Search for Physics Beyond the Standard Model with CMS detector

Leandar Litov
University of Sofia

Sofia, 11 April 2011

Introduction

- Physics Beyond the SM
  - Supersymmetry
  - Hidden Valley
  - Extra dimensions
- The CMS detector
- Recent results'
  - Search for SUSY
  - Search for new gauge bosons W', Z
  - Search for ED
- Conclusions

The Standard Model

- The SM is proved experimentally with high precision
- All fundamental particles (quarks and leptons) and gauge bosons (γ, W,Z, g) are experimentally observed
- Their properties are under investigation
- But
  - ✓ The Higgs boson is still missing
  - ✓ Number of basic questions are not answered

Physics Beyond the SM

- The SM should be considered as a low energy phenomenological model
- A new more general theory (model) should be developed (invented). The SM should be obtained as a low energy limit.
- Models
  - ✓ Grand Unification Theory
  - ✓ Technicolor
  - ✓ SUSY
  - ✓ Models with extra space-time dimensions
  - ✓ Little Higgs
  - ✓ Strings
- In all of them a new phenomena and particles are predicted

What we need:
Observe the Higgs boson
Find an evidence for physics BSM

LHC is supposed to solve this problems

SUSY SM

spin 0	spin 1/2	spin 1	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$
$\tilde{u}_L, \tilde{d}_L$	u_L, d_L		**3**	**2**	$+\frac{1}{3}$
$\tilde{u}_R$	u_R		**3**	**1**	$+\frac{4}{3}$
$\tilde{d}_R$	d_R		**3**	**1**	$-\frac{2}{3}$
$\tilde{\nu}, \tilde{e}_L$	ν, e_L		**1**	**2**	-1
$\tilde{e}_R$	e_R		**1**	**1**	-2
H_u^+, H_u^0	$\tilde{h}_u^+, \tilde{h}_u^0$		**1**	**2**	$+1$
H_d^0, H_d^-	$\tilde{h}_d^0, \tilde{h}_d^-$		**1**	**2**	-1
	$\tilde{g}$	g	**8**	**1**	0
	$\tilde{w}^\pm, \tilde{w}^0$	$W^\pm, W^0$	**1**	**3**	0
	$\tilde{b}^0$	B^0	**1**	**1**	0

SUSY

The bino,wino, zino and higgsino are not mass aigenstates

The observable states are:

$$\tilde{W}, \tilde{Z}, \tilde{\gamma}, \tilde{H}_{u,d} \Rightarrow \tilde{\chi}^{\pm}, \tilde{\chi}^{0}$$

Charginos, neutralinos

To ensure B and L conservation – a new symmetry R-parity

$$P_R = (-1)^{3(B-L)+2s}$$

SM Particles: $P_R = +1$

Superpartners: $P_R = -1$

Stable proton

Supersymmetric partners are created in pairs

Lightest supersymmetric particle – stable (neutralino)

Natural candidate for dark mater

SUSY braking

SUSY should be broken

$$L_{MSSM} = L_{SM} + L_{SUSY} + L_{soft}$$

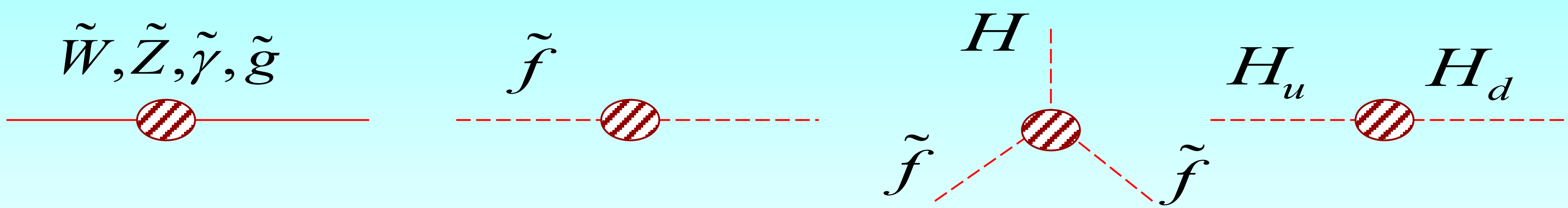
$$L_{soft} \longrightarrow \tilde{M} \neq M$$

Introduces 105 new parameters!

Observable sector
MSSM

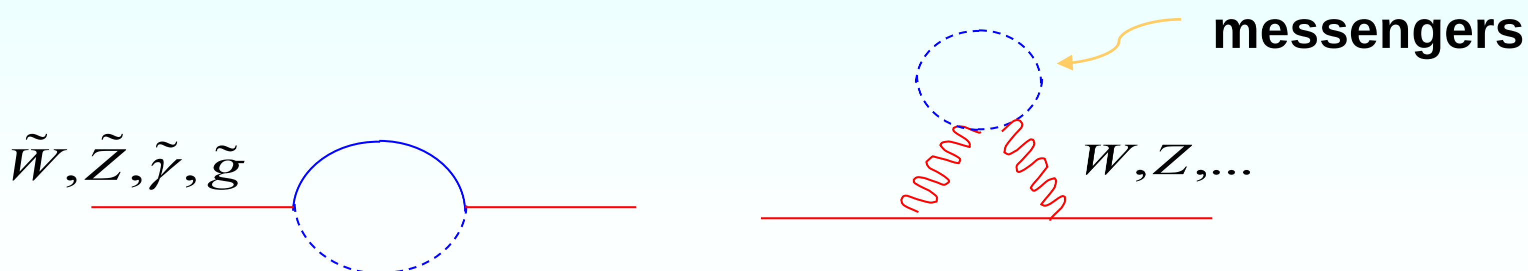
messenger

Hidden sector
SUSY Breaking



Gravity mediated (mSUGRA)

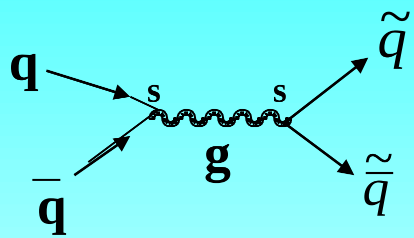
$m_{1/2}$, m_0, $\tan\beta$, sign(μ), A_0

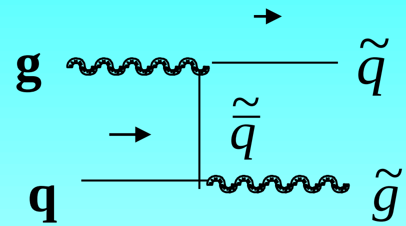


Gauge mediated

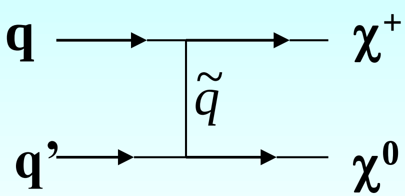
Sparticle production at LHC

Suarks and gluinos are prodiced via strong interactions → large cross section

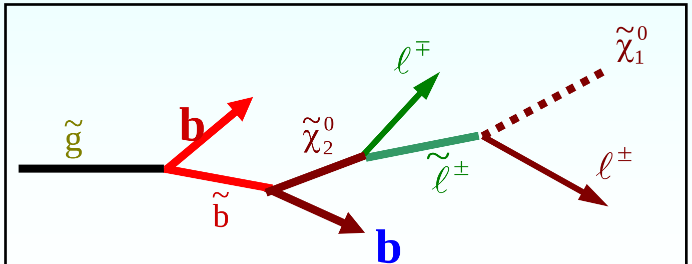




•Charginos, neutralinos, sleptons direct production occurs via electroweak processes → much smaller rate (produced more abundantly in squark and gluino decays)



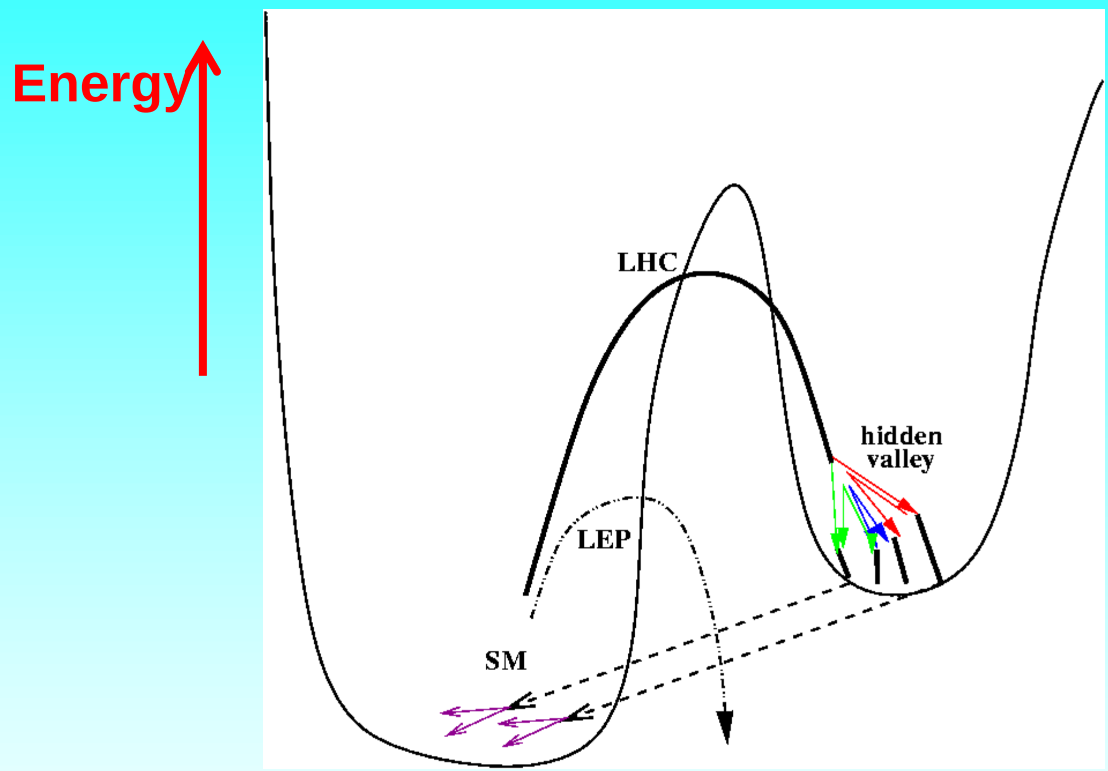
$\sigma \approx$ pb $m_\chi \approx$ 150 GeV



Leandar Litov

Signatures – jets, leptons + $E_{t\ mis}$

Hidden valley models



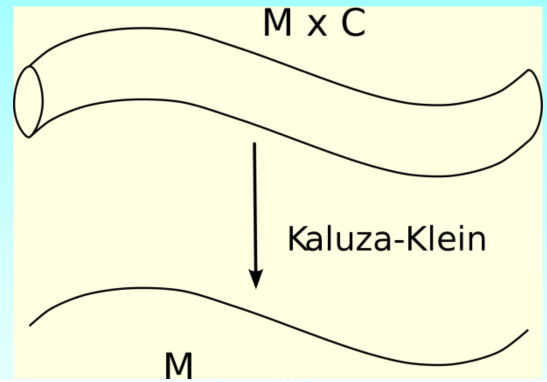
Observable sector
SM

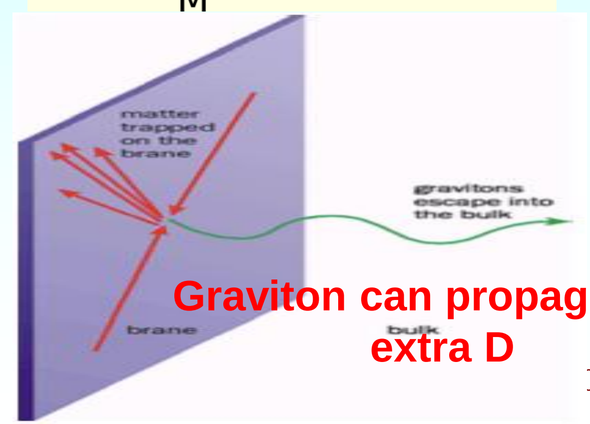
Particles
Charged Under
SM *and* HV

Hidden sector
G_v with v-matter

Extra Dimensions

- Inspired by old Kaluza-Klain idea for unified description of gravity and EM
- Revoked in the context of SUSY and String theories
- Basic idea – we are living in 4 +n dimensions
- The SM particles are bind to the 4- dimensional world
- The graviton and possibly some other particles are able to travel in all dimensions
- Two main approaches
  - The extra dimensions are compactyfied – Large Extra Dimensions (LED)
  - The extra dimensions are flat – Brain world
  - Particular case – warped extra dimensions Randal –Sundrum models with two brains situated at the ends of orbifold
- Many different models





