dark matter & the LHC

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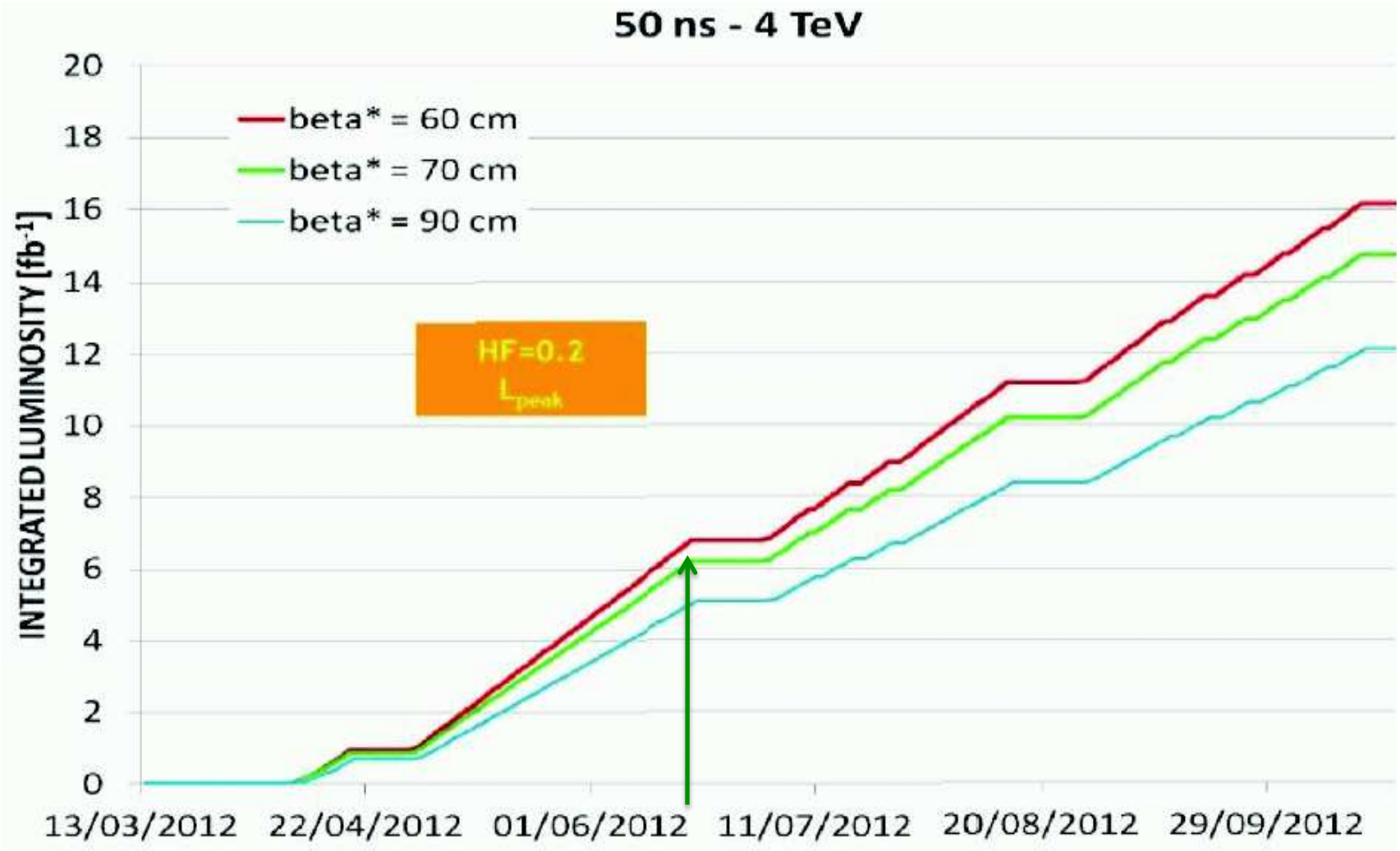
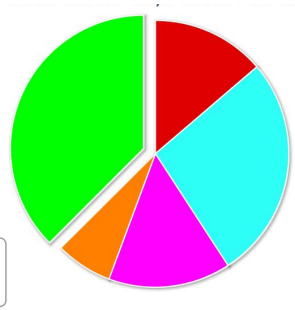
U.S. DEPARTMENT OF ENERGY

March 30, 2012 8 TeV collisions at the LHC collected by CMS (not physics run)

(April 2012)

Luminosity expectations for the LHC 8 TeV 2012





LHC Performance and Statistics

Overview | Run Details | Fill Summaries | Supertable

Filters: 2012 | 4TeV | proton – proton | Stable Beams | Apply fi

Online Integrated Luminosity

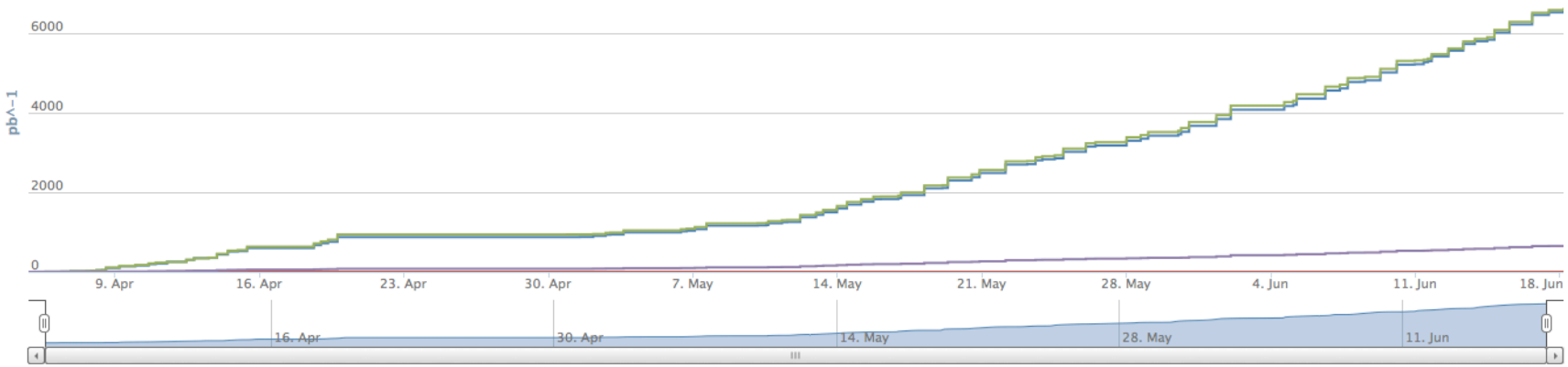
ALICE: 1.15 pb^{-1} ATLAS: 6.57 fb^{-1} CMS: 6.63 fb^{-1} LHCb: 654.48 pb^{-1}

Latest 5 LHC Fills

Fill	Fill Times		Energy [Gev]	Intensity		Bunches		Bunch Collision Scheme [IPI&5/2/8]	Peak Luminosity [Hz/ub] = [10^{30} $cm^{-2}s^{-1}$]				Delivered Luminosity [nb^{-1}] = [10^{33} cm^{-2}]			
	Start	SB Duration [hh:mm]		B1 [10^{12}]	B2 [10^{12}]	Number	Norm Emitt [um]		ATLAS	ALICE	CMS	LHCb	ATLAS	ALICE	CMS	LHCb
2739	06/18/2012 06:46	2:32	4000	205.24	199.24	1374	2.7	1368/0/1262	6479	0	6248	435	50309	0	50543	3332
2737	06/17/2012 13:47	3:36	4000	199.85	199.51	1374	2.79	1368/0/1262	6106	2.11	5952	424	66419	4.21	65792	4960
2736	06/16/2012 18:22	17:29	4000	202.98	199.51	1374	2.64	1368/0/1262	6579	2.01	6352	497	235374	57.78	231248	24795
2734	06/15/2012 16:02	15:33	4000	201.06	200.71	1374	2.71	1368/0/1262	6353	2.69	6162	439	204239	59.66	203186	22032
2733	06/14/2012 22:29	12:34	4000	207.7	202.52	1380	2.63	1377/0/1274	6834	2.42	6514	555	181365	50.56	184639	18626

Integrated Luminosity Evolution

Zoom 1wk 2wk 1m ALL — ATLAS — ALICE — CMS — LHCb From: Apr 4, 2012 To: Jun 18, 2012



Higgs Searches 2011

Summary

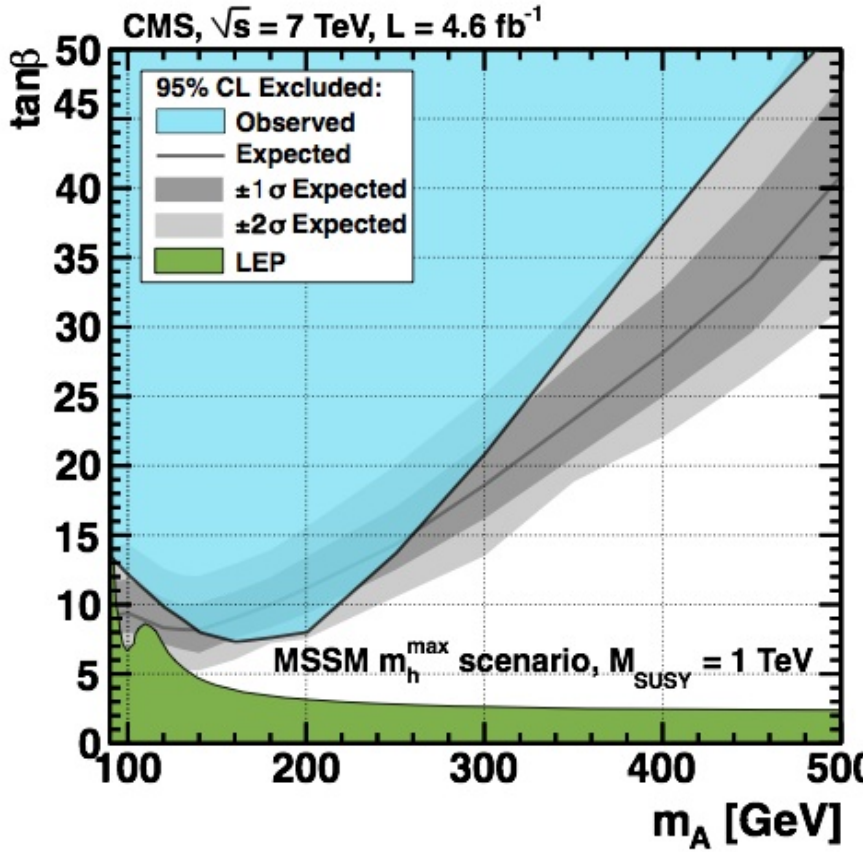
- SM-like Higgs excluded for $M_H \lesssim 114$ GeV
- SM-like Higgs excluded for 130 GeV $\lesssim M_H \lesssim$ 500 GeV
- large regions excluded beyond the 99% CL limit
- large regions excluded for a Higgs with strongly reduced couplings
- observations for 122 GeV $\lesssim M_H \lesssim$ 128 GeV
  - ATLAS: 2.5σ in $\gamma\gamma(+4\ell)$
  - CMS: 2.8σ in $\gamma\gamma$
  - Tevatron: 2.7σ in $b\bar{b}(+\ \ell\nu\ell\nu)$

Priors

- SM fit prefers low M_H
- MSSM predicted M_h in this region for decades

Xiv:1202.4083v1 [hep-

A search for neutral Higgs bosons decaying to tau pairs at a center-of-mass energy of 7 TeV is performed using a dataset corresponding to an integrated luminosity of 4.6 fb^{-1} recorded by the CMS experiment at the LHC. The search is sensitive to both the standard model Higgs boson and to the neutral Higgs bosons predicted by the minimal supersymmetric extension of the standard model (MSSM). No excess of events is observed in the tau-pair invariant-mass spectrum. For a standard model Higgs boson in the mass range of 110–145 GeV upper limits at 95% confidence level (CL) on the production cross section are determined. We exclude a Higgs boson with $m_{\mathrm{H}} = 115$ GeV with a production cross section 3.2 times of that predicted by the standard model. In the MSSM, upper limits on the neutral Higgs boson production cross section times branching fraction to tau pairs, as a function of the pseudoscalar Higgs boson mass, m_{A}, sets stringent new bounds in the parameter space, excluding at 95% CL values of $\tan\beta$ as low as 7.1 at $m_{\mathrm{A}} = 160$ GeV.



Latest CMS results in search for heavy MSSM Higgses ($\tau\tau$, arXiv:1202.4083)

- N.B. low M_A values get excluded with LEP and LHC
- small deviation around $M_A \sim 400$ GeV

LHCb closing the window

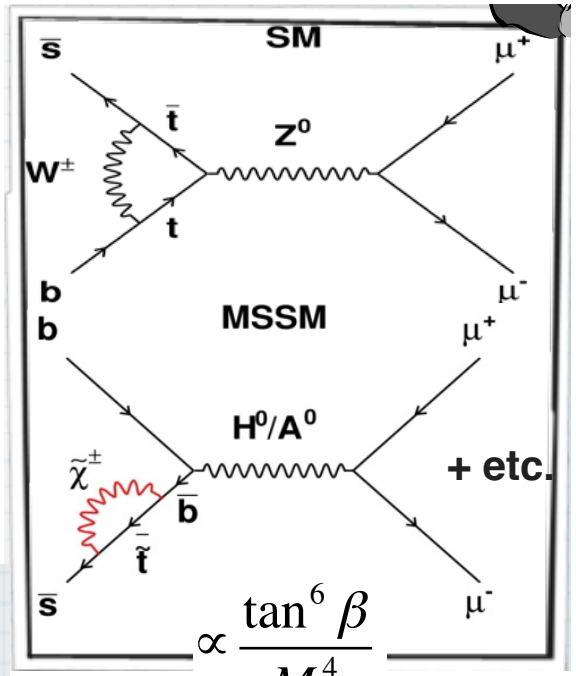
- SM prediction (FCNC, helicity suppressed)
  - SM $B(\mathrm{Bs}\to\mu\mu) = (3.2\pm0.2)\ 10^{-9}$
  - SM $B(\mathrm{B}\to\mu\mu) = (0.1\pm0.01)\ 10^{-9}$

arXiv:1005.5310
arXiv:1012.1447

$B(\mathrm{B_s}\to\mu\mu) < 4.5\ 10^{-9}$ at 95% CL

$B(\mathrm{B}\to\mu\mu) < 10.3\ 10^{-10}$ at 95% CL

best limit!



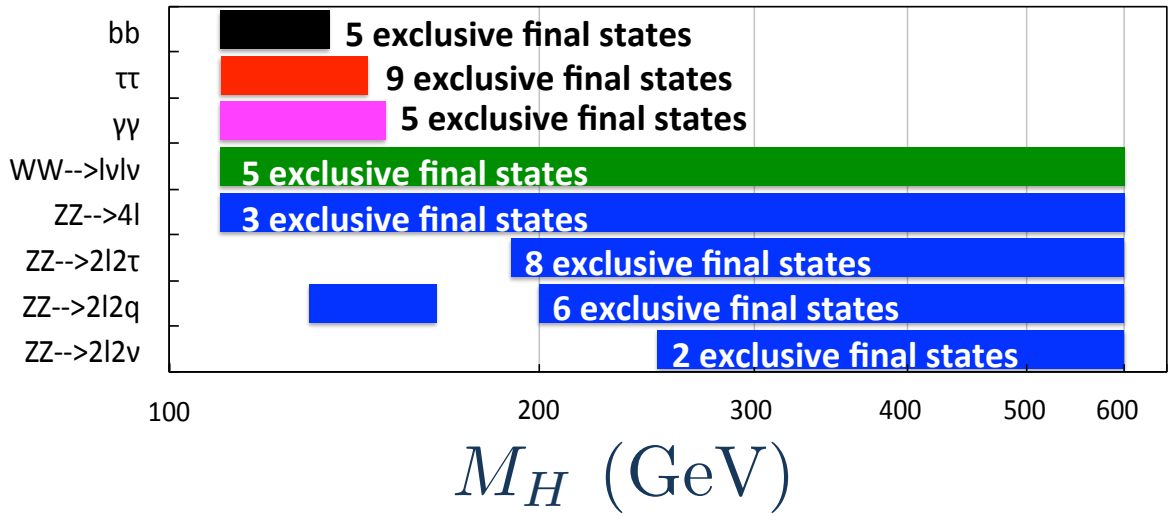
$$\propto \frac{\tan^6\beta}{M_A^4}$$

- **SUSY and 2HDM can make large contributions**
- **For large tan β SUSY you had better have large $\mathrm{M_A}$**
- **Makes the lightest SUSY Higgs more like a SM Higgs**

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults

CMS

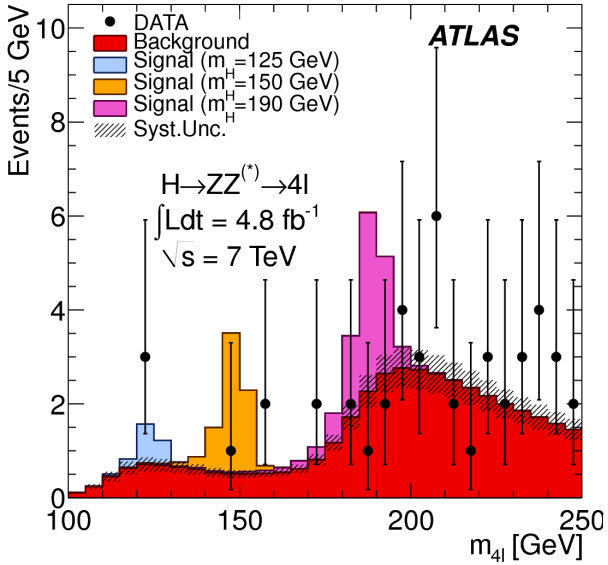
Mode	Mass Range	Data Used (fb^{-1})	Mass resolution	Document
$H \to \gamma\gamma$	110-150	4.8	1-3 %	arXiv:1202.1487
$H \to bb$	110-135	4.7	10 %	arXiv:1202.4195
$H \to \tau\tau$	110-145	4.6	20 %	arXiv:1202.4083
$H \to WW \to 2l\ 2\nu$	110-600	4.6	20%	arXiv:1202.1489
$H \to ZZ \to 4l$	110-600	4.7	1-2%	arXiv:1202.1997
$H \to ZZ \to 2l2\tau$	190-600	4.7	10-15%	arXiV:1202.3617
$H \to ZZ \to 2l2j$	130-165/200-600	4.6	3%	arXiv: 1202.1416
$H \to ZZ \to 2l2\nu$	250-600	4.6	7%	arXiv: 1202.3478

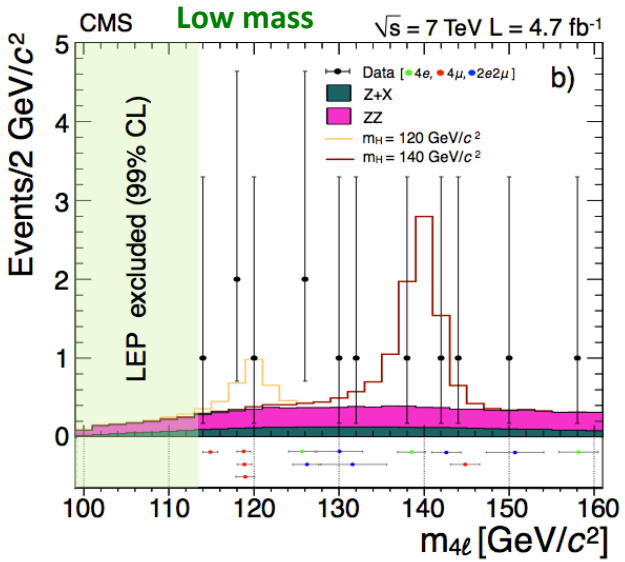


Scenarios considered given 2011 results

- A. SM-like Higgs with $M_H \sim 125$ GeV $\oplus$ some BSM Higgs hint
- B. non-SM-like Higgs with $M_H \sim 125$ GeV $\oplus$ some BSM Higgs hint
- C. something inconclusive $\oplus$ some BSM Higgs hint
- D. nothing : exclusion of a SM-like Higgs, no clear BSM Higgs hint

4 lepton golden mode





BG exp.: 9.5±1.3
Data: 13
In 100-160 GeV

- **2011 actual: 2 events in one bin when you expect 1/3, p-value = 0.04**

H-> ZZ -> 4 lepton final state: can you determine the spin and CP of the resonance?

Use all 5 angles and the off-shell Z mass

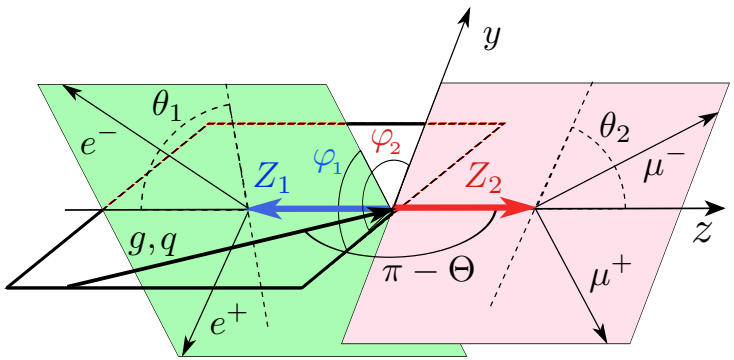


FIG. 1: The Cabibbo-Maksymowicz angles [37] in the $H \to ZZ$ decays.

Use hypothesis testing with the full likelihoods

Just need a handful of events

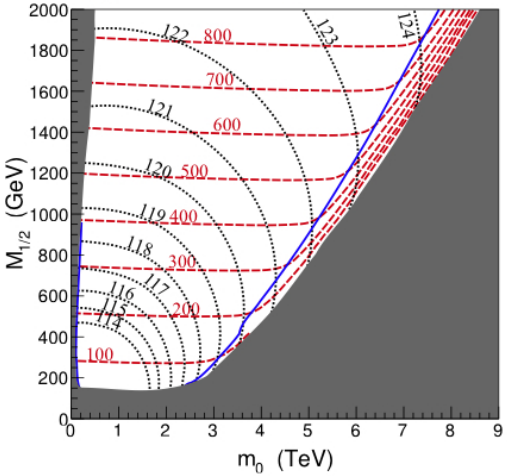
$\mathbb{H}_0 \Downarrow \mathbb{H}_1 \Rightarrow$	0^+	0^-	1^-	1^+
0^+	–	17	12	16
0^-	14	–	11	17
1^-	11	11	–	35
1^+	17	18	34	–

TABLE I: Minimum number of observed events such that the median significance for rejecting $\mathbb{H}_0$ in favor of the hypothesis $\mathbb{H}_1$ (assuming $\mathbb{H}_1$ is right) exceeds $3\,\sigma$ with m_H=145 GeV/c^2.

