Supersymmetry at the LHC

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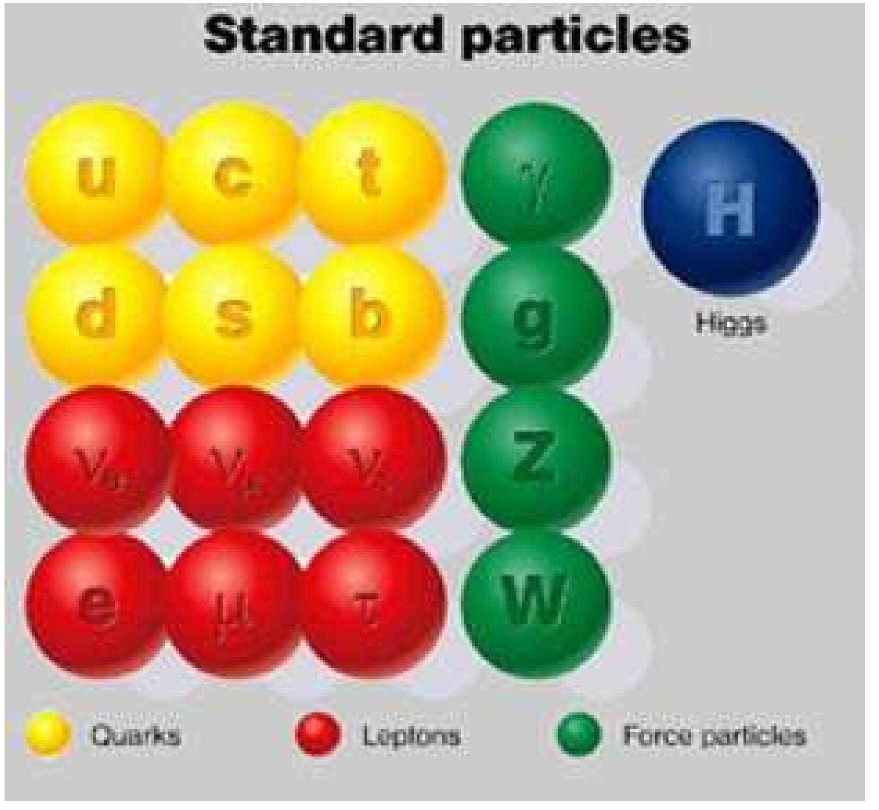
Outline

- Supersymmetry
- Higgs-Boson Production via Vector-Boson Fusion
- Reconstructing the Supersymmetric Lagrangian with SFitter

Remember the Standard Model

- Poincaré group of space-time transformations
- Gauge group $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$
- Two massless gauge bosons: gluon and photon
- $SU(2)_L \otimes U(1)_Y$ broken to $U(1)_{em}$ by the Higgs field
  with vacuum expectation value $v = 246$ GeV
- Massive electroweak gauge bosons: W and Z
- One physical Higgs boson
  (not yet discovered, unknown mass)
- Two types of matter:
  colour-charged: quarks
  colour-neutral: leptons and neutrinos
- Three generations each
- Yukawa coupling of matter to the Higgs
  proportional to the mass



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    $\sim 23\%$ Dark Matter content in the universe

    Possible candidate in the SM: Neutrinos

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    (higher-order corrections to the Higgs-boson mass
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- Look for possible ultra-violet completions $\rightarrow$ Supersymmetry

Supersymmetry

Symmetry between bosons and fermions:

$$Q\,|\text{boson}\rangle = |\text{fermion}\rangle\,; \qquad Q\,|\text{fermion}\rangle = |\text{boson}\rangle$$

$$\{Q,\bar{Q}\} = 2\sigma^\mu P_\mu$$

$$\{Q,Q\} = \{\bar{Q},\bar{Q}\} = 0$$

$$[P_\mu,Q] = [P_\mu,\bar{Q}] = 0$$

Q: Supersymmetry Operator

P_μ: Generator of Lorentz translations

σ^μ: Pauli matrices

$\Rightarrow$ Non-trivial combination of space-time and gauge symmetries

- Equal number of fermionic and bosonic degrees of freedom
- Supersymmetric partner(s) to each particle
- Partners have same mass and same couplings

$\Rightarrow$ Higher-order corrections to the Higgs boson mass cancel
(Relative minus sign between boson and fermion loops due to spin-statistics theorem)

$\Leftrightarrow$ Where are the 511 keV charged scalars?

Supersymmetry

Solution: Soft-supersymmetry breaking

- Explicit breaking of supersymmetry
- Adds additional mass terms to the supersymmetric partners
- Keeps automatic cancellation of quadratic divergencies

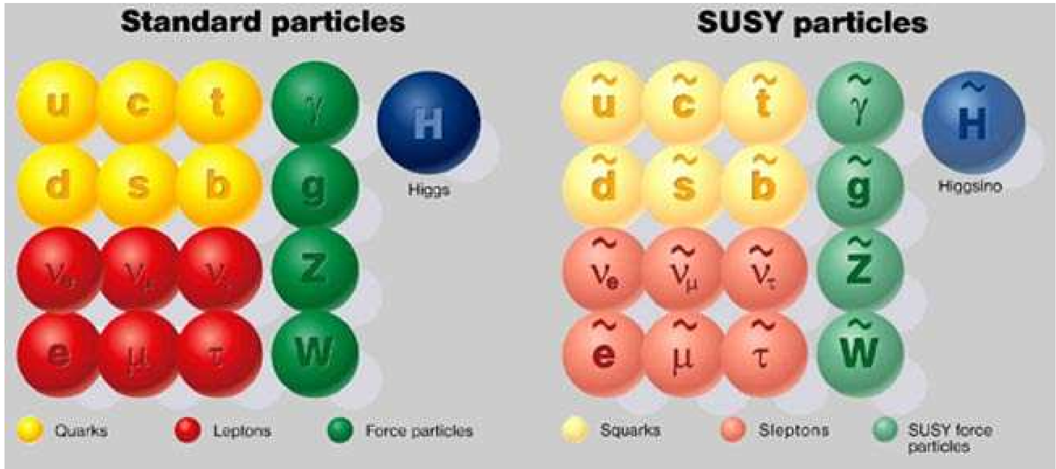
Additional ingredients:
(not absolutely necessary, but normally taken to explain the smallness of some effects)

- R-Parity conservation:
  - Discrete symmetry: $P^R = +1$ for SM particles, $P^R = -1$ for supersymmetric partners
  - Induces baryon and lepton number conservation
  - $\Rightarrow$ Proton decay forbidden (otherwise $\tau \approx \mathcal{O}(\text{hours})$)
  - $\Rightarrow$ SUSY particles can only be produced in pairs
  - $\Rightarrow$ Lightest supersymmetric particle (LSP) stable
- CP-conservation:
  - CP-violation strongly constrained by experimental data (EDMs)
  - Assume CKM matrix is the only source of CP-violation
  - Set all SUSY contributions to zero.

MSSM

Simplest phenomenologically viable model:
Minimal Supersymmetric Standard Model (MSSM)

- Supersymmetric partner to each Standard Model particle
- Two Higgs doublets $\Rightarrow$ 5 Higgs bosons (h^0,H^0,A^0,$H^\pm$)
  $m_{h^0} \lesssim 140$ GeV
- Particles with same quantum numbers mix
  - Zino, Photino, 2 neutral Higgsino $\rightarrow$ 4 Neutralino
  - Wino, charged Higgsino $\rightarrow$ 2 Chargino



mSUGRA

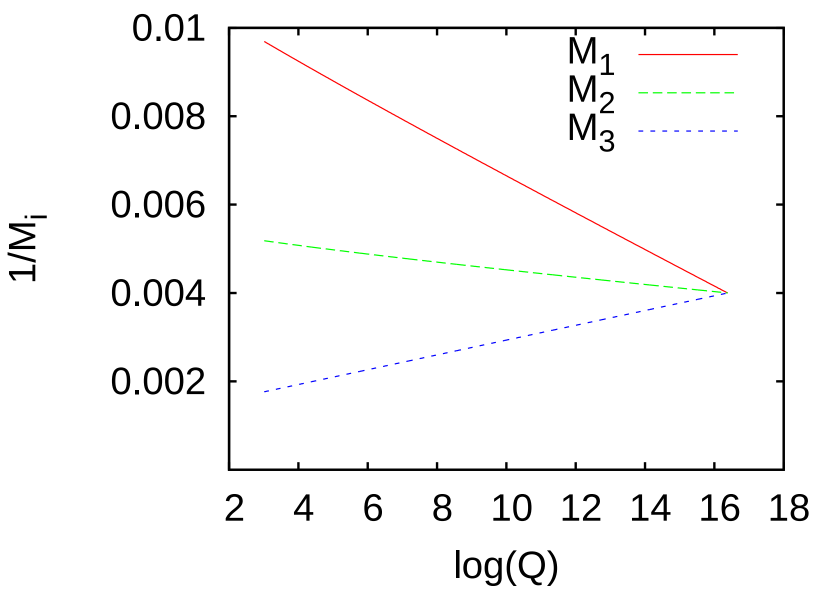
Unification at the GUT scale ($\sim 10^{16}$ GeV):

- Apparent unification of gauge couplings (general feature of MSSM)
- Common scalar mass: m_0
- Common sfermion mass: $m_{1/2}$
- Common trilinear coupling: A_0

plus

- ratio of the Higgs vacuum expectation values at the electro-weak scale: $\tan\beta = \frac{v_2}{v_1}$
- one sign: $\operatorname{sgn}\mu$

Evolve three parameters defined at the GUT scale via renormalisation group equations down to electro-weak scale:
$\Rightarrow$ Weak-scale MSSM parameters
$\Rightarrow$ Masses and couplings



Current Fits

If TeV-scale supersymmetry is out there, what can we tell today?
$\longrightarrow$ Fits of current data to supersymmetry (only mSUGRA)

[Allanach, Cranmer, Lester, Weber 2005-7]

[Roszkowski, Ruiz de Austra, Trotta 2006/7]

[Buchmüller, Cavanaugh, De Roeck, Heinemeyer, Isidori, Paradisi, Ronga, Weber, Weiglein 2007]

Observables:

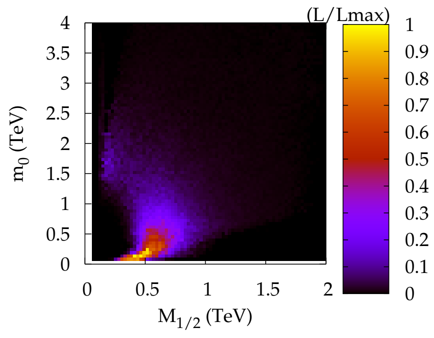
- Dark Matter $\Omega_{\mathrm{DM}} h^2$
- $g - 2_\mu$
- M_W
- $\sin^2 \theta_W$
- BR$(b \to s\gamma)$
- BR$(B_s \to \mu^+\mu^-)$
- $\ldots$

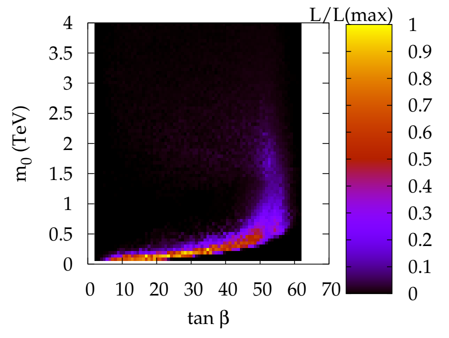
$\Rightarrow$ Predictions for SUSY mass spectrum

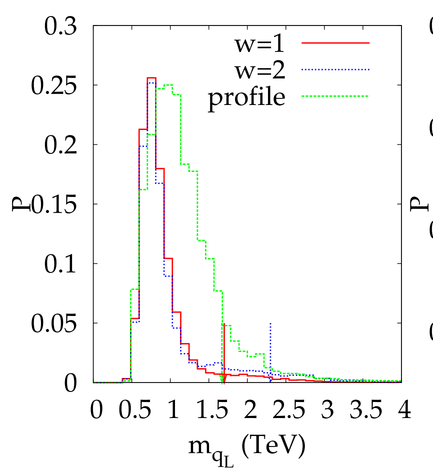
Current Fits

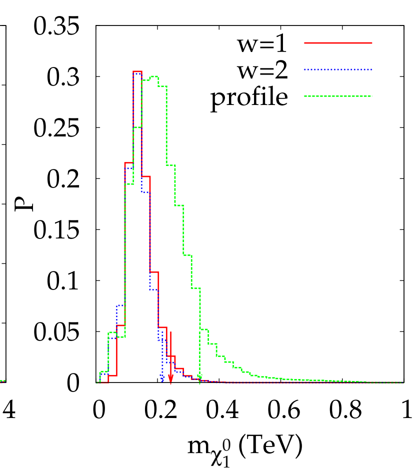
Predictions for SUSY mass spectrum

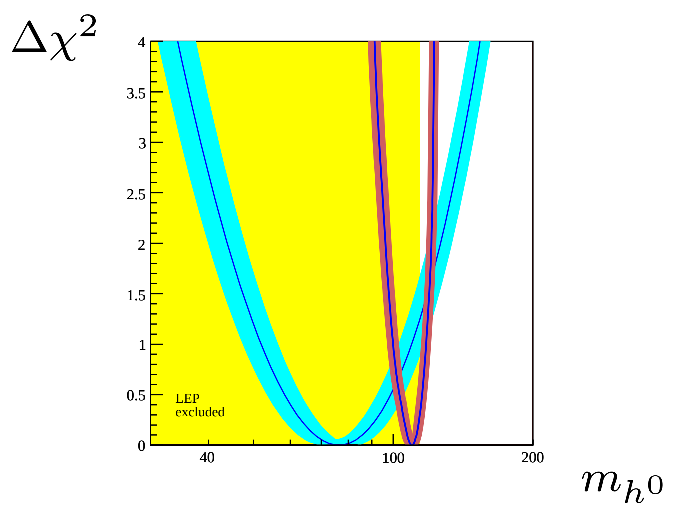
[plots by Allanach et al.]











