New Physics at the LHC

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DESY, Zeuthen, 10/2007

Outline

Standard–Model effective theory

TeV–scale supersymmetry

LHC Basics

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New physics measurements

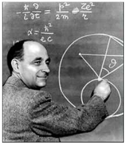
New physics and jets

Higgsless Models

Fundamental parameters

Standard–Model effective theory

A brief history of our Standard–Model mess...



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  $(2 \to 2)$ transition amplitude $\mathcal{A} \propto G_F E^2$
  unitarity violation [transition probability $\propto |\mathcal{A}|^2 \to \infty$]
  pre-80s effective theory for $E < 600$ GeV

– Yukawa 1935: massive particle exchange
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  current effective theory for $E < 1.2$ TeV [LHC energy!!]

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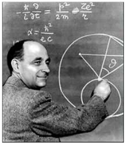

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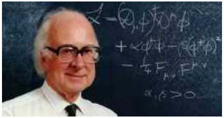

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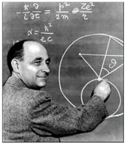

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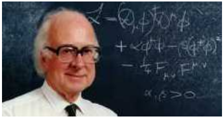

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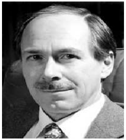
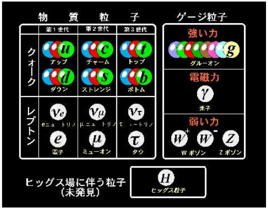


– 't Hooft & Veltman 1971: renormalizability
  beware of $1/M$ in the Lagrangian!
  gauge theories without cut-off
  truly fundamental theory

$\Rightarrow$ 35 years later — going too strong...

Standard–Model effective theory



What is the Standard Model?

– gauge theory with local $SU(3) \times SU(2) \times U(1)$

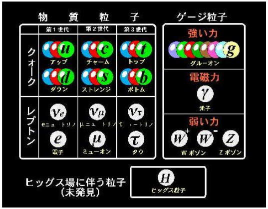
– massless $SU(3)$ and $U(1)$ gauge bosons
massive W, Z bosons [Higgs mechanism with $v = 246$ GeV]

– Dirac fermions in doublets with masses = Yukawas
generation mixing in quark and neutrino sector

– renormalizable Lagrangian a la ’t Hooft [no 1/masses]

⇒ defined by particle content, interactions, renormalizability

Standard–Model effective theory



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And how complete is it experimentally?

– dark matter? [solid evidence for weak–scale new physics!?]

– quark mixing — flavor physics? [new operators above 10^4 GeV?]

– neutrino masses and mixing? [see-saw at 10^{11} GeV?]

– matter–antimatter asymmetry? [universe mostly matter!]

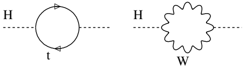
– gravity missing on list of forces? [mostly negligible but definitely nonrenormalizable]

$\Rightarrow$ renormalizable but experimentally incomplete

$\Rightarrow$ cut-off scale unavoidable, size negotiable [SM an effective theory]

$\Rightarrow$ all philosophy — who the hell cares???

Hierarchy problem



Theorists care!!

– compute loop corrections to scalar Higgs mass

– top loop in Higgs self energy Σ

$$\Sigma \sim - \left(\frac{g\, m_t}{v} \right)^2 \int \frac{d^4 q}{(2\pi)^4} \frac{(\not{q} + m_t)\,(\not{q} + \not{p} + m_t)}{[q^2 - m_t^2]\,[(q+p)^2 - m_t^2]} \sim - \frac{1}{(4\pi)^2} \left(\frac{g\, m_t}{v} \right)^2 \Lambda^2 + \cdots$$

– sum to Higgs–mass correction

$$\frac{1}{p^2 - m_H^2} \to \frac{1}{p^2 - m_H^2} + \frac{1}{p^2 - m_H^2} \Sigma \frac{1}{p^2 - m_H^2} + \frac{1}{p^2 - m_H^2} \Sigma \frac{1}{p^2 - m_H^2} \Sigma \frac{1}{p^2 - m_H^2} + \dots$$

$$= \frac{1}{p^2 - m_H^2} \sum_{j=0}^{\infty} \left(\frac{\Sigma}{p^2 - m_H^2} \right)^j = \frac{1}{p^2 - m_H^2} \frac{1}{1 - \dfrac{\Sigma}{p^2 - m_H^2}} = \frac{1}{p^2 - m_H^2 - \Sigma}$$

