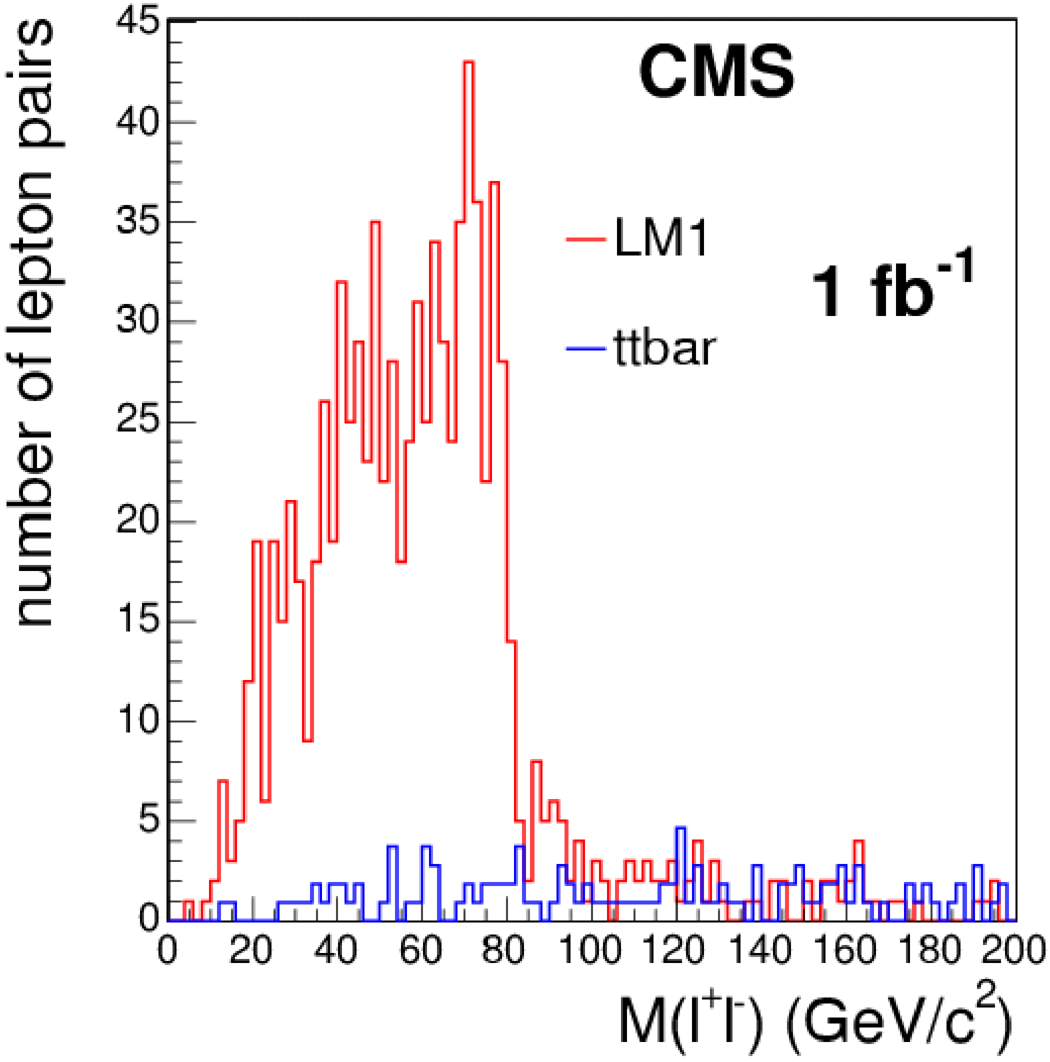




Recent CMS full simulation results

- 2. Single muon + E^{miss}_T + n>2 jets
- For $L_t = 100\ fb^{-1}$ 5 sigma discovery for
- SUSY masses up to 2TeV.
- 3. Opposite same sign leptons + E^{miss}_T
- + n>2 jets
- Basically similar to signature with single muon

Dilepton invariant mass distribution for LM1 test point



LHC SUSY discovery potential

- The main conclusion is that for MSUGRA model LHC will be able to discover SUSY with squark and gluino masses up to 2 .5 TeV for $L_{tot} = 100\ fb^{-1}$
- Chargino and neutralino pairs produced through DY mechanism $pp \to \chi_1^{\pm}\chi_2^{0}$ may be detected through their leptonic decays

$$\chi_1^{\pm}\chi_2^{0} \to lll + E_T^{miss}$$

The signature: 3 isolated leptons without jet activity. LHC is able to detect such DY production with masses up to 200 GeV

Determination of spartile masses

In many cases LHC is able not only to discover SUSY but to determine SUSY breaking parameters (combinations of sparticle masses). For instance, using $l^+ l^-$ invariant mass distribution in reaction

$$\chi_2^0 \rightarrow \chi_1^0 l^+ l^-$$

it is possible to determine the combination

$$M_{\chi_2^0} - M_{\chi_1^0}$$

as endpoint in edge structure with 2-3 percent accuracy

[redacted]

For $\tilde{\chi}_2^0 \to \tilde{\ell}^{\pm}\ell^{\mp} \to \tilde{\chi}_1^0 \ell^+\ell^-$ find triangular mass distribution with

$$M(\ell^+\ell^-) \leq \sqrt{\frac{\left(M^2(\tilde{\chi}_2^0) - M^2(\tilde{\ell})\right)\left(M^2(\tilde{\ell}) - M^2(\tilde{\chi}_1^0)\right)}{M^2(\tilde{\ell})}}\,.$$

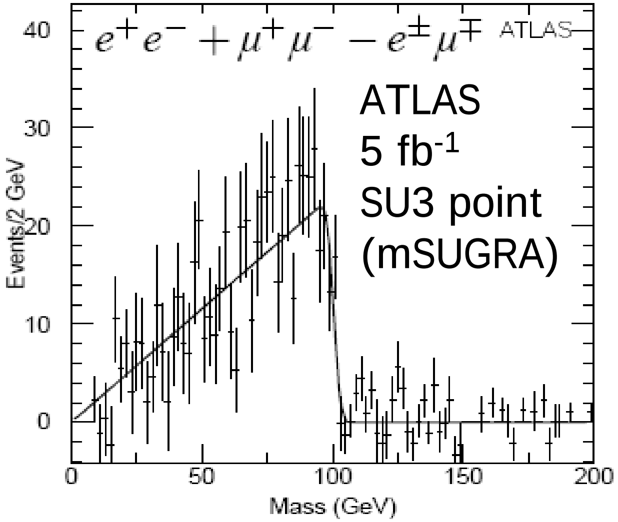
[redacted]

