Topcolor in the LHC Era

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- Top Mass and TopColor
- Effective Field Theory
- New Fermions, Top-Higgs, & Top-Pions
- What LHC Can See... and Has (Not) Seen
- Conclusions

KMIIN (Nagoya) 10 - 26 - 2011

Top Mass and TopColor

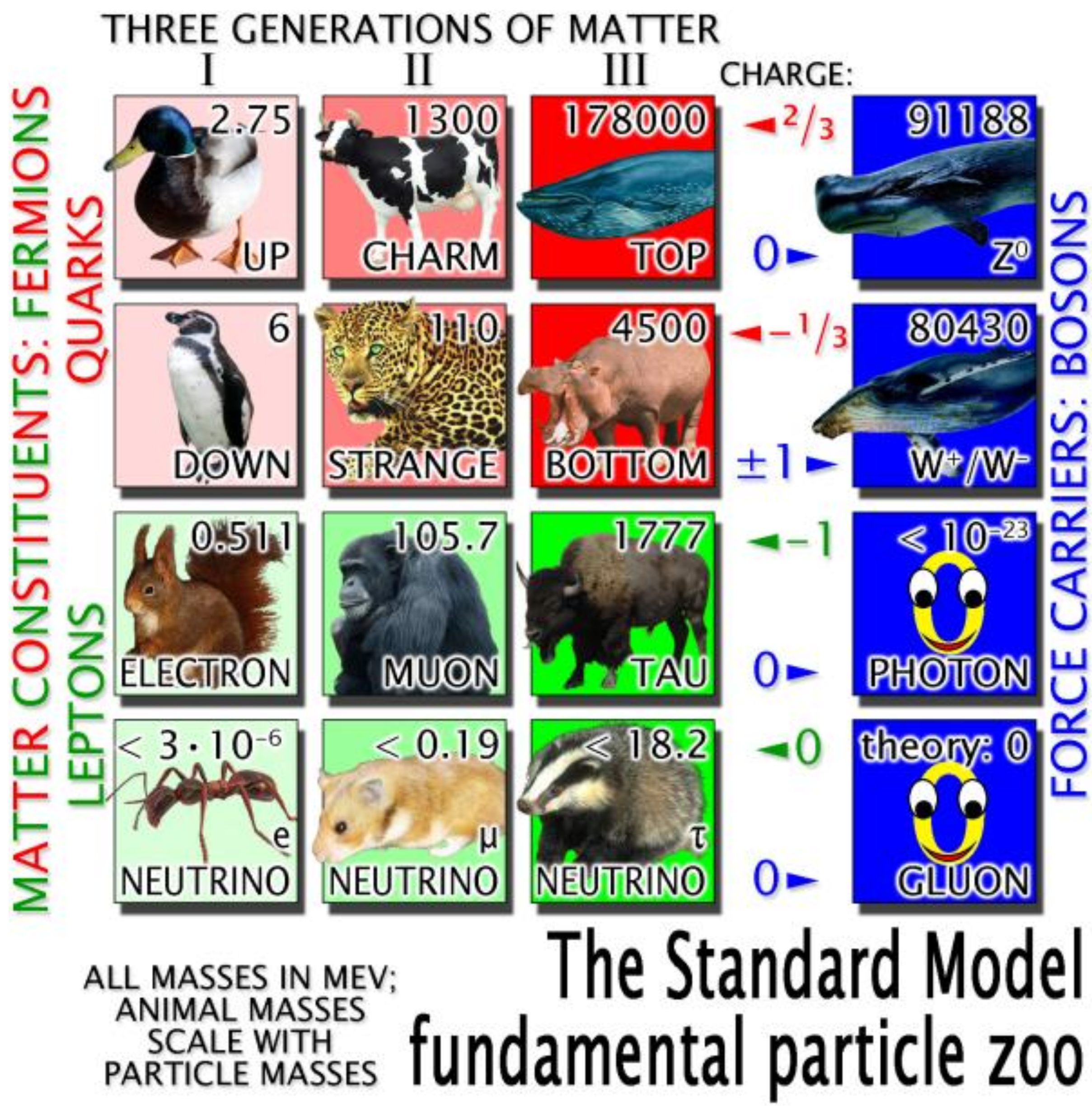
Questions about Broken Symmetries

Electroweak:

Why are the W & Z bosons heavy while the photon is massless?

