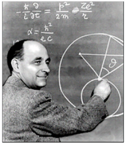
Supersymmetry at the LHC

Tilman Plehn

Heidelberg

PSI, 10/2010

Standard–Model effective theory



Building a fundamental theory

– Fermi 1934: theory of weak interactions [$n \to p e^- \bar{\nu}_e$]
  (2 $\to$ 2) transition amplitude $\mathcal{A} \propto G_F E^2$
  probability/ unitarity violation
  pre-80s effective theory for $E < 600$ GeV

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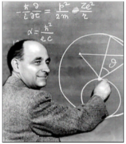

TENTATIVO DI UNA TEORIA DEI RAGGI β

Nota (1) di Enrico Fermi

Sunto. - *Si propone una teoria quantitativa dell'emissione dei raggi β in cui si ammette l'esistenza del «neutrino» e si tratta l'emissione degli elettroni e dei neutrini da un nucleo all'atto della disintegrazione β con un procedimento simile a quello seguito nella teoria dell'irradiazione per descrivere l'emissione di un quanto di luce da un atomo eccitato. Vengono dedotte delle formule per la vita media e per la forma dello spettro continuo dei raggi β, e le si confrontano coi dati sperimentali.*

Ipotesi fondamentali della teoria.

§ 1. Nel tentativo di costruire una teoria degli elettroni nucleari e dell'emissione dei raggi β, si incontrano, come è noto, due difficoltà principali. La prima dipende dal fatto che i raggi β primari vengono emessi dai nuclei con una distribuzione continua di velocità. Se non si vuole abbandonare il principio della conservazione dell'energia, si deve ammettere perciò che una frazione dell'energia che si libera nel processo di disintegrazione β sfugga alle nostre attuali possibilità di osservazione. Secondo la proposta di Pauli si può p. es. ammettere l'esistenza di una nuova particella, il così detto «neutrino», avente carica elettrica nulla e massa dell'ordine di grandezza di quella dell'elettrone o minore. Si ammette poi che in ogni processo β vengano emessi simultaneamente un elettrone, che si osserva come raggio β, e un neutrino che sfugge all'osservazione portando seco una parte dell'energia. Nella presente teoria ci baseremo sopra l'ipotesi del neutrino.

Una seconda difficoltà per la teoria degli elettroni nucleari, dipende dal fatto che le attuali teorie relativistiche delle particelle leggere (elettroni o neutrini) non danno una soddisfacente spiegazione della possibilità che tali particelle vengano legate in orbite di dimensioni nucleari.

(1) Cfr. la nota preliminare in «La Ricerca Scientifica», 2, fasc. 12, 1933.

Versuch einer Theorie der β-Strahlen. I[1]).

Von **E. Fermi** in Rom.

Mit 3 Abbildungen. (Eingegangen am 16. Januar 1934.)

Eine quantitative Theorie des β-Zerfalls wird vorgeschlagen, in welcher man die Existenz des Neutrinos annimmt, und die Emission der Elektronen und Neutrinos aus einem Kern beim β-Zerfall mit einer ähnlichen Methode behandelt, wie die Emission eines Lichtquants aus einem angeregten Atom in der Strahlungstheorie. Formeln für die Lebensdauer und für die Form des emittierten kontinuierlichen β-Strahlenspektrums werden abgeleitet und mit der Erfahrung verglichen.

1. Grundannahmen der Theorie.

Bei dem Versuch, eine Theorie der Kernelektronen sowie der β-Emission aufzubauen, begegnet man bekanntlich zwei Schwierigkeiten. Die erste ist durch das kontinuierliche β-Strahlenspektrum bedingt. Falls der Erhaltungssatz der Energie gültig bleiben soll, muß man annehmen, daß ein Bruchteil der beim β-Zerfall frei werdenden Energie unseren bisherigen Beobachtungsmöglichkeiten entgeht. Nach dem Vorschlag von W. Pauli kann man z. B. annehmen, daß beim β-Zerfall nicht nur ein Elektron, sondern auch ein neues Teilchen, das sogenannte „Neutrino" (Masse von der Größenordnung oder kleiner als die Elektronenmasse; keine elektrische Ladung) emittiert wird. In der vorliegenden Theorie werden wir die Hypothese des Neutrinos zugrunde legen.