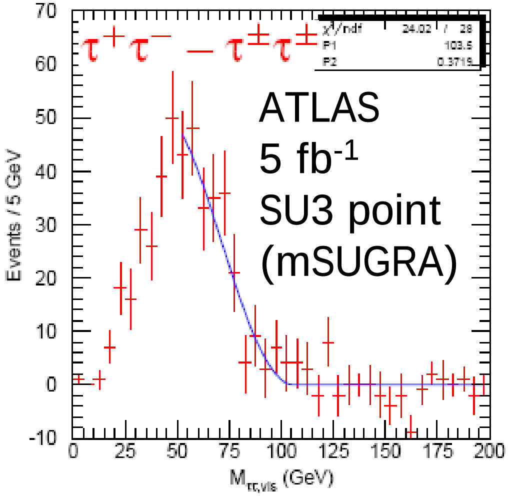
$$\tilde{q}_L \to \tilde{\chi}_2^0 q \to \tilde{\ell}_R^{\pm}\ell^{\mp} q \to \tilde{\chi}_1^0 \ell^+\ell^- q$$

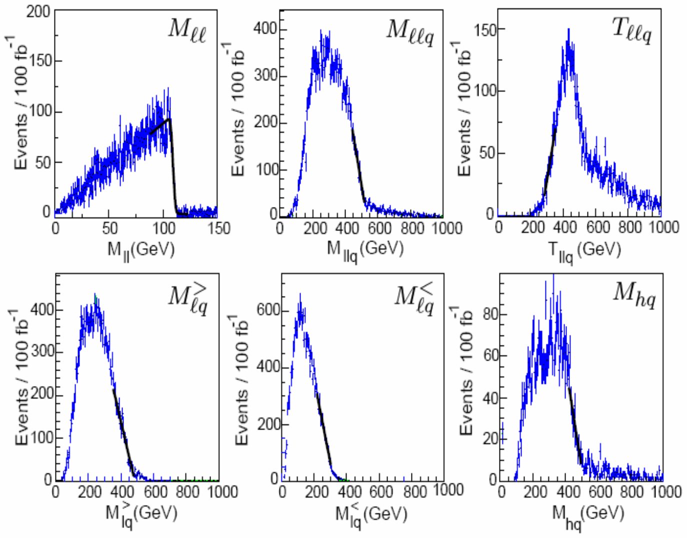
[redacted]

If no flavour violation, we expect same-flavour (ee, mm) pairs only for signal and an equal number of same-flavour and opposite-flavour pairs for background (leptons from two different decay chains, either for SUSY or SM events)

The edge in tt invariant mass can also be measured using the visible decay products of the taus







MSSM Higgs boson searches

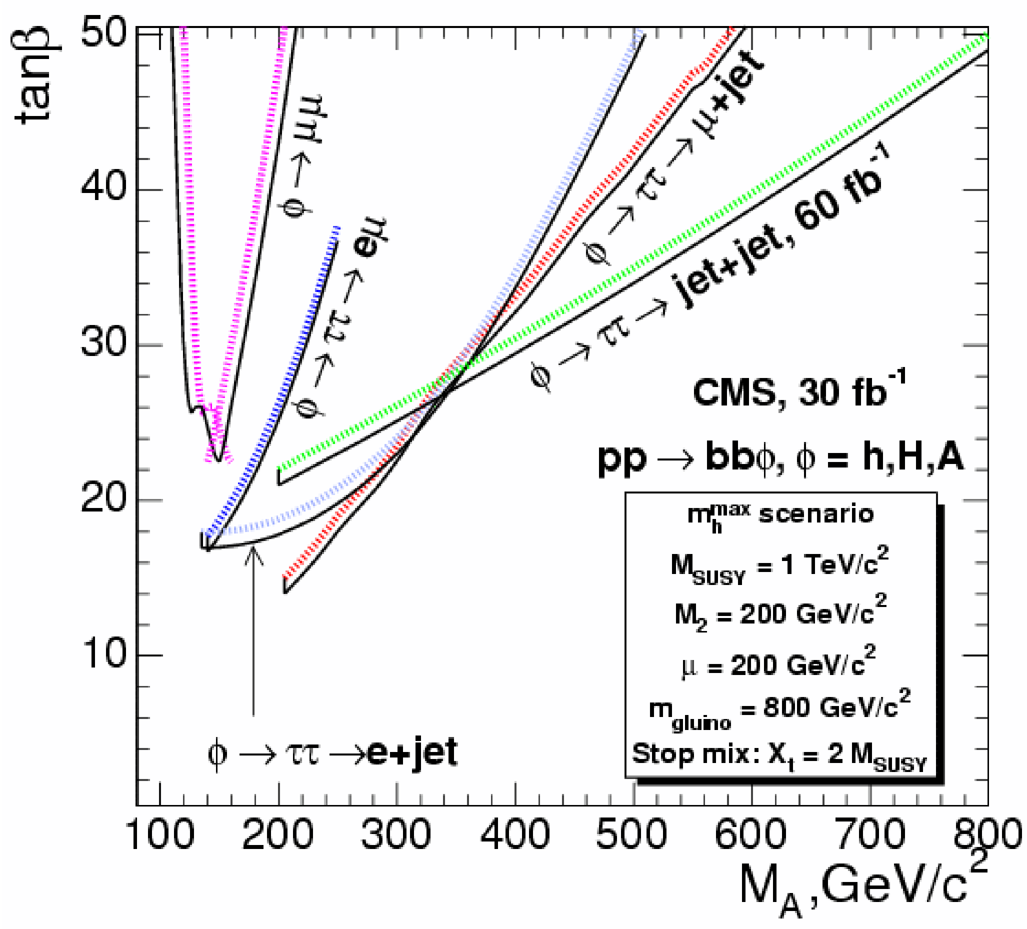
- In the MSSM there are 4 Higgs bosons h, H, A, $H^{+/-}$ the lightest scalar h for $m_A > m_h^{max}$ (decoupling regime) is SM-like Higgs boson.

