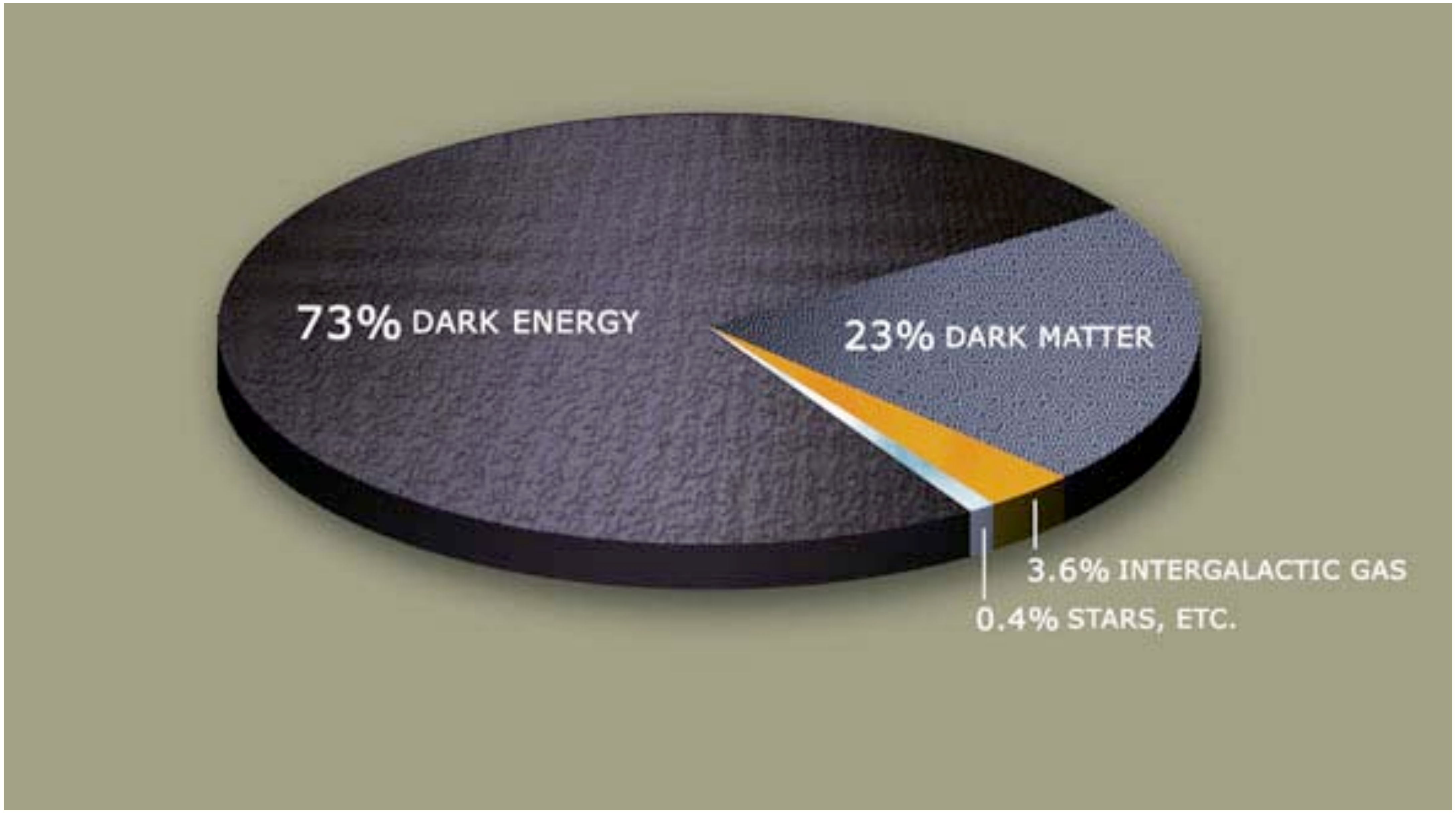
Dynamical Electroweak Symmetry Breaking

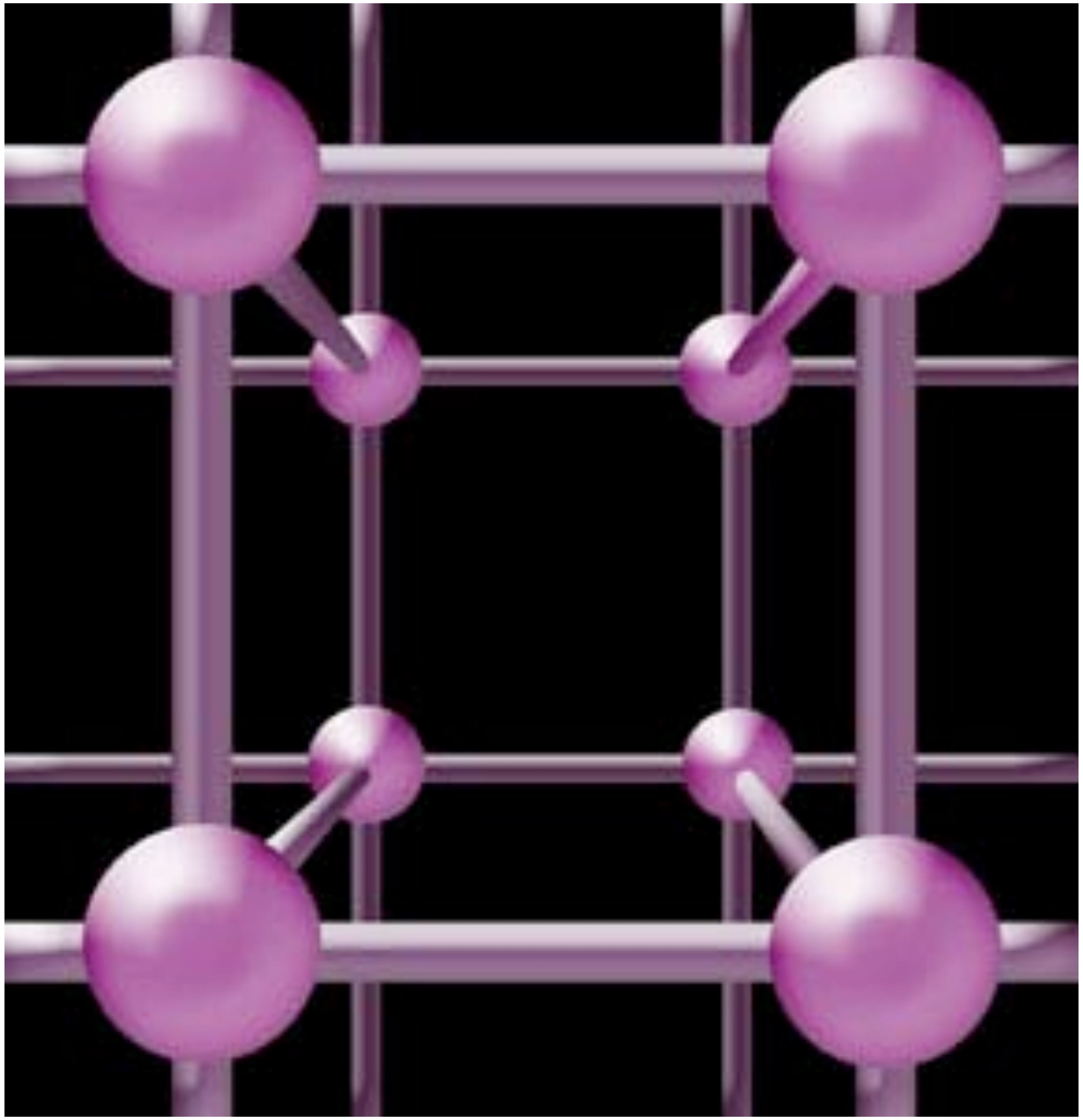
Francesco Sannino

Split 2008


U



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



Dynamical EW Breaking

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

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Dots are partially fixed by Anomalies as well as other principles

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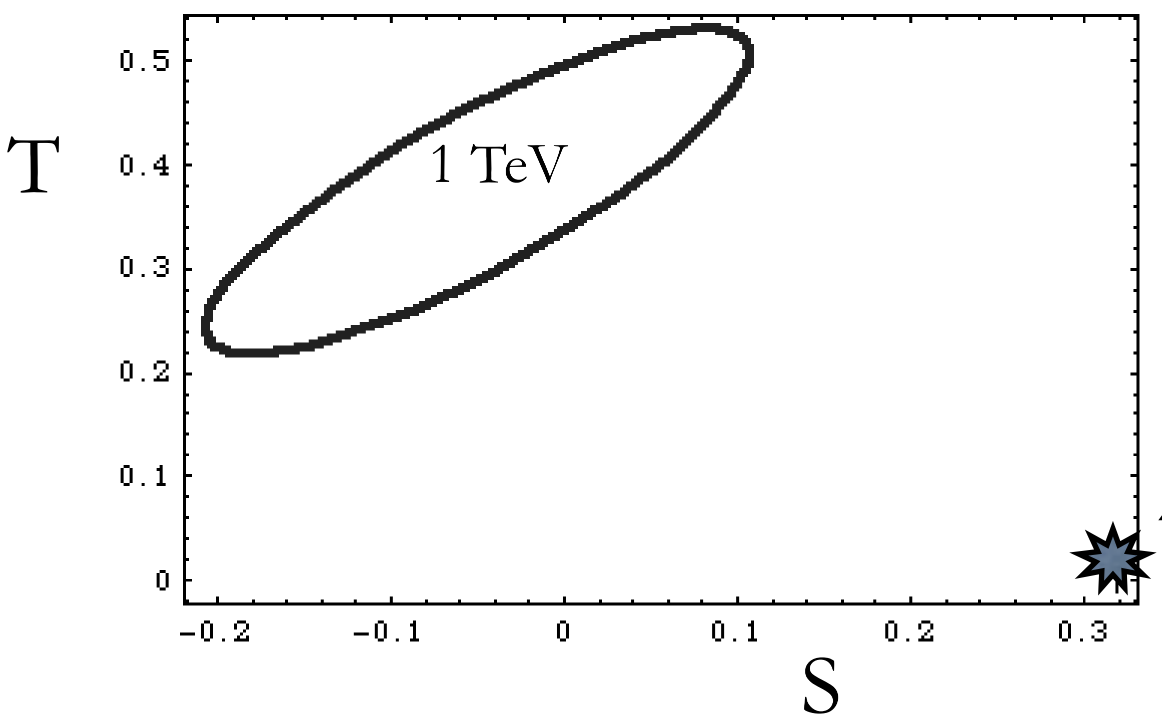
Dots are partially fixed by Anomalies as well as other principles

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

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

The need to Extend Technicolor

$$\bar{L} \cdot H e_R \qquad \longrightarrow \qquad \bar{L} \frac{\bar{Q}Q}{\Lambda_{ETC}^2} e_R$$

