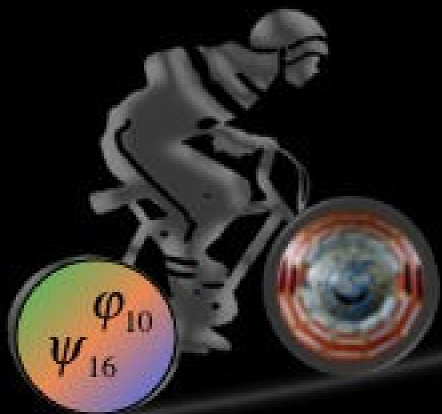
Pursuit of the SO10 SUSY GUTs

in theory and in colliders….



Sezen Sekmen, Florida State University
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IPN Lyon – 06/04/2010

Contents

- *Yukawa unification*
- *Introducing SO(10) SUSY GUTs*
- *Dark matter implications*
- *SO(10) SUSY GUTs at colliders (Tevatron and LHC)*

SUSY GUTs

SUPERSYMMETRY:

- Hierarchy problem and divergences ✓
- EWSB ✓
- More fundamental framework ✓
- Dark matter ✓
- Gauge coupling unification ✓
-

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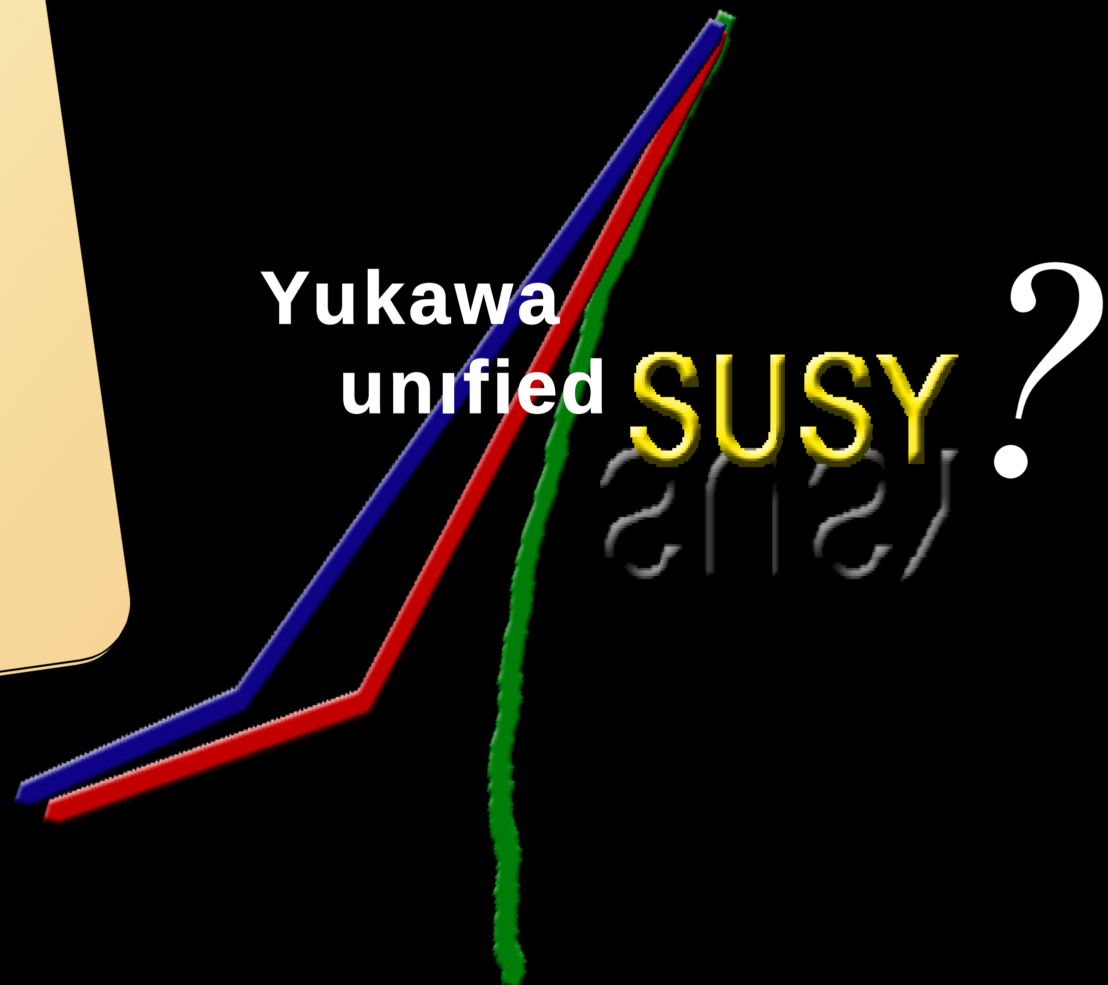
- Hierarchy problem and divergences ✓
- EWSB ✓
- More fundamental framework ✓
- Dark matter ✓
- Gauge coupling unification ✓
- Yukawa coupling unification ???



Setting the stage

At the GUT scale 3rd generation Yukawa couplings should unify at tree level:

$$y_t^G = y_b^G = y_\tau^G = y$$

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$$\frac{m_t}{m_b} = \frac{y_t v_u}{y_b v_d} = \frac{y_t}{y_b} \tan\beta$$

Setting the stage

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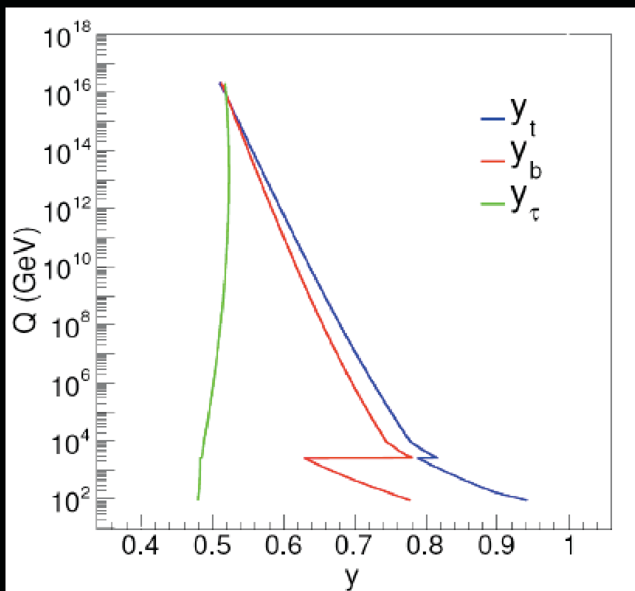
$$y_t^G = y_b^G = y_\tau^G = y$$



RGEs for the MSSM:

$$2\pi \frac{d \ln Y_t}{dt} = 6Y_t + Y_b - \frac{13}{15}\alpha_1 - \frac{16}{3}\alpha_3 - 3\alpha_2$$

$$2\pi \frac{d \ln Y_b}{dt} = 6Y_b + Y_t - \frac{7}{15}\alpha_1 - \frac{16}{3}\alpha_3 - 3\alpha_2$$

$$2\pi \frac{d \ln Y_\tau}{dt} = 4Y_\tau - \frac{9}{5}\alpha_1 - 3\alpha_2$$

$$Y_i \equiv y_i^2 / 4\pi$$

At the weak scale m_t/m_b mass relation should hold

$$\frac{m_t}{m_b} = \frac{y_t v_u}{y_b v_d} = \boxed{\frac{y_t}{y_b}} \boxed{\tan\beta}$$

~ 1 ➡ ~ 50

S 10

One group to rule them all…

SO(10) SUSY GUTs

Unification based on SO(10) Lie group is a highly motivated possibility.

In SO(10) SUSY GUTs:

- All matter in one generation reside in a single, irreducible 16-dimensional representation.
- Two Higgs doublets necessary within the MSSM reside in a single irreducible 10-dmensional representation.

J.C. Pati and A. Salam, Phys. Rev. D10, 275 (1974); H. Georgi and S.L. Glashow, Phys. Rev. Lett. 32, 438 (1974). H. Georgi, H.R. Quinn and S. Weinberg, Phys. Rev. Lett. 33, 451 (1974); S. Weinberg, Phys. Lett. B91, 51 (1980)., etc.

Reviews:
R. Mohapatra, hep-ph/9911272 (1999) and S. Raby, in Phys. Rev. D66, 010001 (2002).

Motivation for SO(10) SUSY GUTs

- Offers a unified framework
- 16 dim representations naturally contain right-handed neutrino (RHN) states. Upon SO(10) breaking they become SM gauge singlets and acquire a Majorana mass $M_N \sim 10^{10\text{-}16}$ GeV. This is necessary for seesaw mechanism which generates non-zero left-handed neutrino masses in accordance with current measurements.
- Structure of the SO(10) neutrino sector leads to a successful theory of baryogenesis via intermediate scale leptogenesis
- GUT scale consistent with bounds from proton decay
- …

Yukawa unification

The superpotential of unbroken SO10 contains the following term

$$\hat{W} \supset y\psi(16)_3\phi(10)_H\psi(16)_3 + \ldots$$

which shows that Yukawa couplings of each generation should be unified at the GUT scale at tree level.

$$y_t = y_b = y_\tau = y_{\nu_\tau} \equiv y$$

Several % corrections arise at the loop level.

Degree of Yukawa unification is given by

$$R = \max(y_t, y_b, y_\tau) / \min(y_t, y_b, y_\tau)$$

Requirement of Yukawa unification constrains the weak scale realization of the SO(10) SUSY GUTs and defines their signature phenomenology.

Breaking the SO(10)

- At $Q = M_{GUT}$, SO(10) SUSY is valid.
- SUSY breaking via gravity mediation.
- At M_{GUT}, SO(10) breaks via a Higgs mechanism or a mechanism involving compactification on 5D or 6D to the SM gauge group.
- Effective theory between $M_{GUT} – M_{SUSY}$ is MSSM or MSSM+RHN.
- Note that rank of SO(10) = rank of G_{SM} + 1:
    - There is an extra $U(1)_X$ factor broken at some high scale M_X.
    - This extra symmetry has its effects on scalars and Higgs masses.
    - m_D, the magnitude of the D terms in $U(1)_X$ scalar potential contributes to the definition of GUT scale sfermion and Higgs mass parameters. It is a free parameter.

Simple parametrizations

At the GUT scale…

m_{16} :	common SSB scalar mass
$m_{1/2}$:	common SSB gaugino mass
m_{10} :	common SSB Higgs mass
m_D :	$U(1)_X$ D term magnitude
A_0,	Trilinear gauge coupling
tanß:	Ratios of VEVs

NEW!

NEW!

