Technicolor @ Colliders

Francesco Sannino

Perugia 2009

CP^3-Origins

Particle Physics & Origins of Mass

LHC

TOM HANKS

ANGELS&DEMONS

Dynamical Electroweak Symmetry Breaking

Unparticle Physics

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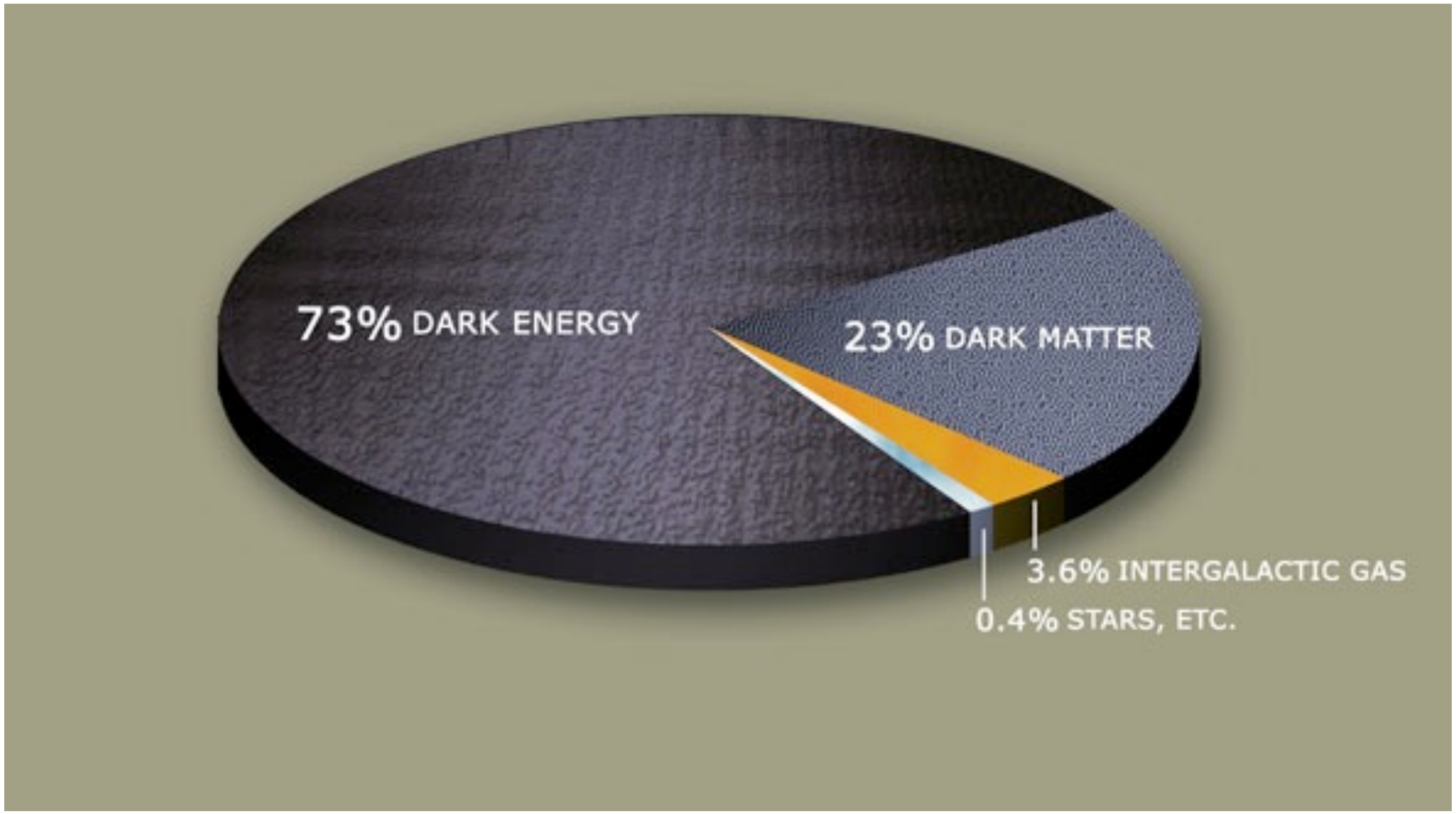
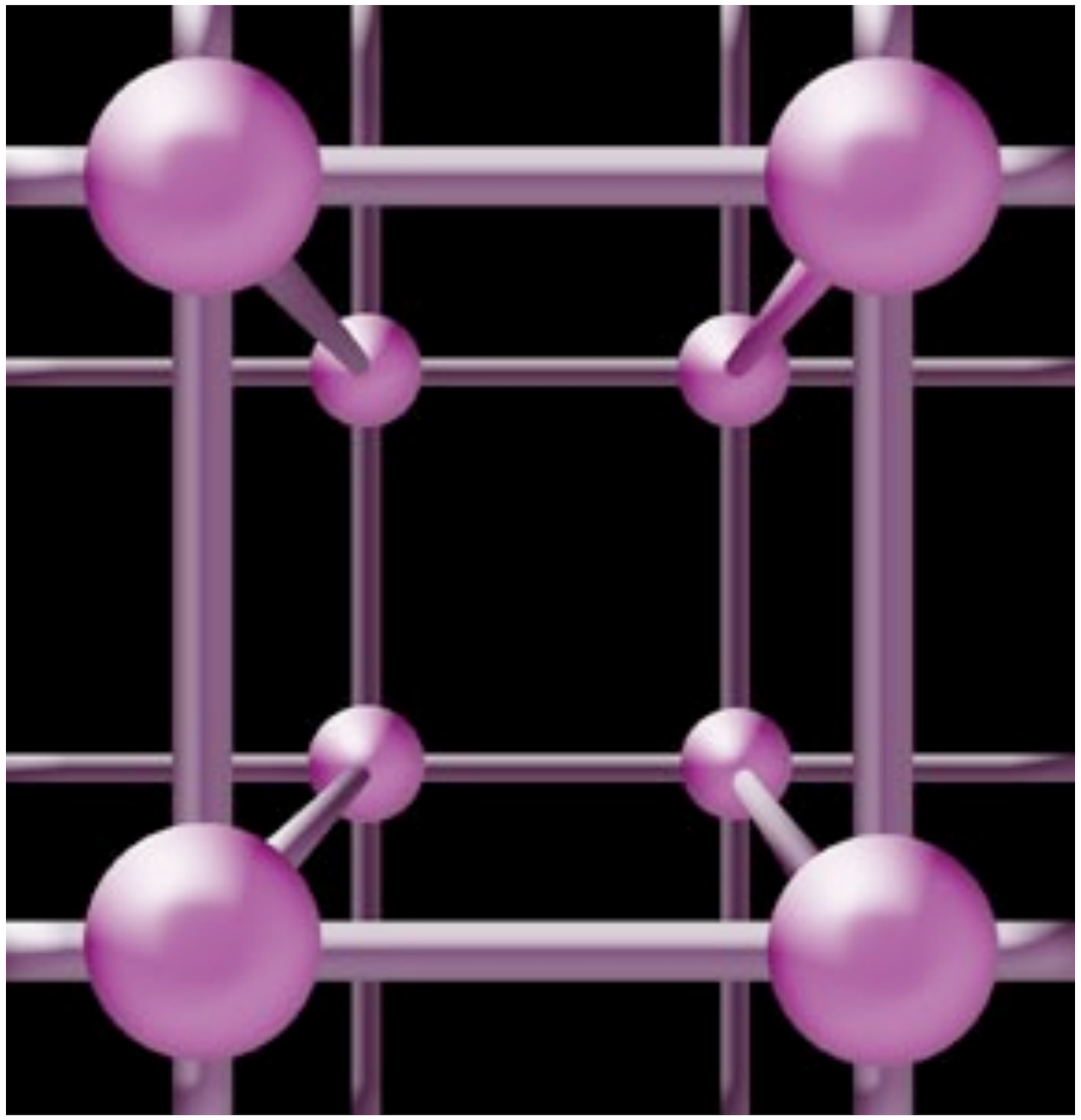

73% DARK ENERGY
23% DARK MATTER
3.6% INTERGALACTIC GAS
0.4% STARS, ETC.

Natural Asymmetric Dark Matter*

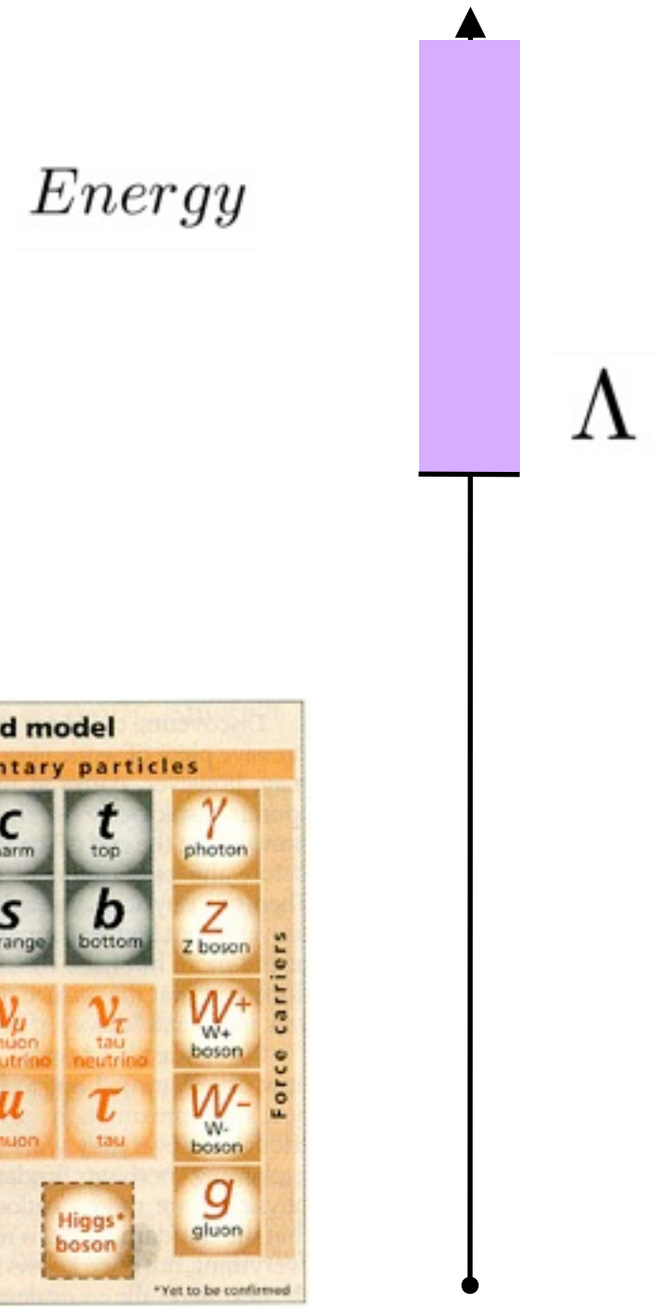
Electroweak Baryogenesis

* Decaying, Composite, ...



