DIAS
Danish Institute
for Advanced Study

UNIVERSITY OF SOUTHERN DENMARK

Future of Composite Dynamics

Francesco Sannino

CP^3 - Origins
Particle Physics & Cosmology

Portoroz 2013

Fermi Scale

$$v = 1/\sqrt{\sqrt{2}G_F} \approx 246\ \mathrm{GeV}$$

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$$M_H^2 = 2\lambda\, v^2$$

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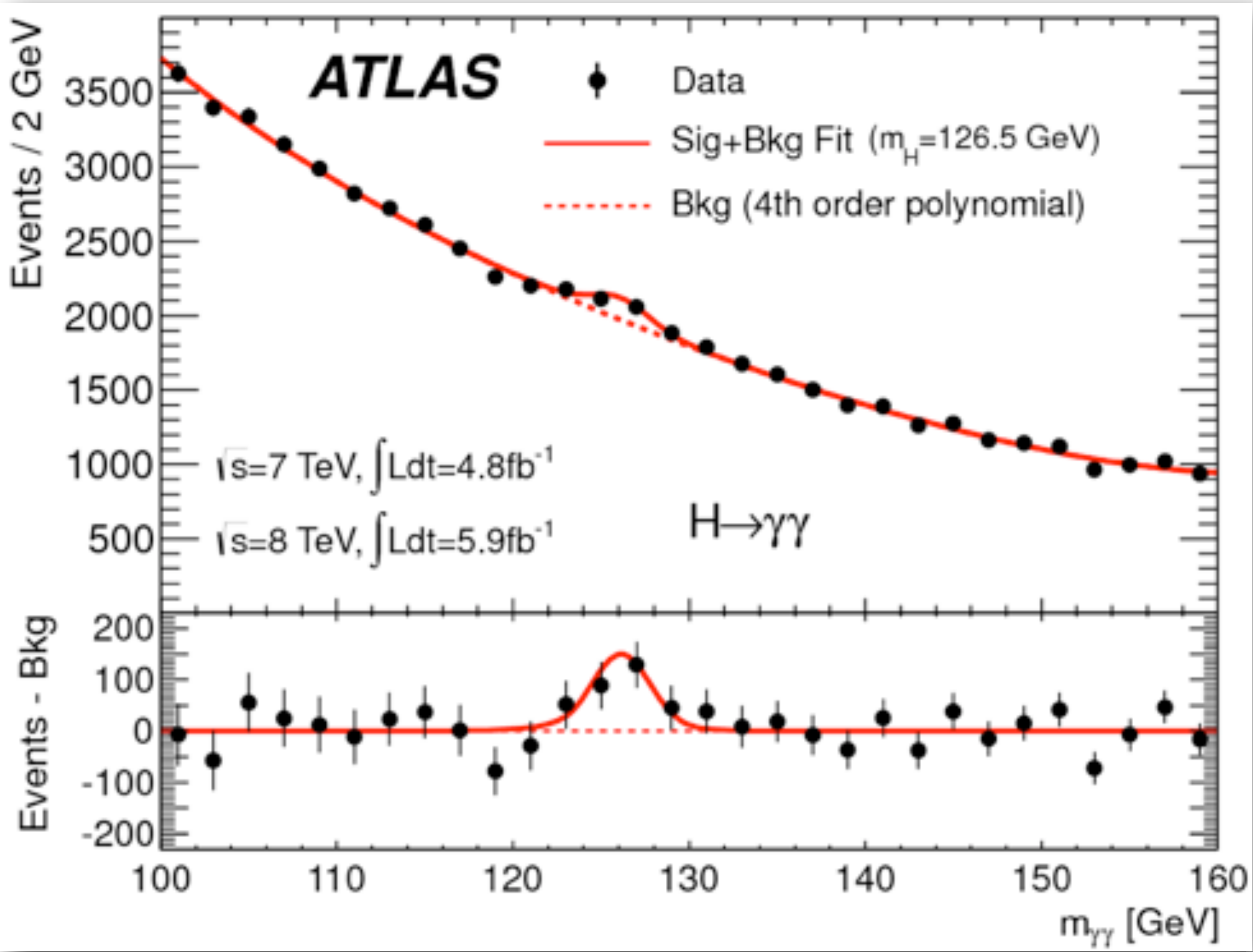
Top has the right energy scale!

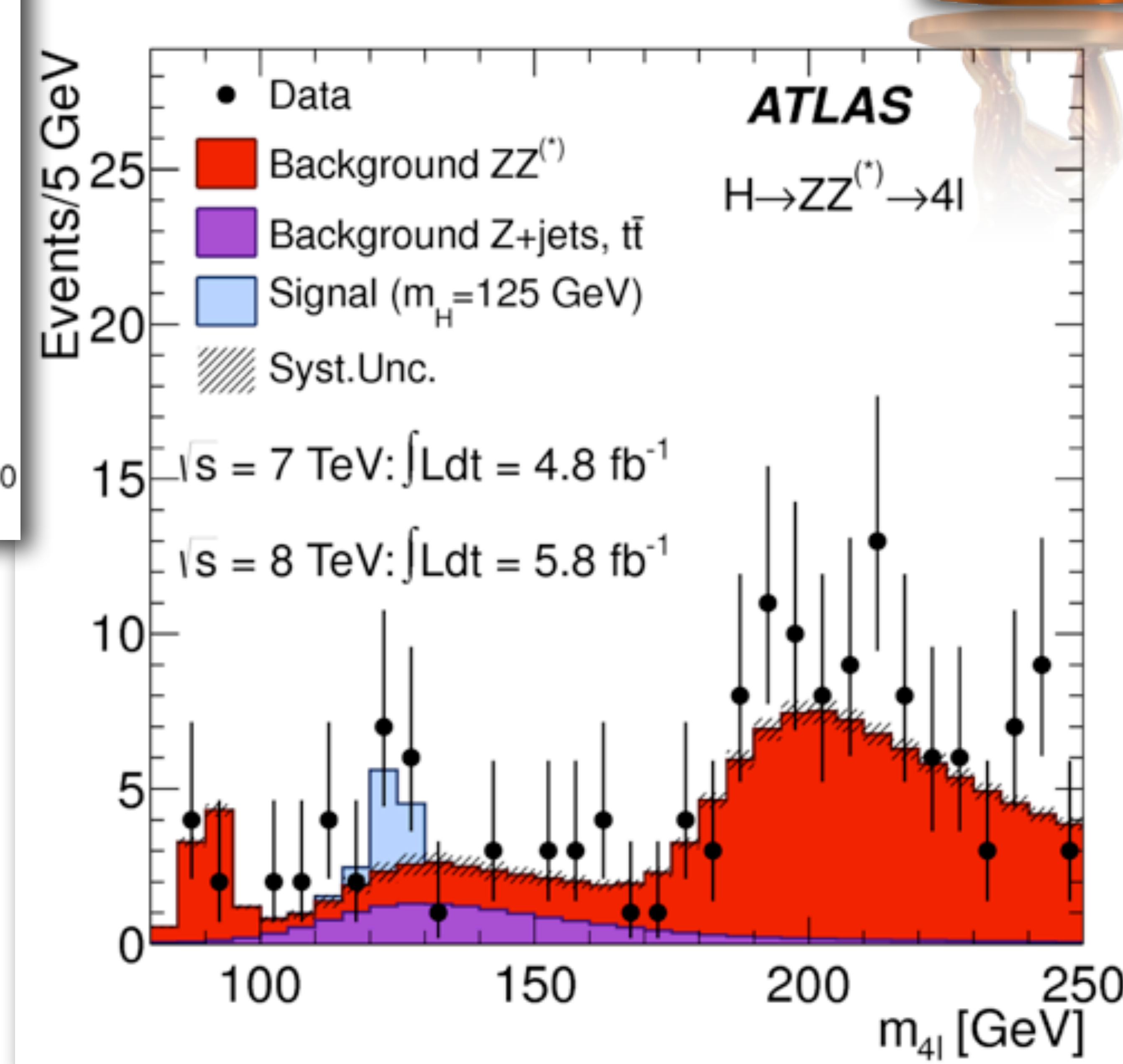
Light quarks and leptons are also natural!

The scent of the Higgs

2 bumps

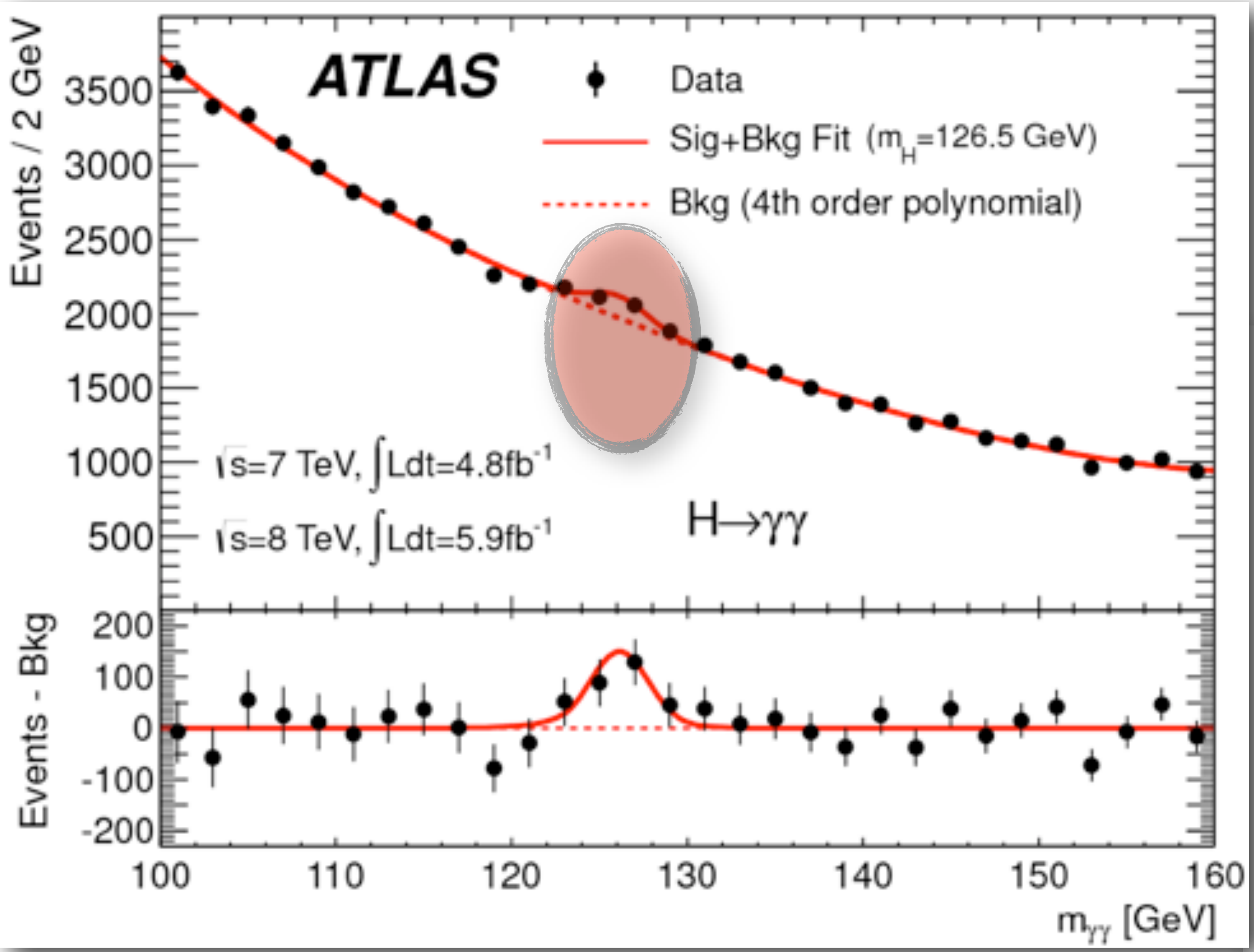


ATLAS
Data
Sig+Bkg Fit (m_H=126.5 GeV)
Bkg (4th order polynomial)
√s=7 TeV, ∫Ldt=4.8fb^-1
√s=8 TeV, ∫Ldt=5.9fb^-1
H→γγ
Events / 2 GeV
Events - Bkg
m_γγ [GeV]

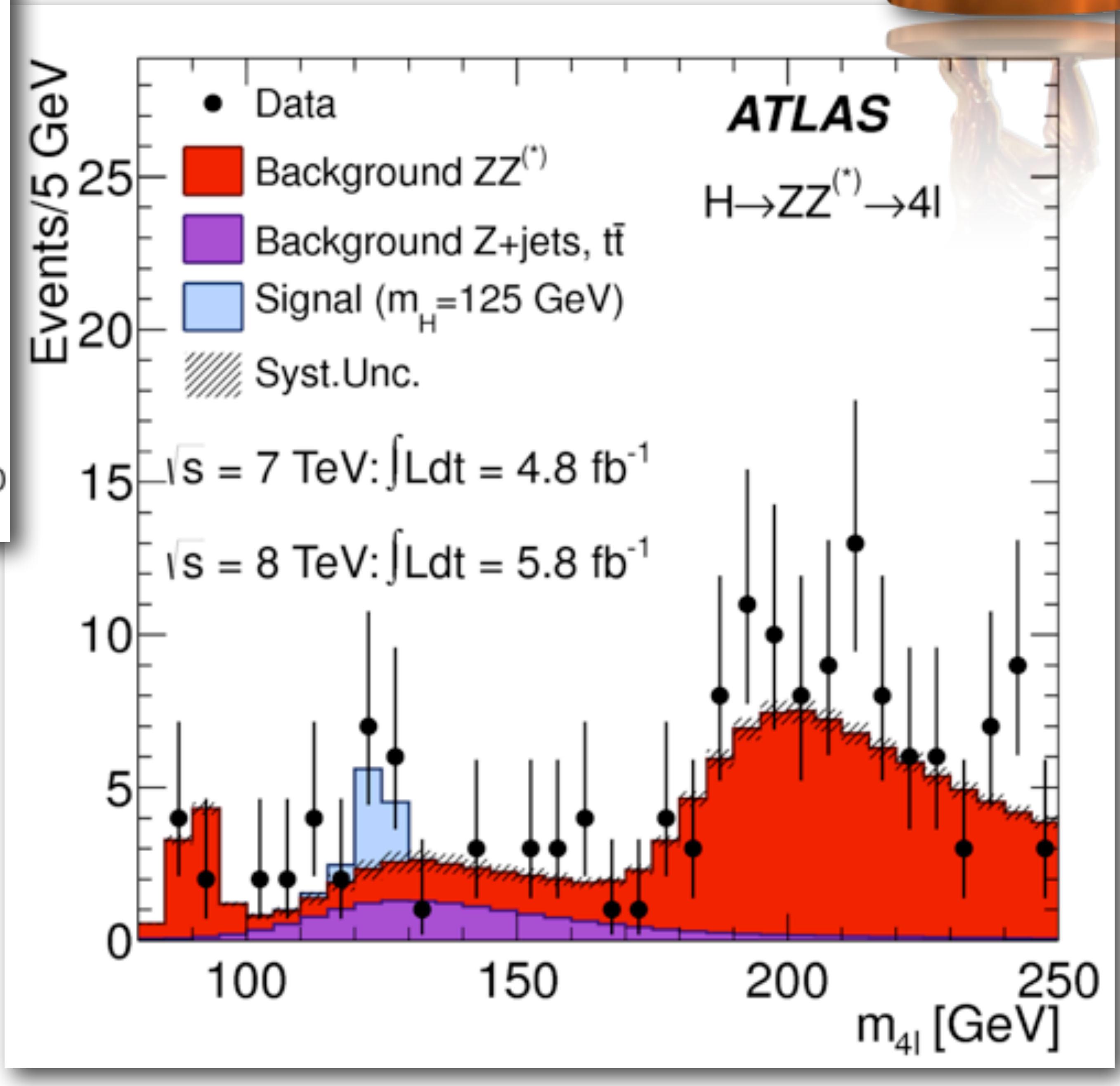


Data
Background ZZ(*)
Background Z+jets, tt̄
Signal (m_H=125 GeV)
Syst.Unc.
ATLAS
H→ZZ(*)→4l
√s = 7 TeV: ∫Ldt = 4.8 fb^-1
√s = 8 TeV: ∫Ldt = 5.8 fb^-1
Events/5 GeV
m_4l [GeV]