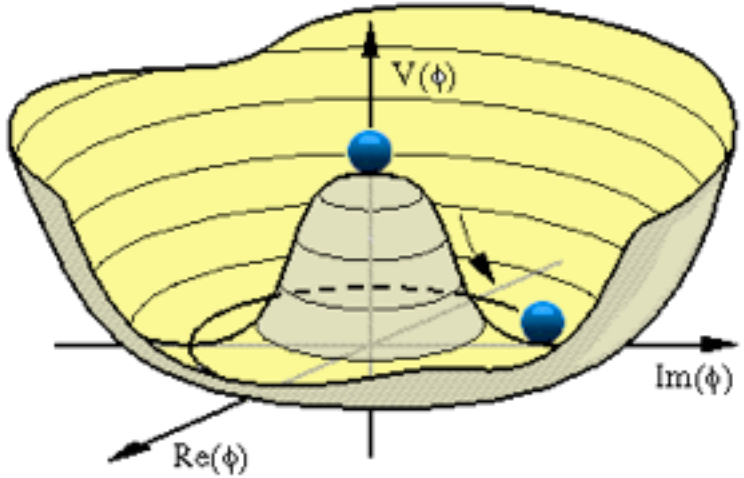
Flavor:

Why do fermions with the same charge have different masses?

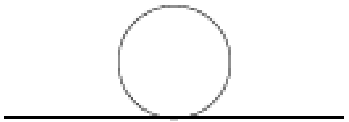
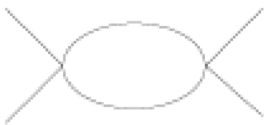


e4.physik.uni-dortmund.de/bin/view/ATLAS/Bildergalerie

Trial Answer: SM with a Higgs Doublet



Problems with the Higgs Model

- No fundamental scalars observed in nature
- No explanation of dynamics causing EWSB
- Hierarchy/Naturalness Problem  $\Rightarrow \quad m_H^2 \propto \Lambda^2$
- Triviality Problem...  $\Rightarrow \beta = \dfrac{3\lambda^2}{2\pi^2} > 0$

Revised Answer for EWSB:

Technicolor: (as in previous talk)

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

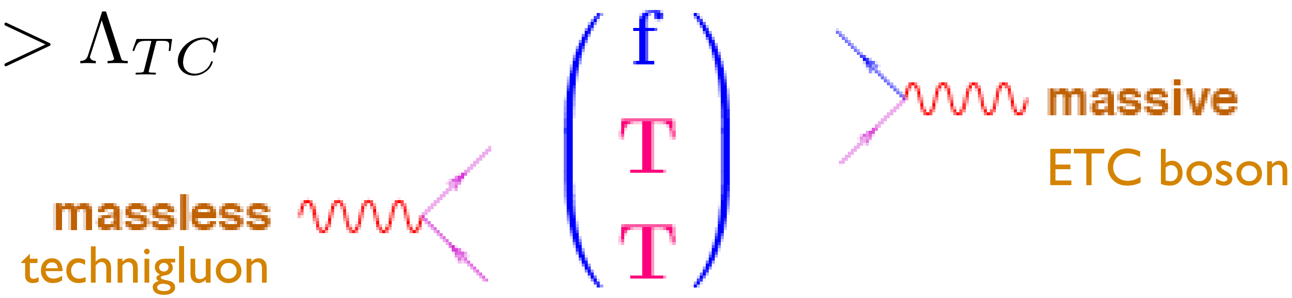
$SU(N)_{TC}$ gauge coupling becomes large at $\Lambda_{TC} \approx 1\mathrm{TeV}$