We can probe the dynamics of our extensions

Low Energy Effective Theory



SM

Dynamical EW Breaking

$$L(H) \rightarrow -\frac{1}{4} F^{a\mu\nu} F^{a}_{\mu\nu} + i\,\bar{Q}\gamma^{\mu} D_{\mu} Q + \cdots$$

Dots are partially fixed by Anomalies as well as other principles

$$\cdots \qquad \rightarrow \qquad L(\text{New SM Fermions})$$

Technicolor

New Strong Interactions at ~ 250 GeV
[Weinberg, Susskind]

Natural to use QCD-like dynamics.

$$SU(N)_{TC} \times SU(3)_C \times SU_L(2) \times U_Y(1)$$

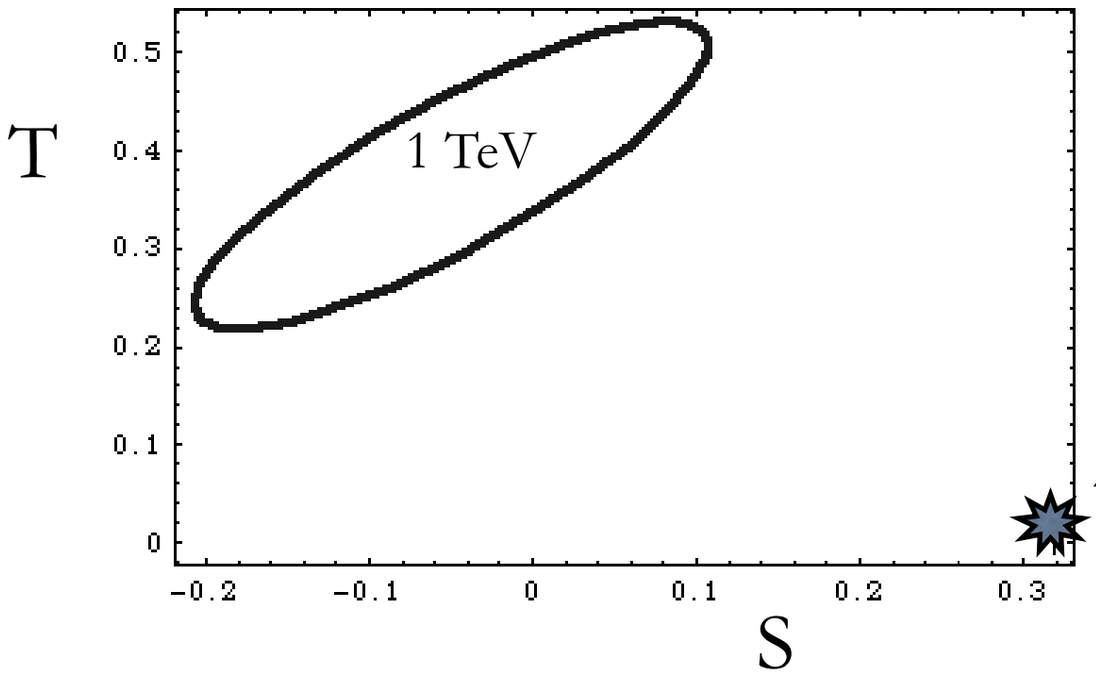
$$\langle Q^f \widetilde{Q}_{f'} \rangle = \Lambda_{TC}^3 \qquad \Lambda_{TC} \simeq 250\ GeV$$

Life in Technicolor

Not the Coldplay album

Large & Positive S from QCD-like Technicolor

Peskin and Takeuchi, 90



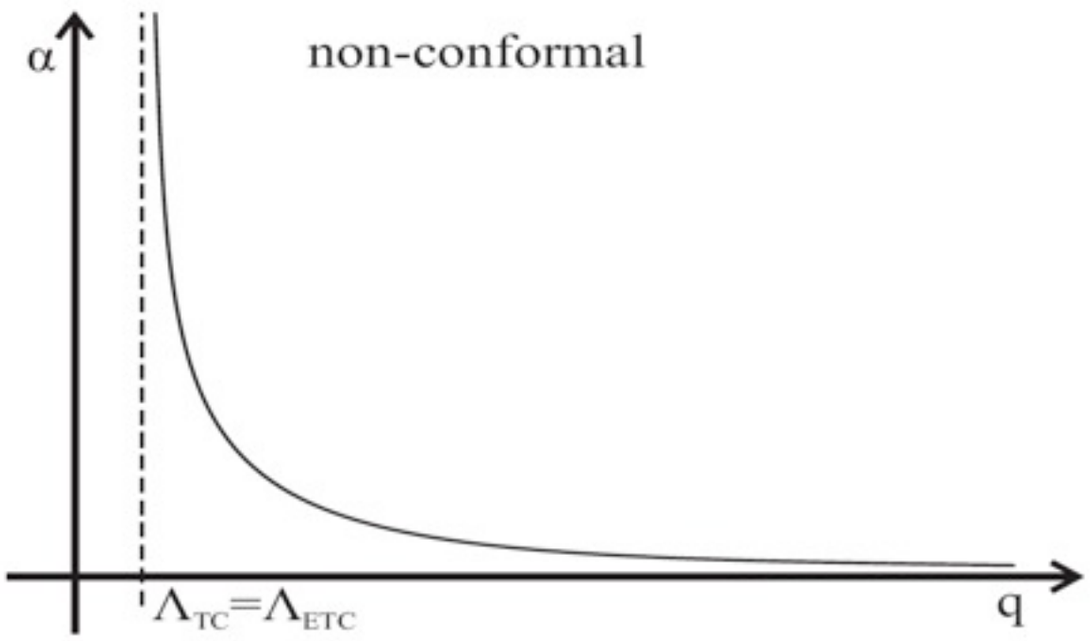
SU(3) + 1 Fund. Doublet

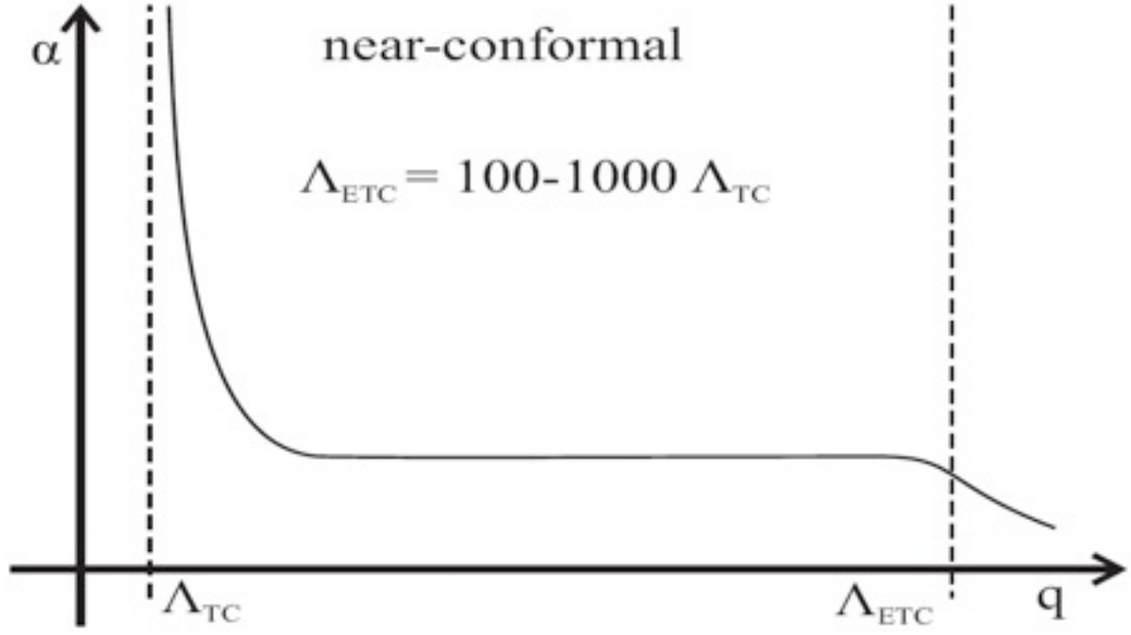
Weinberg, Susskind

Kennedy-Lynn, Peskin-Takeuchi, Altarelli-Barbieri, Bertolini- Sirlin, Marciano-Rosner

