New Physics at the LHC

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University of Sussex, 9/2007

Outline

The LHC

Standard–Model effective theory

Example: TeV–scale supersymmetry

Supersymmetric signatures

New physics measurements

Fundamental parameters

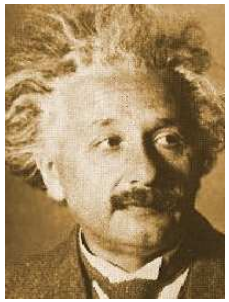
Example: large extra dimensions

Extra–dimensional signatures

The LHC

LHC — Large Hadron Collider: starting Summer 2008

The LHC



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

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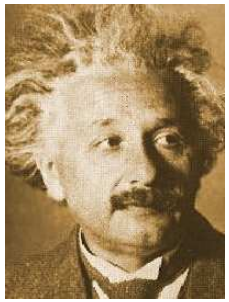

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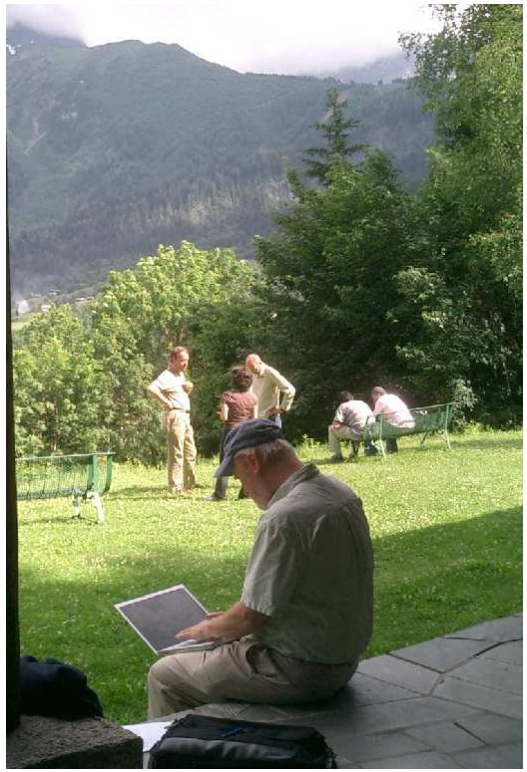
life as an experimentalist

life as a theorist



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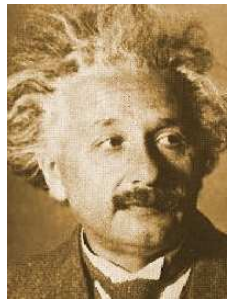

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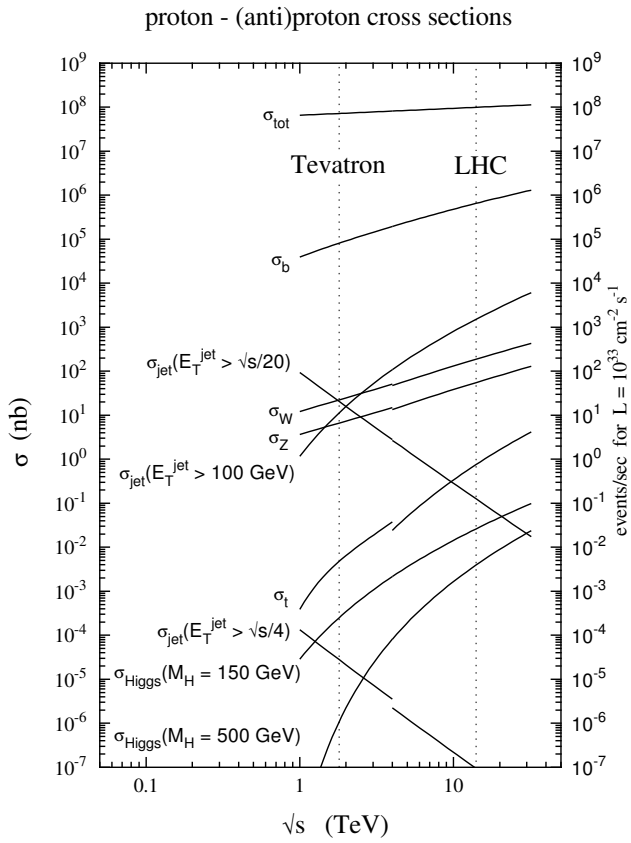
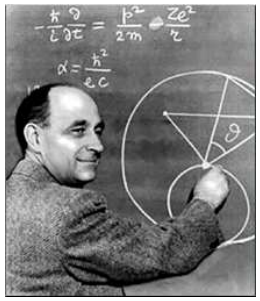
Everything you always wanted to know...

- signal: everything new, exciting and rare
  background: yesterday's signal
- Standard Model: theory of background
  QCD: evil background theory trying to kill us
- $N_{\text{events}} = \sigma \cdot \mathcal{L}$ ['cross section times luminosity']
- trigger: no leptons/photons — not on tape
- jet: everything except for leptons/photons
  crucial: 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...



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

- Yukawa 1935: massive particle exchange
  Fermi's theory for $E \ll M$
  four fermions unitary for $E \gg M$: $\mathcal{A} \propto g^2 E^2/(E^2 - M^2)$
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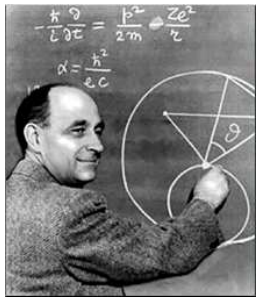

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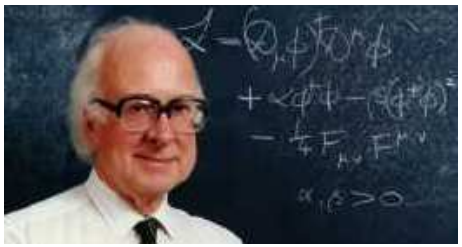

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  unitarity for massive W, Z
  unitarity for massive fermions
  fundamental scalar below TeV [mass unknown]

