Higgs Bosons in Models beyond the SM

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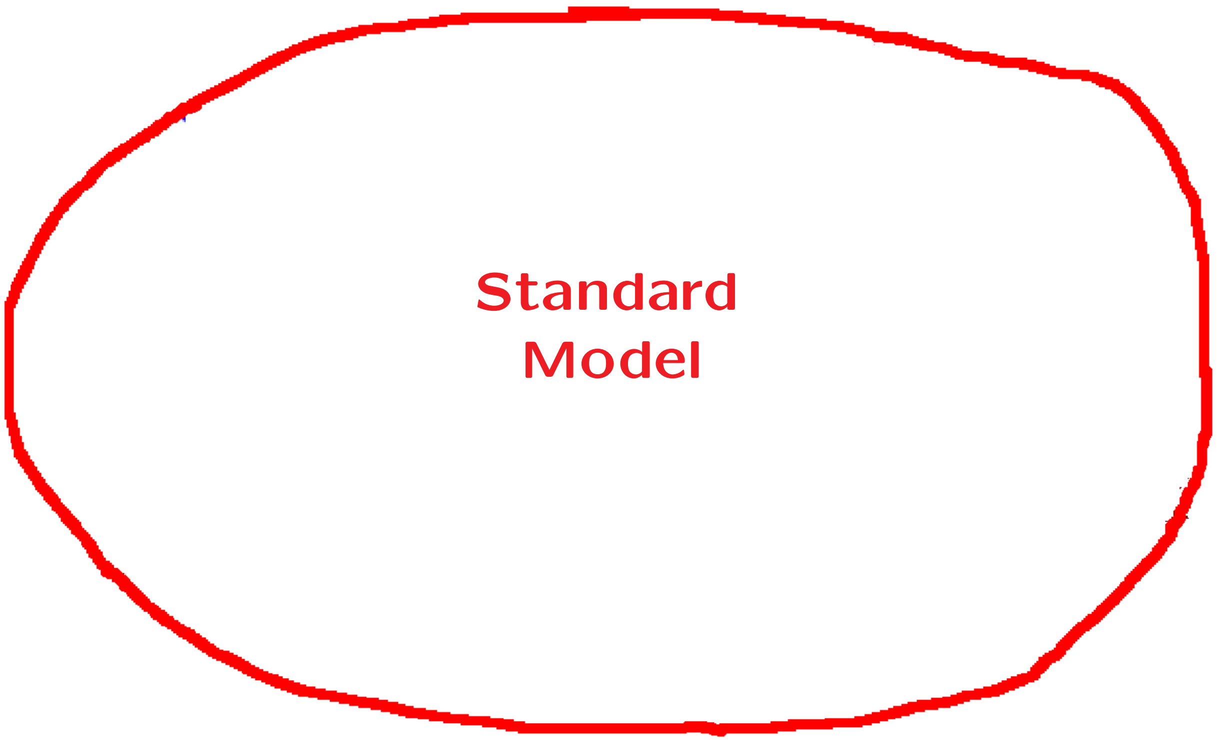
outline

- SM extensions
  - what is anticipated ?
  - what has been studied for ATLAS/CMS ?
- examples of BSM Higgs phenomenology
  - supersymmetric models
  - Little Higgs models
  - extra dimension models
  - simple Higgs sector extensions
- lessons to be learned
  - broader definition of “Higgs boson”
  - generic part of BSM Higgs sectors
  - beyond the standard signatures

• SM extensions

– what is anticipated ?



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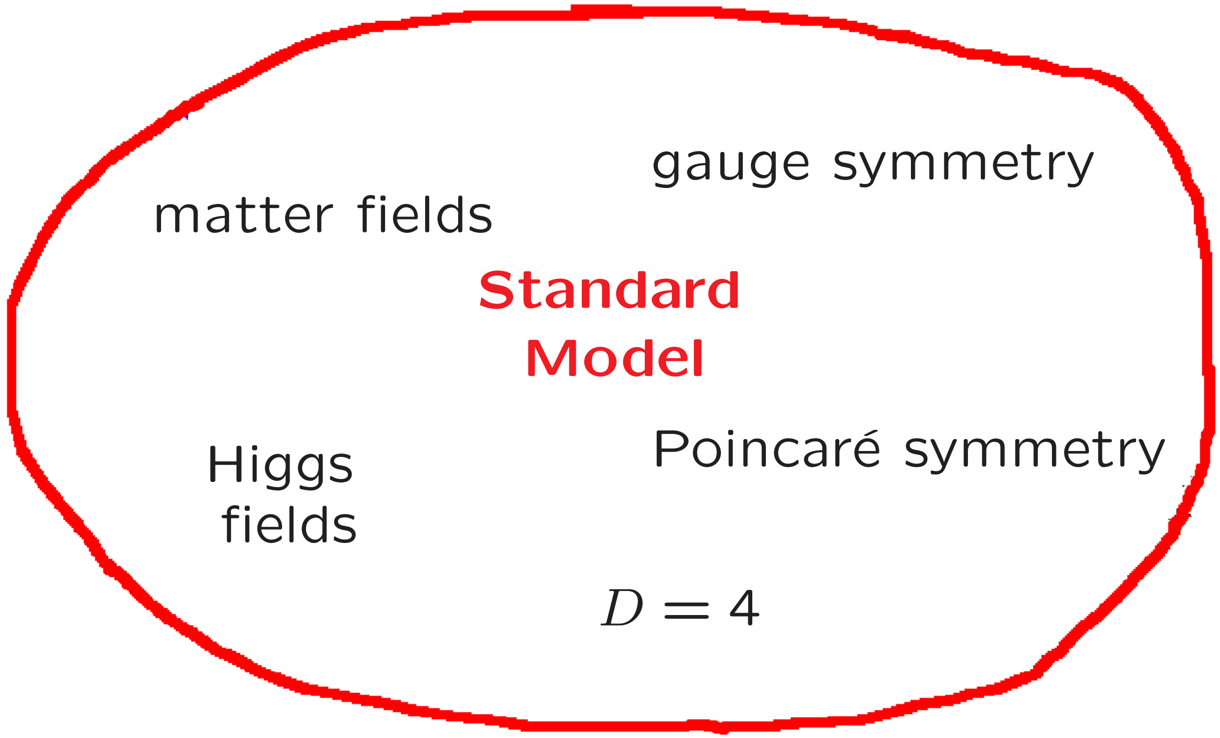