A. De Rujula, J. Lykken, M. Pierini, C. Rogan, M.S.

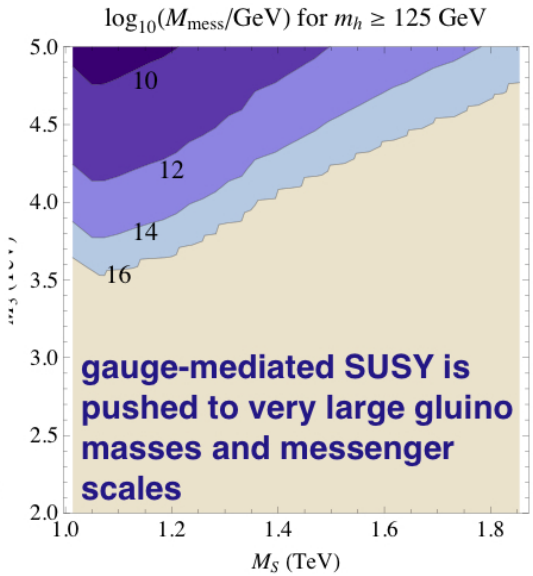
For SUSY, a 125 GeV Higgs is quite heavy

mSUGRA without large mixing doesn't like a Higgs this heavy



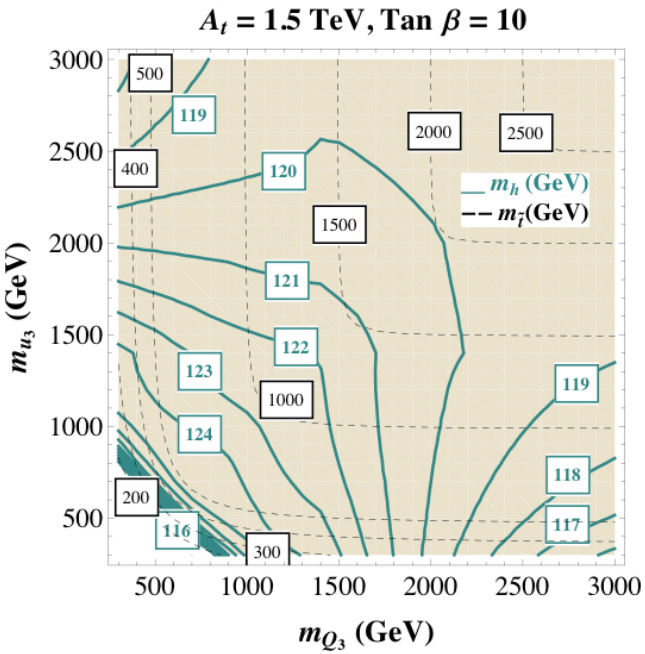
(a) m_h and m_χ in GeV for $\tan\beta = 10$

J. Feng and K. Matchev



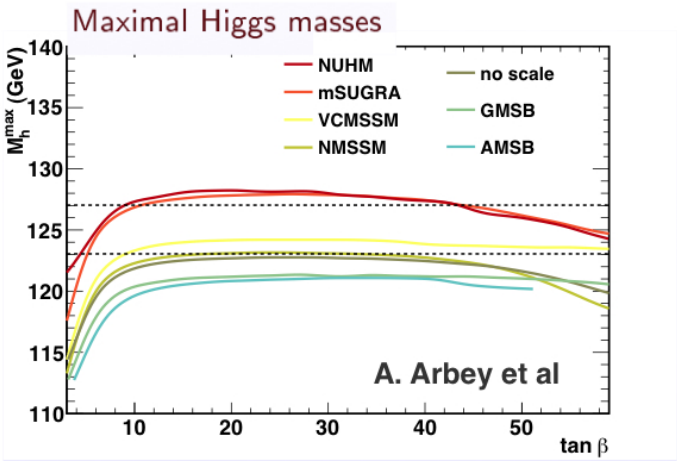
gauge-mediated SUSY is pushed to very large gluino masses and messenger scales

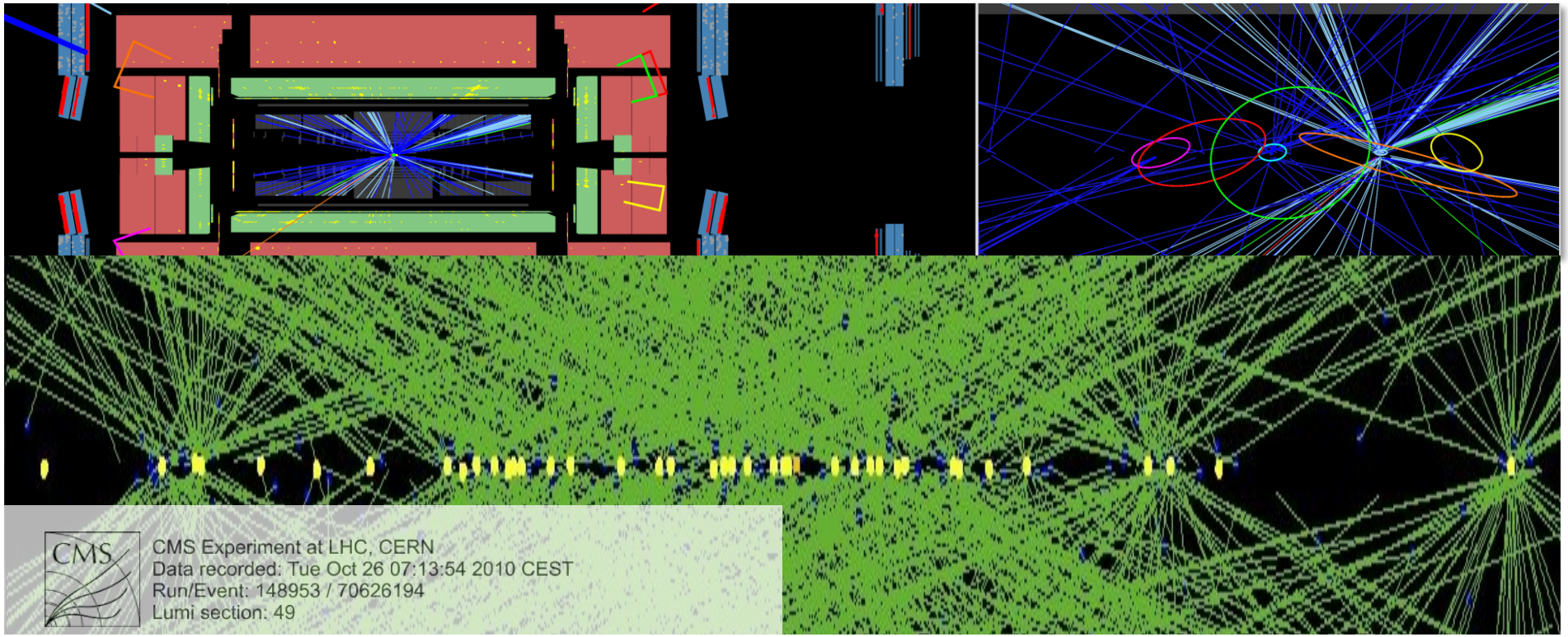
P. Draper, P. Meade, M. Reece, D. Shih

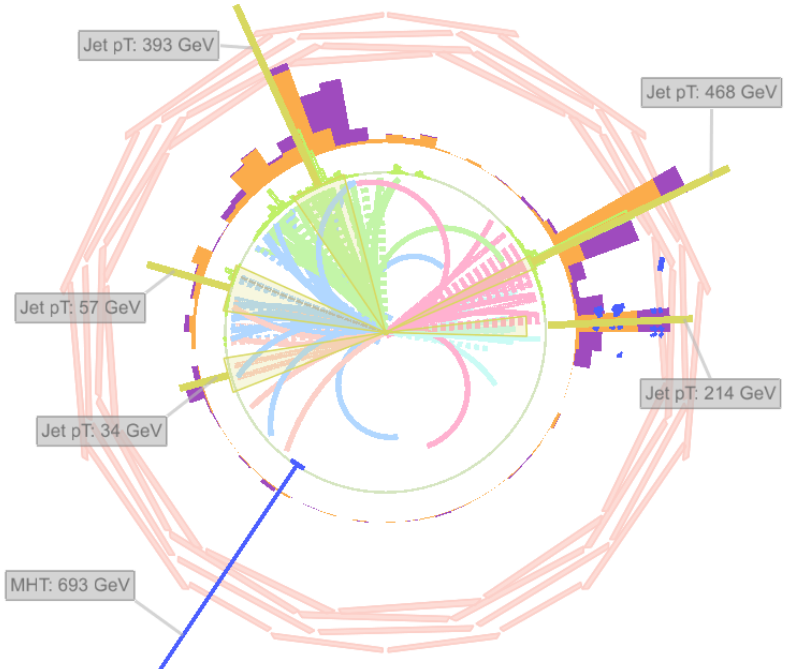


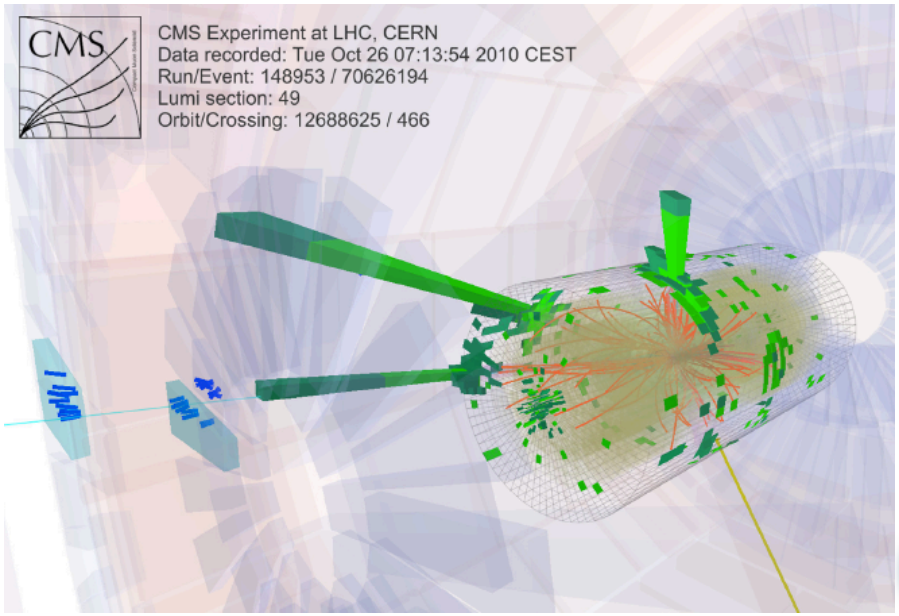
With large mixing, can get 125 GeV Higgs, the lightest stop is less than 600 GeV, and the gluino could be just above current limits

M. Carena, S. Gori, N. Shah, C. Wagner

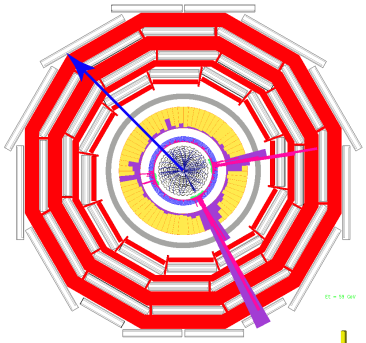


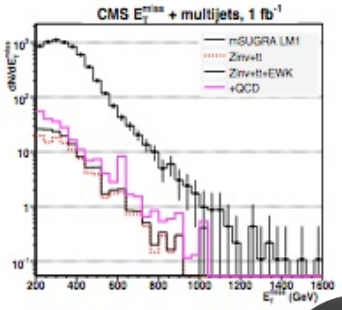

CMS
CMS Experiment at LHC, CERN
Data recorded: Tue Oct 26 07:13:54 2010 CEST
Run/Event: 148953 / 70626194
Lumi section: 49

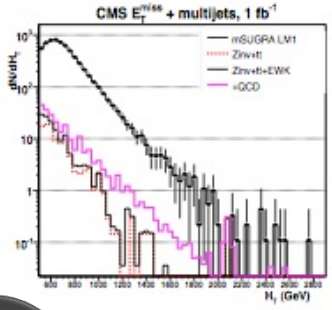

Jet pT: 393 GeV
Jet pT: 468 GeV
Jet pT: 57 GeV
Jet pT: 214 GeV
Jet pT: 34 GeV
MHT: 693 GeV

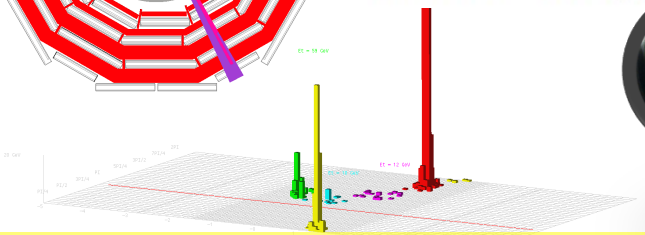

CMS
CMS Experiment at LHC, CERN
Data recorded: Tue Oct 26 07:13:54 2010 CEST
Run/Event: 148953 / 70626194
Lumi section: 49
Orbit/Crossing: 12688625 / 466

- 2007, CMS Physics TDR [preparing the search and discovery program]

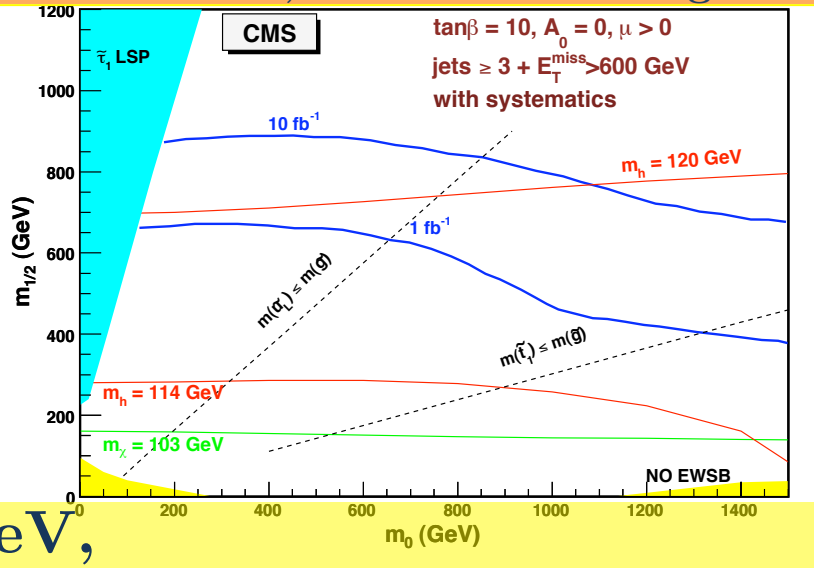






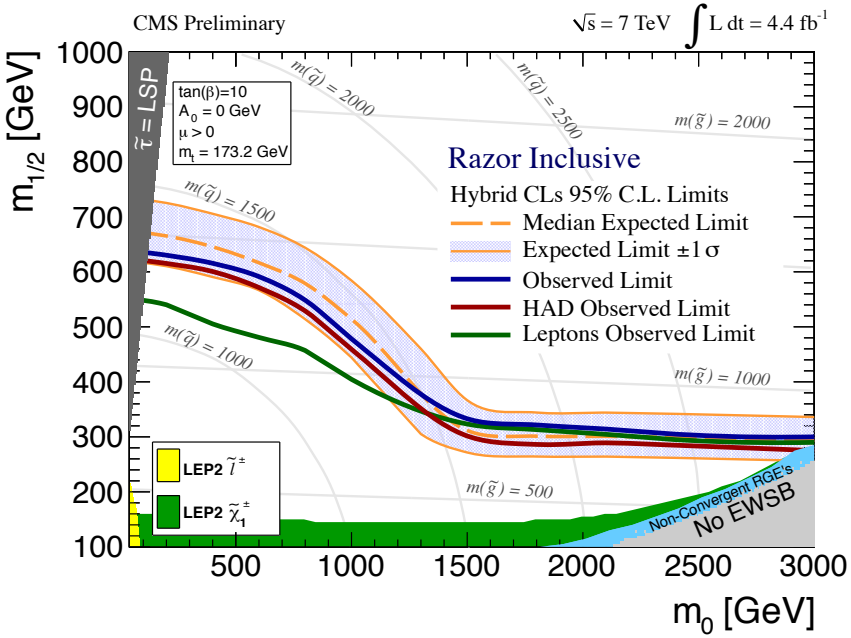


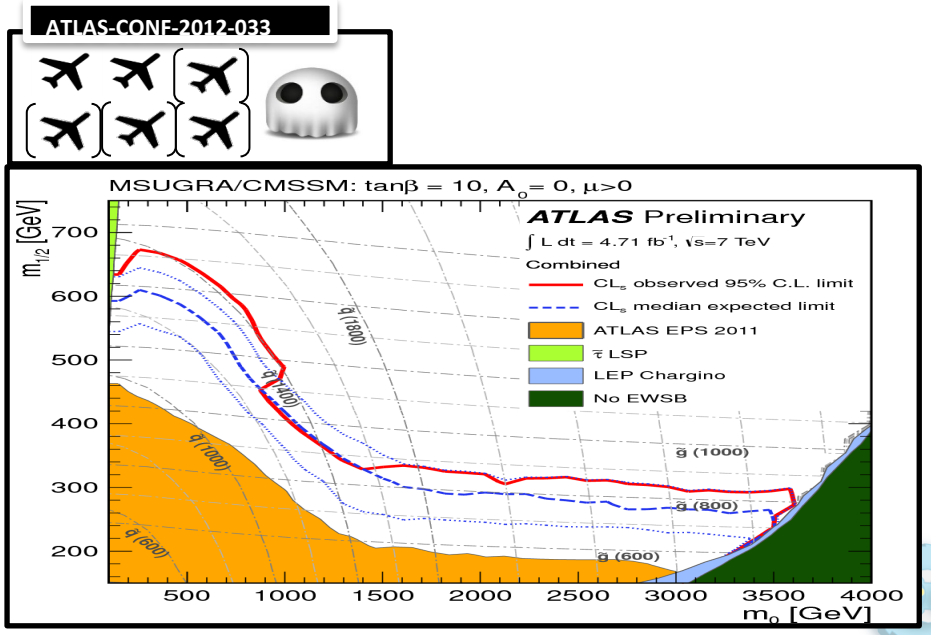
1 fb^{-1} 14 TeV, 5σ reach 1.2 TeV gluino



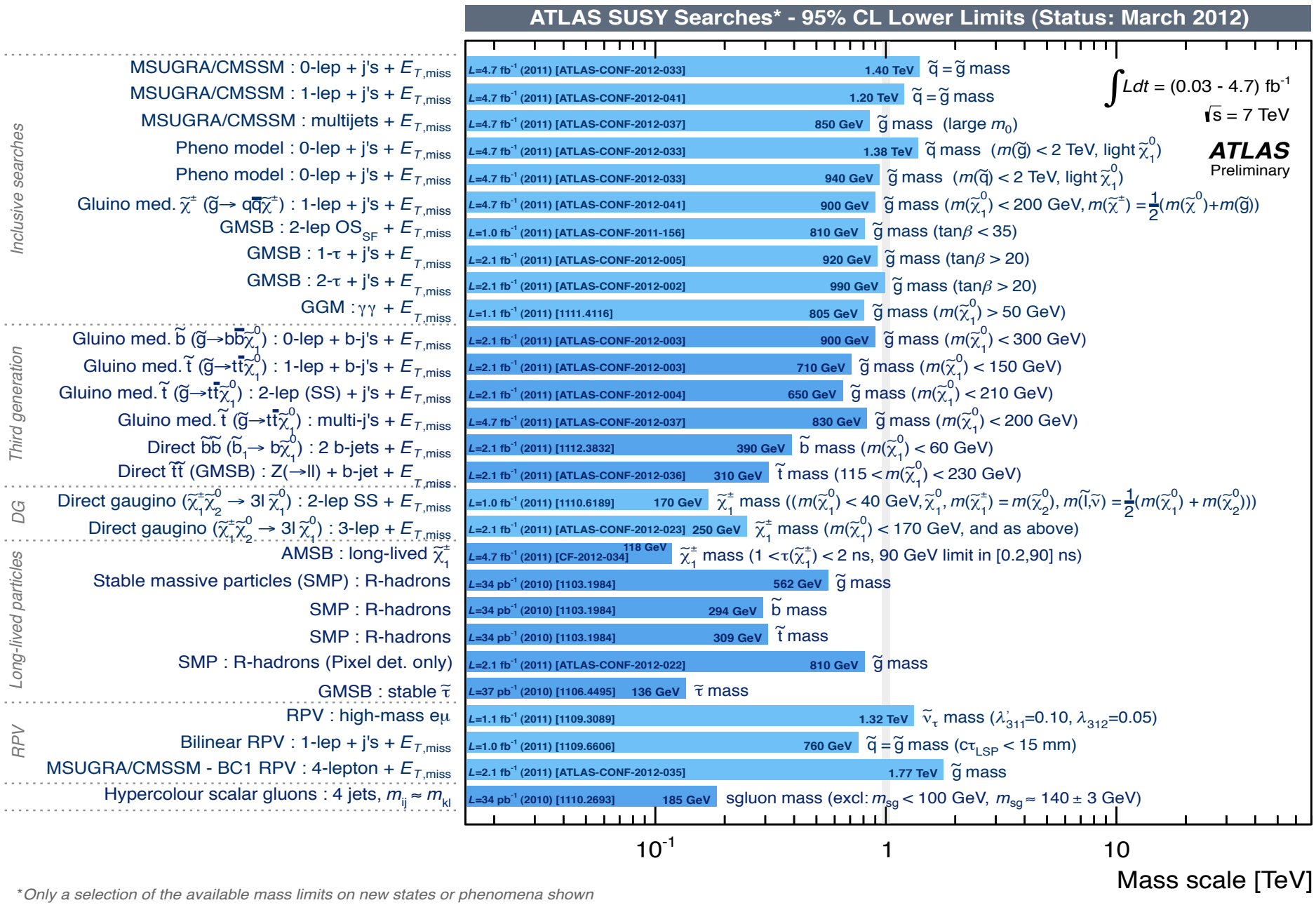
~ 5 fb^{-1} 8 TeV,

— 95% CL exclusion up to ~1.3 TeV squark, ~ 0.9 TeV gluino





https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults

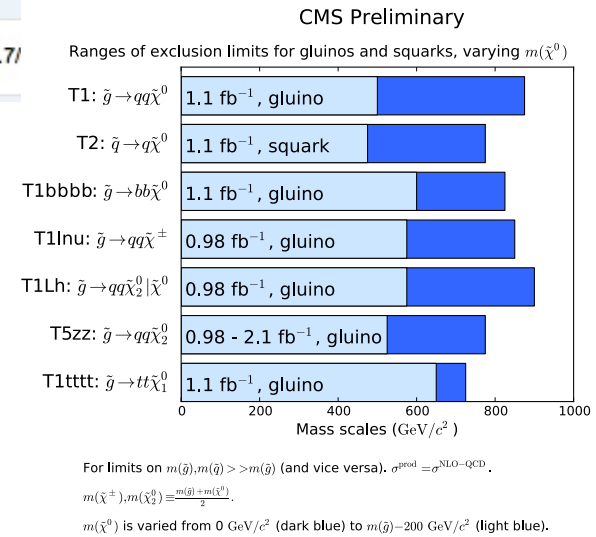


*Only a selection of the available mass limits on new states or phenomena shown

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

/twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS RSS CMS Public re:

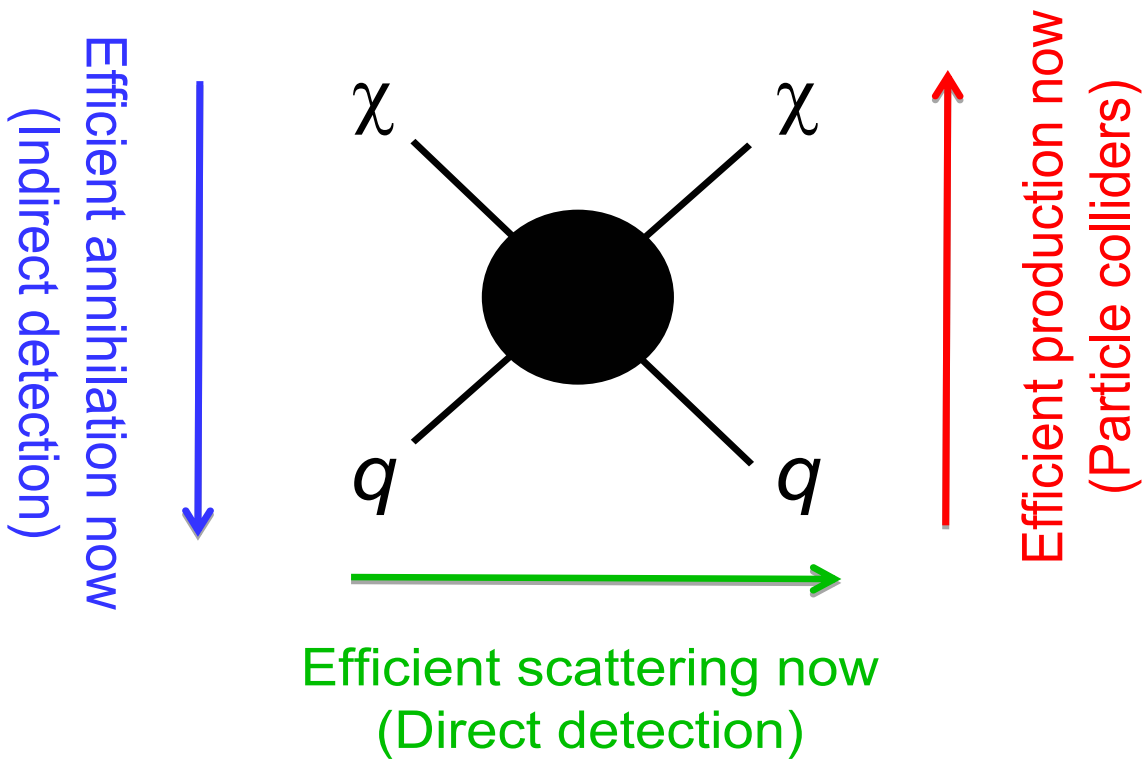
Analysis	Approved Plots	CDS Entry	Luminosity
Search for supersymmetry in events with a lepton and missing energy at the LHC NEW	SUS12010		4.7/fb
Search for new physics in events with opposite-sign leptons, jets and missing transverse energy NEW	SUS11011		4.7/fb
Search for supersymmetry with the razor variables at √s = 7 TeV NEW	SUS12005	PAS-SUS-12-005	4.4/fb
Search for supersymmetry in events with photons and missing energy NEW	SUS12001		4.7/fb
Search for new physics in events with same-sign dileptons, b-tagged jets and missing energy NEW	SUS11020	PAS-SUS-11-020	4.7/fb
Search for new physics with same-sign isolated dilepton events with jets and missing energy NEW	SUS11010		4.7/fb
Search for Anomalous Production of Multilepton Events in pp Collisions at √s = 7 TeV NEW	EXO11045/SUS11013		4.7/fb
Search for supersymmetry in events with opposite-sign dileptons and missing energy using an ANN NEW	SUS11018	PAS-SUS-11-018	2.3/fb
Search for physics beyond the standard model in events with a Z boson, jets and missing transverse energy NEW	SUS11021		4.7/



For limits on $m(\tilde{g}), m(\tilde{q}) >> m(\tilde{g})$ (and vice versa). $\sigma^{\text{prod}} = \sigma^{\text{NLO-QCD}}$.

$m(\tilde{\chi}^{\pm}), m(\tilde{\chi}_2^0) \equiv \frac{m(\tilde{g}) + m(\tilde{\chi}^0)}{2}$.

$m(\tilde{\chi}^0)$ is varied from 0 GeV/c^2 (dark blue) to $m(\tilde{g})$−200 GeV/c^2 (light blue).

