Strong Top Dynamics in Light of LHC Data

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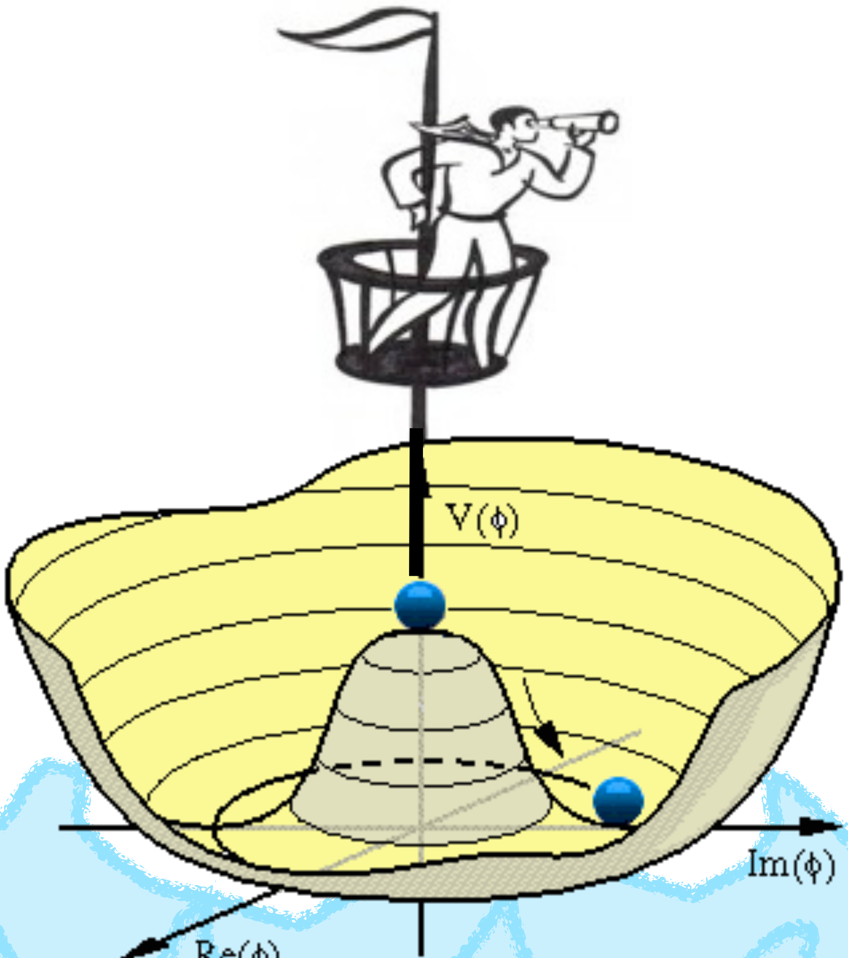
- Dynamical EWSB and Topcolor
- Effective Theory Description
- New Top-Sector States
- LHC Prospects
- Conclusions

New Top Dynamics

Looking Beyond the Standard Model



Fundamental scalars observed?

Hierarchy/Naturalness?

Triviality?

Dynamics causing EWSB?

Dynamical EWSB:

Technicolor: (as in previous talks)

Introduce $SU(N)_{TC}$ with

technigluons, inspired by QCD gluons

techniquarks carrying $SU(N)_{TC}$ charge:

- e.g. weak doublet $T_L = (U_L, D_L)$; weak singlet U_R, D_R
- Lagrangian has $SU(2)_L \times SU(2)_R$ chiral symmetry

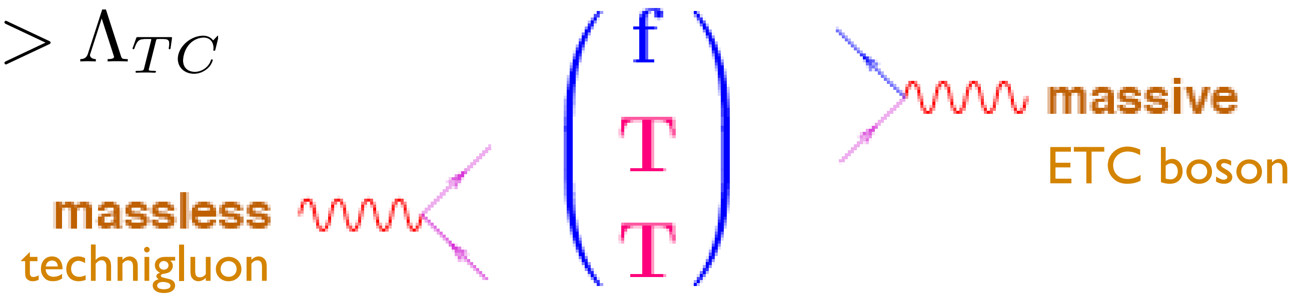
$SU(N)_{TC}$ gauge coupling becomes large at $\Lambda_{TC} \approx 1\mathrm{TeV}$

- $\langle T_L T_R \rangle \approx 250\,\mathrm{GeV}$ causes EWSB
- `**techni**pions' Π_{TC} become the W_L, Z_L

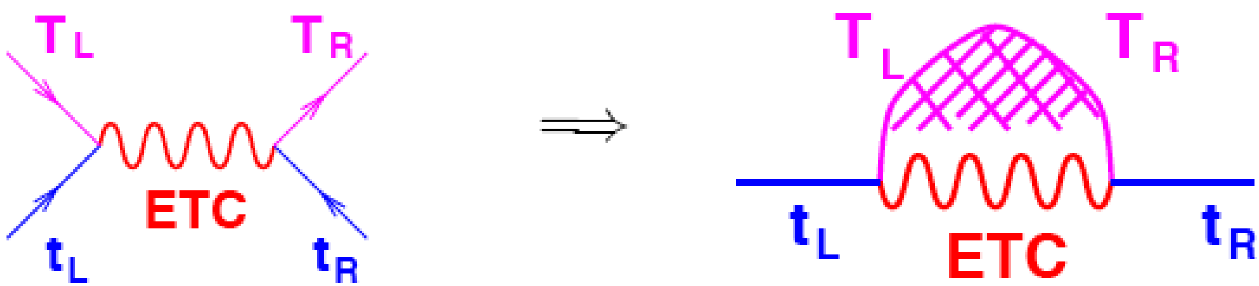
Susskind, Weinberg

Dynamical Fermion Masses: ETC*

$$M_{ETC} > \Lambda_{TC}$$



E.g. the top quark mass arises from:



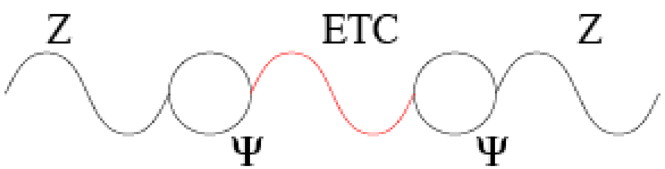
and its size is $\left(\frac{g_{ETC}}{M_{ETC}}\right)^2 \langle \bar{T}T \rangle$ x (flavor-dependent factor)

Challenge: ETC must violate custodial symmetry to make $m_t >> m_b$. But how to avoid large changes to $\Delta\rho$?

*Dimpoulos & Susskind; Eichten & Lane

Isospin Violation (I)

ETC *must* violate weak-isospin to make $\mathrm{m_t} \gg \mathrm{m_b}$.
ETC boson mixing with Z through technifermion loops induces dangerous contributions to $\Delta\rho$



$$\Delta\rho \approx 12\% \cdot \left(\frac{\sqrt{N_D}F_{TC}}{250\ \mathrm{GeV}}\right)^2 \cdot \left(\frac{1\ \mathrm{TeV}}{M_{ETC}/g_{ETC}}\right)^2$$

How to satisfy experimental constraint: $\Delta\rho \leq 0.4\%$?

- make ETC boson heavy ?

$$\frac{M_{ETC}}{g_{ETC}} > 5.5\ \mathrm{TeV} \cdot \left(\frac{\sqrt{N_D}F_{TC}}{250\ \mathrm{GeV}}\right)^2$$

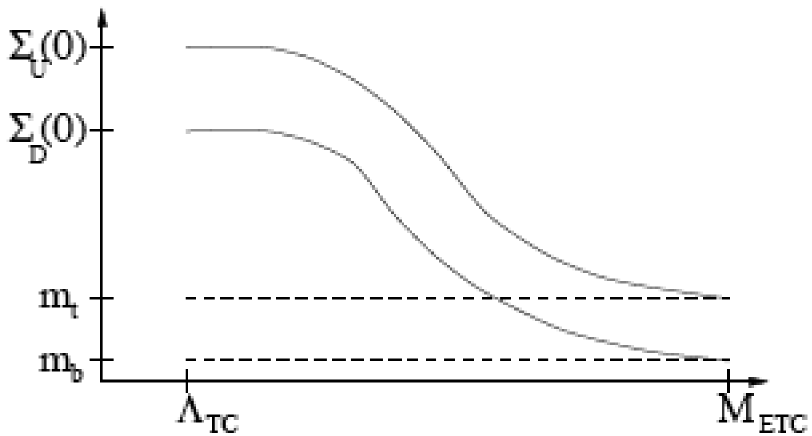
too heavy to provide $m_t = 172\,\mathrm{GeV}$

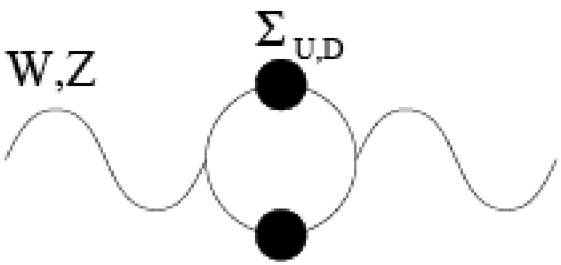
- arrange for $N_D F_{TC}^2 \ll (250GeV)^2$?

  e.g. separate sectors for m_t and EW symmetry breaking

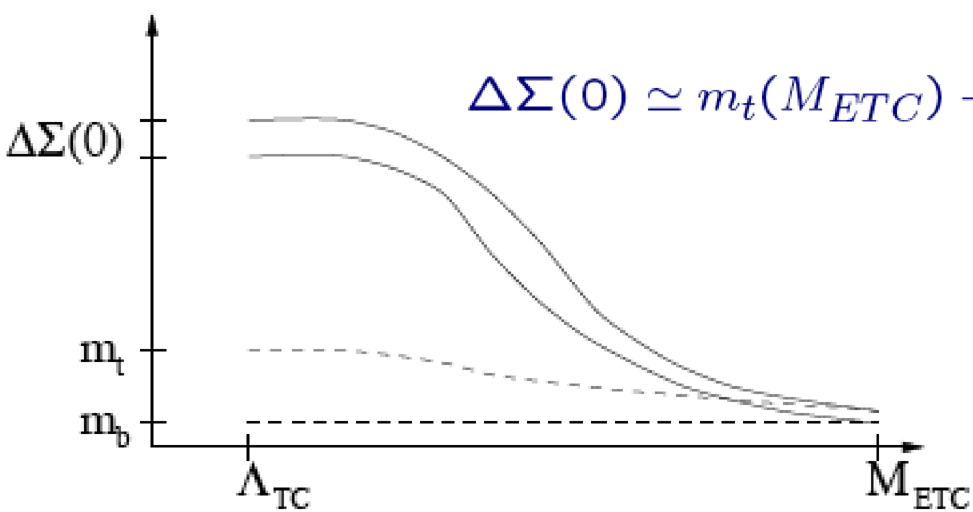
Isospin Violation (2)

What about isospin violation in the technifermion dynamical masses? $\Delta\rho \sim (\Sigma_U(0) - \Sigma_D(0))^2/M_Z^2$





Again, one solution is having t, b get only part of their mass from technicolor:



Conclusion: t,b feel a new strong force not shared by other quarks or technifermions

Top Condensation and EWSB

If the top quark feels a new strong interaction, a top-quark condensate $\langle \bar{t}t \rangle \neq 0$ can provide some or even all of electroweak symmetry breaking

$$v^2 = f_{TC}^2 + f_t^2 \qquad \boxed{\sin\omega \equiv f_t/v}$$

some (topcolor*, topcolor-assisted technicolor*)

in these models the top quark feels an additional gauge interaction that causes top condensation

all (top mode^, top seesaw^^)

in top seesaw models, a heavy partner quark T forms the condensate; the top quark mass eigenstate that we observe is a seesaw mixture between T and the standard model's top quark gauge eigenstate

* Hill ^Bardeen,Hill &Lindner; Yamawaki; Miranski; Nambu ^^Chivukula, Dobrescu, Georgi & Hill

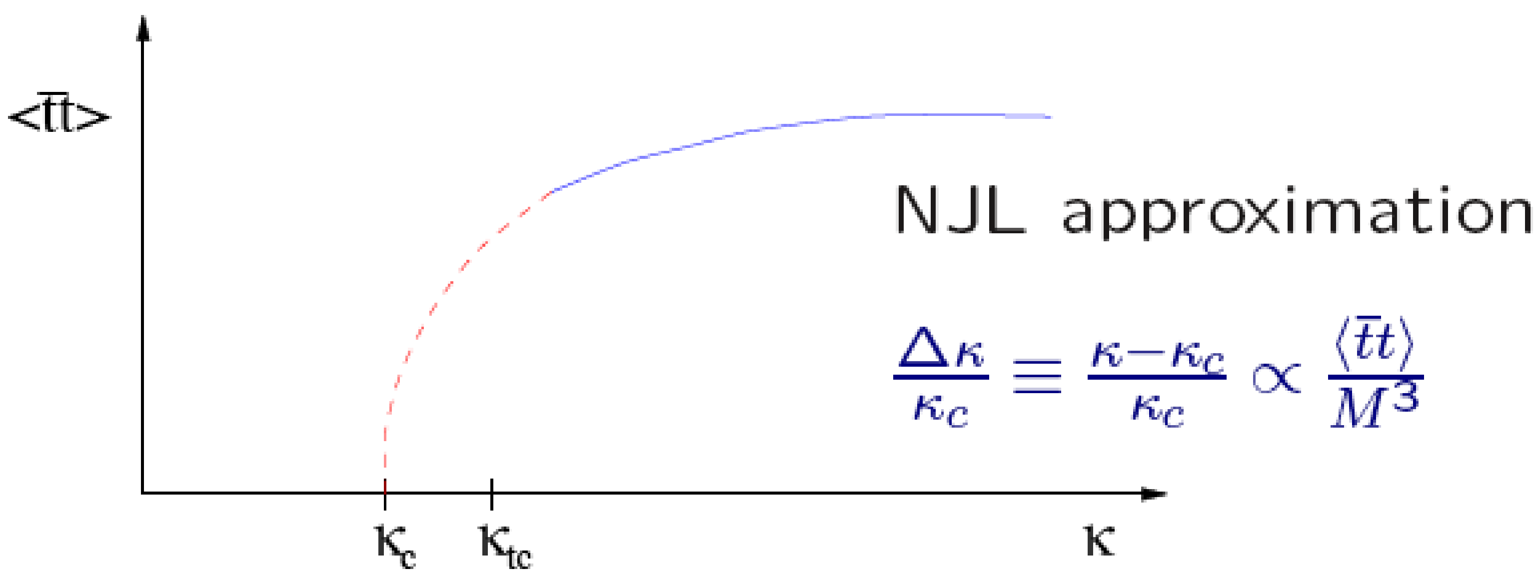
Physical Realization: Topcolor

One physical realization of a new interaction for top is a (spontaneously broken) extended color gauge group: topcolor

$$SU(3)_h \times SU(3)_\ell \xrightarrow{M} SU(3)_{QCD}$$

where (t,b) feel $SU(3)_h$ and (u,c,d,s) feel $SU(3)_l$

Below the scale M, exchange of massive topgluons yields four-fermion interactions among top quarks $-\frac{4\pi\kappa}{M^2}\left(\bar{t}\gamma_\mu\frac{\lambda^a}{2}t\right)^2$