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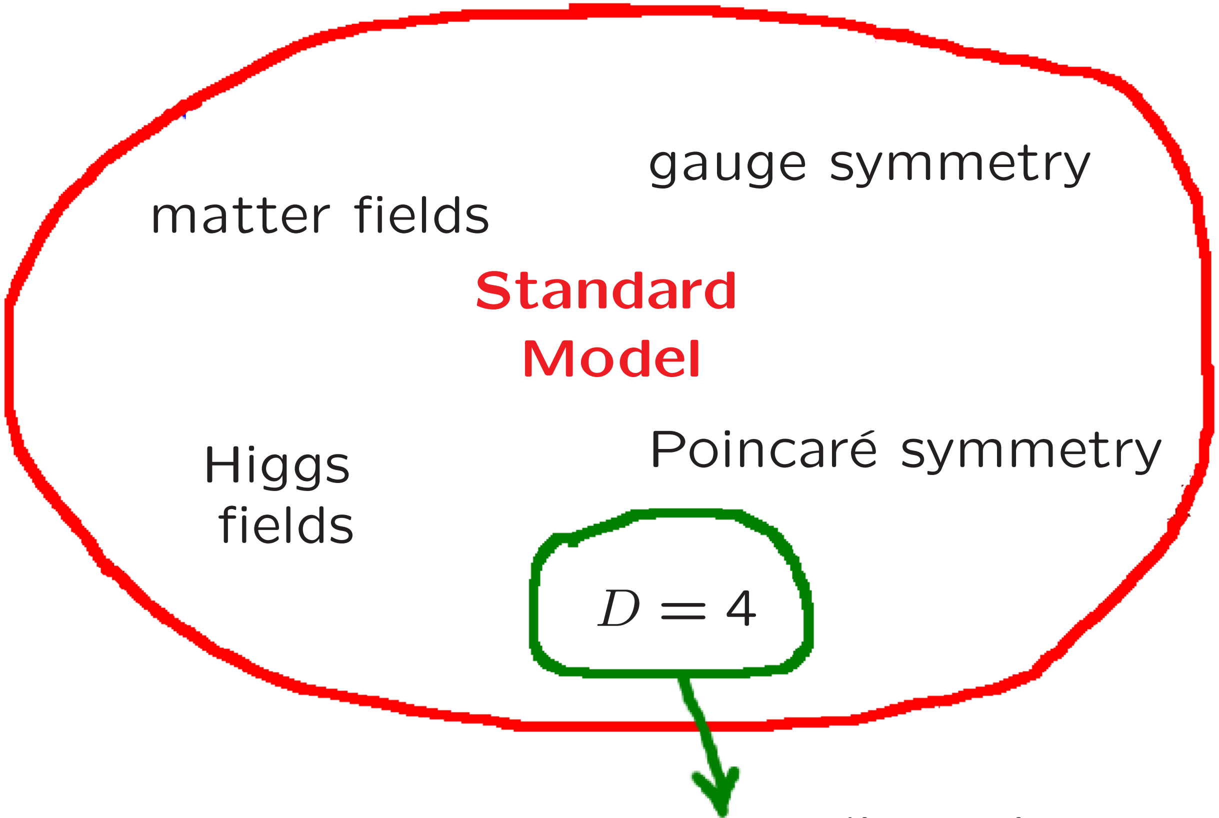

extra dimensions

⋆ universal ED

⋆ Randall-Sundrum

etc.

• SM extensions

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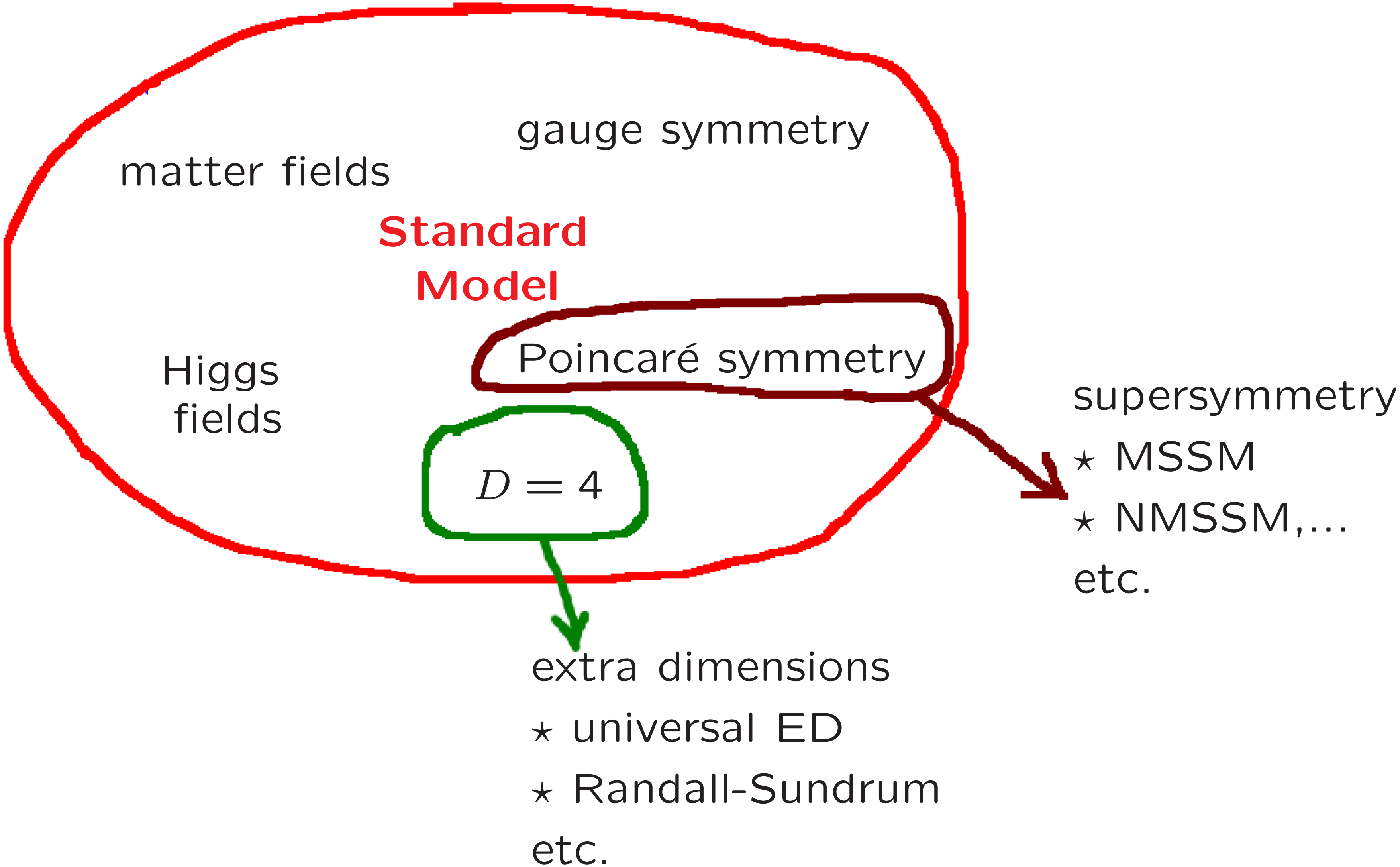


• SM extensions

– what is anticipated ?

