Searching for Supersymmetry at LHC7 and beyond

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arXiv:1004.3594

also arXiv:0909.1922

- ⋆ Supersymmetry phenomenology really took off in the early 1980's when it was realized that supersymmetry stabilized the scalar sector in the presence of radiative corrections. This was then the only rationale for the sparticle mass scale to be in the TeV region.....of interest to the LHC.

TODAY THE SITUATION IS DIFFERENT.

- ⋆ LEP has measured the 3 gauge couplings, and these unify well in a SUSY GUT with two Higgs doublets if the sparticle scale is 100 GeV - 10 TeV.
- ⋆ In SUSY models with a conserved R-parity, the lightest supersymmetric particle is stable, and if electrically neutral and only weakly interacting is consistent with the observed density of cold dark matter if the mass scale is around a TeV....Thermal DM, Standard Big Bang cosmology.

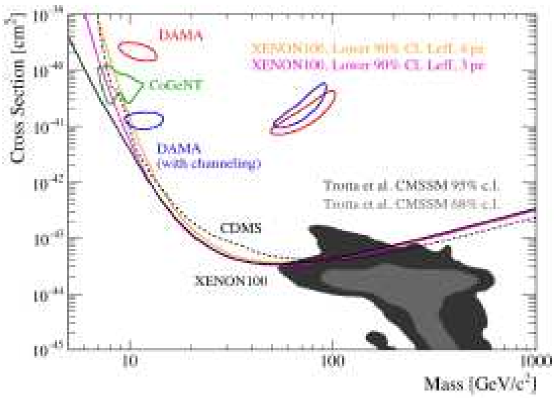
A REMARKABLE TRIPLE COINCIDENCE OF SCALES!!!

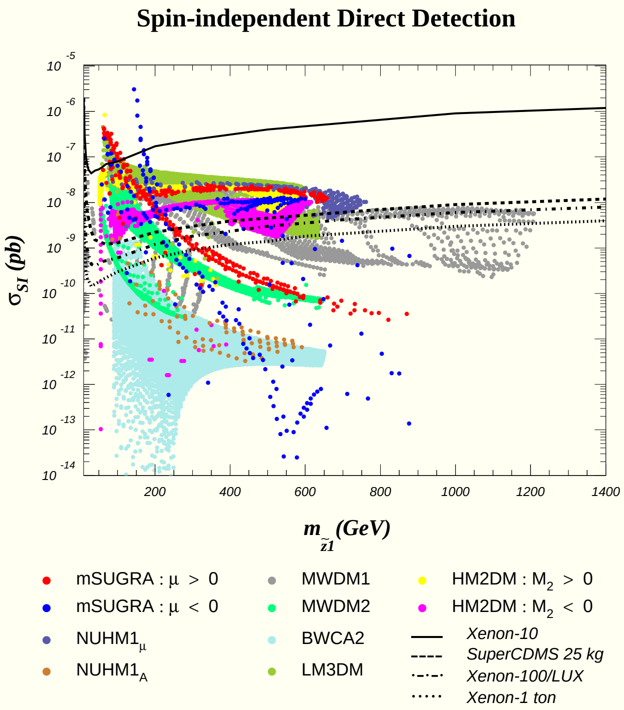
Has led to lot of activity in the last 30 years!!!!

Many new exciting experiments

- ⋆ Direct DM detection: CDMS, XENON-100 (DAMA, COGeNT, COUP....)
- ⋆ Indirect DM detection: Pamela, Fermi, ATIC, AMS-02, GAPS.....
- ⋆ The Large Hadron Collider, $\sqrt{s} = 14$ TeV pp collider, currently operating at 7 TeV (LHC7).

DIRECT DETECTION OF DARK MATTER

- 



I won't comment here on the low mass neutralino controversy.

Currently, XENON-100 and CDMS running neck and neck.

XENON-100 will imminently probe mixed higgsino DM models.

Indirect Detection

- ⋆ In my view, recent excitement over ATIC, Pamela is premature. No spectral structure in Pamela, interesting structures in ATIC.
- ⋆ Because there is no SM of cosmic rays, it is difficult to determine excess over smooth background (Pamela, Fermi mid-latitude data).
- ⋆ Watch for AMS results; FERMI-LAT data from galactic centre; confirmed antiparticle signals with spectral structures, and of course, neutrino telescopes.

LHC

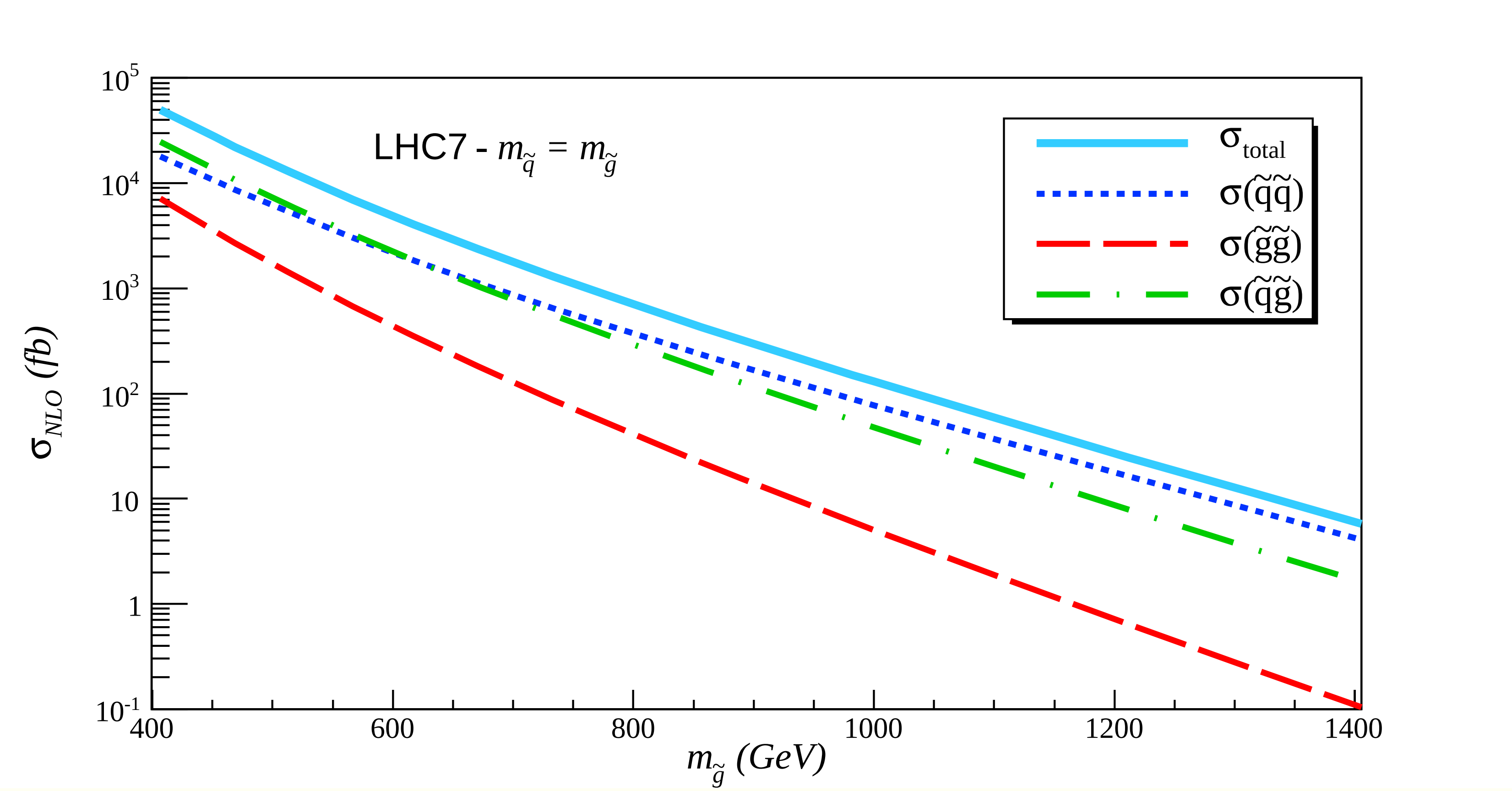
Outcome from Chamonix: Better in the long run

