Fun Physics at LHC

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Pizzanacht, 4/2009

Outline

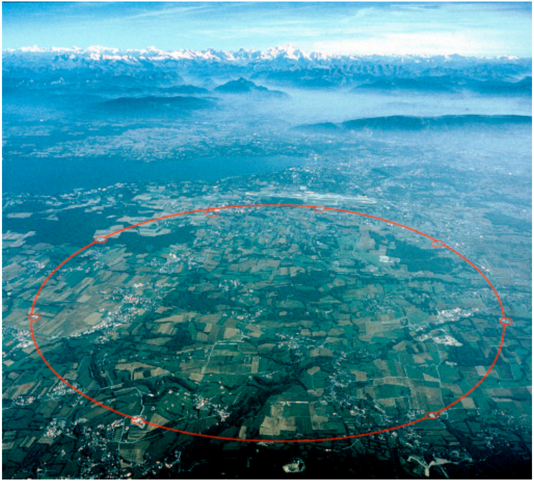
The LHC

Standard–Model effective theory

Example projects

The LHC

LHC — Large Hadron Collider: starting Summer 20XX



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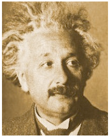

– Einstein: beam energy to particle mass $E = mc^2$
  smash 7 TeV protons onto 7 TeV protons [energy unit GeV: proton mass]
  produce anything that couples to quarks and gluons
  search for it in decay products
  repeat every 25 ns

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

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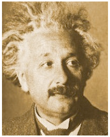

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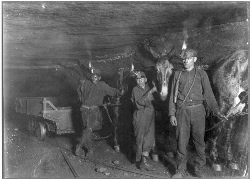

life as a theorist

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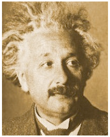

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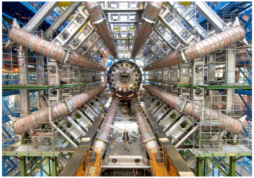

life as a theorist

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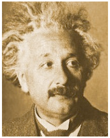

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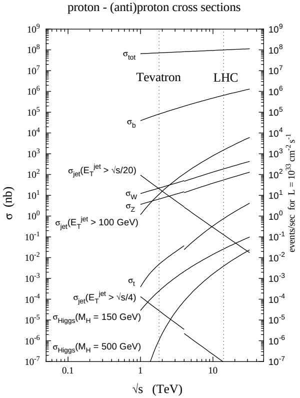
Everything you always wanted to know...

- 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 $N_S/\sqrt{N_B} > 5$



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Why BSM?

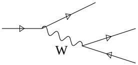
Example projects

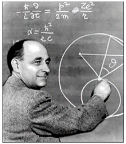
Standard–Model effective theory

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
  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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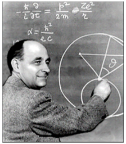

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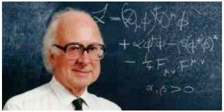

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  unitarity for massive W, Z
  unitarity for massive fermions
  fundamental scalar below TeV

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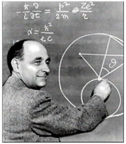

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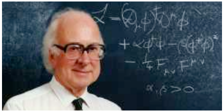

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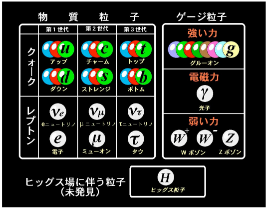
– 't Hooft & Veltman 1971: renormalizability
  beware of $1/M$ in the Lagrangian!
  gauge theories without cut-off
  truly fundamental theory

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

Standard–Model effective theory

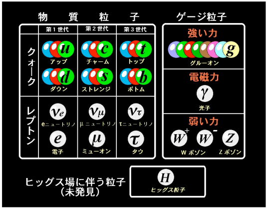


What is the Standard Model?

- 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]
- Dirac fermions in doublets with masses = Yukawas
  generation mixing in quark and neutrino sector
- renormalizability $\mathcal{L} \sim -m_W^2 W_\mu W^\mu - m_f \overline{\Psi}\Psi + gH\overline{\Psi}\Psi \overset{?}{+} gHW_{\mu\nu}W^{\mu\nu}/M$

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

Standard–Model effective theory



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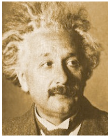
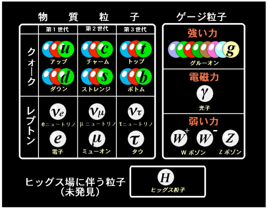


Standard–Model effective theory



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

And how complete is it 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?]

