SUSY Theory Review

Physics at LHC, Cracow, 3-8 July 2006

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Outline

- Key questions
- Why SUSY
- Uncovering low-energy SUSY
- Off the beaten track
- New scenarios
- Cosmological connection
- Summary and outlook

Key questions

- Origin of mass? Is it the Higgs mechanism, or ...?
- Origin of matter-antimatter asymmetry?
- Properties of neutrinos?
- Unification of forces, including gravity?
- Dark matter, dark energy?

  - New Physics at the TeV scale ?
  - How can we test it ?
  - LHC will cut into the TeV territory !

LHC era coming soon!

- Expands significantly discovery frontier
- Exploration of TeV scale physics
- Hadron collider -- experiment ⇔ theory more difficult
- Better know what you are looking for
- But remain sceptical, be prepared for surprises

LHC experiments:

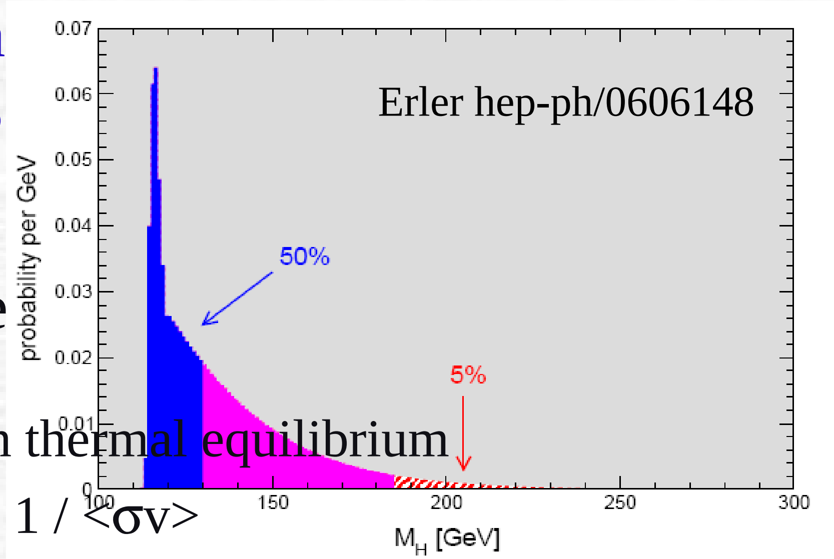
- the outcome far more important than any other in the past
- all future projects: ILC, superB, super..., depend on LHC discovery
- huge responsibility to provide quick and reliable answers

Hints for TeV physics

- Precision measurements of EW observables => light Higgs

- Naturalness => new TeV sca
divergent contributions from S

- Solid evidence of DM particle



neutral stable WIMP in thermal equilibrium

=> relic density ~ 1 / <σv>

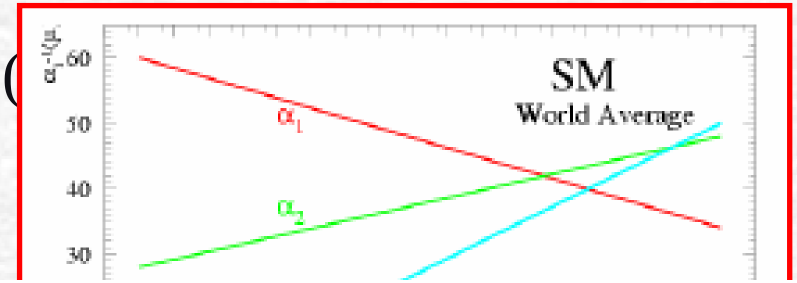
WMAP => <σv> ~ 1 pb

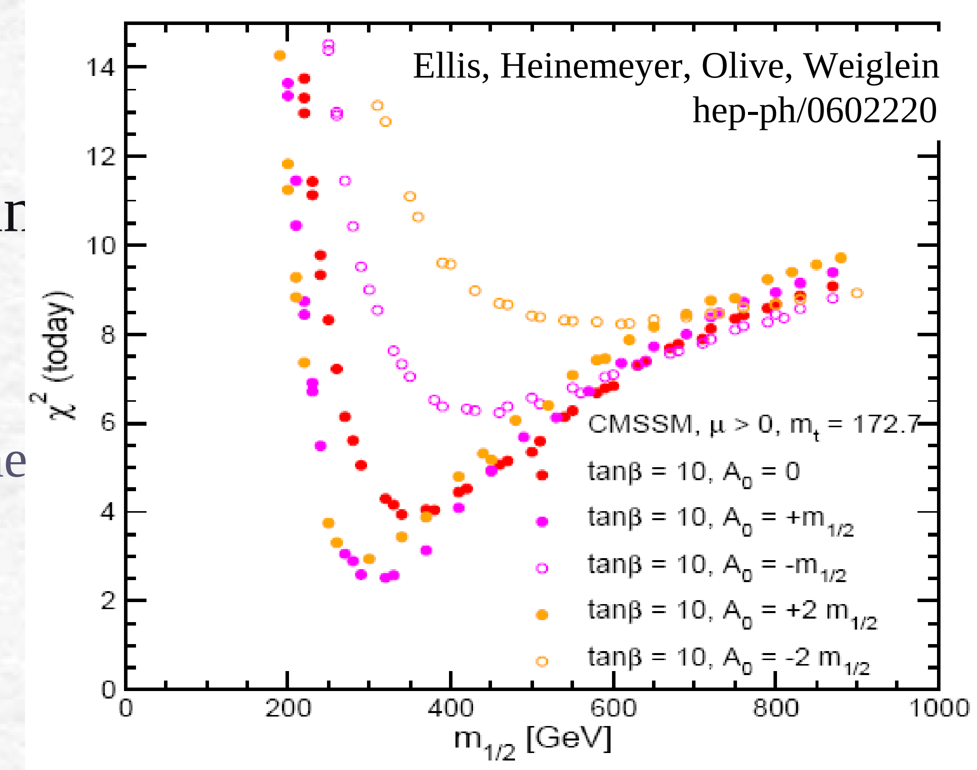
$\langle\sigma v\rangle = \pi\alpha^2/8m^2$ => m ~ 100 GeV

Supersymmetry – best candidate for New Physics

Why weak-scale SUSY ?

- stabilises the EW scale: $|m_F - m_B| < O($
- predicts a light Higgs $m_h < 130$ GeV
- accomodates heavy top quark
- predicts gauge unification
- dark matter candidate: neutralir
  - •WMAP constrains models, e.g.
  - • but relaxing models, opens up the parameter space
- consistent with EW data





Weak-scale SUSY

- May be related to all key questions
- Can be tested and disproved
- LHC provides essential tools for discovery answers

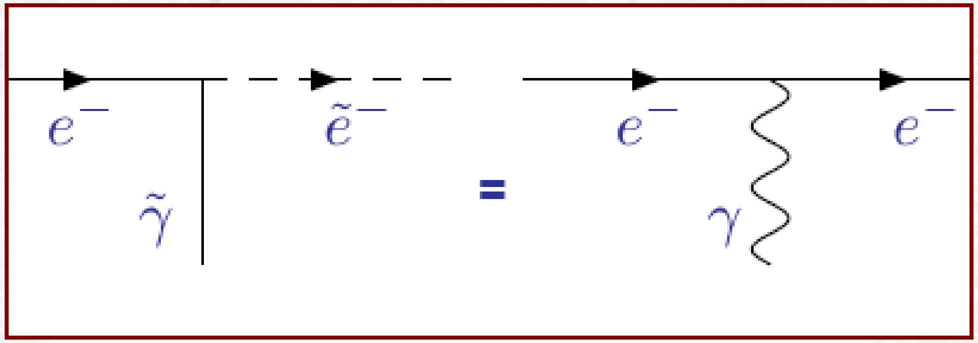
Discovering SUSY – a revolution in particle physics

Exact SUSY

- In minimal extenson of the SM, no new parameters

$$W = h_E H_1 L E^c + h_D H_1 Q D^c + h_U H_2 Q U^c - \mu H_1 H_2$$

  - **we know sparticles**
  - **we know their couplings, e.g.**



- but $m_{particle} \neq m_{sparticle}$ (> 100 GeV)

- SUSY must be broken
- No viable models of SUSY breaking within MSSM itself

Soft-SUSY breaking terms

Terms in the Lagrangian that break SUSY 'softly'

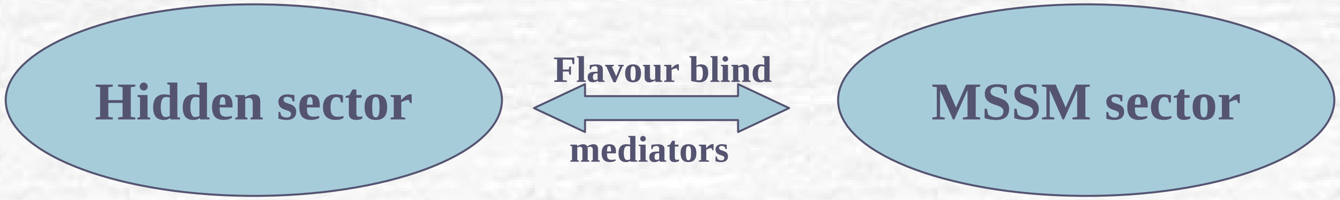
(i.e. does not (re)introduce quadratic divergencies)

- gaugino masses $M_a \lambda^a \lambda^a + \text{h.c.}$
- scalar (masses)^2 $M^2_{ij} \phi_\iota^+ \phi_j$
- bilinear scalar couplings $b_{ij} \phi_i \phi_j + \text{h.c.}$
- trilinear scalar couplings $A_{ijk} \phi_i \phi_j \phi_k + \text{h.c.}$

In general 105 new parameters, but …

Hidden-sector SUSY breaking

- Invoke a hidden sector where SUSY breaking occurs



- In the HS the F and/or D terms of some non-MSSM develop VEV

$$m_{soft} \sim \frac{\langle F \rangle}{M_{mess}}$$

Hidden-sector SUSY breaking

- A plethora of hidden-sector models

- Phenomenologically Lagrangian depends crucially on

  - what is the mediation mechanism: gravity, gauge, ... ?
  - which fields get the largest F or D term VEV's ?
  - what are dominant effects producing couplings of hidden sector and MSSM fields: tree-level, loop-induced, ..., ?

Soft parameters

GUT scale ⇔ low scale MSSM ⇔ physical

mSUGRA:
M_0,$m_{1/2}$,A,tanβ,sgn(μ)

String inspired models

GMSB

AMSB

…..