1. Higgs splitting (HS):

$$m^2_{Q,E,U,D,L,N} = m^2_{16}$$

$$m^2_{H_{u,d}} = m^2_{10} \mp 2M^2_D$$

2. Full D-term splitting (DT)

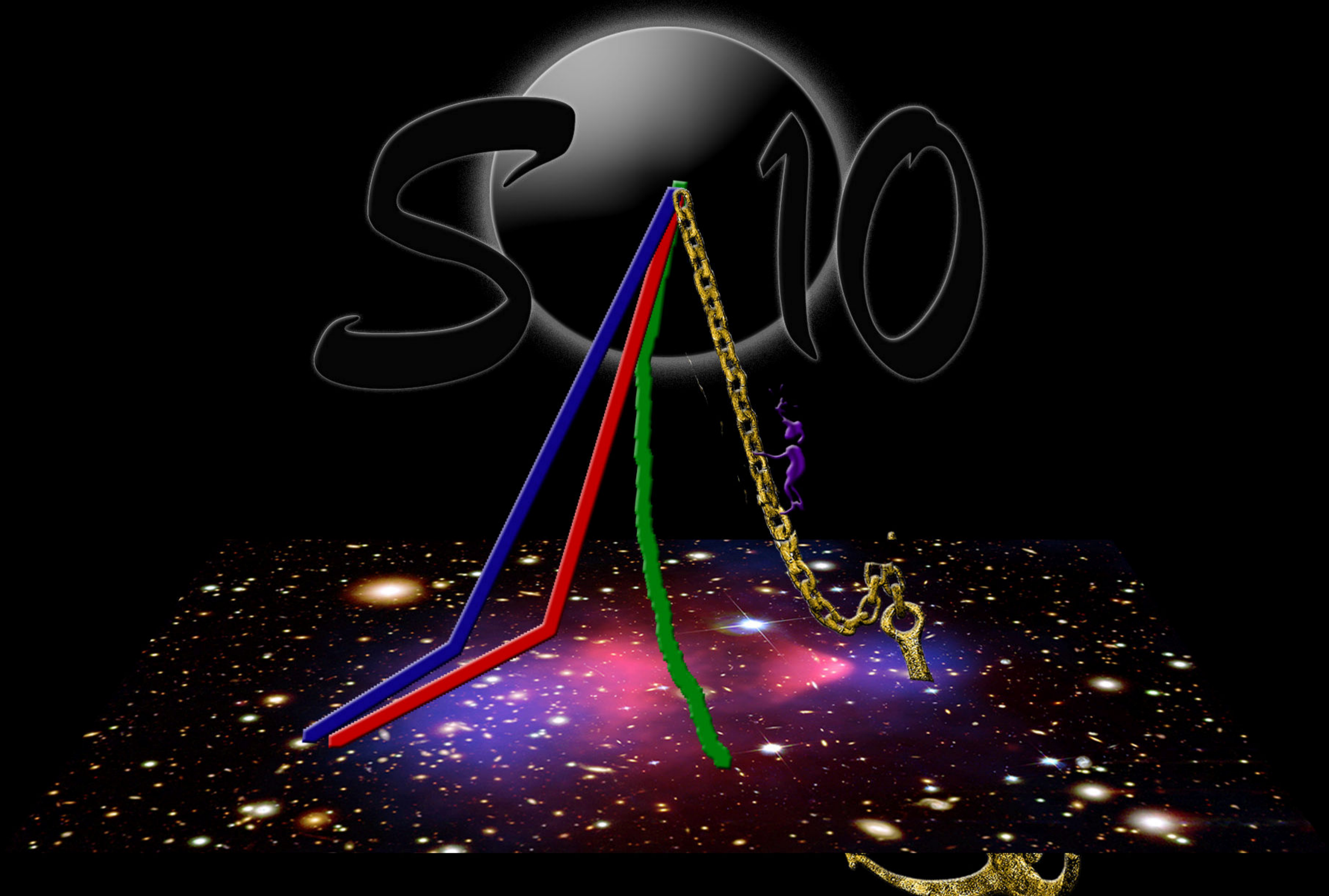
$$m^2_{Q,E,U} = m^2_{16} + M^2_D$$

$$m^2_{D,L} = m^2_{16} - 3M^2_D$$

$$m^2_{H_{u,d}} = m^2_{10} \mp 2M^2_D$$

$$m^2_N = m^2_{16} + 5M^2_D$$

$g_\mu - 2$ measurements favor sign(μ) positive.

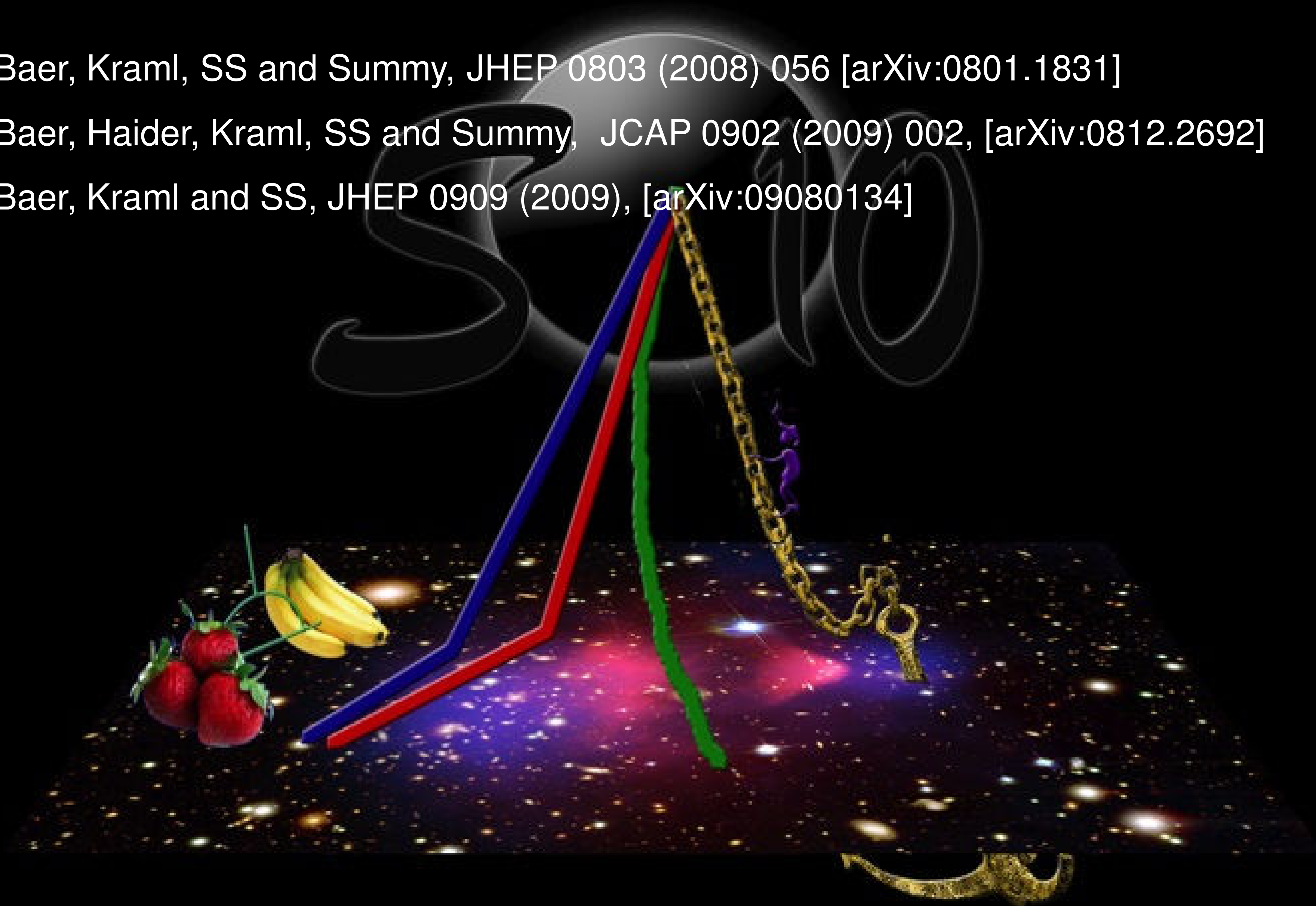

S10


S10

Baer, Kraml, SS and Summy, JHEP 0803 (2008) 056 [arXiv:0801.1831]

Baer, Haider, Kraml, SS and Summy, JCAP 0902 (2009) 002, [arXiv:0812.2692]

Baer, Kraml and SS, JHEP 0909 (2009), [arXiv:09080134]



Search for SO(10) SUSY GUTs

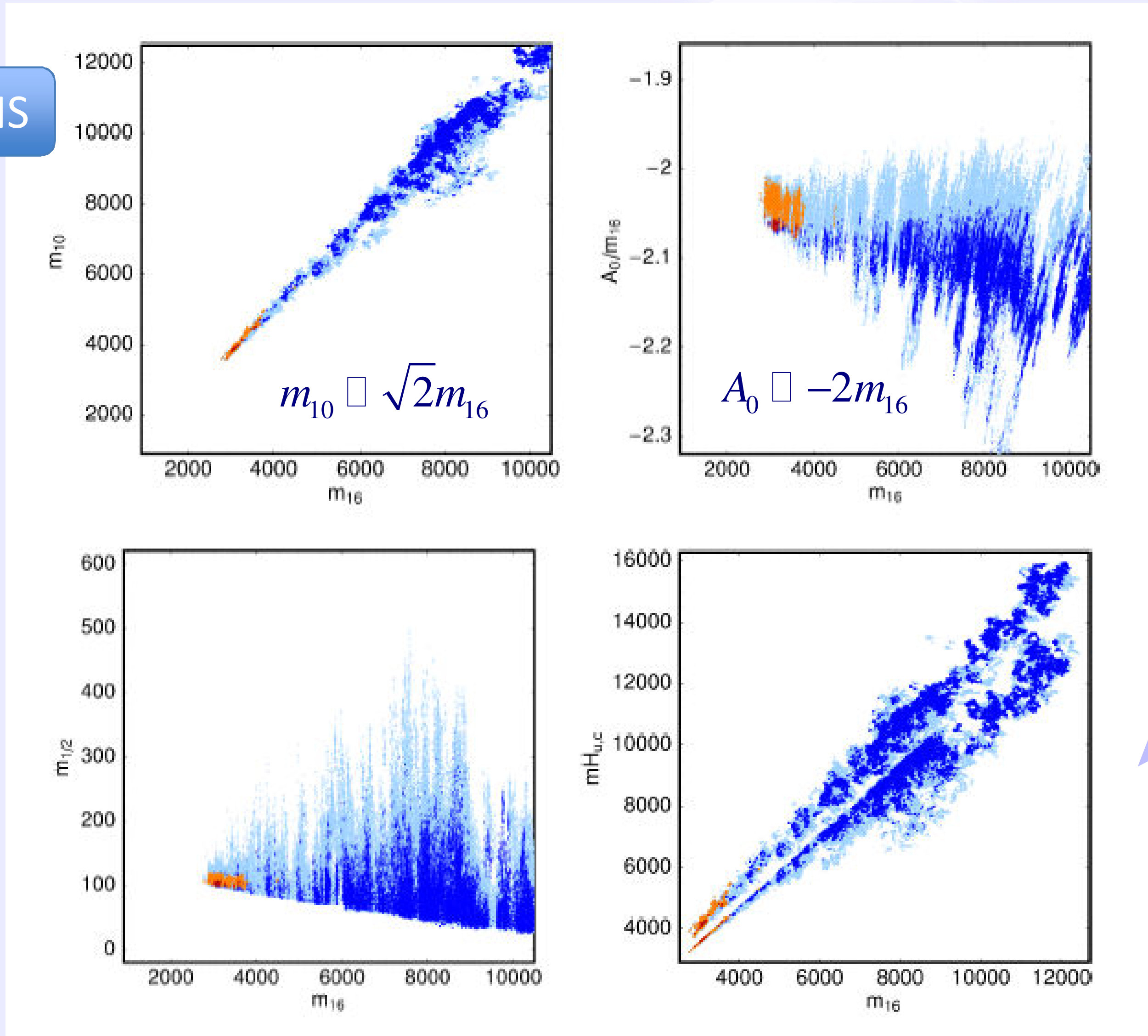
- Input HS or DT parameters at the GUT scale.
- Input measured values of EW observables at low scale.
- Start RG running at m_Z using full 2-loop RGEs for for the soft terms, and get the solution.
- Check degree of Yukawa unification R.
- Use Markov Chain Monte Carlo (MCMC) technique to efficiently find parameter space reasons with good Yukawa unification (i.e.: < 5-10%)
- Also check DM relic density and EW precision observables:

$$\Omega h^2;\ \Delta\rho;\ g_\mu - 2;\ BR(b \to s\gamma);\ BR(B_s \to \mu\mu);\ \sigma_{sc}(\tilde{\chi}_1^0 p)$$