– and watch desaster after collecting all loops

$$m_H^2 \longrightarrow m_H^2 - \frac{3 g^2}{32 \pi^2} \frac{\Lambda^2}{m_W^2} \left[m_H^2 + 2 m_W^2 + m_Z^2 - 4 m_t^2 \right] + \cdots$$

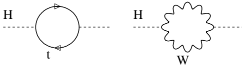
$\Rightarrow$ Higgs mass including loops wants to be cut-off scale Λ

$\Rightarrow$ Standard–Model effective theory destabilized between v and Λ

[Higgs wants to be at Λ, but would not function as Higgs there]

$\Rightarrow$ hierarchy problem: why not a Σ model if fundamental Higgs unworkable

TeV–scale new physics



Starting from data which...

...indicates a light Higgs [e-w precision data]
...indicates higher–scale physics [at least dark matter...]

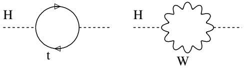
- easy solution: counter term to cancel loops ⇒ artificial, unmotivated, ugly
- or new physics at TeV scale:
  - supersymmetry [my favorite]
  - extra dimensions [Dan Hooper's favorite]
  - little Higgs [nobody's favorite, too hard]
  - composite Higgs, TopColor [wish they were gone...]
  - YourFavoriteNewPhysics...
- typically cancellation by new particles or discussing away high scale

⇒ beautiful concepts, but problematic in reality [data seriously in the way]

- discrete symmetry for ρ parameter, FCNC, proton decay
- stable lightest particle: dark matter? [correct relic density]

⇒ TeV–scale models in baroque state

TeV–scale new physics



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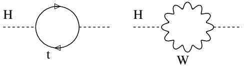
Alternative motivations for TeV–scale new physics

– Uli Baur's rule: new energy scales bring new physics
– Cologne philosophy: et hät noch immer joot jejange [applied to multi-billion LHC]
– gauge coupling unification almost perfect

TeV–scale supersymmetry



Supersymmetry

– give each Standard–Model particle a partner [with different spin]

– SUSY obviously broken by masses [soft breaking, mechanism unknown]

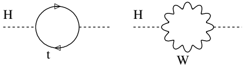
– sooo not an LHC paradigm: maximally blind mediation [MSUGRA, CMSSM]

scalars — m_0 fermions — $m_{1/2}$ tri-scalar — A_0 Higgs sector — $\text{sign}(\mu)$, $\tan\beta$

– assume dark matter, stable lightest partner

⇒ measure BSM spectrum with missing energy at LHC

TeV–scale supersymmetry



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LHC searches: MSSM

– conjugate Higgs field not allowed
→ give mass to t and b?
→ five Higgs bosons

– SUSY–Higgs alone interesting

⇒ would be another talk...

⇒ list of SUSY partners

		spin	d.o.f.	
fermion	f_L, f_R	1/2	1+1	
→ sfermion	$\tilde{f}_L, \tilde{f}_R$	0	1+1	
gluon	G_μ	1	n-2	
→ gluino	$\tilde{g}$	1/2	2	Majorana
gauge bosons	γ, Z	1	2+3	
Higgs bosons	h^o, H^o, A^o	0	3	
→ neutralinos	$\tilde{\chi}_i^o$	1/2	$4 \cdot 2$	LSP
gauge bosons	$W^\pm$	1	$2 \cdot 3$	
Higgs bosons	$H^\pm$	0	2	
→ charginos	$\tilde{\chi}_i^\pm$	1/2	$2 \cdot 4$	

LHC Basics

LHC — Large Hadron Collider

– smash 7 TeV protons onto 7 TeV protons
  produce anything that couples to quarks and gluons
  search for it in decay products

– huge detectors, computers, analysis $\longrightarrow$ experimental physics
  prejudice and fun $\longrightarrow$ theoretical physics

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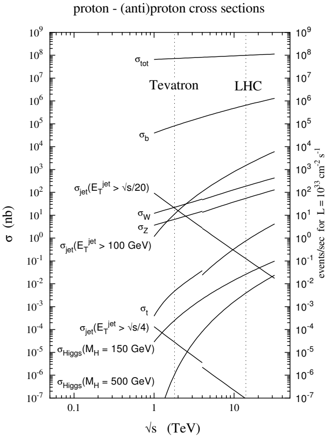
Everything you always wanted to know...