Eine weitere Schwierigkeit für die Theorie der Kernelektronen besteht darin, daß die jetzigen relativistischen Theorien der leichten Teilchen (Elektronen oder Neutrinos) nicht imstande sind, in einwandfreier Weise zu erklären, wie solche Teilchen in Bahnen von Kerndimensionen gebunden werden können.

Es scheint deswegen zweckmäßiger, mit Heisenberg[2]) anzunehmen, daß ein Kern nur aus schweren Teilchen, Protonen und Neutronen, besteht. Um trotzdem die Möglichkeit der β-Emission zu verstehen, wollen wir versuchen, eine Theorie der Emission leichter Teilchen aus einem Kern in Analogie zur Theorie der Emission eines Lichtquants aus einem angeregten Atom beim gewöhnlichen Strahlungsprozeß aufzubauen. In der Strahlungstheorie ist die totale Anzahl der Lichtquanten keine Konstante: Lichtquanten entstehen, wenn sie von einem Atom emittiert werden, und verschwinden, wenn sie absorbiert werden. In Analogie hierzu wollen wir der β-Strahlentheorie folgende Annahmen zugrunde legen:

[1]) Vgl. die vorläufige Mitteilung: La Ricerca Scientifica **2**, Heft 12, 1933. — [2]) W. Heisenberg, ZS. f. Phys. **77**, 1, 1932.

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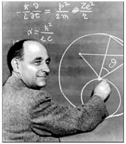

– Yukawa 1935: massive particles
  Fermi's theory for $E \ll M$
  four fermions unitary for $E \gg M$: $\mathcal{A} \propto g^2 E^2/(E^2 - M^2)$
  unitarity violation in $WW \to WW$
  current effective theory for $E < 1.2$ TeV [LHC energy!!]

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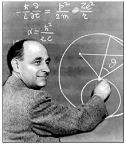

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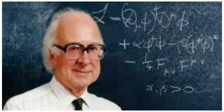

- Higgs 1964: spontaneous symmetry breaking
  unitarity for massive W, Z
  unitarity for massive fermions
  fundamental scalar below TeV

Standard–Model effective theory

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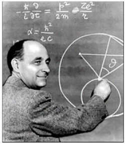

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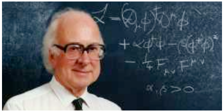

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  - fundamental scalar below TeV

- 't Hooft & Veltman 1971: renormalizability
  - beware of $1/M$ couplings!
  - theory valid to high energy
  - truly fundamental theory

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]

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

– renormalizability $\mathcal{L} \sim -m_W^2 W_\mu W^\mu - m_f \overline{\Psi}\Psi + gH\overline{\Psi}\Psi \stackrel{?}{+} gHW_{\mu\nu}W^{\mu\nu}/M$

$\Rightarrow$ fundamental theory: particle content, interactions, renormalizability

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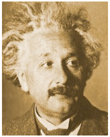

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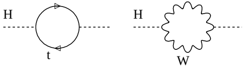
And how complete is it experimentally?

- dark matter? [scale of new physics? WIMP miracle?]
- 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?]
- gauge coupling unification?
- gravity missing? [mostly negligible but definitely unrenormalizable]

$\Rightarrow$ large cut-off scale unavoidable, size negotiable, renormalizability desirable

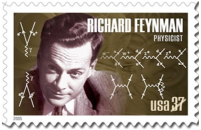
$\Rightarrow$ all experimental, so who the hell cares???

Standard–Model effective theory



Theorists do!!

– quantum corrections to Higgs mass... [$\Delta t\, \Delta E < 1$]



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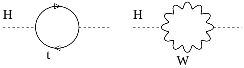


Theorists do!!

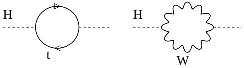
– quantum corrections to Higgs mass...
...imply effective field theory desaster

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

– Higgs mass pulled to cut-off Λ where unitarization does not work

$\Rightarrow$ hierarchy problem — Higgs without stabilization incomplete

Standard–Model effective theory



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Starting from data which...