Spectrum calculator: ISAJET/ISASUGRA
DM, EWPO: micrOMEGAs

Yukawa-unified regions

HS



$R \leq 1.10$
$R \leq 1.05$
$R \leq 1.10$ & $\Omega \leq 0.136$
$R \leq 1.05$ & $\Omega \leq 0.136$

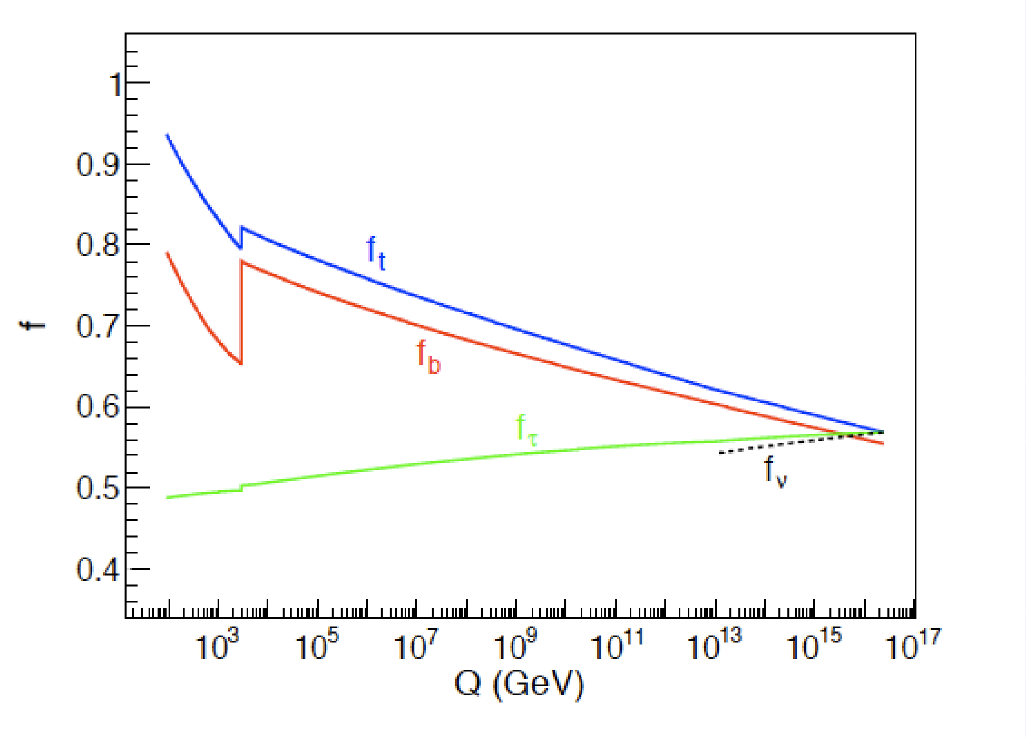
Consistent with the relations predicted by radiatively-driven inverted scalar mass hierarchy

DT to DR3

The full D-term (DT) splitting case does not give good Yukawa unification. So we proposed the DR3 scenario which has:

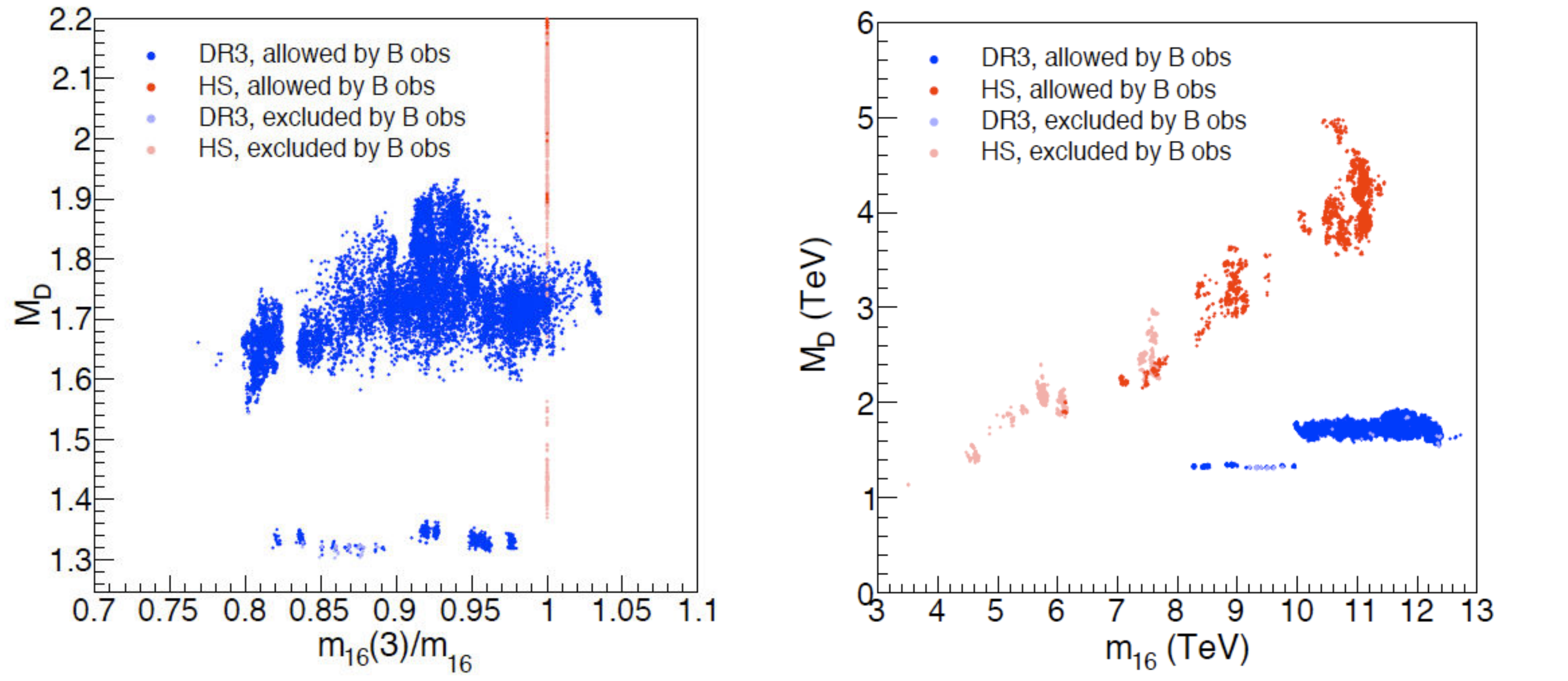
✓ Full DT splitting case (including a RHN with mass scale 10^{13} GeV).

✓ Additional non-universality of 3rd generation scalars – now we have $m_{16}(1,2) \neq m_{16}(3)$.



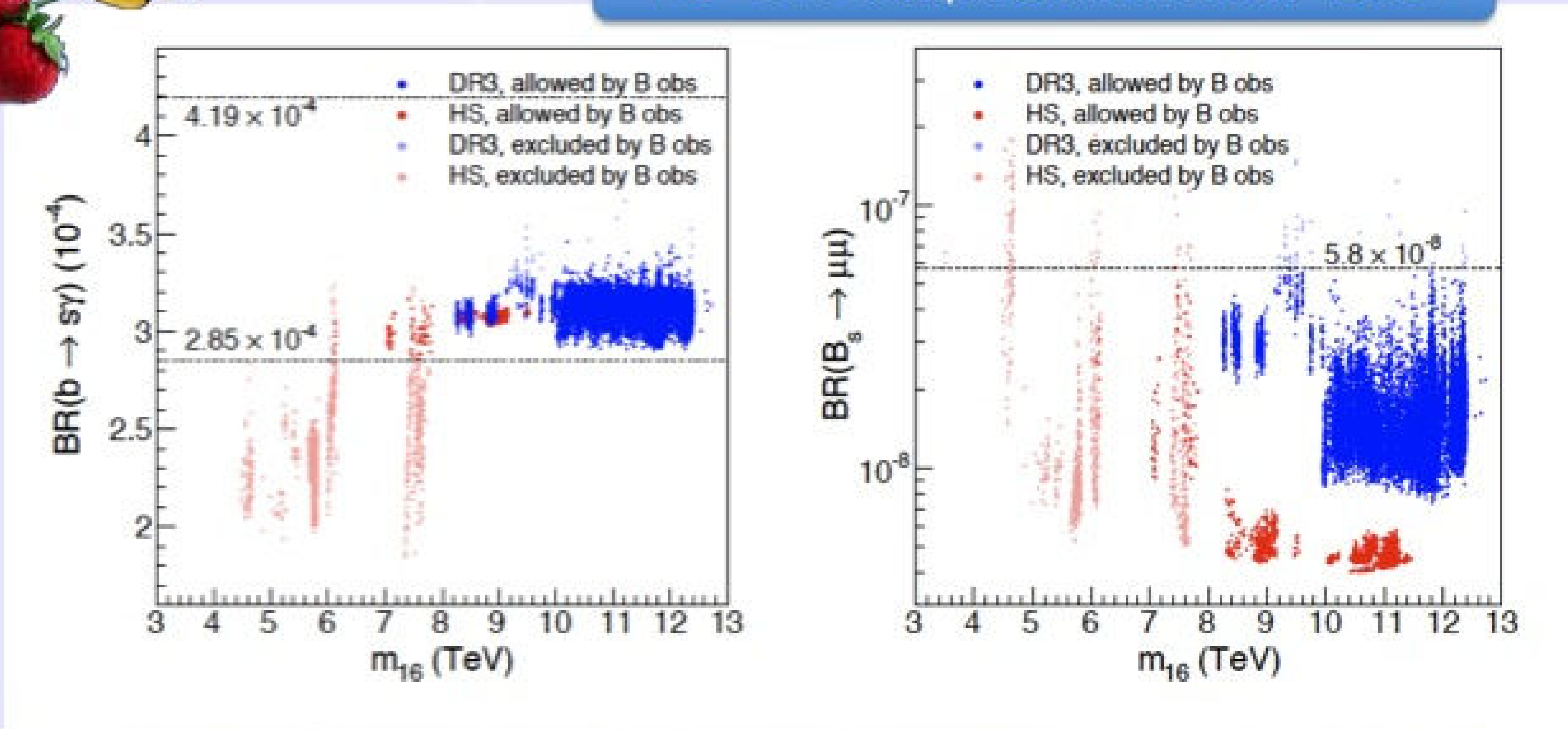
DR3 space

HS – DR3 comparison: Shows R < 1.05



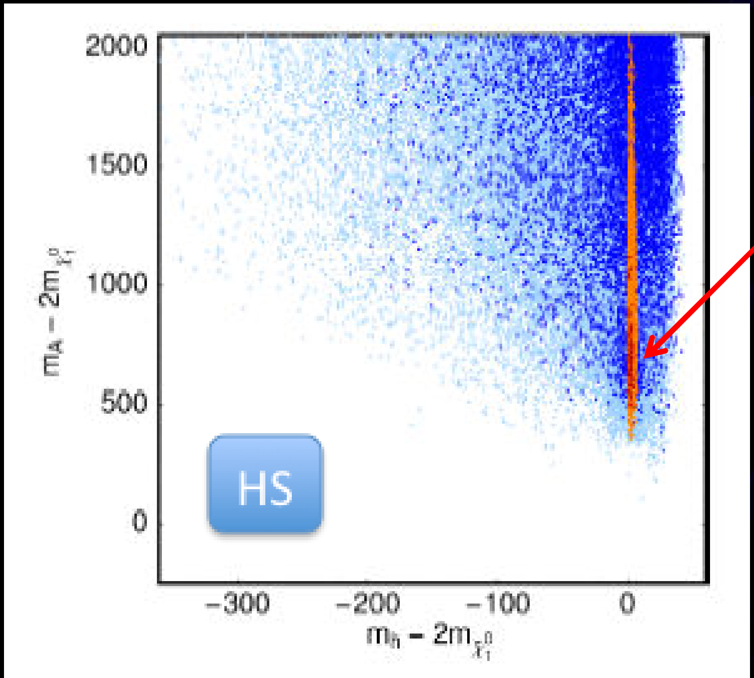
Flavor changing neutral currents

HS – DR3 comparison: Shows R < 1.05



DR3 solutions are 99.7% consistent with BR(b -> sγ) and BR(B -> μμ) measurements.

