PHYSICS BEYOND LHC

Risky subject…

Let’s try to draw a roadmap,
with only the main roads marked,
based on the best available hints

We all expect physics beyond SM

Fantastic success of SM (LEP!)

But strong, concrete hints for physics beyond

Two categories of hints, nicely organized on the (logarithmic) energy scale

M_W 1 TeV 10^{10}-10^{16} GeV

„naturalness” of the Fermi scale

dark matter

Neutrino masses (see-saw)

Grand unification; Unification of couplings but even more important - the spectrum of fermions

Leptogenesis

Standard Model with a Higgs particle is fine if it is the Theory of Everything but it is theoretically problematic when embedded into a bigger theory, with a new, high, scale *M*

$$V = m^2 H^+ H + \lambda (H^+ H)^2, \qquad v = -\frac{m^2}{\lambda}$$

$$m^2 = m_0^2 + \delta m^2$$

quantum corrections

In the presence of a new scale *M*

$$\delta m^2 = \delta^2_{SM} + \delta m^2_{NEW}$$

$$\delta m^2_{SM} = (2m^2_W + m^2_Z + m^2_H - 4m^2_t)\frac{3M^2}{32\pi^2 v^2}$$

$$|\delta m^2_{SM}| \sim m^2_W \Rightarrow M < 0.6\,\text{TeV}$$

$$|\delta m^2_{SM}| < 10 M^2_W \Rightarrow M < 2\text{TeV}$$

$$|\delta m^2_{SM}| < 100 M^2_W \Rightarrow M < 6\text{TeV}$$

We expect low scale *M*

We expect it to be built into a structure such that δm^2_{NEW} is also small

Indeed….

Hierachical mass scales in particle physics have, so far, „natural” explanations

Proton mass and Planck scale

$K_L - K_S$ mass difference, $\Delta M = 3\times10^{-12}$ MeV instead of 10^{-6} MeV

$\pi^+ \pi^-$ electromagnetic mass difference

No light scalars in nature except
for Nambu-Goldstone bosons (pions)

Dark matter – interesting coincidence

For a stable, neutral particle χ in thermal equilibrium with hot plasma, annihilating into unstable ones

$$\chi\chi \to f\bar{f}$$

The present relic energy density (from Boltzman equation) is

$$\Omega h^2 \sim 0.1 \frac{\text{pb}}{\sigma_{ann}}$$

Interesting: $\sigma_{ann} \sim$ pb for weakly interacting particles with $m_\chi \sim 0(0.1 - 1)$ TeV;
observed $\Omega h^2 \sim 0.1$!

LHC cannot answer all questions in particle physics (proton must finally decay!);

but we hope to discover new physics around 1 TeV and to build the Next Standard Model (NSM) valid up to TeV scale

Hundreds of theoretical models but only few basic concepts; Furthermore - we have waited too long for the data-therefore

Motivated

Unmotivated

Unparticles
Hidden valleys
.
.

Supersymmetry

Higgs doublet as a pseudo-Goldstone boson

we know of only two possible explanations for naturally light scalar

Higgsless models

Gravity (in suitably compactified extra dimensions) as a low cut-off to the SM; if only gravity in extra dimensions - radically different from the other scenarios, with little insight into particle physics;
If also gauge fields in extra dimensions – in the effective *4d* theory can lead to some of the possibilities mentioned above

General remark about Next Standard Model:

strongly constrained by precision electroweak data

More concretely – scale *M* of new physics which contributes to the electroweak observables at tree level or with strong coupling must be > *O*(*5*) TeV, unless supressed by
a) some symmetries
b) weak coupling to quarks and leptons

Supersymmetry – exceptional for many reasons but also straightforwardly compatible with electroweak precision data

Main questions for the NSM (those based in the SM):

1) What unitarizes the WW scattering amplitude?

massive W → $A \sim G_F E^2 \sim s/v^2$

2) What is the origin of G_F?

Two related but not identical questions: for instance, in the SM WW is unitarized by an elementary scalar (Higgs boson) but we have no idea what is the origin of G_F and moreover - naturality problem

For sure, we need new physics to answer (2) but we also may be wrong about (1) and then even more new physics.

3) Who is dark matter particle - would be nice to get it as a byproduct of 1) and 2)

What shall we learn from the LHC on the way towards NSM and what will be left for the post–LHC period, say after (100-300) fb^{-1} integrated luminosity at the LHC?

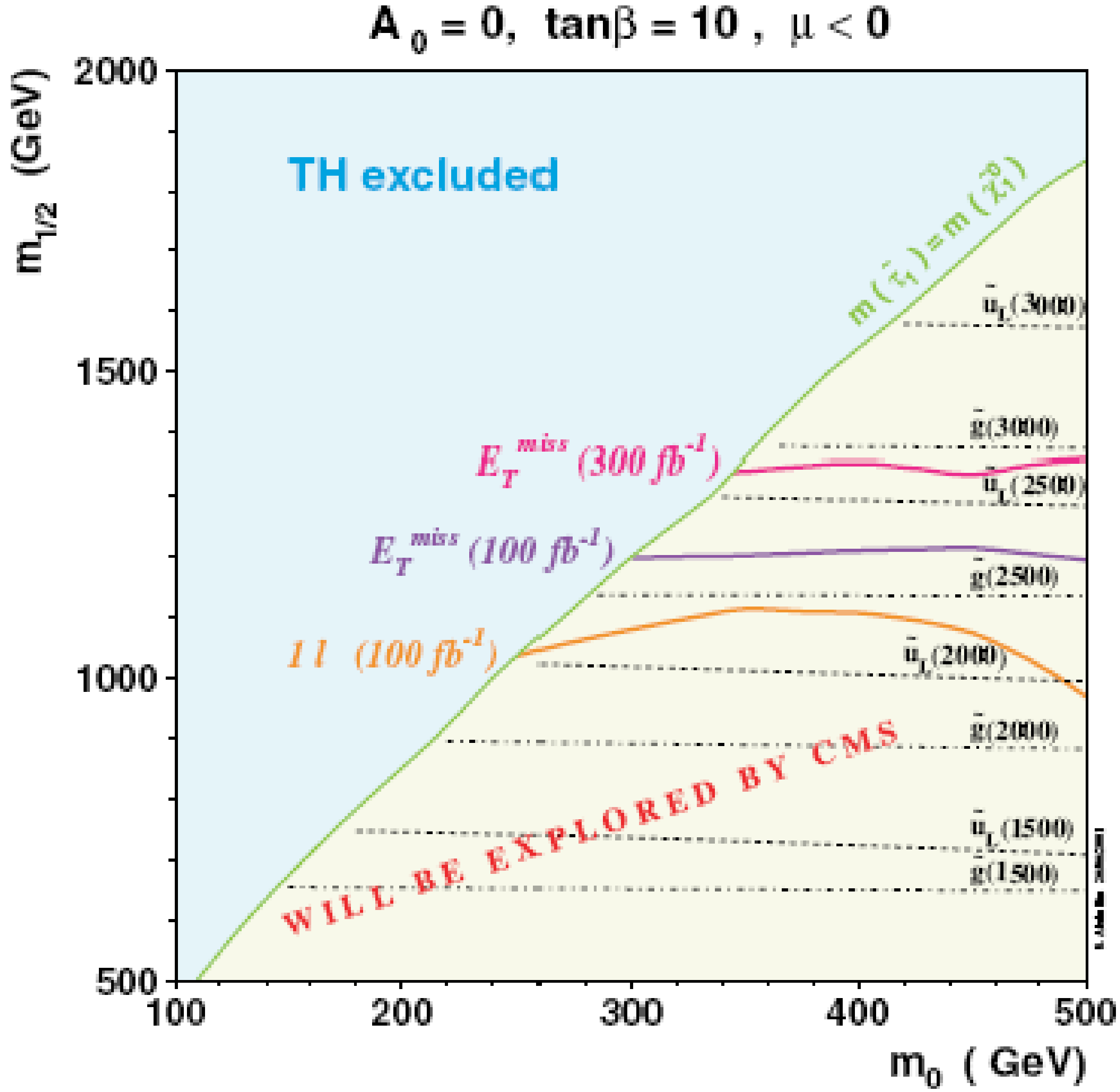
One can envisage several scenarios (let's assume we can discriminate between them at the LHC)