  The production of H and A proceeds mainly through gg → H/A and gg/qq →bbH/A
- At large tan(beta) bbH/A production dominates and it is ~90% for tan(beta) >10 and m_A > 300 GeV

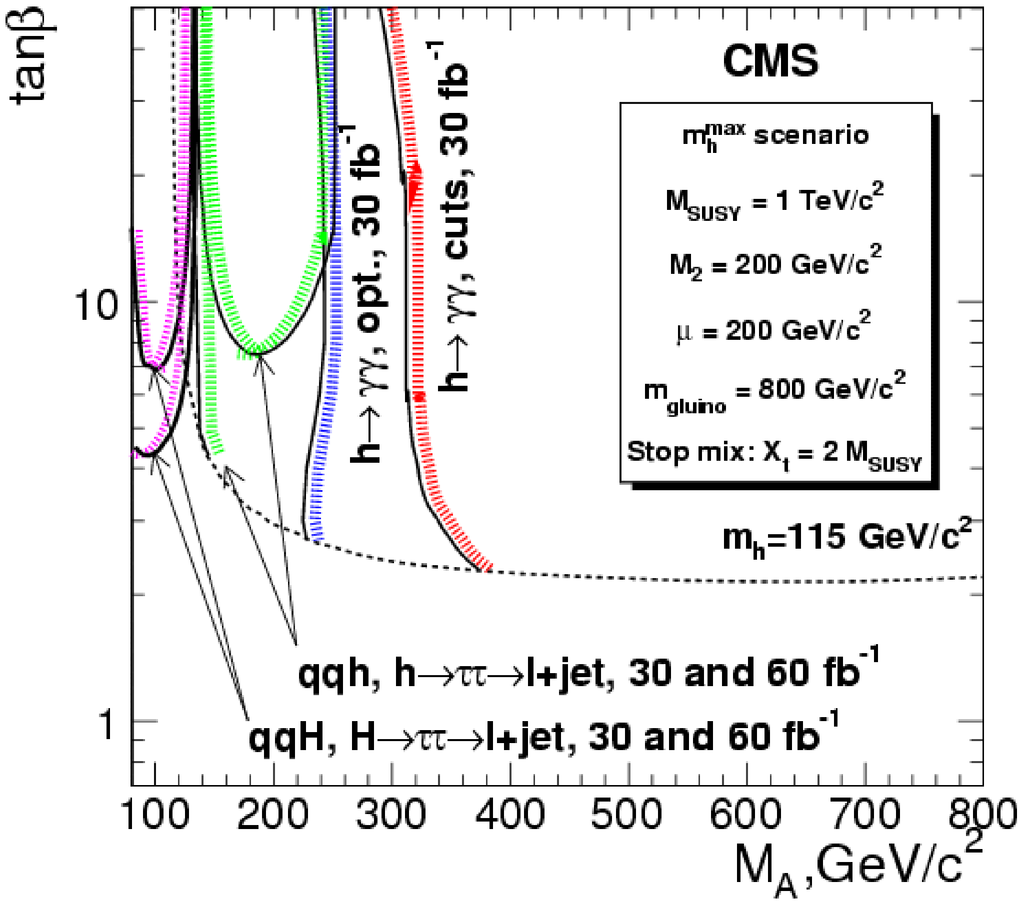
The MSSM Higgs boson signatures

- Light charged Higgs boson $m_{H+/} < m_{top}$ is produced in tt events with $t \to H^{+/} b$
- The most important production mechanisms for $m_{H+/} > m_{top}$ are $gb \to tH^{+}$, $gg \to tbH^{+/}$, $qqbar \to H^{+/}$ with cross sections ~$\tan^2(\beta)$
- The $H,A \to b,bbar$ decay dominates at large tan(beta). The branching to $\tau^+\tau^-$ is ~10% and to $\mu^+\mu^-$ is about $3*10^{-4}$

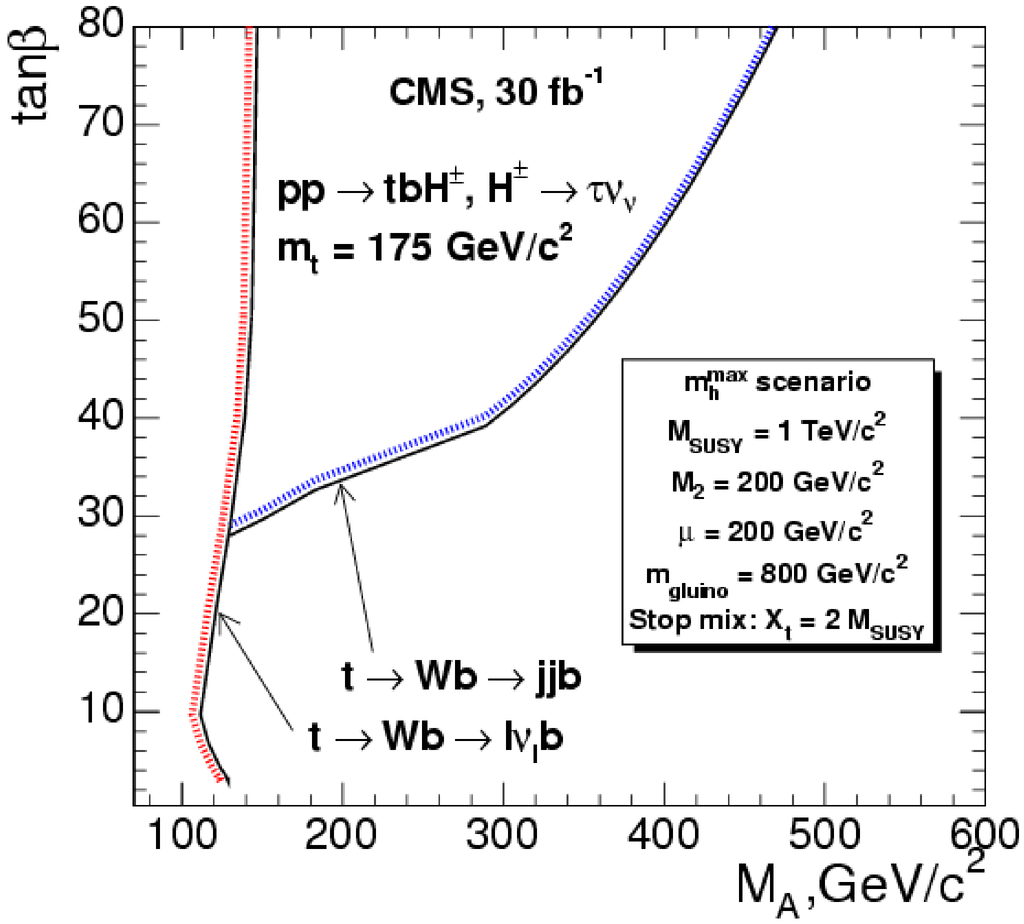
MSSM Higgs boson discovery potential



MSSM light Higgs discovery potential



Charged Higgs discovery potential



Recent CMS full simulation results

- 1. H/A → mu mu decay signature
- For L_t = 30 fb^{-1} 5 sigma discovery for tan(beta) > 25 and $M_{A/H}$ < 250 GeV
- 2. H/A → tau tau decay signature
- For L_t = 30 fb^{-1} 5 sigma discovery for
- tan(beta) > 20 and $M_{A/H}$ < 500 GeV
- 3. H/A →bb channel, looks hopeless.
- The ratio N_s/N_B = 0.03 is small

Recent CMS full simulation results

- 4. A → Zh , Z→ l^+l^-, h → bb decay sign.
- At L_t = 30 fb^{-1} 5 sigma discovery for

tan(beta) < 3 and 250 GeV $< M_{A/H} < 350$ GeV

5.Charged Higgs boson

H+/- → tau+/- nu - the single discovery signature. Discovery possible for

tan(beta) > 20 and $M_{A/H} < 300$ GeV for

L_t = 30 fb^{-1}

4.Search for new physics beyond SM and MSSM

There are a lot of models:

- Additional dimensions
- Additional gauge bosons
- Heavy neutrino
- Scalar leptoquarks
- Compositeness
- ......
- ......