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

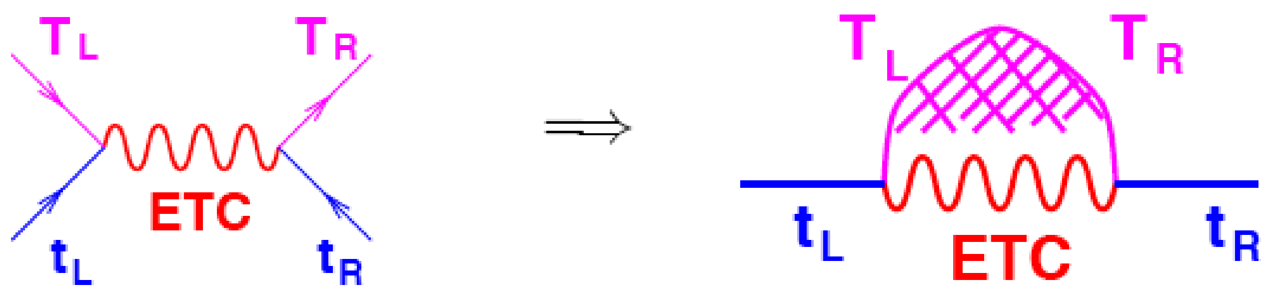
Susskind, Weinberg

Revised Answer For Fermion Masses: ETC*

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



E.g. the top quark mass arises from:



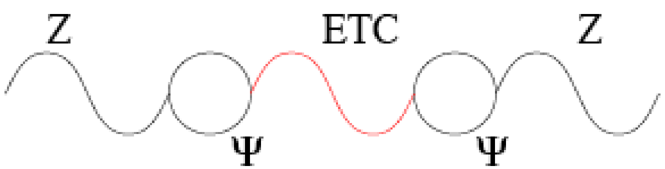
and its size is $\left(\frac{g_{ETC}}{M_{ETC}}\right)^2 \langle \bar{T}T \rangle$ x (flavor-dependent factor)

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

Size of Isospin Violation

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 $\Delta\rho$



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

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

- make ETC boson heavy ?

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

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

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

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

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

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

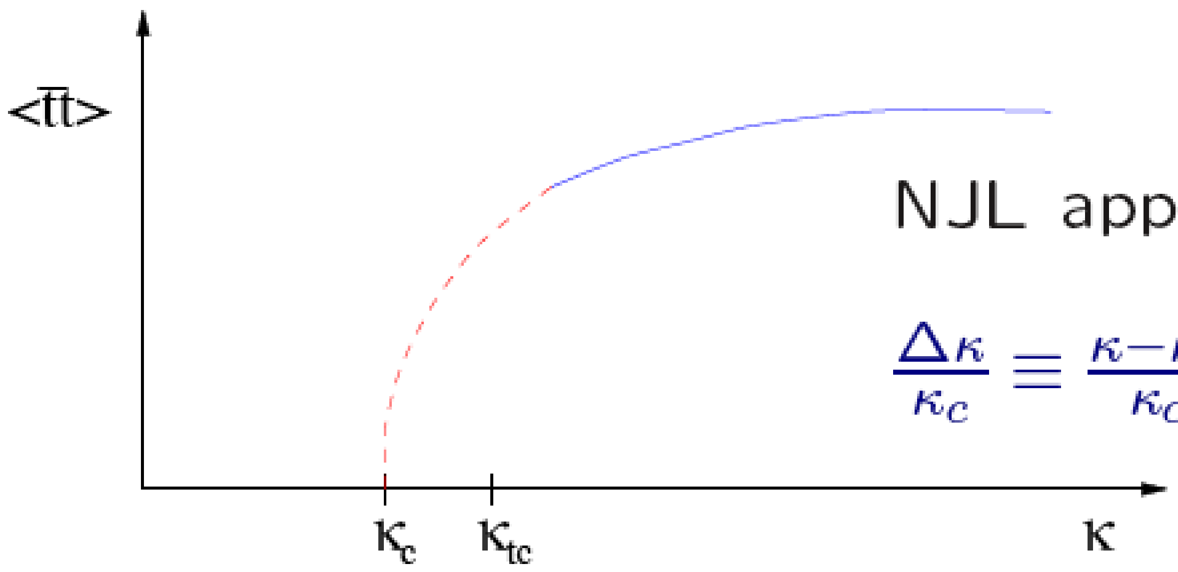
One physical realization of a new interaction for top is a (spontaneously broken) extended color gauge group: topcolor

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

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

$$-\frac{4\pi\kappa}{M^2}\left(\bar{t}\gamma_\mu\frac{\lambda^a}{2}t\right)^2$$



NJL approximation

$$\frac{\Delta\kappa}{\kappa_c} \equiv \frac{\kappa-\kappa_c}{\kappa_c} \propto \frac{\langle \bar{t}t\rangle}{M^3}$$