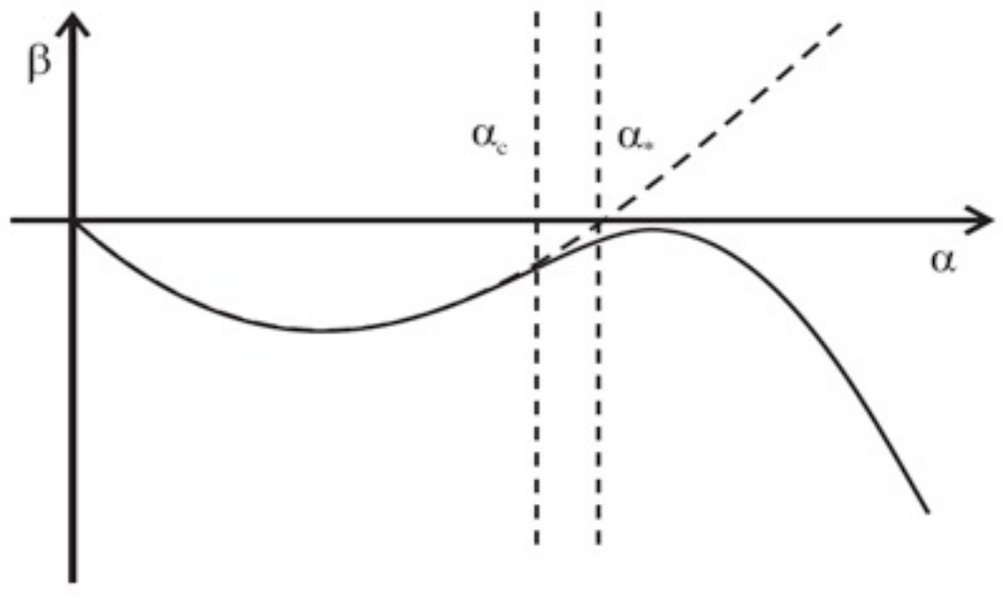
Walking versus Running

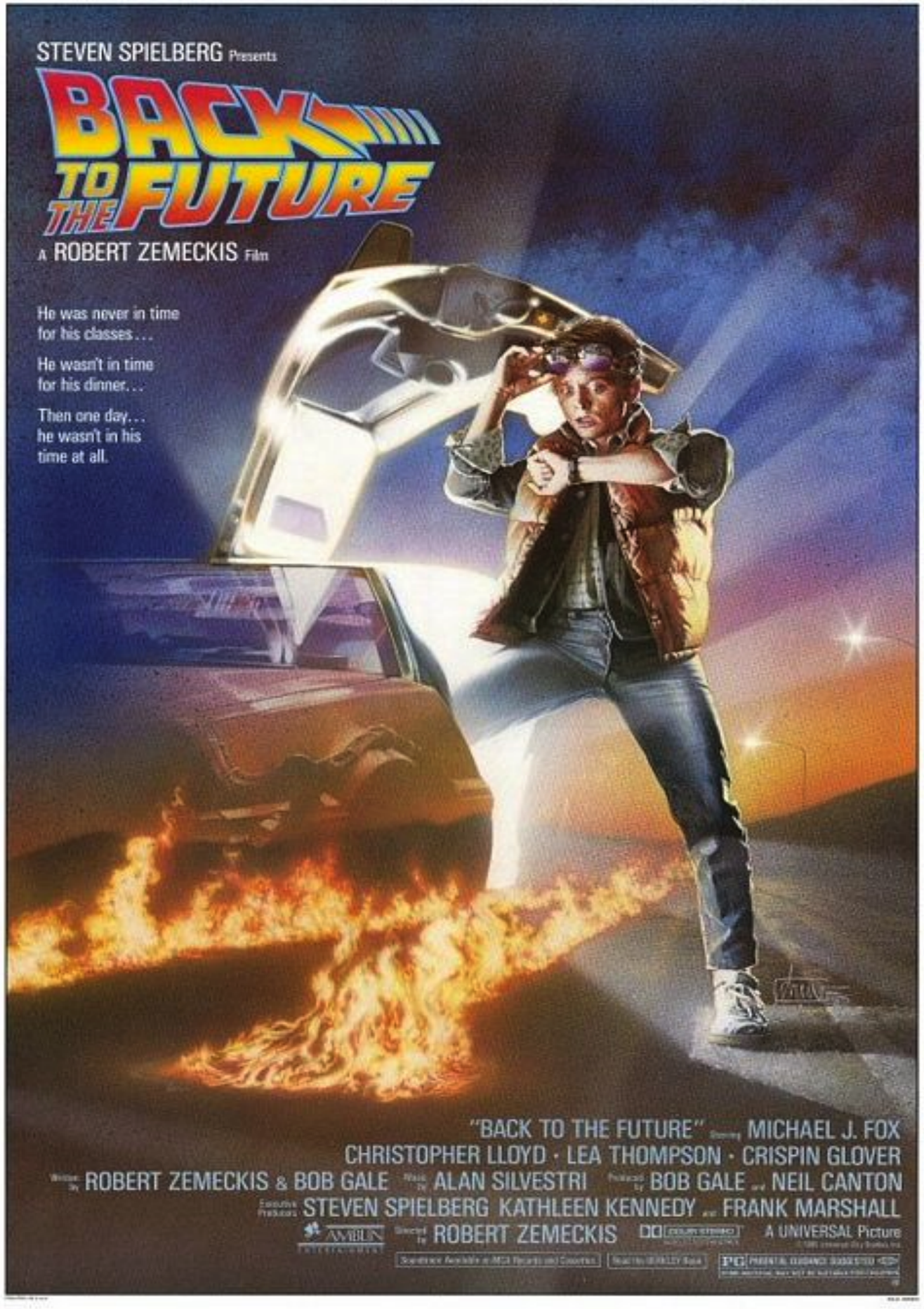
Near Conformal Properties





Appelquist, Bowick, Chivukula, Cohen, Da Silva, Doff, Eichten, Georgi, Hill, Holdom, Karabali, Lane, Mahanta, Miransky, Natale, F.S., Shrock, Simmons, Terning, Wijewardhana, Yamawaki




STEVEN SPIELBERG Presents
BACK TO THE FUTURE
A ROBERT ZEMECKIS Film
He was never in time for his classes...
He wasn't in time for his dinner...
Then one day... he wasn't in his time at all.
"BACK TO THE FUTURE" Starring MICHAEL J. FOX
CHRISTOPHER LLOYD · LEA THOMPSON · CRISPIN GLOVER
Written by ROBERT ZEMECKIS & BOB GALE Music by ALAN SILVESTRI Produced by BOB GALE and NEIL CANTON
Executive Producer STEVEN SPIELBERG KATHLEEN KENNEDY and FRANK MARSHALL
AMBLIN ENTERTAINMENT
Directed by ROBERT ZEMECKIS
DOLBY STEREO
A UNIVERSAL Picture
Soundtrack Available on MCA Records and Cassettes
Read the BERKLEY Book
PG PARENTAL GUIDANCE SUGGESTED

S in Walking Technicolor

$$S_{WTC} < S_{TC}$$

Appelquist, F.S.

Da Silva, Duan, F.S.

We will take as an estimate:

$$S_{WTC} \approx S_{\rm naive} = \frac{1}{6\pi}\frac{N_f}{2}d(R)$$

Besides

$$S = S_{(W)TC} + S_{NS}$$

Offset the first term

Rule:

Find Walking Theories with EW embedding minimizing S

Progress in Strong Dynamics I:

Analytically discovered a universal picture

Phase Diagrams for SO(N) and Sp(2N)	F.S. 09 Ryttov, F.S. 07
Phase Diagrams for SU(N)	F.S. and Tuominen 04 Dietrich, F.S. 06

Useful methods to understand Near-Conformal Dynamics

Newly Conjectured all-orders beta function	Ryttov, F.S. 07
Conformal Chiral Dynamics	F.S. 08 F.S. and R. Zwicky 08

Strong Lattice Activity

Lattice

Any Rep.

Catterall, F.S. 07

Catterall, Giedt, F.S., Schneible 08

Del Debbio, Frandsen, Panagopoulos, F.S. 08

Del Debbio, Patella, Pica. 08

Hietanen, Rantaharju, Rummukainen, Tuominen 08

DeGrand, Shamir, Svetitsky, 08

Del Debbio, Patella, Pica, 08

Hietanen, Rummukainen, Tuominen 09

Fodor, Holland, Kuti, Nogradi, Schroeder, 09

.....

Fund. Rep

Appelquist, Fleming, Neil 07

Deuzman, Lombardo, Pallante 08

Fodor, Holland, Kuti, Nogradi, Schroeder, 08

.....

Viable Models

(Ultra) Minimal Walking Technicolor (MWT)

Higher Dimensional Representations

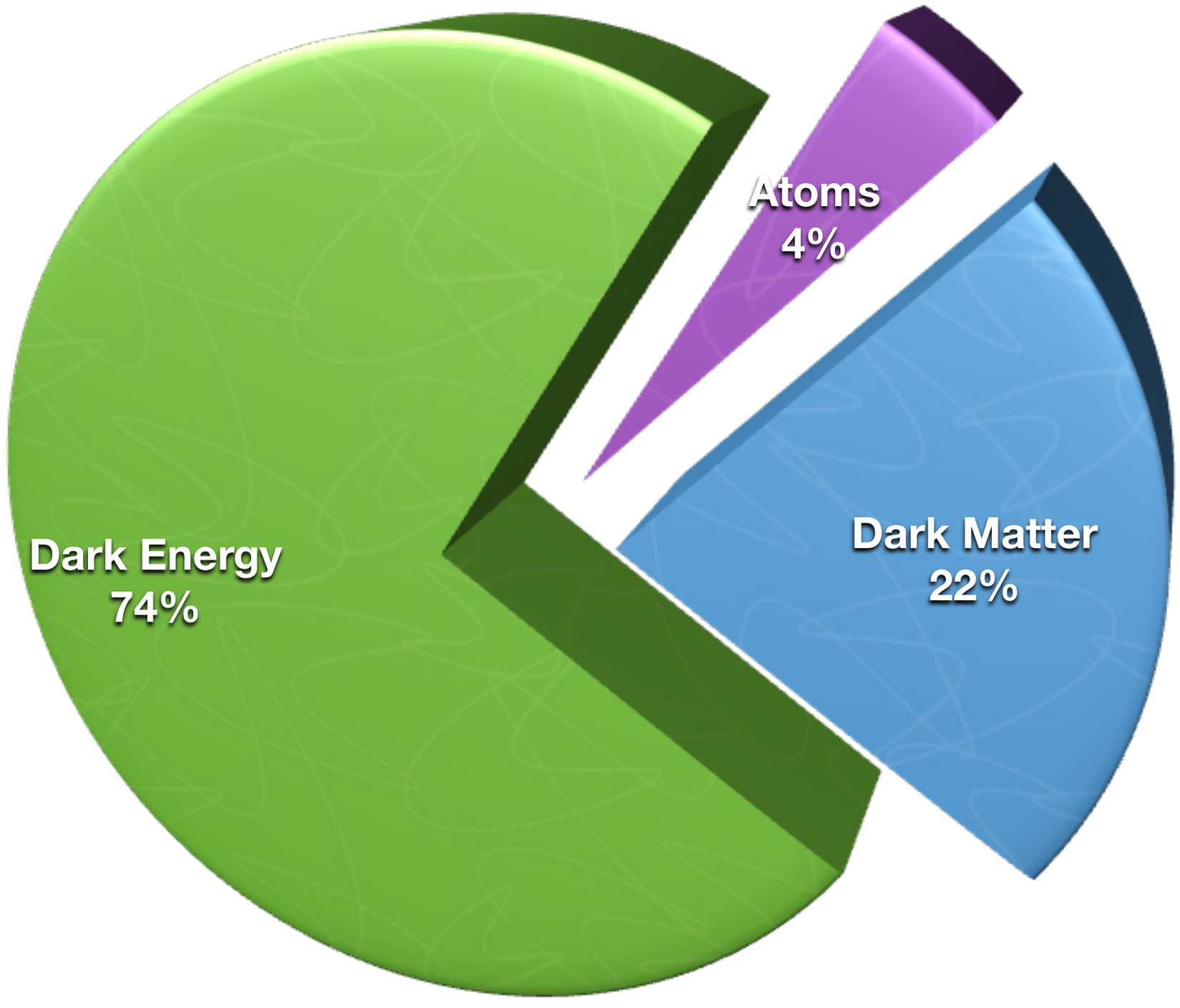
Beyond Minimal Walking Technicolor

Partially EW Gauged Technicolor

Split Technicolor

Additional Fermions in SM

Custodial TC


Atoms
4%
Dark Matter
22%
Dark Energy
74%

Dark Matter

$$\frac{\Omega_{DM}}{\Omega_B} \sim 5$$

Technicolor Interacting Massive Particle (**TIMP**)

Technibaryon is similar to the nucleon

TB number like the B number

At most EW-type cross sections

EW scale and interactions built in

Ultra Minimal Technicolor is the first physical realization
Ryttov - F.S. 08

PAMELA/ATIC Decaying Dark Matter + Unification,
Nardi, F.S., Strumia, 08.