Each scenario has ITS OWN POST-LHC CHALLENGES, if we want to reach a new theoretical synthesis.

SCENARIO I

SUPERSYMMETRY IS DISCOVERED!

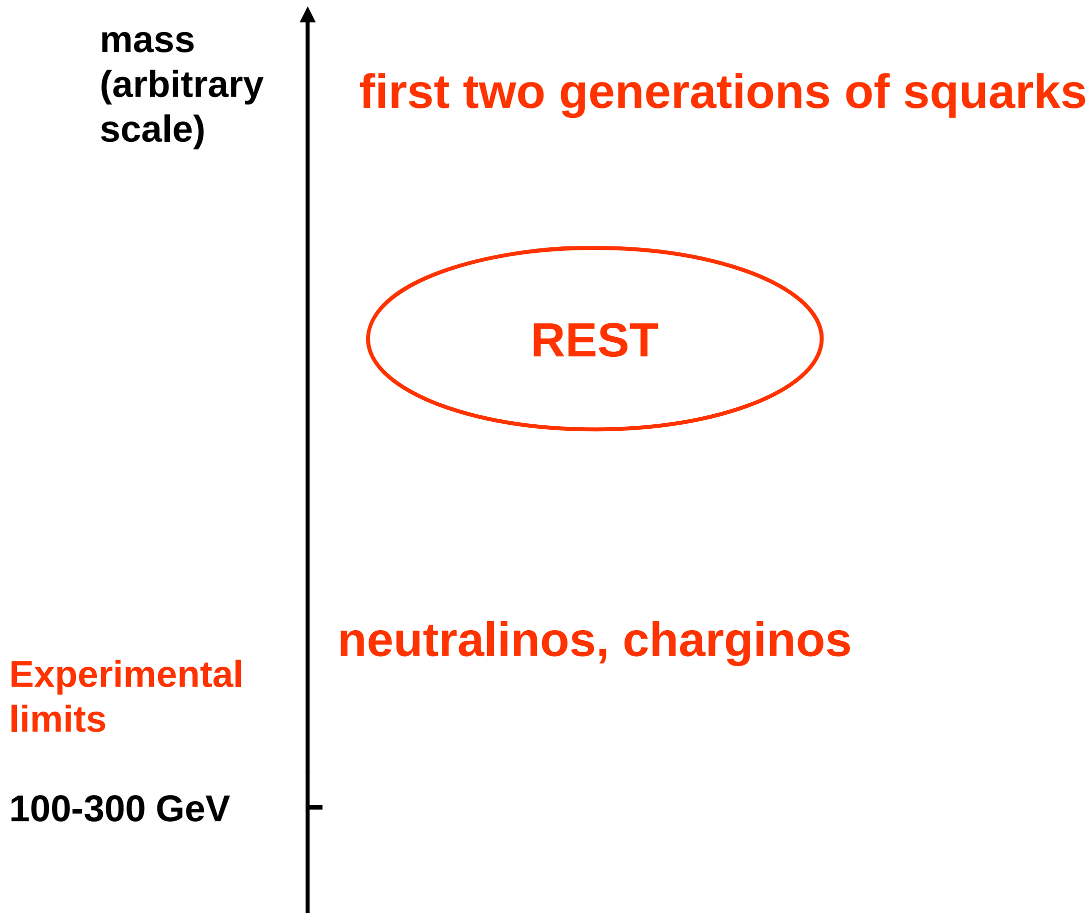
Supersymmetric NSM is more plausible than anything else.



A 0 = 0, tanβ = 10 , μ < 0
m1/2 (GeV)
m0 (GeV)
TH excluded
m(τ̃1) = m(χ̃10)
ũL(3000)
g̃(3000)
ũL(2500)
g̃(2500)
ũL(2000)
g̃(2000)
ũL(1500)
g̃(1500)
ET miss (300 fb-1)
ET miss (100 fb-1)
l l (100 fb-1)
WILL BE EXPLORED BY CMS

From the discovery of supersymmetry to the construction of the supersymmetric NSM is a very long way

Scan of supersymmetric models gives the following picture for the supersymmetric spectra



This variety is linked to many different models of supersymmetry breaking and mediation

Measuring the details of supersymmetric spectra is crucial for the supersymmetric NSM

Furthermore, supersymmetric Higgs sector (masses and couplings) is of crucial importance for fixing the correct theory and its parameters (e.g. tan β)

MSSM versus extended versions, some with additional global or gauge symmetries;

Even in supersymmetric scenarios $W_L W_L$ scattering is of interest, to study the role of heavier scalars in its unitarization

Supersymmetry discovered → beyond LHC physics straightforward (a lot of work) but choice of the best tools depends on whether

superpartners at 0.5 - 1 TeV
superpartners at 2 - 3 TeV

However, scan of the models strongly suggests that neutralino/chargino/ Higgsino spectrum is expected below *O*(0.5) GeV and precision measurements of that sector are very important, in particular for understanding the origin of dark matter.