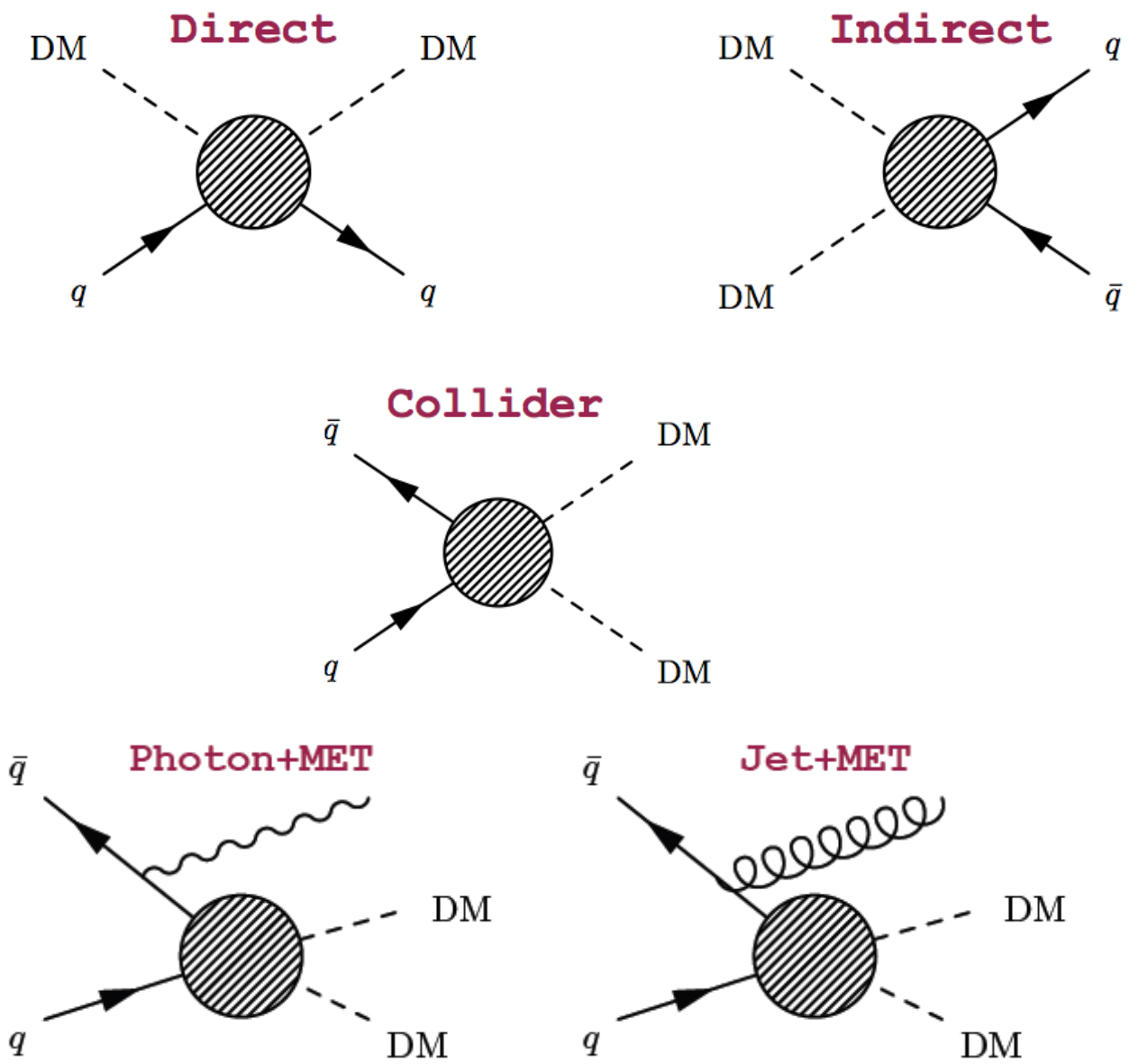


The LHC search for DM

- **Produce dark matter in the laboratory and study it under controlled conditions.**
- **Study the new unstable "relatives" of dark matter particles, giving a much broader and deeper picture of the "dark sector"**

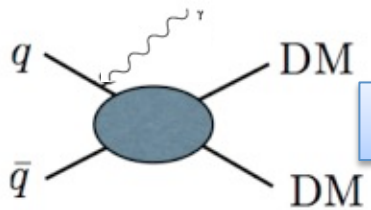
Dark matter at the LHC?

- What can you say about dark matter candidates and the dark sector?
- Do you have evidence for a WIMP dark matter candidate?
- What is its mass?
- What kind of particles decay into it?
- Can you see direct production or associated production?
- Does it carry electroweak charge and/or some new charge?
- What is its spin?
- What are the LHC predictions for direct DM detection, indirect DM detection, and early universe cosmology (e.g. relic abundances)?

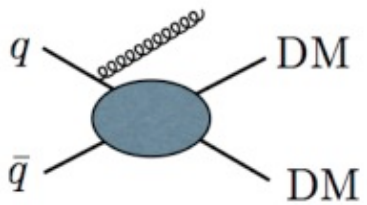

Direct
DM
DM
q
q
Indirect
DM
q
DM
q̄
Collider
q̄
DM
q
DM
Photon+MET
q̄
DM
q
DM
Jet+MET
q̄
DM
q
DM

Pair-produced DM particles via monojets & monophotons (ISR)

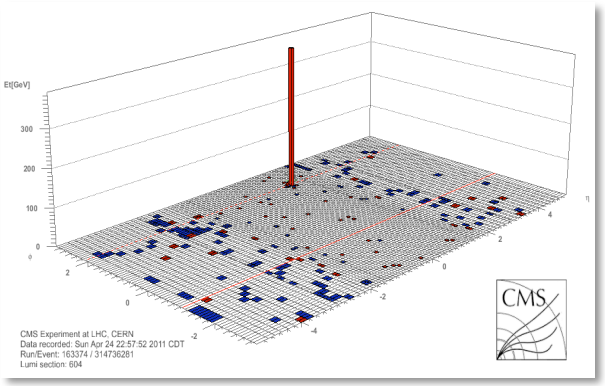
- Probing the same effective operators as in direct detection
- 10^3 better sensitivity to spin-dependent couplings than direct DM searches
- Extends direct detection below 5 GeV for spin-independent couplings

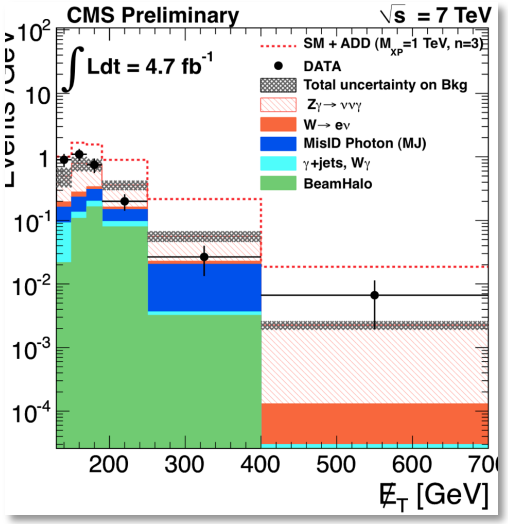


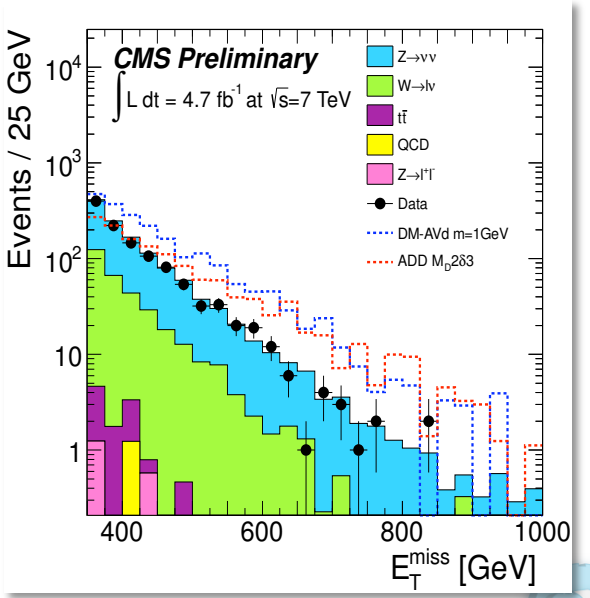
EXO-11-096



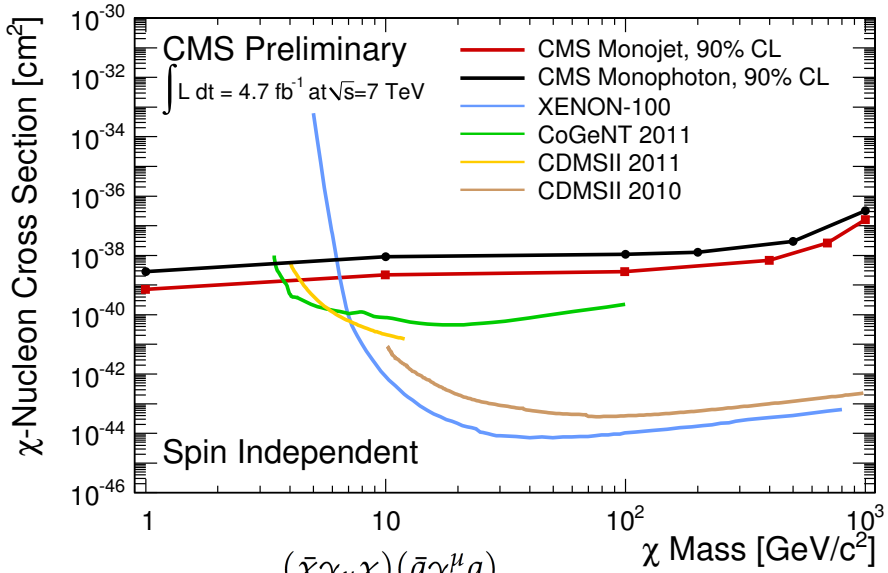
EXO-11-059

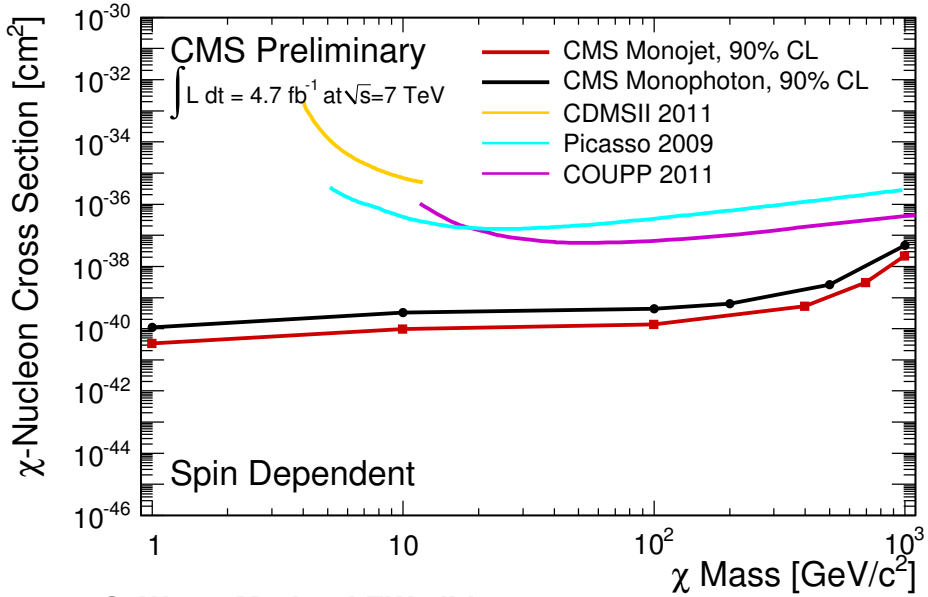






CDMS vs CMS??





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

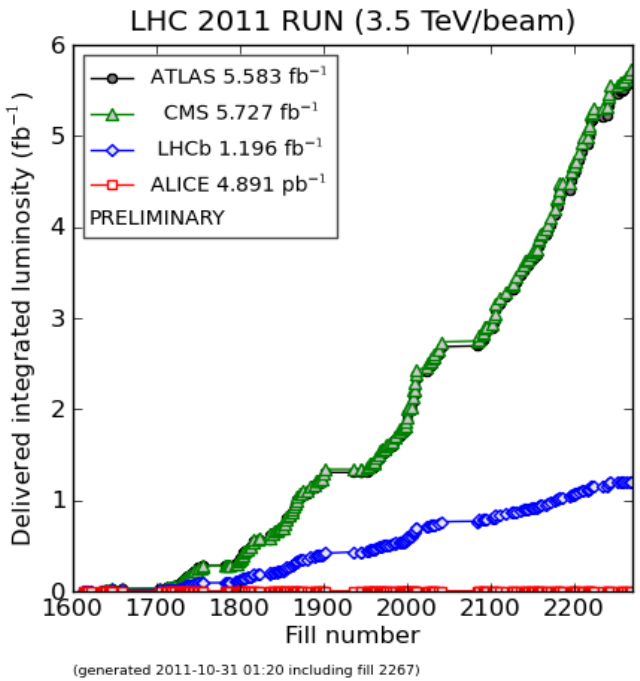
S. Worm Moriond EW slides

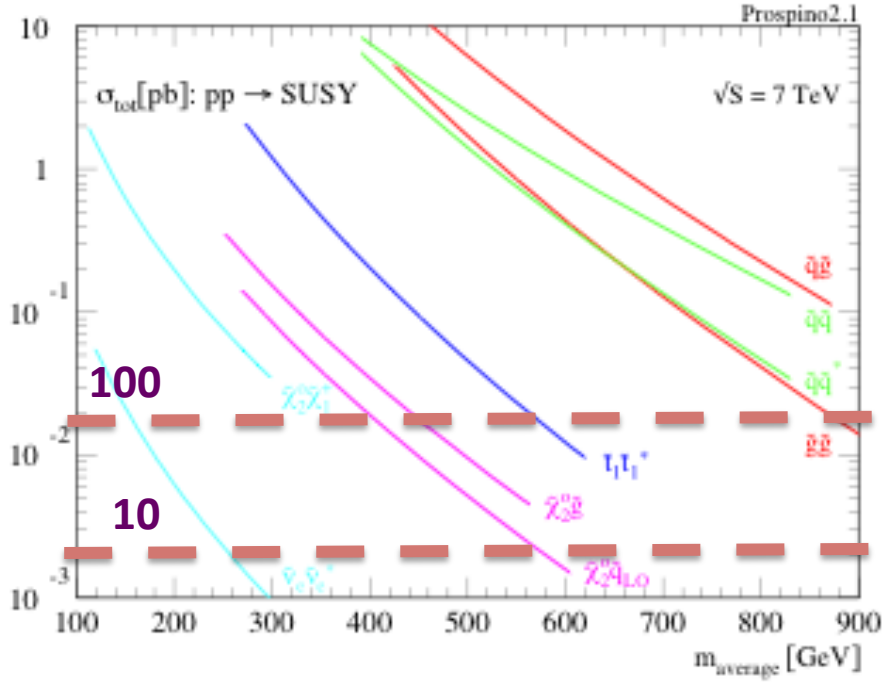
$$\mathcal{O}_{AV} = \frac{(\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{q}\gamma^\mu\gamma_5 q)}{\Lambda^2}$$

Y. Bai, P. Fox, R. Harnik

- **Assuming a heavy mediator, can use effective operator analysis to relate collider monojet and monophoton searches to direct DM searches**
- **Already gives strong limits**

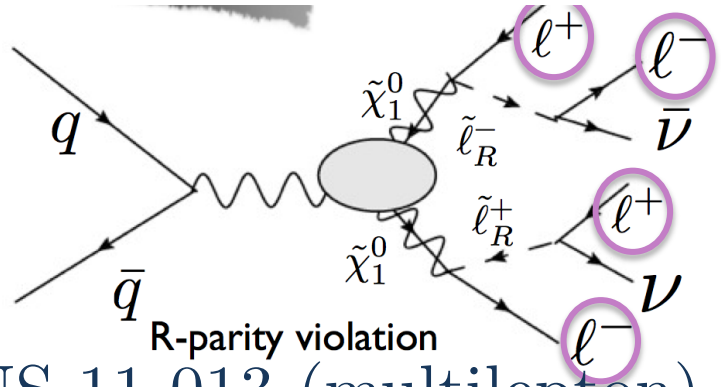
SUSY at 7 TeV with 5 fb^{-1}





- probe high mass particle production
- search the high mass/transverse momenta/MET/HT part of the phase space
- integrated luminosity puts the cap on how much of the phase space (and model parameter spaces) we can explore. Trigger-rate specifications result in pre-selecting the ps

- event topologies rarely seen in the SM
  → control/measure object fake-rates and underst
  simulation of rare SM processes ($Z + jets$, $Z\gamma$, V

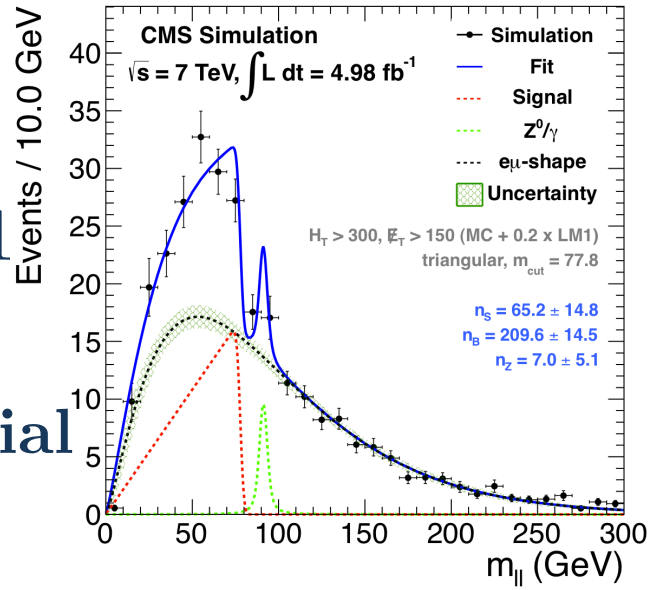


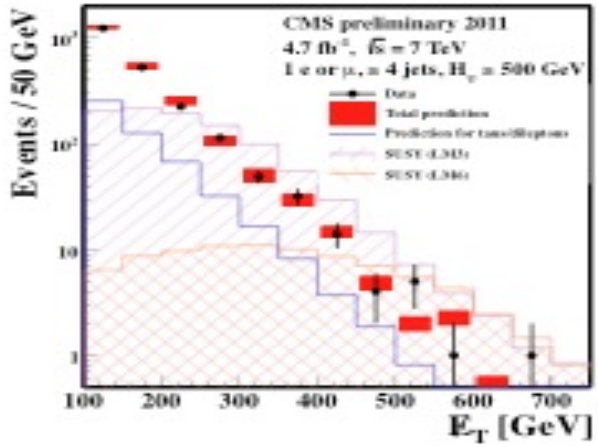
CMS SUS-11-013 (multilepton)

- kinematic features: bumps, edges ...

→ understanding/measuring/improving physics object reconstruction **essential**

CMS SUS-11-011





- smooth excesses

→ reference SM **essential**

CMS SUS-11-010

Implications of the LHC Results for TeV-scale Physics

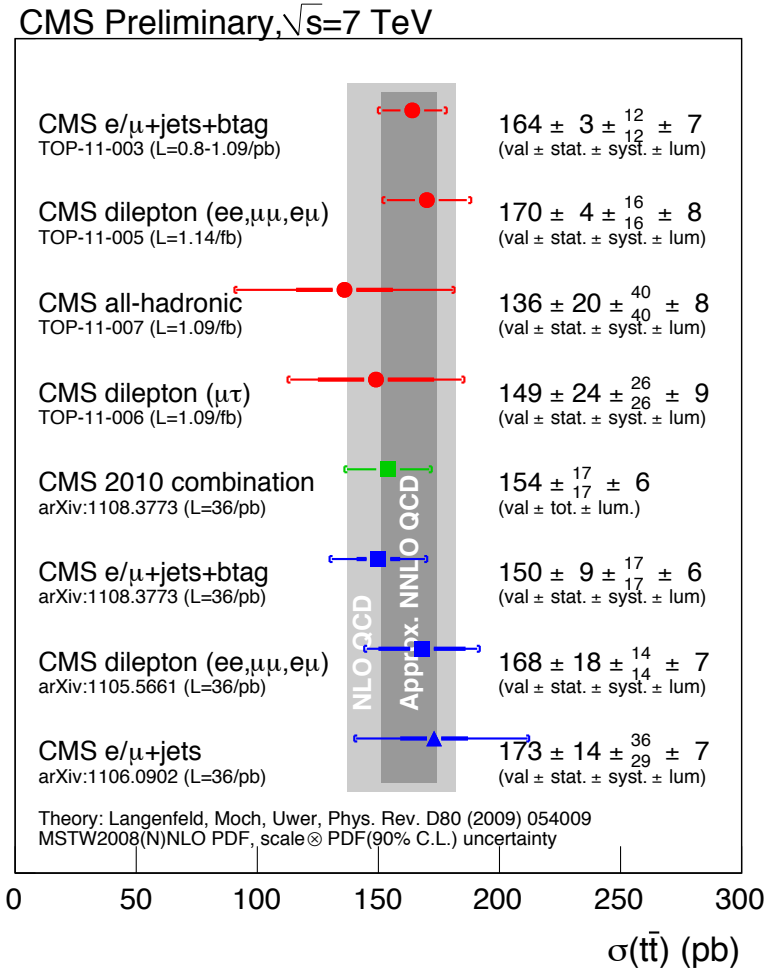
– CERN 26-30 March 2012

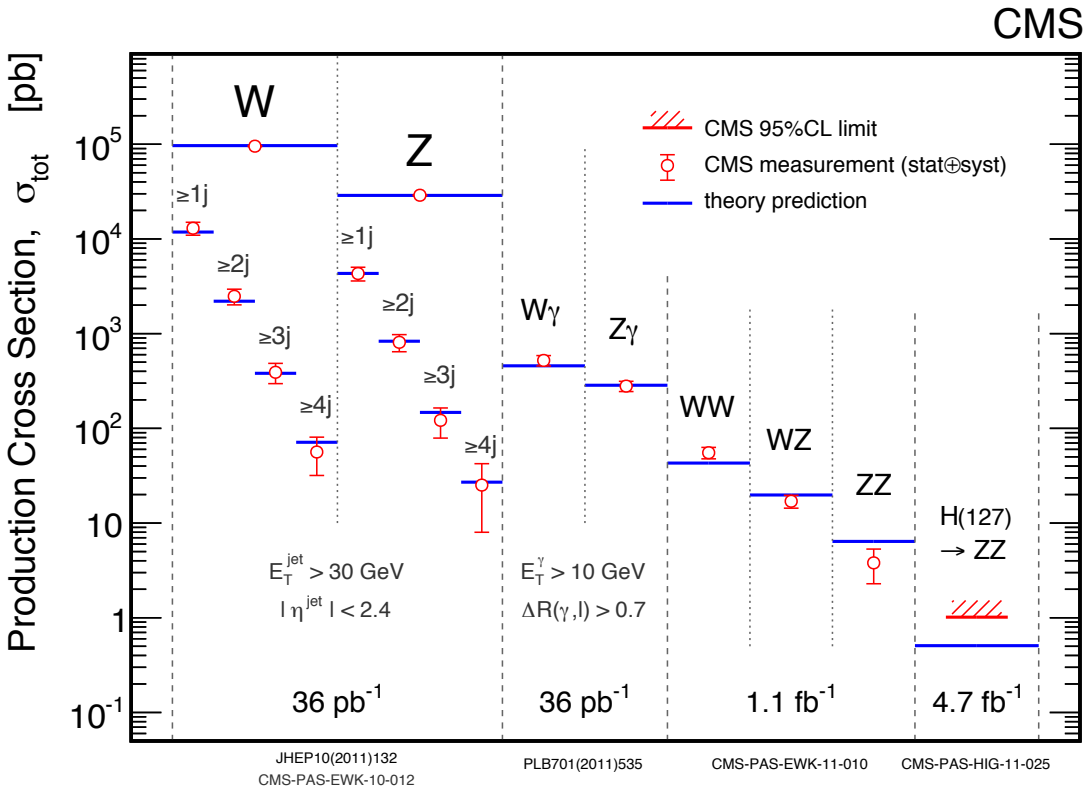
Christopher Rogan - Cal

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

SUSY searches begin with SM candles: Z+j W+j, t+X …

- Used to: select control samples of leptons, photons, b-jets, …
  calibrate/measure object reconstruction performance, fake-rates, energy scales
  validate our understanding of the SM





Chris Rogan (LPCC, March 2012)
http://indico.cern.ch/conferenceDisplay.py?confId=162621

Searching for general excesses

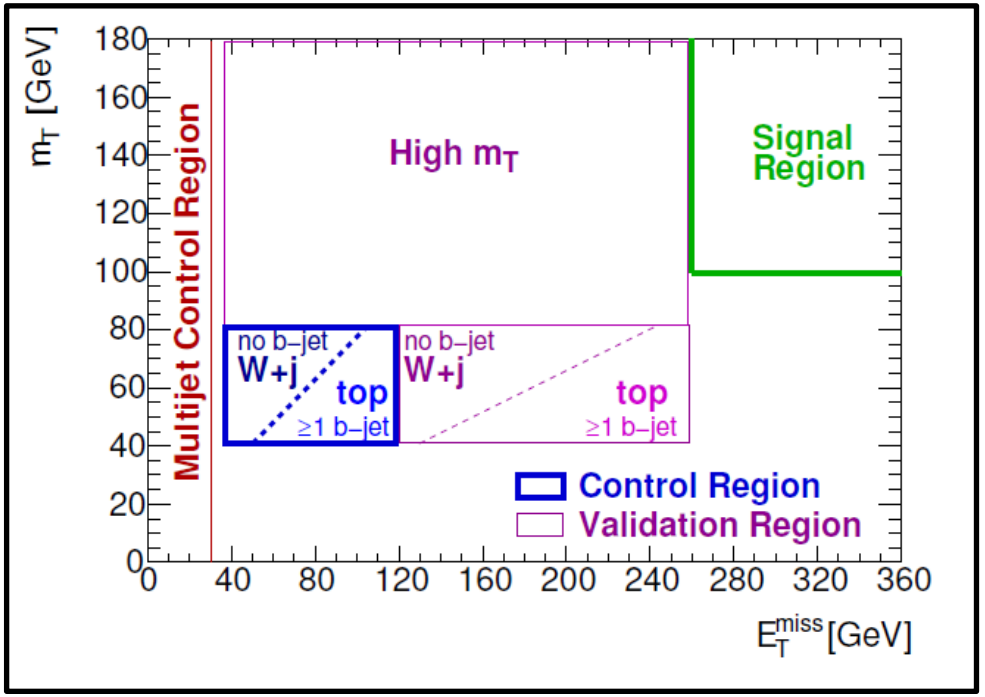
10

- Nearby regions of phase space are often necessary to contextualize our observations in signal sensitive regions – sidebands, control regions, …
- Many different ways to constrain our SM expectations:
  - sidebands in kinematic variables
  - inversion/loosening of object ID requirements
  - exploiting symmetries of the SM [ex. γ+jets → Z+jets]
  - control samples of leptons/b+jets/photons and even particular kinematic configurations

