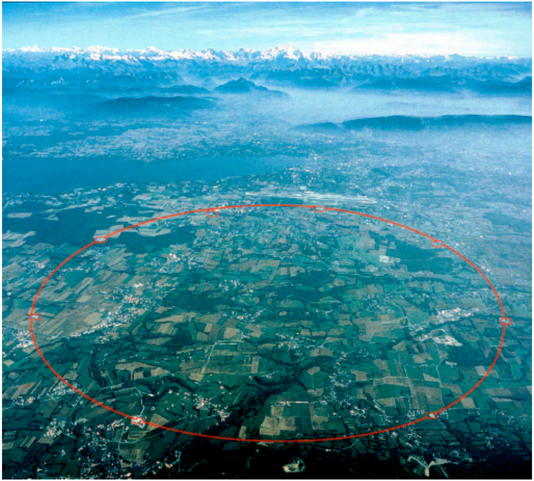
Outline

The LHC

LHC — Large Hadron Collider: starting Summer 20XX



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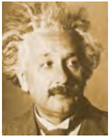

– Einstein: beam energy to particle mass $E = mc^2$
  smash 7 TeV protons onto 7 TeV protons [energy unit GeV: proton mass]
  produce anything that couples to quarks and gluons
  search for it in decay products
  repeat every 25 ns

– huge detectors, computers, analysis... $\longrightarrow$ experimental particle physics
  prejudice, fun and smart comments... $\longrightarrow$ theoretical particle physics

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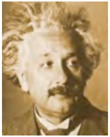

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life as an experimentalist

life as a theorist

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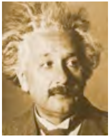

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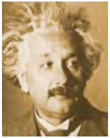

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Everything you always wanted to know...

– Atlas/CMS: measure anything flying around

– signal: everything new, exciting and rare
  background: yesterday's signal

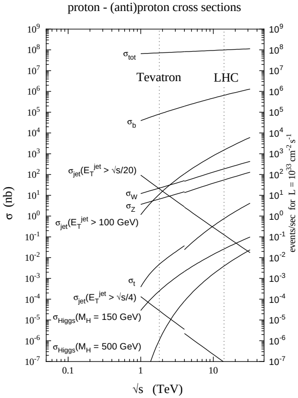
– Standard Model: theory of background
  QCD: evil background theory trying to kill us

– $N_{\text{events}} = \sigma \cdot \mathcal{L}$ ['cross section times luminosity']

– trigger: soft jets — not on tape

– jet: everything except for leptons/photons
  crucial: what is inside a jet [q, g, b, τ tagged?]

– discovery $N_S/\sqrt{N_B} > 5$

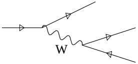


Standard–Model effective theory

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

– 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

– Yukawa 1935: massive particle exchange
  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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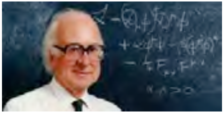

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  fundamental scalar below TeV

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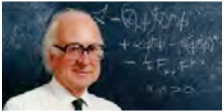

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  unitarity for massive W, Z
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– 't Hooft & Veltman 1971: renormalizability
  beware of $1/M$ couplings
  gauge theories without cut-off
  truly fundamental theory

⇒ 35 years later — no sign of weakness...

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 $\mathcal{L} \sim -m_W^2 W_\mu W^\mu - m_f \overline{\psi}\psi + gH\overline{\psi}\psi \overset{?}{+} \dfrac{g}{M} HW_{\mu\nu}W^{\mu\nu}$

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

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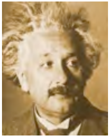

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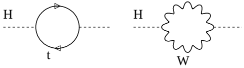
And how complete experimentally?

- dark matter? [solid evidence for low–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?]
- gauge coupling unification real?
- gravity missing? [mostly negligible but definitely unrenormalizaby]

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

$\Rightarrow$ who the hell cares???

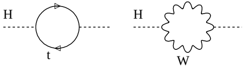
Standard–Model effective theory



Theorists care!!