...indicates light Higgs [e-w precision data]
...indicates effective Standard Model

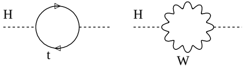
– easy solution: counter term — but against idea of symmetries

– or new physics at TeV scale: supersymmetry
extra dimensions
little Higgs
composite Higgs, TopColor
YourFavoriteNewPhysics...

$\Rightarrow$ typically cancellation by new particles or discussing away high scale

$\Rightarrow$ beautiful concepts, models in baroque state

Standard–Model effective theory



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⇒ hierarchy problem — Higgs without stabilization incomplete

Expectations from the LHC [Uli Baur's rule: always new physics at new scales]

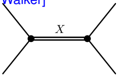
– find light Higgs?
– find new physics stabilizing Higgs mass?
– see dark–matter candidate?

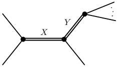
Supermodels

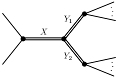
Political motivation: consideration for early LHC [Bauer, Ligeti, Schmaltz, Thaler, Walker]

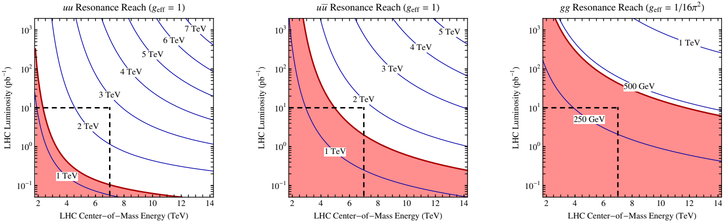
– 10 LHC events in 10 pb^{-1}
  not ruled out by LEP and flavor physics
  not ruled out by Tevatron for 10 fb^{-1} [shaded red]
  decay to (leptonic) background-free signatures

– $2 \to 1$ production via $g_\text{eff}^2 G^{\mu\nu} G_{\mu\nu}$ [similar for $q\bar{q}$, qq]









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- Z' or $q\bar{q}$ resonance
  decaying to leptons or new stable particles ['heavy leptons']
- diquarks/lepto-diquarks $uu \to D$, $D \to \ell^- L$, $L \to \ell^+ 2j$
- R parity violating squarks $\tilde{b}^c \to b\,\chi_1$, $\chi_1 \to \ell^+ \tilde{\ell}$, $\tilde{\ell} \to \ell^- 3j$

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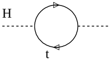
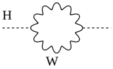
$\Rightarrow$ unconvincing — LHC below 100 pb^{-1} a Standard Model machine

Supersymmetry



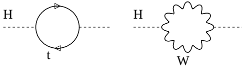


Physics motivation: supersymmetry

- partner for each Standard–Model particle
- cancellation because of different spins
- obviously broken by masses, mechanism unknown
- assume dark matter, stable lightest partner

$\Rightarrow$ LHC: measure spectrum with missing energy

Supersymmetry



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Particle spectrum

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

Signatures

New physics at the LHC

1– discovery — inclusive signals for new physics

2– measurements — spectrum, quantum numbers

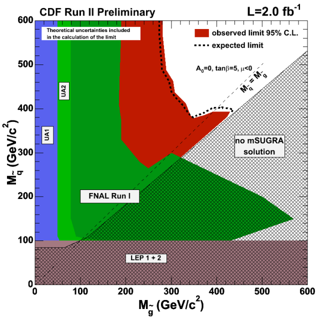
3– parameters — TeV–scale Lagrangian, underlying theory

$\Rightarrow$ approach independent of new physics model

SUSY signals at Tevatron

- production of strongly interacting particles cascade decay to DM candidate
- jets and $\not{E}_T$: $pp \to \tilde{q}\tilde{q}^*, \tilde{g}\tilde{g}, \tilde{q}\tilde{g}$
- like–sign dileptons: $pp \to \tilde{g}\tilde{g}$
- funny tops: $pp \to \tilde{t}_1 \tilde{t}_1^*$
- tri-leptons: $pp \to \tilde{\chi}_2^0 \tilde{\chi}_1^-$

  $[\tilde{\chi}_2^0 \to \tilde{\ell}\bar{\ell} \to \tilde{\chi}_1^0 \ell\bar{\ell};\ \tilde{\chi}_1^- \to \tilde{\chi}_1^0 \ell\bar{\nu}]$



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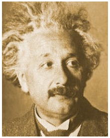