ATLAS-CONF-2012-041

1-lepton: background determination

- Control regions split by jet multiplicity (up to 9 jets)
- Nuisance parameters fitted
  - B-tagging
  - $k_T$fact (Alpgen)
  - Normalisations
- Over-constrained system



Control & validation regions

Alan Barr (LPCC, March 2012)

http://indico.cern.ch/conferenceDisplay.py?confId=162621

Multi-Lepton Search

CMS-SUS-11-013
CMS-EXO-11-045

Selection

- Look for deviations from SM in final states with 3 or 4 isolated leptons (e, μ, τ_h)

- Look in a 'matrix' of phase-space:
  - low vs. high H_T
  - low vs. high ME_T
  - presence of opposite-sign (OS) same flavor (SF) lepton pairs (DY)
  - OSSF pairs in / out Z mass window

52 different regions

Backgrounds

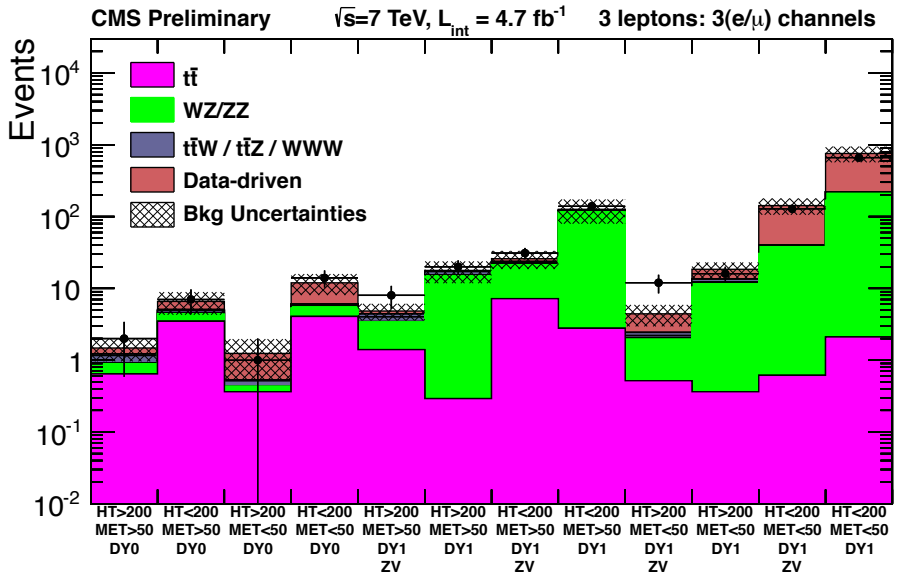
- SM sources of 3 or 4 prompt, isolated leptons:

$$t\bar{t}, WZ, ZZ, t\bar{t}Z, t\bar{t}W$$

  - Contribution predicted from simulation – control region validations
- Z+jets with lepton(s) from jet(s)
  - rate of reconstructed leptons coming from jets inferred from data
- Drell-Yan → 4 leptons
  - internal and external photon conversions yield leptons – estimate rate from data

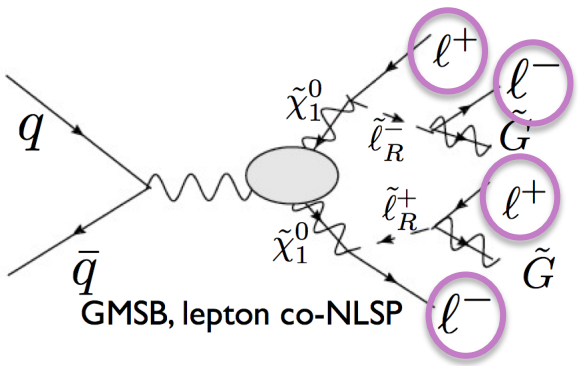
Multi-Lepton Search

CMS-SUS-11-013
CMS-EXO-11-045

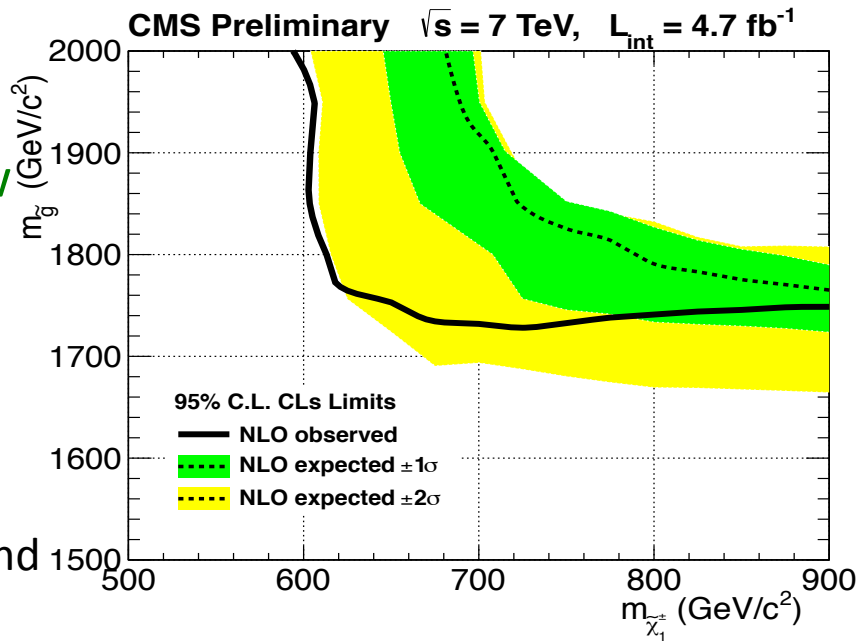


Yields are consistent with SM expectations

Null result interpreted as constraint on new physics

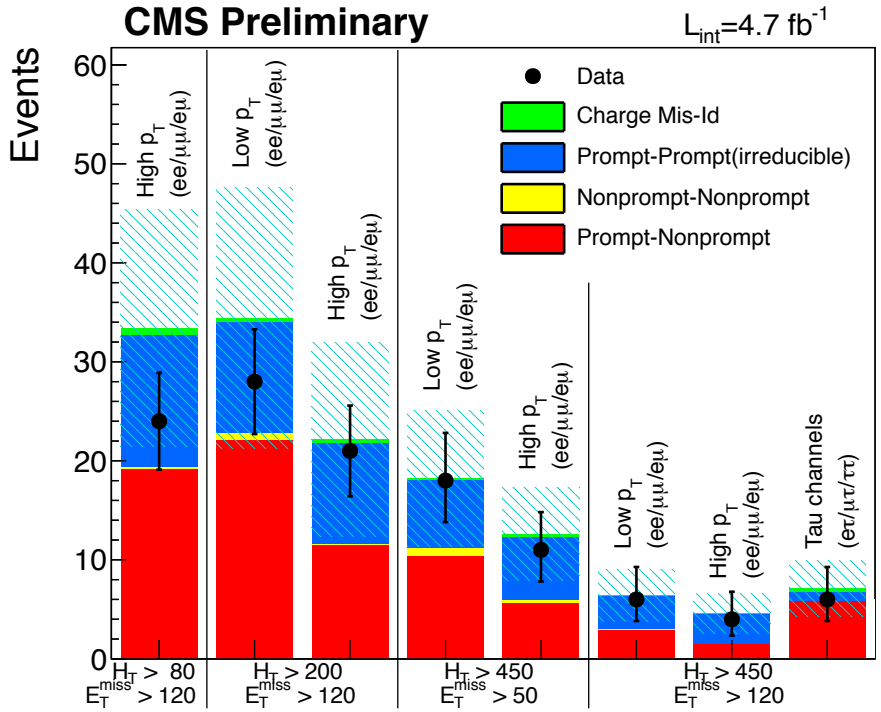


Here, GMSB model:
- gravitino LSP
- degenerate sleptons: co-NLSP
- neutralino is bino and next in mass

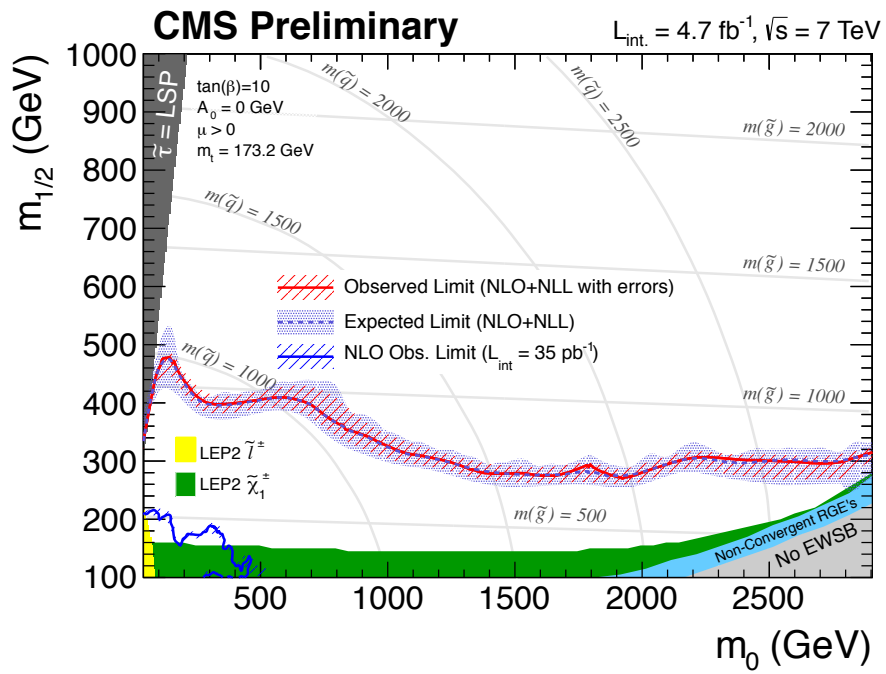


SS di-lepton Search

CMS-SUS-11-010



Observed event yields consistent with SM expectations



Null result interpreted in CMSSM

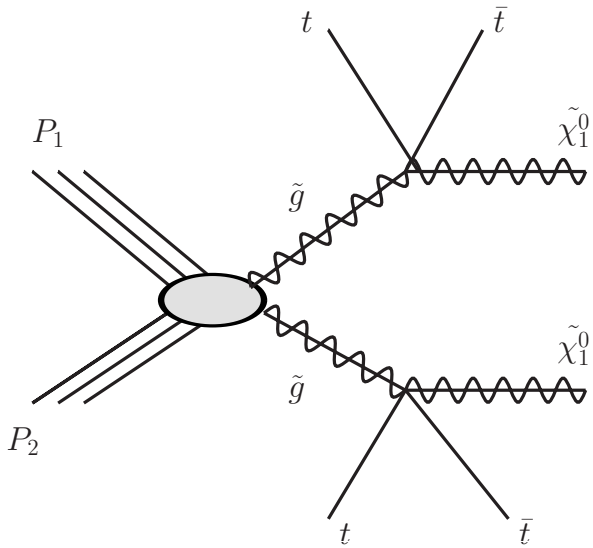
SS di-lepton + b-tags Search

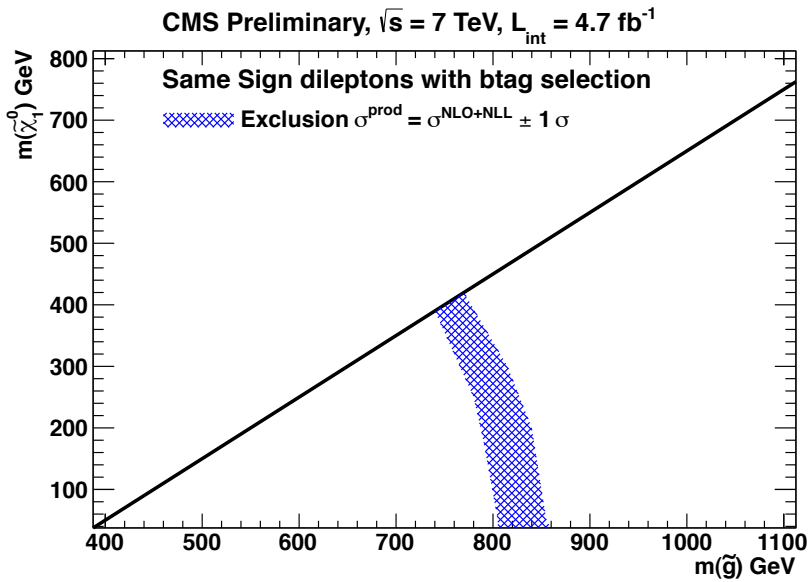
No significant deviation from SM expectation observed ➔ constrain SUSY

CMS-SUS-11-020

Here, interpretation of result in gluino-mediated 4-top production model

See backup for other interpretations





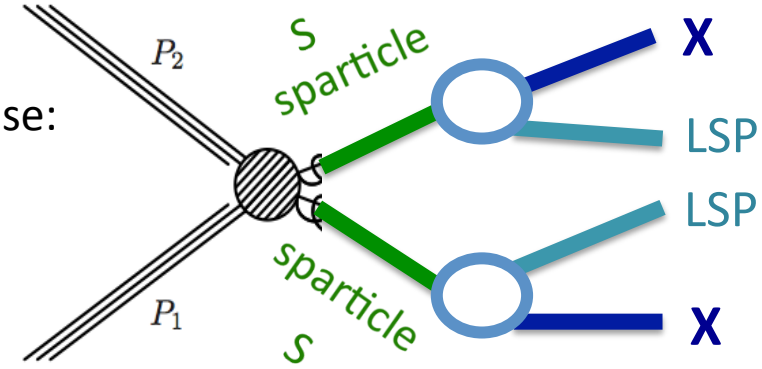
Example of interpretation in Simplified Model of exclusive kinematic final state

Many CMS analyses provide these results interpretations:

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

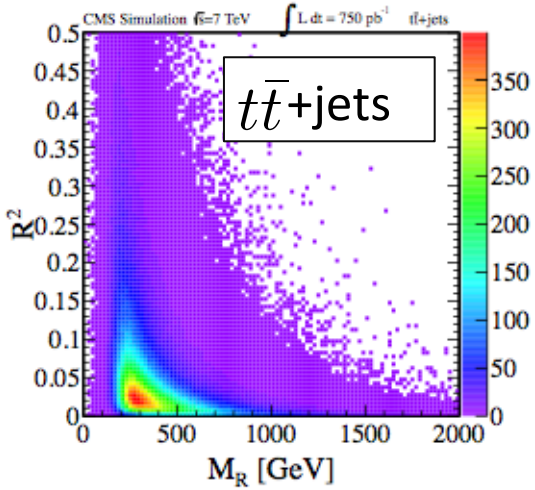
Inclusive Razor (change of variables)

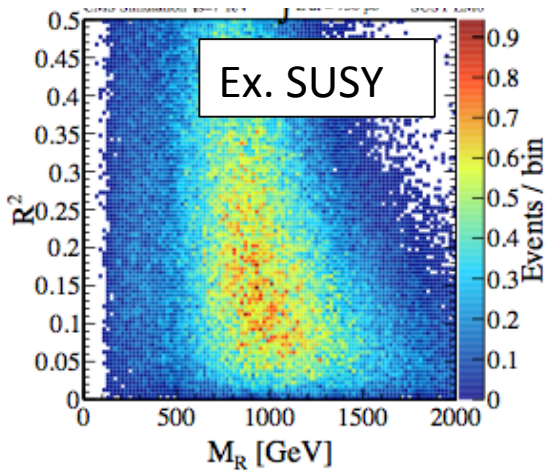
In simple case:
S = squark
X = jet



CMS-SUS-12-005

General final state topology characteristic of R-parity SUSY





Selection:

Group all final state objects (jets, leptons) into two mega-jets

Calculate Razor variables R/M_R designed for this topology

$$M_R = \sqrt{(|\vec{p}_{j_1}| + |\vec{p}_{j_2}|)^2 - (p_z^{j_1} + p_z^{j_2})^2}$$

$$M_T^R = \sqrt{\frac{E_T^{miss}(p_T^{j_1} + p_T^{j_2}) - \vec{E}_T^{miss} \cdot (\vec{p}_T^{j_1} + \vec{p}_T^{j_2})}{2}}$$

$$R = \frac{M_T^R}{M_R}$$

Ratio of two estimators of SUSY scale – describes transverse shape of event

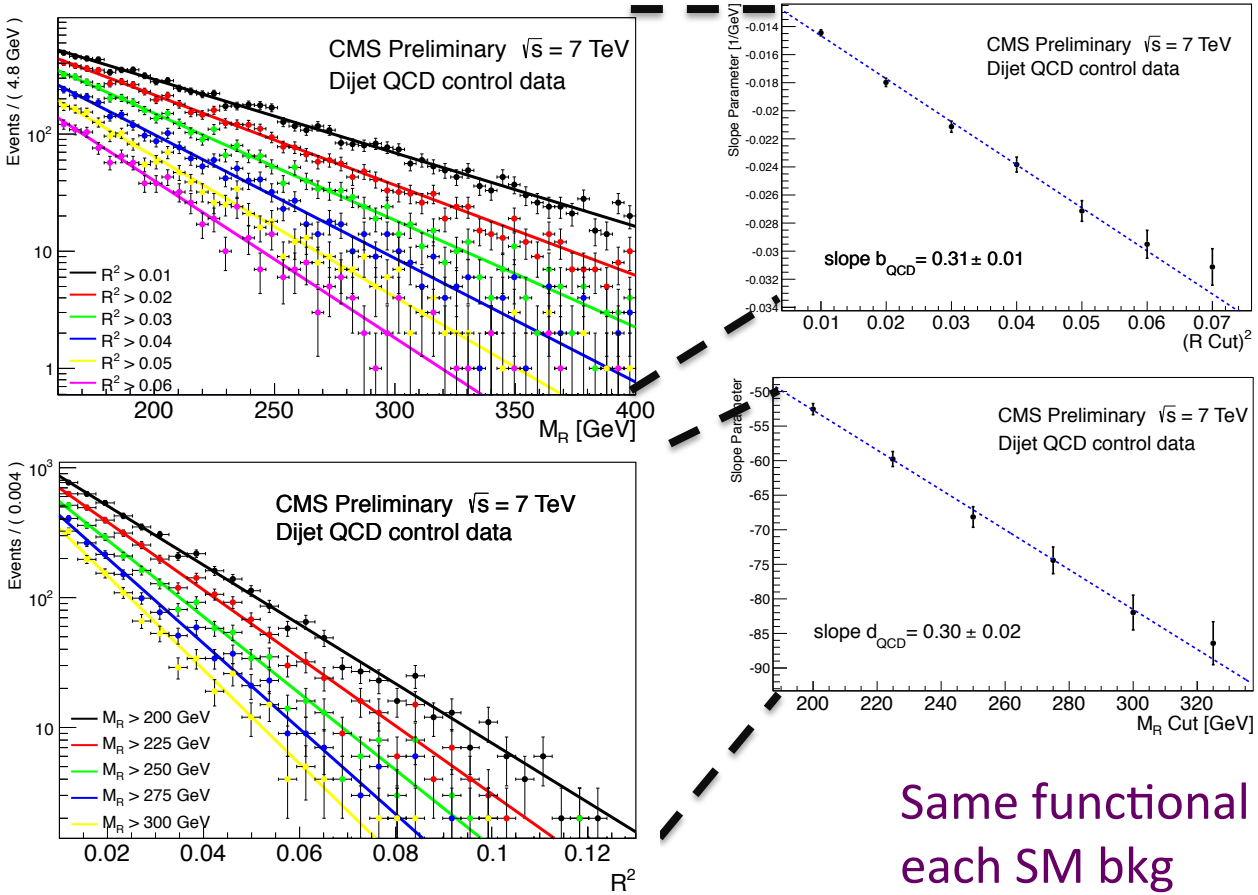
Peaks at

$$M_\Delta = \frac{M_S^2 - M_{\mathrm{LSP}}^2}{M_S}$$

Edge at M_Δ

Inclusive Razor (change of variables)

CMS-SUS-12-005



$$f(M_R) \propto e^{-SM_R}$$

$$S = a + b(R\ \mathrm{cut})^2$$

$$f(R^2) \propto e^{-SR^2}$$

$$S = c + d(M_R\ \mathrm{cut})$$

Same functional phenomenology describes each SM bkg

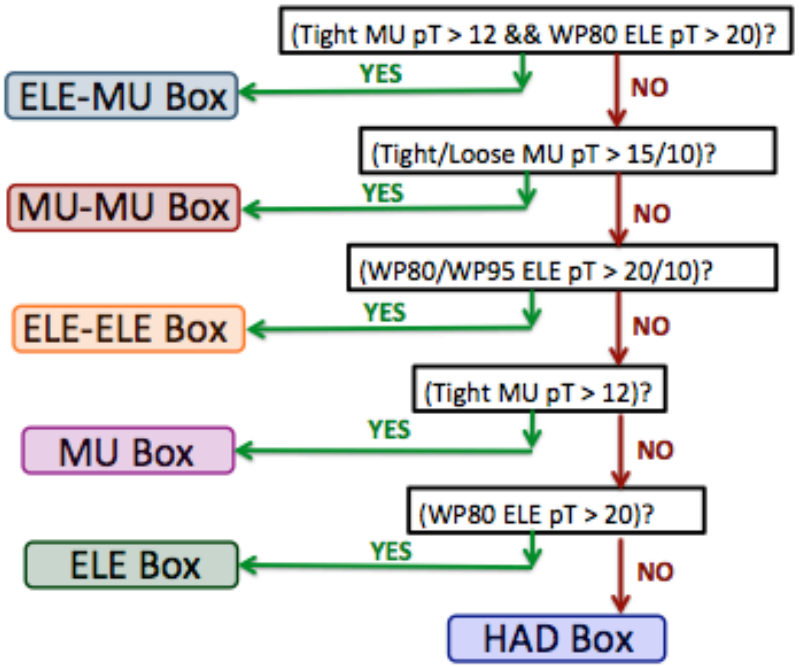
$$f(R^2, M_R) \propto \left[k(M_R - M_R^0)(R^2 - R_0^2) - 1\right] e^{-k(M_R - M_R^0)(R^2 - R_0^2)}$$

With:

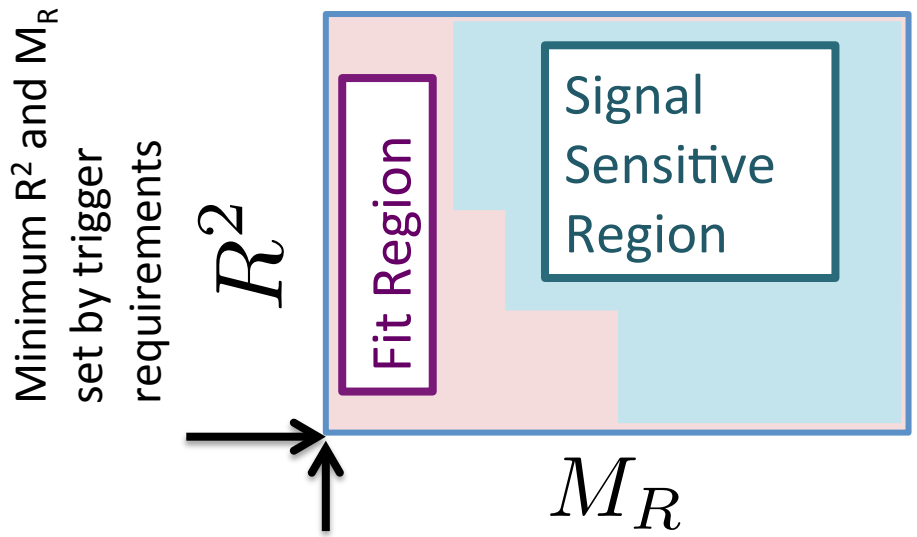
$$b\ (\text{from } M_R \text{ view}) = d\ (\text{from } R^2 \text{ view}) = k\ (\text{from 2D view})$$

Inclusive Razor

CMS-SUS-12-005



Final state BOX classification based on lepton ID



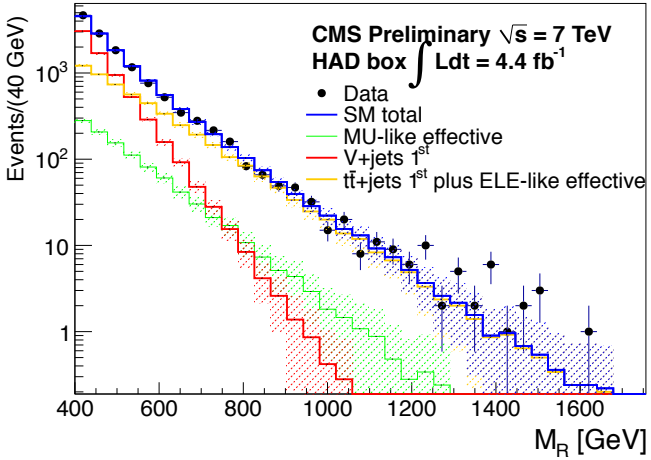
$$\mathcal{L}_b = \frac{e^{-(\sum_{j\in SM} N_j)}}{N!} \prod_{i=1}^{N} \left(\sum_{j\in SM} N_j P_j(M_{R,i}, R_i^2) \right)$$