- signal: everything new, exciting and rare
  background: yesterday's signal
- Standard Model: theory of background
  QCD: evil background theory trying to kill us
- $N_{\text{events}} = \sigma \cdot \mathcal{L}$ ['cross section times luminosity']
- trigger: no leptons/photons — not on tape
- jet: everything except for leptons/photons
  crucial: inside a jet [q, g, b, τ tagged?]
- discovery $N_S/\sqrt{N_B} > 5$



Supersymmetric signatures

New physics at the LHC

(1) discovery — signals for new physics

(2) measurements — masses, cross sections, decays

(3) parameters — TeV–scale Lagrangian, underlying theory

$\Rightarrow$ approach independent of new physics model

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SUSY signals at Tevatron

– jets and $\not{E}_T$: $pp \to \tilde{q}\tilde{q}^*, \tilde{g}\tilde{g}, \tilde{q}\tilde{g}$

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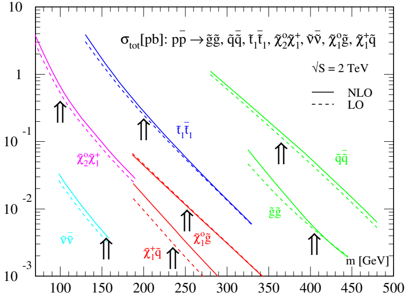

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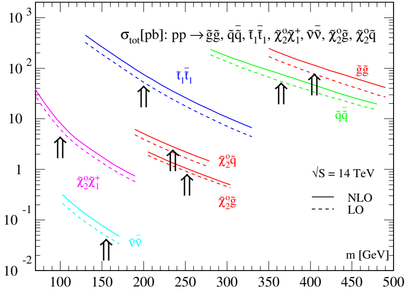
⇒ plenty squarks and gluinos to study



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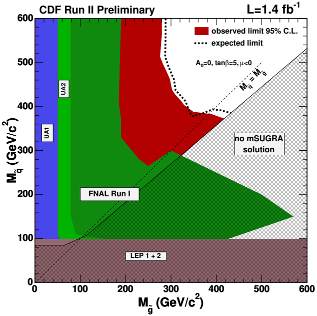

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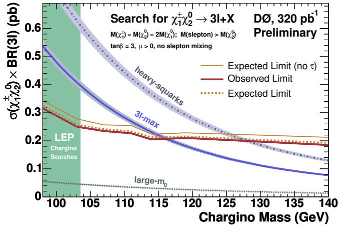

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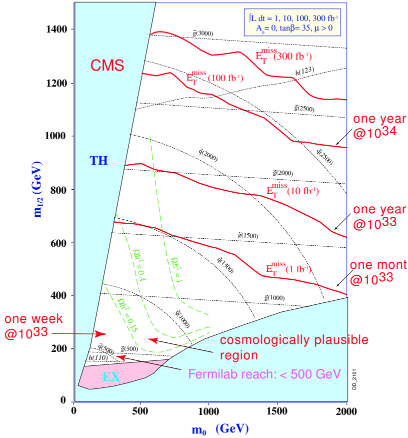

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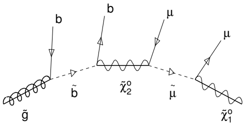


Spectra from cascade decays [Atlas, Cambridge-SUSY]

– more than 10^7 squark–gluino events

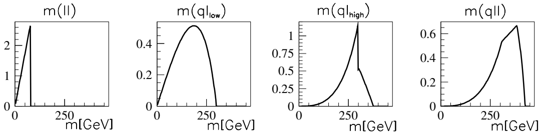
– target decay $\tilde{g} \to \tilde{b}\bar{b} \to \tilde{\chi}_2^0 b\bar{b} \to \mu^+\mu^- b\bar{b}\tilde{\chi}_1^0$