Nussinov, 86
Barr - Chivukula - Farhi 90
Sarkar 96
Gudnason - Kouvaris - F.S. 06

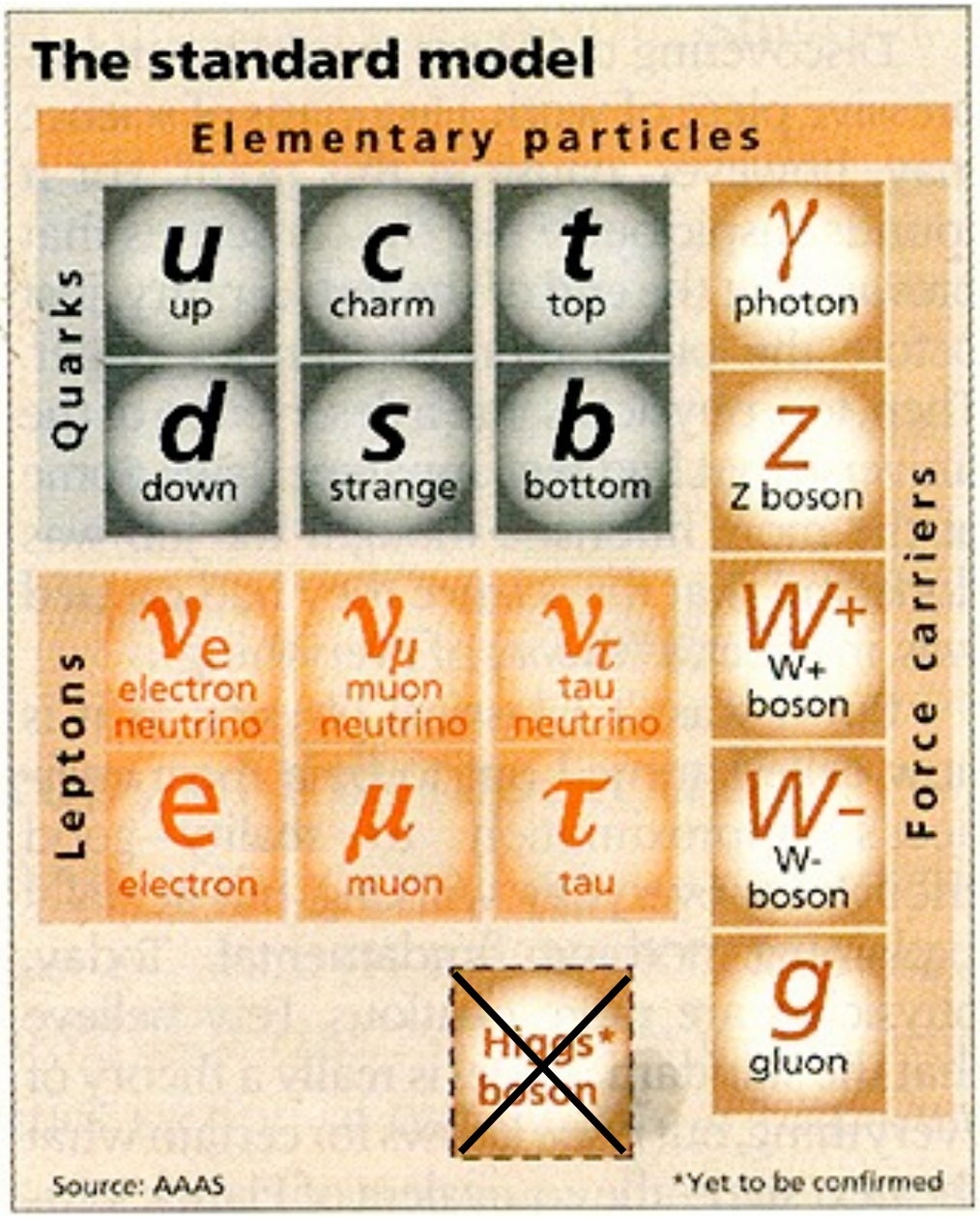
Asymmetric DM Relic Density

$$\frac{m_{TB}}{m_p} \approx \frac{1\ \text{TeV}}{1\ \text{GeV}} = 10^3$$

$$\frac{TB}{B} \propto \exp\left[-\frac{m_{TB}(T^*)}{T^*}\right] \sim 10^{-3} \qquad T^* \sim 200\ \text{GeV}$$

$$\frac{\Omega_{TB}}{\Omega_B} = \frac{TB}{B}\frac{m_{TB}}{m_p} \sim \mathcal{O}(1)$$

Minimal Walking Technicolor



N
Extra Neutrino

E
Extra Electron

U(1)

SU(2)

SU(3)

U
t-up

G
t-glue

SU(2)

D
t-down

F.S. + Tuominen 04

Dietrich, F.S., Tuominen 05

U and D: Adj of SU(2)

MWT Features

The most economical WT theory

Compatible with precision measurements

Possible DM candidates and nice Unification

Can support 1st order Electroweak Phase Transition

Can feature a light composite Higgs

Dietrich, F.S., Tuominen 05.
Da Silva, Doff, Natale 08, 09.

Lattice studies have begun

The MWT Lagrangian

$$\mathcal{L}_H \rightarrow -\frac{1}{4}\mathcal{F}^a_{\mu\nu}\mathcal{F}^{a\mu\nu} + i\bar{Q}_L\gamma^\mu D_\mu Q_L + i\bar{U}_R\gamma^\mu D_\mu U_R + i\bar{D}_R\gamma^\mu D_\mu D_R$$
$$+i\bar{L}_L\gamma^\mu D_\mu L_L + i\bar{N}_R\gamma^\mu D_\mu N_R + i\bar{E}_R\gamma^\mu D_\mu E_R$$

$$\mathcal{F}^a_{\mu\nu} = \partial_\mu \mathcal{A}^a_\nu - \partial_\nu \mathcal{A}^a_\mu + g_{TC}\epsilon^{abc}\mathcal{A}^b_\mu \mathcal{A}^c_\nu \qquad a, b, c = 1, \ldots, 3$$

$$D_\mu Q^a_L = \left(\delta^{ac}\partial_\mu + g_{TC}\mathcal{A}^b_\mu \epsilon^{abc} - i\frac{g}{2}\vec{W}_\mu \cdot \vec{\tau}\delta^{ac} - ig'\frac{y}{2}B_\mu \delta^{ac}\right) Q^c_L$$

What you see is “not” what LHC will see

MWT effective lagrangian

$$\mathcal{L}(\text{Composites}) + \mathcal{L}(\text{Mixing with SM}) + \mathcal{L}(\text{New Leptons}) + \mathcal{L}(\text{SM} - \text{Higgs})$$

Initial investigation we include:

Composite Higgs	H
Composite Axial - Vector States	$R_{1,2}$
Heavy V/V coupling	$\tilde{g}$
Bare mass of the Axial	M_A