M_1
M_2
M_3

$M^2_{L_1}$
$M^2_{E_1}$

$M^2_{Q_1}$
$M^2_{U_1}$
$M^2_{D_1}$

μ, tanβ, A_f

Masses, branching ratios, Cross-sections

Neutralino/chargino

Sleptons

Squarks

Higgs (h,H,A)

At present

RGE

M_{GUT}, M_X, M_S, HO corrections, renormalisation scheme..., ?

Soft parameters

GUT scale ⬄ low scale MSSM ⬄ physical

mSUGRA:
M_0,$m_{1/2}$,A,tanβ,sgn(μ)

String inspired models

GMSB

AMSB

…..

In future

M_1
M_2
M_3

$M^2_{L_1}$
$M^2_{E_1}$

$M^2_{Q_1}$
$M^2_{U_1}$
$M^2_{D_1}$

μ, tanβ, A_f

Masses, branching ratios, Cross-sections

Neutralino/chargino

Sleptons

Squarks

Higgs (h,H,A)

all obstacles solvable with sufficient precision data -- need new techniques at hadron colliders

Practical questions

- How precisely can we predict masses, cross sections, branching ratos, couplings etc. ?
  - **many relations between sparticle masses already at tree-level, much worse at loop-level**
  - **no obvious choice of renormalizaton scheme**
- What precision can be achieved on parameters of the MSSM Lagrangian ?
  - **Lagrangian parameters not directly measurable**
  - some **parameters are not directly related to one particular observable, e.g., tanβ, μ**
  - **fitting procedure, ...**

$$M_{\tilde{C}} = \begin{pmatrix} M_2 e^{i\phi_2} & \sqrt{2} M_W \sin\beta \\ \sqrt{2} M_W \cos\beta & \mu e^{i\phi_\mu} \end{pmatrix}$$

$$M_{\tilde{C}_1}^2 + M_{\tilde{C}_2}^2 = \mathrm{Tr}\, M_{\tilde{C}}^{\dagger} M_{\tilde{C}} = M_2^2 + \mu^2 + 2M_W^2$$

- Can we reconsruct the fundamental theory at high scale ?
  - **unification of couplings, soft masses etc.???**
  - **which SUSY breaking mechanism ??**

→ Goals of the SPA Project

SPA Project and Convention

- Supersymmetry particles have been discovered at the LHC
- In future ILC provides additional precision data on masses and couplings

Will everybody be happy?

We would like to know the relation of the visible sector to the fundamental theory:

- **what is the origin of SUSY breaking**
- **what is the role of neutrinos**
- **is it related to the theory of early universe**
- **how to embed gravity, etc., etc.**

Probably we won't have a direct experimental access to these questions

But SUSY is a predictive framework !

We can analyse precision data and state how well within some specific SUSY/GUT model the relation of observable to fundamental physics can be established

The SPA Conventon and Project

- SPA Convention

  renorm. schemes / LE parameters / observables

- Program repository

  th. & exp. analyses / LHC+ILC tools / Susy Les Houches Accord

- Theoretical and experimental tasks

  short- and long-term sub-projects

- Reference point SPS1a'

  derivative of SPS1a, consistent with all data

- Future developments

  CP-MSSM, NMSSM, R_pV, effective string th., etc.

http://spa.desy.de/spa

SPA

SUPERSYMMETRY PARAMETER ANALYSIS

The SPA project is a joint study of theorists and experimentalists working on LHC and Linear Collider phenomenology. The study focuses on the supersymmetric extension of the Standard Model. The main targets are

- High-precision determination of the supersymmetry Lagrange parameters at the electroweak scale
- Extrapolation to a high scale to reconstruct the fundamental parameters and the mechanism for supersymmetry breaking

The SPA convention and the SPA Project are described in t SPA report [Eur.Phys.J.C46:43-60,2006].

Coordinators

This list contains the coordinators from Europe only; for each sector, the coordinators from America and Asia will be added soon.

The SPA Convention

- The masses of the SUSY and Higgs: pole masses
- The SUSY Lagrangian parameters: mass parameters and couplings, including tanβ, defined in the DRbar scheme at a scale M= 1 TeV
- Gaugino/higgsino and scalar mass matrices, rotation matrices and the corresponding mixing angles defined in the DRbar, except for the Higgs, in which mixing is defined in the on-shell scheme at m_h
- The SM input parameters: G_F, α, M_Z, $\alpha_s^{MSbar}(M_Z)$

  lepton masses on-shell

  t quark mass on-shell

  b, c quark masses in MSbar taken at masses themselves

  light quarks in MSbar at a scale of 2 GeV
- σ, Γ, BR, …, calculated for parameters as above

DRbar scheme

- On-shell, MSbar, DRbar ?
- Drbar = DRED + modified min. subtraction
- most convenient, natural for GUT-inspired parameter sets
- but problems with DRED?

SUSY, Consistency

- Does DRED preserve SUSY?
- Mathematical inconsistency

  [Siegel'80]
- Symmetry-restoring countert-erms necessary in calculations?

QCD-Factorization

- Hadron processes in DRED:

$$\sigma_{\text{had}} = f_{\text{parton}} \otimes \sigma_{\text{parton}} + \text{non-factorizing terms?}$$

[Beenakker,Kuijf,Neerven,Smith'88]

[Beenakker,Höpker,Spira,Zerwas'96]

$$\sigma(G,\ \ldots) = \sigma(g,\ \ldots) + \sigma(\phi,\ \ldots)$$

$$\downarrow \qquad \downarrow \qquad \downarrow$$

4-dim gluon — D-dim gluon — $4-D$ scalars

Stockinger, Signer
hep-ph/0508203

The SPA Repository

Nowadays real physics done by computer: a repository with links to:

- Scheme translation tools

  DRbar ⟺ MSbar ⟺ on-shell
- Spectrum calculators: Lagrangian ⟺ masses, couplings,…

  ex: FeynHiggs, SPheno, SuSpect, SoftSusy,IsaJet, …
- Other observables: cross sections, decay rates, LE param., astrophysics, cosmology

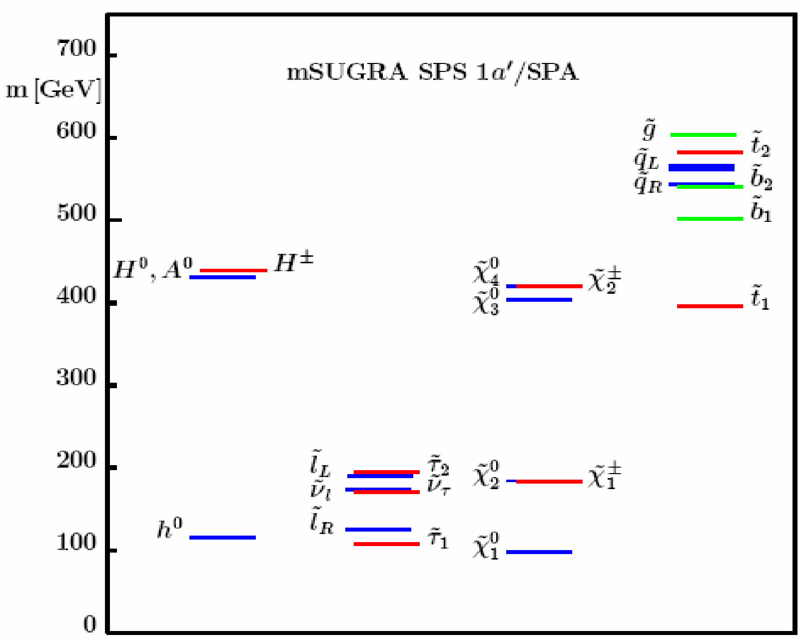
  ex: HDecay, NMHDecay, SDecay, Prospino, micrOMEGAs, DarkSUSY,
- Event generators: IsaJet, Phytia, Whizard, …
- Analysis programs: SFitter, Fittino
- RGE: M ⟺ $M_{GUT/Pl}$: SPheno, SoftSusy, IsaJet/IsaSusy, …

codes interfaced by the Susy Les Houches Accord

→ http://spa.desy.de/spa

Testing the SPA project

- SPS1a'- derivative of the SPS1a point



LHC friendly:
+ beautiful chain decays
+ many end in leptons

ILC friendly:
+ all H's and –inos within reach (at 1 TeV)
+ light sleptons

m_0	70 GeV
$m_{1/2}$	250 GeV
A_0	-300 GeV
$\tan\beta$	10
sign μ	$+$

$$BR(b \to s\gamma) = 3.0 \times 10^{-4}$$
$$\Delta[g_\mu - 2]/2 = 33 \times 10^{-10}$$
$$\Omega_{cdm} h^2 = 0.10$$

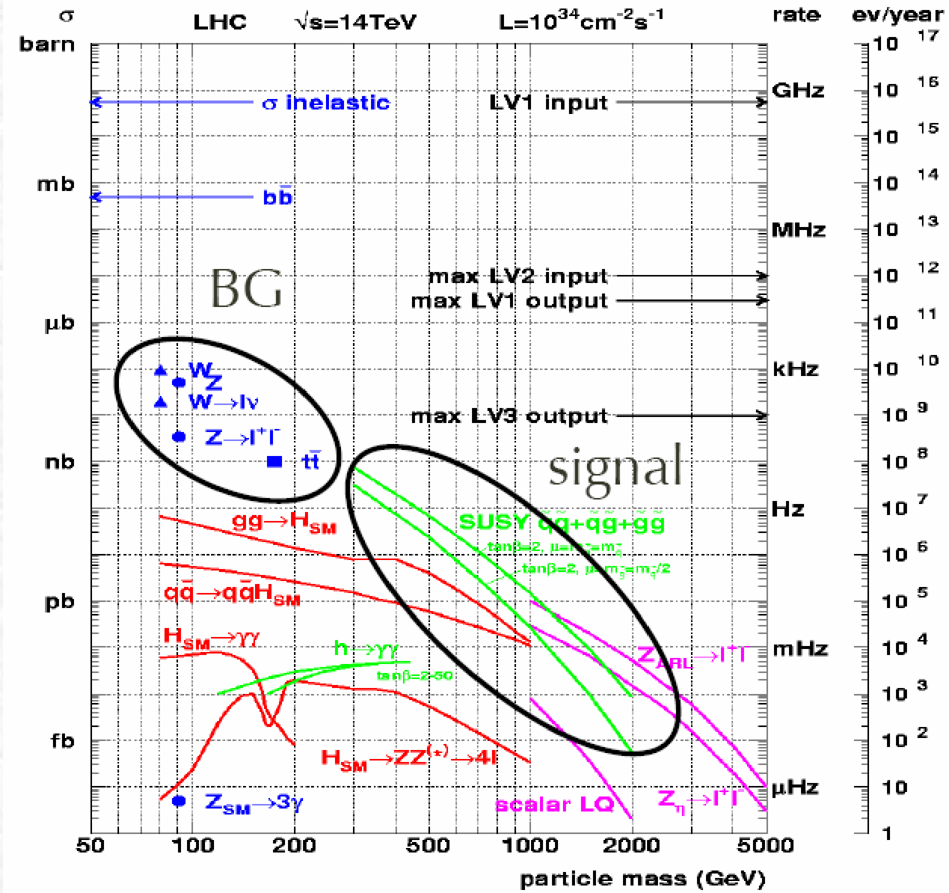
LHC: signal and background

Dominant production of colored sparticles which will decay to leptons, jets + LSP