Additional dimensions

- In ADD(Arkani-Hamed, Dimopoulos,Dvali) model gravity lives in (4+d) -space-time, observable world lives on 4-brane. After compactification on torus of d additional dimensions

  $M^2_{PL} = V_d M_D^{2+d}$, $V_d = (2\pi R_c)^d$

  If $M_D \sim 1$ TeV → $R_c^{-1} = (10^{-3}$ eV – 10 MeV) for d = 2 – 6 . The masses of KK gravitons $m_n \sim (n^a n^a)^{1/2} R_c^{-1}$, $n^a = (n_1,\dots n_d)$
- Graviton mass splitting $\Delta m \sim R_c^{-1}$

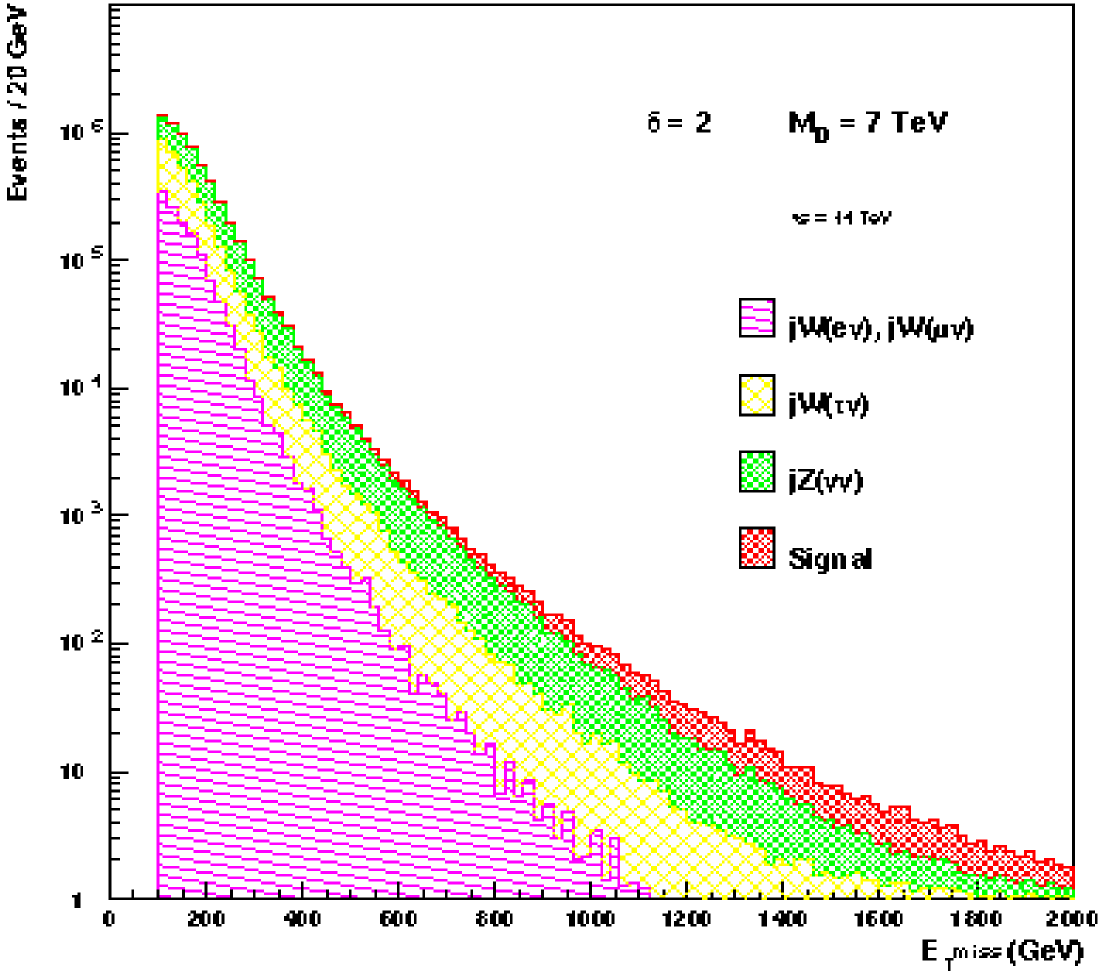
ADD model

- We have an almost continuous spectrum of gravitons which behave as massive stable noninteracting spin 2 particle
- Supercollider signature

  $qg \rightarrow q\, G^{(n)}$ at parton level and

  $pp \rightarrow jet + E_T^{miss}$ at particle level .
- For $d = 2$ R_c^{-1} can be probed up to 10 TeV. The contribution of ADD massive gravitons contributes into DY cross section that allow to restrict $R_c^{-1} > 8$ TeV

Distributions for missing transverse energy for ADD model



RS model

- In RS model (Randall-Sundrum) gravity
  lives in a 5-dimensional Anti-de Sitter
  space with a single extra dimension compactified to the orbifold S^1/Z_2
  The metric is

$$ds^2 = e^{-2k[y]}\eta_{\mu\nu}dx^\mu dx^\nu + dy^2 \ldots, y = r_c\theta$$

$$M_{PL}^2 = \frac{M_5^3}{k}(1-e^{-2kr_c\pi})$$

There are two 3-dimensional branes (TeV brane,our world) and Planck brane

RS model predictions

- The main prediction of the RS model –

  KK excitations with $m_{gr}(1) \sim O(1)$ TeV

  The most promising signature is

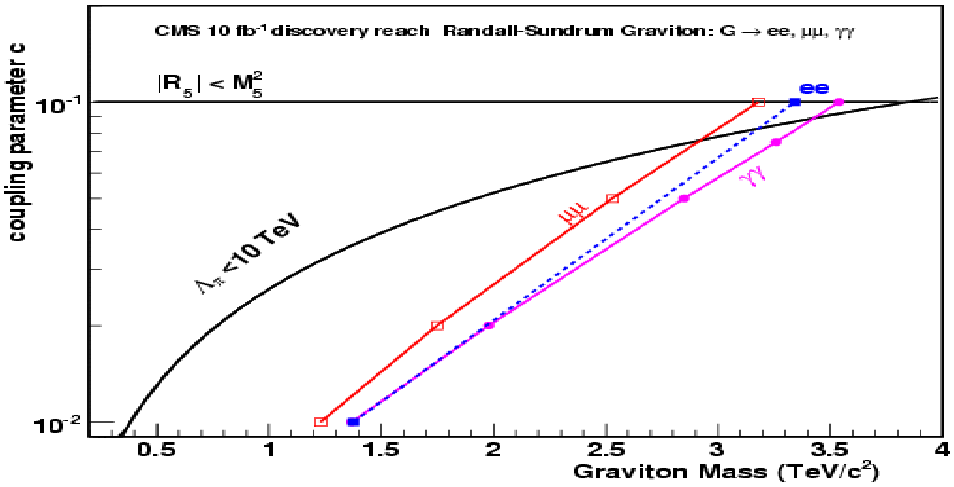
  $$q\bar{q}, gg \rightarrow G_{res,1} \rightarrow e^+e^-, \mu^+\mu^-$$