[right-hand plot by Buchmüller et al.]

- Low-energy TeV-scale SUSY fits data very well
- $\Rightarrow$ Mass ranges for SUSY particles
- Mass of the lightest Higgs boson compatible with LEP limit

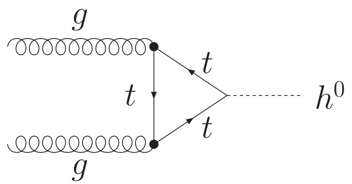
Higgs-Boson Production via Vector-Boson Fusion

(in collaboration with Wolfgang Hollik, Tilman Plehn, Heidi Rzehak)

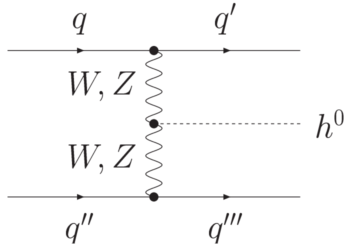
Production Modes

Main (MSSM-)Higgs Boson production modes:

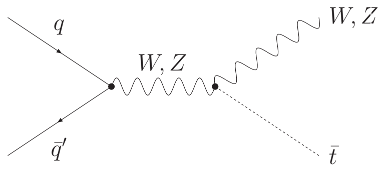
- Gluon-Gluon Fusion



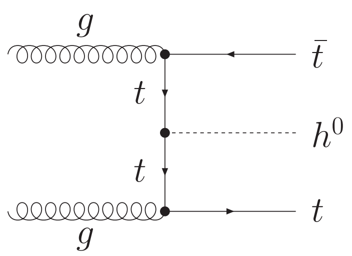
- Vector-Boson Fusion

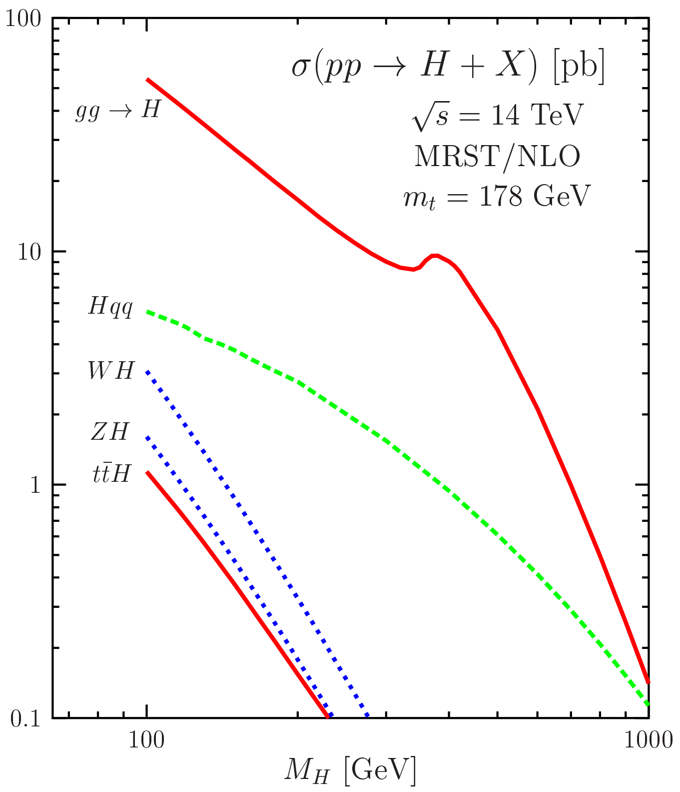


- Associated Production with a Gauge Boson



- Associated Production with Top-Quark–Antiquark Pair

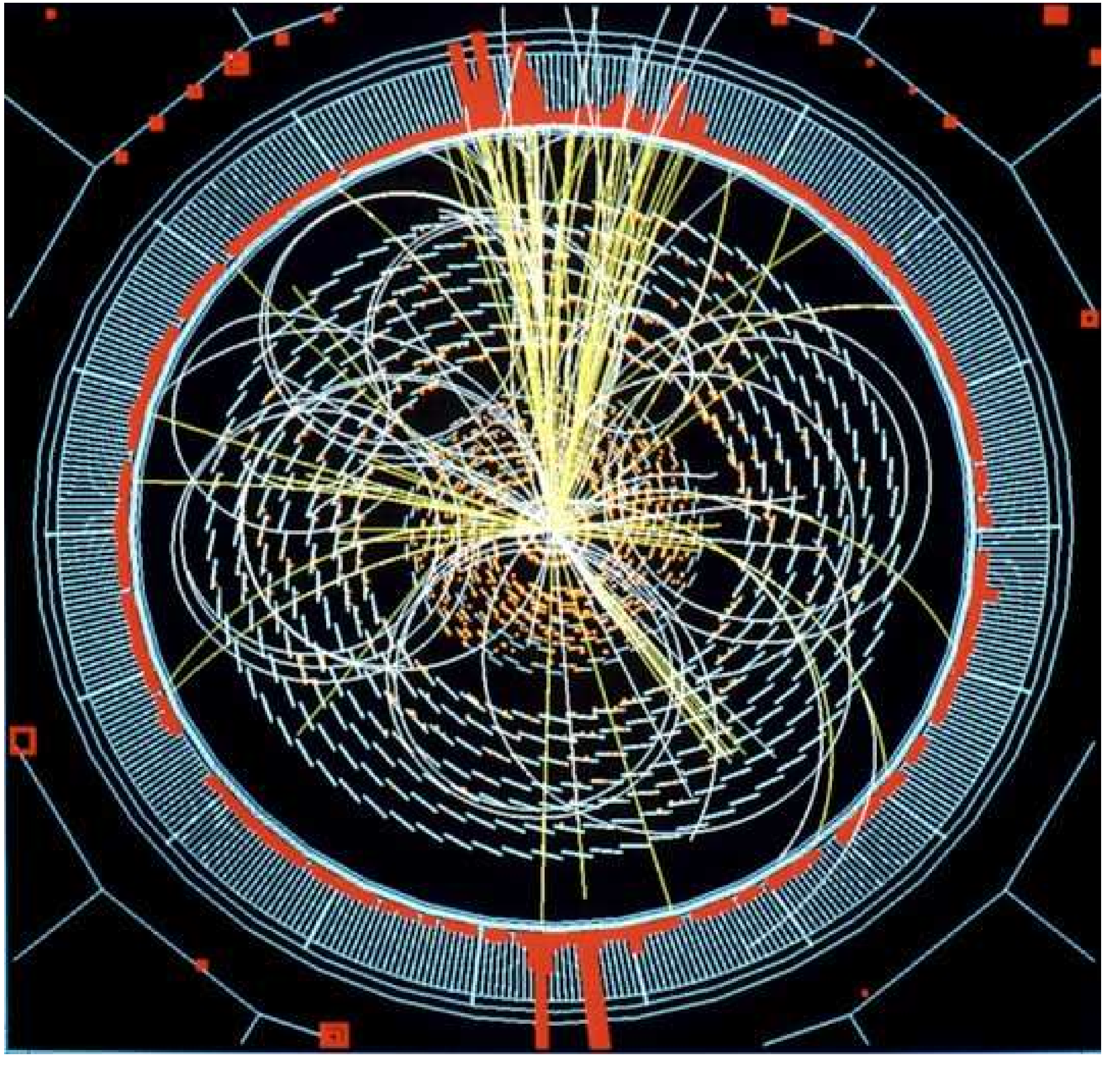




A Higgs event

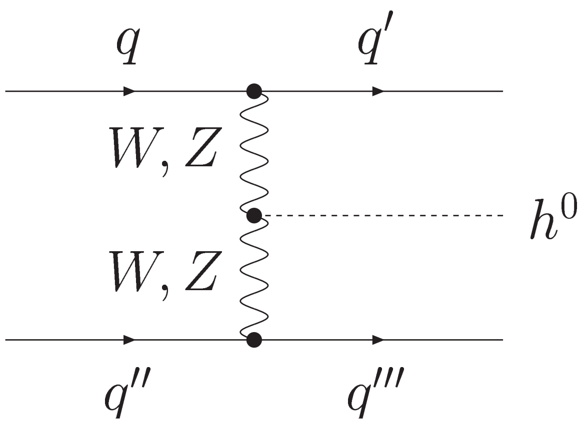
[picture by Alan Walker/CERN]

A Higgs event



CMS event $H \to ZZ \to e^+e^-\bar{q}q$ [CMS/CERN]

Higgs Production via Vector Boson Fusion



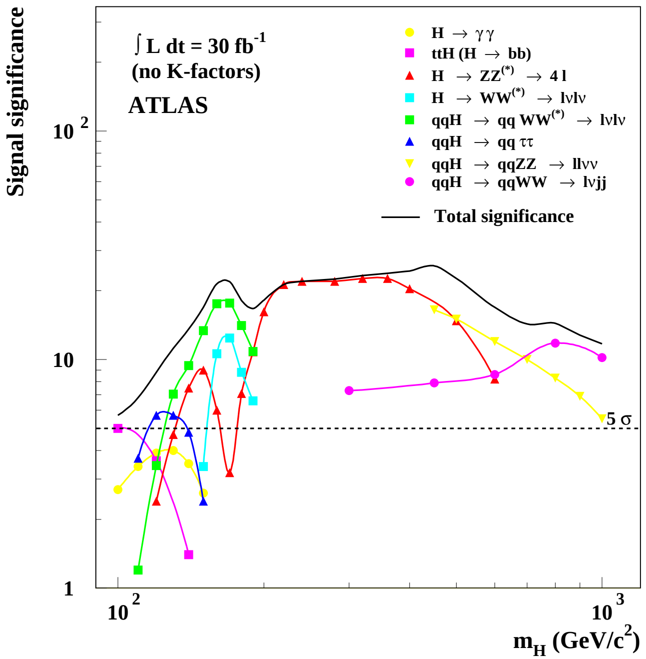
- Second-largest production cross section of Higgs bosons at the LHC (after gluon-gluon fusion)
- Distinct kinematic properties:
  - 2 jets in forward regions of the detector
  - Reduced jet activity in central region
  - central Higgs boson
- Most promising channel for early discovery of the Higgs with $h^0 \to \tau^+\tau^-$ decay
- SM-NLO corrections completely known: $\mathcal{O}(\alpha_s) \sim 5 - 10\%$, $\mathcal{O}(\alpha) \sim 5\%$

  [Djouadi, Spira, Zerwas; Han, Valencia, Willenbrock]

  [Figy, Oleari, Zeppenfeld; Berger, Campbell]

  [Ciccolini, Denner, Dittmaier]
- Vector-boson-fusion–gluon-guon interference negligible