SUSY signal:
jets and leptons with large Pt
+ missing transverse energy
(typical e.g. for mSUGRA, GMSB)

BG from W, Z and tt production:
need strong rejection ~10^{-4}

Exploit kinematics to maximum extent:
mass reconstruction method



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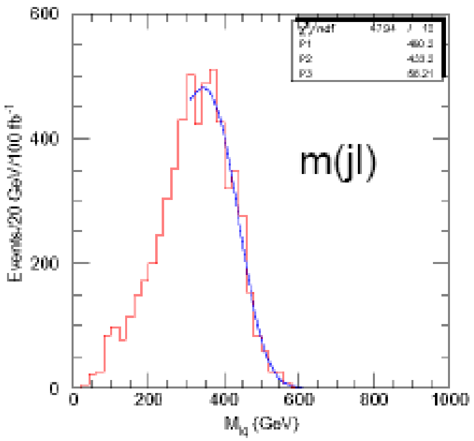
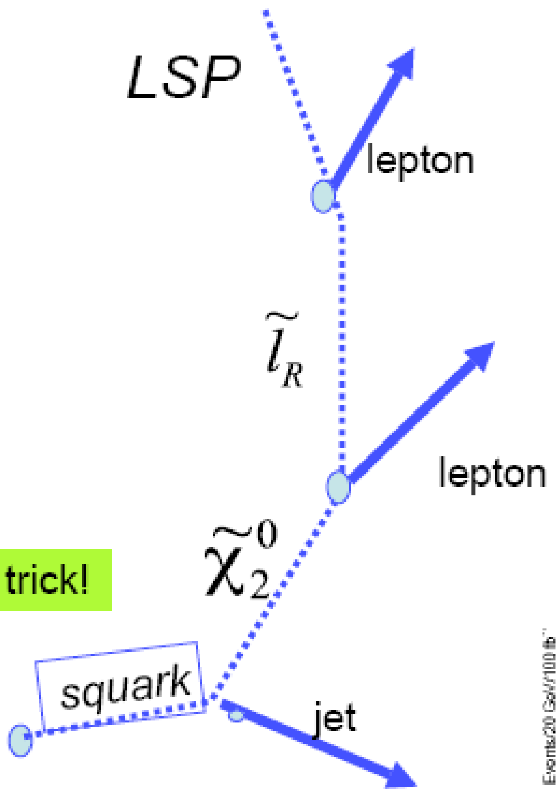
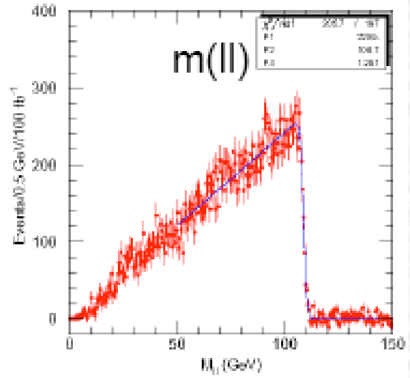
Mass reconstruction

determination of the boundary of phase space
for mass determination.

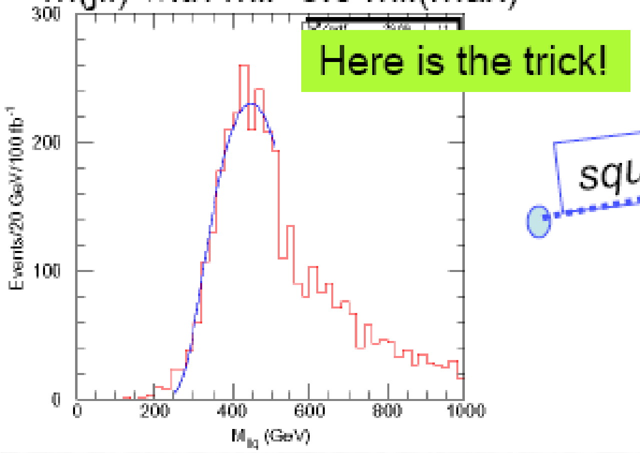


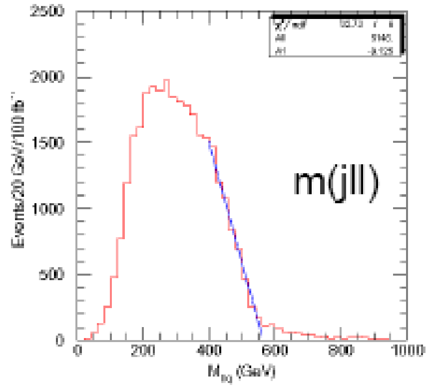




ee+μμ-eμ subtraction is effective to select single channel

m(jll) with mll>0.5 mll(max)





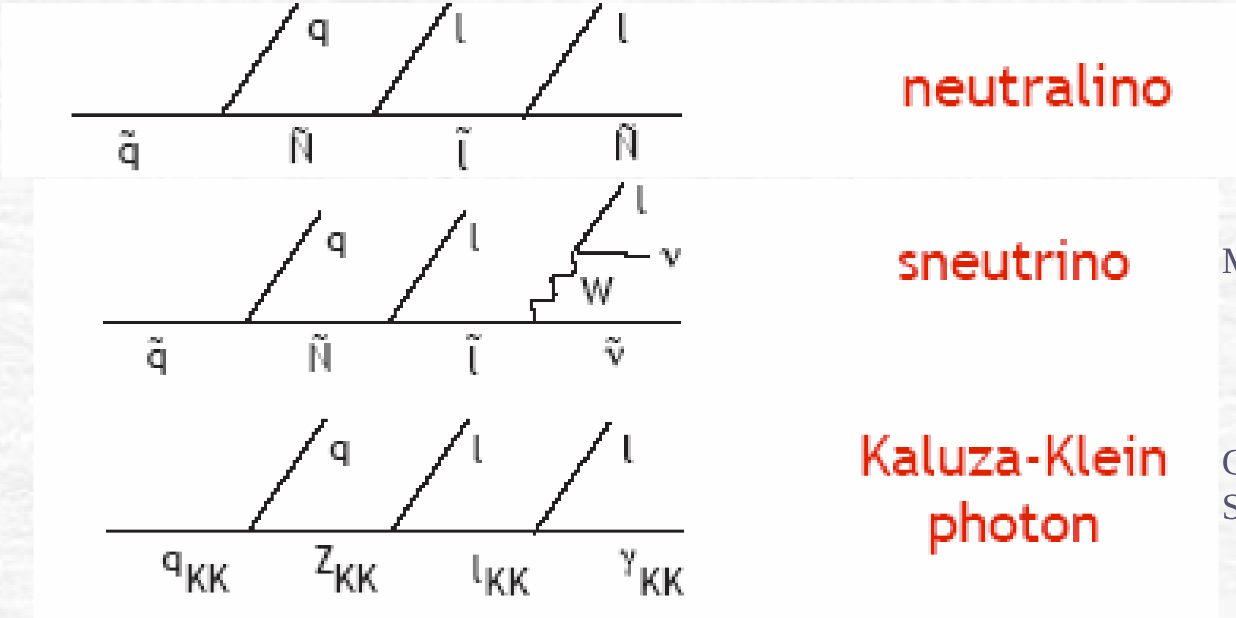
Kawagoe, Nojiri, Polesello hep-ph/0410160

Gjelsten, Miller, Osland hep-ph/0410303 hep-ph/0511008

Nojiri, SUSY06

Mass determination

- with long decay chain, enough constraints to determine masses in the process
- with masses known, reconstruct LSP momentum (up to 2-fold ambiguity)
- are we done?



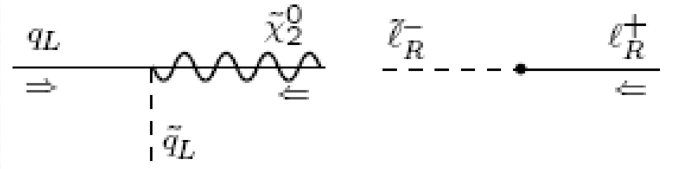
Murayama

Cheng, Matchev, Schmaltz

Can the LHC distinguish?

spin determination

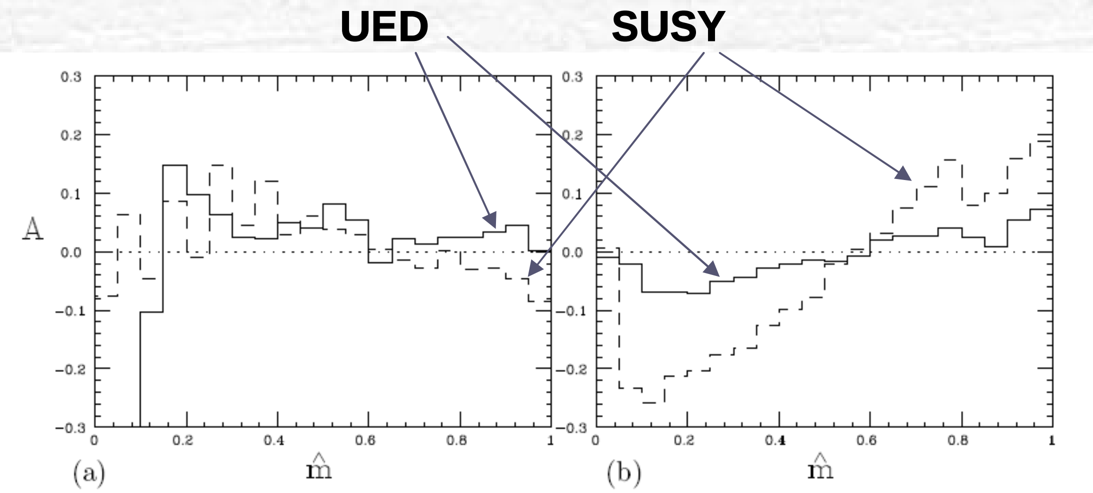
SUSY/KK differ in spins in the decay chain
need sensitivity to the particle spin



eg. lepton charge asymmetries

$$A = \frac{(l^+q)-(l^-q)}{(l^+q)+(l^-q)}$$

Barr hep-ph/0405052; Smillie, Webber hep-ph/0507170
Allanach,Mahmoudi hep-ph/0602198

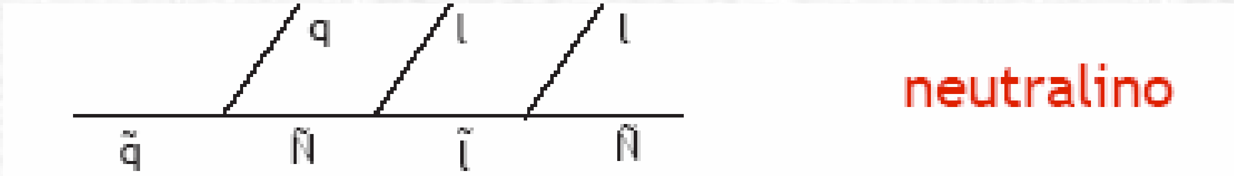


KK-like masses SPS1a-like masses

efficiency depends on sparticle masses

Lesson: need spin correlations in generators of cascade decays !!