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If TC/QCD - Like Dynamics

The need to Extend Technicolor

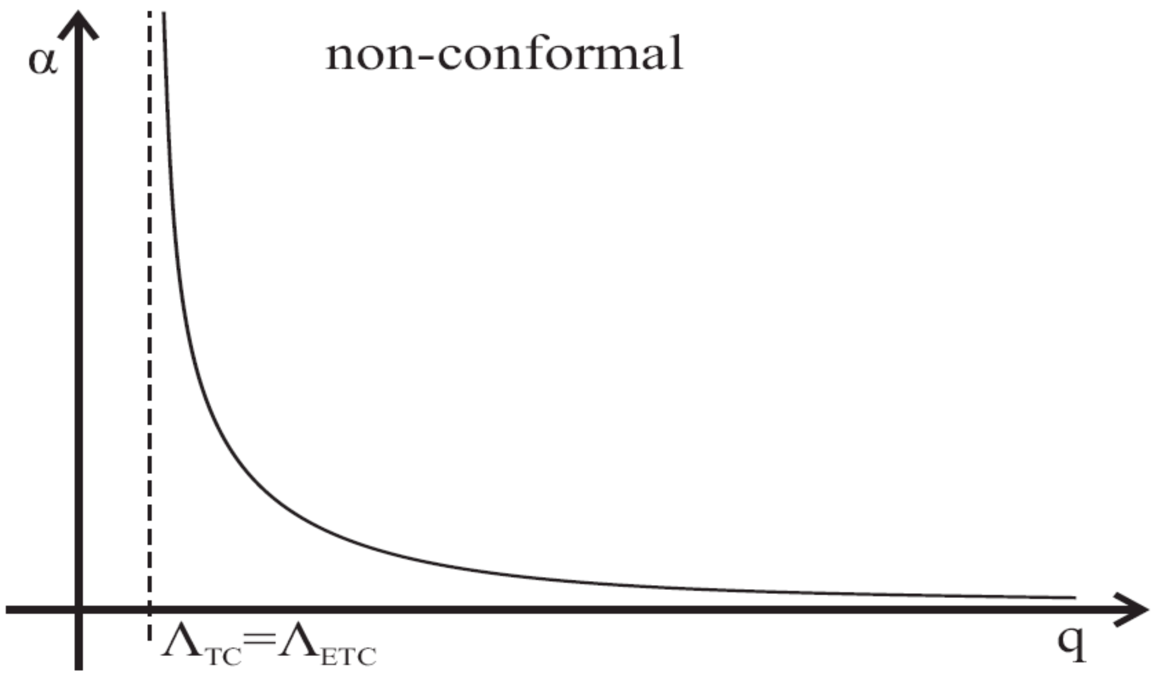
$$\bar{L} \cdot H e_R \qquad \longrightarrow \qquad \bar{L} \frac{\bar{Q}Q}{\Lambda^2_{ETC}} e_R$$

If TC/QCD - Like Dynamics

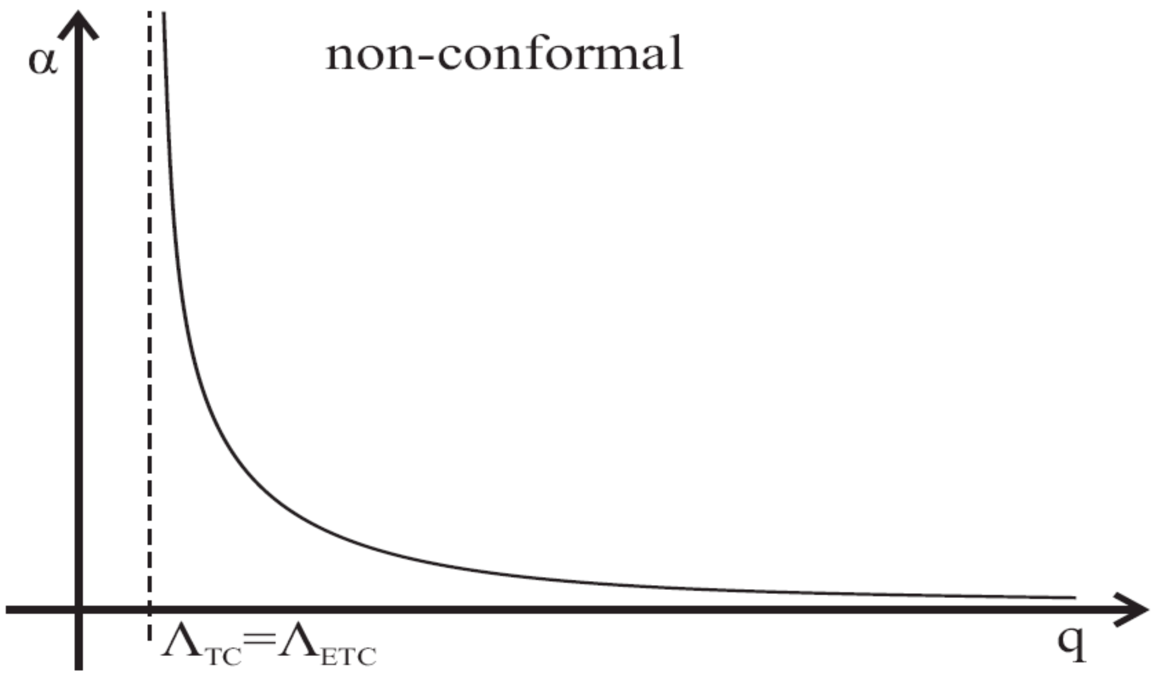
Heavy Quarks $\Leftrightarrow$ Large FCNC