Note:
M >> 1 TeV
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

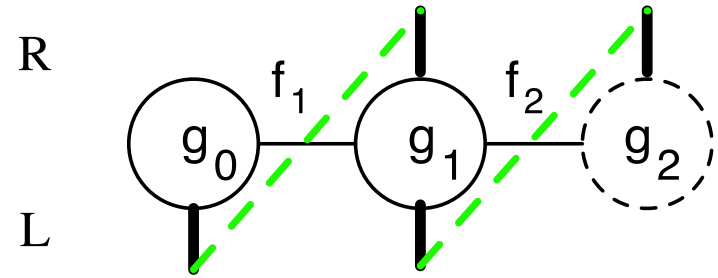
hypercharge: keeps m_b small

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

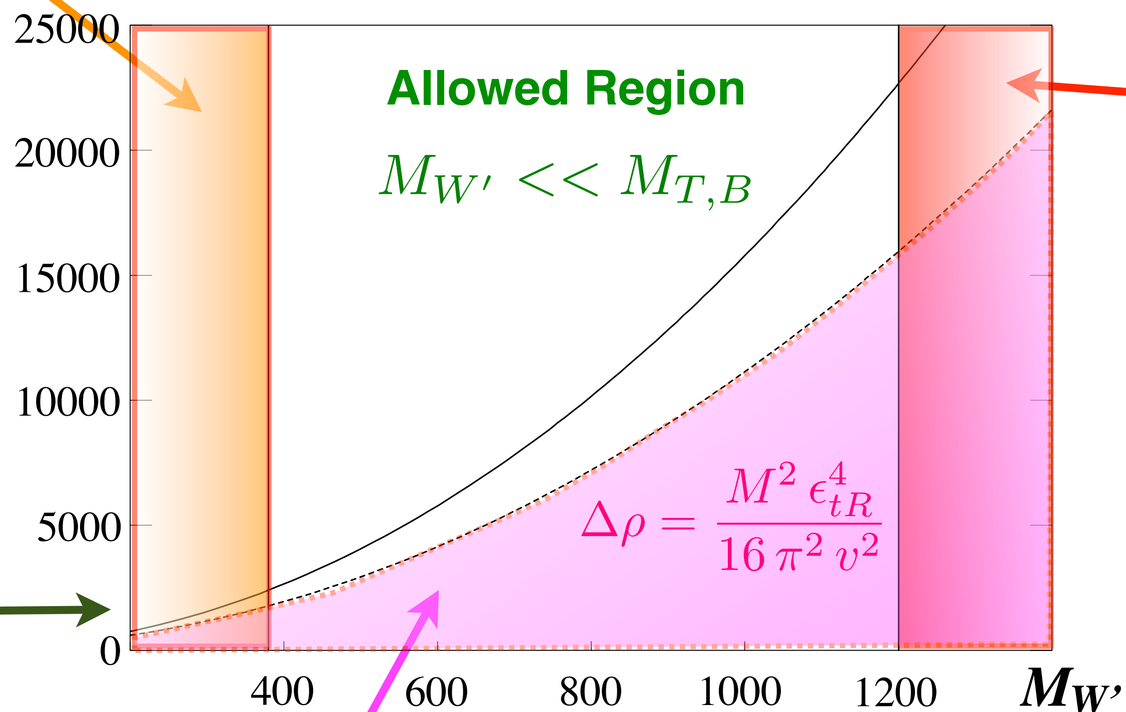
Reminder: 3-Site Model



WWZ vertex visibly altered

M_{TB}

KK fermion mass (GeV)



W' mass (GeV)

Unitarity violated

Minimum allowed fermion mass

1-loop fermionic EW precision corrections too large

The Top Triangle Moose

Gauge structure:

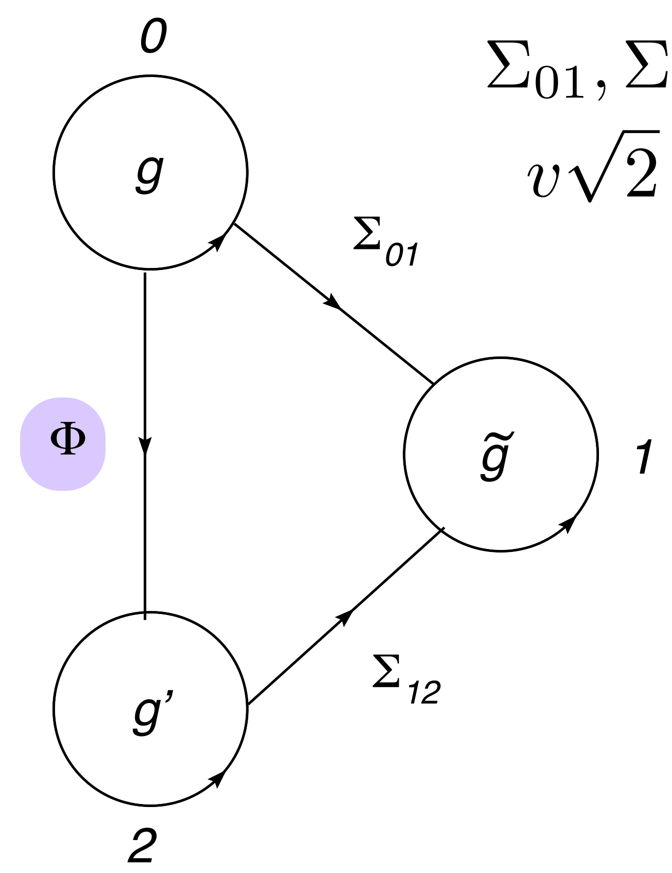
$$SU(2) \times SU(2) \times U(1)$$

$$g_0,\ g_2 \ll g_1$$

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}

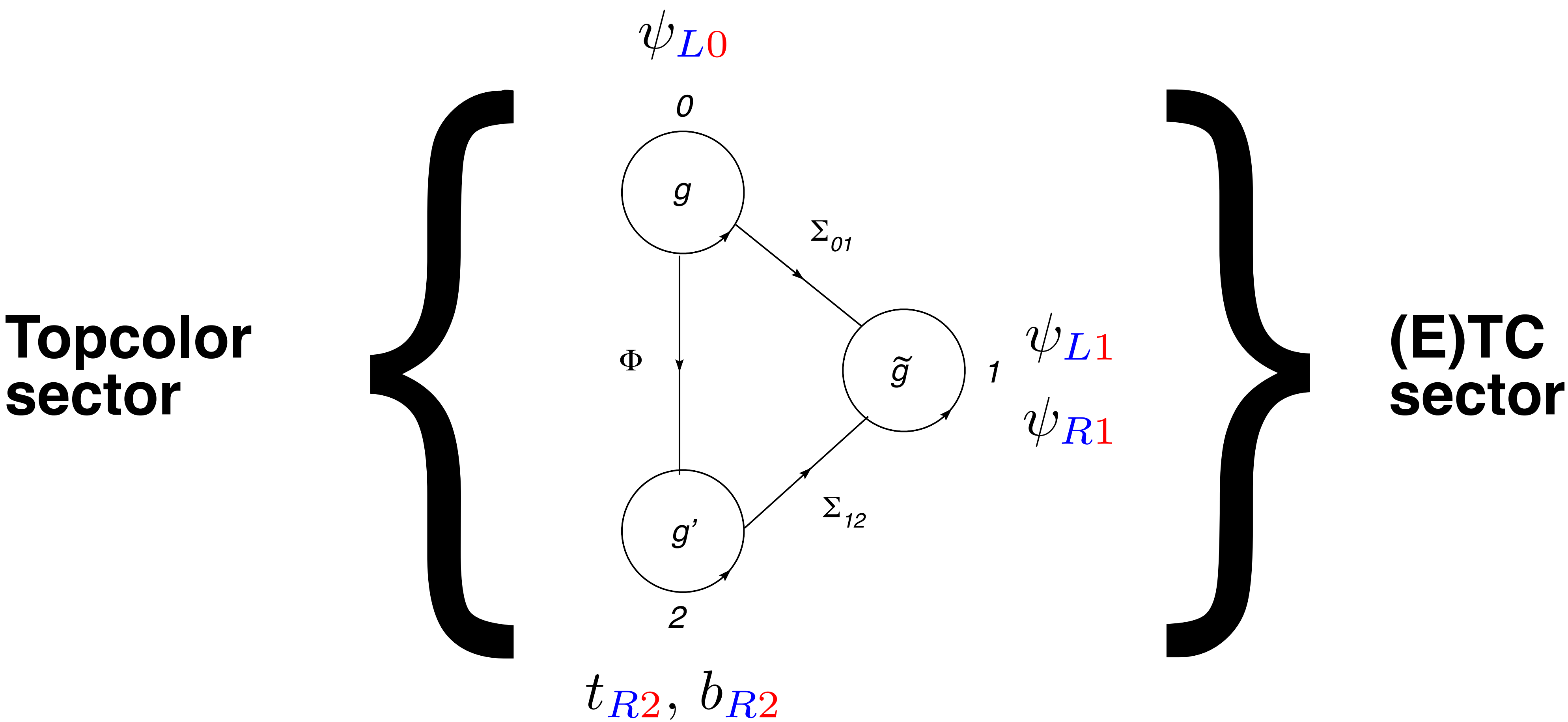
ψ_{R1}

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

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