Note:
M >> 1TeV
implies fine
tuning

Topcolor-Assisted Technicolor (TC2)

$$\overset{}{G_{TC} \times \overbrace{SU(3)_h \times SU(3)_\ell}^{(g_h > g_\ell)} \times SU(2)_W \times \overbrace{U(1)_h \times U(1)_\ell}^{(g_h > g_\ell)}}$$

$$\downarrow \quad M \gtrsim 1\ \text{TeV}$$

$$G_{TC} \times SU(3)_{QCD} \times SU(2)_W \times U(1)_Y$$

$$\downarrow \quad \Lambda_{TC} \sim 1\ \text{TeV}$$

$$G_{TC} \times SU(3)_{QCD} \times U(1)_{EM}$$

technicolor: provides most of EWSB

topcolor: provides most of m_t

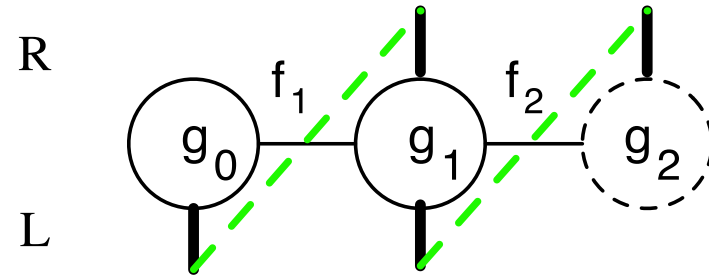
hypercharge: keeps m_b small

C.T. Hill

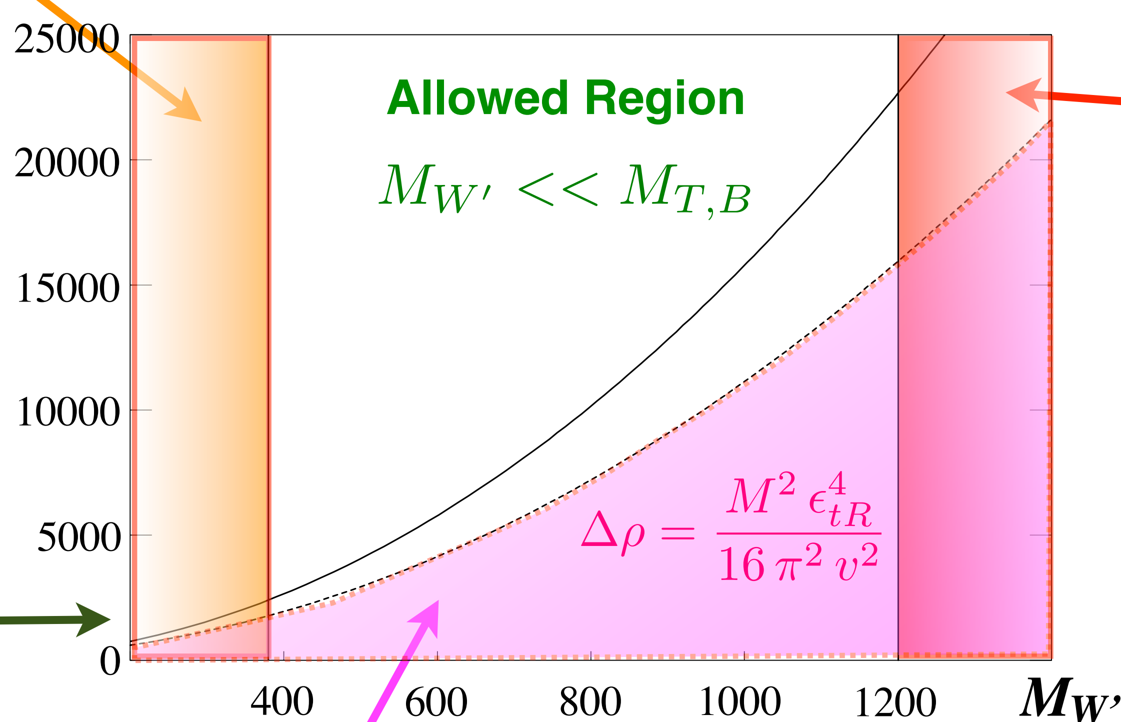
Effective Field Theory: The Top-Triangle Moose

Chivukula, Christensen, Coleppa, Simmons
arXiv:0906.5667
Chivukula, Coleppa, Logan, Martin, Simmons
arXiv:1101.6023

Reminder: 3-Site Model



WWZ vertex visibly altered



M_{TB}

KK fermion mass (GeV)

Unitarity violated

W' mass (GeV)

Minimum allowed fermion mass

1-loop fermionic EW precision corrections too large

The Top Triangle Moose

Gauge structure:

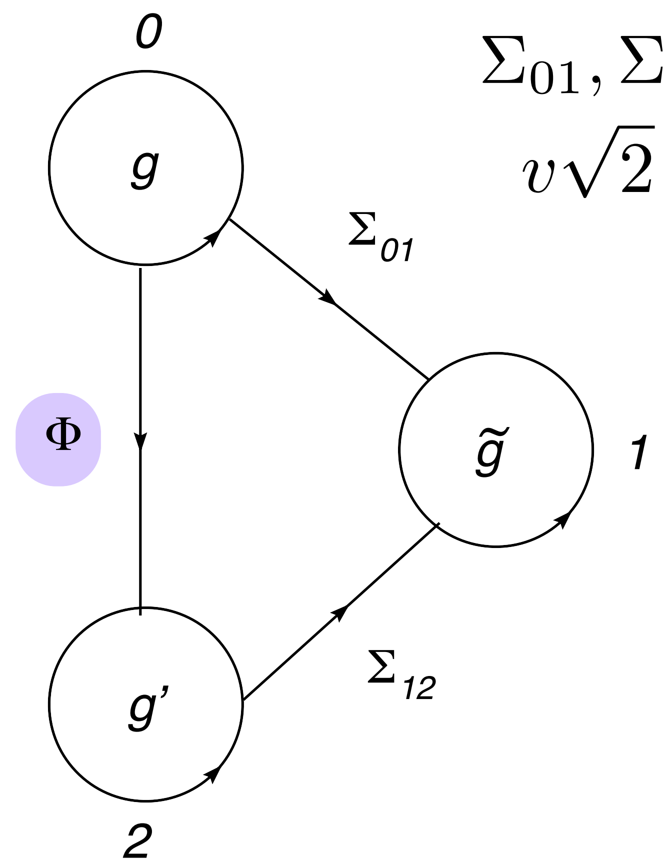
$SU(2) \times SU(2) \times U(1)$

$g_0,\ g_2 \ll g_1$

Top-Higgs

$\langle \Phi \rangle = v\ \sin\omega$

ψ_{L0}



f-constants of Σ_{01}, Σ_{12} are $v\sqrt{2}\cos\omega$

ψ_{L1}

ψ_{R1}

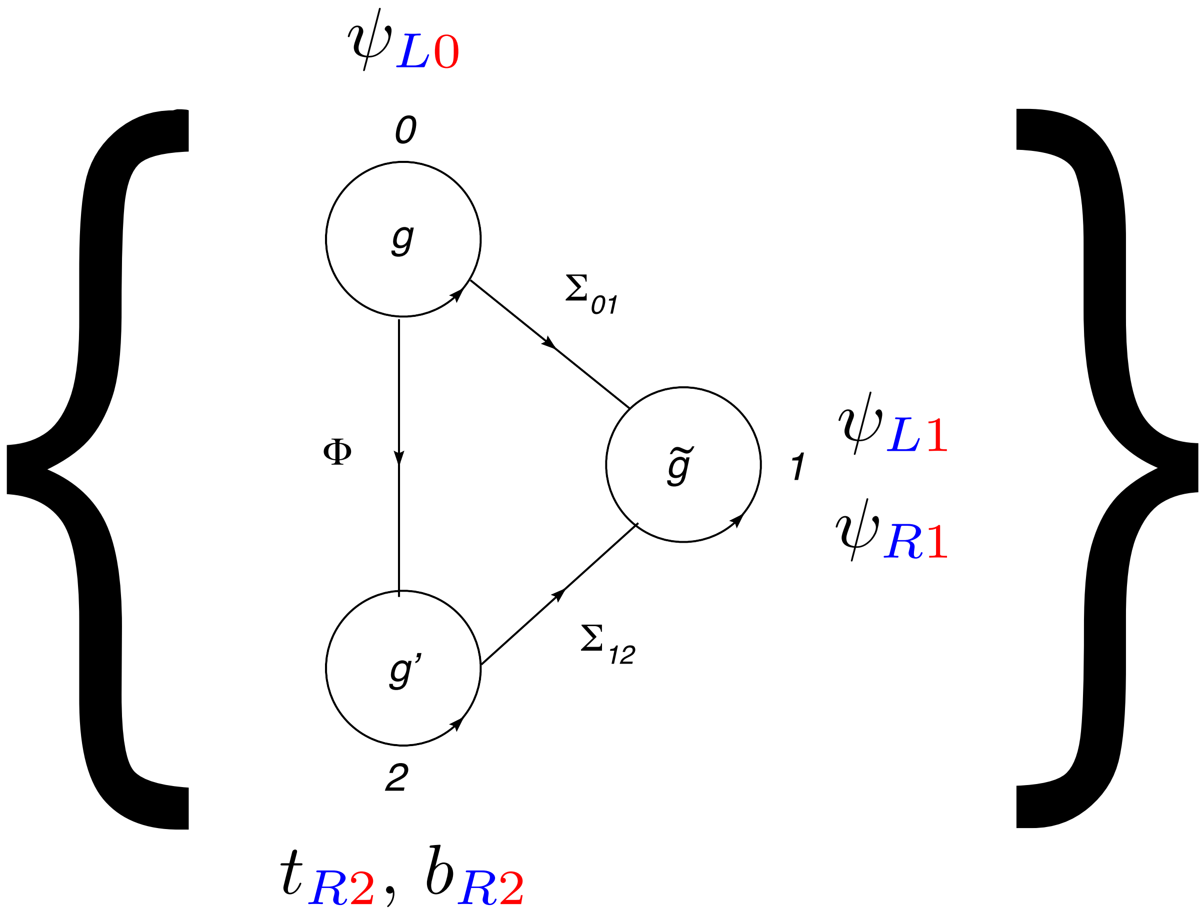
$t_{R2},\ b_{R2}$

Gauge boson spectrum:
photon, Z, Z', W, W'
(as in 3-site, BESS or HLS)

Fermion spectrum:
t, T, b, B; similar for light quarks & leptons
only top couples to Φ

Triangle Moose and Topcolor-Assisted TC

Topcolor sector

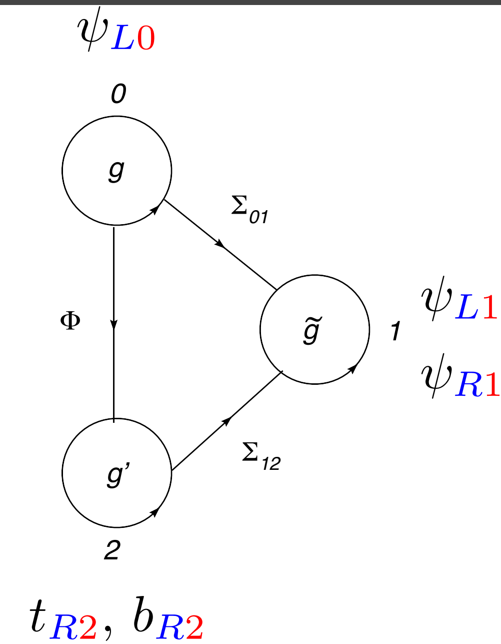


(E)TC sector

Key MASS Terms

Top quark: $-\lambda_t \bar{\psi}_{L0}\, \Phi\, t_R$

Top-pions: $4\pi\kappa v^3 \mathrm{Tr}\left(\Phi \Sigma_{01} \Sigma_{12}^\dagger\right)$



All fermions (including top) :

$$M_D \left[\epsilon_L \bar{\psi}_{L0} \Sigma_{01} \psi_{R1} + \bar{\psi}_{R1} \psi_{L1} + \bar{\psi}_{L1} \Sigma_{12} \begin{pmatrix} \epsilon_{uR} & 0 \\ 0 & \epsilon_{dR} \end{pmatrix} \begin{pmatrix} u_{R2} \\ d_{R2} \end{pmatrix} \right]$$

ideal delocalization says $\epsilon_L^2 = M_W^2 / 2 M_{W'}^2$

light fermion masses are <u>still</u> of the form $m_f \approx M_D\, \epsilon_L \epsilon_{fR}$

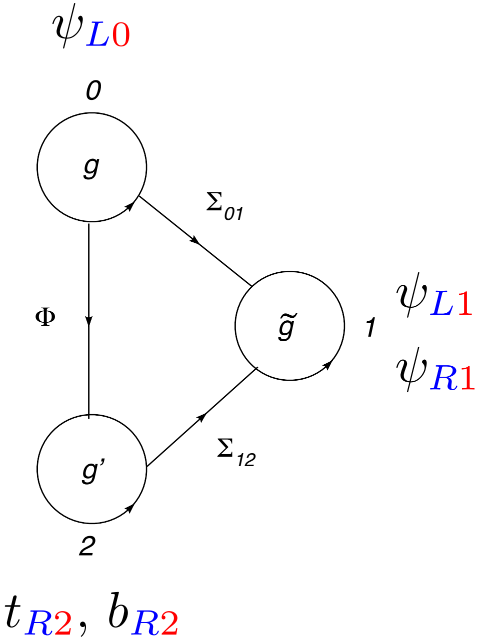
each light mass value is tied to the value of ϵ_{fR}

Top mass value is different...