- The graviton resonance can be detected for

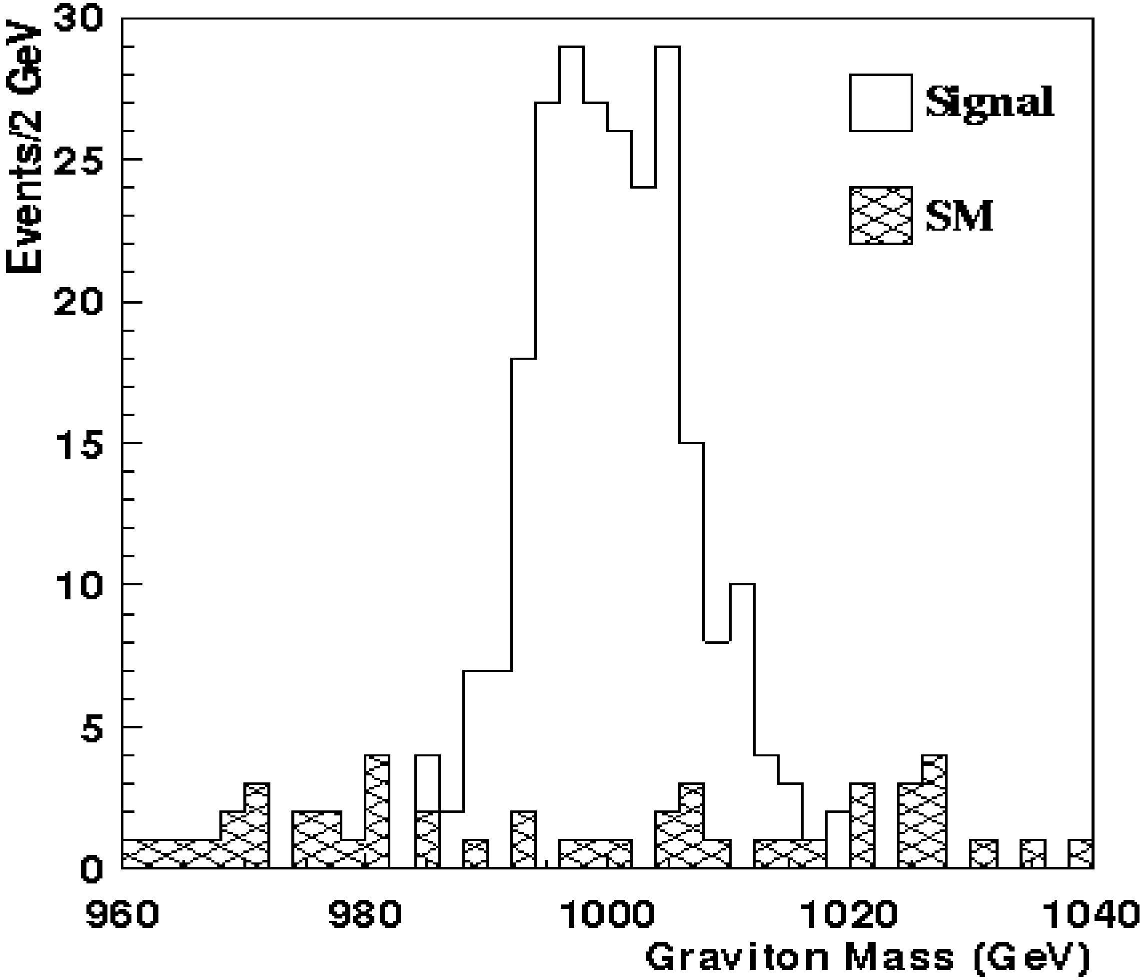
  $M_{gr}(1) < 4$ TeV

- Other conseqence → radion field (similar to Higgs boson, couples with trace of energy-momentum)

RS graviton discovery potential



Distribution of the e^+e^- invariant mass for a graviton resonance



Additional gauge bosons

- Additional gauge bosons arise in many extensions of SM containing additional

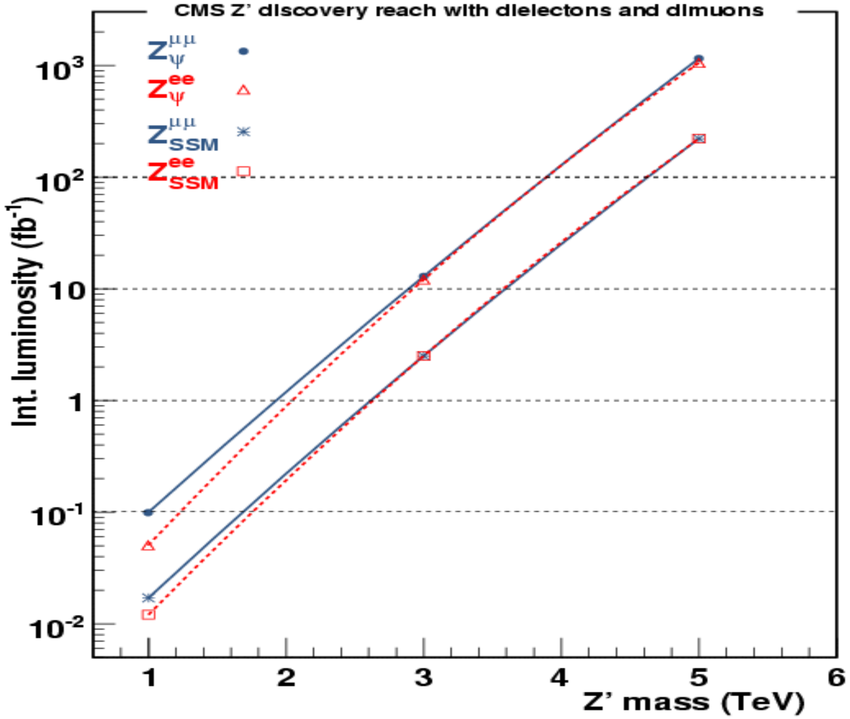
  U(1) gauge group. Such extensions arise

  in the context of SO(10) and E(6) gauge groups. The most promising way to discover Z'-boson is to use its leptonic modes $Z' \rightarrow e^+e^-, \mu^+\mu^-$

  The manifestation of the Z' boson is the resonance structure in DY process.