2 bumps



ATLAS
Data
Sig+Bkg Fit (m_H=126.5 GeV)
Bkg (4th order polynomial)
Events / 2 GeV
3500
3000
2500
2000
1500
1000
500
$\sqrt{s}$=7 TeV, $\int$Ldt=4.8fb^{-1}
$\sqrt{s}$=8 TeV, $\int$Ldt=5.9fb^{-1}
H→γγ
Events - Bkg
200
100
0
-100
-200
100
110
120
130
140
150
160
$m_{\gamma\gamma}$ [GeV]



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$\sqrt{s}$ = 7 TeV: $\int$Ldt = 4.8 fb^{-1}
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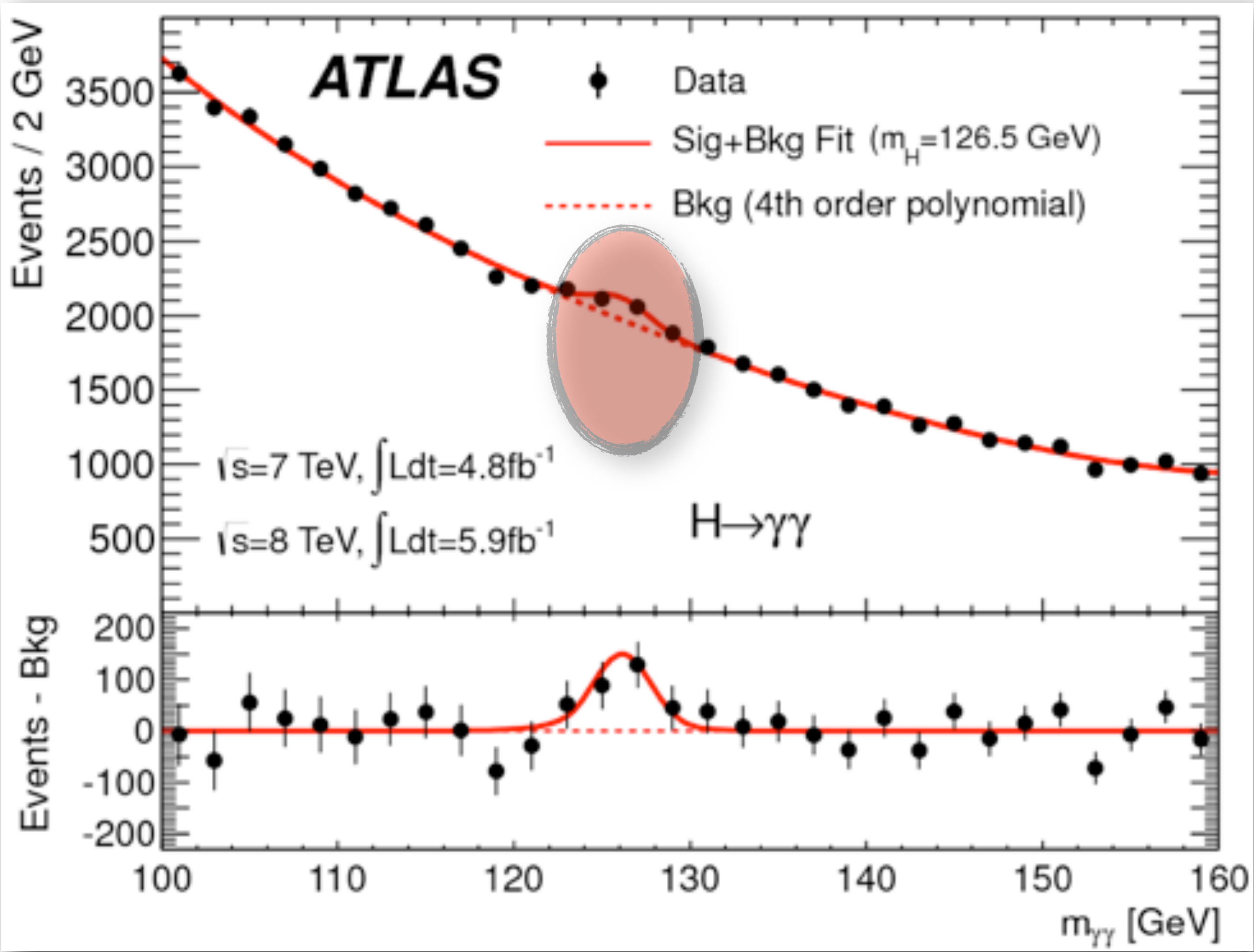
Events/5 GeV
25
20
15
10
5
0
100
150
200
250
m_{4l} [GeV]

2 bumps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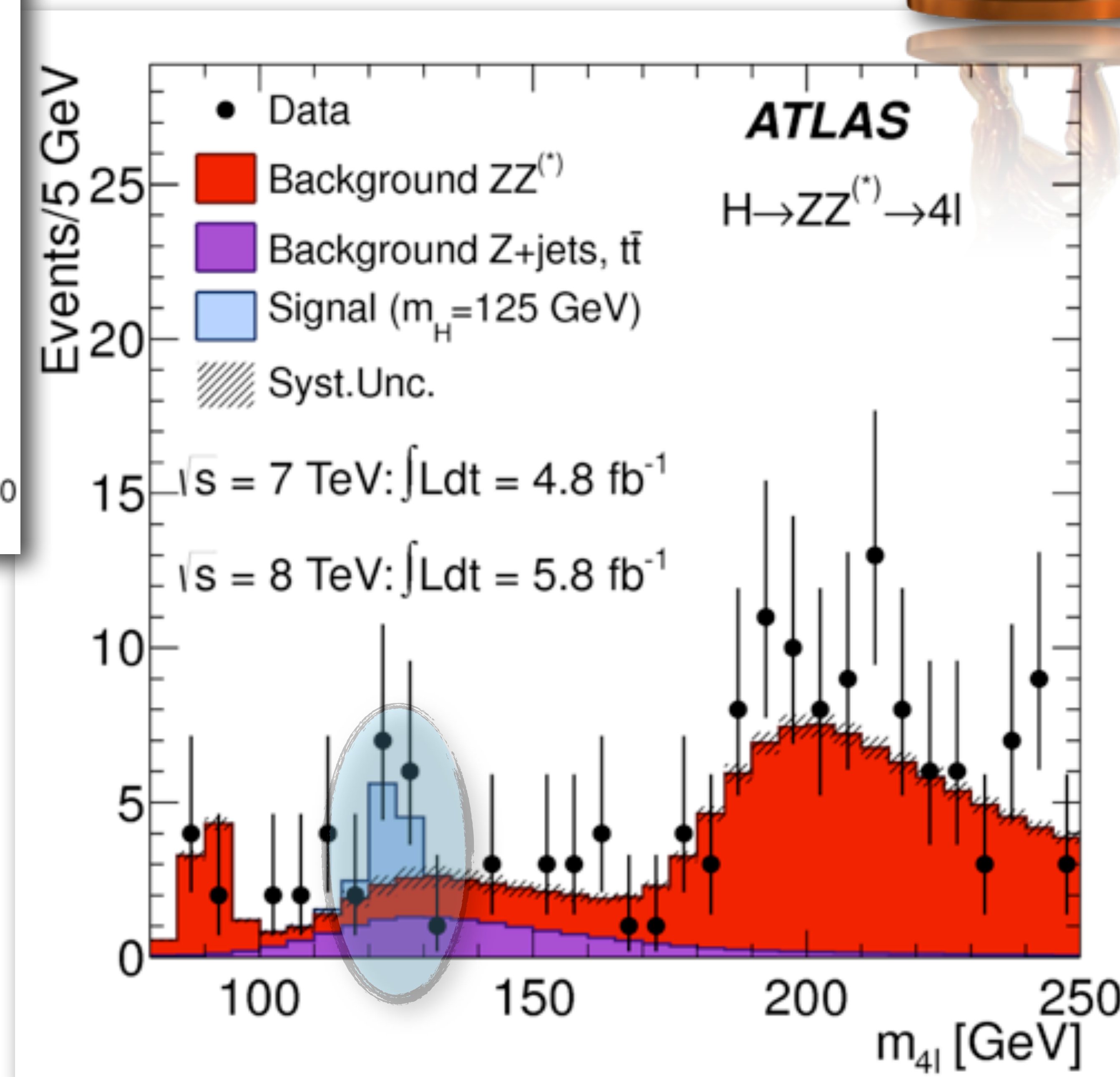
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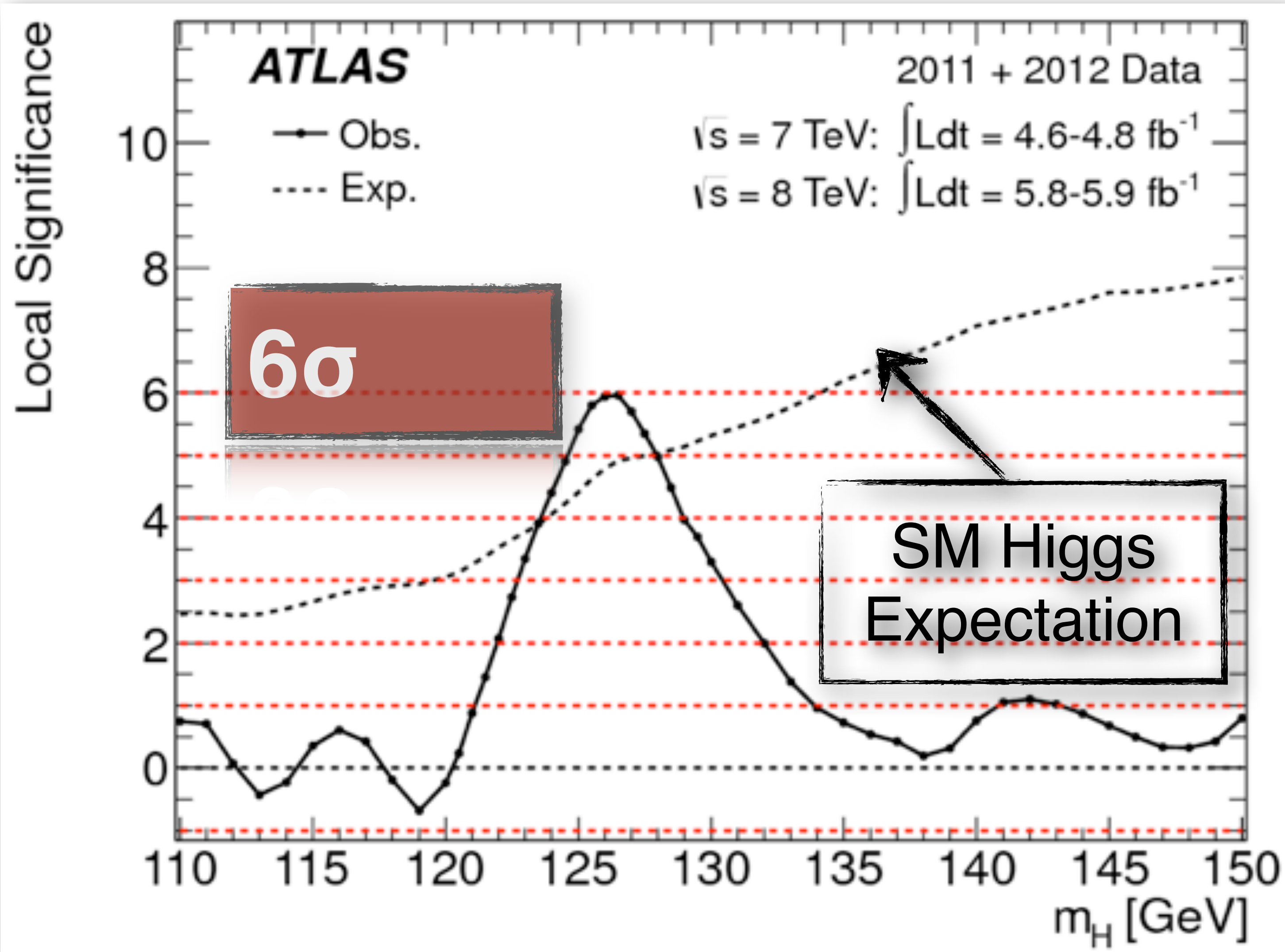
Higgs discovery