Top Mass

Top mass matrix:

$$M_t = M_D \begin{pmatrix} \epsilon_{tL} & a \\ 1 & \epsilon_{tR} \end{pmatrix} \qquad a \equiv \frac{\lambda_t \, v \sin\omega}{M_D}$$



Perturbative diagonalization yields...

$$m_t = \lambda_t v \sin\omega \left[1 + \frac{\epsilon_{tL}^2 + \epsilon_{tR}^2 + \frac{2}{a}\epsilon_{tL}\epsilon_{tR}}{2(-1+a^2)} \right]$$

Top mass now depends strongly on λ_t, weakly on ϵ_{tR}

A large top mass no longer conflicts with making ϵ_{tR} small to minimize $\Delta\rho$

$$\Delta\rho = \frac{M_D^2 \, \epsilon_{tR}^4}{16\,\pi^2\, v^2}$$

KK fermions are light enough to produce at LHC

New States Connected to Top Dynamics

topgluon / coloron: C^a

- can be flavor (non)universal

top-Higgs state: H_t

- production in $gg \rightarrow H_t$ higher than in SM by factor $[\sin\omega]^{-1}$

top-Pion states: $\Pi_t^{\pm},\ \Pi_t^0$

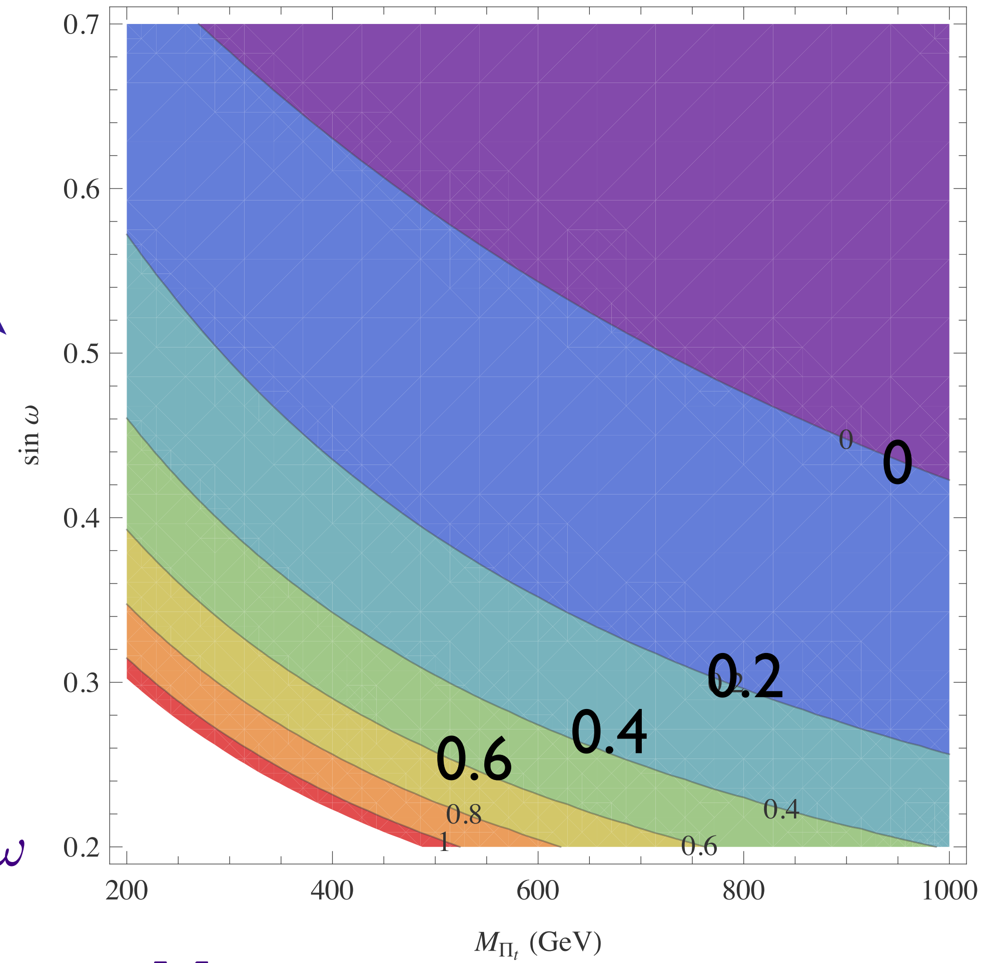
- one-loop R_b contributions minimized by (tree) non-ideal delocalization of t_L as indicated in <u>plot at right</u>:

top's seesaw partner: T

- can be produced at LHC

fractional shift in ϵ_{tL}
to help R_b agree with data

$\sin\omega$



M_{Π_t}

Top sector at LHC

Sample strategy to find states in the top sector and confirm their connection to EWSB:

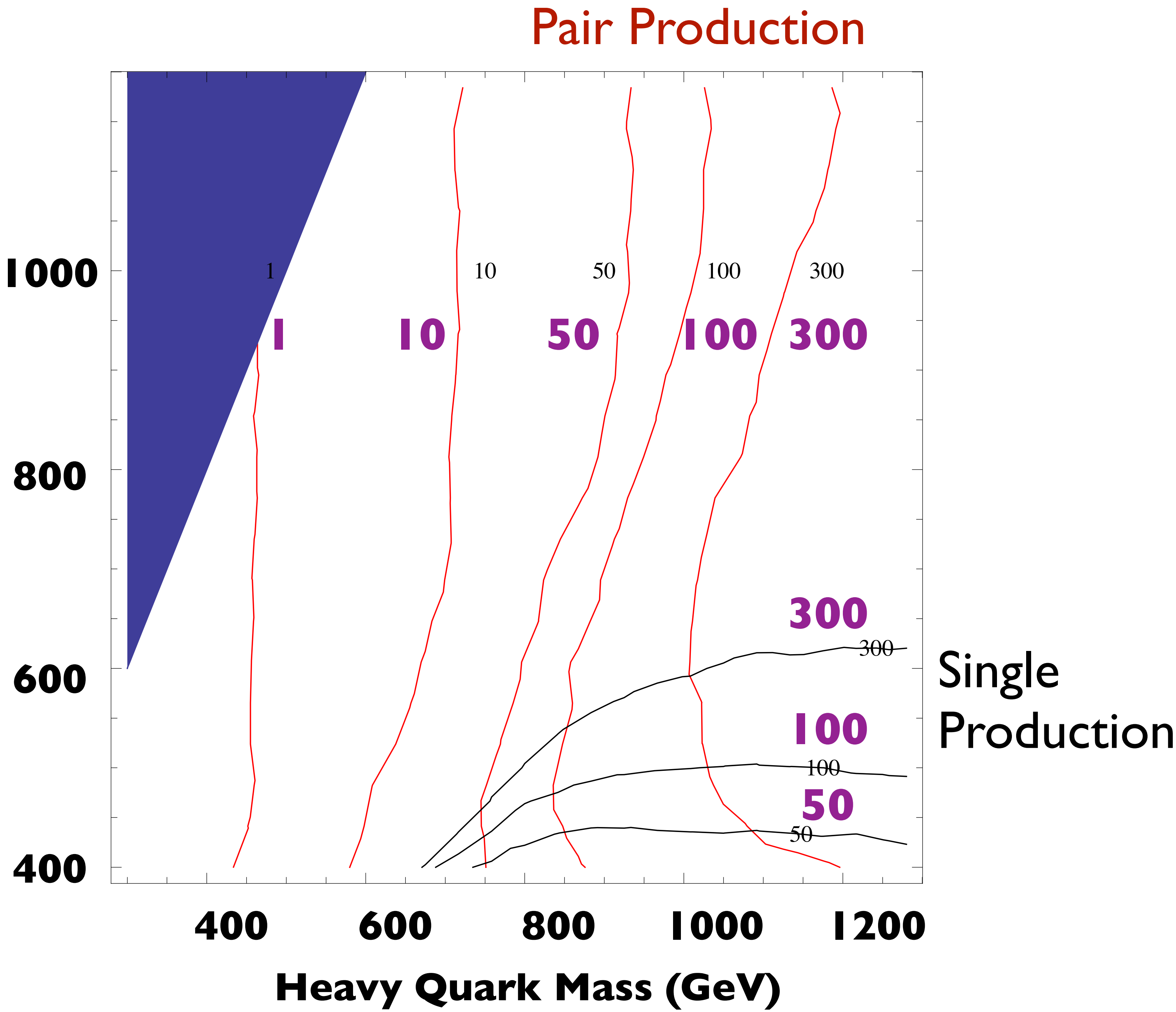
1. With initial LHC data, find $\mathbf{H_t}$ in $\mathbf{H_t} \rightarrow$ **WW, ZZ**; higher-than-SM production rate will indicate that it is exotic
2. As integrated luminosity grows, find top quark's KK partner **T** via its dominant decay to $T \rightarrow Wb$
3. Confirm the $T \rightarrow H_t\, t$ decay; this shows $\mathbf{H_t}$ is strongly coupled to the top sector as well as the EW sector
4. Discover $\mathbf{\Pi_t}$ in $pp \rightarrow t\, \Pi_t^{\pm}$; this establishes the top-pion's strong link to the top sector
5. Confirm $\mathbf{\Pi_t}$ in $pp \rightarrow H_t\, \Pi_t^{\pm}$; this links the top-pion to the EW sector as well

LHC vs. Top Partner (T)

Chivukula, Christensen, Coleppa, Simmons
arXiv:0906:5567 [hep-ph]
Chivukula, Coleppa, Logan, Martin, Simmons
arXiv:1101.6023 [hep-ph]

LHC Detection of KK Quarks

Integrated Luminosity (fb^{-1}) for 5σ discovery of KK quarks in LHC at 14 TeV



LHC vs. Colorons

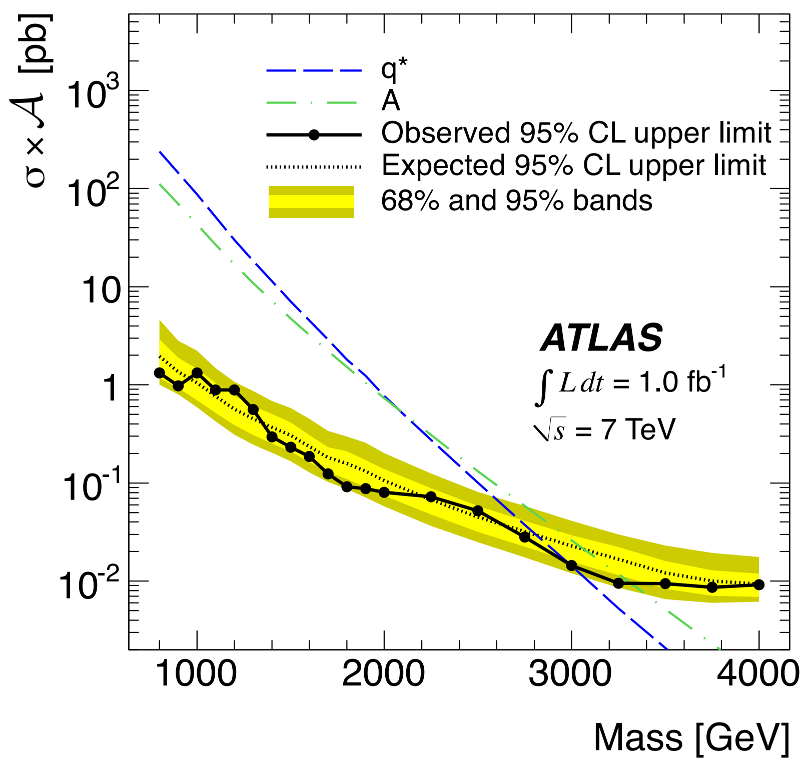
ATLAS: CERN-PH-EP-2011-127
CMS: CERN-PH-EP/2011-119

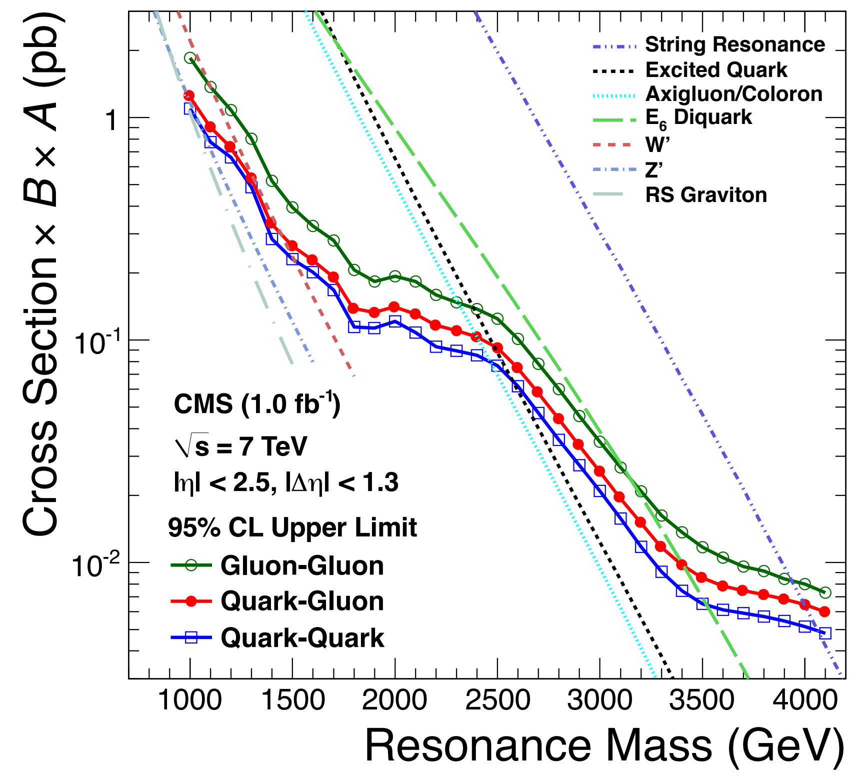
Braam, Chivukula, DiChiara, Flossdorf, Simmons arXiv:0711.1127
Han, Lewis, Liu arXiv:1010.4309
Chivukula, Farzinnia, Foadi, Simmons arXiv:1111.7261