  It is possible to discover Z ' with a mass up to 4.3 TeV for L_{tot} = 100 fb^{-1} using dimuon mode

Z` CMS discovery potential



Heavy neutrino

- Left-right symmetric models based on

$$SU_c(3) \otimes SU_L(2) \otimes SU_R(2) \otimes U(1)$$

gauge group naturally include heavy Majorana neutrino. For heavy neutrino lighter than W_R -boson it is possible to look for heavy neutrino

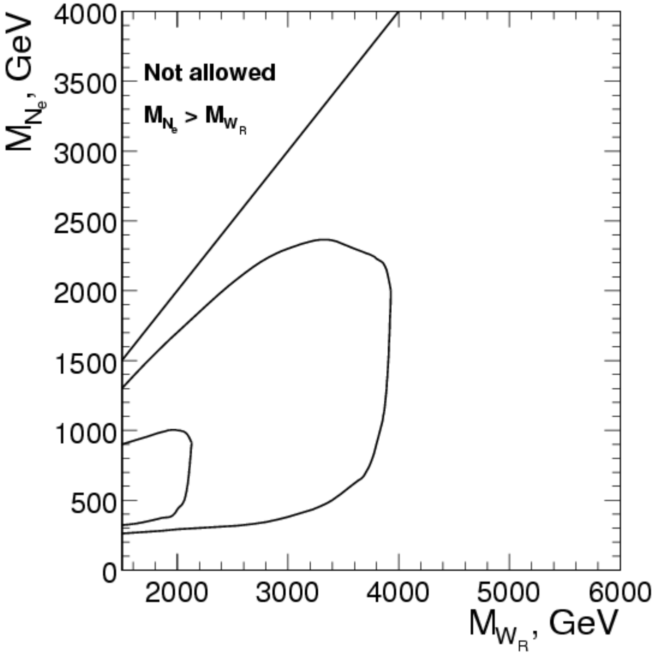
in W_R decay using the signature

$pp \rightarrow W_R + \ldots \rightarrow e(\nu_{R,l} \rightarrow ejj) + \ldots$

Due to Majorana nature of neutrino halph of events will be with the same sign leptons .

It is possible to discover heavy neutrino with a masss up to 2.8 TeV for L_{tot} = 30 fb^{-1}

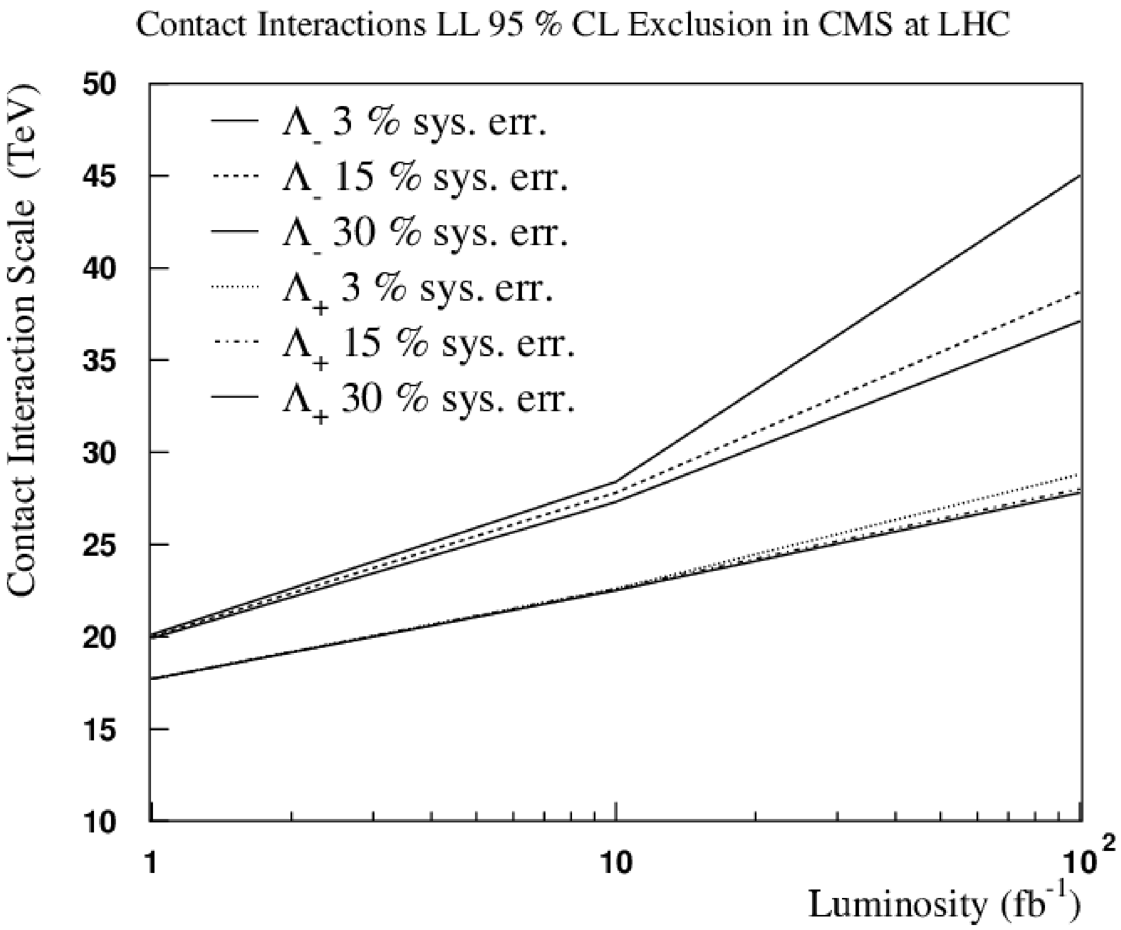
Heavy neutrino, W_R discovery potential



Compositeness

- If squarks and leptons are composite particles made from “preons” we can expect deviations from SM predictions for high p_T cross sections (Drell-Yan, jet cross sections). At L_{tot} = 100 fb^{-1} LHC will be able to probe point like stucture of quarks with a scale up to 20 TeV

Bound on compositeness scale



Conclusions

- ✓ CMS & ATLAS have significant discovery potential
- ✓ LHC will be able to discover Higgs boson and to check its basic properties
- ✓ LHC will be able to discover SUSY with squark and gluino masses up to 2.5 TeV.

There is nonzero probability to find something beyond SM or MSSM(extra dimensions, Z'-boson, compositeness ...)