Angels and Demons of LHC & LC

LHC Phenomenology

In collaboration with

A. Belyaev
R. Foadi
M. T. Frandsen
M. O. Jarvinen
A. Pukhov

BFFJPS arXiv:0809.0793

CalcHep

Comprehensive Effective Technicolor Lagrangian

Vector Mesons

Yukawas

** Link to MWT via Modified Weinberg Sum Rules **

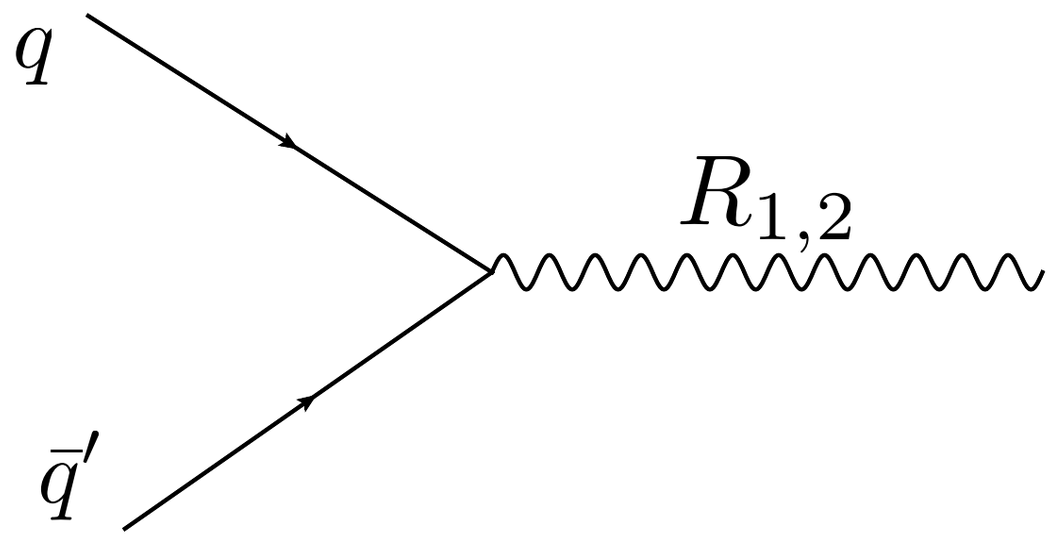
Written in a renormalizable form

With imposed constraints from Precision Data

A working technicolor benchmark

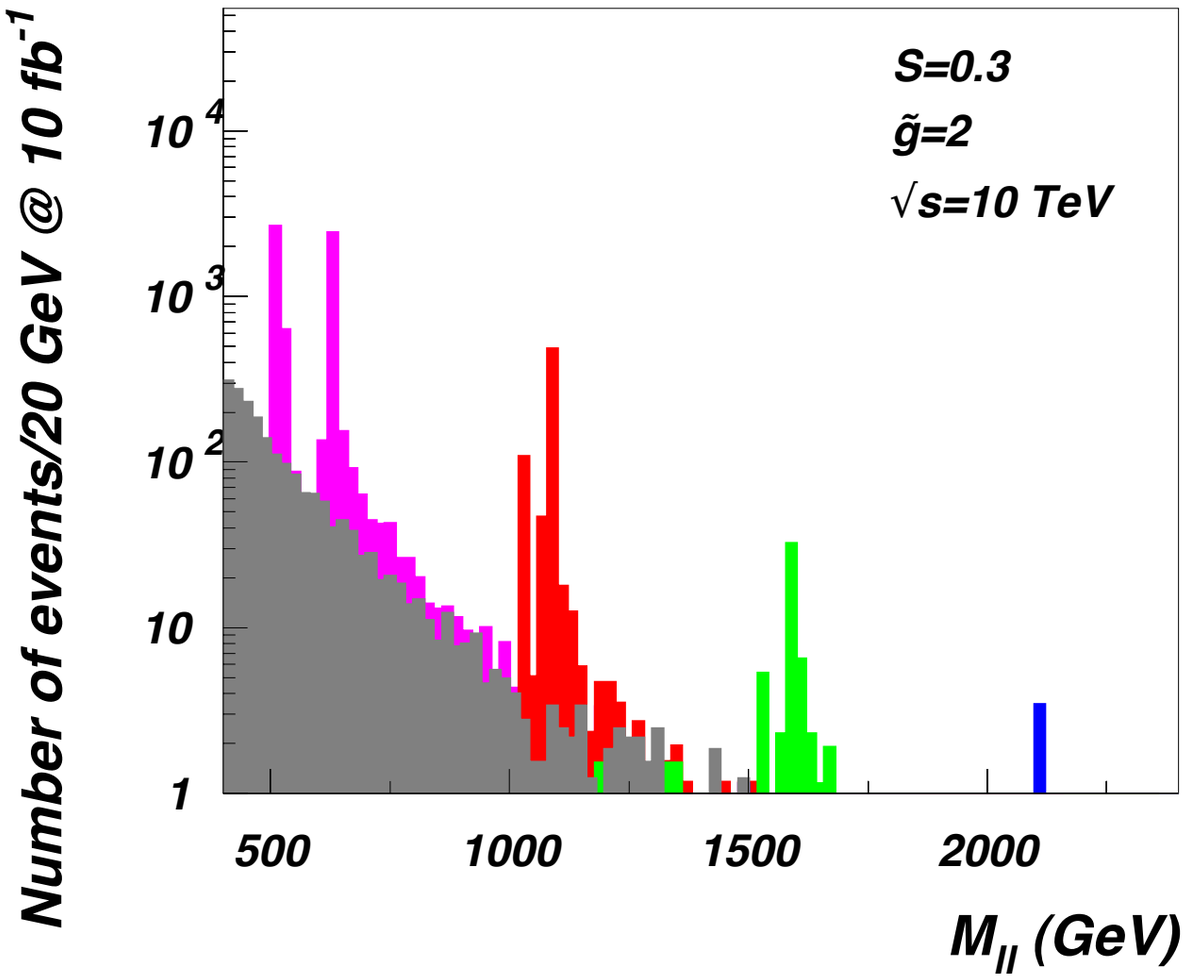
Foadi, Frandsen, Ryttov & F.S. 07

Drell Yan Production



Drell-Yan

$$pp \longrightarrow R^0_{1,2} \longrightarrow \ell^+\ell^-$$



Undetectable

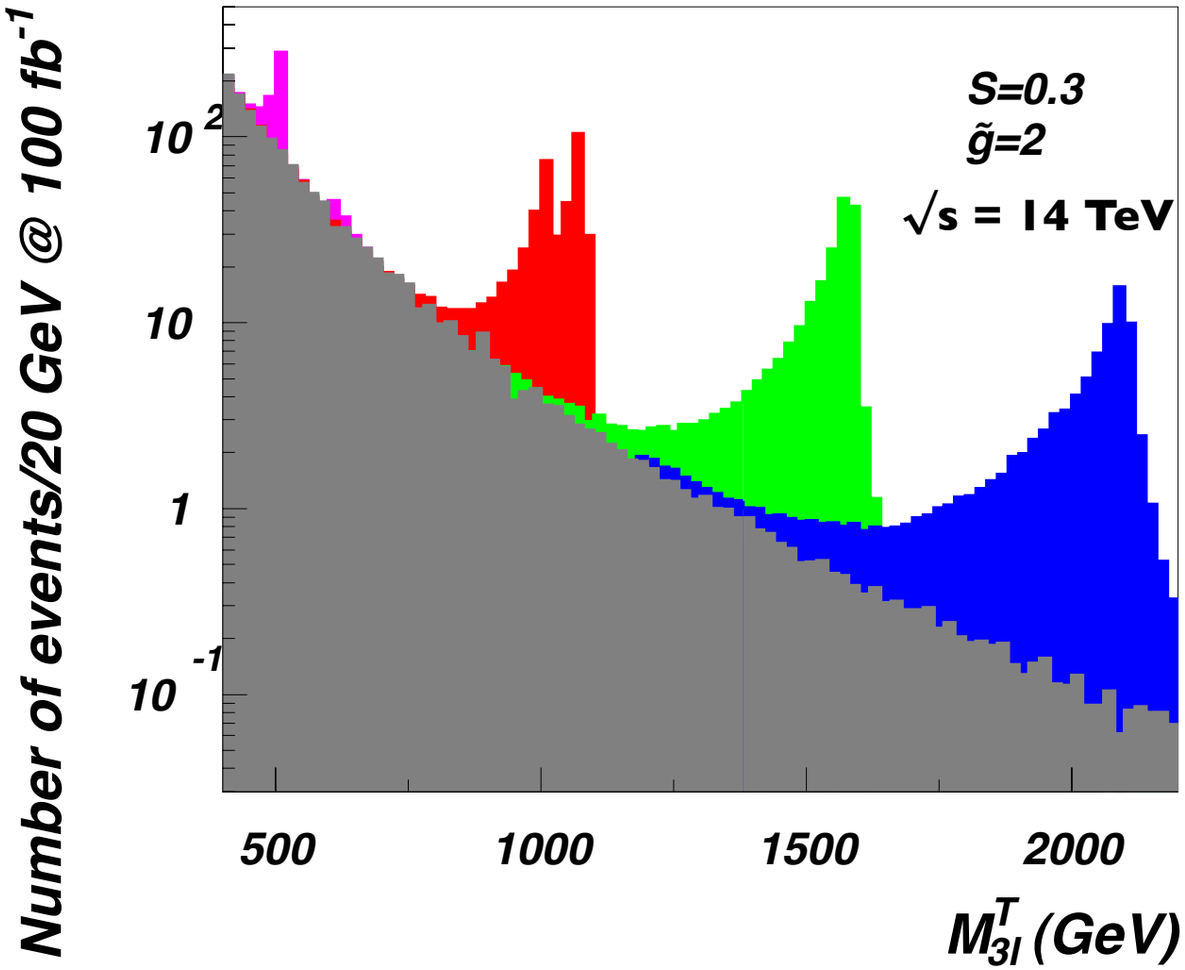
$\tilde{g} = 5$

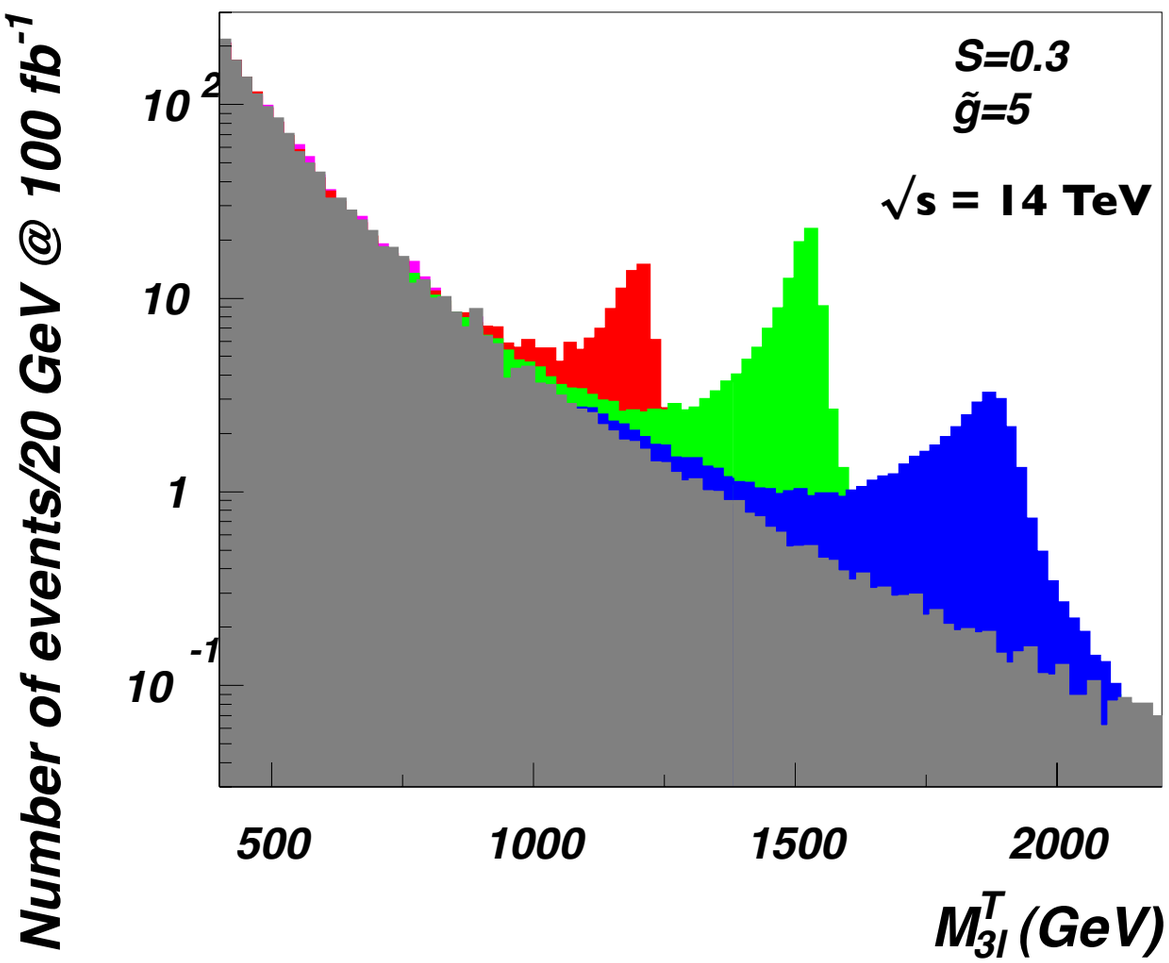
Dilepton invariant mass distribution $M_{\ell\ell}$ for $pp \to R^0_{1.2} \to \ell^+\ell^-$ signal and background processes.

We consider $\tilde{g} = 2, 5$ respectively and masses $M_A = 0.5$ Tev (purple), $M_A = 1$ Tev (red), $M_A = 1.5$ Tev (green) and $M_A = 2$ Tev (blue)

Drell-Yan

$$pp \to R^{\pm}_{1,2} \to ZW^{\pm} \to 3\ell\nu$$





$M^T_{3\ell}$ mass distribution for $pp \to R^{\pm}_{1,2} \to ZW^{\pm} \to 3\ell\nu$ signal and background processes. We consider $\tilde{g} = 2, 5$ respectively and masses $M_A = 0.5$ Tev (purple), $M_A = 1$ Tev (red), $M_A = 1.5$ Tev (green) and $M_A = 2$ Tev (blue).

