Imperial College London

Searches for Supersymmetry and Dark Matter at CMS

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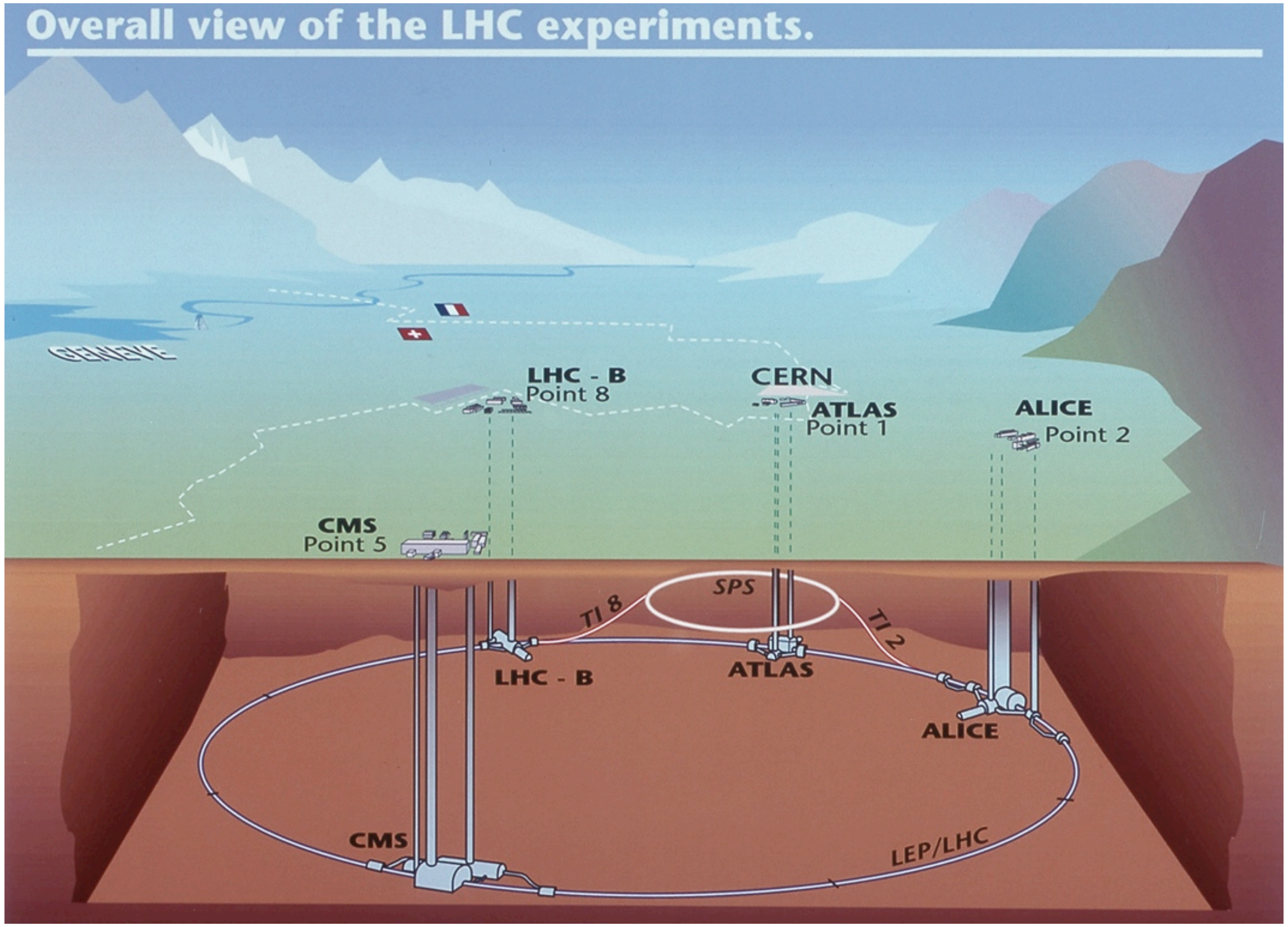
Outline

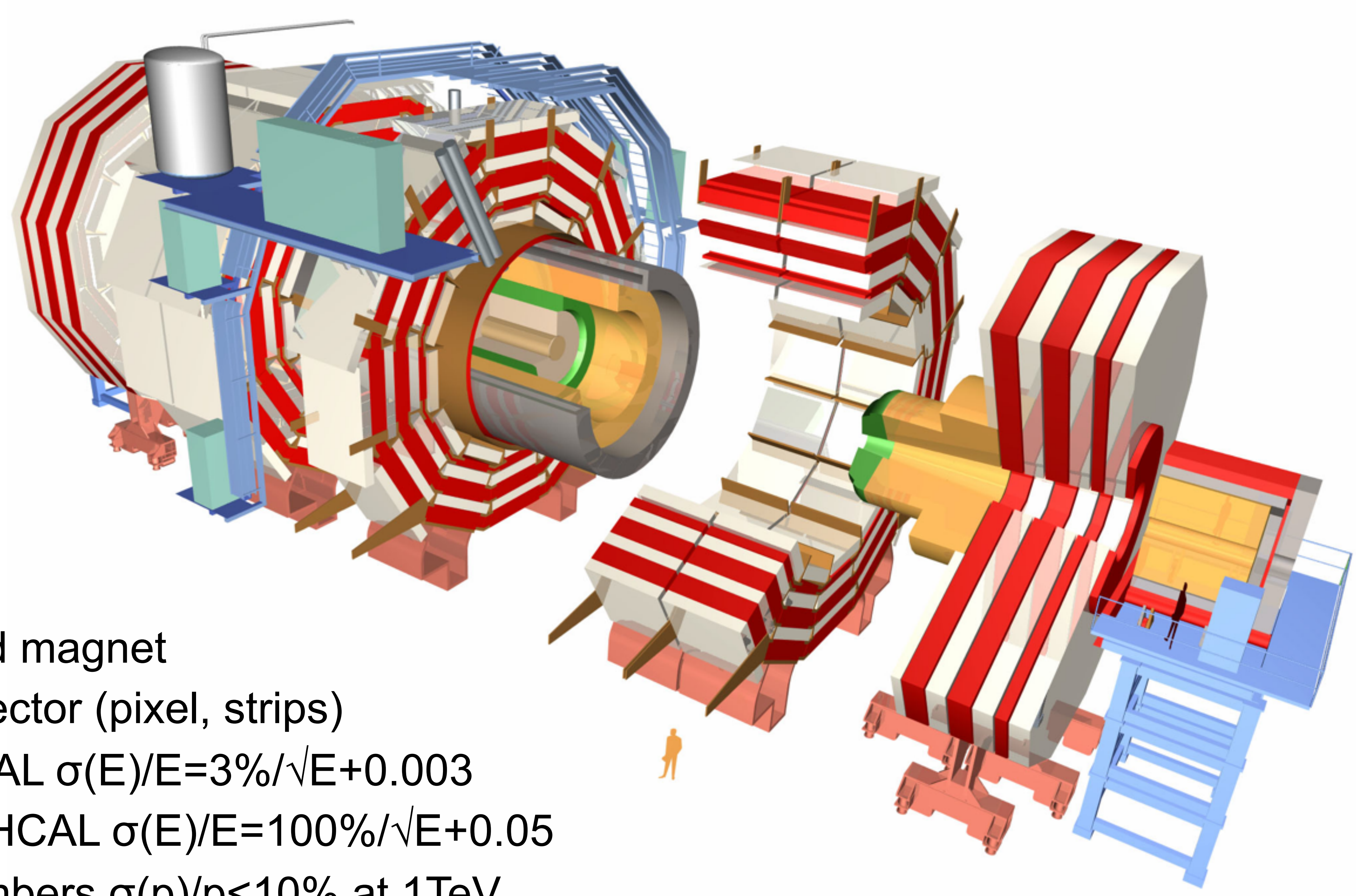
- The LHC and the CMS detector
- Search strategy
- Some examples of searches
  - Strong production
  - Weak production
  - Initial state radiation searches
- Summary and outlook

The Large Hadron Collider



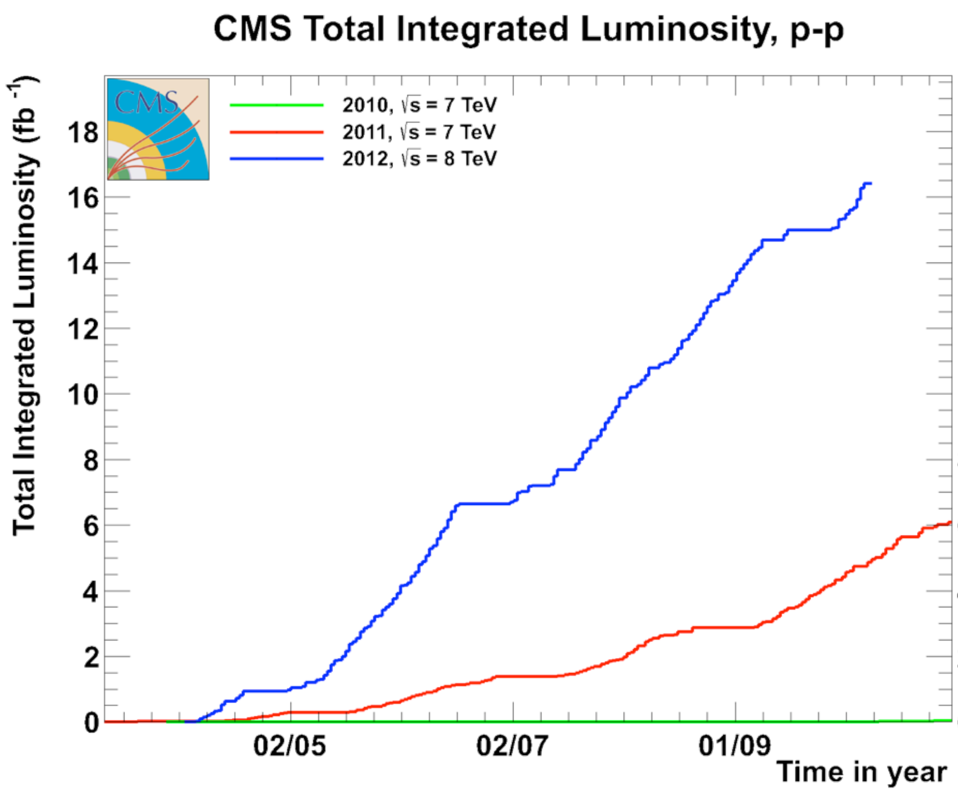
The CMS detector

JINST3:S08004 (2008)



- 4T solenoid magnet
- Silicon detector (pixel, strips)
- Crystal ECAL $\sigma(E)/E=3\%/\sqrt{E}+0.003$
- Brass/sci. HCAL $\sigma(E)/E=100\%/\sqrt{E}+0.05$
- Muon chambers $\sigma(p)/p<10\%$ at 1TeV

The CMS detector

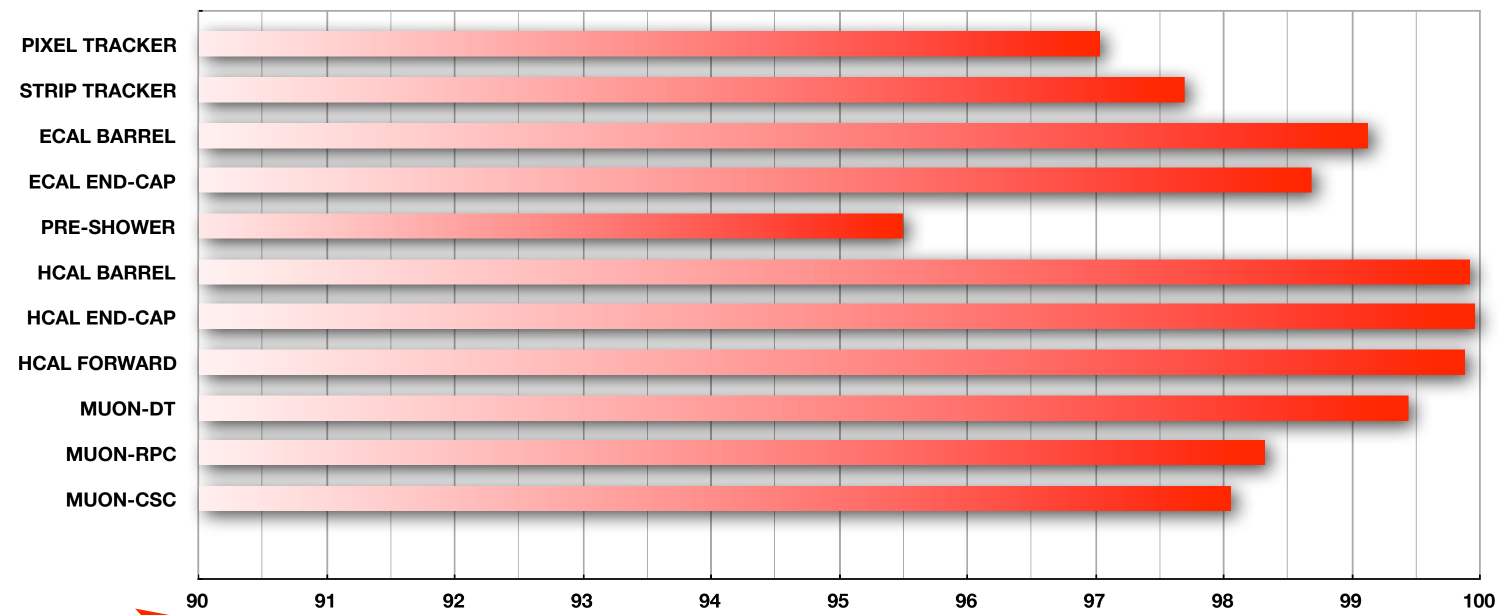


- LHC delivered ~6 fb^{-1} in 2011
- CMS collected ~5.6 fb^{-1} (93%)
- Results based on ~5 fb^{-1} (83%)

More than 16 fb^{-1} delivered in 2012 so far!

CMS in 2011:

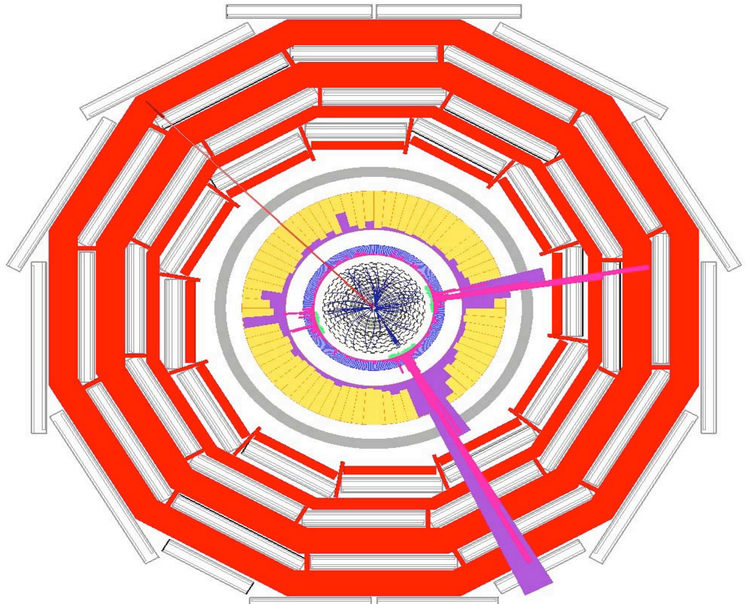
- Average fraction of functional detector channels > 98.5%
- Lowest still > 95%



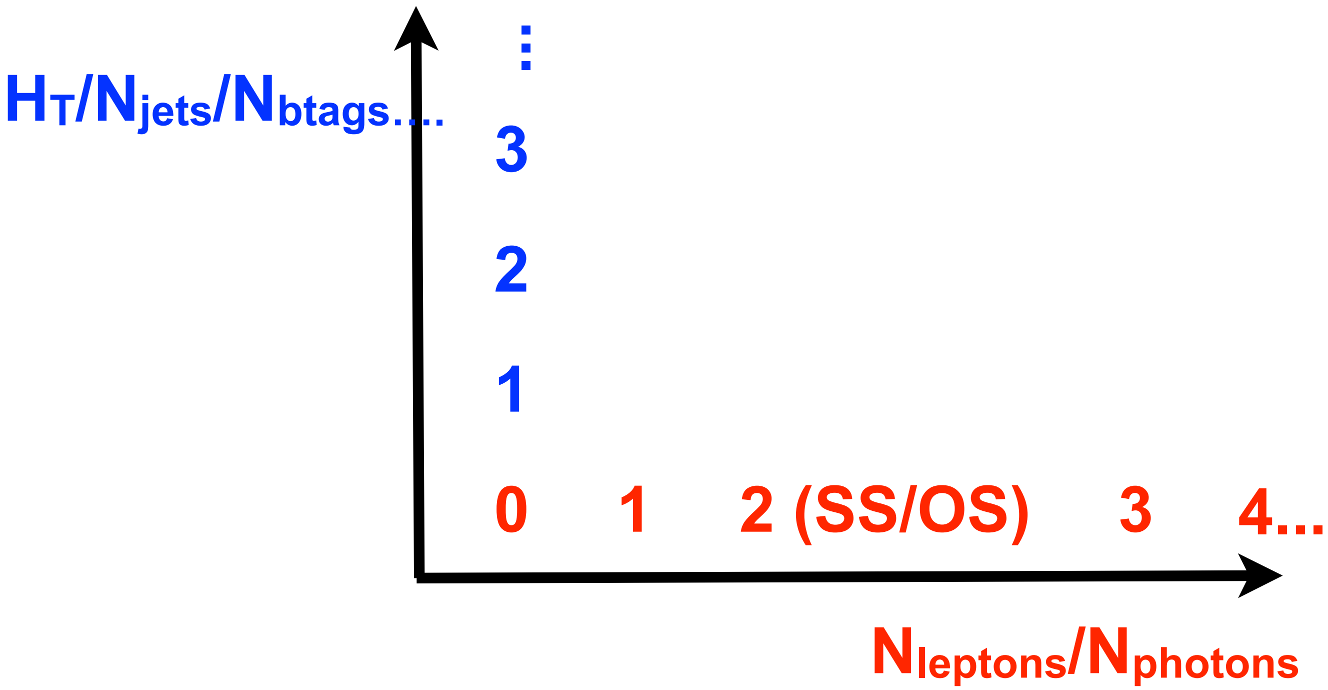
90%!

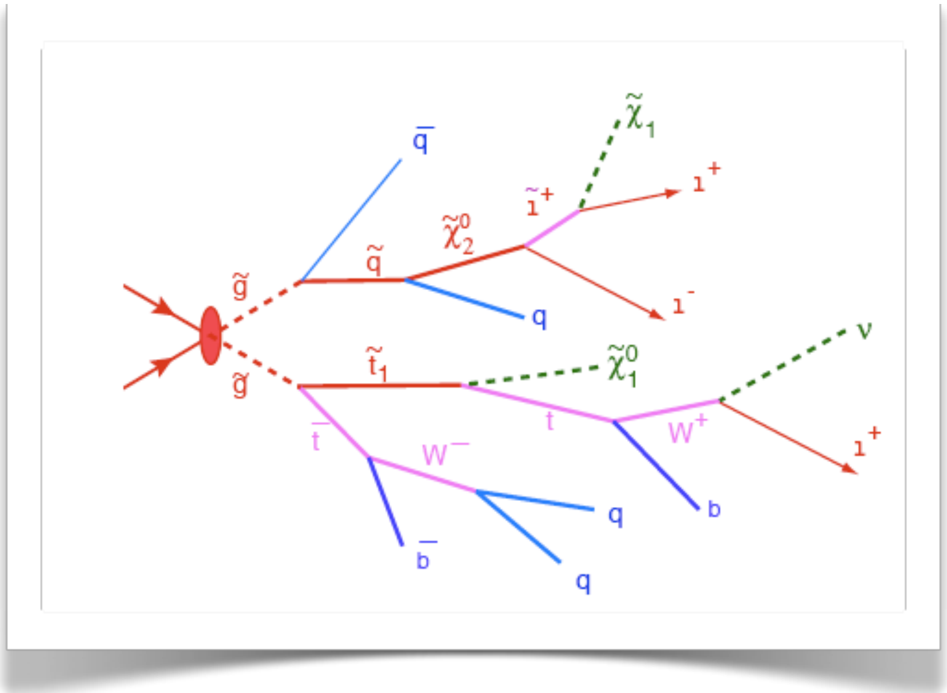
Dark Matter @ LHC

- Neutral and weakly interacting so difficult to observe
  - No signal in LHC detectors ➔ missing transverse energy
- Direct production has small cross section and no signal in detector ➔ difficult searches
- Production in conjunction with Standard Model particles easier option for detection
- Design searches based on MET ➔



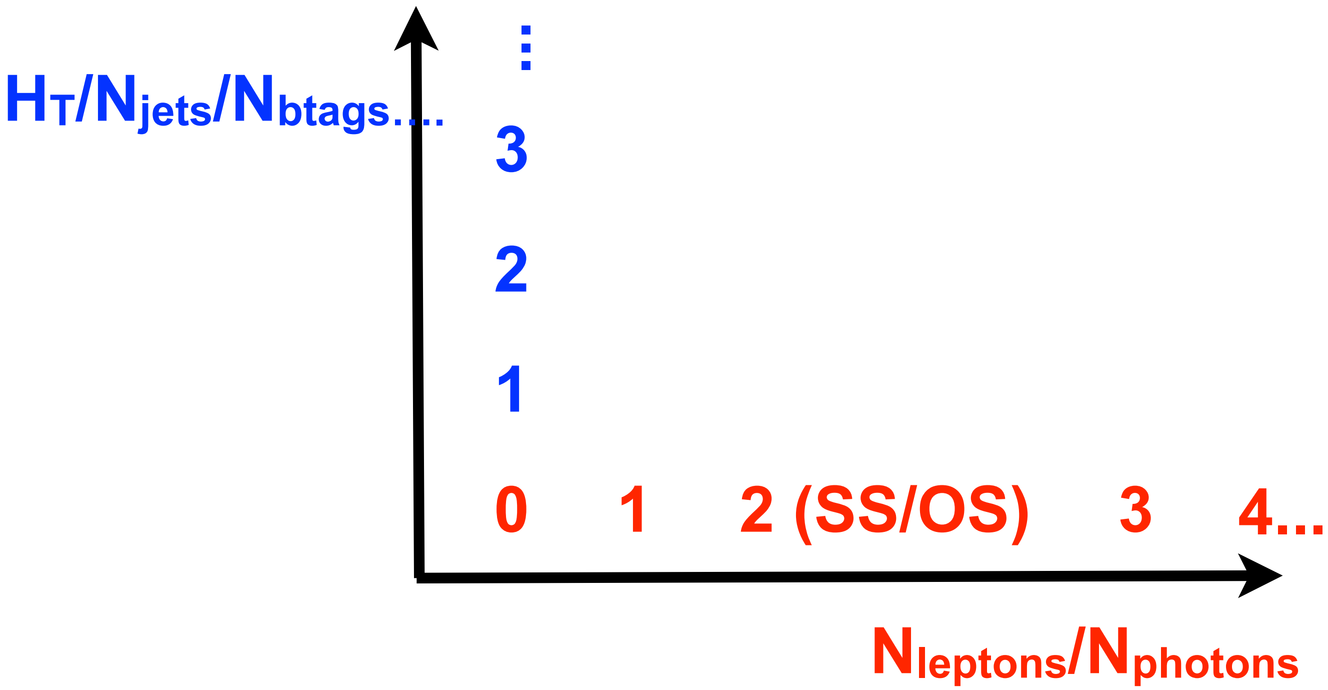
Search strategy

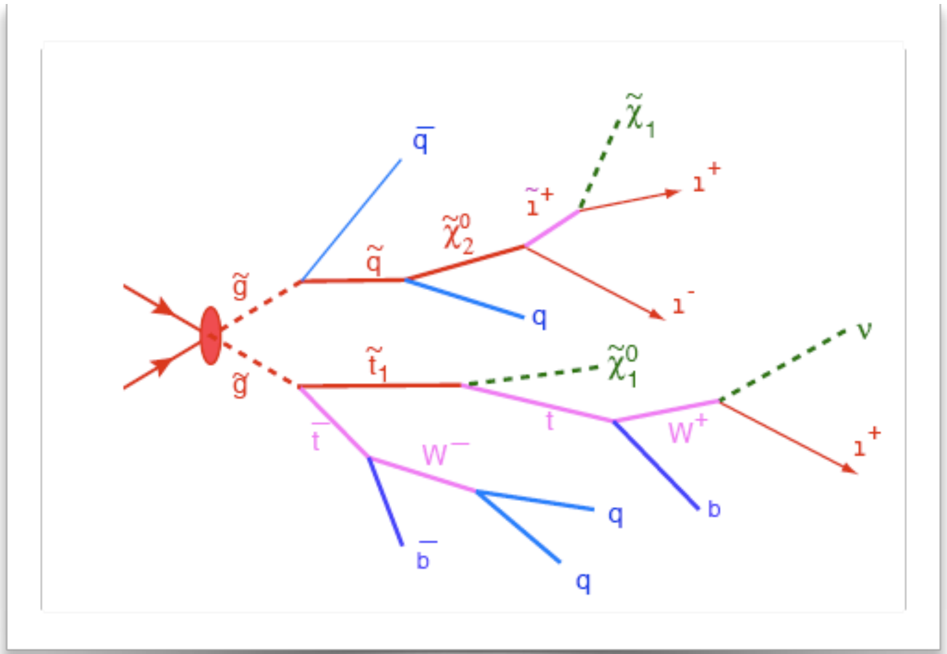




- Strong production ➔ Long cascades, jets, maybe leptons
- Weak production ➔ no hadronic jets (χ pair-production)
- Direct production ➔ QED/QCD initial state radiation
- More exotic ➔ stopped gluinos, HSCP…