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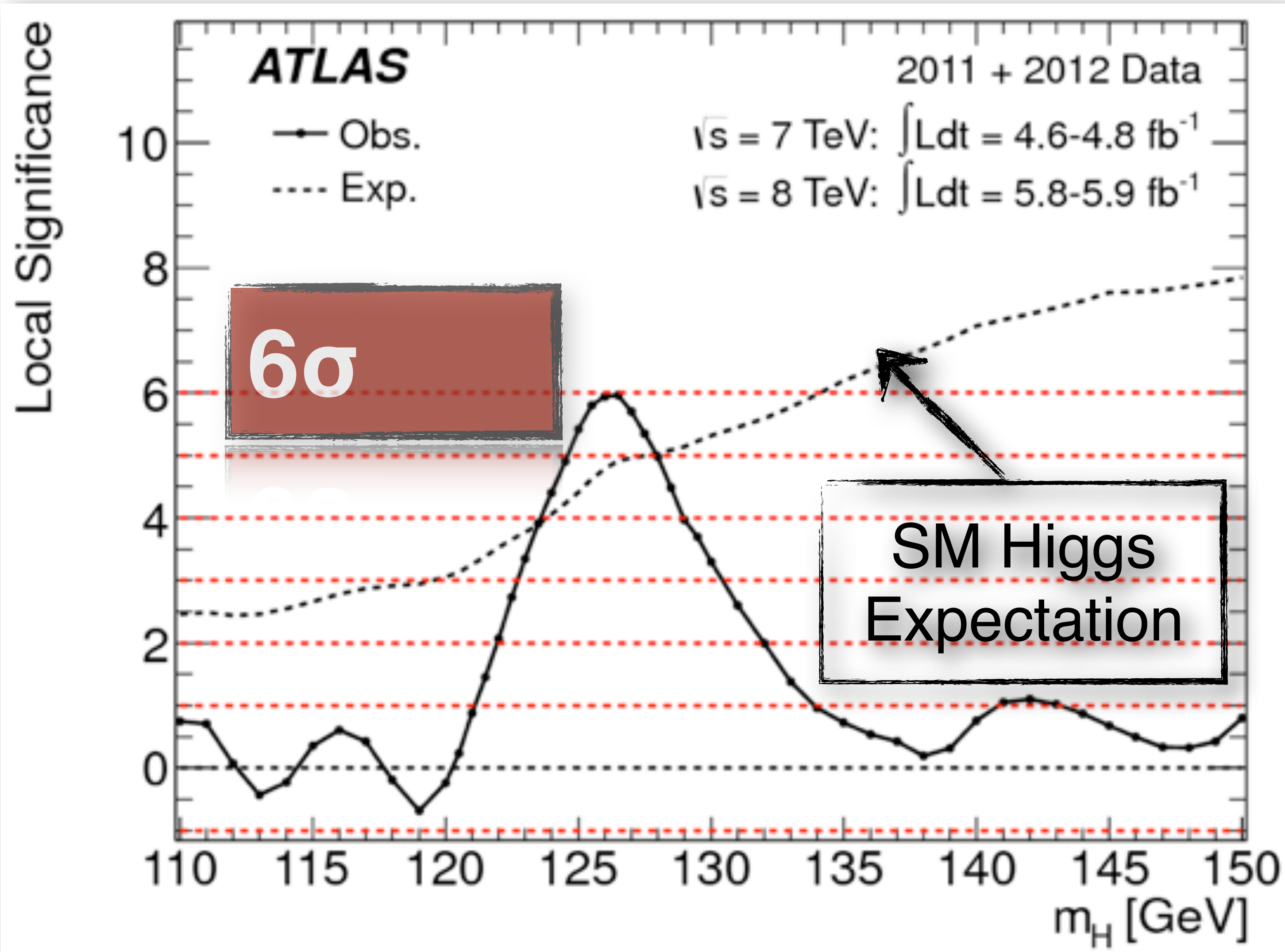
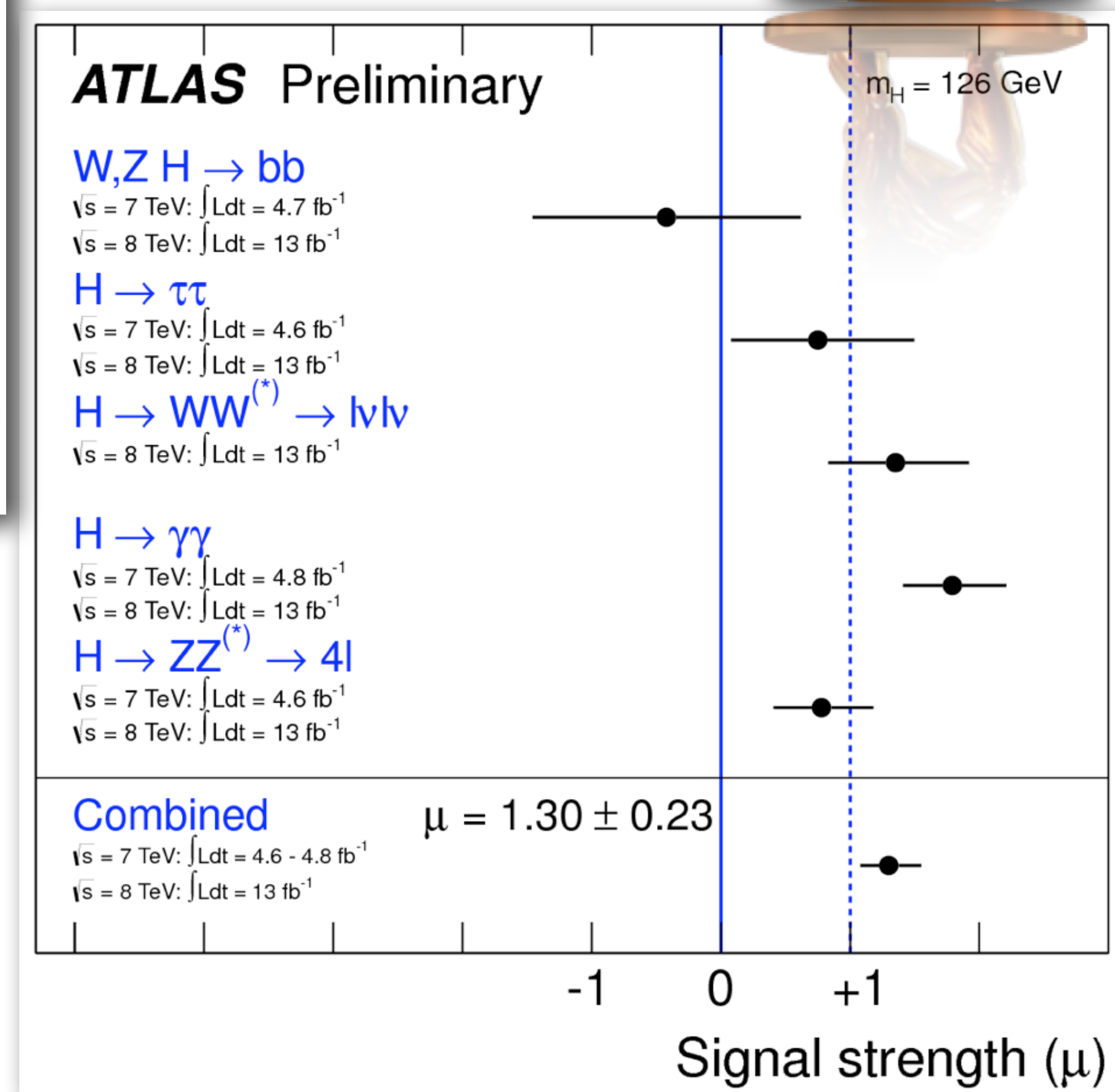


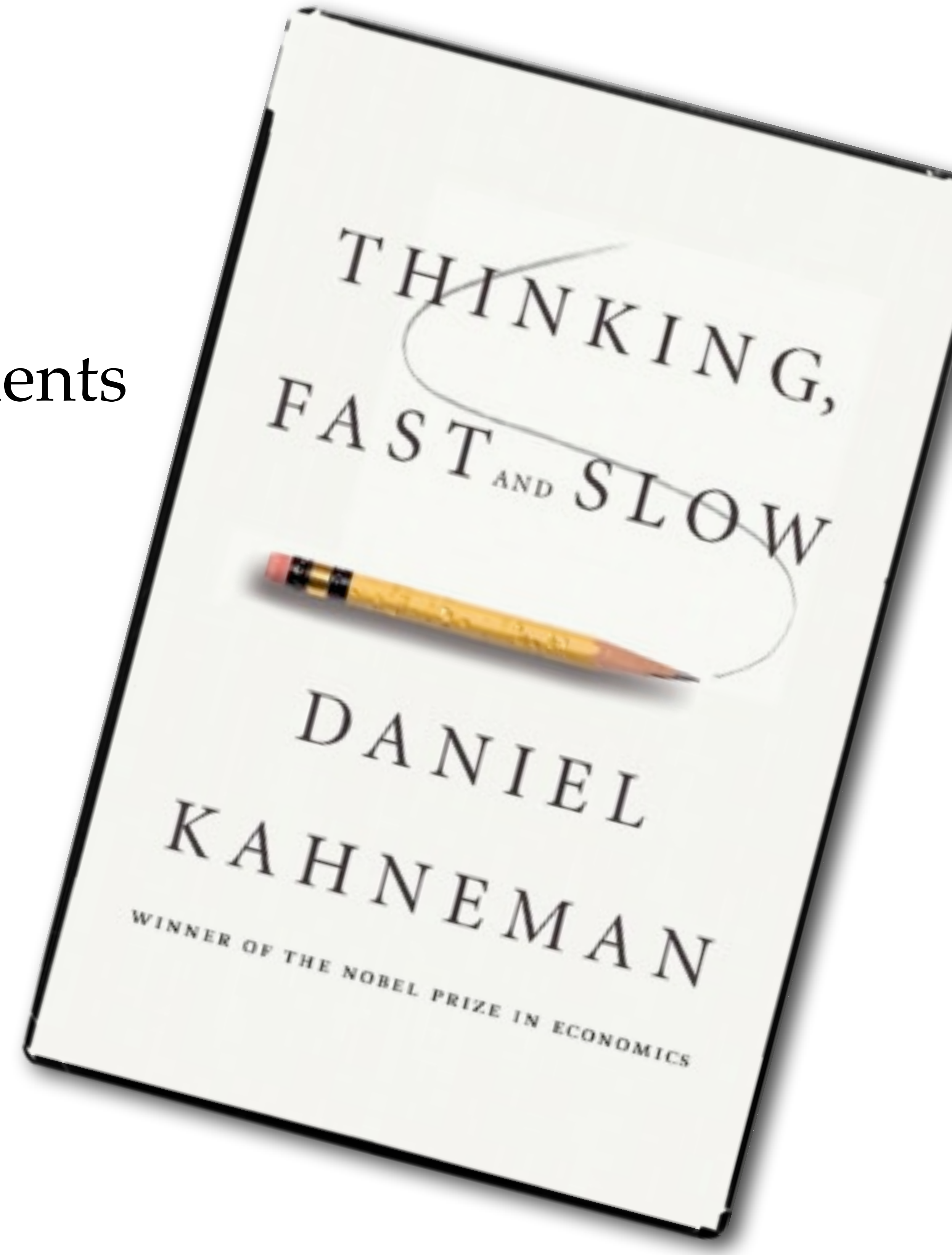


Fundamental ?

- Would be the first time
- Spinors are space-time constituents
- Scalars are derived
- Susy? Can be emergent

  In <4d: Sung-Sik Lee 06

  4d: Antipin, Mojaza, Pica, Sannino 10



Compositeness

- Only Higgs sector is composite [Technicolor]
- Standard Model Fermions are composite [Preons]
- Partial compositeness: Bosonic/SUSY Technicolor ...
- X compositeness [Magnetic Standard Model] Sannino 11

What has LHC not seen ?

- Extra large, small or medium dimensions [kk states,..]
- Any sign of supersymmetry [gluino,...]
- Extra, mini, large Black-Holes [low scale gravity]

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In line with:

Composite dynamics

Technicolor

From SM to TC

$$DH^{\dagger}DH - V(H) + \overline{\Psi}_L H \psi_R$$

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Extended TC

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TC ⟷ Extended TC

Technicolor vs Composite Higgs

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  Composite Higgs theory with a 4D underlying theory

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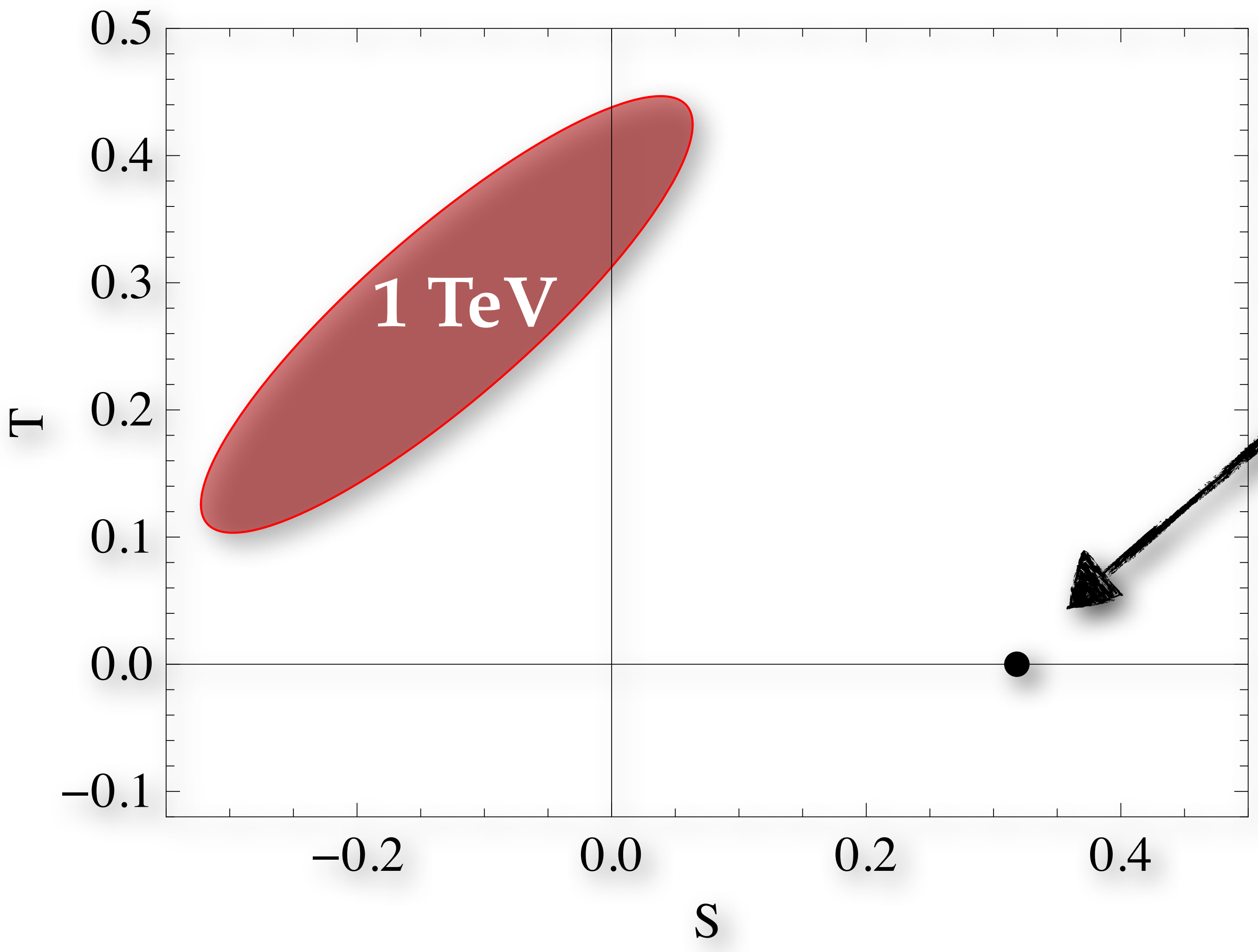
  If 4D underlying exists probably similar to Technicolor ?