Graviton can propagate in extra D

LED

Graviton propagate in all dimensions

$$M_D^{n_{ED}+2} = M_{Pl}^2 / r^{n_{ED}}$$

r – is the size of the extra dimensions, n_{ED} – is the number of extra dimensions

Production of massive Kauza-Klain modes is expected

KK decay to SM particles (di-photon, di-lepton etc)

Sum on KK modes – ultraviolet cut M_s is needed

The contribution of the virtual graviton production is parameterized by single variable

$$\eta_G = F / M_s^4$$

LED

$F = 1$

Guidice, Rattazzi and Wells,
GRW

$F = \log(\frac{M_s^2}{\hat{s}})$ if $n_{ED} = 2$

Han, Lykken and Zhang
(HLZ)

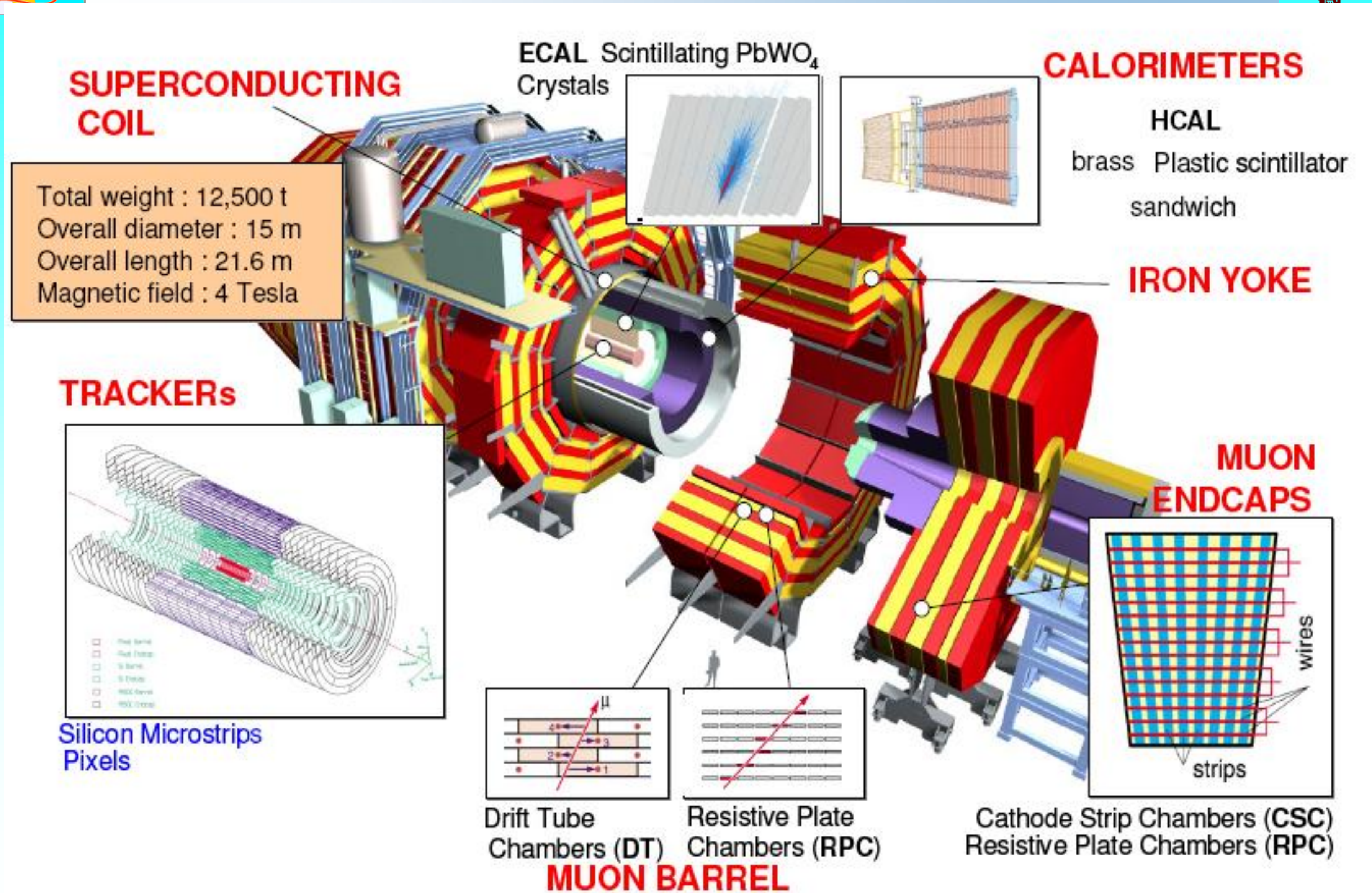
$F = \frac{2}{n_{ED} - 2}$ if $n_{ED} > 2$

In the GRW convention the leading order phenomenology is controlled by a single Parameter

$$\Lambda_T^4 = \frac{8\pi\Gamma(n/2)}{2\pi^{n/2}c_1}\frac{M_D^{n+2}}{\Lambda^{n-2}}$$

Results for Λ can be connected with M_s and n parameterization in the HLZ convention

The CMS detector



Search for SUSY

- In all cases we expect missed E_t due to LSP and some jets and leptons
- Several investigations
  - Jets + missing E_t
  - Lepton pairs + jets + missing E_t
  - Two or more photons + jets + missing E_t

SUSY – jets and $\not{E}_t$

We reconstruct events with at least two jets and significant $\not{E}_t$

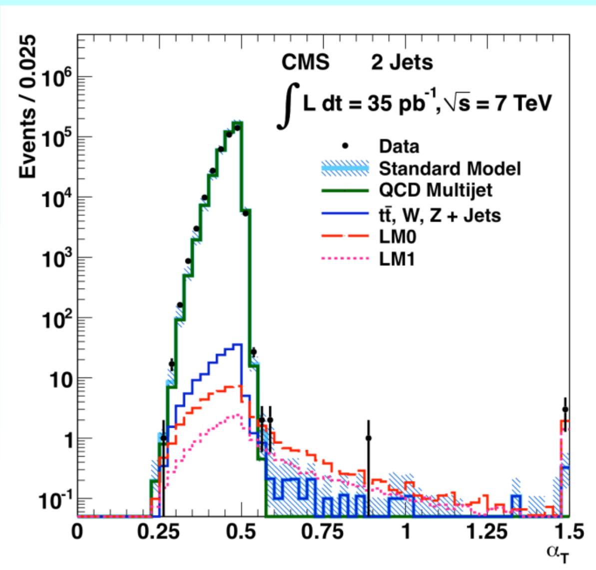
Reconstructed jets with E_t > 50 GeV

Define hadron transfer energy $$H_t = \sum_{j=1}^{N_{jet}} E_T^j$$

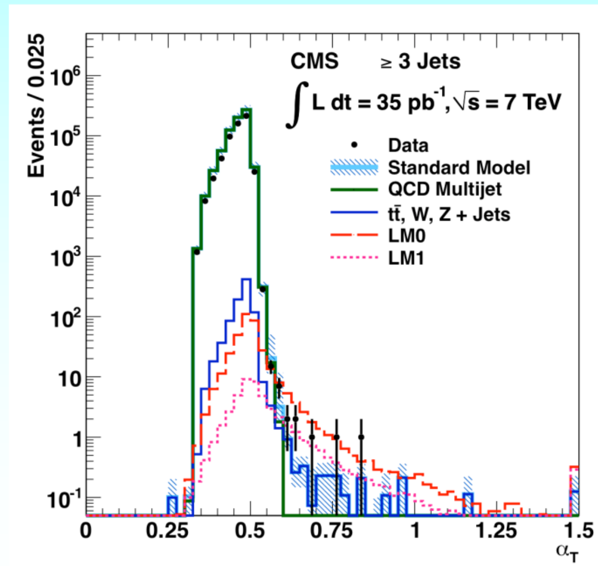
LM0 m_0 = 200 GeV, $m_{1/2}$ = 160 GeV, A_0 =−400 GeV, tanβ = 10, and sign(μ) > 0

LM1 m_0 = 60 GeV, $m_{1/2}$ = 250 GeV, A_0 = 0, tanβ = 10, and sign(μ) > 0.

To supress background – use $\alpha_T = E_T^{j2} / M_T$



H_t > 350 GeV
N_{jet} = 2



H_t > 350 GeV
N_{jet} > 2

SUSY – jets and $\not{E}_t$

Background was estimated from data

3 regions $250 < H_t < 300$, $300 < H_t < 350$, $H_t > 350$ GeV

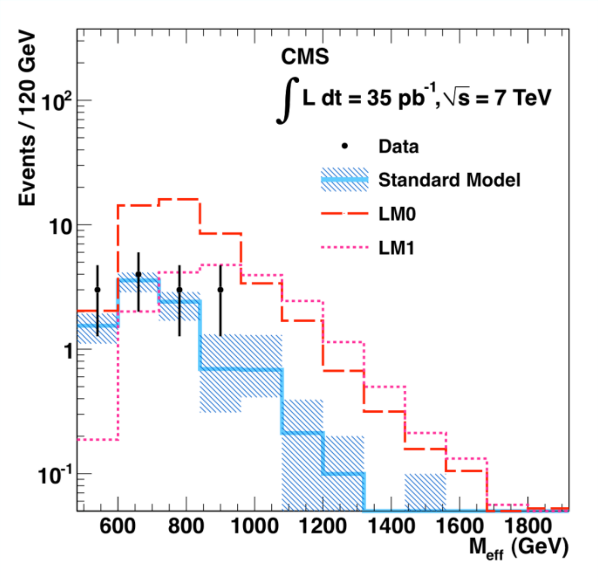
Two independent methods– inclusive *9.4+4.8−4.0(stat) ± 1.0(syst)*

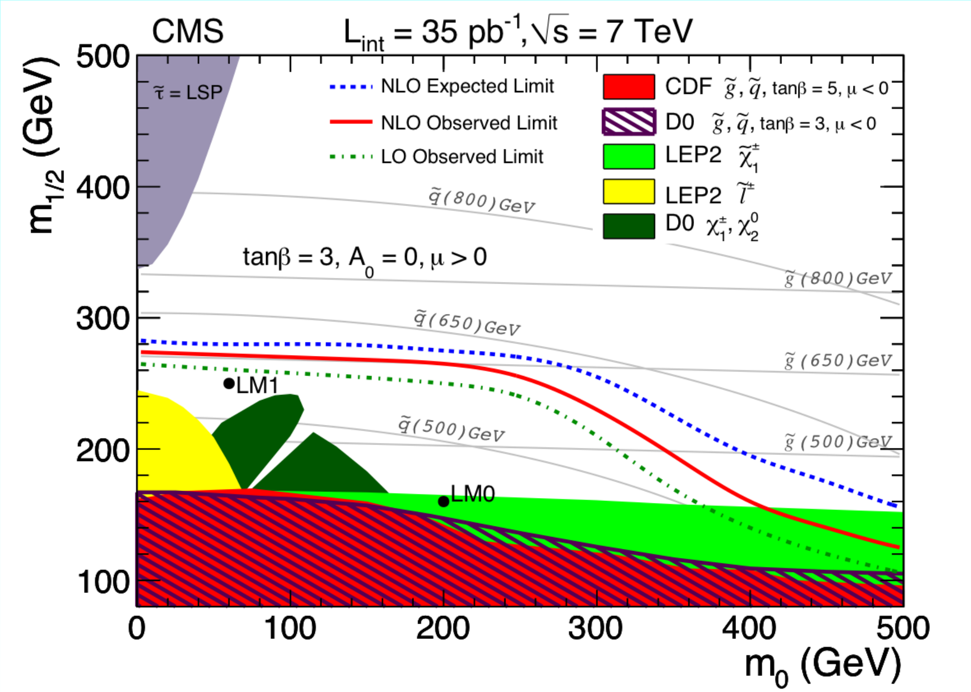
W → *μν + jet* *6.1+2.8−1.9(stat) ± 1.8(syst)*

