CLIC Physics after LHC

September 2, 2011

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Where does Higgs, SUSY, Xdim, etc. fit in?

What'll be most important physics >2020?

No answer can be given now.

LHC will guide us. Limits guiding us now

We are showing that LC can make new discoveries* of the leading theories of today beyond the experiments that precede it.

*** "discoveries" is all encompassing (e.g., new particles, new interactions, precision, etc.)**

“Leading Theories of Today”

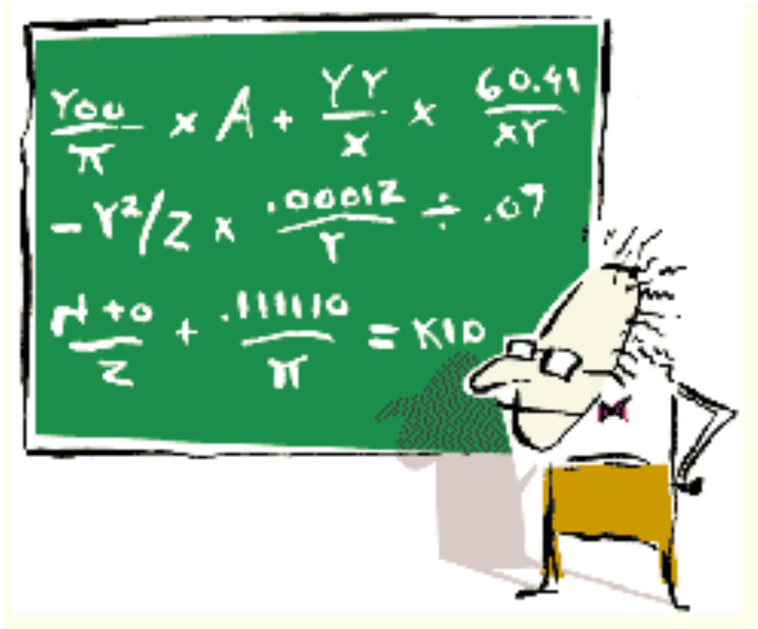
Standard Model

Supersymmetry

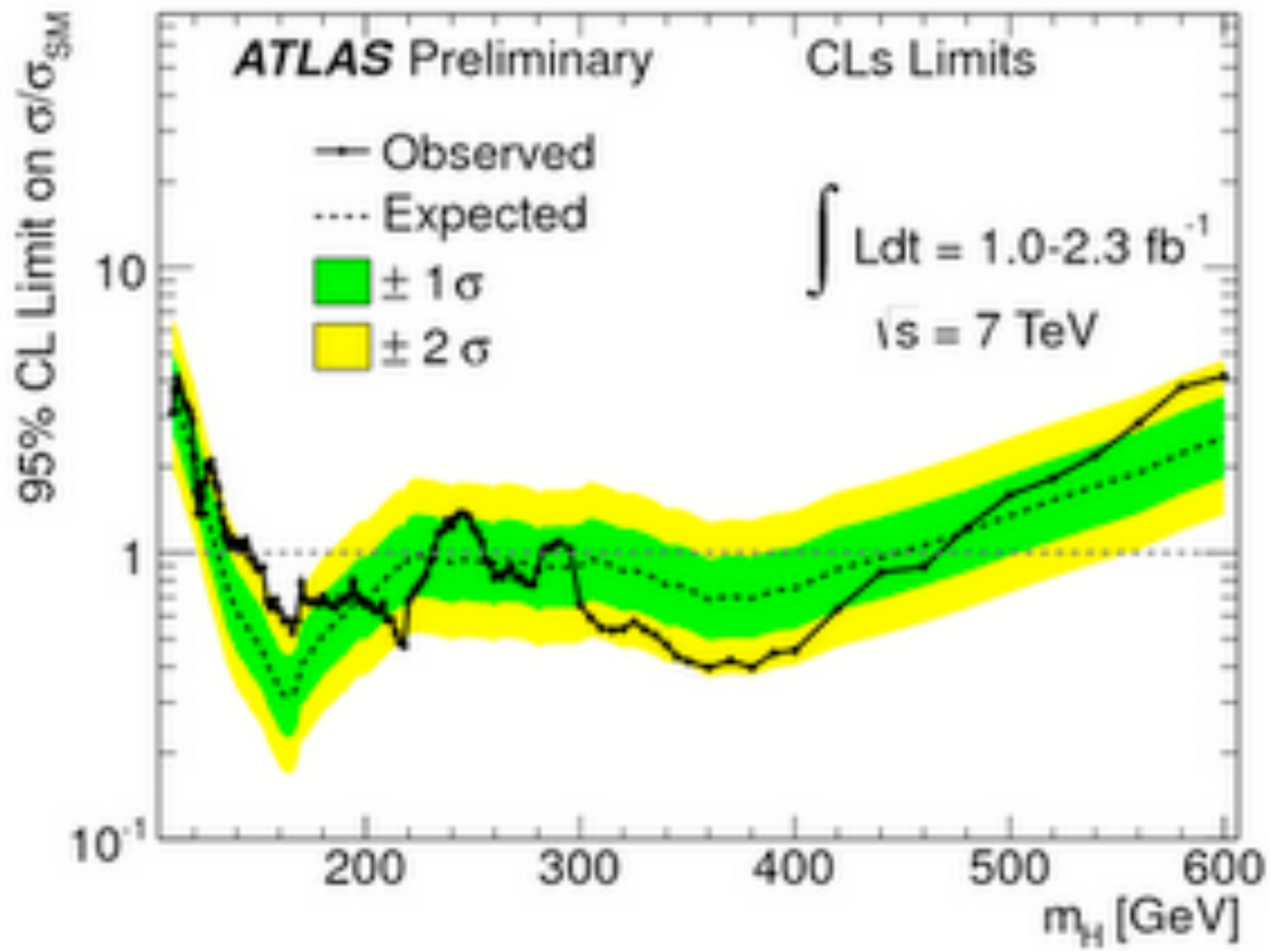
Alternatives: Xdims, SCTs, etc.