– thresholds & edges

$$m_{ij}^2 = E_i E_j - |\vec{p}_i||\vec{p}_j| \cos\theta_{ij}$$

$$0 < m_{\mu\mu}^2 < \frac{m_{\tilde{\chi}_2^0}^2 - m_{\tilde{\mu}}^2}{m_{\tilde{\mu}}} \; \frac{m_{\tilde{\mu}}^2 - m_{\tilde{\chi}_1^0}^2}{m_{\tilde{\mu}}}$$

$\Rightarrow$ new–physics mass spectrum from cascade decays



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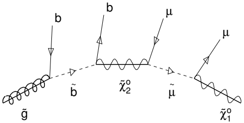

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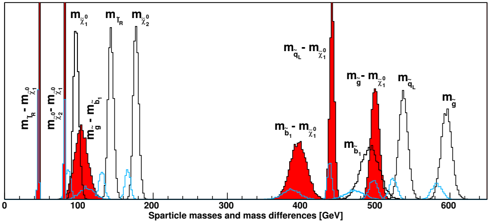
$\Rightarrow$ new–physics mass spectrum from cascade decays

Cascade masses from kinematics [Gjelsten, Miller, Osland,...]

- all decay jets b quarks [otherwise dead by QCD]
- gluino mass to $\sim 1\%$
- not just mass differences

$\Rightarrow$ what's more in m_{ij}?

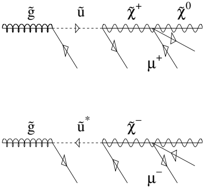


New physics measurements

Step back: when is it SUSY–QCD? [Barger,...; Barnett,...; Baer,...]

- gluinos: strongly interacting Majorana fermions
  Majorana = its own antiparticle
- first jet in gluino decay: q or $\bar{q}$
- final–state leptons with charges 50% − 50%

$\Rightarrow$ gluino = like–sign dileptons in SUSY–like events



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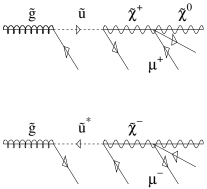


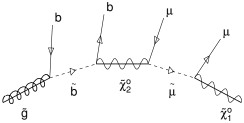
All new physics is hypothesis testing [Lester, Smillie, Webber]

- loop hole: ‘gluino is Majorana if it is a fermion’

  [bosonic gluino always with likesign dileptons]
- gluino a fermion?
- assume gluino cascade observed
- straw-man model where ‘gluino’ is a boson: universal extra dimensions

  [spectra degenerate — ignore; cross section larger — ignore; extra dimensions — in 15 minutes]

$\Rightarrow$ compare model predictions between threshold and edge



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Gluino–bottom cascade [Alves, TP, Eboli; Cornell]

– decay chain like for gluino mass [simulated for SUSY]

– compare SUSY with excited g, b, Z, μ, γ

– shape below edge: $m_{b\mu}/m_{b\mu}^{\max} = \sin\theta/2$

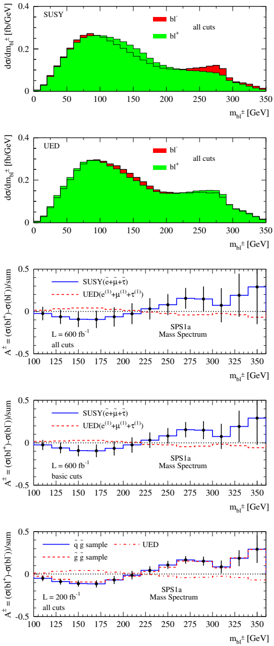
– better: asymmetry b vs. $\bar{b}$ [independent of production]

$$\mathcal{A}(m_{\mu b}) = \frac{\sigma(b\mu^+) - \sigma(b\mu^-)}{\sigma(b\mu^+) + \sigma(b\mu^-)}$$

– plus more observables... [still visible after cuts and smearing?]

– gluino spin from cascade decays

$\Rightarrow$ gluino = fermionic like-sign dileptons



New physics measurements

Step back: when is it SUSY–QCD? [Barger,...; Barnett,...; Baer,...]