LHC searches

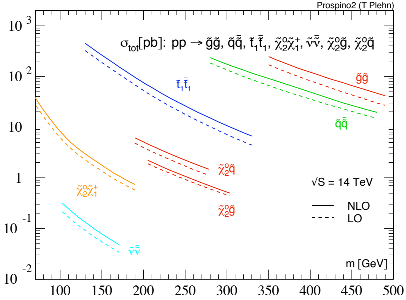
– beyond inclusive searches
lots of strongly interacting particles

– general theme: try to survive QCD

– rate prediction not $\alpha_s/(4\pi) \sim 0.01$
(collinear) jets everywhere
better observables needed

– hep-ph/hep-ex cross listings crucial

$\Rightarrow$ aim at underlying theory



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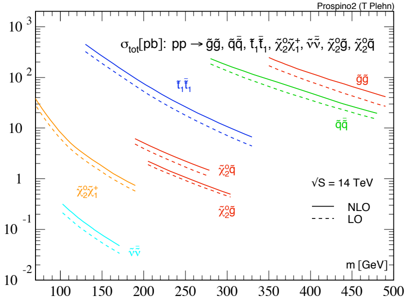

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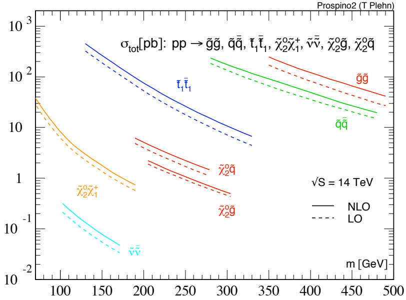


Signatures

New physics at the LHC

1– discovery — inclusive signals for new physics

2– measurements — spectrum, quantum numbers

3– parameters — TeV–scale Lagrangian, underlying theory

⇒ approach independent of new physics model

LHC searches

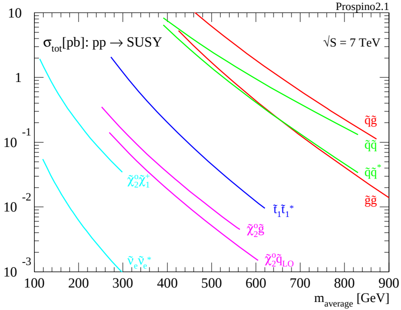
– beyond inclusive searches
lots of strongly interacting particles

– general theme: try to survive QCD

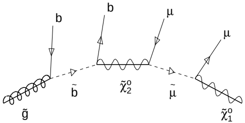
– rate prediction not $\alpha_s/(4\pi) \sim 0.01$
(collinear) jets everywhere
better observables needed

– hep-ph/hep-ex cross listings crucial

⇒ aim at underlying theory



Mass measurements



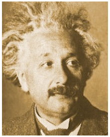
Exercise in relativistic kinematics

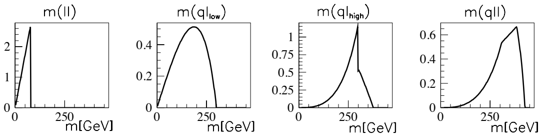
- more than 10^7 squark–gluino events at 14 TeV
- all decays to hard jets, missing energy, (leptons)
  example $\tilde{g} \to \tilde{b}\bar{b} \to \tilde{\chi}_2^0 b\bar{b} \to \mu^+\mu^- b\bar{b}\tilde{\chi}_1^0$
- thresholds & edges [Cambridge, ATLAS TDR]

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

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

$\Rightarrow$ new–physics masses from cascade decays





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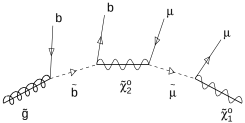

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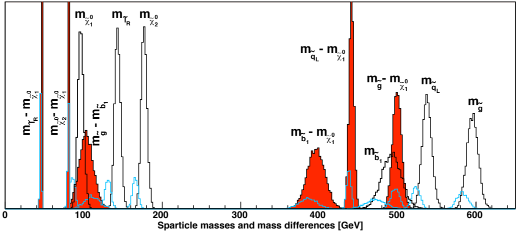
⇒ new–physics masses from cascade decays

Masses from cascade decays [Gjelsten, Miller, Osland, Raklev...]