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

Standard–Model effective theory



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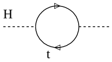
...and watch the field–theory desaster unfold

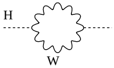
$$m_H^2 \longrightarrow m_H^2 - \frac{g^2}{(4\pi)^2} \, \frac{3}{2} \, \frac{\Lambda^2}{m_W^2} \left[m_H^2 + 2m_W^2 + m_Z^2 - 4m_t^2 \right] + \cdots$$

– Higgs mass pulled to physical cut-off Λ [where Higgs at Λ is not a Higgs]

$\Rightarrow$ hierarchy problem — Higgs without stabilization incomplete

Standard–Model effective theory





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Starting from data which...

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

– easy solution: counter term — but gauge theories don't do tuning

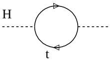
– or new physics at TeV scale: supersymmetry
extra dimensions
little Higgs
composite Higgs, TopColor [wish they were gone...]
YourFavoriteNewPhysics...

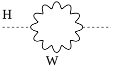
$\Rightarrow$ typically cancellation by new particles or discussing away high scale

$\Rightarrow$ beautiful concepts, but problematic in reality

$\Rightarrow$ TeV–scale models in baroque state

Standard–Model effective theory





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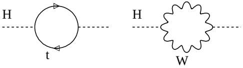
Expectations from the LHC

– find light Higgs?

– find new physics stabilizing Higgs mass?

– see dark–matter candidate?

Example: TeV–scale supersymmetry



Supersymmetry

– partner for each Standard–Model particle

– SUSY obviously broken by masses, mechanism unknown

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

scalars — m_0 fermions — $m_{1/2}$ tri-scalar — A_0 Higgs sector — sign(μ), tan β

– assume dark matter, stable lightest partner

⇒ measure BSM spectrum with missing energy at LHC

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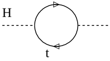

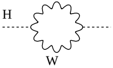

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LHC searches: MSSM

– conjugate Higgs field not allowed
$\rightarrow$ give mass to t and b?
$\rightarrow$ five Higgs bosons

– SUSY–Higgs alone interesting

$\Rightarrow$ would be another talk...

$\Rightarrow$ list of SUSY partners

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

Supersymmetric signatures

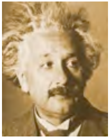
New physics at the LHC

(1) discovery — signals for new physics

(2) measurements — spectrum, quantum numbers

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

$\Rightarrow$ approach independent of new physics model



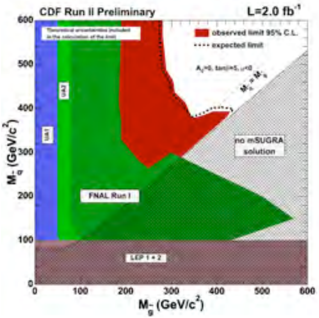
Special about LHC, except bigger than Tevatron

– beyond inclusive searches [that was Tevatron]
lots of strongly interacting particles
cascade decays to DM candidate

– general theme: try to survive QCD

– rates not good in $\alpha_s/(4\pi) \sim 0.01$
(collinear) jets everywhere
good LHC observables needed

$\Rightarrow$ aim at underlying theory



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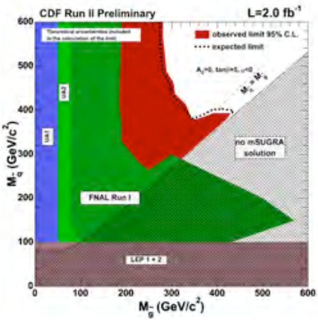

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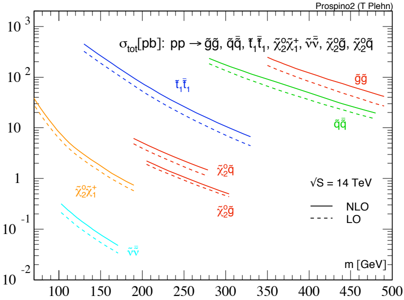

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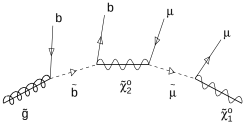


Spectra from cascade decays

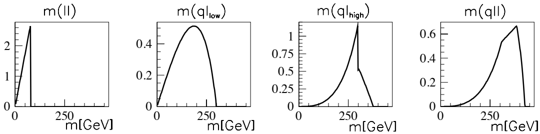
- more than 10^7 squark–gluino events
- thresholds & edges

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

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

- the longer decay chain the better

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



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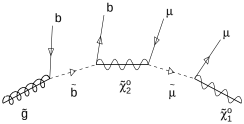