extra gauge groups

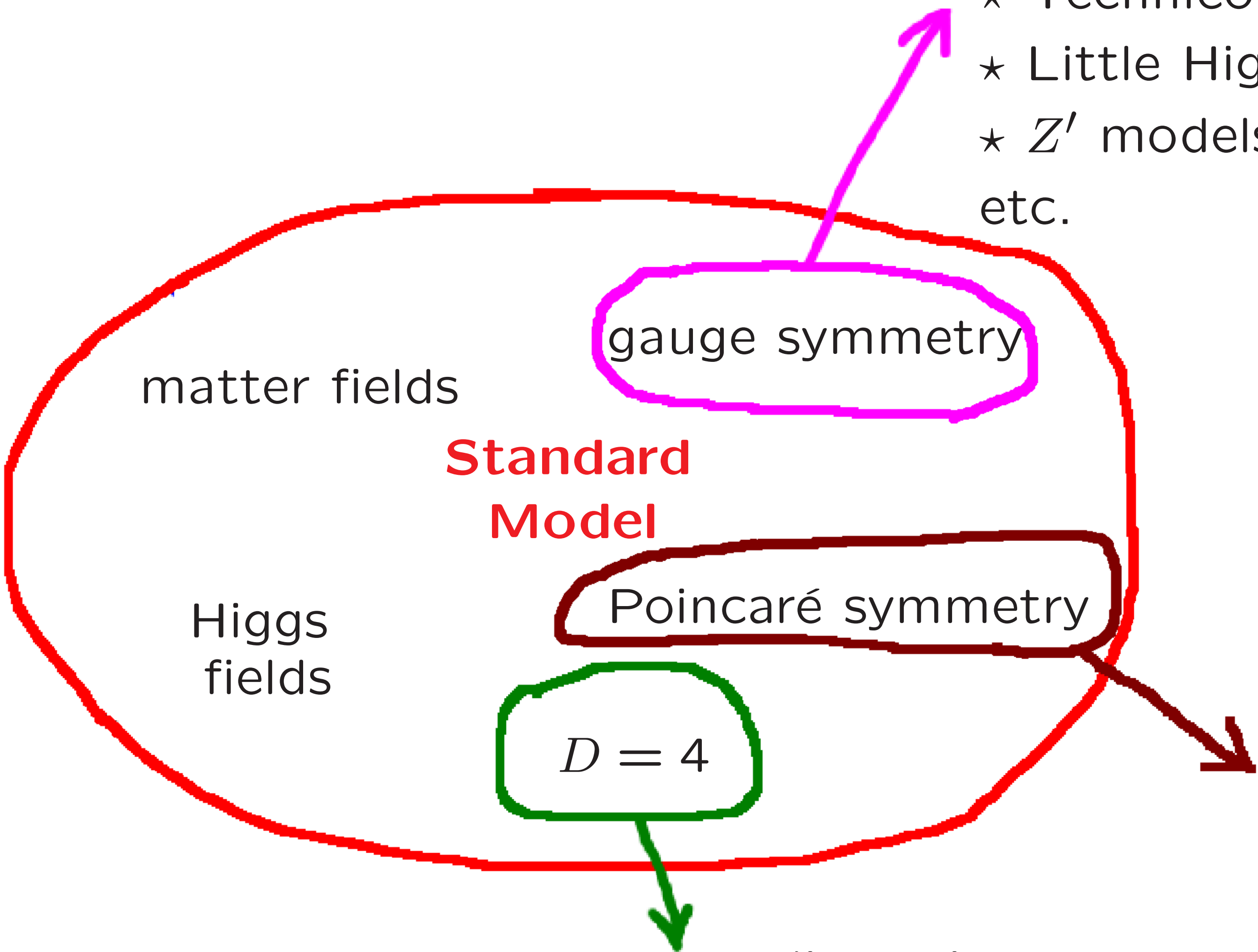
⋆ GUT

⋆ Technicolor

⋆ Little Higgs models

⋆ Z' models

etc.



supersymmetry

⋆ MSSM

⋆ NMSSM,...

etc.

extra dimensions

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etc.

• SM extensions

– what is anticipated ?

extra matter fields

⋆ SUSY

⋆ Little Higgs

⋆ 4th generation

etc.

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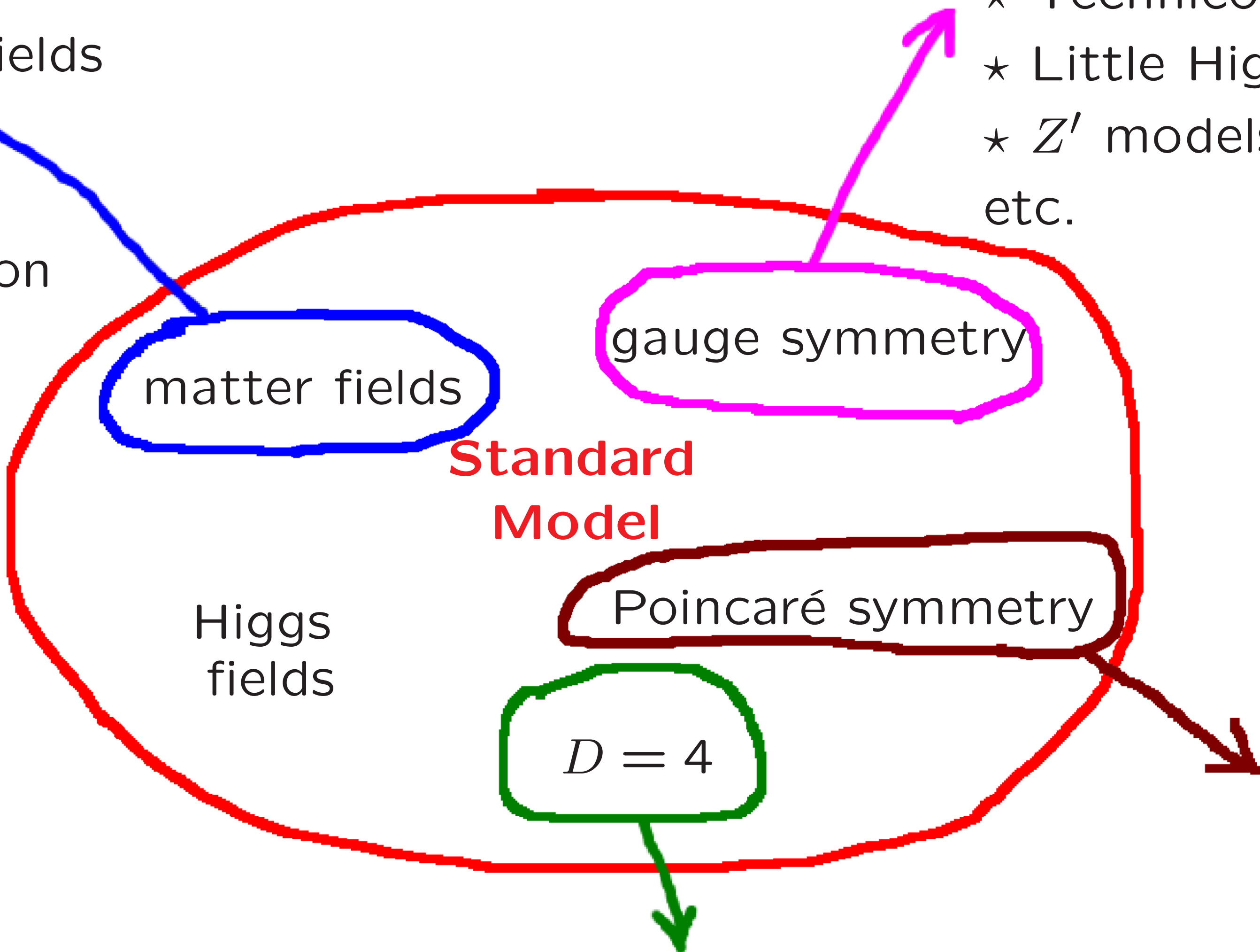
etc.