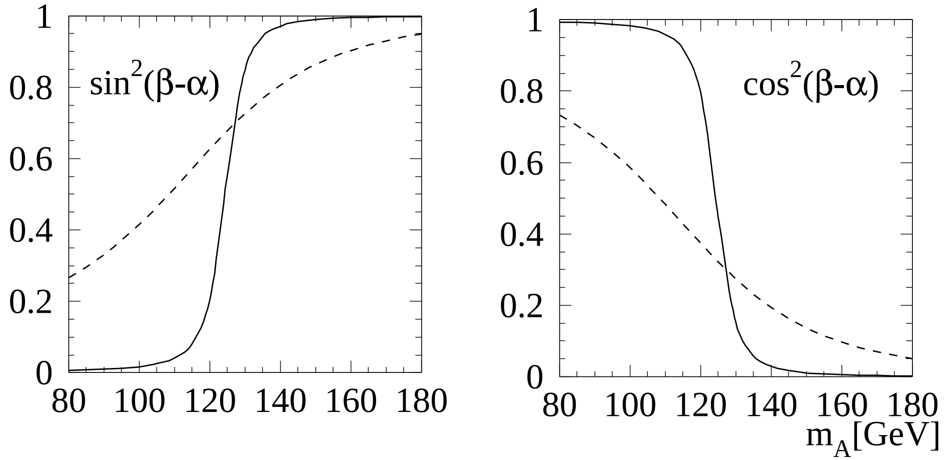
  [Andersen, Binoth, Heinrich, Smillie; Bredenstein, Hagiwara, Jäger]



Corrected Tree-level Result

Conversion from the known SM result to the MSSM:

- Replace SM-Higgs boson with (SM-like) MSSM h^0-Boson
- Vector-Boson–Vector-Boson–Higgs coupling modified by
  $\Gamma^{MSSM}_{WWh^0,ZZh^0} = \Gamma^{SM}_{WWH,ZZH} \cdot \sin(\beta-\alpha)$
- Therefore change of total cross section as
  $\sigma^{MSSM} = \sigma^{SM} \cdot \sin(\beta-\alpha)^2$



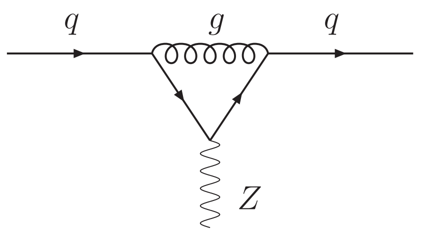
$\tan\beta = \begin{cases} 4 & \text{dashed} \\ 30 & \text{solid} \end{cases}$

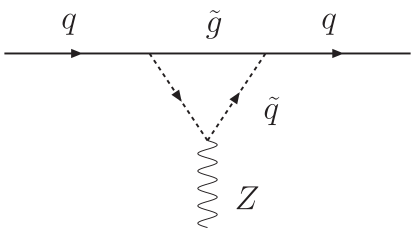
[Plehn, Rainwater, Zeppenfeld 1999]

- $\sin(\beta-\alpha)^2$ close to 1 for large parts of the parameter space
- $\Rightarrow$ Couplings of the h^0 SM-like
- Loop corrections induced by SUSY particles?
- Additional contributions to cross sections

Additional Loop Corrections

- SM is subsector of the full MSSM
- $\Rightarrow$ SM loop corrections form part of the full MSSM set
- R-parity conservation allows separation of SM and SUSY part at one-loop level

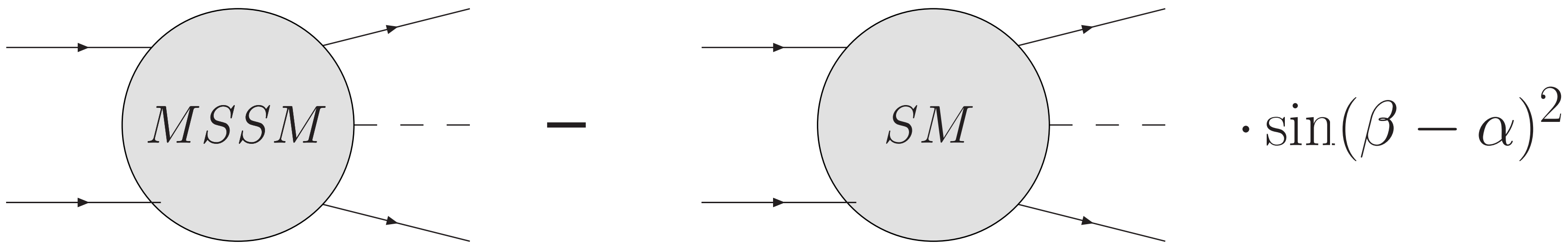
  (loop consists either of SM 

  or SUSY 

  particles)
- Not completely true in the Higgs sector:
  - MSSM is a (type-II) Two-Higgs doublet model (THDM)
  - Some THDM parameters fixed by SUSY relations
    (e.g. m_{h^0} not a free parameter any longer)
  - Renormalisation in the Higgs sector requires both SM and SUSY part so that divergencies cancel
    (depending on renormalization scheme)
- Split between SM and additional SUSY contribution more difficult

SUSY=MSSM-SM

- SM part (QCD and EW) already calculated
- Simple transfer to MSSM by $\sigma^{SM(MSSM)} = \sigma^{SM} \cdot \sin(\beta - \alpha)^2$
- In the end want one-loop corrections for complete MSSM
- $\Rightarrow$ Subtract SM part from MSSM to obtain additional SUSY contribution

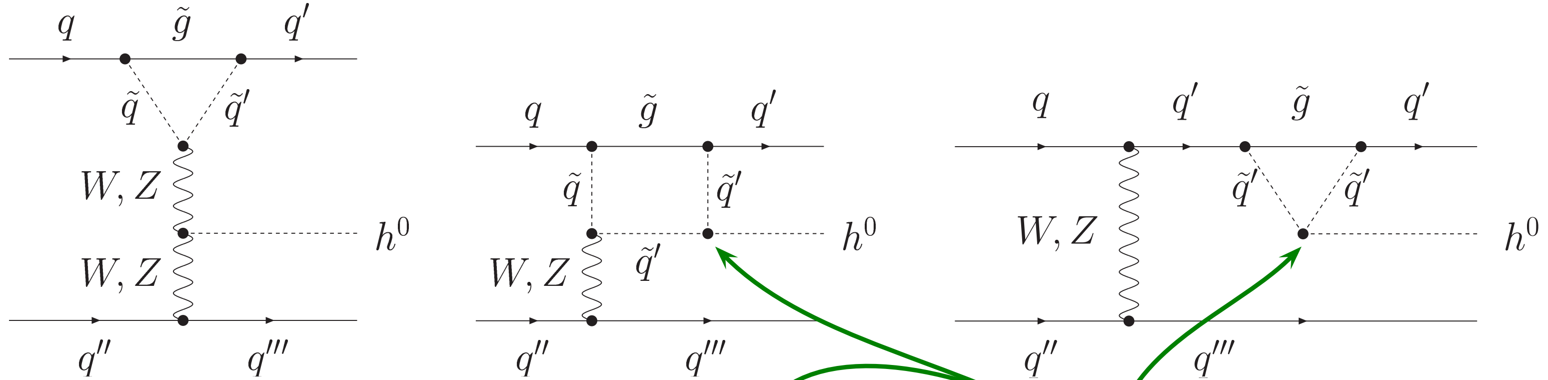


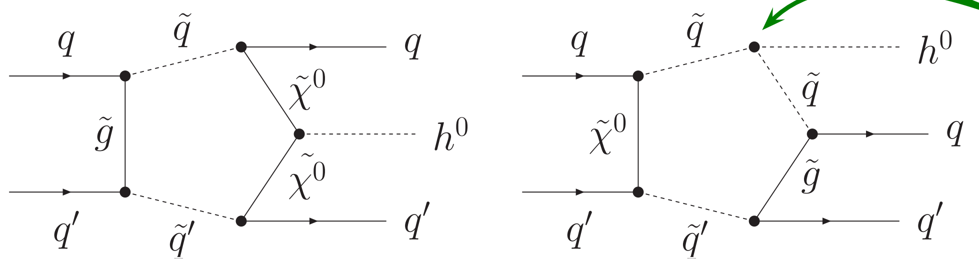
using $m_H^{SM} = m_{h^0}^{MSSM}$

- Subtraction performed on amplitude level
- Cross-check that for non-Higgs couplings this corresponds to just omitting the SM particles

Strong Corrections

Strong ($\mathcal{O}(\alpha_s)$) corrections:

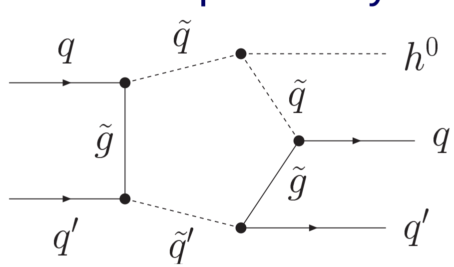




$\tilde{q}\tilde{q}h^0$-coupling contains gauge part (from D-terms)

$\Rightarrow$ Does not vanish even if neglecting Yukawa coupling

Additional possibility for pentagon diagrams:



$\propto \alpha_s^2 \alpha^2$

Using $\alpha_s^2 \sim \alpha$ same order as tree-level

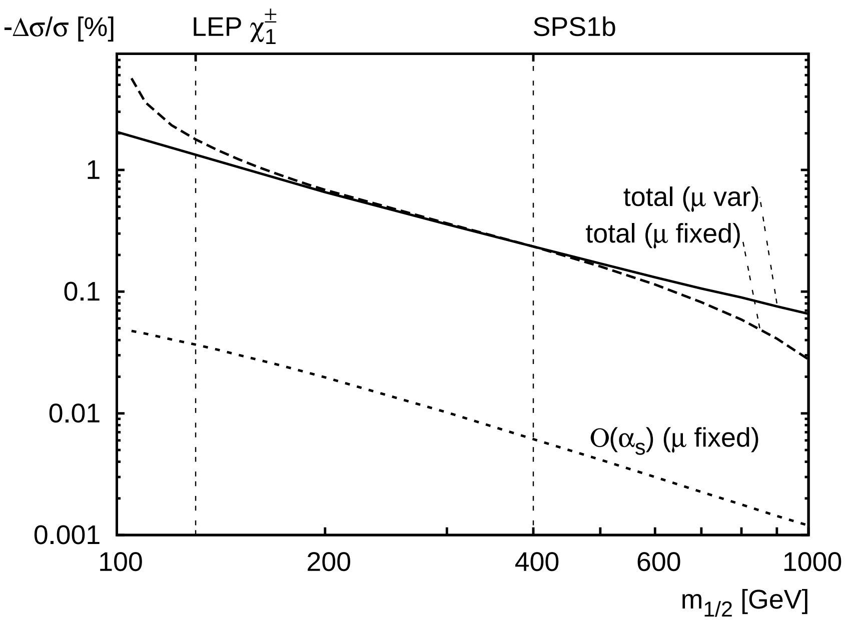
However, not same kinematic structure as tree-level diagram

$\Rightarrow$ Greatly reduced by kinematic cuts

Numerical Results

Size of the supersymmetric corrections:

(SPS: Set of reference points
which probe "typical" parts of the
supersymmetric parameter space)



$\Delta\sigma/\sigma$ [%]

	WWh $+ZZh$	$\mathcal{O}(\alpha)$	$\mathcal{O}(\alpha_s)$	all
SPS1a	-0.329	-0.469	-0.015	-0.484
SPS1b	-0.162	-0.229	-0.006	-0.235
SPS2	-0.147	0.129	-0.002	-0.131
SPS3	-0.146	-0.216	-0.006	-0.222
SPS4	-0.258	-0.355	-0.008	-0.363
SPS5	-0.606	-0.912	-0.010	-0.922
SPS6	-0.226	-0.309	-0.010	-0.319
SPS7	-0.206	-0.317	-0.006	-0.323
SPS8	-0.157	-0.206	-0.004	-0.210
SPS9	-0.094	-0.071	-0.003	-0.074

$\Rightarrow$ Typical corrections at or below 1%

$\Rightarrow$ Can reach up to 4% for parameter points still allowed

$\Rightarrow$ Need to be included for a precision analysis of the Higgs sector

Reconstructing the Supersymmetric Lagrangian with SFitter

(in collaboration with Rémi Lafaye, Tilman Plehn, Dirk Zerwas)

Determining SUSY parameters

nowadays:

Parameters in the Lagrangian

m_0, μ, $\tan(\beta)$, $M_{\{1,2,3\}}$, ...

Feynman diagrams,
RG evolution, ...

Observables:

- Masses
- Kinematic endpoints
- Cross sections
- Branching ratios
- ...

after SUSY discovery:

Observables

m_{h^0}, $\Delta m_{\tilde{g}\chi_1^0}$, three-particle edge($\chi_4^0$,$\tilde{e}_L$,$\chi_1^0$), BR, ...

?

Lagrangian parameters

M_1	$\square \pm \square$ GeV
M_2	$\square \pm \square$ GeV
M_3	$\square \pm \square$ GeV
μ	$\square \pm \square$ GeV
$\tan\beta$	$\square \pm \square$
...	...