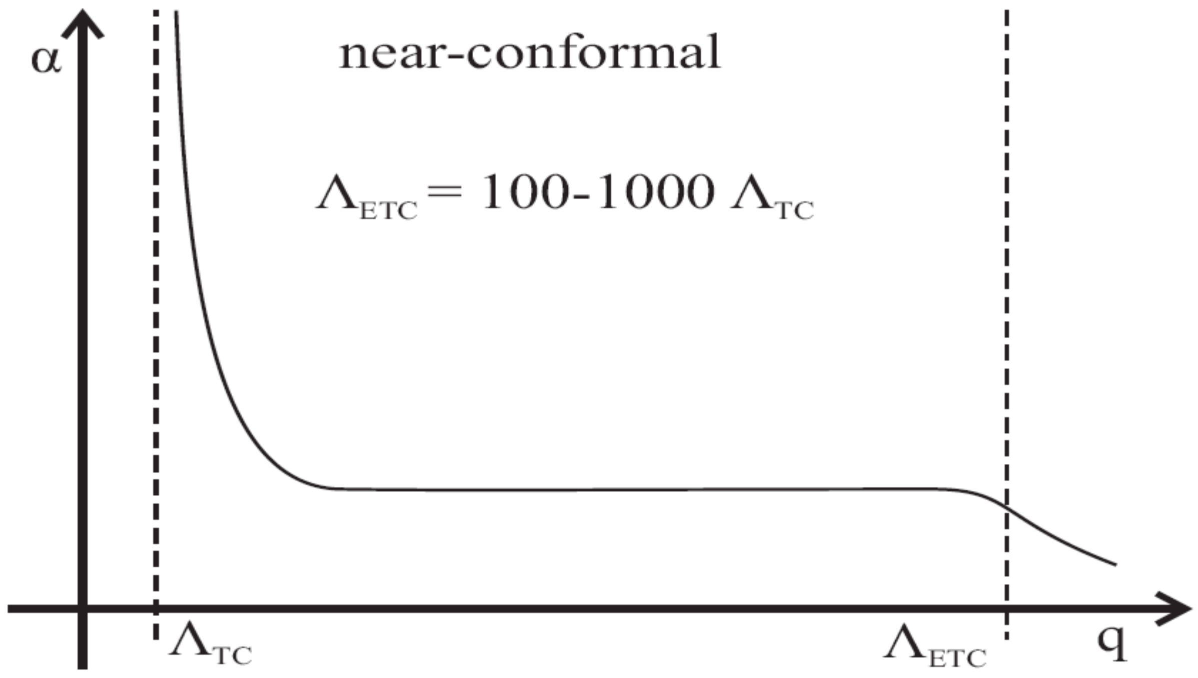
Walking versus Running

Near Conformal Properties

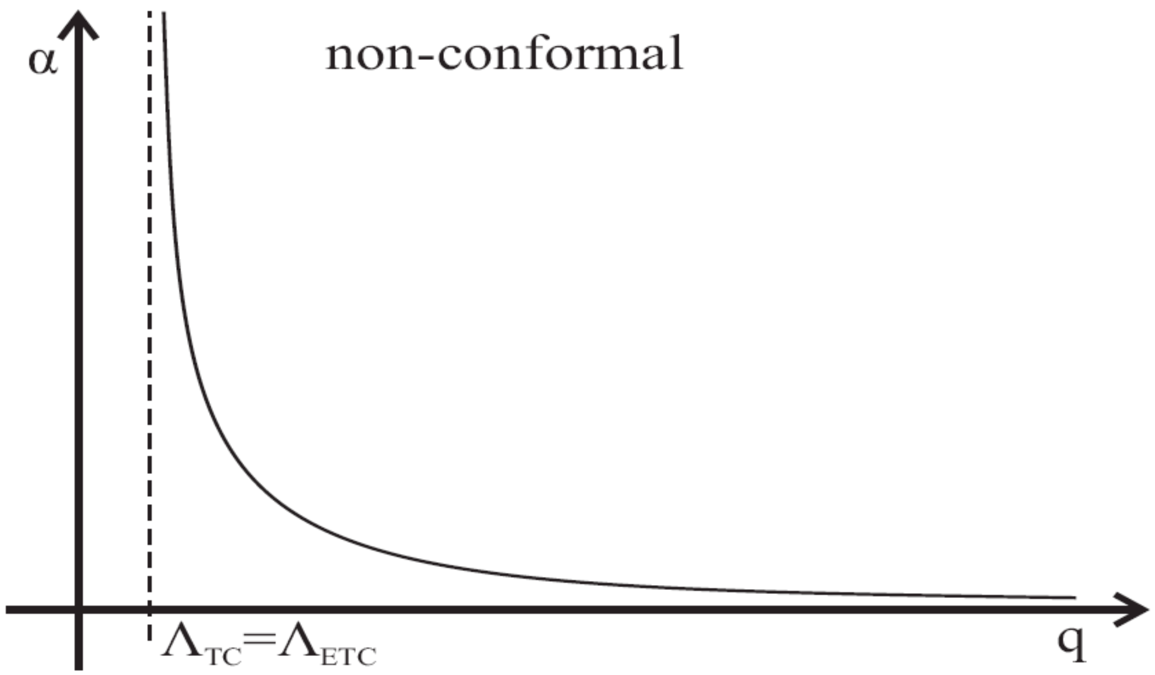


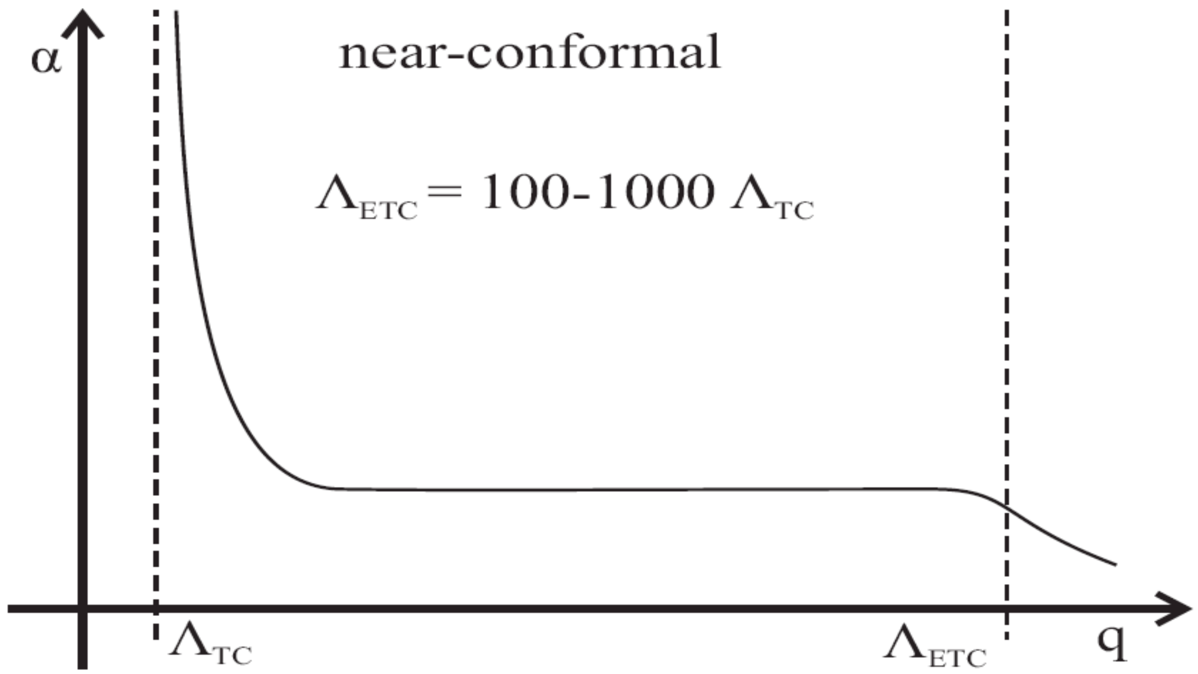
Near Conformal Properties

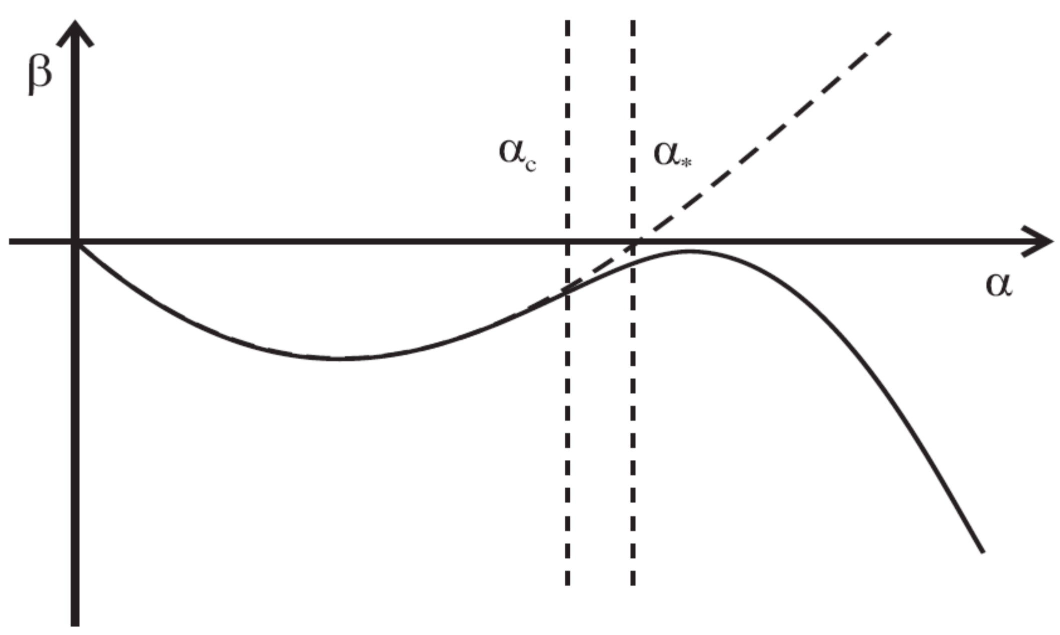




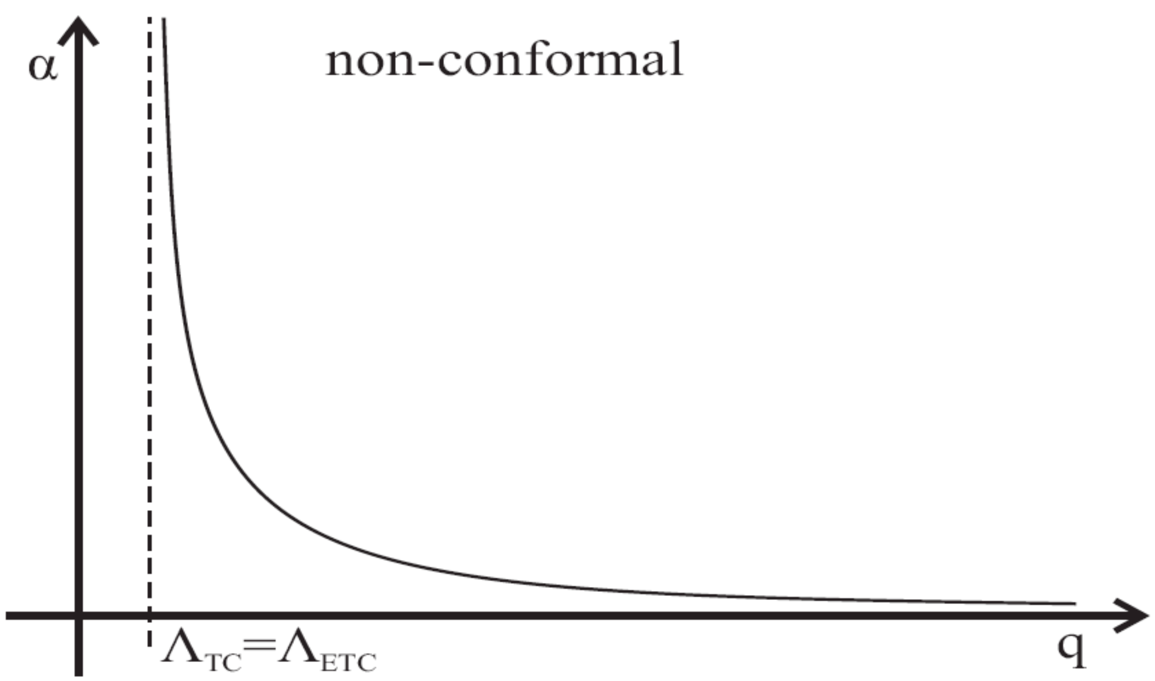
Near Conformal Properties

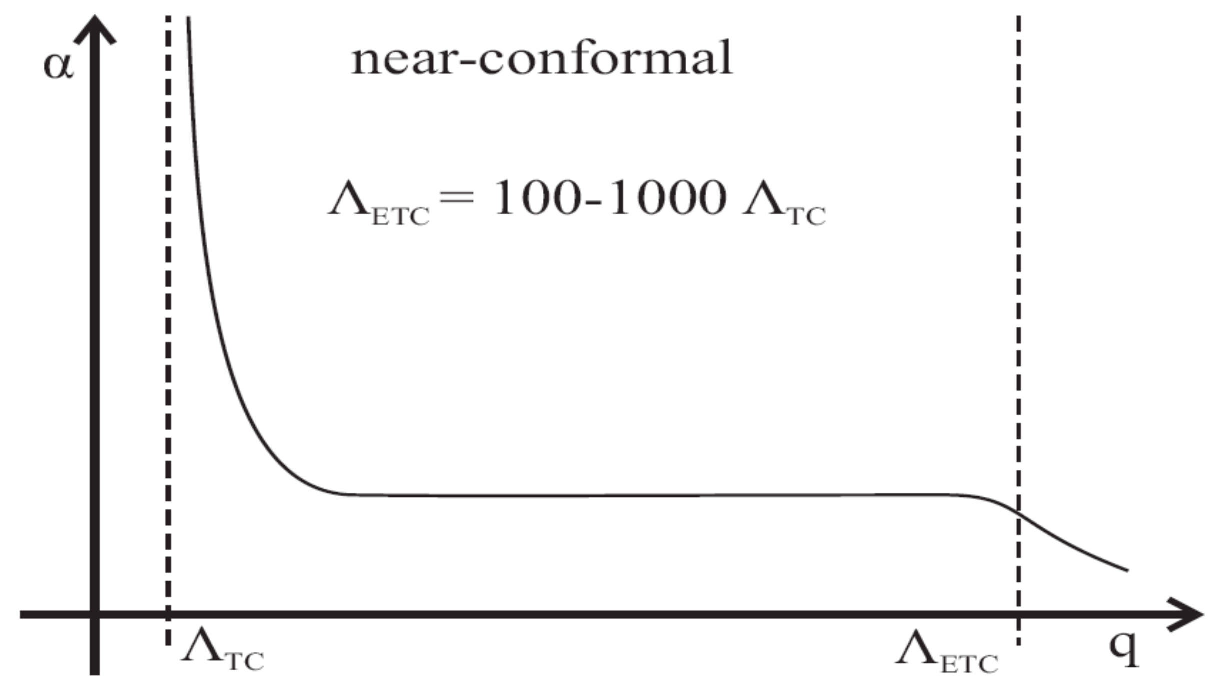




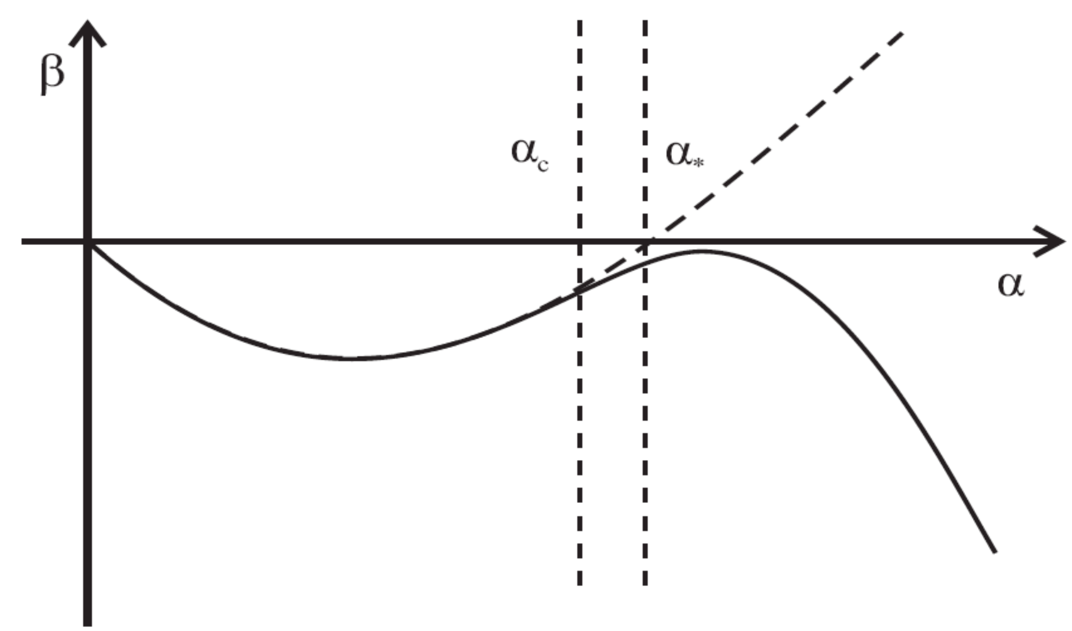


Near Conformal Properties





Holdom
Eichten and Lane
Appelquist,Yamawaki, Miransky
Georgi, Cohen
Shrock
....



S in Walking Technicolor

S in Walking Technicolor

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

Appelquist, F.S.

S in Walking Technicolor

$$S_{WTC} < S_{TC}$$ Appelquist, F.S.