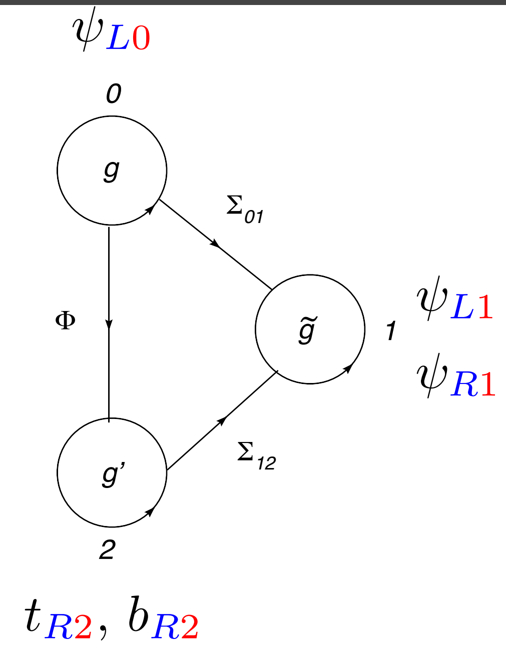
Triangle Moose and Topcolor-Assisted TC



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

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

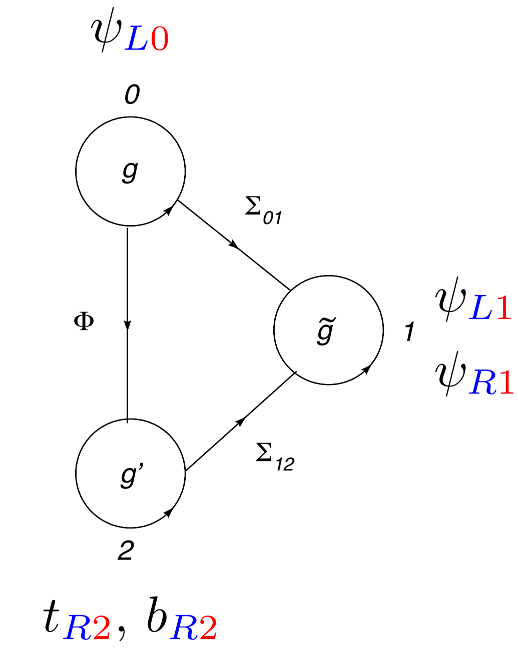
each light mass value is tied to the value of ϵ_{fR}