$\Rightarrow$ Tools to reconstruct SUSY parameters

What SFitter does

- Set of measurements
  - LHC measurements:
    kinematic edges, thresholds, masses, mass differences
    cross sections, branching ratios
  - ILC measurements
  - Indirect Constraints
    electro-weak: M_W, $\sin^2\theta_W$; $(g-2)_\mu$
    flavour: BR$(b \to s\gamma)$, BR$(B_s \to \mu^+\mu^-)$; dark matter: Ωh^2
  - or even ATLAS and CMS measurements separately
- Compare to theoretical predictions
  - Spectrum calculators: SoftSUSY, SuSPECT, ISASUSY [Allanach; Djouadi, Kneur, Moultaka; Baer, Paige, Protopopescu, Tata]
  - LHC cross sections: Prospino2 [Plehn et al.]
  - LC cross sections: MsmLib [Ganis]
  - Branching Ratios: SUSYHit (HDecay + SDecay) [Djouadi, Mühlleitner, Spira]
  - micrOMEGAs [Bélanger, Boudjema, Pukhov, Semenov]
  - g-2 [Alexander, Stöckinger]
- Using as glue: SLHAio [Kreiss]

Parameter Scans

- MSSM parameter space is high-dimensional:
  - SM: 3+ parameters (m_t, α_s, α, $\ldots$)
  - mSUGRA: 5 parameters (m_0,$m_{1/2}, A_0, \tan(\beta), \mathrm{sgn}(\mu)$)
  - General MSSM: 105 parameters
- On loop-level observables depend on every parameter
  Simple inversion of the relations not possible
  $\Rightarrow$ Parameter scans
- Error estimates on parameters in the minimum

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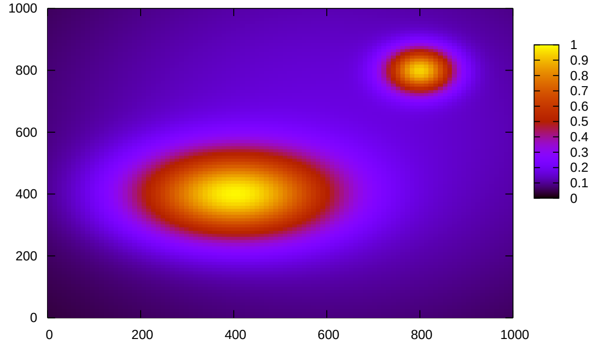
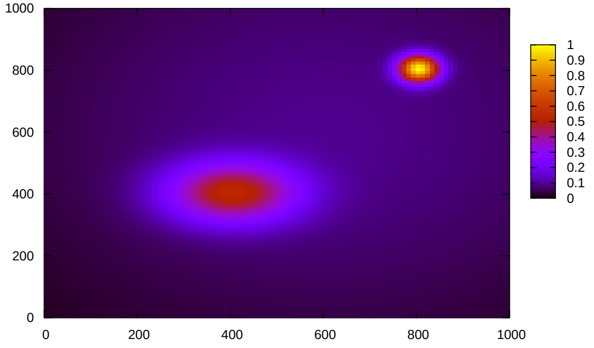
Find best points (best χ^2) using different fitting techniques:

- Gradient search (Minuit) $\left(\begin{array}{c} + \text{ Reasonably fast} \\ - \text{ Limited convergence, only best fit} \end{array}\right)$





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- (Simulated Annealing $\longrightarrow$ Fittino) [Bechtle, Desch, Wienemann]
- Weighted Markov Chains

Markov Chains

Markov Chain (MC):

- Sequence of points, chosen by an algorithm (Metropolis-Hastings), only depending on its direct predecessor
- Picks a set of ”average” points according to a potential V (e.g. inverse log-likelihood, $1/\chi^2$)
- Point density resembles the value of V (i.e. more points in region with high V)
- Scans high dimensional parameter spaces efficiently [Baltz, Gondolo 2004]
- mSUGRA MC scans with current exp. limits

  [Allanach, Cranmer, Lester, Weber 2005-7; Roszkowski, Ruiz de Austra, Trotta 2006/7]

Weighted Markov Chains

Weighted Markov Chains:

Improved evaluation algorithm for binning: [Plehn, MR]

- Weight points with value of V:
- Take care of
  - Overcounting because point density is already weighted ($\frac{\text{number of points}}{\sum_{\text{points}} 1/V(\text{point})}$)
    [based on Ferrenberg, Swendsen 1988]
  - Correct account for regions with zero probability
    (maintain additional chain which stores points rejected because $V(\text{point}) = 0$)

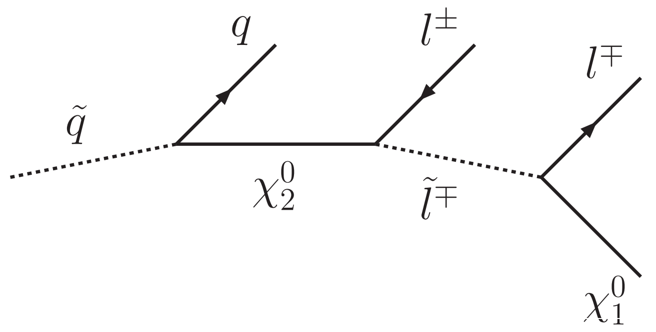
$+$ Fast scans of high-dimensional spaces $\mathcal{O}(N)$
$+$ Does not rely on shape of χ^2 (no derivatives used)
$+$ Can find secondary distinct solutions
$-$ Exact minimum difficult to find $\Rightarrow$ Additional gradient fit
$-$ Bad choice of proposal function for next point leads to bad coverage of the space

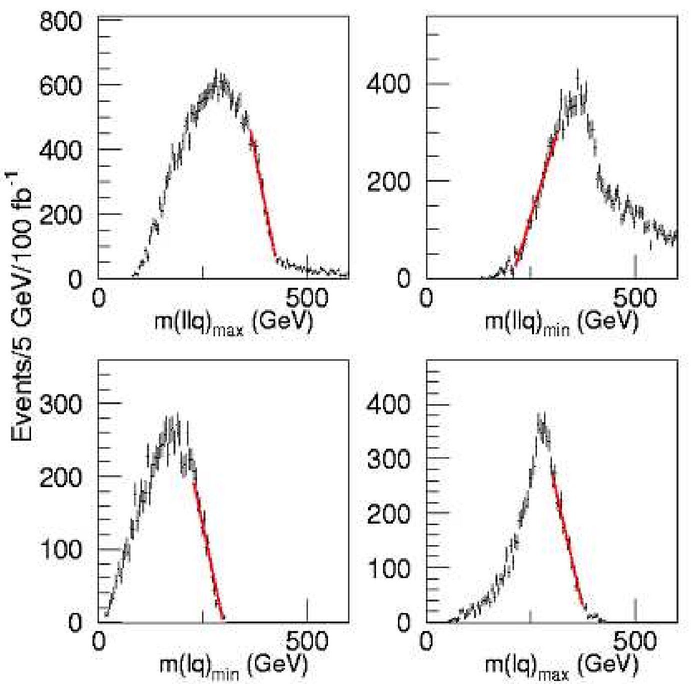
Experimental Input (Edges)

mSUGRA SPS1a as a benchmark point:

$m_0 = 100$ GeV , $m_{1/2} = 250$ GeV , $A_0 = -100$ GeV , $\tan\beta = 10$, $\mathrm{sgn}\,\mu = +1$, $m_t = 171.4$ GeV

LHC “experimental” data from cascade decays (best precision obtainable)





Measurement	Value (GeV)	Errors (GeV) (stat)	Errors (GeV) (syst)
$(m_{llq}^{\max})$:Edge($\tilde{q}_L$,χ_2^0,χ_1^0)	446.44	1.4	4.3
$(m_{llq}^{\min})$:Thres($\tilde{q}_L$,χ_2^0,$\tilde{\mu}_R$,χ_1^0)	211.95	1.6	2.0
(m_{lq}^{low}) :Edge($\tilde{c}_L$,χ_2^0,$\tilde{\mu}_R$)	316.51	0.9	3.0
(m_{lq}^{high}):Edge($\tilde{c}_L$,χ_2^0,$\tilde{\mu}_R$,χ_1^0)	392.80	1.0	3.8
...	...	...	

Theoretical Errors:

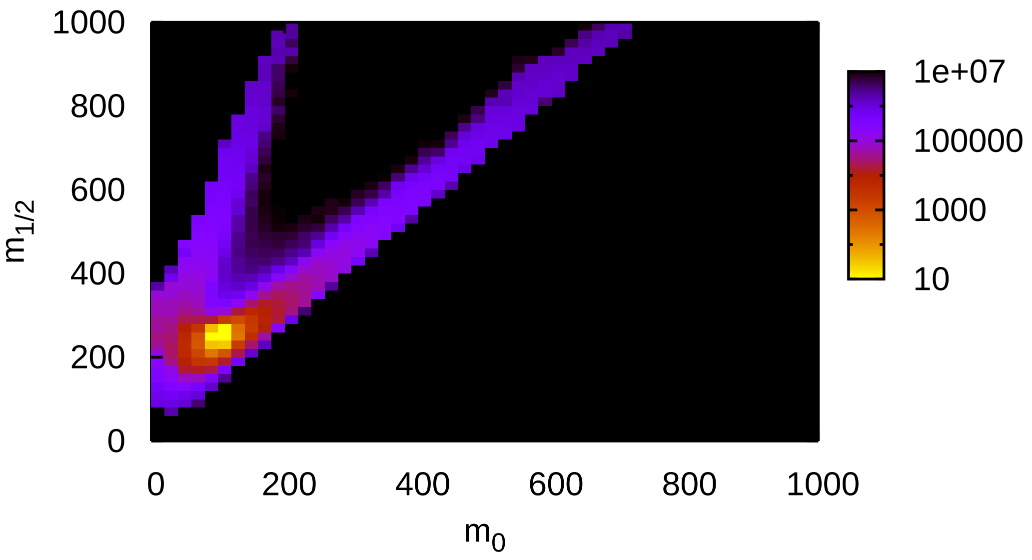
- mSUGRA: 3% for gluino and squark masses,
  1% for all other sparticle masses
- MSSM: 1% for gluino and squark masses,
  0.5% for all other sparticle masses
- m_{h^0}: 2 GeV (unknown higher order terms)

mSUGRA as a Toy Model

mSUGRA with LHC measurements (SPS1a kinematic edges):
pick one set of ”measurements”, randomly smeared from the true values

Free parameters:
m_0, $m_{1/2}$, $\tan(\beta)$, A_0, $\mathrm{sgn}(\mu)$, m_t

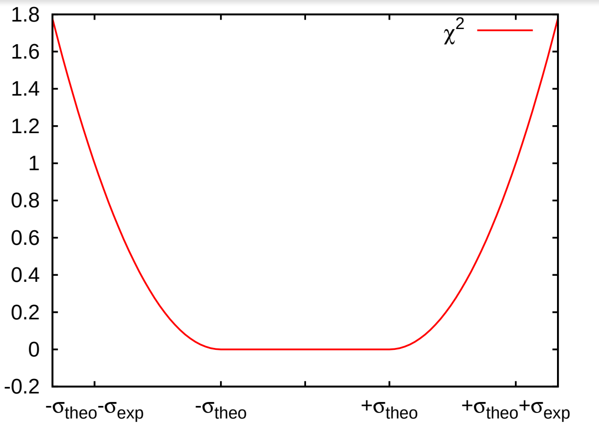
SFitter output 1:
Fully-dimensional exclusive likelihood map
(colour:
minimum χ^2 over all unseen parameters)



SFitter output 2:
Ranked list of minima:

	χ^2	m_0	$m_{1/2}$	$\tan(\beta)$	A_0	μ	m_t
SPS1a		100.0	250.0	10.0	-100.0	$+$	171.4
1)	0.09	102.0	254.0	11.5	-95.2	$+$	172.4
2)	1.50	104.8	242.1	12.9	-174.4	$-$	172.3
3)	73.2	108.1	266.4	14.6	742.4	$+$	173.7
4)	139.5	112.1	261.0	18.0	632.6	$-$	173.0

Error determination



Treatment of errors:

- All experimental errors are Gaussian
  $$\sigma^2_{\text{exp}} = \sigma^2_{\text{stat}} + \sigma^2_{\text{syst}(j)} + \sigma^2_{\text{syst}(l)}$$
- Systematic errors from jet ($\sigma_{\text{syst}(j)}$) and lepton energy scale ($\sigma_{\text{syst}(l)}$) assumed 99% correlated each
- Theory error added as box-shaped (RFit scheme [Hoecker, Lacker, Laplace, Lediberder])
  $$\Rightarrow -2\log L \equiv \chi^2 = \sum_{\text{measurements}} \begin{cases} 0 & \text{for } |x_{\text{data}} - x_{\text{pred}}| < \sigma_{\text{theo}} \\ \left(\frac{|x_{\text{data}} - x_{\text{pred}}| - \sigma_{\text{theo}}}{\sigma_{\text{exp}}}\right)^2 & \text{for } |x_{\text{data}} - x_{\text{pred}}| \geq \sigma_{\text{theo}} \end{cases}$$

$\Rightarrow$ Parameter errors:

	SPS1a	$\Delta^{\text{theo}-\text{exp}}_{\text{zero}}$	$\Delta^{\text{theo}-\text{exp}}_{\text{zero}}$	$\Delta^{\text{theo}-\text{exp}}_{\text{gauss}}$	$\Delta^{\text{theo}-\text{exp}}_{\text{flat}}$
		LHC masses	LHC edges		
m_0	100	4.11	0.50	2.97	2.17
$m_{1/2}$	250	1.81	0.73	2.99	2.64
$\tan\beta$	10	1.69	0.65	3.36	2.45
A_0	-100	36.2	21.2	51.5	49.6
m_t	171.4	0.94	0.26	0.89	0.97

$\Rightarrow$ Use kinematic edges for parameter determination instead of masses

Weak-scale MSSM

- No need to assume specific SUSY-breaking scenario
  $\Rightarrow$ SUSY-breaking mechanism should be induced from data
- Use of Markov Chains makes scanning the 19-dimensional parameter space feasible
- Lack of sensitivity on one parameter does not slow down the scan
  (no need to fix parameters)
- Same SFitter output as before: Minima list and Likelihood map

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Full scan of 19D parameter space challenging
Four-step procedure yields better and faster results:

- Weighted-Markov-Chain run with flat pdf over full parameter space
  5 best points additionally minimised
  (full scan, no bias on starting point)

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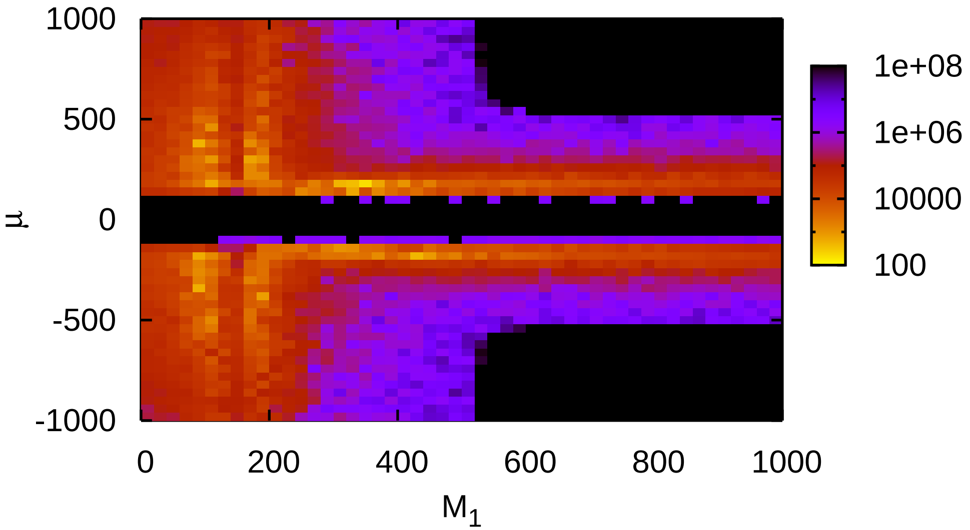
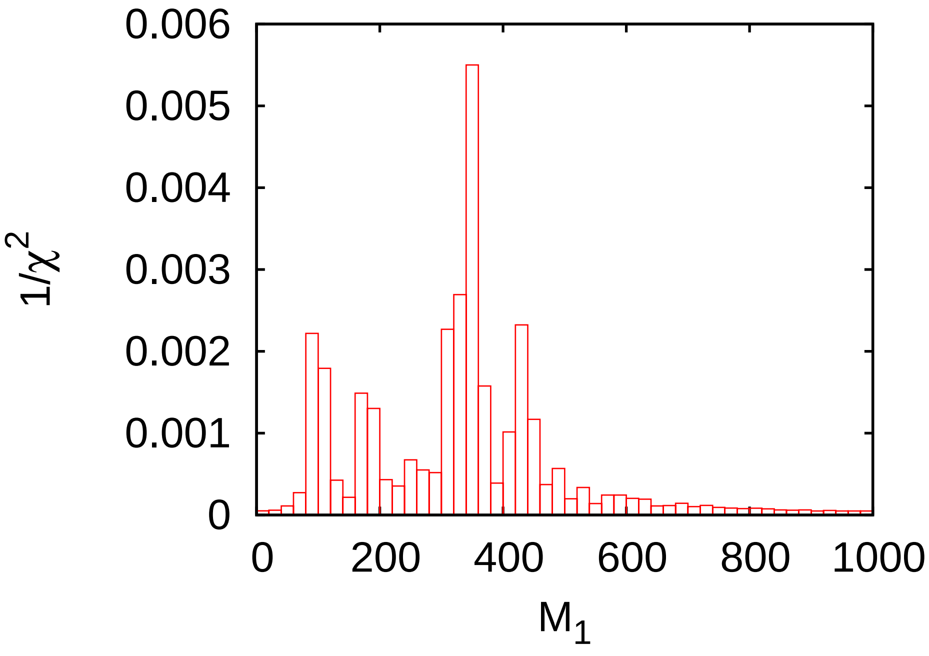
- Weighted-Markov Chain with flat pdf on Gaugino-Higgsino subspace:
  M_1, M_2, M_3, μ, $\tan\beta$, m_t
  Additional Minuit run with 15 best solutions

Search Strategy (2) - results

- Only three neutralinos (χ_1^0, χ_2^0, χ_4^0) with masses (97.2 GeV , 180.5 GeV , 375.6 GeV) and no charginos observable at the LHC in SPS1a
- $\Rightarrow$ Mapping (M_1, M_2, μ) $\rightarrow$ (χ_1^0, χ_2^0, χ_4^0) not unique
- $\mathrm{sgn}\,\mu$ basically undetermined by collider data
- $\Rightarrow$ 8-fold solution





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	$\mu < 0$				$\mu > 0$			
					SPS1a			
M_1	96.6	175.1	103.5	365.8	98.3	176.4	105.9	365.3
M_2	181.2	98.4	350.0	130.9	187.5	103.9	348.4	137.8
μ	-354.1	-357.6	-177.7	-159.9	347.8	352.6	178.0	161.5
$\tan\beta$	14.6	14.5	29.1	32.1	15.0	14.8	29.2	32.1
M_3	583.2	583.3	583.3	583.5	583.1	583.1	583.3	583.4
m_t	171.4	171.4	171.4	171.4	171.4	171.4	171.4	171.4

Search Strategy (3+4)

Full scan of 19D parameter space challenging
Four-step procedure yields better and faster results:

- Weighted-Markov-Chain run with flat pdf over full parameter space
  5 best points additionally minimised
  (full scan, no bias on starting point)
- Weighted-Markov Chain with flat pdf on Gaugino-Higgsino subspace:
  M_1, M_2, M_3, μ, $\tan\beta$, m_t
  Additional Minuit run with 15 best solutions
- Weighted-Markov Chain with Breit-Wigner-shaped pdf on remaining parameters for all solutions of previous step
  Minimisation for best 5 points
- Minuit run for best points of last step keeping all parameters variable

Best points

	$\mu < 0$				$\mu > 0$			
					SPS1a			
M_1	96.6	175.1	103.5	365.8	98.3	176.4	105.9	365.3
M_2	181.2	98.4	350.0	130.9	187.5	103.9	348.4	137.8
μ	-354.1	-357.6	-177.7	-159.9	347.8	352.6	178.0	161.5
$\tan\beta$	14.6	14.5	29.1	32.1	15.0	14.8	29.2	32.1
M_3	583.2	583.3	583.3	583.5	583.1	583.1	583.3	583.4
$M_{\tilde{\tau}_L}$	114.9	2704.3	128.3	4794.2	128.0	229.9	3269.3	118.6
$M_{\tilde{\tau}_R}$	348.8	129.9	1292.7	130.1	2266.5	138.5	129.9	255.1
$M_{\tilde{\mu}_L}$	192.7	192.7	192.7	192.9	192.6	192.6	192.7	192.8
$M_{\tilde{\mu}_R}$	131.1	131.1	131.1	131.3	131.0	131.0	131.1	131.2
$M_{\tilde{e}_L}$	186.3	186.4	186.4	186.5	186.2	186.2	186.4	186.4
$M_{\tilde{e}_R}$	131.5	131.5	131.6	131.7	131.4	131.4	131.5	131.6
$M_{\tilde{q}3_L}$	497.1	497.2	494.1	494.0	495.6	495.6	495.8	495.0
$M_{\tilde{t}_R}$	1073.9	920.3	547.9	950.8	547.9	460.5	978.2	520.0
$M_{\tilde{b}_R}$	497.3	497.3	500.4	500.9	498.5	498.5	498.7	499.6
$M_{\tilde{q}_L}$	525.1	525.2	525.3	525.5	525.0	525.0	525.2	525.3
$M_{\tilde{q}_R}$	511.3	511.3	511.4	511.5	511.2	511.2	511.4	511.5
$A_t\ (-)$	-252.3	-348.4	-477.1	-259.0	-470.0	-484.3	-243.4	-465.7
$A_t\ (+)$	384.9	481.8	641.5	432.5	739.2	774.7	440.5	656.9
m_A	350.3	725.8	263.1	1020.0	171.6	156.5	897.6	256.1
m_t	171.4	171.4	171.4	171.4	171.4	171.4	171.4	171.4

Degenerate Solutions

- In total 19 parameters constrained by 22 measurements
- Measurements constructed from only 15 underlying masses
- $\Rightarrow$ Complete determination of parameter set not possible
- Five parameters not well constrained
  - m_A
    $\leftarrow$ no heavy Higgses measurable
  - $M_{\tilde{t}_R}$
  - A_t
    $\leftarrow$ stop sector parameters do not enter edge measurements
  - $M_{\tilde{\tau}_L}$ or $M_{\tilde{\tau}_R}$
    $\leftarrow$ only the lighter stau measured
  - $\tan\beta$
    $\leftarrow$ change can always be accomodated by rotating M_1, M_2, $M_{\tilde{q}_3}$, ...
- Single common link: m_{h^0}
- $\Rightarrow$ 4-dimensional hyperplane in parameter space undetermined
- Can still assign errors to some of the badly determined parameters

Error analysis

- Technical procedure as in mSUGRA case:
  - 10000 smeared data sets
  - Minimum determined for each data set individually
  - Error determined from fit with Gaussian
- Most constrained parameters determinable with $\sim 5\%$ accuracy
- Inclusion of theory errors leads to an increase of factor 2 on the parameter errors
- ILC data complementary to LHC
- Combination of the two experiments allows for precise determination of all parameters

	LHC	ILC	LHC+ILC	SPS1a
M_1	102.1$\pm$ 7.8	103.0$\pm$ 1.1	103.1$\pm$0.84	103.1
$M_{\tilde{e}_R}$	135.0$\pm$ 8.3	135.8$\pm$ 0.81	135.9$\pm$0.77	135.8
m_A	406.3$\pm\mathcal{O}(10^3)$	393.8$\pm$ 1.6	393.9$\pm$ 1.6	394.9
$M_{\tilde{t}_R}$	415.8$\pm\mathcal{O}(10^2)$	440.0$\pm\mathcal{O}(4 \cdot 10^2)$	410.7$\pm$48.4	408.3