- all decay jets b quarks [otherwise dead by QCD]

⇒ what's more in m_{ij}?



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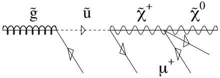

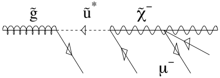

When will I believe it's SUSY?

- 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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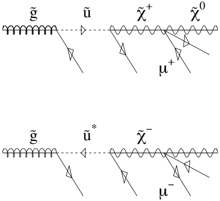

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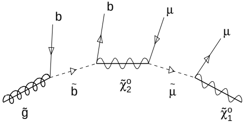
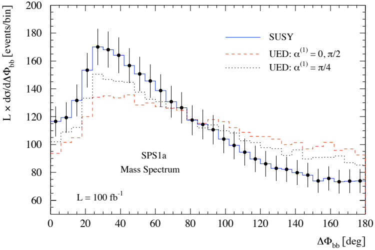
All new physics is hypothesis testing



- loop hole: 'gluino is Majorana if fermion' [Alves, TP]
- assume gluino cascade observed
- straw-man model where 'gluino' is a boson: universal extra dimensions

  [spectra degenerate — ignore; cross section larger — ignore]

⇒ compare angular correlations



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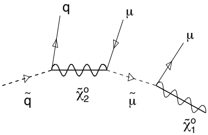
Asymmetries [Smillie, PhD 2006; Barr, Lester, Webber]

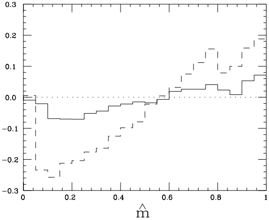


- shorter squark decay chain
- shape between endpoints: $\hat{m} = m_{q\mu}/m_{q\mu}^{\max} \sim \sin\theta/2$
- dominant $pp \to \tilde{q}\tilde{g}$ with $\tilde{q} : \tilde{q}^* \sim 2 : 1$
- production asymmetry with reduced errors

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

- similar for gluino decay

$\Rightarrow$ gluino = fermion with like-sign dileptons



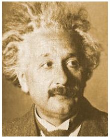
Fat jets

Fat jets from boosted particles

1– decay products too collinear to resolve

2– dangerous signal combinatorics

3– improved multi-jet mass reconstruction



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Boosted particles for LHC

1994 boosted $W \to 2$ jets from heavy Higgs [Seymour]

1994 boosted $t \to 3$ jets [Seymour]

2002 boosted $W \to 2$ jets from strongly interacting WW [Butterworth, Cox, Forshaw]

2006 boosted $t \to 3$ jets from heavy resonances [Agashe, Belyaev, Krupovnickas, Perez, Virzi]

2008 boosted $H \to b\bar{b}$ [Butterworth, Davison, Rubin, Salam]

2009 boosted $\tilde{\chi}_1^0 \to 3$ jets in R parity violating SUSY [Butterworth, Ellis, Raklev, Salam]

2009 boosted $t \to 3$ jets from top partners [TP, Salam, Spannowsky, Takeuchi]

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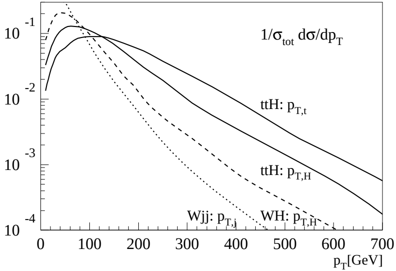
Boosted Higgs

Hadronic Higgs decays [Butterworth, Davison, Rubin, Salam]

– S: large m_{bb}, boost-dependent R_{bb}
  B: large m_{bb} only for large R_{bb}
  S/B: large m_{bb} and small R_{bb}, so boosted Higgs

– fat Higgs jet $R_{bb} \sim 2m_H/p_T < 1$



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$\Rightarrow$ challenge to jet algorithms [$pp \to WH/ZH$]

	σ_S/fb	σ_B/fb	$S/\sqrt{B}_{30}$
C/A, $R = 1.2$, MD-F	0.57	0.51	4.4
$k_\perp$, $R = 1.0$, y_{cut}	0.19	0.74	1.2
SISCone, $R = 0.8$	0.49	1.33	2.3