Search strategy





- Strong production ➔ Long cascades, jets, maybe leptons
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- Direct production ➔ QED/QCD initial state radiation
- More exotic ➔ stopped gluinos, HSCP… not covered here

The key: backgrounds

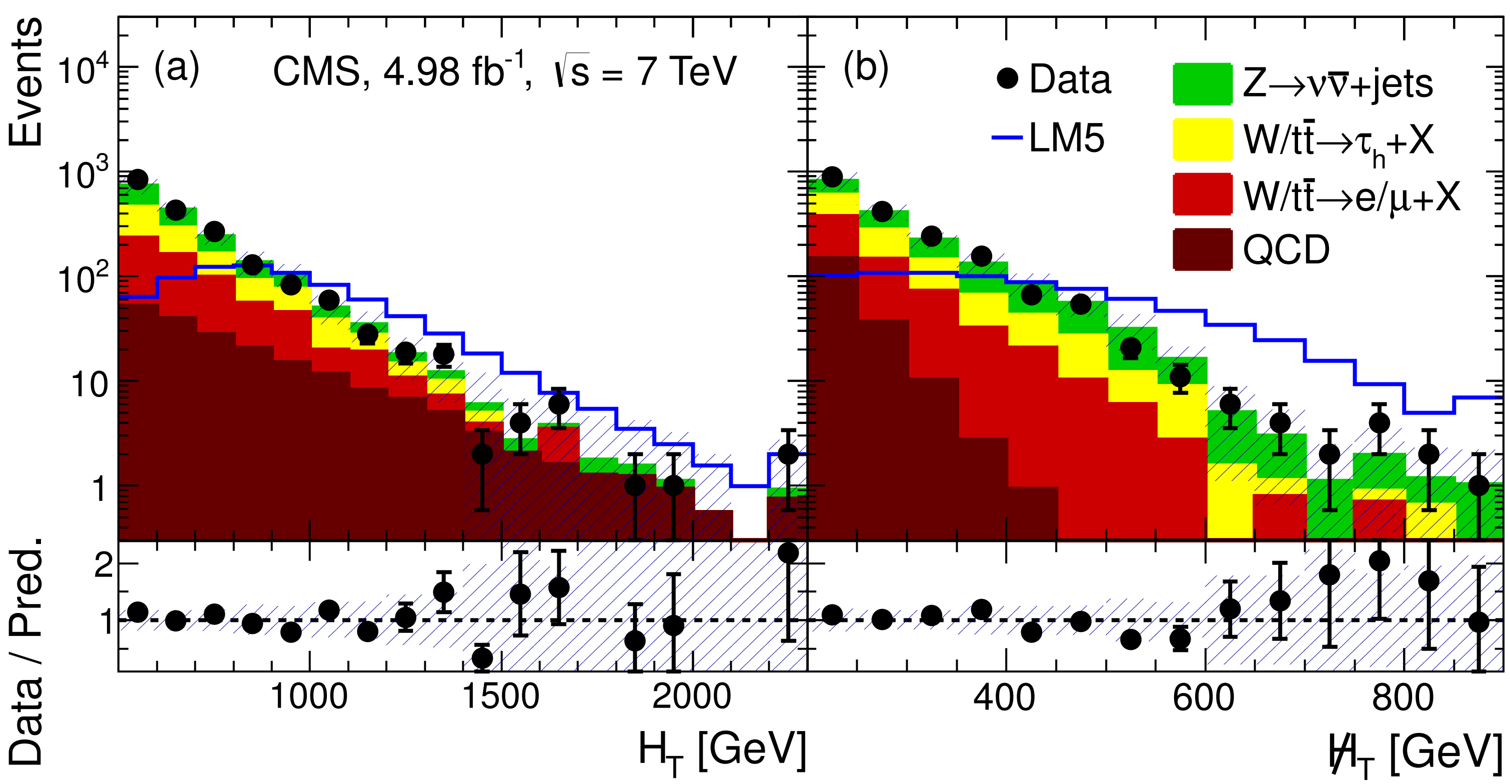
- Physics
  - Standard Model processes that give the same signatures as SUSY
  - Cannot/do not (yet?) rely on Monte Carlo simulations ➔ measure in data
- Detector effects
  - Detector noise, mis-measurements etc. that generate MET or extra jets
  - Commissioning and calibration ➔ good performance
- Other
  - Beam-halo muons and cosmic-ray muons, beam-gas events
  - Data and simulation already ➔ measure in situ too

Jets + MET

- All hadronic channel, just jets and missing energy in event
  - Very challenging due to large amount and wide range of backgrounds
  - However most sensitive search for strongly produced SUSY
  - CMS pursues several complementary strategies based on kinematics and detector understanding ➔ this analysis the “classic” version

arXiv:1207.1898

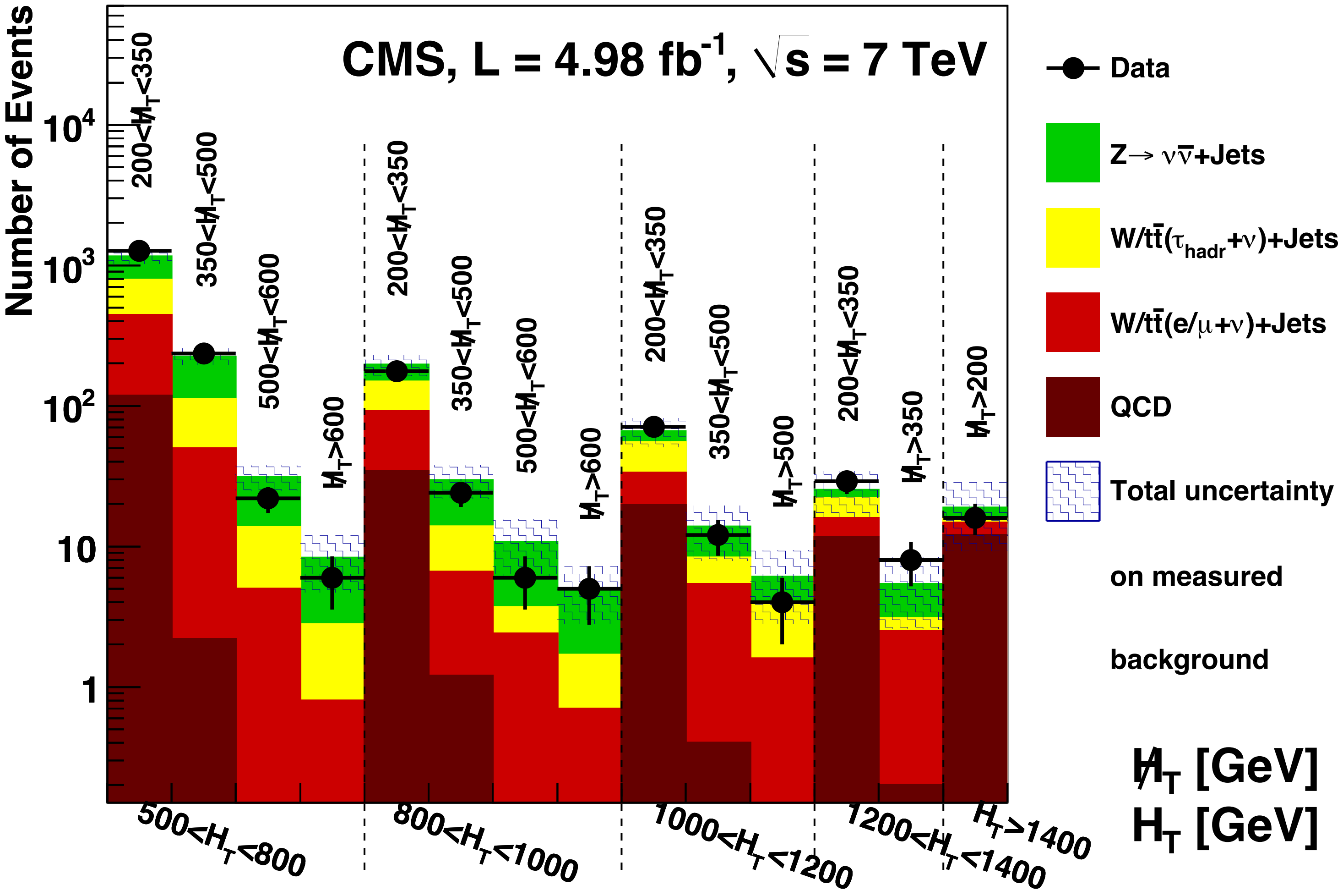
- Selection
  - No leptons (e or μ)
  - At least 3 jets > 50 GeV
  - Δφ between jets and MET
  - Examine data in bins
    - H_T^{miss} (MET from jets)
    - H_T ($\sum$ of jet p_T)



Jets + MET

arXiv:1207.1898

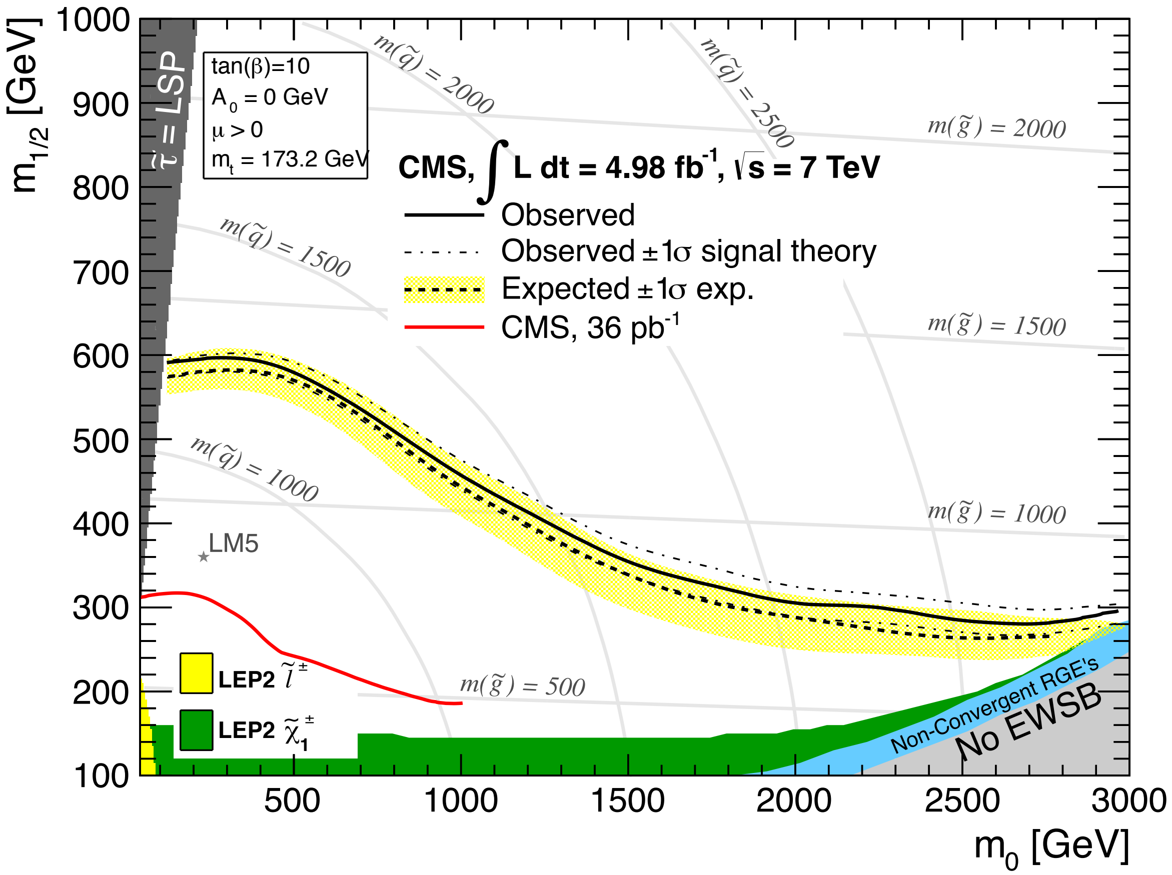
- All background estimates taken from **data**
- Multi-bin approach in H_T^{miss} and H_T
  - Wide sensitivity
  - Bins combined for final limits

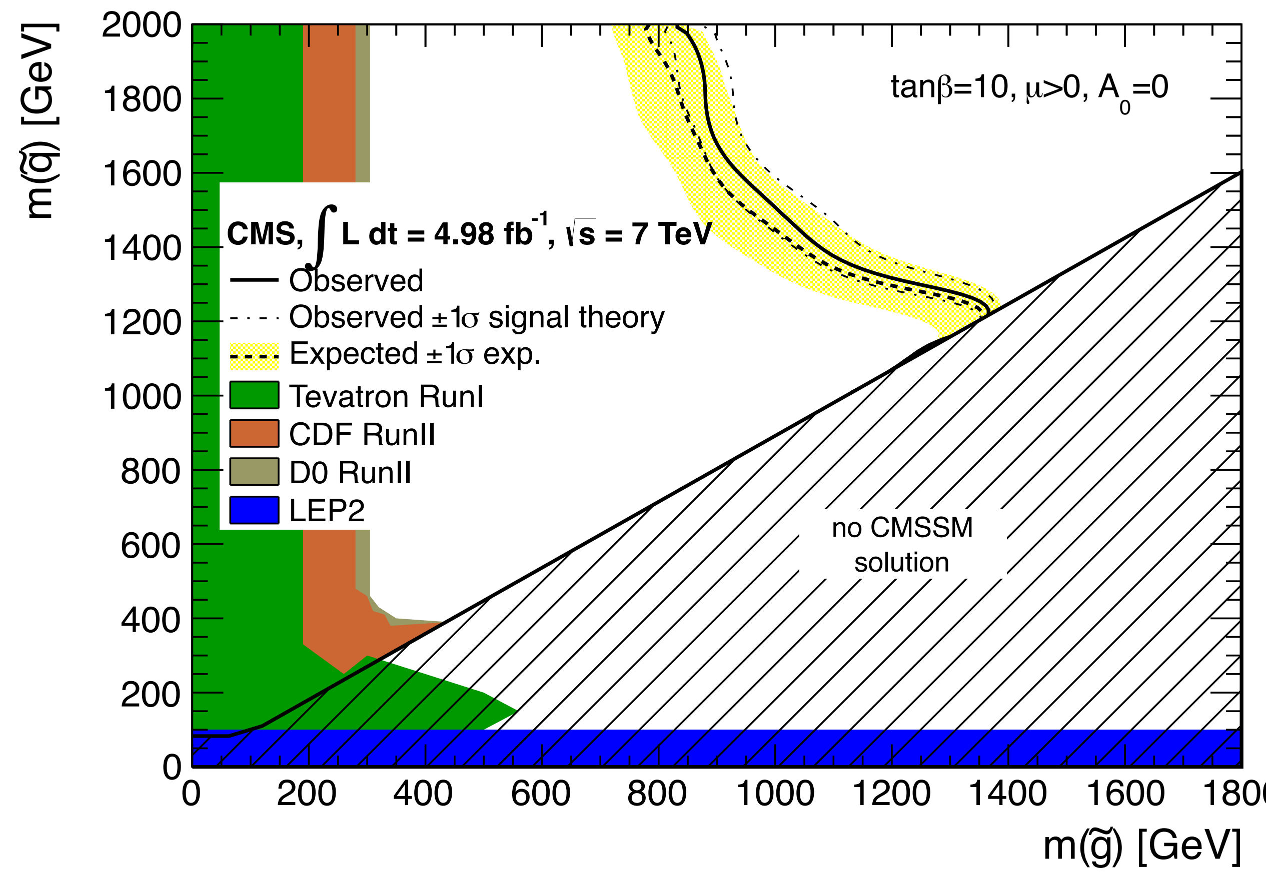


No excess seen in data
→ set limits

Jets + MET

arXiv:1207.1898

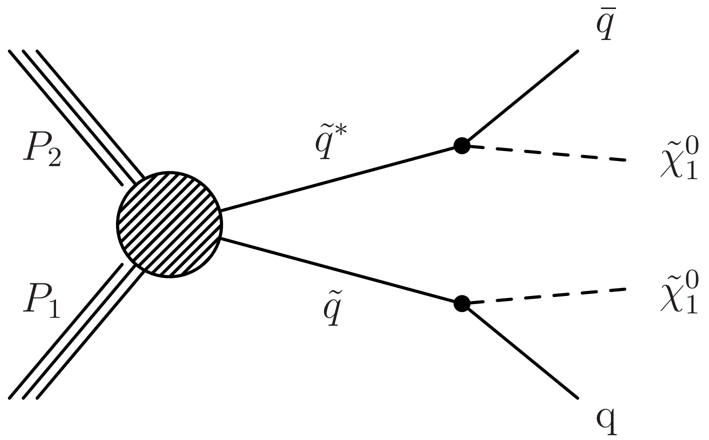




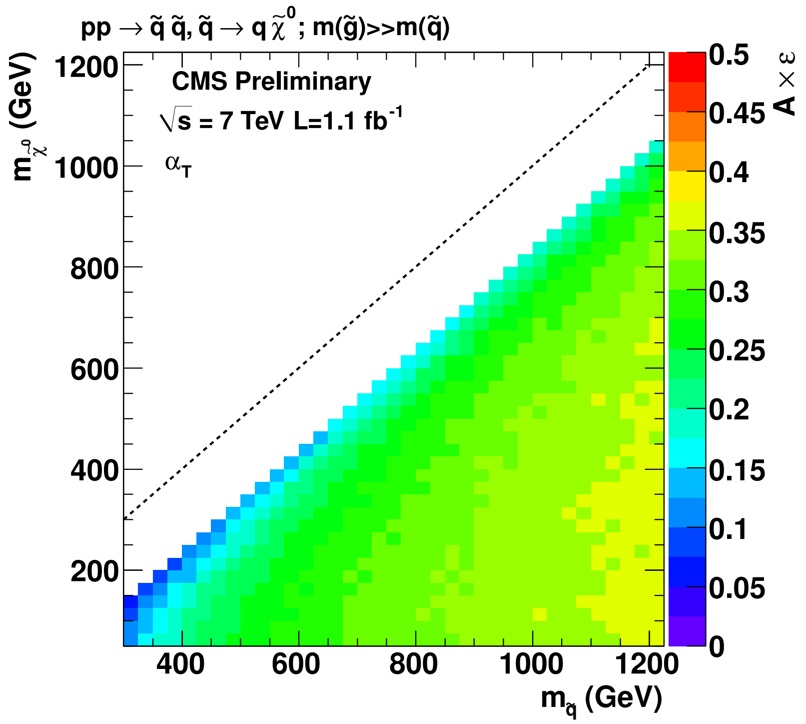
- Limit in the usual CMSSM plane (tanβ=10, A_0=0, μ>0)

Interpretation Intermezzo

- Simplified Model Spectra
  - Limited set of hypothetical particles and decays
  - Less specific mass patterns and signatures
  - Give acceptance x efficiency and cross-section limit
  - Models proposed at: http://www.lhcnewphysics.org



- Hadronic searches
  - Squark anti-squark pair production with decay
    - squark → quark + χ^0
  - Kinematics specified by masses
  - Direct case m_{squark} vs m_{LSP} 2D plot
  - For cascade decays (arbitrary but sensible) slices of intermediate particle (25%, 50%, 75%)
  - "Reference" cross sections (from PROSPINO) given to illustrate limits



Jets + MET

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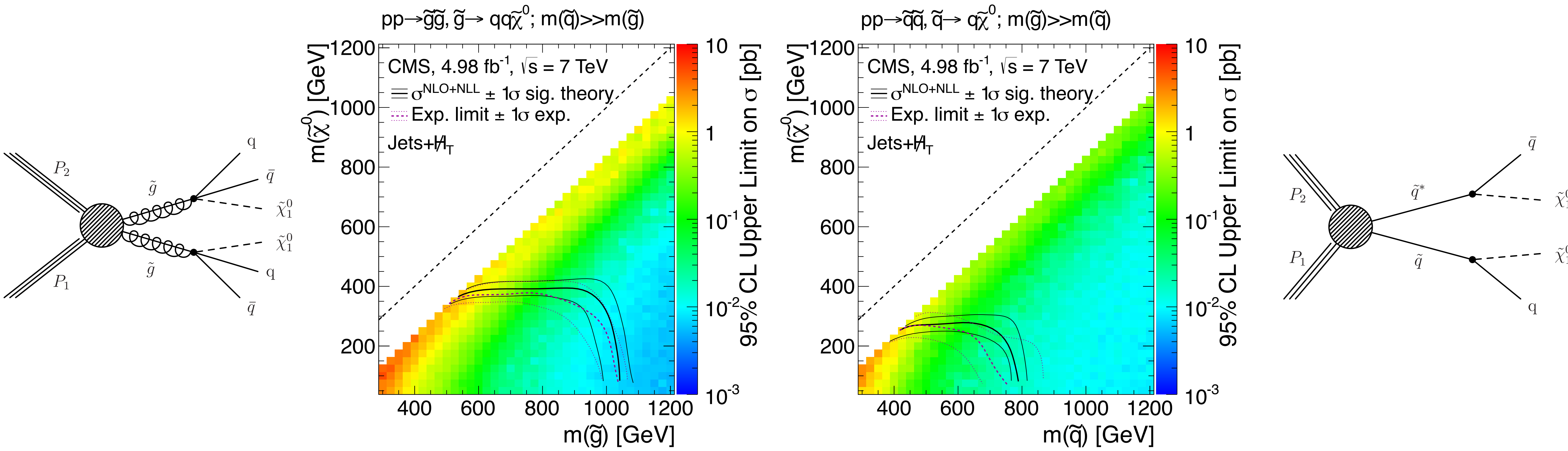
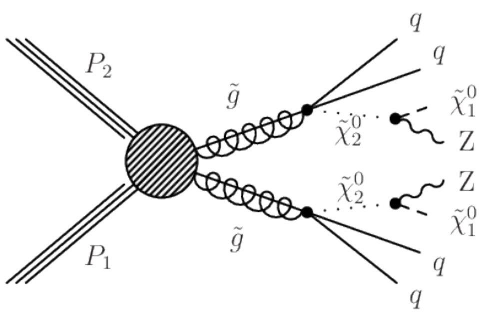
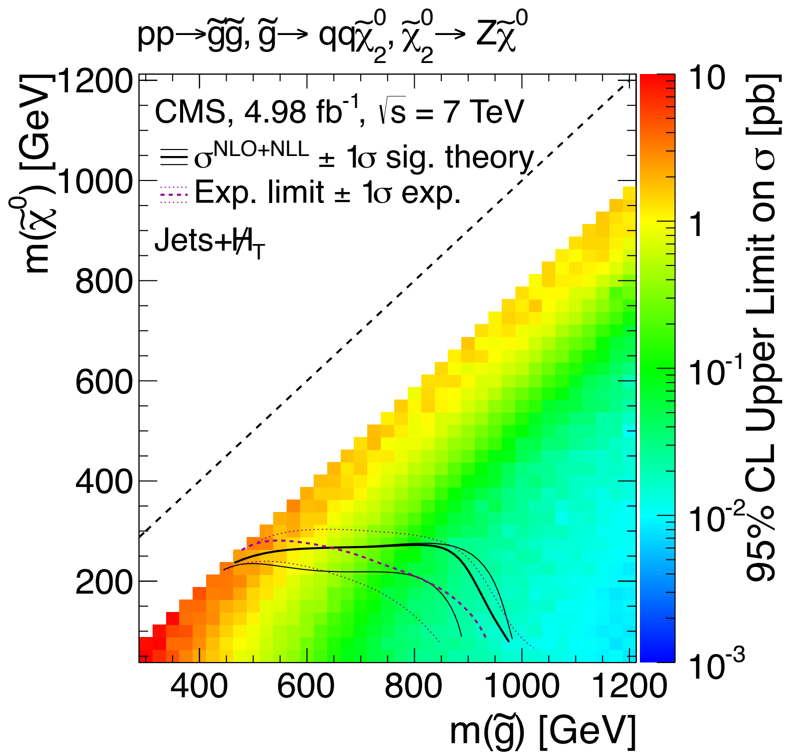


