Channels & Challenges – New Physics at LHC

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Carleton University, Ottawa

Southampton, 15. January 2007

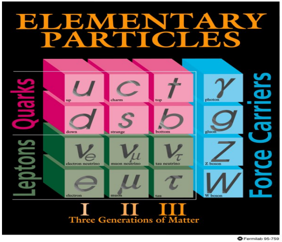
The success of the Standard Model

Standard Model describes microcosm

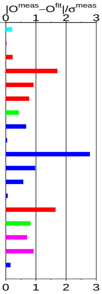
gauge interactions:

- strong
- electroweak broken to electromagnetic

Higgs mechanism



	Measurement	Fit
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02758 ± 0.00035	0.02766
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4957
σ^0_{had} [nb]	41.540 ± 0.037	41.477
R_l	20.767 ± 0.025	20.744
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01640
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1479
R_b	0.21629 ± 0.00066	0.21585
R_c	0.1721 ± 0.0030	0.1722
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1037
$A^{0,c}_{fb}$	0.0707 ± 0.0035	0.0741
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1479
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.392 ± 0.029	80.371
Γ_W [GeV]	2.147 ± 0.060	2.091
m_t [GeV]	171.4 ± 2.1	171.7



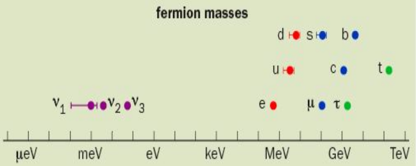
Standard Model tested better than 1 %

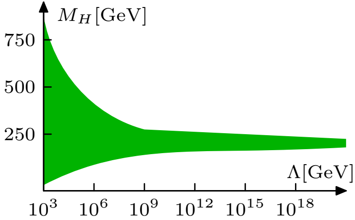
No significant deviations found since 1970s

Theory and Experiment agree

Why New Physics?

- Electroweak Symmetry Breaking, Higgs
- Dark Matter: $m_{DM} \sim 100\,\text{GeV}$
- 28 free parameters
- 3 families
- unification, gravity





Hierarchy/Fine-Tuning Problem

Quantum corrections to Higgs mass are sensitive for cut-off Λ

$$\delta M_H^2 \propto \Lambda^2$$

10000 GeV^2 = (10000000000000000000000000010000 –

10000000000000000000000000000000) GeV^2

Protective Symmetry ?

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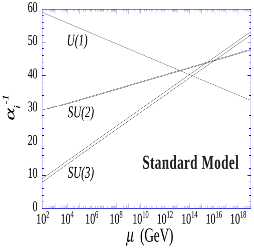

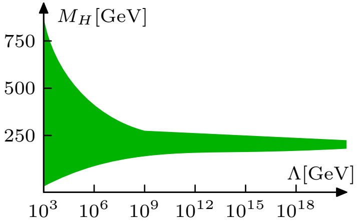

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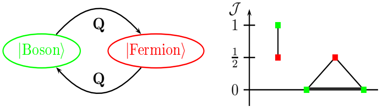
Protective Symmetry ?

Supersymmetry

Spin-statistics: Corrections from bosons and fermions cancel

connects gauge and space-time symmetries



multiplets of equal-mass fermions & bosons ⇒ SUSY broken

M_H protected to all orders

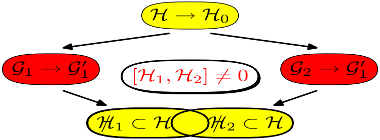
embedded in grand unified theory

R-parity: dark matter

Little Higgs

Global symmetries: Corrections from like-statistics particles cancel

Higgs: Goldstone-Boson of spontan. broken global symmetry



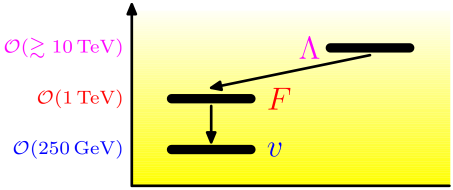
collective breaking of global symmetries protects Higgs mass