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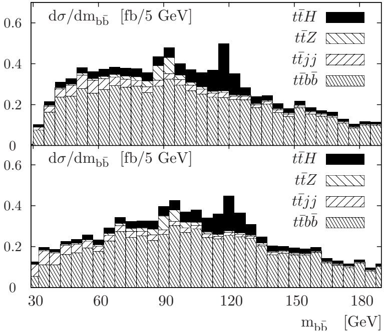
Higgs tag plus top tag [TP, Salam, Spannowsky]

- $t\bar{t}H$ thought dead for many reasons
- tag top and tag Higgs
  trigger on lepton
  that's pretty much it!
- side bin in continuum $t\bar{t}b\bar{b}$
- promising for 100 fb^{-1}

$\Rightarrow$ SUSY applications?



Boosted top

Highly boosted top quarks [Kaplan, Rehermann, Schwartz, Tweedie; Princeton, Seattle...]

– identify hadronic tops with $p_T \gtrsim 800$ GeV
isolation and b tagging challenging

– C/A algorithm with p_T drop criterion
all top decay jets identified
3 kinematic constraints: $m_W, m_t, \cos\theta_{\text{hel}}$ [no b tag]

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Standard Model: HEPTopTagger [TP, Salam, Spannowsky, Takeuchi]

- extend lower $p_T \gtrsim 250$ GeV
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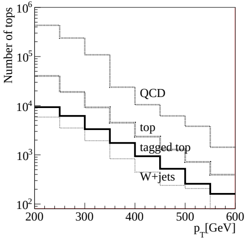

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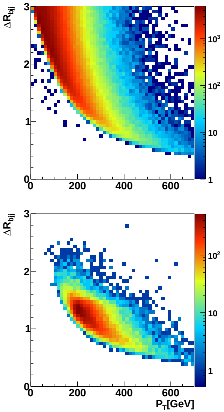

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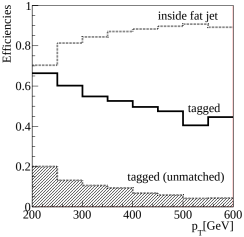
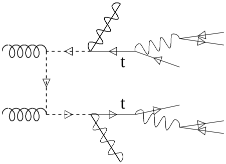
– top reconstruction possible

– first tests by ATLAS [Kasieczka & Schätzel]

– hadronic top like tagged b



Stops

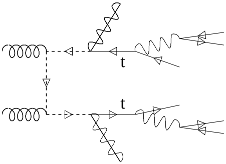


Stop pairs [TP, Spannowsky, Takeuchi, Zerwas]

- stop most important particle for hierarchy problem comparison to other top partners [Meade & Reece]
- dark matter means difficult semi-leptonic channel
- purely hadronic: $\tilde{t}\tilde{t}^* \to t\tilde{\chi}_1^0\ \bar{t}\tilde{\chi}_1^0$ [CMS TDR: leptons as spontaneous life guards]

events in 1 fb^{-1}	$\tilde{t}_1\tilde{t}_1^*$						$t\bar{t}$	QCD	W+jets	Z+jets	S/B	$S/\sqrt{B}_{10\ \text{fb}^{-1}}$
$m_{\tilde{t}}$ [GeV]	340	390	440	490	540	640					340	
$p_{T,j} > 200$ GeV, ℓ veto	728	447	292	187	124	46	87850	$2.4 \cdot 10^7$	$1.6 \cdot 10^5$	n/a	$3.0 \cdot 10^{-5}$	
$\not{E}_T > 150$ GeV	283	234	184	133	93	35	2245	$2.4 \cdot 10^5$	1710	2240	$1.2 \cdot 10^{-3}$	
first top tag	100	91	75	57	42	15	743	7590	90	114	$1.2 \cdot 10^{-2}$	
second top tag	15	12.4	11	8.4	6.3	2.3	32	129	5.7	1.4	$8.3 \cdot 10^{-2}$	
b tag	8.7	7.4	6.3	5.0	3.8	1.4	19	2.6	$\lesssim 0.2$	$\lesssim 0.05$	0.40	5.9
$m_{T2} > 250$ GeV	4.3	5.0	4.9	4.2	3.2	1.2	4.2	$\lesssim 0.6$	$\lesssim 0.1$	$\lesssim 0.03$	0.88	6.1

Stops



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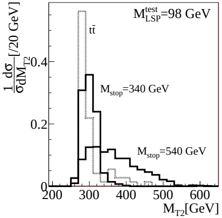
- stop mass from m_{T2} endpoint [like sleptons or sbottoms]
- not even a hard analysis



Model parameters

From kinematics to weak–scale parameters

– parameters: weak-scale Lagrangian

– measurements: kinematics,
production or decay rates,...
flavor, dark matter, electroweak constraints,...