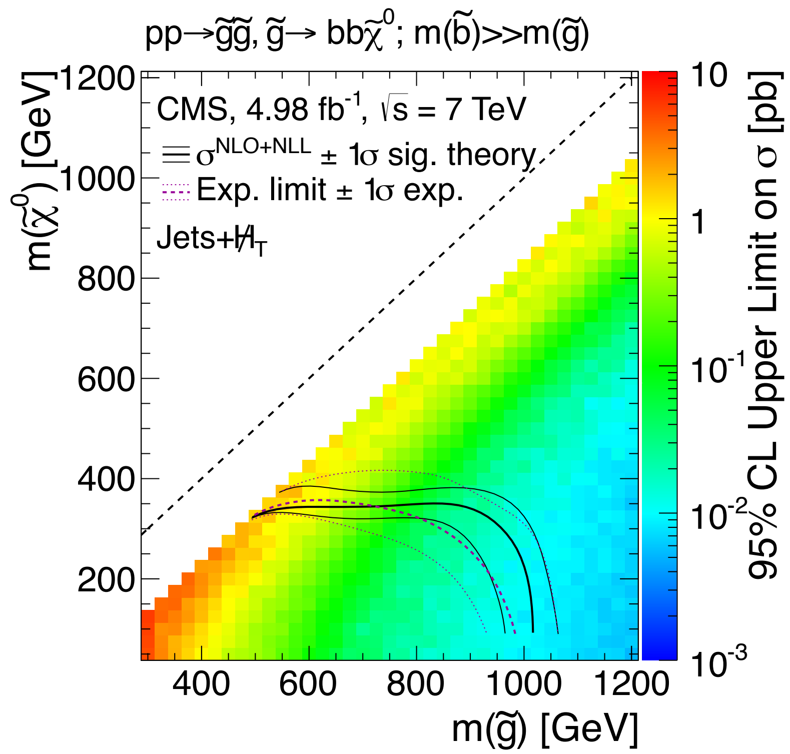
- Clean way to communicate results of our searches and compare different channels ➔ no hidden theory dependence
- Areas of small mass splittings removed to reduce sensitivity to signal modeling

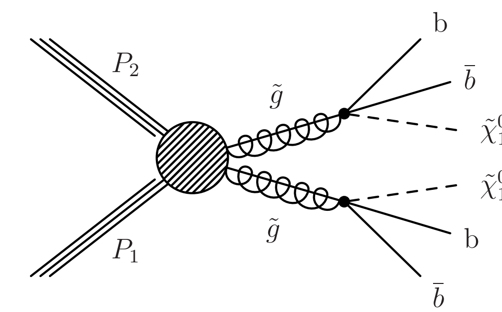
Jets + MET

arXiv:1207.1898



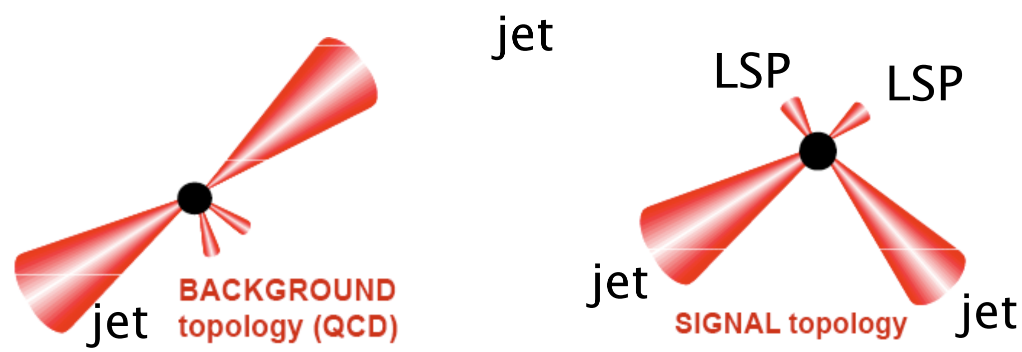






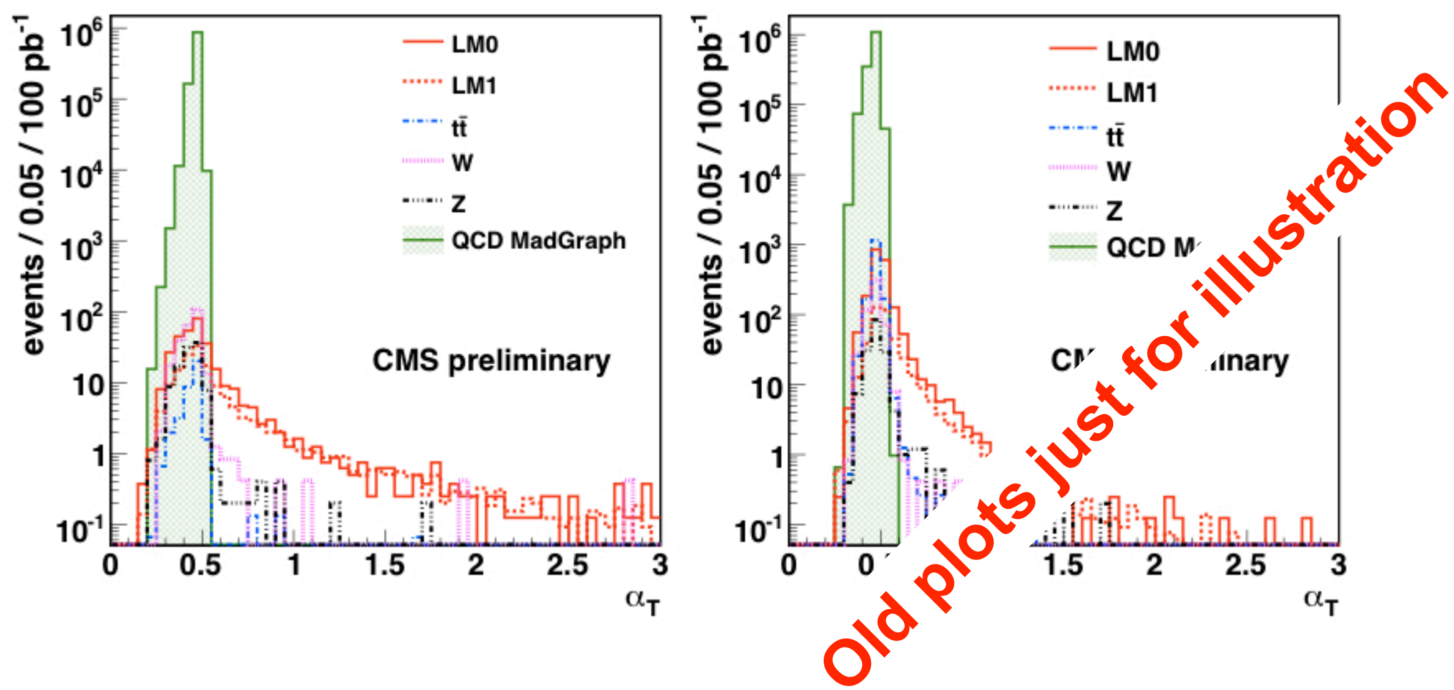
- ZZ channel allows comparison with leptonic anayses
- b-quark rich channel sets limits on 3rd generation SUSY decays

α_T search



$$\alpha_T = \frac{E_{T\,j2}}{M_{T\,j1j2}} = \frac{\sqrt{E_{T\,j2}/E_{T\,j1}}}{\sqrt{2(1-\cos\Delta\varphi)}}$$

PRL101:221803 (2008) & CMS-PAS-SUS-09-001



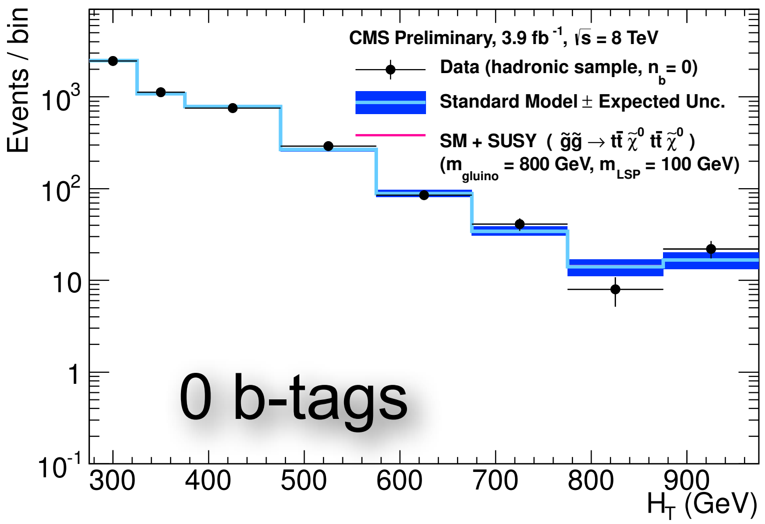
α_T and H_T based search:

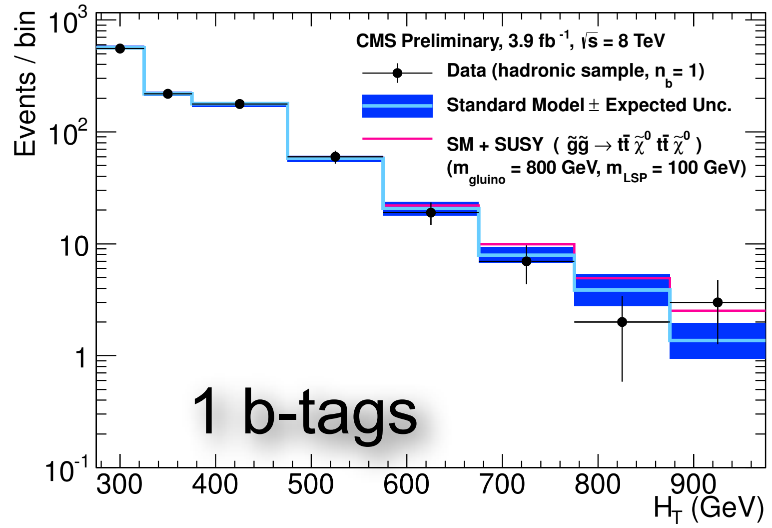
- $\alpha_T > 0.55$
- $H_T > 275$ GeV
- At least two jets with $p_T > 100$ GeV
- Lepton veto

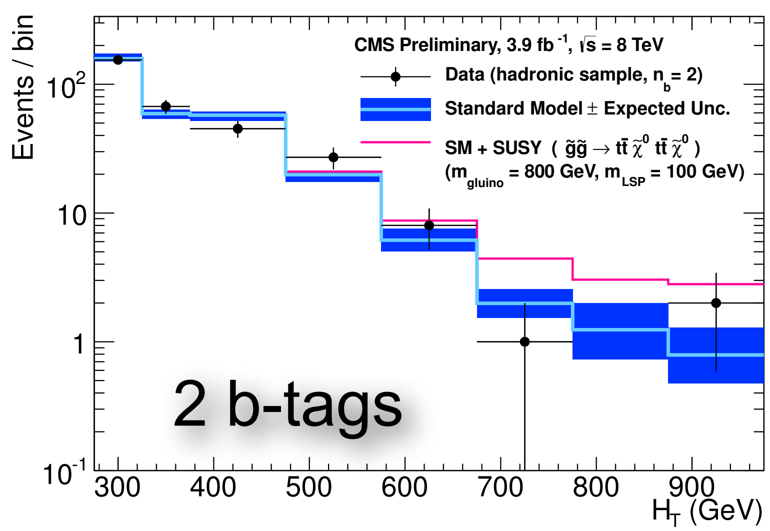
- Backgrounds
  - Z ➔ νν from γ+jets sample with MC translation factor
  - W/top from μ(μ)+jets control sample with MC translation factor
  - QCD background shape from lower α_T control sample

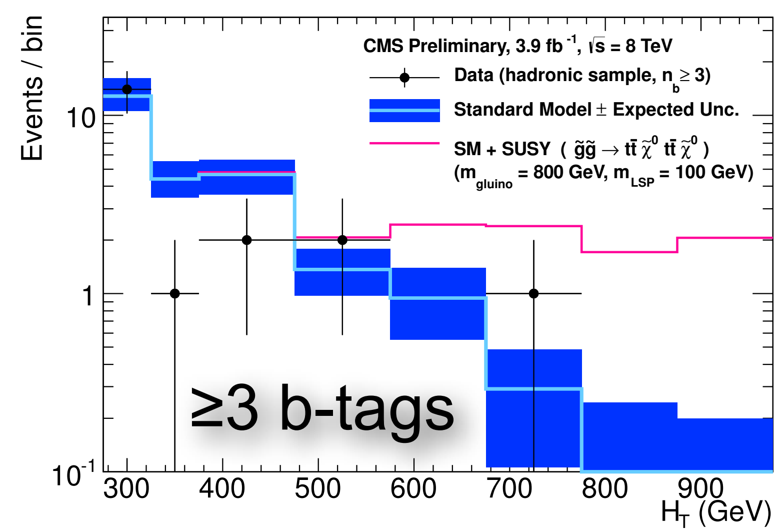
α_T search

SUS-12-016









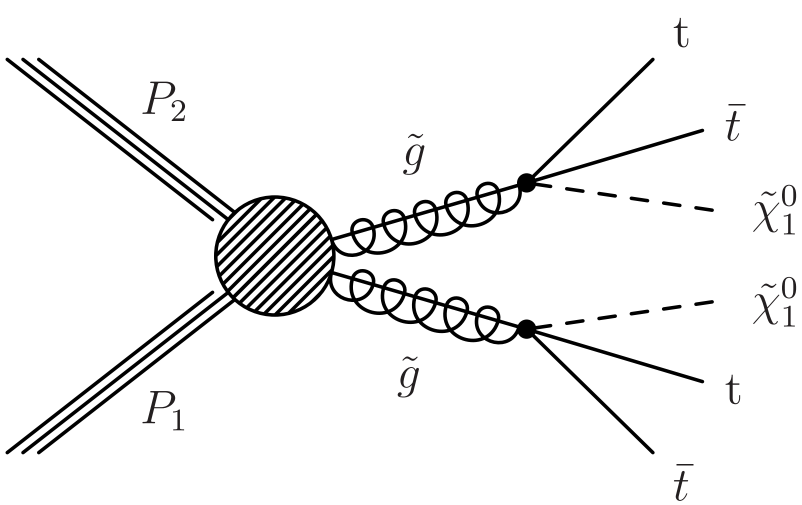
- Multi-bin approach in H_T and number of b tagged jets
  - Wide sensitivity to both inclusive and 3rd generation signatures
  - Top-rich signal example
  - Bins combined statistically for final limits

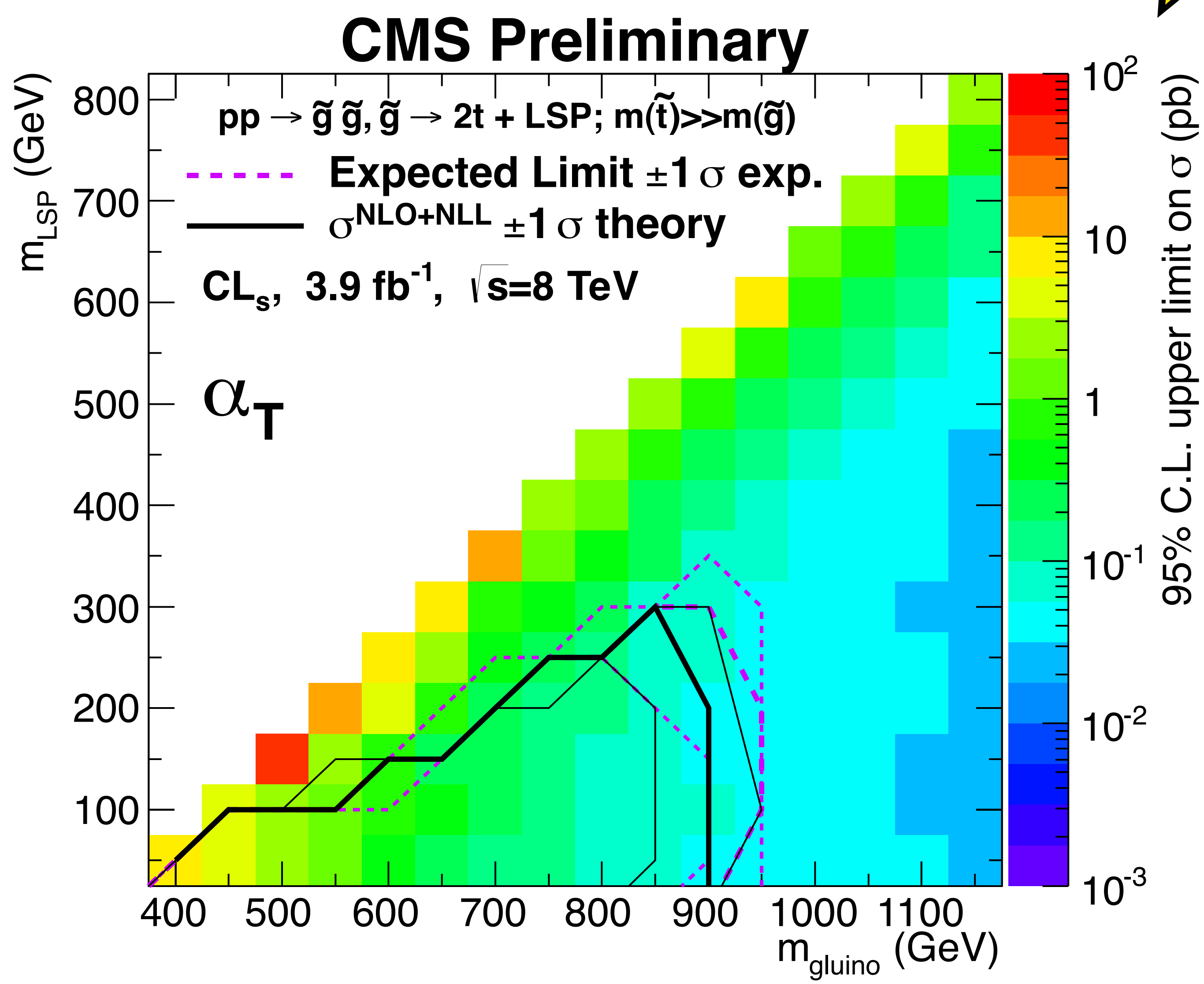
No excess seen in data
➔ set limits

α_T search

8 TeV

- Exploit the b-tag dimension in top-rich decay topologies

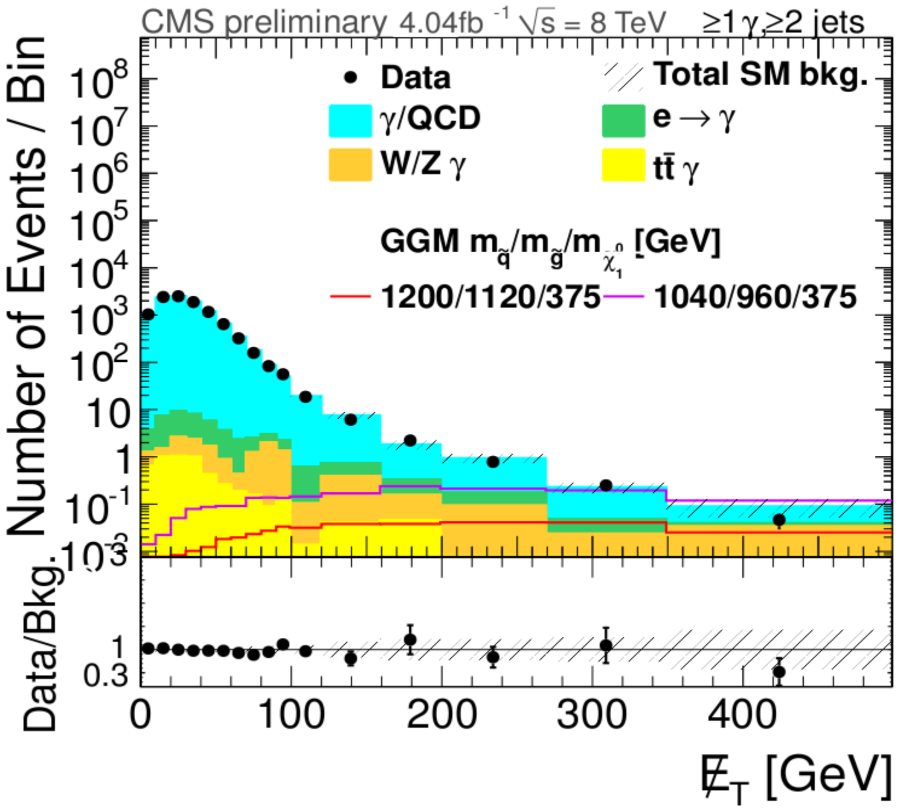


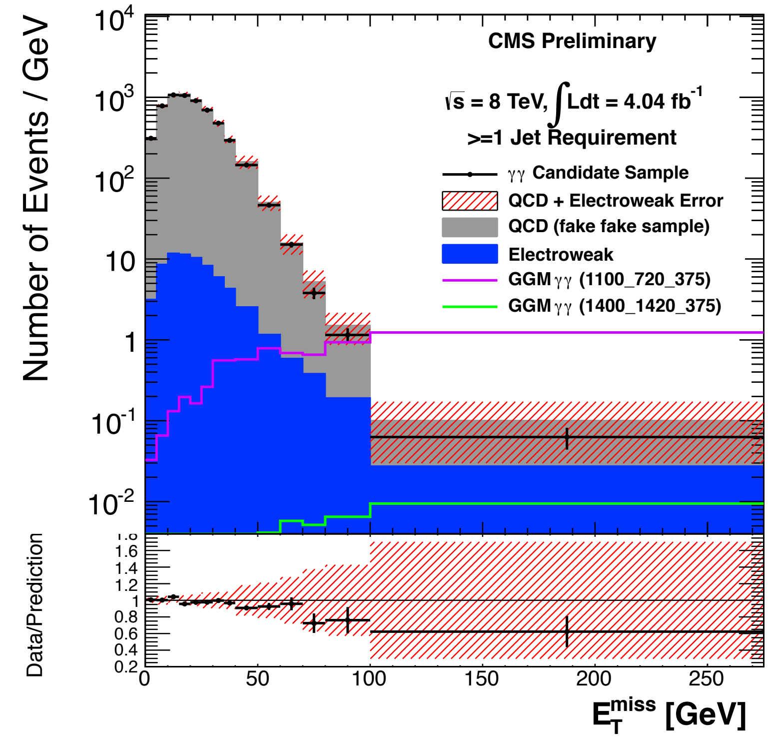


Further 3[rd] generation examples @ 7 TeV in backup

SUS-12-016

Photon(s) + MET





Single photon + jets + MET:

$P_{T\gamma}$ > 80 GeV
H_T (≥2 Jets) > 450 GeV
MET > 100 GeV

Diphoton + jet + MET:

$P_{T\gamma}$ > 40/25 GeV
At least one jet
MET > 50 GeV

- QCD bkgd. dominant ➔ shape from control samples - norm. at low MET
- e ➔ γ fake rate measured on Z peak and used to estimate EWK bkgds.