– gluinos: strongly interacting Majorana fermions
  Majorana = its own antiparticle

– first jet in gluino decay: q or $\bar{q}$

– final–state leptons with charges 50% − 50%

⇒ gluino = like–sign dileptons in SUSY–like events

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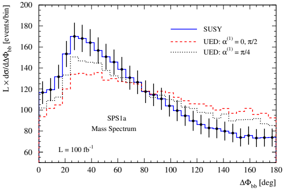


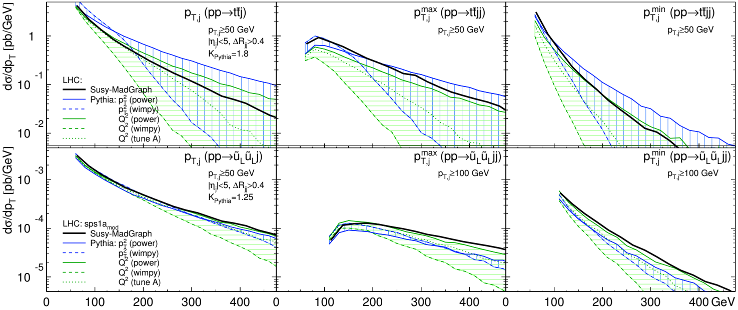
New physics and jets

Squarks and gluinos always with many jets [Rainwater, TP, Skands]

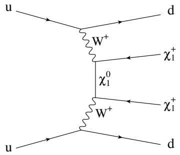
– cascade studies sensitive to jet simulation?
– matrix element $\tilde{g}\tilde{g}$+2j and $\tilde{u}_L\tilde{g}$+2j [$p_{T,j} > 100$ GeV]
– compared with Pythia shower [recent tune!]
– hard scale μ_F huge for SUSY
– angular correlations better than 10% [miracle?]

⇒ QCD not a problem in new–physics signals

σ [pb]	tt_{600}	$\tilde{g}\tilde{g}$	$\tilde{u}_L\tilde{g}$
σ_{0j}	1.30	4.83	5.65
σ_{1j}	0.73	2.89	2.74
σ_{2j}	0.26	1.09	0.85



Spins and jets



More hypothesis testing: spin of LSP [Alwall, Rainwater, TP]

– Majorana LSP with like-sign charginos?

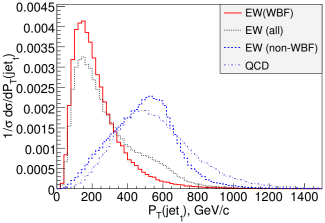
– hypotheses: like–sign charginos (SUSY)
like–sign scalars (scalar dark matter model)
like–sign vector boson (like litte Higgs)

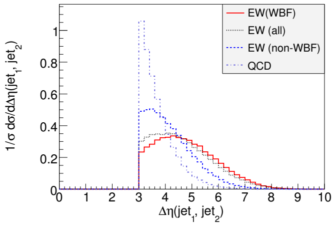
– stable for simplicity — chargino kinematics not used [SM backgrounds]

– WBF signal: two key distributions $\Delta\phi_{jj}, p_{T,j}$ [like $H \to ZZ \to 4\mu$ or WBF-Higgs]

⇒ distinct WBF signal? [$p_{T,j} \sim m_W$, forward jets]
visible over backgrounds? [SUSY–QCD backgrounds dominant]

⇒ long shot, but not swamped by SUSY-QCD





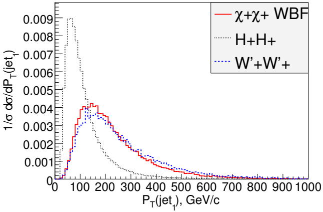
Spins and jets

Like-sign scalars instead

- assume stable charged Higgs (type-II two-Higgs doublet model)
- H^+H^- same as simple heavy H^0
- W radiated off quarks [Goldstone coupling to Higgs]

$$P_T(x,p_T) \sim \frac{1+(1-x)^2}{2x}\,\frac{1}{p_T^2} \qquad\qquad P_L(x,p_T) \sim \frac{(1-x)^2}{x}\,\frac{m_W^2}{p_T^4}$$

$\Rightarrow$ scalars identified by softer $p_{T,j}$



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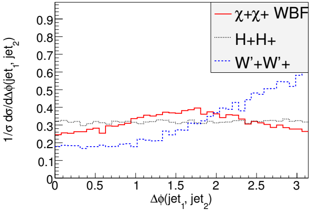
Like-sign vectors instead