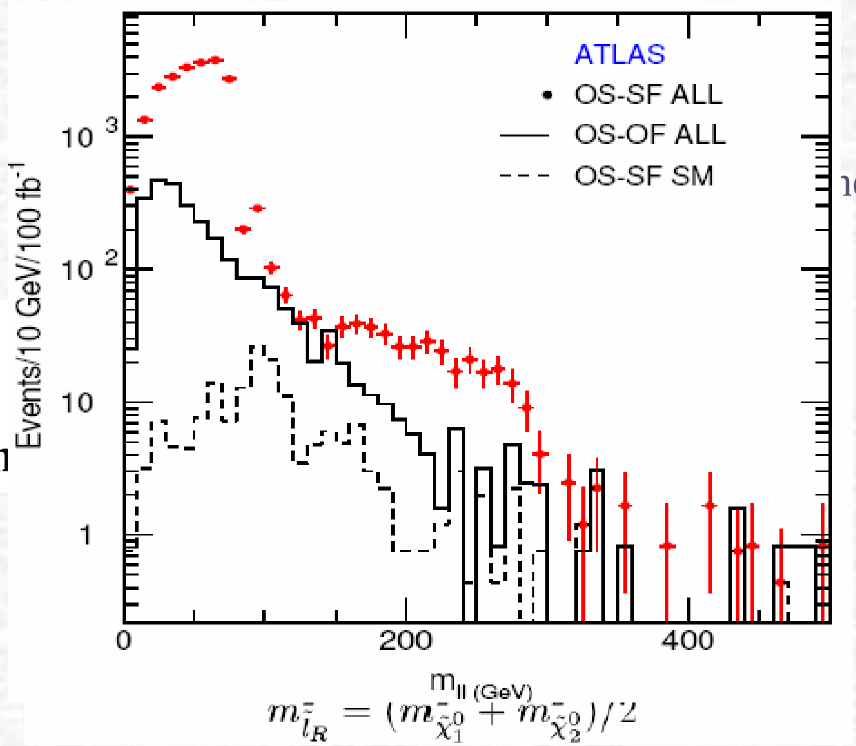
even if SUSY



moreover, ILC can help identifying heavy neutralino at LHC

false solutions may occur

need ILC to eliminate them



Desch, JK, Moortgat-Pick, Nojiri, Polesello, hep-ph/0312069

- More on LHC/ILC interplay, see G. Weiglein et al., hep-ph/0410364

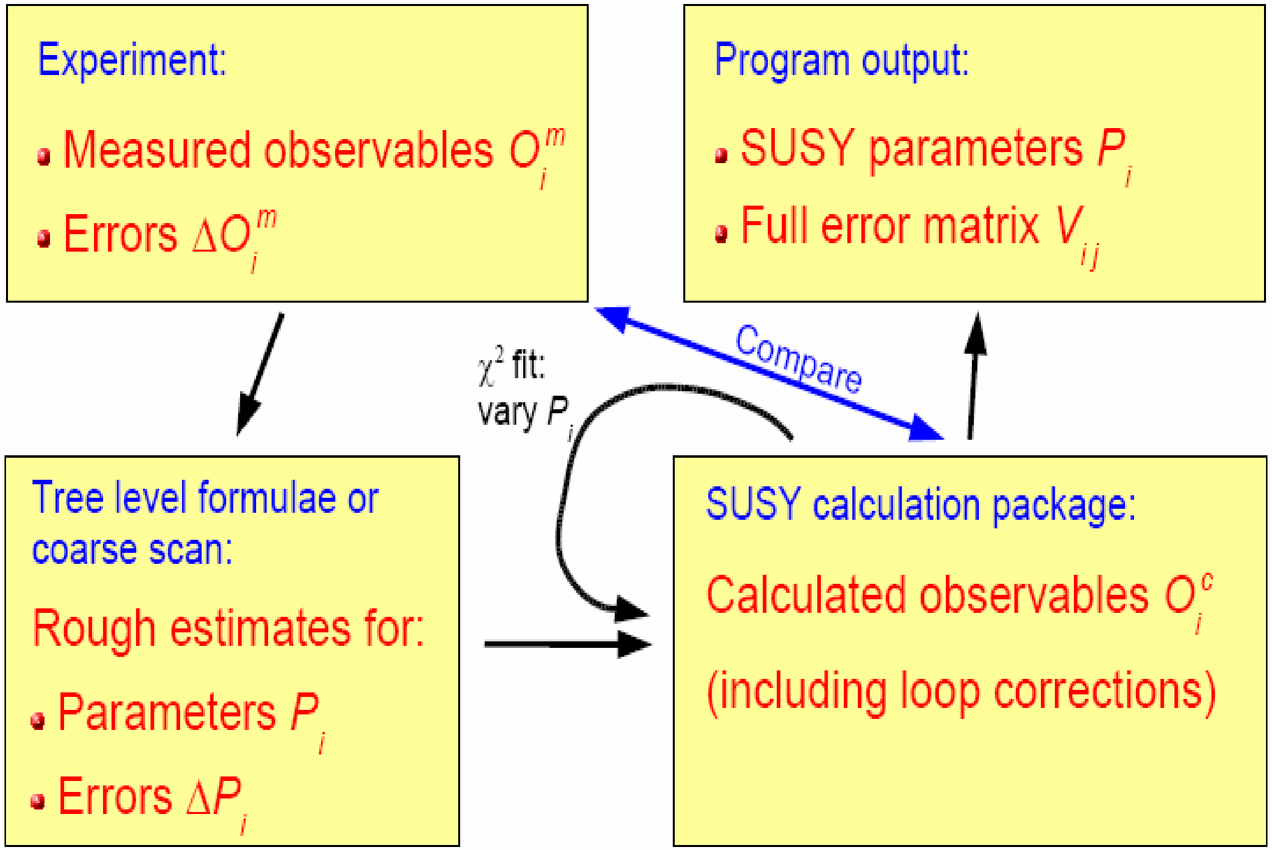
SPS1a': Measurements

- edges at LHC
- decay spectra at ILC
- threshold scans at ILC
- results:

	Mass	"LHC"	"LC"	"LHC+LC"
h^0	115.4	0.25	0.05	0.05
H^0	431.1		1.5	1.5
$\tilde{\chi}_1^0$	97.75	4.8	0.05	0.05
$\tilde{\chi}_2^0$	184.4	4.7	1.2	0.08
$\tilde{\chi}_4^0$	419.6	5.1	$3-5$	2.5
$\tilde{\chi}_1^\pm$	184.2		0.55	0.55
$\tilde{e}_R$	125.2	4.8	0.05	0.05
$\tilde{e}_L$	190.1	5.0	0.18	0.18
$\tilde{\tau}_1$	107.4	$5-8$	0.24	0.24
$\tilde{q}_R$	547.7	$7-12$	–	$5-11$
$\tilde{q}_L$	565.7	8.7	–	4.9
$\tilde{t}_1$	368.9		1.9	1.9
$\tilde{b}_1$	506.3	7.5	–	5.7
$\tilde{g}$	607.6	8.0	–	6.5

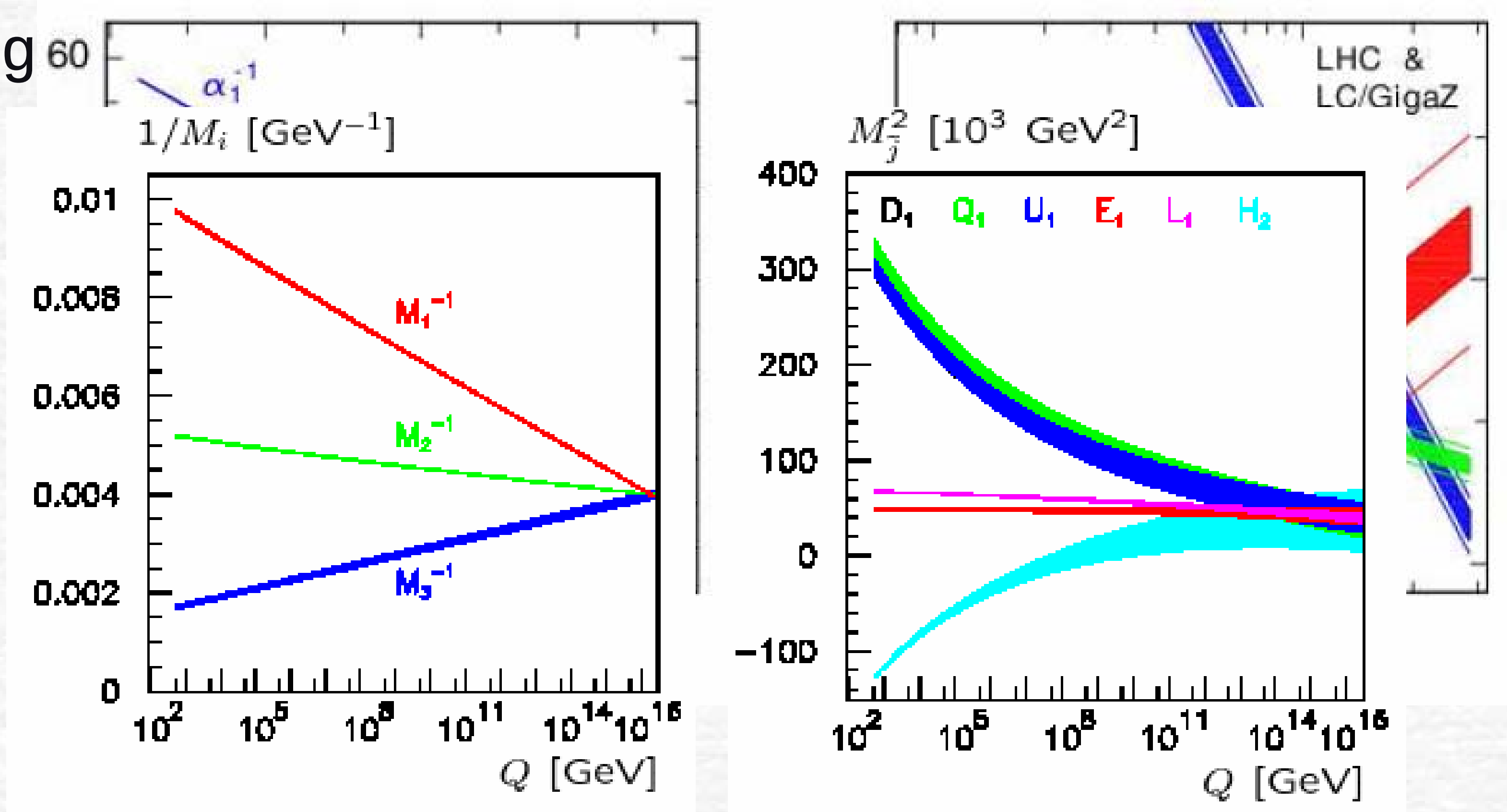
Reconstructing Lagrange param.