M_H protected at first order

strongly interacting @10 TeV

T-parity: dark matter

Characteristics of Standard Model Extensions

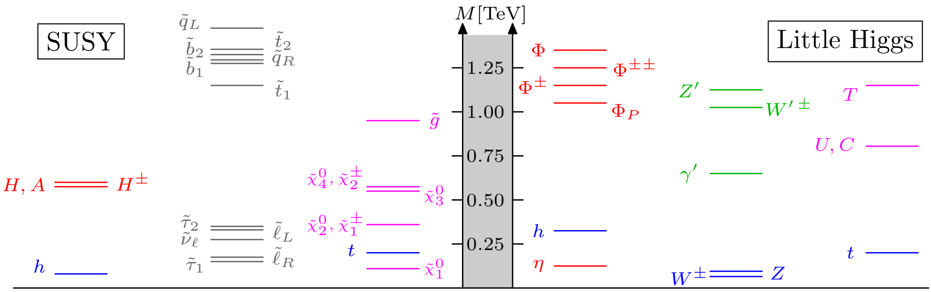


Scale Λ: "hidden sector", symmetry breaking

Scale F: new particles

Scale v: Higgs, W/Z, $\ell^\pm$, ...

Rich spectrum of new particles @ Terascale, complicated decay structures



Constraints on new models?

Flavour structure: Meson mixing & rare decay modes, CP violation

Astrophysical constraints: relic abundance

Gauge structure: electroweak precision observables

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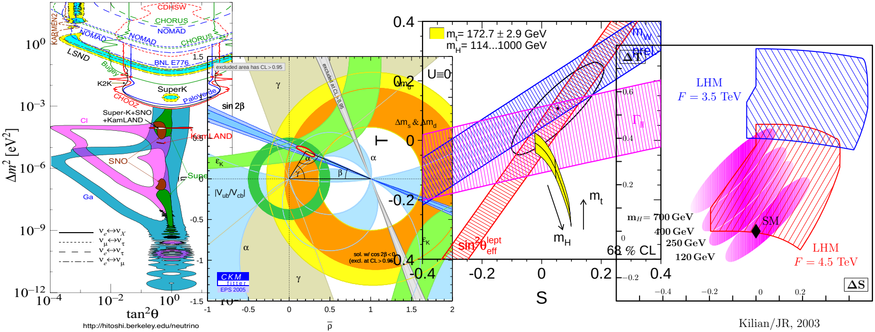
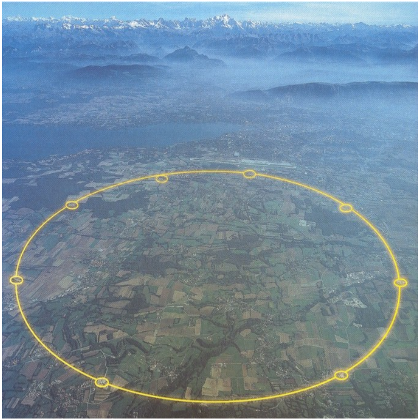


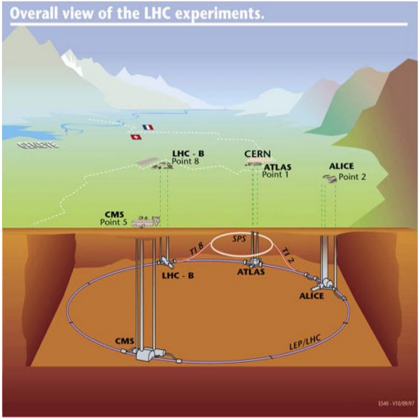
New particle scale $F \gtrsim 1 - 3$ TeV

Direct Searches: Large Hadron Collider

LHC @ CERN: from 2007/08

pp collider $\sqrt{s} = 14$ TeV

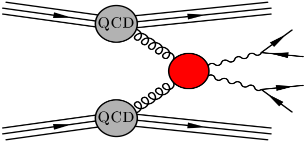


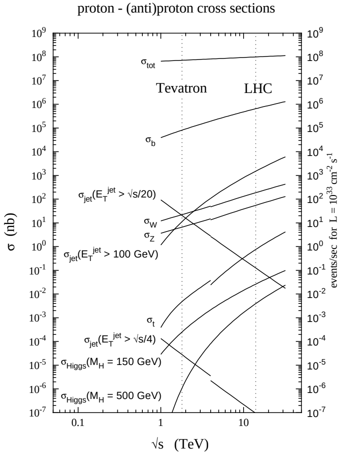


The Challenge of LHC

Partonic subprocesses: qq, qg, gg

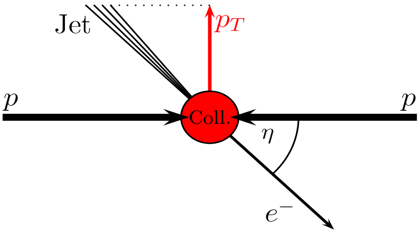
No fixed partonic energy





High event rates for t, W/Z, H, $\Rightarrow$ **huge backgrounds**

Cuts for background reduction



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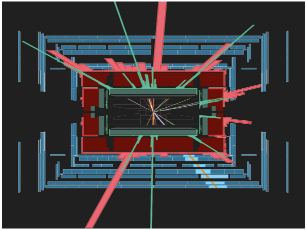