Z → *ν.ν + jets* *4.4+2.3−1.6(stat) ± 1.8(syst).*

Total EWK *10.5+3.6−2.5*

Observed events - 13





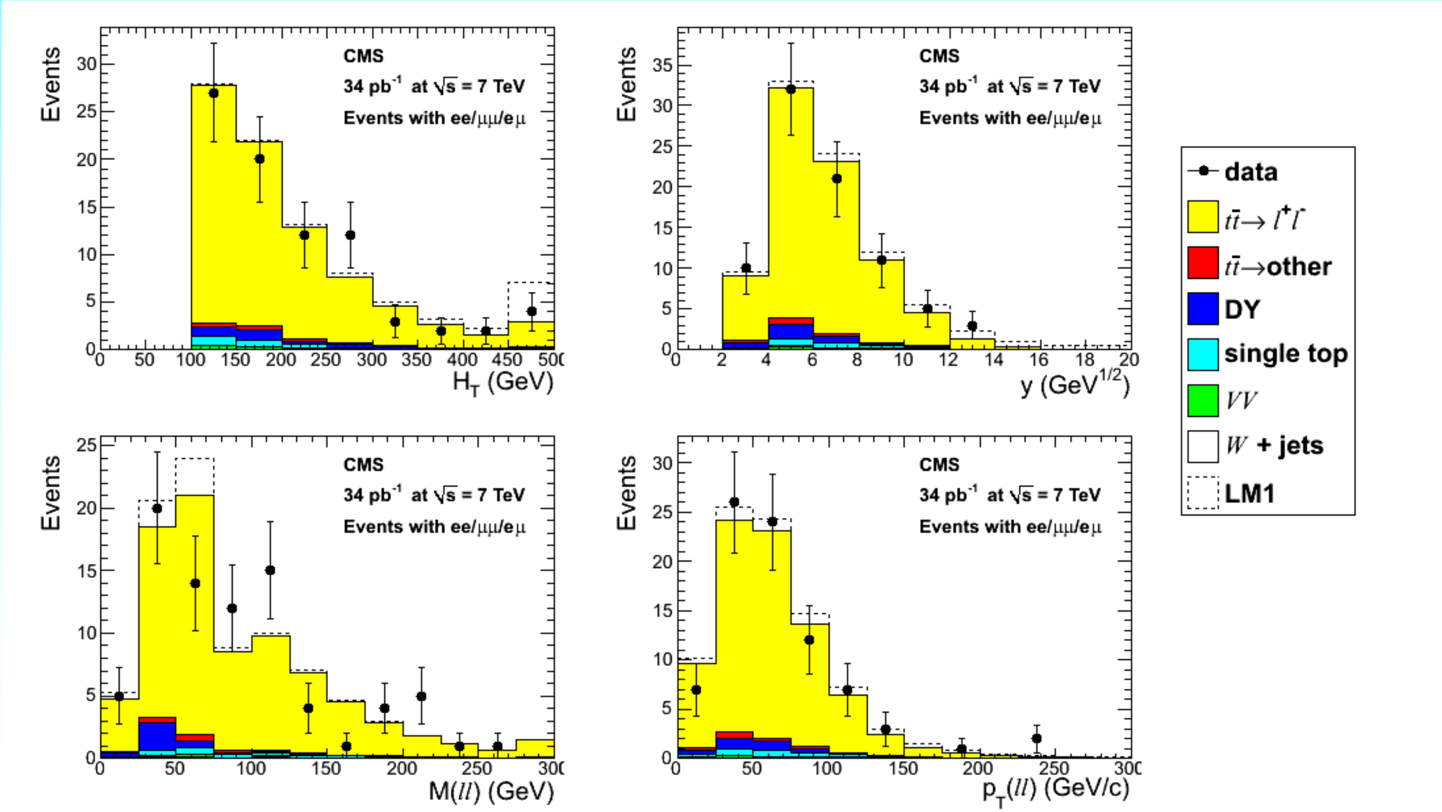
SUSY – di-lepton search

Lepton pairs with opsite charges $e^+e^-, e^\pm\mu^\mp, \mu^+\mu^-$

Selections – two leptons with E_t > 20 GeV and E_t >10 GeV

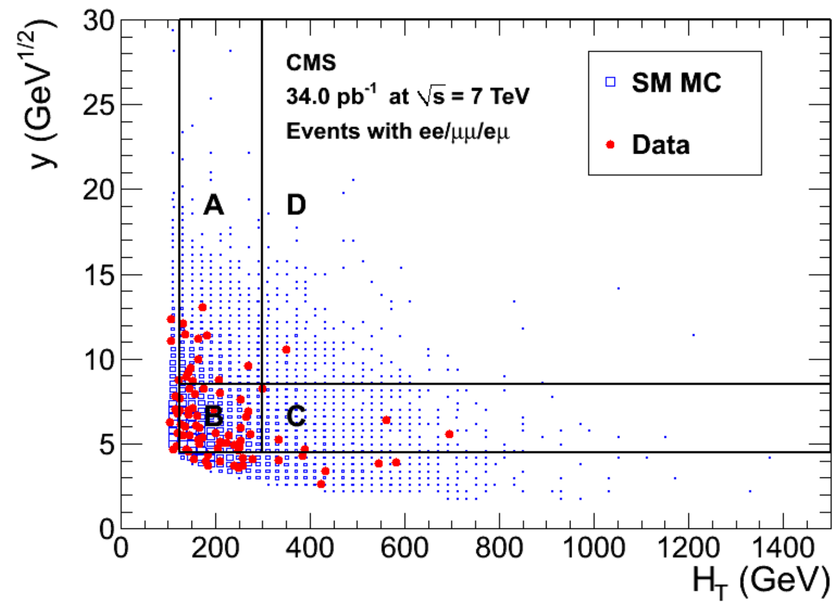
At least two jets with p_t > 30 GeV and H_t > 100 GeV, $\not{E}_t$ > 50 GeV

Signal region H_t > 300 GeV and y > 8.5 GeV$^{1/2}$, $y = E_t^{miss} / \sqrt{H_t}$



SUSY – di-lepton search

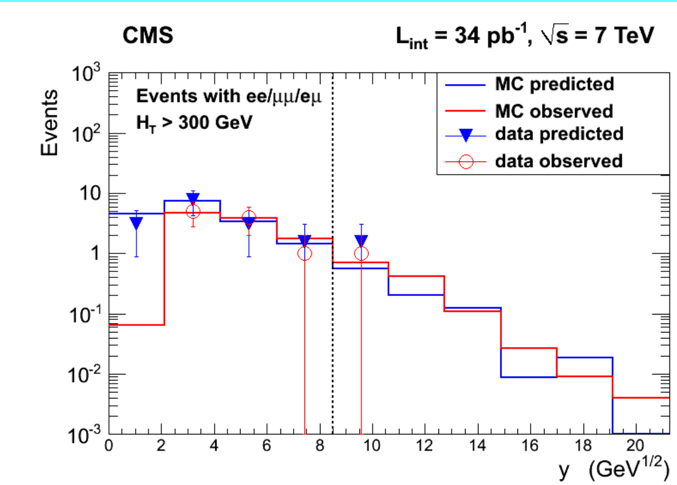
sample	N_A	N_B	N_C	N_D	$N_A \times N_C/N_B$
$t\bar{t} \to \ell^+\ell^-$	8.44 ± 0.18	32.83 ± 0.35	4.78 ± 0.14	1.07 ± 0.06	1.23 ± 0.05
$t\bar{t} \to$ other	0.12 ± 0.02	0.78 ± 0.05	0.16 ± 0.02	0.02 ± 0.01	0.02 ± 0.01
Drell Yan	0.17 ± 0.08	1.18 ± 0.22	0.04 ± 0.04	0.12 ± 0.07	0.01 ± 0.01
$W^\pm$ + jets	0.00 ± 0.00	0.09 ± 0.09	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
W^+W^-	0.11 ± 0.01	0.29 ± 0.02	0.02 ± 0.01	0.03 ± 0.01	0.01 ± 0.00
$W^\pm Z$	0.01 ± 0.00	0.04 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
ZZ	0.01 ± 0.00	0.02 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
single top	0.29 ± 0.01	1.04 ± 0.03	0.04 ± 0.01	0.01 ± 0.00	0.01 ± 0.00
total SM MC	9.14 ± 0.20	36.26 ± 0.43	5.05 ± 0.14	1.27 ± 0.10	1.27 ± 0.05
data	12	37	4	1	1.30 ± 0.78
LM0	4.04 ± 0.19	4.45 ± 0.20	13.92 ± 0.36	8.63 ± 0.27	12.63 ± 0.88
LM1	0.52 ± 0.02	0.26 ± 0.02	1.64 ± 0.04	3.56 ± 0.06	3.33 ± 0.27

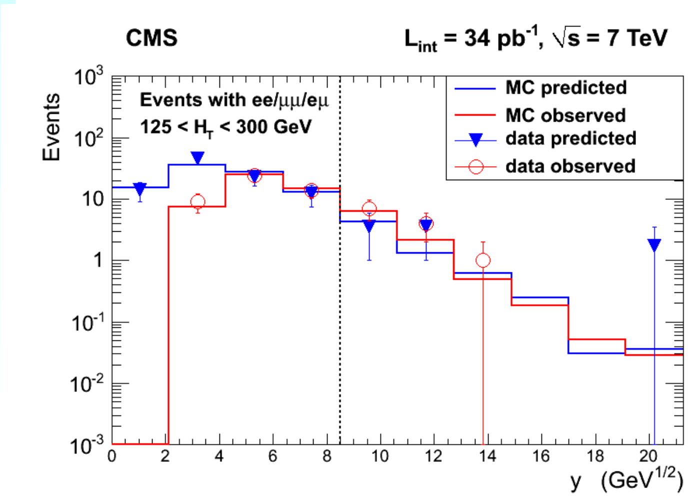


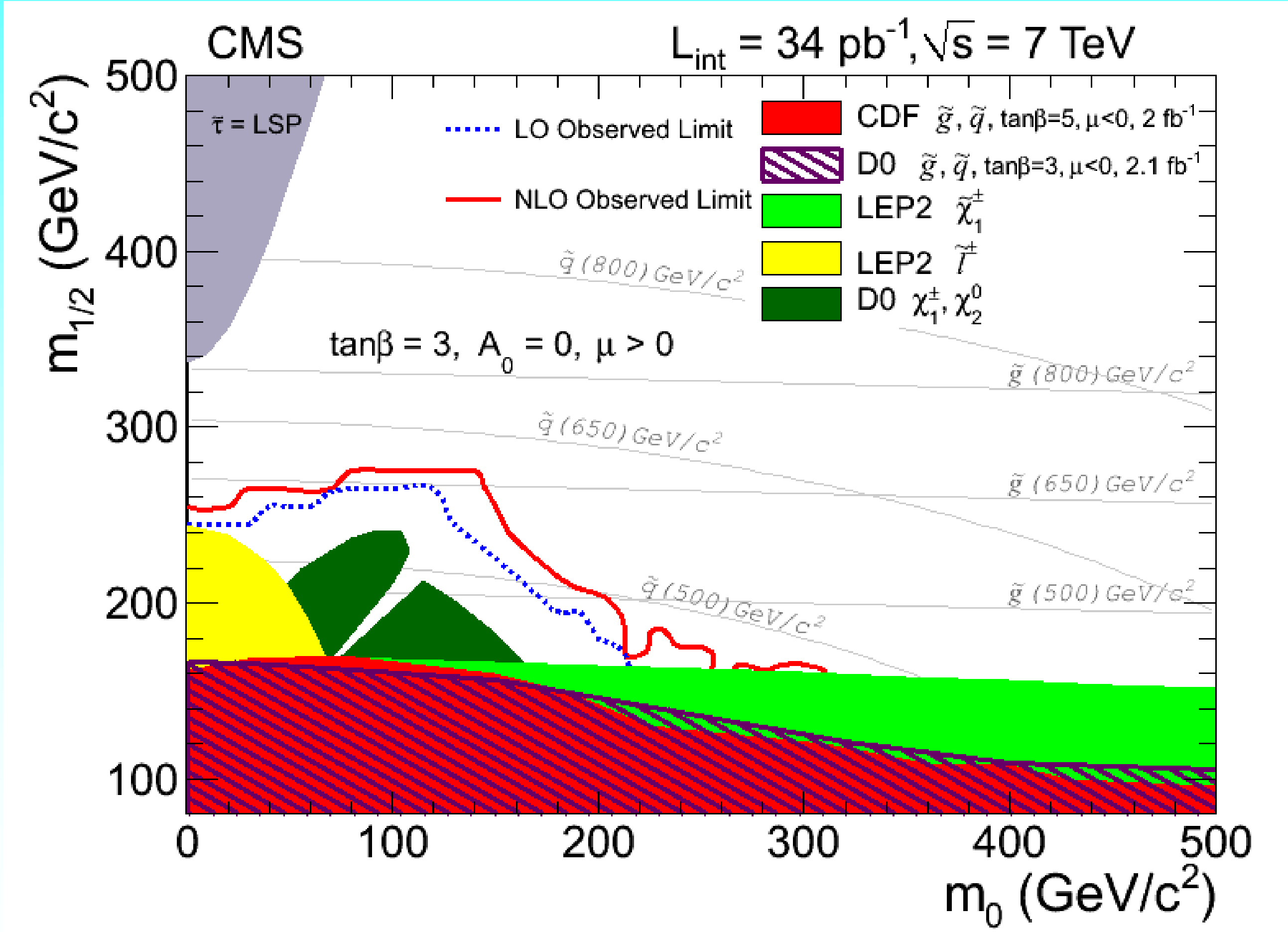
SUSY – di-lepton search

Background estimated from data, Three control regions and one signal

$H_t > 300$ GeV and $y > 8.5$ GeV$^{1/2}$ l Expected 1.27 +/- 0.05, Observed 1 event