Is "Old" Technicolor dead?



SU(3) + 1 Fund. Doublet

Weinberg, Susskind

$$M_H = \frac{F_{TC}}{F_\pi} M_\sigma \simeq 1.5 \text{ TeV}$$

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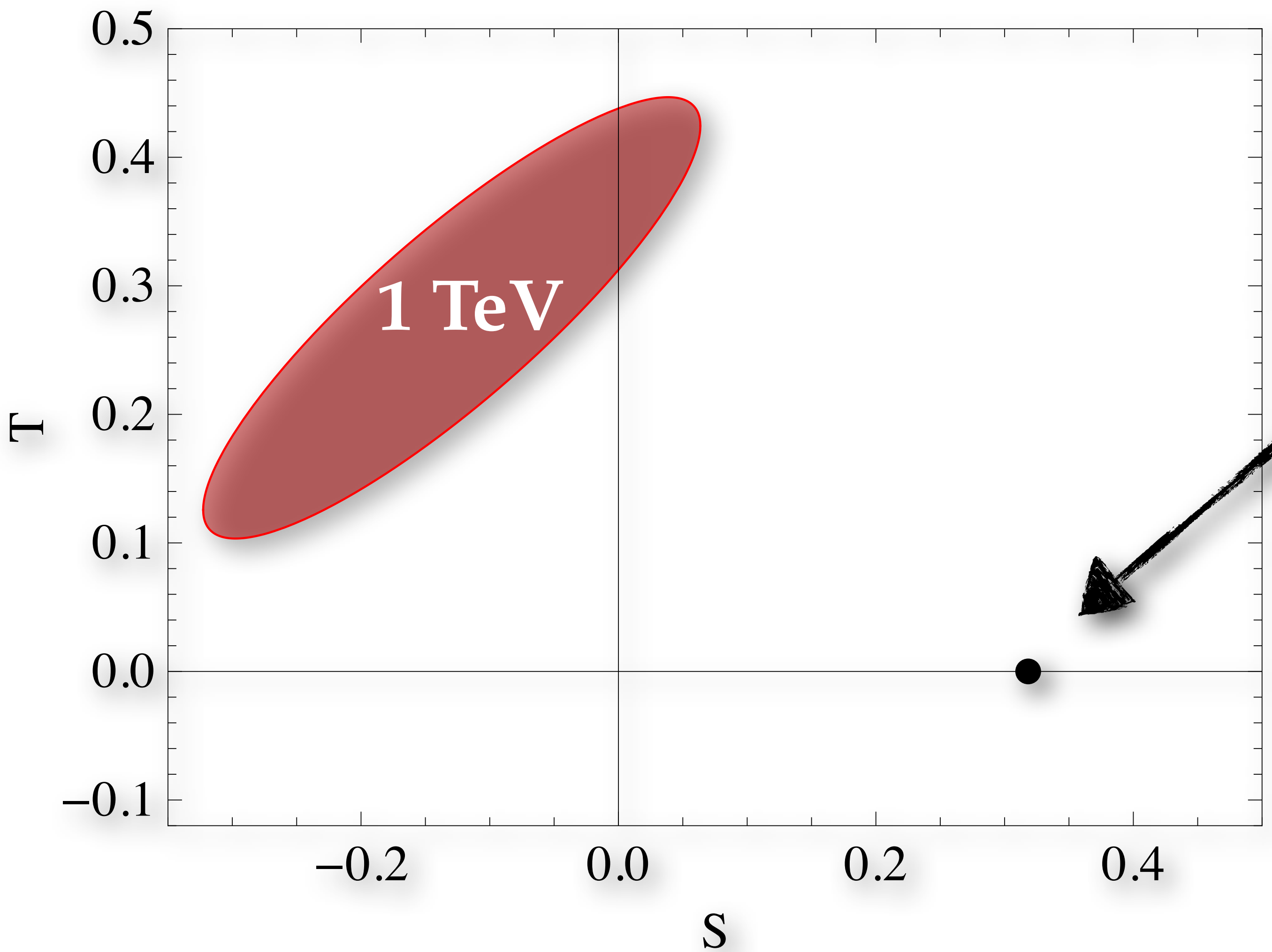

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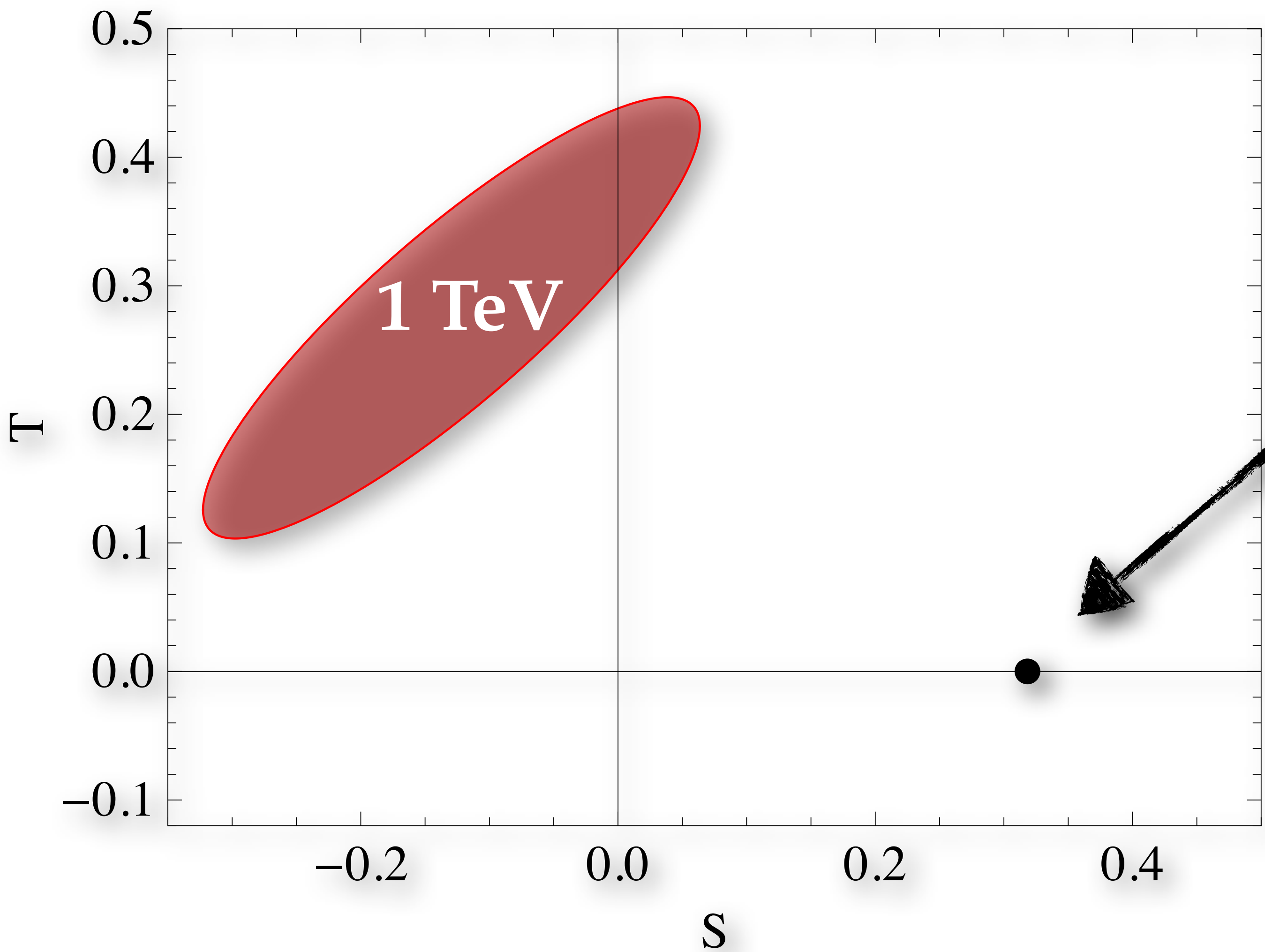

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Extend TC to generate fermion masses [Eichten & Lane]

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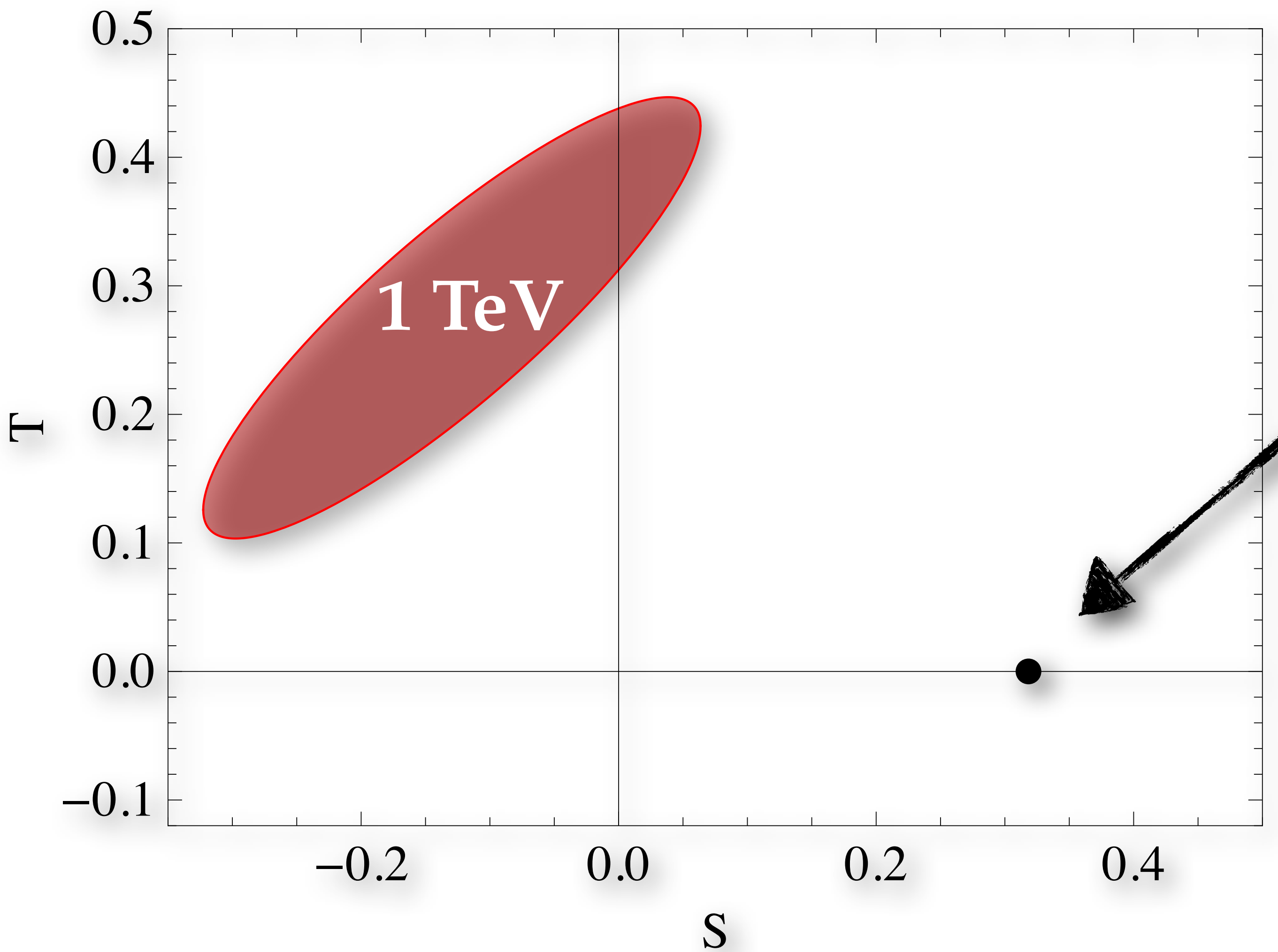

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Extend TC to generate fermion masses [Eichten & Lane]

Old TC was dead 2 decades ago

Need to go beyond QCD

- TC-fermion condensate enhancement / FCNC decoupling
- Minimal TC passing precision tests
- Need a TC Higgs
- Dark matter candidates

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QCD lightest scalar is $f_0(500)$ with mass ~ 400-550 MeV

Sannino & Schechter 95 PRD [‘t Hooft 1/N, crossing, chiral, pole mass]
Harada, Sannino & Schechter 95 PRD [$f_0(980)$], 96PRL
Pelaez - Confinement X - lecture

Narrow state in Strong Dynamics?