– errors: general correlation, statistics & systematics & theory

– problem in grid: no local maximum
problem in fit: no global maximum
problem in interpretation: secondary maxima

Probability maps of new physics

– want to evaluate probability of model being true $p(m|d)$

– can compute likelihood map $p(d|m)$ over m

– Bayesian: $p(m|d) \sim p(d|m)\, p(m)$ with theorists' bias $p(m)$ [cosmology, BSM]
frequentist: best–fitting point $\max_m p(d|m)$ [flavor, Higgs]

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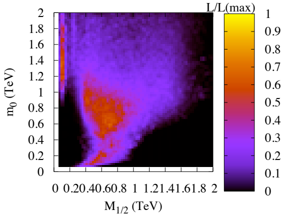
Bayesian probabilities vs profile likelihood [Allanach, Cranmer, Lester, Weber]

– ‘Which is the most likely parameter point?’

– ‘How does dark matter annihilate/couple?’

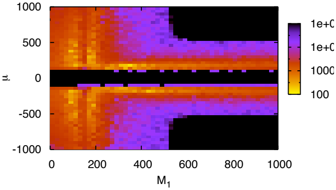
⇒ discussions about ‘scientific’ childish!



SUSY parameters

MSSM map for LHC [SFitter: Lafaye, TP, Rauch, Zerwas; Fittino]

– four neutralinos with (diagonal) mass parameters M_1, M_2, μ
– three of four mass-eigenstate neutralinos observed
– alternative solutions in parameter space



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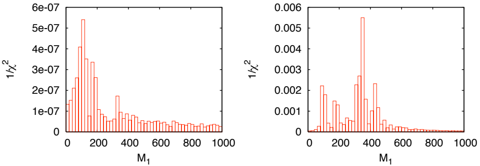

– quality of fit not useful: all the same...

	$\mu < 0$				$\mu > 0$			
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
$M_{\tilde{\mu}_L}$	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
$A_t\,(-)$	-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

$\Rightarrow$ let's try to not miss too many particles... [stop pairs]

Testing a GUT

Renormalization group analysis [Adams, Kneur, Lafaye, TP, Rauch, Zerwas; SFitter+SuSpect]

– are all mass parameters defined at high scales? [tachyonic solutions]
  do they unify?
  where is the GUT scale?
  what are the unified fudamental parameters?

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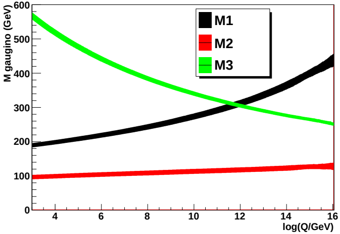
Starting from LHC results

– measuring $m_{1/2}$: 8-fold degeneracy solved [modulo sign of μ]



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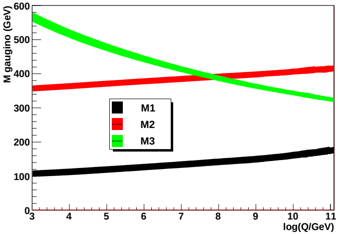

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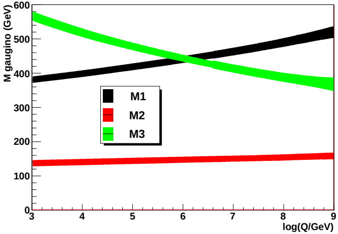

Testing a GUT

Renormalization group analysis [Adams, Kneur, Lafaye, TP, Rauch, Zerwas; SFitter+SuSpect]

– are all mass parameters defined at high scales? [tachyonic solutions]
  do they unify?
  where is the GUT scale?
  what are the unified fudamental parameters?