Limits on Topgluons / Colorons

Flavor-universal colorons:

- LHC searches for colorons in dijet constrain $M_C > 2.5$ TeV

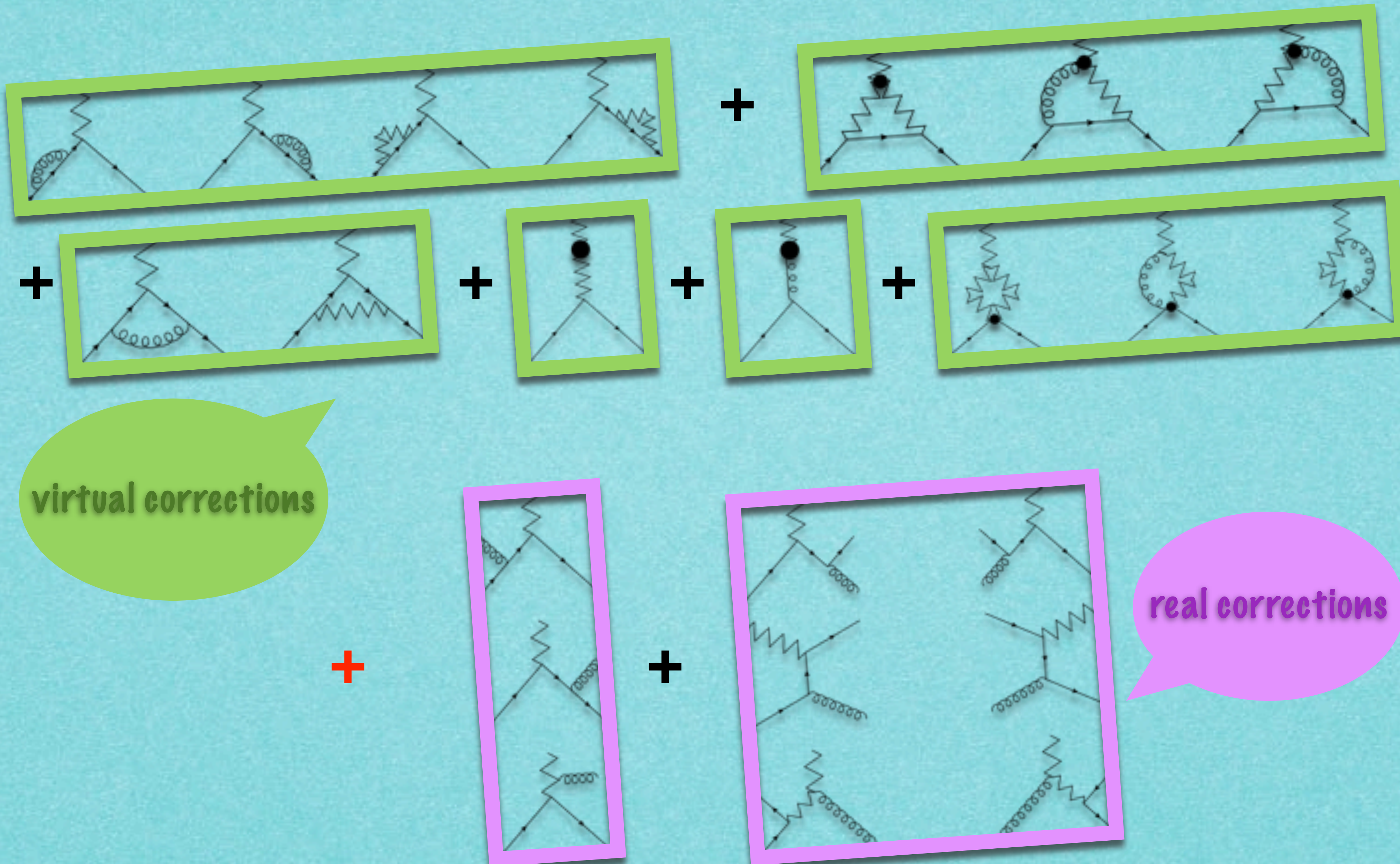




Topgluons coupled preferentially to 3rd generation:

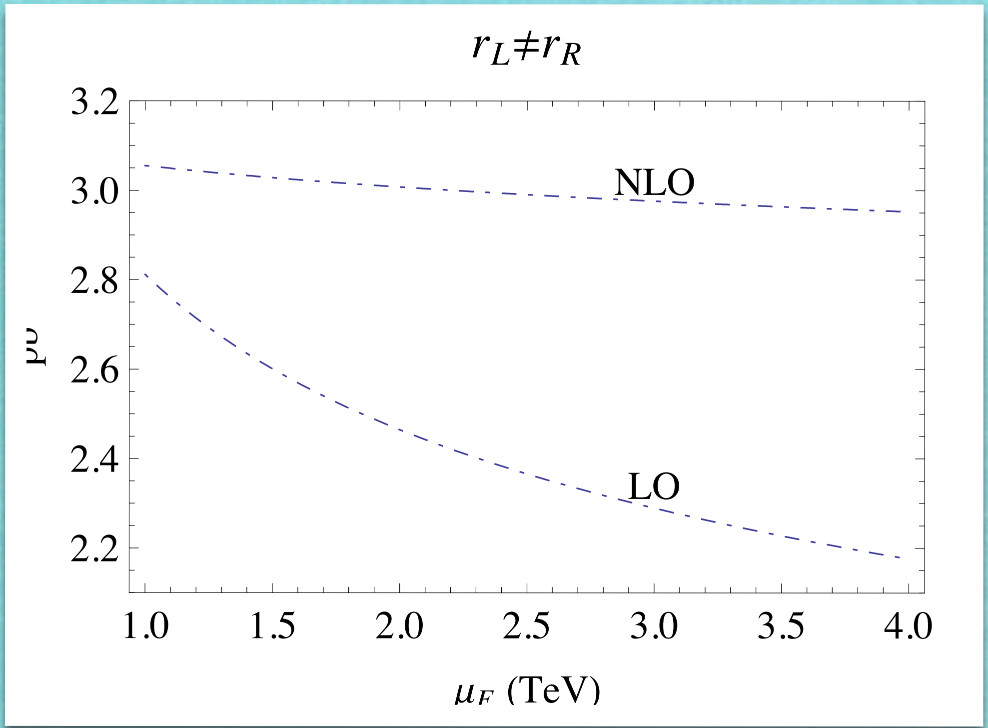
- FCNC bounds from B-meson mixing: $M_C > 6$ TeV
- Fits of TC2 to precision electroweak data: $M_C \sim 18$ TeV

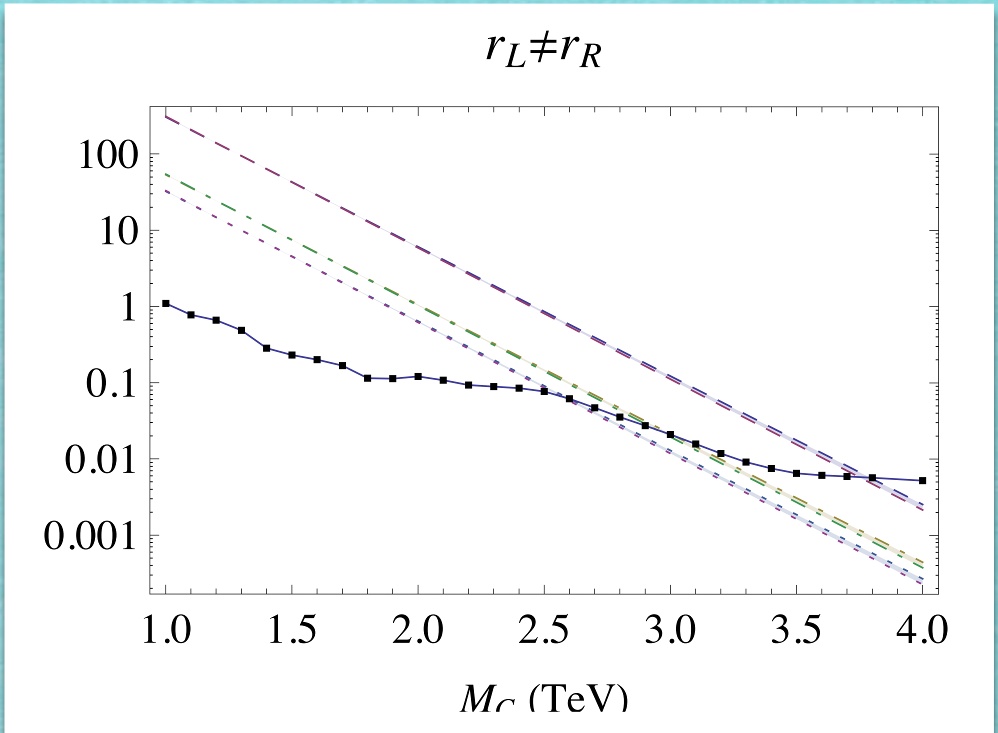
Colorons at NLO



RSC, Farzinnia, Foadi, EHS arXiv:1111.7261

Impact of NLO Corrections

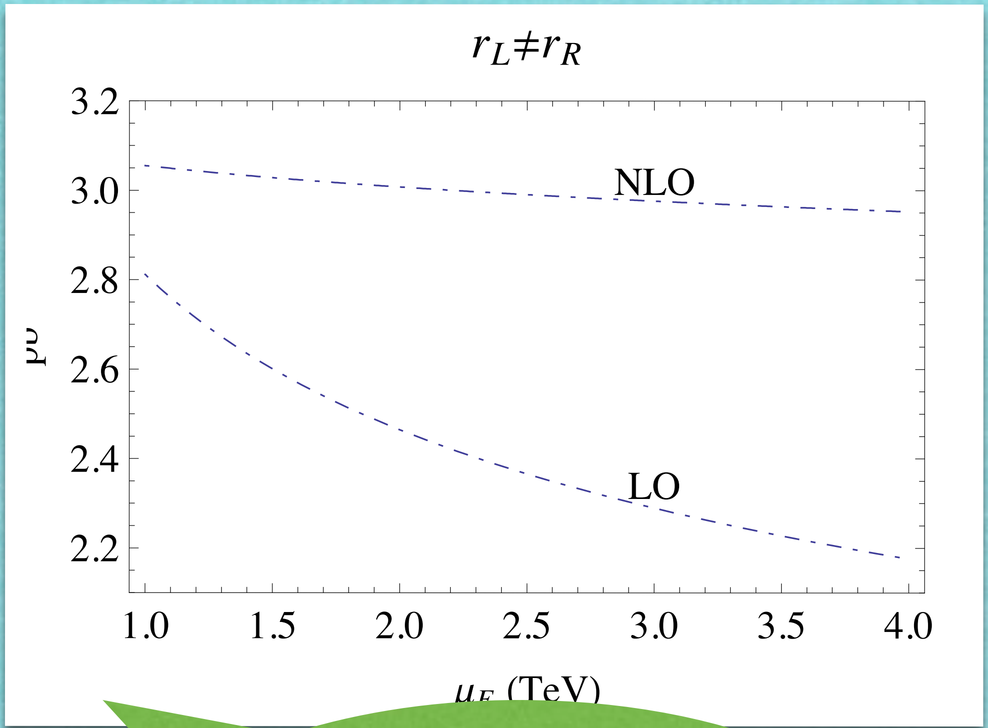


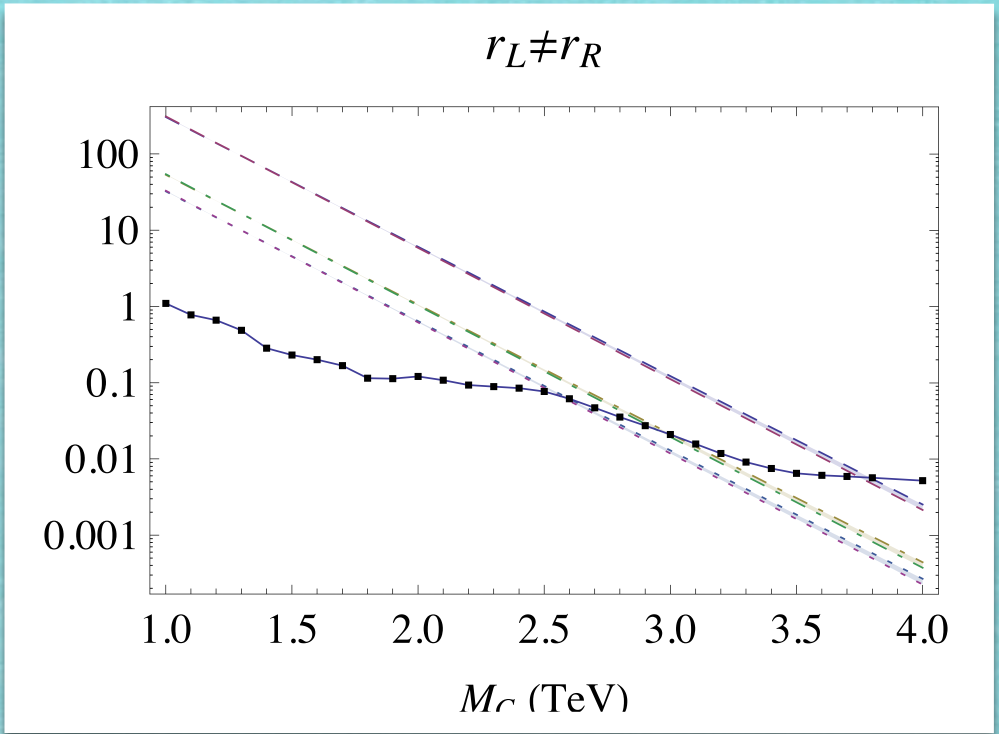


- K-factor: $\sigma_{NLO}/\sigma_{LO} \sim 30\%$
- 30% of produced colorons have p_T > 200 GeV!