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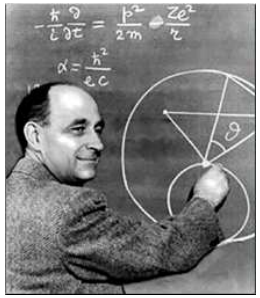

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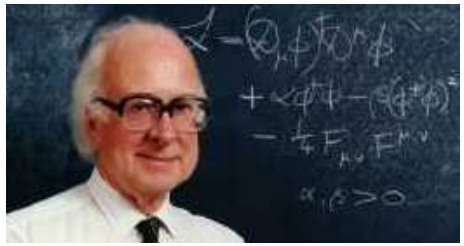

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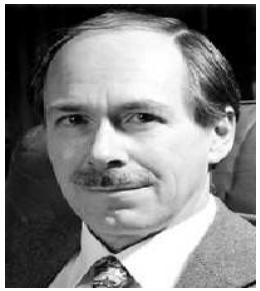
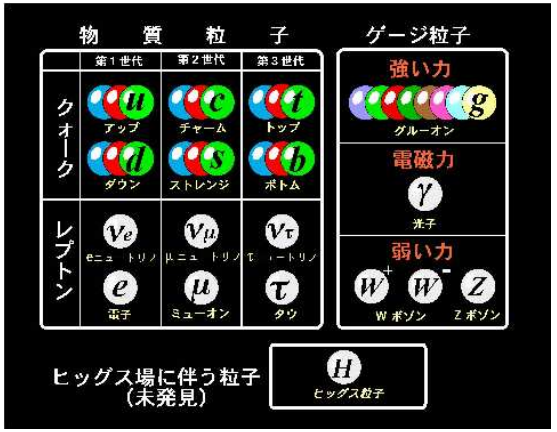


- 't Hooft & Veltman 1971: renormalizability
  beware of $1/M$ in the Lagrangian!
  gauge theories without cut-off
  truly fundamental theory

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

Standard–Model effective theory



What is the Standard Model?

- gauge theory with local $SU(3) \times SU(2) \times U(1)$
- massless $SU(3)$ and $U(1)$ gauge bosons
  massive W, Z bosons [Higgs mechanism with $v = 246$ GeV]
- Dirac fermions in doublets with masses = Yukawas
  generation mixing in quark and neutrino sector
- renormalizable Lagrangian a la 't Hooft [no 1/masses]

$\Rightarrow$ defined by particle content, interactions, renormalizability

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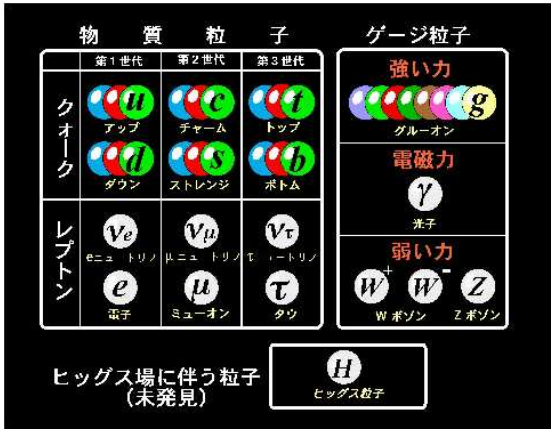

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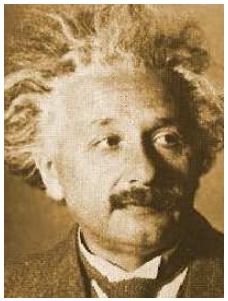

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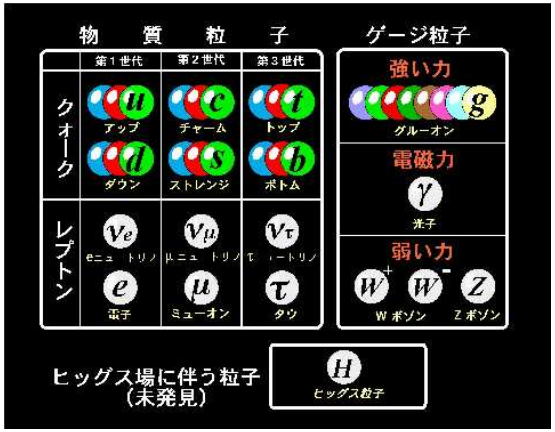

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And how complete is it experimentally?

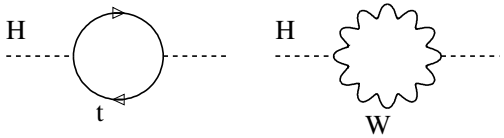
- neutrino masses and mixing? [see-saw at 10^{11} GeV?]
- quark mixing — flavor physics? [new operators above 10^4 GeV?]
- matter–antimatter asymmetry? [universe mostly matter?]
- dark matter? [solid evidence for low–scale new physics!?]
- gravity missing on list of forces? [mostly negligible but definitely unrenormalizaby]

$\Rightarrow$ renormalizable but experimentally incomplete

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

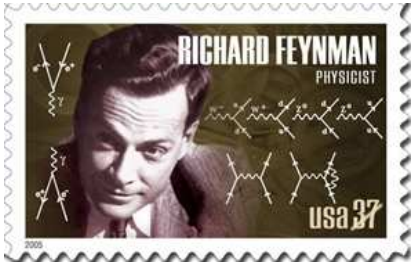
$\Rightarrow$ who the hell cares???

Standard–Model effective theory



Theorists care!!

– Heisenberg: compute quantum corrections to Higgs mass...



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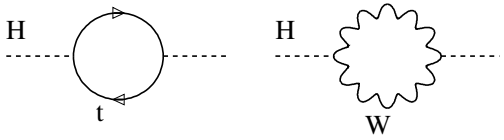

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- Heisenberg: compute quantum corrections to Higgs mass...
  ...and watch the field–theory desaster unfold

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

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

$\Rightarrow$ hierarchy problem — Standard Model destabilized between v and Λ

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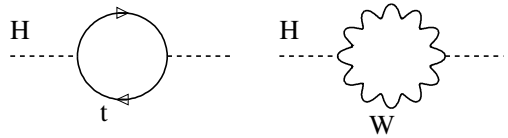

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Starting from data which...