SUS-12-018

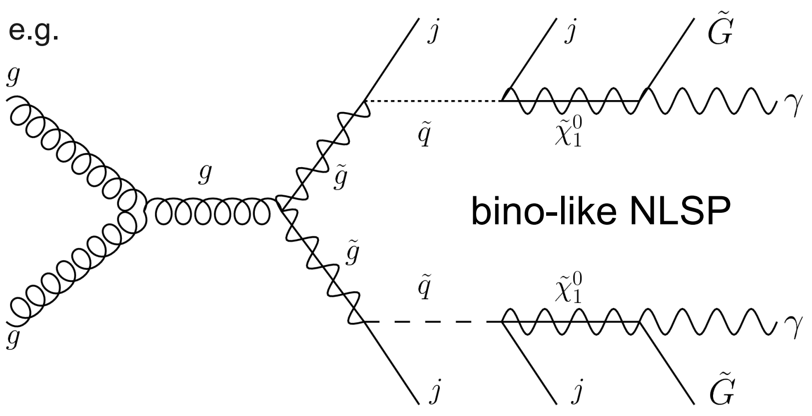
Photon(s)+MET

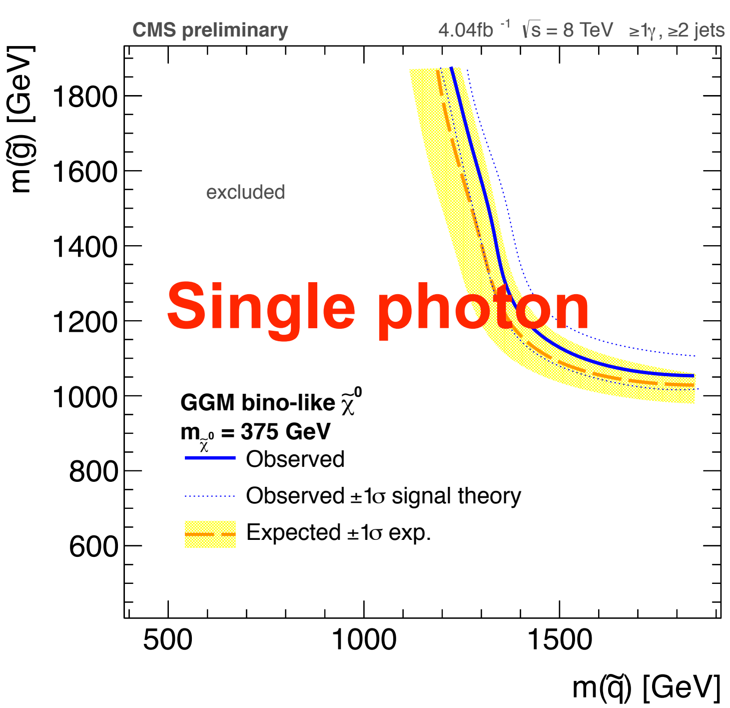
SUS-12-018

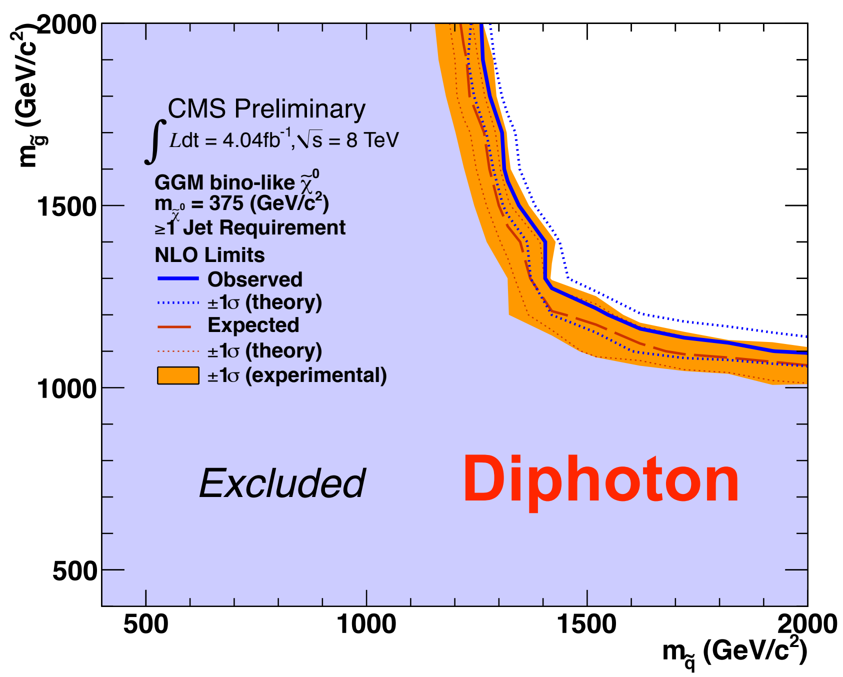
	2γ MET > 100 GeV	γ MET > 350 GeV
Data	11	8
SM	17.8 ± 12.4	14.6 ± 6.4

GGM model (J. Ruderman, D.Shih arXiv:1103.6083)

- Gravitino LSP
- Neutralino NLSP
- χ^0 (bino/wino-like) gives > 1 photon (BR γ vs Z^0)
- Limit for fixed χ^0 mass of 375 GeV







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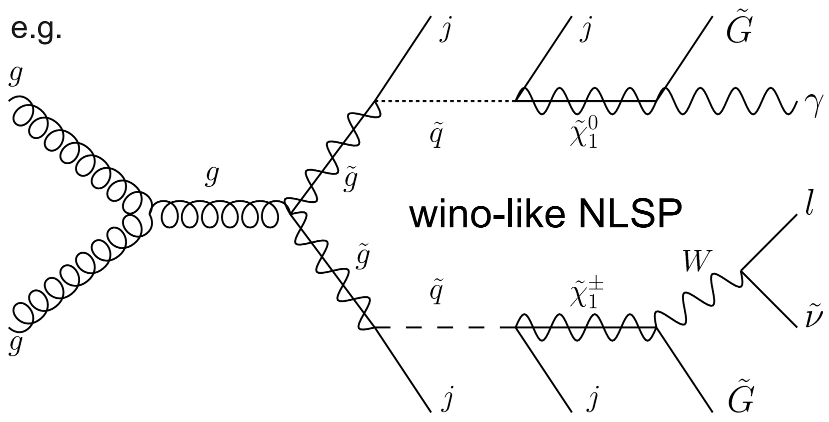
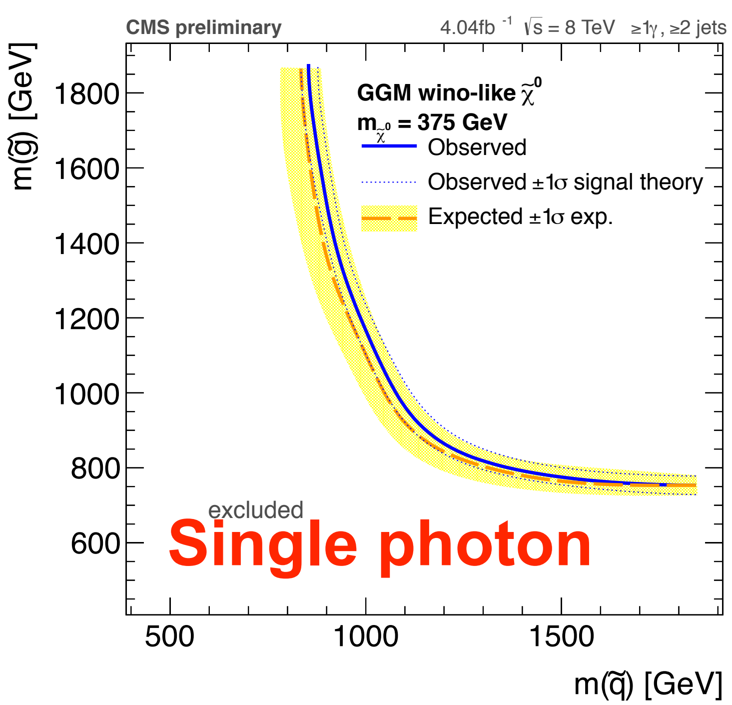
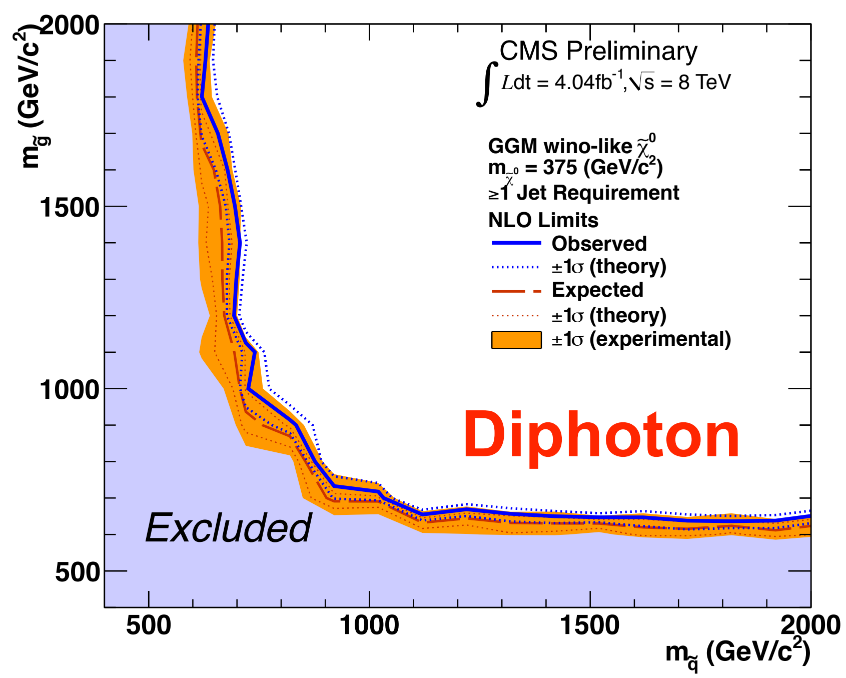




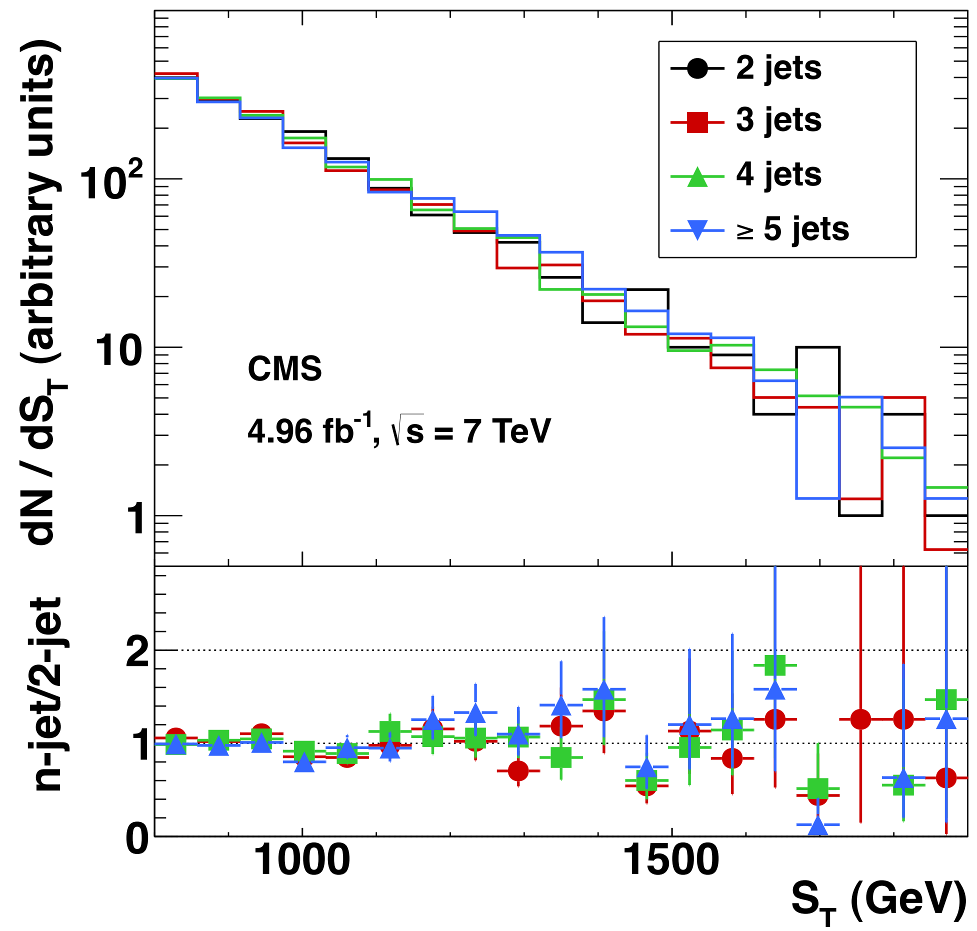


Photons+MET

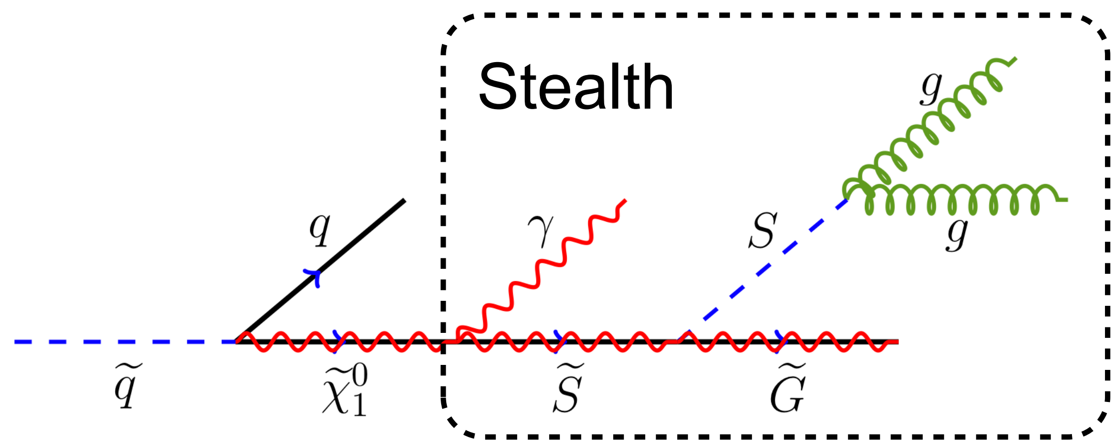
- Extend diphoton search to low MET
  - Predict background in high jet mult. signal region from low jet mult. sideband using S_T [cf CMS black hole searches]

$$S_T = MET + \Sigma_\gamma E_T + \Sigma_j p_T^j$$

  - S_T shape independent of object mult.
  - Normalisation from low S_T sideband



arXiv:1210.2052



Stealth SUSY model

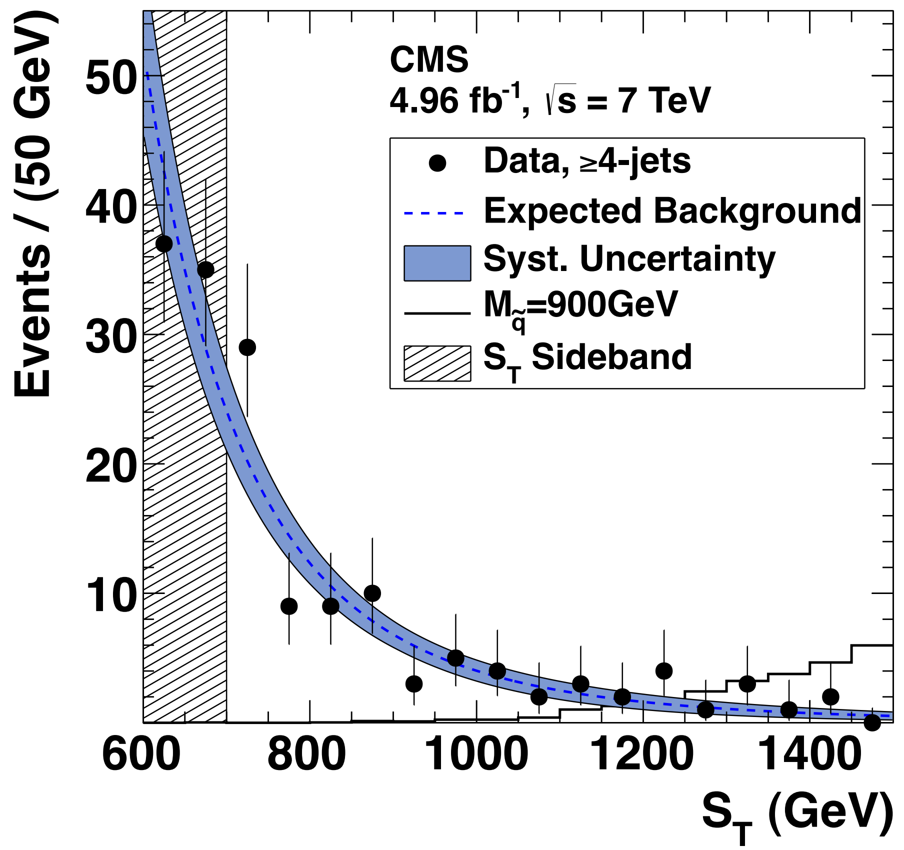
(Fan, Reece, Ruderman arXiv:1105:5135)

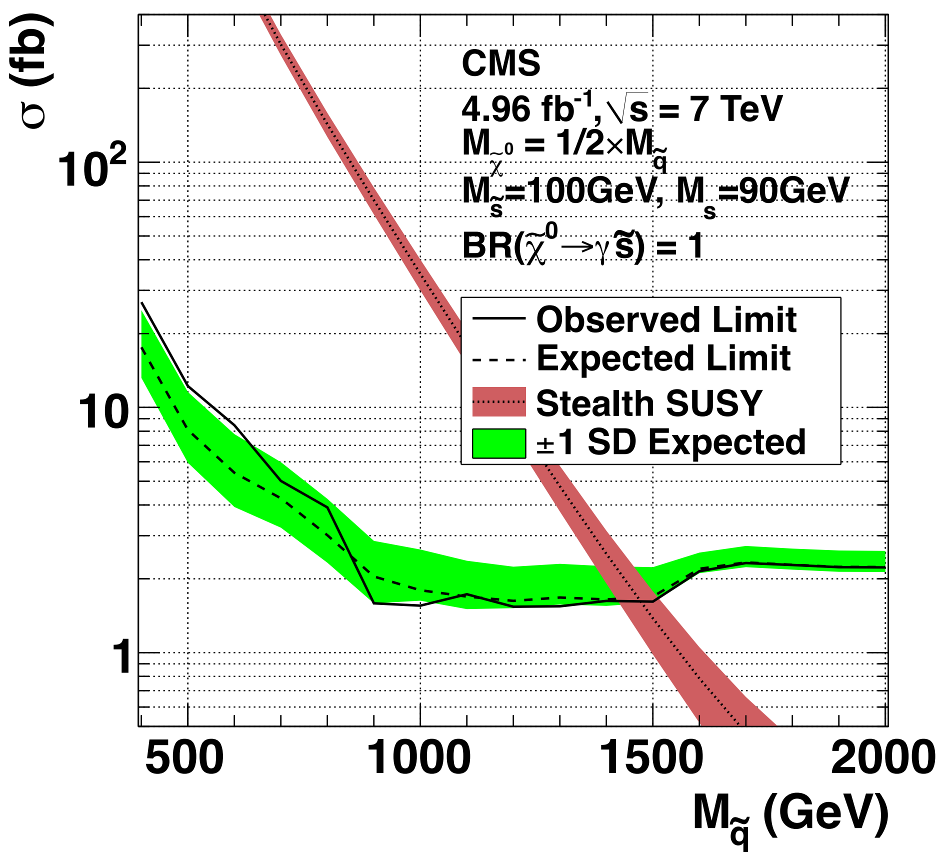
- Stealth sector superpartners nearly mass degenerate
- Soft MET spectrum from LSP (RPC)
- More details in backup

Photons+MET

arXiv:1210.2052

- Background shape from 2-3 jet bins
- Normalise in $600<S_T<700$ GeV sideband
- Signal region: ≥4 jets and S_T>700 GeV





- No excess over background prediction
- Set limits in model (and on cross section)
- M(squark) > 1430 GeV

Multilepton searches

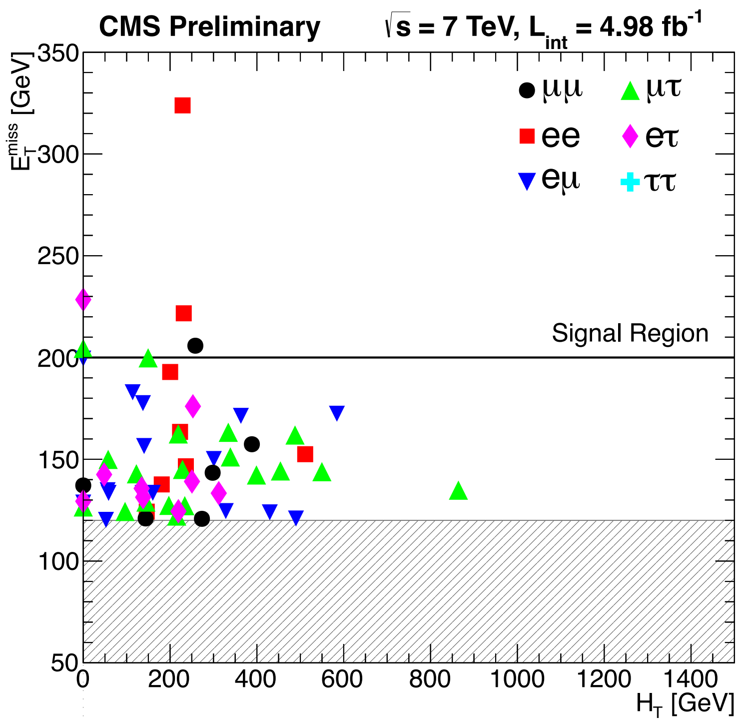
- Adding leptons reduces background compared to hadronic searches
  - Allows looser cuts, particularly on hadronic quantities ➔ sensitivity to weakly produced new physics with lower cross sections

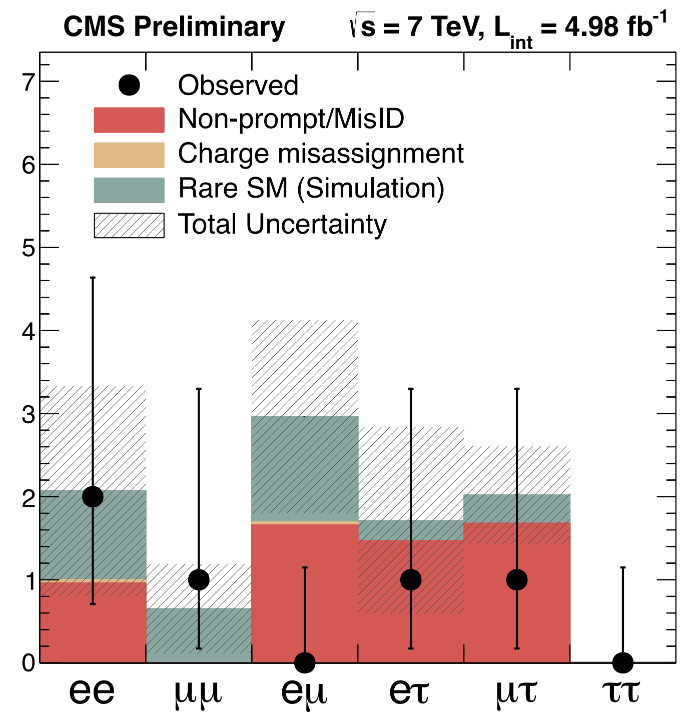
- Consider two, three and four lepton searches to search for electroweak production of SUSY particles
  - Dilepton (opposite-charge, same-charge, Z(➔ll)+V(➔jj))
  - Trilepton (based on MET, based on M_{ll} and M_T)
  - Four lepton

