The Physics of the Christmas Colloquium

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Heidelberg, 11/2009

Outline

The LHC

Standard–Model effective theory

Example: TeV–scale supersymmetry

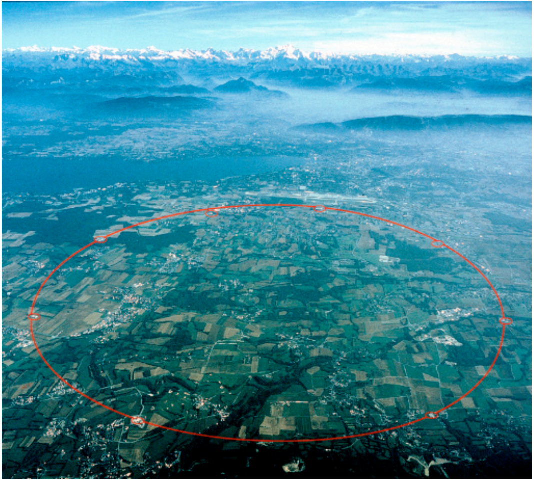
New physics measurements

Weak boson fusion

Fundamental parameters

The LHC

Large Hadron Collider: on physics mission since Wednesday



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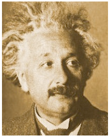

- Einstein: beam energy to particle mass $E = mc^2$
  smash 7 TeV protons onto 7 TeV protons [energy unit GeV: proton mass]
  produce anything that interacts with quarks and gluons
  search for it in decay products
  repeat every 25 ns
- huge detectors, soldering, analysis... $\longrightarrow$ experiment
  prejudice, fun, Philosophenweg villas... $\longrightarrow$ theory

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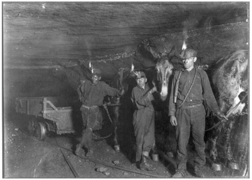
life as an experimentalist



life as a theorist

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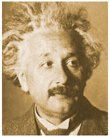

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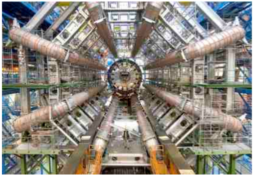

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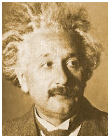

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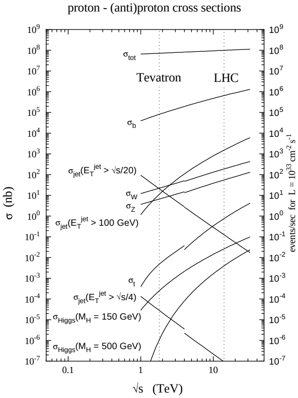
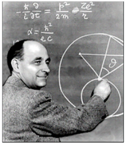
Everything you always wanted to know...

– 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']
– 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 → 2) transition amplitude $\mathcal{A} \propto G_F E^2$
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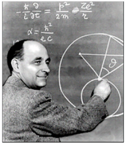

TENTATIVO DI UNA TEORIA DEI RAGGI β

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.

161

Versuch einer Theorie der β-Strahlen. I¹).

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 Heisenberg²) 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.

11*

Standard–Model effective theory

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- Yukawa 1935: massive particles
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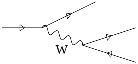
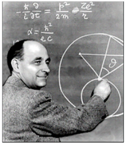
  current effective theory for $E < 1.2$ TeV [LHC energy!!]





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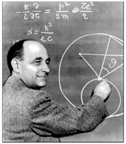

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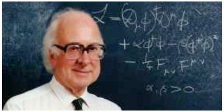

– Higgs 1964: spontaneous symmetry breaking
  unitarity for massive W, Z
  unitarity for massive fermions
  fundamental scalar below TeV

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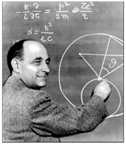

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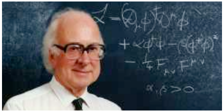

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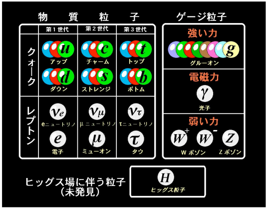
- 't Hooft & Veltman 1971: renormalizability
  beware of $1/M$ couplings!
  theory valid to high energy
  truly fundamental theory

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

Standard–Model effective theory



What is the Standard Model?