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

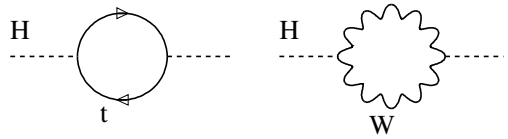
- easy solution: counter term to cancel loops $\Rightarrow$ artificial, unmotivated, ugly
- or new physics at TeV scale:
  supersymmetry [my favorite]
  extra dimensions [Daniel's and Stefan's favorite]
  little Higgs [nobody's favorite, too hard]
  composite Higgs, TopColor [wish they were gone...]
  YourFavoriteNewPhysics...

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

$\Rightarrow$ beautiful concepts, but problematic in reality [data seriously in the way]

$\Rightarrow$ TeV–scale models in baroque state

Example: TeV–scale supersymmetry



Supersymmetry

- give each Standard–Model particle a partner [with different spin]
- SUSY obviously broken by masses [soft breaking, 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

$\Rightarrow$ measure BSM spectrum with missing energy at LHC

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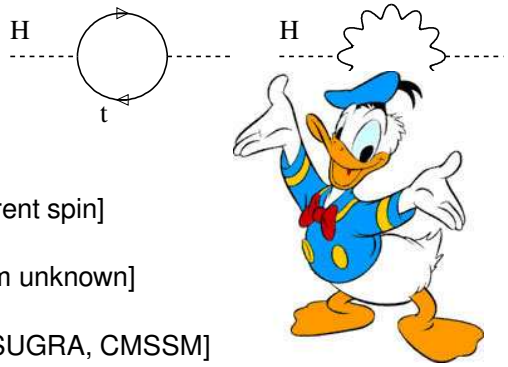

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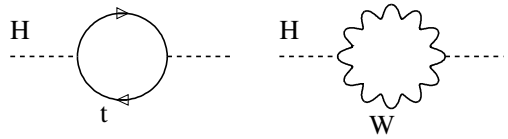

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LHC searches: MSSM

- conjugate Higgs field not allowed
  $\longrightarrow$ give mass to t and b?
  $\longrightarrow$ 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	
$\longrightarrow$ 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^0, H^0, A^0	0	3	
$\longrightarrow$ neutralinos	$\tilde{\chi}_i^0$	1/2	$4 \cdot 2$	LSP
gauge bosons	$W^\pm$	1	$2 \cdot 3$	
Higgs bosons	$H^\pm$	0	2	
$\longrightarrow$ charginos	$\tilde{\chi}_i^\pm$	1/2	$2 \cdot 4$	

Supersymmetric signatures

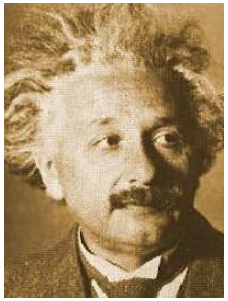
New physics at the LHC

(1) discovery — signals for new physics

(2) measurements — masses, cross sections, decays

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

$\Rightarrow$ approach independent of new physics model



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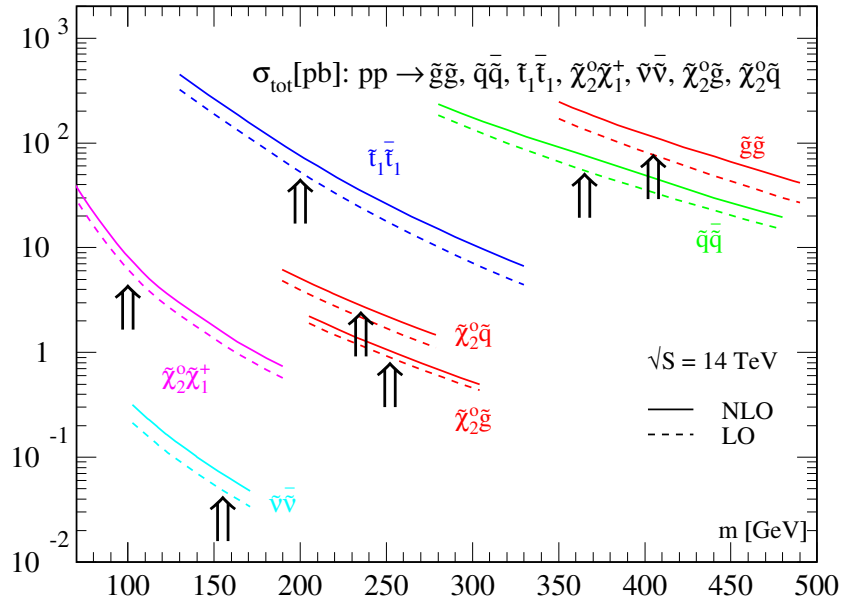
- like–sign dileptons: $pp \to \tilde{g}\tilde{g}$
- funny tops: $pp \to \tilde{t}_1 \tilde{t}_1^*$
- tri-leptons: $pp \to \tilde{\chi}_2^0 \tilde{\chi}_1^-$