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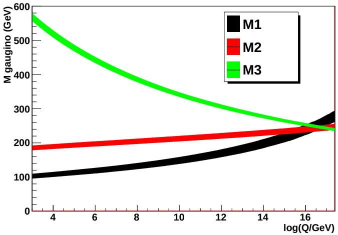

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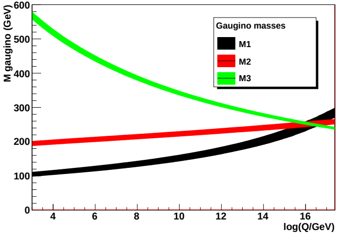

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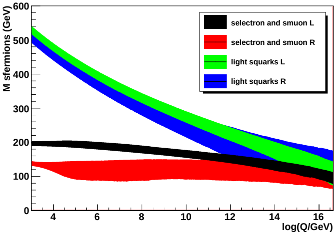

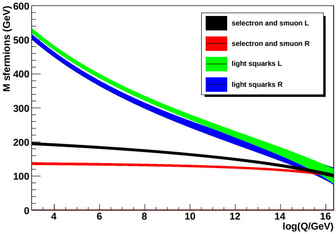

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– measured high-scale masses

	$\Delta m_{\text{top-down}}$	$\Delta m_{\text{bottom-up}}$	$\log M_{\text{GUT}}/\text{GeV}$
$m_{1/2} = 250$ GeV	2.5	5.9	16.23±0.29
$m_0 = 100$ GeV	2.0	10.5	16.5±0.6

$\Rightarrow$ one more aspects to better do right

New physics at the LHC

New physics at the TeV scale

– there is physics beyond our Standard Model

– Higgs and new physics the same question

Supersymmetry a well-studied example

– solves the hierarchy problem

– easily explains dark matter

– exciting LHC predictions

LHC more than 'discovery machine'

– anomalies first

– cascade decays rule

– jets can be useful

$\Rightarrow$ LHC to find and measure whatever there is

New physics at the LHC

	missing energy (p.89)	cascade decays (p.91)	mono-jets/photon (p.15)	lepton resnce (p.109)	di-jet resnce (p.109)	top resnce (p.120)	WW/ZZ resnce (p.15)	W' resnce (p.93)	top partner (p.116)	charged tracks (p.123)	displ. vertex (p.123)	multi-photons (p.29)	spherical events (p.47,76)
SUSY (heavy grav.) (p.17,26)	✓✓	✓✓							✓				
SUSY (light grav.) (p.17,27)	✓	✓	✓						✓	✓	✓		
large extra dim (p.39)	✓✓		✓✓										✓
universal extra dim (p.47)	✓✓	✓✓		✓	✓	✓	✓	✓	✓				
technicolor (vanilla) (p.51)				✓	✓	✓	✓	✓✓					
topcolor/top seesaw (p.53,54)					✓	✓✓	✓						
little Higgs (w/o T) (p.55,58)				✓	✓	✓	✓	✓					
little Higgs (w T) (p.55,58)	✓✓	✓✓	✓	✓	✓	✓	✓	✓	✓				
warped extra dim (IR SM) (p.61,63)				✓	✓	✓	✓						
warped extra dim (bulk SM) (p.61,64)				✓	✓	✓✓	✓	✓					
Higgsless/comp. Higgs (p.69,73)				✓	✓	✓✓	✓✓						
hidden valleys (p.75)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

[arXiv:0912.3259, Morrissey, TP, Tait]

Higgs tagger for $t\bar{t}H$ [TP, Salam, Spannowsky]

- uncluster one-by-one: $j \to j_1 + j_2$ [C/A algorithm, $R = 1.2$]
  1– mass drop: $m_{j_1} > 0.8 m_j$ means QCD; discard j_2
  2– soft $m_{j_1} < 30$ GeV means QCD; keep j_1
- double b tag [possibly add balance criterion]
  three leading $J = p_{T,1} p_{T,2} (\Delta R_{12})^4$ vs m_{bb}^{filt}
  no mass constraint — side bin
- jets everywhere; underlying event and pileup deadly
  filter reconstruction jets [Butterworth–Salam]
  decay plus one add'l jet at $R_{\text{filt}} \sim R_{jj}/2$
  reconstruct masses w/ QCD jet