- ✓ Heavy gauge bosons up to ~5-6 TeV
- ✓ Heavy neutrino up to 2.6 TeV
- ✓ RS model ED up to ~4 TeV

Conclusions

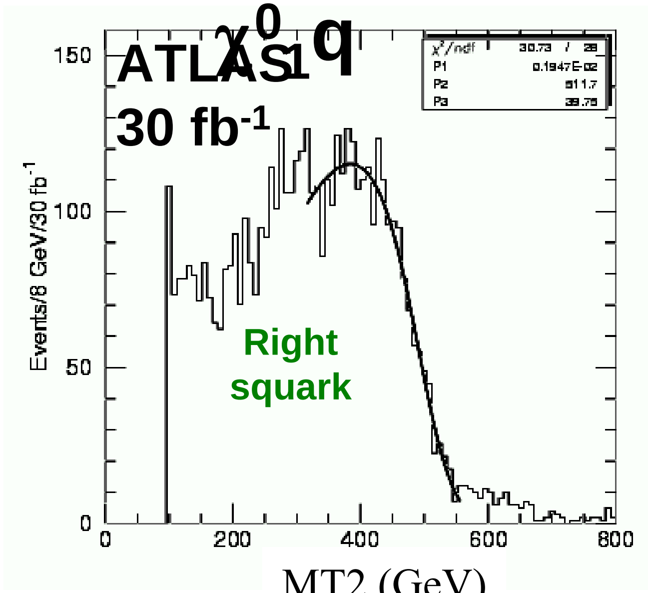
- At any rate after LHC we will know the mechanism of electroweak symmetry breaking (Higgs boson or something more exotic?) and the basic properties of the matter structure at TeV scale.

Backup

- Additional slides

Other mass measurements

$\tilde{q}_R \rightarrow \chi^0_1 q$



MT2 (GeV)

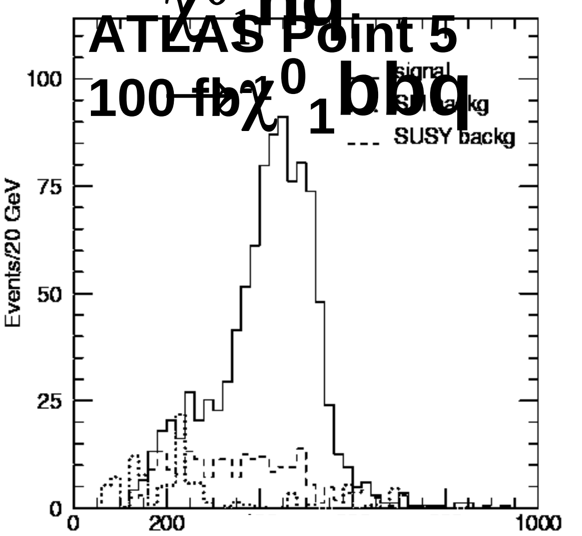
2 hard jets and lots of E_T^{miss}.

Reconstruct with

$$M_{T2}^2 = \min_{\not p_1 + \not p_2 = \not p_T}\left[\max\left\{m_T^2(p_T^{\ell_1}, \not p_1), m_T^2(p_T^{\ell_2}, \not p_2)\right\}\right]$$

$m(\tilde{q}_R)-m(\chi^0_1) = (424.2 \pm 10.9)$ GeV

$\tilde{q}_L \rightarrow \chi^0_2 q \rightarrow \chi^0_1 hq \rightarrow \chi^0_1 bbq$

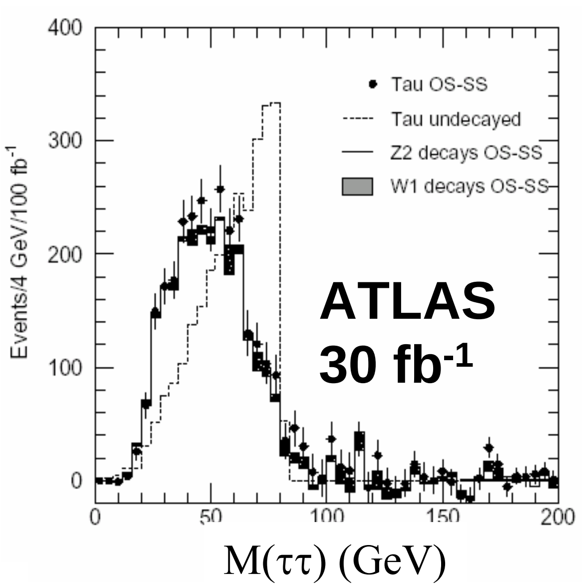


M(bbq) (GeV)

Two body decay of χ^0_2 to higgs and χ^0_1.

Reconstruct higgs mass (2 b-jets) and

$\chi^o_2 \rightarrow \tilde{\tau}\tau \rightarrow \chi^0_1\ \tau\tau$



M(ττ) (GeV)

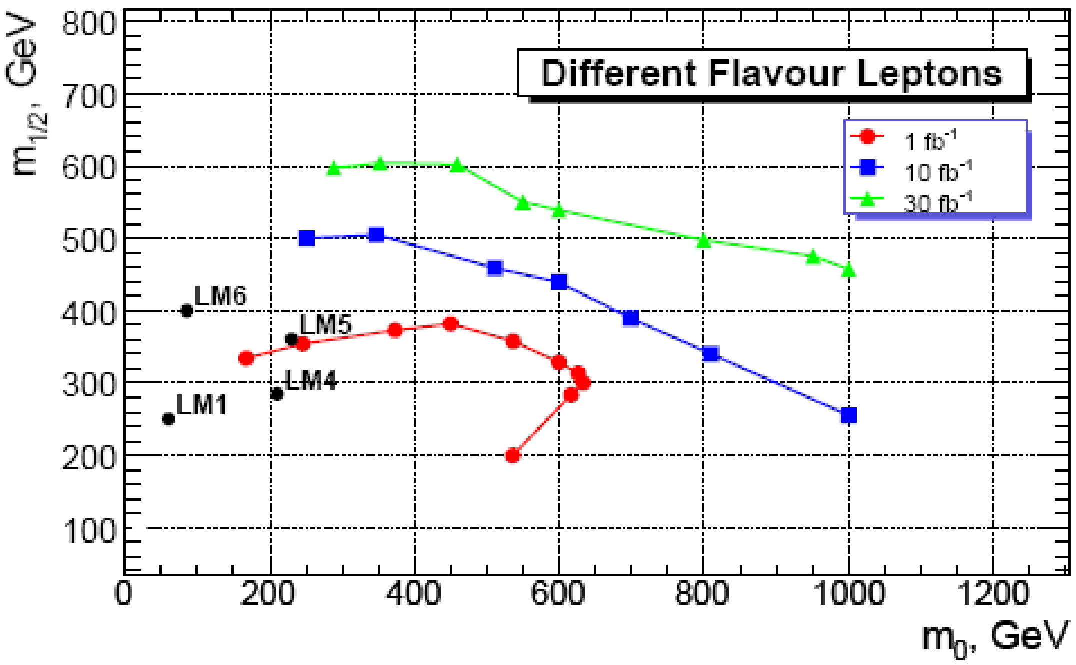
Tau decay dominates neutralino BR at large tanβ.