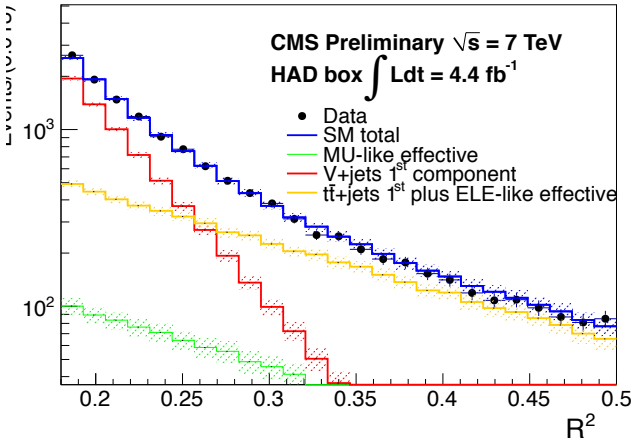
Extended and unbinned maximum likelihood fit performed in 2D R^2-M_R plane independently in each BOX

background functionally extrapolated to signal region –
Exclusively a kinematic extrapolation – not object based

Inclusive Razor

1D projections of 2D ML Fit – HAD Box



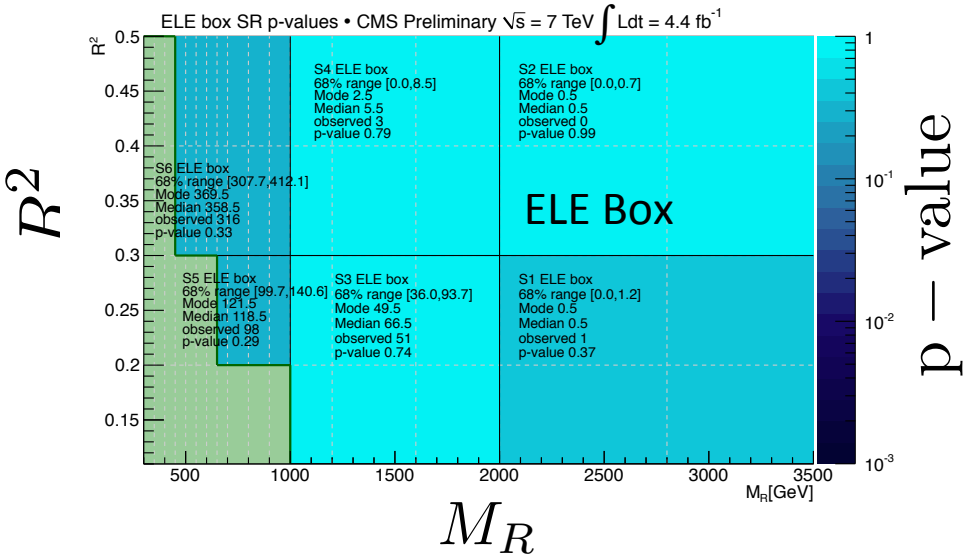


CMS-SUS-12-005

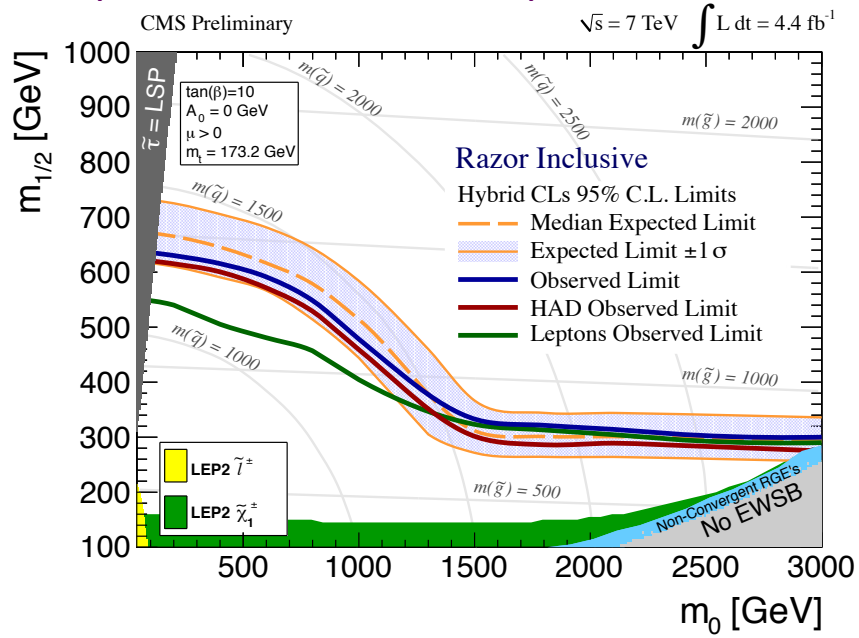
Observations consistent with SM expectations

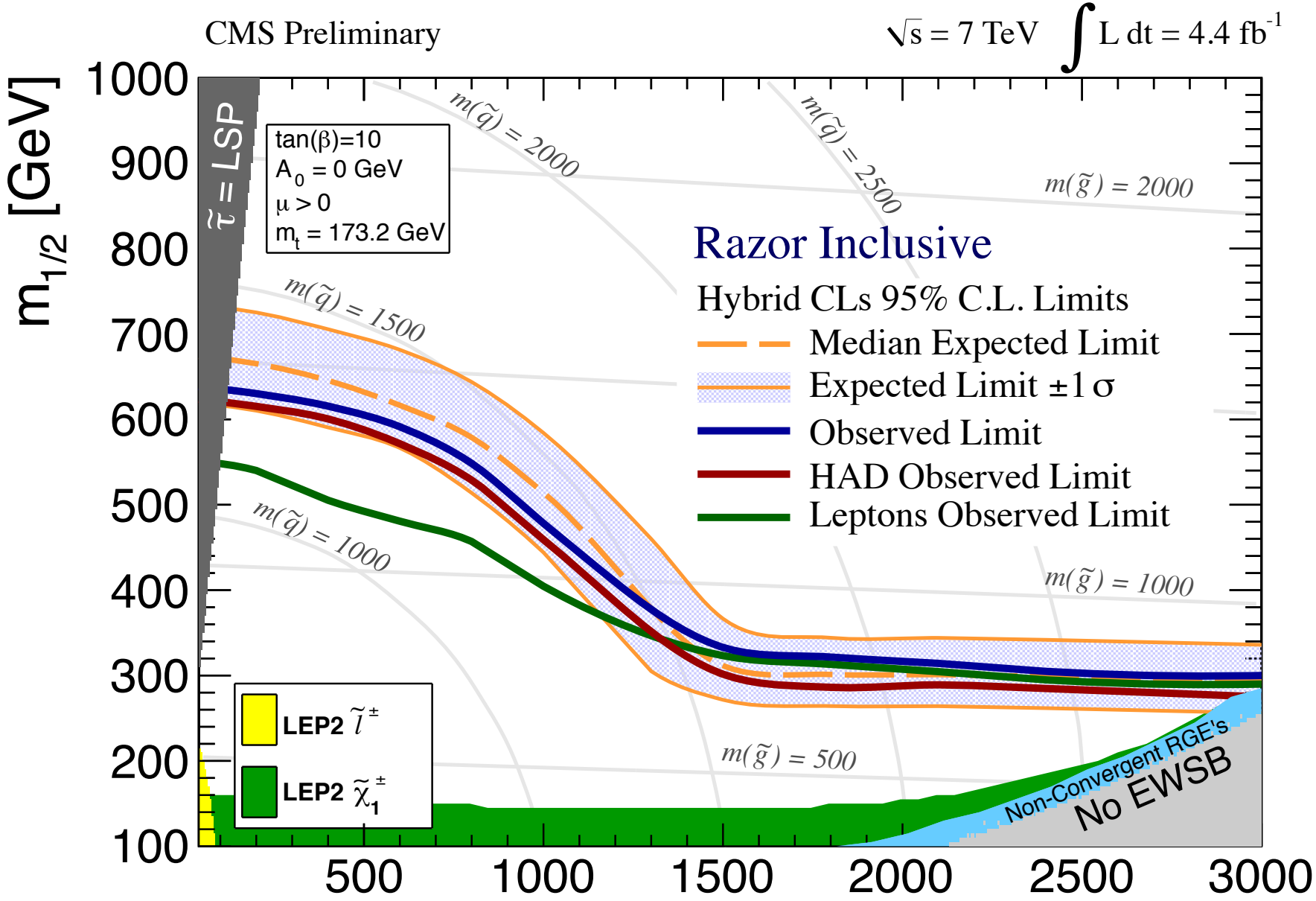
Results from all boxes in public twiki

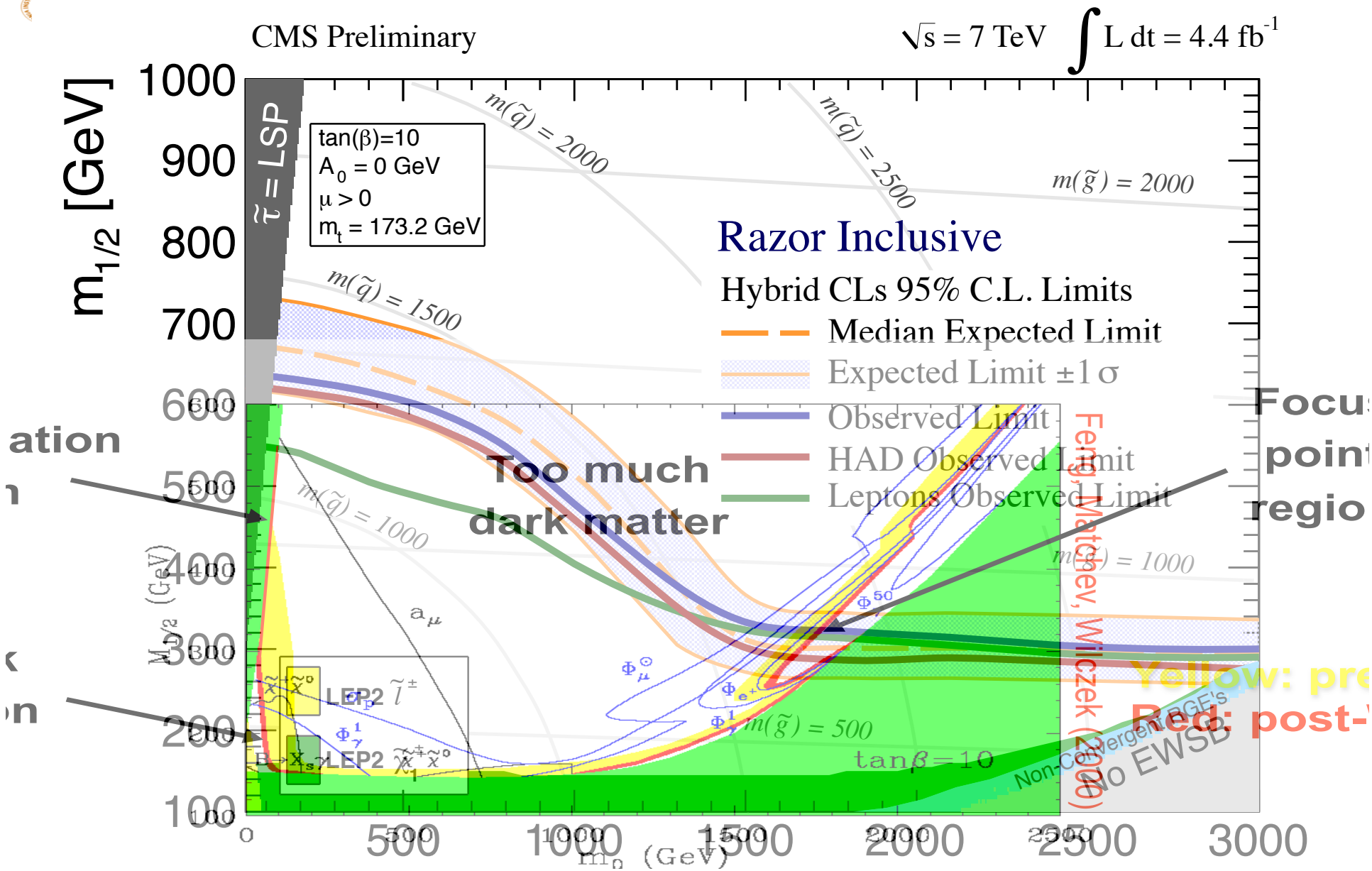
Model independent results showing data/ prediction compatibility



Model dependent CMSSM interpretation




CMS Preliminary
√s = 7 TeV ∫ L dt = 4.4 fb⁻¹
m1/2 [GeV]
1000
900
800
700
600
500
400
300
200
100
500
1000
1500
2000
2500
3000
τ̃ = LSP
tan(β)=10
A0 = 0 GeV
μ > 0
mt = 173.2 GeV
m(q̃) = 2000
m(q̃) = 2500
m(q̃) = 1500
m(q̃) = 1000
m(g̃) = 2000
m(g̃) = 1000
m(g̃) = 500
Razor Inclusive
Hybrid CLs 95% C.L. Limits
Median Expected Limit
Expected Limit ±1 σ
Observed Limit
HAD Observed Limit
Leptons Observed Limit
LEP2 l̃±
LEP2 χ̃1±
Non-Convergent RGE's
No EWSB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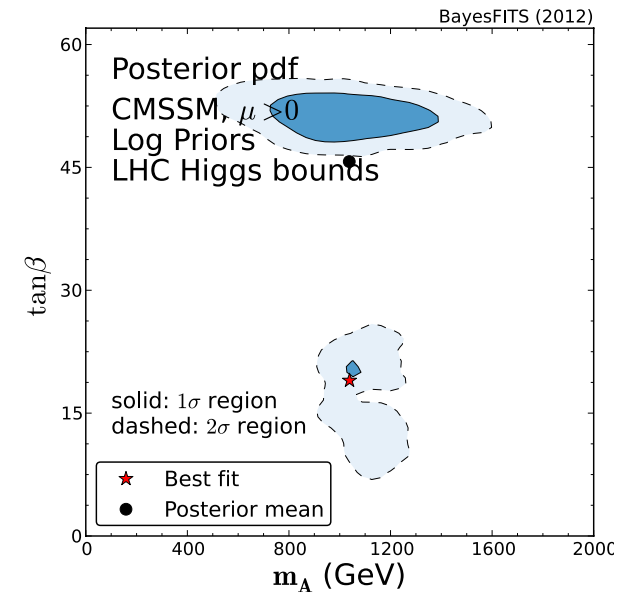
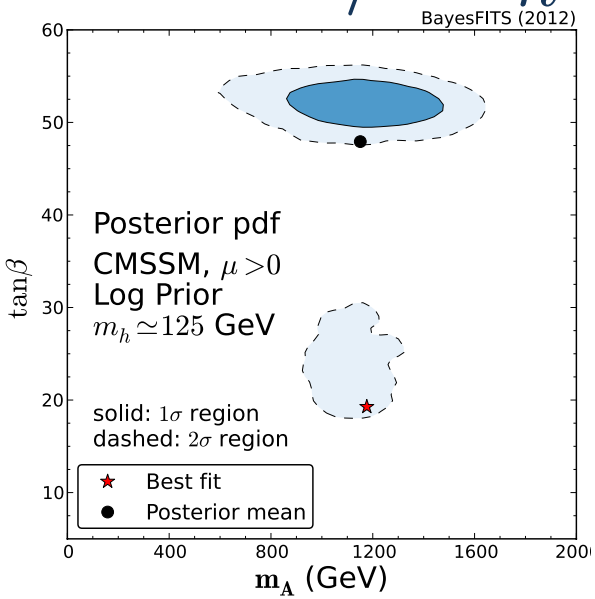
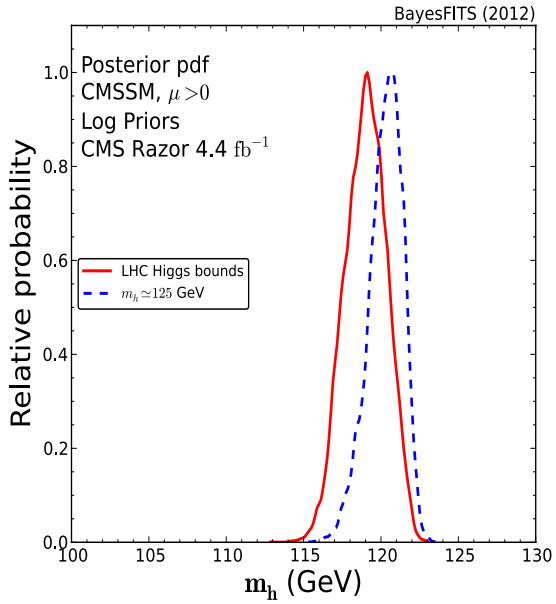
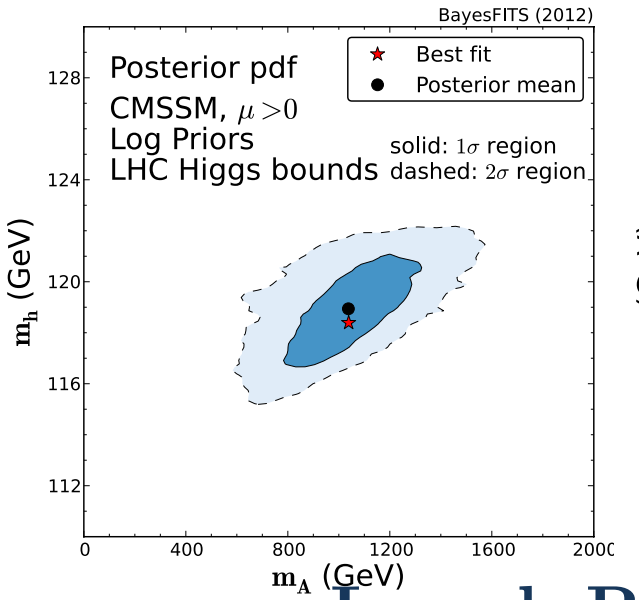
m1/2 [GeV]
tan(β)=10
A0 = 0 GeV
μ > 0
mt = 173.2 GeV
τ̃ = LSP
Razor Inclusive
Hybrid CLs 95% C.L. Limits
Median Expected Limit
Expected Limit ±1 σ
Observed Limit
HAD Observed Limit
Leptons Observed Limit
Too much dark matter
m(q̃) = 2000
m(q̃) = 2500
m(g̃) = 2000
m(q̃) = 1500
m(q̃) = 1000
m(g̃) = 500
tanβ = 10
aμ
LEP2
Ferg, Matchev, Wilczek (2006)
Non-Convergent RGE's
No EWSB
Yellow: pre
Red: post-
Focus point region
ation
m0 (GeV)

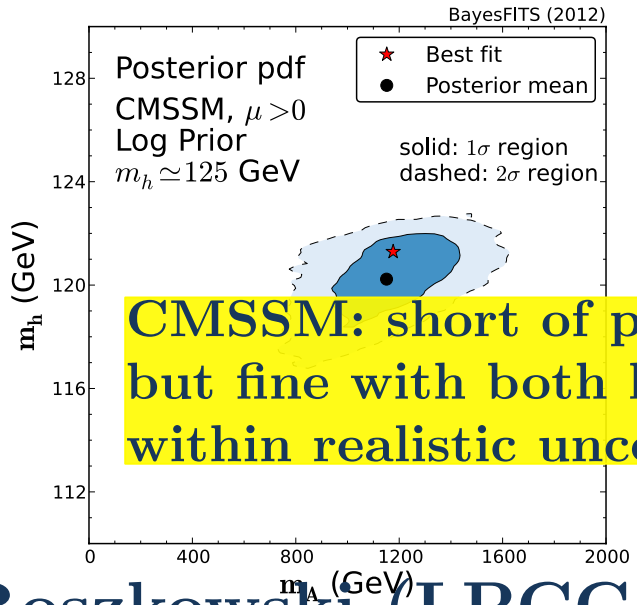
CMSSM w/o and w/ $M_h \sim$125 GeV











CMSSM: short of producing M_h=125 GeV, but fine with both limits and "signal" within realistic uncertainties!

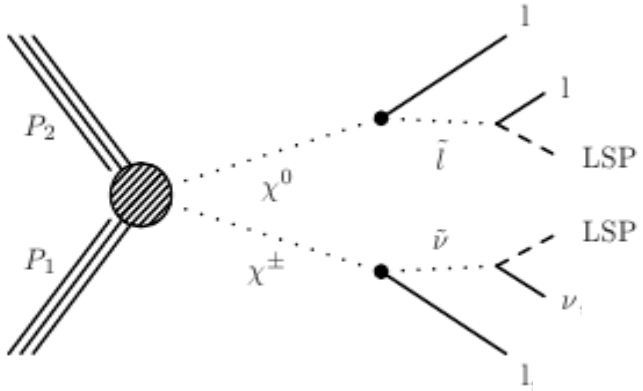
BayesFit analyses fo CMSSM/NUHM w/o and w/ M_h ∼125 GeV and razor results:

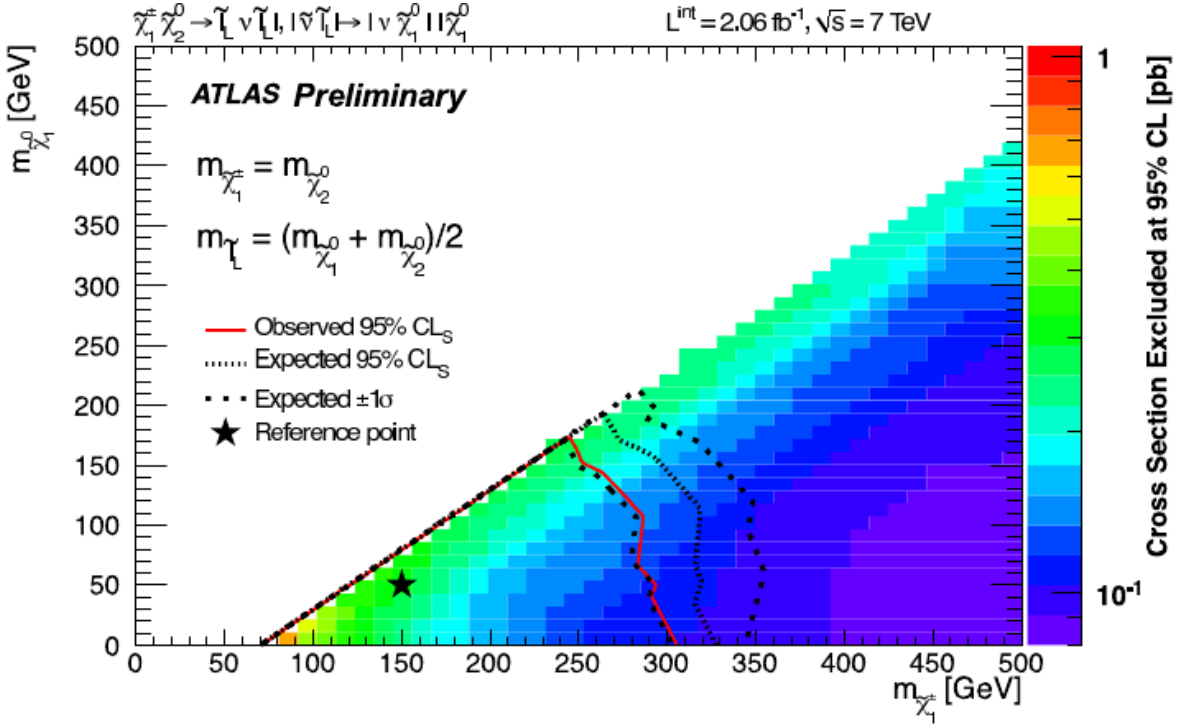
- CMSSM similar w/ and w/o 125 GeV M_h, with uncertainties taken into account but getting heavier and with poorer fit
- NUHM similar w/ and w/o 125 GeV M_h, lighter spartners preferred

http://indico.cern.ch/conferenceDisplay.py?confId=162621

Did we miss some lighter superpartners?