We will take as an estimate:

S in Walking Technicolor

$$S_{WTC} < S_{TC}$$ Appelquist, 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

Besides

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

Besides

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Besides

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Offset the first term

Besides

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

Offset the first term

Rule:

Find Walking Theories with EW embedding minimizing S

Progress in Strong Dynamics:

Progress in Strong Dynamics:

Schwinger Dyson results for Higher Dim. Rep

F.S. and Tuominen 04

Dietrich, F.S. 06

Progress in Strong Dynamics:

Schwinger Dyson results for Higher Dim. Rep — F.S. and Tuominen 04; Dietrich, F.S. 06

Conjectured all-orders beta function — Ryttov, F.S. 07

Progress in Strong Dynamics:

Schwinger Dyson results for Higher Dim. Rep — F.S. and Tuominen 04; Dietrich, F.S. 06

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Lattice

Catterall, F.S. 07
Appelquist, Fleming, Neil 07
Catterall, Giedt, F.S., Schneible 08
Del Debbio, Frandsen, Panagopoulos, F.S. 08
DeGrand, Shamir, Svetitsky, 08
Del Debbio, Patella, Pica, 08
Deuzman, Lombardo, Pallante 08

Minimal Walking Technicolor

F.S. and Tuominen 04

Minimal Walking Technicolor

F.S. and Tuominen 04

Dietrich, F.S. Tuominen 06

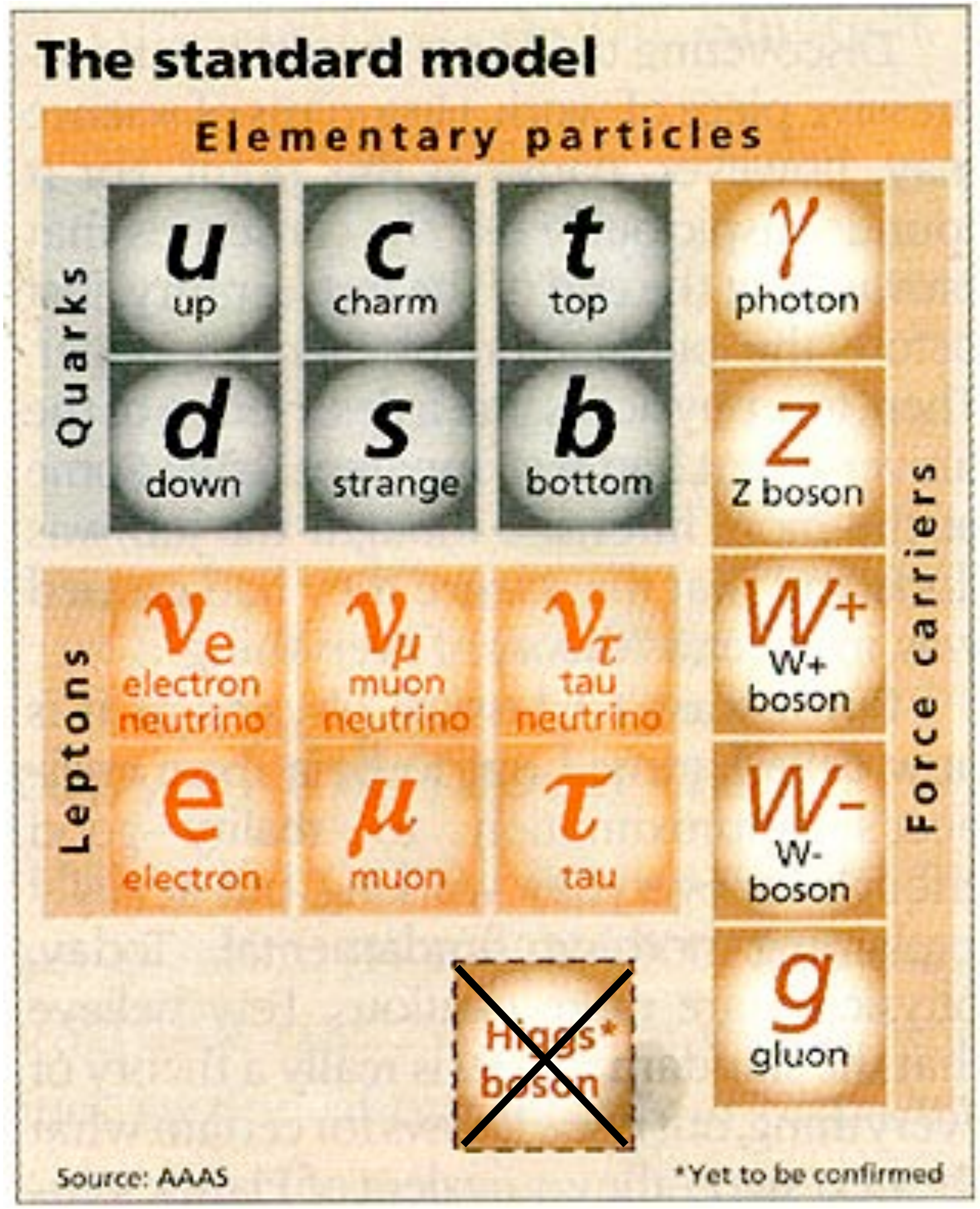
Gudnason, Kouvaris, F.S. 06

Gudnason, Ryttov, F.S. 06

Foadi, Frandsen, Ryttov, F.S. 07

Cline, Jarvinen, F.S. 08

Belyaev, Foadi, Frandsen, Jarvinen, Pukhov, F.S. 08

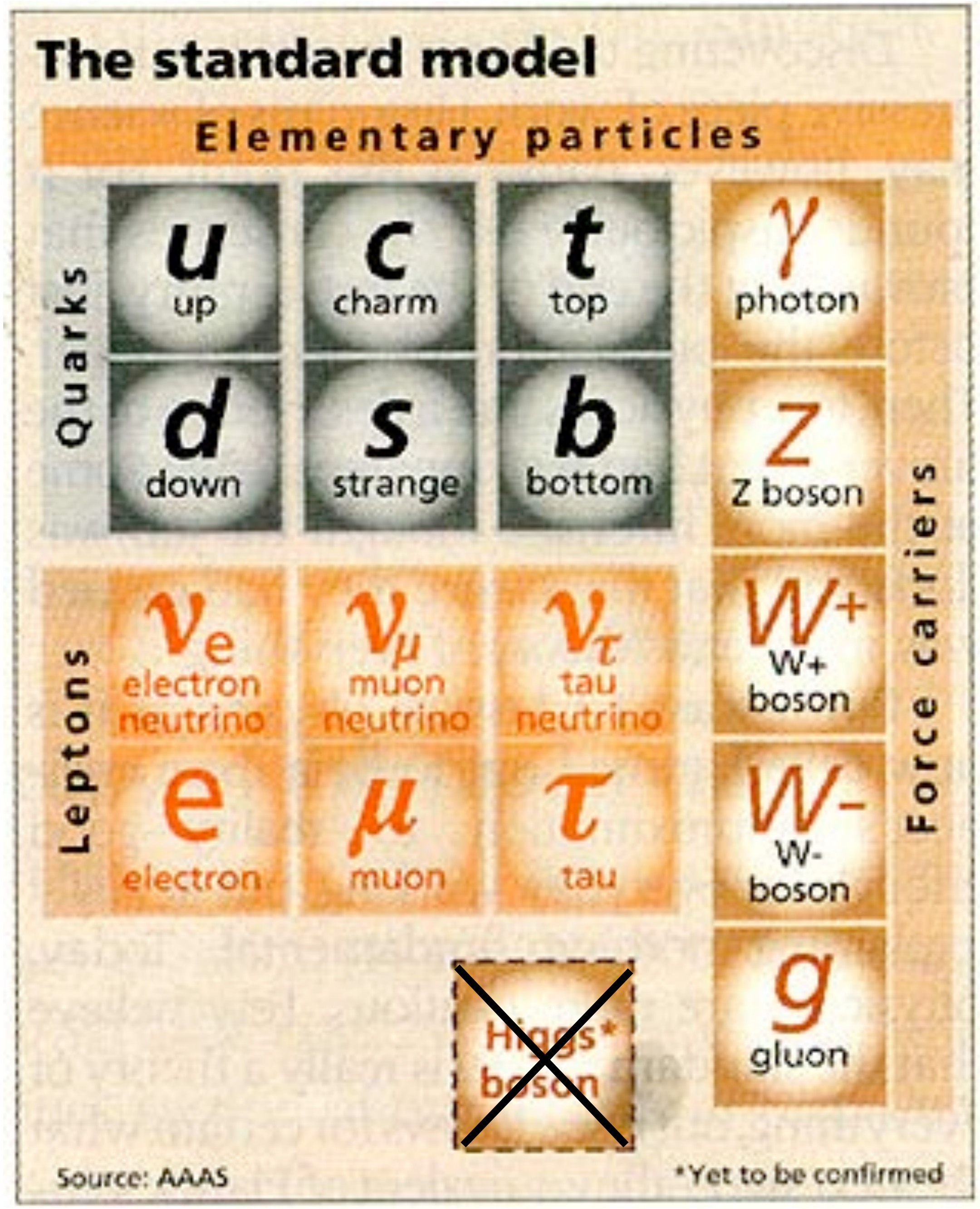


The standard model
Elementary particles
Quarks
u
up
c
charm
t
top
d
down
s
strange
b
bottom
Leptons
ν_e
electron neutrino
ν_μ
muon neutrino
ν_τ
tau neutrino
e
electron
μ
muon
τ
tau
Force carriers
γ
photon
Z
Z boson
W^+
W+ boson
W^-
W- boson
g
gluon
Higgs* boson
Source: AAAS
*Yet to be confirmed

U(1)

SU(2)

SU(3)



U(1)

SU(2)

SU(3)

N
Extra Neutrino

E
Extra Electron

U
t-up

G
t-glue

D
t-down

SU(2)

U and D: Adj of SU(2)

MWT Features

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The most economical WT theory

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Compatible with precision measurements

MWT Features

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Possible DM candidates and Unification investigated

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Compatible with precision measurements