– gauge theory with local $SU(3) \times SU(2) \times U(1)$

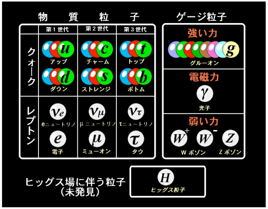
– massless $SU(3)$ and $U(1)$ gauge bosons
massive W, Z bosons [Higgs mechanism]

– Dirac fermions in doublets with masses = Yukawas
generation mixing in quark and neutrino sector [colloquium Stech]

– 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

Standard–Model effective theory



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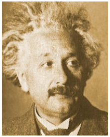

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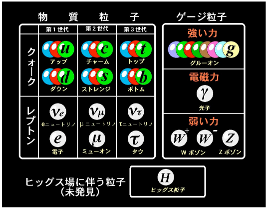

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And how complete is it experimentally?

– 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?]

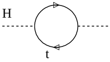
– gauge coupling unification?

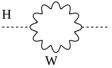
– gravity missing? [mostly negligible but definitely unrenormalizable]

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

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

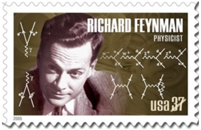
Standard–Model effective theory





Theorists have to care!!

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



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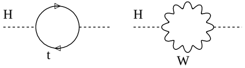

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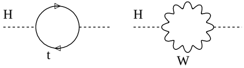
...implies effective field theory desaster

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

– Higgs mass pulled to cut-off Λ [where 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 light Higgs [e-w precision data]
...indicates effective Standard Model

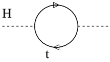
– easy solution: counter term — but against idea of symmetries

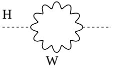
– or new physics at TeV scale: supersymmetry
extra dimensions
little Higgs
composite Higgs, TopColor
YourFavoriteNewPhysics...

⇒ typically cancellation by new particles or discussing away high scale

⇒ beautiful concepts, models in baroque state

Standard–Model effective theory





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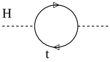
Expectations from the LHC

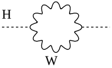
– find light Higgs? [1990 Nachtmann]

– find new physics stabilizing Higgs mass?

– see dark–matter candidate?

Example: TeV–scale supersymmetry





Supersymmetry

– partner for each Standard–Model particle

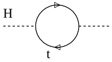
– cancellation because of different spins

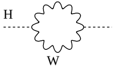
– obviously broken by masses, mechanism unknown

– assume dark matter, stable lightest partner

$\Rightarrow$ LHC: measure spectrum with missing energy

Example: TeV–scale supersymmetry





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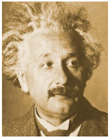
Particle spectrum

		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	$2 \cdot 4$	

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
⇒ approach independent of new physics model



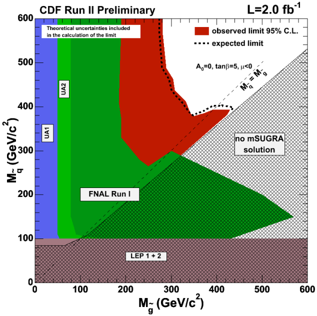
Special about LHC, except bigger than Tevatron

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

– rates not good
(collinear) jets everywhere
better observables needed

– general theme: try to survive QCD

⇒ aim at underlying theory



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

⇒ 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

– rates not good
(collinear) jets everywhere
better observables needed

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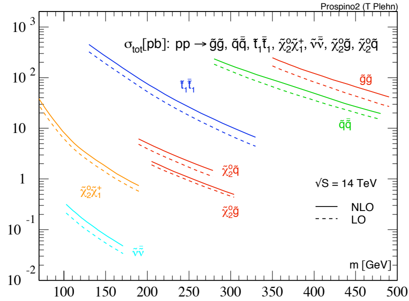

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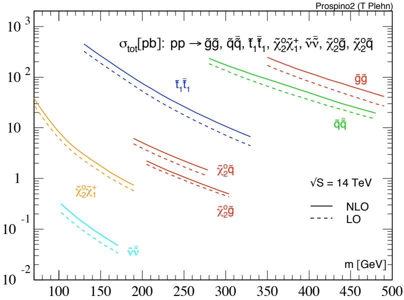