Last week, the Chamonix workshop once again proved its worth as a place where stakeholders in the CERN LHC can come together, take difficult decisions and reach a consensus on important issues for the future of particle physics. The most important decision we reached last week is to run the LHC for 18 to 24 months at a collision energy of 7 TeV (3.5 TV per beam). After that, we will go into a long shutdown in which we'll do all the necessary work to allow us to reach the LHC's design energy of 14 TeV for the next run. This means that when the beams go back into the LHC later this month, we'll be entering the longest phase of accelerator operation in CERN's history, scheduled to take us into summer or autumn 2011.

.......And for the experiments, 18 to 24 months will bring enough data across all the potential discovery areas to firmly establish the LHC as the world's foremost facility for high energy particle physics.

Steve Myers, Director for Accelerators and Technology, Feb 3, 2010.

Integrated luminosity of 1 fb^{-1} per experiment by end of the run.

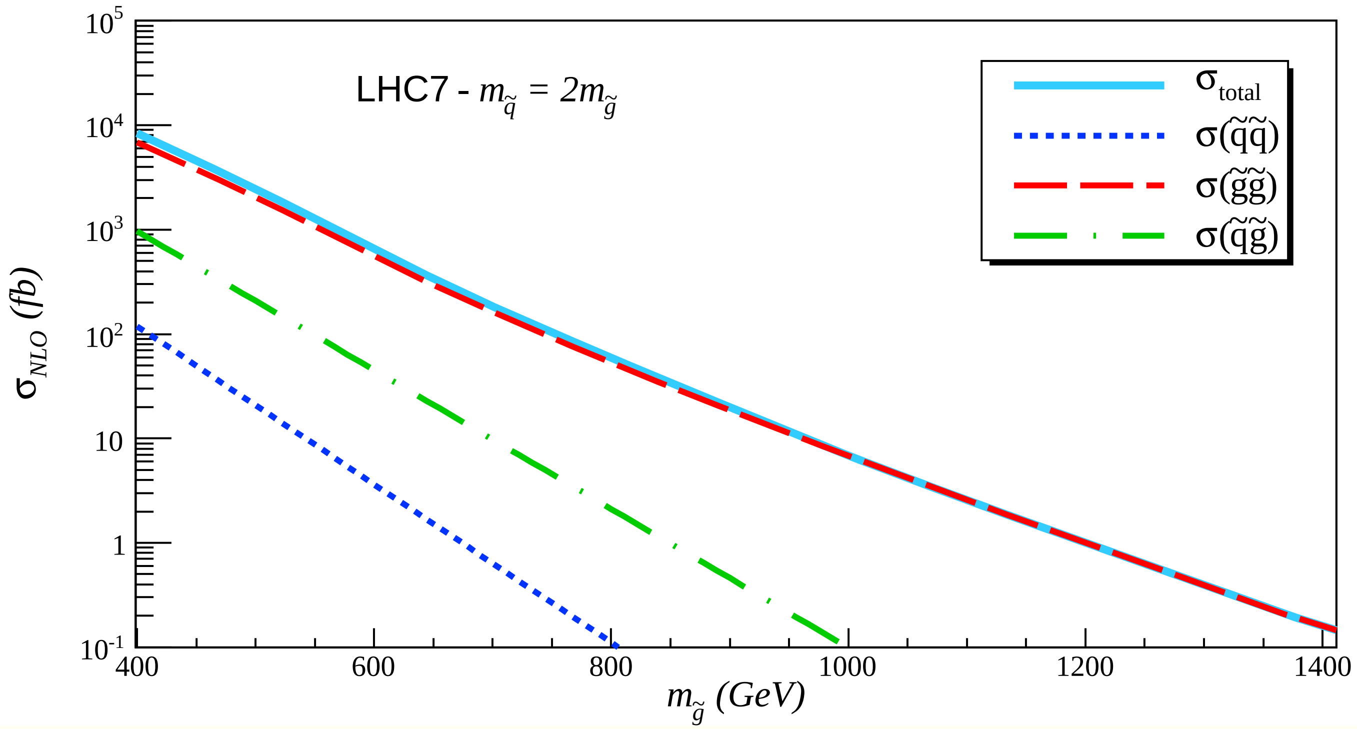


Cross section exceeds 100 fb if $m_{\tilde{q}} = m_{\tilde{g}} < 1$ TeV.

Mostly $\tilde{q}\tilde{g}$ and $\tilde{q}\tilde{q}$ production.