Higgs boson physics

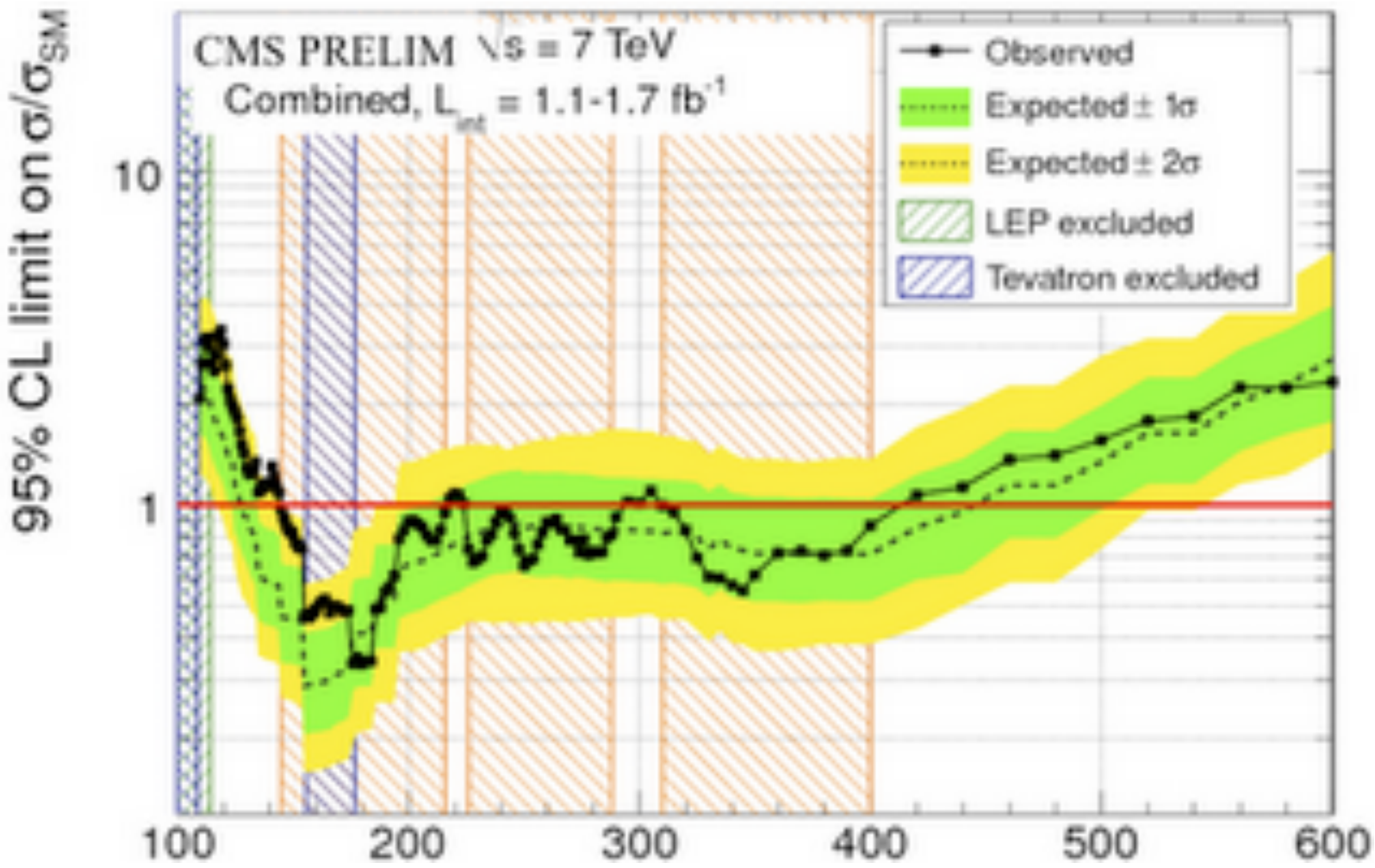
chcr.umich.edu

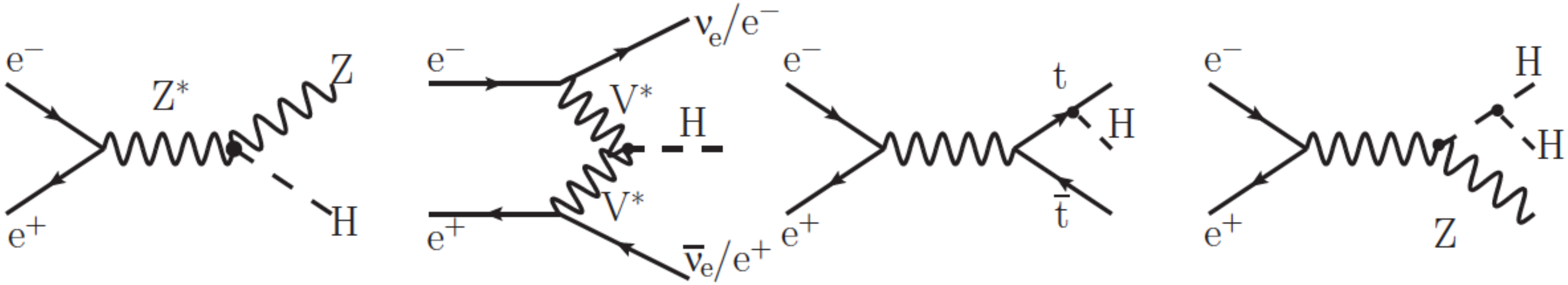


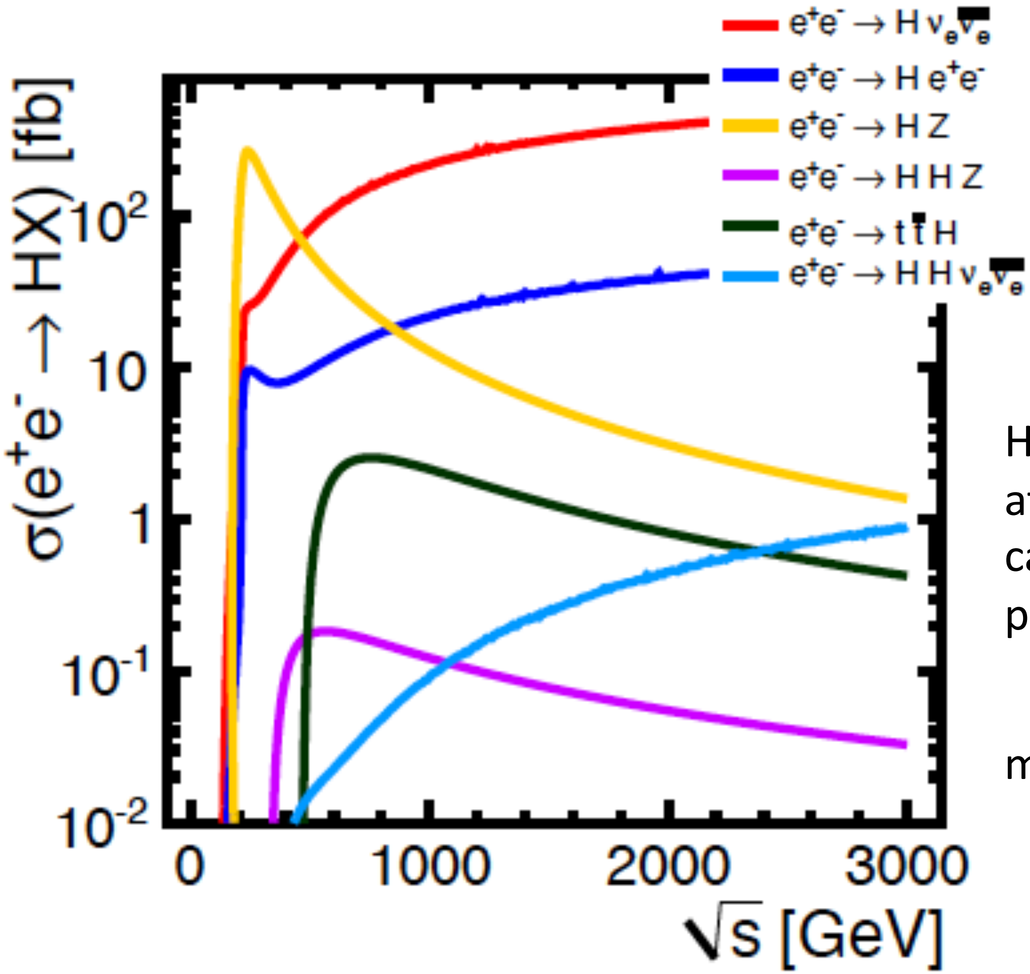
Higgs limit ATLAS



Higgs limit CMS

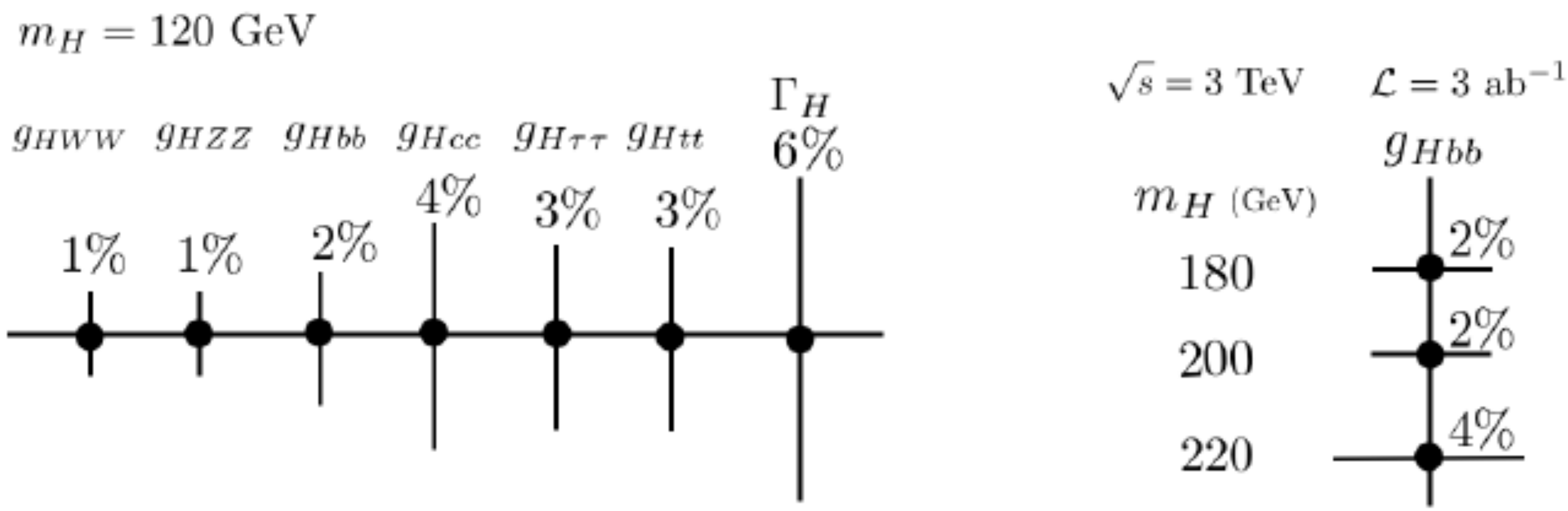






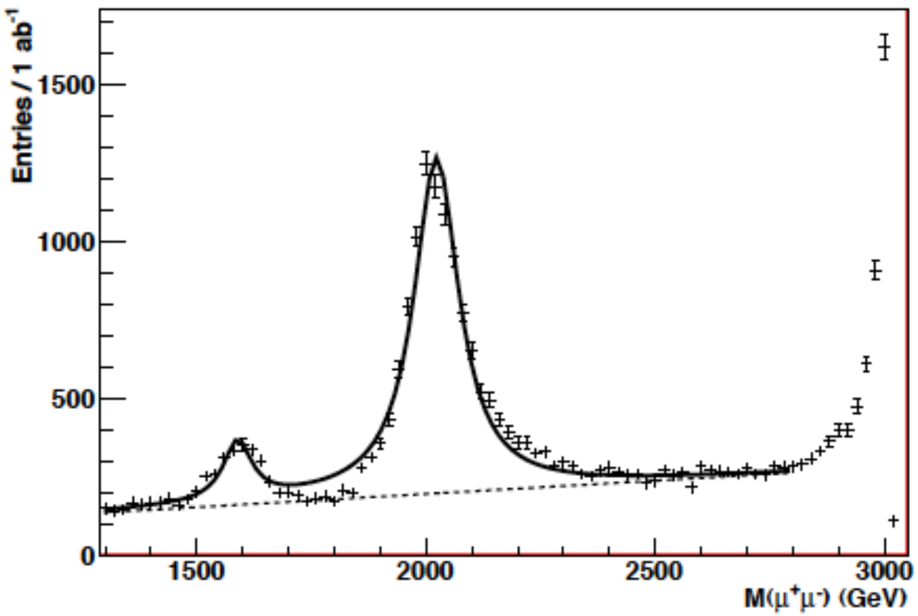
Higgs will be discovered at LHC eventually, and can be studied very precisely at CLIC.