- We expect lighter charginos and second neutralinos
- Naturalness would prefer lighter stops and perhaps sbottoms
- Inclusive searches can capture some of this, but better to have targeted searches too





Hiding SUSY

H_1	125 GeV	$\tilde{b}_1$	499 GeV
$\tilde{t}_1$	188 GeV	A_2	509 GeV
N_1	216 GeV	H_3	530 GeV
$H^{\pm}$	307 GeV	$\tilde{t}_2$	580 GeV
H_2	326 GeV	N_3	602 GeV
A_1	368 GeV	N_4	635 GeV
C_1	406 GeV	N_5	805 GeV
N_2	426 GeV	C_2	876 GeV

$\tilde{t}_1$	$\to t + LSP$	100%
C_1	$\to \tilde{t}_1 + b^{\dagger}$	84%
C_1	$\to N_1 + W^{\pm}$	16%
$\tilde{b}_1$	$\to \tilde{t}_1 + W^{-}$	97%
$\tilde{b}_1$	$\to \tilde{t}_1 + H^{-}$	3%
$\tilde{t}_2$	$\to \tilde{t}_1 + Z$	51%
$\tilde{t}_2$	$\to t + N_1$	27%
$\tilde{t}_2$	$\to b + C_1^{+}$	11%
$\tilde{t}_2$	$\to \tilde{t}_1 + H_1$	10%

C. Csaki, L. Randall, J. Terning

A recent attempt by clever theorists to hide SUSY:

- LSP is a nearly massless gravitino
- NLSP is the lightest stop, only 15 GeV heavier than top
- Suppression of missing transverse momentum in SUSY decays

Hiding SUSY

H_1	125 GeV	$\tilde{b}_1$	499 GeV
$\tilde{t}_1$	188 GeV	A_2	509 GeV
N_1	216 GeV	H_3	530 GeV
$H^\pm$	307 GeV	$\tilde{t}_2$	580 GeV
H_2	326 GeV	N_3	602 GeV
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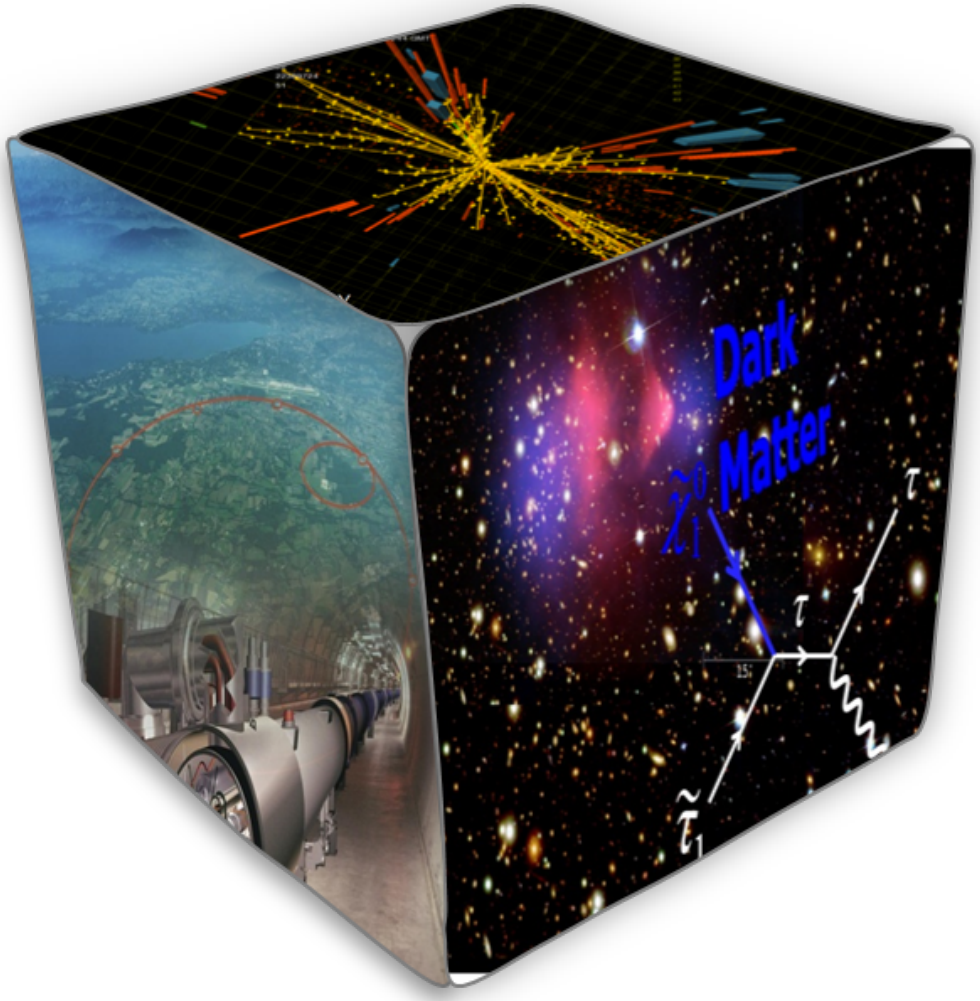
$\tilde{t}_1$	$\to t + LSP$	100%
C_1	$\to \tilde{t}_1 + b^\dagger$	84%
C_1	$\to N_1 + W^\pm$	16%
$\tilde{b}_1$	$\to \tilde{t}_1 + W^-$	97%
$\tilde{b}_1$	$\to \tilde{t}_1 + H^-$	3%
$\tilde{t}_2$	$\to \tilde{t}_1 + Z$	51%
$\tilde{t}_2$	$\to t + N_1$	27%
$\tilde{t}_2$	$\to b + C_1^+$	11%
$\tilde{t}_2$	$\to \tilde{t}_1 + H_1$	10%

C. Csaki, L. Randall, J. Terning

Can this model be discovered/ruled out in 2012?

- As it turns out, LHC experimentalists are also ok-clever
- Already with the 2011 data there are novel analyses aimed at light stops
- This particular model will certainly be within reach in 2012

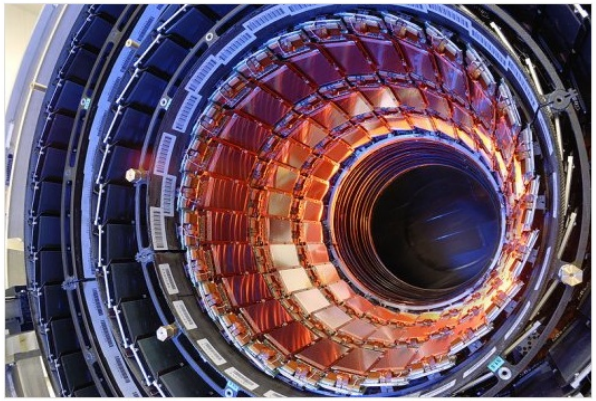
It is just the beginning



LHC Reports Failure To Create Black Holes, a Setback For String Theory

At least not yet

By Rebecca Boyle Posted 12.20.2010 at 2:40 pm 15 Comments



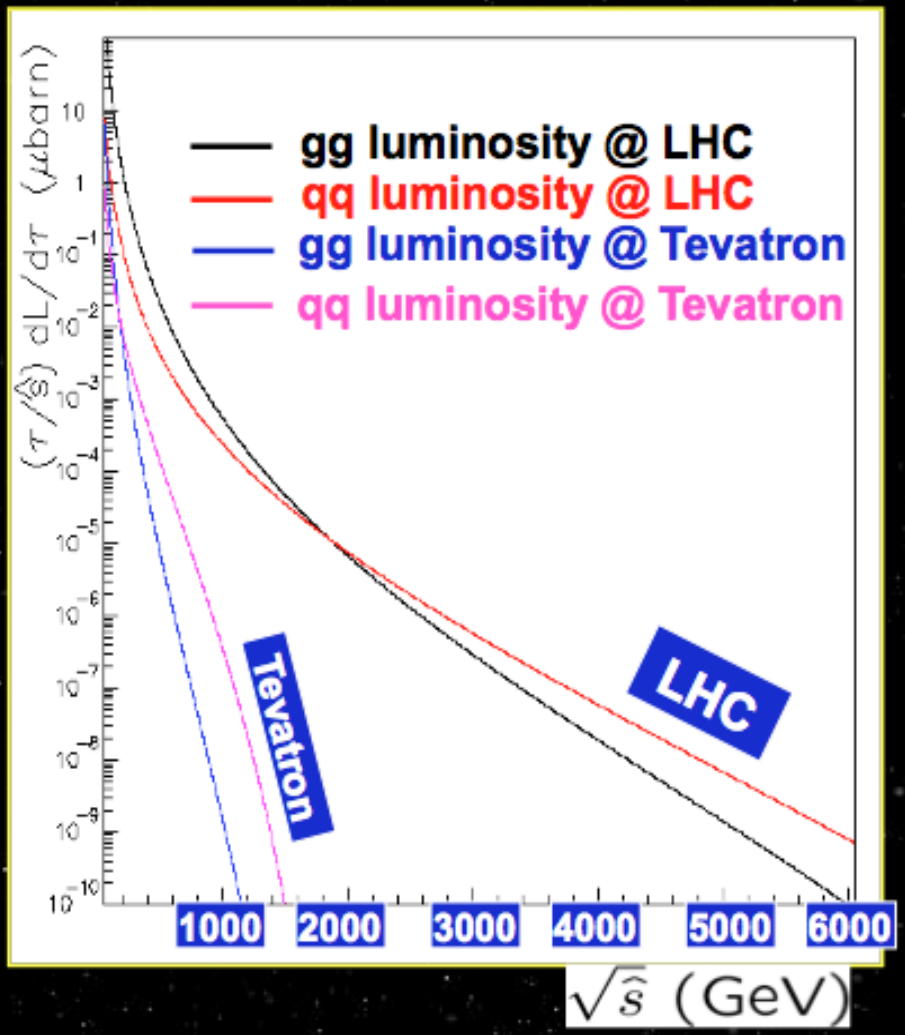
CMS Black Hole The Compact Muon Solenoid seen under construction in late 2008. *Wikimedia Commons*

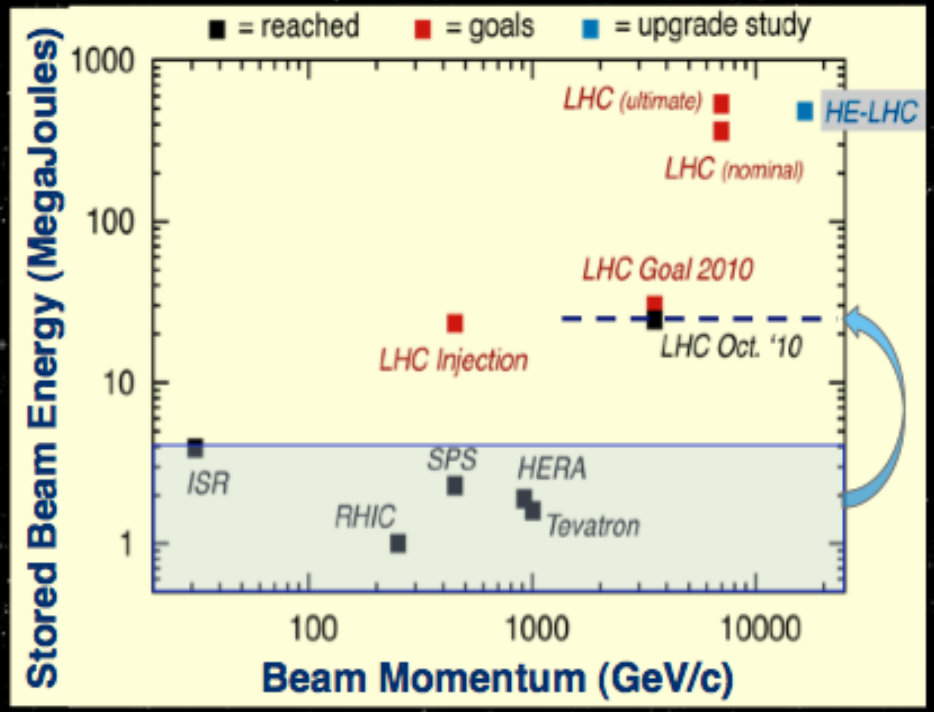
Physicists working at the Large Hadron Collider report that after a series of tests, they have not seen any **mini black holes**, to the chagrin of string theorists and the relief of disaster theorists.

2012 and Beyond

- more flavor constraints
- Higgs, no Higgs, Higgs look-alikes
- looking for SUSY and other BSM
- connect with DM direct searches with LHC

The Power and the Glory of the LHC

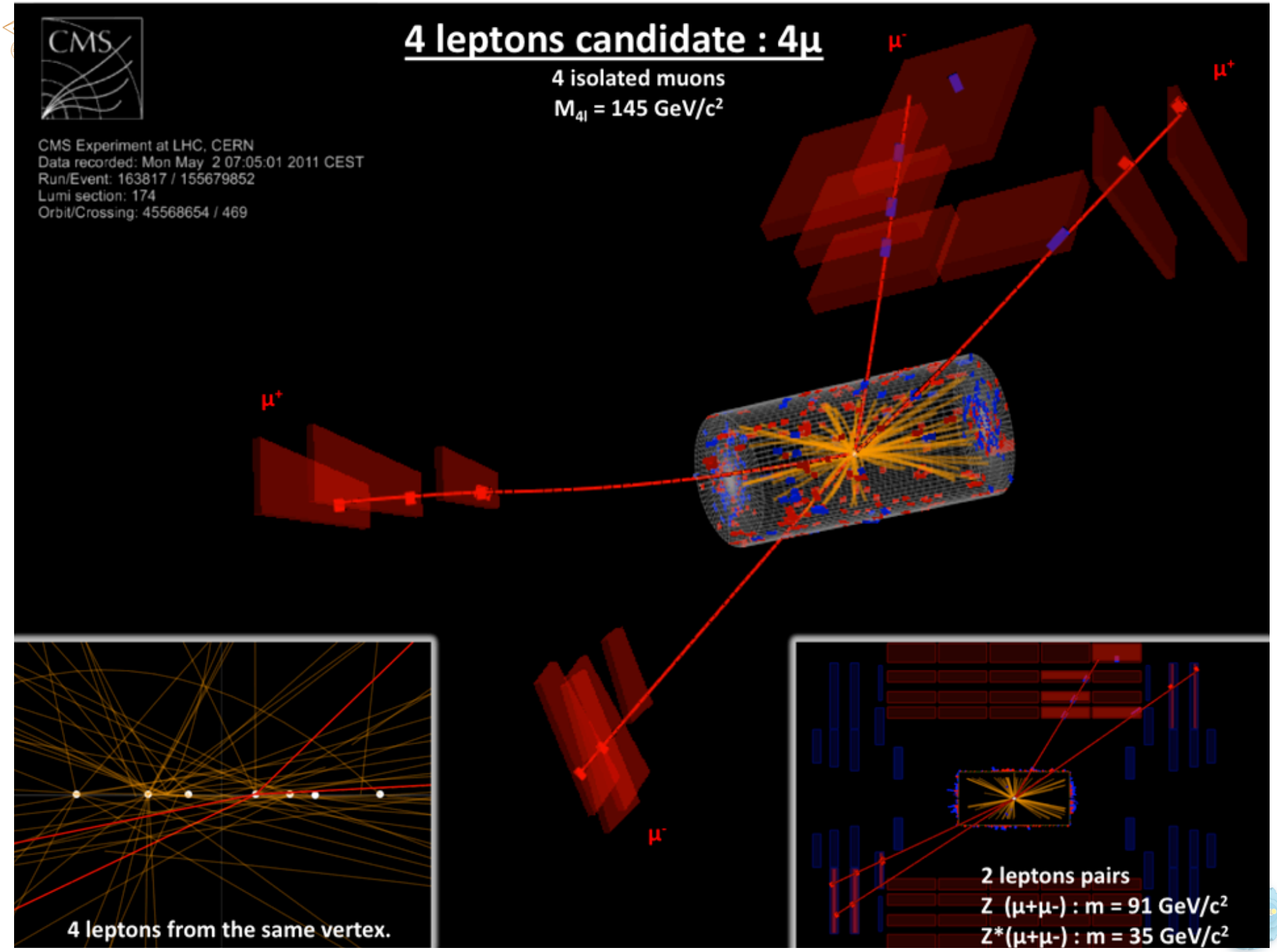




In the first year of operation achieved

- factor of 10 above the state-of-the-art
- 28 MJ, (24 MJ w/ collisions)

- Discovery Machine
- Probing deep into the terascale
- Good reasons to expect new physics


4 leptons candidate : 4μ
4 isolated muons
M4l = 145 GeV/c2
CMS Experiment at LHC, CERN
Data recorded: Mon May 2 07:05:01 2011 CEST
Run/Event: 163817 / 155679852
Lumi section: 174
Orbit/Crossing: 45568654 / 469
μ-
μ+
μ+
μ-
4 leptons from the same vertex.
2 leptons pairs
Z (μ+μ-) : m = 91 GeV/c2
Z*(μ+μ-) : m = 35 GeV/c2

No Higgs found
Some immediate questions:

- **Do you have enough data / good enough analyses?**
- **Is it a non-SM Higgs with invisible and/or cascade decays? Is it lighter than the LEP SM lower bound?**
- **Are you in a "Higgsless" scenario where Kaluza-Klein tree-level exchanges replace Higgs exchange in unitarizing WW and WZ scattering?**
- **Are you in a "technicolor" scenario where new strong dynamics takes over before you reach the 1.6 TeV unitarity bound? Do you see techni-resonances?**
- **Is quantum field theory the wrong way to think about this problem?**

Discovery a 120 GeV resonance consistent with a SM Higgs

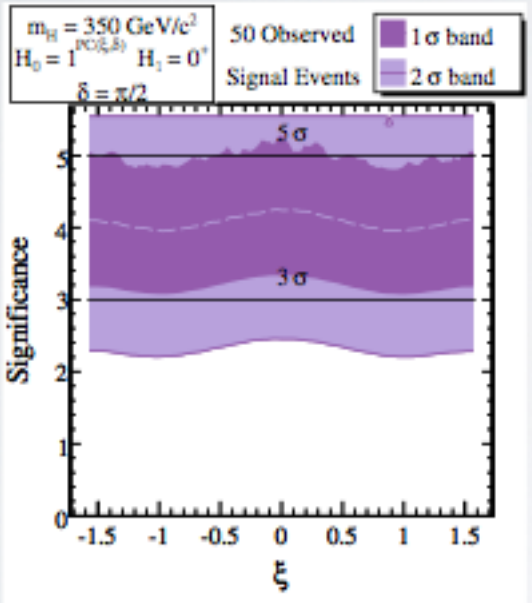
Some immediate questions:

- **Is it spin 0?**
- **Is it CP even? To what extent can you exclude a CP odd component?**
- **Does it come from a weak doublet?**
- **Are its couplings proportional to masses?**
- **Is it composite or an elementary scalar?**
- **Are there other neutral or charged resonances?**
- **Does other things decay into it?**
- **Did you look at all possible associated production of it?**

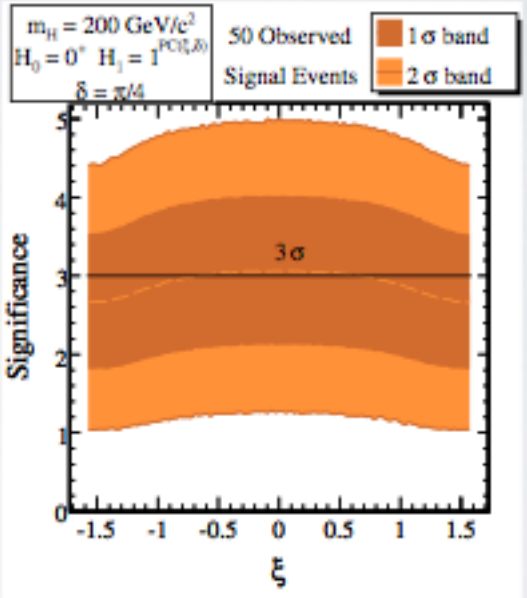
Some of this may happen around the moment of discovery

Example: ZZ -> 4 lepton final state:
0+ neutral resonance versus any spin 1 look-alike

how well do I exclude arbitrary spin 1 when in fact I have a SM Higgs?



how well do I exclude an SM Higgs when in fact I have some arbitrary spin 1?



A. De Rujula, J.L., M. Pierini, C. Rogan, M. Spiropulu, arXiv:1001.5300

- for 145 GeV SM Higgs we can exclude the general spin one hypothesis at 5 sigma with 60 signal events

Look-Alike work (Higgs look-alikes (HLL)

- The mission of the HLL work was to use the full decay information and likelihood ratios to discriminate between different Higgs-look-alike families. (NP hypothesis testing, marginalized likelihoods etc)

PHYSICAL REVIEW D **82,** 013003 (2010)

Higgs boson look-alikes at the LHC

A. De Rújula,[1,2,3] Joseph Lykken,[4] Maurizio Pierini,[3] Christopher Rogan,[5] and Maria Spiropulu[3,5]
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(Received 2 March 2010; published 14 July 2010)

The discovery of a Higgs particle is possible in a variety of search channels at the LHC. However, the true identity of any putative Higgs boson will, at first, remain ambiguous until one has experimentally excluded other possible assignments of quantum numbers and couplings. We quantify the degree to which one can discriminate a standard model Higgs boson from "look-alikes" at, or close to, the moment of discovery at the LHC. We focus on the fully-reconstructible golden decay mode to a pair of Z bosons and a four-lepton final state. Considering both on-shell and off-shell Z's, we show how to utilize the full decay information from the events, including the distributions and correlations of the five relevant angular variables. We demonstrate how the finite phase space acceptance of any LHC detector sculpts the decay distributions, a feature neglected in previous studies. We use likelihood ratios to discriminate a standard model Higgs from look-alikes with other spins or nonstandard parity, CP, or form factors. For a resonance mass of 200 GeV/c^2, we achieve a median discrimination significance of 3σ with as few as 19 events, and even better discrimination for the off-shell decays of a 145 GeV/c^2 resonance.

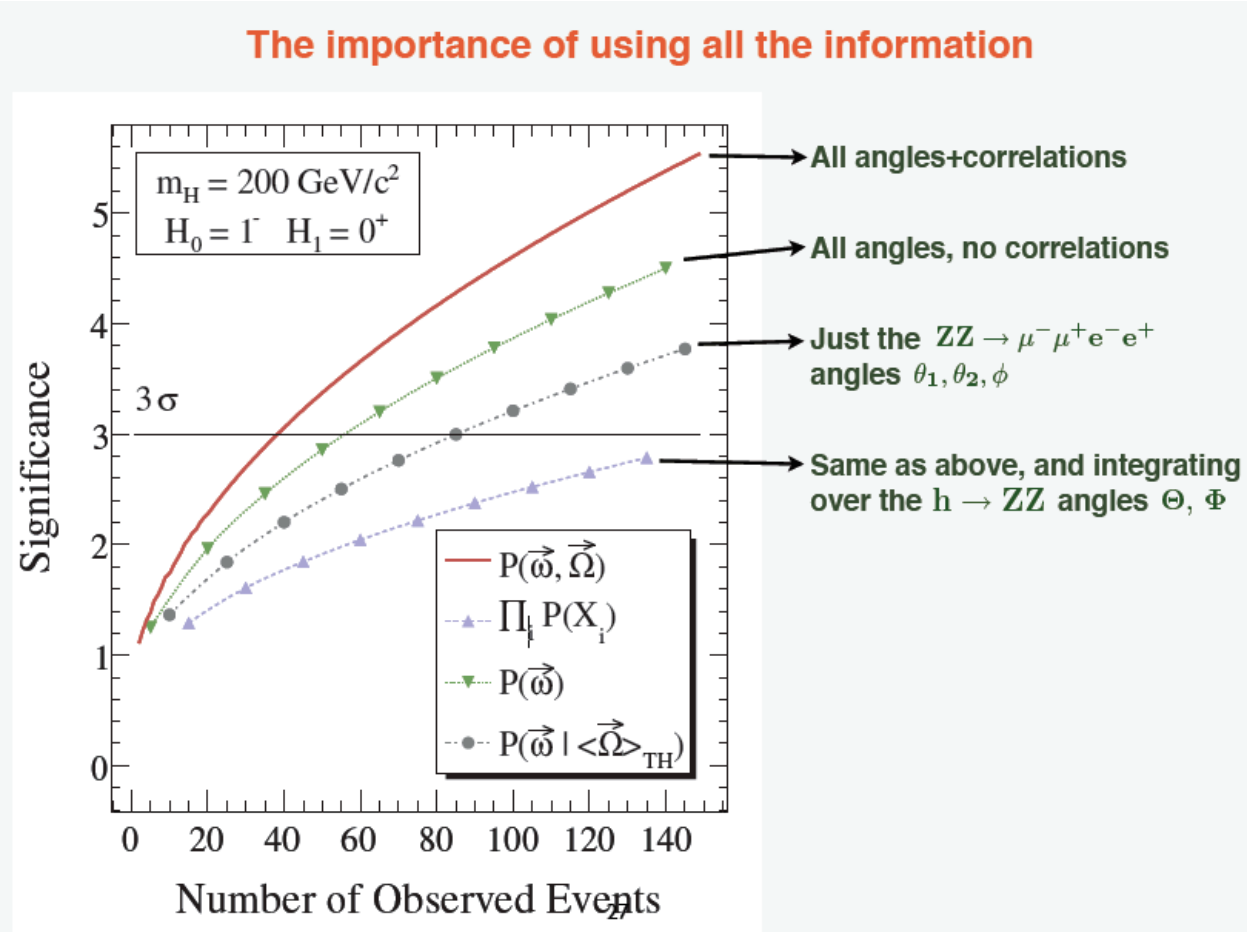
DOI: 10.1103/PhysRevD.82.013003 PACS numbers: 14.80.Bn

D. Outlook

We have seen that by exploiting the full decay information in the golden channel we should be able to say a lot about the identity of a putative Higgs resonance around the moment of discovery. Our results also show that asymptotically, utilizing the full physics run of the LHC, it should be possible to explore very detailed properties of such a resonance.

It has not escaped our attention that there are many processes other than the ZZ decays of a heavy resonance whose characterization may benefit from an analysis of the kind that we have performed here.

Look-Alike work (Higgs look-alikes (HLL)



Discovery of new heavy particles consistent with supersymmetry
Some immediate questions:

- **Is it really SUSY? (The look-alike problem) [N.Arkani-Hamed, G. Kane, J.Thaler, L-T Wang, hep-ph/0512190 J. Hubisz, Joe Lykken, M. Pierini, M.S. arXiv:0805.2398 etc.]**
- **If it is SUSY, what kind of SUSY? What is the soft-breaking mechanism? (The look-alike problem again, distinguishing different "footprints")**
- **Can you reconstruct all the decay chains and production mechanisms?**
- **Can you make an unambiguous mapping back to the parameters of the soft-breaking Lagrangian? (The inverse problem)**

game change in searches: re-engineering the LHC discovery analyses

Kinematical variables towards new dynamics at the LHC

At the LHC, many new physics signatures feature the pair-production of massive particles with subsequent direct or cascading decays to weakly-interacting particles, such as SUSY scenarios with conserved conserved R-parity or $H \to W(\ell\nu)W(\ell\nu)$. We present a set of dimension-less variables that can assist the early discovery of processes of this type in conjunction with a set of variables with mass dimension that will expedite the characterization of these processes.

arXiv:1006.2727v2

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (

CERN-PH-EP/2011-099
2011/07/07

CMS-SUS-10-009

Inclusive search for squarks and gluinos in pp collisions at $\sqrt{s} = 7\,\text{TeV}$

Author: J. Lykken, M. Pierini, C. Rogan and M. Spiropulu
The CMS Collaboration*

arXiv:submit/0278505 [hep-ex] 7 Jul 2011

Abstract

A search is performed for heavy particle pairs produced in $\sqrt{s} = 7\,\text{TeV}$ proton-proton collisions with $35\,\text{pb}^{-1}$ of data collected by the CMS experiment at the LHC. The search is sensitive to squarks and gluinos of generic supersymmetry models, provided they are kinematically accessible, with minimal assumptions on properties of the lightest superpartner particle. The kinematic consistency of the selected events is tested against the hypothesis of heavy particle pair production using the dimensionless *razor* variable R, related to the missing transverse energy E_T^{miss}. The new physics signal is characterized by a broad peak in the distribution of M_R, an event-by-event indicator of the heavy particle mass scale. This new approach is complementary to E_T^{miss}-based searches. After background modeling based on data, and background rejection based on R and M_R, no significant excess of events is found beyond the standard model expectations. The results are interpreted in the context of the constrained minimal supersymmetric standard model as well as two simplified supersymmetry models.