CTN=360 GeV*

*CTN refers only to gluino and squark cross sections



Cross section exceeds 100 fb if squarks are very heavy but $m_{\tilde{g}} \lesssim 700$ GeV.

Mostly $\tilde{g}\tilde{g}$ production.

CTN=320 GeV*

*CTN refers only to gluino and squark cross sections

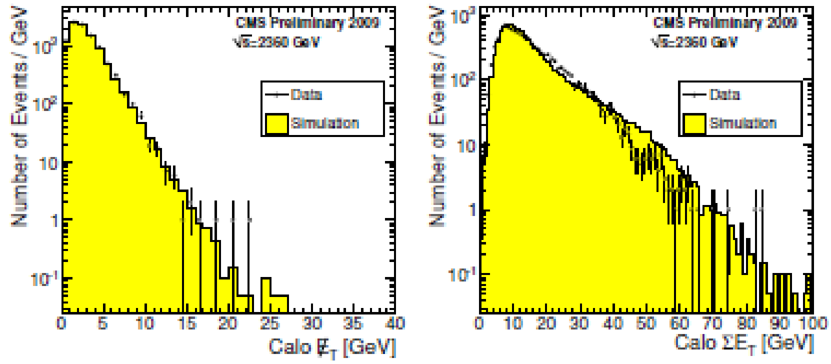
How long will it take LHC detectors to do physics?

I was amazed that:

- ⋆ The detectors worked "out of the box".
- ⋆ The software worked "out of the box"
- ⋆ The data and the simulation agreed amazingly well

Ian Hinchliffe (ATLAS) West Coast LHC meeting, May 21, 2010.

How about our friends at CMS?



(a) Calo$\not{E}_T$ distribution (b) Calo$\sum E_T$ distribution

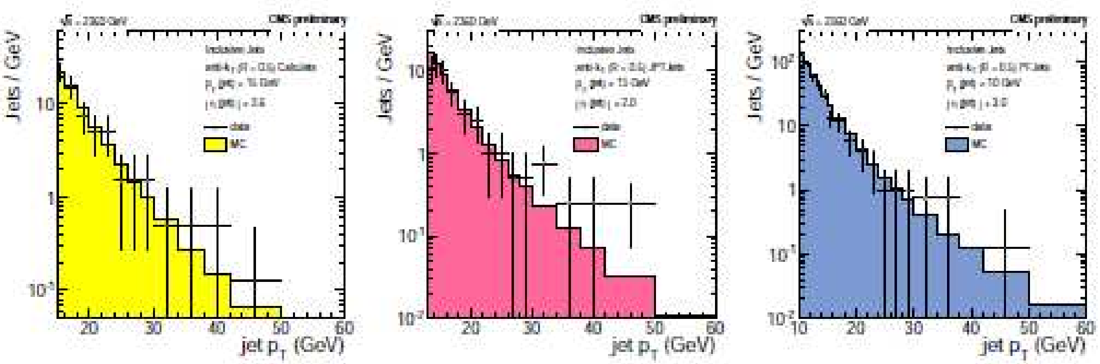
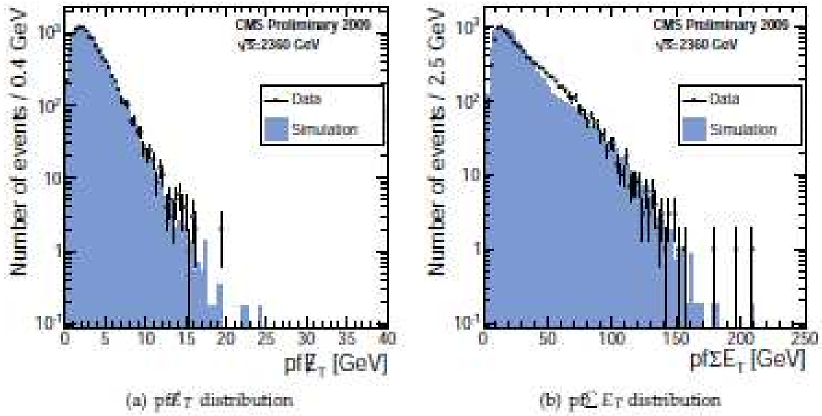
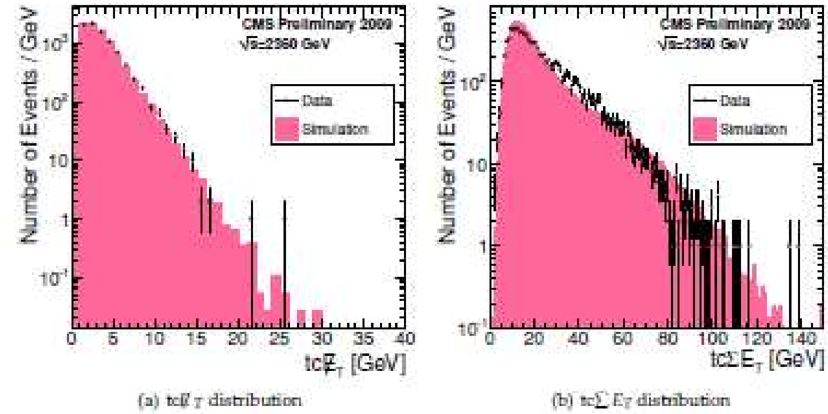


Figure 13: Comparisons of data and MC inclusive calorimeter (left), JPT (center) and particle flow jet p_T spectra.





CMS guys utilize their excellent segmentation to improve the measurements from the purely calorimetric ones. Tracking and particle flow algorithms seem to be working!

These considerations suggest that, contrary to expectations just a year ago when it was thought that detectors would take time to be well-enough understood for $\not\!\!E_T$ (and perhaps also electron ID) analyses, it now appears that these analyses will be possible even at an early stage of the LHC data.

Very Important

We need, of course, to realize the

$$n \to p \to f$$

transformation to accomplish this.

However, keep in mind that....

- ★ The previous plots were from the 2.36 TeV run, and Signore Murphy could play tricks.
- ★ $\not{E}_T \lesssim 30$ GeV, $\sum E_T \lesssim 200$ GeV in what I showed you. Even after naive scaling for increased energy, we need to go beyond these values for many SUSY analyses. (Fake $\not{E}_T \sim \sqrt{\sum E_T}$.)