Possible DM candidates and Unification investigated

Can support 1st order Electroweak Phase Transition

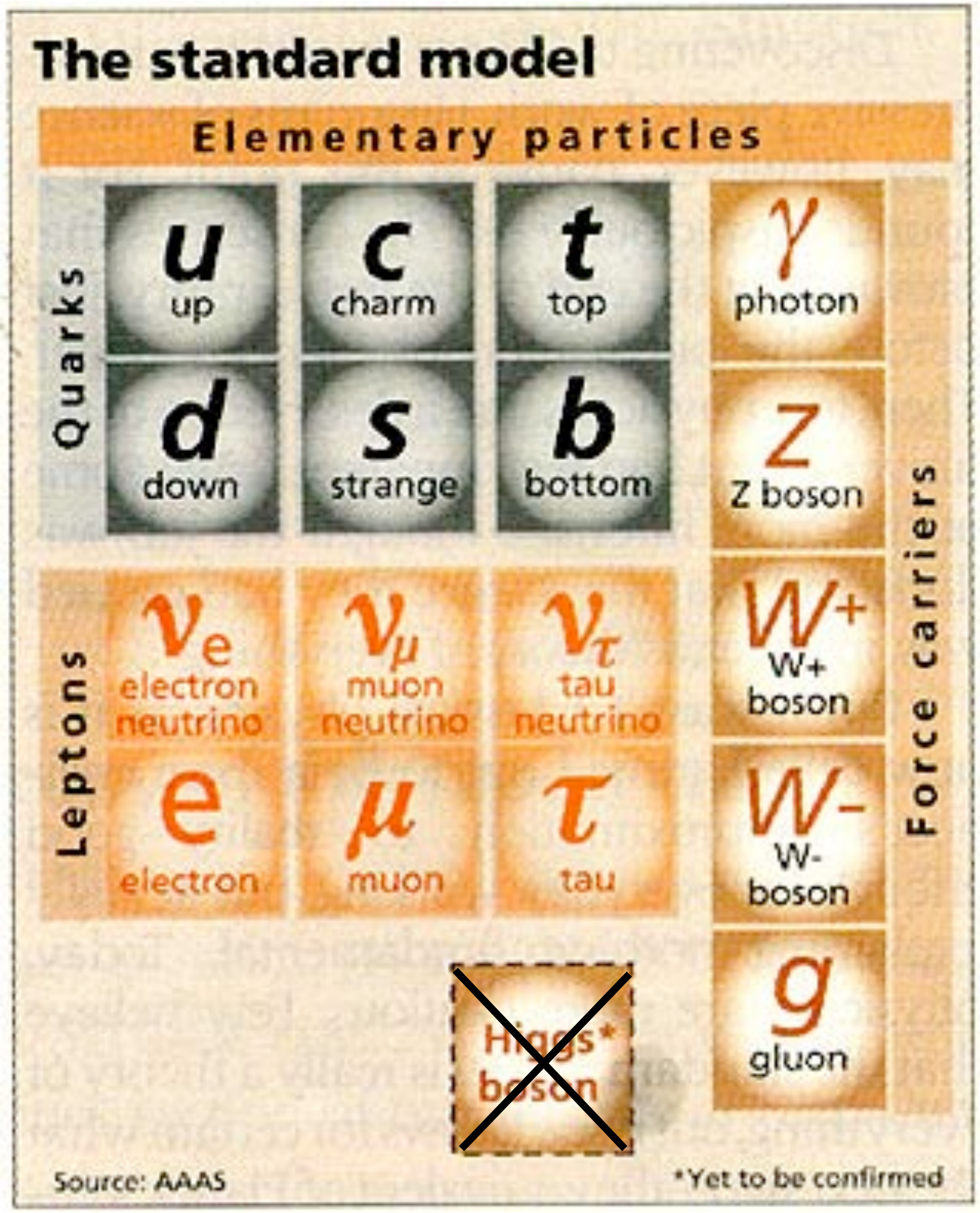
Can support exotic electric charges

Lattice studies have begun

Ultra Minimal Walking Technicolor

Ryttov and F.S. 08

Eichten and Lane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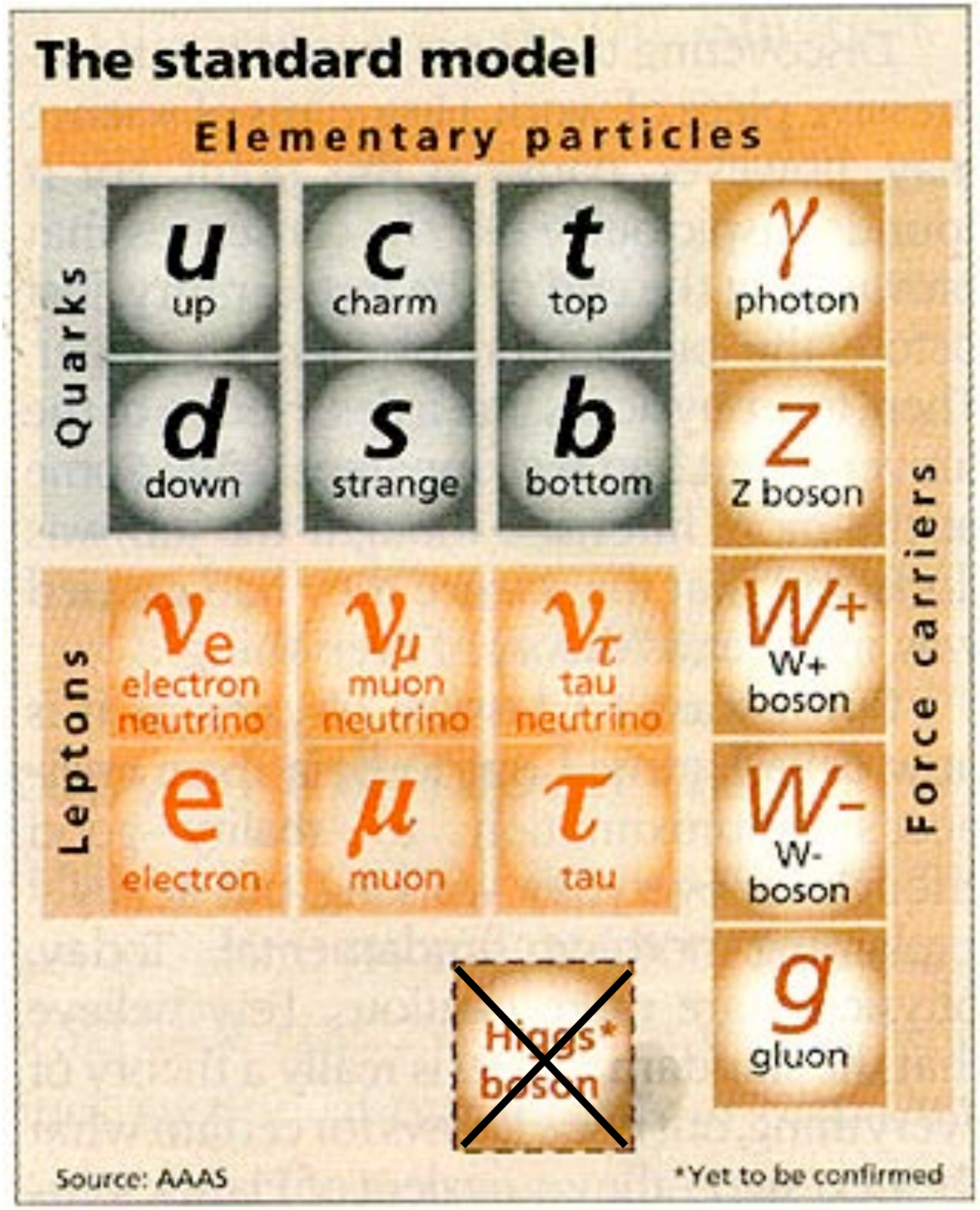
muon neutrino
ν_τ
tau neutrino
e
electron
μ
muon
τ
tau
Force carriers
γ
photon
Z
Z boson
W^+
W+ boson
W^-
W- boson
g
gluon
Higgs* boson
Source: AAAS
*Yet to be confirmed

U(1)

SU(2)

SU(3)



U(1)

SU(2)

SU(3)

U t-up	**G** t-glue
D t-down	λ^1 λ^2 t-lambda

SU(2)

U and D: Fund of SU(2)

t-lambdas: Adj of SU(2)
Singlet of SM
Weyl Fermions

UMT Features

UMT Features

The most economical “2 rep” WT theory

UMT Features

The most economical “2 rep” WT theory

Smallest naive S-parameter & # of fermions

UMT Features

The most economical “2 rep” WT theory

Smallest naive S-parameter & # of fermions

Natural DM candidate visible at LHC

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Order of the Electroweak PT under investigation

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The most economical “2 rep” WT theory

Smallest naive S-parameter & # of fermions

Natural DM candidate visible at LHC

Order of the Electroweak PT under investigation

Rich unexplored Collider Phenomenology

The MWT Lagrangian

The MWT Lagrangian

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

The MWT Lagrangian

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

The MWT Lagrangian

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

The MWT Lagrangian

$$\mathcal{L}_H \rightarrow -\frac{1}{4}\mathcal{F}^a_{\mu\nu}\mathcal{F}^{a\mu\nu} + i\bar{Q}_L\gamma^\mu D_\mu Q_L + i\bar{U}_R\gamma^\mu D_\mu U_R + i\bar{D}_R\gamma^\mu D_\mu D_R$$
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What you see is “not” what LHC will see

MWT effective lagrangian

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

MWT effective lagrangian

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MWT effective lagrangian

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

Initial investigation we include:

Composite Higgs	H
Composite Axial - Vector States	$R_{1,2}$

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

Foadi, Frandsen, Ryttov & F.S. 07

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

LHC Phenomenology

In collaboration with

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

BFFJPS arXiv:0809.0793

CalcHep

Heavy Vectors Signals

Drell-Yan production of heavy vectors

Vector Boson Fusion production of heavy vectors

Can be seen via HW and HZ production

$$R_{1,2}$$

Composite Higgs Signals

Associate Higgs Production BFFJPS 08, Zerwekh 05

Higgs $\rightarrow \gamma\gamma$ Belyaev, Blum, Chivukula, Simmons 05

Further Signatures

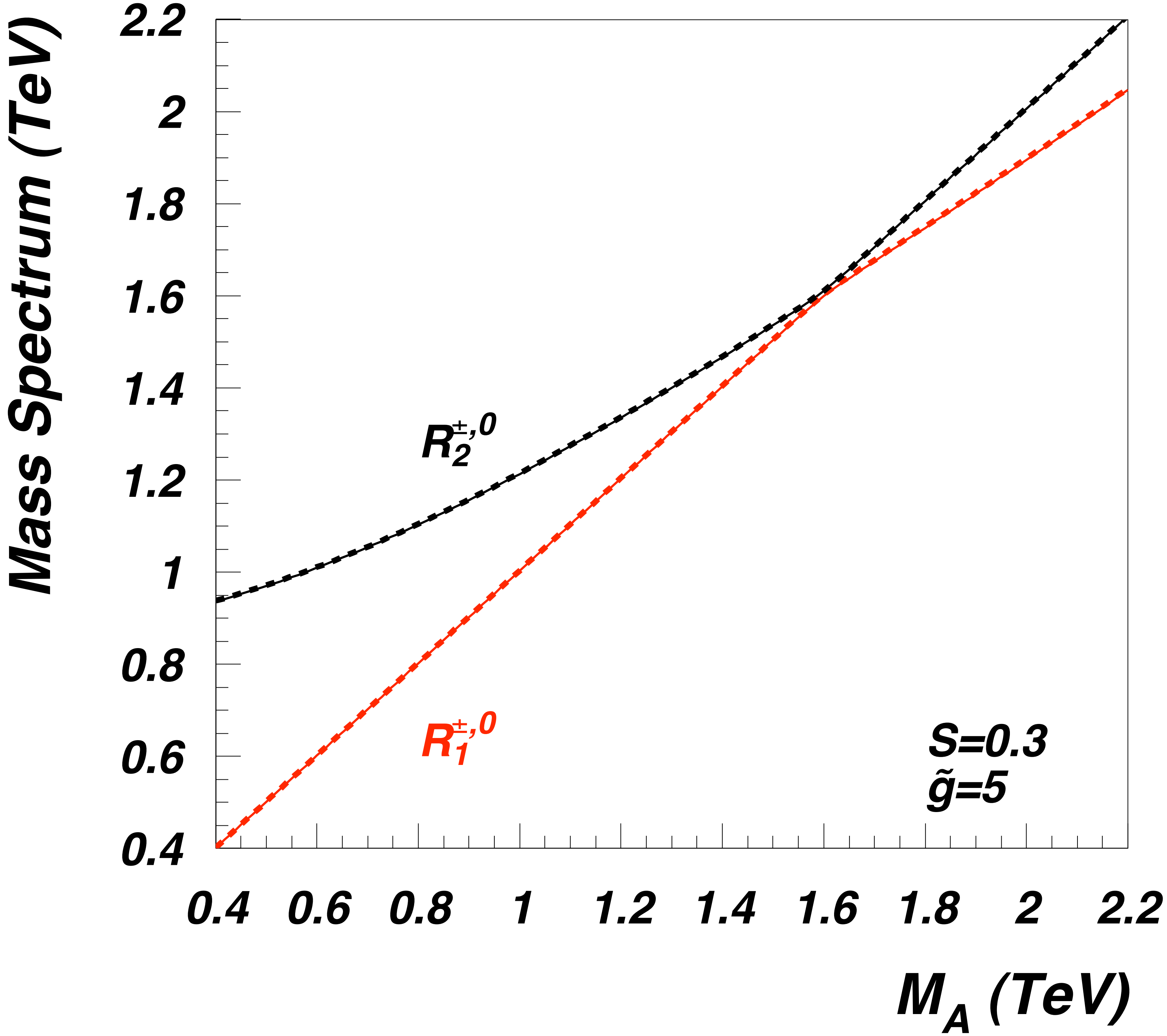
New SM Fermions

Dietrich, F.S., Tuominen 05
Gudnason, Ryttov & F.S. 08

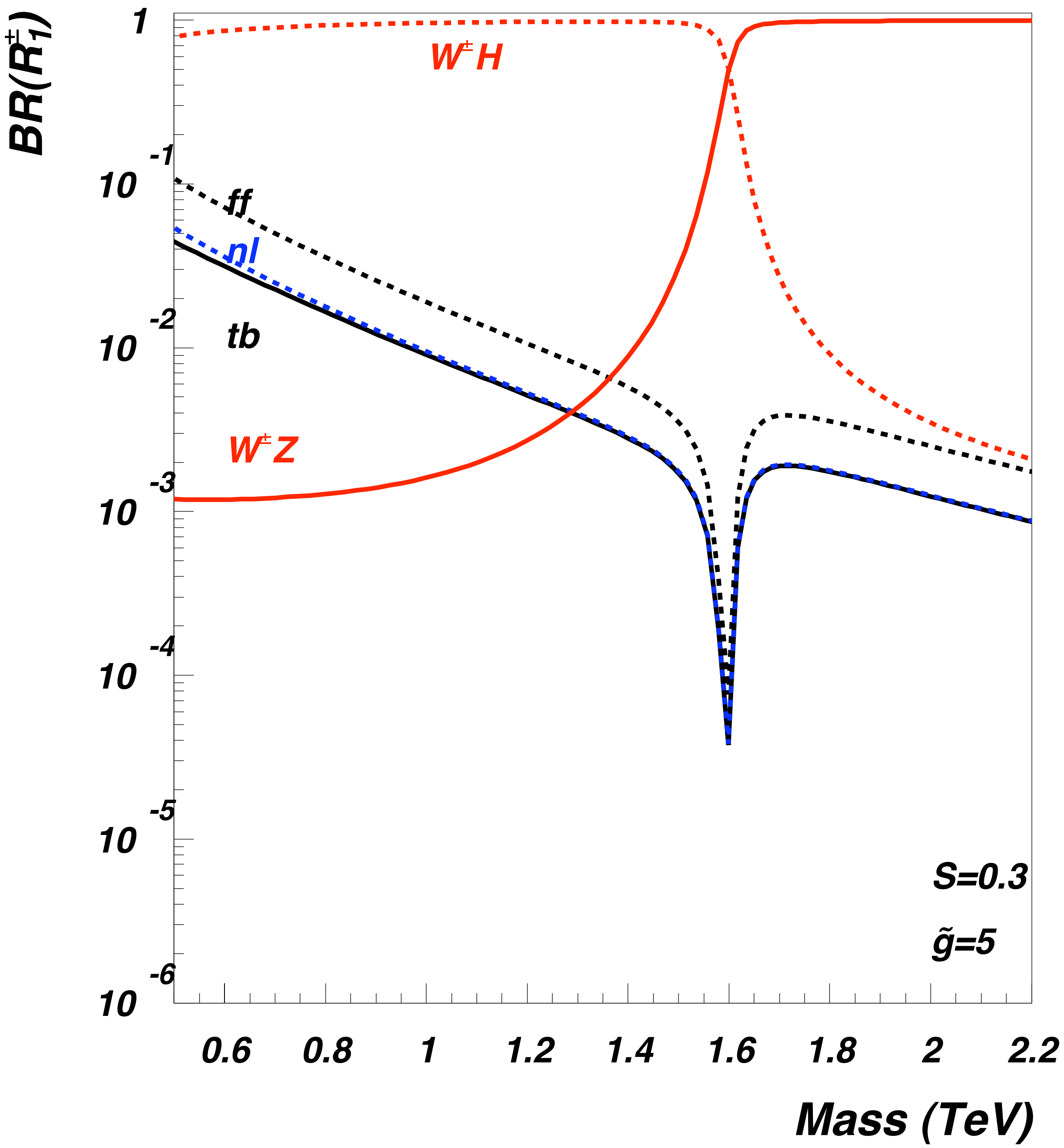
DM candidates

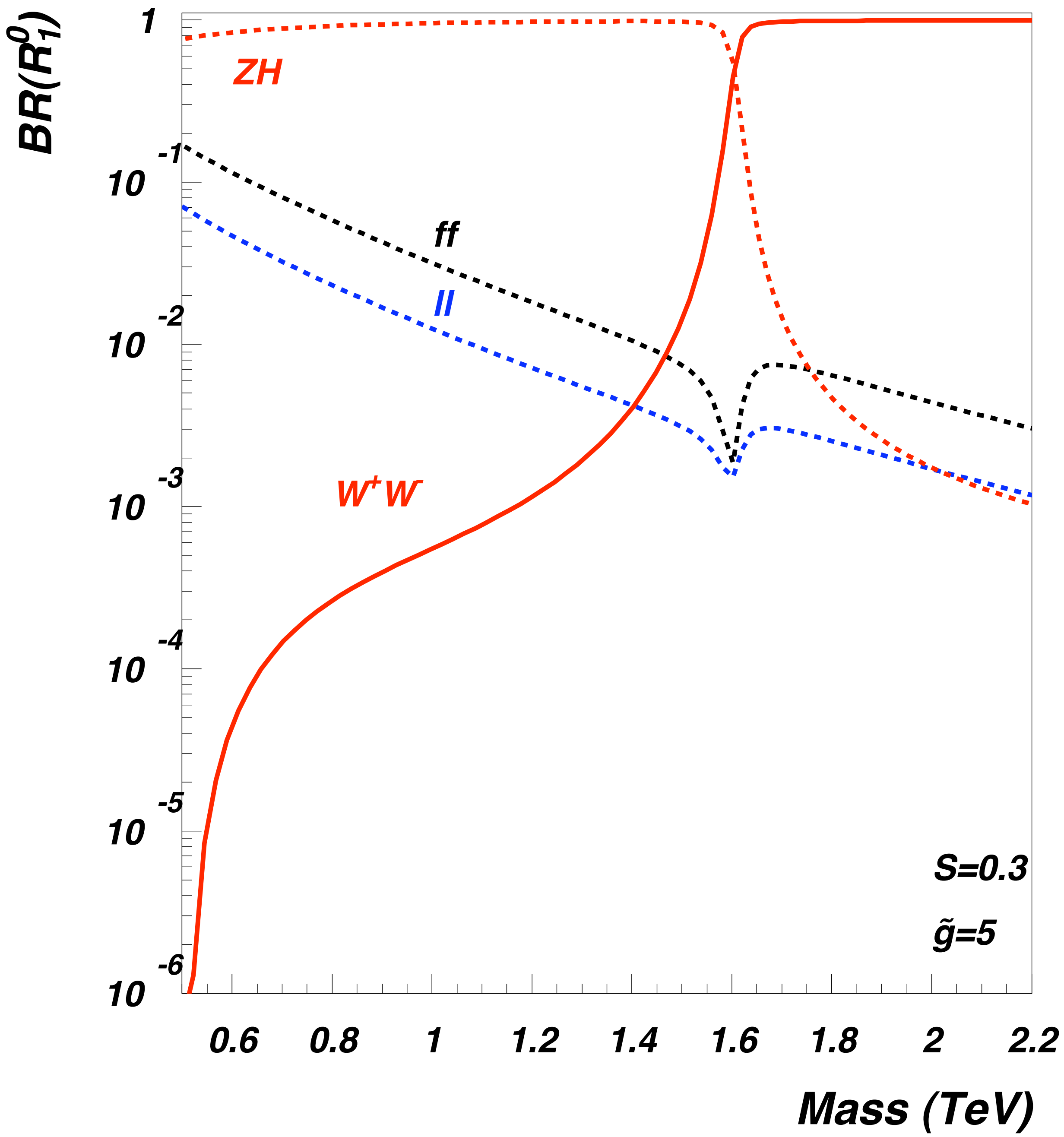
Ryttov & F.S. 08
Gudnason, Kouvaris & F.S. 05
Kainulainen, Tuominen, Virkajarvi 06
Kouvaris 07; Kouvaris, Khlopov 08

Vector-Axial Spectrum



Vector Resonances Branching Ratios





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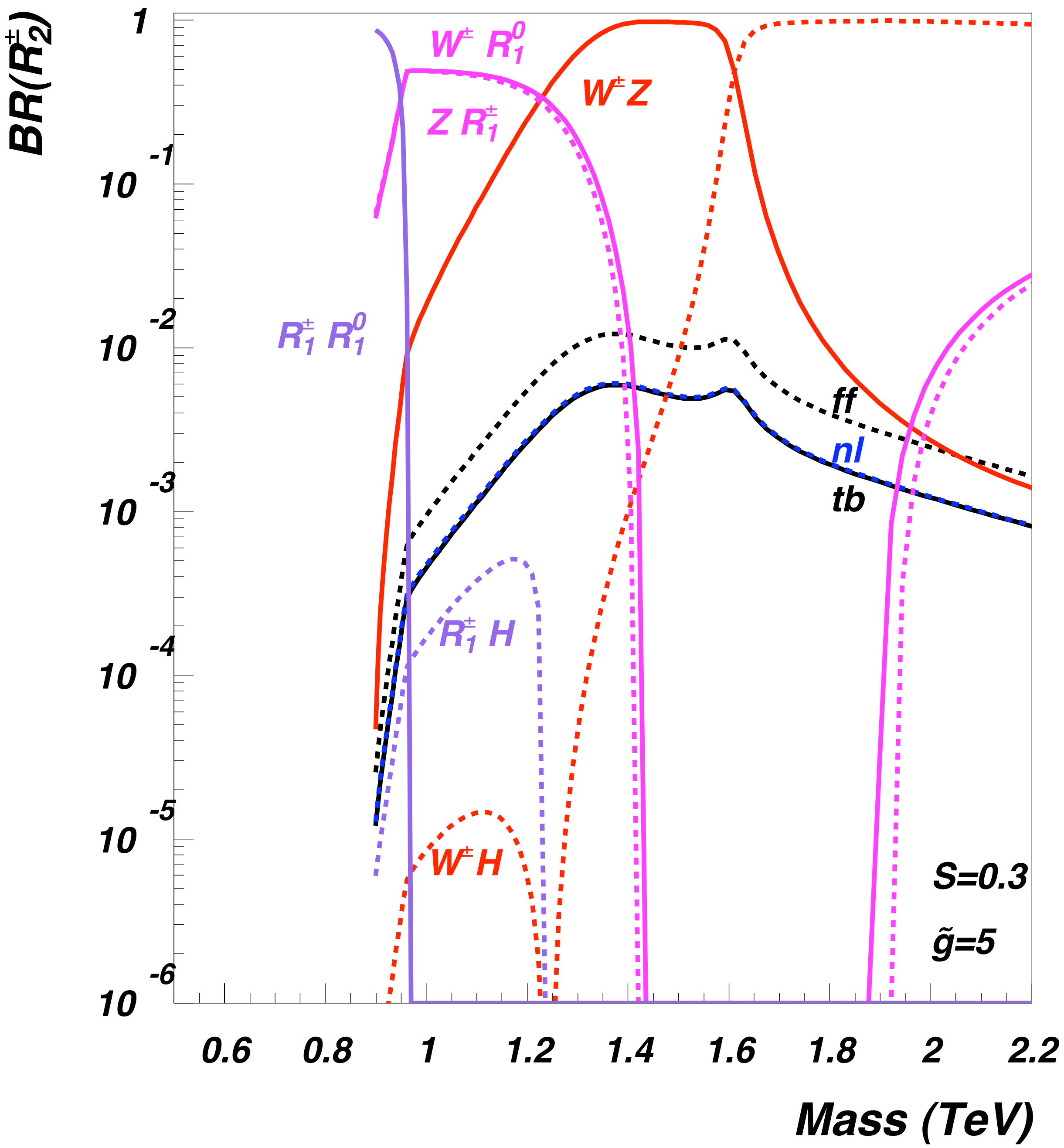
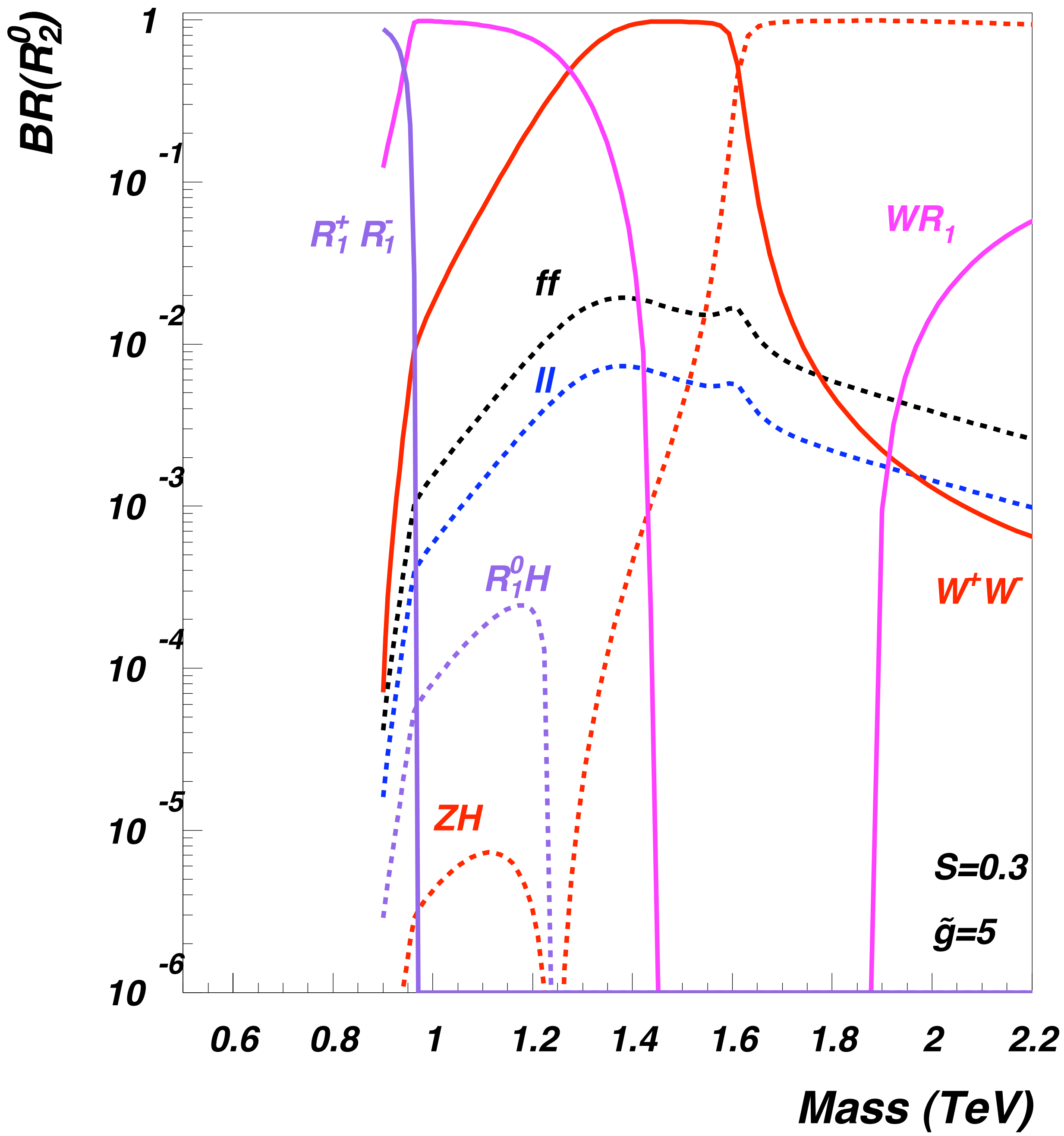