- global analysis codes:
  SFitter (Lafaye, Plehn, D. Zerwas)
  Fittino (Bechtle, Desch, Wienemann)
- fit masses + xsecti
  and BR
- radiative correction
- ex: Fittino



High-scale extrapolation

- gauge couplings α^{-1}
- g



- universality can be tested in bottom-up approach

Off the beaten track

- SPS1a is just a scenario
- Reality might be quite different than SPS1a, or mSUGRA, or …

- Other possibilities:

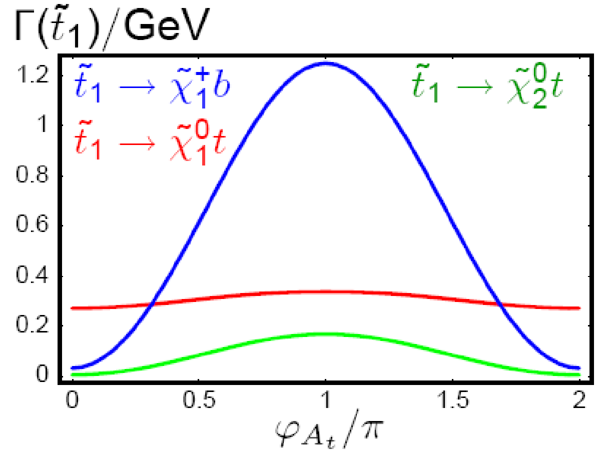
• complex parameters (baryogenesis)
• lepton flavour violation (neutrino masses)
• R-parity violation (neutrino masses)
• mixed scenarios of SUSY breaking
• additional matter fields
• or additional gauge factors
• or additional dimensions
• or ...

From the LHC perspective: different signatures

CP phases

- CKM matrix – the only source of CP?
- CP violating SUSY might explain baryon asymmetry in the universe
- strong constraints from EDMs on phases in 1st and 2nd generation sfermions and charginos/neutralinos
- phases will not only generate CP-odd, but also affect CP-even observables: cross sections, branching fractions, ...

e.g.



In SPS1a-like scenario

Bartl et al.

- knowledge of CP phases important for model-building
- at LHC measurement of CP phases difficult
- develop techniques to measure jet charges -- sensitivity to CP-odd
- ILC would greatly help

Lepton flavour violation

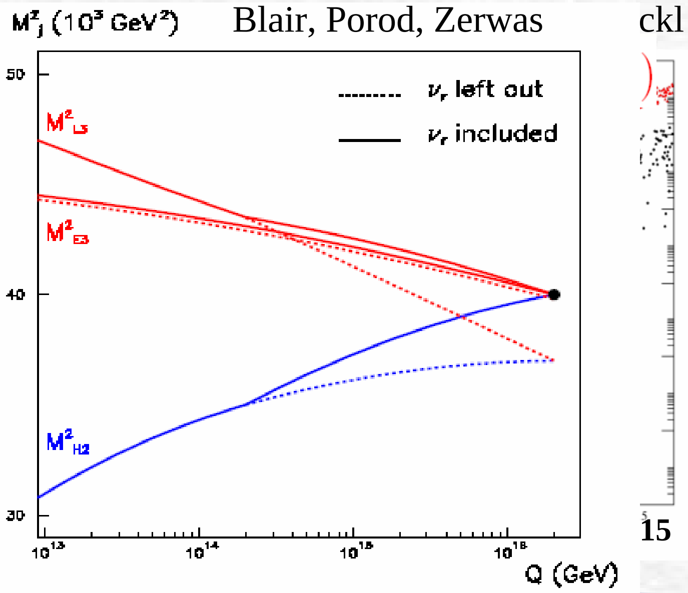
- Neutrino masses and mixings in MSSM+ RH neutrinos

$$W_\nu = -\frac{1}{2}\nu_R^{cT} M \nu_R^c + \nu_R^{cT} Y_\nu L \cdot H_2$$

- EWSB => Dirac mass $m_D = Y_\nu \langle H_2 \rangle \ll$ Majorana mass M ~ 10^{14} GeV

- massive neutrinos affect RGE of slepton masses: flavour off-diagonal terms
- lepton flavour violation in slepton pair production and rare decays

Blair, Porod, Zerwas



ckl et al.

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- measurable at the LHC??

- with future ILC precision measurements

Lepton flavour violation – $\tilde{N}_R$ LSP

- but Majorana mass M can be as low as ~ EW scale
- neutrino mass => Yukawa $Y_\nu \sim 10^{-6}$
- tiny left-right sneutrino mixing
- the LSP can be almost pure $\tilde{N}_R$
- interesting non-thermal dark matter candidate — Asaka, Ishiwata, Moroi hep-ph/ 051218
- distinct collider signature — Gouvea, Gopalakrishna, Porod hep-ph/0606296

NLSP long-lived, displaced vertices similar to GMSB, but

- **LSP carries lepton number => associated leptons in the final state**
- **NLSP can be strongly interacting, e.g. lightest stop**
- **stops could form narrow bound states**
- **non-universal rates for e, mu and tau leptons**

LHC could probe stops up to ~ 650 GeV

R-parity

- Is R-parity broken?   No good arguments to impose it.
- To prove LSP decays, two conditions:

  short enough decay length,   OK. for couplings >~ 10^-6
  visible decay,   model dependent

- Lepton number violation **(proton stable!)**

$$\mathcal{W} = \epsilon_i \widehat{L}_i \widehat{H}_u + \lambda_{ijk} \widehat{L}_i \widehat{L}_j \widehat{E}^c_k + \lambda'_{ijk} \widehat{L}_i \widehat{Q}_j \widehat{D}^c_k$$

  +soft terms

- explicit violation:

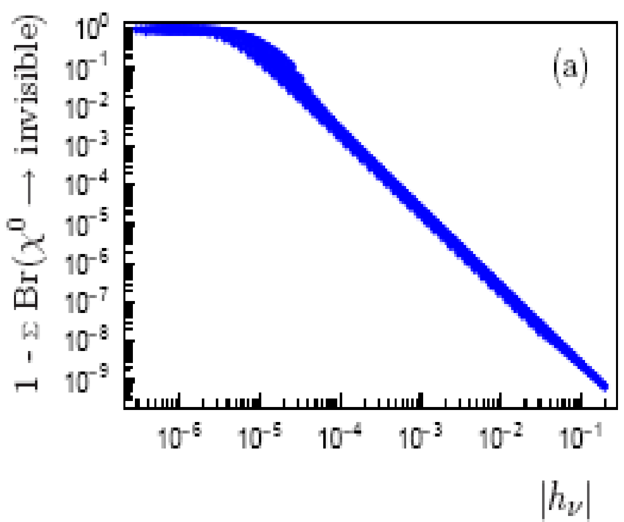
  trilinear: χ ->qq, ll

  bilinear: χ ->3ν, but rate controlled by Z->inv.

- spontaneous violation **(generates neutrino masses)**:

  neutralino decays to Majoron+neutrino

  model mimics R-parity conserved MSSM



Hirsch, Porod hep-ph/0606061

→ Models with larger relic density deserve studies at LHC

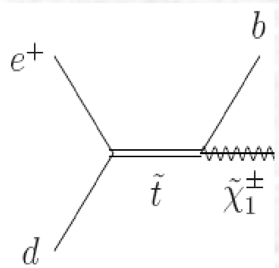
R-parity

H1 events with isolated leptons

$$e^+p \;\rightarrow\; e^+/\mu^+ + \text{jet} + \not{E}_T + X$$

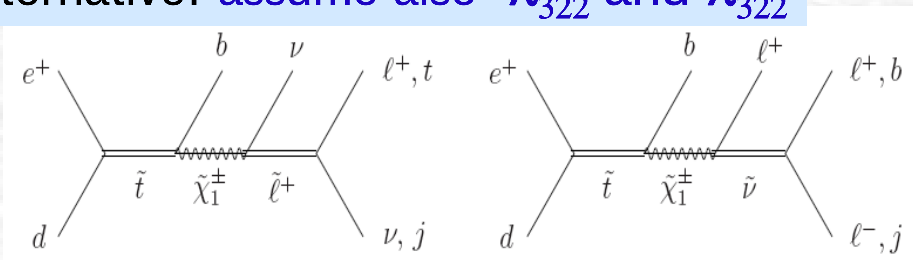
Popular interpretation: stop production via λ'_{131}

Kon, Matsushita, Kobayashi



chargino -> W + neutralino
but difficult to arrange long-lived neutralino
=> no H1 signature

Alternative: assume also λ_{322} and λ_{322}



H1 signature requires moderate tanβ and higgsino-like light chargino and neutralinos

Choi, JK, Martyn, Zerwas

Possible tests:

- HERA:
  - **additional signatures**

$\tilde{\chi}_1^+$ decay	λ_{322}	λ_{321}	λ'_{131}
$\tilde{e}_L^+\nu_e$	–	–	$t\bar{d}$
$\tilde{\mu}_L^+\nu_\mu$	μ^+	e^+	–
$\tilde{\tau}_L^+\nu_\tau$	μ^+	e^+	–
$\tilde{\nu}_e e^+$	–	–	$d\bar{b}$
$\tilde{\nu}_\mu \mu^+$	$\mu^-\tau^+$	$e^-\tau^+$	–
$\tilde{\nu}_\tau \tau^+$	$\mu^-\mu^+$	$e^-\mu^+$	–