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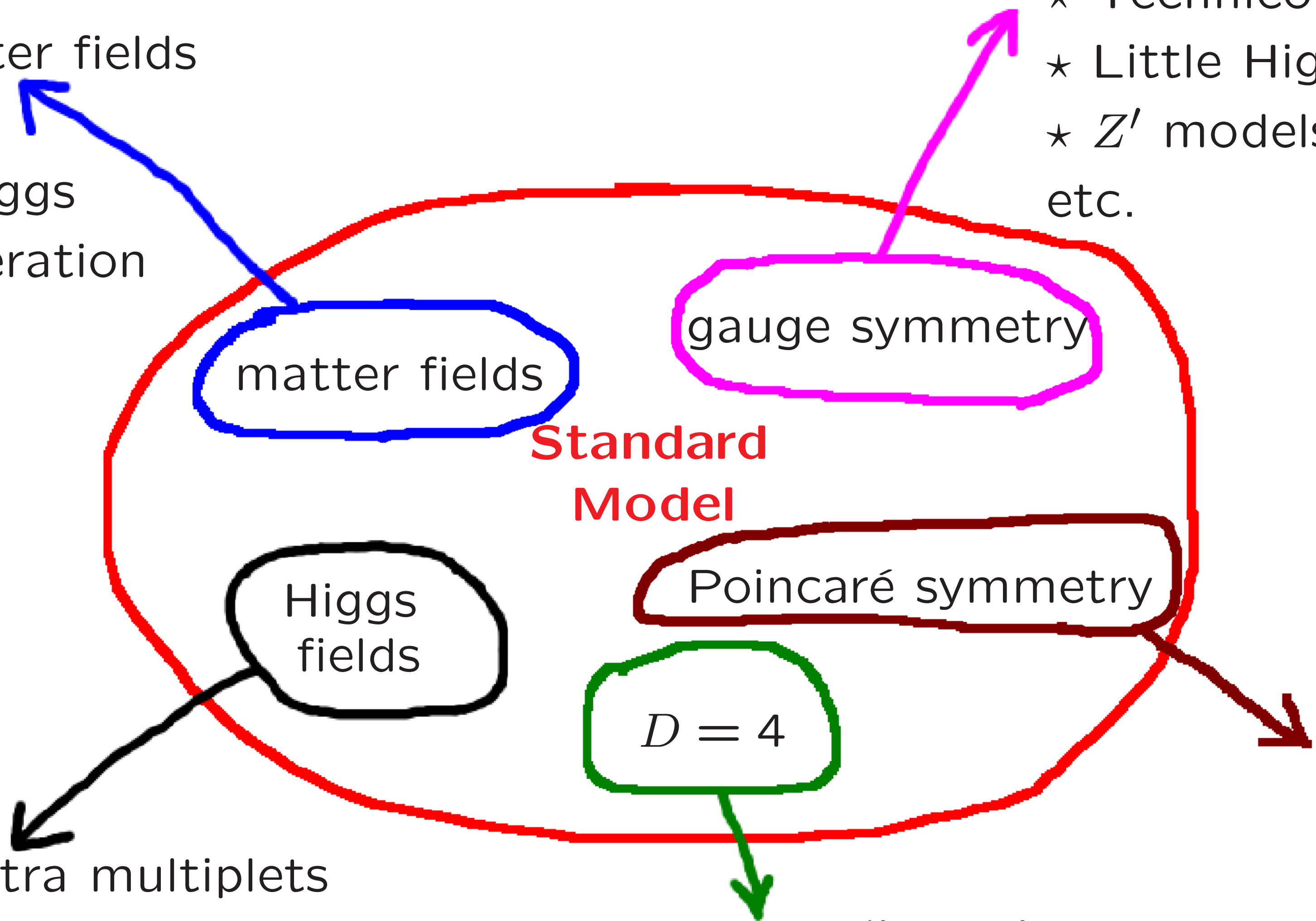

supersymmetry
⋆ MSSM
⋆ NMSSM,...
etc.

change/extra multiplets
⋆ SUSY
⋆ Little Higgs
⋆ Higgs triplet models
etc.

extra dimensions
⋆ universal ED
⋆ Randall-Sundrum
etc.

– what has been studied for ATLAS/CMS ?

BSM Higgs physics in the TDRs:

ATLAS-TDR ('99)	:	CP-conserving MSSM Higgs	:	59 pages
		strongly int. Higgs sector	:	7 pages
CMS-TDR('06)	:	CP-conserving MSSM Higgs	:	56 pages
		Higgs in RS model, $H^{\pm\pm}$ in LHM	:	14 pages

Recently, the report on the
"Workshop on CP studies and non-standard Higgs physics" (500+ pages)
appeared (including some ATLAS/CMS studies).

[Kraml et al. (eds.), hep-ph/0608079]

The following topics on Higgs physics beyond the common lore,
SM and MSSM (R-parity conserving & without CP phases that is),
have been identified and discussed:

- The CP-Violating Two-Higgs Doublet Model
- The Minimal Supersymmetric Standard Model with CP Phases [ATLAS]
- Supersymmetric Models with an Extra Singlet
- The MSSM with R-Parity Violation
- Extra Gauge Groups
- Little Higgs models [ATLAS/CMS]
- Large Extra Dimensions [CMS]
- Warped Extra Dim. and the Randall-Sundrum Model [ATLAS/CMS]
- Higgsless Models
- Strongly Interacting Higgs Sector and Anomalous Couplings
- Technicolor
- Higgs Triplets

I will touch the following topics from the report:

- The CP-Violating Two-Higgs Doublet Model
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+ simple Higgs sector extensions

• examples of BSM Higgs phenomenology

outline for the following:

- supersymmetric models
- Little Higgs models
- extra dimension models
- simple Higgs sector extensions

– supersymmetric models

Supersymmetry ...

... is *the* extension of the Poincaré-symmetry of space-time

... leads to a symmetry between Fermions & Bosons

gauge theory with minimal SUSY :

- same # of fermionic & bosonic d. o. f.
  $\longrightarrow$ a superpartner of different spin exists for each particle

- couplings are correlated
  $\longrightarrow$ e.g. scalar 4-point int. $\longleftrightarrow$ gauge couplings

- superpartners have the same mass
  $\longrightarrow$ SUSY must be broken at the electroweak scale

gauge theory with broken SUSY :

- superpartner masses enter as additional free parameters (essentially)

- MSSM (R-parity conserved & no new CP-phases):

The MSSM with R-parity intact and no new CP-phases is (by far) the most well studied model beyond the SM so far.

– content: SM matter, SM gauge bosons
+ 2 Higgs doublets Φ_1, Φ_2 (*only* consistent with 2 doublets)
+ Superpartners

– R-parity: discrete, multiplicative quantum number

$$R\left(\left\{\begin{array}{c}\text{regular particles}\\ \text{superpartners}\end{array}\right\}\right) = \left\{\begin{array}{l}+1\\ -1\end{array}\right. \quad \rightarrow \text{FCNC}, \not{L}, \not{B} \text{ avoided}$$

– real-valued SUSY parameters $\rightarrow$ no new CP-phases introduced

- MSSM (R-parity conserved & no new CP-phases):

  Higgs sector:

– $\Phi_1, \Phi_2 \rightarrow$ 5 physical Higgs bosons: h^0, H^0, A^0, H^+, H^-

– all Φ^4-interactions determined by gauge couplings
  $\longrightarrow$ only two Higgs sector input parameters: m_{A^0}, $\tan\beta$ $(= v_2/v_1)$
  $\longrightarrow$ bound on lightest neutral Higgs mass $(m_{h^0} \lesssim 135\,\text{GeV})$

– large quantum corrections to Higgs masses (esp. to m_{h^0})

  present status: two-loop precision, see [Heinemeyer, Hollik, Weiglein '06]

- MSSM (R-parity conserved & no new CP-phases):

  Higgs phenomenology: well developed

  example: status of predictions for main neutral Higgs production processes ($H^0_{1,2,3} = h^0, H^0, A^0\}$):

– gluon fusion, $gg \to H^0_i$
NLO QCD, no superpartners [Djouadi, Spira, Zerwas, Graudenz '91/'93]
NLO SUSY-QCD
[Harlander, Steinhauser '04; Harlander, Hofmann '06; Mühlleitner, Spira '06]

– weak boson fusion, $qq \to qqH^0_i$
NLO SUSY-QCD [Djouadi, Spira '00]

– Higgs Strahlung, $q\bar{q}' \to VH^0_i (V = W, Z)$
NLO SUSY-QCD [Djouadi, Spira '00]

– $t\bar{t}H^0_i, b\bar{b}H^0_i$
LO, $Q\bar{Q} \to H^0_i, gg \to Q\bar{Q}H^0_i$ $(Q = t, b)$ [Dicus, Willenbrock '89]
NLO QCD, no superpartners [Dawson, Jackson, Reina, Wackeroth '03]