SCENARIO II

Light or not so light Higgs boson, say below 300 GeV, is discovered and no supersymmetry

IIa: Higgs boson and a signal of new physics;

IIb: Higgs boson and nothing else;

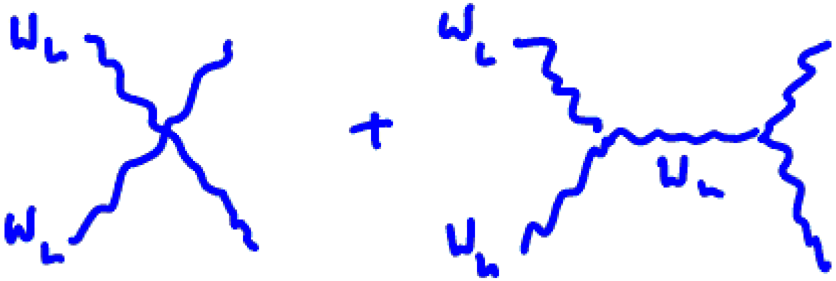
In both cases

Higgs doublet as a pseudo-Goldstone boson is a serious option;
Usually linked to a new strong dynamics; best to discuss together with no Higgs boson scenario (less likely Scenario III)

Strongly coupled theory as NSM

Unitarity of $W_LW_L(Z_L)$ scattering amplitude

SM:



$\sim \frac{s}{v^2}$

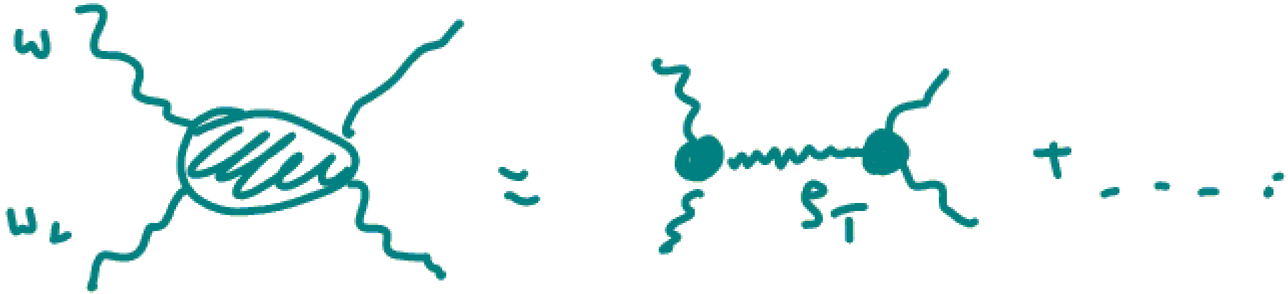
violates unitarity around $\sqrt{s} \sim 1.5$ TeV

$\sim - \frac{s}{v^2} \frac{s}{s - m_h^2}$

restores unitarity

Prototype of strongly coupled NSM:

Higgsless theory with strong interactions at Λ ~ 1.5 TeV

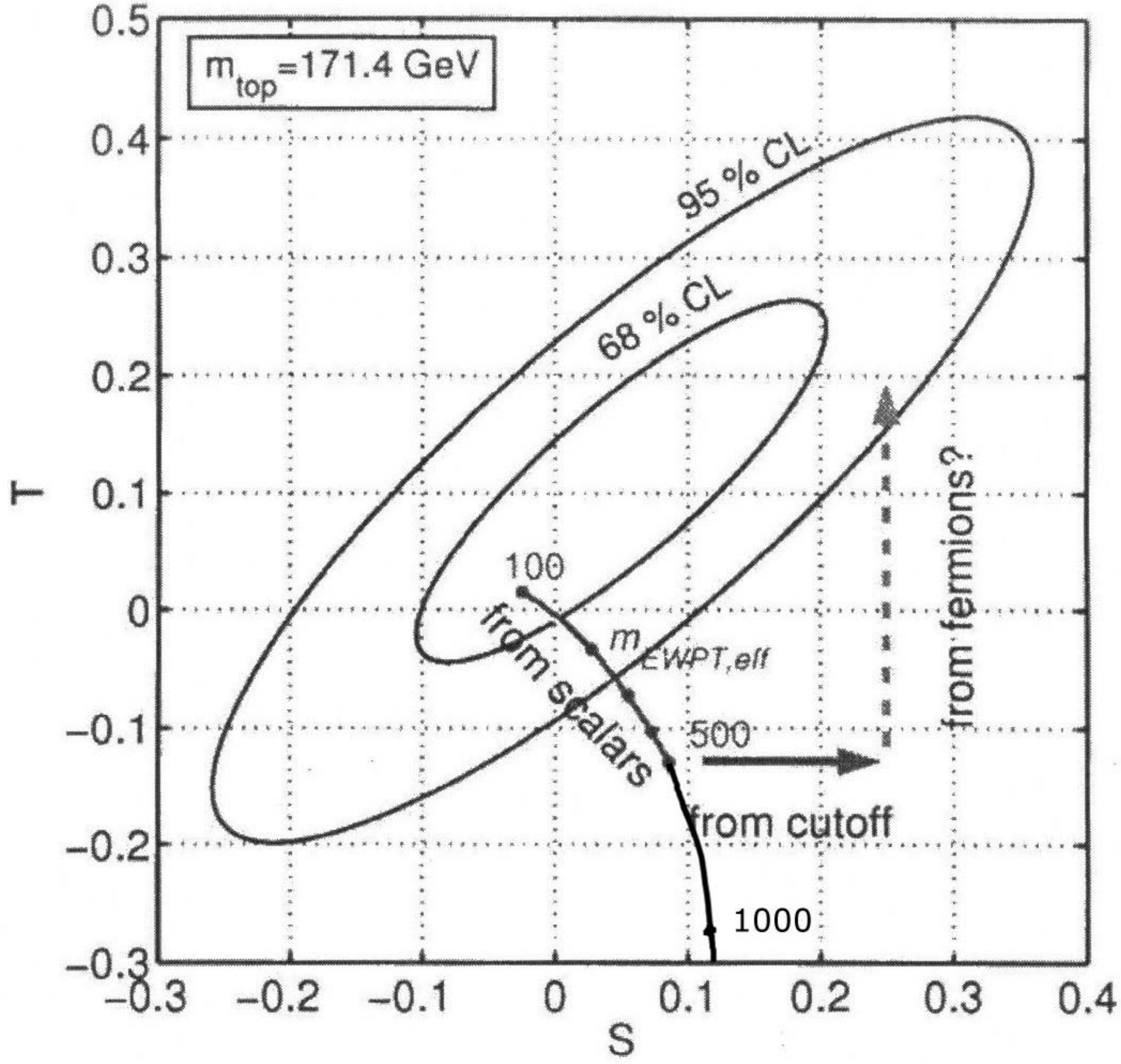


Strongly coupled resonances unitarize WW; electroweak symmetry is broken together with spontaneously broken global symmetry of strong interactions; 3 Goldstone bosons are „eaten" by W,Z.