Dark Matter relic density

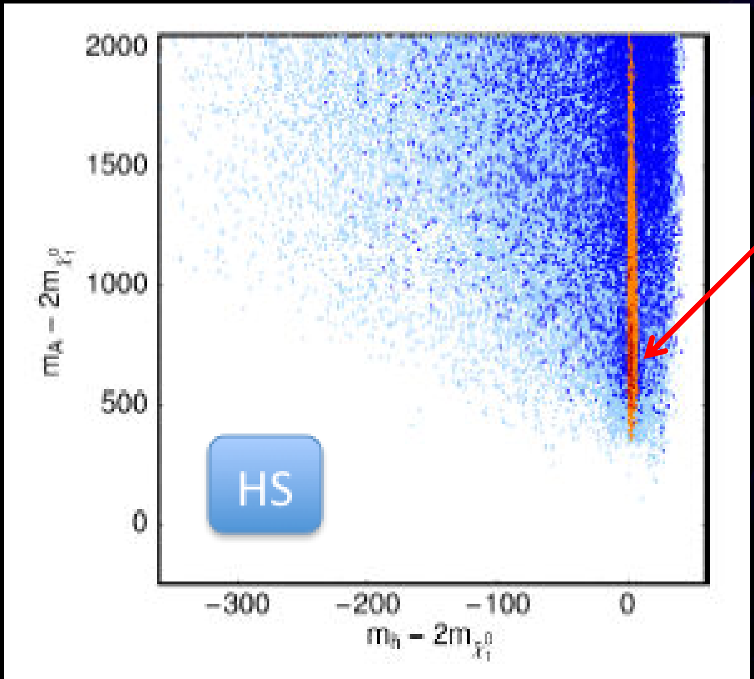


R ≤ 1.10
R ≤ 1.05,
R ≤ 1.10 & Ω ≤ 0.136
R ≤ 1.05 & Ω ≤ 0.136

$\Omega_{\tilde{\chi}_1^0} h^2$ is generally too high.
Few compatible solutions due to efficient $\tilde{\chi}_1^0$ annihilation at h^0 resonance.

How to reconcile the relic density without sacrificing Yukawa unification?

Dark Matter relic density



R ≤ 1.10
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$\Omega_{\tilde{\chi}_1^0} h^2$ is generally too high. Few compatible solutions due to efficient $\tilde{\chi}_1^0$ annihilation at h^0 resonance.

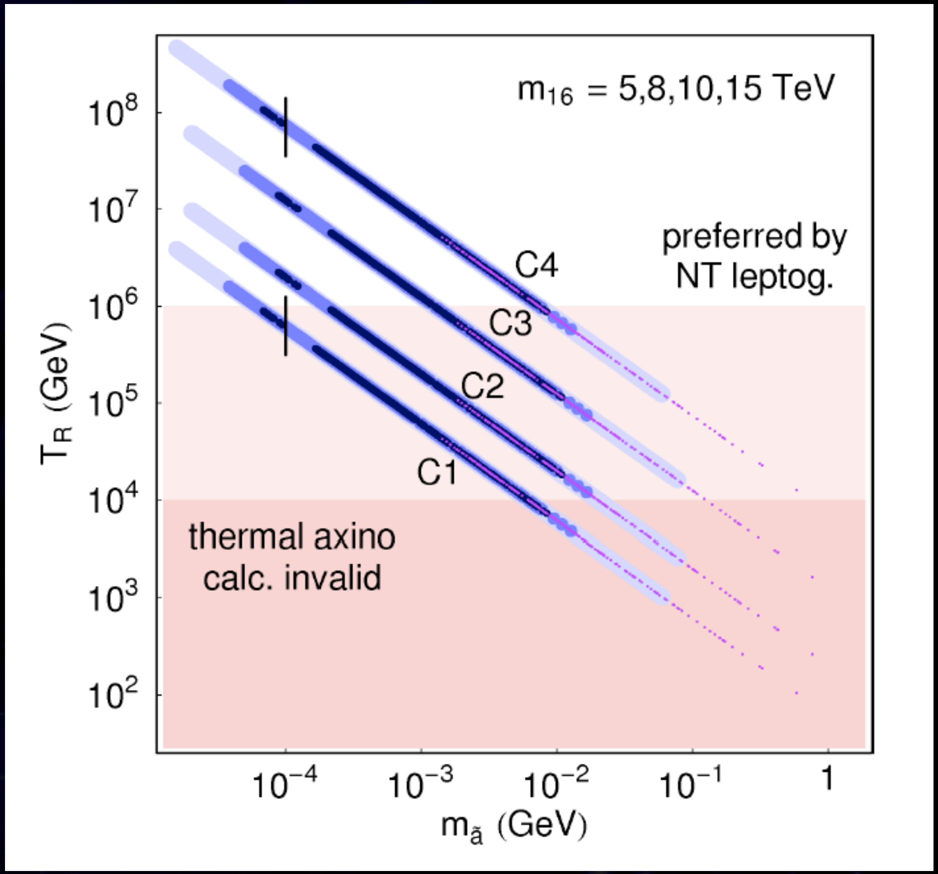
How to reconcile the relic density without sacrificing Yukawa unification?

- ***Introduce non-universalities in m_{16} and $m_{1/2}$. ✓***
- ***Assume $\tilde{\chi}_1^0$ is unstable and decays into an axino + photon. Light axinos are LSPs – Ωh^2 decreases drastically. ✓***

Axion-axino cold-warm dark matter

We propose a dark matter cocktail that consists of:

- Thermal axions prodced via vacuum misallignment (CDM)
- Non-thermal axinos via neutralino1 decays (CDM for axino mass > 1GeV)
- Thermal axinos from early Universe produced via scattering (CDM for axino mass > 100keV)



Checked compliance with

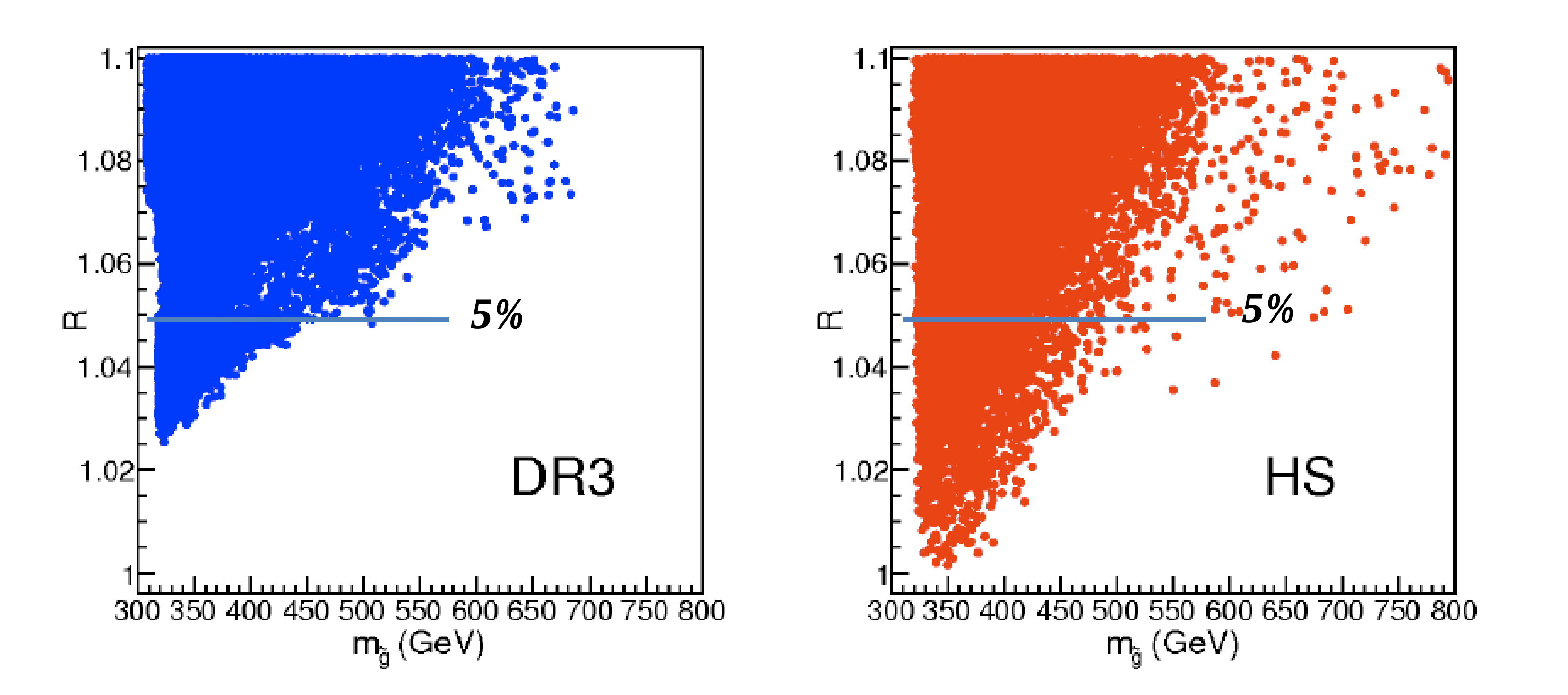
- BBN grivitino mass limits
- Non-thermal leptogenesis

Can be cosmologically consistent!