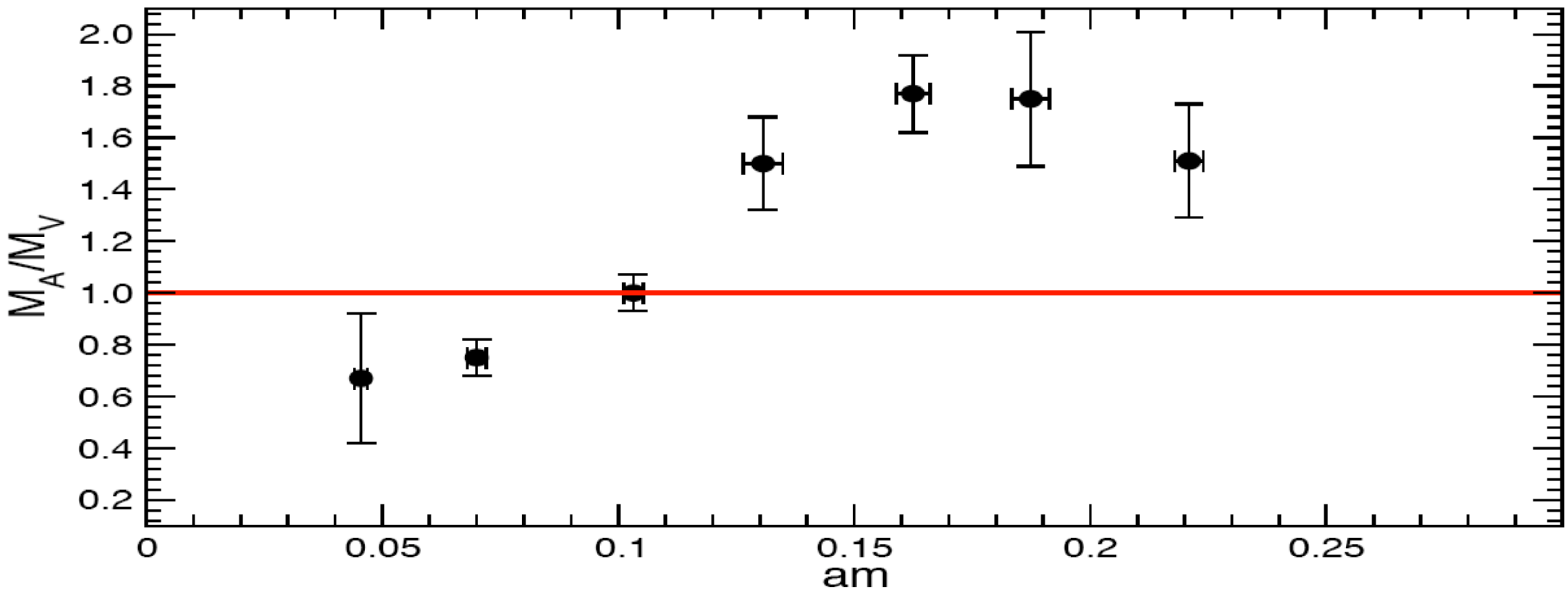
$$pp \to HV$$

Walking/Higher dim. rep. can allow for:

Light Composite Higgs — F.S. 08; Hong, Hsu, F.S. 04; Dietrich, F.S., Tuominen 05

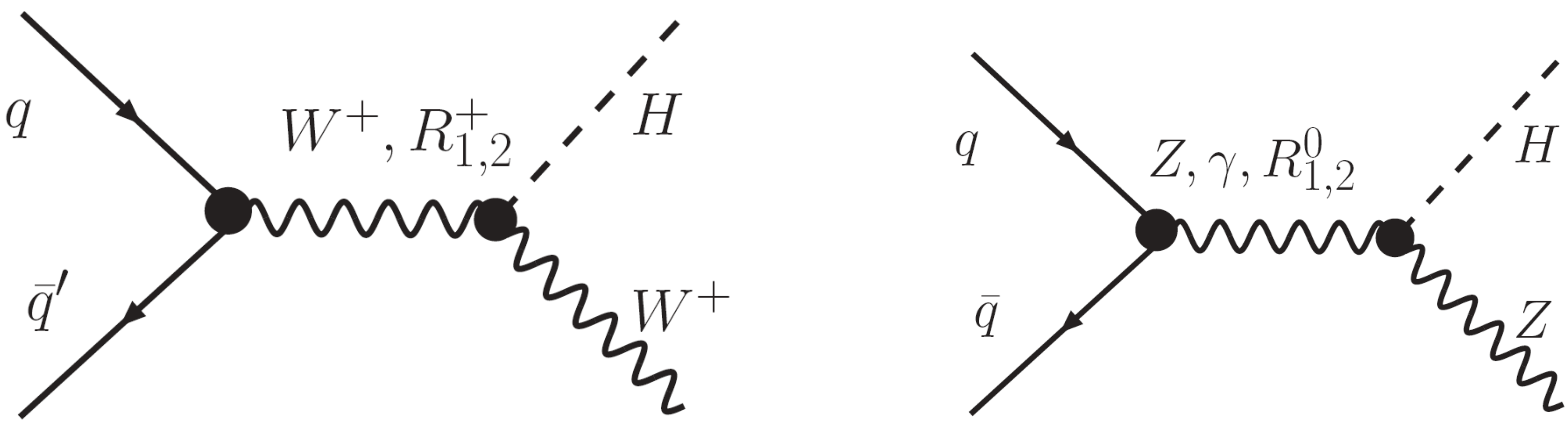
Light Composite Axial — Foadi, Frandsen, Ryttov F.S., 07