Prototype: technicolor (rescaled QCD)

Global $SU(2)_L$ x $SU(2)_R \rightarrow SU(2)_{L+R}$ is source of technipions „eaten” by gauge bosons; technirho in $W_L W_L$ scattering

Hardly compatible with precision electroweak data (No Higgs boson and Λ too low)



m_top=171.4 GeV
95 % CL
68 % CL
100
from scalars
m_EWPT,eff
500
from cutoff
1000
from fermions?
T
S

STRONGLY COUPLED NMS:

New developments based on new ideas in modelling strongly interacting theories in *4d* by perturbative physics;

Higgsless models and models with light Higgs doublet as a pseudo-Goldstone boson (more interesting)

***4d* world with more complicated spontaneously broken gauge and global symmetries; origin of new vector bosons with perturbative couplings**

It can be technically linked to „fake” extra dimensions by so-called deconstruction

The main advantage: the on-set of strongly coupled theory is delayed to higher Λ; saturation of unitarity in $W_L W_L$ is postponed in calculable way (perturbative) by exchange of new vector bosons

Similar effects when extra dimensions are real (physical) but this is not needed.

If real $\rightarrow$ heavy gravitons as experimental signature

Origin of new vector bosons in *4d* world for Higgsless models

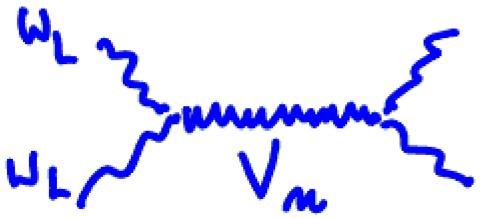
SU(2)xU(1) $\rightarrow$ SU(2)$_1$ x SU(2)$_2$…SU(2)$_N$ x U(1)

$$\phi_1(2,\bar{2})......\phi_N(2,\bar{2})$$

Vev's of scalars ϕ_i can break SU(2) $\rightarrow$ U(1), and no light physical scalar in the spectrum

One gets massive W, Z and tower of *n* W_i', Z_i';

Saturation of unitarity is delayed by perturbative physics – exchange of W_i', , Z_i'



On-set of strong interactions (origin of vev's for ϕ's) at

$$\Lambda \sim \frac{3\pi^4}{g^2}\frac{M_W^2}{M_{W'}}$$

$\geq$ 5 TeV for $M_{W'}$ ~ 1 TeV

Some improvement for precision data but strong tension generically remains, making Higgsless models less attractive (there are some models consistent with EWPD)

More attractive: strongly coupled theories with a light Higgs doublet as a Goldstone boson

But first: signatures for vector resonances in Higgsless models compared with unitarized models based on effective chiral lagrangians parametrization

Model independent – but cannot replace construction of NSM

Effective chiral lagrangian and its „unitarization”

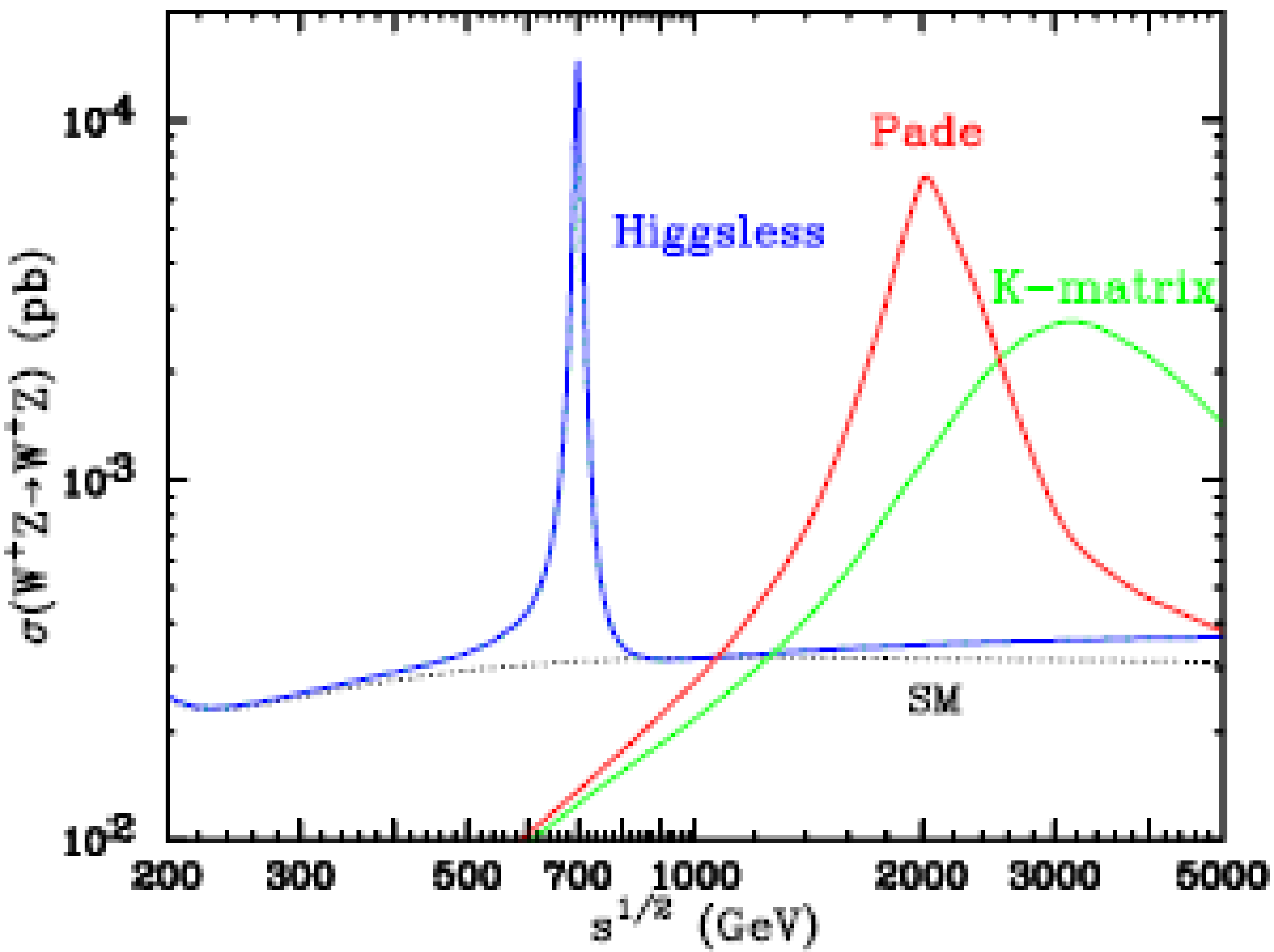
$$\mathcal{L} = \frac{v^2}{4} D_\mu U D^\mu U^+ + a_4 (D_\mu U D^\nu U^+)^2 +$$