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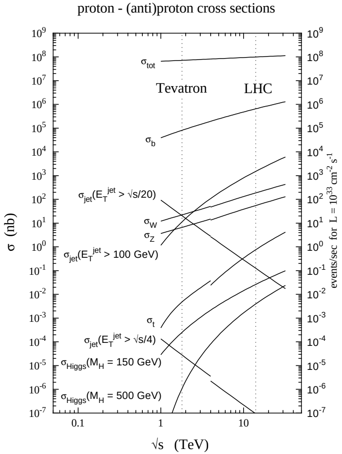

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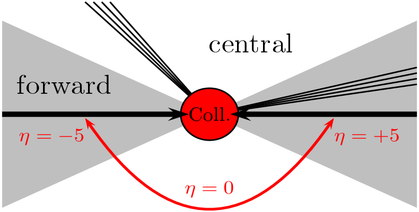
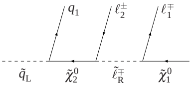
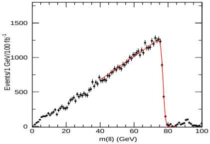


New Physics: Observables/Precision Measurements

Signals for New Physics:
$\not{E}_T$, high-p_T jets, many hard leptons,
but: Which model?





– Cascade decays: mass differences from endpoints of decay spectra
– Spin of new particles: Angular distribution, . . .
– Determining the model: Measurement of coupling constants

⇒ Precise prediction for signal and background

- Consideration of cuts
  Distributions: $d\sigma/dX$, $X = \cos\theta, \eta, p_T, \ldots$
- Multi-particle final states: $2 \to 4$ bis $2 \to 10$
- Quantum corrections: real and virtual

Simulations: O'Mega Ω / Whizard

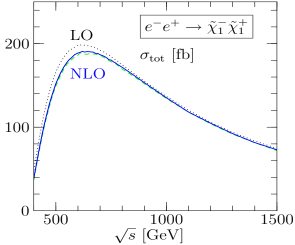
Matrix Element Generator O'Mega: Ohl, 2000/01; M.Moretti/Ohl/JR, 2001

Multi-purpose Event Generator Whizard: Ohl, 1996; Kilian, 2000; Kilian/Ohl/JR, 2007

- Multi-Channel adaptive Monte-Carlo integration
- very well tested JR et al., 2006; Hagiwara/. . . /Krauss/Plehn/JR/. . . , 2006
- Virtual Corrections: NLO Monte Carlo

NLO MC for $e^+e^- \to \tilde\chi_1^+\tilde\chi_1^-$ Kilian/JR/Robens, 2006

Arbitrary distributions @ NLO



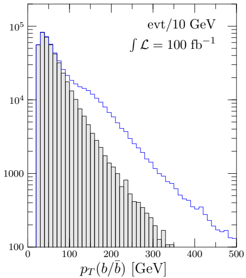
Sbottom production at LHC

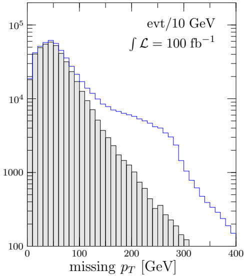
Hagiwara/.../JR/..., 2006

$\tilde{b}_1$ production with subsequent decay $\tilde{b}_1 \to \tilde{\chi}^0_1 b$

Process $A_1 A_2 \to P^{(*)} \to F_1 F_2$, 3 different levels:

Narrow Width	$\sigma(A_1A_2 \to P) \times \mathrm{BR}(P \to F_1F_2)$
Breit-Wigner	$\sigma(A_1A_2 \to P) \times \frac{M_P^2 \Gamma_P^2}{(s-M_P^2)^2+\Gamma_P^2 M_P^2} \times \mathrm{BR}(P \to F_1F_2)$
Full matrix element	$\sigma(A_1A_2 \to F_1F_2)$