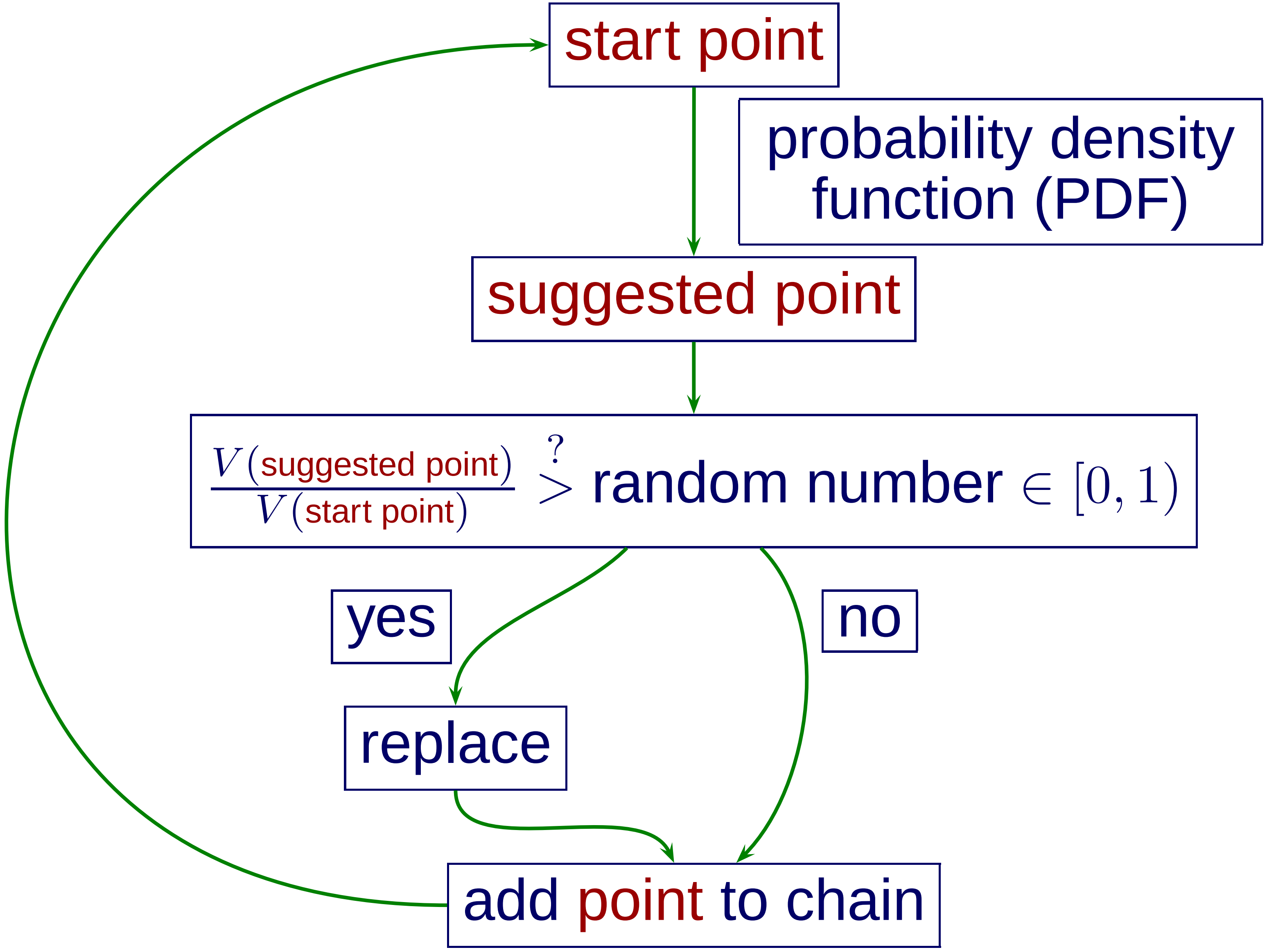
Summary & Outlook

- Higgs-boson production via Vector Boson Fusion important discovery mode for the Higgs boson and to study electroweak symmetry breaking
- Supersymmetric QCD corrections strongly suppressed
- Supersymmetric electro-weak corrections modify cross section on the percent level

- Parameter scans important to determine Lagrangian parameters from observables
- Low-energy supersymmetry fits precision data very well
- Problem of high-dimensional parameter spaces
- Markov Chains can do this effectively
- Improved algorithm developed
- Two types of output: Likelihood map and list of best points
- SFitter (despite its name) not tied to SUSY
  $\longrightarrow$ extend to other models/problems

Backup Slides

Metropolis-Hastings Algorithm

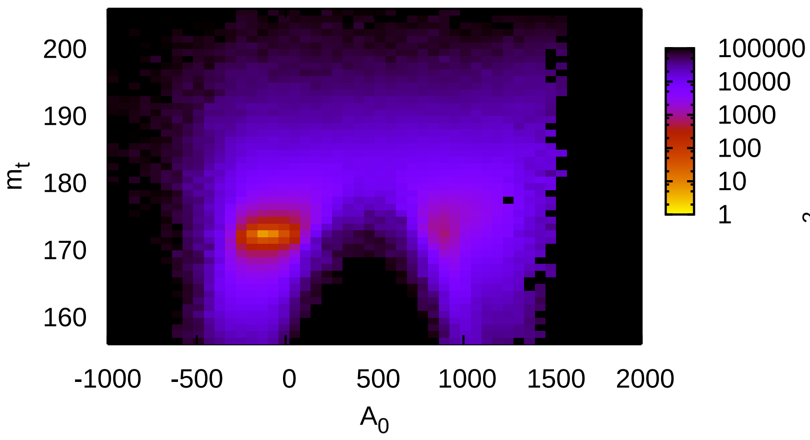


Experimental Input (edges)

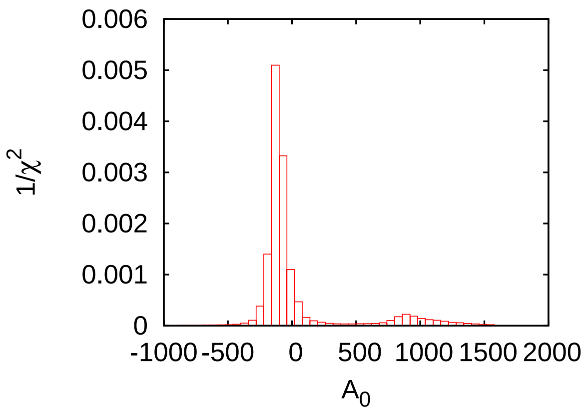
(Obs)	= (meas) ± (exp) ± (theo)			
m_{h^0}	$= 109.53 \pm$	$0.25 \pm$	2.0	
m_t	$= 171.4 \pm$	$1.0 \pm$	0.0	
$\Delta m_{\tilde{\mu}_L,\chi_1^0}$	$= 106.26 \pm$	$1.6 \pm$	0.1	
$\Delta m_{\tilde{g},\chi_1^0}$	$= 509.96 \pm$	$2.3 \pm$	6.0	
$\Delta m_{\tilde{c}_R,\chi_1^0}$	$= 450.52 \pm$	$10.0 \pm$	4.2	
$\Delta m_{\tilde{g},\tilde{b}_1}$	$= 98.971 \pm$	$1.5 \pm$	1.0	
$\Delta m_{\tilde{g},\tilde{b}_2}$	$= 64.016 \pm$	$2.5 \pm$	0.7	
Edge(χ_2^0,$\tilde{\mu}_R$,χ_1^0)	$= 79.757 \pm$	$0.03 \pm$	0.08	$(m_{ll}^{\max})$
Edge($\tilde{c}_L$,χ_2^0,χ_1^0)	$= 446.44 \pm$	$1.4 \pm$	4.3	$(m_{llq}^{\max})$
Edge($\tilde{c}_L$,χ_2^0,$\tilde{\mu}_R$)	$= 316.51 \pm$	$0.9 \pm$	3.0	(m_{lq}^{low})
Edge($\tilde{c}_L$,χ_2^0,$\tilde{\mu}_R$,χ_1^0)	$= 392.8 \pm$	$1.0 \pm$	3.8	(m_{lq}^{high})
Edge(χ_4^0,$\tilde{\mu}_R$,χ_1^0)	$= 257.41 \pm$	$2.3 \pm$	0.3	$(m_{ll}^{\max}(\chi_4^0))$
Edge(χ_4^0,$\tilde{\tau}_L$,χ_1^0)	$= 82.993 \pm$	$5.0 \pm$	0.8	$(m_{\tau\tau}^{\max})$
Threshold($\tilde{c}_L$,χ_2^0,$\tilde{\mu}_R$,χ_1^0)	$= 211.95 \pm$	$1.6 \pm$	2.0	$(m_{llq}^{\min})$
Threshold($\tilde{b}_1$,χ_2^0,$\tilde{\mu}_R$,χ_1^0)	$= 211.95 \pm$	$1.6 \pm$	2.0	$(m_{llb}^{\min})$