– $b\bar{b} \to H^0_i$
NLO SUSY-QCD & NLO EW, [Dittmaier, Krämer, Mück, Schlüter '06]

- MSSM (R-parity conserved & no new CP-phases):

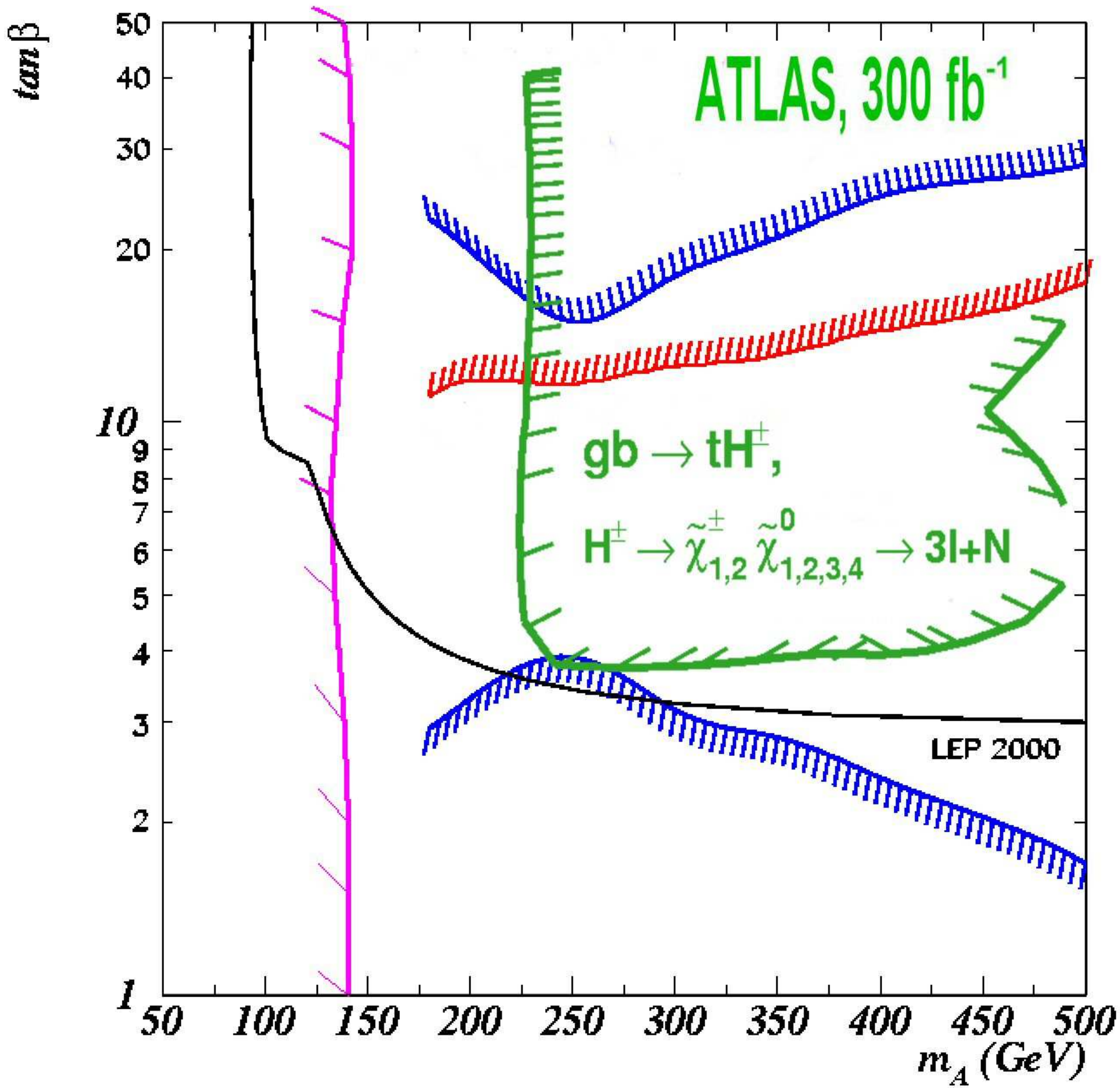
  Higgs phenomenology: some thoughts on future directions

– provide all relevant predictions also for light (allowed) superpartners
  LHC Higgs physics: many relevant loop-induced processes
  e.g. 3-point vertices: ggH_i^0, $\gamma\gamma H_i^0$, $\gamma W^{\pm}H^{\mp}$, $ZW^{\pm}H^{\mp}$,
  4-point vertices: $ggH_i^0H_j^0$, $ggH_i^0\{\gamma, Z\}$, $ggH^{\pm}W^{\mp}$, $gg\{\gamma, Z, W^+\}\{\gamma, Z, W^-\}$
  SM + superpartner particles appear both at LO (= one-loop)

– take full $\hat{s}$- and $\hat{t}$-dependence into account in physics simulations
  (not just K-factors, angular distributions may change as well)

– study scenarios with allowed decays $H_i^0 \rightarrow$ superpartners
  $\rightarrow$ may allow for new search strategies
  example: improvement of $H^{\pm}$ search in the wedge-region ($\rightarrow$ plot)

example: $H^{\pm}$ search with $H^{\pm} \to \chi_1^0 \chi_1^{\mp}$ allowed:



great improvement of the ATLAS $H^{\pm}$ discovery reach in the wedge-region

if $m_{H^{\pm}} > m_{\chi_1^0} + m_{\chi_1^+}$

[Hansen et al.'05]

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  SM + superpartner particles appear both at LO (= one-loop)

– take full $\hat{s}$- and $\hat{t}$-dependence into account in physics simulations
  (not just K-factors, angular distributions may change as well)

– study scenarios with allowed decays $H_i^0 \to$ superpartners
  $\to$ may allow for new search strategies
  example: improvement of $H^\pm$ search in the wedge-region ($\to$ plot)

– adopt refined SM Higgs search strategies (where possible)
  e.g. $gg \to h^0$ + high-p_T jet [OBr, Hollik '03 and work in progress]

– precise predictions for signals require SUSY-loops in background too
  (not just SM background), e.g. superpartner loops in $gg \to WW, \gamma\gamma$, etc.

– ...

- MSSM with R-parity violation:

well motivated: introducing R-parity violating interactions with $\not{L}$

consequences for Higgs phenomenology :

– Higgs bosons mix with sleptons (5 doublets, 3 complex singlets)

6 sneutrino d.o.f.	$+$	3 neutral Higgs d.o.f	$\rightarrow$	5 H_i^0, 4 A_i^0
12 charged slepton d.o.f.	$+$	2 charged Higgs d.o.f	$\rightarrow$	7 $H_i^\pm$

– Higgs-like and slepton-like decay channels open up

– couplings not entirely $\propto$ mass

$\rightarrow$ typical Higgs-signature can be obscured if mixing is strong

- SUSY models with an extra singlet (NMSSM,mnSSM):

Superpotential of MSSM contains μ-term (μ: mass dimension 1):

$$W_{\text{MSSM}} = W_{\text{super-Yukawa}} + \epsilon_{ij}\mu\widehat{H}_d^i\widehat{H}_u^i$$

$$\mathcal{L}_{\text{soft}} = -m_{H_d}^2|H_d|^2 - m_{H_u}^2|H_u|^2 - (\mu B_\mu \epsilon_{ij} H_u^i H_d^j + \text{h.c.})$$
$$+ \text{[sfermion + gaugino mass terms]}$$

problem:

Higgs mass formulae:		supersymmetric GUT:
μ should be $\approx \mathcal{O}$(SUSY breaking scale)	$\leftrightarrow$	μ should be of order M_{GUT}

solution: MSSM + singlet superfield $\hat{S}$ (contains complex scalar field S):

– in the minimum of the scalar potential H_u, H_d, S acquire VEVs

– MSSM μ-term generated dynamically $\mu_{\text{eff}} = \lambda\langle S\rangle$ (λ dimensionless)

– μ_{eff} is naturally $\mathcal{O}$(SUSY breaking scale)

- SUSY models with an extra singlet (NMSSM,mnSSM):

variant 1: NMSSM (Next-to-minimal supersymmetric Standard Model)

$$W_{\text{NMSSM}} = W_{\text{super-Yukawa}} + \epsilon_{ij}\lambda\widehat{S}\widehat{H}_d^i\widehat{H}_u^i + \frac{\kappa}{3}\widehat{S}^3$$

$$\begin{aligned}\mathcal{L}_{\text{soft}} = & -m_{H_d}^2|H_d|^2 - m_{H_u}^2|H_u|^2 - m_S^2|S|^2 \\ & - (\lambda A_\lambda \epsilon_{ij} S H_u^i H_d^j + \frac{\kappa}{3}A_\kappa S^3 + \text{h.c.}) \\ & + [\text{sfermion + gaugino mass terms}]\end{aligned}$$

variant 2: mnSSM (minimal non-minimal supersymmetric Standard Model)

[Panagiotakopoulos, Pilaftsis '00; Dedes et al. '00]

$$W_{\text{mnSSM}} = W_{\text{super-Yukawa}} + \epsilon_{ij}\lambda\widehat{S}\widehat{H}_d^i\widehat{H}_u^i \;[+t_F\widehat{S}]$$

$$\begin{aligned}\mathcal{L}_{\text{soft}} = & -m_{H_d}^2|H_d|^2 - m_{H_u}^2|H_u|^2 - m_S^2|S|^2 + t_S S \\ & - (\lambda A_\lambda \epsilon_{ij} S H_u^i H_d^j + \text{h.c.}) \\ & + [\text{sfermion + gaugino mass terms}]\end{aligned}$$

t_F-term usually too suppressed to play a role at TeV-colliders

- SUSY models with an extra singlet (NMSSM,mnSSM):
  (some) consequences for Higgs phenomenology :

similar for both models:

– Higgs sector: 2 doublets + 1 complex singlet $\rightarrow H_1^0, H_2^0, H_3^0, A_1^0, A_2^0, H^\pm$

– relaxed theoretical upper bound on the lightest Higgs mass ($\approx$ 150 GeV)

– relaxed LEP-bound on mass of H_1^0 and $H^\pm$ (about 80 GeV, $\rightarrow$ plot)

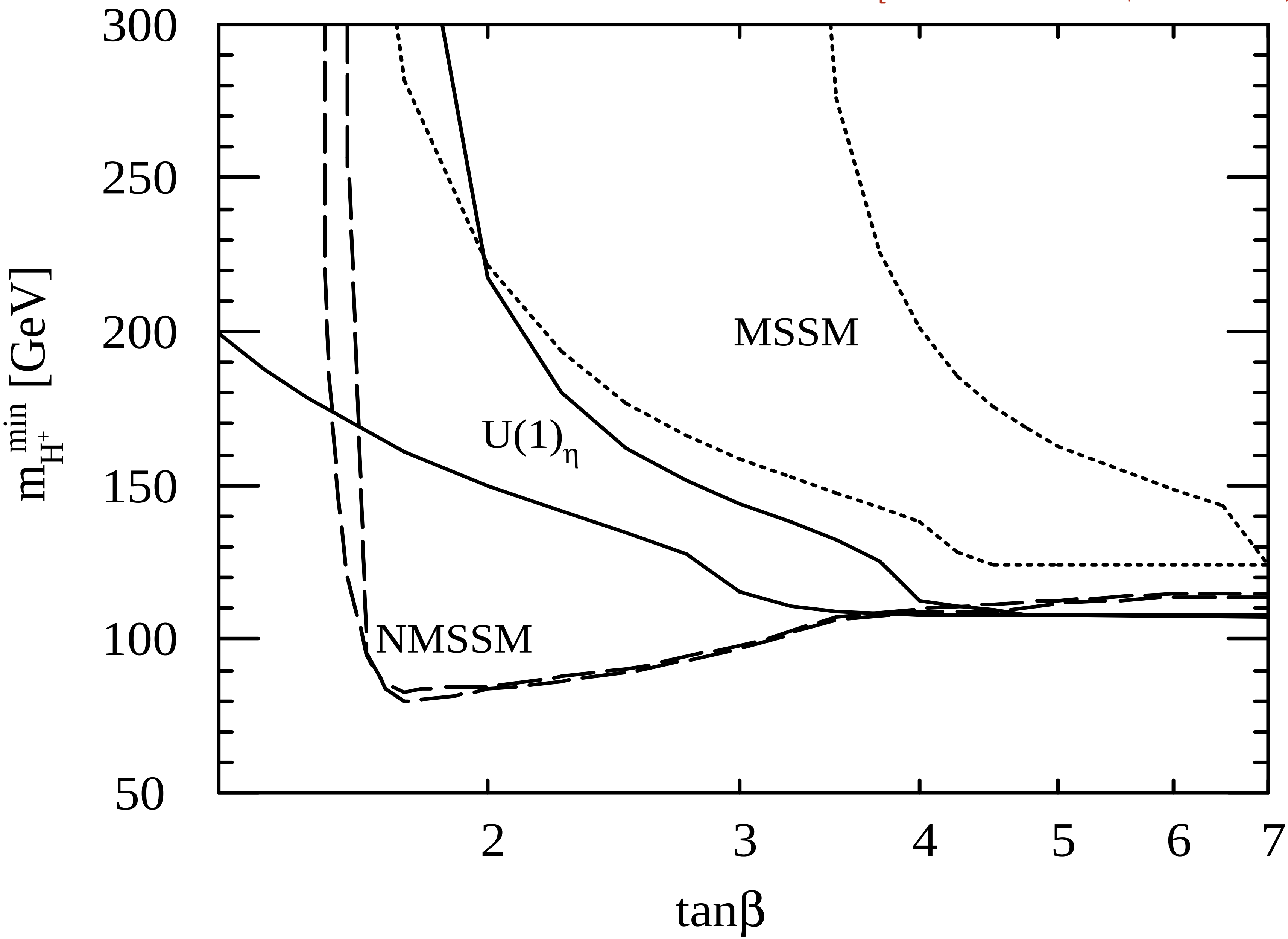
– $H^\pm$ production and decay in LO unchanged compared to MSSM

– Decays heavy Higgs $\rightarrow$ 2 Higgs bosons often possible
$\rightarrow$ problematic to see at LHC if lighter Higgs bosons decay mainly to $b\bar{b}$

example: relaxed indirect $H^{\pm}$ mass bound in NMSSM:

$m_{H^{\pm}} \approx m_W^2 + m_{A_1}^2 - \lambda^2 v^2/2$ and LEP-bound on m_{A_1} lower than on m_A^{MSSM}

[Drees et al.'98; Godbole, Roy '06]



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distinctive features:

– # of Higgs sector parameters: 6 (NMSSM) and 5 (mnSSM)

→ mnSSM more restrictive than NMSSM, e.g.:

– mnSSM mass sum rule (not present in NMSSM) :

$$m^2_{H_1} + m^2_{H_2} + m^2_{H_3} = m^2_Z + m^2_{A_1} + m^2_{A_2}$$

– mnSSM Higgs-Z coupling complementarity :

$$g^2_{H_1 ZZ} = g^2_{H_2 A_1 Z}\,, \qquad\qquad g^2_{H_2 ZZ} = g^2_{H_1 A_1 Z}$$

→ testing such relations crucial to distinguish between the models

– Little Higgs models

motivation: Higgs boson naturally light if Higgs mass protected
by a symmetry (i.e. mass $\to 0$ should increase symmetry)

well-known: supersymmetry

here: shift symmetry $\to$ Higgs bosons as pseudo-Goldstone bosons

classical naturalness argument:

Higgs mass m_H sensitive to cut-off scale Λ of the theory:

one expects $M_H \propto (\frac{g}{4\pi})\Lambda$ (from one-loop rad. cor.)