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

$\Rightarrow$ plenty squarks and gluinos to study



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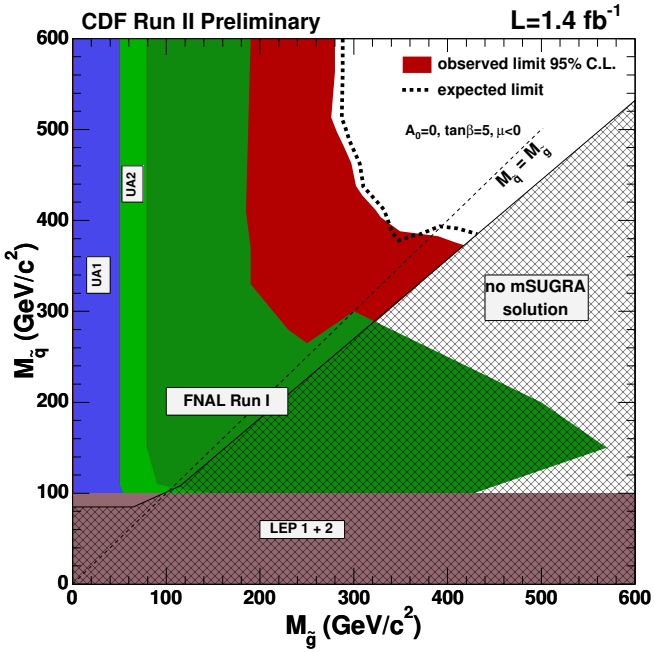
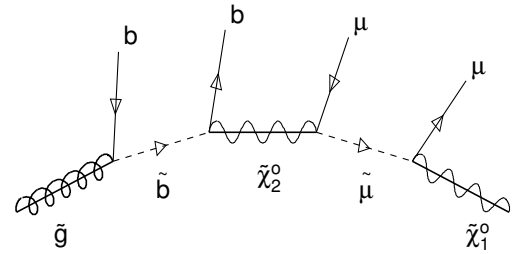


New physics measurements



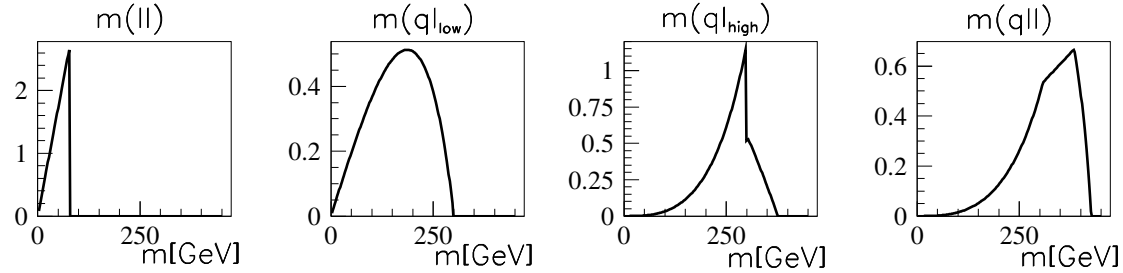
Spectra from cascade decays [Atlas, Cambridge-SUSY]

- more than 10^7 squark–gluino events
- target decay $\tilde{g} \to \tilde{b}\bar{b} \to \tilde{\chi}_2^0 b\bar{b} \to \mu^+\mu^- b\bar{b}\tilde{\chi}_1^0$
- thresholds & edges

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

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

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



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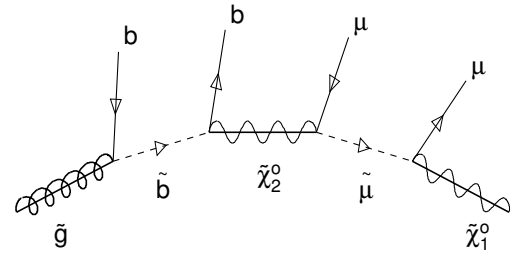

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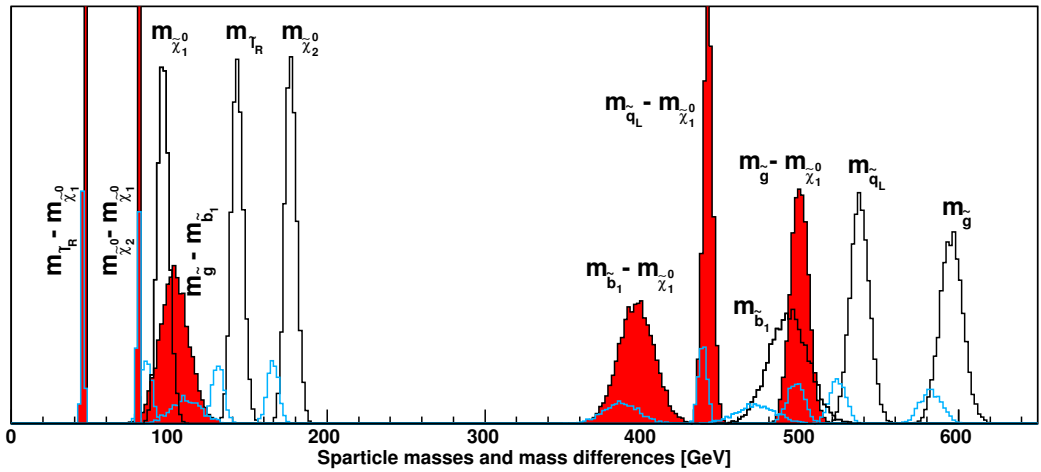
$\Rightarrow$ new–physics mass spectrum from cascade decays

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

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

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

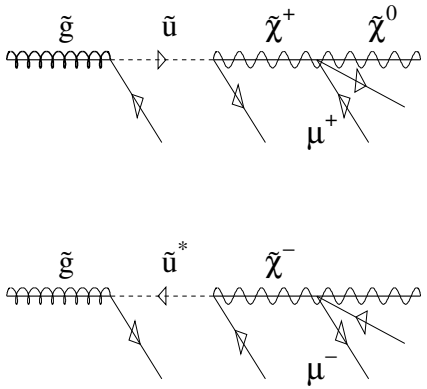


New physics measurements

When do I believe it's SUSY–QCD? [Barger,...; Barnett,...; Baer,...]