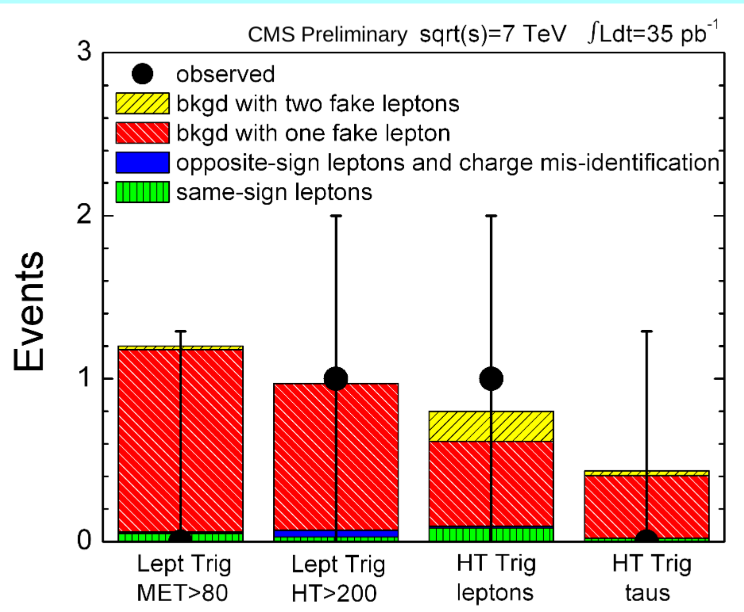


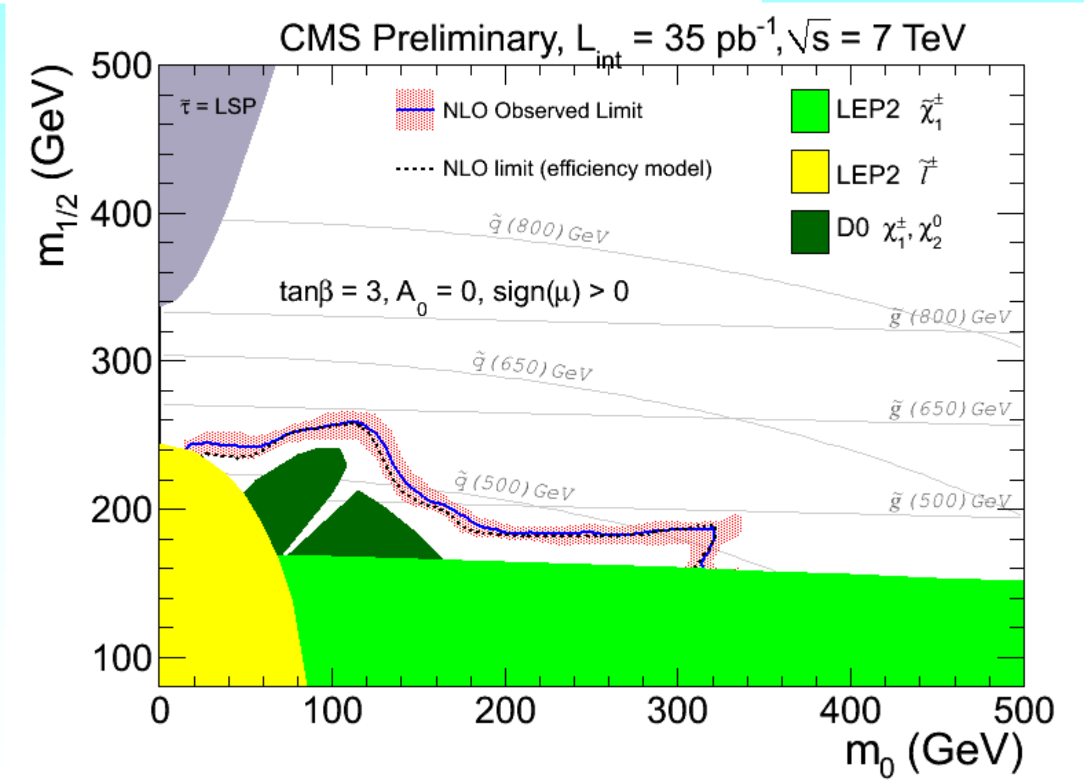


SUSY – di-lepton search

Search with same sign leptons

	Simulation Only SM BKG		Data Relaxed selection	
Channel	Observed	Predicted	Observed	Predicted
$\tau\tau$	0.08±0.03	0.15±0.15	14	14.0±4.3±2.6
$e\tau$	0.35±0.12	0.30±0.11	1	0.8±0.4±0.1
$\mu\tau$	0.47±0.15	0.49±0.20	2	2.9±0.6 ±0.4





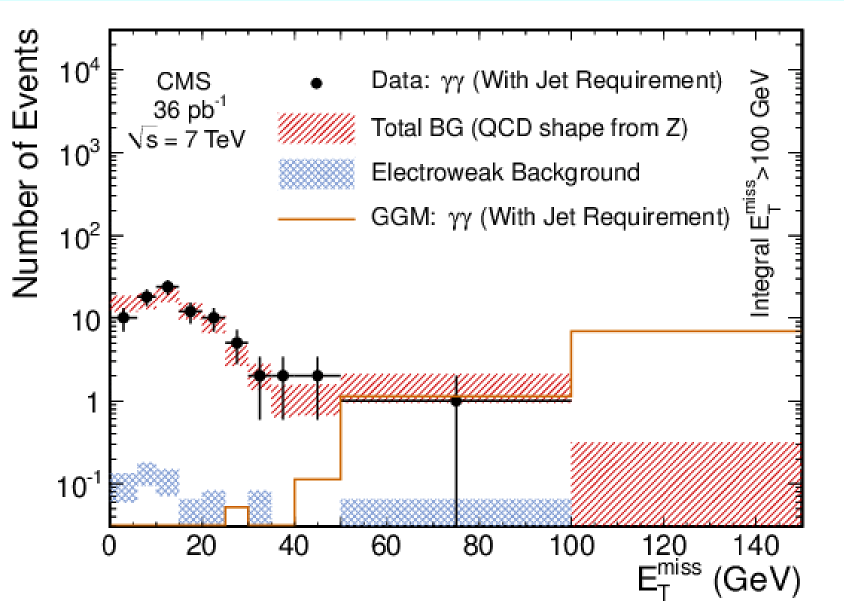
SUSY - two photons and $\not{E}_t$

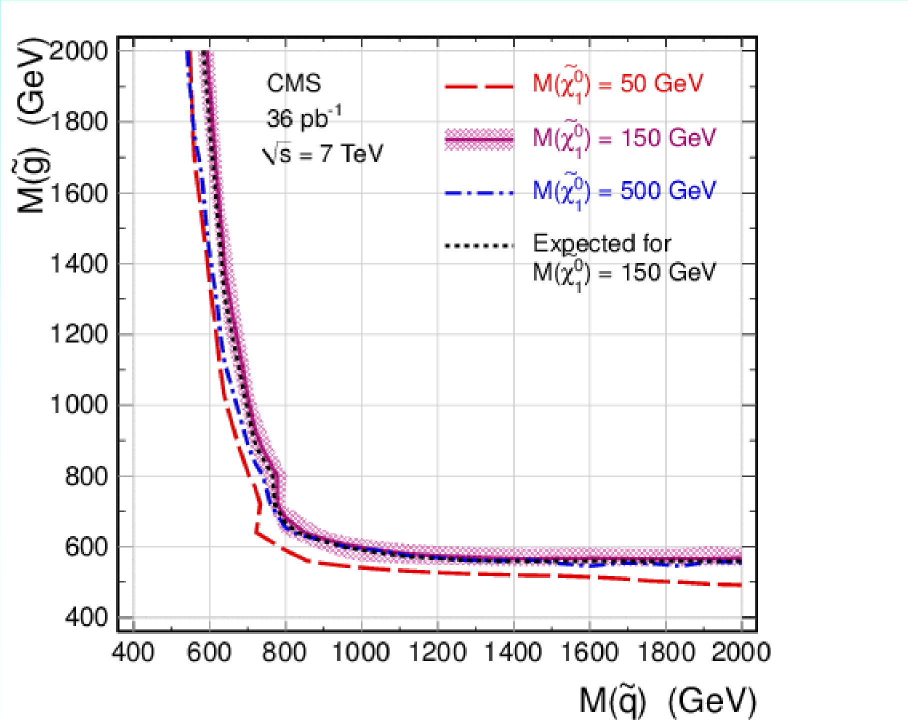
In SUSY models with Gauge Mediated SUSY (GGM) breaking LSP is gravitino, NLSP neutralino, $G \to \chi^0 + \gamma$, we are looking for events with at least 2 or more isolated photons (E_t > 30 GeV), at least one jet (E_t > 30 GeV) and Large $\not{E}_t$ > 50 GeV.

Expected events (BG) – 1.71+/-0.64 events

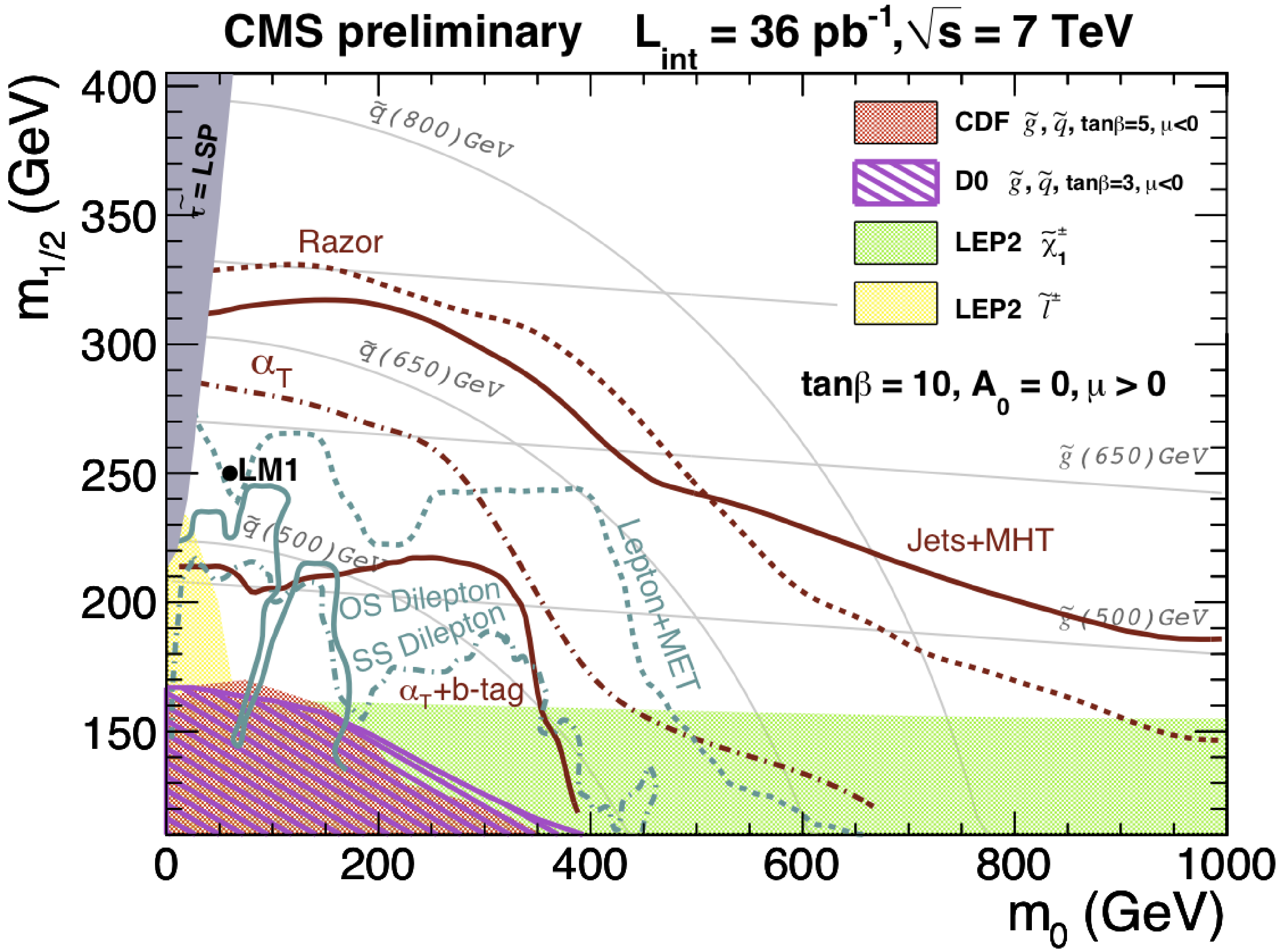
Expected from GGM – 8 +/- 1.7 events

Observed – 1 event





SUSY - CMS



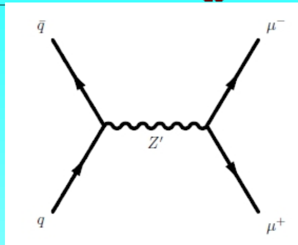
CMS preliminary L_{int} = 36 pb^{-1}, $\sqrt{s}$ = 7 TeV
$m_{1/2}$ (GeV)
m_0 (GeV)
CDF $\tilde{g}, \tilde{q}$, tanβ=5, μ<0
D0 $\tilde{g}, \tilde{q}$, tanβ=3, μ<0
LEP2 $\tilde{\chi}_1^{\pm}$
LEP2 $\tilde{l}^{\pm}$
tanβ = 10, A_0 = 0, μ > 0
$\tilde{\tau}$ = LSP
Razor
α_T
LM1
Jets+MHT
Lepton+MET
OS Dilepton
SS Dilepton
α_T+b-tag
$\tilde{q}$(800)GeV
$\tilde{q}$(650)GeV
$\tilde{q}$(500)GeV
$\tilde{g}$(650)GeV
$\tilde{g}$(500)GeV