$$+ a_5 (D_\mu U D^\mu U^+)^2 + \ldots \qquad U = e^{i\vec{\pi}\vec{\tau}/v}$$

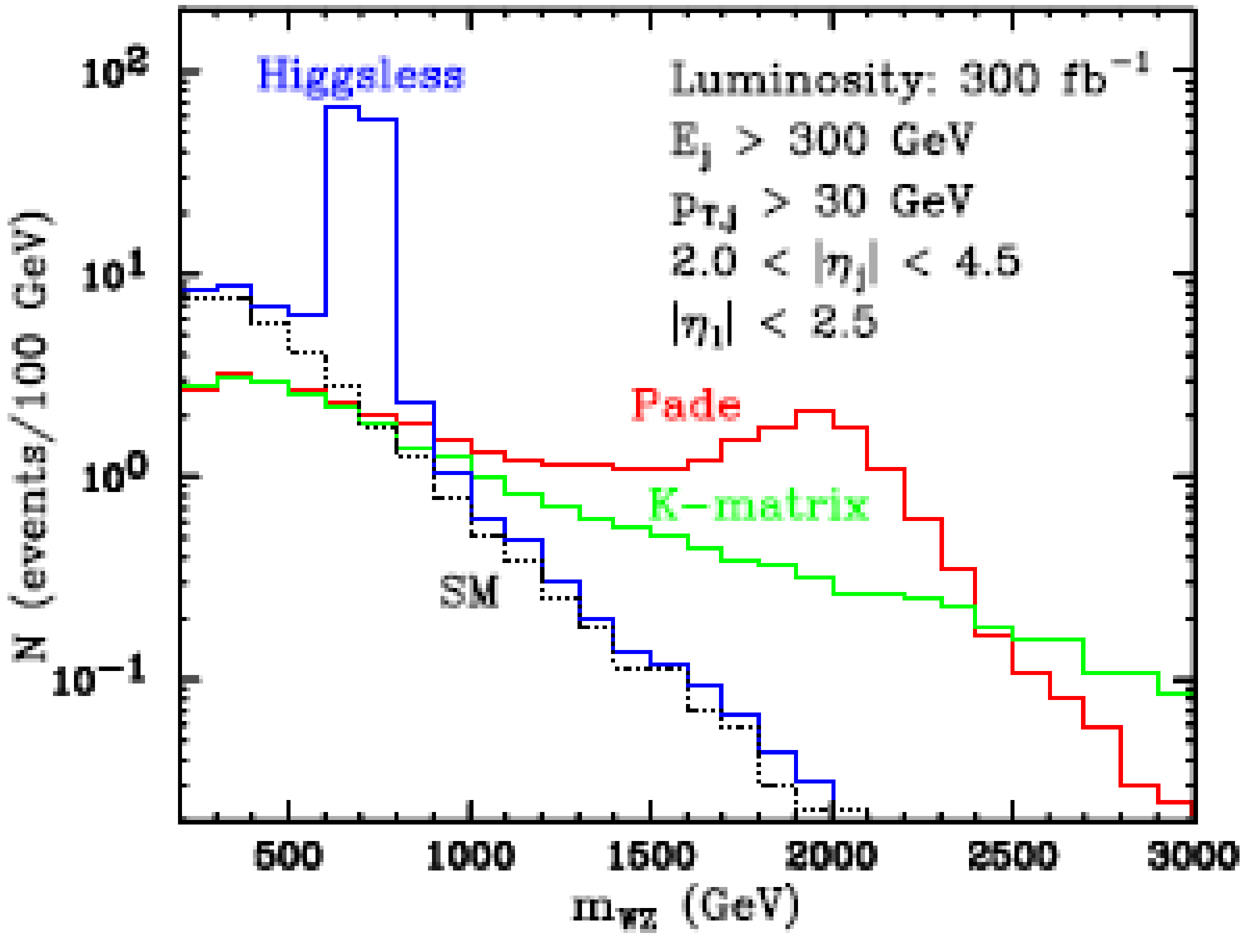
Effective WWZ(γ) vertices (V=Z,γ)

$$\mathcal{L}_{WWV} = g_{WWV} [i\kappa_V W^-_\mu W^+_\nu V_{\mu\nu} +$$

$$+ \frac{\lambda_V}{m_W^2} W^-_{\lambda\mu} W^+_{\mu\nu} V_{\nu\lambda} + \ldots]$$



Higgsless
Pade
K−matrix
SM
10^4
10^3
10^2
$\sigma(W^+Z \to W^+Z)$ (pb)
200
300
500
700
1000
2000
3000
5000
$s^{1/2}$ (GeV)



Higgsless
Luminosity: 300 fb^{-1}
E_j > 300 GeV
p_{Tj} > 30 GeV
2.0 < $|\eta_j|$ < 4.5
$|\eta_l|$ < 2.5
Pade
K-matrix
SM
N (events/100 GeV)
10^{2}
10^{1}
10^{0}
10^{-1}
500
1000
1500
2000
2500
3000
m_{WZ} (GeV)

Strongly coupled theories with Higgs doublets as Golstone bosons

$$SU(2)^N \to SO_1(5) \times SO_2(5)...SO_N(5)$$

$$\phi_1(5,\bar{5}).......\phi_N(5,\bar{5})$$

Vev's of ϕ_i's break SO(5) $\to$ SO(4) = $SU_L(2)$ x $SU_R(2)$ and doublet H remains as Goldstone boson; Vev of H (to break EW) is then obtained from some explicit breaking of SO(5) (e.g. top quark Yukawa)