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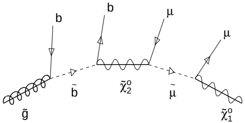

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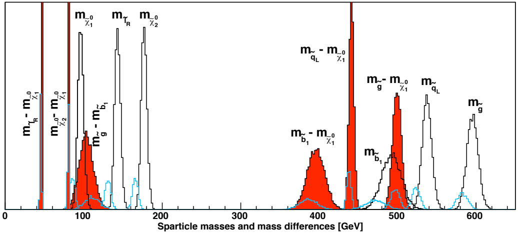
Cascade masses from kinematics

- all decay jets *b* quarks [otherwise dead by QCD]
- gluino mass to $\sim 1\%$

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



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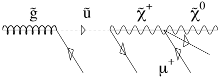
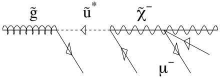


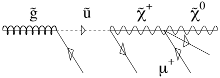


When do I believe it's SUSY–QCD?

- 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

New physics measurements



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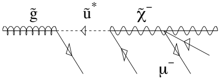

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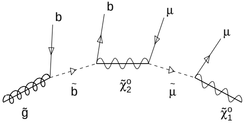


All new physics is hypothesis testing

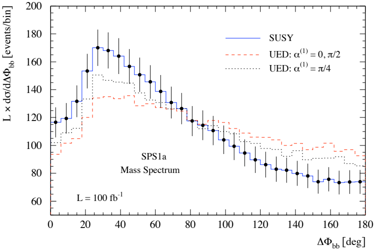
– loop hole: 'gluino is Majorana if it is a fermion'

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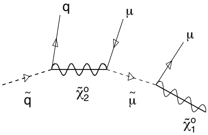
⇒ gluino = like–sign dileptons in SUSY–like events

Asymmetries

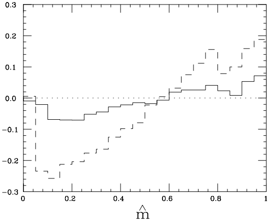


– shorter sqark decay chain
– shape between endpoints: $\hat{m} = m_{q\mu}/m_{q\mu}^{\max} \sim \sin\theta/2$
– dominant $pp \to \tilde{q}\tilde{g}$ with $\tilde{q} : \tilde{q}^* \sim 2 : 1$
– production asymmetry with reduced errors

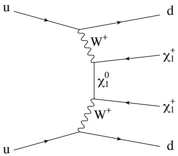
$$\mathcal{A}(m_{\mu j}) = \frac{\sigma(j\mu^+) - \sigma(j\mu^-)}{\sigma(j\mu^+) + \sigma(j\mu^-)}$$

– kind of similar for gluino decay

⇒ gluino = fermion with like-sign dileptons



Weak boson fusion



Illustrating useful jets: spin of LSP

- Majorana LSP with like-sign charginos?
- hypotheses: like–sign charginos (SUSY)
  like–sign scalars (scalar dark matter)
  like–sign vector bosons (little–Higgs inspired)
- chargino decay/kinematics not used
- want to bet we can tell them apart just using the jets?

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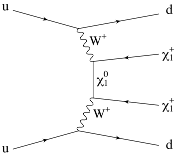

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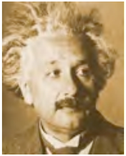


Weak boson fusion

Like-sign scalars or fermions?

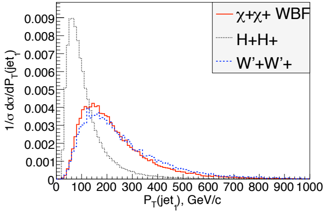
– charged Higgs in 2HDM

– H^+H^- same as simple 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 with softer $p_{T,j}$



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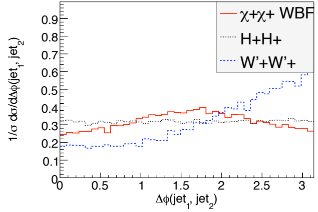

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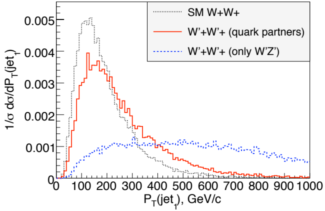
Or else...