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

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



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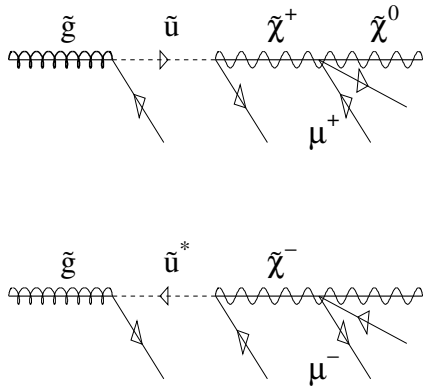
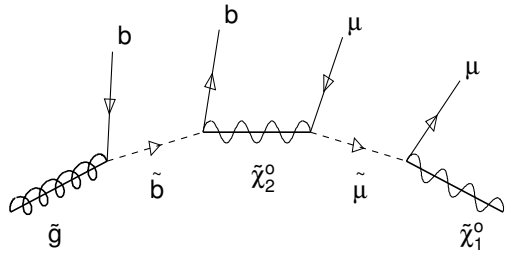


- gluinos: strongly interacting Majorana fermions
  Majorana = its own antiparticle
- first jet in gluino decay: q or $\bar{q}$
- final–state leptons with charges 50% – 50%

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

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



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

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

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

$\Rightarrow$ compare model predictions between threshold and edge

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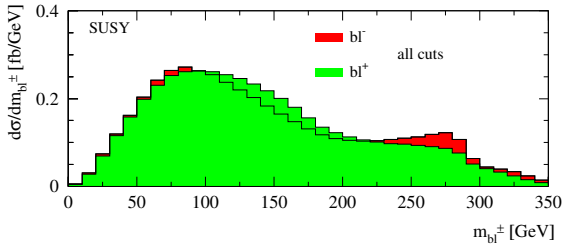
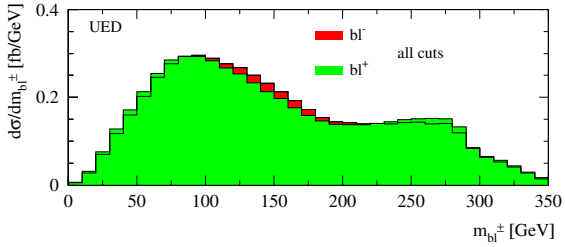




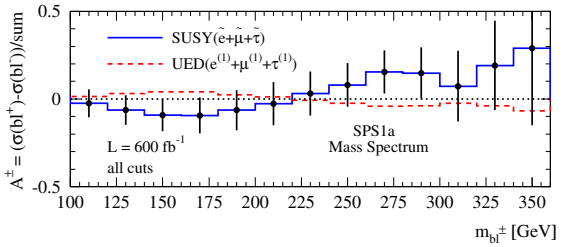
Gluino–bottom cascade [Sao Paulo; Cornell]

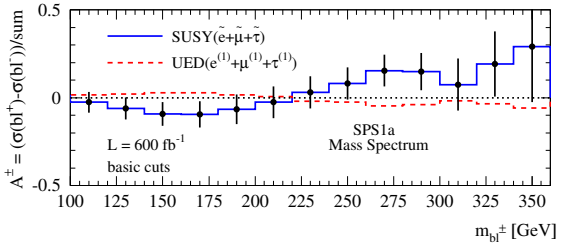
- decay chain like for gluino mass [simulated for SUSY]
- compare SUSY with excited g, q, Z, μ, γ
- shape below edge: $m_{b\mu}/m_{b\mu}^{\max} = \sin\theta/2$
- better: asymmetry b vs. $\bar{b}$ [independent of production]

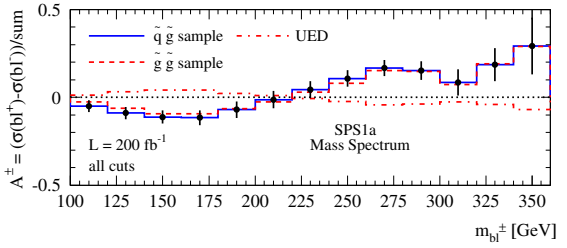
$$\mathcal{A}(m_{\mu b}) = \frac{\sigma(b\mu^+) - \sigma(b\mu^-)}{\sigma(b\mu^+) + \sigma(b\mu^-)}$$

- plus more observables... [still visible after cuts and smearing?]
- gluino spin from cascade decays

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





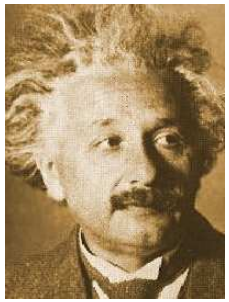


Fundamental parameters

New physics at the LHC

- parameters: weak-scale Lagrangian
- measurements: masses or edges
  branching fractions
  cross sections
  dark matter density, Planck, LEP,...
- errors: general correlation, statistics & systematics & theory

$\Rightarrow$ what is the underlying physics?



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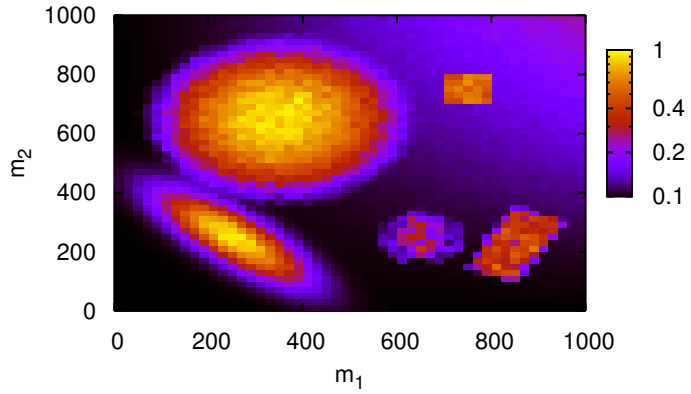
Probability maps of new physics [Baltz,...; Roszkowski,...; Allanach,...; SFitter]

- likelihood map $p(d|m)$ over model–parameter space m
- Bayes' theorem: $p(m|d) = p(d|m)\ p(m)/p(d)$
- Bayesian: theorist's prejudice $p(m|d)$ using $p(m)$
  frequentist: best–fitting point $\max_m p(d|m)$
- real problem: remove bad directions from $p(d|m)$
- challenge in LHC era: (1) compute map $p(m|d)$ of parameter space
  (2) find local maxima in $p(m|d)$
  (3) do your Bayesian/frequentist thing...

Fundamental parameters

Bayesian or frequentist?