Composite Higgs Signals

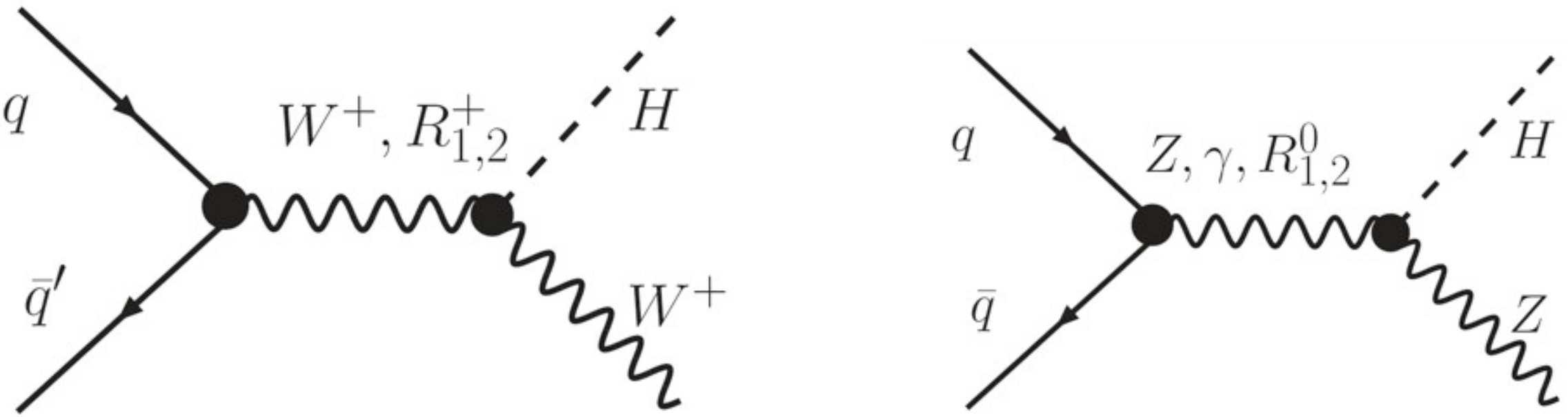
Associate Higgs Production

BFFJPS 08, Zerwekh 05

Higgs $\longrightarrow \gamma\gamma$

To be done!

$$pp \longrightarrow HV$$



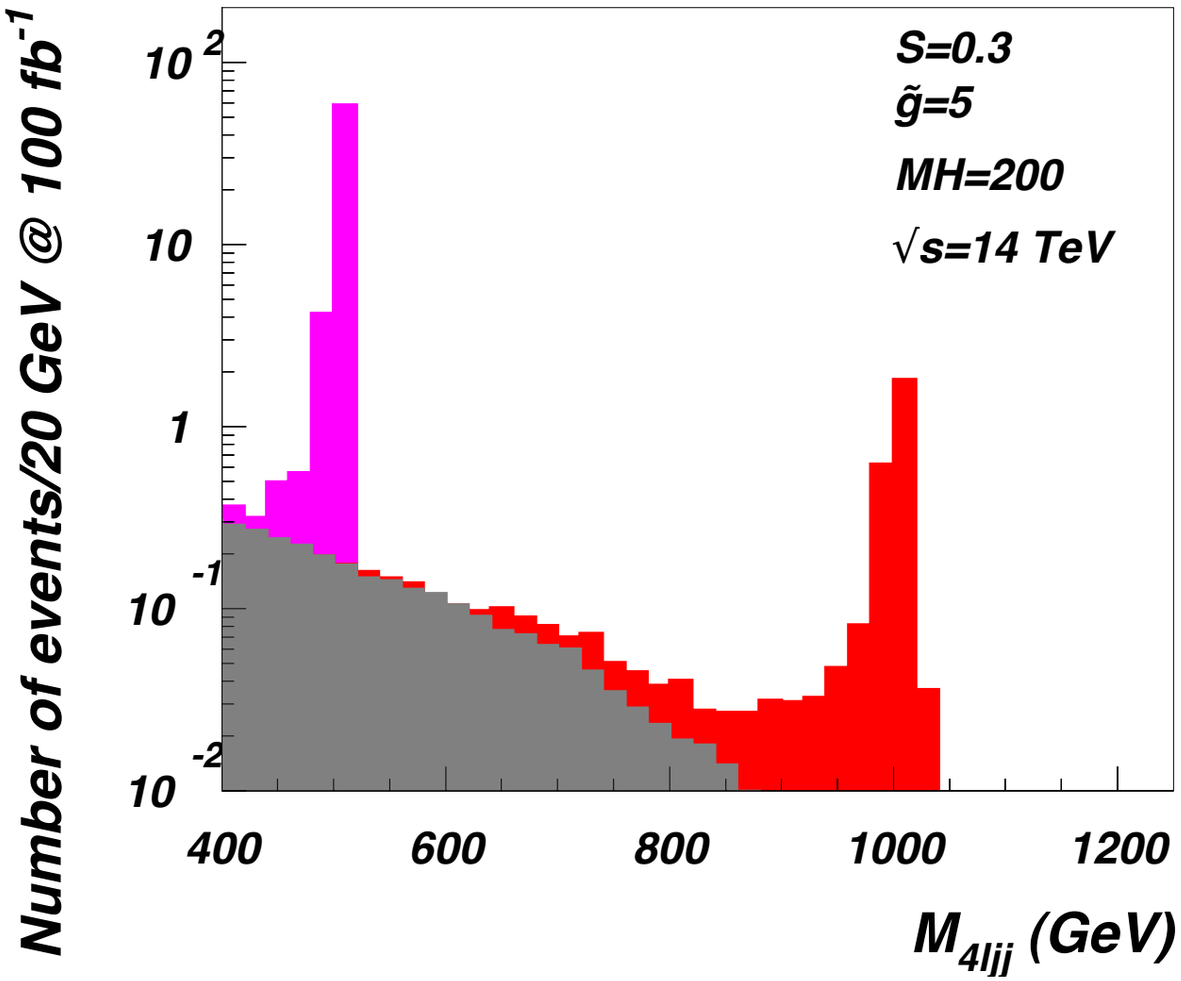
$$HV \rightarrow VVV \rightarrow \text{leptons+jets}$$

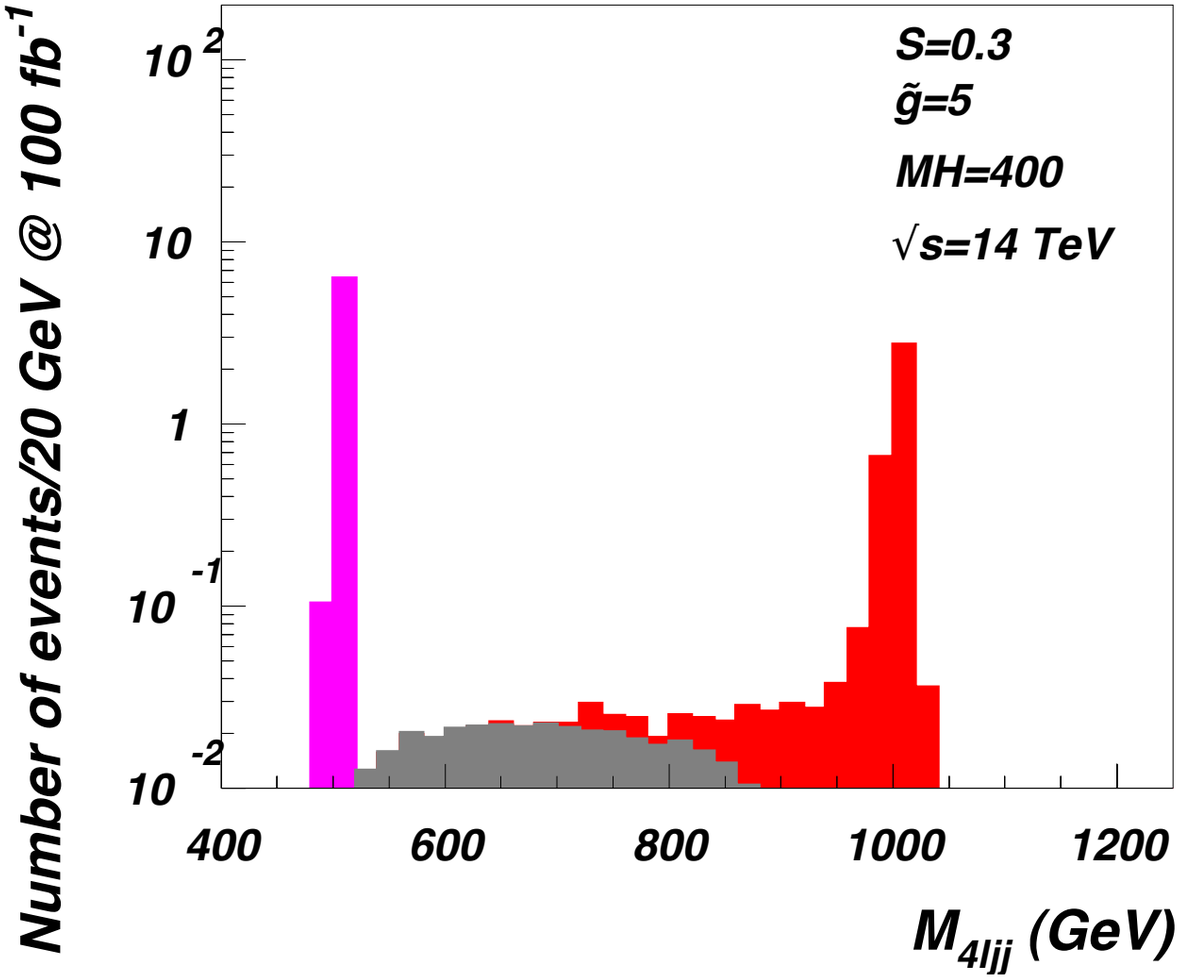
$$pp \longrightarrow HV$$

Walking/Higher dim. rep. can allow for:

Light Composite Higgs	F.S. 08 Hong, Hsu, F.S. 04 Dietrich, F.S., Tuominen 05 Doff, Natale, Rodrigues da Silva 08 Doff, Natale, 09.
Light Composite Axial	Foadi, Frandsen, Ryttov F.S., 07 Eichten, Lane 07

$$pp \to HW^{\pm} \to W^{\pm}ZZ \to 4l + 2j$$

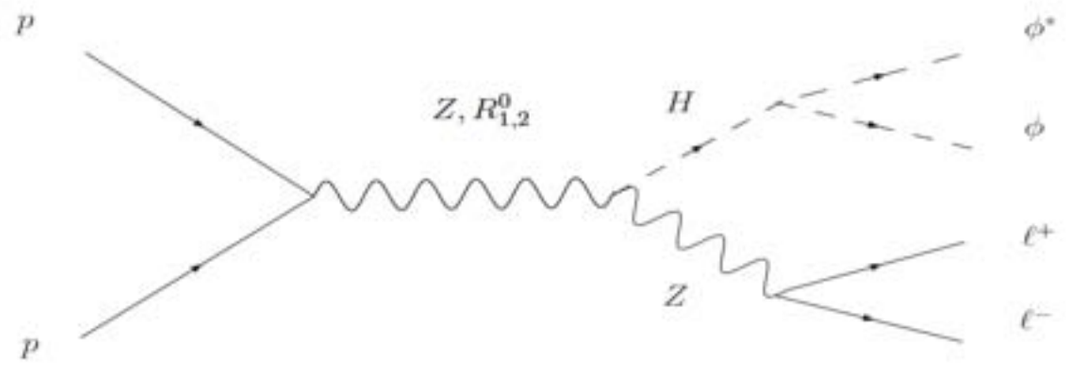


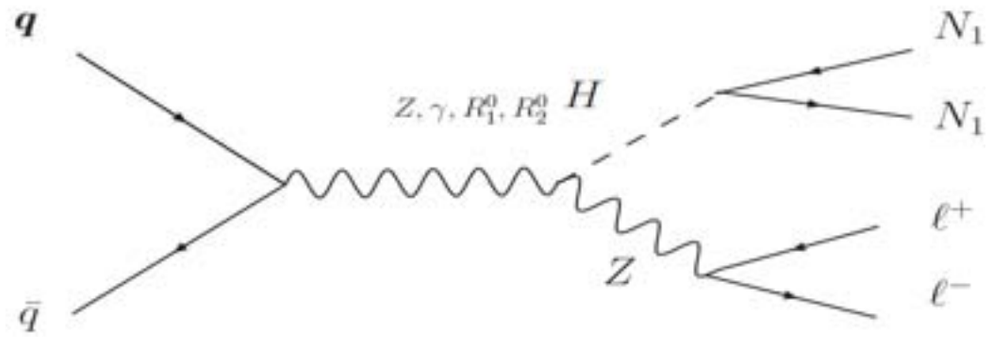


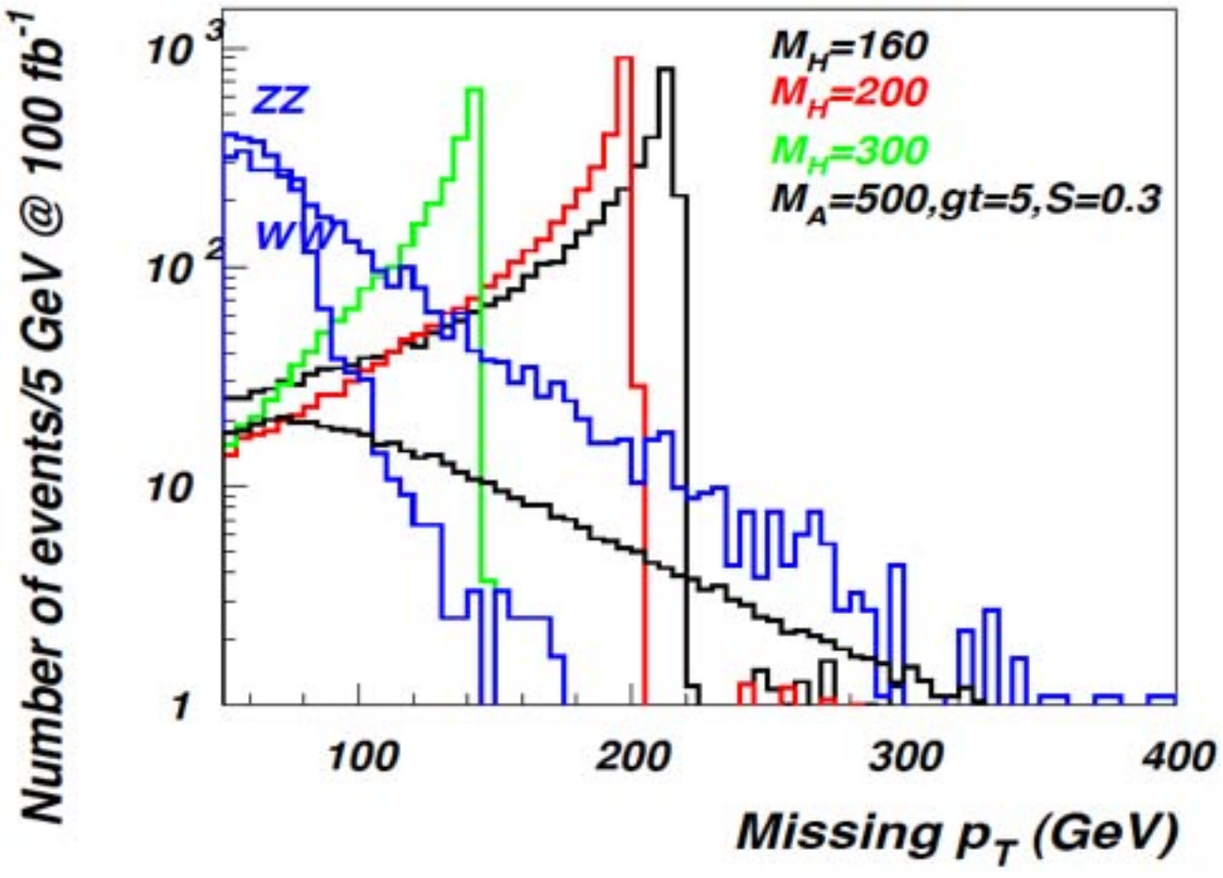
$$|\eta^J| < 4.5, \quad p_T^j > 30 \text{ GeV}, \qquad |\eta^l| < 2.5, \quad p_T^l > 15 \text{ GeV}, \quad \Delta R(jj/jl) > .5$$

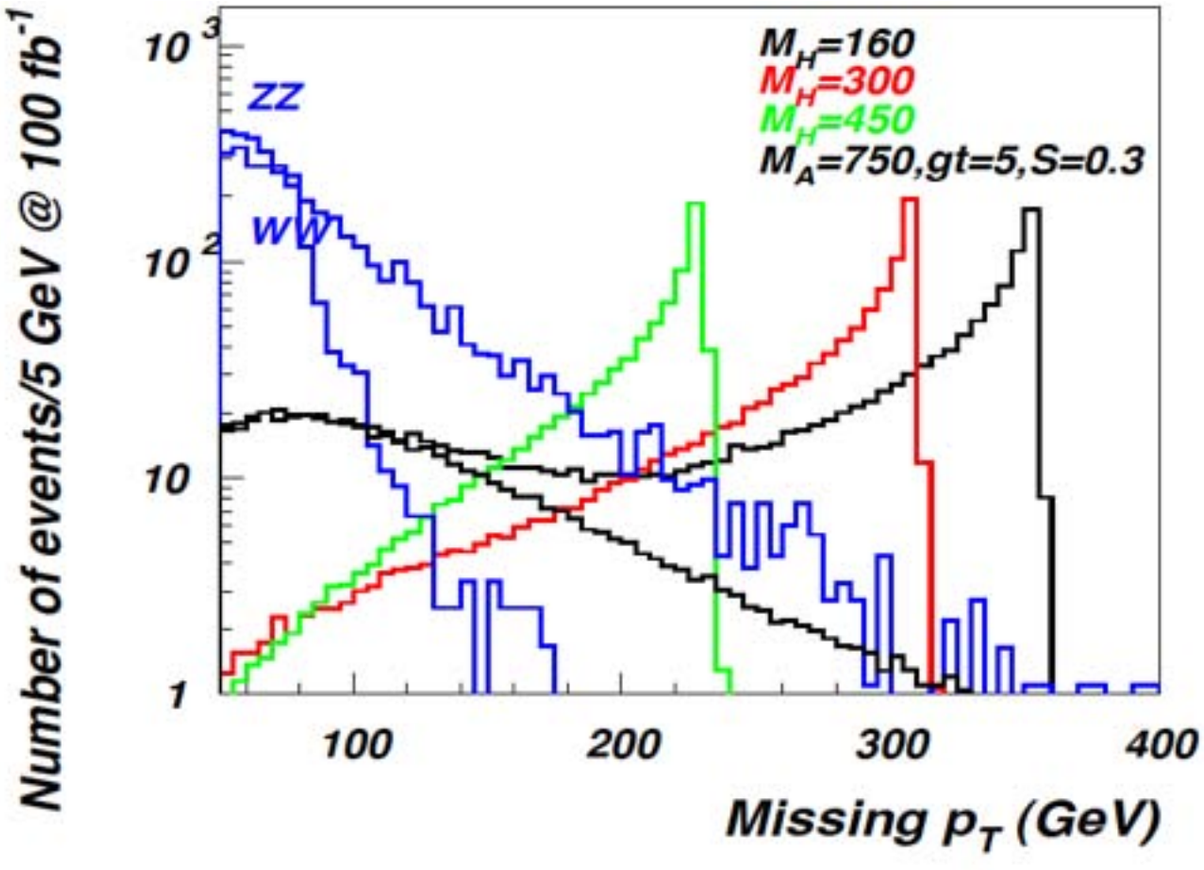
$$65 \text{ GeV} < M_{jj} < 95 \text{ GeV}$$