mSUGRA around Minima – positive μ

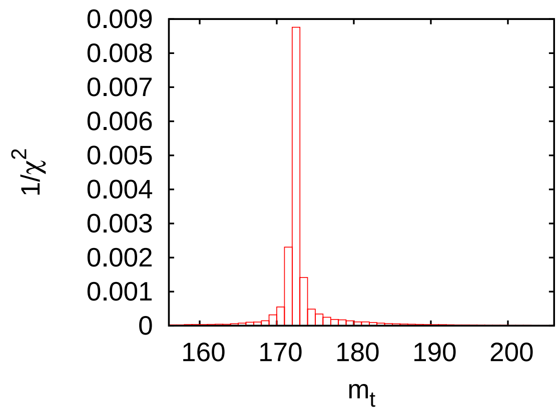
Bayesian



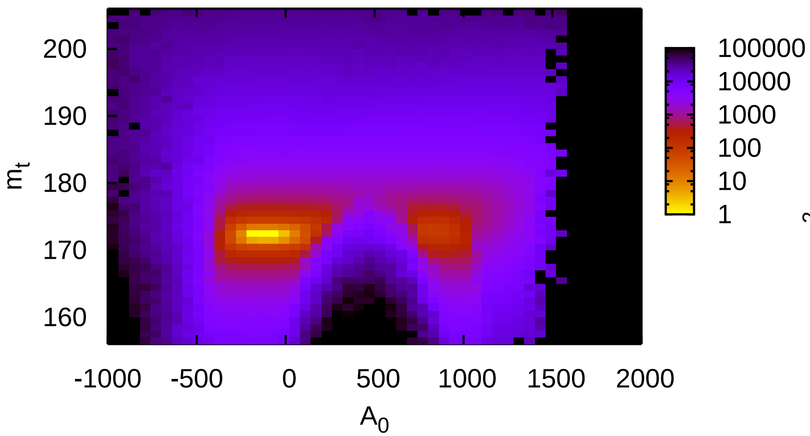
A_0



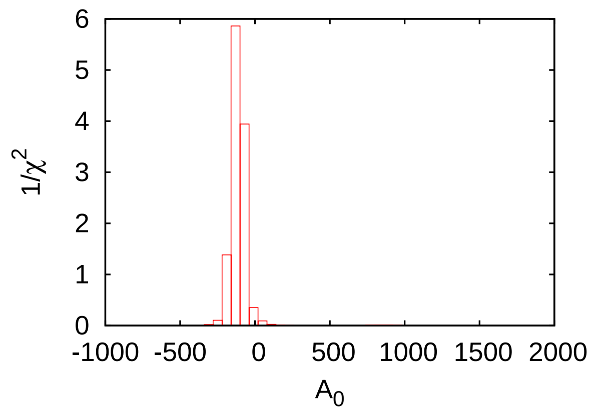
m_t



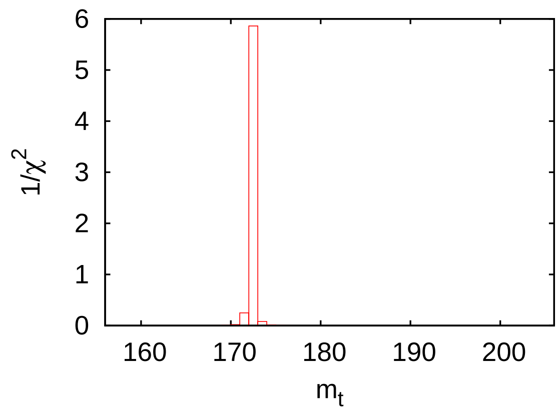
Frequentist



A_0

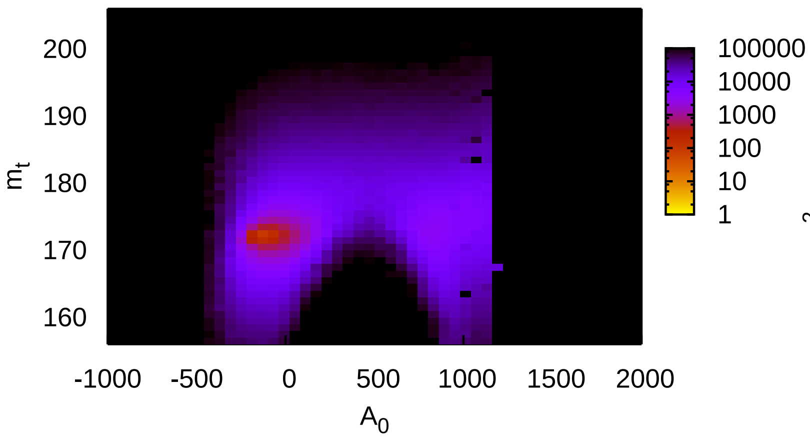


m_t

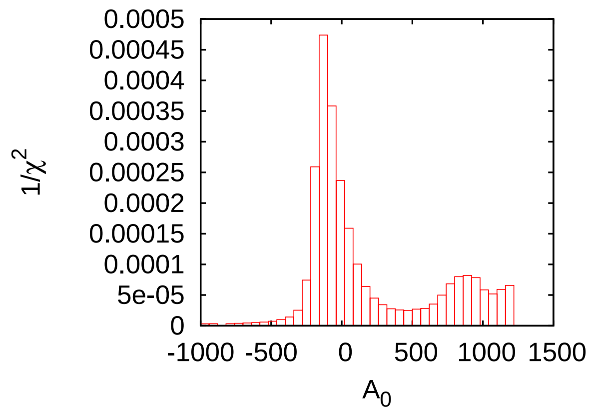


mSUGRA around Minima – negative μ

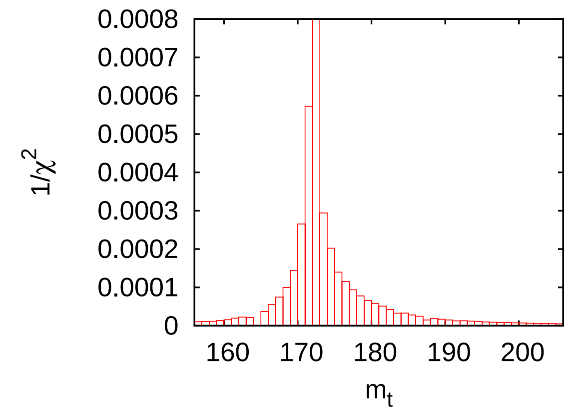
Bayesian



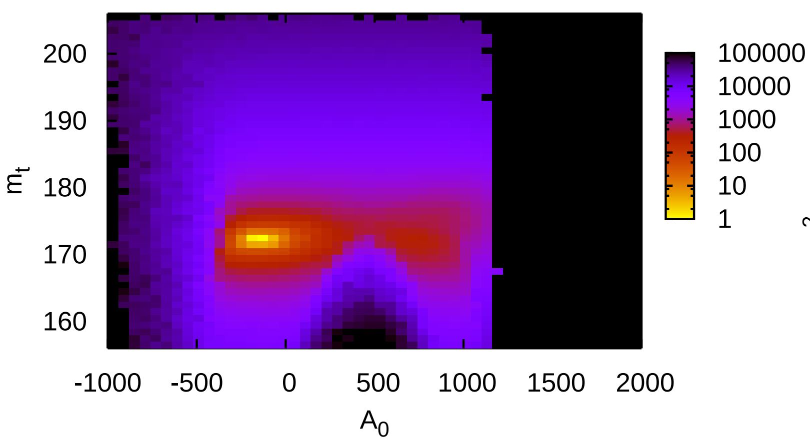
A_0



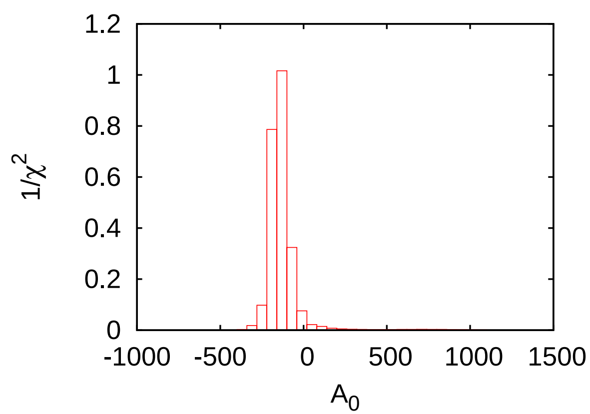
m_t



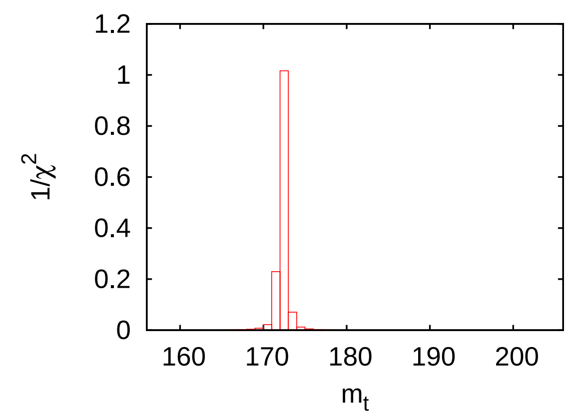
Frequentist



A_0



m_t



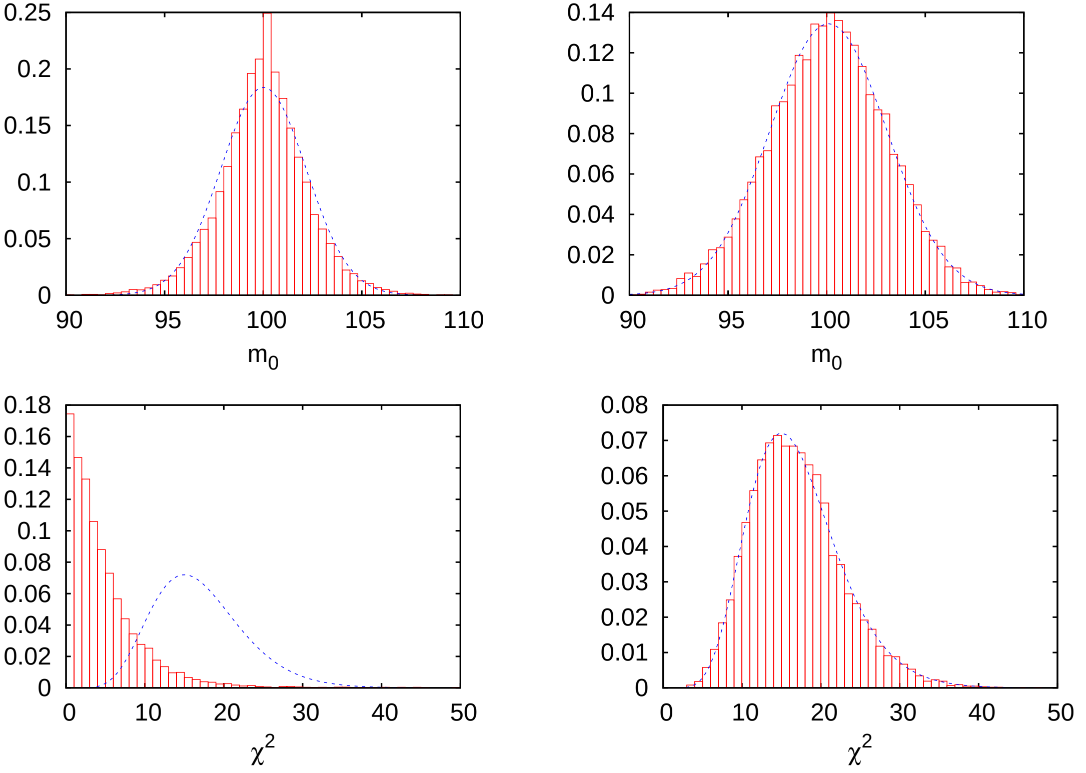
Error determination

Minuit output not usable for flat theory errors:

- Migrad function depends on parabolic approximation
- Cannot determine $\Delta\chi^2$ for Minos to yield 68% CL intervals

$\Rightarrow$ Need more general approach

- Perform $10,000$ toy experiments with measurements smeared around correct value
- Minimise each toy experiment
- Plot resulting distribution of parameter points and fit with Gaussian



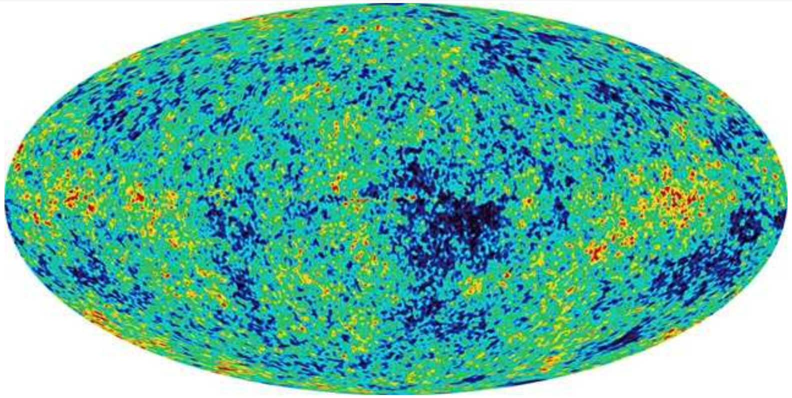
Flat theory errors

Gaussian theory errors

MSSM errors

	LHC		ILC		LHC+ILC		SPS1a
$\tan\beta$	10.0$\pm$	4.5	13.4$\pm$	6.8	12.3$\pm$	5.3	10.0
M_1	102.1$\pm$	7.8	103.0$\pm$	1.1	103.1$\pm$	0.84	103.1
M_2	193.3$\pm$	7.8	193.4$\pm$	3.1	193.2$\pm$	2.3	192.9
M_3	577.2$\pm$	14.5	fixed 500		579.7$\pm$	12.8	577.9
$M_{\tilde{\tau}_L}$	227.8$\pm\mathcal{O}(10^3)$		183.8$\pm$	16.6	187.3$\pm$	12.9	193.6
$M_{\tilde{\tau}_R}$	164.1$\pm\mathcal{O}(10^3)$		143.9$\pm$	17.9	140.1$\pm$	14.1	133.4
$M_{\tilde{\mu}_L}$	193.2$\pm$	8.8	194.4$\pm$	1.1	194.5$\pm$	1.0	194.4
$M_{\tilde{\mu}_R}$	135.0$\pm$	8.3	135.9$\pm$	1.0	136.0$\pm$	0.89	135.8
$M_{\tilde{e}_L}$	193.3$\pm$	8.8	194.4$\pm$	0.89	194.4$\pm$	0.84	194.4
$M_{\tilde{e}_R}$	135.0$\pm$	8.3	135.8$\pm$	0.81	135.9$\pm$	0.77	135.8
$M_{\tilde{q}3_L}$	481.4$\pm$	22.0	507.2$\pm\mathcal{O}(4\cdot10^2)$		486.6$\pm$	19.5	480.8
$M_{\tilde{t}_R}$	415.8$\pm\mathcal{O}(10^2)$		440.0$\pm\mathcal{O}(4\cdot10^2)$		410.7$\pm$	48.4	408.3
$M_{\tilde{b}_R}$	501.7$\pm$	17.9	fixed 500		504.0$\pm$	17.4	502.9
$M_{\tilde{q}_L}$	524.6$\pm$	14.5	fixed 500		526.1$\pm$	7.2	526.6
$M_{\tilde{q}_R}$	507.3$\pm$	17.5	fixed 500		508.4$\pm$	16.7	508.1
A_τ	fixed 0		633.2$\pm$	$\mathcal{O}(10^4)$	139.6$\pm\mathcal{O}(10^4)$		-249.4
A_t	-509.1$\pm$	86.7	-516.1$\pm$	$\mathcal{O}(10^3)$	-500.1$\pm$	143.4	-490.9
A_b	fixed 0		fixed 0		-686.2$\pm\mathcal{O}(10^4)$		-763.4
m_A	406.3$\pm\mathcal{O}(10^3)$		393.8$\pm$	1.6	393.9$\pm$	1.6	394.9
μ	350.5$\pm$	14.5	343.7$\pm$	3.1	354.8$\pm$	2.8	353.7
m_t	171.4$\pm$	1.0	171.4$\pm$	0.12	171.4$\pm$	0.12	171.4