$pp \to b\bar{b}\tilde{\chi}^0_1\tilde{\chi}^0_1$

Main background:

$gg \to b\bar{b}\nu\bar{\nu}$

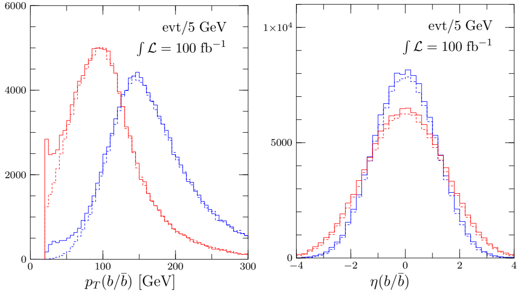
Signal jets harder

Off-Shell effects at LHC:

PS: Harder jet more central

Off-Shell effects ($b\bar{b}Z^*$): only for low $p_{T,b}$ $\longrightarrow$ is cut out

Not generally guaranteed



Prozeß	$\sigma\times$ BR [fb]	σ_{BW} [fb]	$\sigma_{\text{BW}}^{\text{cut}}$ [fb]
Zh	1.342	1.335	0.009
HA	0.320	0.314	0.003
$\tilde{\chi}_1^0\tilde{\chi}_2^0$	13.078	13.954	0.458
$\tilde{\chi}_1^0\tilde{\chi}_3^0$	3.675	4.828	0.454
$\tilde{\chi}_1^0\tilde{\chi}_4^0$	0.061	0.938	0.937
$\tilde{b}_1\tilde{b}_1^*$	0.759	0.757	0.451
Sum	**19.238**	**22.129**	**2.314**
Exact		**19.624**	**0.487**

ILC:

$e^+e^- \longrightarrow b\bar{b}\tilde{\chi}_1^0\tilde{\chi}_1^0$ [800 GeV]

Cuts for $M_{b\bar{b}}$ eliminate other resonances

Real corrections: bottom-jet radiation

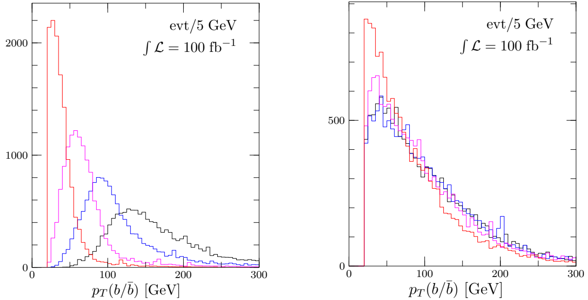
K. Hagiwara/.../JR/..., 2006

$g \to b\bar{b}$-splitting, b-ISR als combinatorial background

$pp \to \tilde{\chi}_1^0\tilde{\chi}_1^0 b\bar{b}b\bar{b}$: 32112 diagrams, 22 color flows, $\sim$ 4000 PS channels

$\sigma(pp \to b\bar{b}\tilde{\chi}_1^0\tilde{\chi}_1^0) = 1177\,\text{fb} \quad \longrightarrow \quad \sigma(pp \to b\bar{b}b\bar{b}\tilde{\chi}_1^0\tilde{\chi}_1^0) = 130.7\,\text{fb}$

Forward discrimination between ISR and decay-b jets difficult:



Only the most forward b jet considerably softer

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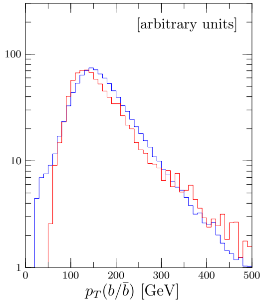
Only minor differences in $p_{T,b}$, PDF: maximum for smaller value



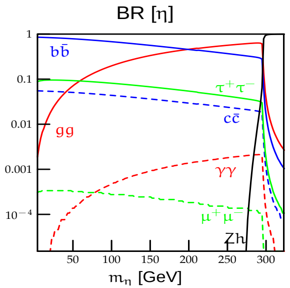
shifted to smaller $\not{p}_T$: light particles balance out the event

What if not SUSY?