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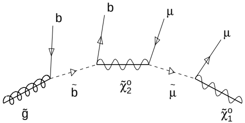


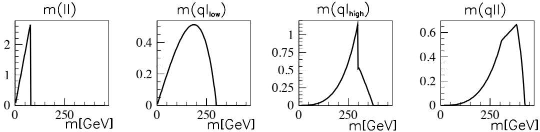
Exercise in relativistic kinematics

- 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

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

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

⇒ new–physics mass spectrum from cascade decays



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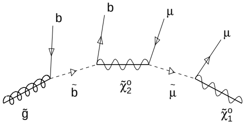

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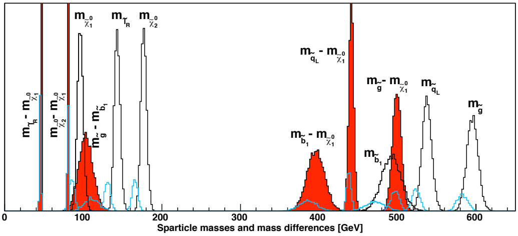
$\Rightarrow$ new–physics mass spectrum from cascade decays

Cascade masses from kinematics

- 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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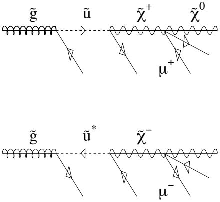

When do I believe it's SUSY–QCD?

- 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

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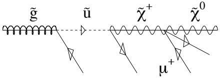

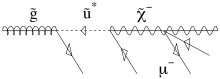

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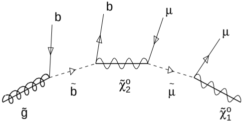
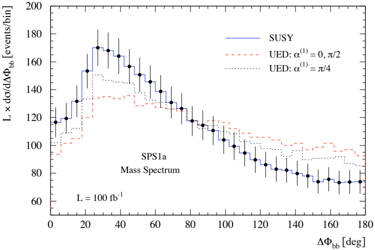


All new physics is hypothesis testing

- 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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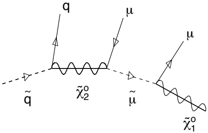
Asymmetries

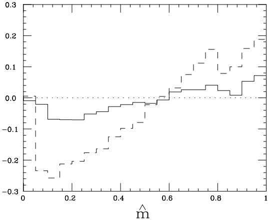


- shorter sqark decay chain
- shape between endpoints: $\hat{m} = m_{q\mu}/m_{q\mu}^{\max} \sim \sin\theta/2$
- dominant $pp \to \tilde{q}\tilde{g}$ with $\tilde{q} : \tilde{q}^* \sim 2 : 1$
- production asymmetry with reduced errors

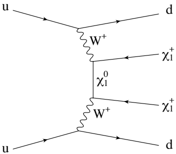
$$\mathcal{A}(m_{\mu j}) = \frac{\sigma(j\mu^+) - \sigma(j\mu^-)}{\sigma(j\mu^+) + \sigma(j\mu^-)}$$

- kind of similar for gluino decay

⇒ gluino = fermion with like-sign dileptons



Weak boson fusion



Jets being useful: spin of dark matter

- Majorana neutralino with like-sign charginos?
- hypotheses: like–sign charginos (SUSY)
  like–sign scalars (scalar dark matter)
  like–sign vector bosons (little–Higgs inspired)
- want to bet this man can tell them apart just using the jets?

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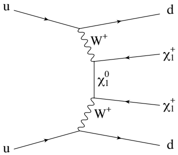

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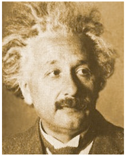


Weak boson fusion

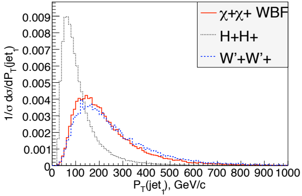
Like-sign scalars?