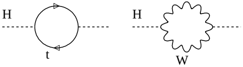
– gauge coupling unification real?

– gravity missing? [mostly negligible but definitely unrenormalizaby]

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

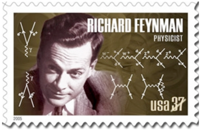
$\Rightarrow$ who the hell cares???

Standard–Model effective theory



Theorists care!!

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



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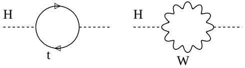

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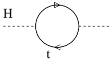
– Heisenberg: compute quantum corrections to Higgs mass...
...and watch the field–theory desaster unfold

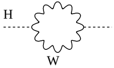
$$m_H^2 \longrightarrow m_H^2 - \frac{g^2}{(4\pi)^2}\,\frac{3}{2}\,\frac{\Lambda^2}{m_W^2}\left[m_H^2 + 2m_W^2 + m_Z^2 - 4m_t^2\right] + \cdots$$

– Higgs mass pulled to cut-off Λ [where Higgs at Λ does not work]

$\Rightarrow$ hierarchy problem — Higgs without stabilization incomplete

Standard–Model effective theory





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⇒ hierarchy problem — Higgs without stabilization incomplete

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

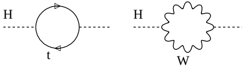
– or new physics at TeV scale: supersymmetry
extra dimensions
little Higgs
composite Higgs, TopColor [wish they were gone...]
YourFavoriteNewPhysics...

⇒ typically cancellation by new particles or discussing away high scale

⇒ beautiful concepts, but problematic in reality

⇒ 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?

$\Rightarrow$ let's go through a few fun projects...

Supersymmetry searches

Supersymmetry

– partner for each Standard–Model particle

– SUSY obviously broken by masses, mechanism unknown

– assume dark matter, stable lightest partner

$\Rightarrow$ find signals with missing energy at LHC

Special about LHC, except bigger than Tevatron

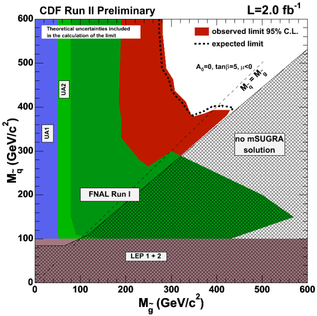
– beyond inclusive searches [that was Tevatron]
lots of strongly interacting particles
cascade decays to DM candidate

– general theme: try to survive QCD

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

– predict and simulate SUSY@LHC

$\Rightarrow$ aim at underlying theory



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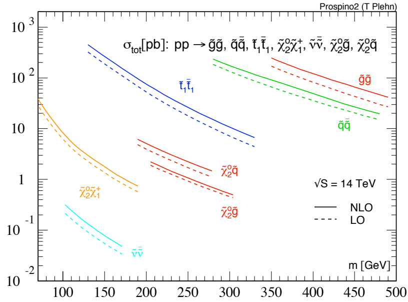
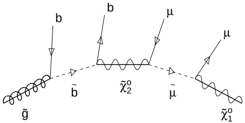


Masses and quantum numbers



Spectra from cascade decays

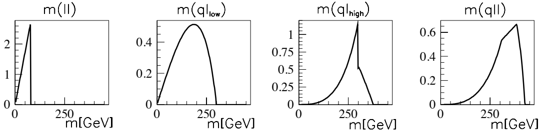
– more than 10^7 squark–gluino events

– thresholds & edges

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

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

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



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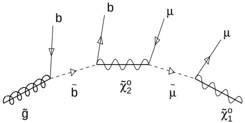

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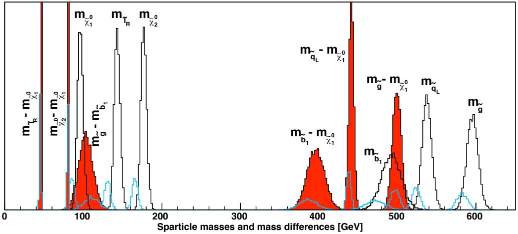
⇒ new–physics mass spectrum from cascade decays

Cascade masses from kinematics

– gluino mass to $\sim 1\%$

⇒ what's more in m_{ij}?