  - **clustering of invariant masses**

- LHC:
  - **stop production and decay**
  - **DY sneutrino production**
  - **degenerate spectrum signature**

New scenarios

- Radiative EWSB driven by top Yukawa seen as a key success
- but LEP Higgs mass limit requires large radiative correction => $m_{\tilde{t}} \geq 500 \text{ GeV}$
- the RGE evolution due to stop

$$\Delta m_{H_u}^2 \sim -\frac{3}{4\pi^2} y_t^2 m_{\tilde{t}}^2 \ln \frac{\Lambda}{m_{\tilde{t}}}$$

which is close to $m_{\tilde{t}}^2$ for $\Lambda \sim 10^{16}$ GeV

- minimization condition $\frac{M_Z^2}{2} \simeq -\mu^2 - m_{H_u}^2$ requires "little fine-tuning"

Alternative models for mediating SUSY breaking

- mixed gauge-anomaly mediation Hsieh, Luty
- mixed modulus-anomaly mediation Kachru, Kallosh, Linde, Trivoli; Choi, Jeong, Okumura; Falkowski, Lebedev, Mambrini
- low effective scale and sizable A_t Choi, Jeong, Kobayashi, Okumura; Kitano, Nomura
- top Yukawa generated at low scale Kobayashi, Nakano, Terao
- Higgs as a pseudo-Goldstone Birkedal, Chacko, Gaillard; Berezhiani, Chankowski, Falkowski, Pokorski,
- Higgs as a composite Harnic, Kribs, Larson, Murayama; Delgado, Tait; ...
- additional gauge group factors Maloney, Pierce, Wacker; ...
- twin Higgs, twin SUSY Chang, Hall, Weiler; Falkowski, Pokorski, Schmaltz
- additional dimensions ......

Mixed modulus-anomaly

- volume moduli T and anomaly contribute to SUSY breaking KKLT
- soft terms controlled by $M_s = m_{3/2}/16\pi^2$ and $\alpha = F_T/(T+T^*)M_s$

$$
\begin{aligned}
M_a &= M_s\left[\alpha + b_a g_a^2\right] \;, \\
m_i^2 &= M_s^2\left[\alpha^2 - \dot{\gamma}_i + 2\alpha(T+\overline{T})\partial_T\gamma_i\right] \\
A_{ijk} &= M_s\left[3\alpha - \gamma_i - \gamma_j - \gamma_k\right] + \Delta A_{ijk}
\end{aligned}
$$

Falkowski, Lebedev, Mambrini

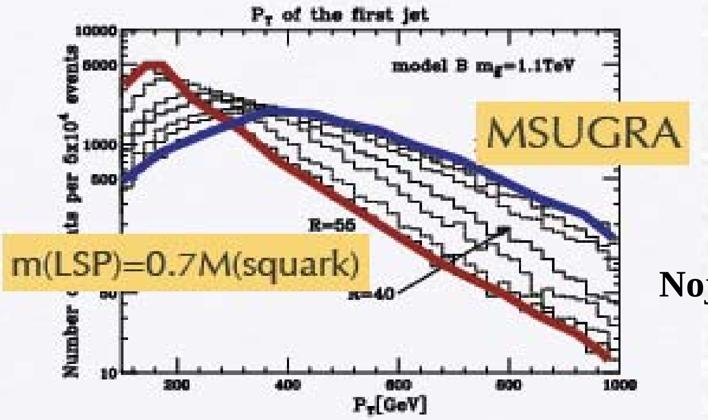
- for α-->0 pure anomaly, for α >> 5 modulus (gravity) mediation

Features:

- advantageous moderate hierarchy $m_{\rm MSSM} \ll m_{3/2} \ll m_{\rm moduli}$
- no tachons for α > 4
- DM higgsino like: degenerate light neutralinos and chargino
- sleptons and squarks generically heavier -> no FCNC
- soft masses unify at $\mu_{mir} = M_{GUT}\, e^{-8\pi^2/\alpha}$ which can be much lower than M_{GUT}
- quite different signature at the LHC

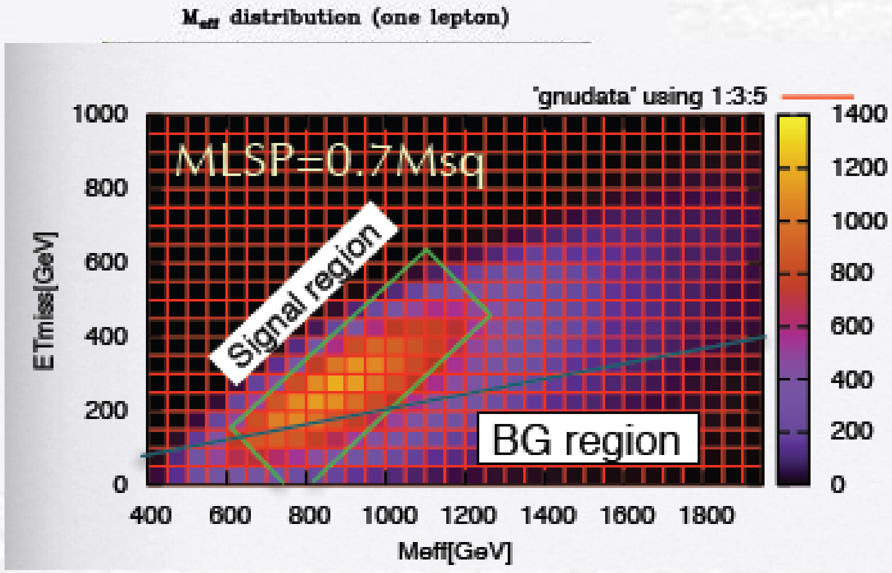
SUSY at LHC in degenerated limit

- degenerate SUSY= lower P_T jets, small M_{eff}. Discovery gets difficult (no chance if all masses are same)
- "Benchmark" of degenerate scenario
- Need to take into account the background unlike MSUGRA.
- S/N<1, discovery is in ?? because of the background uncertainty



R~1/α

Nojiri, SUSY06



- **correlations in M_{eff} and E_{tmiss} may help**
- **better control of SM background critical**

NMSSM, UMSSM, ESSM, …

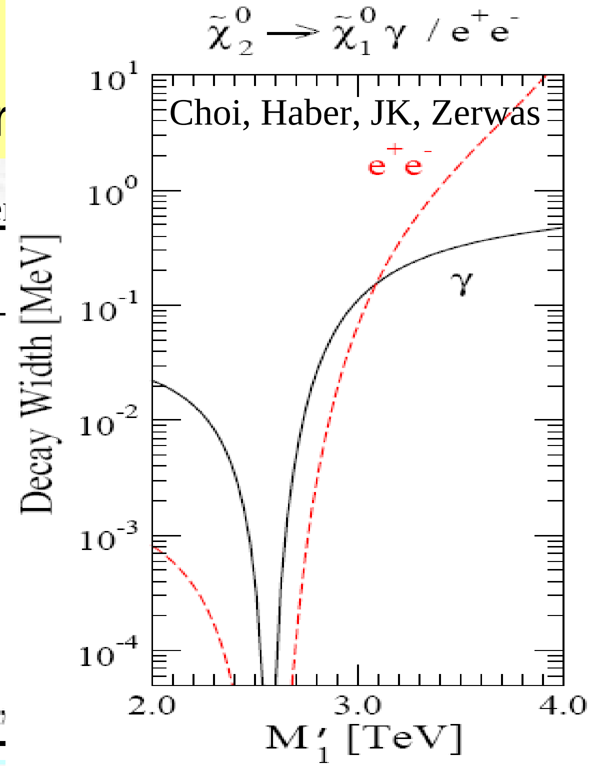
- in MSSM the μ problem $W = \mu \hat{H}_u \cdot \hat{H}_d$
- μ the only dimensionful MSSM parameter not related to EW or SUSY breaking
- add a singlet field S – well motivated in string constructs
- replace $W = \mu \hat{H}_u \cdot \hat{H}_d$ by $W = h_s \hat{S} \hat{H}_u \cdot \hat{H}_d$
- effective μ_{eff} generated by the S-field vev $\mu_{eff} = h_s \langle S \rangle = O(1\ \text{TeV})$
- singlet-doublet Higgs mixing eases the LEP tension
- hundreds of papers and models, too many contributor

Features:

- v
- r
- h
- li
- Z
- r

Barge

Model	Symmetry	Superpotential	CP-even
MSSM	–	$\mu \hat{H}_u \cdot \hat{H}_d$	H_1^0, H_2^0
NMSSM	$\mathbb{Z}_3$	$h_s \hat{S} \hat{H}_u \cdot \hat{H}_d + \frac{\kappa}{3} \hat{S}^3$	H_1^0, H_2^0, H_3^0
nMSSM	$\mathbb{Z}_5^R, \mathbb{Z}_7^R$	$h_s \hat{S} \hat{H}_u \cdot \hat{H}_d + \xi_F M_n^2 \hat{S}$	H_1^0, H_2^0, H_3^0
UMSSM	$U(1)'$	$h_s \hat{S} \hat{H}_u \cdot \hat{H}_d$	H_1^0, H_2^0, H_3^0
sMSSM	$U(1)'$	$h_s \hat{S} \hat{H}_u \cdot \hat{H}_d + \lambda_s \hat{S}_1 \hat{S}_2 \hat{S}_3$	$H_1^0, H_2^0, H_3^0, H_4^0, H_5^0,$

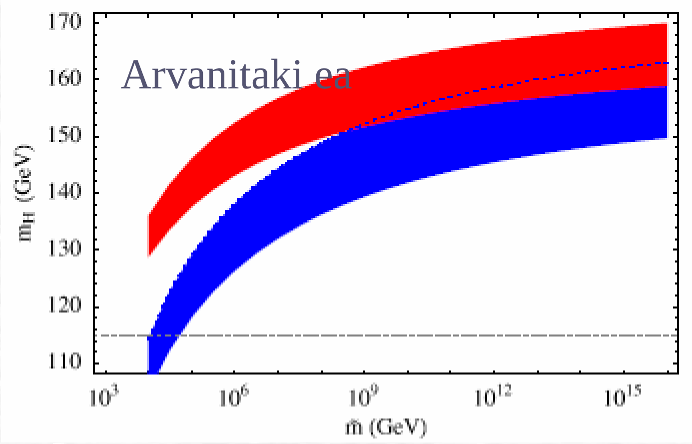


What if fine-tuning no longer a principle

Split SUSY

Arkani-Hamed, Dimopoulos

$$\mathcal{L} \supset \tilde{B}(\kappa_1' h^\dagger \tilde{H}_1 + \kappa_2' h \tilde{H}_2) + \tilde{W}^a(\kappa_1 h^\dagger \tau^a \tilde{H}_1 + \kappa_2 \tilde{H}_2 \tau^a h) - \lambda |h|^4 - \mu \tilde{H}_1 \tilde{H}_2 - \frac{1}{2}(M_1 \tilde{B}\tilde{B} + M_2 \tilde{W}\tilde{W} + M_3 \tilde{g}\tilde{g})$$