Pseudo-Axions in Little Higgs

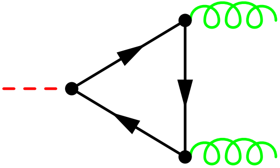
Kilian/Rainwater/JR, 2004, 2006; JR, 2007

- gauged $U(1)$ group: Z' $\longleftrightarrow$ ungauged: η
- couples to fermions like a pseudoscalar
- $m_\eta \lesssim$ 400 GeV
- SM singlet, couplings to SM particles v/F suppressed



- η axion-like particle:

Anomalous $U(1)$:



$\longrightarrow \quad \frac{1}{F}\frac{\alpha_s}{8\pi^2}\eta F_{\mu\nu}F_{\rho\sigma}\epsilon^{\mu\nu\rho\sigma}$

- $U(1)$ explicitly broken $\Rightarrow$ Axion limits from astroparticle physics not applicable

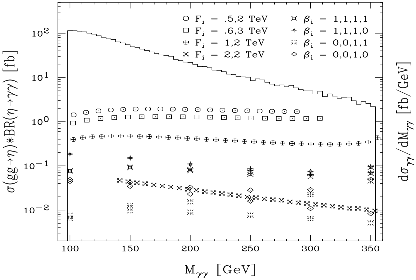
The Glimpse of a Discovery

Kilian/Rainwater/JR, 2004, 2006

LHC: Gluon fusion, diphoton signal für $m_\eta \gtrsim 200\,\text{GeV}$, 7σ possible

LHC: $T \to t\eta$ Godfrey/Rainwater/JR

ILC: $e^+e^- \to t\bar{t}\eta$



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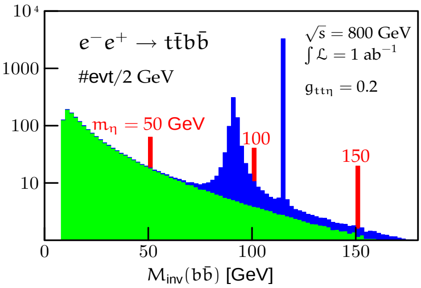

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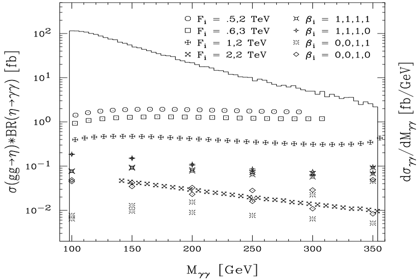

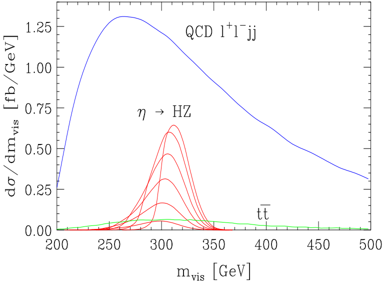

$ZH\eta$ coupling

forbidden in Product Group Models

Discriminator of diff. model classes

$$gg \to \left\{ \begin{array}{ll} H \to Z\eta & \to \ell\ell bb \\ \eta \to ZH & \to \ell\ell bb, \ell\ell\ell jj \end{array} \right\}$$

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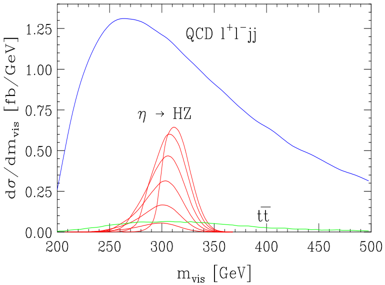

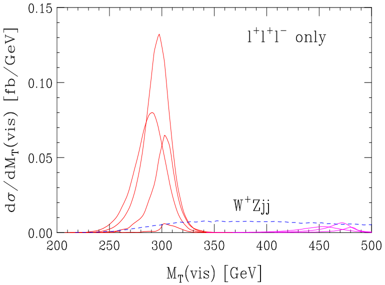

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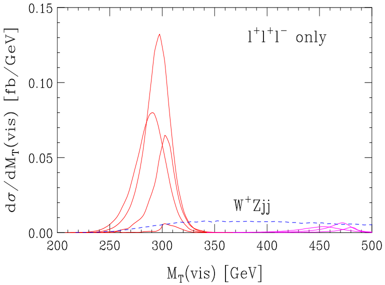

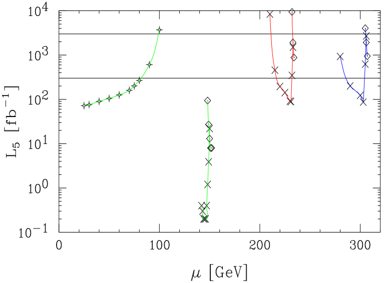

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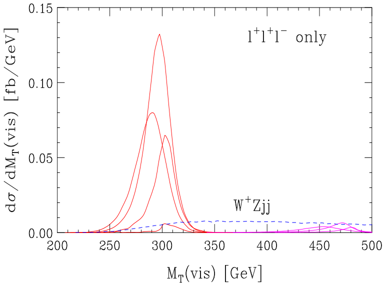