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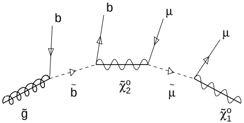

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Cascade masses from kinematics

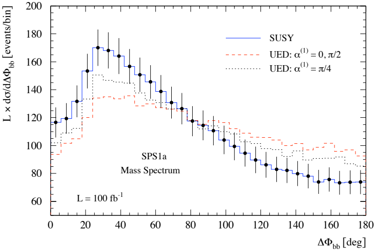
– gluino mass to $\sim 1\%$

⇒ what's more in m_{ij}?

– gluino really Majorana fermion?

– compare with bosonic 'gluino': universal extra dimensions

⇒ distinguish UV completions



Fundamental parameters

From LHC data to weak–scale parameters

– parameters: weak-scale Lagrangian

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

– errors: statistics & systematics & theory

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

Probability maps of new physics

– want 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]

$\Rightarrow$ complete picture of BSM and Higgs sectors

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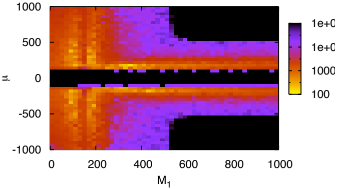
– neutralinos with mass parameters M_1, M_2, μ
three of four observed

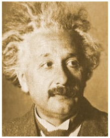
– alternative solutions in parameter space

– combination with $\Omega_h, (g-2)_\mu$?

$\Rightarrow$ complete picture of BSM and Higgs sectors



Quantum gravity



Again solving the hierarchy problem

- weak gravity = large Planck scale $G_N \sim 1/M^2_{\text{Planck}}$
- Einstein–Hilbert action in $4+n$ dimensions

$$\int d^4x \sqrt{|g|}\, M^2_{\text{Planck}} R \to \int d^{4+n}x \sqrt{|g|}\, M_*^{2+n} R = (2\pi r)^n \int d^4x \sqrt{|g|}\, M_*^{2+n} R$$

$$M_{\text{Planck}} = M_* \;(2\pi r M_*)^{n/2} \gg M_* \sim 1\,\text{TeV}$$

$\Rightarrow$ fundamental Planck scale at TeV

UV regime of gravity

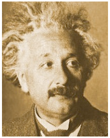
- Kaluza-Klein effective theory

$$(\Box + m_k^2)\; G^{(k)}_{\mu\nu} = -\frac{T_{\mu\nu}}{M_{\text{Planck}}} \qquad\qquad \delta m \sim \frac{1}{r} = 2\pi M_* \left(\frac{M_*}{M_{\text{Planck}}}\right)^{2/n} \lesssim 0.05\,\text{GeV}$$

- string theory: complete with Veneziano form factor

$$\mathcal{S}(s,t) = \frac{\Gamma(1-s/M_S^2)\,\Gamma(1-t/M_S^2)}{\Gamma(1-(s+t)/M_S^2)} = 1 - \frac{\pi^2}{6}\,\frac{st}{M_S^4} + \mathcal{O}\left(M_S^{-6}\right)$$

Quantum gravity



Again solving the hierarchy problem

- weak gravity = large Planck scale $G_N \sim 1/M_\text{Planck}^2$
- Einstein–Hilbert action in $4+n$ dimensions

$$\int d^4x \sqrt{|g|}\, M_\text{Planck}^2 R \to \int d^{4+n}x \sqrt{|g|}\, M_*^{2+n} R = (2\pi r)^n \int d^4x \sqrt{|g|}\, M_*^{2+n} R$$

$$M_\text{Planck} = M_* \; (2\pi r M_*)^{n/2} \gg M_* \sim 1 \text{ TeV}$$

$\Rightarrow$ fundamental Planck scale at TeV

UV regime of gravity

- Kaluza-Klein effective theory

$$(\Box + m_k^2)\; G_{\mu\nu}^{(k)} = -\frac{T_{\mu\nu}}{M_\text{Planck}} \qquad\qquad \delta m \sim \frac{1}{r} = 2\pi M_* \left(\frac{M_*}{M_\text{Planck}}\right)^{2/n} \lesssim 0.05 \text{ GeV}$$

- fixed-point gravity: complete by construction

$$P(s, m_k) = \begin{cases} \dfrac{1}{s + m_k^2} & \sqrt{s}, m_k < M_* \\ \dfrac{M_*^{n+2}}{(s+m_k^2)^{n/2+2}} & \sqrt{s}, m_k > M_* \end{cases}$$

$\Rightarrow$ probe UV completion of gravity