Submitted to Physical Review D

game change in searches: re-engineering the LHC discovery analyses

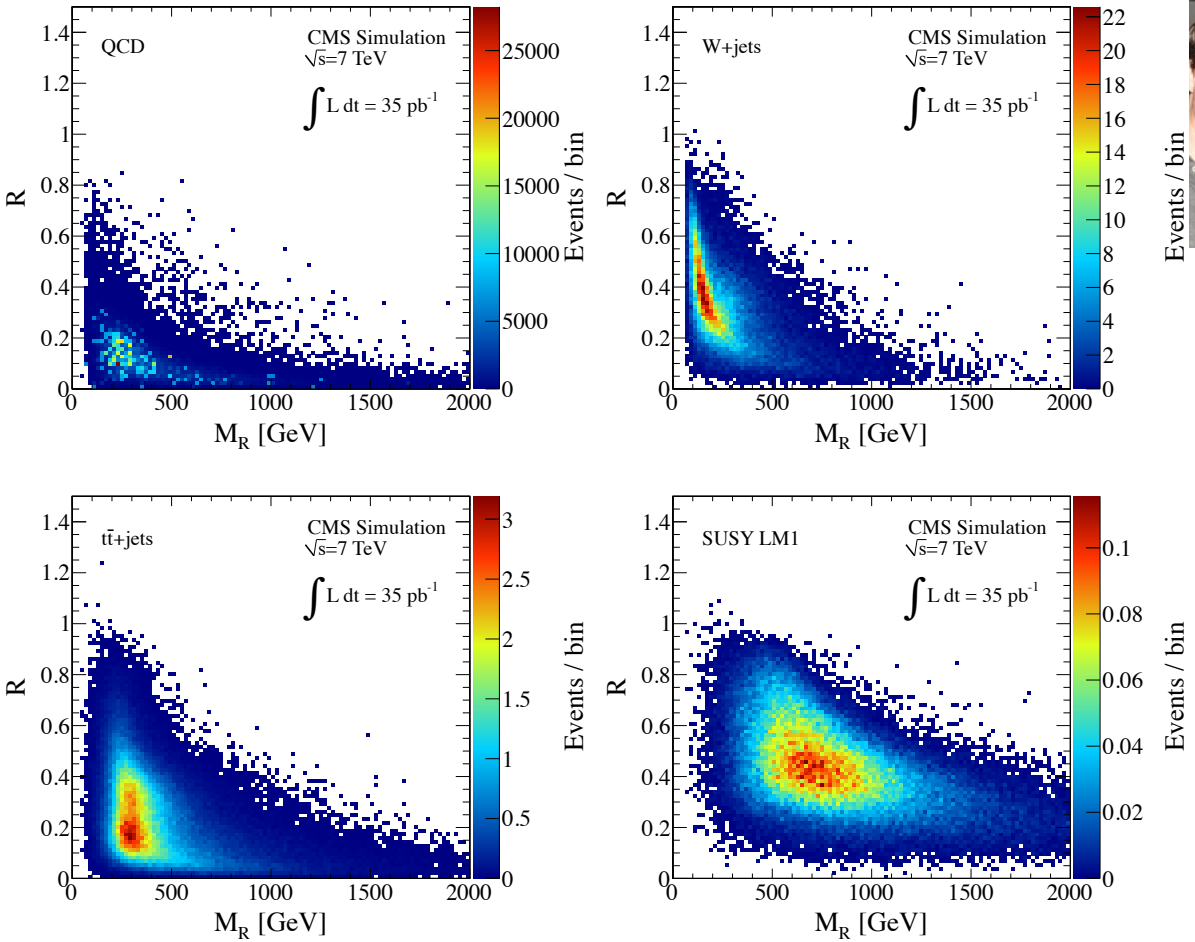
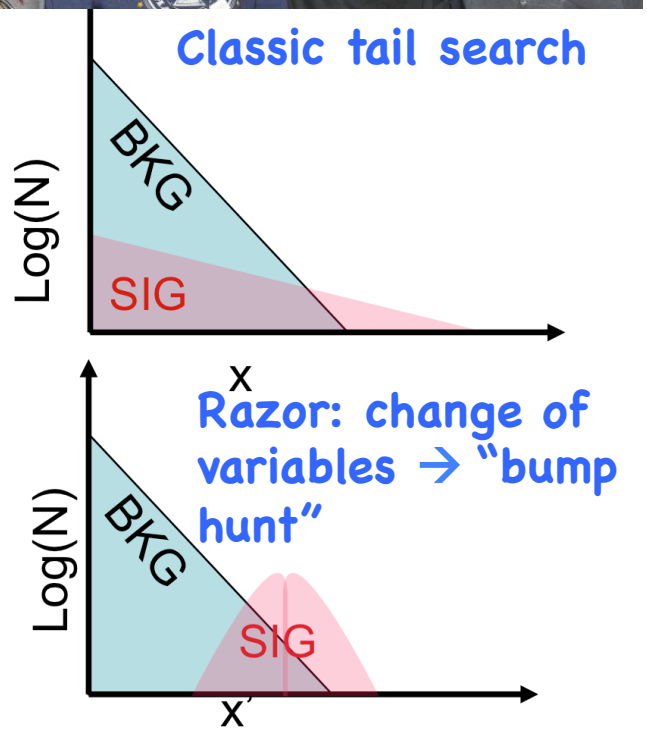
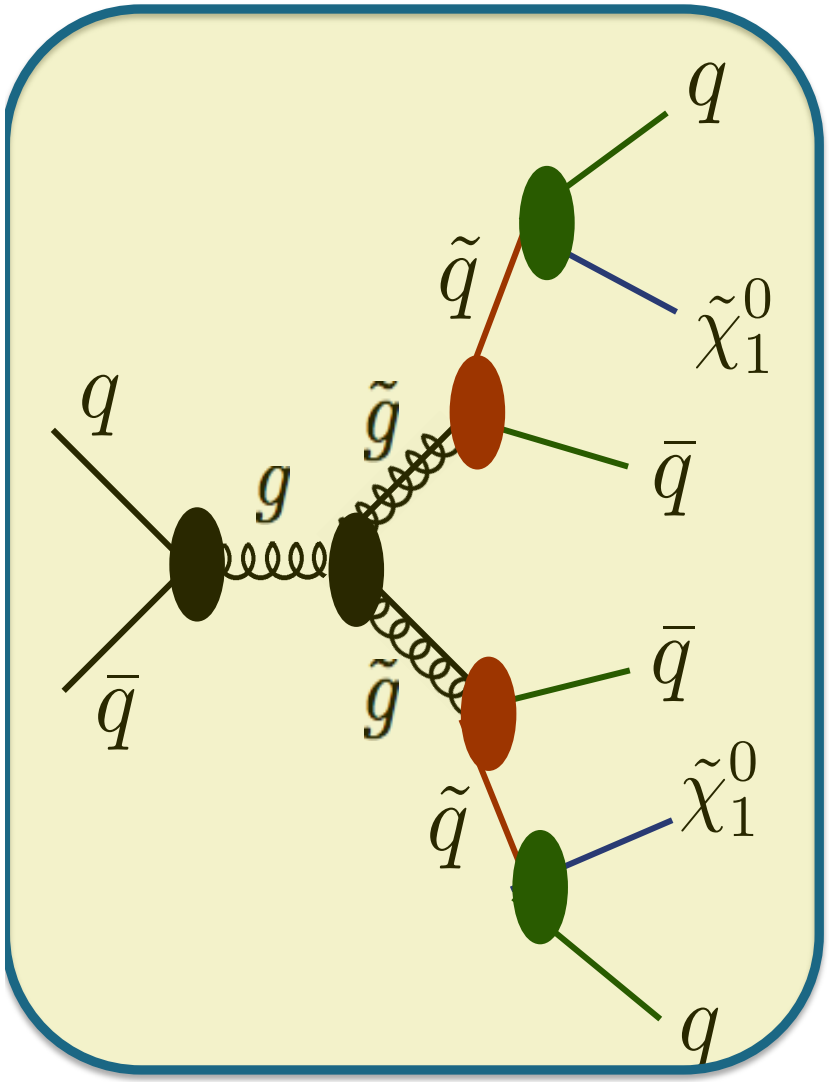
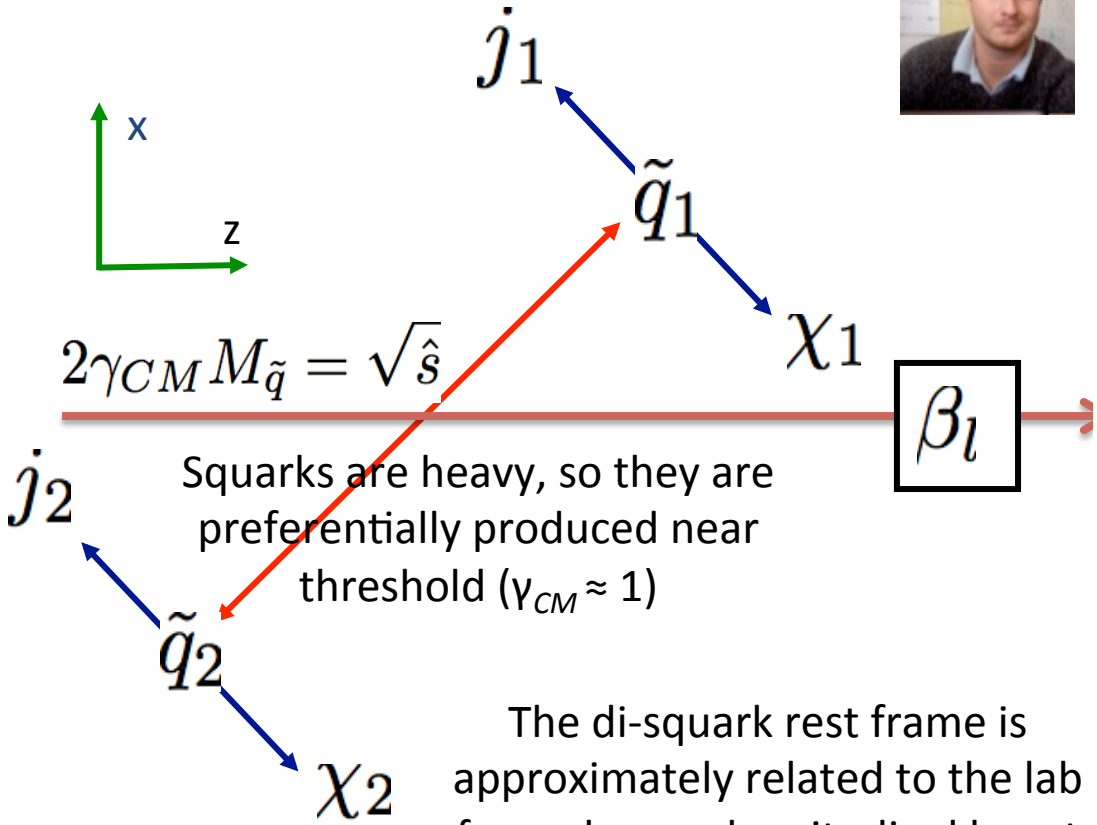


Figure 1: Scatter plot in the (M_R, R) plane for simulated events: (top left) QCD multijet, (top right) W+jets, (bottom left) $t\bar{t}$+jets, and (bottom right) the SUSY benchmark model LM1 [18] with $M_\Delta = 597$ GeV. The yields are normalized to an integrated luminosity of 35 pb^{-1}. The bin size is (20 GeV $\times$ 0.015).



$$R \equiv \frac{M_T^R}{M_R} = \frac{M_T^R \equiv \sqrt{\dfrac{E_T^{\rm miss}(p_T^{j_1} + p_T^{j_2}) - \vec{E}_T^{\rm miss}\cdot(\vec{p}_T^{\,j_1} + \vec{p}_T^{\,j_2})}{2}}\,.}{M_R \equiv 2|\vec{p}_{j_1}^{\,R}| = 2|\vec{p}_{j_2}^{\,R}|\,,}$$

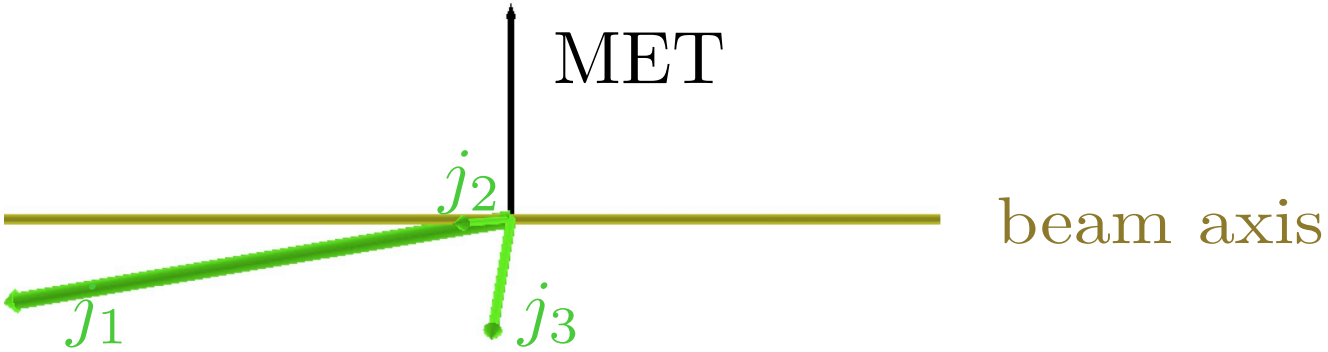


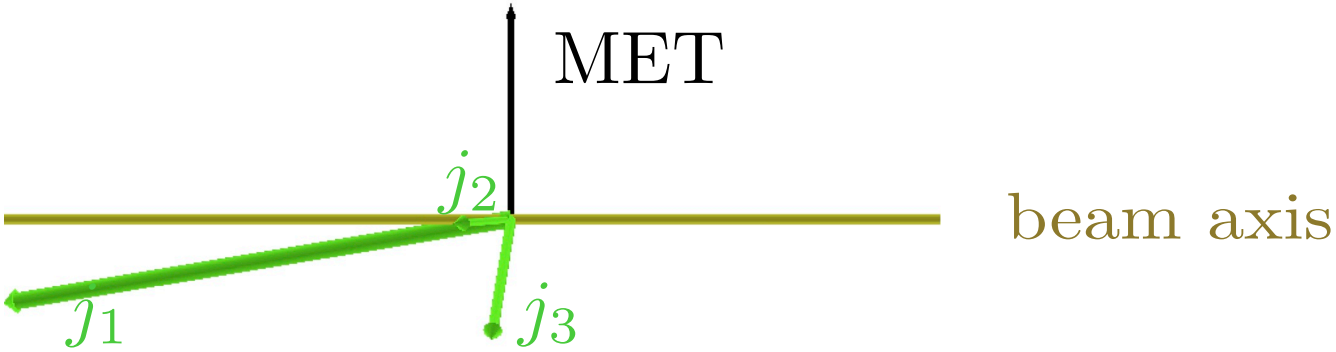


Squarks are heavy, so they are preferentially produced near threshold ($\gamma_{CM} \approx 1$)

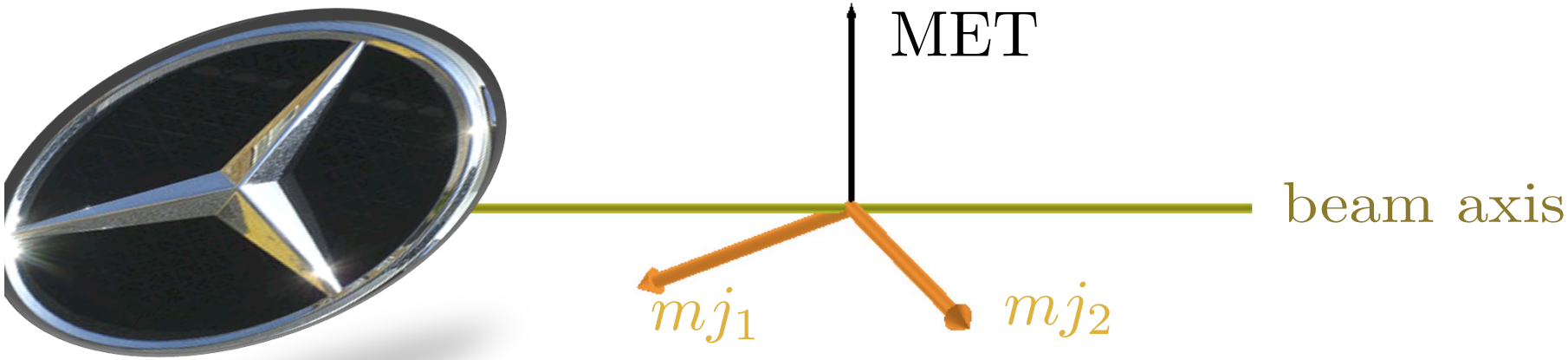
The di-squark rest frame is approximately related to the lab frame by one longitudinal boost

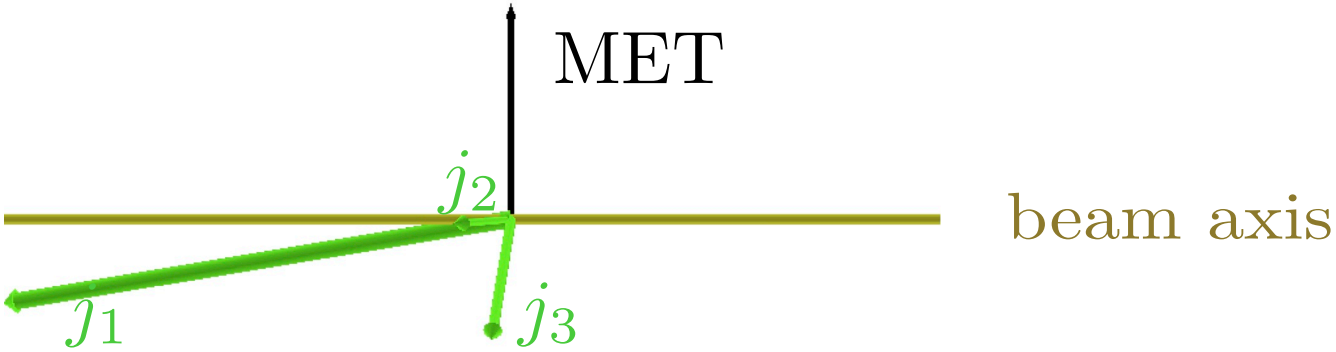
Characteristic scale of process is reflected in momenta of quarks and LSP's $M_\Delta = \dfrac{M_{\tilde{q}}^2 - M_\chi^2}{M_{\tilde{q}}}$


MET
j_2
beam axis
j_1
j_3

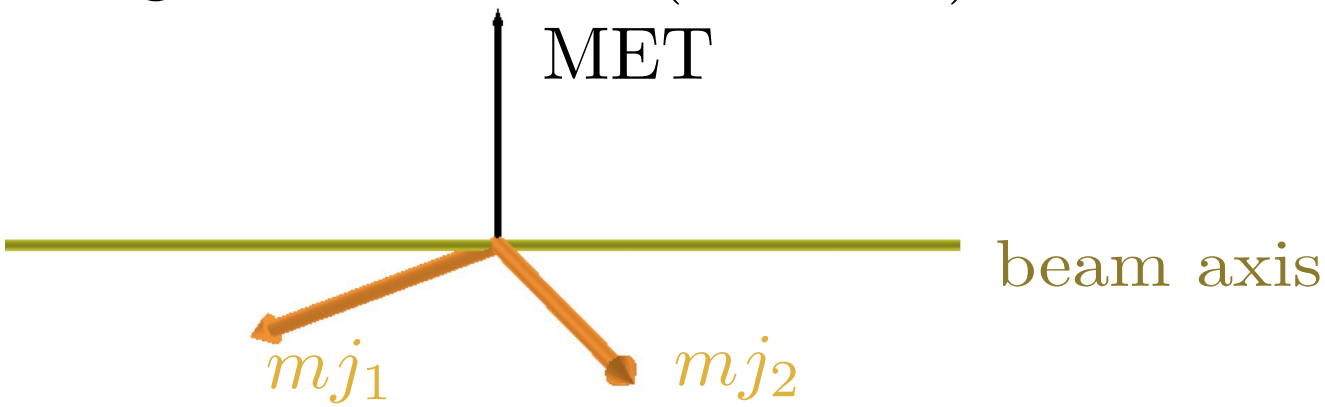


longitudinal boost (R-frame)

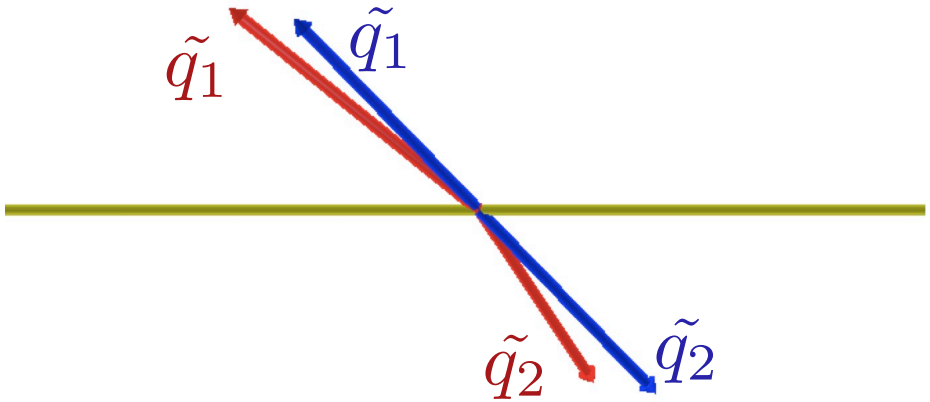




longitudinal boost (R-frame)



R-frame $\sim$ CM frame



M_R exponential scaling with R : data-driven modeling (QCD)

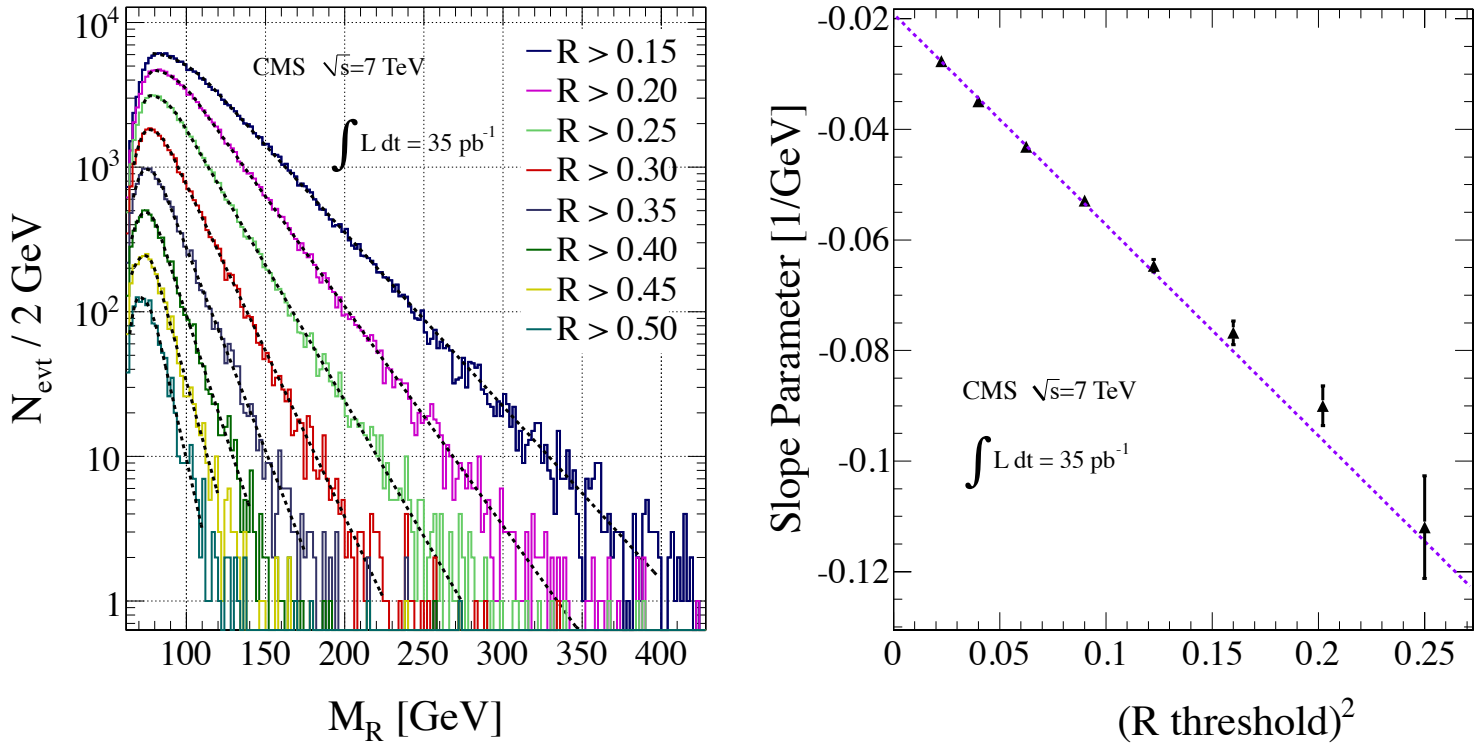


Figure 2: (Left) M_R distributions for different values of the R threshold for data events in the QCD control box. Fits of the M_R distribution to an exponential function and an asymmetric Gaussian at low M_R, are shown as dotted black curves. (Right) The exponential slope S from fits to the M_R distribution, as a function of the square of the R threshold for data events in the QCD control box.