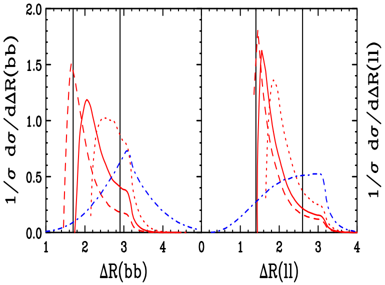

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Outlook

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- Higgs mechanism
- New particles, symmetries: SUSY, Little Higgs
- Pheno:
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- Exciting times ahead!

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- Higgs mechanism
- New particles, symmetries: SUSY, Little Higgs
- Pheno:
  precision calculations/simulations of multi-particle final states
- Exciting times ahead!
- There is light
  at the end of the tunnel!

Ideas for New Physics since 1970

(1) **New Ingredients**

– Technicolour: Higgs a bound state of strongly-interacting particles

(2) **Symmetries for cancellation of quantum corrections**

– Supersymmetry: Spin-statistics $\Rightarrow$ corrections from bosons and fermions cancel each other
– Little Higgs models: Global symmetries $\Rightarrow$ corrections from like-statistics particles cancel each other

(3) **Nontrivial Space-time structure eliminates hierarchy**

– Additional space dimensions: gravity appears only week
– Noncommutative space-time: coarse-grained space-time

(4) **Ignoring the Hierarchy**

– Anthropic Principle: parameters have their values, *because* we (can) measure them

Constraints on new models?

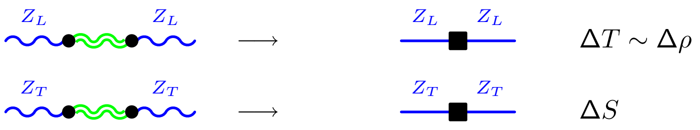
Flavour structure: K, D, B mixing, rare K, D, B decay modes

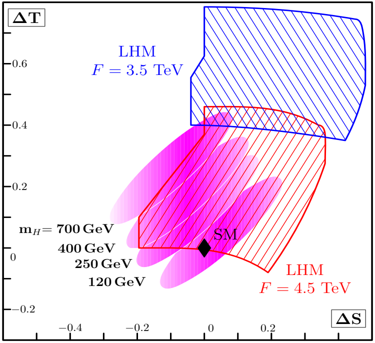
CP violation: CP asymmetries, electric dipole moments

Astrophysical constraints: relic abundance

Gauge structure: electroweak precision observables

Constraints on new models?





Kilian/JR, 2003

Tree-Level mixing Z, Z' induces big corrections

Scale $F \gtrsim 1 - 3$ TeV

Higgs compensates for Z'

Naturally heavy Higgs in Little Higgs Models

Kilian/JR, 2003

Tests and Checks: Example MSSM

JR et al., 2005; K. Hagiwara/W. Kilian/F. Krauss/T. Ohl/T. Plehn/D. Rainwater/JR/S. Schumann, 2006

– MSSM: spectrum doubled, 100 parameters, 5000 vertices

$\Rightarrow$ **Implementation enforces tests and consistency checks**

– Unitarity check: $\sigma(2 \to 2, s), \sigma(2 \to 3, s) \sim const$ or $1/s$ ✓

– Gauge invariance: Ward- and Slavnov-Taylor identities ✓

– Supersymmetry: Ward-/Slavnov-Taylor identities ✓ JR, 2002; Ohl/JR, 2002

– Comparison of independent codes ($\mathcal{O}(600)$ processes): JR et al., 2005; K. Hagiwara/.../JR/..., 2006