E. g. Little Higgs models
Models with a tower of resonances (usually referred to as K-K modes; but extra dimension is only a technical device linked by deconstruction)

Striking experimental signatures related to the presence of three physical scales:

$<H> = v$, $<\phi> = f$, $\Lambda \sim 4\pi f$

breaks SU(2)xU(1) breaks SO(5) cut-off to perturbative physics

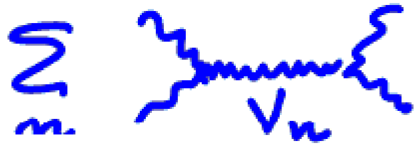
$v/f \leq 10$ for v to be natural

1) New fermions – to protect Goldstone nature of H above scale f

heavy top quark T, $m_T \sim O(f)$

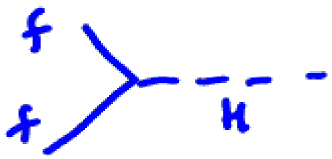
2) Partial unitarization of the WW scattering by the light Higgs boson

$$A_{WW} \sim \frac{s}{v^2} - \left(1 - \frac{v^2}{f^2}\right)\frac{s}{v^2}\frac{t}{t-m_h^2} +$$



$$\approx \frac{s}{f^2} +$$

3) Higgs boson couplings to fermions



$$Y\left(1 - \frac{v^2}{f^2}\right)^{\frac{1}{2}}$$

Physical large extra dimensions

Similar signatures to strongly interacting theories if gauge fields propagate in extra dimension,
plus graviton production and decay (main signature)

	Higgsless	Higgs as Goldstone boson
$A(W_L W_L \to W_L W_L)$	$\frac{s}{v^2}$	$\frac{s}{f^2}$
$V_n W W$	$g_n \sim 0(5) g$	$g_n \sim 0(5) g$
$V_n f f$	$g(\frac{g}{g_n})$	$g(\frac{g}{g_n})$
m_{KK}	$g_n v$	$g_n f$
hWW	-	$(1 - \frac{v^2}{f^2})^{\frac{1}{2}} \frac{1}{v}$
$hf\bar{f}$	-	$(1 - \frac{v^2}{f^2})^{\frac{1}{2}} Y$

Summary

MAIN GOAL FOR PARTICLE PHYSICS: CONSTRUCT NEXT STANDARD MODEL = DISCOVER NEW SCALE(S) AND SYMMETRY(IES) IN ELEMENTARY INTERACTIONS AT (1 – 5) TeV (serious hints)

There are more and less plausible scenarios (SUPERSYMMETRY SHOULD BE MENTIONED AS THE LEADING CANDIDATE) but LHC is a real discovery machine and an open attitude towards possible signals of new physics is necessary

Post-LHC tasks depend on the results from the LHC

Priority for precision or discovery after LHC? Probably both…

Summary cont...

Low energy supersymmetry is unlikely to be totally missed by the LHC but constructing the theory will require much more experimental work (energy depends on the spectrum);

Neutralino/chargino/higgsino sector is expected to be light in all known models and its precision measurements would be universally important, particularly in the context of dark matter

INTERFACE: PARTICLE PHYSICS –COSMOLOGY BECOMES VERY IMPORTANT IN GENERAL

Summary cont…

Theoretical results of the last several years → NSM with the Higgs doublet as a pseudo-Goldstone boson is a serious option to supersymmetry; its signals may be discovered or may remain (just) hidden for the LHC;

Light Higgs boson and nothing else at the LHC is not unlikely for such scenarios and should be given more attention in advance

testing the nature of the Higgs boson will then be crucial

Summary cont…

Universally important precision measurements for post-LHC period (independently of a particular scenario):

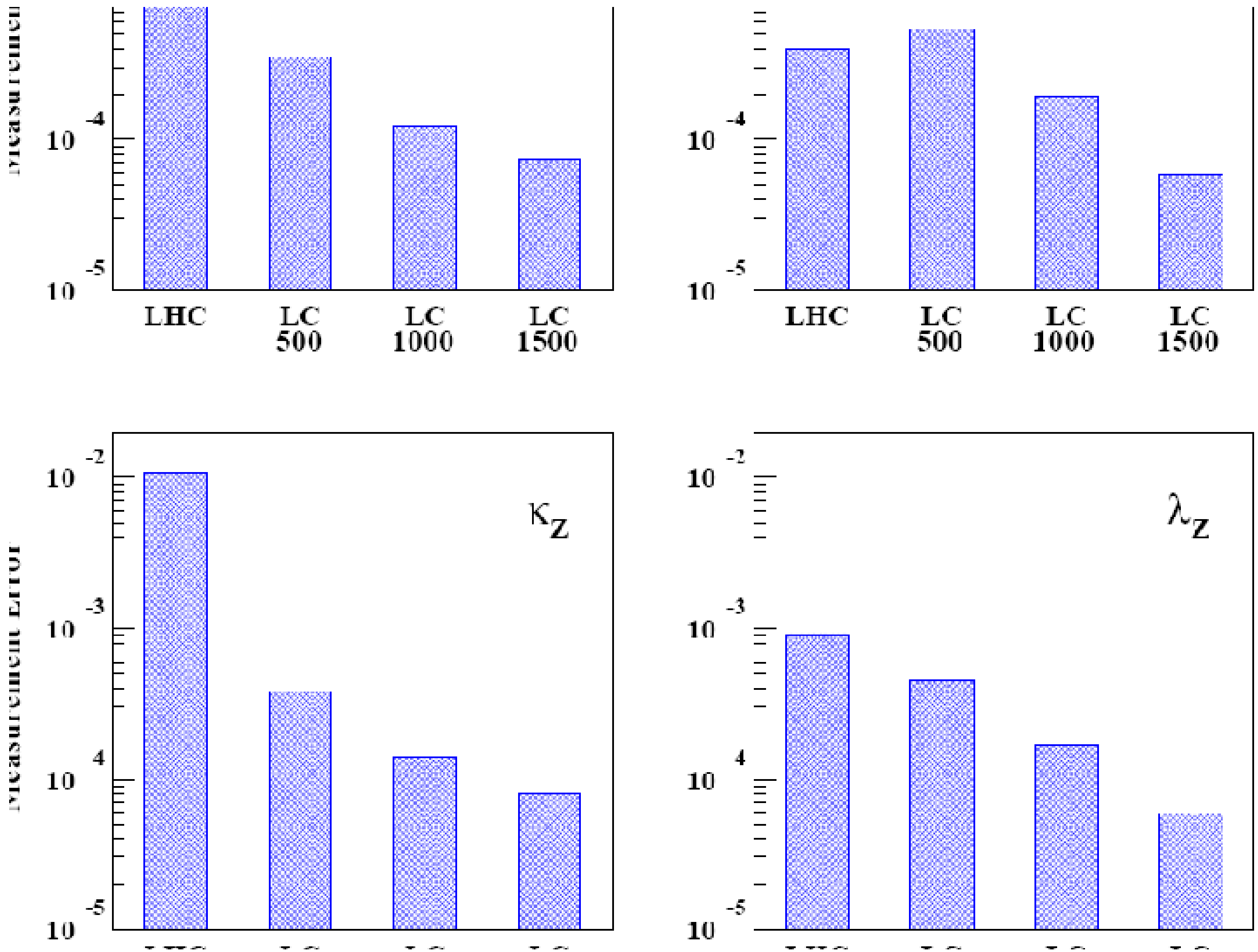
WW scattering from threshold up to several TeV