  Though I hope that everything will go well, I will present results both for the situation where we can utilize $\not{E}_T$ and electron information, and also in the (nearly) worst case scenario where $\not{E}_T$ cannot be utilized and where jet-electron mis-ID poses a problem.

Early LHC reach with an "understood detector"

The search channels include:

- ⋆ multi-jet $+ \not{E}_T$ events;
- ⋆ $1\ell, 2\ell$ (OS or SS), 3ℓ + jets $+\not{E}_T$ events;
- ⋆ Events with 1-3 tagged b-jets ($\epsilon_b = 60\%$).

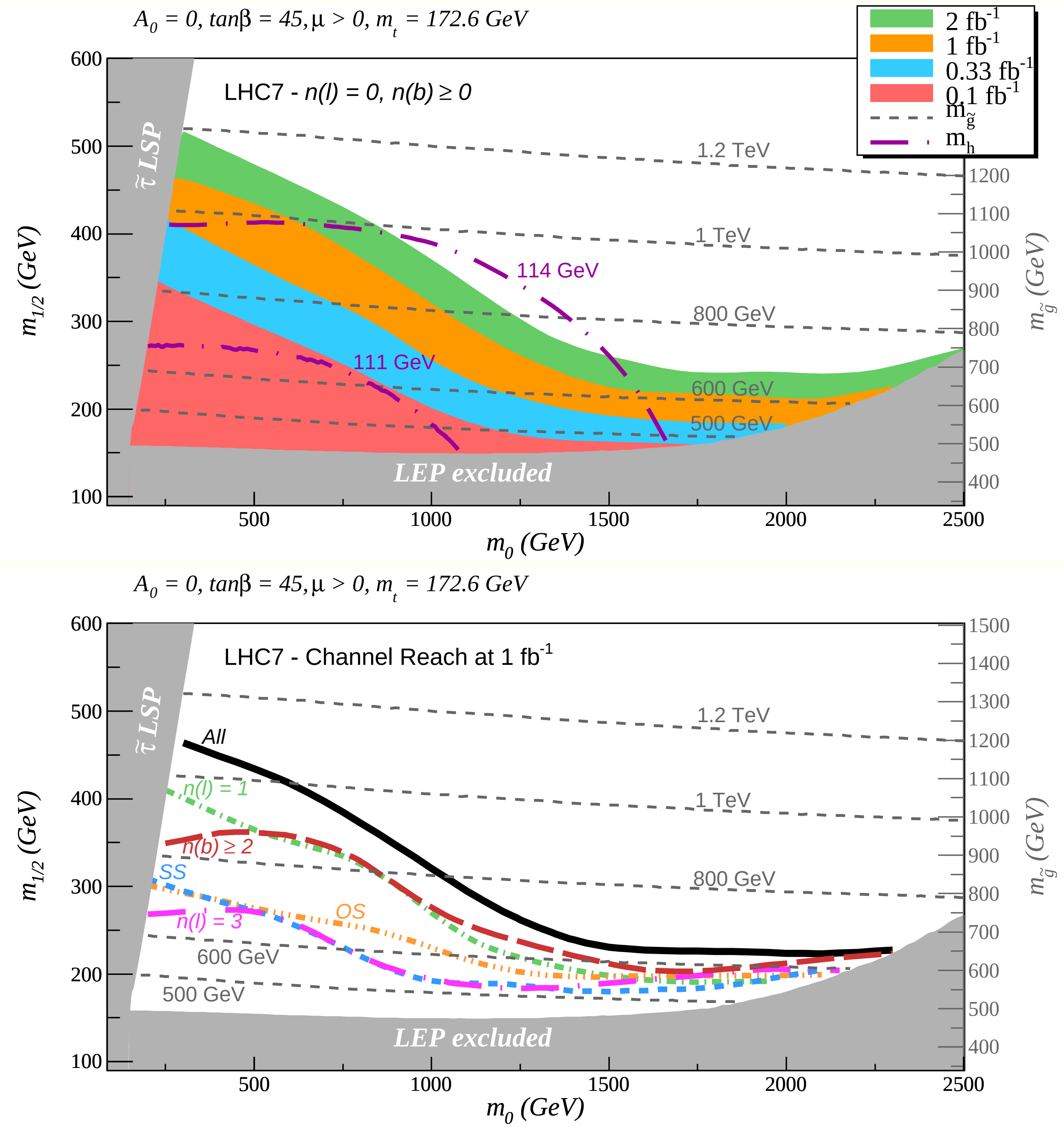
Multiple sources of SM backgrounds

SM process	Generator	Cross section	number of events
QCD: 2, 3 and 4 jets (40 GeV$< E_T(j1) <$ 100 GeV)	AlpGen	2.6×10^9 fb	26M
QCD: 2, 3 and 4 jets (100 GeV$< E_T(j1) <$ 200 GeV)	AlpGen	3.9×10^8 fb	44M
QCD: 2, 3 and 4 jets (200 GeV$< E_T(j1) <$ 500 GeV)	AlpGen	1.6×10^7 fb	16M
QCD: 2, 3 and 4 jets (500 GeV$< E_T(j1) <$ 3000 GeV)	AlpGen	9.4×10^4 fb	0.3M
$t\bar{t}$: $t\bar{t}$ + 0, 1 and 2 jets	AlpGen	1.6×10^5 fb	5M
$b\bar{b}$: $b\bar{b}$ + 0, 1 and 2 jets	AlpGen	8.8×10^7 fb	91M
Z + jets: $Z/\gamma(\to l\bar{l}, \nu\bar{\nu})$ + 0, 1, 2 and 3 jets	AlpGen	8.6×10^6 fb	13M
W + jets: $W^{\pm}(\to l\nu)$ + 0, 1, 2 and 3 jets	AlpGen	1.8×10^7 fb	19M
$Z + t\bar{t}$: $Z/\gamma(\to l\bar{l}, \nu\bar{\nu}) + t\bar{t}$ + 0, 1 and 2 jets	AlpGen	53 fb	0.6M
$Z + b\bar{b}$: $Z/\gamma(\to l\bar{l}, \nu\bar{\nu}) + b\bar{b}$ + 0, 1 and 2 jets	AlpGen	2.6×10^3 fb	0.3M
$W + b\bar{b}$: $W^{\pm}(\to l\nu) + b\bar{b}$ + 0, 1 and 2 jets	AlpGen	6.4×10^3 fb	9M
$W + t\bar{t}$: $W^{\pm}(\to l\nu) + t\bar{t}$ + 0, 1 and 2 jets	AlpGen	1.8×10^2 fb	9M
$W + tb$: $W^{\pm}(\to l\nu) + \bar{t}b(t\bar{b})$	AlpGen	6.8×10^2 fb	0.025M
$t\bar{t}t\bar{t}$	MadGraph	0.6 fb	1M
$t\bar{t}b\bar{b}$	MadGraph	1.0×10^2 fb	0.2M
$b\bar{b}b\bar{b}$	MadGraph	1.1×10^4 fb	0.07M
WW: $W^{\pm}(\to l\nu) + W^{\pm}(\to l\nu)$	AlpGen	3.0×10^3 fb	0.005M
WZ: $W^{\pm}(\to l\nu) + Z(\to all)$	AlpGen	3.4×10^3 fb	0.009M
ZZ: $Z(\to all) + Z(\to all)$	AlpGen	4.0×10^3 fb	0.02M