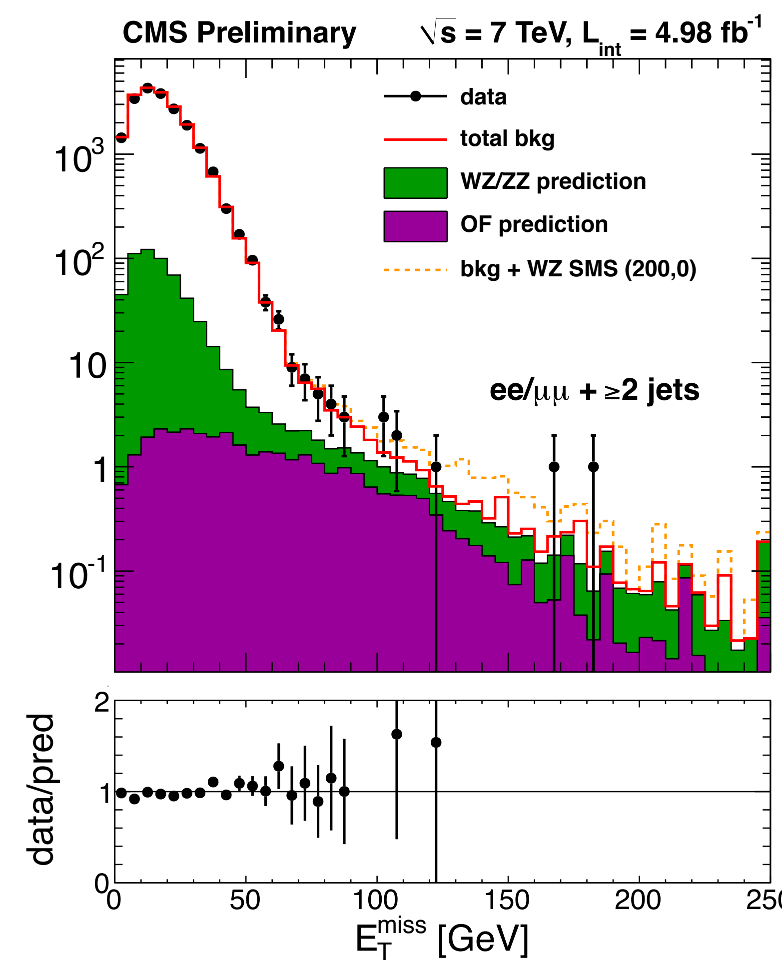
- Paper bringing previous and new results together
  - arXiv:1209.6620

Dilepton searches

arXiv:1209.6620





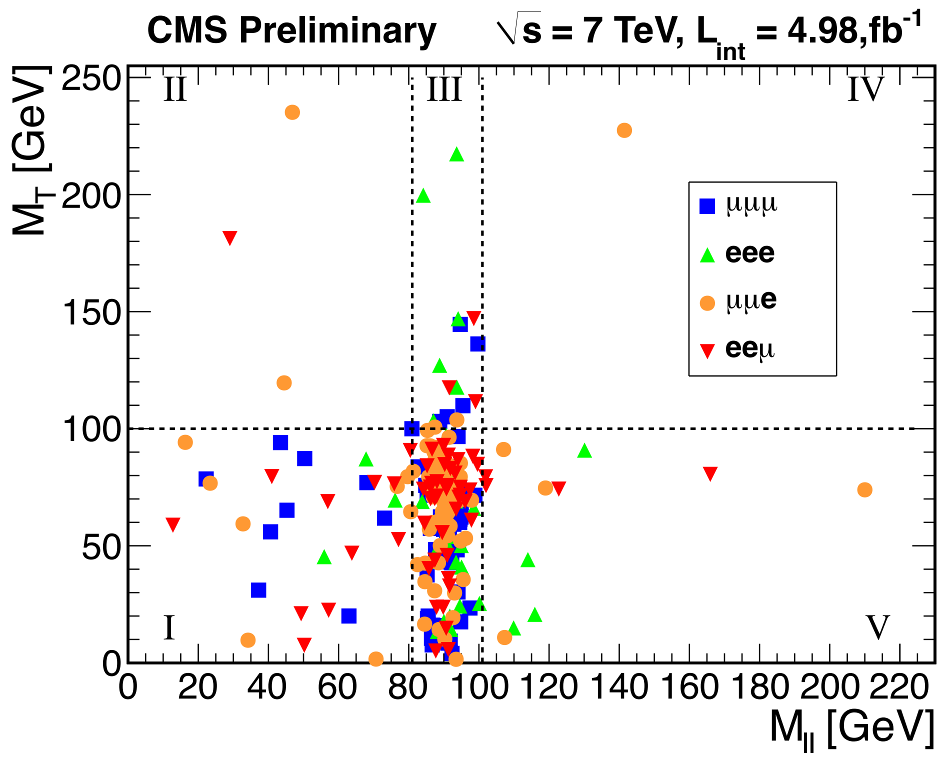


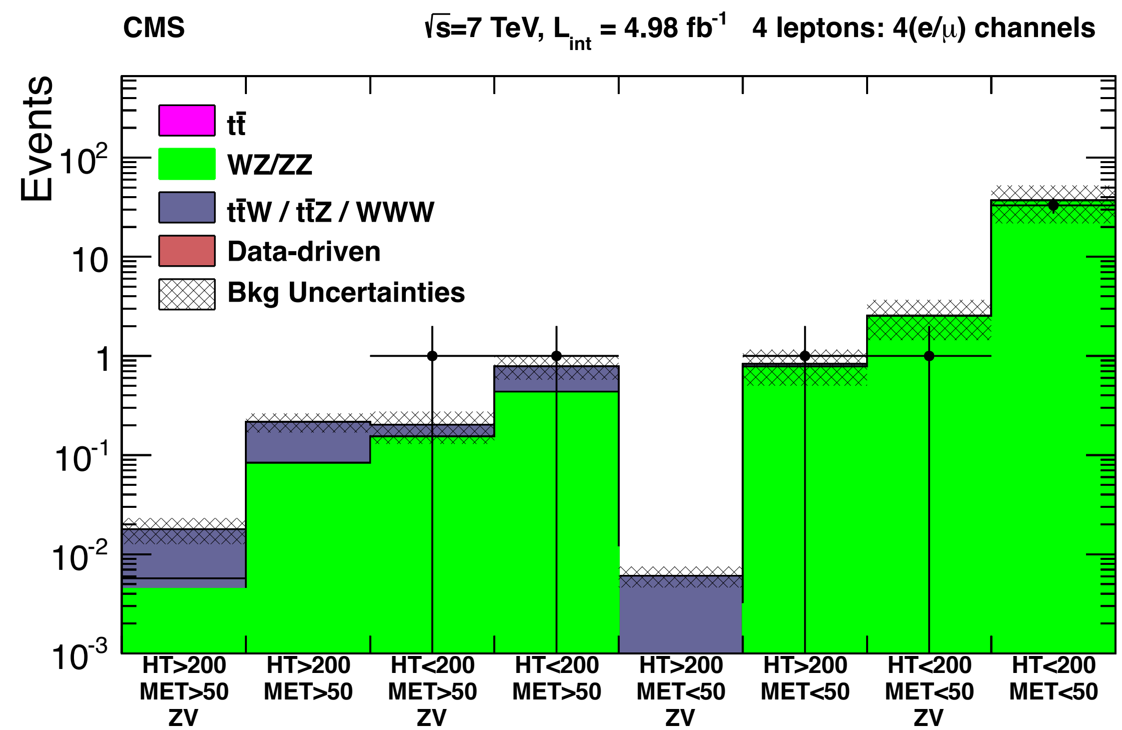
- Backgrounds
  - Same-sign: ttbar ➔ data-driven fake rate, rare processes from simulation
  - Opposite sign: Z+jets estimated from data templates, ttbar from opposite flavour events ➔ here analysis targets Z(➔ll)+Z/W(➔jj) 70 < M_{jj} < 100 GeV

Three and four lepton searches

arXiv:1209.6620

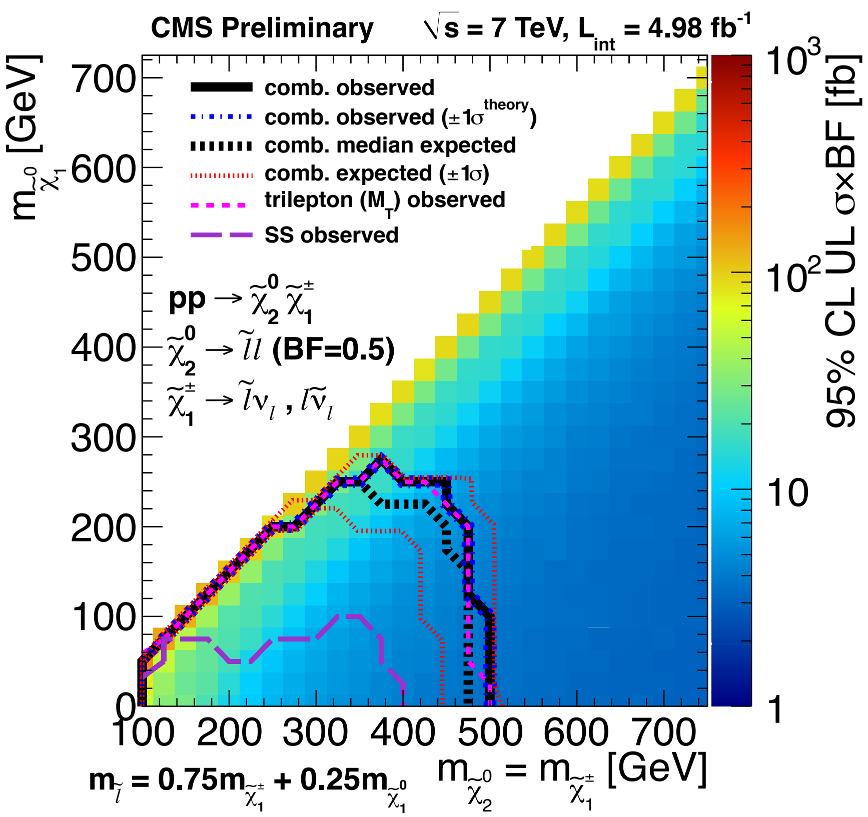
arXiv:1204.5341

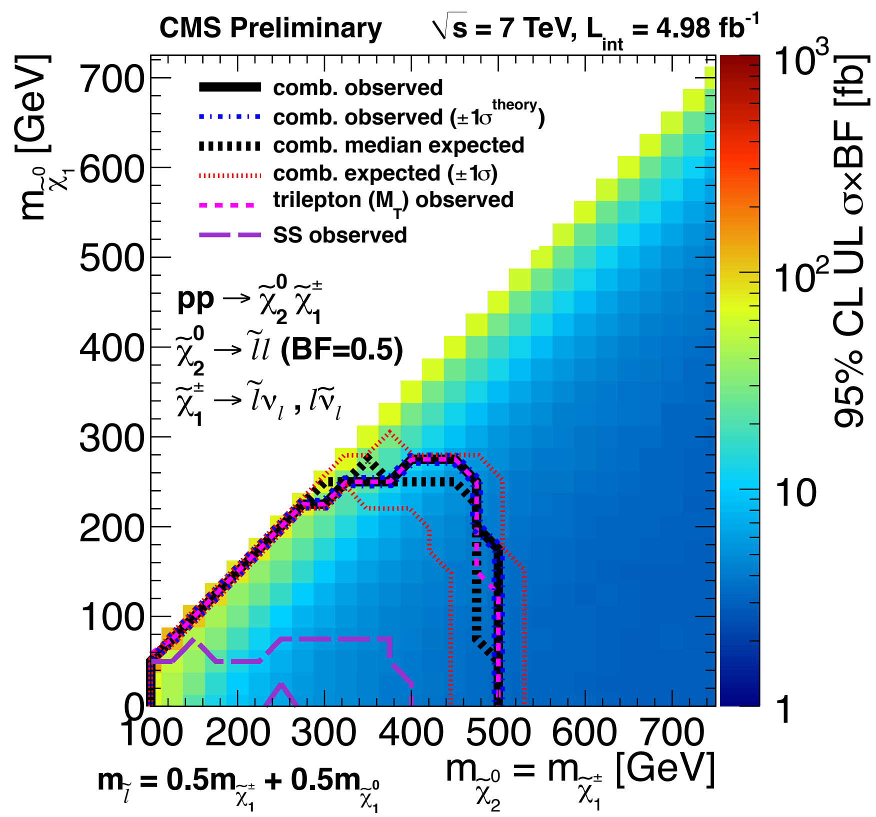


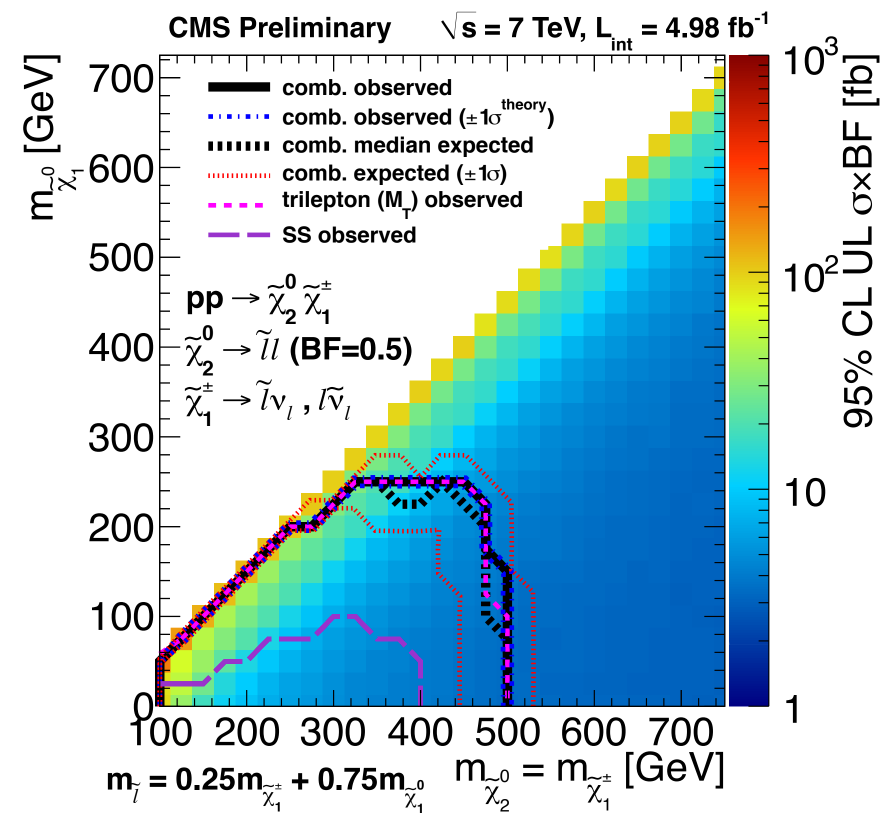


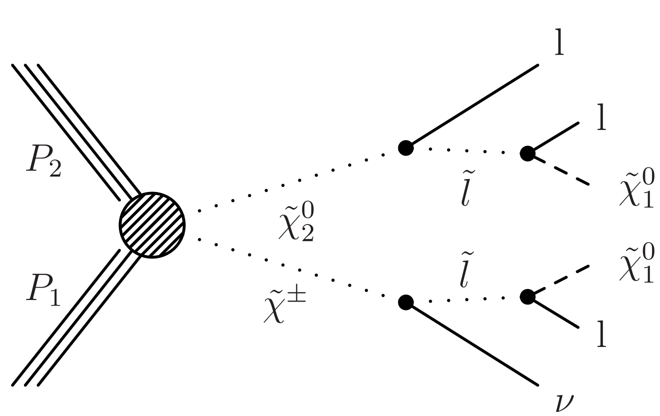
- Backgrounds
  - Irreducible: WZ+jets, ZZ+jets ➔ estimated from simulation
  - ttbar ➔ simulation with study in control regions
  - Z+jets, WW+jets, W+jets, QCD ➔ data-driven fake rate

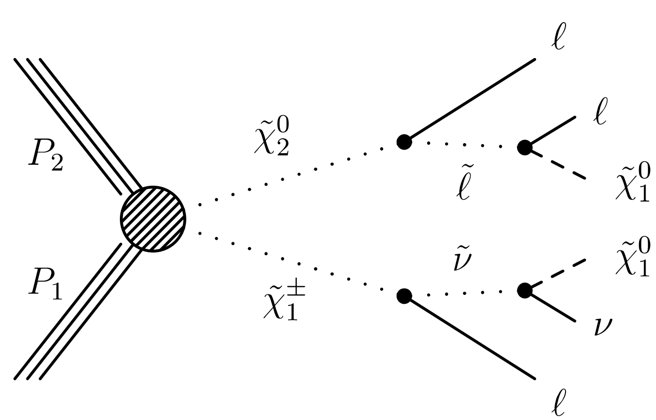
Multilepton searches







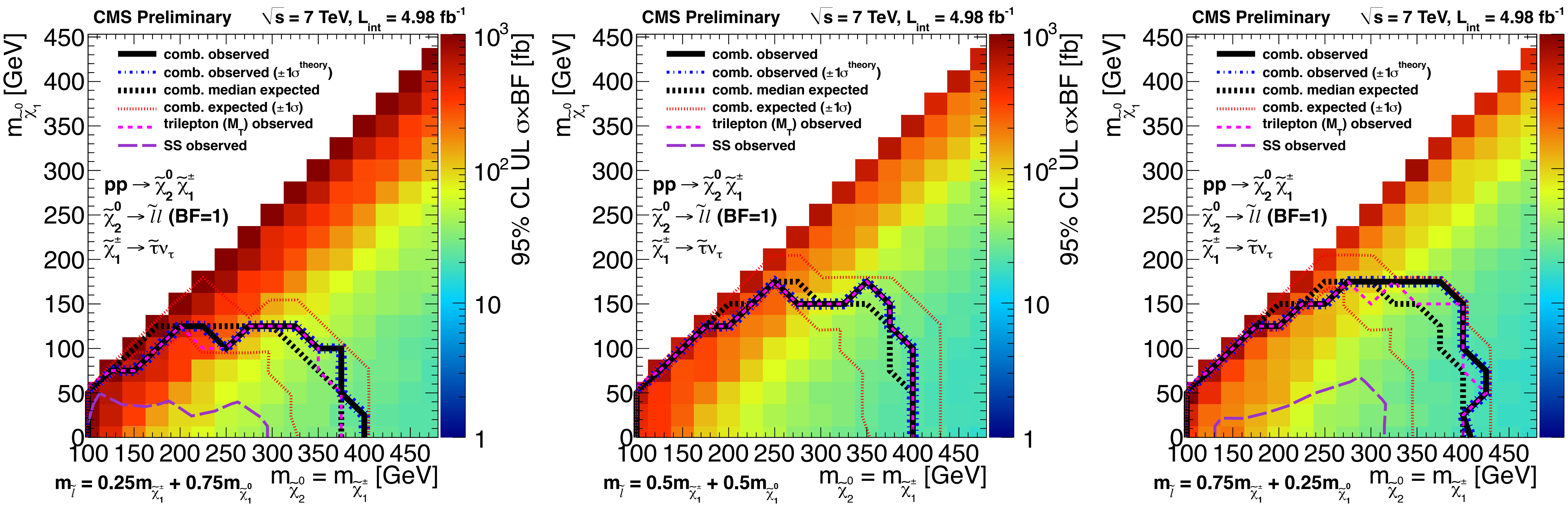


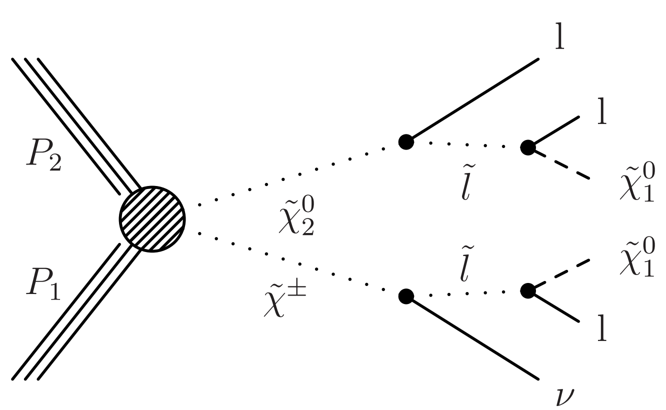


Dilepton search adds sensitivity when mass splitting gives soft 3rd lepton

arXiv:1209.6620

Multilepton searches

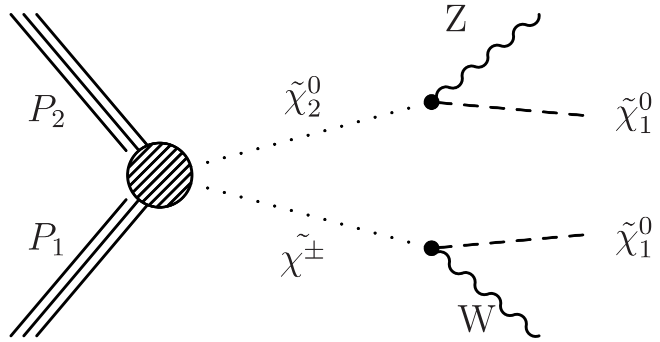


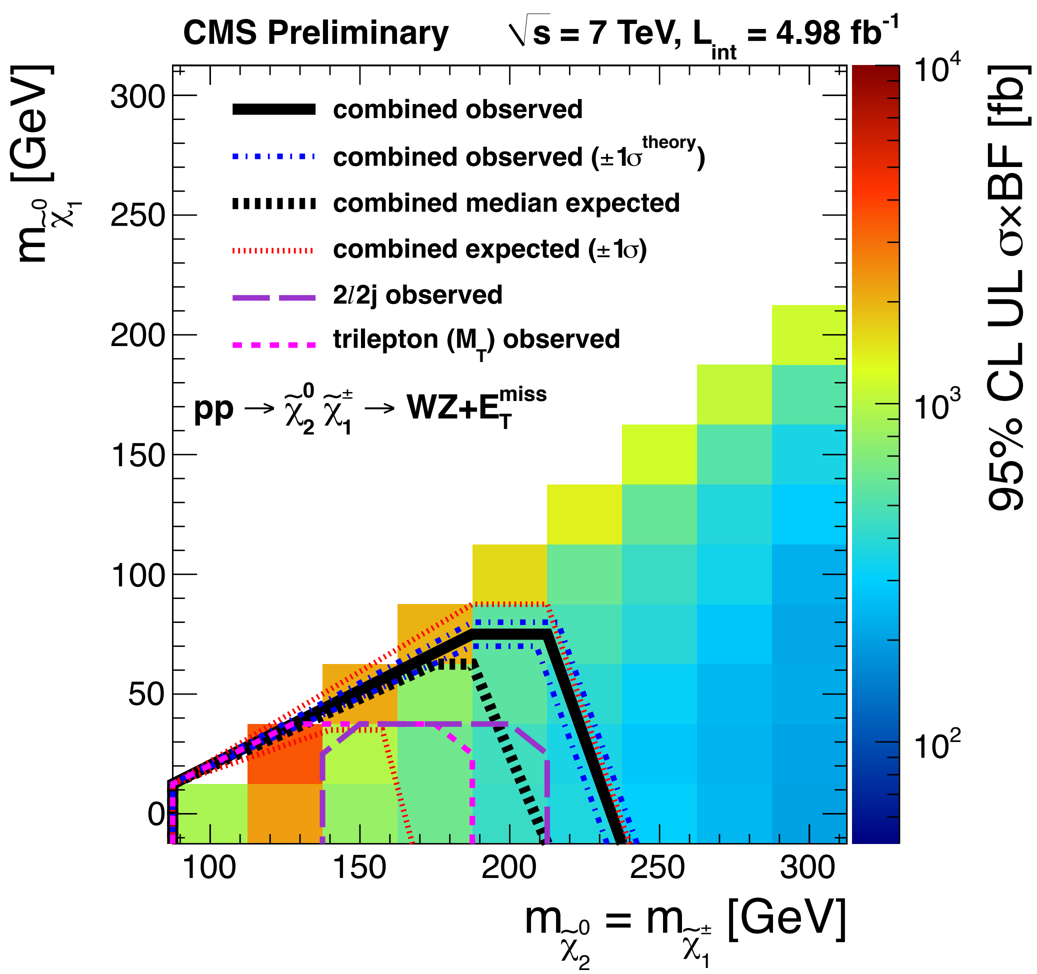


Tau enriched scenario: only right-handed sleptons participate and couple to the chargino via Higgsino component ➔ chargino decays exclusively to τ leptons