Baer, Kraml, Haider, SS, Summy, JCAP 0902:002, 2009

SO(10) sparticle spectrum

- Very heavy 1st/2nd gen scalars (>3TeV)
- 3rd gen scalars, heavy gauginos, heavy higgses ~TeV
- Light gauginos ~O(100 GeV)
- Gluino ~300 – 600 GeV



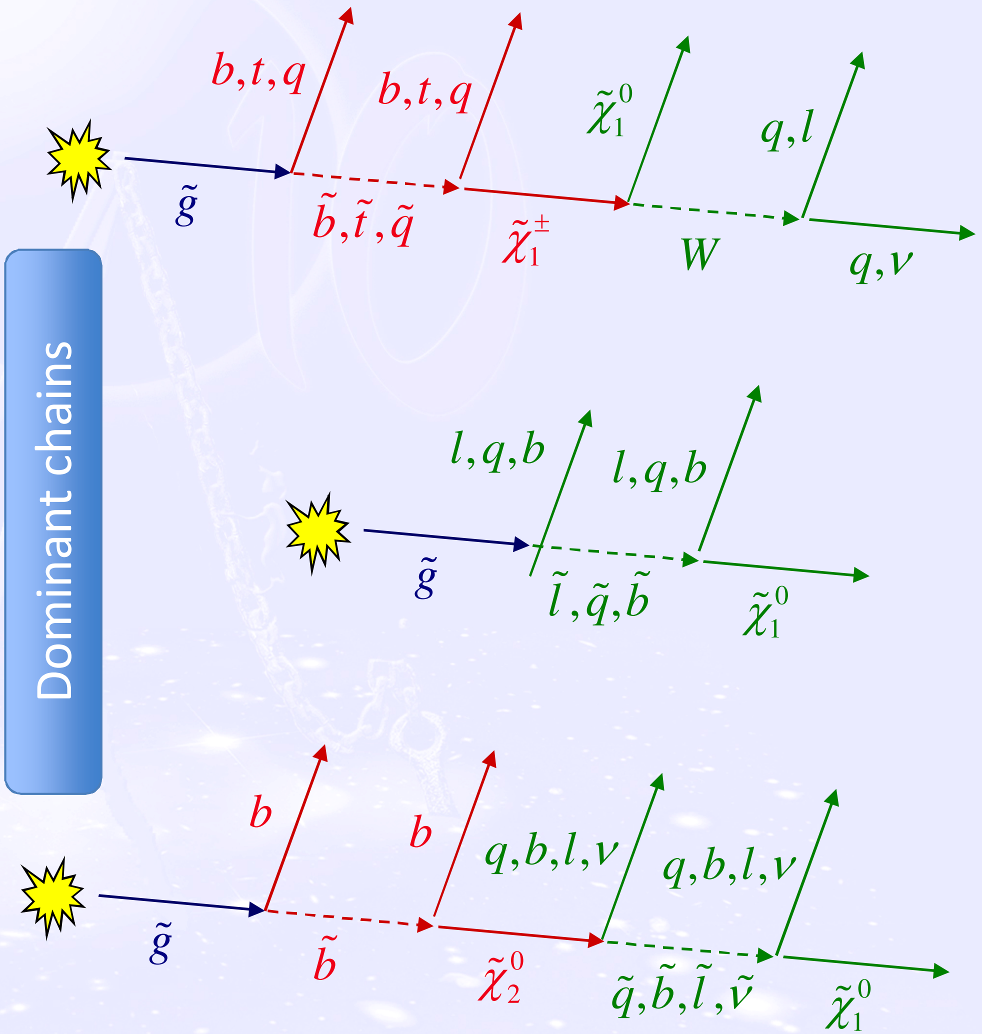
Example SO(10) benchmarks

parameter	HSb	DR3b
$m_{16}(1,2)$	10000	11805.6
$m_{16}(3)$	10000	10840.1
m_{10}	12053.5	13903.3
M_D	3287.1	1850.6
$m_{1/2}$	43.9442	27.414
A_0	−19947.3	−22786.2
$\tan\beta$	50.398	50.002
R	1.025	1.027
μ	3132.6	2183.4

parameter	HSb	DR3b
$m_{\tilde{g}}$	351.2	321.4
$m_{\tilde{u}_L}$	9972.1	11914.2
$m_{\tilde{t}_1}$	2756.5	2421.6
$m_{\tilde{b}_1}$	3377.1	1359.5
$m_{\tilde{e}_R}$	10094.7	11968.5
$m_{\widetilde{W}_1}$	116.4	114.5
$m_{\widetilde{Z}_2}$	113.8	114.2
$m_{\widetilde{Z}_1}$	49.2	46.5
m_A	1825.9	668.3
m_h	127.8	128.6

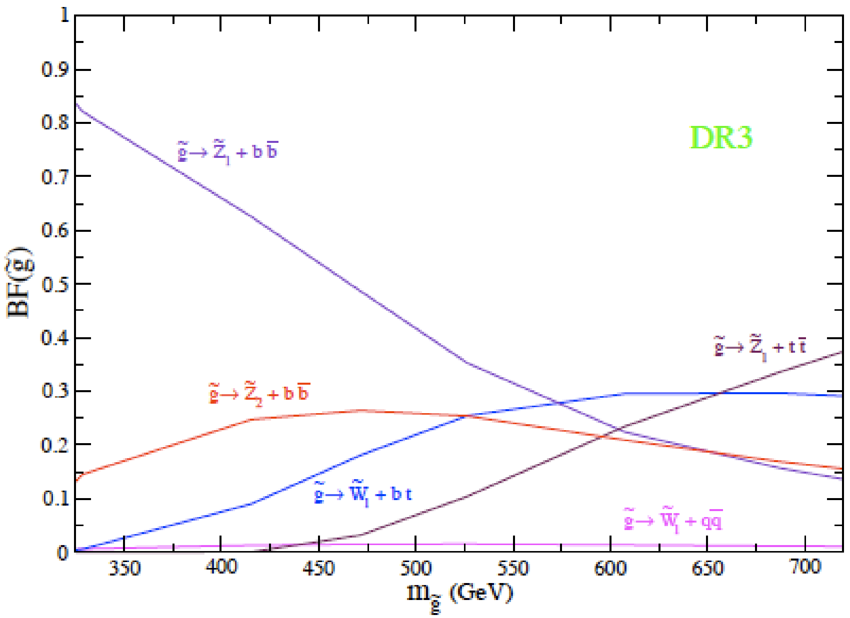
SO(10) sparticle decays

- Only gluinos and light gauginos can be produced at Tevatron and LHC.
- These mostly decay through 3-body modes, because the 2-body modes are closed due to the very heavy scalars.
- Only exception is neutralino 2s decaying via Zs for some cases.
- Decay structure enables edge studies.

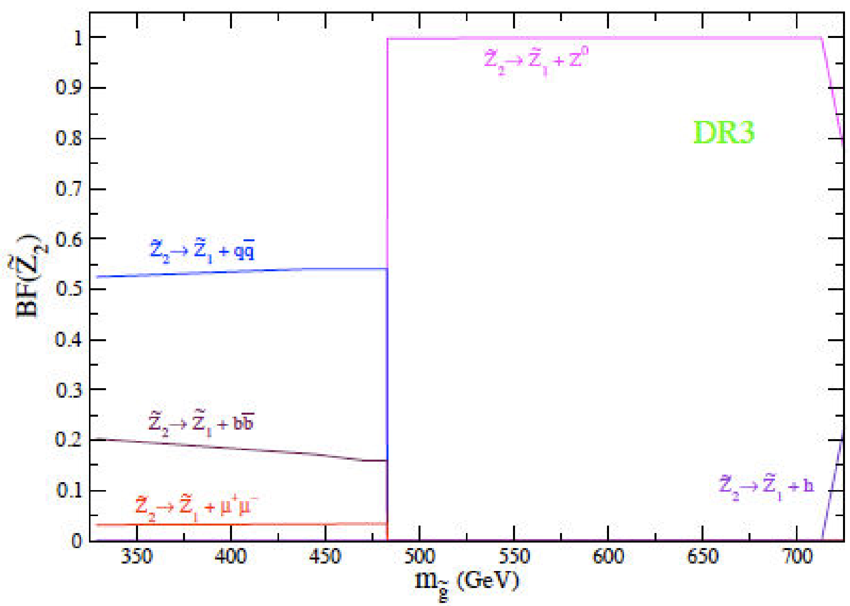


Branching ratios

Gluino



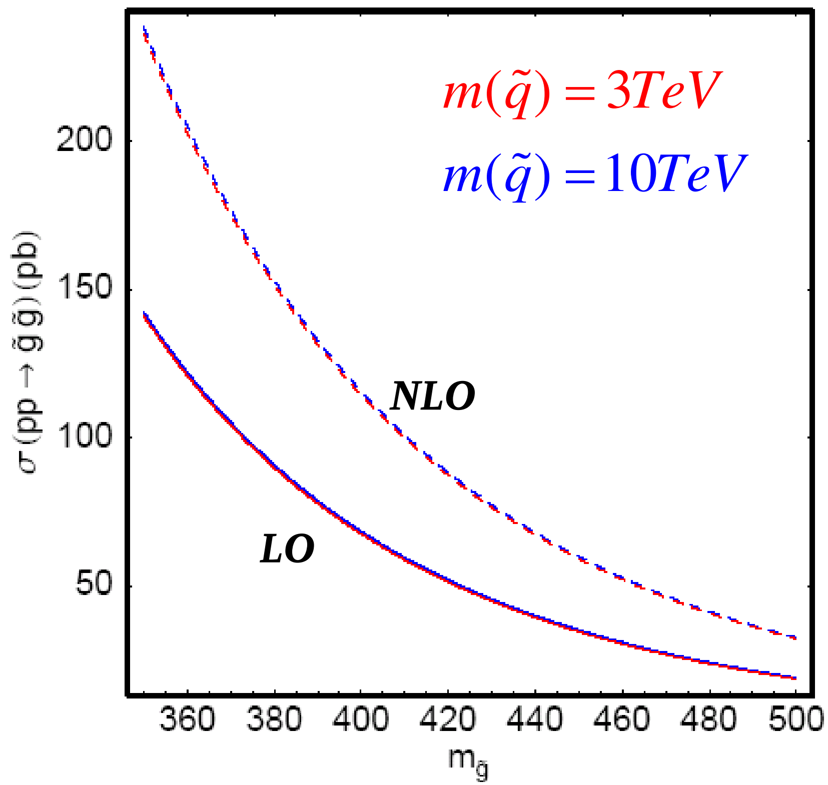
Neutralino 2

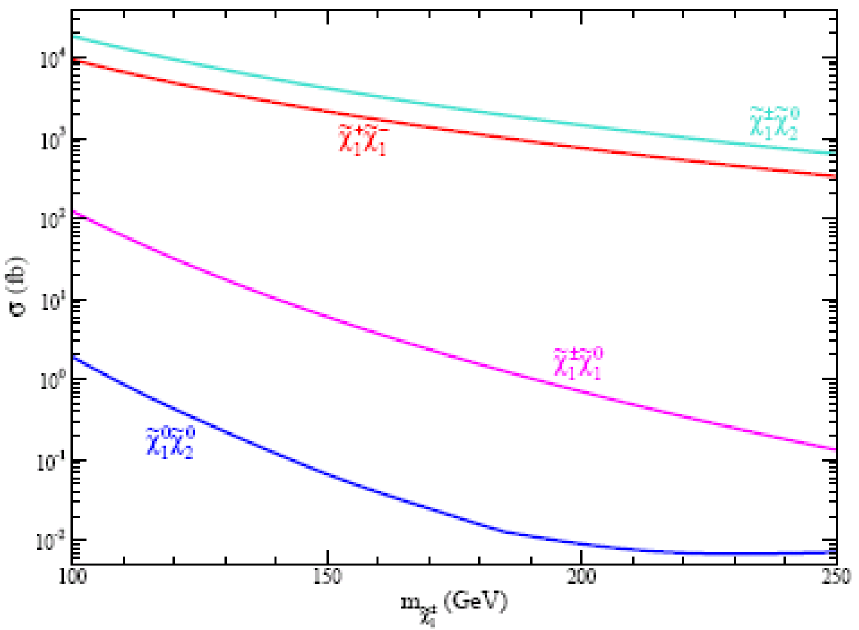


Baer, Kraml, SS and Summy, JHEP 0810 (2008) 079 [arXiv:0809.0710]

SS, Spiropulu, Zeyrek, CERN CMS AN 2008/018

Cross sections@14TeV





Signal benchmarks

Point	m_{16}	m_{10}	m_D	$m_{1/2}$	A_0	$\tan\beta$	$\Omega_{\tilde{\chi}_1^0}h^2$
SO10A	9292.9	10966.1	3504.4	62.5	-19964.5	49.1	220
SO10D	2976.5	3787.9	1020.8	107.0	-6060.3	49.05	0.06

Lepton channals (LepCh)

Look for multi-lepton + multi b-jet signature.