Example $f_0(980)$

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Harada, Sannino & Schechter 95 PRD [f_0(980)], 96PRL [Large N apparent violation]

S. Weinberg 2013

Higgs Effective Theory

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$$\begin{aligned}
\mathcal{L} &= \mathcal{L}_{\overline{\rm SM}} + \left(1 + \frac{2r_\pi}{v} H + \frac{s_\pi}{v^2} H^2\right) \frac{v^2}{4} {\rm Tr}\ D_\mu U^\dagger D^\mu U + \frac{1}{2}\ \partial_\mu H\ \partial^\mu H \\
&- \ m_t \left(1 + \frac{r_t}{v} H\right) \left[\overline{q}_L\ U\ \left(\frac{1}{2} + T^3\right)\ q_R + {\rm h.c.}\right] \\
&- \ m_b \left(1 + \frac{r_b}{v} H\right) \left[\overline{q}_L\ U\ \left(\frac{1}{2} - T^3\right)\ q_R + {\rm h.c.}\right] + \cdots \\
&- \ \Delta S\ W^a_{\mu\nu} B^{\mu\nu}\ {\rm Tr}\ T^a U T^3 U^\dagger + \mathcal{O}\left(\frac{1}{M_\rho}\right)
\end{aligned}$$

$$q \equiv (t, b)$$

Higgs Effective Theory

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$$q \equiv (t, b)$$

$$U = \exp\left(i\pi^a T^a/v\right)$$

$$v \simeq 246\ \mathrm{GeV}$$

$$D_\mu U \equiv \partial_\mu U - igW^a_\mu T^a U + ig' U B_\mu T^3$$

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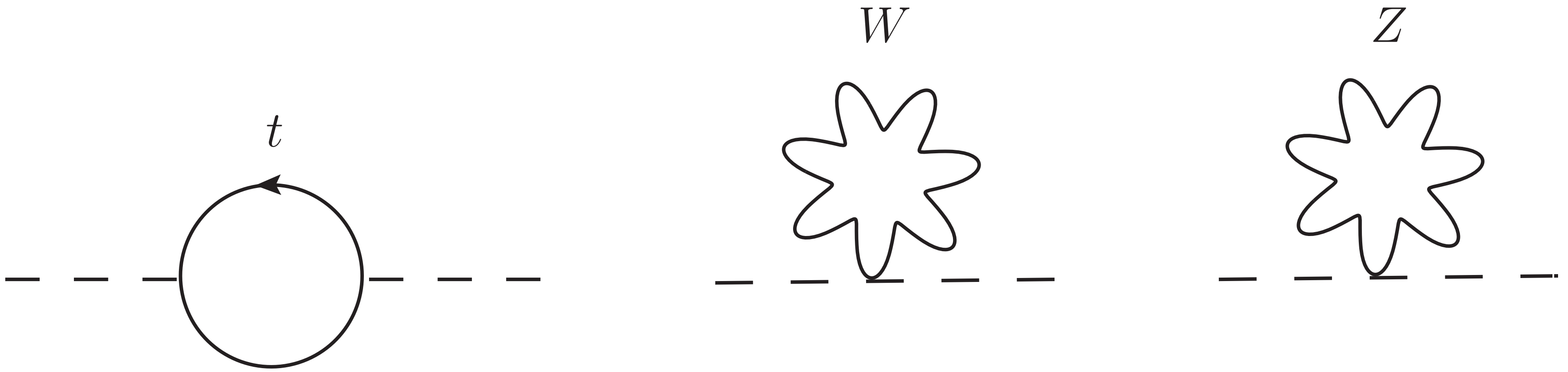

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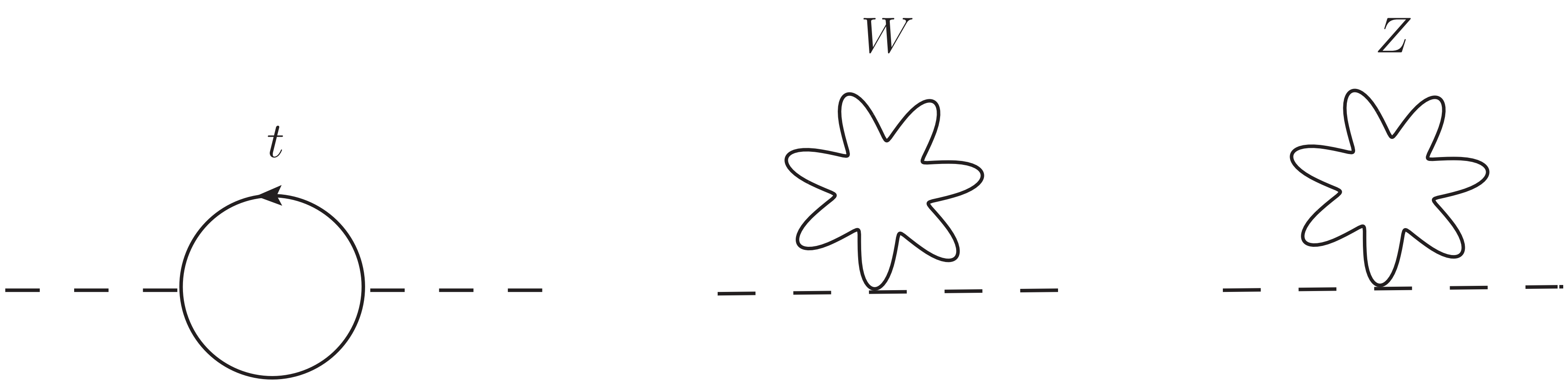

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Foadi, Frandsen, Sannino, 1211.1083

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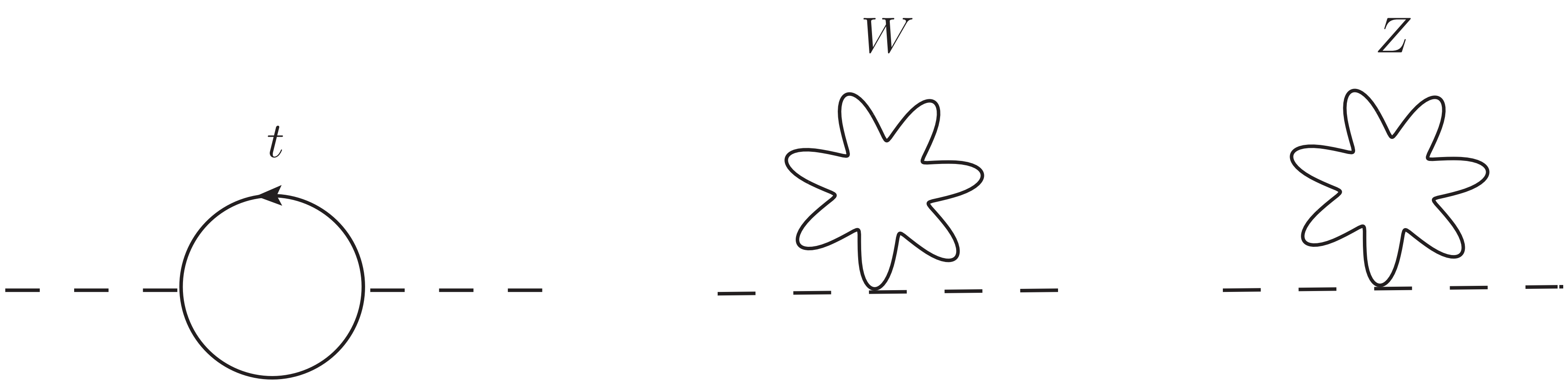

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How light is the TC-Higgs ?

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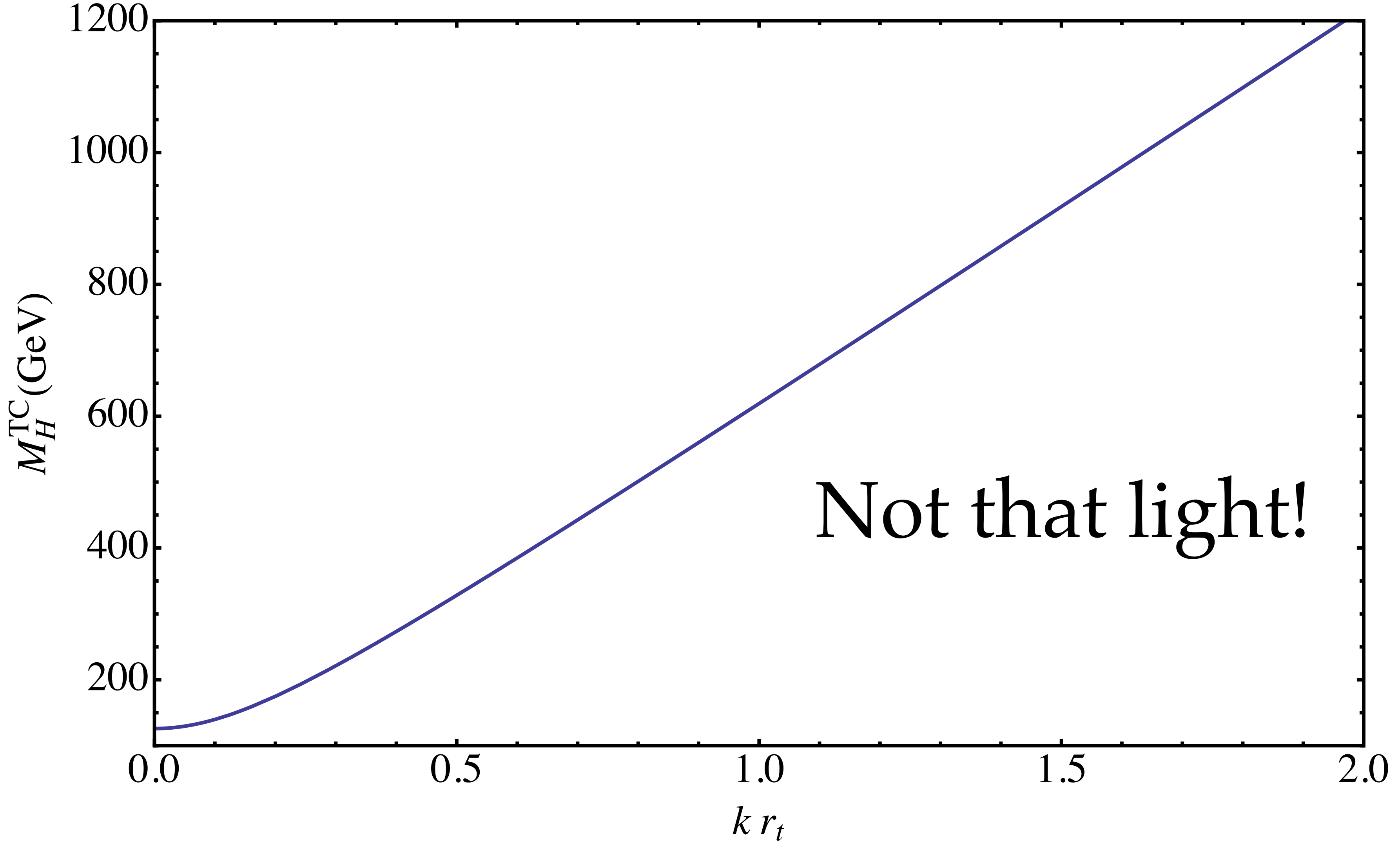

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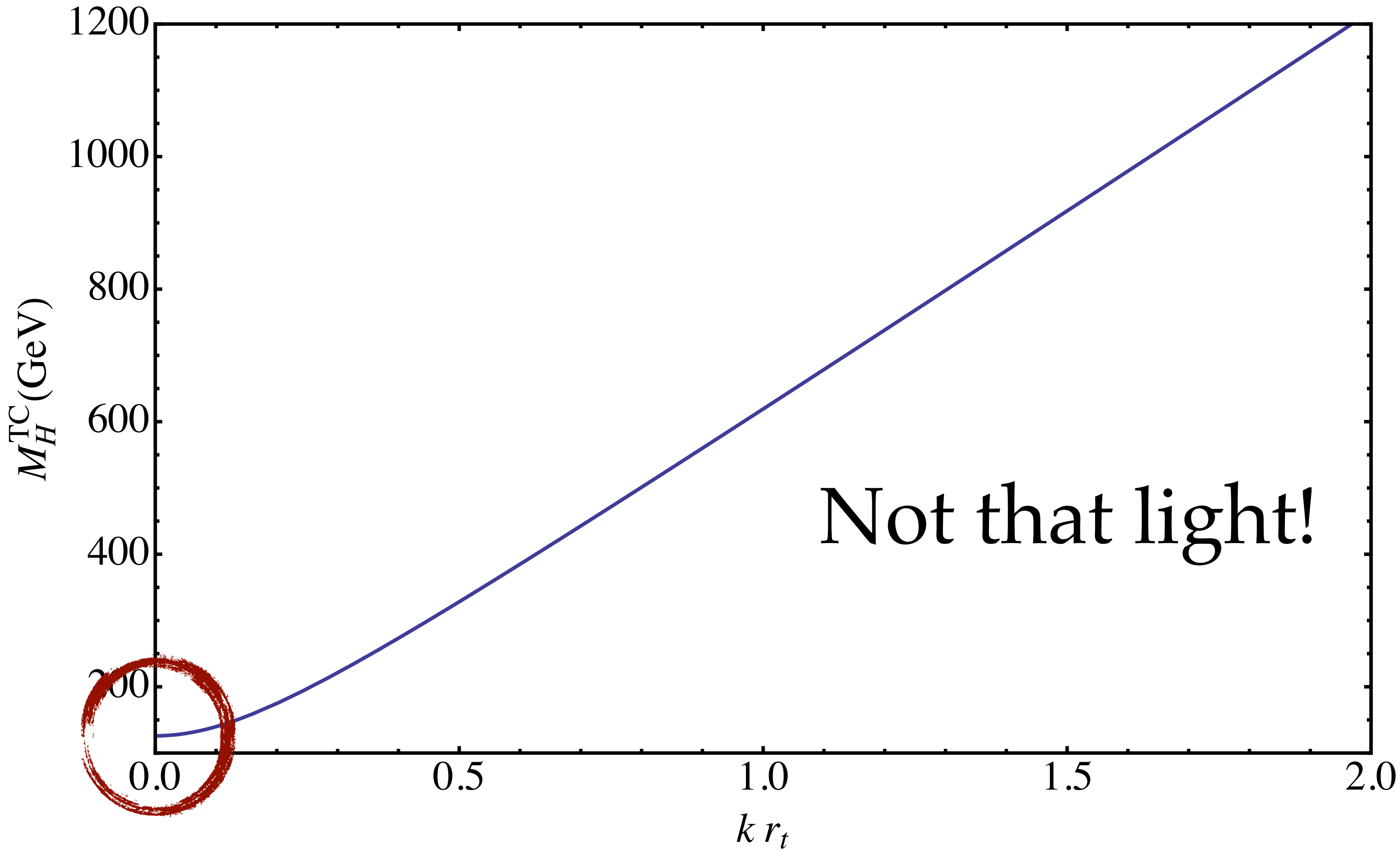