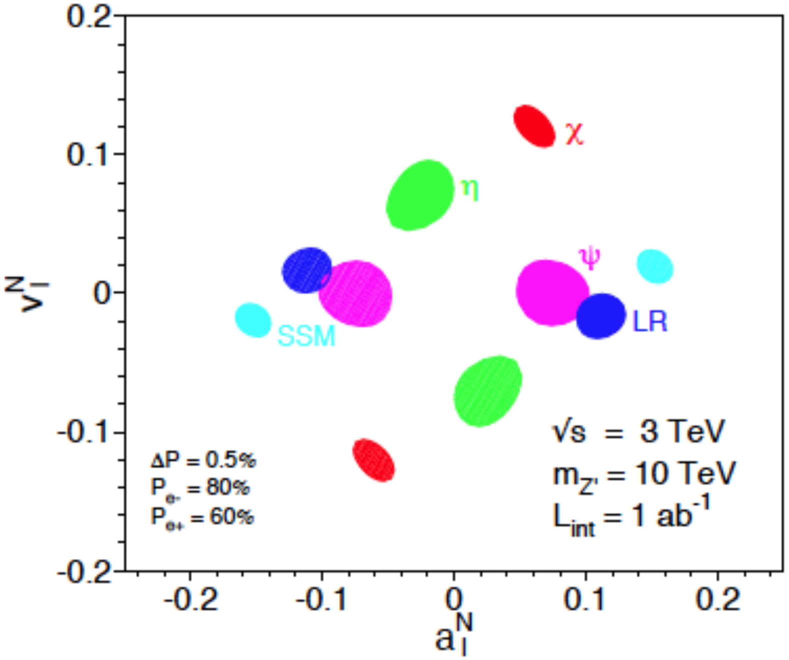
m_H = 120 GeV



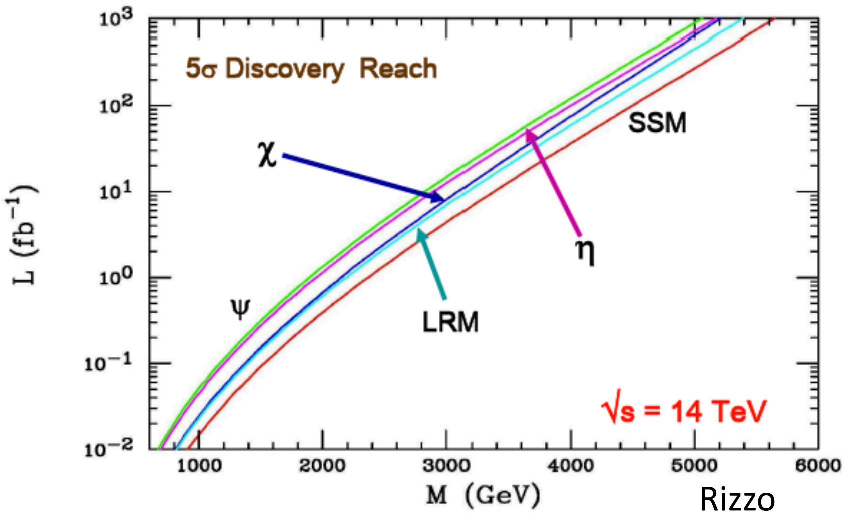
$m_H = 120$ GeV
g_{HWW}
g_{HZZ}
g_{Hbb}
g_{Hcc}
$g_{H\tau\tau}$
g_{Htt}
Γ_H
6%
4%
3%
3%
1%
1%
2%
$\sqrt{s} = 3$ TeV
$\mathcal{L} = 3$ ab^{-1}
g_{Hbb}
m_H (GeV)
180
200
220
2%
2%
4%

Z': Easy physics well above LHC capabilities



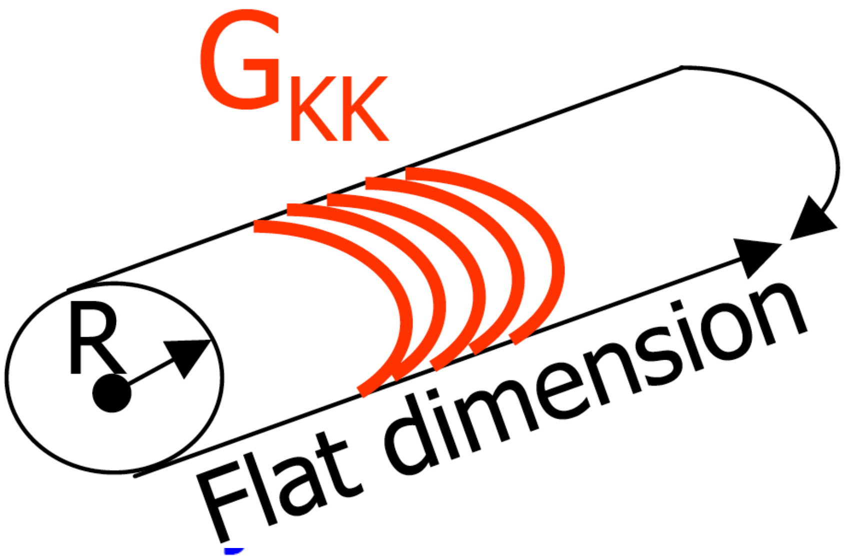


Eventually the 14 TeV LHC will cover the mass range up to ~5-6 TeV for a typical Z' w/ electroweak coupling strength & a luminosity of 1 ab^{-1} …