M_R exponential scaling with R : data-driven modeling (W+jets)

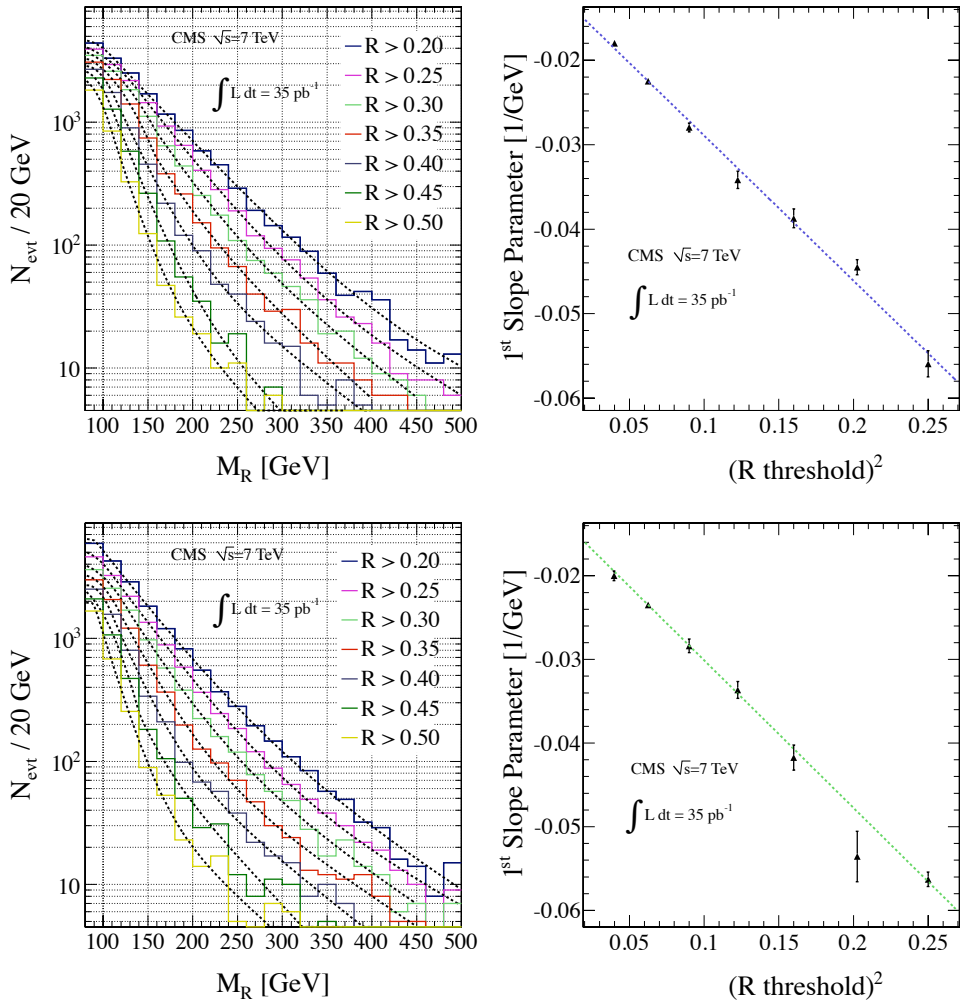
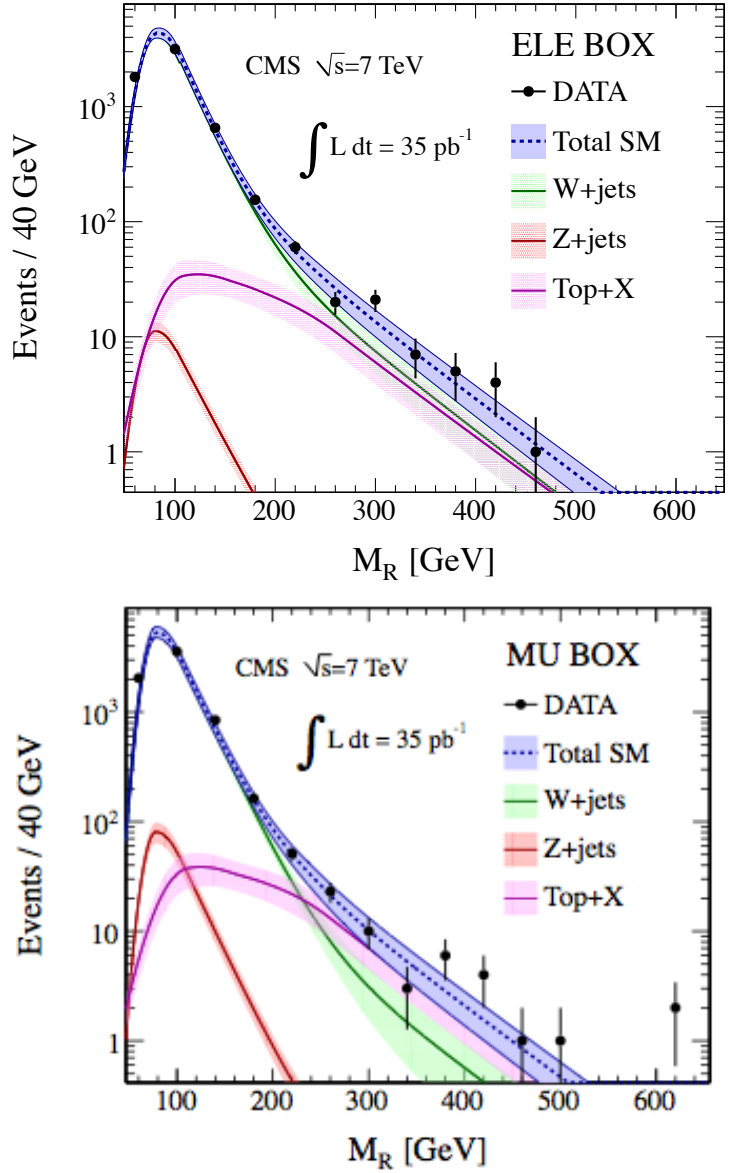
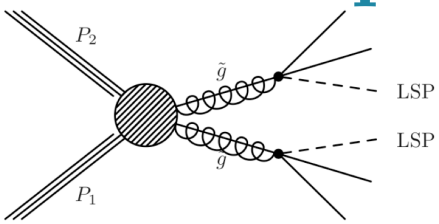


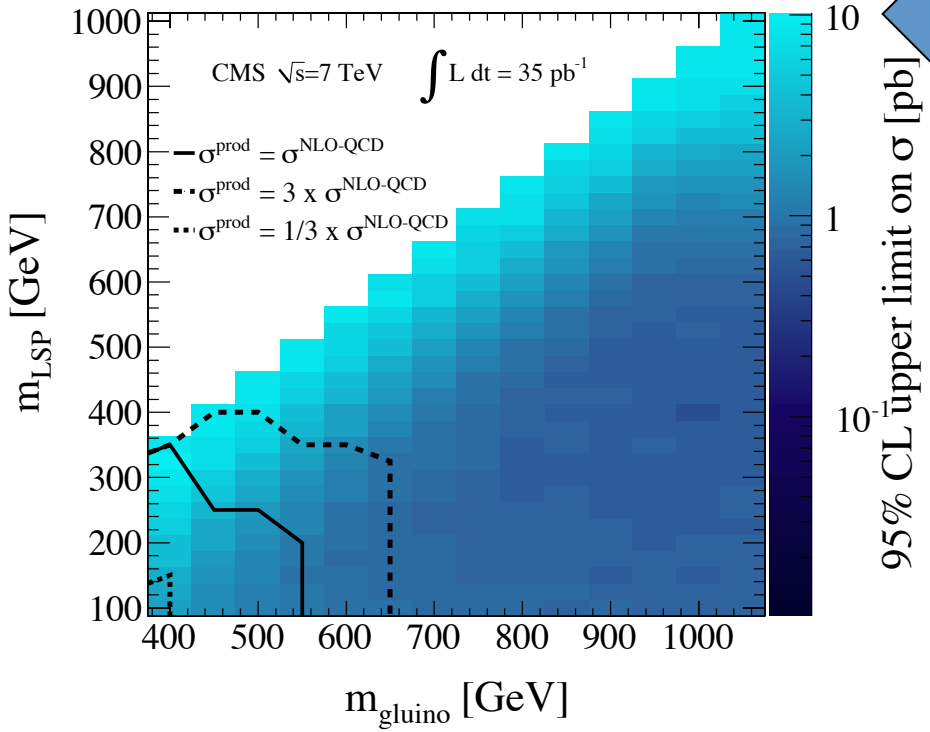
Figure 3: (Left) M_R distributions for different values of the R threshold from data events selected in the MU (upper) and ELE (lower) boxes. Dotted curves show the results of fits using two independent exponential functions and an asymmetric Gaussian at low M_R. (Right) The slope S of the first exponential component as a function of the square of the R threshold in the MU (upper) and ELE (lower) boxes. The dotted lines show the results of the fits to the form $S = a + bR^2$.



model independent interpretation

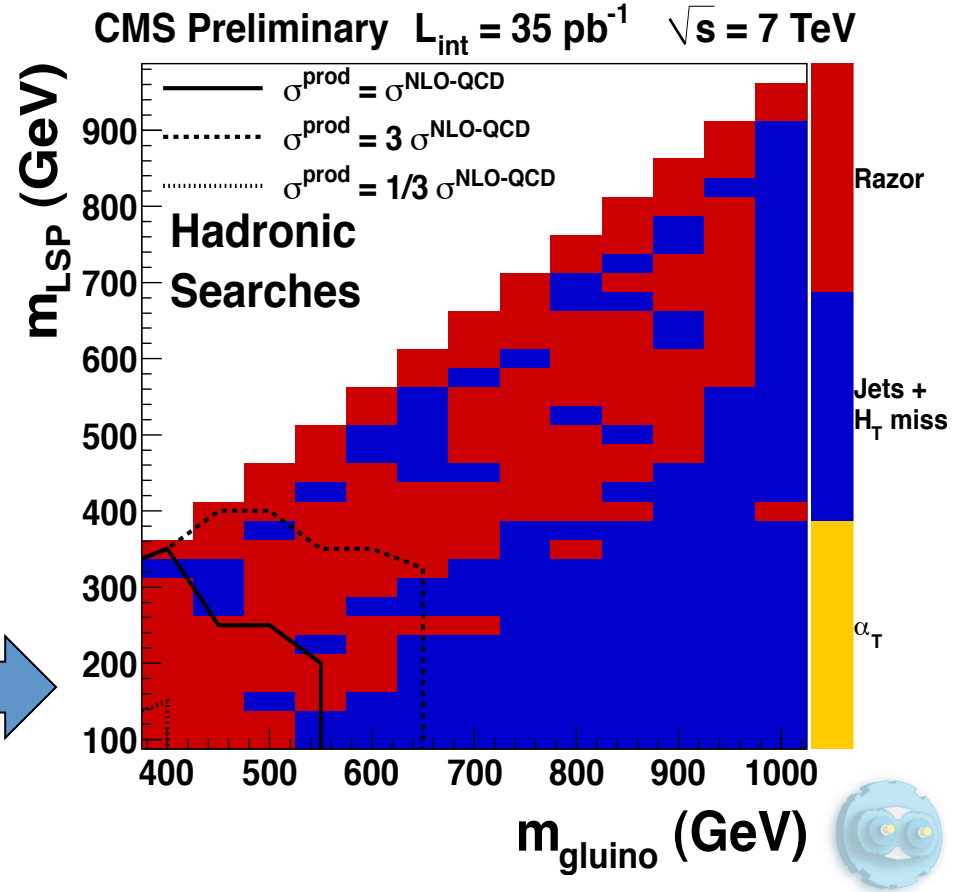


$$\tilde{g}\tilde{g} \rightarrow (qq\tilde{\chi}_1^0)(qq\tilde{\chi}_1^0)$$



Example Simplified (model independent) Interpretation

~0.5 TeV squaks/gluinos excluded



Extended razor reach complementary to to traditional MET+jets type-analyses

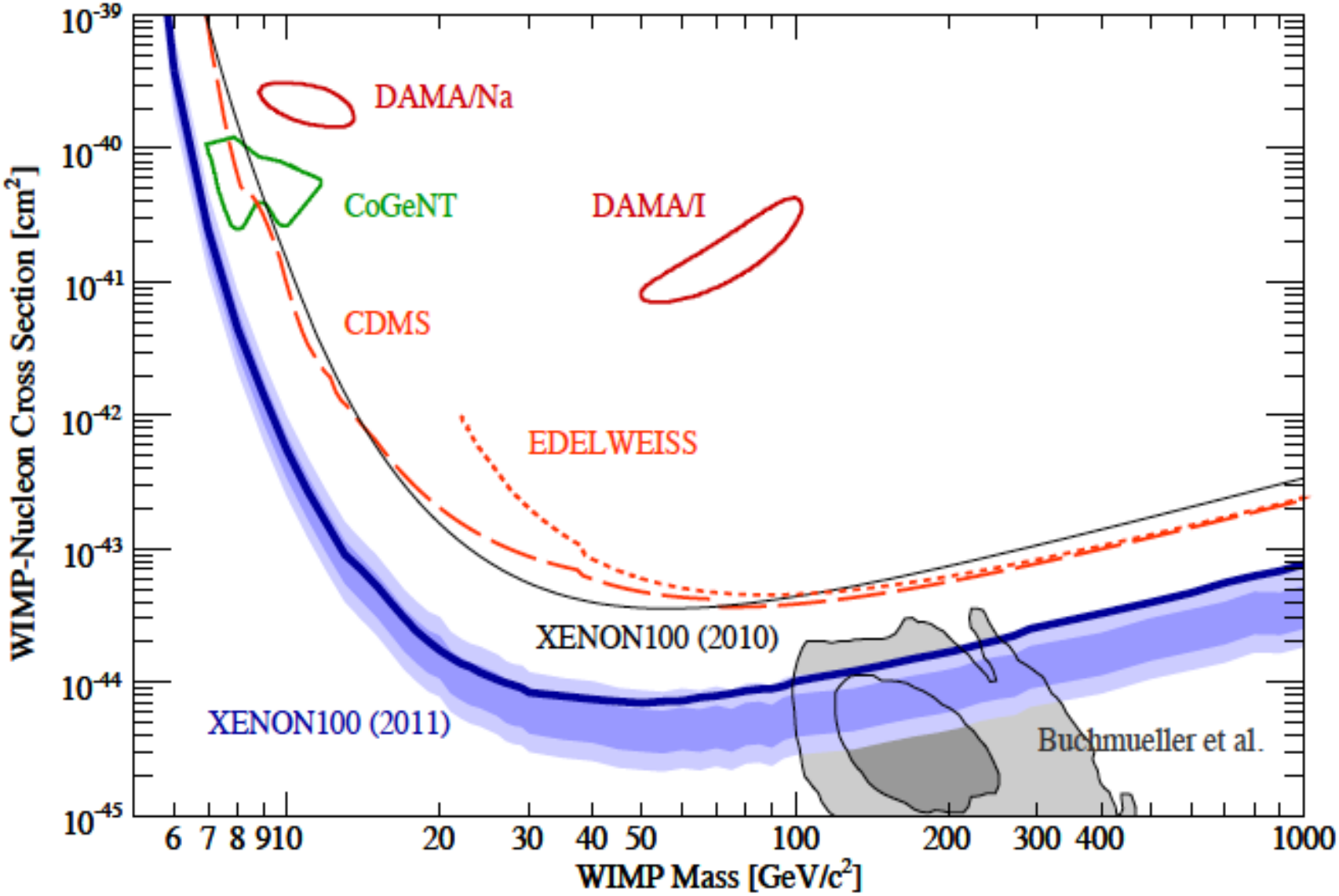
Facility	Original purpose, Expert Opinion	Discovery with Precision Instrument
P.S. CERN (1960)	π N interactions	Neutral Currents -> Z, W
AGS Brookhaven (1960)	π N interactions	2 kinds of neutrinos, Time reversal non-symmetry, New form of matter (4th Quark)
FNAL Batavia (1970)	Neutrino physics	*5th Quark, 6th Quark*
SLAC Spear (1970)	ep, QED	Partons, 4th Quark, 3rd electron
ISR CERN (1980)	PP	*Increasing PP Cross section*
PETRA Hamburg (1980)	6th Quark	*Gluon*
Super Kamiokande (2000)	Proton decay	Neutrinos have mass
Hubble Space Telescope	Galactic survey	*Curvature of the universe, dark energy*

Direct neutralino production

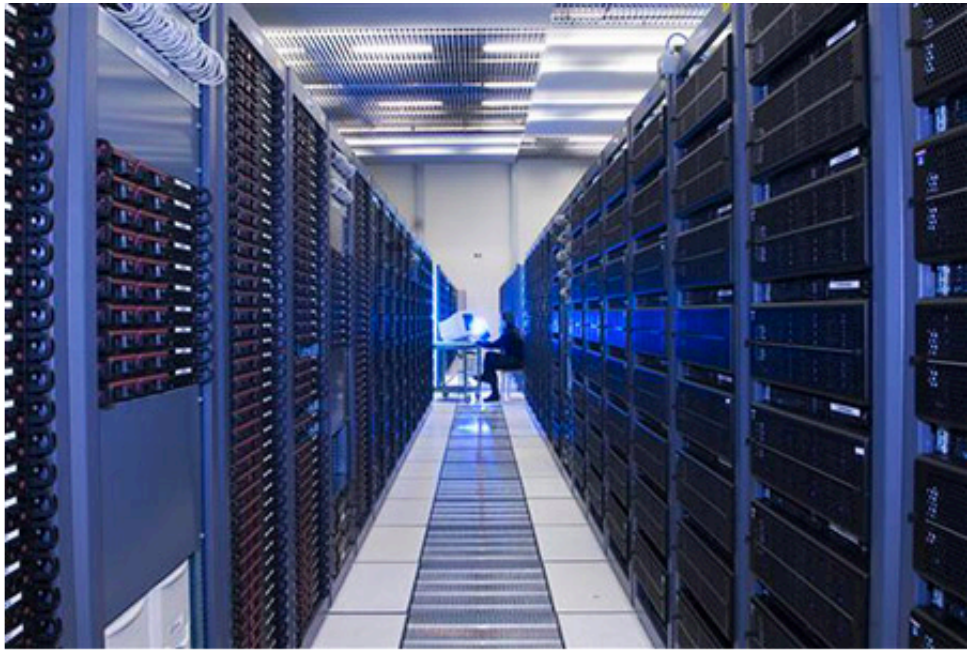
Example: LM5 mSUGRA benchmark model

- LSP mass 144 GeV
- gluino mass 850 GeV
- squark masses ~750 GeV
- LSP-LSP pair production cross section 130 fb (at 7 TeV)
  - asking for a hard ISR monojet knocks this down to ~10 fb
- LSP-gluino associated production 10 fb
- LSP-squark associated production 24 fb

We should be able to see direct WIMP DM production as long as the couplings are not *too* weak and the mass is reasonably light

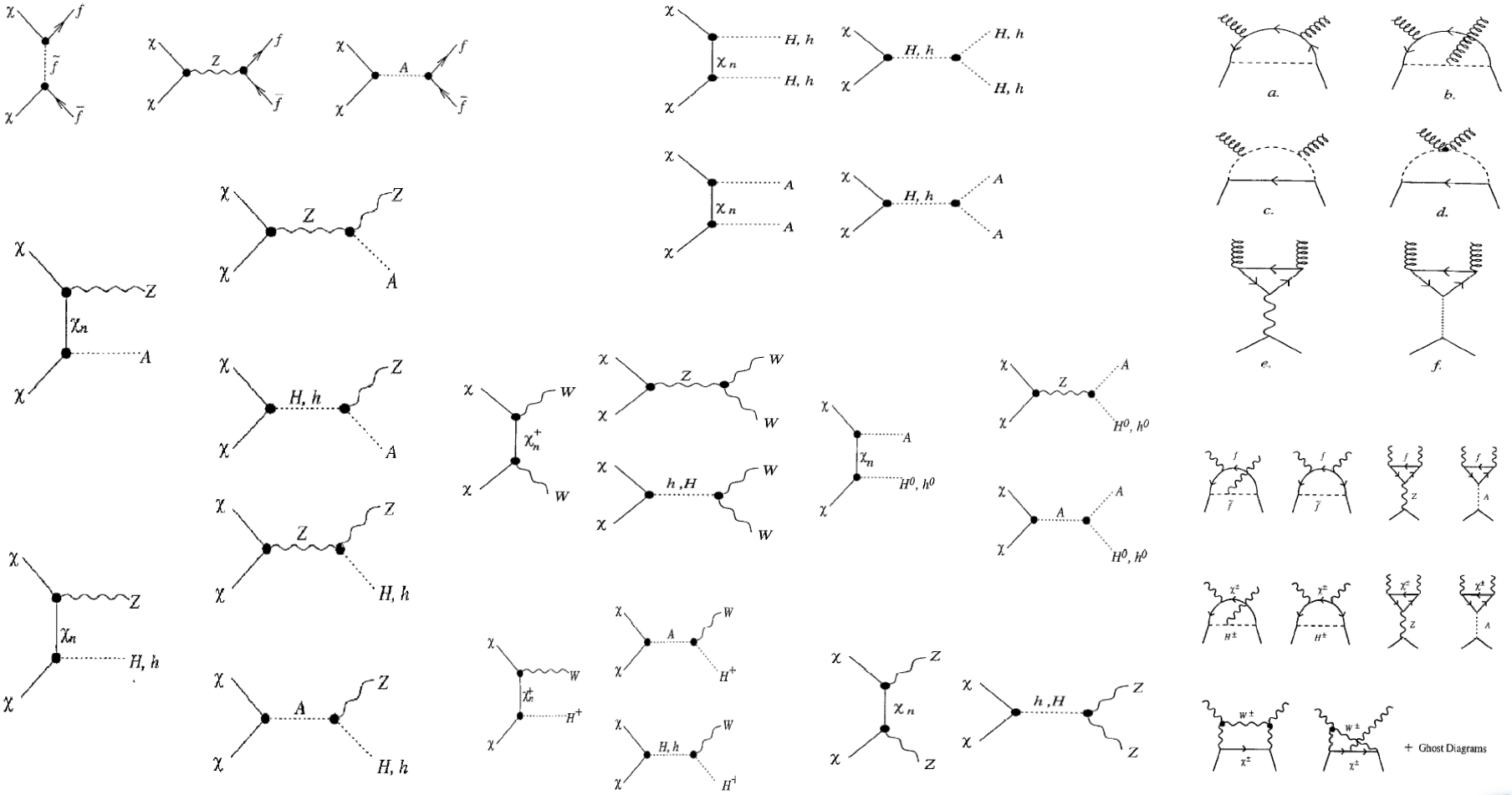

DAMA/Na
CoGeNT
DAMA/I
CDMS
EDELWEISS
XENON100 (2010)
XENON100 (2011)
Buchmueller et al.
WIMP-Nucleon Cross Section [cm²]
WIMP Mass [GeV/c²]
10⁻³⁹
10⁻⁴⁰
10⁻⁴¹
10⁻⁴²
10⁻⁴³
10⁻⁴⁴
10⁻⁴⁵
6 7 8 9 10
20
30
40
50
100
200
300
400
1000

CMS data rate



- The raw data rate is 100 million channels divided by 25 nanoseconds = 1 Petabyte/second
- Compare this to total global WWW traffic = 5 Terabytes/sec
- Compare this data load to Google, which processes 20 Petabytes per day

Contributions to Neutralino WIMP Annihilation



Jungman, Kamionkowski, Griest (1995)

There exist two principal methods to compute the pole masses:

- Common-scale approach (CSA)

  The $\overline{\mathrm{DR}}$ SUSY parameters are all extracted collectively at a scale $Q = M_{\mathrm{SUSY}}$, and the (logarithmic + finite) self-energy corrections are added at that scale.

  $\longrightarrow$ SoftSusy, SPheno and SuSpect

- Step-beta function approach (SFA)

  Each $\overline{\mathrm{DR}}$ SUSY parameter m_i is extracted at its own mass scale $m_i(m_i)$. For un-mixed sparticles, this corresponds to a leading-log approximtion of the pole mass. The finite corrections are added separatly.

  $\longrightarrow$ method followed in Isajet

NB: mismatch of ren. scales in Isajet <7.73, mostly affected lightest states

[Baer, Ferrandis, SK, Porod, hep-ph/0511123]

[Allanach, SK, Porod, hep-ph/0302102]

Tricky corners

- Large $\tan\beta$: bottom Yukawa coupling important for calculation of m_A

$$m_A^2 = \frac{1}{c_{2\beta}}\left(\overline{m}_{H_2}^2 - \overline{m}_{H_1}^2\right) + s_\beta^2 \frac{t_1}{v_1} + c_\beta^2 \frac{t_2}{v_2} - M_Z^2 - \ldots$$

- Large m_0: μ parameter becomes extremely sensitive to top Yukawa coupling

$$\mu^2 = \frac{\overline{m}_{H_1}^2 - \overline{m}_{H_2}^2 \tan^2\beta}{\tan^2\beta - 1} - 0.5(M_Z^2 + \Re\Pi_{ZZ}^T)$$

$$\overline{m}_{H_i}^2 = m_{H_i}^2 - t_i/v_i \quad (i = 1, 2)$$

$$16\pi^2 \frac{t_1}{v_1} = -\sum_{f_d} 2N_c^f h_d^2 A_0(m_d) + \sum_f \sum_{i=1}^{2} N_c^f \frac{gh_{s_1\tilde{f}_i\tilde{f}_i}}{2m_W c_\beta} + \ldots.$$

$$16\pi^2 \frac{t_2}{v_2} = -\sum_{f_u} 2N_c^f h_u^2 A_0(m_u) + \sum_f \sum_{i=1}^{2} N_c^f \frac{gh_{s_2\tilde{f}_i\tilde{f}_i}}{2m_W c_\beta} + \ldots.$$

$\Rightarrow$ want Yukawa couplings + tadpoles as precisely as possible (2–loops?) $\Leftarrow$