arXiv:1209.6620

Multilepton searches



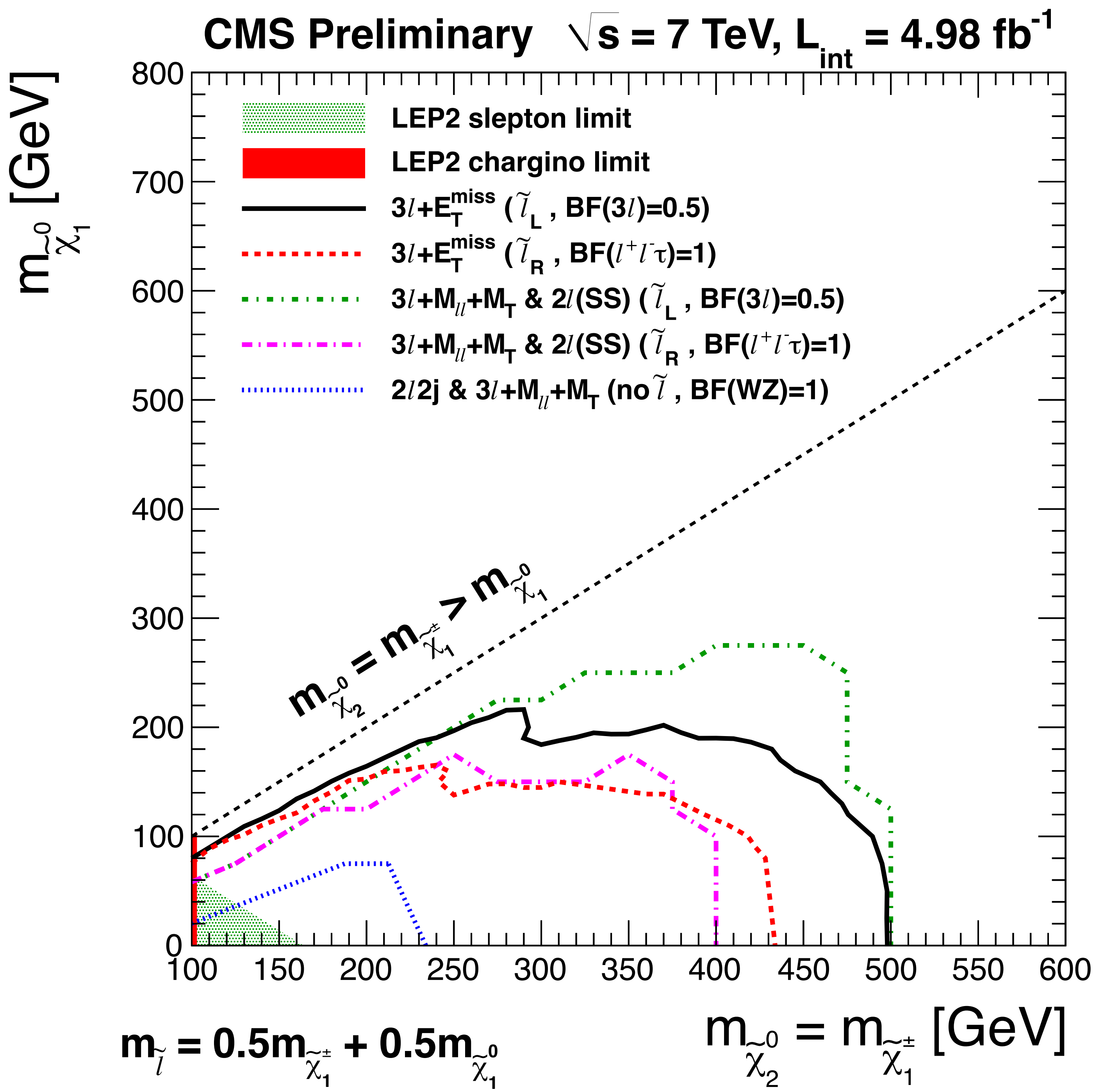


Dilepton Z➔ll+V➔jj complementary to trilepton search

Trade off purity for higher branching ratio

arXiv:1209.6620

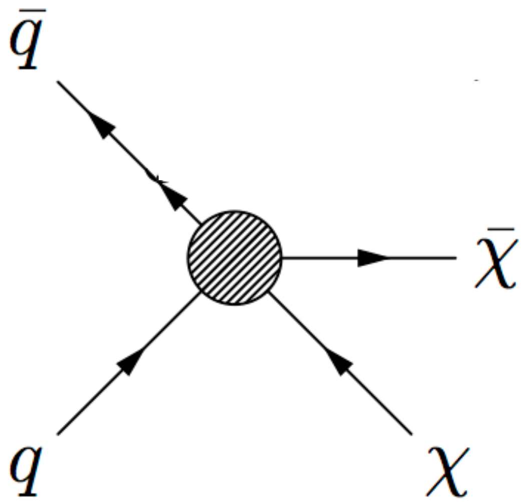
Electroweak production limits



arXiv:1209.6620

Monojets/monophotons

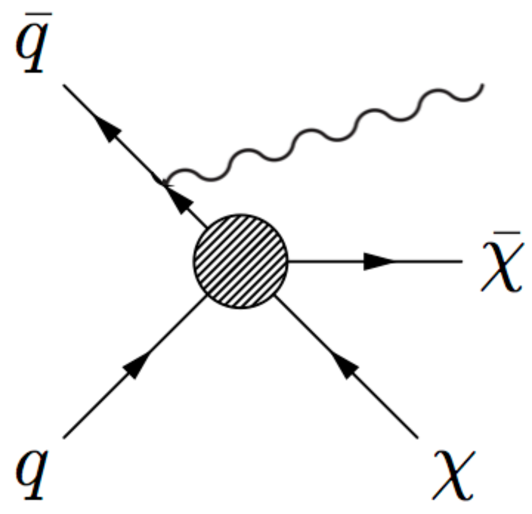
- Dark matter production at LHC

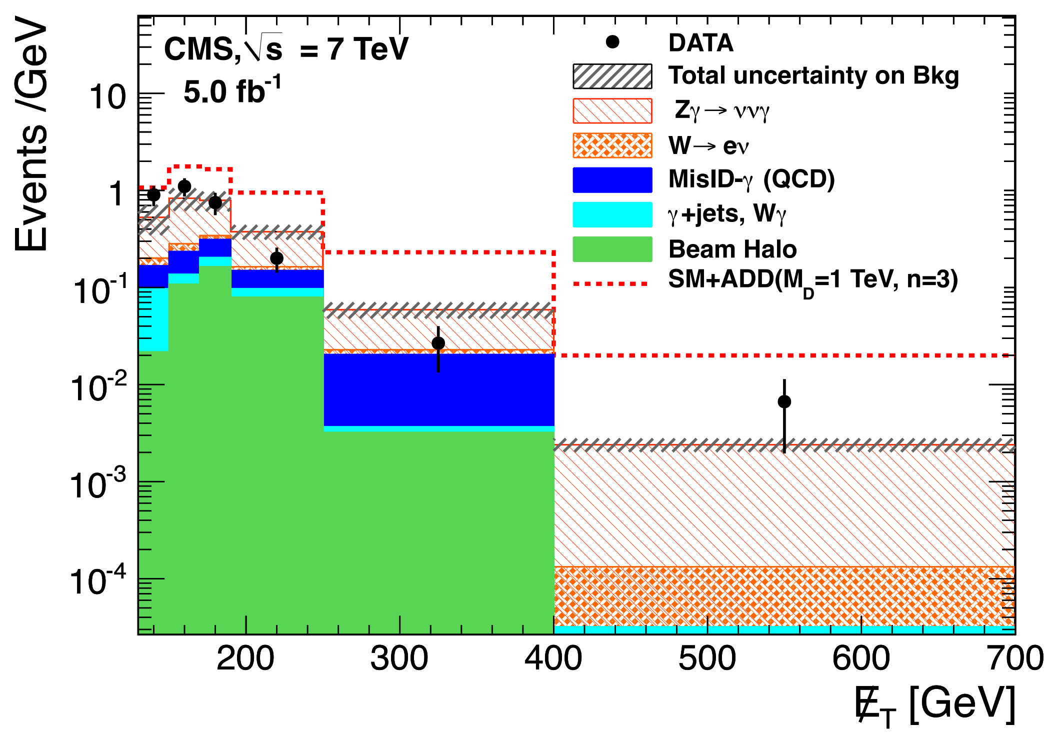


Monojets/monophotons

- Dark matter production at LHC

arXiv:1204.0821





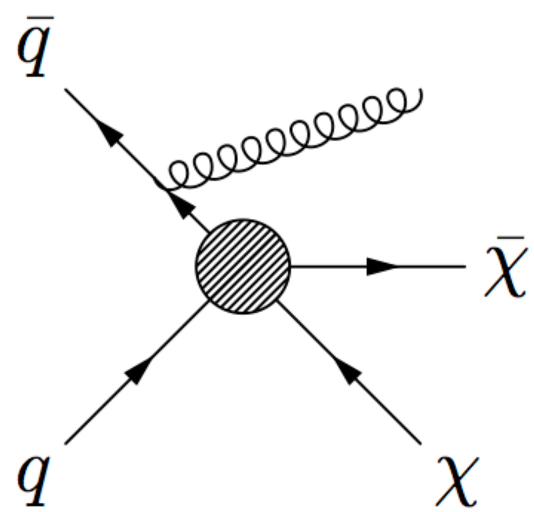
- Selection
  - $P_{T\gamma} > 145$ GeV
  - MET > 130 GeV
  - Veto on jets ($p_T > 30$ GeV)

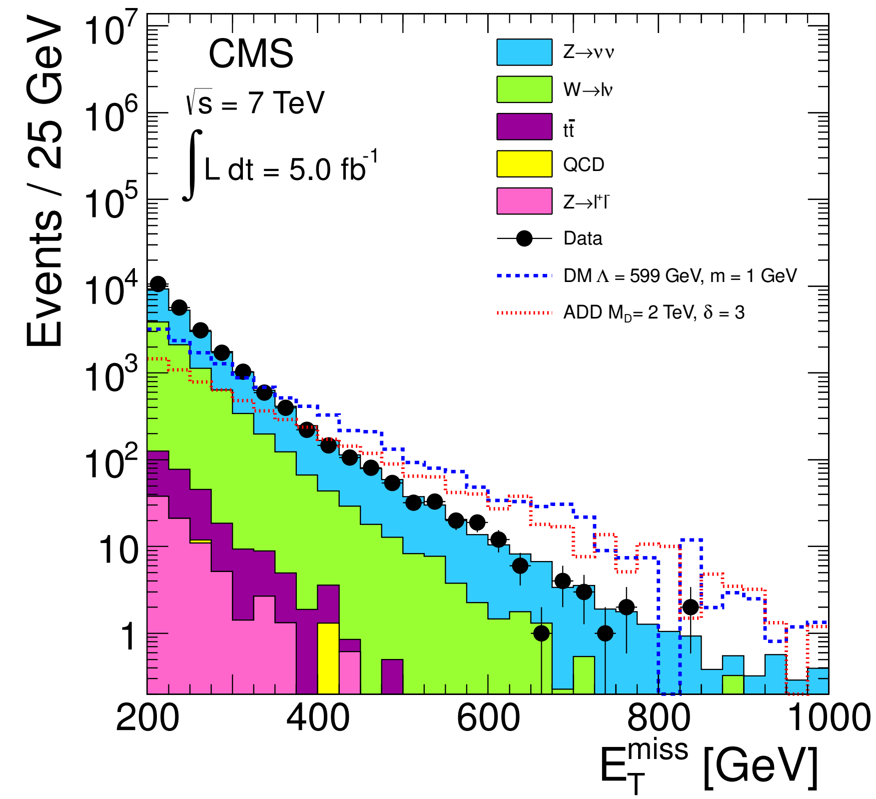
Source	Estimate
Jet Mimics Photon	11.2 ± 2.8
Beam Halo	11.1 ± 5.6
Electron Mimics Photon	3.5 ± 1.5
$W\gamma$	3.0 ± 1.0
γ+jet	0.5 ± 0.2
$\gamma\gamma$	0.6 ± 0.3
$Z(\nu\bar{\nu})\gamma$	45.3 ± 6.9
Total Background	75.1 ± 9.5
Total Observed Candidates	73

Monojets/monophotons

- Dark matter production at LHC

arXiv:1206.5663

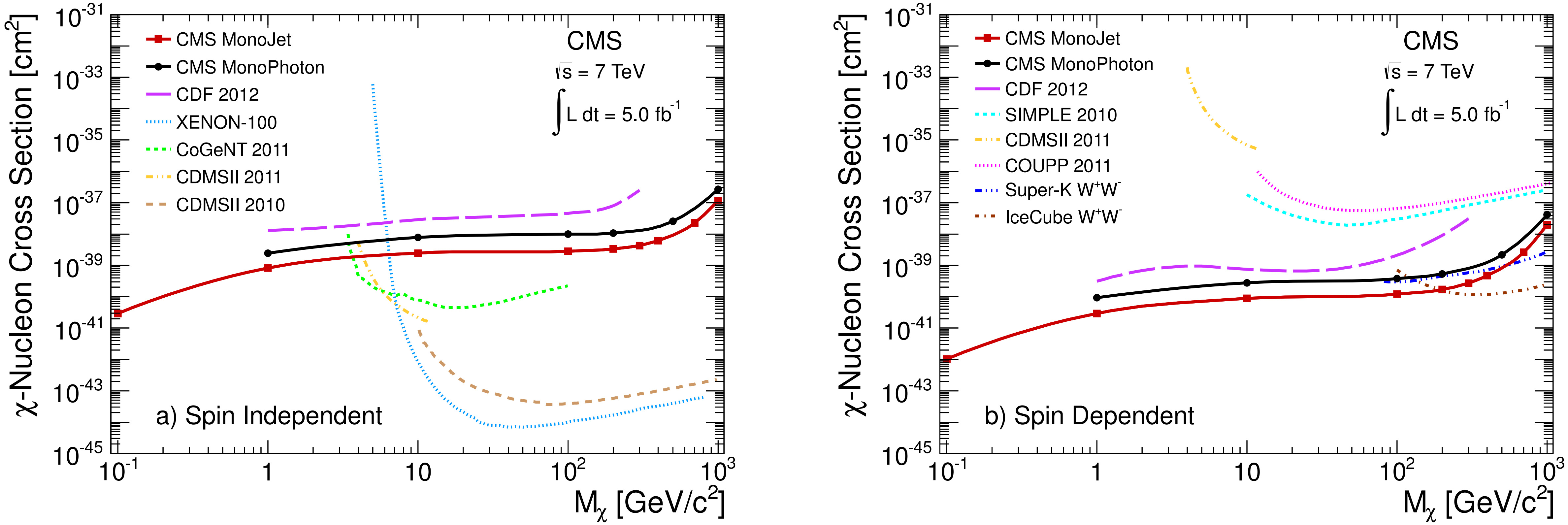




- Selection
  - One or two jets with p_T > 100 (30) GeV
  - MET > 200 GeV
  - Δφ between jets < 2.4

E_T^{miss} (GeV/c) →	≥ 250	≥ 300	≥ 350	≥ 400
Process	Events			
$Z(\nu\bar{\nu})$+jets	5106 ± 271	1908 ± 143	900 ± 94	433 ± 62
W+jets	2632 ± 237	816 ± 83	312 ± 35	135 ± 17
$t\bar{t}$	69.8 ± 69.8	22.6 ± 22.6	8.5 ± 8.5	3.0 ± 3.0
$Z(\ell\ell)$+jets	22.3 ±22.3	6.1 ± 6.1	2.0 ± 2.0	0.6 ± 0.6
Single t	10.2 ±10.2	2.7 ± 2.7	1.1 ± 1.1	0.4 ± 0.4
QCD Multijets	2.2 ±2.2	1.3 ±1.3	1.3 ±1.3	1.3 ±1.3
Total SM	7842 ± 367	2757 ± 167	1225 ± 101	573± 65
Data	7584	2774	1142	522
Expected upper limit non-SM	779	325	200	118
Observed upper limit non-SM	600	368	158	95

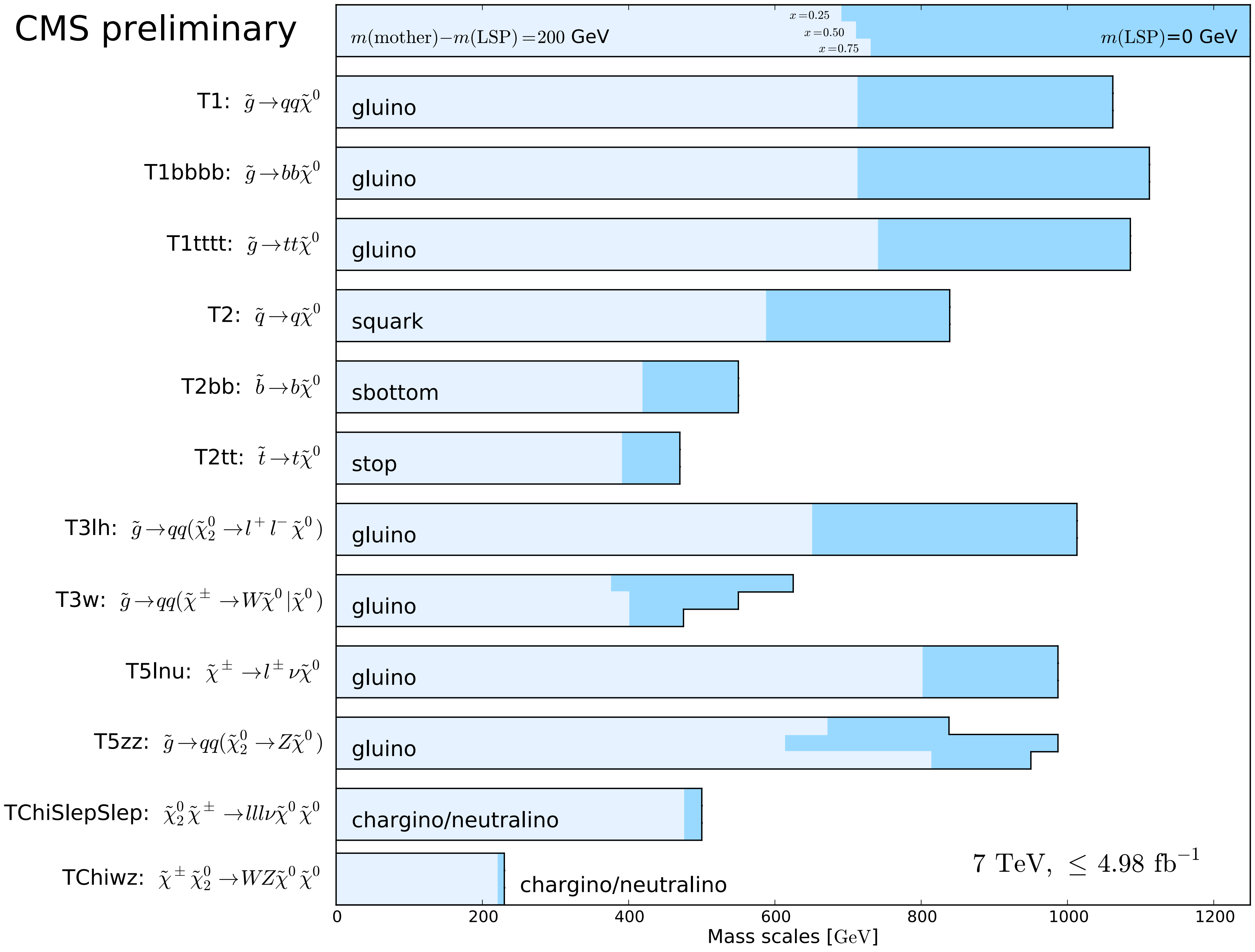
Monojets/monophotons



- Interpret searches in contact interaction model
  - Bai et al. JHEP 1012:048(2010) ➔ more details in backup
- Independent of astrophysical experiments
- CMS results extend to lower masses
- Strong constraints on spin-dependent cross section

Results at a glance

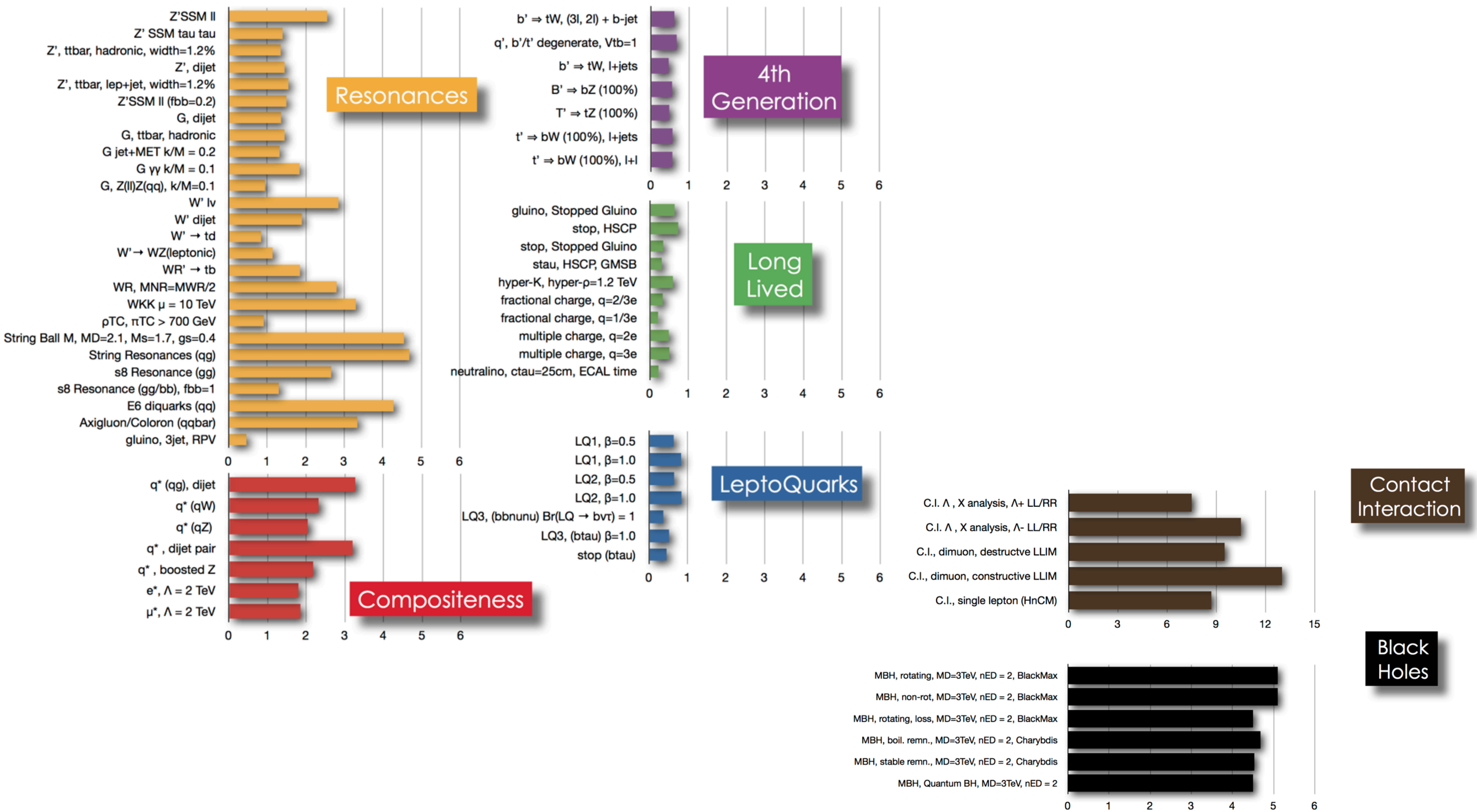
SUS-11-016



Warning!

Strong dependence on LSP mass and BRs assumed to be 100%

Many other searches at CMS…

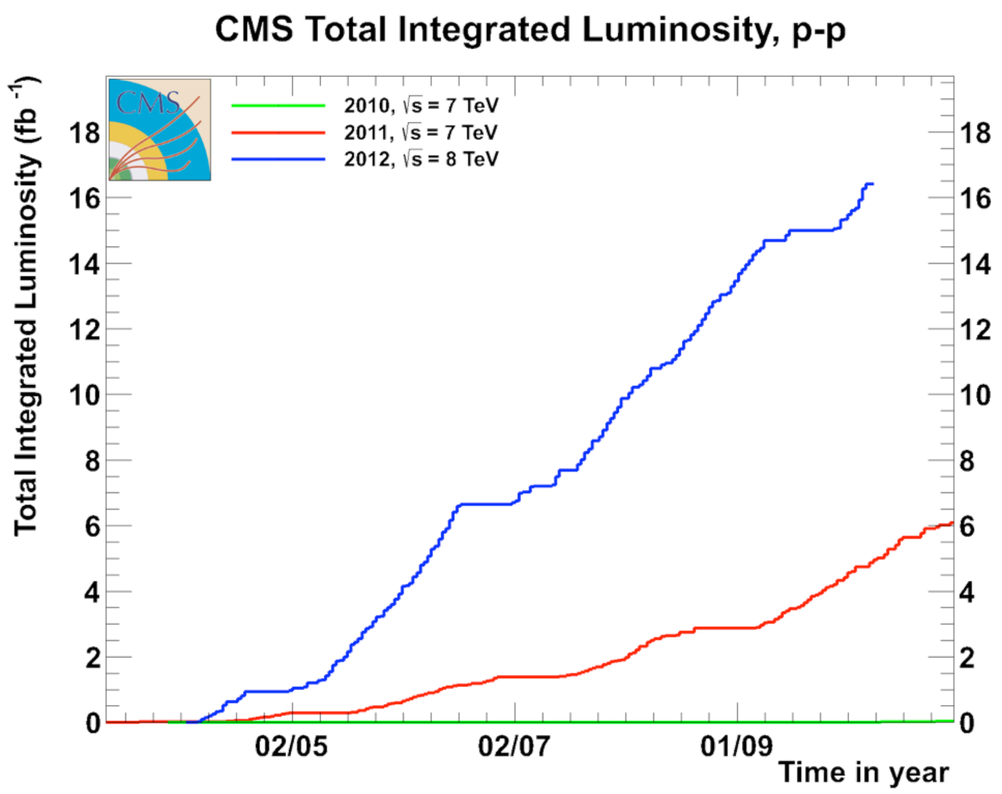


Summary & outlook

- Wide range of MET based searches performed with 5 fb^{-1} 2011 data
  - No significant deviation from the Standard Model
  - First few results with 2012 data ➔ many more to come

- Larger data samples
  - Weak production modes
  - More exclusive channels

- 14 TeV collisions
  - Much larger reach!