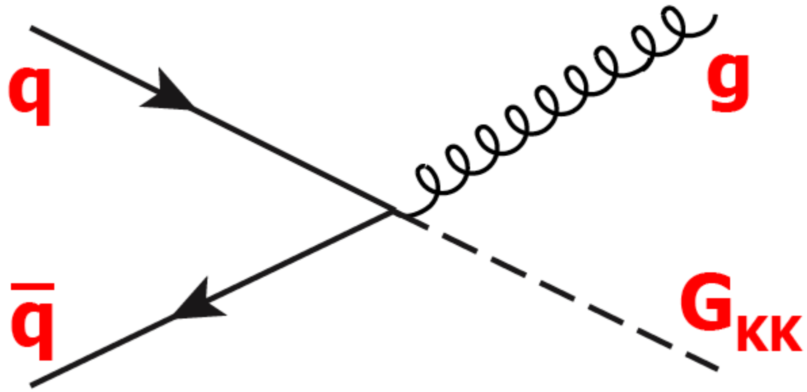
Rizzo

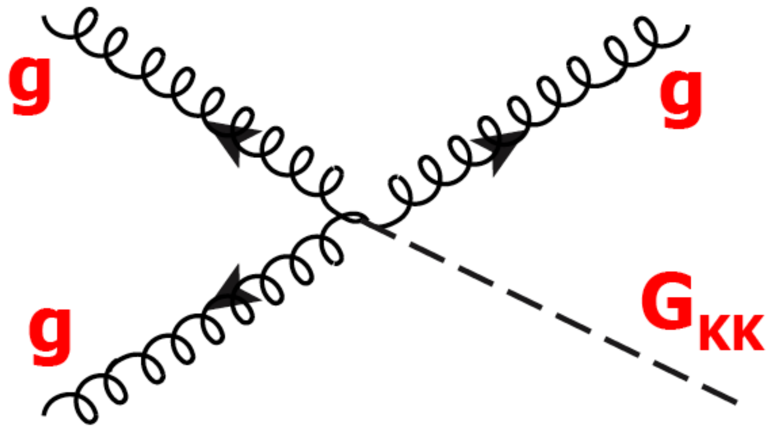
Implications of Large Extra Dimensions



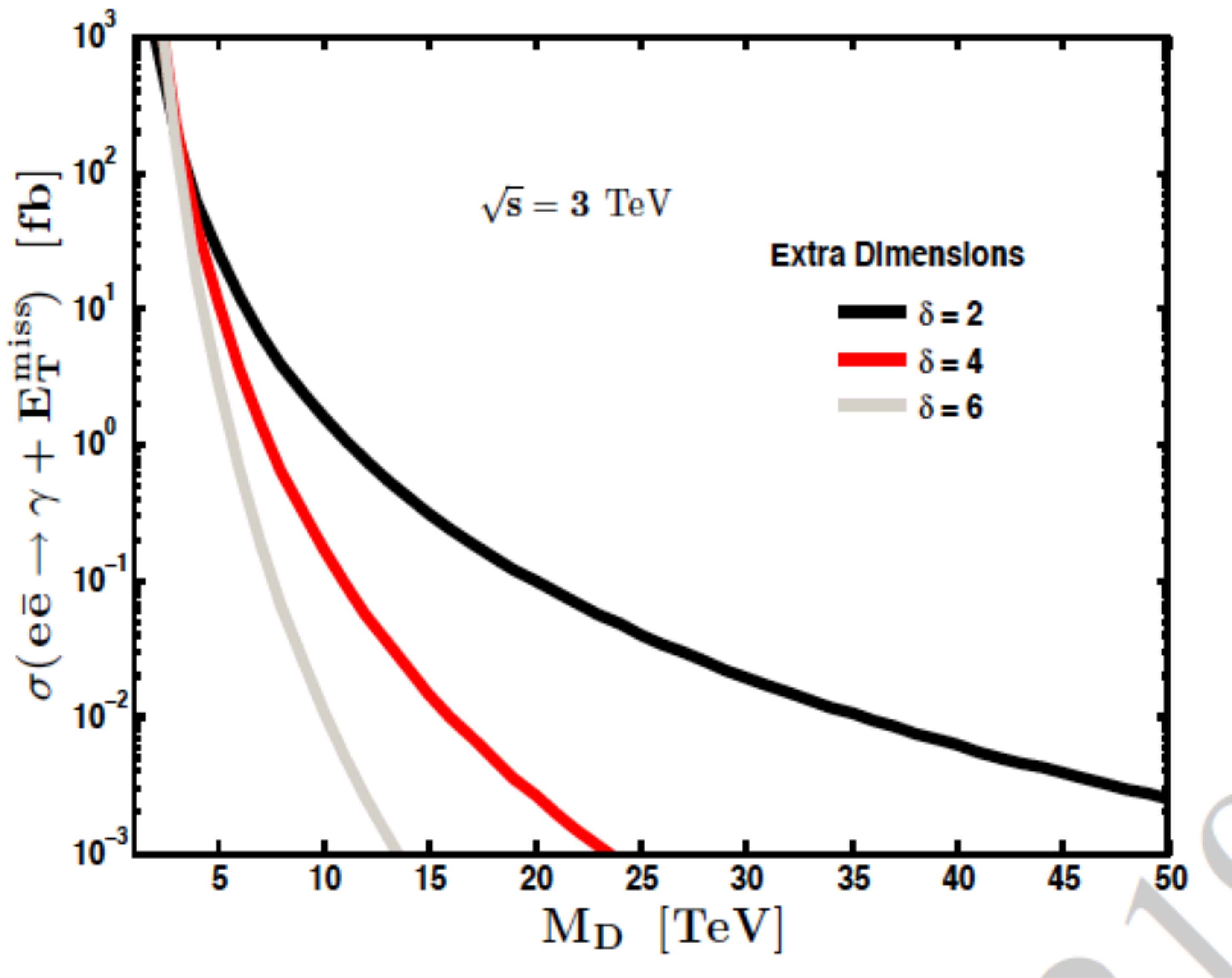
Higgs boson can be SM-like, and no quadratic divergences, but no additional explanatory power. (Explaining V is hard.)

Kaluza-Klein copies of
The graviton accessible
At high-energy colliders.
(Giudice, Rattazzi, JW; Hewett; Peskin, Perelstein, etc.)





Landsberg, 2001



LHC can probe up to 8-10 TeV, CLIC3 up to 20-30 TeV

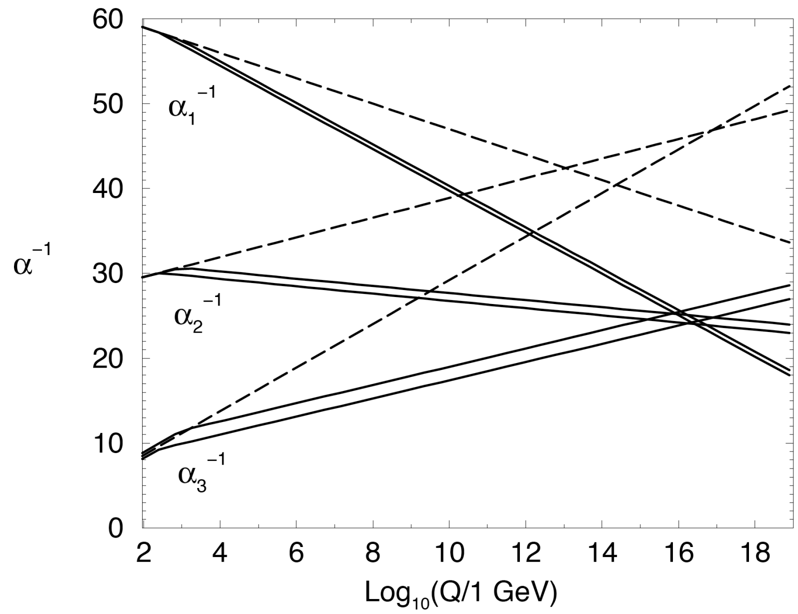
Minimal Supersymmetric Standard Model Particle Content

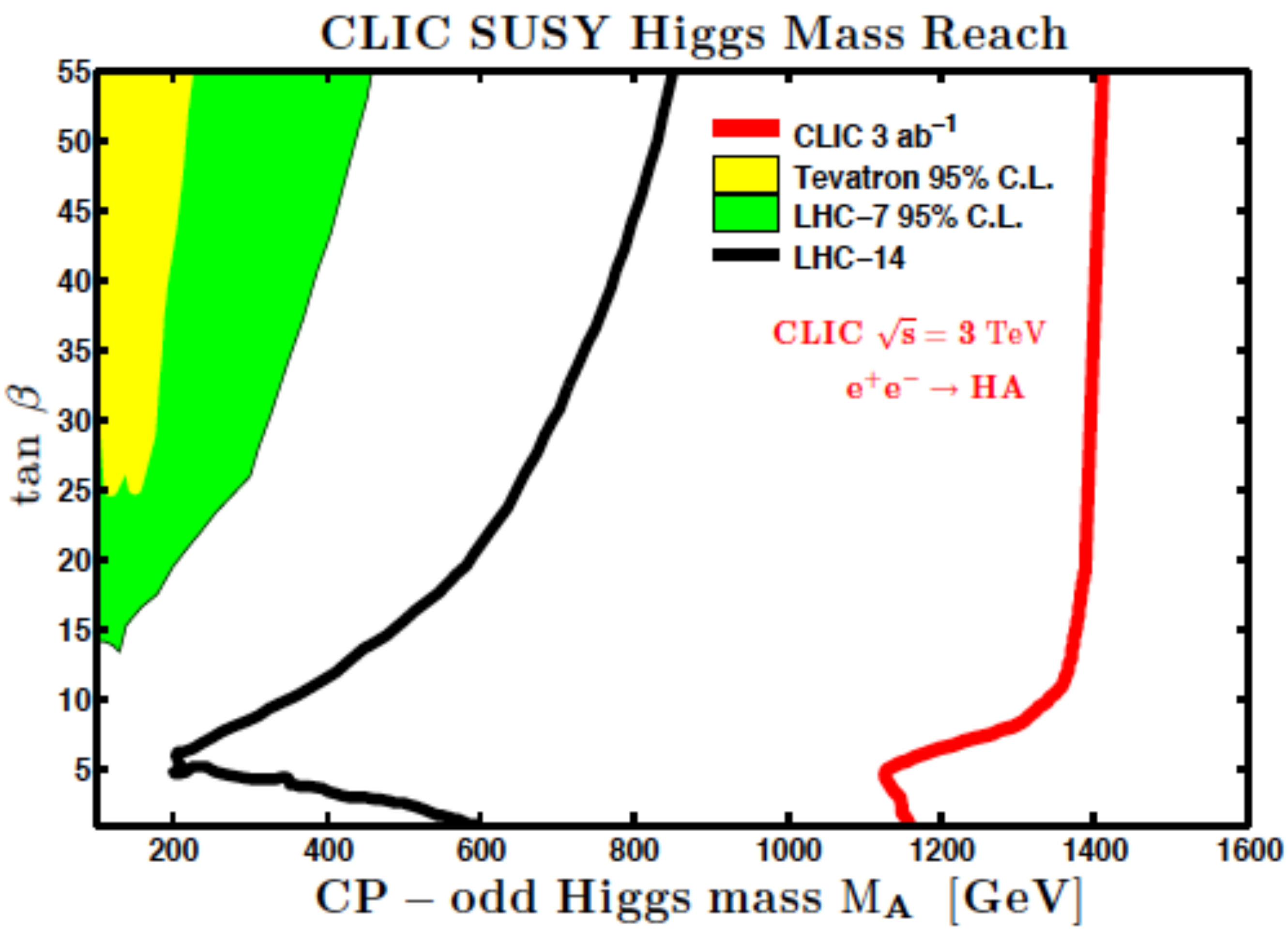
Names		spin 0	spin 1/2	$SU(3)_C, SU(2)_L, U(1)_Y$