- $H^+ H^-$ same as simple H^0
- W radiated off quarks [Goldstone coupling to Higgs]

$$P_T(x, p_T) \sim \frac{1 + (1-x)^2}{2x} \, \frac{1}{p_T^2}$$

$$P_L(x, p_T) \sim \frac{(1-x)^2}{x} \, \frac{m_W^2}{p_T^4}$$

$\Rightarrow$ scalars with softer $p_{T,j}$



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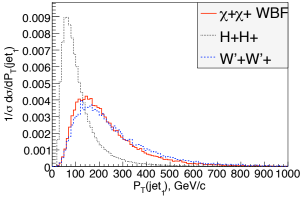
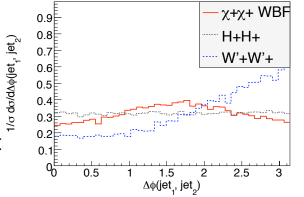


Like-sign vectors?

- heavy W', Z', f', little–Higgs inspired
- Lorentz structure reflected in angle between jet

$\Rightarrow$ vectors with peaked $\Delta\phi_{jj}$



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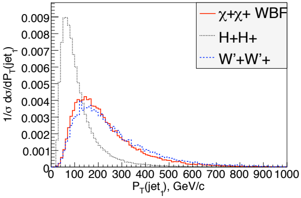

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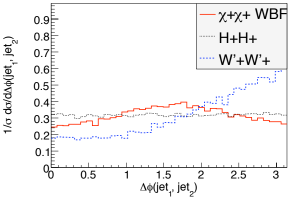
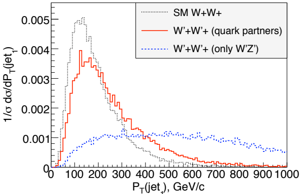


Or violating unitarity.... [old trauma]



Fundamental 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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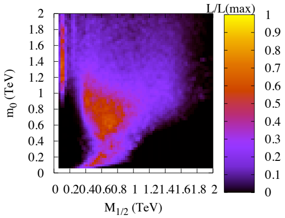
Bayesian probabilities vs profile likelihood

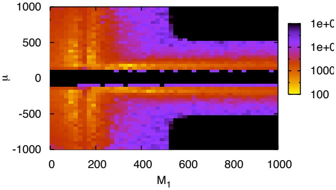
- 'Which is the most likely parameter point?'
- 'How does dark matter annihilate/couple?'



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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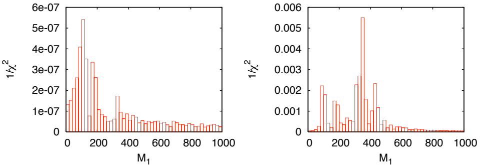


– quality of fit not useful: all the same...

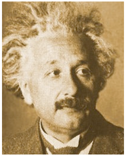
	$\mu < 0$				$\mu > 0$			
M_1	96.6	175.1	103.5	365.8	98.3	176.4	105.9	365.3
M_2	181.2	98.4	350.0	130.9	187.5	103.9	348.4	137.8
μ	-354.1	-357.6	-177.7	-159.9	347.8	352.6	178.0	161.5
$\tan\beta$	14.6	14.5	29.1	32.1	15.0	14.8	29.2	32.1
M_3	583.2	583.3	583.3	583.5	583.1	583.1	583.3	583.4
$M_{\tilde{\mu}_L}$	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



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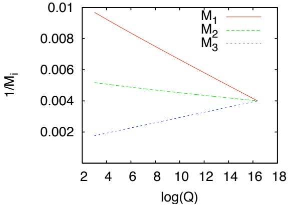
- scale-invariant sum rules?



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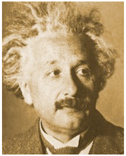

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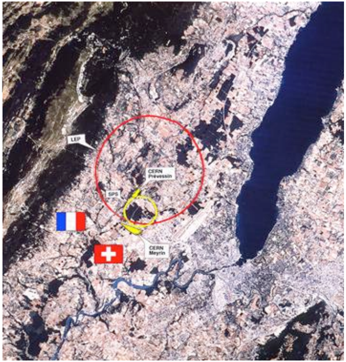

Need for new physics

- know there is physics beyond our Standard
- 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!