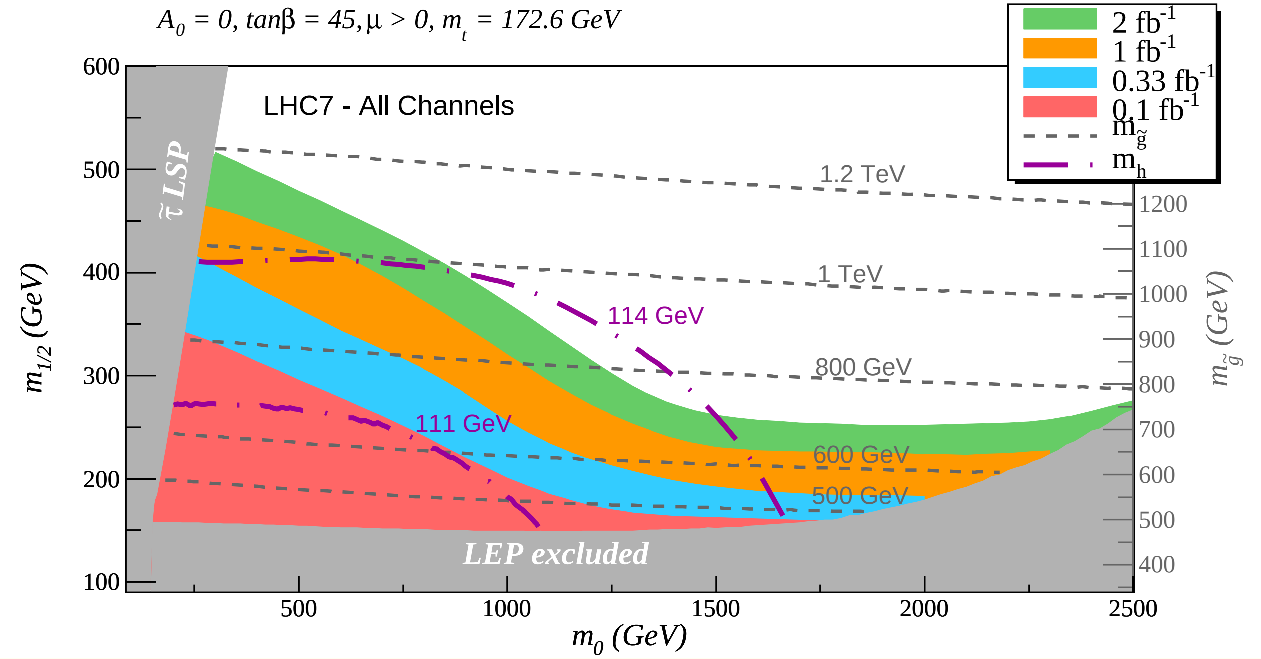
Optimized reach using $\not{E}_T$

- $\not{E}_T >$ 100 - 1000 GeV (in steps of 100 GeV),
- $n(jets) \geq$ 2, 3, 4, 5 or 6,
- $n(b - jets) \geq$ 0, 1, 2 or 3,
- $E_T(j_1) >$ 50 - 300 GeV (in steps of 50 GeV) and 400-1000 GeV (in steps of 100 GeV) (jets are ordered $j_1 - j_n$, from highest to lowest E_T),
- $E_T(j_2) >$ 50 - 200 GeV (in steps of 30 GeV) and 300, 400, 500 GeV,
- $n(\ell) =$ 0, 1, 2, 3, OS, SS and inclusive channel: $n(\ell) \geq$ 0. (Here, $\ell = e, \ \mu$).
- 10 GeV$\leq m(\ell^+\ell^-) \leq 75$ GeV or $m(\ell^+\ell^-) \geq 105$ GeV (for the OS, same flavor (SF) dileptons only),
- transverse sphericity $S_T > 0.2$.

We define the signal to be observable if $S \geq max[5\sqrt{B}, 5, 0.2B]$



$A_0 = 0, \tan\beta = 45, \mu > 0, m_t = 172.6$ GeV
LHC7 - n(l) = 0, n(b) ≥ 0
2 fb⁻¹
1 fb⁻¹
0.33 fb⁻¹
0.1 fb⁻¹
$m_{\tilde g}$
m_h
$\tilde\tau$ LSP
1.2 TeV
1 TeV
800 GeV
600 GeV
500 GeV
114 GeV
111 GeV
LEP excluded
$m_{1/2}$ (GeV)
m_0 (GeV)
$m_{\tilde g}$ (GeV)
$A_0 = 0, \tan\beta = 45, \mu > 0, m_t = 172.6$ GeV
LHC7 - Channel Reach at 1 fb⁻¹
All
n(l) = 1
n(b) ≥ 2
SS
OS
n(l) = 3
LEP excluded