- nightmare: strongly interacting WW



Fundamental parameters

From kinematics to weak–scale parameters

– parameters: weak-scale Lagrangian

– measurements: better edges than masses,
branching fractions, rates,...
flavor, dark matter, electroweak constraints,...

– errors: general correlation, statistics & systematics & theory

– problem in grid: huge phase space, no local maximum?
problem in fit: domain walls, no global maximum?
problem in interpretation: bad observables, secondary maxima?

Probability maps of new physics

– want probability of model being true $p(m|d)$
have exclusive 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]

– getting rid of parameters: integration vs projection

– LHC era: (1) compute high-dimensional map $p(d|m)$
(2) find and rank local best-fitting points
(3) predict additional observables

Markov chains

Define set of representative points in new–physics space

– measure of ‘representative’: likely to agree with data [Markov chain]

– evaluate any function over chain

(1) probability to agree with data

(2) Higgs mass from LEP and DM relic density
LHC rates from LEP and DM relic density
dark matter detection from LEP and/or LHC
dates of birth of people on shift...

⇒ anything goes

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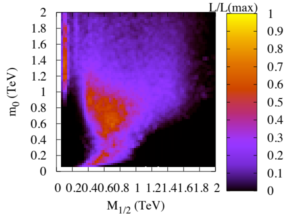
Bayesian probabilities vs profile likelihood

– ‘Which is the most likely parameter point?’

– ‘How does dark matter annihilate/couple?’



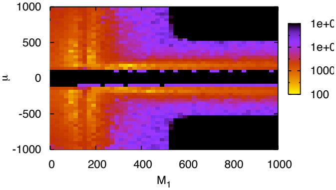
Fundamental parameters

MSSM map for LHC

– 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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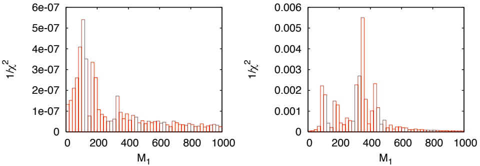

– quality of fit not useful: all the same...

	$\mu < 0$				$\mu > 0$			
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...

Beyond the LHC

Why theorists involved?

- want to learn statistics
- know about theory errors
- know about link with other observations and models

Beyond the LHC

- remember: unknown sign(μ), believe–based $\tan\beta$ from m_h

(1) maybe it's new physics: $(g-2)_\mu \sim \tan\beta$

- strongly correlated and promising

	LHC	LHC $\otimes(g-2)$	SPS1a
$\tan\beta$	**10.0± 4.5**	**10.3± 2.0**	**10.0**
M_1	102.1± 7.8	102.7± 5.9	103.1
M_2	193.3± 7.8	193.2± 5.8	192.9
M_3	577.2±14.5	578.2± 12.1	577.9
$M_{\tilde{\mu}_L}$	193.2± 8.8	194.0± 6.8	194.4
$M_{\tilde{q}3_L}$	481.4±22.0	485.6± 22.4	480.8
$M_{\tilde{b}_R}$	501.7±17.9	499.2± 19.3	502.9
μ	350.5±14.5	352.5± 10.8	353.7

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– prediction of f_{B_s} missing

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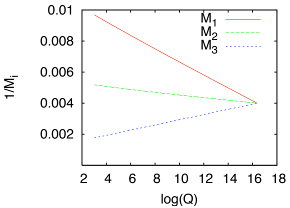
Renormalization group analysis

– SUSY breaking, unification, GUT?
– scale-invariant sum rules?



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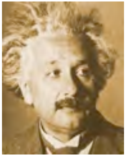
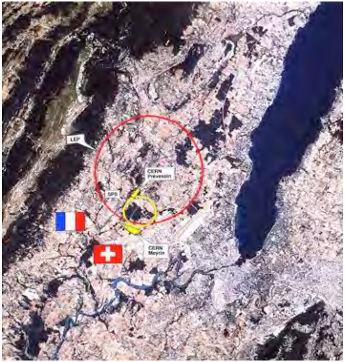
– scale-invariant sum rules?
⇒ fundamental theory at all scales — happy neighbors!



New physics at the LHC



Need for new physics

- there is physics beyond Standard Model
- Higgs and new physics the same question
- LHC should find and study it

Supersymmetry one well-studied example

- solves the hierarchy problem
- easily explains dark matter
- cascade decays rule
- LHC to determine underlying model

LHC not only the biggest, but also the coolest machine!