RSC, Farzinnia, Foadi, EHS arXiv:1111.7261

Impact of NLO Corrections



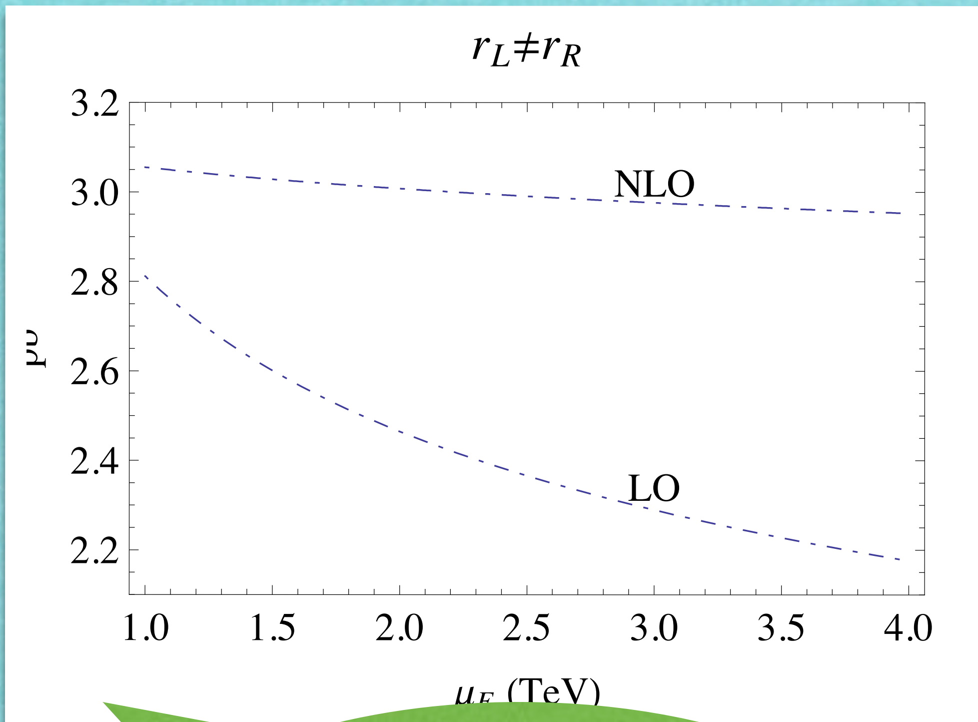


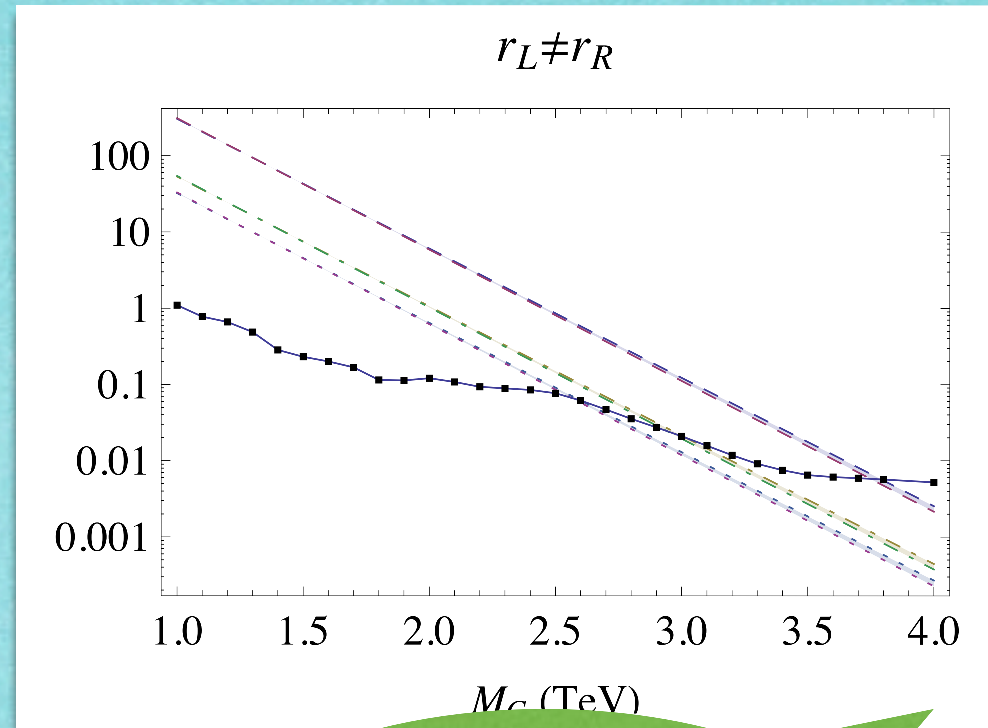
scale dependence
at LO: 30%
at NLO: 2%

- K-factor: $\sigma_{NLO}/\sigma_{LO} \sim 30\%$
- 30% of produced colorons have p_T > 200 GeV!

RSC, Farzinnia, Foadi, EHS arXiv:1111.7261

Impact of NLO Corrections





scale dependence
at LO: 30%
at NLO: 2%

Axigluon mass
limit from CMS Data
rises to 2.6 TeV

- K-factor: $\sigma_{NLO}/\sigma_{LO} \sim 30\%$
- 30% of produced colorons have p_T > 200 GeV!

RSC, Farzinnia, Foadi, EHS arXiv:1111.7261

LHC vs. Top-Higgs

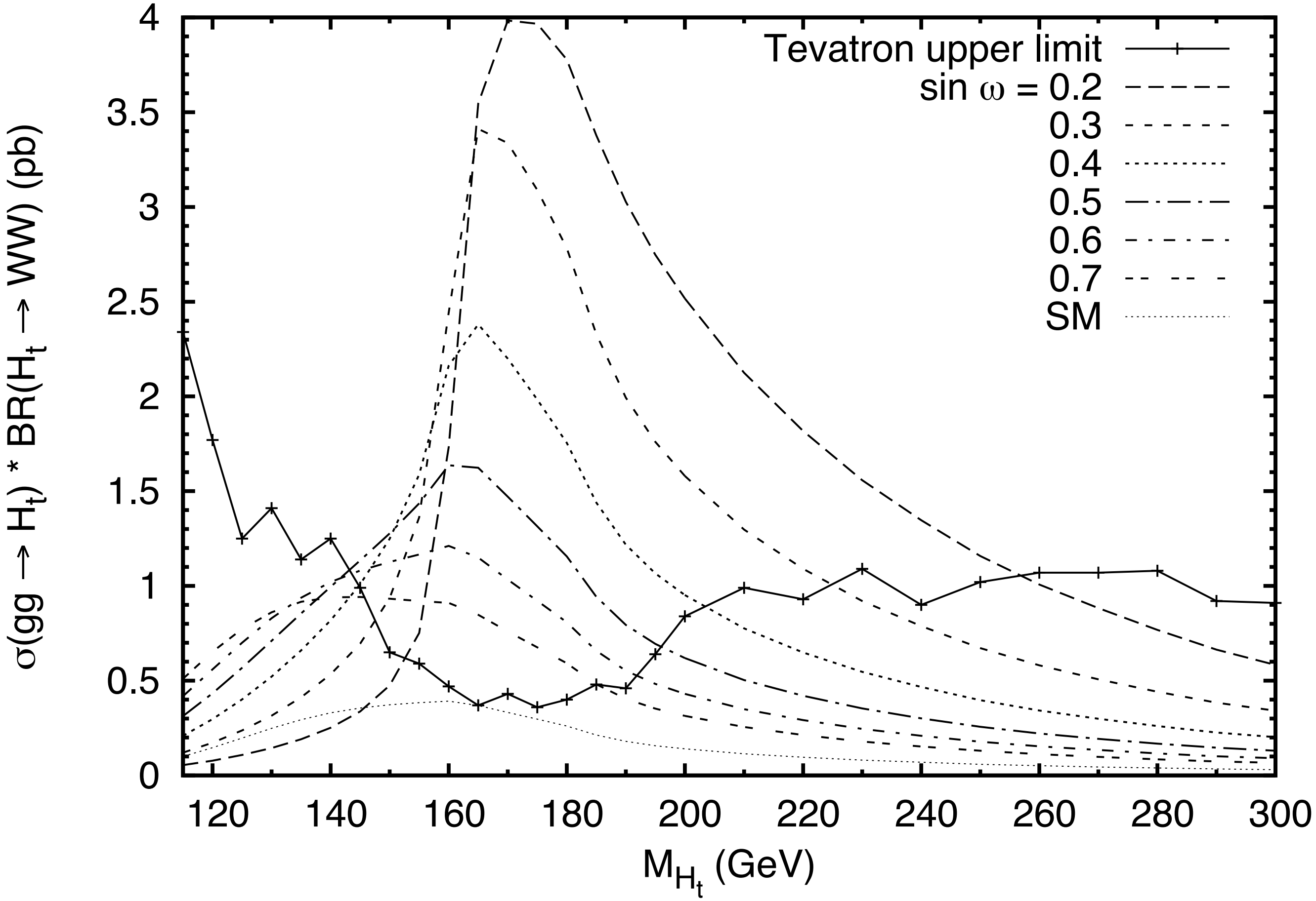
Chivukula, Coleppa, Logan, Martin, Simmons
arXiv:1108.4000 [hep-ph]

Chivukula, Coleppa, Ittisamai, Logan, Martin,
Ren, Simmons [in preparation]

Top sector at FNAL: H_T

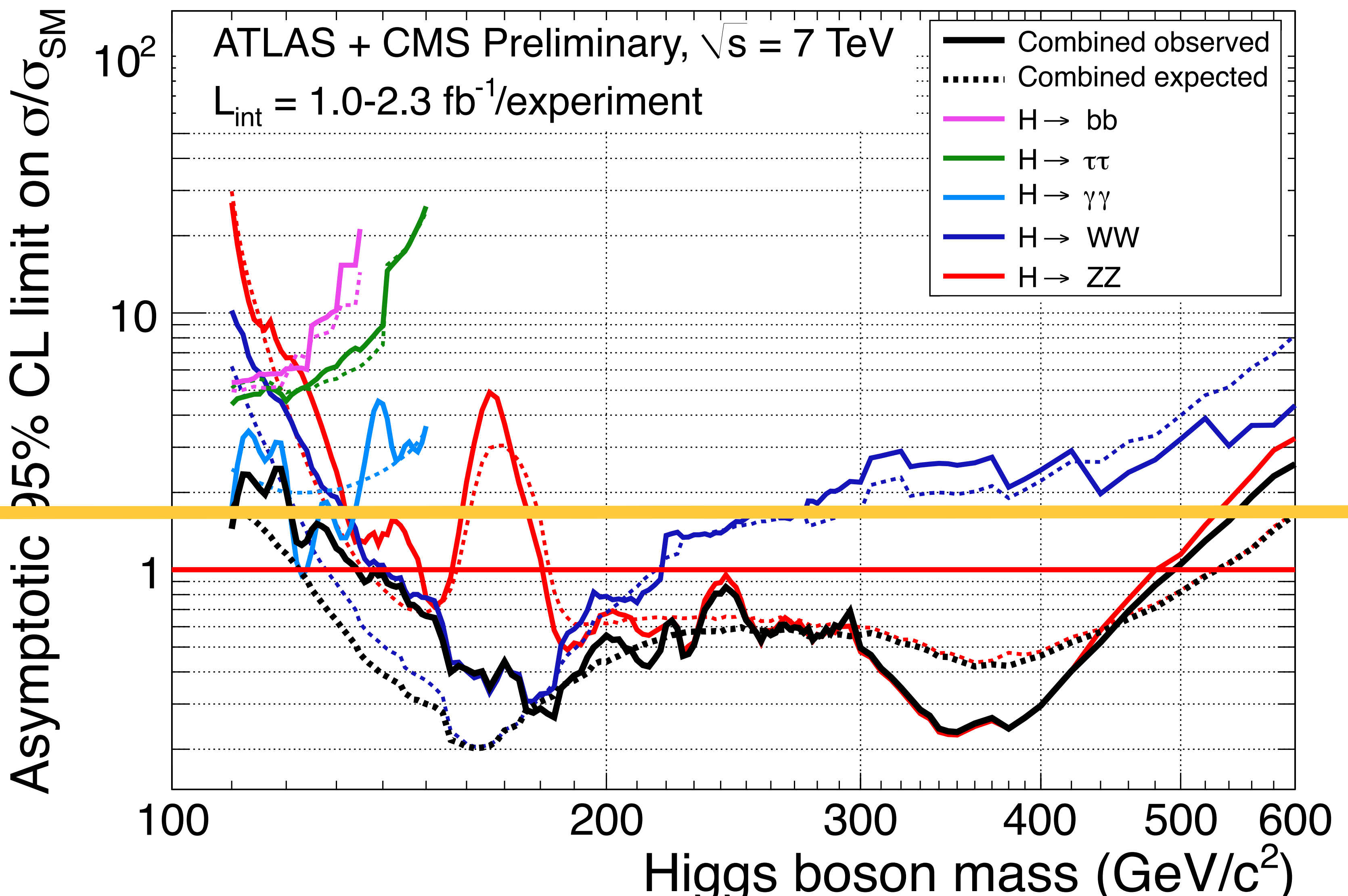
A top-Higgs of moderate mass would be visible in WW/ZZ due to enhancement of $gg \to H_t$ production by $[\sin\omega]^{-1}$.