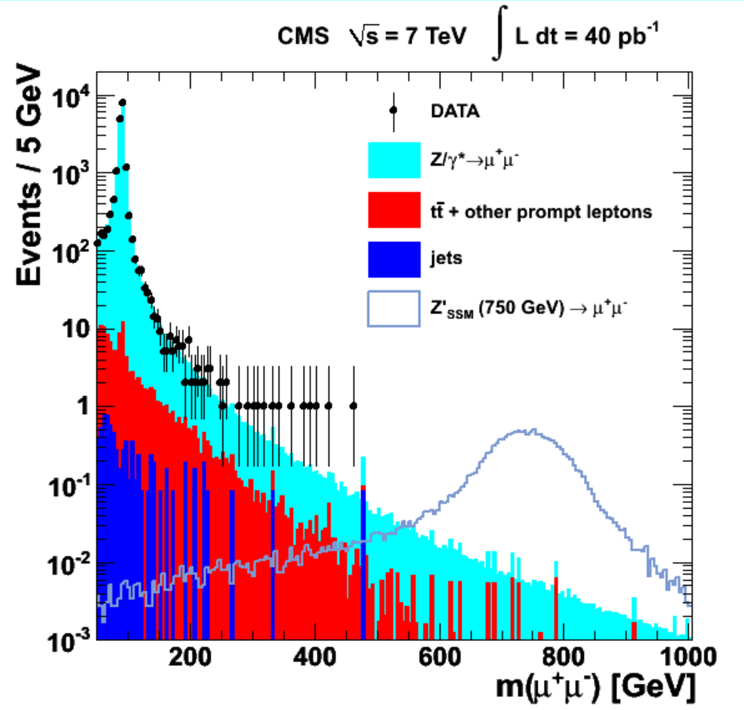
Search for Z'/RS Graviton

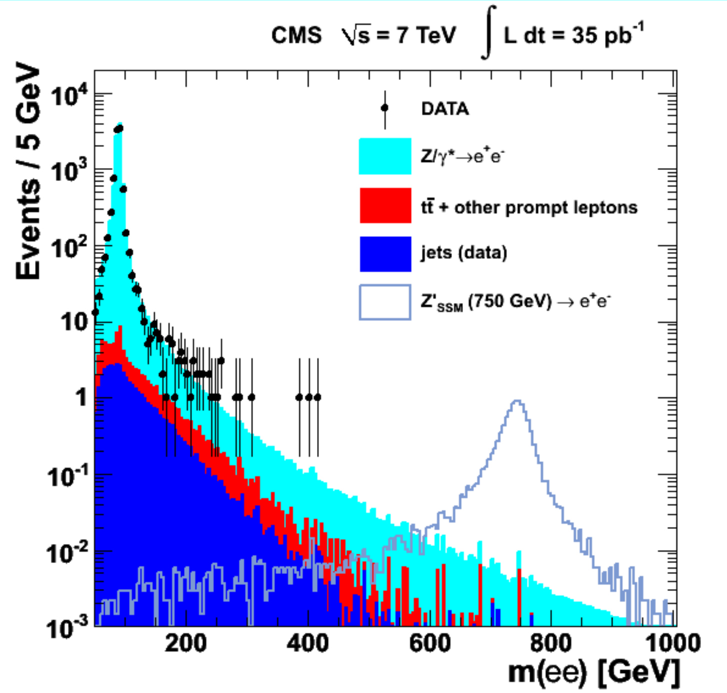
Search for heavy narrow resonances decaying to two leptons

$Z' \rightarrow l^+ l^-$ and $G_{kk} \rightarrow l^+ l^-$

L_{int} = 40 pb^{-1} for dimuon channel and 35 pb^{-1} for dielectron channel



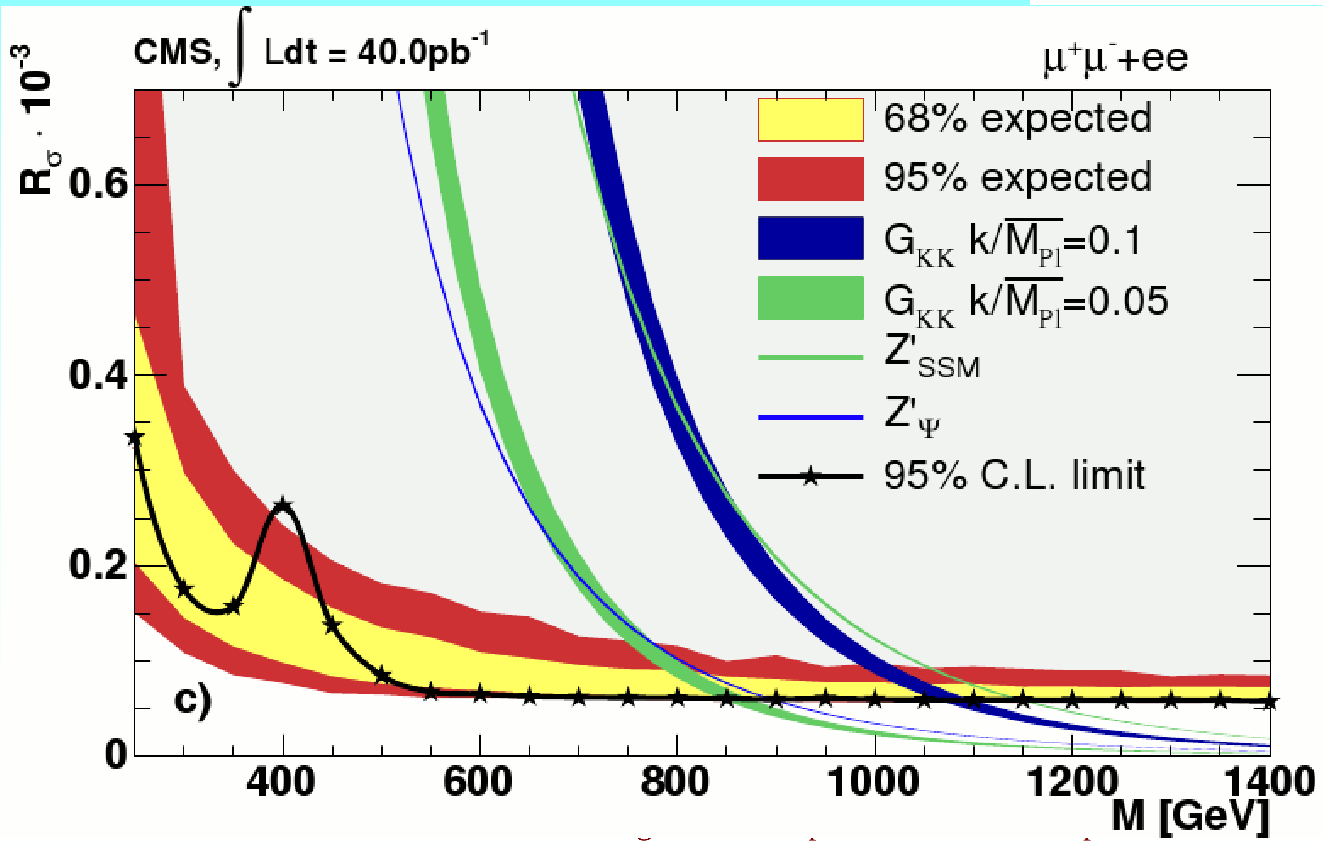




Search for Z'/RS Graviton

$$R_\sigma = \frac{\sigma(pp \to Z' + X \to \ell\ell + X)}{\sigma(pp \to Z + X \to \ell\ell + X)}$$

Channel	μμ	ee	Combined
Z_{SSM}	1027 GeV	958 GeV	1140 GeV
Z_ψ	792 GeV	731 GeV	887 GeV
G_{KK}, k/M_{Pl} = 0.05	778 GeV	729 GeV	855 GeV
G_{KK}, k/M_{Pl} = 0.10	987 GeV	931 GeV	1079 GeV

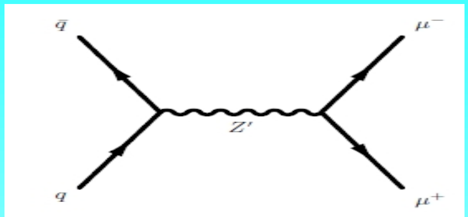


Results more restrictive than or comparable to those previously published by Tevatron (5/fb) & LEP experiments

larXiv: 1103.0981, submitted to JHEP

W’ Searches (eν+μν)

Define $M_T = \sqrt{2E_T^{\ell} E_T^{miss}[1 - \cos \Delta\phi(\ell, E_T^{miss})]}$