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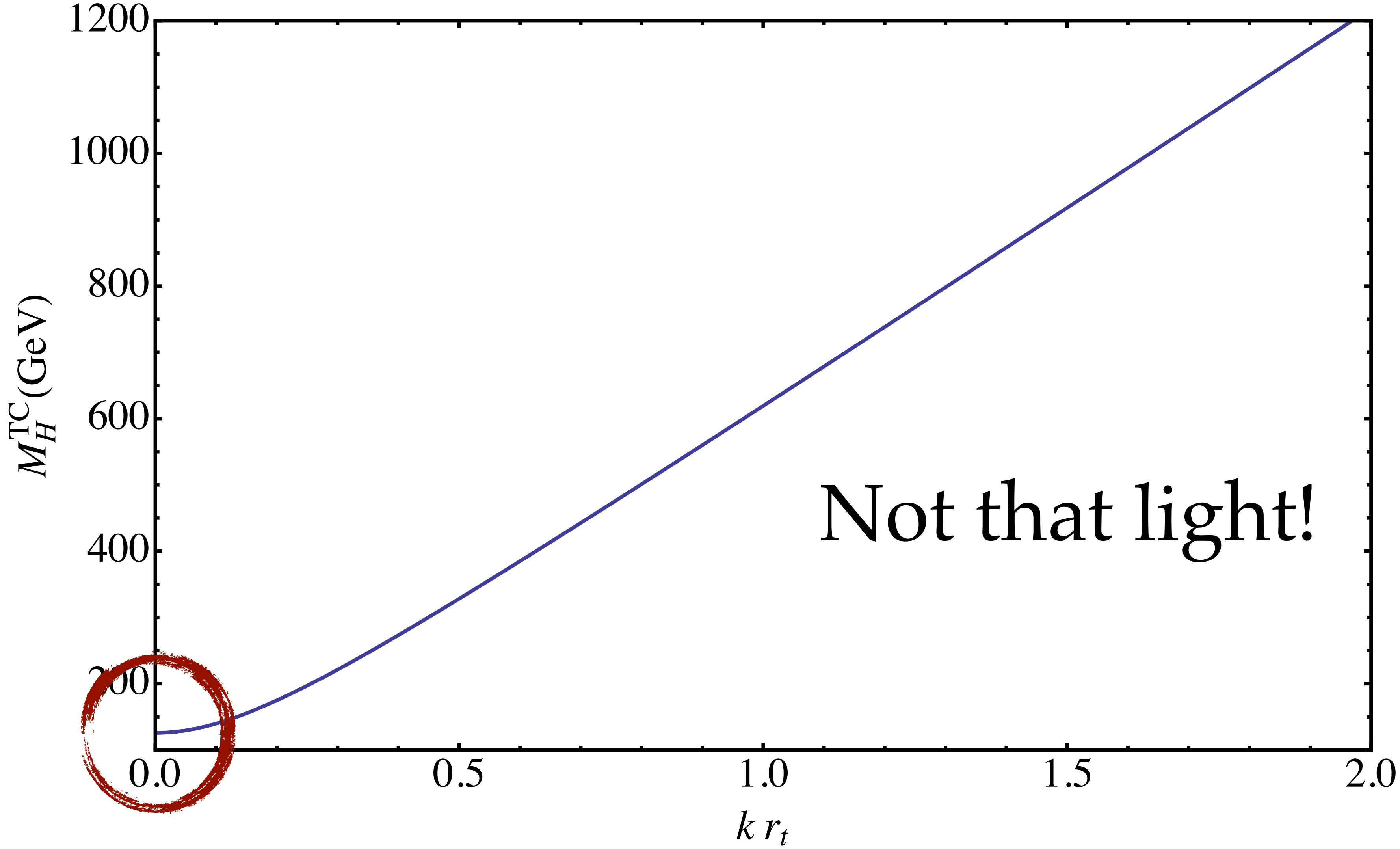

Narrow due to kinematics [Similar to $f_0(980)$ in QCD]

How to make a TC Higgs ?

Sannino 08

Sannino & Schechter 07

Foadi, Frandsen, Sannino 12

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Change # of TC-colors, matter repr., EW doublets

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$$M_H^{TC} \simeq 1.8 \frac{1}{\sqrt{N_D d(R_{TC})}} \ \text{TeV}$$

$$d(2-\text{index}_{TC}) = N_{TC}\frac{N_{TC}\pm 1}{2}$$

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Physical Higgs mass via gauge geometry

Sannino 08

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Realistic theories ?

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**Next to Minimal Walking TC

Sannino & Tuominen hep-ph/0405209

Lattice: Fodor, Holland, Kuti, Nogradi, Schroeder, Wong, 1209.0391:

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$M_\rho \simeq 1754 \pm 104 \text{ GeV}$ $\qquad$ $M_{A_1} \simeq 2327 \pm 121 \text{ GeV}$

Realistic theories ?

$N_D = 1 \quad d(\text{Symmetric}) = 6$ **

$$M_H^{TC} \simeq 735 \text{ GeV}$$

Observed Higgs mass for $\kappa \; r_t \simeq 1.2$

**Next to Minimal Walking TC

Sannino & Tuominen hep-ph/0405209

Lattice: Fodor, Holland, Kuti, Nogradi, Schroeder, Wong, 1209.0391:

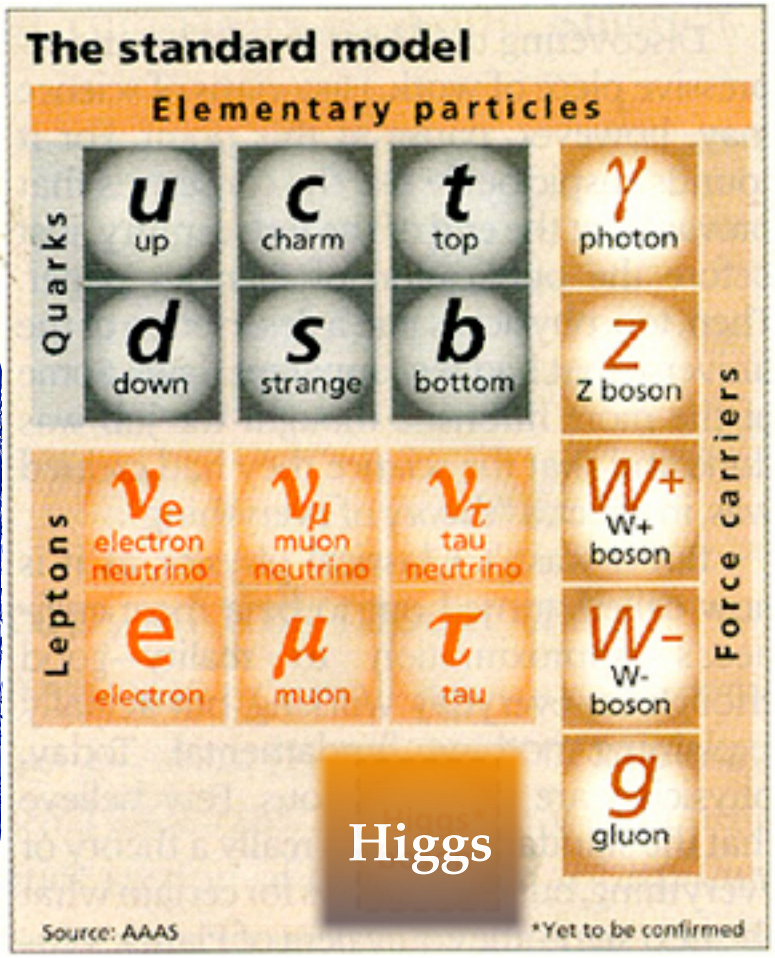
$M_\rho \simeq 1754 \pm 104 \text{ GeV}$ $\qquad$ $M_{A_1} \simeq 2327 \pm 121 \text{ GeV}$

Beware: F_π not well determined

A Minimal TC template

Since 2004 - Minimal WTC is Higgsfull

[Original Name: Light Composite Higgs]



U(1)

SU(2)

SU(3)

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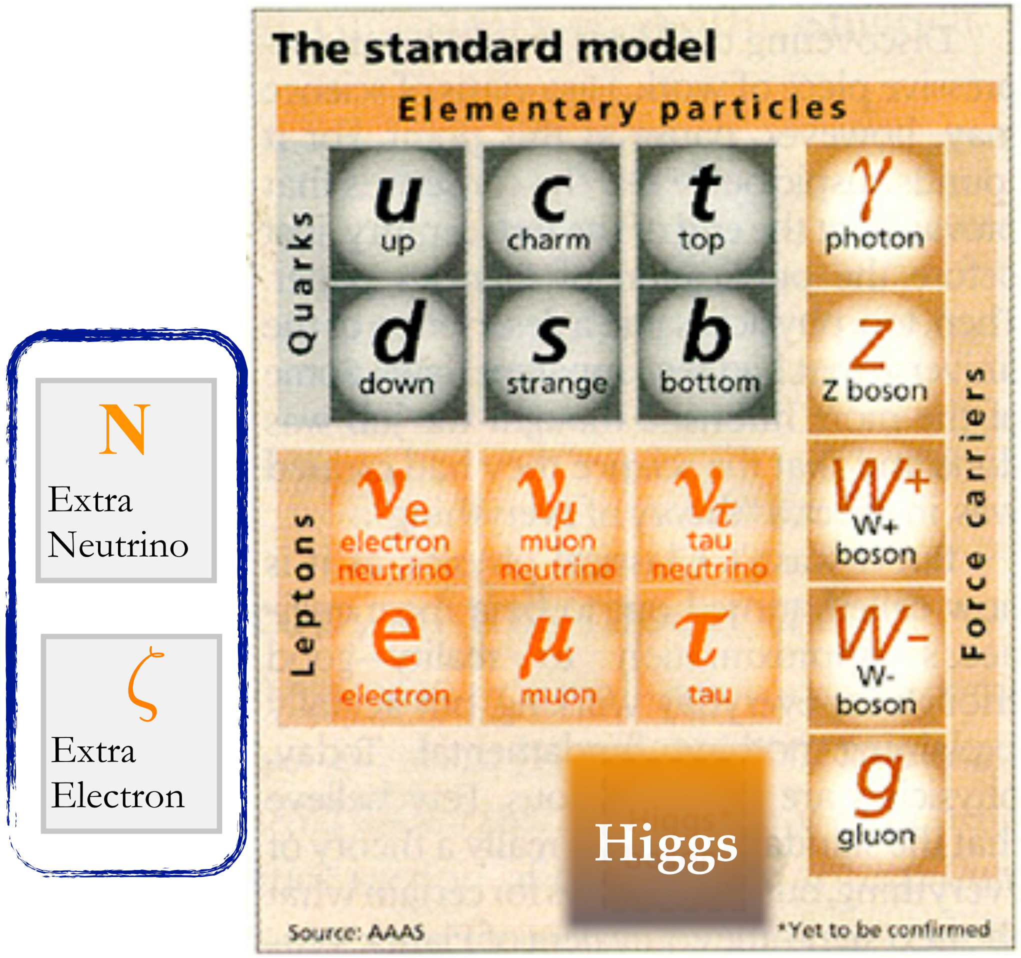

U(1)

SU(2)

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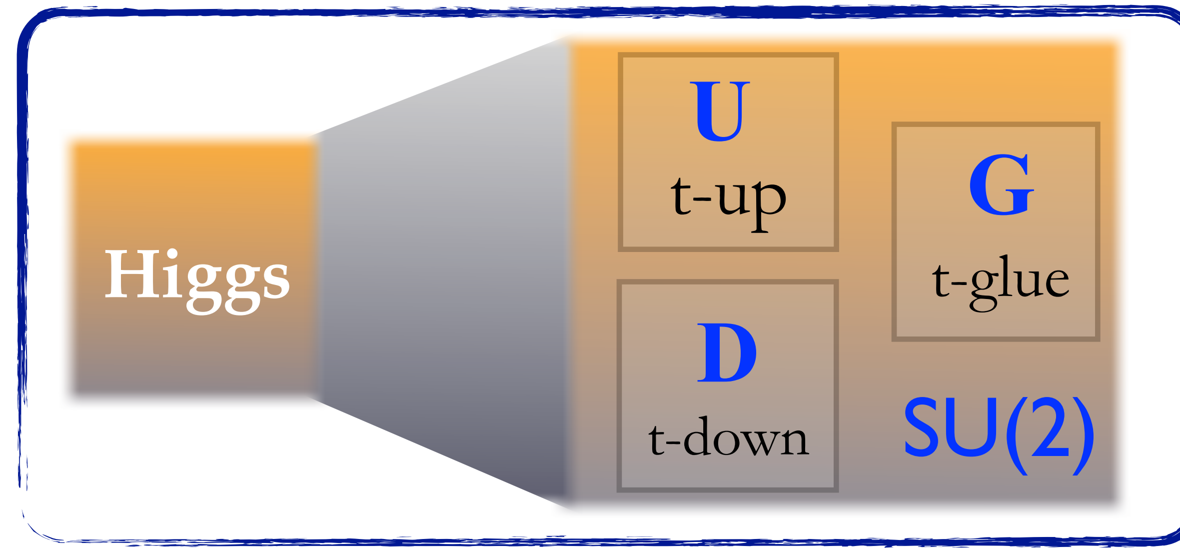

Sannino, Tuominen 04

Hong, Hsu, Sannino 04

Dietrich, Sannino, Tuominen 05

Since 2004 - Minimal WTC is Higgsfull

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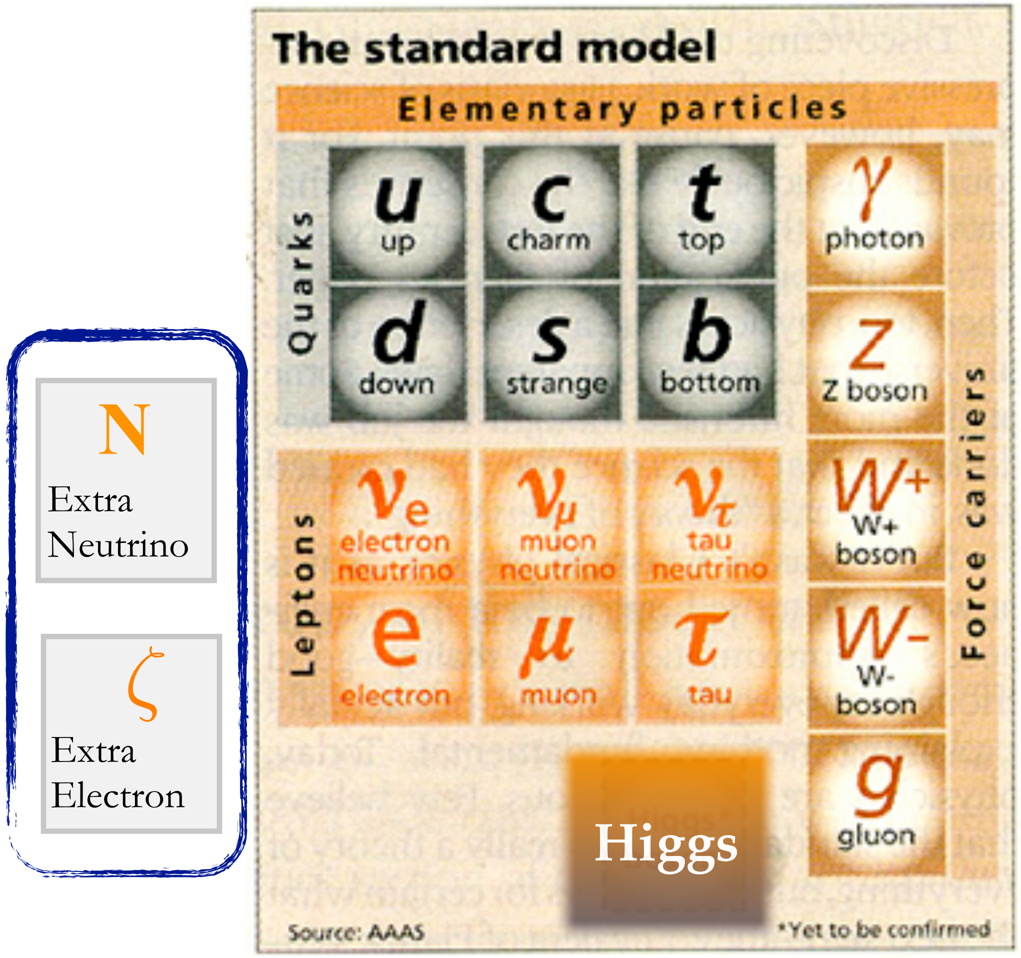