- toy potential $V(\vec{x})$ in 5 dimensions [2 spheres, cigar, 2 cubes]
- best–fitting point: small sphere
  most likely scenatio: large sphere [water in spoon/cloud]



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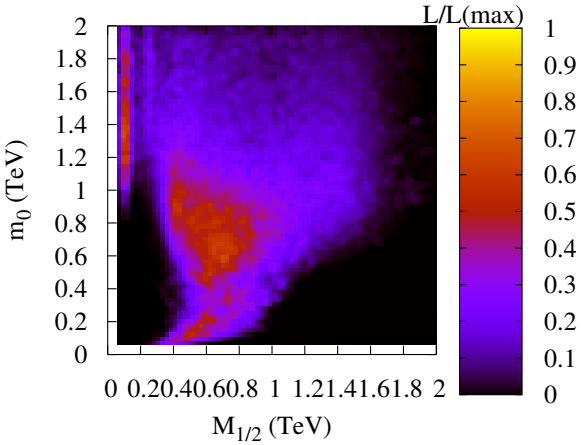
...

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

- 'Which is the most likely parameter point?'
- 'How does dark matter annihilate/couple?'



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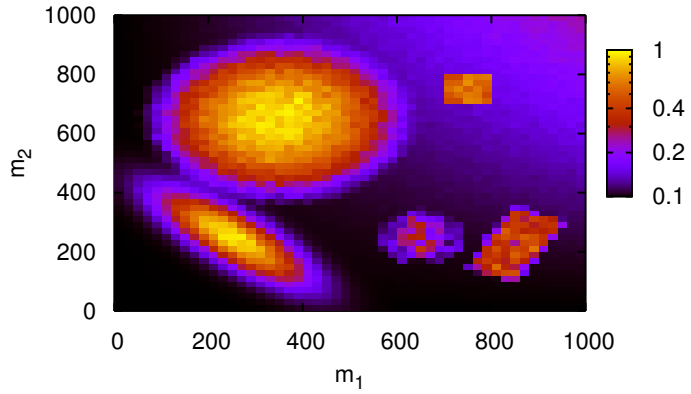

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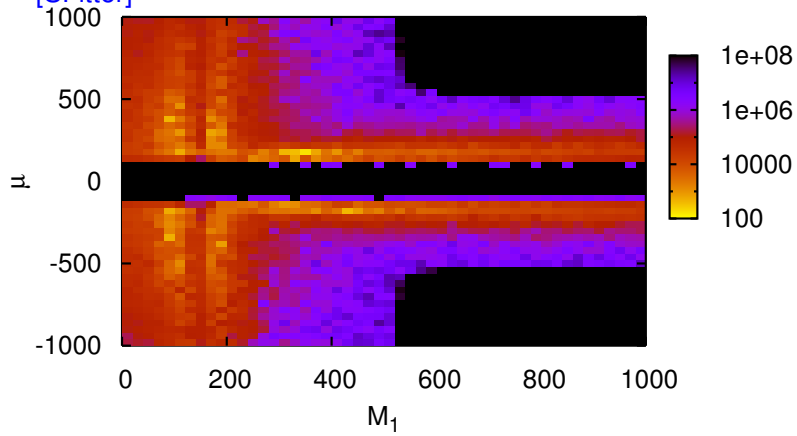
MSSM parameters with LHC measurements [SFitter]

- decay kinematics only
- two–dimensional likelihood



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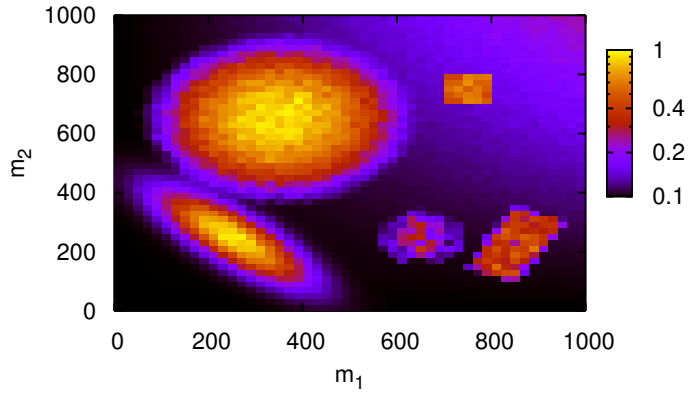

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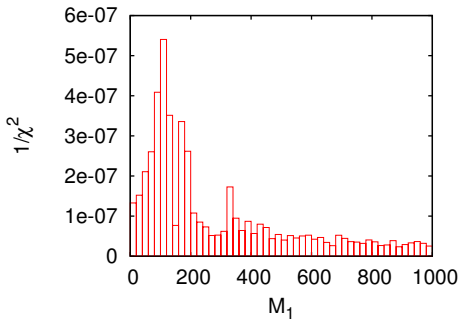

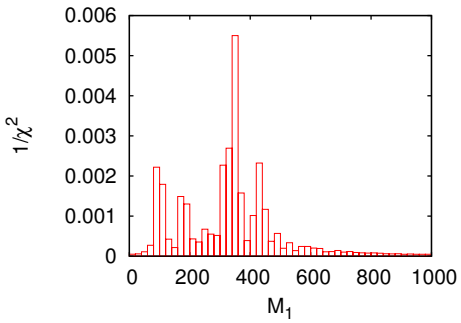

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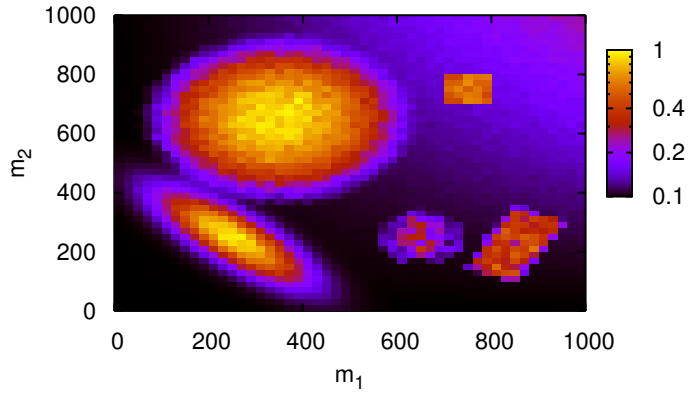