squarks, quarks	Q	$(\widetilde{u}_L \quad \widetilde{d}_L)$	$(u_L \quad d_L)$	$(\mathbf{3}, \mathbf{2}, \frac{1}{6})$
(×3 families)	$\overline{u}$	$\widetilde{u}^*_R$	$u^\dagger_R$	$(\overline{\mathbf{3}}, \mathbf{1}, -\frac{2}{3})$
	$\overline{d}$	$\widetilde{d}^*_R$	$d^\dagger_R$	$(\overline{\mathbf{3}}, \mathbf{1}, \frac{1}{3})$
sleptons, leptons	L	$(\widetilde{\nu} \quad \widetilde{e}_L)$	$(\nu \quad e_L)$	$(\mathbf{1}, \mathbf{2}, -\frac{1}{2})$
(×3 families)	$\overline{e}$	$\widetilde{e}^*_R$	$e^\dagger_R$	$(\mathbf{1}, \mathbf{1}, 1)$
Higgs, higgsinos	H_u	$(H^+_u \quad H^0_u)$	$(\widetilde{H}^+_u \quad \widetilde{H}^0_u)$	$(\mathbf{1}, \mathbf{2}, +\frac{1}{2})$
	H_d	$(H^0_d \quad H^-_d)$	$(\widetilde{H}^0_d \quad \widetilde{H}^-_d)$	$(\mathbf{1}, \mathbf{2}, -\frac{1}{2})$