Signal and background production at 14 TeV with ISAJET 7.75

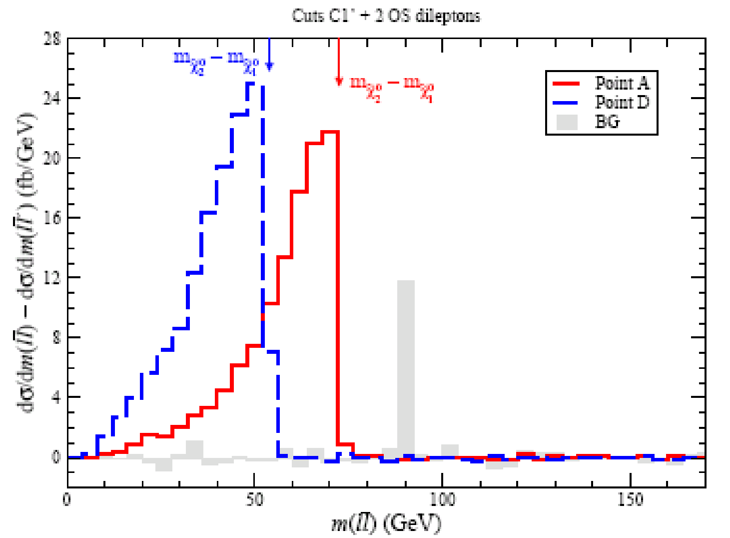
Toy simulation for a generic LHC detector.

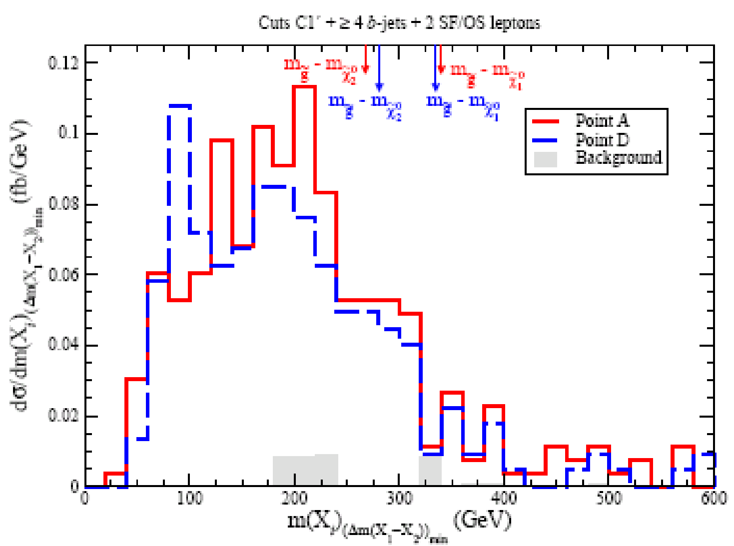
SM backgrounds: W+jets, Z+jets, tt+jets, WW, ZZ, WZ

Major cuts:

- n(jets) ≥ 4, E_T(j1, j2, j3, j4) ≥ 100,50,50,50 GeV
- transverse sphericity $S_T \geq 0.2$
- Either MET>150 or n(leptons) ≥ 4.
- For hadronic edge reconstruction, require n(b jets) ≥ 2 or ≥ 4.

LepCh: Results





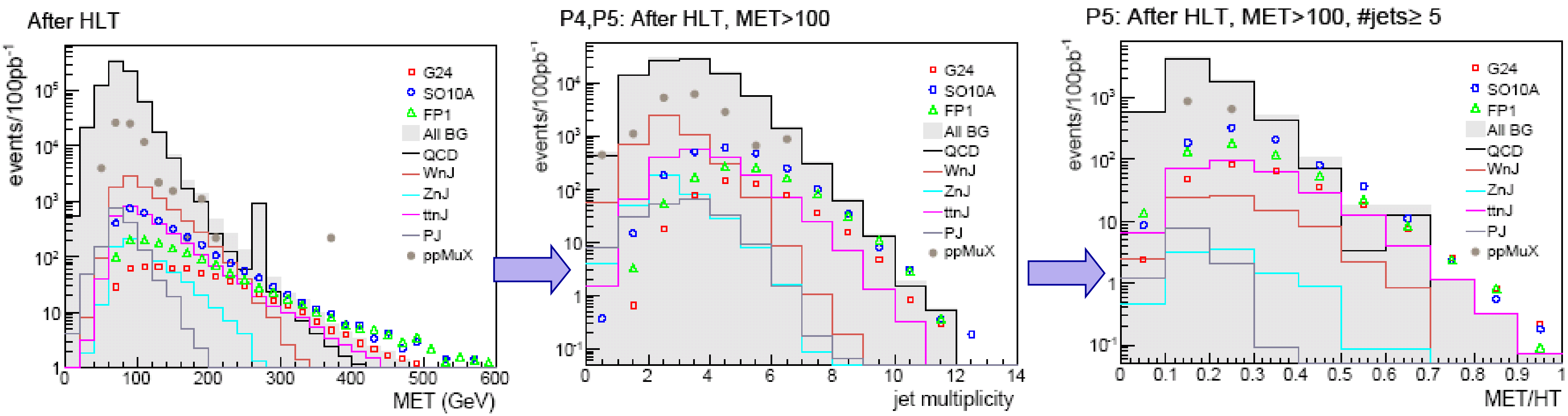
- $pp \to \tilde{g}\tilde{g}$ signal visible in 4jets + 3leptons channel without a MET cut for <1fb^{-1}.
- For ~100fb^{-1}, reconstruction of m(ll), m(bb) and m(llbb) invariant mass edges are possible. These would lead to determination of $m(\tilde{g})$, $m(\tilde{\chi}_1^0)$ and $m(\tilde{\chi}_2^0)$ to O(%10) accuracy.
- A complementary signature is the trilepton signal from $pp \to \tilde{\chi}_2^0 \tilde{\chi}_1^\pm$ which can be visible for O(10) fb^{-1}.

Hadron Channels (HadCh) at CMS

- Look for the b-rich mulijets + missing energy signature at CMS.
- <u>Side remark:</u> Besides the SO(10)s, also analyzed two SUSY scenarios scenarios with very heavy scalars and light gauginos:
  - G2-MSSM: A consistent low energy N=1 SUSY realization of M theory compactified on a G2 manifold (Kane et. al.)
  - Focus point mSUGRA (FP): High m_0-low/moderate $m_{1/2}$ consistent with naturalness and WMAP DM constraints (Feng et. al.)
- Signal production at 14 TeV with PYTHIA
- SM backgrounds: QCD, photon+jets (PYTHIA), tt+jets, W+jets, Z+jets (Alpgen)
- Full simulation for the CMS detector using CMSSW.

HadCh: Prototype selection paths

Six prototype paths based on MET, njets and MET/HT



Step	var	P1	P2	P3	P4	P5	P6
1	MET	> 200	> 300	–	> 100	> 100	> 150
2	#jets	≥ 4	≥ 4	≥ 5	≥ 4	≥ 5	≥ 3
3	$\not{E}_T/H_T$	–	–	> 0.1	> 0.1	> 0.1	–

HadCh: BG rejection

- Leptonic background rejection:
  - Indirect lepton veto (ILV – Spiropulu 2000) uses combined tracker and calorimeter information to reject events having leptons as their hardest object.
- Hadronic (mostly QCD) background rejection:
  - Background due to fake missing ET caused by mismeasured jets.   Detect events with fake MET. PRINCIPLE: Fake MET alligns with mostly mismeasured jet.

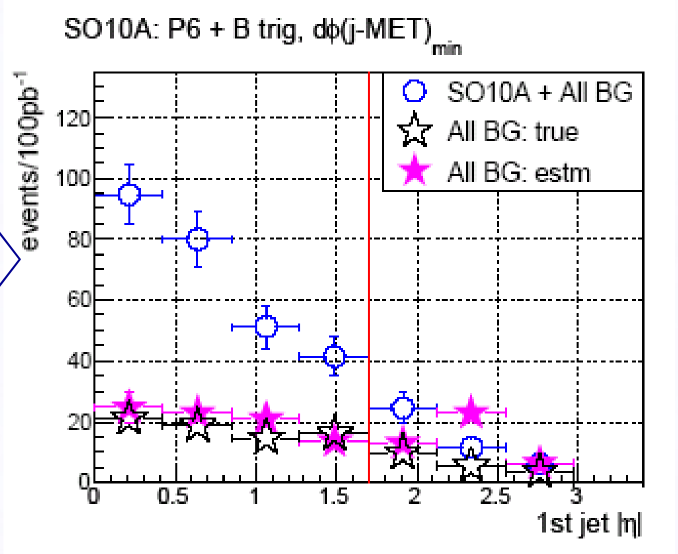
HadCh: Results for 100pb^{-1} - I

Selection results:

	Path	1	2	3	4	5	6
	MET	> 200	> 300	–	> 100	> 100	> 150
	njets	≥ 4	≥ 4	≥ 5	≥ 4	≥ 5	≥ 3
	MET/MHT	–	–	> 0.1	> 0.1	> 0.1 –	
SO10A	nevts	53	9	270	348	171	197
	efficiency	0.78	0.13	3.96	5.10	2.51	2.89
	S/B	4.42	9.00	0.65	1.33	1.88	2.81
	significance	6.57	2.85	10.32	14.1	10.56	12.06
Total BG	nevts	12	1	414	261	91	70

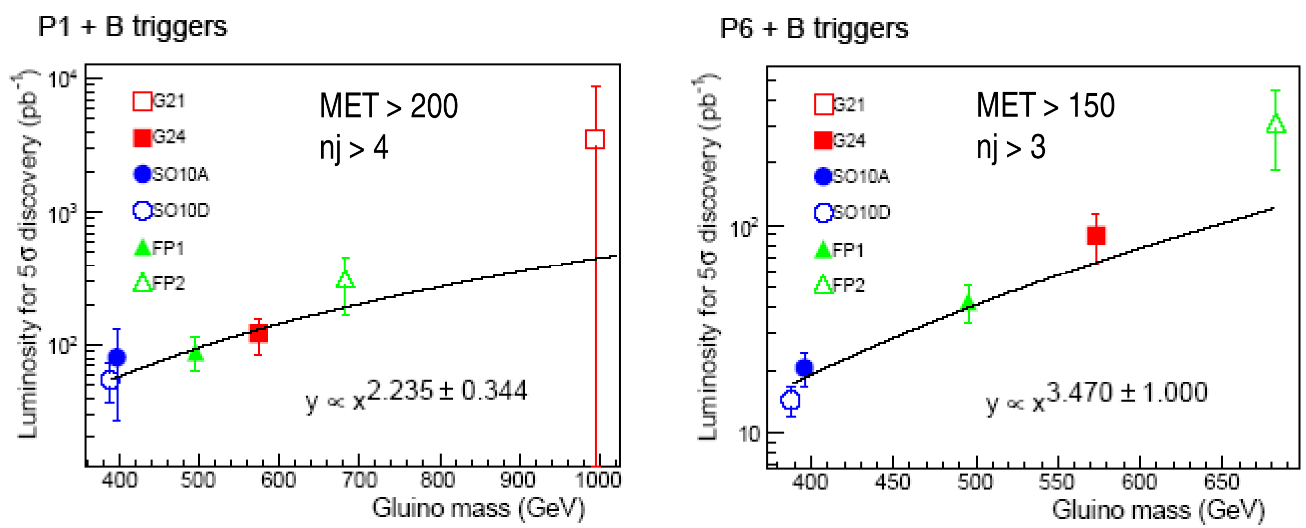
Optimal for SUSY with heavy scalars.

Background estimation: We must be able to estimate backgrounds from the data in order to claim a discovery.