- alternative hypothesis like little Higgs
- start with copy of SM, heavy W', Z', H', f' [H' necessary for unitarity, but irrelevant at LHC]
- Lorentz structure reflected in angle between jets

⇒ vectors identified by peaked $\Delta\phi_{jj}$



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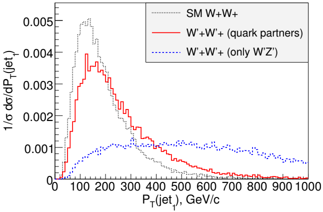
Heavy fermions in little–Higgs models

– not part of the naive set of WBF diagrams

– huge effect on $p_{T,j}$

$\Rightarrow$ some hypotheses simply bad



Higgsless Models

What if no Higgs [Csaki,...; Birkedal, Matchev, Perelstein]

– strongly interacting alternatives to fundamental Higgs [also solving hierarchy problem?]

– symmetry breaking by 5D boundary conditions [Randall–Sundrum metric]

– KK excitations of weak gauge bosons in *WW* scattering [*s* and *t* channel]

– perturbative unitarity violation above $2.8 \cdots 7.5$ TeV

– unitarity via sum rule: $g_{WWWW} = g^2_{WWZ} + g^2_{WW\gamma} + \sum_j g^2_{WWV_j} \cdots$ [truncated?]

– KK excitations fermiophobic [no heavy fermions needed]

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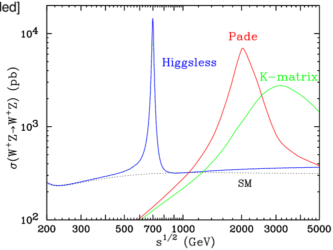

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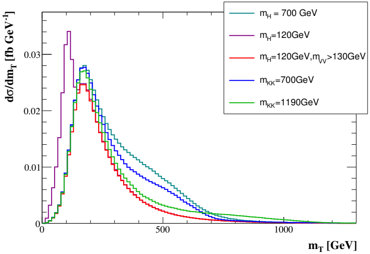
Simulate WBF $\ell\nu\ell\nu$ production [Englert & Zeppenfeld; Christoph's talk next week]

– light Higgs $m_H = 120$ GeV [continuum for $m_{WW} > 130$ GeV]
– heavy Higgs $m_H = 700$ GeV
– light KK: $1/R = 10^8$ GeV [$m_{\text{KK}} \sim 700$ GeV]
– heavy KK: $1/R = M_{\text{Planck}}$ [$m_{\text{KK}} \sim 1.2$ TeV]
– jet observables less promising
lepton correlations key

$\Rightarrow$ even more hypothesis testing



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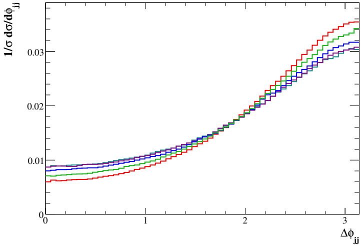

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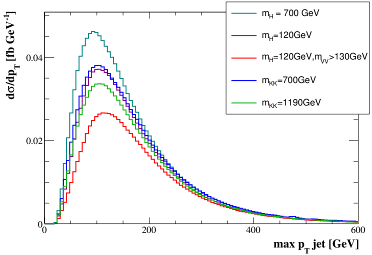

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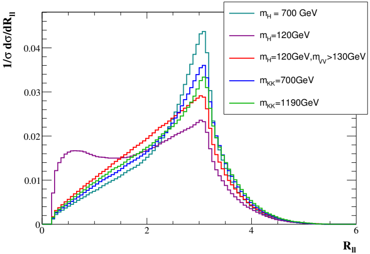

Fundamental parameters

New physics at the LHC

- parameters: weak-scale Lagrangian ['top-down' analyses one big cheat]
- measurements: masses or edges
  branching fractions
  cross sections
  dark matter density, Planck, LEP,...
- errors: correlated, statistics & systematics & theory [theory errors flat, CKMfitter]

$\Rightarrow$ what is the underlying physics?

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$\Rightarrow$ what is the underlying physics?