E.g., see enhanced production relative to Tevatron* limit:



*T. Aaltonen et al. [CDF and D0 Collaborations], arXiv:1005.3216

LHC limits on Higgs Production



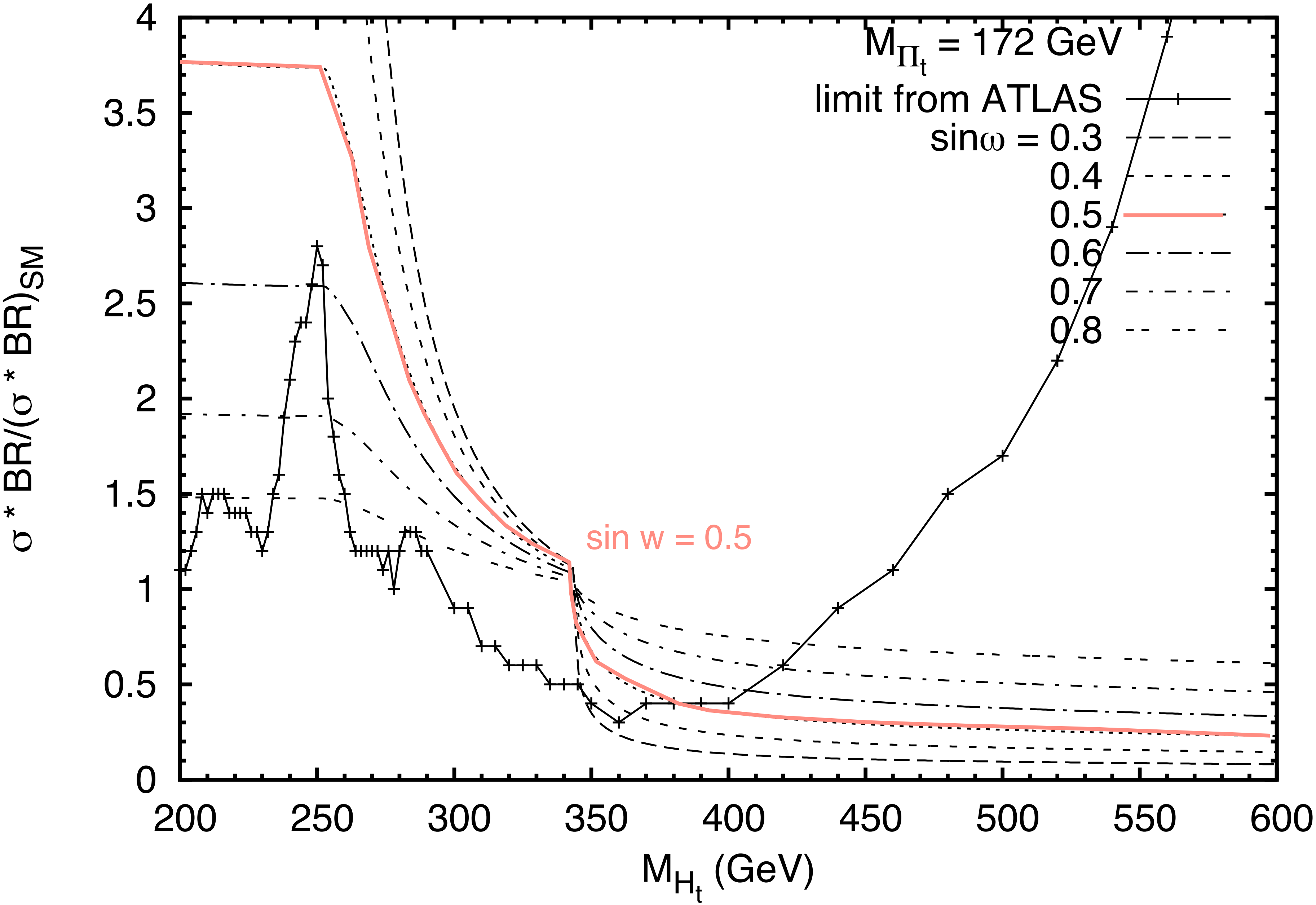
sinω < 0.7

sinω > 0.7

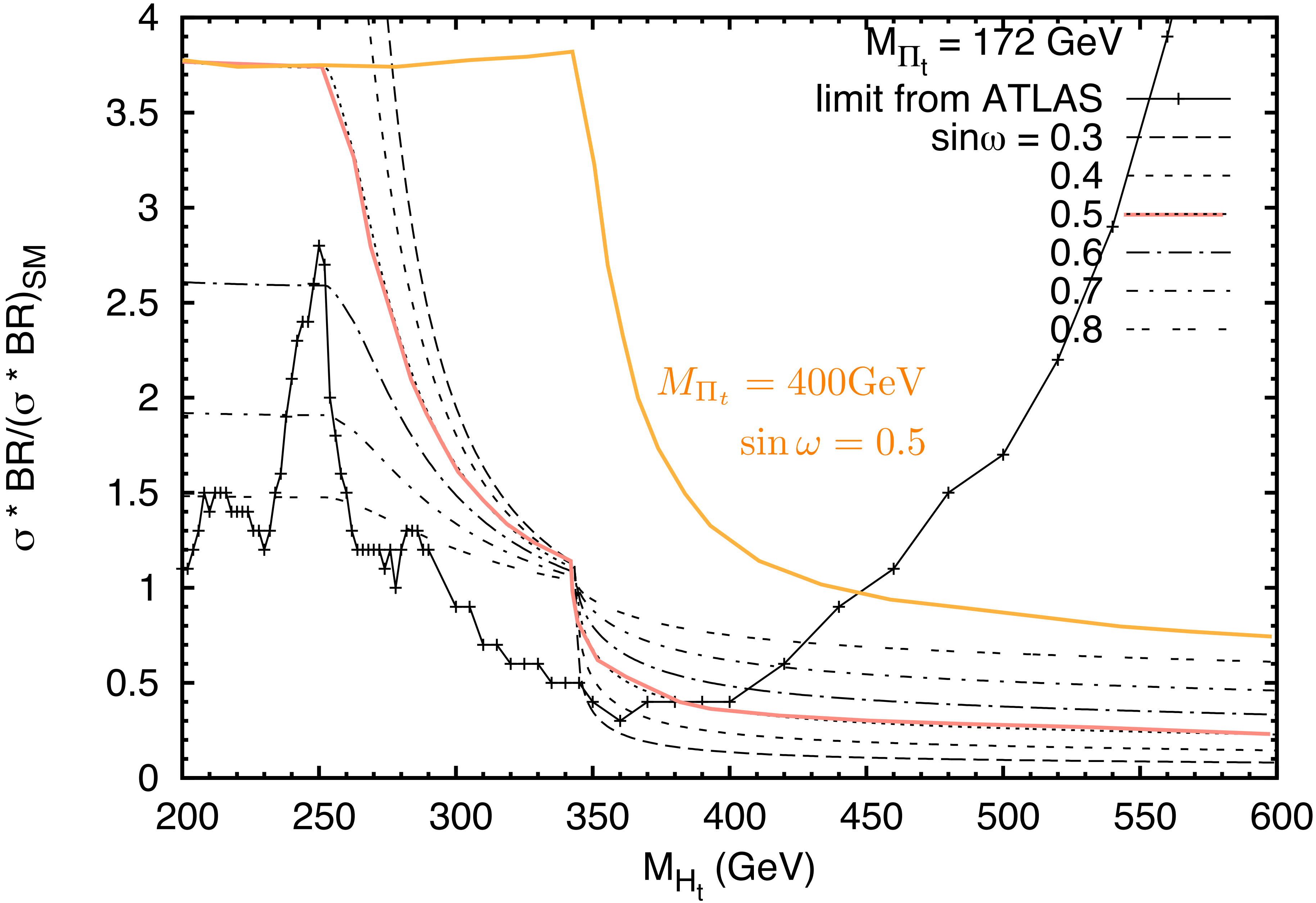
Non-standard H_t are tightly constrained

CMS PAS HIG-11-011

ATLAS vs H_T (if top-pion is light)



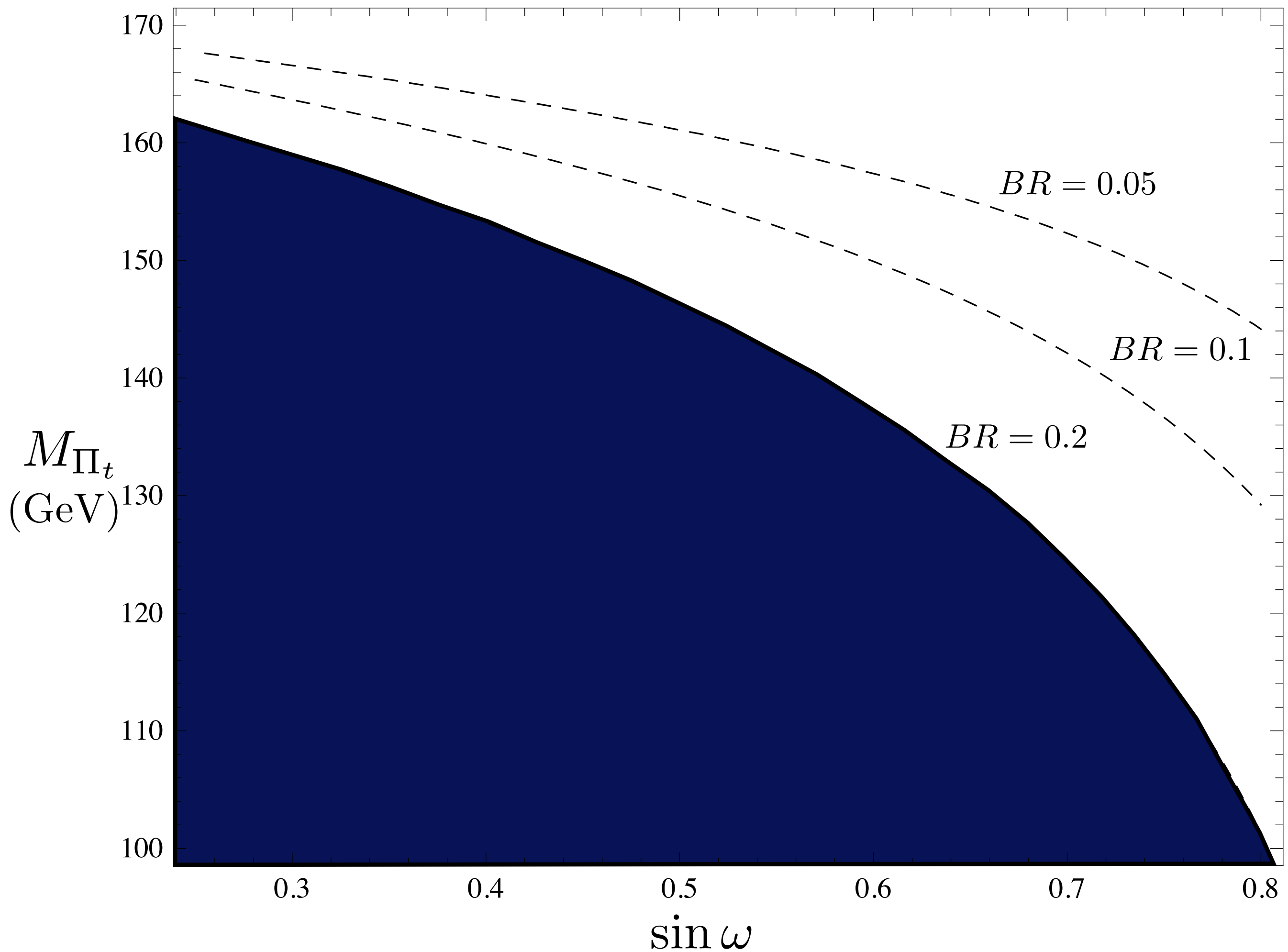
ATLAS vs H_T (if top-pion is heavier)



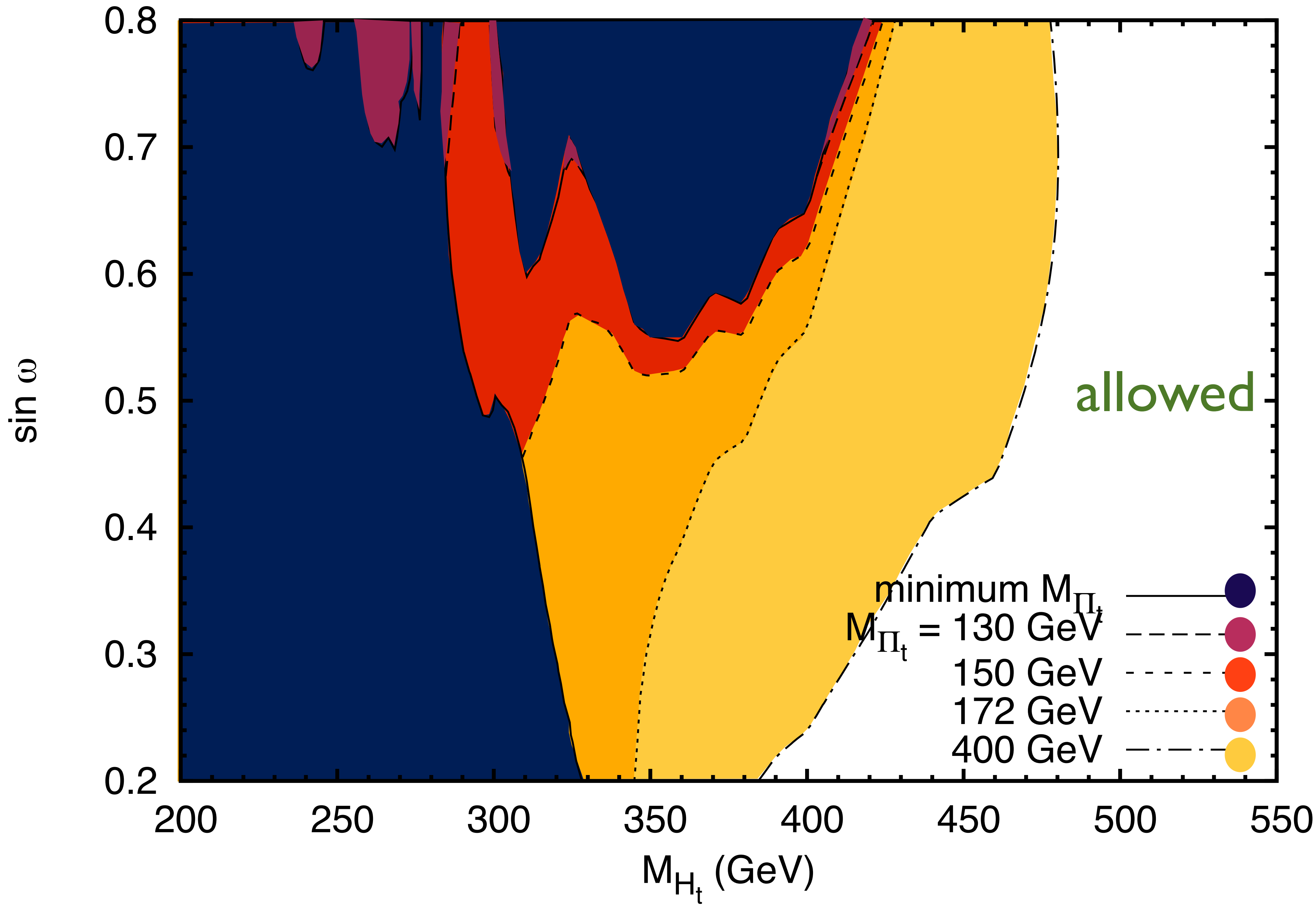
Bounds on Top-Pion Mass

Tevatron bounds on top decays to charged Higgs bosons imply that $BR(t \to \Pi_t^+ b) \leq 0.2$ and exclude the dark-blue region below:

top-pion mass (GeV)



LHC Limits on Top-Higgs (H_T)