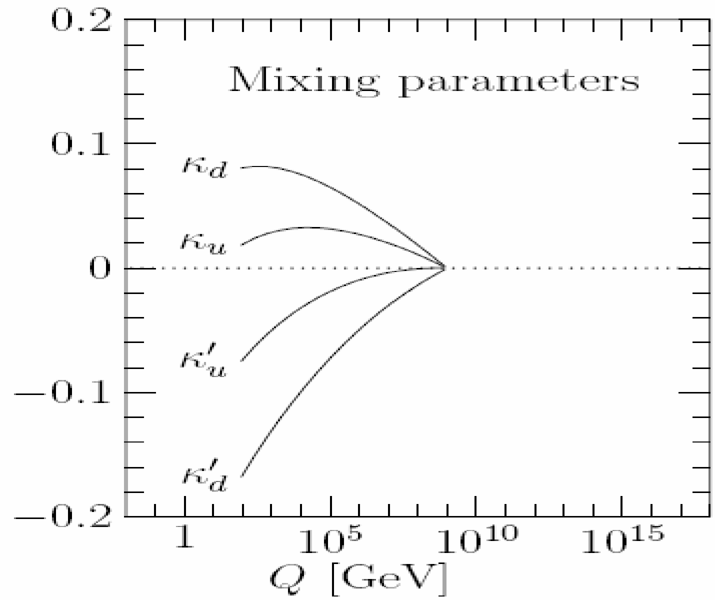


Signature:

- heavier SM-like Higgs boson
- LHC: long-lived gluino
- ILC: measure Yukawa couplings

→ testable at LHC+ILC

Kilian, Plehn, Richardson, Schmidt



New variants:

- high-μ or low -μ spit SUSY Cheung, Chiang
- split SUSY based on anomaly mediationn Kaplan
- D-brane inspired split SUSY Gioutsos, Leontaris, Psallidas
- ...

Cosmological connection

- Extremely tempting to assume that EWSB and Dark Matter characterised by the same energy scale
- Likely that new physics contains a stable particle that can be copiously produced at the LHC

There are counterexamples, but

if above true => large cross sections for jets + missing energy events at the LHC

=> LHC will provide data for astrophysics

=> infer DM properties from masses and cross sections

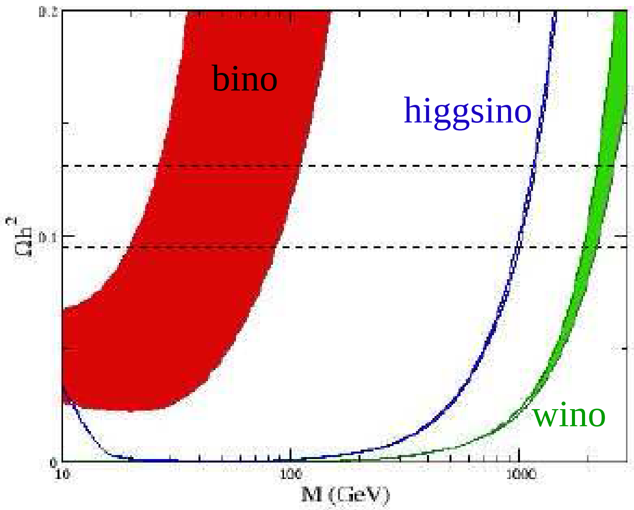
Relic density $\Omega_X h^2 \sim 3 \times 10^{-27}\ \mathrm{cm}^3\mathrm{s}^{-1} / \langle\sigma v\rangle$

requires typical weak interaction annihilation cross sections

How well $\langle\sigma v\rangle$ can be predicted from LHC depends on model for NP

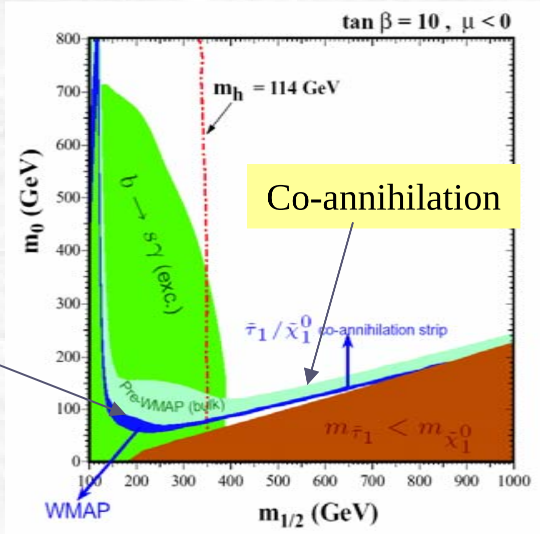
WMAP and SUSY DM

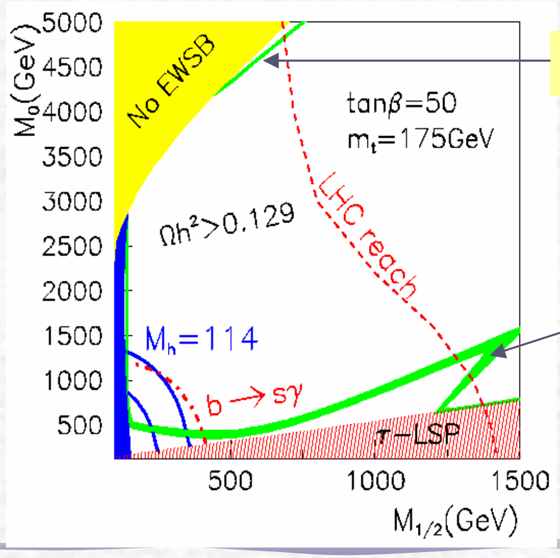
neutralino being a pure
- bino: NN -> fermion pairs
- higgsino: NN -> WW,ZZ
- wino: NN-> WW,ZZ



Arkani-Hamed, Delgado, Giudice

DM models seem fine tuned





LCC benchmark points

American LCC + Snowmass05 benchmark points

LCC1 = SPS1a 'bulk region'

annihilation through slepton exchange

σ_{NN} depends on the light slepton masses and couplings

LCC2 'focus point region'

annihilation to WW, ZZ

σ_{NN} depends on $m_1, m_2, \mu, \tan\beta$

LCC3 'coannihilation region'

annihilation of $\widetilde{\tau}$ is actually dominant

σ_{NN} depends on $m(\widetilde{\chi}_1^0), m(\widetilde{\tau}), \theta_\tau$

LCC4 'A funnel region'

annihilation through A resonance

σ_{NN} depends on $m(\widetilde{\chi}_1^0), m(A), \Gamma(A), \tan\beta$

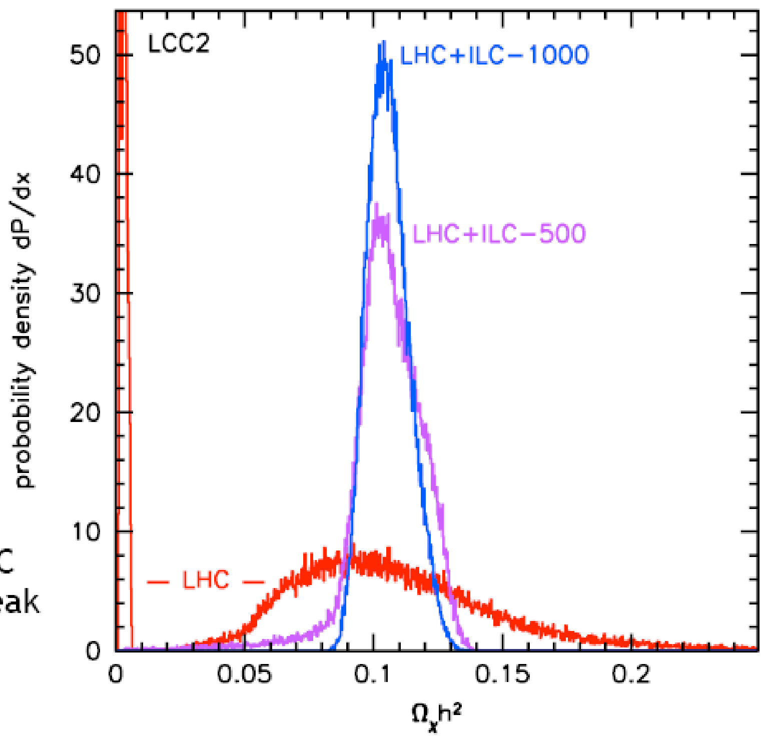
Peskin, LCWS06

LCC2

Squarks and sleptons heavy,
relevant param. M_1, M_2, $\tan\beta$, μ

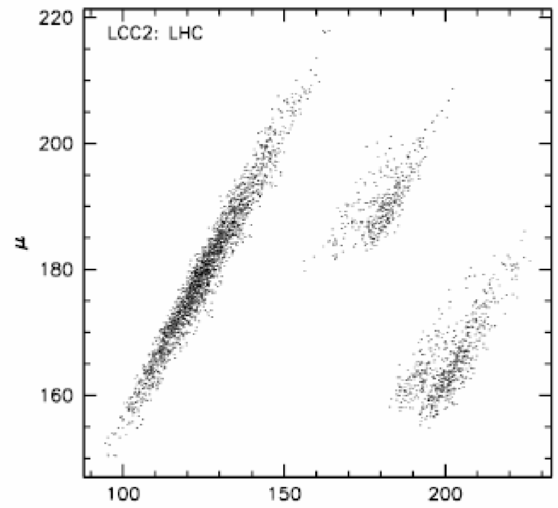
at LHC measure

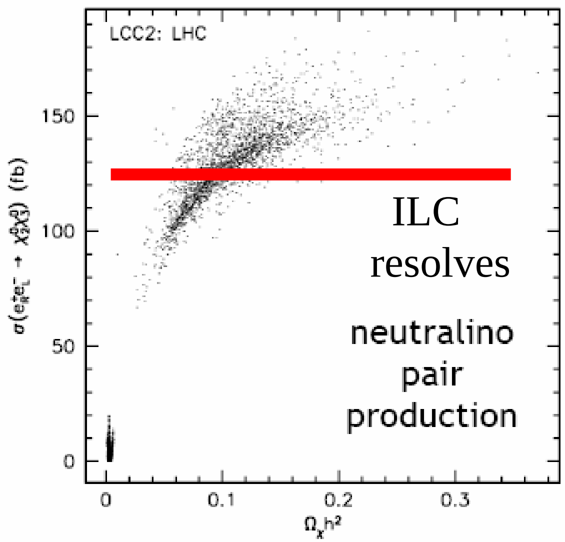
Prediction of the neutralino relic abundance:



Note for LHC
the large peak
near Ω = 0.