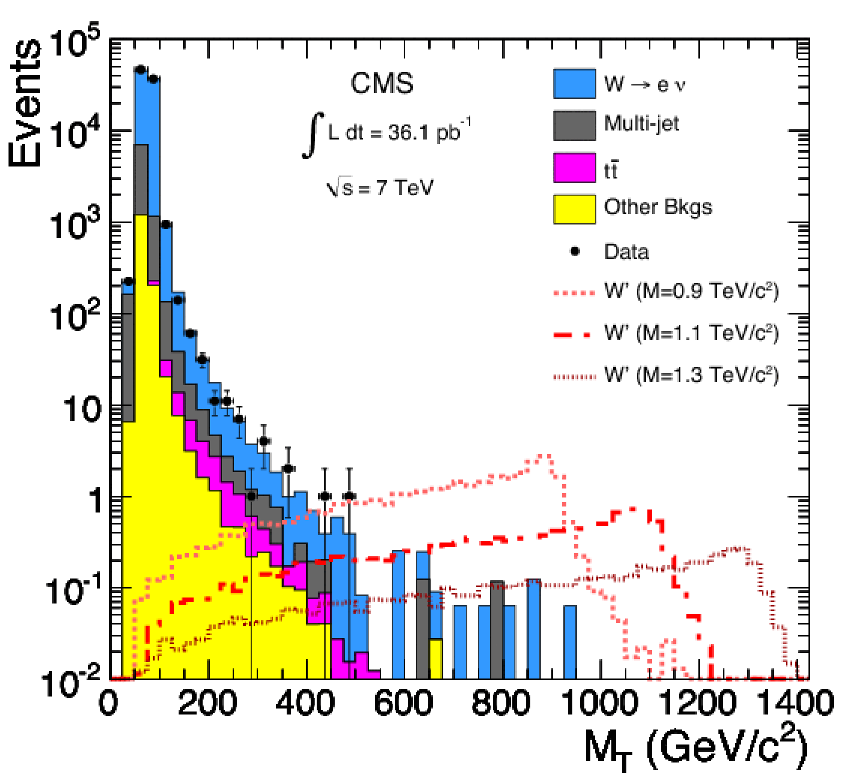
And look at Jakobian peak

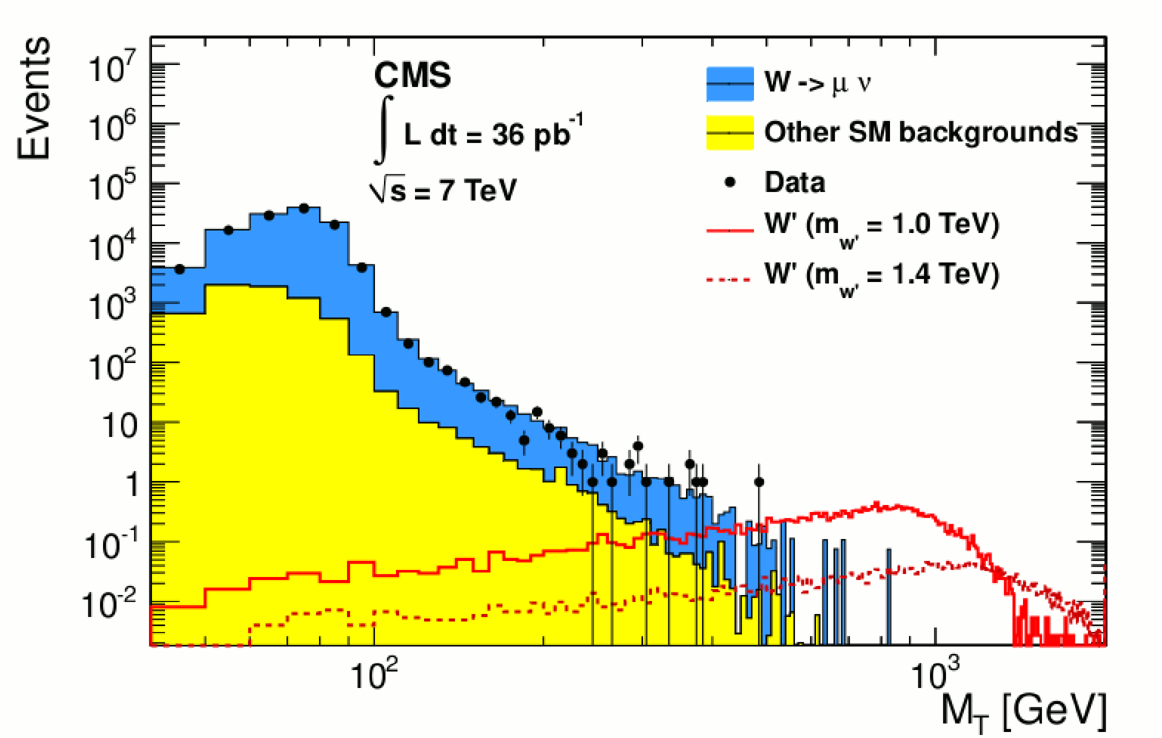
Search for $M_{W'}$ in the range 0.6-2 TeV

– $M_T(e\nu)$>400-675 GeV; 2-0 obs. ev.

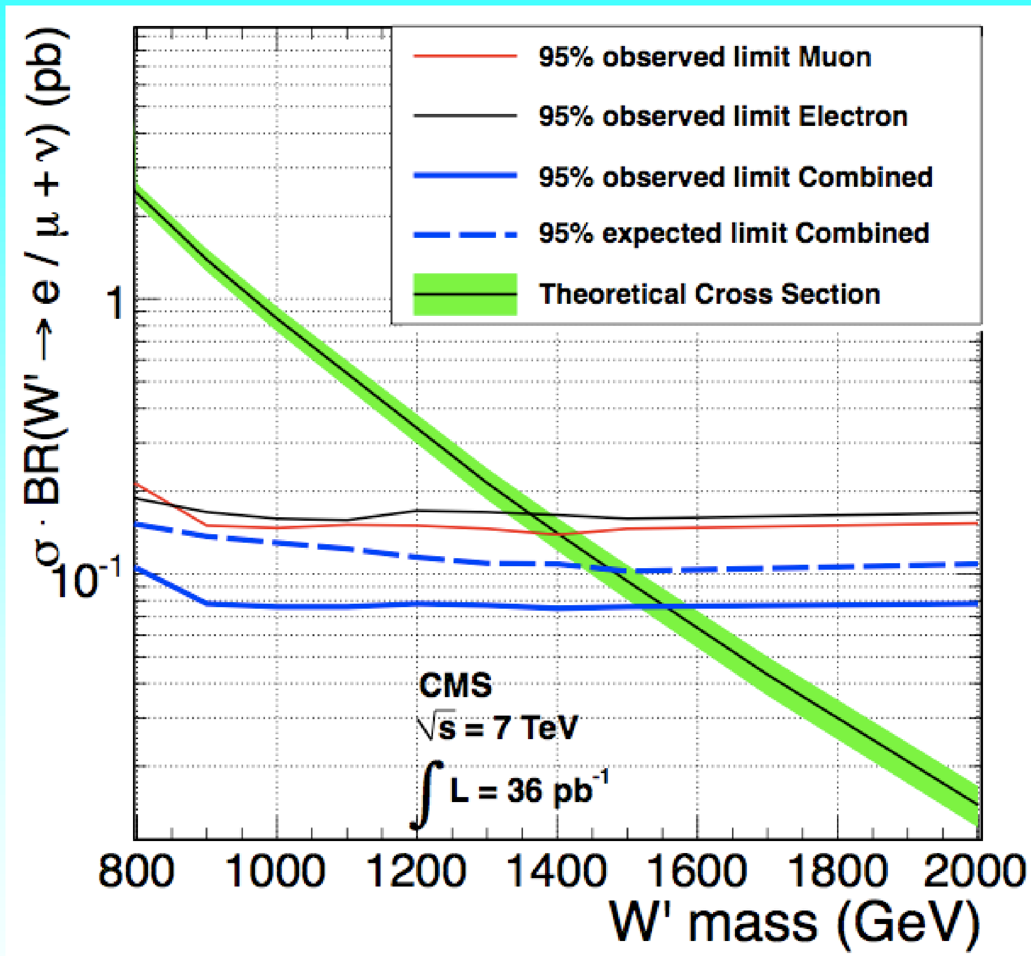
– $M_T(\mu\nu)$>390-690 GeV; 1-0 obs. ev.

Consistent with SM, set limits





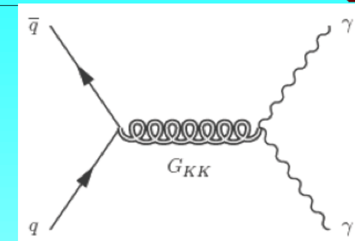
W' Searches (eν+μν)



$M_{W'}$ >1.36 TeV (eν)
$M_{W'}$ >1.4 TeV (μν)
$M_{W'}$ >1.58 TeV (eν+μν)
Significant improvement over previously published limits

eν □ arXiv:1012.5945, submitted to PLB
μν □ arXiv:1103.0030, submitted to PLB

Search for extra dimensions



μ

μ

No event observed with Mγγ (Mμμ) >500 (600) GeV

- **Set lower limits on Ms for different theory conventions**

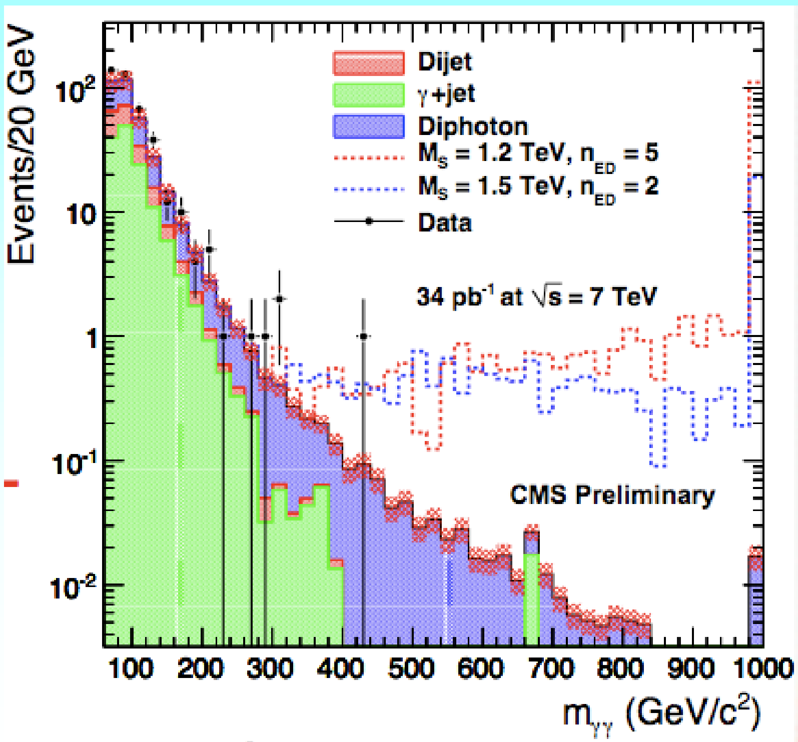
M_s

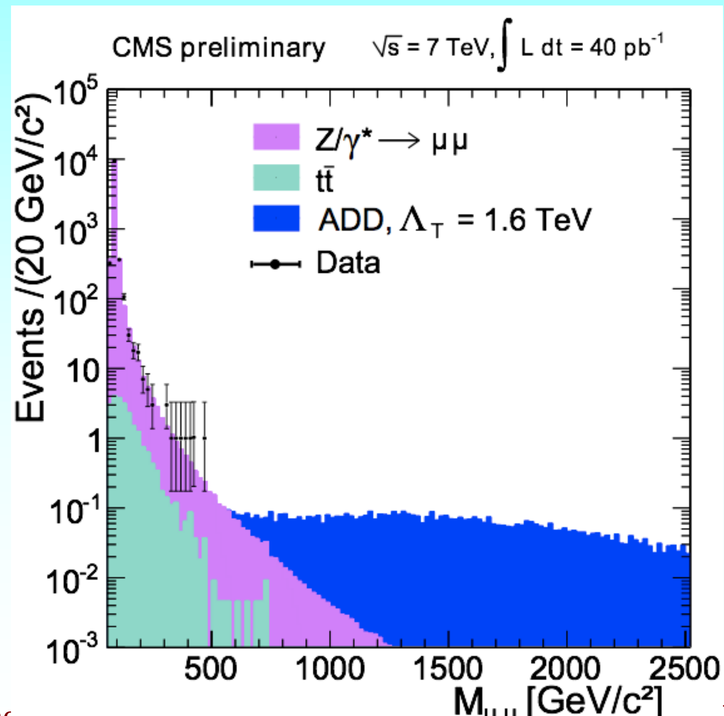
	GRW	Hewett Pos.	Hewett Neg.	HLZ $n_{ED}=2$	HLZ $n_{ED}=3$	HLZ $n_{ED}=4$	HLZ $n_{ED}=5$	HLZ $n_{ED}=6$	HLZ $n_{ED}=7$
Full	1.94	1.74	1.71	1.89	2.31	1.94	1.76	1.63	1.55
Trunc.	1.84	1.60	1.50	1.80	2.23	1.84	1.63	1.46	1.31

γγ

	Λ_T [TeV] (GRW)	M_s [TeV/c^2] (HLZ) $n=2$	$n=3$	$n=4$	$n=5$	$n=6$	$n=7$
Full	1.80	1.75	2.15	1.80	1.63	1.52	1.43
Truncated	1.68	1.67	2.09	1.68	1.49	1.34	1.24

μμ





Search for microscopic Black Holes

If gravity scale is lowered to M_d, black holes with mass M_{BH} could be produced when partons interact at distances closer than r_S

- Democratic BH decay (via Hawking radiation) to all SM degrees of freedom (75% are quarks and gluons thanks to color)
- **Search for deviation in S_T distribution in "object multiplicity" (N) inclusive bins**
- S_T shape invariant w.r.t. multiplicity
- Use S_T spectrum from N=2 to predict N>=3,4,5, where signal would be present

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

$$\sigma \sim \pi r_S^2$$

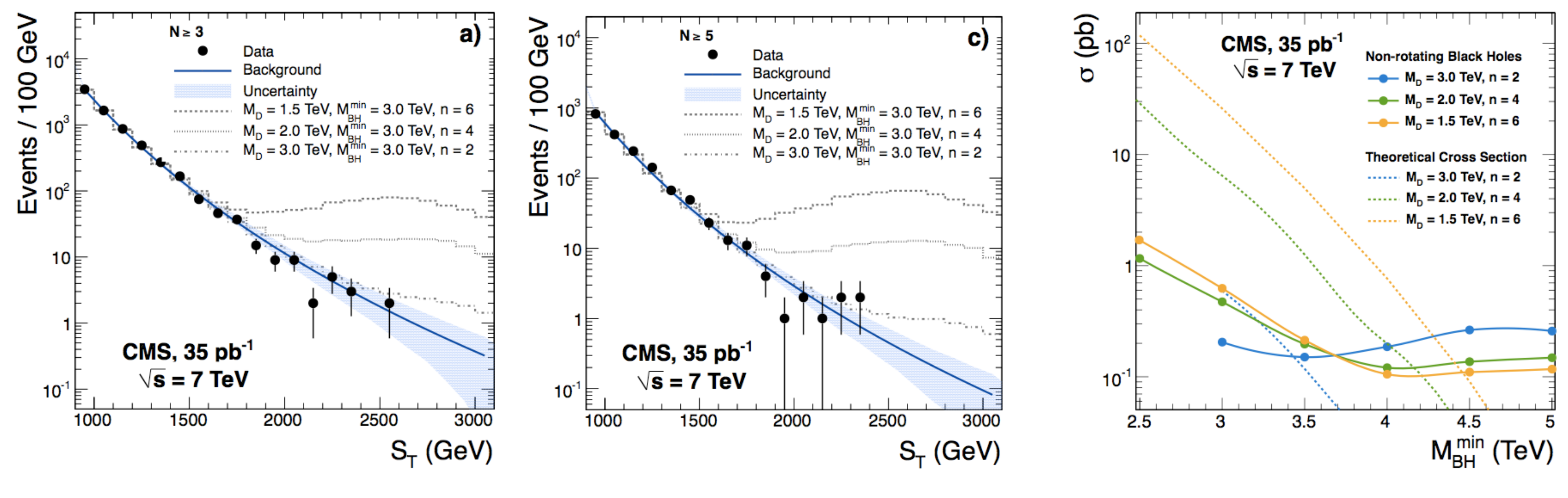
$$S_T = \sum_N E_T$$

jets,e,γ,μ with ET>50 GeV + MET (if >50 GeV)

Search for microscopic Black Holes

No excess observed, set limits on the min.