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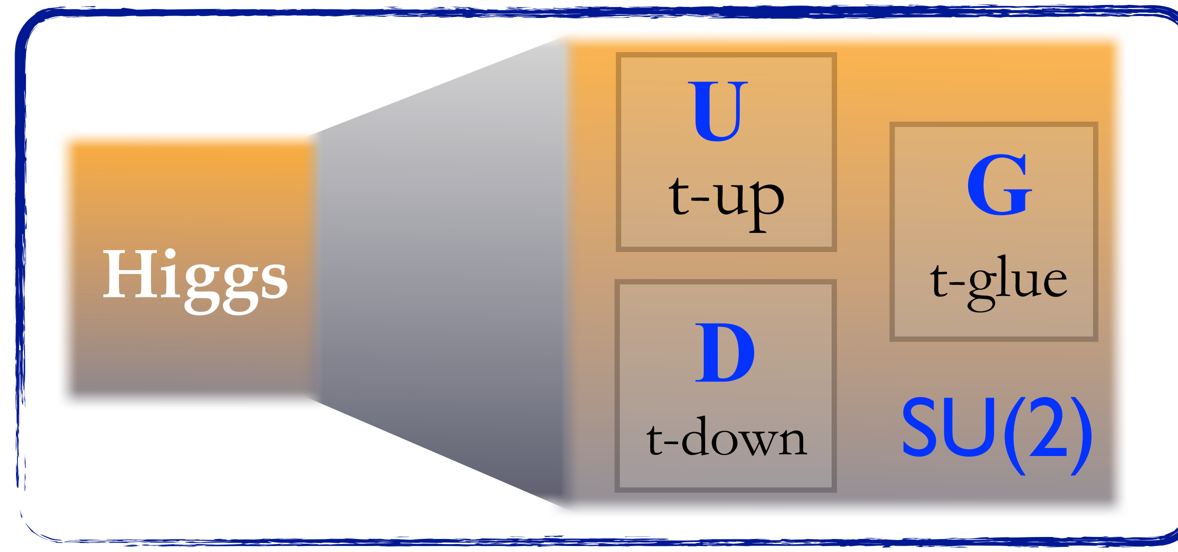


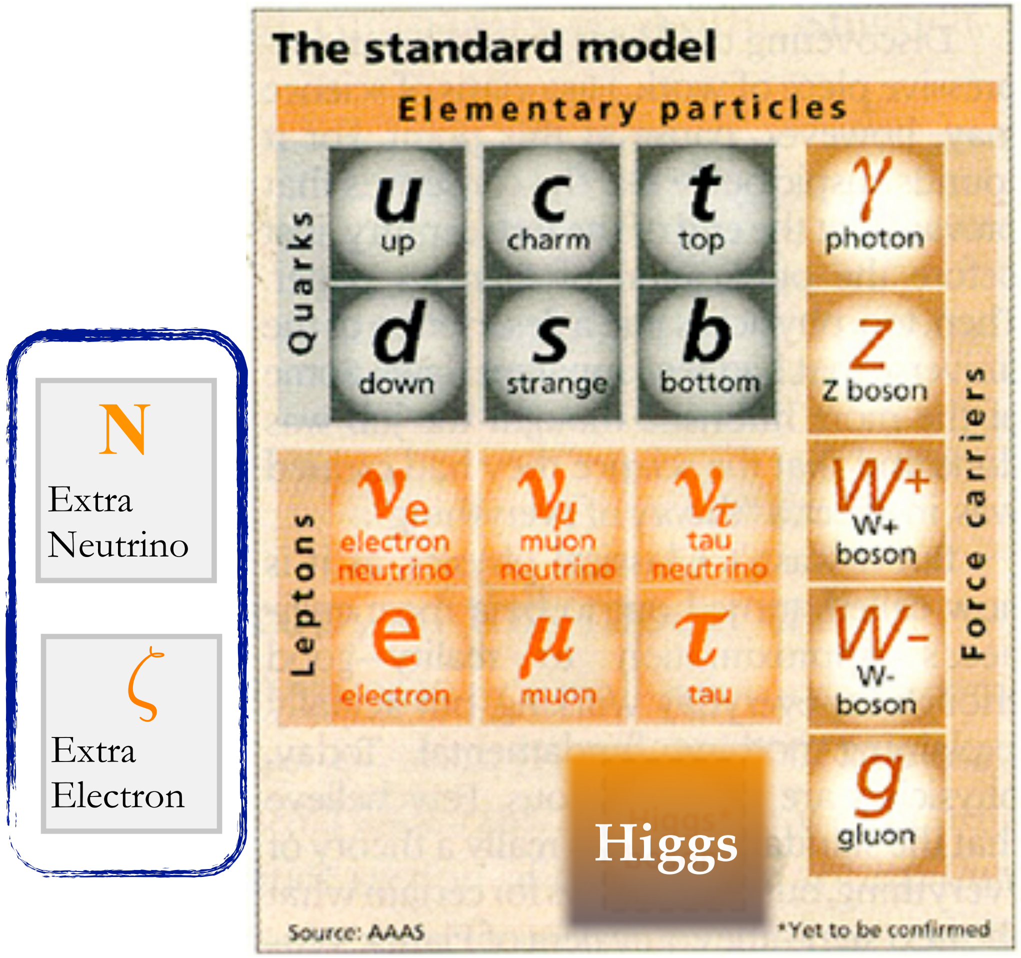
- Can feature Light TC/Dilaton Higgs

Sannino, Tuominen 04

Hong, Hsu, Sannino 04

Dietrich, Sannino, Tuominen 05

Since 2004 - Minimal WTC is Higgsfull
[Original Name: Light Composite Higgs]



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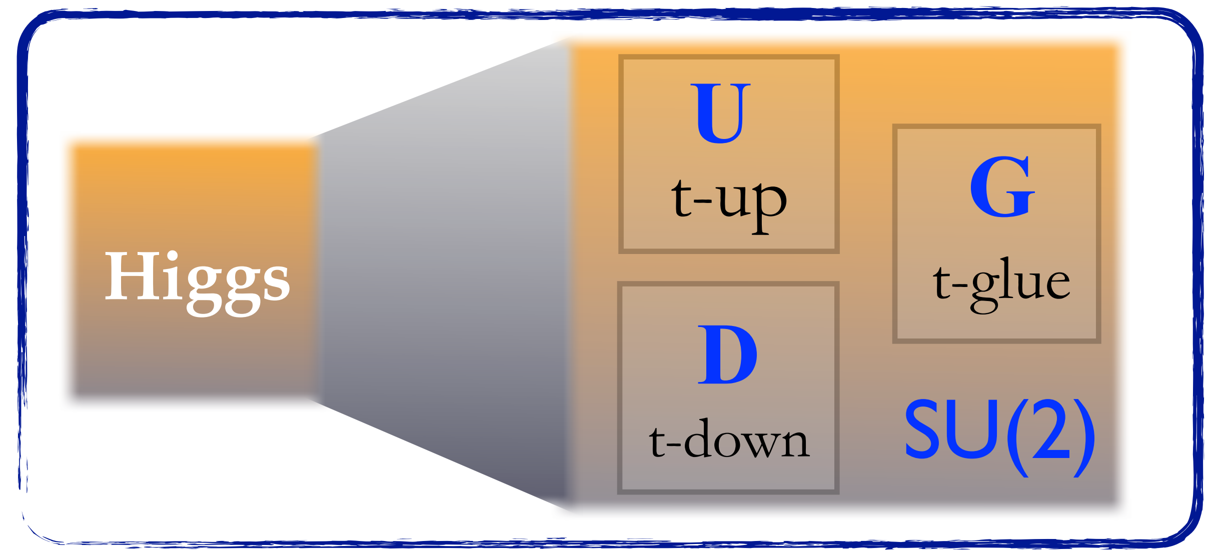

- Can feature Light TC/Dilaton Higgs
- Smallest S-parameter & FCNC

Sannino, Tuominen 04

Hong, Hsu, Sannino 04

Dietrich, Sannino, Tuominen 05

Since 2004 - Minimal WTC is Higgsfull

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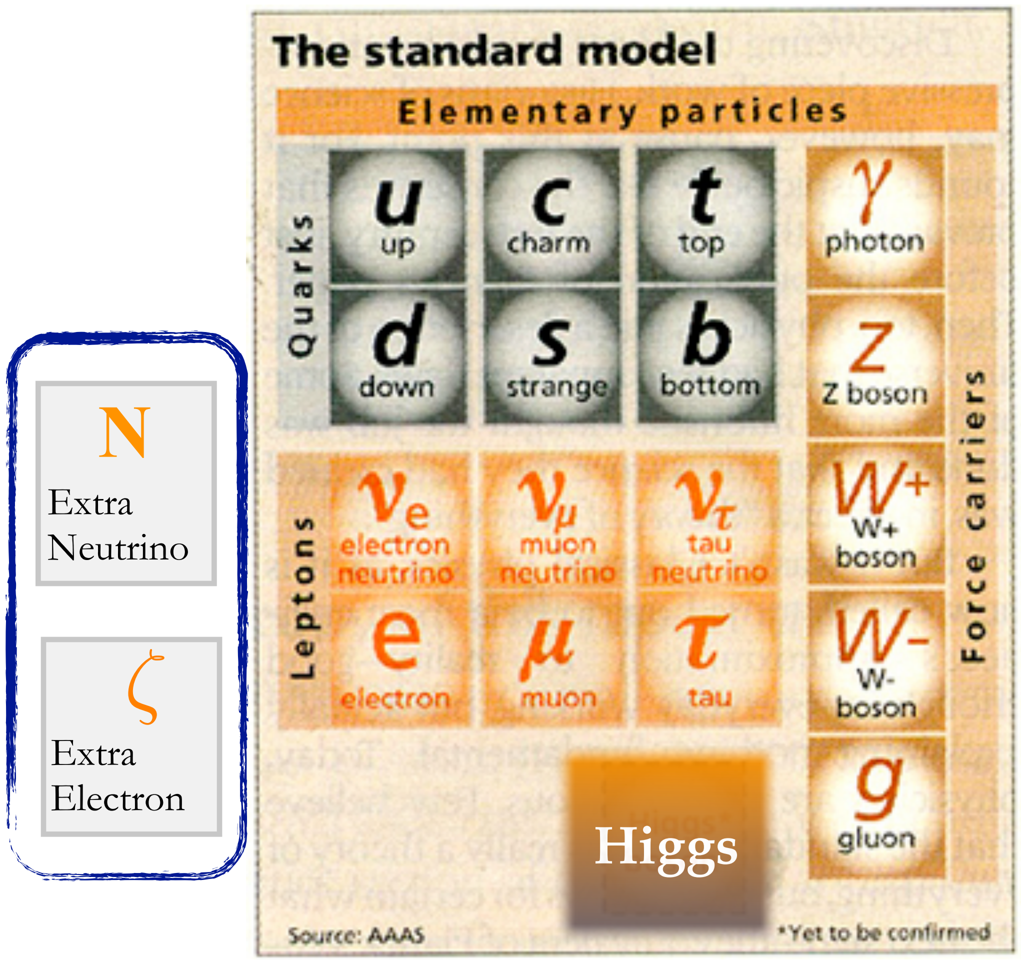
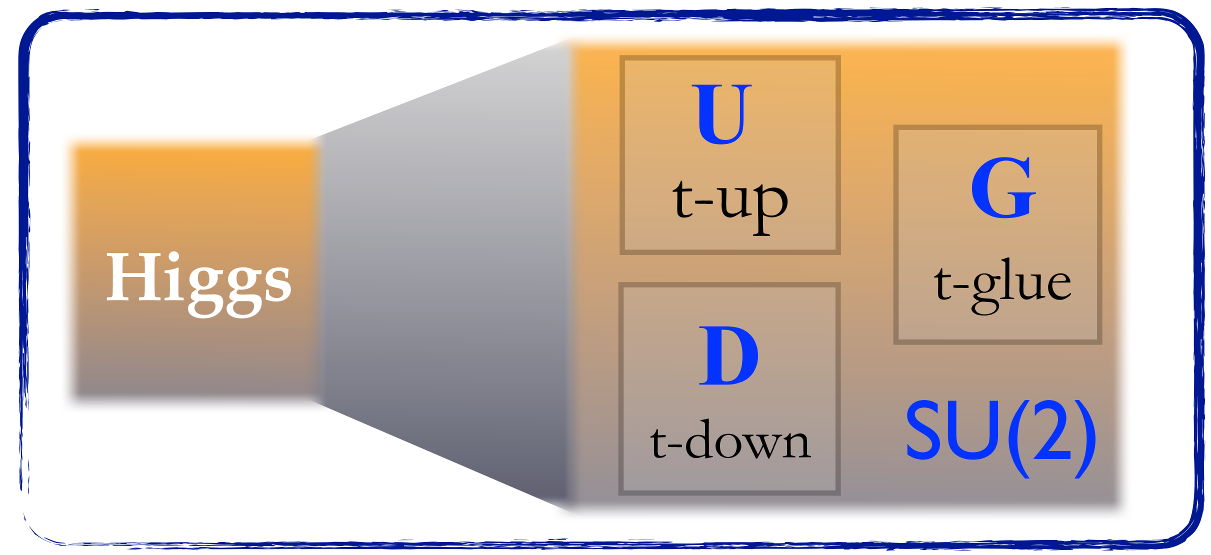