Probability maps of new physics [Baltz,...; Roszkowski,...; Allanach,...; SFitter]

– likelihood map $p(d|m)$ over model–parameter space m

– Bayes' theorem: $p(m|d) = p(d|m)\, p(m)/p(d)$

– real problem: remove bad directions from $p(d|m)$

– Bayesian: theorist's prejudice $p(m|d)$ using $p(m)$ [cosmology]
frequentist: best–fitting point $\max_m p(d|m)$ [B physics]

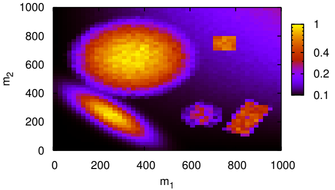
– challenge in LHC era: (1) compute map $p(m|d)$ of parameter space
(2) find local maxima in $p(m|d)$
(3) do your Bayesian/frequentist dance...

Fundamental parameters

Bayesian or frequentist?

– toy potential $V(\vec{x})$ in 5 dimensions [2 spheres, cigar, 2 cubes]

– best–fitting point: small sphere
most likely scenatio: large sphere [water in spoon/cloud]



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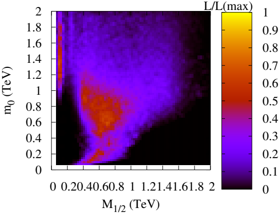
. . .

Parameters from today's measurements [Allanach,...]

– 'Which is the most likely parameter point?'

– 'How does dark matter annihilate/couple?'



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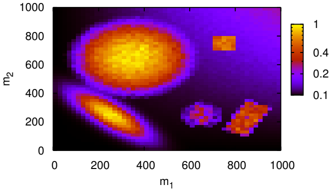

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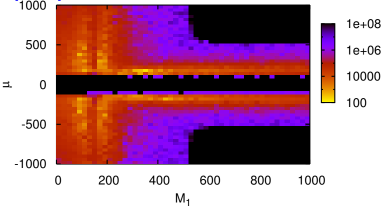
MSSM parameters with LHC measurements [SFitter]

- decay kinematics only
- two–dimensional likelihood



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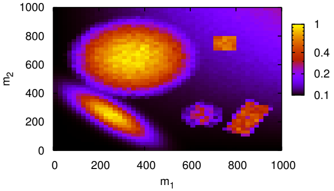

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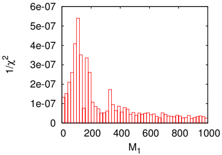
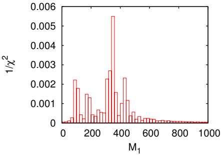
MSSM parameters with LHC measurements [SFitter]

– decay kinematics only

– Bayesian — frequentist?

⇒ no ‘correct approach’





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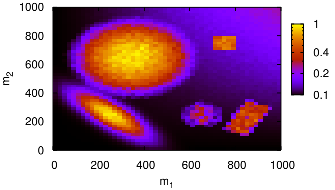

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MSSM parameters with LHC measurements [SFitter]

– decay kinematics only
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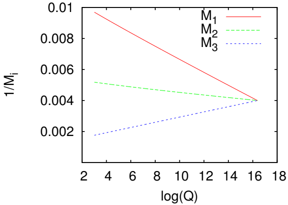
⇒ no ‘correct approach’
– unification in bottom-up running?
⇒ waiting for LHC data!



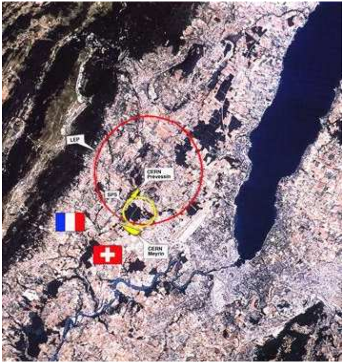
New physics at the LHC

Why new physics

- know there is physics beyond our Standard Model
- trust something to solve the hierarchy problem
- LHC should find and study it in spite of QCD

Supersymmetry one well-studied example

- solves hierarchy problem
- can explain dark matter
- suggests GUT structure
- cascade decays rule
- LHC much more than 'discovery machine'



Extra dimensions, etc.

- might solve hierarchy problem
- can explain dark matter
- workable LHC hypotheses crucial

LHC not only really big machine, but also lots of fun physics!