Dark Matter



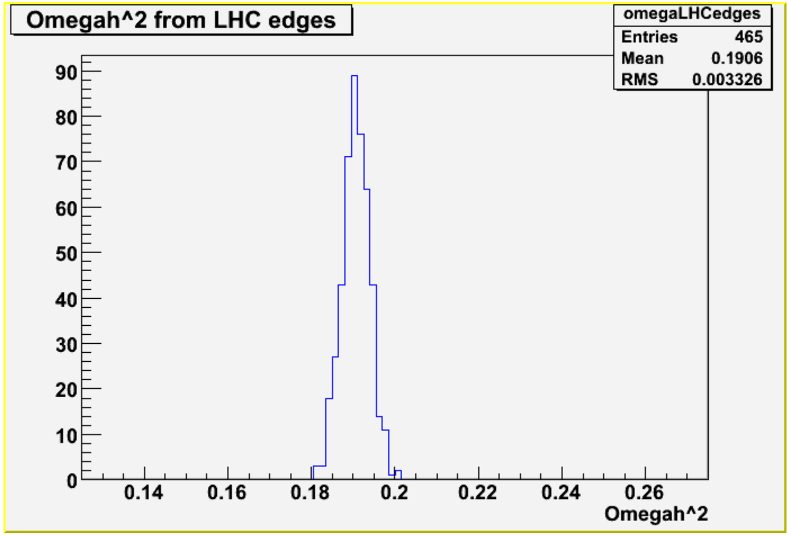
[NASA/WMAP Science Team]

Content of the universe:

- 73% Dark energy
- 4% Ordinary matter
- 23% Dark matter

MSSM: χ_1^0 as LSP ideal candidate for cold dark matter (CDM): massive, weakly interacting

- SFitter: Determine Lagrangian parameters $\Rightarrow$ Spectrum and couplings
- e.g. micrOMEGAs: Calculate relic density $\Omega_{\text{CDM}} h^2 = n_{\text{LSP}} m_{\text{LSP}}$ [Bélanger et al.]
- $\Rightarrow$ Prediction of $\Omega_{\text{CDM}} h^2$
  LHC : $\Omega_{\text{CDM}} h^2 = 0.1906 \pm 0.0033$
  LHC+ILC: $\Omega_{\text{CDM}} h^2 = 0.1910 \pm 0.0003$
  (improvement by one order of magnitude)
- Compare with experiment
  (Measurement of the fluctuations of the
  cosmic microwave background):



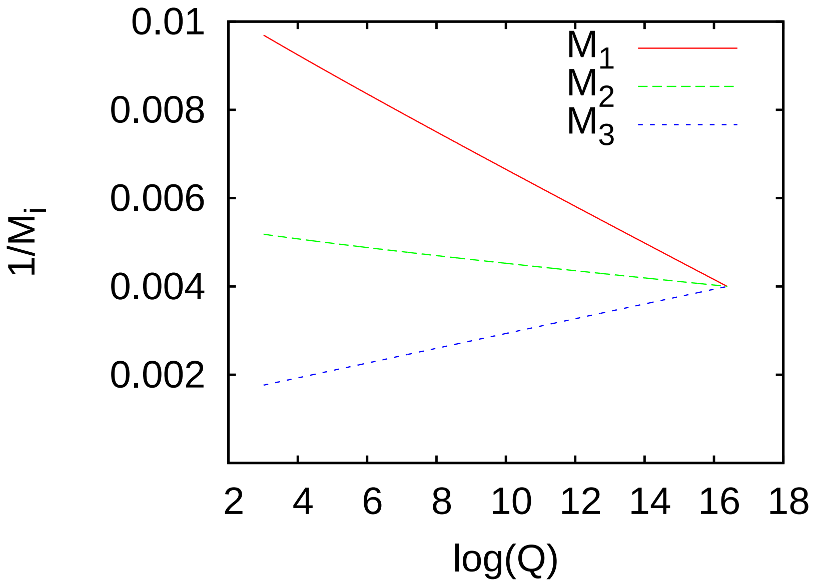
WMAP: $\Omega_{\text{CDM}} h^2 = 0.1277 \pm 0.008$ [astro-ph/0603449]
Planck: $\Omega_{\text{CDM}} h^2 = \quad ? \pm 0.0016$

Testing Unification

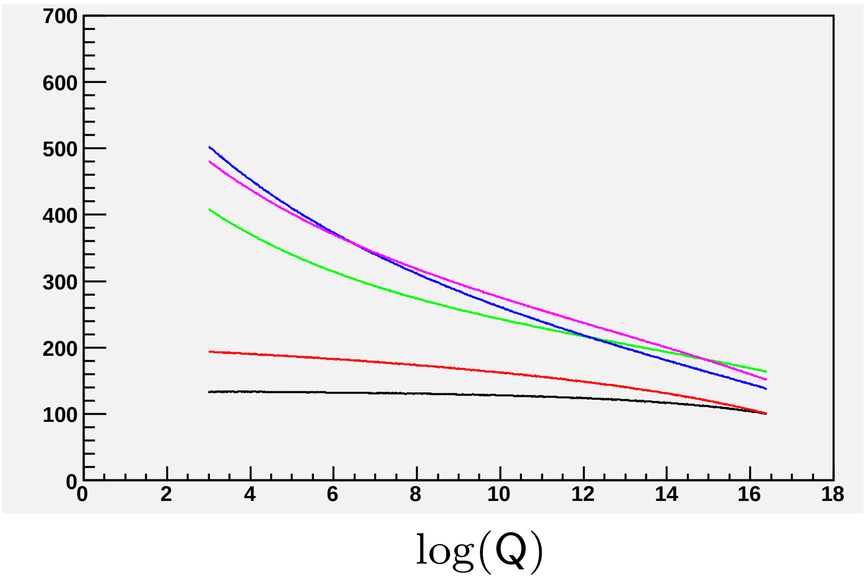
Apparent unification of gauge coupling parameters in the MSSM

Question arises: Do other parameters unify as well?
⇒ Should be tested by bottom-up running from weak scale to Planck scale
⇒ Can give hints about supersymmetry breaking
(e.g. test scalar-mass sum rules with a sliding scale) [Schmaltz et al.]

Bottom-up running of gaugino masses and 3rd-generation sfermion masses:



$M_{\tilde{\tau}_R}, M_{\tilde{\tau}_L}, M_{\tilde{t}_R}, M_{\tilde{b}_R}, M_{\tilde{q3}_L}; \Delta M_3 = -10$ GeV



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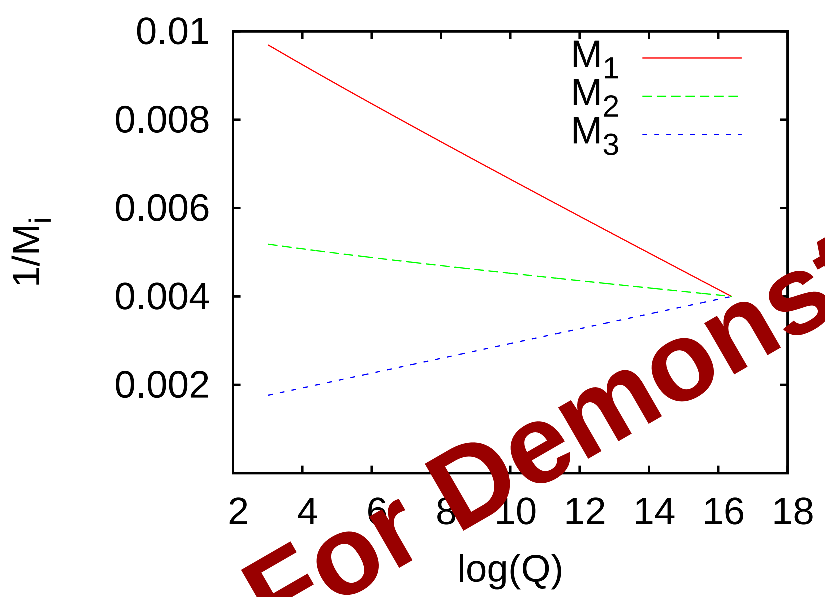

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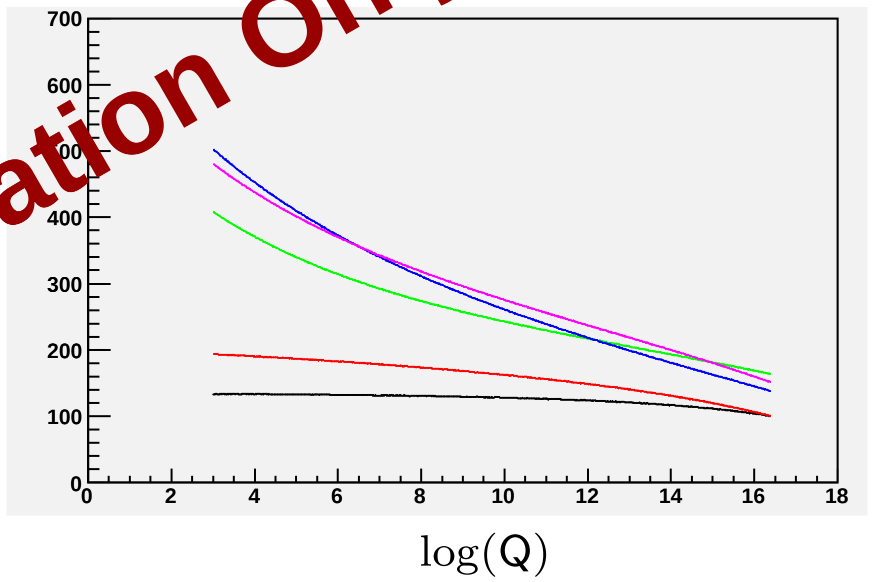
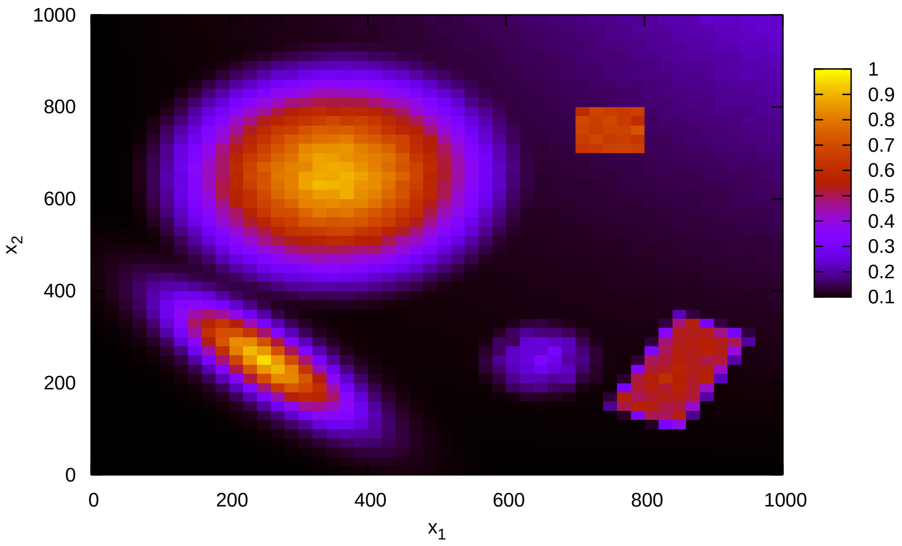


Example

Test function (5-dim):

- Small Hypersphere $r = 100$, $V_{\mathsf{max}} = 75$ @ $(650, 250, 350, 350, 350)$
- Cuboid $d = (173, 120, 200, 200, 200)$, $V_{\mathsf{max}} = 60$ @ $(850, 225, 650, 650, 650)$
- Cube $d = (100, 100, 300, 300, 300)$, $V_{\mathsf{max}} = 25$ @ $(750, 750, 450, 450, 450)$
- Gaussian $\sigma = (50, 150, 150, 150, 150)$, $V_{\mathsf{max}} = 16$ @ $(250, 250, 550, 550, 550)$
- Big Hypersphere $r = 300$, $V_{\mathsf{max}} = 12$ @ $(350, 650, 650, 650, 650)$
- Background $V = 0.1 + 4 \cdot 10^{-30} \cdot x_1^2 x_2^2 x_3^2 x_4^2 x_5^2$




```
1. V=74.929@(655.00,253.72,347.83,348.57,349.59)
2. V=59.972@(850.04,224.99,650.00,649.99,654.56)
3. V=58.219@(849.97,225.01,587.08,650.01,650.02)
4. V=25.110@(750.00,749.99,450.00,450.01,450.01)
5. V=16.042@(245.45,253.44,552.51,542.58,544.75)
6. V=12.116@(350.70,650.40,650.36,650.40,650.38)
7. ...
```

Plot Details

- Parameters: $x_1, \ldots, x_5 \in [0, 1000]$
- Bins: 50×50
- PDF: Breit-Wigner ($\frac{1}{1+\Delta x_i^2/\sigma^2}$) with $\sigma = 100$
- Number of Markov chains: 9
- Number of points per chain: 10^7
- Number of function evaluations: $33,797,153$
- Acceptance ratio: 0.19
- Final r (measure of convergence): 1.815
- CPU time (3 GHz): 150 min