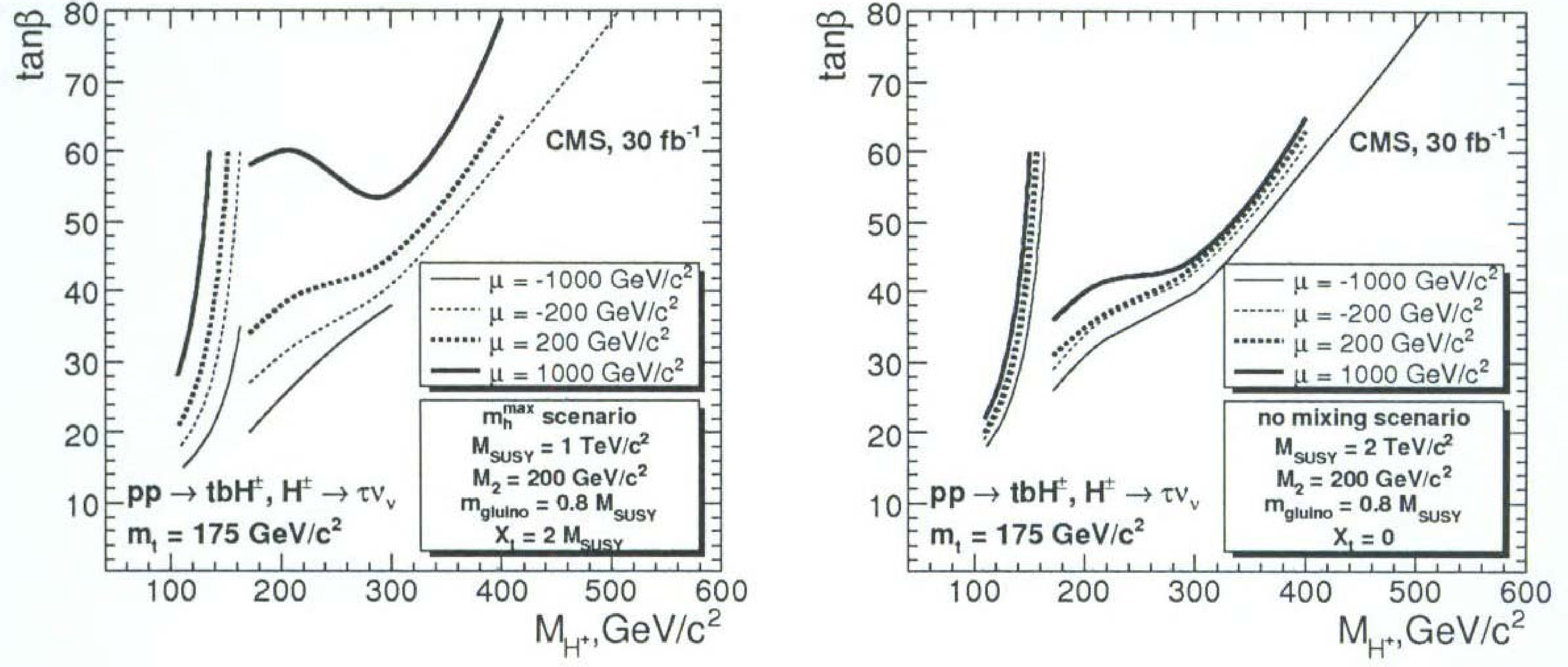
Higgs couplings to fermions and its self-couplings (except if no Higgs, of course)