- LHC running well in 2012

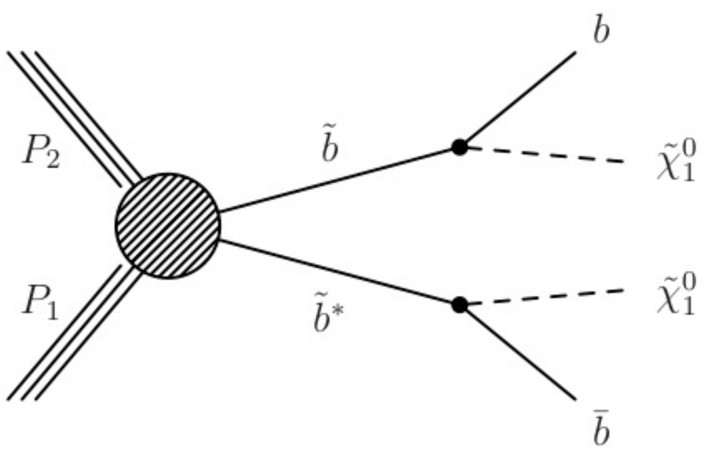
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS

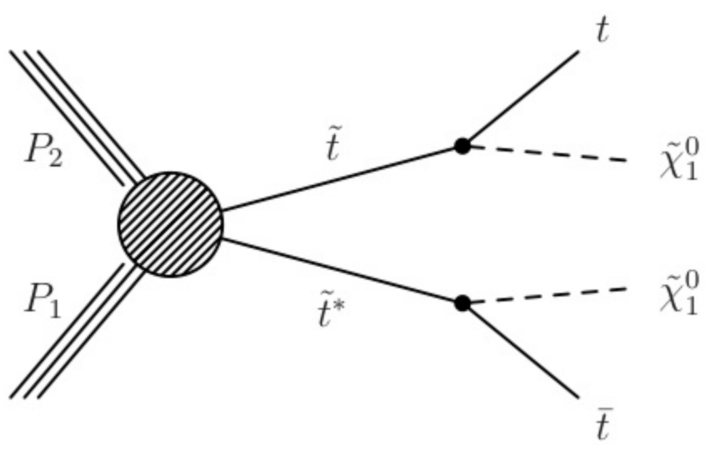
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO

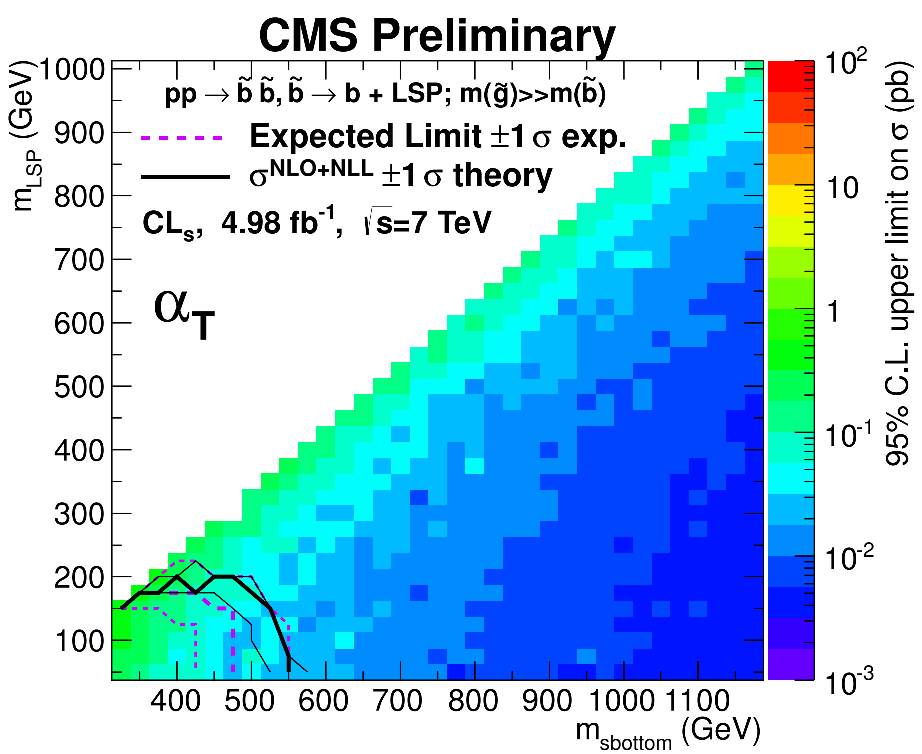
Backup

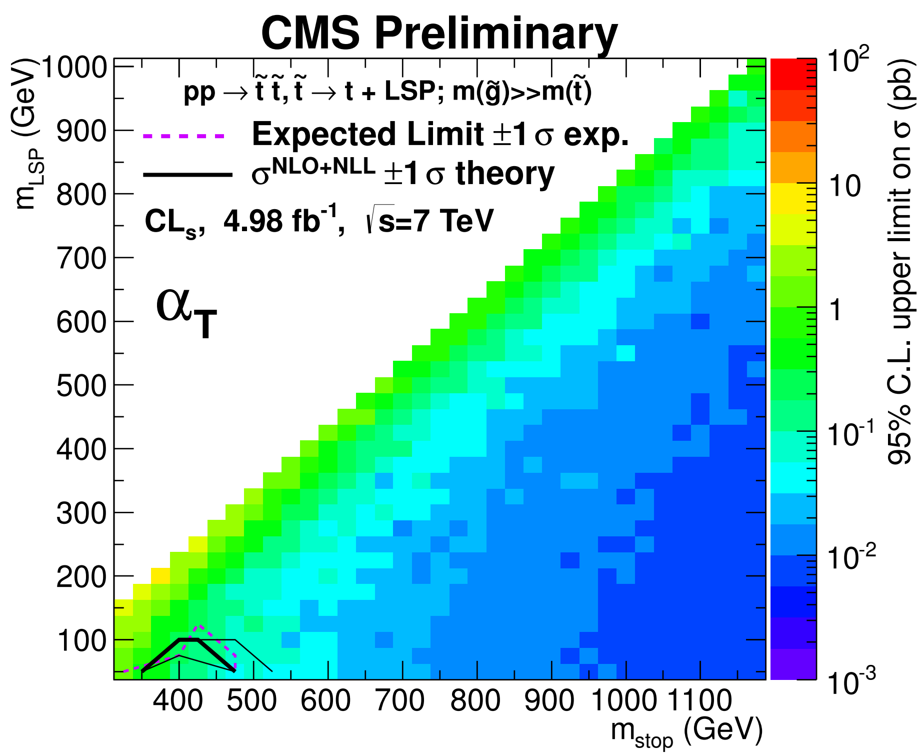
SUSY
LAS MAS ORIGINALES HISTORIAS DE AMOR
SECRETOS DEL CORAZON
¿CUÁNDO ENCONTRARÉ AL HOMBRE DE MIS SUEÑOS?
$ 10.00
COLOMBIA

Direct production of 3rd gen

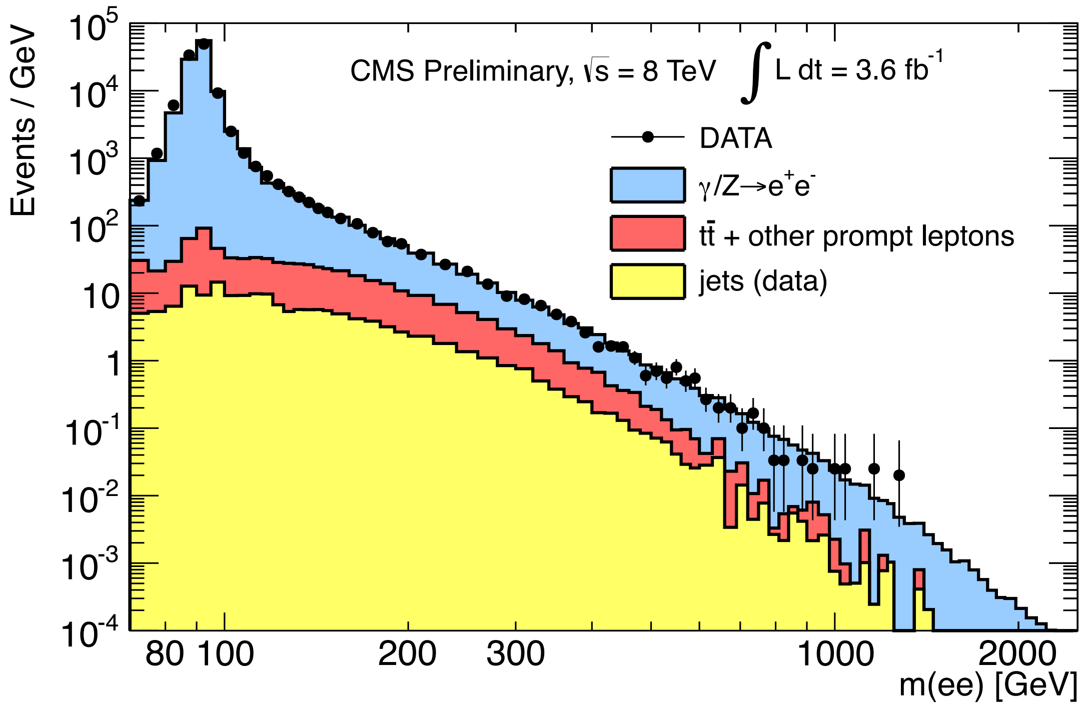


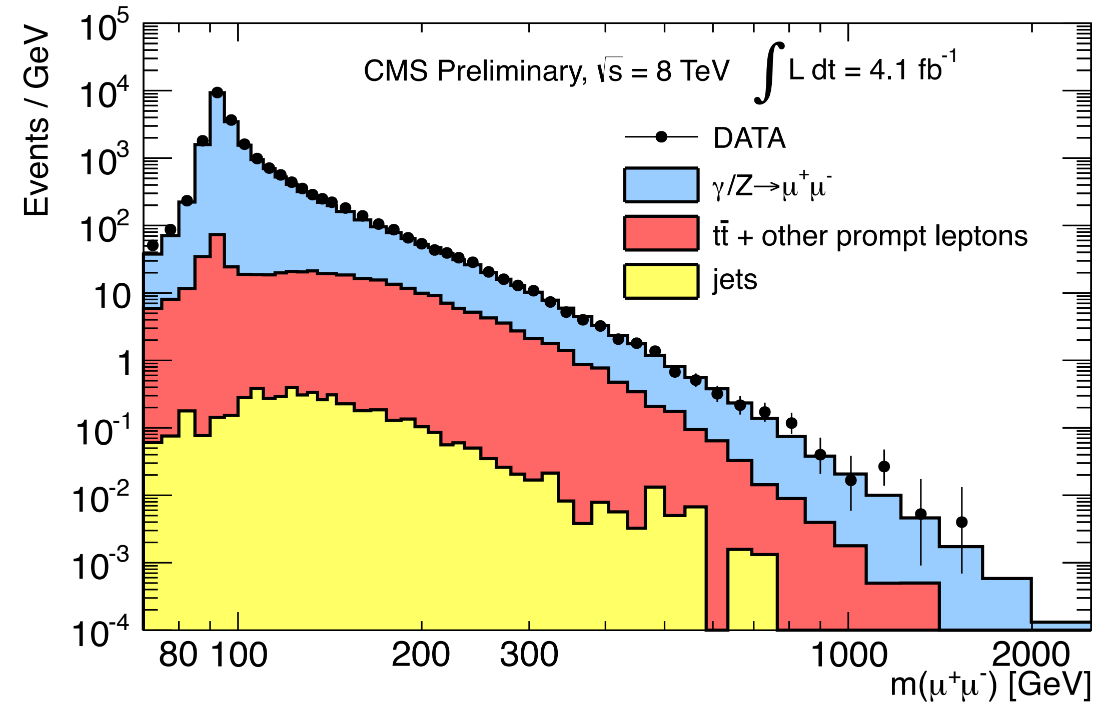






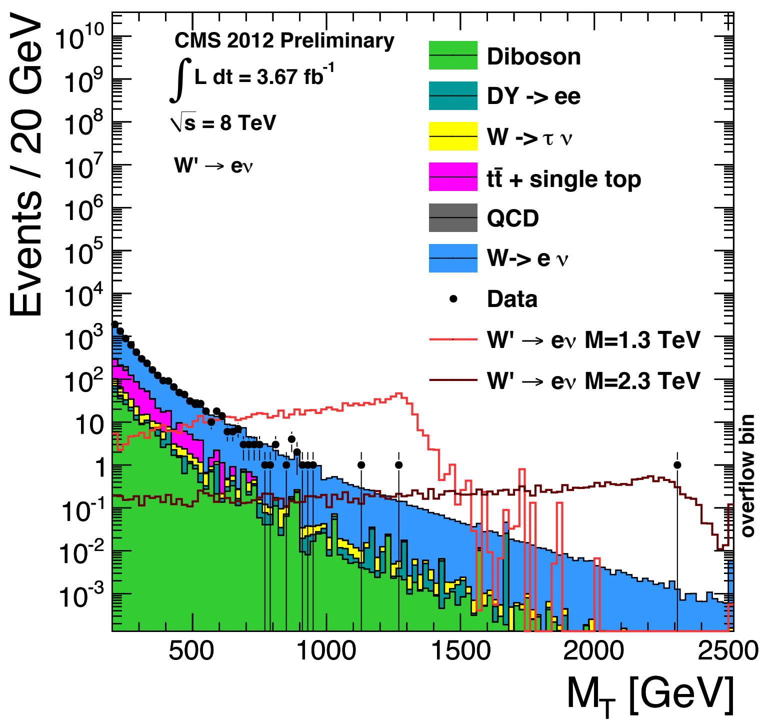
Z' searches

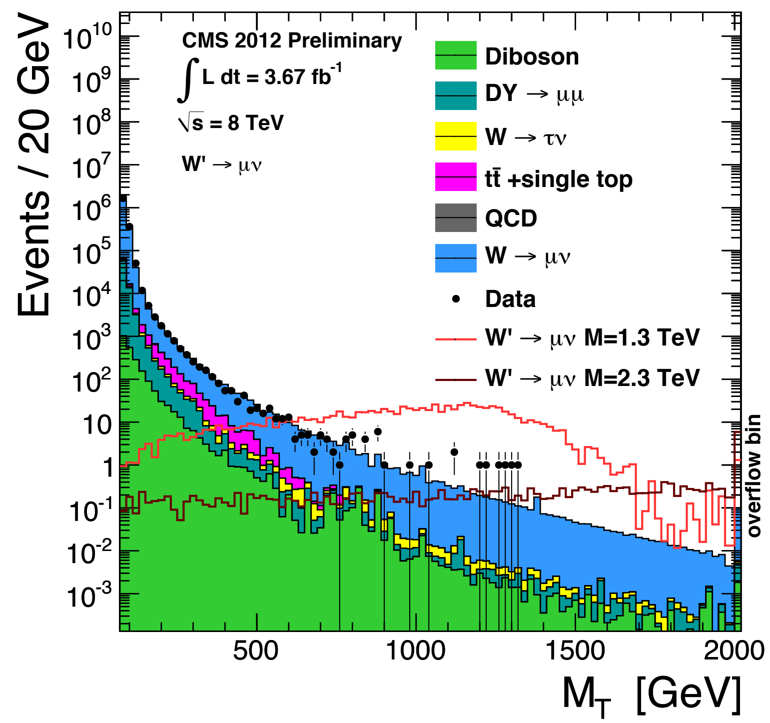


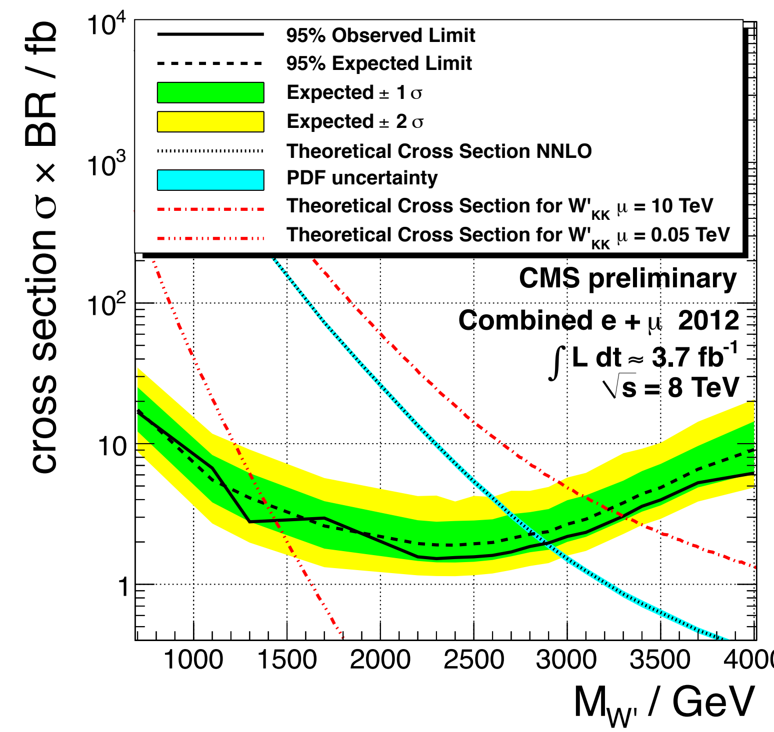


- Electrons:
  - $E_T > 35$ GeV
- Muons:
  - $P_T > 45$ GeV

W’ searches







- Electrons:
  - E_T > 90 GeV
- Muons:
  - p_T > 45 GeV

Jets + MET results

Selection H_T (GeV)	$\not{H}_T$ (GeV)	$Z \rightarrow \nu\overline{\nu}$	$t\overline{t}/W \rightarrow e, \mu$+X	$t\overline{t}/W \rightarrow \tau_h$+X	QCD multijet	Total background	Data
500–800	200–350	359 ± 81	327 ± 47	349 ± 40	119 ± 77	1154 ± 128	1269
500–800	350–500	112 ± 26	48 ± 9	62.5 ± 8.7	2.2 ± 2.2	225 ± 29	236
500–800	500–600	17.6 ± 4.9	5.0 ± 2.2	8.7 ± 2.5	0.0 ± 0.1	31.3 ± 5.9	22
500–800	>600	5.5 ± 2.6	0.8 ± 0.8	2.0 ± 1.8	0.0 ± 0.0	8.3 ± 3.2	6
800–1000	200–350	48 ± 19	58 ± 15	56.3 ± 8.3	35 ± 24	197 ± 35	177
800–1000	350–500	16.0 ± 6.7	5.4 ± 2.3	7.2 ± 2.0	$1.2^{+1.3}_{-1.2}$	29.8 ± 7.5	24
800–1000	500–600	7.1 ± 3.7	2.4 ± 1.5	1.3 ± 0.6	$0.0^{+0.2}_{0.0}$	10.8 ± 4.0	6
800–1000	>600	3.3 ± 1.7	0.7 ± 0.7	1.0 ± 0.3	$0.0^{+0.1}_{0.0}$	5.0 ± 1.9	5
1000–1200	200–350	10.9 ± 5.1	13.7 ± 3.8	21.9 ± 4.6	19.7 ± 13.3	66 ± 15	71
1000–1200	350–500	5.5 ± 3.0	5.0 ± 4.4	2.9 ± 1.3	$0.4^{+0.7}_{-0.4}$	13.8 ± 5.5	12
1000–1200	>500	2.2 ± 1.7	1.6 ± 1.2	2.3 ± 1.0	$0.0^{+0.2}_{0.0}$	6.1 ± 2.3	4
1200–1400	200–350	3.1 ± 1.8	4.2 ± 2.1	6.2 ± 1.8	11.7 ± 8.3	25.2 ± 8.9	29
1200–1400	>350	2.3 ± 1.5	2.3 ± 1.4	$0.6^{+0.8}_{-0.6}$	$0.2^{+0.6}_{-0.2}$	5.4 ± 2.3	8
>1400	>200	3.2 ± 1.8	2.7 ± 1.6	1.1 ± 0.5	12.0 ± 9.1	19.0 ± 9.4	16

Multilepton results

Selection	N(τ)=0 obs	N(τ)=0 expect	N(τ)=1 obs	N(τ)=1 expect	N(τ)=2 obs	N(τ)=2 expect
4ℓ Lepton Results						
4ℓ (DY0) S_T(High)	0	0.0010 ± 0.0009	0	0.01 ± 0.09	0	0.18 ± 0.07
4ℓ (DY0) S_T(Mid)	0	0.004 ± 0.002	0	0.28 ± 0.10	2	2.5 ± 1.2
4ℓ (DY0) S_T(Low)	0	0.04 ± 0.02	0	2.98 ± 0.48	4	3.5 ± 1.1
4ℓ (DY1, no Z) S_T(High)	1	0.009 ± 0.004	0	0.10 ± 0.07	0	0.12 ± 0.05
4ℓ (DY1, Z) S_T(High)	1	0.09 ± 0.01	0	0.51 ± 0.15	0	0.43 ± 0.15
4ℓ (DY1, no Z) S_T(Mid)	0	0.07 ± 0.02	1	0.88 ± 0.26	1	0.94 ± 0.29
4ℓ (DY1, Z) S_T(Mid)	0	0.45 ± 0.11	5	4.1 ± 1.2	3	3.4 ± 0.9
4ℓ (DY1, no Z) S_T(Low)	0	0.09 ± 0.04	7	5.5 ± 2.2	19	13.7 ± 6.4
4ℓ (DY1, Z) S_T(Low)	2	0.80 ± 0.34	19	17.7 ± 4.9	95	60 ± 31
4ℓ (DY2, no Z) S_T(High)	0	0.02 ± 0.01	–	–	–	–
4ℓ (DY2, Z) S_T(High)	0	0.89 ± 0.34	–	–	–	–
4ℓ (DY2, no Z) S_T(Mid)	0	0.20 ± 0.09	–	–	–	–
4ℓ (DY2, Z) S_T(Mid)	3	7.9 ± 3.2	–	–	–	–
4ℓ (DY2, no Z) S_T(Low)	1	2.4 ± 1.1	–	–	–	–
4ℓ (DY2, Z) S_T(Low)	29	29 ± 12	–	–	–	–
3ℓ Lepton Results						
3ℓ (DY0) S_T(High)	2	1.14 ± 0.43	17	11.2 ± 3.2	20	22.5 ± 6.1
3ℓ (DY0) S_T(Mid)	5	7.4 ± 3.0	113	97 ± 31	157	181 ± 24
3ℓ (DY0) S_T(Low)	17	13.5 ± 4.1	522	419 ± 63	1631	2018 ± 253
3ℓ (DY1, no Z) S_T(High)	6	3.5 ± 0.9	10	13.1 ± 2.3	–	–
3ℓ (DY1, Z) S_T(High)	17	18.7 ± 6.0	35	39.2 ± 4.8	–	–
3ℓ (DY1, no Z) S_T(Mid)	32	25.5 ± 6.6	159	141 ± 27	–	–
3ℓ (DY1, Z) S_T(Mid)	89	102 ± 31	441	463 ± 41	–	–
3ℓ (DY1, no Z) S_T(Low)	126	150 ± 36	3721	2983 ± 418	–	–
3ℓ (DY1, Z) S_T(Low)	727	815 ± 192	17631	15758 ± 2452	–	–
Total 4ℓ	37	42 ± 13	32.0	32.1 ± 5.5	124	85 ± 32
Total 3ℓ	1021	1137 ± 198	22649	19925 ± 2489	1808	2222 ± 255
Total	1058	1179 ± 198	22681	19957 ± 2489	1932	2307 ± 257