Missing Energy from DM and heavy Neutrinos









Missing Energy from DM and heavy Neutrinos

Foadi, Frandsen, F.S. 08

Frandsen, Masina, F.S. 09

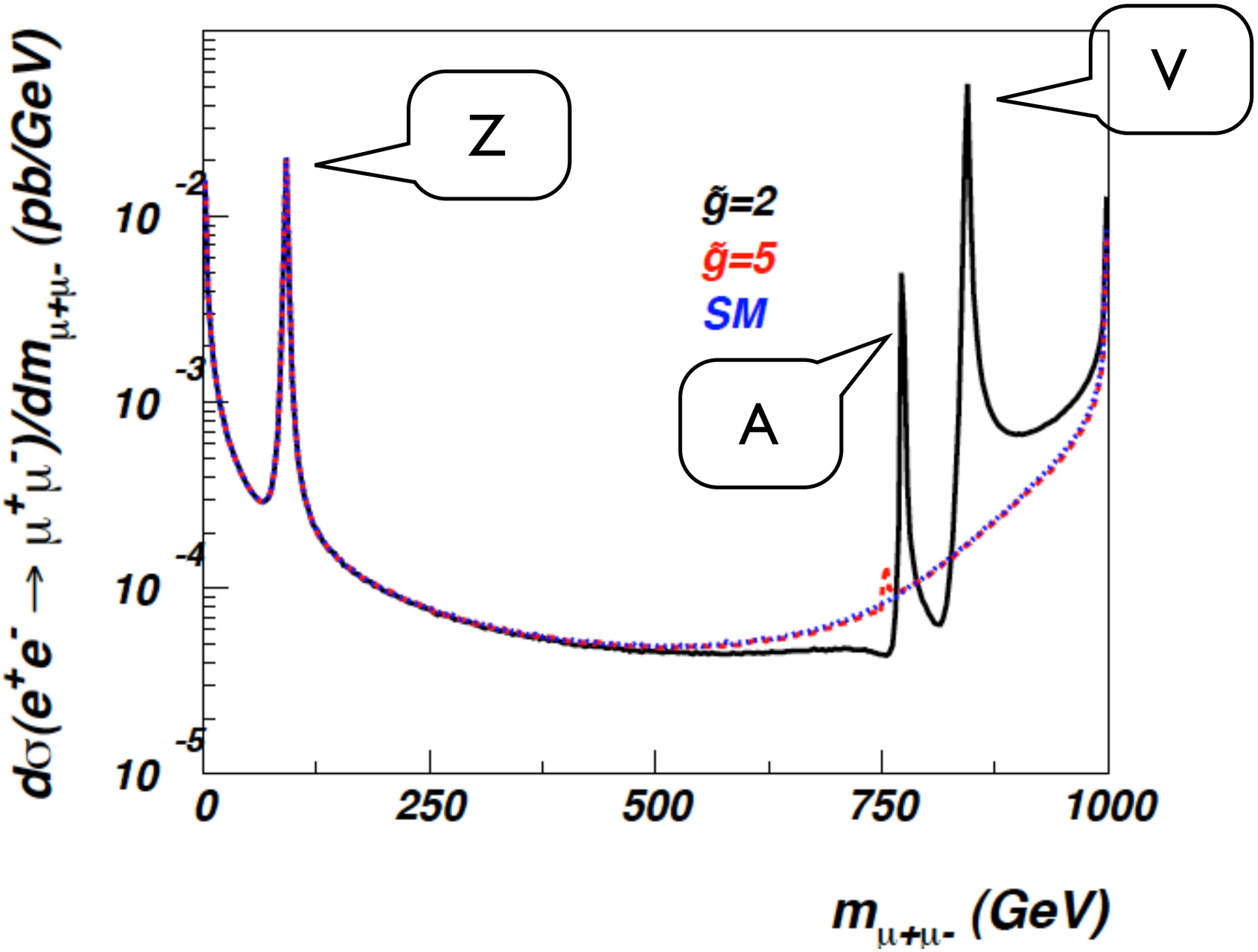
LC Phenomenology

In collaboration with

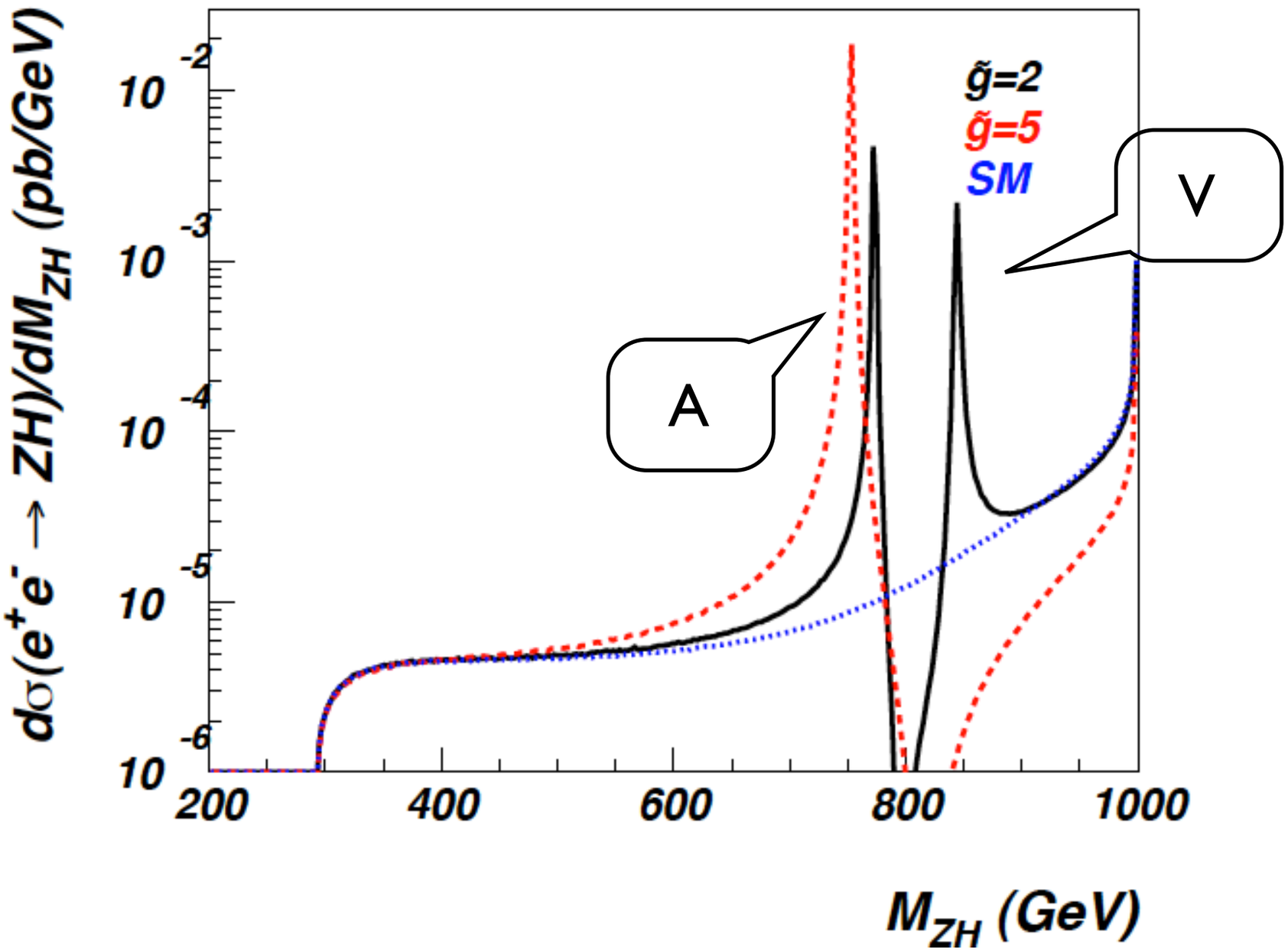
A. Belyaev
R. Foadi
M. T. Frandsen
M. O. Jarvinen

CalcHep

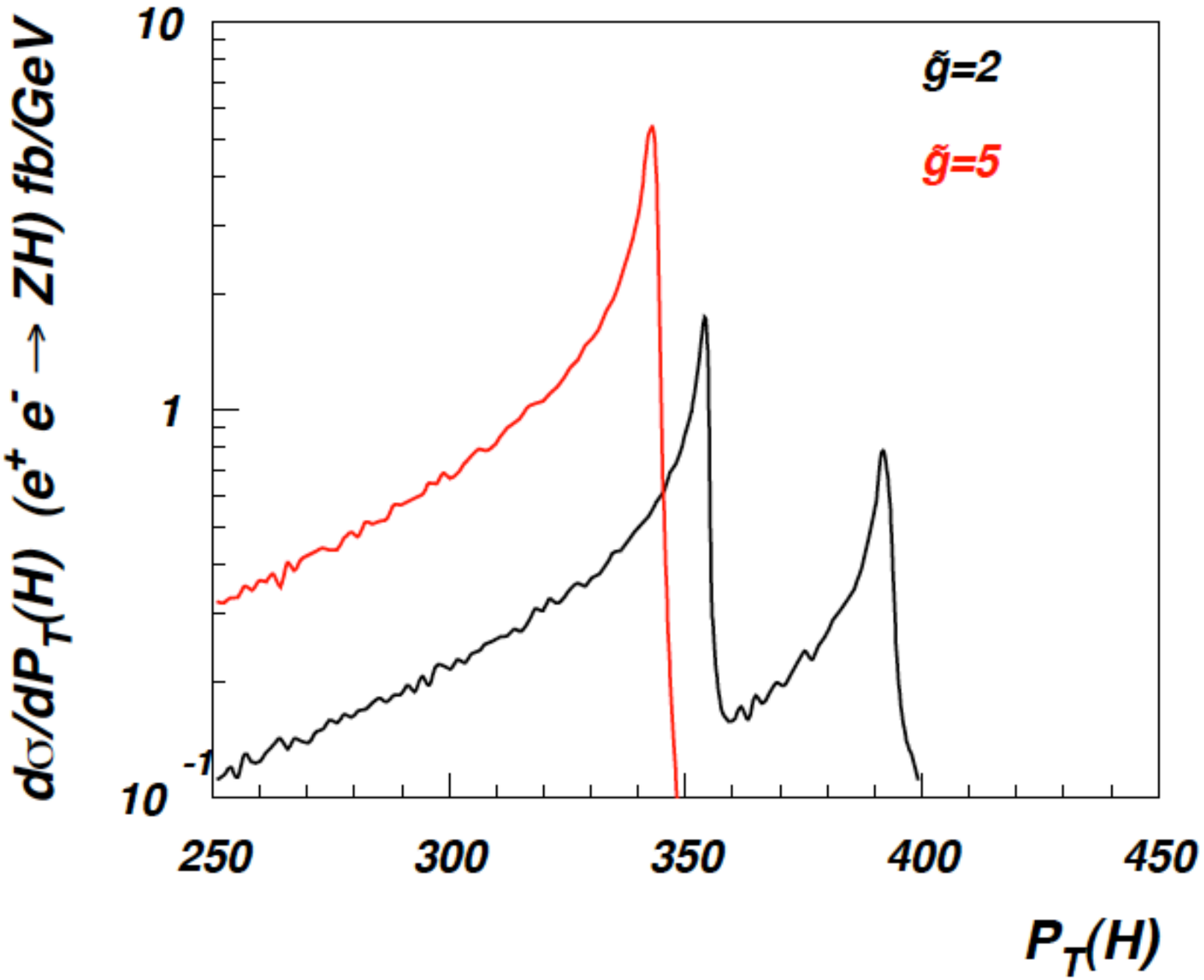
$\sqrt{s} = 1$ TeV $S = 0.3$ $M_A = 0.75$ TeV



$\sqrt{s} = 1$ TeV $S = 0.3$ $M_A = 0.75$ TeV



$\sqrt{s}$ = 1 TeV S = 0.3 M_A=0.75 TeV M_H= 0.2 TeV



Summary

- DEWSB is very much alive
- DEWSB Cosmology is exciting
- Associate production of the composite Higgs
- LC can help discovering technicolor