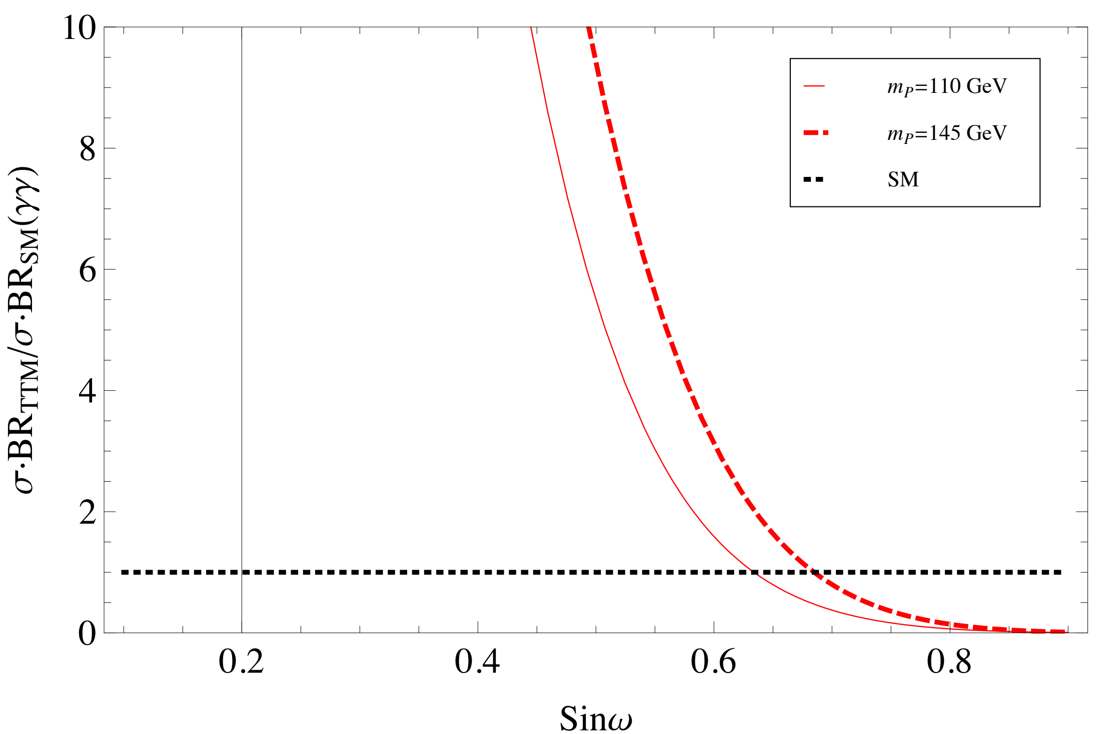


New Limits From $\Pi_t^0 \to \gamma\gamma$

- As in RSC's talk, LHC searches for $H_{SM} \to \gamma\gamma$ set strict bounds on technipions containing colored technifermions

- Those searches also constrain Π_t^0 in the top triangle moose, mainly since Π_t^0 production is enhanced (relative to H_{SM}) by $\cot^2\omega$

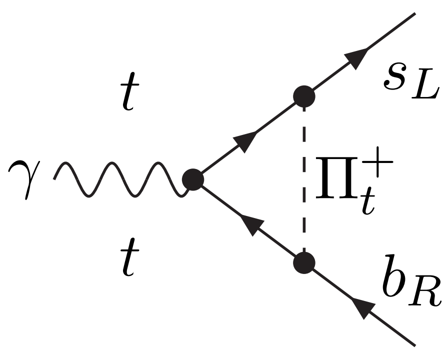
This excludes Π_t^0 for $M_{\Pi_t^0} < 150\ GeV$ if $0.2 \le \sin\omega \le 0.6$

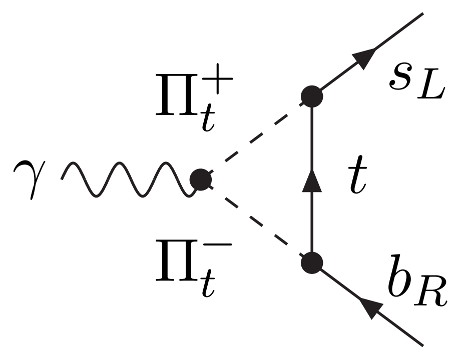


New Limits From $b \to s\gamma$

Charged top-pions would contribute to $b \to s\gamma$ like the charged Higgs state in a Type II 2HDM with couplings going as $(\beta \leftrightarrow \omega)$

$$[m_t V_{tb} \cot\omega\, \bar{t}_R b_L + m_t V_{ts} \cot\omega\, \bar{t}_R s_L + m_b V_{tb} \tan\omega\, \bar{t}_L b_R]\Pi_t^+ + h.c.$$





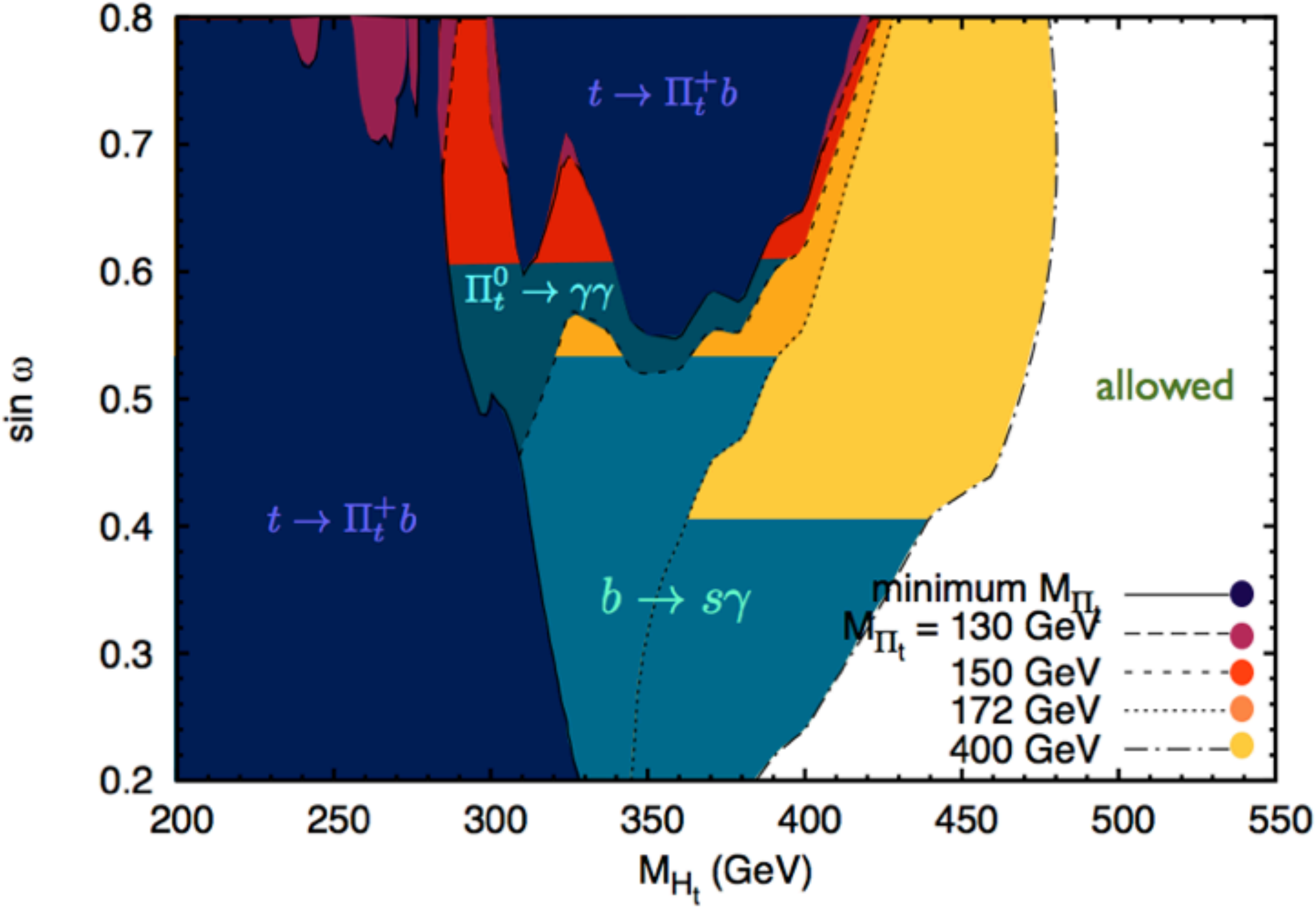
resulting lower bound on Π_t^+ mass

$\sin\omega$	0.26	0.30	0.34	0.40	0.46	0.53
$m_{\Pi_t^+}^{low}(GeV)$	551	500	440	396	363	332

$m_b m_t^2 \cot^2\omega$ dominates

$m_b m_t^2$ dominates

Updated H_T Limits



TC2 Dynamics

The limits above were derived in an effective field theory (top triangle moose) for TC2 and related models:

- A combination of topcolor dynamics and ETC give rise to the top quark mass: $m_t \approx m_t^{dyn} + m_t^{ETC}$ where the latter is only 0.5% - 10% of the total.
- The Pagels-Stokar relation $f_{\Pi_t}^2 = \frac{N_c}{8\pi^2} m_{t,dyn}^2 \ln\left(\frac{\Lambda^2}{m_{t,dyn}^2}\right)$ relates $\sin\omega \equiv f_{\Pi_t}/v$ to the top mass
- The top-pion mass $M_{\Pi_t}^2 = \frac{N_c}{4\pi^2} m_{t,ETC} m_{t,dyn} \left(\frac{\Lambda^2}{f_{\Pi_t}^2}\right)\gamma$ should exceed the top mass to respect bounds on $t \to bH^+$
- The dynamics imply $M_{H_t} \lesssim 2m_{t,dyn}$

LHC vs. TC2

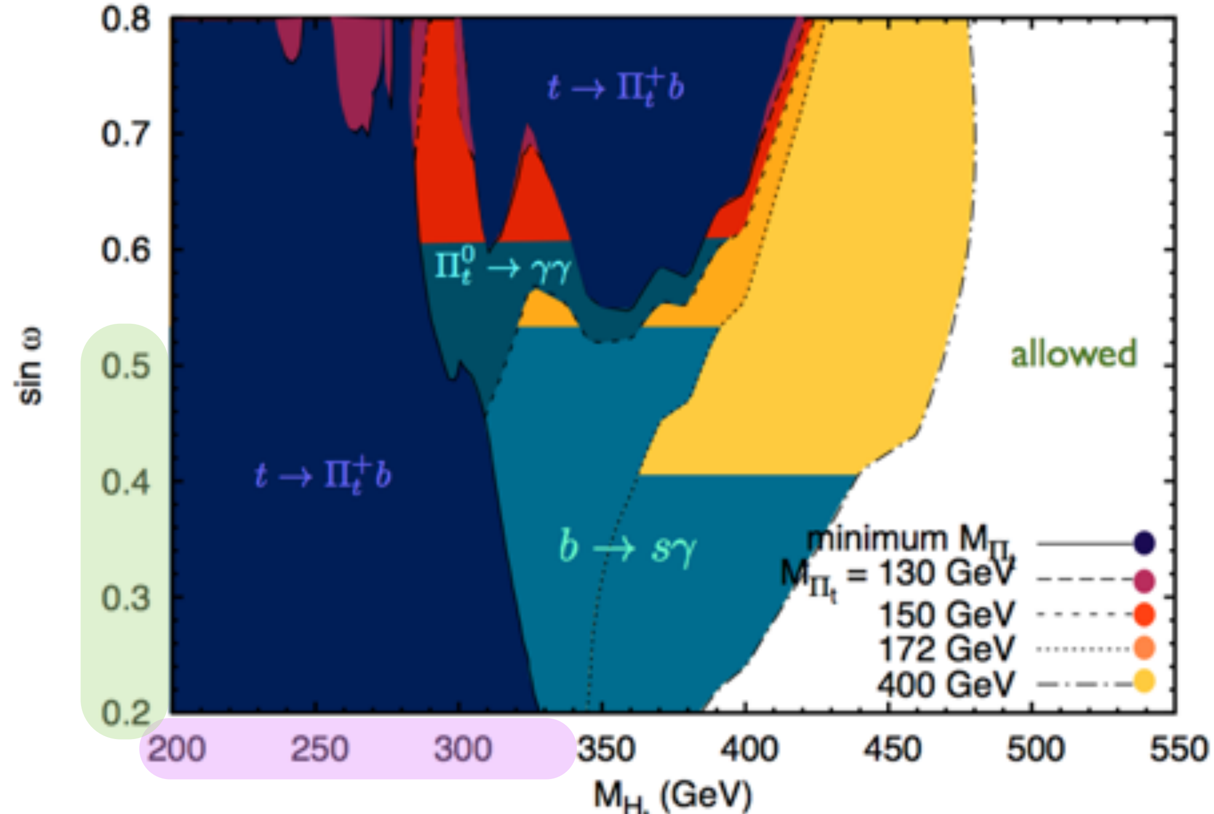
Within the larger effective theory, one would then expect the TC2 model parameters to lie in the following ranges:

$$185 \text{ GeV} < M_{H_t} < 340 \text{ GeV}$$

$$172 \text{ GeV} < M_{\Pi_t} < M_{H_t}$$

$$0.2 < \sin\omega < 0.5$$

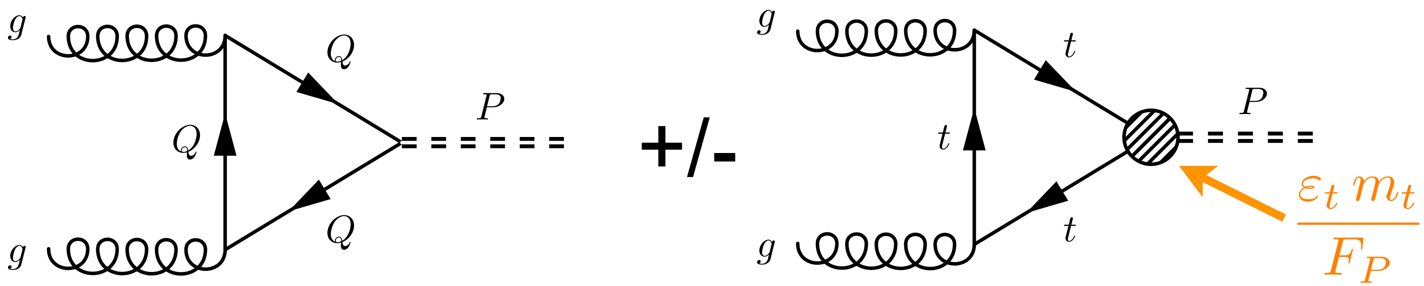
The data from FNAL, LHC, and $b \to s\gamma$ appears to exclude precisely this region.