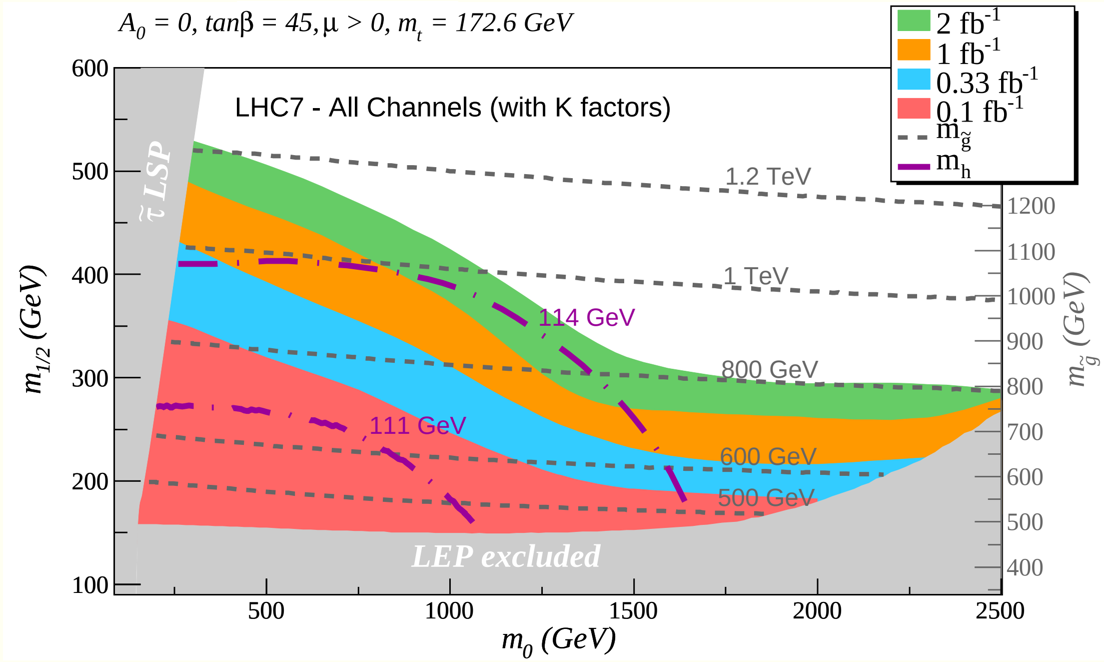
Combined reach essentially the reach in the multi-jet$+\not{E}_T$ channel.

Reach in other channels lends support to the hypothesis that one is seeing SUSY cascade decays.

We have not used any NLO enhancement on the signal in these reach plots.

NLO enhancements and other matters

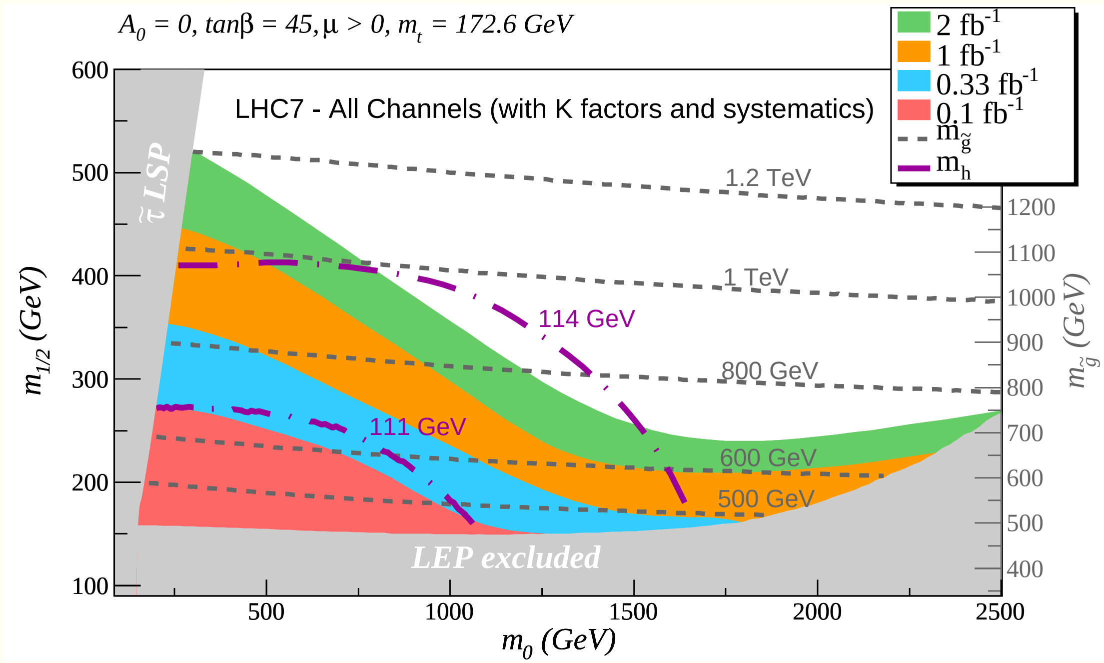
Here is what happens if we normalize $\tilde{g}\tilde{g} + \tilde{g}\tilde{q} + \tilde{q}\tilde{q}$ production to Prospino NLO value



Reach in $m_{1/2}$ increased by $\sim 5\%$ for low value of m_0 and by 15-20% for large m_0 values.

Backgrounds will be determined using data. Background fluctuations, and also systematic errors guesstimated by ATLAS guys to be $\sim 50\%$.

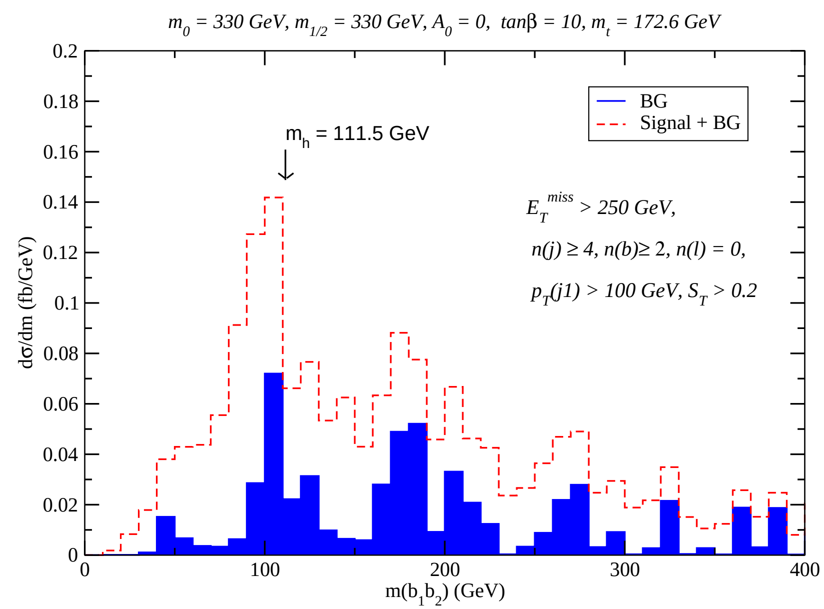
This will reduce the reach from the value that we projected.