$\to$ with $g \approx \mathcal{O}(1)$ and $m_H = \mathcal{O}(100)$ GeV from EW precision data
one gets $\Lambda \approx 1$ TeV

$\to$ strong coupling dynamics should set in at around 1 TeV
$\to$ ruled out by EW precision data!

idea of Little Higgs models: one-loop rad. cor. cancel due to a symmetry

Then $M_H \propto (\frac{g}{4\pi})^2\Lambda \to m_H = \mathcal{O}(100)$ GeV for $\Lambda \approx 10$ TeV

$\to$ Higgs naturally light *and* no problems with EW precision data idea of Little Higgs models: one-loop rad. cor. cancel due to a symmetry

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$\to$ Higgs naturally light *and* no problems with EW precision data

realization: collective symmetry breaking principle

$\to$ class of models (effective theories, applicable up to ≈ 10 TeV)

$\to$ new TeV-scale (f) gauge bosons, fermions and scalars appear

$\to$ at the EW-scale only scalars appear

Higgs sectors of LH models

Model	EW-scale scalars	TeV-scale f scalars
Minimal moose	$\Phi_1, \Phi_2, \Sigma, S^c$	(none)
Minimal moose with SU(2)$_C$	Φ_1, Φ_2	$\Sigma^r, S^c_\pm, S^r$
Moose with T-parity	Φ_1, Φ_2	$\Phi_{3,4,5}, \Sigma^r_{1,2,3}, S^c_{1,..,5}, P_{1,2,3}$
Littlest Higgs	Φ	Σ
SU(6)/Sp(6) model	Φ_1, Φ_2	S^c
Littlest Higgs with SU(2)$_C$	Φ	Σ, Σ^r, P
Littlest Higgs with T-parity	Φ	Σ
SU(3) simple group	Φ, P	(none)
SU(4) simple group	Φ_1, Φ_2, P_1, P_2	S^c_1, S^c_2, S^c_3
SU(9)/SU(8) simple group	Φ_1, Φ_2	S^c_1, S^c_2

with Φ scalar doublet,
S^c complex scalar singlet,
S^r real scalar singlet,
P pseudoscalar singlet,
Σ complex triplet,
Σ^r real triplet.

(some) consequences for Higgs phenomenology:

example: Littlest Higgs model : 1 doublet at EW scale

– Higgs couplings identical to SM up to $\frac{v}{f}$-corrections ($\frac{v}{f} \approx \frac{250}{1000} = \frac{1}{4}$)
  $\rightarrow$ $\sigma \times$BR deviates from SM by $(\frac{v}{f})^2 \approx$ few %.
  $\rightarrow$ requires % accuracy measurements to distinguish from SM

– Test of divergency cancellation relations
  The 4-point interactions of a Higgs bosons H
  with heavy gauge bosons V_i have to fulfil

$$\sum_i G_{HHV_iV_i} = 0$$

  in order to cancel one-loop quadratic divergencies
  in the Higgs self energy.
  After EWSB the $G_{HHV_iV_i}$ give rise to corresponding $G_{HV_iV_i}$-couplings.
  $\rightarrow$ Measurement of all $\sigma(q\bar{q} \rightarrow V_i^\star \rightarrow HV_i)$
  could give information on $G_{HHV_iV_i}$.

– extra dimension models

example: 5D universal extra dimensions (UED)

– mass scale $1/R > 250 - 500\,\text{GeV}$ [Apelquist,.. '..]

→ mainly KK-modes n=0,1,2 relevant at LHC

– KK-parity conserved: multiplicative quantum number $(-1)^n$

→ $n = 1$ Higgs-KK-modes can't decay into just SM particles

→ appearent Higgs sector:

$n = 0$ equivalent to SM Higgs sector

$n = 1$ doesn't look like Higgs

$n = 2$ KK-modes can decay again in $n = 0$-modes

→ look like heavy Higgs bosons

→ effective Higgs sector: $h^0, H^0 = h^0_{(2)}, A^0 = G^0_{(2)}, H^\pm = G^\pm_{(2)}$ (like 2HDM)

– simple Higgs sector extensions

• singlet extensions

motivation: the SM Higgs doublet Φ is the only multiplet which can have renormalizable interactions with a hidden, SM-singlet sector:

$$\mathcal{L}_{\text{Higgs-hidden sector int.}} \propto (\Phi^\dagger \Phi)(\phi^{(\dagger)}\phi)_{\text{hidden}}$$

Extension of the SM by ...

... a complex SU(2)-singlet scalar: Higgs sector: H_1^0, H_2^0, A_1^0

- hidden sector singlet:
  A_1^0 eaten by spontaneously broken $U(1)_{\text{hidden}} \to H_1^0, H_2^0$ remain
  [Schabinger, Wells '05,...]
- minimal phantom sector (contains extended neutrino sector):
  global $U(1)$ symmetry broken $\to H_1^0, H_2^0, A_1^0 (= J$, massless Goldstone)
  [Cerdeño, Dedes, Underwood '06]

... a real SU(2)-singlet scalar: Higgs sector : H_1^0, H_2^0

[v.d. Bij '06; O'Connell et al. '06; Bahat-Treidel, et al.'06]