Preliminary V-A Spectrum from Lattice



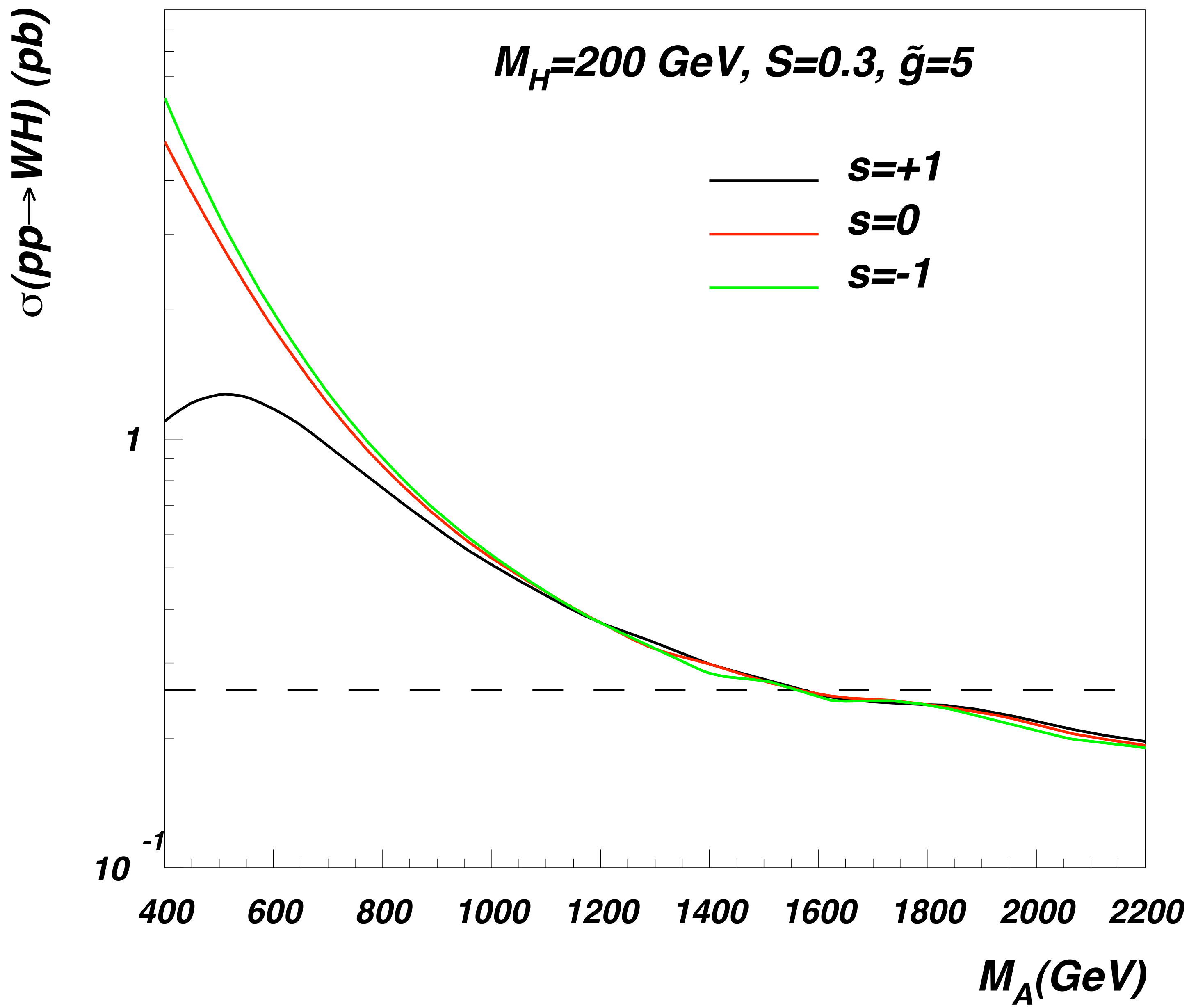
Del Debbio, Patella and Pica 08

$$pp \to HV$$



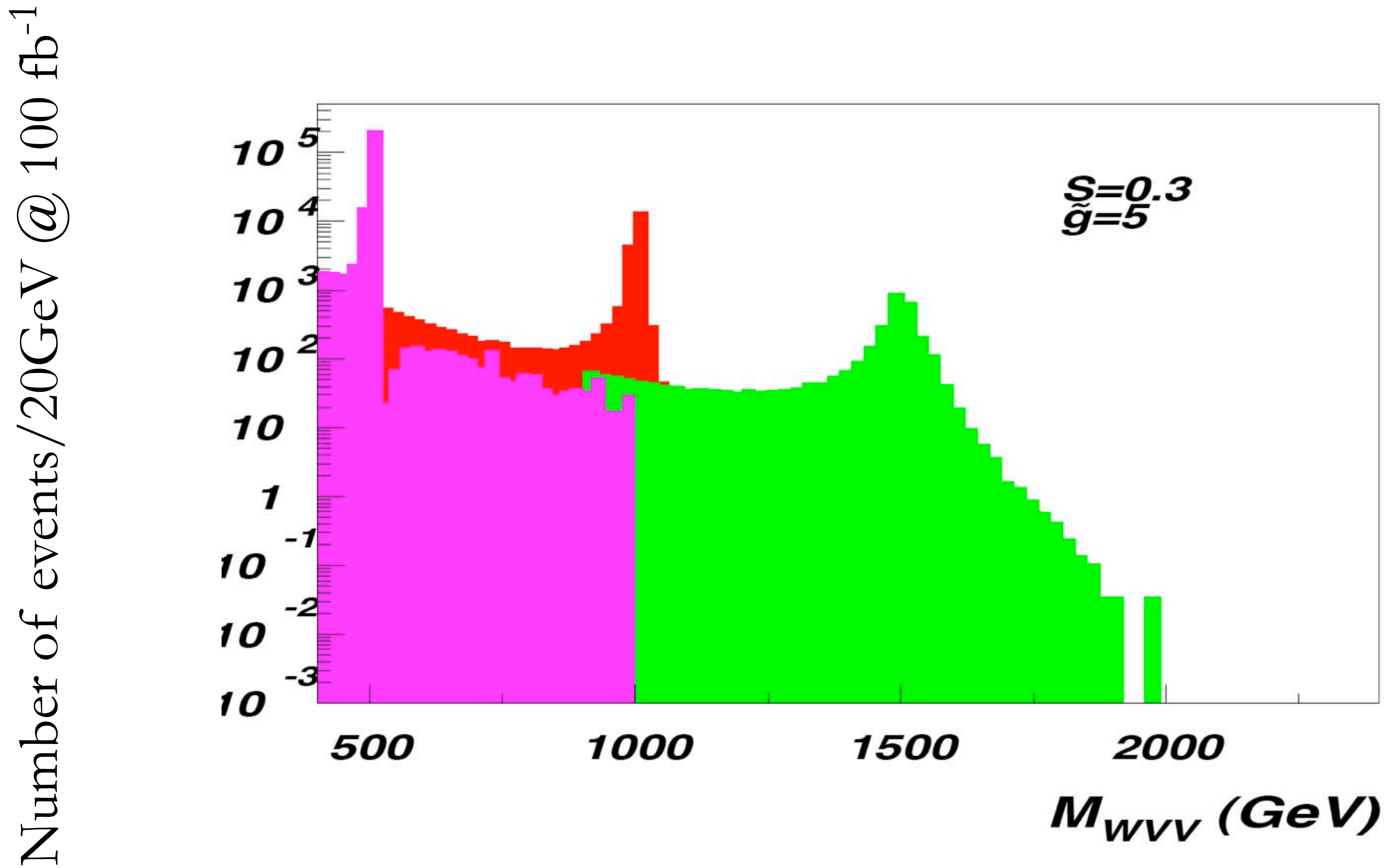
$$HV \to VVV \to \text{leptons+jets}$$

$$pp \to HV$$



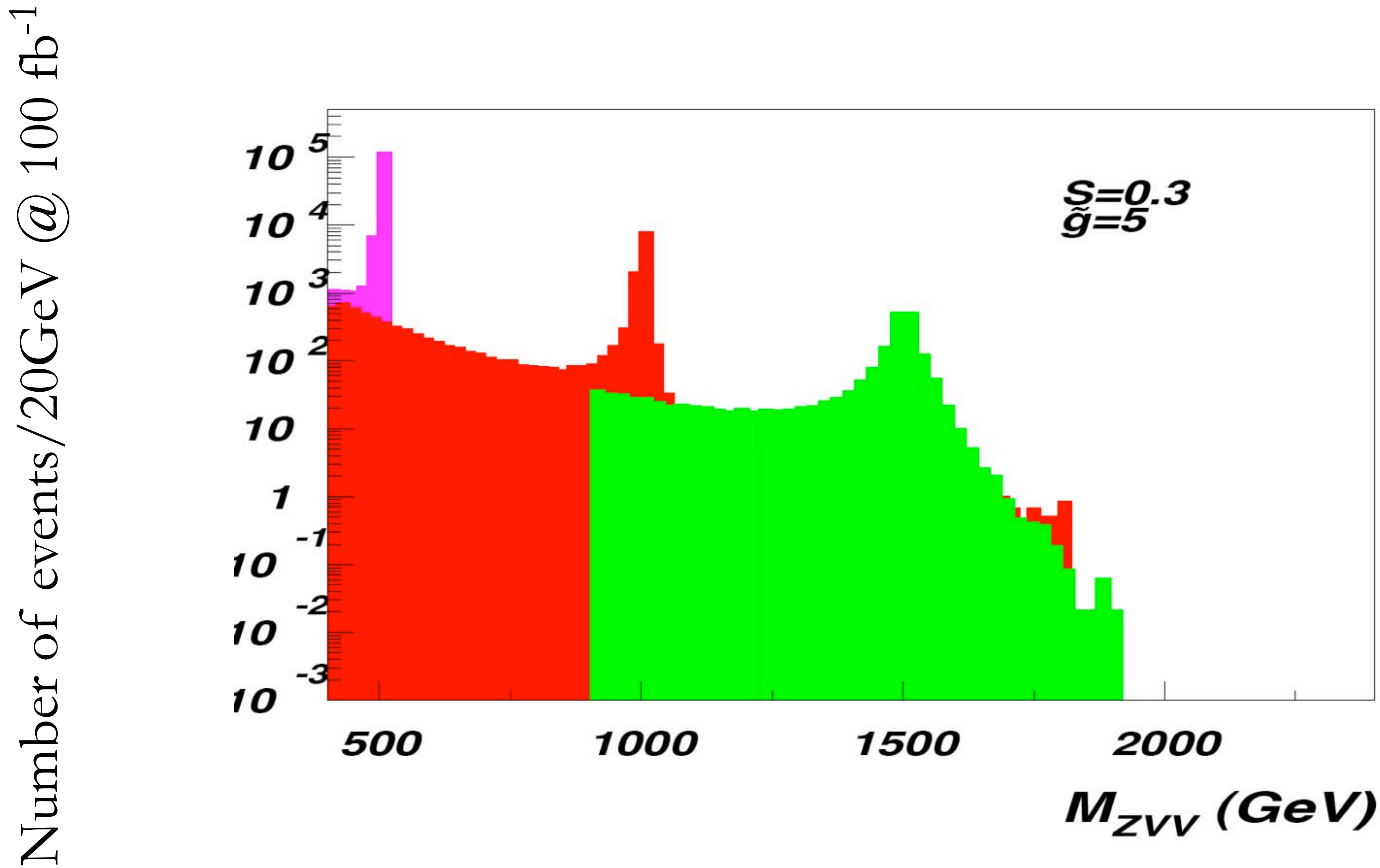
$$HV \to VVV \to \text{leptons+jets}$$

$$pp \to HW^{\pm} \to VVW^{\pm}$$



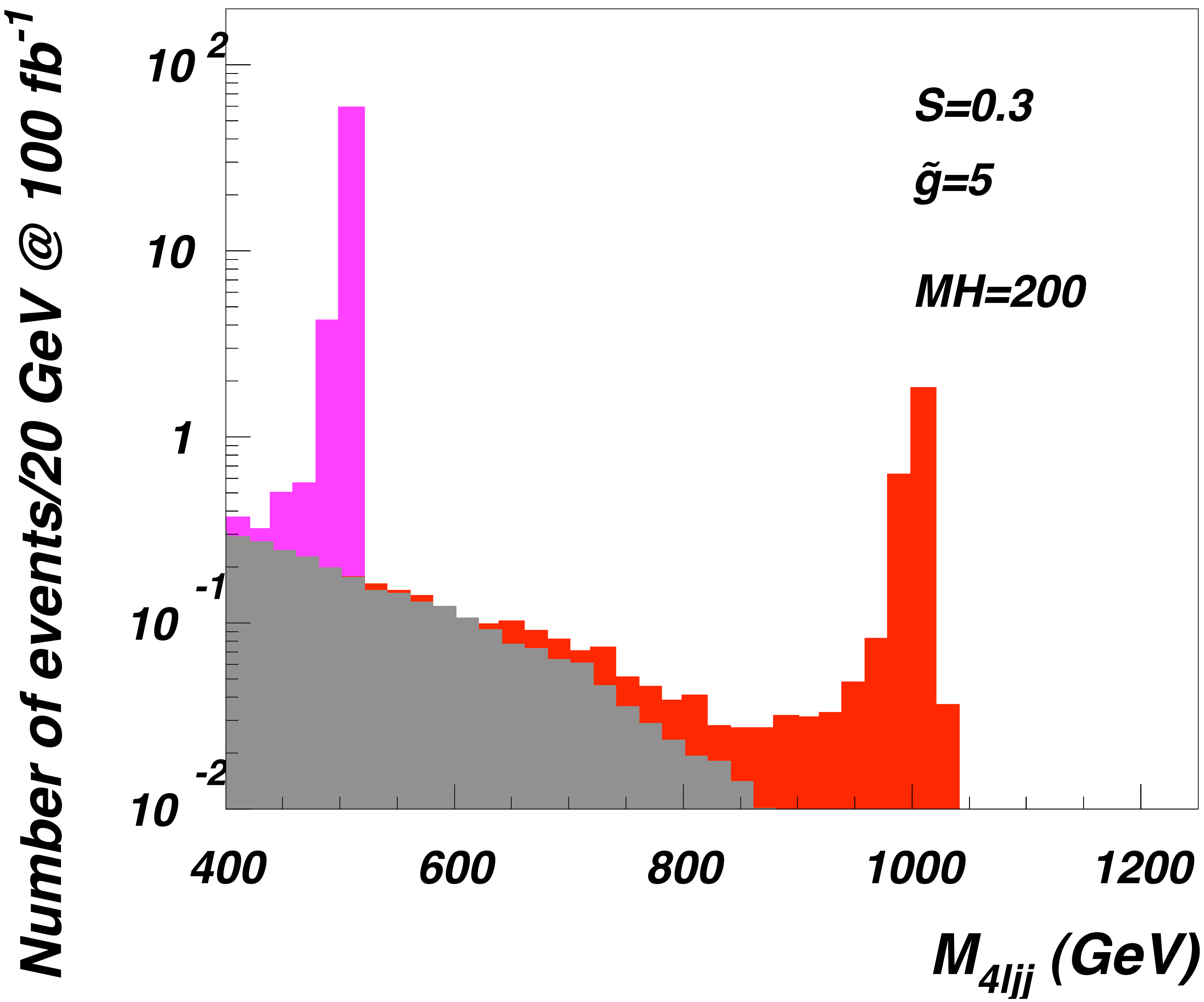
Axial vector intermediate state peaks

$$pp \to HZ \to VVZ$$



Axial vector intermediate state peaks

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



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

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

Preliminary Results from M.T. Frandsen

Summary

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- (Ultra) Minimal Walking Technicolor

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- (Ultra) Minimal Walking Technicolor
- Associate Production of the Composite Higgs

Summary

- (Ultra) Minimal Walking Technicolor
- Associate Production of the Composite Higgs
- Heavy Vectors are best produced and detected via Drell-Yan