Just few percent reduction from original projection for 1 fb^{-1}, but as much as 25% reduction for 100 pb^{-1}!

Discovery of h may also be possible via SUSY cascades if we are lucky.

Often $\tilde{g}$ or $\tilde{q}_L \to \widetilde{Z}_2 \to h$ has a healthy branching fraction if $\widetilde{Z}_2 \to h\widetilde{Z}_1$ is open.



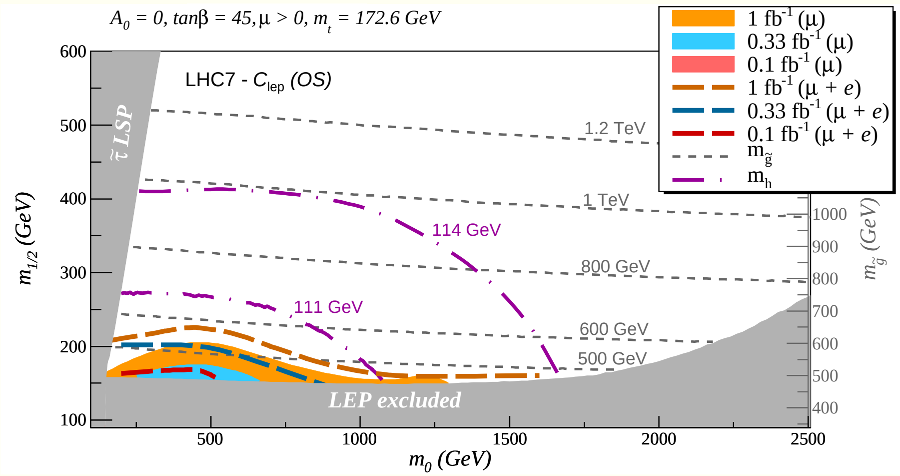
$$B(\tilde{g} \to \tilde{t}_1 t) = 0.46;\ B(\tilde{g} \to \tilde{b}_1 b) = 0.29;\ B(\tilde{q}_L \to q\widetilde{Z}_2) = 0.3;$$
$$B(\tilde{t}_1 \to t\widetilde{Z}_2) = 0.15;\ B(\tilde{b}_1 \to b\widetilde{Z}_2) = 0.20;\ B(\widetilde{Z}_2 \to h\widetilde{Z}_1) = 0.79.$$

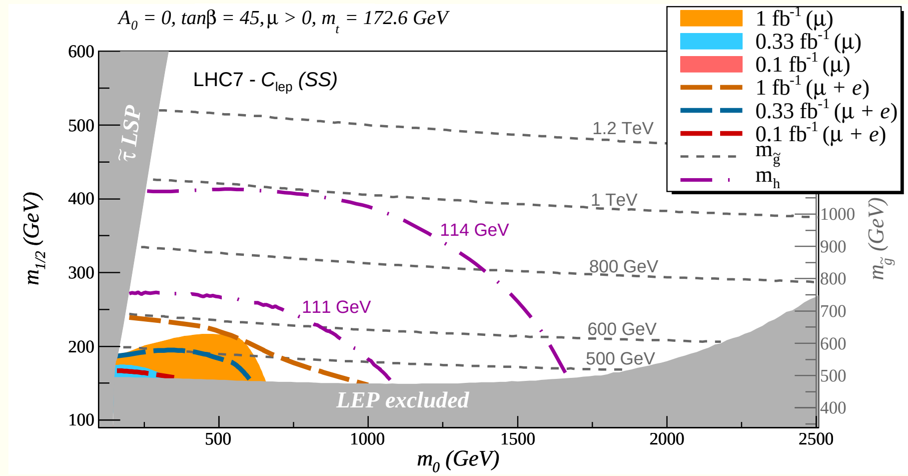
Can see a bump with 2-3 fb^{-1} total (combined ATLAS + CMS analysis)

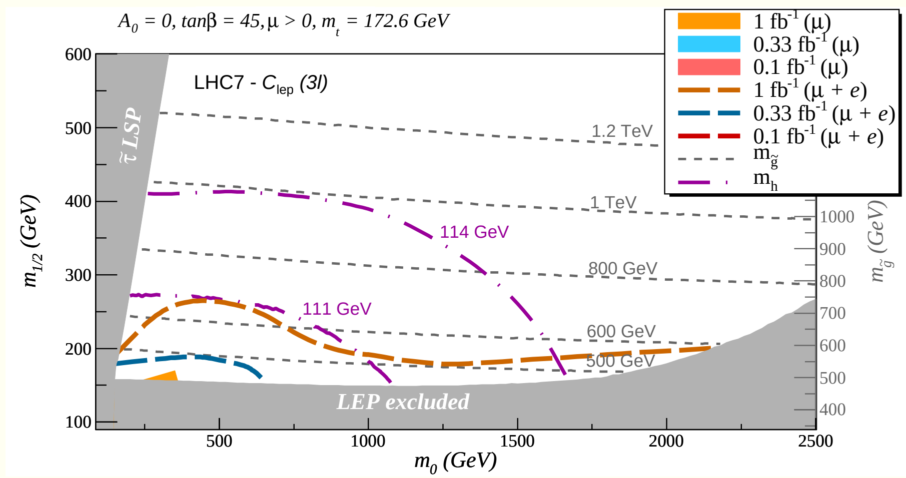
LHC7 reach without $\not\!\!E_T$

- ⋆ Isolated multilepton searches; $E_T(\ell) > 10$ GeV; $n_j \geq 4, E_T(j_1) \geq 100$ GeV; $E_T(j) \geq 50$ GeV; Z-veto.
- ⋆ Acollinear di-jets, since jet directions can be relatively well-determined even with incompletely understood detectors. $n_j = 2$; $E_T(j) \geq 50$ GeV; $E_T(j_1) + E_T(j_2) \geq 650$ GeV; $\Delta\phi(jj) < 2.4$.