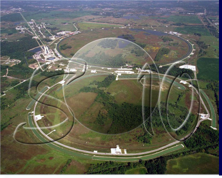
HadCh: Results for $100pb^{-1}$ - II

Integrated luminosity required for 5σ discovery



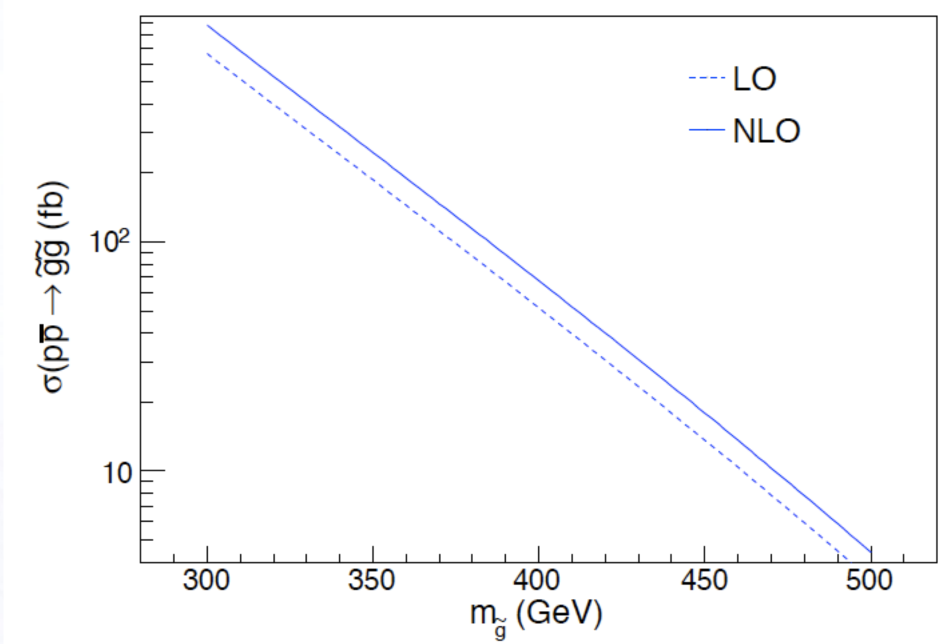
Heavy-scalar SUSY scenarios having gluinos with masses up to 1 TeV are accessible at the LHC with over 5σ significance for 50-100 fb^{-1} [corresponding to 3-5 year running with L = 2 x 10^{33} $cm^{-2}s^{-1}$].
For gluino mass < 700 GeV, 5σ discovery with luminosity > $1fb^{-1}$, providing results within the first year

Baer, Kraml, Lessa, SS and Summy, [arXiv:0910.2988]



Hadronic channels

- Look for the b-rich mulijets + missing energy signature.
- Signals with ISAJET, BGs with Alpgen/MadGraph
- Toy detector simulation



Cuts:

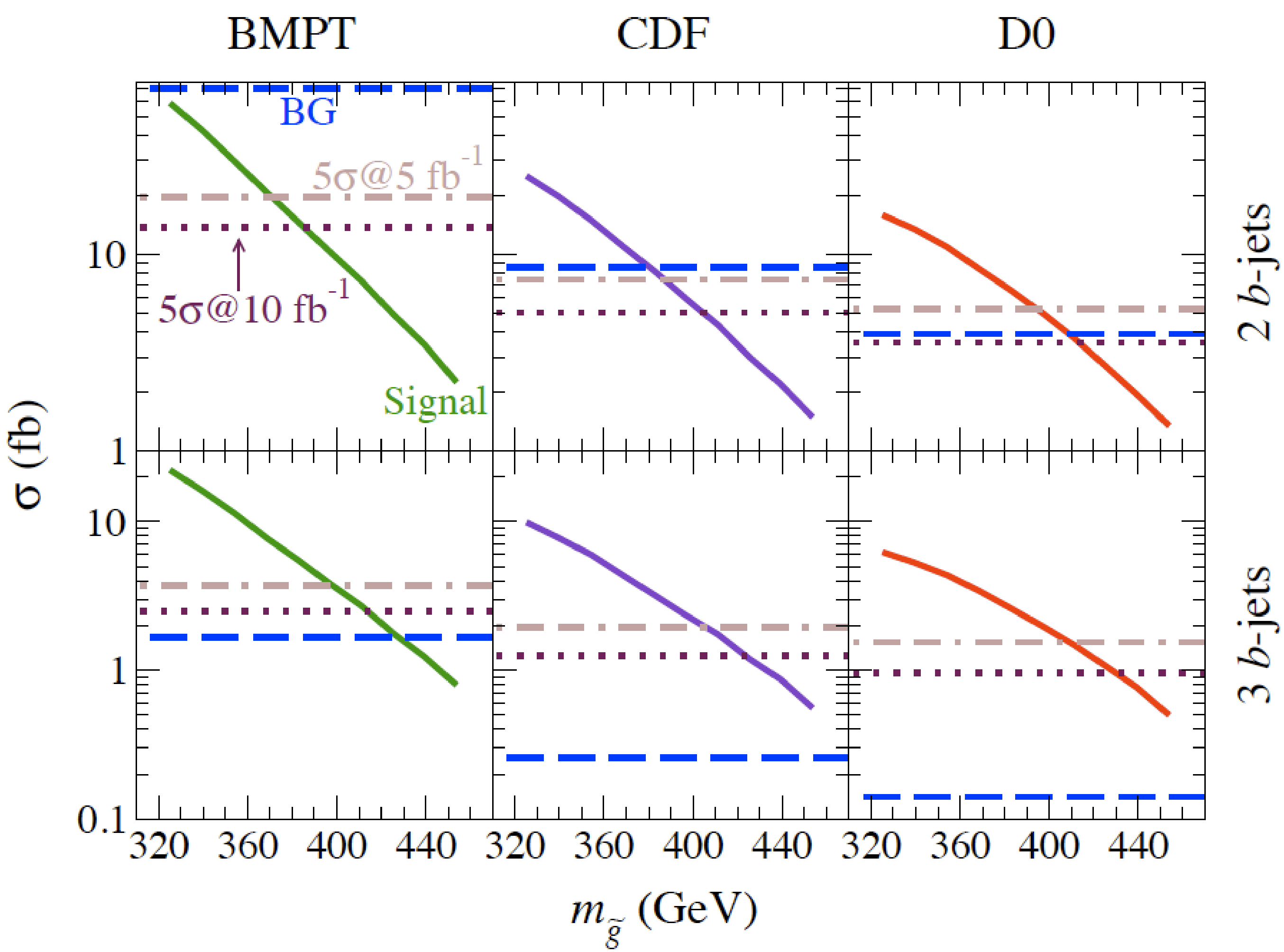
cuts	$E_T^{\rm miss}$	H_T	$E_T(j1)$	$E_T(j2)$	$E_T(j3)$	$E_T(j4)$
BMPT	≥ 75 GeV	–	15	15	15	15
CDF	≥ 90 GeV	280	95	55	55	25
D0	≥ 100 GeV	400	35	35	35	20

Earlier study by Baer et. al.

\+

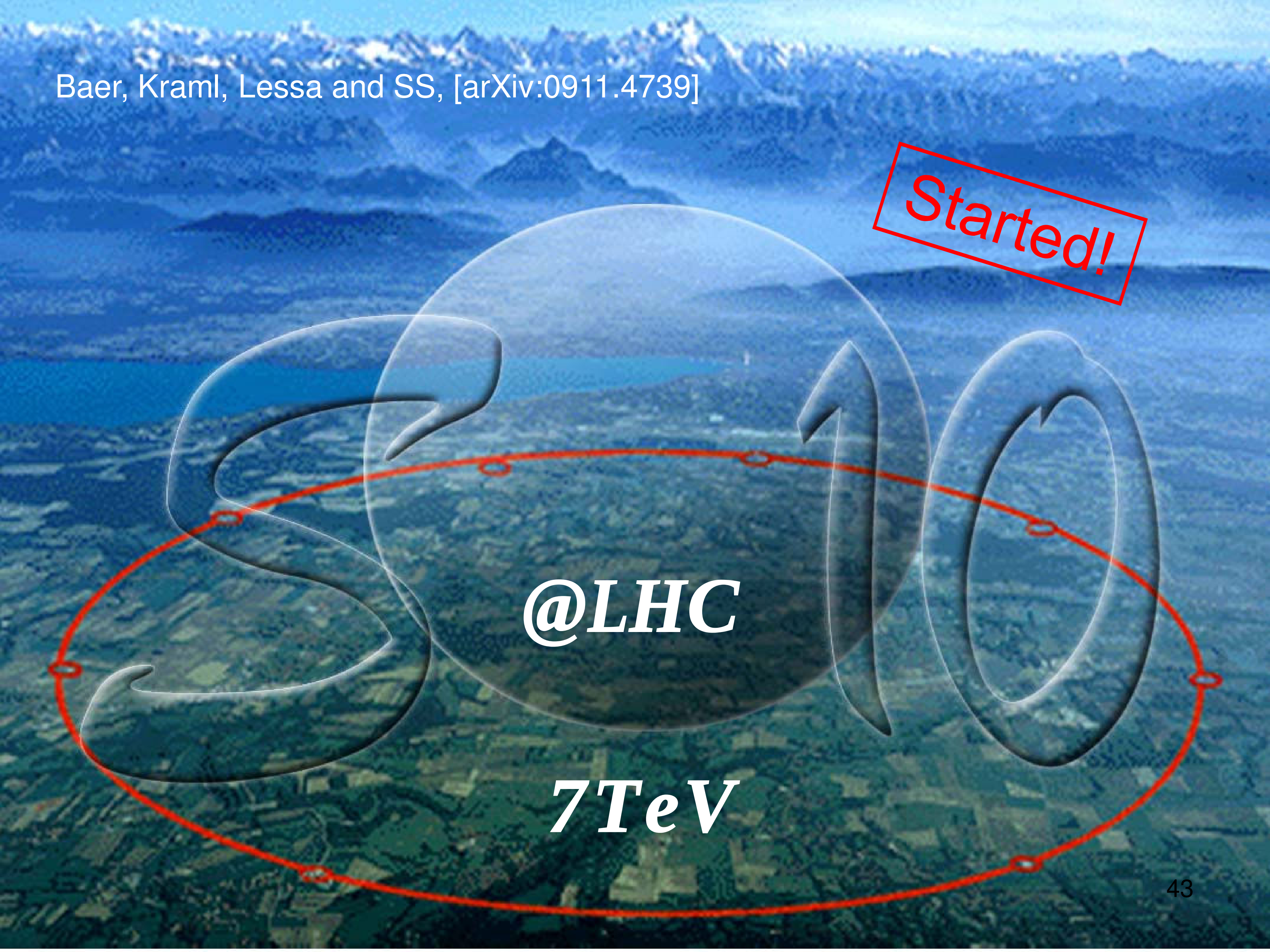
- $n_{jets} \geq 4$
- *No isolated leptons*
- $d\phi(j1, j2) < 160°$
- $n_{b\ jets} \geq$ 2 or 3

Hadronic search results



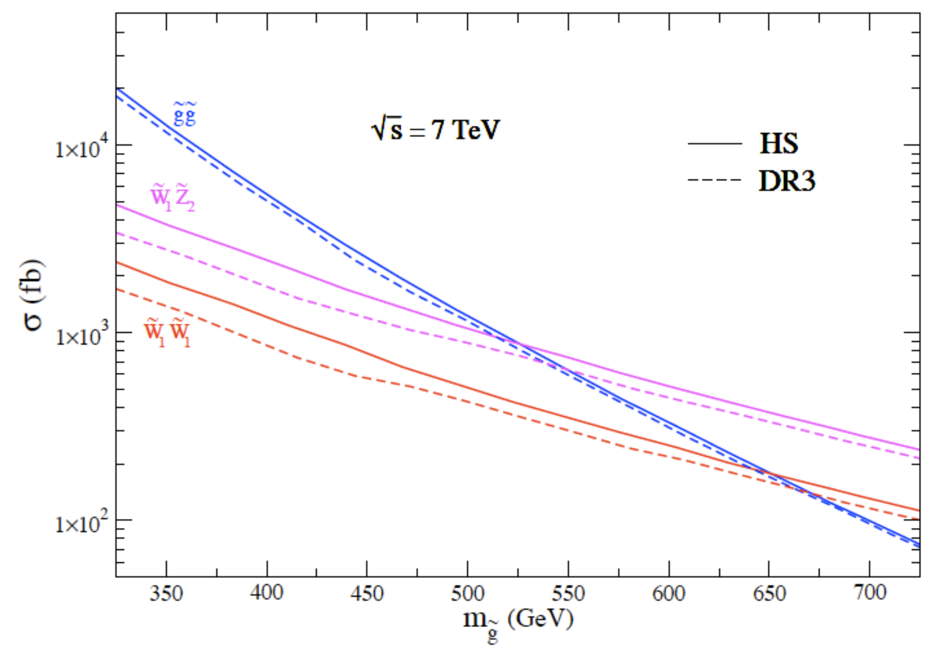
CDF/D0 could search for gluinos with mass beyond the reported ~300 GeV for SO(10) SUSY if b jet multiplicity is considered as a cut.