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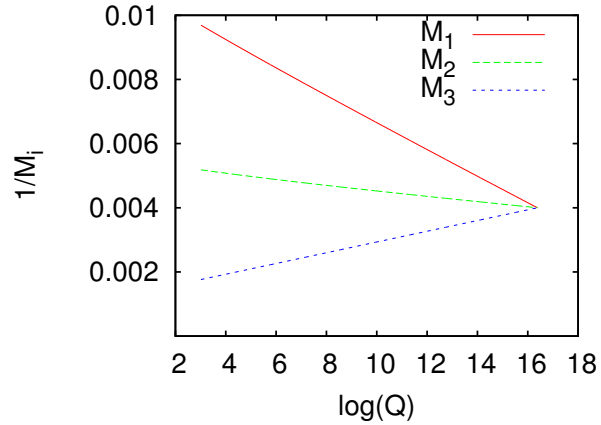
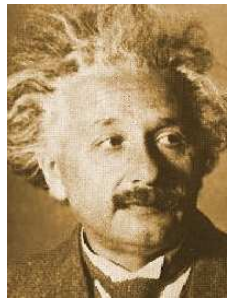
MSSM parameters with LHC measurements [SFitter]

- decay kinematics only
- two–dimensional likelihood
- Bayesian — frequentist?
- any sign of unification?

$\Rightarrow$ all ready for LHC data!



Example: large extra dimensions



Again solving the hierarchy problem [Arkani-Hamed, Dimopoulos, Dvali]

- weak gravity = large Planck scale $G_N \sim 1/M^2_{\text{Planck}}$ [$M_{\text{Planck}} \sim 10^{19}$ GeV]
- Einstein–Hilbert action in $4+n$ dimensions [on torus — periodic boundaries]

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

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

- to get numbers right: $r = 10^{12}, 10^{-3}, \ldots 10^{-11}$ m for $n = 1, 2, \ldots 6$

$\Rightarrow$ fundamental Planck scale at TeV

Kaluza–Klein gravitons

- periodic boundaries: Fourier–transform in extra dimensions [QCD massless]

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

- universal extra dimensions: KK towers also of Standard–Model particles
- graviton couplings to quarks and gluons

$$f(k_1) - f(k_2) - G_{\mu\nu}: \quad -\frac{i}{4M_{\text{Planck}}} (W_{\mu\nu} + W_{\nu\mu}) \qquad \text{with} \quad W_{\mu\nu} = (k_1 + k_2)_\mu \gamma_\nu$$

$\Rightarrow$ single gravitons light and weakly coupled

Extra–dimensional signatures

Hope for collider searches

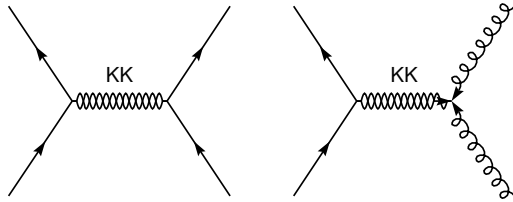
- real radiation of continuous KK tower $[dm/d|k| \sim 1/r]$

$$\sigma^{\text{tower}} \sim \sigma^{\text{graviton}} \int dm\, S_{\delta-1}\, m^{n-1} r^n = \sigma^{\text{graviton}} \int dm\, \frac{S_{\delta-1}\, m^{n-1}}{(2\pi M_*)^n} \left(\frac{M_{\text{Planck}}}{M_*}\right)^2$$

- higher-dimensional operator from virtual gravitons

$$\mathcal{A} = \frac{1}{M_{\text{Planck}}^2} T_{\mu\nu} T^{\mu\nu} \frac{1}{s - m^2} \to \frac{S_{\delta-1}}{2} \frac{\Lambda^{n-2}}{M_*^{n+2}}$$

$\Rightarrow$ $1/M_*$ coupling after summing KK tower



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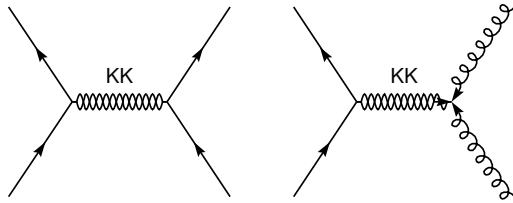
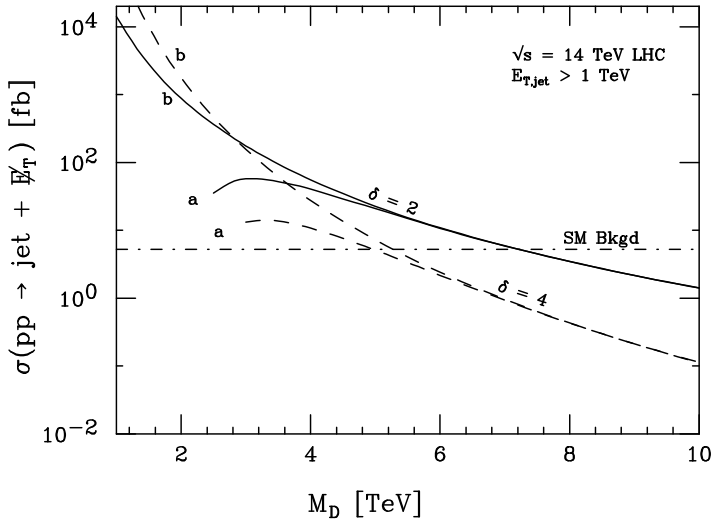


Graviton radiation at LHC [Giudice, Rattazzi, Wells]

- off single–jet production
  jets plus missing energy — like SUSY
- background $Z \to \nu\bar{\nu}$
  measure $Z \to \mu\mu$ and subtract