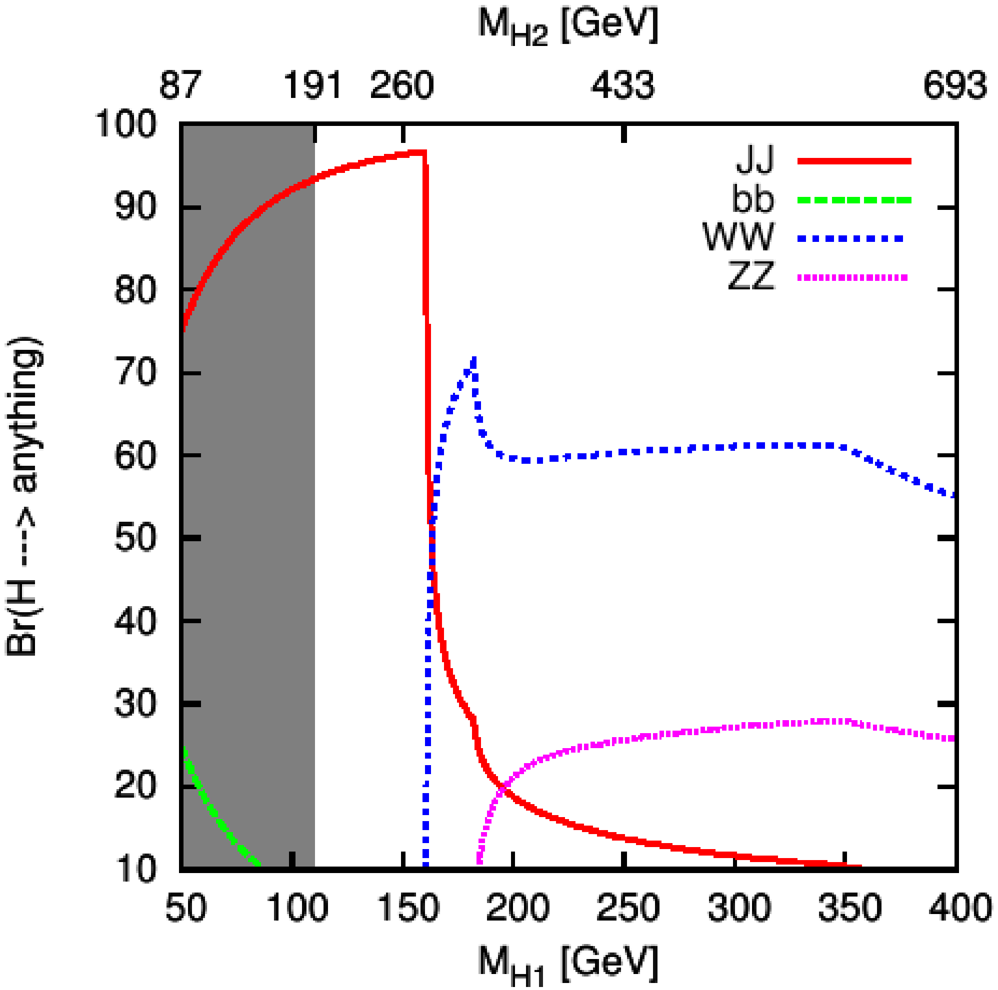
consequences for Higgs phenomenology

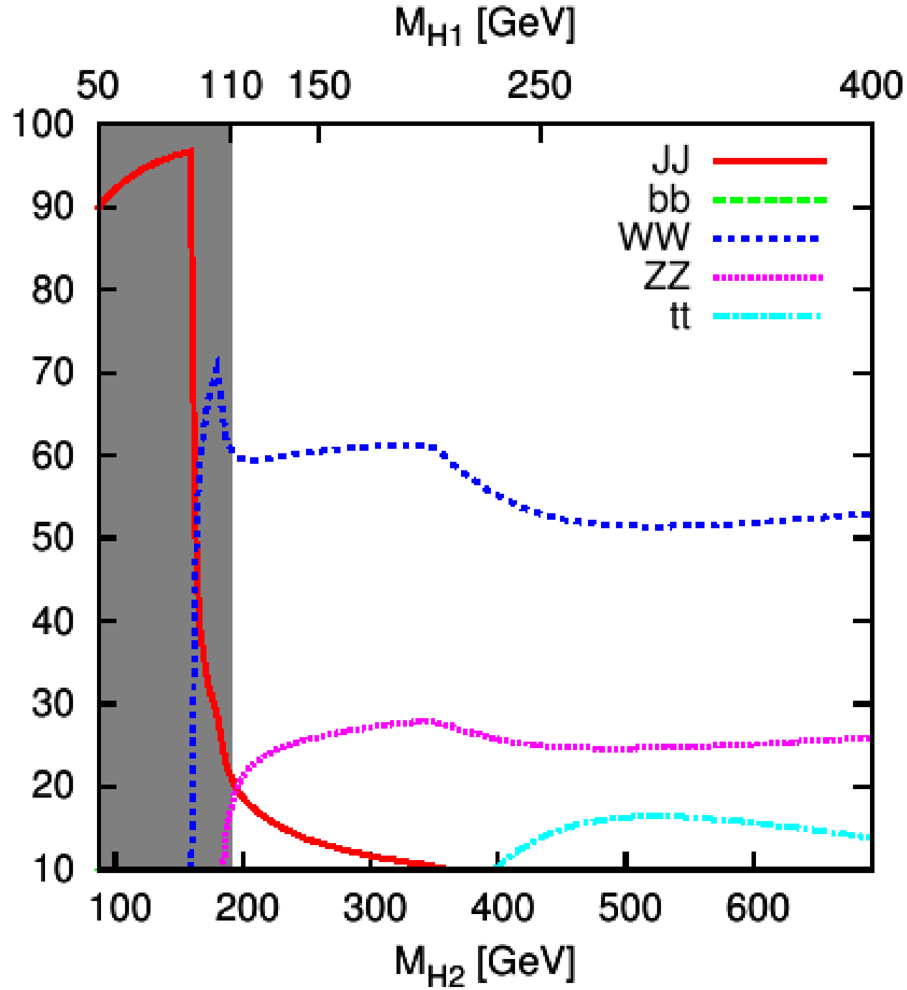
– mixing of new scalar(s) with ordinary Higgs d.o.f.

– couplings of scalars to SM particles reduced by mixing angles

– potentially large BR(Higgs $\to$ invisible)

example: almost invisible decay of lightest Higgs in phantom sector model





[Cerdeño, Dedes, Underwood '06]

• lessons to be learned

– broader definition of "Higgs boson"

⋆ in the SM a transparent definition exists:

one scalar doublet (4 real d.o.f.) acquires a VEV

$\longrightarrow$ 3 would-be Goldstone bosons form W_L^+, W_L^- and Z_L

$\longrightarrow$ one massive physical scalar: the Higgs boson

⋆ in extended models an unambiguous definition can be tricky:

problems:

– several scalar weak multiplets, not all acquiring a VEV, mix among each other due to self-interaction (e.g. Inert Higgs model)

– SUSY models with $\not{L}$: sneutrino/selectron mix with "Higgs" multiplets (e.g. R-parity violating MSSM)

– electroweak singlet scalars can mix with neutral "Higgs" state (e.g. singlet extension of SM, NMSSM, RS model)

suggested definition:

A Higgs boson is a physical scalar d.o.f from

a) an electroweak multiplet triggering EWSB by its VEV

or

b) a multiplet mixing with such states

– generic part of BSM Higgs sectors

a typical BSM Higgs sector is a combination of a few

scalar (real, S^r, complex, S^c) or pseudoscalar electroweak singlets P,
electroweak doublets Φ ,
electroweak triplets Σ (real or complex)

multiplets		physical states		models
Φ	:	H^0	:	SM
Φ, S^r	:	H_1^0, H_2^0	:	simple extension, RS model, ...
Φ, S^c	:	H_1^0, H_2^0, A^0	:	simple extension, ...
Φ_1, Φ_2	:	$h^0, H^0, A^0, H^\pm$	:	2HDM, MSSM, some LH models, 5D-UED (effectively), ...
Φ_1, Φ_2, S^c	:	$H_1^0, H_2^0, H_3^0, A_1^0, A_2^0, H^\pm$	:	NMSSM, mnSSM, some LH models, ...
Φ, Σ	:	$H_1^0, H_2^0, A_1^0, H^\pm, H^{\pm\pm}$	:	Higgs triplet model, ...
$5\Phi_i, 3S_i^c$	:	$5H_i^0, 4A_i^0, 7H_i^\pm$	:	R-parity viol. MSSM with $\not{L}$
...	:	...	:	some LH models, ...

→ large parts of Higgs phenomenology is rather model independent.

– beyond the standard signatures

expect the unexpected ! as for example:

- scalar particles strongly but not entirely coupling $\propto$ mass
  could be: MSSM with explicit R-parity violation

- scalar particles strongly decaying invisibly
  could be: singlet extensions of SM, large extra dimensions, Majoron of MSSM with spontaneous R-parity violation

- 2 CP-even scalars, 1 CP-odd, 1 charged found
  could be: MSSM, NMSSM, 5D-UED model, several LH models

- almost SM behaviour but significant small deviations
  could be: MSSM/2HDM almost in decoupling limit, Littlest Higgs model

- CP-violation in the Higgs sector