LHC alone allows multiple solutions



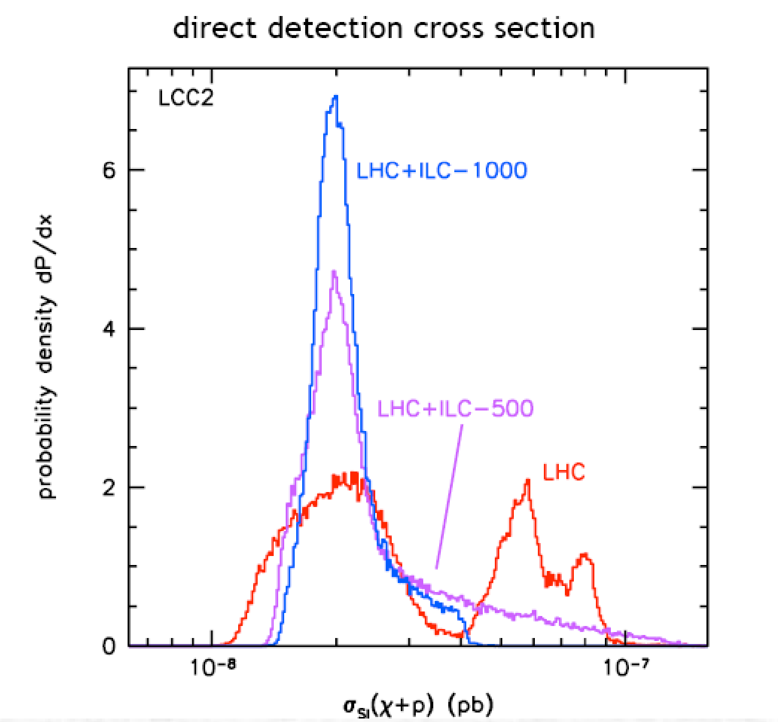


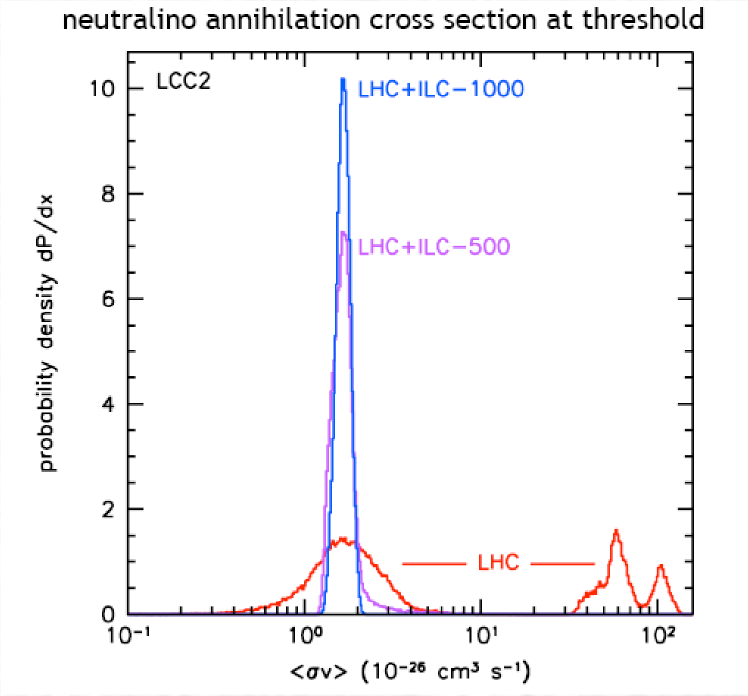
LCC2: cross-checks, predictions

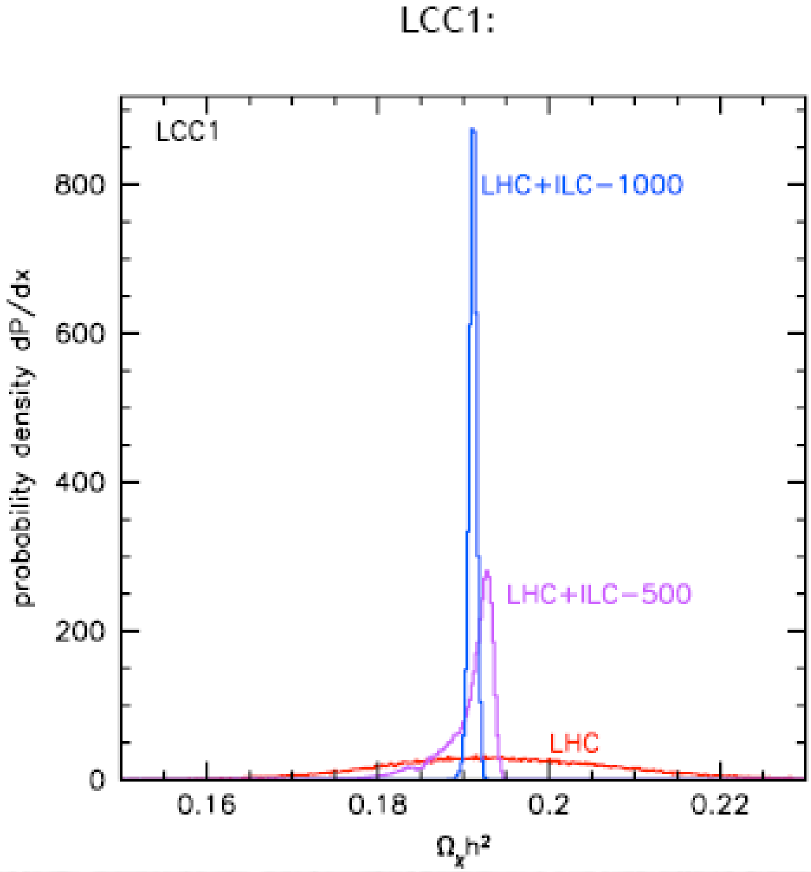
With the LSP properties determined, calculate

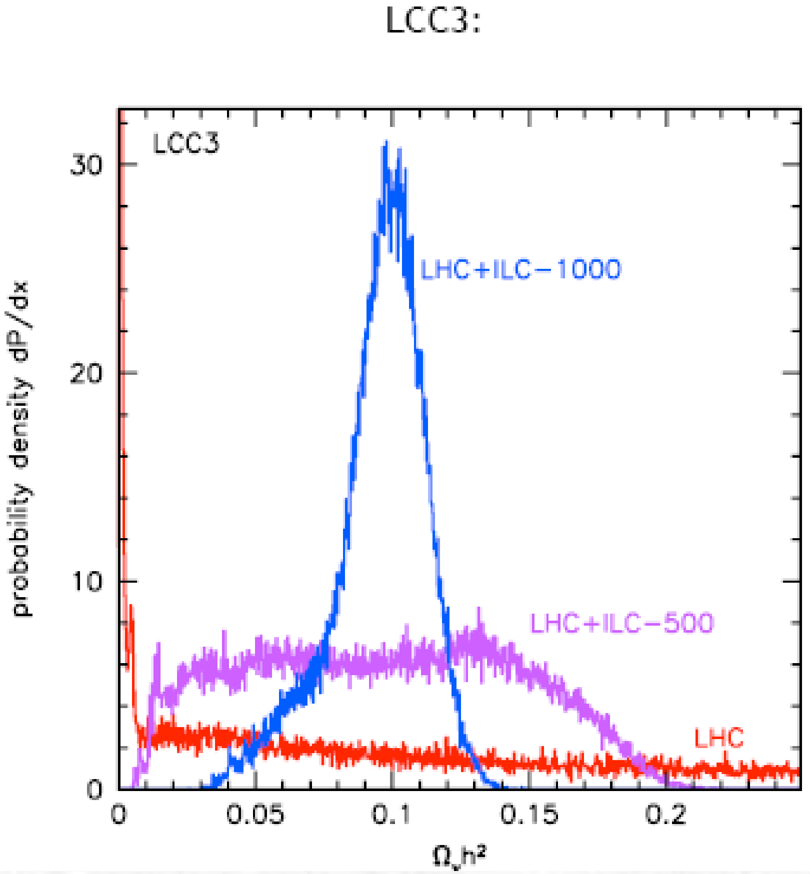
- neutralino-proton cross section for direct DM search experiments,
  or using measured cross section determine the flux of DM

- rate of γ from DM annihilation in the galactic center,
  or using measured rate determine the DM density









for LCC1 the LHC+ILC could match PLANCK measurement

point	Ωh^2	LHC	ILC 500	ILC 1000
LCC1	0.192	7.2%	1.8%	0.24%
LCC2	0.109	82%	14%	7.6%
LCC3	0.101	167%	50%	18%
LCC4	0.114	405%	85%	19%

agrees with
Nojiri Polesello, Tovey

The LHC will start testing cosmology. In some cases the ILC will be invaluable.

Summary and outlook

- Many interesting avenues explored
- New theoretical ideas are popping up
- Cosmology constrains SUSY,   SUSY => tests cosmology
- Too much theory?

We need data !!!

- LHC – last chance to understand EWSB??
- First discovery/non-discovery is not enough
- New ideas to exploit spin, jet charge, production cross sections, etc. badly needed
- Huge responsibility on LHC experiments
- Theory has to compensate for no ILC in near future

Summary and outlook

- Exploit low-scale data whenever SUSY related
- Complementarity of accelerator, direct and indirect exploration of dark matter
- Prove that a new invisible particle is dark matter

The road to revealing new laws of physics will be rocky

- How to feed back reality to theorists, especially when experiments will start to see deviations from SM/SUSY/... Need quick publications
- And how to feed back new theoretical ideas to experimenters. Provide tools !
- Extensive cooperation of theorists and experimenters is needed to go beyond basic discovery

The SPA project -- a forum for discussion