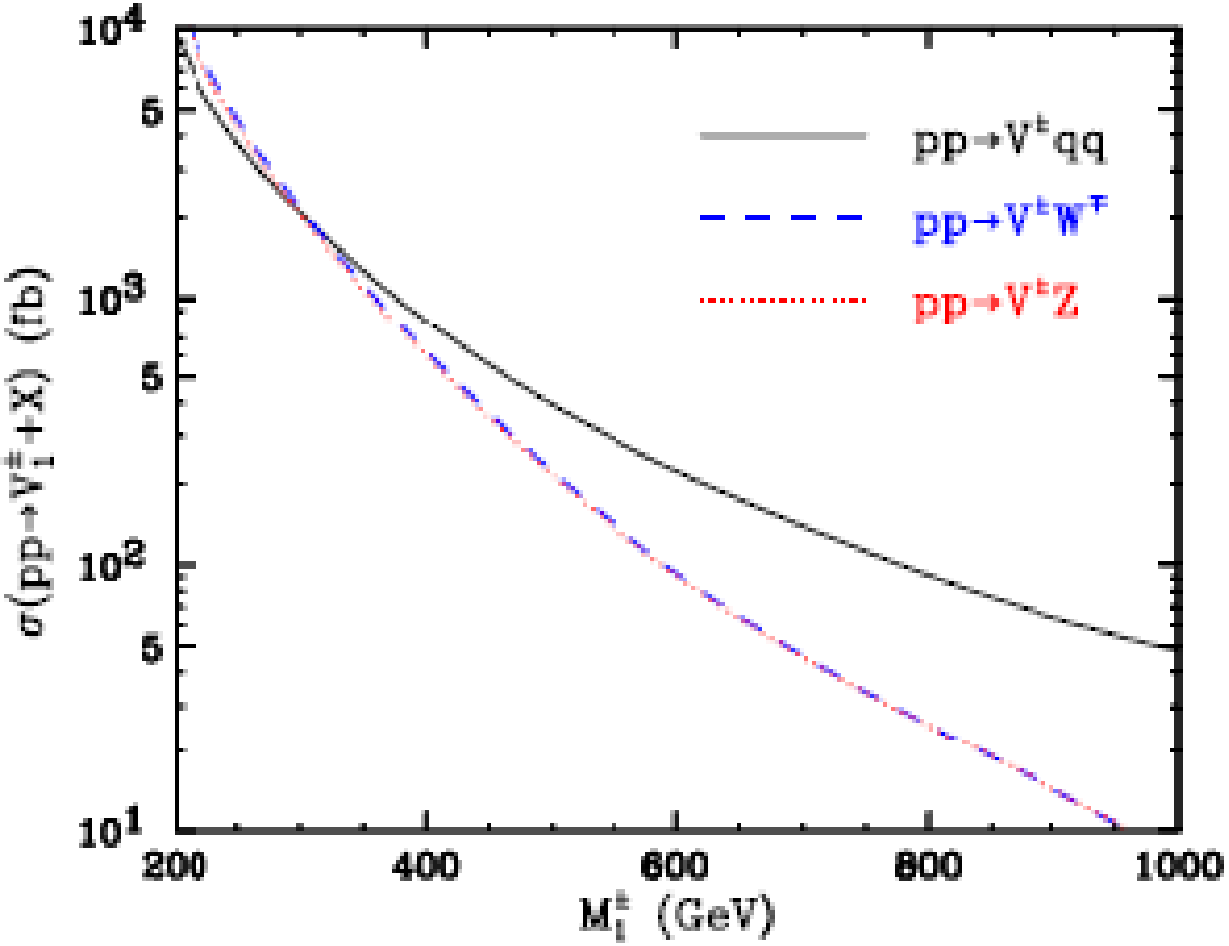
TOP QUARK PROPERTIES

END

SPECIAL THANKS TO SLAWEK TKACZYK (FERMILAB/CERN) FOR HIS CONSULTANCY ON VARIOUS EXPERIMENTAL QUESTIONS


Measurement Error
10 -4
10 -5
LHC
LC 500
LC 1000
LC 1500
κZ
λZ
10 -2
10 -3


tanβ
CMS, 30 fb-1
μ = -1000 GeV/c2
μ = -200 GeV/c2
μ = 200 GeV/c2
μ = 1000 GeV/c2
mhmax scenario
MSUSY = 1 TeV/c2
M2 = 200 GeV/c2
mgluino = 0.8 MSUSY
Xt = 2 MSUSY
pp → tbH±, H± → τντ
mt = 175 GeV/c2
MH+, GeV/c2
tanβ
CMS, 30 fb-1
μ = -1000 GeV/c2
μ = -200 GeV/c2
μ = 200 GeV/c2
μ = 1000 GeV/c2
no mixing scenario
MSUSY = 2 TeV/c2
M2 = 200 GeV/c2
mgluino = 0.8 MSUSY
Xt = 0
pp → tbH±, H± → τντ
mt = 175 GeV/c2
MH+, GeV/c2



10^4
5
10^3
5
10^2
5
10^1
200
400
600
800
1000
$M_1^\pm$ (GeV)
$\sigma(pp \to V_1^\pm + X)$ (fb)
$pp \to V^\pm qq$
$pp \to V^\pm W^\mp$
$pp \to V^\pm Z$

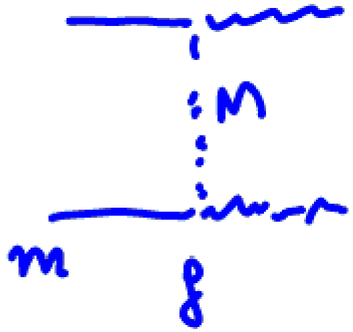
Dark matter

Standard approach, based in solving the kinetic Boltzmann equation, gives for the relic abundance of some species:

$$\Omega h^2 \simeq \frac{10^{-37}\,\mathrm{cm}^2}{\langle \sigma_{ann} v \rangle}$$

→ thermal average at freeze-out

Suppose the annihilation of a particle of mass m proceeds via the exchange of a particle with mass M, coupled with strength g



On dimensional grounds

$$\langle \sigma_{ann} v \rangle \sim \begin{cases} \frac{m^2}{M^4} \frac{g^4}{16\pi^2} & m \ll M \\ \sim \frac{g^4}{16\pi^2} \frac{1}{m^2} & m \gg M \end{cases}$$

Writing $M^2 = x M_Z^2$, $g^2 = y g^2_{ZWW}$:

$$\langle \sigma_{ann} v \rangle \sim \begin{cases} \frac{y^2}{x^2} \left(\frac{m}{1\,\mathrm{GeV}} \right)^2 * 0.4 * 10^{-37}\,\mathrm{cm}^2 & m \ll M \\ y^2 \left(\frac{m}{1\,\mathrm{TeV}} \right)^{-2} * 0.2 * 10^{-37}\,\mathrm{cm} & m \gg M \end{cases}$$

$\Omega h^2 \sim 0.1 \Rightarrow m \sim O(0.1 - 1)\,\mathrm{TeV}$

Higgs boson and new physics are discovered

Motivated new physics is based on the well known
Fact that scalars that are light relative to the next
Physical scale are generically theoretically inconsistent

Therefore:

Softly broken supersymmetry

New strong interactions with the Higgs doublet as a Goldstone boson
different from old (higgsless) technicolour; strong interactions
Modelled (in technical sense) on models with extra spacial dimensions
Or directly in four dimensions- on their deconstructed versions; some
Perturbative calculability in spite of strong interactions
Little Higgs models, AdS/CFT correspondence

Real extra dimensions, with gravity playing the role of cut-off to the SM

But....NEW PHYSICS also has its own cut-off Λ. In general, if perturbative

$$\delta m^2_{NEW} = A\,\Lambda^2_{NEW} + B \ln \Lambda_{NEW} + \ldots$$

Arrange for $A = 0$!

If non-perturbative, δm^2_{NEW} uncalculable but precision data fits in the SM (with light Higgs) tell us $M \gtrsim 5$ TeV $\Rightarrow$ 1:100 tuning in SM

Will LHC be able to firmly discriminate between different classes?

Probably, if one is able to say something about the spectrum
Of new particles, masses and spins.
may depend on the discovery signature;

e.g. if excess of missing transverse energy in both hemispheres-
first two more likely thanThe third one (one hemisphere)

Spin of new particles- important signature to distinguish between thw first two