No sharp edge because of ν, but end-point can still be measured.

Using the $e^{\pm}m^{-}+E^{T}_{miss}$ signature in the search for Supersymmetry and lepton flavour violation in neutralino decay

A search was performed using the CMS detector simulation. The optimal cut set was found to be:

- Isolated leptons with p_t > 20 GeV
- EtMiss > 300 GeV



[redacted]

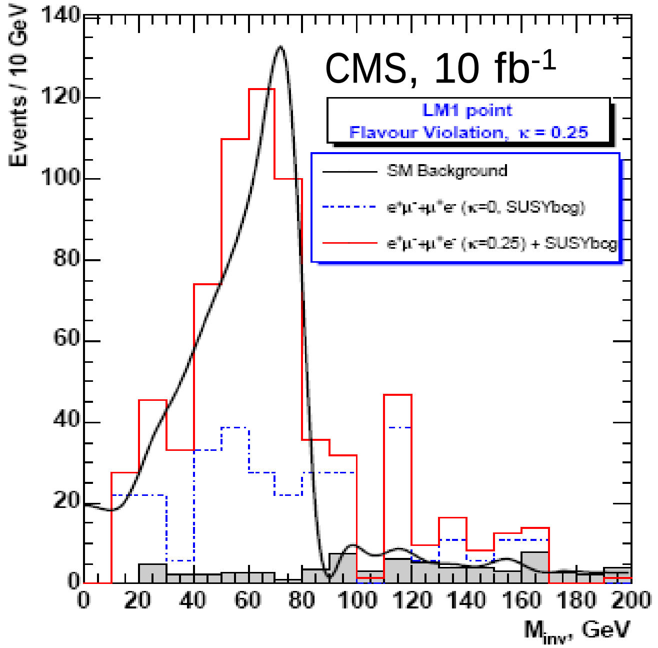
$$\mathrm{BR}(\ell_i\ell_j) \equiv \mathrm{BR}(\tilde{\chi}_2^0 \to \ell_i\ell_j\tilde{\chi}_1^0).$$

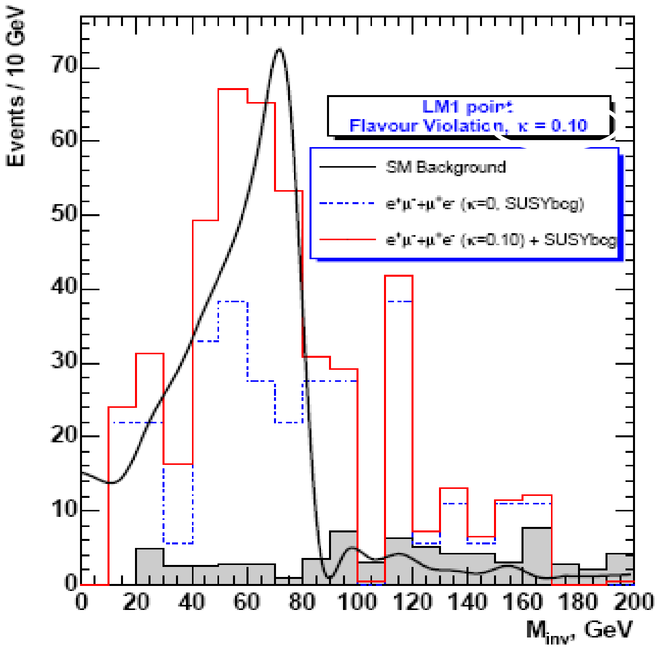
[redacted]

$$\kappa = 2x\sin^2\theta\cos^2\theta,$$

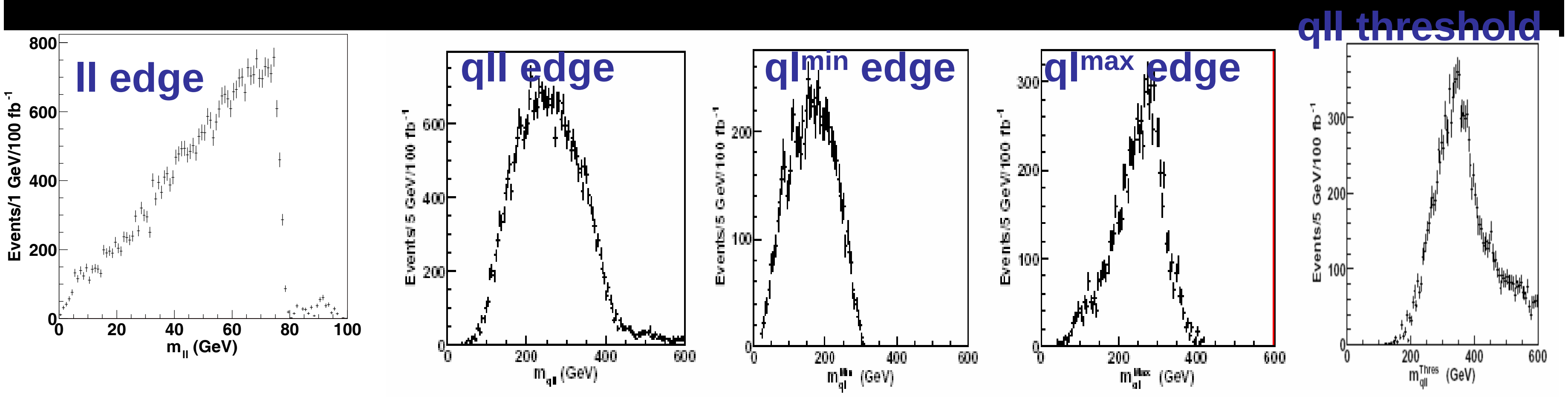
$$x = \frac{\Delta m^2_{\tilde{e}\tilde{\mu}}}{\Delta m^2_{\tilde{e}\tilde{\mu}} + \Gamma^2},$$

[redacted]





SUSY (s)lepton flavour studies with ATLAS



Gjelsten, Lytken, Miller, Osland, Polesello,ATL-PHYS-2004-007

5 relations
4 masses

SPS1a (bulk region)
m_0= 100 GeV,
$m_{1/2}$= 250 GeV,
A_0= -100 GeV,
tan(β)=10 , μ>0

Expected errors on the masses

$\Delta m(\chi_1^0)$= 4.8 GeV, $\Delta m(\chi_2^0)$= 4.7 GeV,
$\Delta m(l_R)$ = 4.8 GeV, $\Delta m(q_L)$= 8.7 GeV