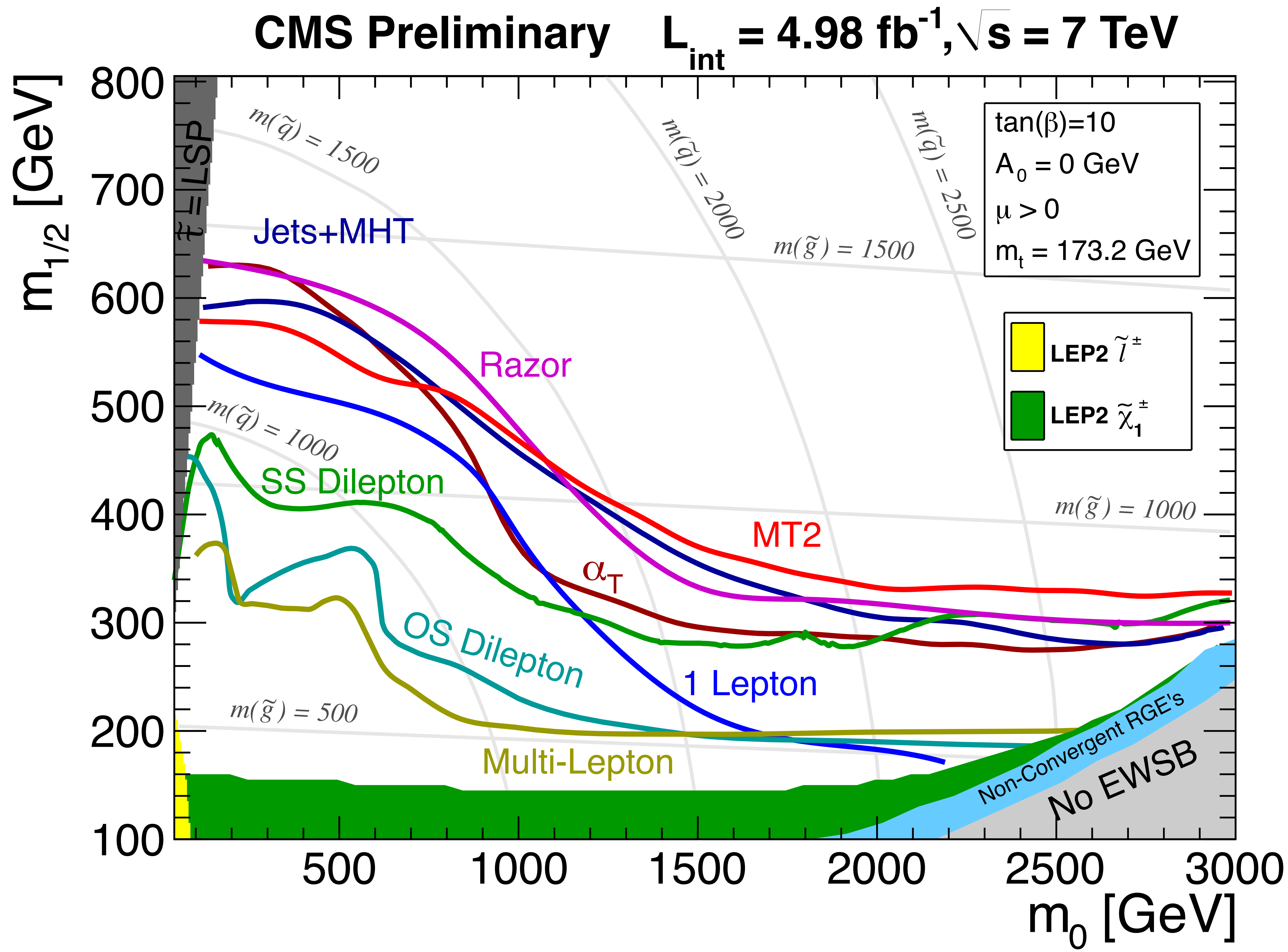
Selection	N(τ)=0 obs	N(τ)=0 expect	N(τ)=1 obs	N(τ)=1 expect	N(τ)=2 obs	N(τ)=2 expect
4ℓ Lepton Results						
4ℓ >50,>200, no Z	0	0.018 ± 0.005	0	0.09 ± 0.06	0	0.7 ± 0.7
4ℓ >50,> 200, Z	0	0.22 ± 0.05	0	0.27 ± 0.11	0	0.8 ± 1.2
4ℓ >50,<200, no Z	1	0.20 ± 0.07	3	0.59 ± 0.17	1	1.5 ± 0.6
4ℓ >50,<200, Z	1	0.79 ± 0.21	4	2.3 ± 0.7	0	1.1 ± 0.7
4ℓ <50,>200, no Z	0	0.006 ± 0.001	0	0.14 ± 0.08	0	0.25 ± 0.07
4ℓ <50,>200, Z	1	0.83 ± 0.33	0	0.55 ± 0.21	0	1.14 ± 0.42
4ℓ <50,<200, no Z	1	2.6 ± 1.1	5	3.9 ± 1.2	17	10.6 ± 3.2
4ℓ <50,<200, Z	33	37 ± 15	20	17.0 ± 5.2	62	43 ± 16
3ℓ Lepton Results						
3ℓ >50,>200,no-OSSF	2	1.5 ± 0.5	33	30.4 ± 9.7	15	13.5 ± 2.6
3ℓ >50,<200,no-OSSF	7	6.6 ± 2.3	159	143 ± 37	82	106 ± 16
3ℓ <50,>200,no-OSSF	1	1.2 ± 0.7	16	16.9 ± 4.5	18	31.9 ± 4.8
3ℓ <50,<200,no-OSSF	14	11.7 ± 3.6	446	356 ± 55	1006	1026 ± 171
3ℓ >50,>200, no Z	8	5.0 ± 1.3	16	31.7 ± 9.6	–	–
3ℓ >50,>200, Z	20	18.9 ± 6.4	13	24.4 ± 5.1	–	–
3ℓ >50,<200, no Z	30	27.0 ± 7.6	114	107 ± 27	–	–
3ℓ <50,>200, no Z	11	4.5 ± 1.5	45	51.9 ± 6.2	–	–
3ℓ >50,<200, Z	141	134 ± 50	107	114 ± 16	–	–
3ℓ <50,>200, Z	15	19.2 ± 4.8	166	244 ± 24	–	–
3ℓ <50,<200, no Z	123	144 ± 36	3721	2907 ± 412	–	–
3ℓ <50,<200, Z	657	764 ± 183	17857	15519 ± 2421	–	–
Total 4ℓ	37	42 ± 15	32.0	24.9 ± 5.4	80	59 ± 16
Total 3ℓ	1029	1138 ± 193	22693	19545 ± 2457	1121	1177 ± 172
Total	1066	1180 ± 194	22725	19570 ± 2457	1201	1236 ± 173

Monphoton/monojet results

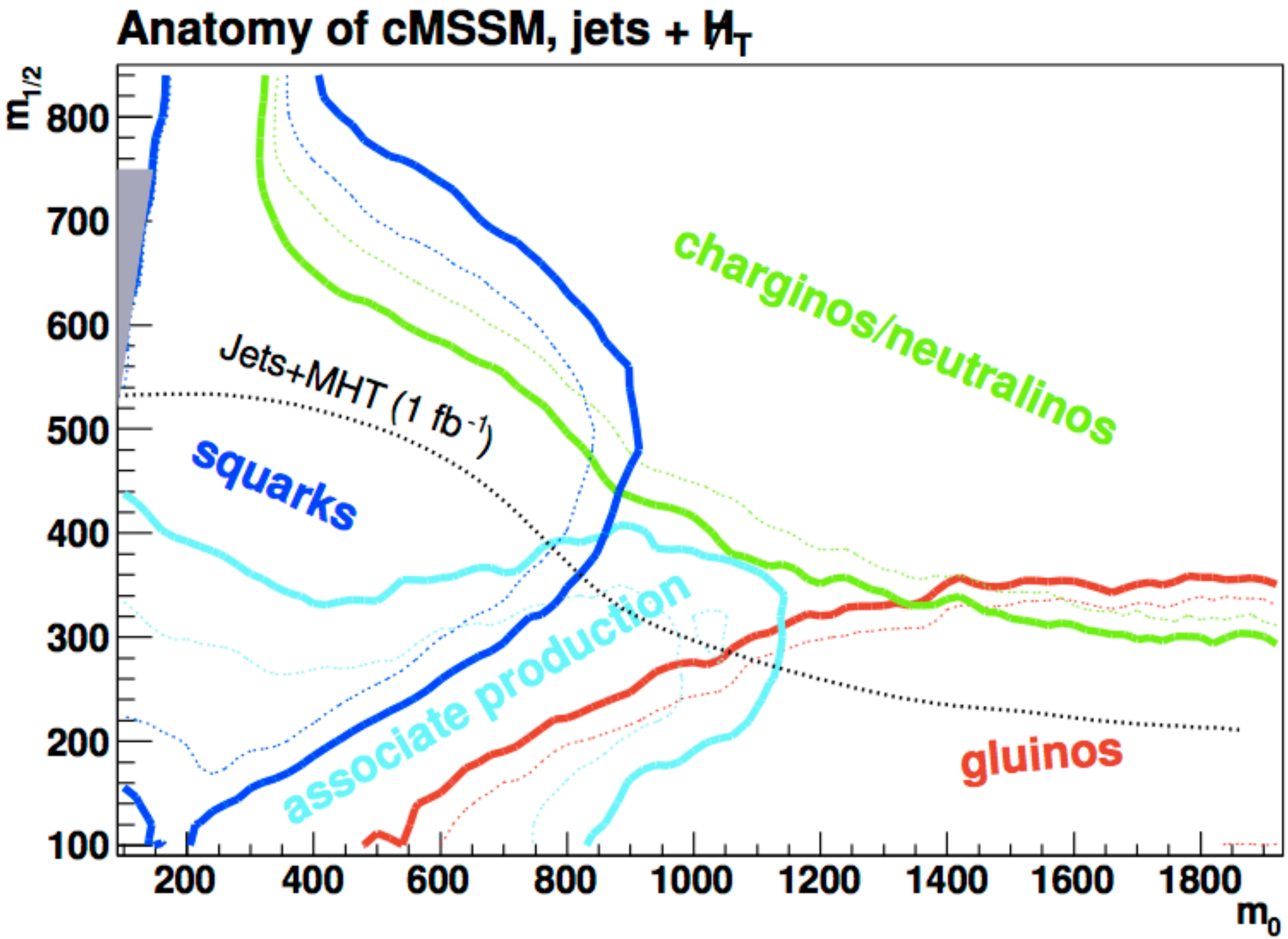
M_χ [GeV]	Vector σ [fb]	Vector Λ [GeV]	Axial-Vector σ [fb]	Axial-Vector Λ [GeV]
1	14.3 (14.7)	572 (568)	14.9 (15.4)	565 (561)
10	14.3 (14.7)	571 (567)	14.1 (14.5)	573 (569)
100	15.4 (15.3)	558 (558)	13.9 (14.3)	554 (550)
200	14.3 (14.7)	549 (545)	14.0 (14.5)	508 (504)
500	13.6 (14.0)	442 (439)	13.7 (14.1)	358 (356)
1000	14.1 (14.5)	246 (244)	13.9 (14.3)	172 (171)

M_χ (GeV/c^2)	Spin-dependent Λ (GeV)	Spin-dependent $\sigma_{\chi N}$ (cm^2)	Spin-independent Λ (GeV)	Spin-independent $\sigma_{\chi N}$ (cm^2)
0.1	754	1.03×10^{-42}	749	2.90×10^{-41}
1	755	2.94×10^{-41}	751	8.21×10^{-40}
10	765	8.79×10^{-41}	760	2.47×10^{-39}
100	736	1.21×10^{-40}	764	2.83×10^{-39}
200	677	1.70×10^{-40}	736	3.31×10^{-39}
300	602	2.73×10^{-40}	690	4.30×10^{-39}
400	524	4.74×10^{-40}	631	6.15×10^{-39}
700	341	2.65×10^{-39}	455	2.28×10^{-38}
1000	206	1.98×10^{-38}	302	1.18×10^{-37}

CMSSM limits

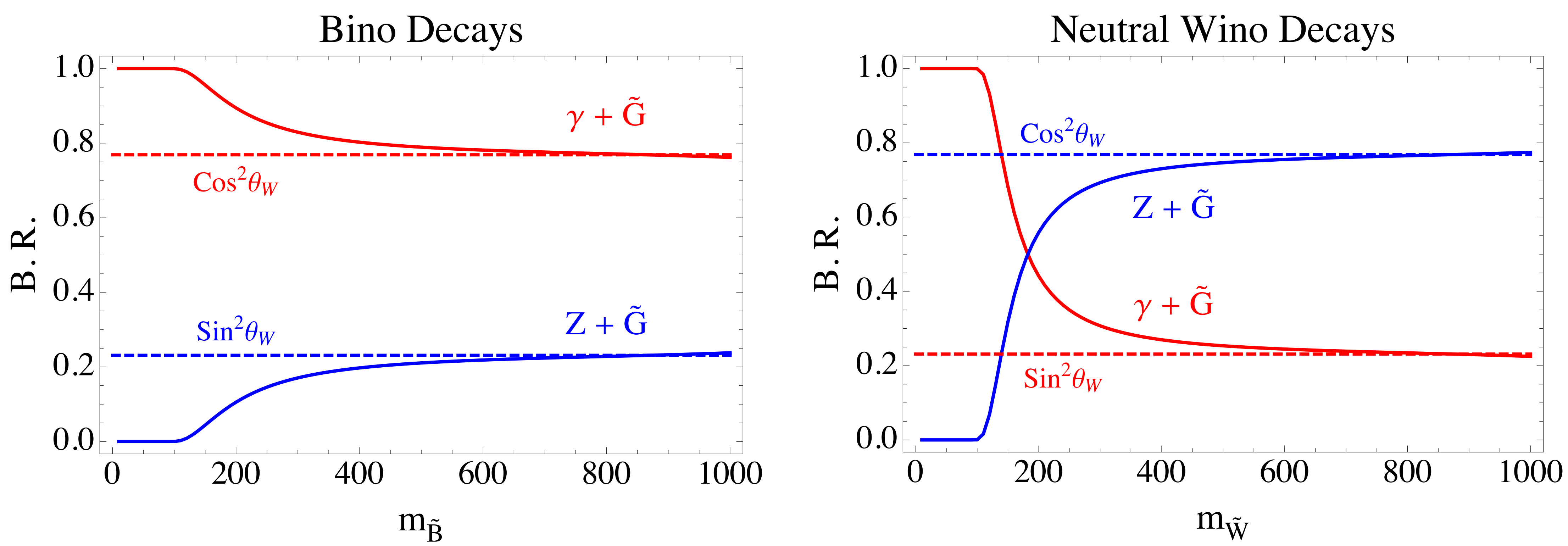


CMSSM event topologies



Photon GGM Model

- Gravitino LSP
- Neutralino NLSP
  - Bino-like gives BR(γ)>>BR(Z) ➔ two photons >> γ + Z (➔ jets, leptons)
  - Wino-like gives BR(Z)>>BR(γ) ➔ γ + Z (➔ jets, leptons)
  - Wino-like NLSP also chargino co-NLSP ➔ γ + W (➔ jets, leptons)
  - Higgsino gives h^0 or Z ➔ BR depends on tanβ and sign(μ)

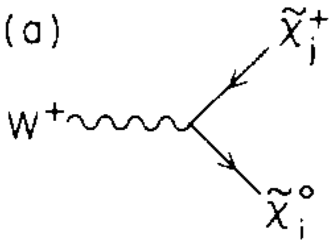


EWKino Model

Haber & Kane Physics Report Volume 117, pages 75-265 (1985)

[from Frank Wuerthwein]

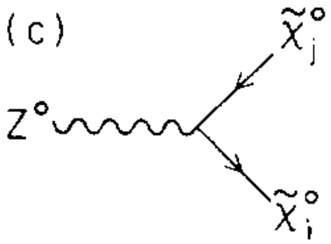
(a)



$$\frac{ig}{2}\gamma^\mu\left[O^L_{ij}(1-\gamma_5)+O^R_{ij}(1+\gamma_5)\right]$$

Couples to all neutralino and chargino mass eigenstates

(c)



$$\frac{ig}{2\cos\theta_W}\gamma^\mu\left[O''^L_{ij}(1-\gamma_5)+O''^R_{ij}(1+\gamma_5)\right]$$

Couples to Higgsino neutralino mass eigenstates

- For WZ maximal Wino couplings (pure wino-like) and maximal Higgsino couplings (even split of two electroweak eigenstates)
- For ZZ maximal Higgsino couplings (even split of two electroweak eigenstates)
- Set chargino/heavy neutralino masses equal, light neutralino=0 and slepton mass in between

Monophoton/monojet Model

- Pair production of DM contact interaction with operators

$$\mathcal{O}_V = \frac{(\bar{\chi}\gamma_\mu\chi)(\bar{q}\gamma^\mu q)}{\Lambda^2}$$

vector ➔ spin independent

$$\mathcal{O}_{AV} = \frac{(\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{q}\gamma^\mu\gamma_5 q)}{\Lambda^2}$$

axial-vector ➔ spin dependent

- Cross sections depend on mass (m_χ) and scale Λ (couplings)

$$\sigma_{SI} = 9\frac{\mu^2}{\pi\Lambda^4}$$

$$\sigma_{SD} = 0.33\frac{\mu^2}{\pi\Lambda^4}$$

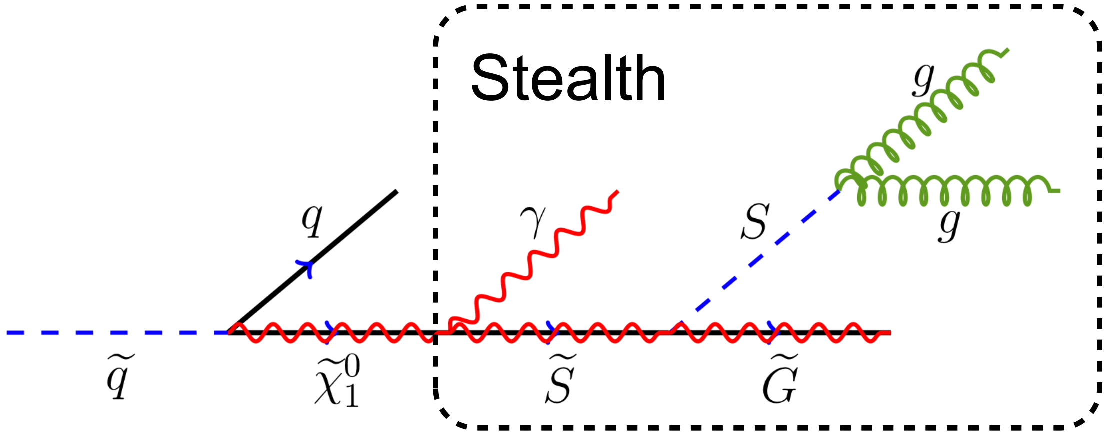
$$\Lambda = M/\sqrt{g_\chi g_q}$$

$$\mu = \frac{m_\chi m_p}{m_\chi + m_p}$$

- M=10(40) TeV for monophoton(jet) analysis

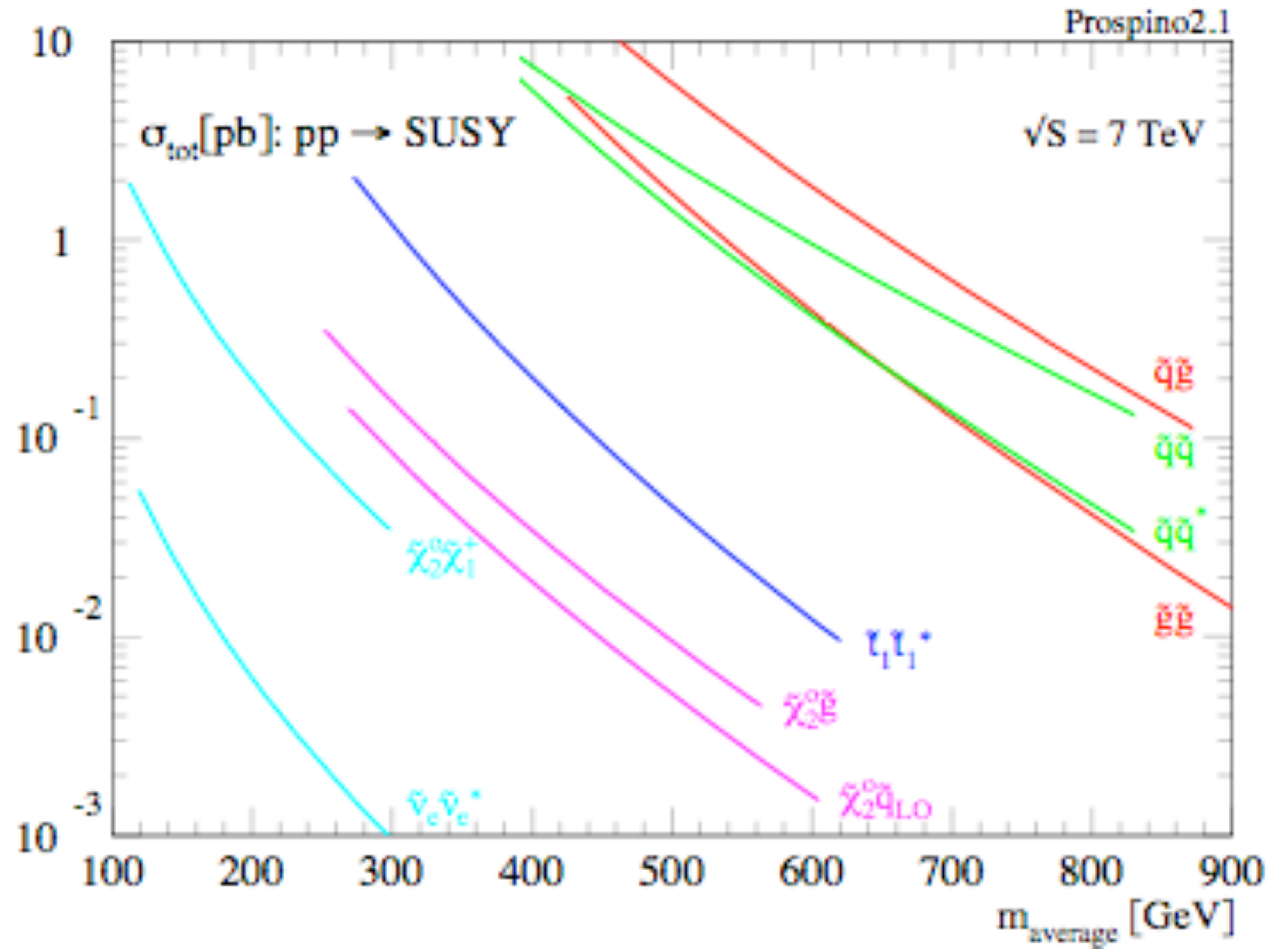
Stealth SUSY model

- Hidden sector at weak scale, low scale SUSY breaking
- SUSY approximately conserved in hidden sector
- Hidden sector superpartners nearly mass degenerate
- Soft MET spectrum from LSP, R-parity conserved



- Squark pair-production with M(gluino) = 1500 GeV
- $M(X_1) = 1/2\ M(\text{squark})$
- M(S~)=100 GeV, M(S)=90 GeV
- $BR(X_1 \rightarrow \gamma S\sim)=1$

SUSY cross sections



8 TeV vs 14 TeV – Gain Factors

- Use parton luminosities to illustrate the gain of 14 vs 8 TeV

Higgs:
pp → H, H→WW, ZZ and γγ
mainly gg: factor ~2

SUSY – 3rd Generation:
Mass scale ~ 500 GeV
qq and gg: factor ~2 to 4

SUSY – Squarks/Gluino:
Mass scale ~ 2.0 TeV
qq,gg,qg: factor ~6 to 10

Z′ :
Mass scale ~ 5 TeV
qq: factor ~200