Reference: http://www-ttp.physik.uni-karlsruhe.de/~reuter/susy_comparison.html

$ff \to X$							
Process	stat.	Madgraph/Helas 0.5 TeV	Madgraph/Helas 2 TeV	Whizard/O'Mega 0.5 TeV	Whizard/O'Mega 2 TeV	Sherpa/A'Megic 0.5 TeV	Sherpa/A'Megic 2 TeV
$uu \to \tilde{u}_L \tilde{u}_L$	●	—	716.9(1)	—	716.973(4)	—	716.99(4)
$uu \to \tilde{u}_R \tilde{u}_R$	●	—	679.6(1)	—	679.627(4)	—	679.54(4)
$uu \to \tilde{u}_L \tilde{u}_R$	●	—	1212.52(6)	—	1212.52(5)	—	1212.60(6)
$dd \to \tilde{d}_L \tilde{d}_L$	●	—	712.6(1)	—	712.668(4)	—	712.68(4)
$dd \to \tilde{d}_R \tilde{d}_R$	●	—	667.4(1)	—	667.448(4)	—	667.38(3)
$dd \to \tilde{d}_L \tilde{d}_R$	●	—	1206.22(6)	—	1206.22(5)	—	1206.30(7)

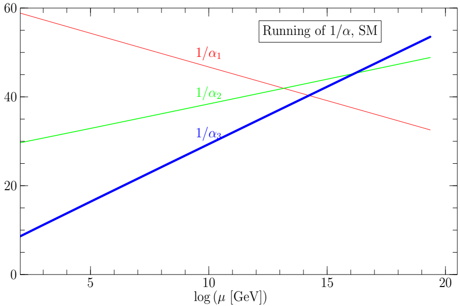
SUSY Exotics at LHC

Gauge couplings run: $\frac{dg_a}{d\log\mu} = \frac{g_a^3}{16\pi^2} B_a$, B_a depends on field content

Sparticles make couplings unify

e.g.: $SU(5) \to SU(3)_c \times SU(2)_w \times U(1)_Y$

Doublet-triplet splitting problem: Proton decay by Higgs partner D



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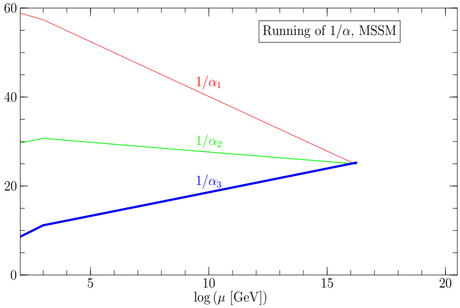
Dqq, $D\ell q$



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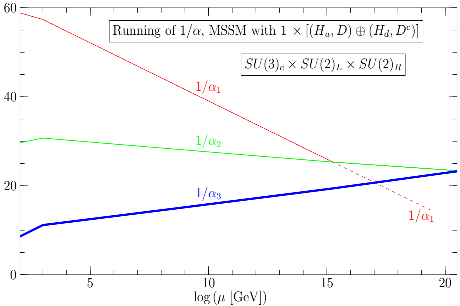

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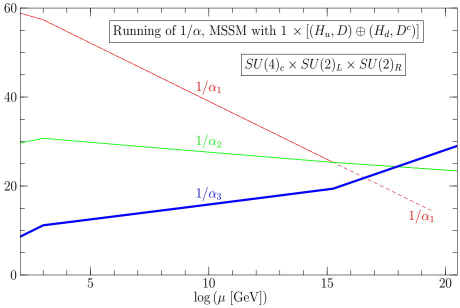

Kilian/JR, 2006

Extended MSSM Higgs sector

- relaxed Higgs bounds (light pseudoscalars)
- possibly large invisible decay ratio
- lightest unhiggs: H parity protected dark matter
- dark matter mix: interesting relic abundance (relaxes all neutralino bounds!)
- Pair production of unhiggses/unhiggsinos, cascade decays

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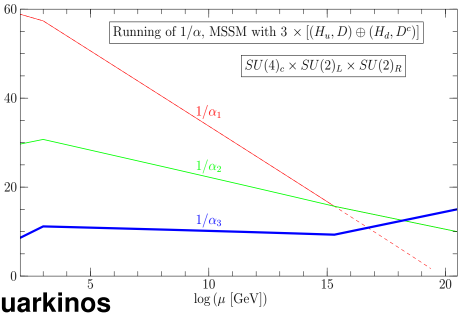

(Down-type) **Leptoquarks, Leptoquarkinos**

- 3 generations at TeV scale
- produced in gluon fusion, single production
- final states: $t\tau, b\nu_\tau, \tilde{t}\tau, \ldots$
- if flavor symmetry leaves traces: $gq \to D\ell$ enhanced, decays $t\mu, te$

Extended neutralino sector like in NMSSM