BH mass in semi-classical approximation



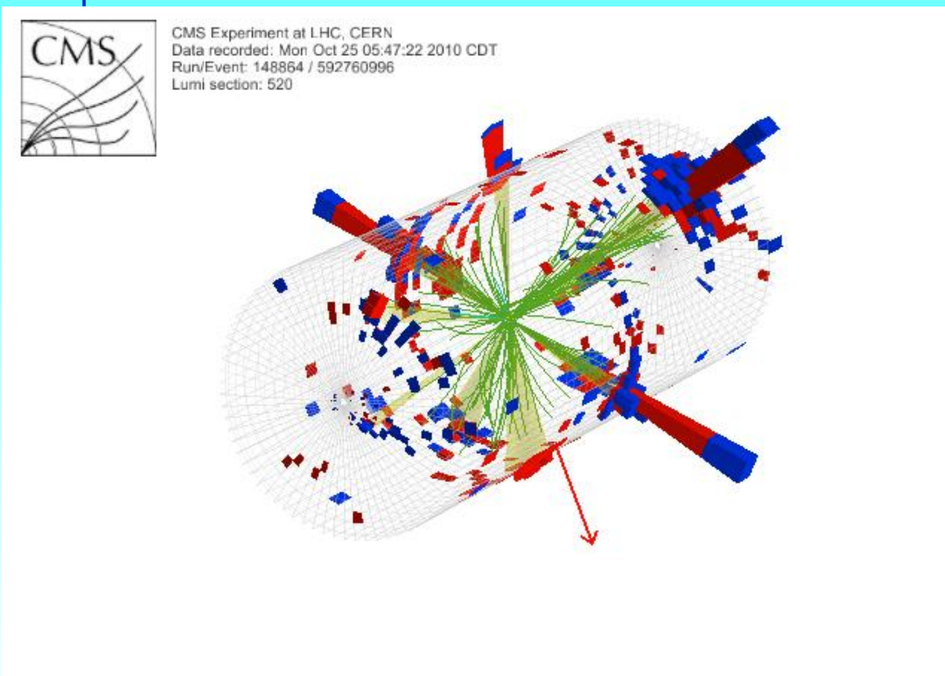
$$M_{BH}^{\min} > 3.5 - 4.5 TeV$$

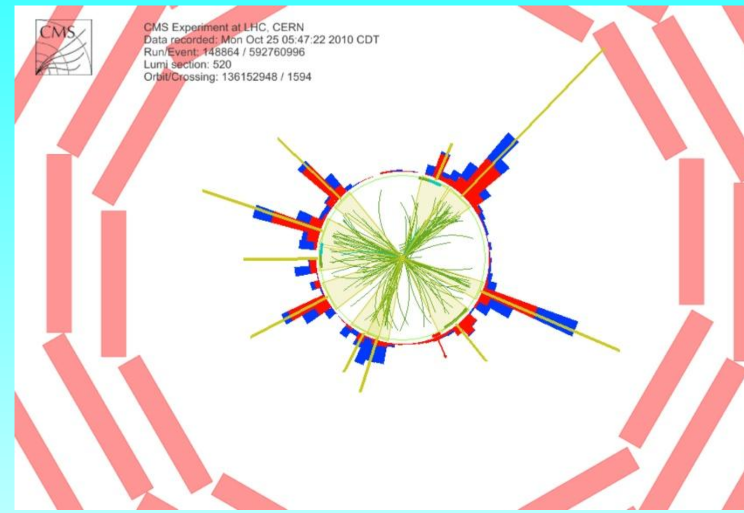
PLB 697:434-453 (2011)

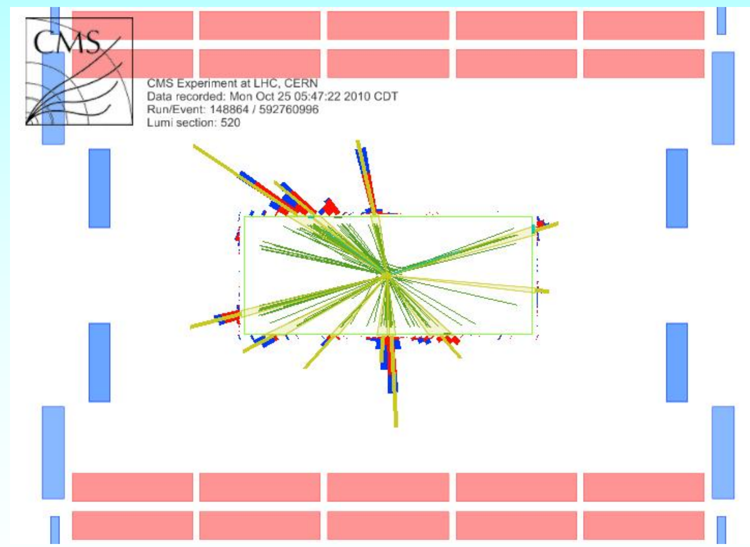
Search for microscopic Black Holes

10 - jet event BH candidate

S_T = 1.3 TeV

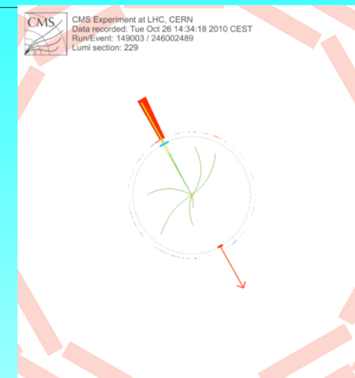


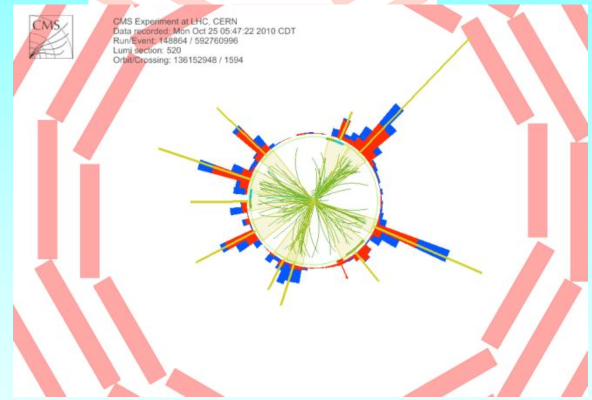


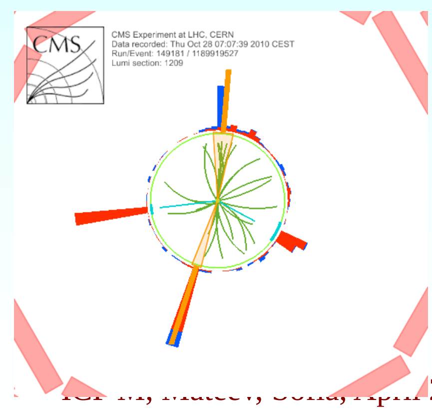


Conclusions

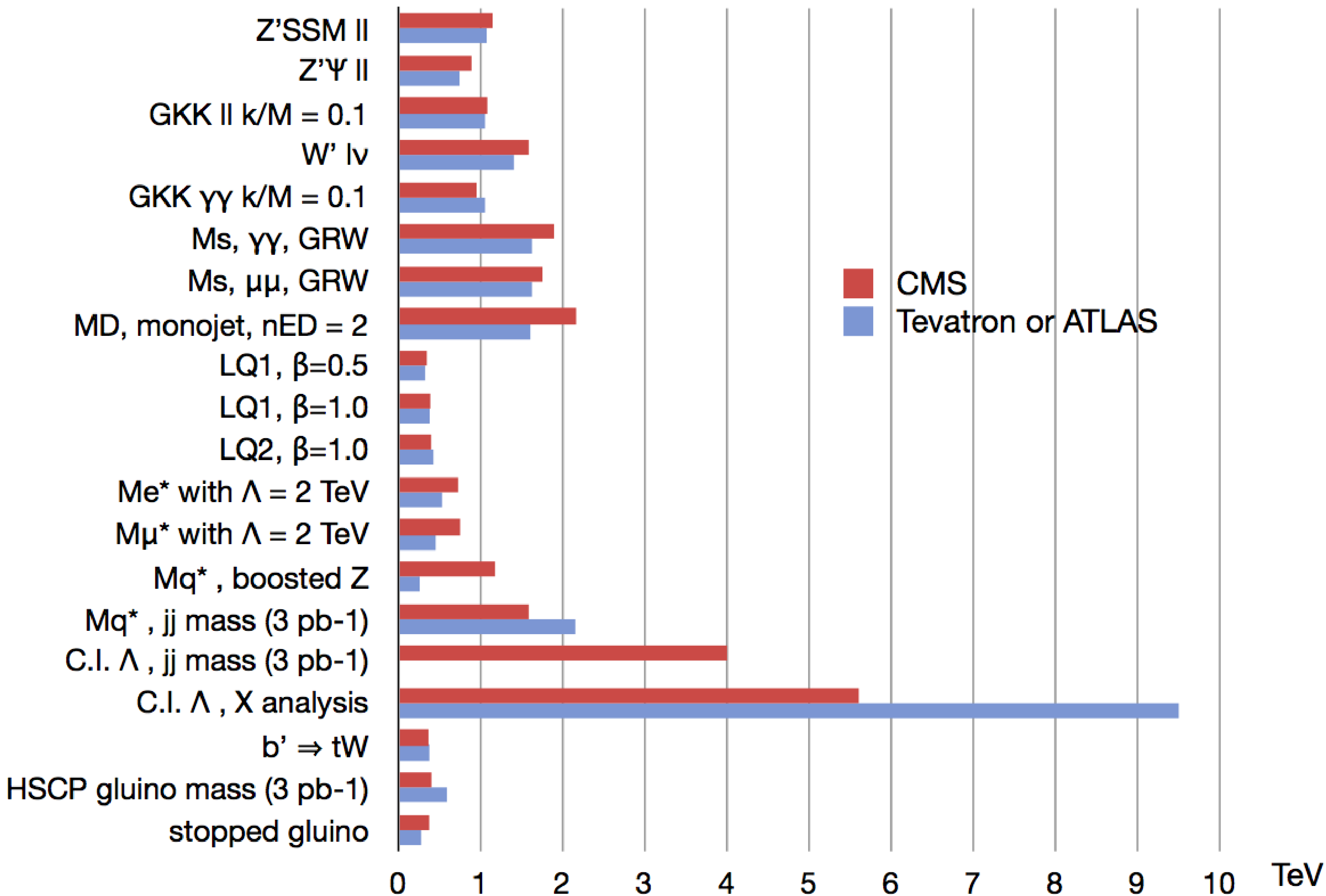
- Search for physics beyond the SM was performed with the CMS detector using data collected in 2010
- There are no statistically significant evidence for new particles or phenomena
- A new more stringent limits on this new phenomena ware set
- These results demonstrate good understanding of the detector and backgrounds
- This ensures the successful searches in view of forthcoming new 2011 data