U(1)

SU(2)

SU(3)



- Can feature Light TC/Dilaton Higgs
- Smallest S-parameter & FCNC
- Dark matter candidates

Sannino, Tuominen 04

Hong, Hsu, Sannino 04

Dietrich, Sannino, Tuominen 05

Lattice

Catterall, Sannino 0705.1664

Hietanen, Rantaharju, Rummukainen, Tuominen 0812.1467

Del Debbio, Lucini, Patella, Pica, Rago 1004.3206

Minimal TC states to discover

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

Minimal TC states to discover

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

Beyond minimal: (E)TC model dependent

TC pions	Π
TC composite fermions	Ψ
Elementary Leptons	L
Unexpected	U

LHC Search **Strategy**

- Indirect hints of heavy states
  - Modified Higgs couplings wrt SM
  - Study Higgs in association with W/Z
- Direct discovery of heavy states
  - Drell-Yan production of TC-rho/axial (R1,R2)
  - (exotic) pions
  - composite fermions
  - 4th heavy lepton family

Higgs to γγ

Sensitive TC-fermion content

$$\Gamma(H \to \gamma\gamma) \sim \left(r_t - 7 r_W + \frac{3}{4} \sum_{Q_{\rm TC}} d(R_{\rm TC}) e_{\rm TC}^2 \right)^2$$

and to the H-tt coupling r_t (Extended TC)

$$pp \to H \sim r_t^2$$

H to γγ can help discriminate different models

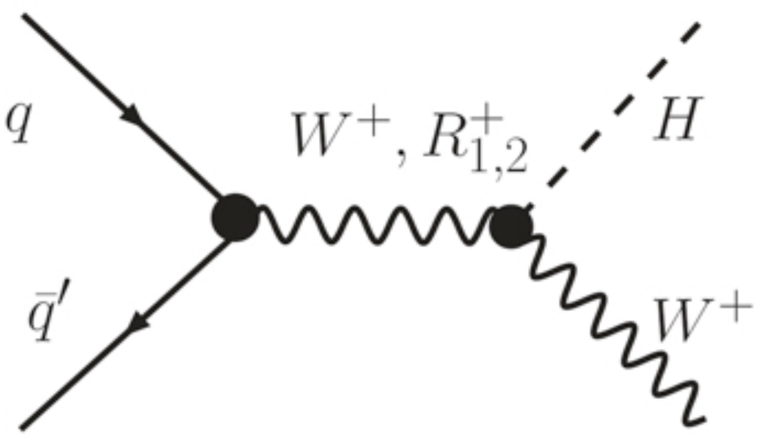
$$\mathcal{L}_H \supset \frac{2\ m_W^2\ r_W}{v}\ H\ W_\mu^+\ W^{-\mu} - \frac{m_t\ r_t}{v}\ H\ \bar{t}\ t$$

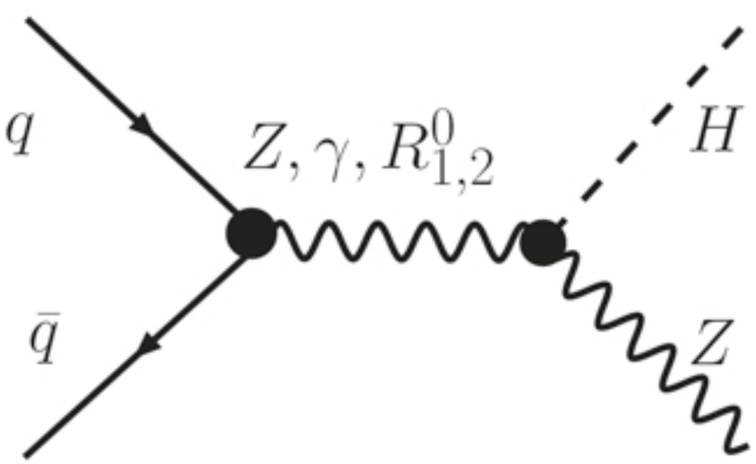
Associate TC-Higgs production

Potential discovery of composite dynamics at the LHC

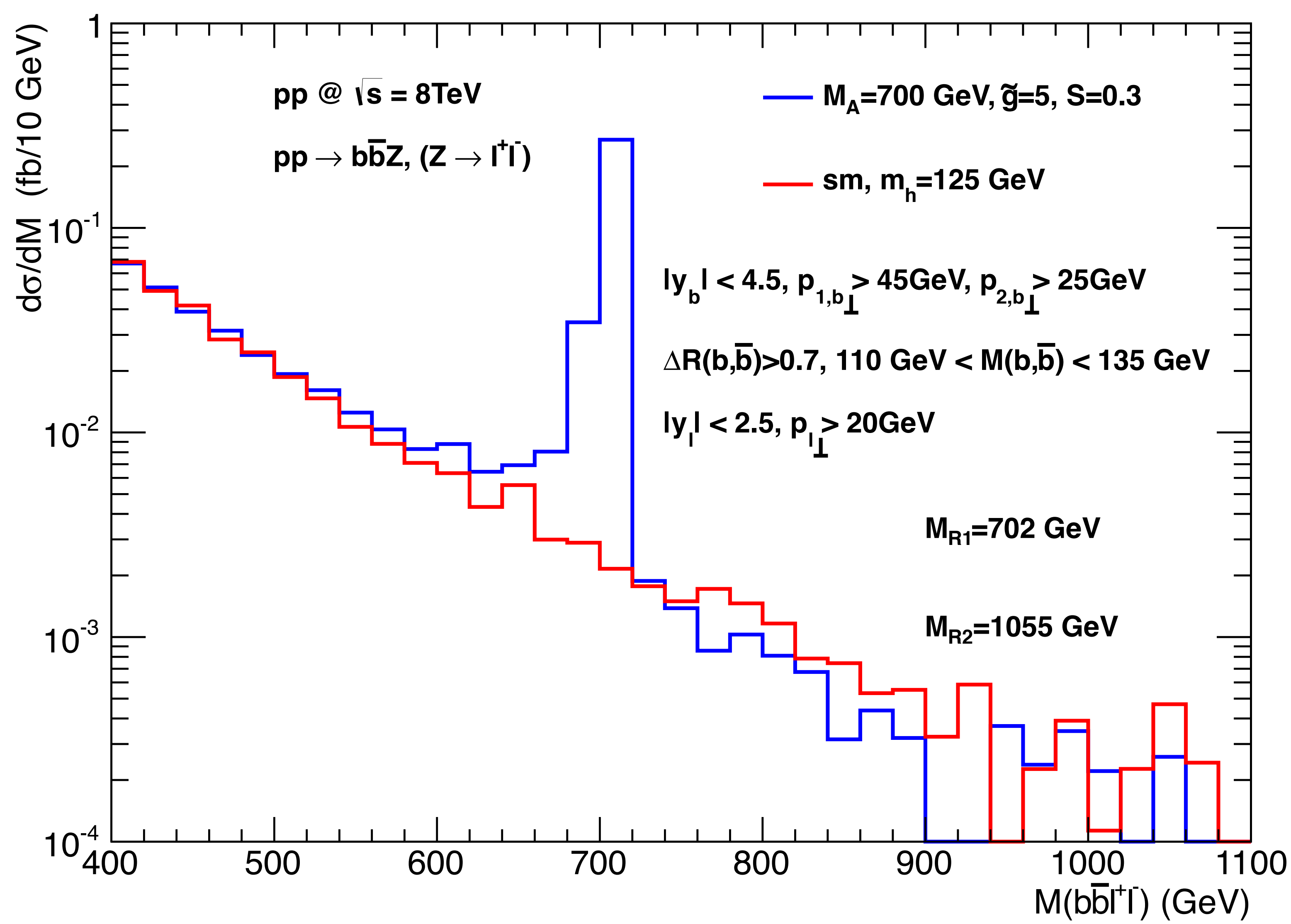
Composite spin-1 mesons like QCD ϱ & a_1

Belyaev, Foadi, Frandsen, Jarvinen & Sannino 08





$$pp \to HZ \to \bar{b}b + 2\ell$$



Preliminary MWTC - theoretical updated analysis by T. Hapola

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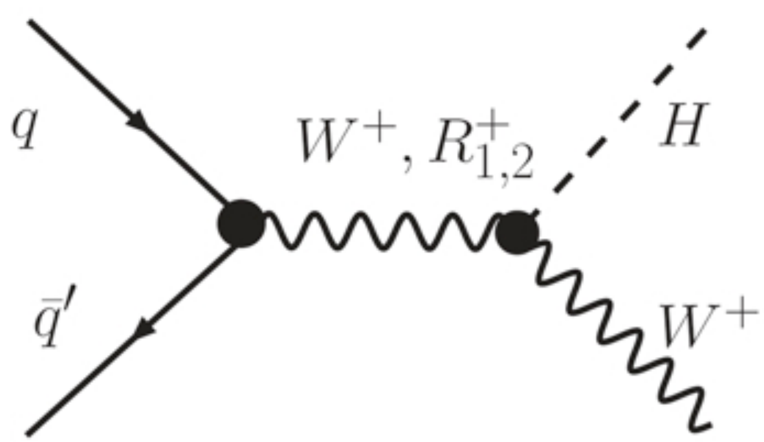

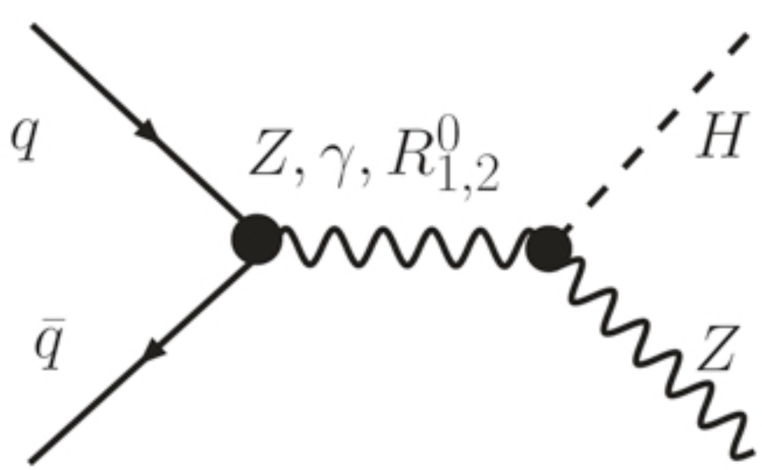

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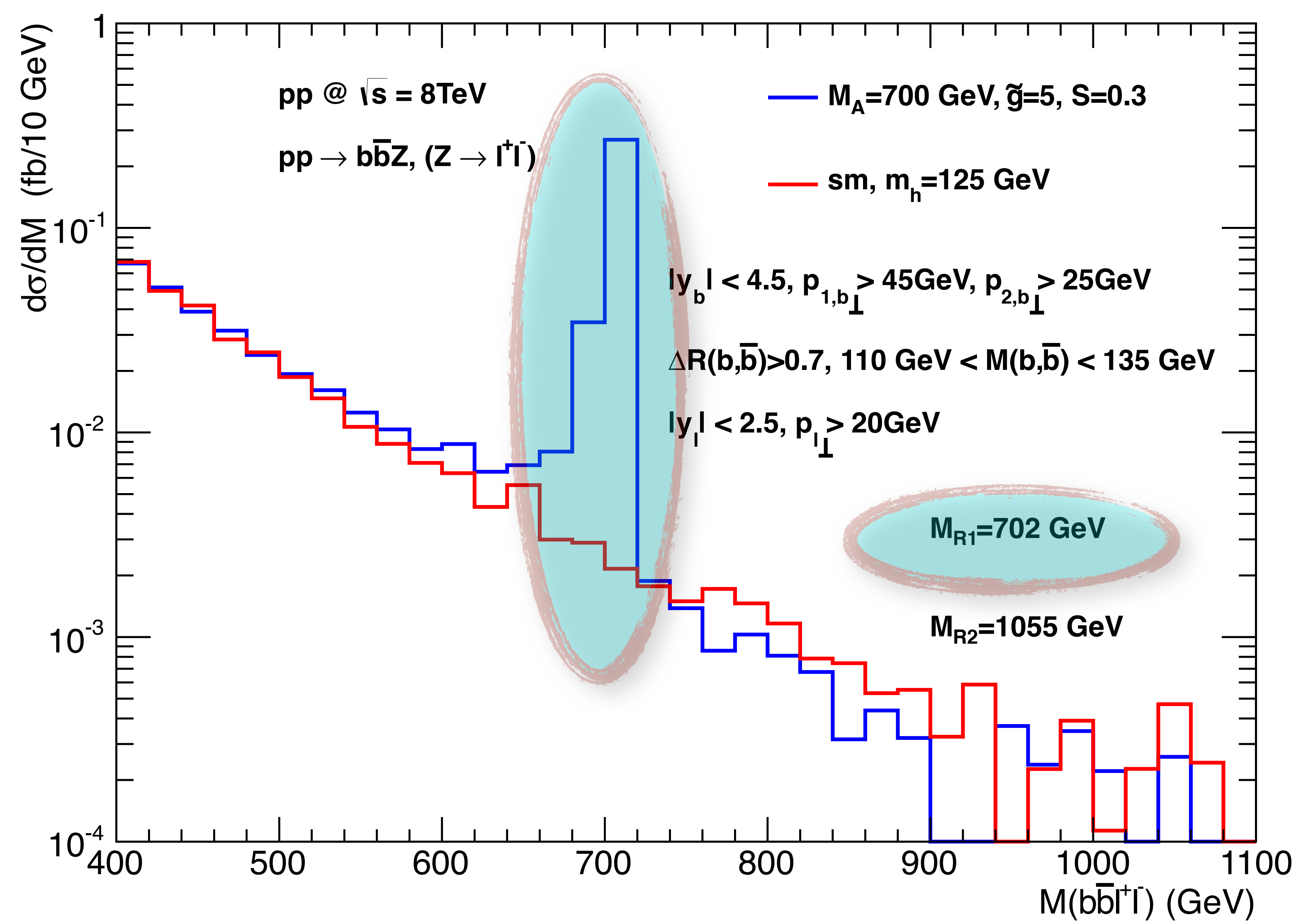

Preliminary MWTC - theoretical updated analysis by T. Hapola

Conclusions

- Discovered the TC Higgs?
- 125 Higgs via a not too light TC Higgs!
- Minimal TC & LHC signatures

Lots of fun ahead !