MULTI-LEPTON SEARCHES WITHOUT $\not{E}_T$







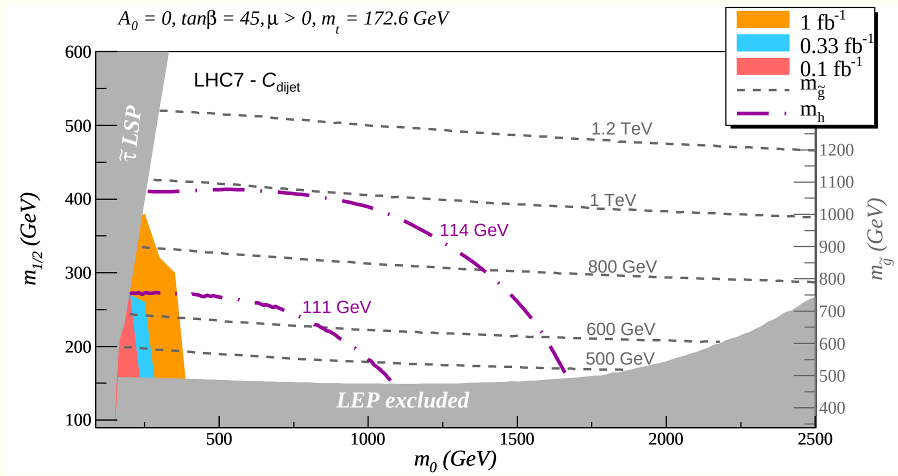
- ⋆ With only multimuons, no reach in the trilepton channel This is because the signal is severely rate-limited. Earliest reach is in the OS dimuon channel, but SS dimuons (because of smaller b/g) yield the greater reach i there is enough integrated luminosity.
- ⋆ With electrons included, the situation is different. The trilepton channel yields the best reach. W/in mSUGRA, the reach effectively probes $m_{\tilde{g}}$ out to 680 GeV. Small event numbers, but OS (same flavour) dilepton events would tend to cluster a bit below the dilepton mass edge

An excursion to 10 TeV

The multi-muon signal situation is completely different at even LHC10. In this case, the higher signal cross section implies:

- ⋆ LHC10 can begin to see signals in parameter regions not accessible to the Tevatron in the OS dimuon channel with just 100 pb^{-1}. Events cluster below but close to the dilepton mass edge.
- ⋆ As the integrated luminosity is increased, the greater reach is again obtained in the SS and trimuon channels. With 1 fb^{-1}, parameter regions with $m_{\tilde{g}} \sim 700$ GeV (800 GeV, with optimized cuts) may be probed within mSUGRA.
- ⋆ Characteristic distributions may make a circumstantial case for a SUSY signal.

Acollinear di-jets



For (approximately degenerate gluinos and squarks) the reach extends out to $m_{\tilde{q}} \sim 0.9$ TeV with 1 fb^{-1}, and is somewhat complementary to the multilepton search.

★ With just 1 fb^{-1}, the signal in the acollinear di-jet channel can probe gluinos and squarks out to 1.1 TeV or so if $m_{\tilde{q}} \sim m_{\tilde{g}}$ at LHC10.

In Summary

We have an exciting decade ahead of us.

During the first LHC run, we will be probing SUSY well beyond what is accessible at the Tevatron, including an interesting scenario that our workshop organizer has recently concocted.

	0.1 fb^{-1}	0.33 fb^{-1}	1 fb^{-1}	2 fb^{-1}
$\sqrt{s} = 7$ TeV	0.8 TeV	0.9 TeV	1.1 TeV	1.2 TeV
$\sqrt{s} = 10$ TeV	1.0 TeV	1.1 TeV	1.4 TeV	1.5 TeV
$\sqrt{s} = 14$ TeV	1.3 TeV	1.6 TeV	1.8 TeV	2.0 TeV

Up-coming XENON-100 results will be interesting for $m \gtrsim 20 - 30$ GeV neutralino LSP that can make MHDM.

Watch for results from Fermi, AMS, ...interprete with caution.ICECUBE more robust?

LHC Agenda for 2011-2020

⋆ Establish a clear New Physics signal.

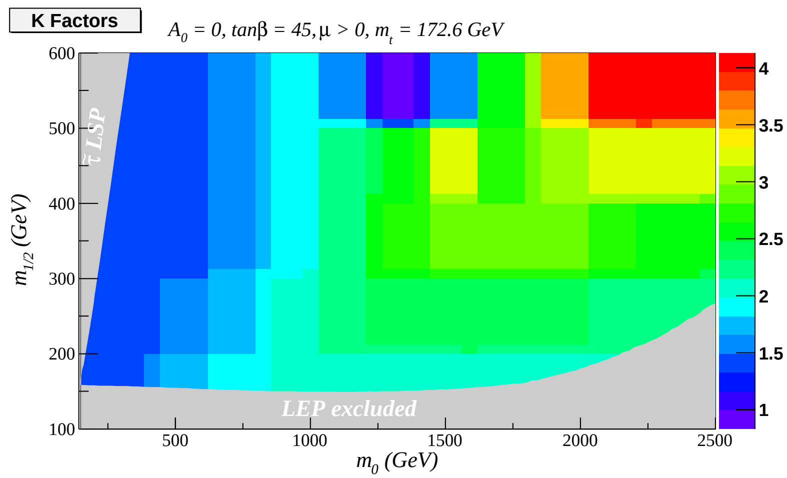
⋆ Make the case it is SUSY. The case will be circumstantial.

- Rates vs. mass. Strong vs. EW $\Longrightarrow$ Q. Nos.
- Same sign dileptons+jet+$\not{E}_T$ signal $\Longrightarrow$ strongly interacting Majorana particles. ($N(\ell^+\ell^+)$ vs. $N(\ell^-\ell^-)$)
- Cascade decays evidence of charginos and neutralinos?
- Clean trileptons as evidence of charginos and neutralinos
- Higgs bosons and stops in gluino cascade decays
- Sparticle Spin measurements (Cambridge, São Paulo,....)

BUILD A CONSISTENT PICTURE.

While we are at it, probe the KM structure as hard as possible.

WE HAVE A LOT OF WORK AHEAD OF US, BUT THE NEXT DECADE SHOULD BE FUN!



K Factors
A_0 = 0, tanβ = 45, μ > 0, m_t = 172.6 GeV
τ̃ LSP
LEP excluded
m_0 (GeV)
m_1/2 (GeV)
500
1000
1500
2000
2500
100
200
300
400
500
600
1
1.5
2
2.5
3
3.5
4