Martin, hep-ph/9709356

Nice Features of Supersymmetry

1. Higgs boson naturally light (Z data compatible).
2. Dynamical explanation of Higgs vev.
3. Motivated by string theory.
4. Lightest supersymmetric particle good CDM.
5. Gauge couplings unify.




CLIC SUSY Higgs Mass Reach
tan β
CP – odd Higgs mass M_A [GeV]
55
50
45
40
35
30
25
20
15
10
5
200
400
600
800
1000
1200
1400
1600
CLIC 3 ab^{-1}
Tevatron 95% C.L.
LHC−7 95% C.L.
LHC−14
CLIC $\sqrt{s} = 3$ TeV
$e^+e^- \rightarrow HA$

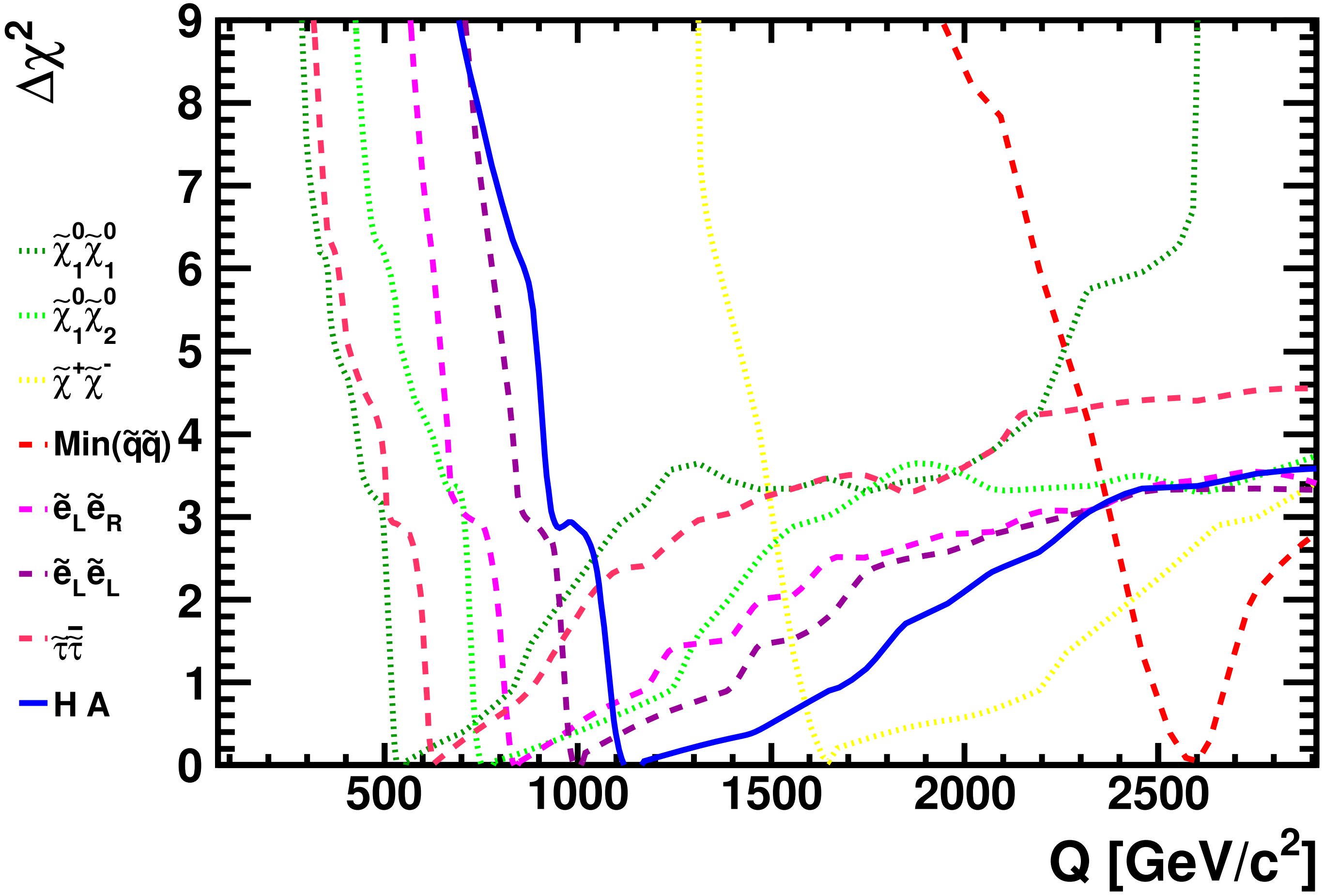
Data

- **Electroweak precision observables**
- **Flavour physics observables**
- g_μ - 2
- Higgs mass
- Dark matter
- **LHC**

MasterCode: O.Buchmueller, JE et al.