Baer, Kraml, Lessa and SS, [arXiv:0911.4739]



SO10@early.lhc.cern.ch

- Look for light gluinos in the 1st year of LHC. Two phases:
  - Early phase: No MET and electrons (jets and μs)
  - Later phase: MET and electrons included
- Signals with ISAJET, BGs with Alpgen/MadGraph.
- Toy detector simulation



Investigate the effect of b tagging.

Cuts:

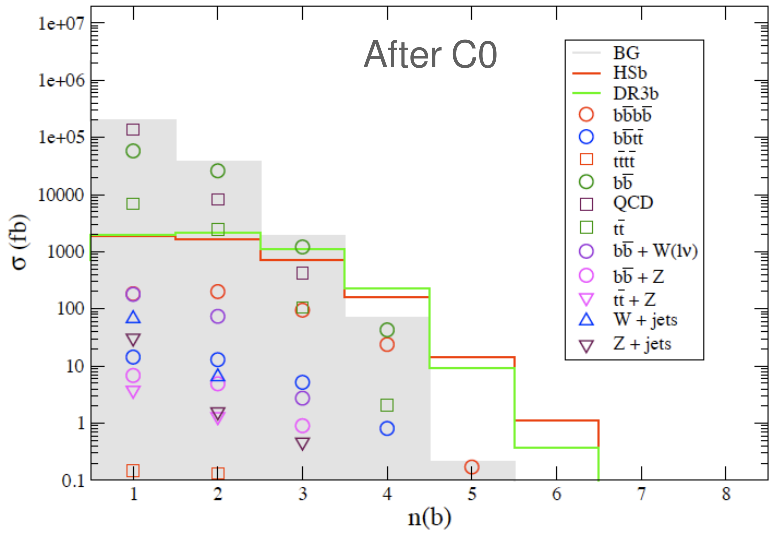
C0:

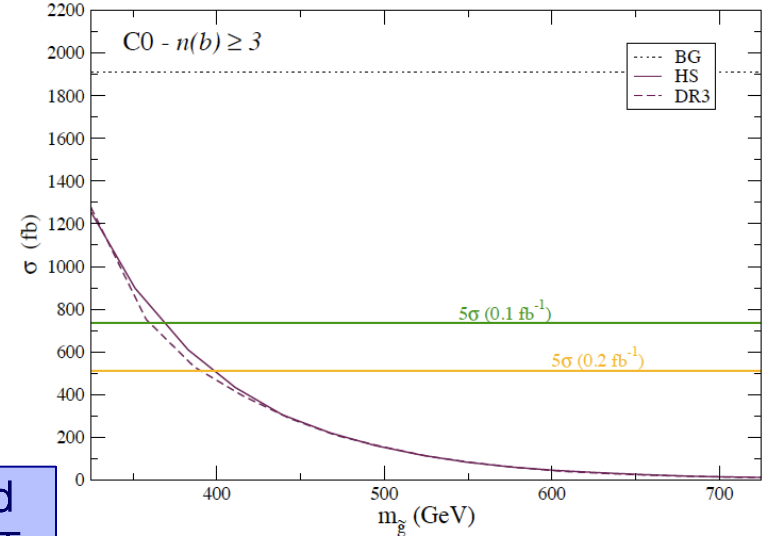
- nj > 3; ET(j1) > 100
- ST > 0.2

C1:

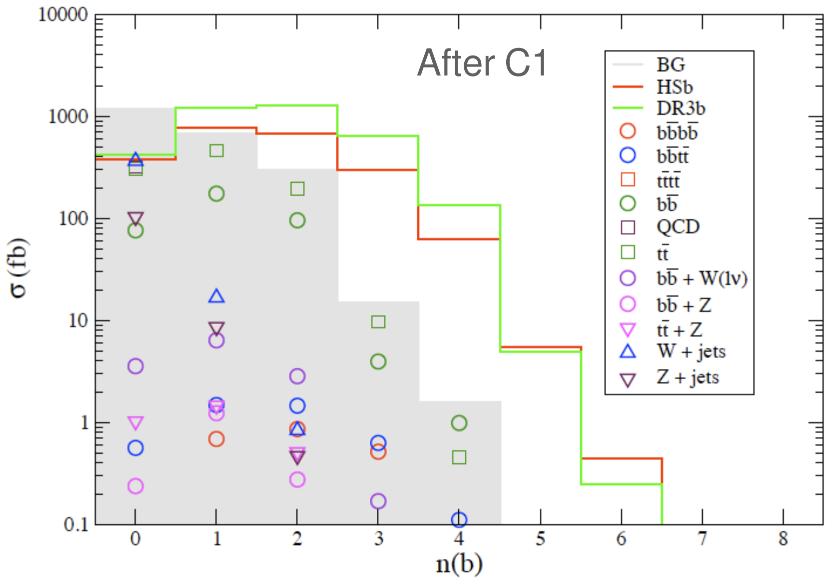
- nj > 3; ET(j1) > 100
- ST > 0.2
- MET > 100

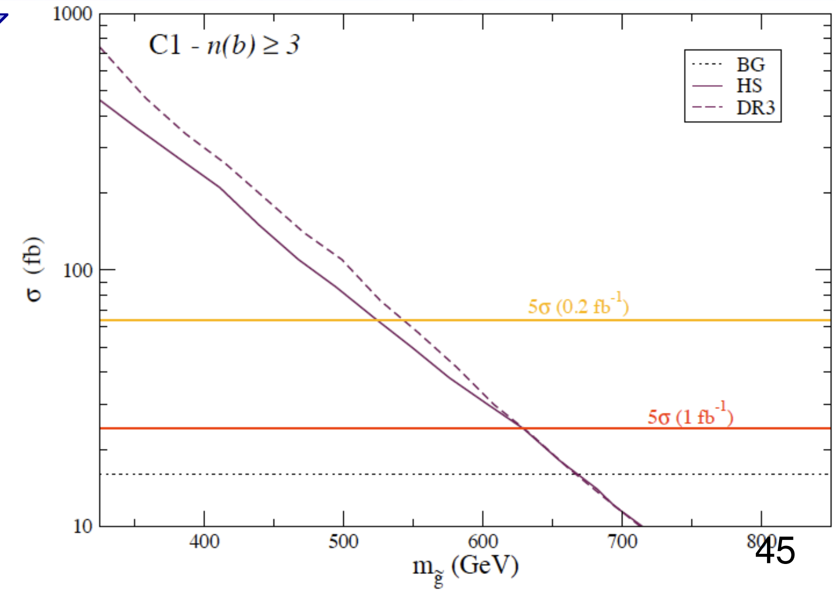
SO(10) early LHC results - I



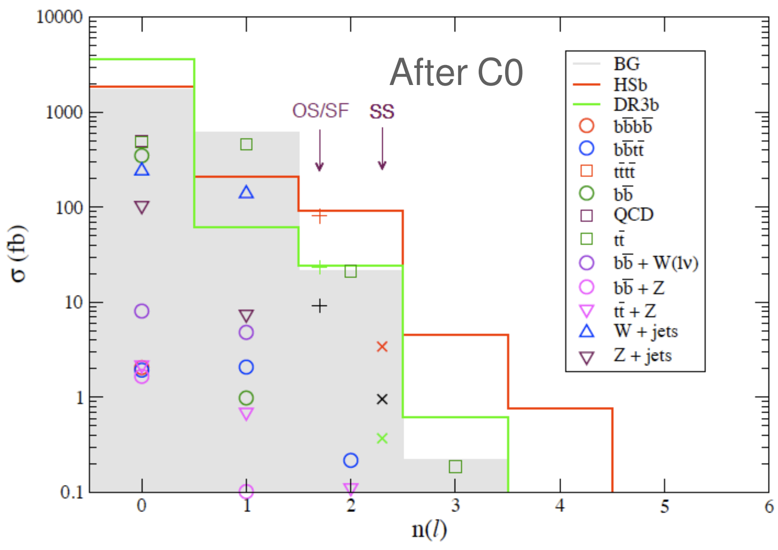


Add MET

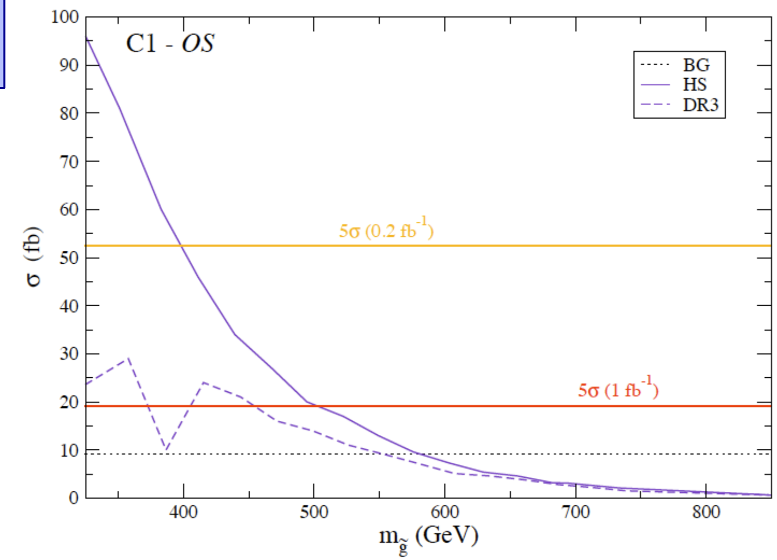




SO(10) early LHC results - II



Add leptons



- Gluino mass reach at early phase up to 400 GeV for 0.2fb^{-1}.
- Including MET increases the reach to ~630 GeV for 1fb^{-1}.
- Lepton cuts leave enough events for preliminary edge studies.
- b tagging is crucial!
- Yukawa-unified SO(10) SUSY can be tested with 1st year data!

Summary

- SO(10) SUSY GUTs offer a well-motivated theoretical framework – feature Yukawa unification.
- Neutralino relic density is high, but axion/axino DM solution gives consistent cosmology.
- Characteristic spectrum has multi TeV $1^{st}/2^{nd}$ gen scalars, ~TeV 3^{rd} gen scalars and sub-TeV gauginos.
- Preferred gluino mass is 350-500 GeV. Gluino pair production dominant at Tevatron and LHC.
- Tevatron reach is m(gluino) < 400 GeV.
- LHC reach for 7 TeV is 400 (630) GeV in year 1.
- LHC at 14 TeV can fully explore these scenarios.

Merci beaucoup