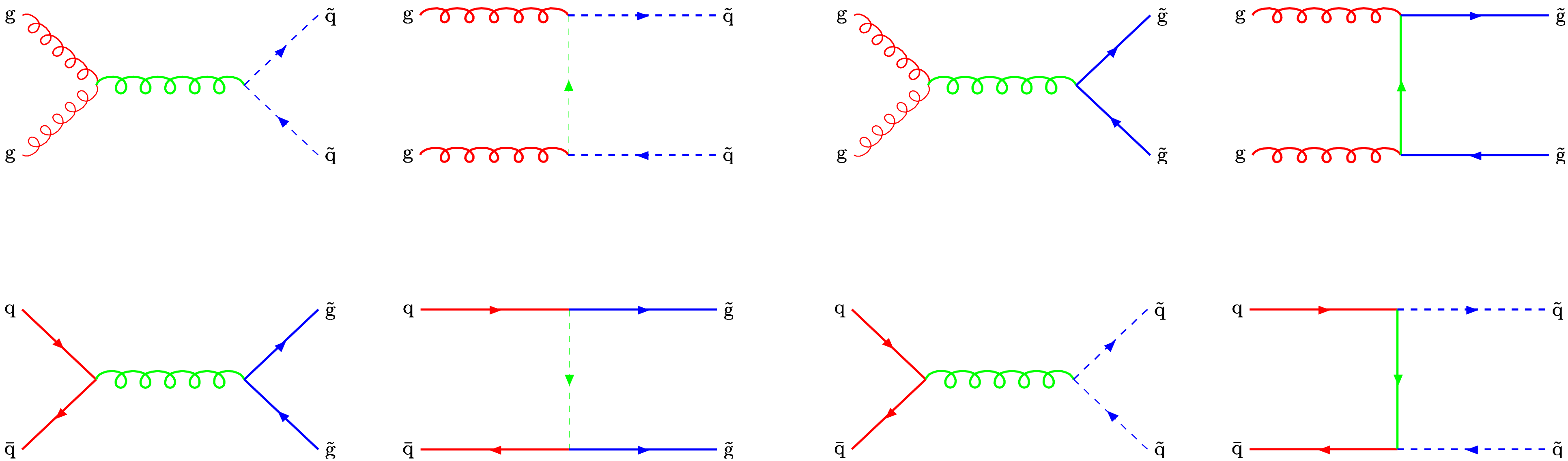
Summary



Z'SSM ll
Z'Ψ ll
GKK ll k/M = 0.1
W' lν
GKK γγ k/M = 0.1
Ms, γγ, GRW
Ms, μμ, GRW
MD, monojet, nED = 2
LQ1, β=0.5
LQ1, β=1.0
LQ2, β=1.0
Me* with Λ = 2 TeV
Mμ* with Λ = 2 TeV
Mq* , boosted Z
Mq* , jj mass (3 pb-1)
C.I. Λ , jj mass (3 pb-1)
C.I. Λ , X analysis
b' ⇒ tW
HSCP gluino mass (3 pb-1)
stopped gluino
CMS
Tevatron or ATLAS
0
1
2
3
4
5
6
7
8
9
10
TeV

SUSY Production

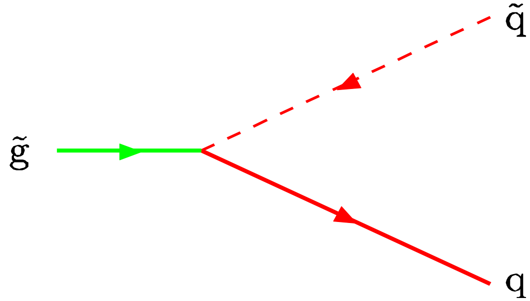
In hadron collisions the strongly interacting particles are dominantly produced. Therefore in SUSY squark and gluino production has the highest cross section.

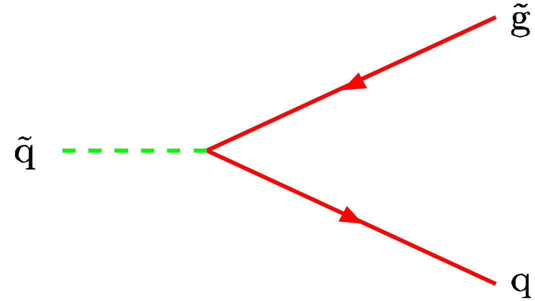


SUSY Decays

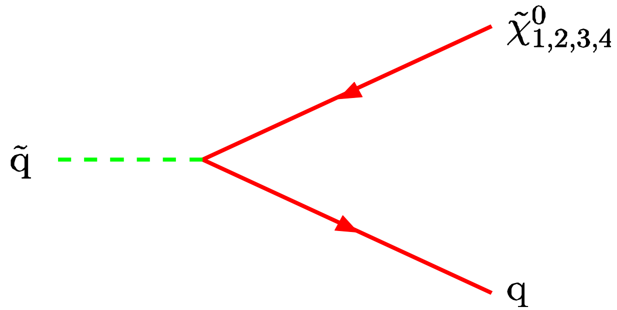
These particles then decay in a number of ways.

Some of them have strong decays to other strongly interacting SUSY particles.





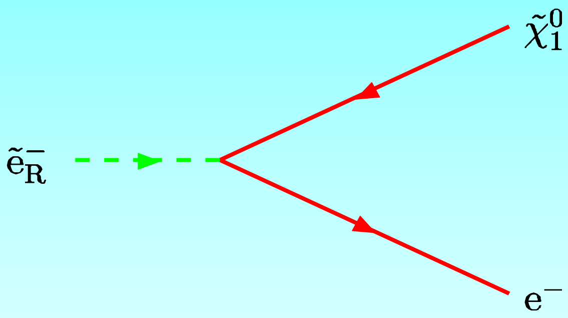
However the lightest squark/gluino can only decay weakly.

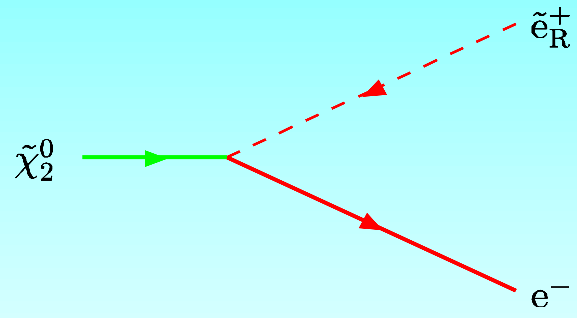


The gluino can only have weak decays with virtual squarks or via loop diagrams.

SUSY Decays

- This is the main production mechanism for the weakly interacting SUSY particles.
- The decays of the squarks and gluinos will produce lots of quarks and antiquarks.
- The weakly interacting SUSY particles will then decay giving more quarks and leptons.





- **Eventually the lightest SUSY particle which is stable will be produced.**
- **This behaves like a neutrino and gives missing transverse energy.**
- **So the signal for SUSY is large numbers of jets and leptons with missing transverse energy.**
- **This could however be the signal for many models containing new heavy particles.**

The Standard Model

The SM is based on $SU_c(3) \times SU_L(2) \times U_Y(1)$ gauge group

quarks		leptons		Bosons
u	d	e	ν_e	γ
c	s	μ	ν_μ	Глуон g
t	b	τ	ν_τ	$W^\pm$ и Z
Spontaneous symmetry breaking				Higgs? H

SUSY

The problem with masses – a physical variable defined by the space-time symmetry.

Way out – unification of strong and eletroweak interactions with gravity.

The solution is a new kind of symmetry – between fermions and bosons

Group → Super group – new spinor generators

Super Algebra – commuting and anticommuting generators

$Q_\alpha|F\rangle \rightarrow |B\rangle$ and $Q_\alpha|B\rangle \rightarrow |F\rangle$

SM particles form supermultiplets

Equal number fermions and bosons – new particles

However particles in one multiplet have equal masses

Supersymmetry should be broken

Problems

- Many parameters

  Values of couplings, masses and mixings?
- The origin of the electroweak symmetry breaking
- The mechanism of mass generation (Higgs mechanism)
- The fine tuning problem
  - ✓ The cosmological constant puzzle
  - ✓ The strong CP-problem
  - ✓ The gauge hierarchy problem
- The SM is logically not complete

  Unification with gravity
- Describes only 4% of the Universe
  - ✓ Dark mater
  - ✓ Dark energy

Search for long – lived particles

- Many extensions of the SM predict existence of new heavy quasi-stable particles (some SUSY models, hidden valley, GUT, ..)
- Long-lived gluinos are also a hallmark of **“split SUSY”, where gluino decay is suppressed due to the** large gluino-squark mass splitting
- **Gluinos hadronize forming R-Hadrons** – bound states of SUSY particle + gluons or quarks
- We have performed searches for two distinctive signatures of long-lived particles:
  - Massive Charged long-lived particles with high momentum tracks and small velocity β (p/m), highly ionizing (dE/dX) in the silicon tracker
  - Long-lived massive particles stopping in the detector due to electromagnetic and nuclear int. and decaying out-of-time with the collisions

Search for long – lived particles

Heavy stable charged particles β > 0.5

Muons with high p_T and dE/dX

Mass is reconstructed with approximated "Bethe-Bloch formula"

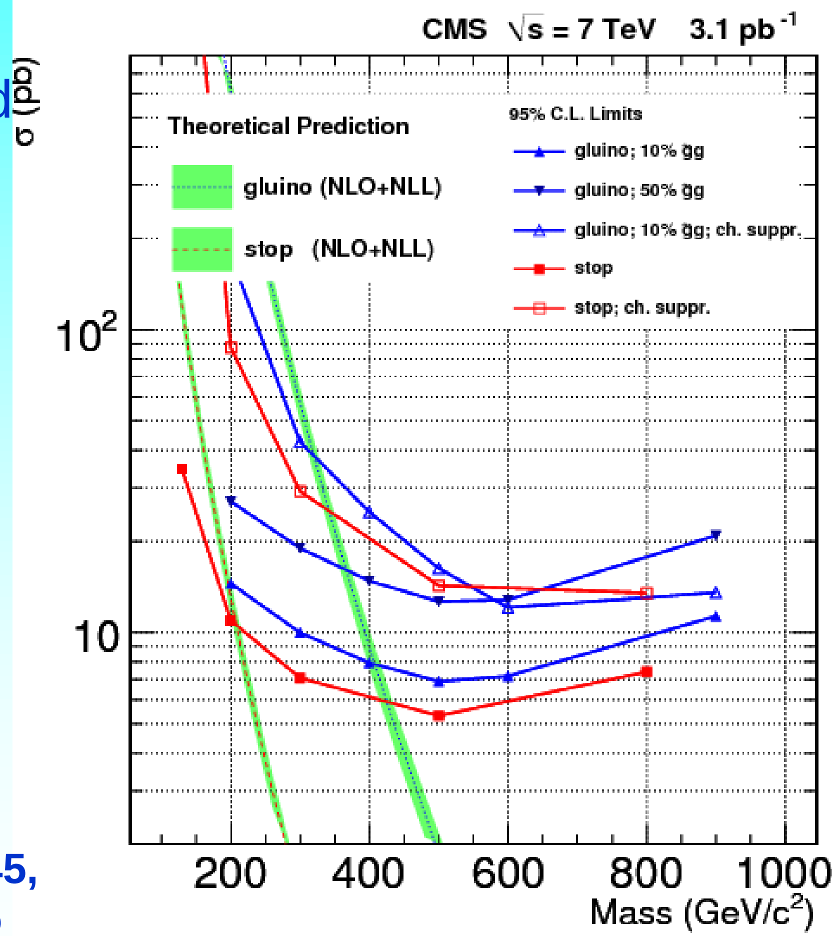
$$\frac{dE}{dx} \propto \frac{1}{\beta} \approx K\frac{m^2}{p^2} + C$$

Zero high mass candidates

Limits on cross section and mass set

M_{gluino}>311-398 GeV

Very recent preliminary ATLAS result with 34/pb extends our limits



arXiv:1101.1645, submitted to JHEP

Search for long – lived particles

Stopped Gluinos β < 0.5

Slow-moving R-Hadrons can lose enough energy in HCAL material to stop

Search **for decay during times with no beam (time between bunch crossings)**

PRL 106, 011801 (2011)

$BR(\tilde{g} \rightarrow g\,\tilde{\chi}_1^0) = 100\%$

Single-jet-like signature

Both counting experiment and time-profile analysis consistent with background only hypothesis

Limits:

$$M_{\tilde{g}} > 370\ \text{GeV}, \tau = 10\ \mu s - 1000\ s$$