Observable	Source Th./Ex.	Constraint
m_t [GeV]	[39]	173.2 ± 0.90
$\Delta\alpha^{(5)}_{\rm had}(m_Z)$	[38]	0.02749 ± 0.00010
M_Z [GeV]	[40]	91.1875 ± 0.0021
Γ_Z [GeV]	[24] / [40]	$2.4952 \pm 0.0023 \pm 0.001_{\rm SUSY}$
$\sigma^0_{\rm had}$ [nb]	[24] / [40]	41.540 ± 0.037
R_l	[24] / [40]	20.767 ± 0.025
$A_{\rm fb}(\ell)$	[24] / [40]	0.01714 ± 0.00095
$A_\ell(P_\tau)$	[24] / [40]	0.1465 ± 0.0032
$R_{\rm b}$	[24] / [40]	0.21629 ± 0.00066
$R_{\rm c}$	[24] / [40]	0.1721 ± 0.0030
$A_{\rm fb}(b)$	[24] / [40]	0.0992 ± 0.0016
$A_{\rm fb}(c)$	[24] / [40]	0.0707 ± 0.0035
A_b	[24] / [40]	0.923 ± 0.020
A_c	[24] / [40]	0.670 ± 0.027
A_ℓ(SLD)	[24] / [40]	0.1513 ± 0.0021
$\sin^2\theta^\ell_{\rm w}(Q_{\rm fb})$	[24] / [40]	0.2324 ± 0.0012
M_W [GeV]	[24] / [40]	$80.399 \pm 0.023 \pm 0.010_{\rm SUSY}$
$\mathrm{BR}^{\rm EXP}_{b\to s\gamma}/\mathrm{BR}^{\rm SM}_{b\to s\gamma}$	[41] / [42]	$1.117 \pm 0.076_{\rm EXP}$ $\pm 0.082_{\rm SM} \pm 0.050_{\rm SUSY}$
$\mathrm{BR}(B_s \to \mu^+\mu^-)$	[27] / [37]	$(< 1.08 \pm 0.02_{\rm SUSY}) \times 10^{-8}$
$\mathrm{BR}^{\rm EXP}_{B\to\tau\nu}/\mathrm{BR}^{\rm SM}_{B\to\tau\nu}$	[27] / [42]	$1.43 \pm 0.43_{\rm EXP+TH}$
$\mathrm{BR}(B_d \to \mu^+\mu^-)$	[27] / [42]	$< (4.6 \pm 0.01_{\rm SUSY}) \times 10^{-9}$
$\mathrm{BR}^{\rm EXP}_{B\to X_s\ell\ell}/\mathrm{BR}^{\rm SM}_{B\to X_s\ell\ell}$	[43]/ [42]	0.99 ± 0.32
$\mathrm{BR}^{\rm EXP}_{K\to\mu\nu}/\mathrm{BR}^{\rm SM}_{K\to\mu\nu}$	[27] / [44]	$1.008 \pm 0.014_{\rm EXP+TH}$
$\mathrm{BR}^{\rm EXP}_{K\to\pi\nu\bar\nu}/\mathrm{BR}^{\rm SM}_{K\to\pi\nu\bar\nu}$	[45]/ [46]	< 4.5
$\Delta M^{\rm EXP}_{B_s}/\Delta M^{\rm SM}_{B_s}$	[45] / [47, 48]	$0.97 \pm 0.01_{\rm EXP} \pm 0.27_{\rm SM}$
$\frac{(\Delta M^{\rm EXP}_{B_s}/\Delta M^{\rm SM}_{B_s})}{(\Delta M^{\rm EXP}_{B_d}/\Delta M^{\rm SM}_{B_d})}$	[27] / [42, 47, 48]	$1.00 \pm 0.01_{\rm EXP} \pm 0.13_{\rm SM}$
$\Delta\epsilon^{\rm EXP}_K/\Delta\epsilon^{\rm SM}_K$	[45] / [47, 48]	$1.08 \pm 0.14_{\rm EXP+TH}$
$a^{\rm EXP}_\mu - a^{\rm SM}_\mu$	[49] / [38, 50]	$(30.2 \pm 8.8 \pm 2.0_{\rm SUSY}) \times 10^{-10}$
M_h [GeV]	[26] / [51, 52]	$> 114.4 \pm 1.5_{\rm SUSY}$
$\Omega_{\rm CDM}h^2$	[29] / [53]	$0.1109 \pm 0.0056 \pm 0.012_{\rm SUSY}$
$\sigma^{\rm SI}_p$	[23]	$(m_{\tilde\chi^0_1}, \sigma^{\rm SI}_p)$ plane
jets + $\not{E}_T$	[16, 18]	$(m_0, m_{1/2})$ plane
$H/A, H^\pm$	[19]	$(M_A, \tan\beta)$ plane

NUHM Model



From Ellis et al.

Indirect constraints for this model:

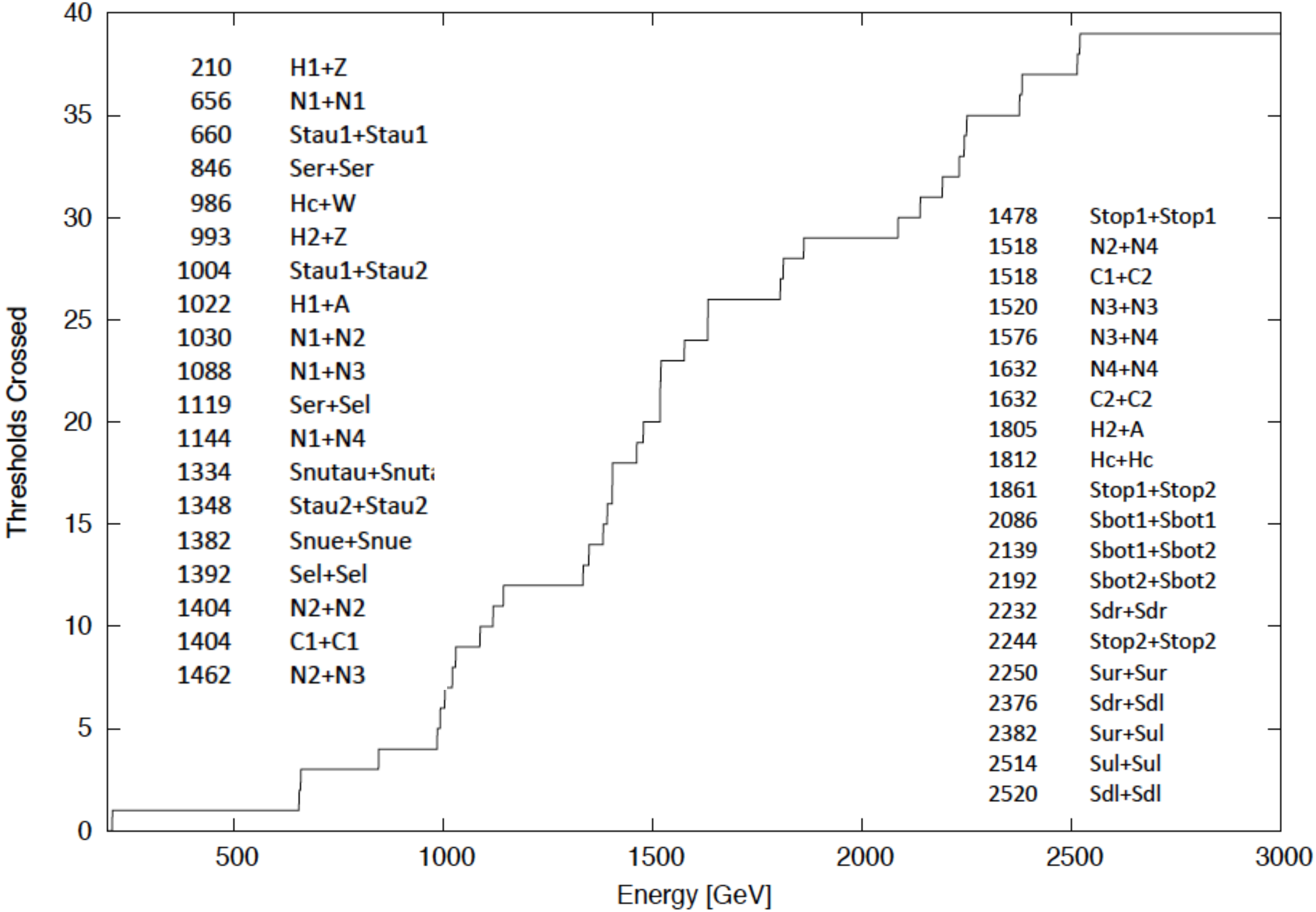
MODEL I Benchmark of CLIC CDR

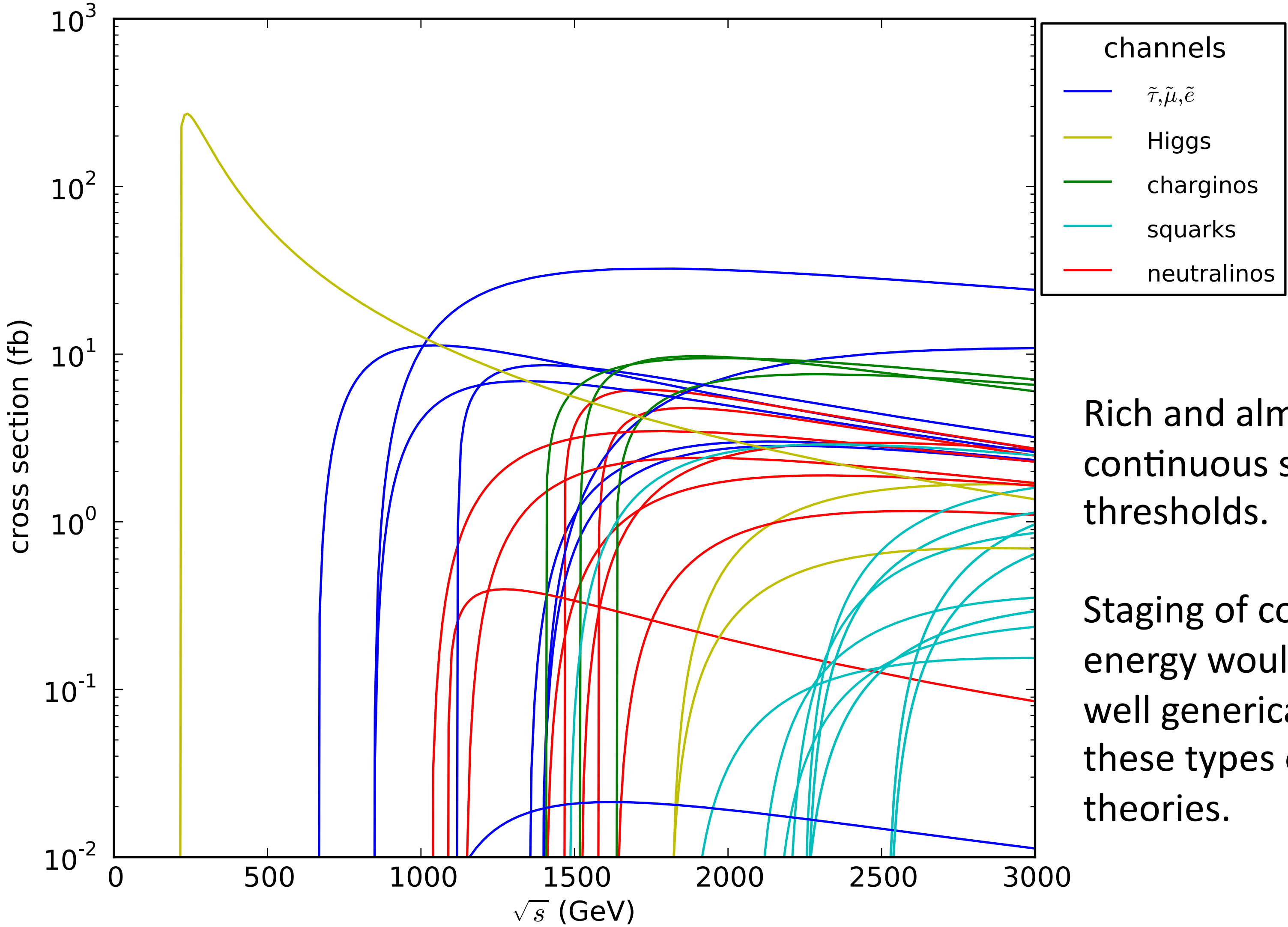
$$\begin{aligned}\Omega_{\rm DM} h^2 &= 0.1105 \\ \Delta a_\mu &= 6.04 \times 10^{-10} \\ BR(b \to s\gamma) &= 3.01 \times 10^{-4} \\ BR(B_s \to \mu^+\mu^-) &= 3.9 \times 10^{-9}\end{aligned}$$

Complete mass spectrum:

```
h, H, A, Hpm = 119.13  902.4  902.6  906.3
Neutralinos = 328.3  701.8  760.2  816.2
Charginos = 701.6  816.1
stau1, stau2, snutau = 330.2  674.3  666.8
stop1, stop2 = 739.4  1121.8
sbot1, sbot2 = 1043.3  1096.0
seR, seL, snue = 422.8  696.1  691.3
suR, suL, sdR, sdL = 1125.7  1257.7  1116.1  1260.0
Gluino = 1239.7
```

Thresholds Crossed as a function of Energy (GeV)





Rich and almost continuous set of thresholds.

Staging of collider energy would work well generically for these types of theories.

Jan Strube plot of cross-sections

Conclusions

LHC will guide us to the new physics

Much to discover well beyond LHC capabilities
(e.g., in susy, the sleptons for example, heavier Z', etc.)

Precision studies require CLIC as well
(e.g., in Higgs physics, establishing its full coupling patterns, composite nature, triple gauge couplings, etc.)