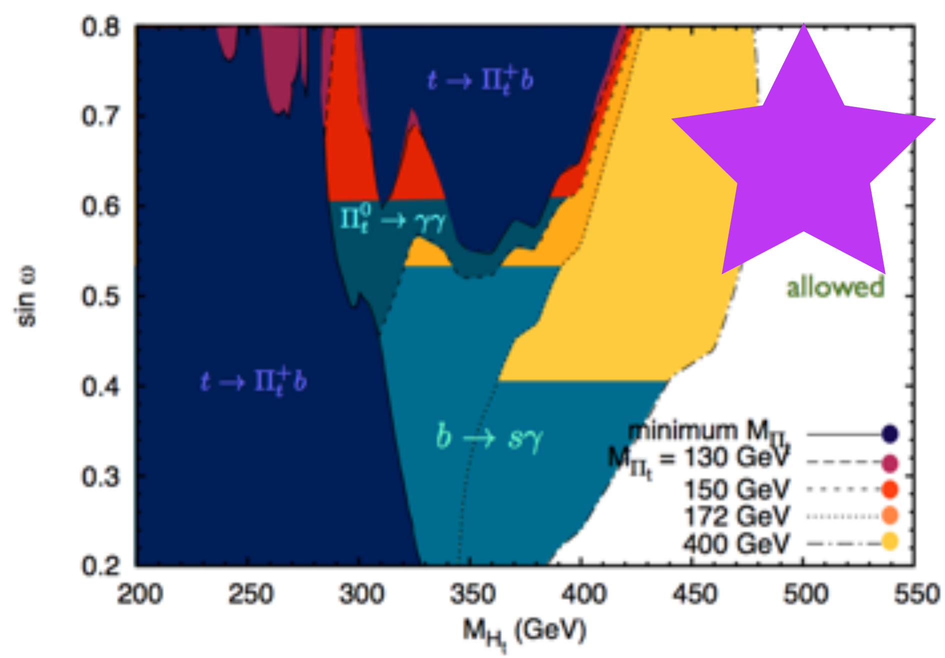
New DEWSB Model Directions

What kinds of models can evade the LHC constraints on neutral states in TC2 Models (colorons, technipions, top-Higgs)?

- Technicolor with substantial ETC contribution to m_t ?



- Top-Seesaw Assisted Technicolor?
- Stay Tuned!



Conclusions

Conclusions and Next Steps

- Avoiding large weak isospin violation is a challenge for dynamical EWSB. Models with new top-quark dynamics (topcolor, top seesaw) offer solutions; the top triangle moose is an effective theory interpolating among them

- LHC can search for **colorons**, incorporating recent one-loop results for the K-factor and p_T distribution.

- New states in the top sector includes **T, H_t and Π_t** states; all should be visible at LHC. Interplay among these states would signal that top dynamics plays a role in EWSB.

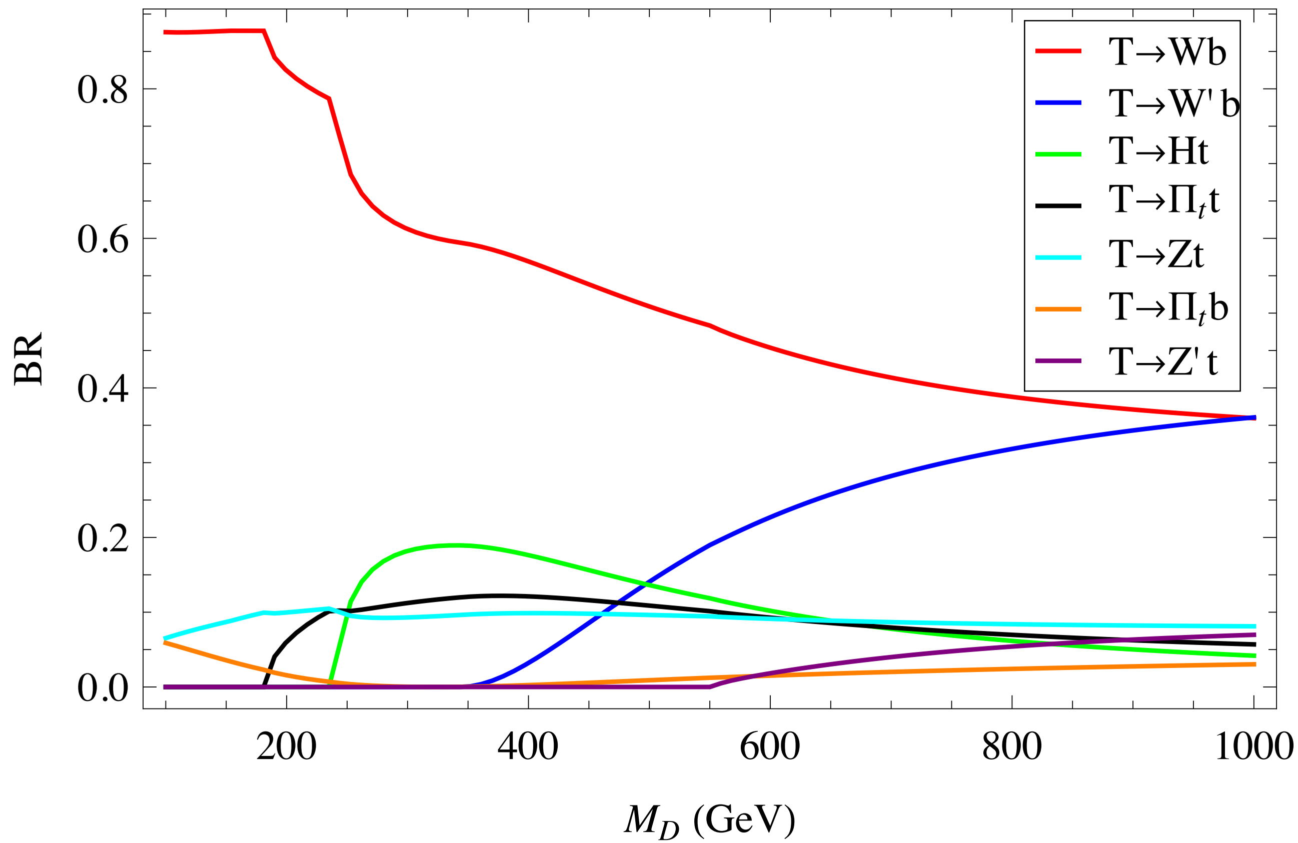
- Recent LHC data on $H \to WW, ZZ, \gamma\gamma$ combined with data on $b \to s\gamma$ exclude the most favored TC2 parameter space. New models with heavier H_t (e.g. top-seesaw-assisted TC) are required.

Top sector at LHC: T

Top's KK partner, T, will be most visible in $T \rightarrow Wb$.

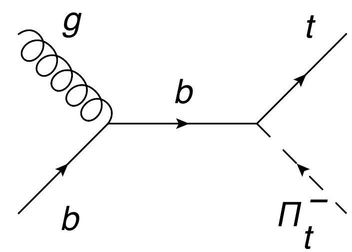
Analysis for other KK quark partners (assuming $W \rightarrow l\nu$) still roughly applies; the channel with one hadronically-decaying W should offer larger signal and full reconstruction of T.

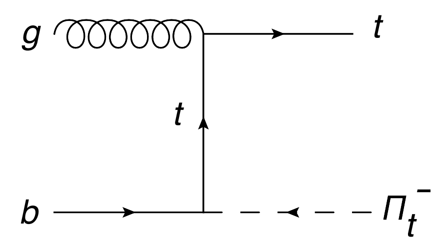
The $T \rightarrow H_t\, t$ decays will also be helpful.



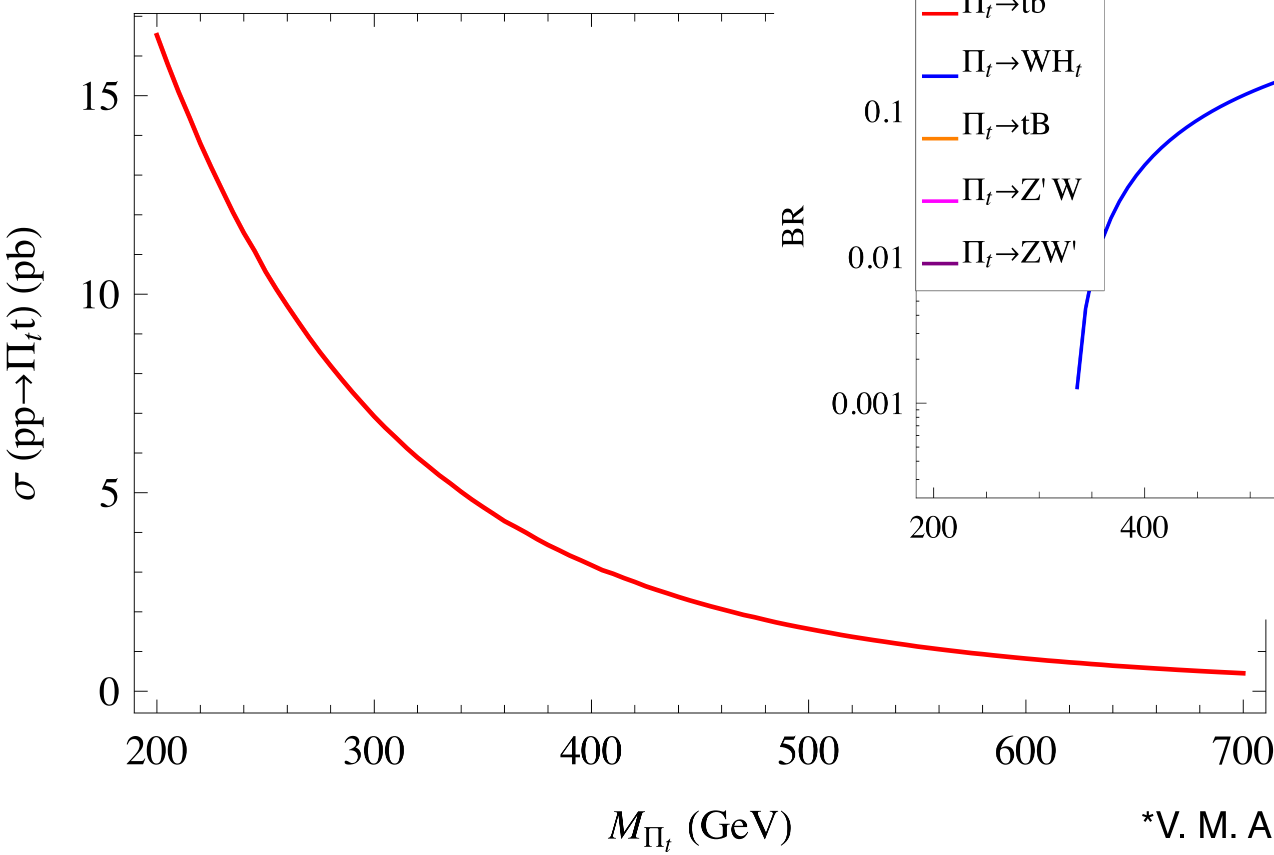
Top sector at LHC: Π_T

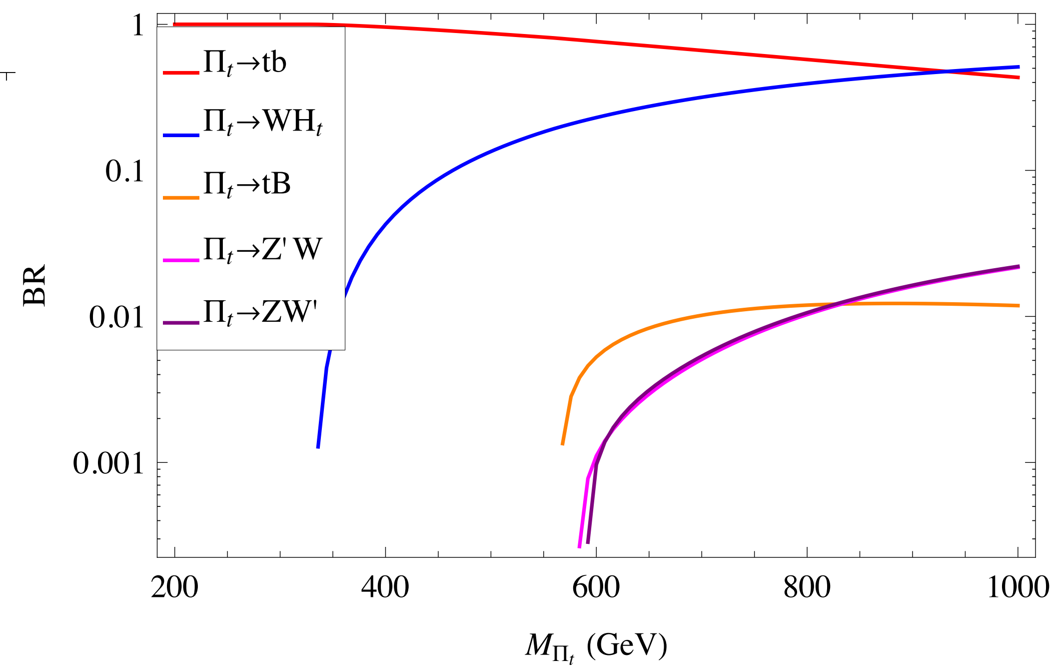
FNAL limits* on $t \rightarrow H^{\pm} b$ imply Π_t is heavier than t, so the main production process is $pp \rightarrow t\,\Pi_t \rightarrow t\,t\,b$.





CMS studies** of $H^{\pm} \rightarrow t\,b$ imply 30 fb^{-1} of data can find a Π_t up to 400 GeV





Note: Π_t can also decay to $W\,H_t$.

*V. M. Abazov et al. [D0 Collaboration], arXiv:0908.1811

**Lowette, D'Hondt, Vanlaer CERN-CMS-NOTE-2006-109

Top sector at LHC: Π_T

Associated production pp → W* → H_t Π_t can provide useful confirmation of the relationship between H_t and Π_t.

Single production followed by either $H_t \rightarrow W\Pi_t$ or $\Pi_t \rightarrow WH_t$ would be similarly informative.