$\Rightarrow$ no challenge at LHC



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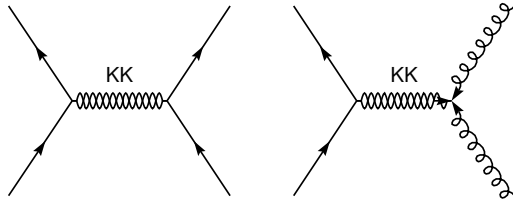
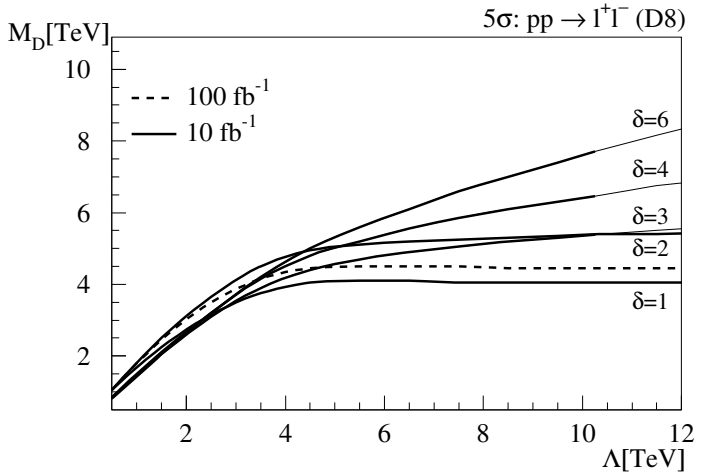


Virtual gravitons at LHC [Litim, TP]

- s–channel $gg \to \mu^+\mu^-$
- LHC reach dependent on cut-off Λ??



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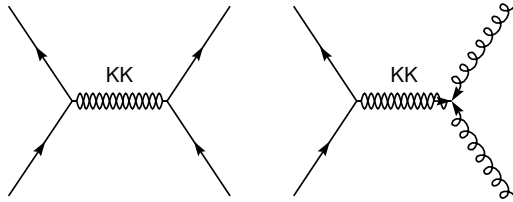

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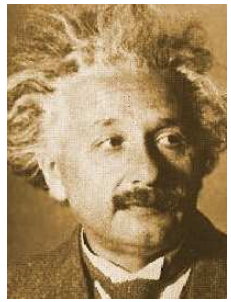

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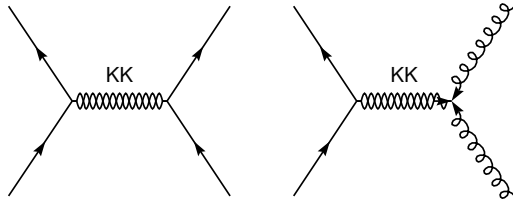

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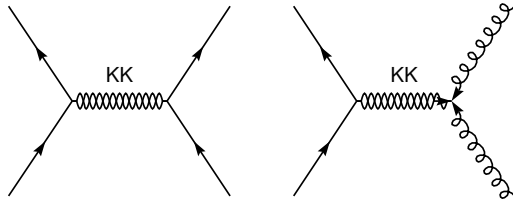
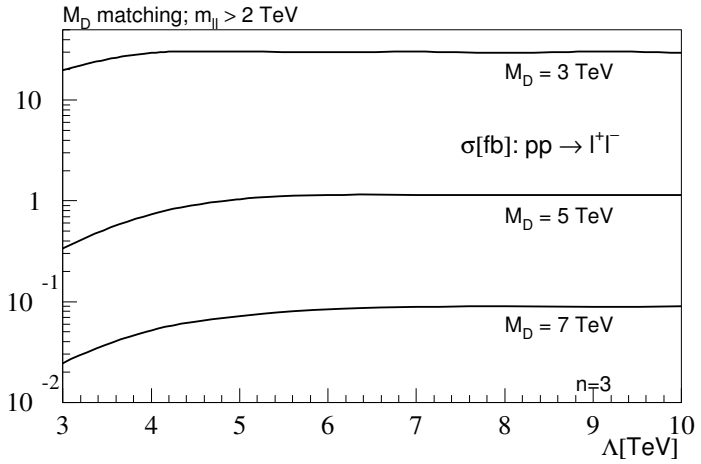


Virtual gravitons at LHC [Litim, TP]

- s–channel $gg \to \mu^+\mu^-$
- LHC reach dependent on cut-off Λ??
- gravity at large energies weak?!
- no need for a cut-off Λ

$\Rightarrow$ ready for LHC studies?!



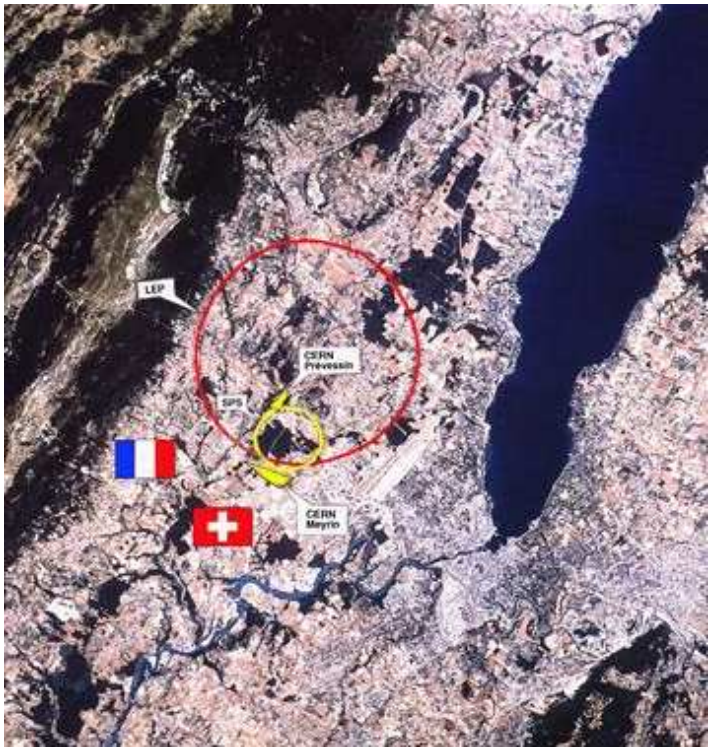
New physics at the LHC

Need for new physics

- know there is physics beyond our Standard Model
- trust something to solve the hierarchy problem
- 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



Extra dimensions another great idea

- solves the hierarchy problem
- might explain dark matter
- real vs virtual gravitons the key?
- LHC with more than hints?

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