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

Top States of Interest

top's KK partner: T

- can be produced at LHC

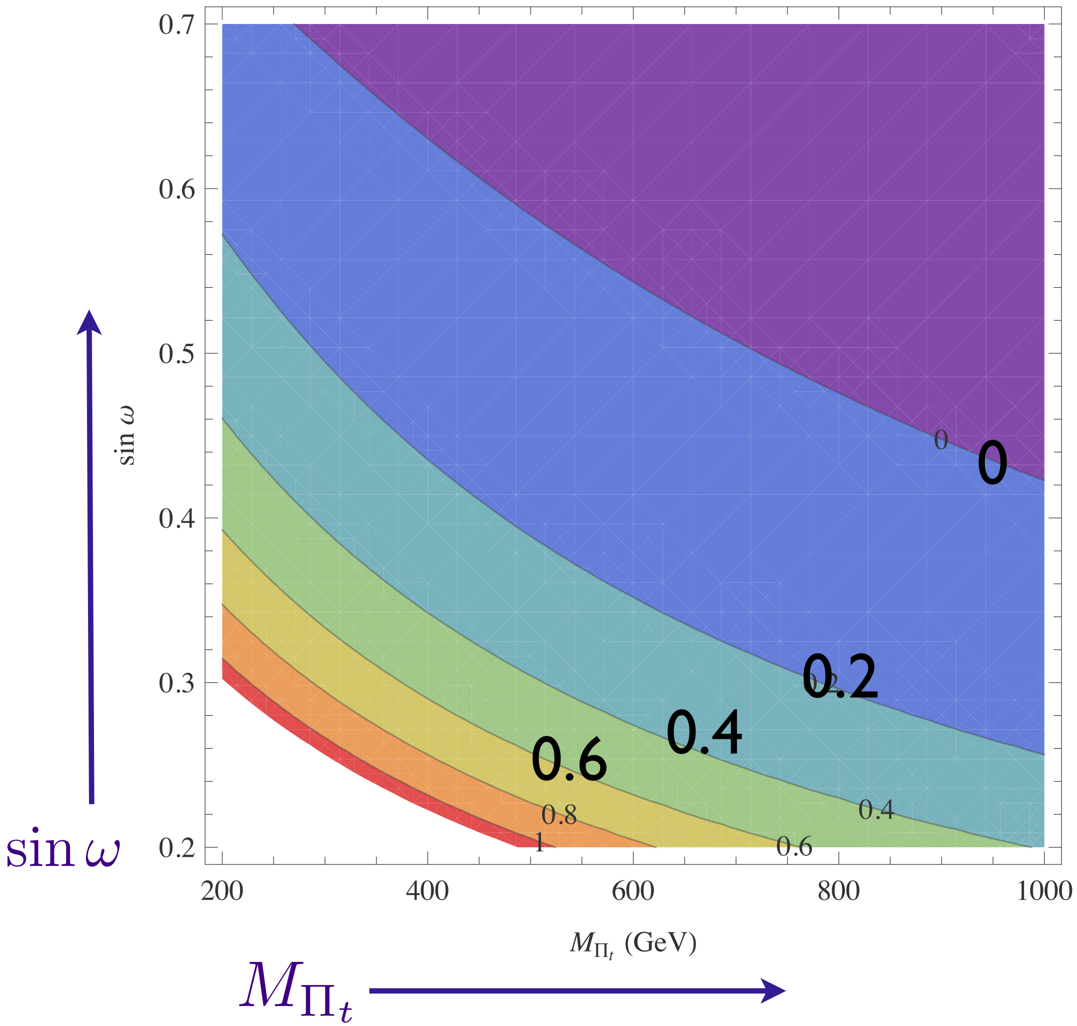
top-Higgs state: H_t

- production in gg → 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 non-ideal delocalization of t_L as indicated in plot at right:

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



What the LHC Can See

W' searches:

Belyaev, et al., arXiv:0708.2588 [hep-ph]

KK quarks:

Chivukula, Christensen, Coleppa, Simmons
arXiv:0906.5667 [hep-ph]

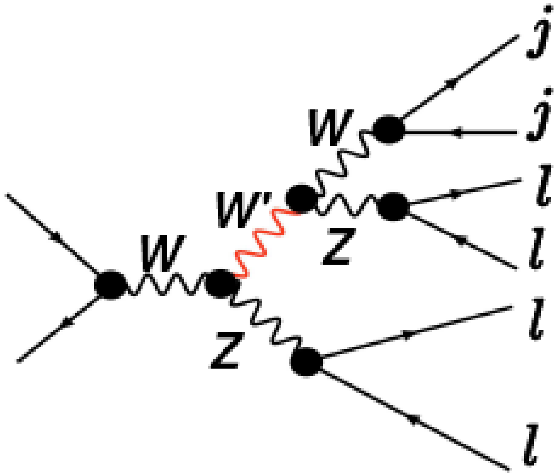
KK top quark, top-Higgs, and top-Pions

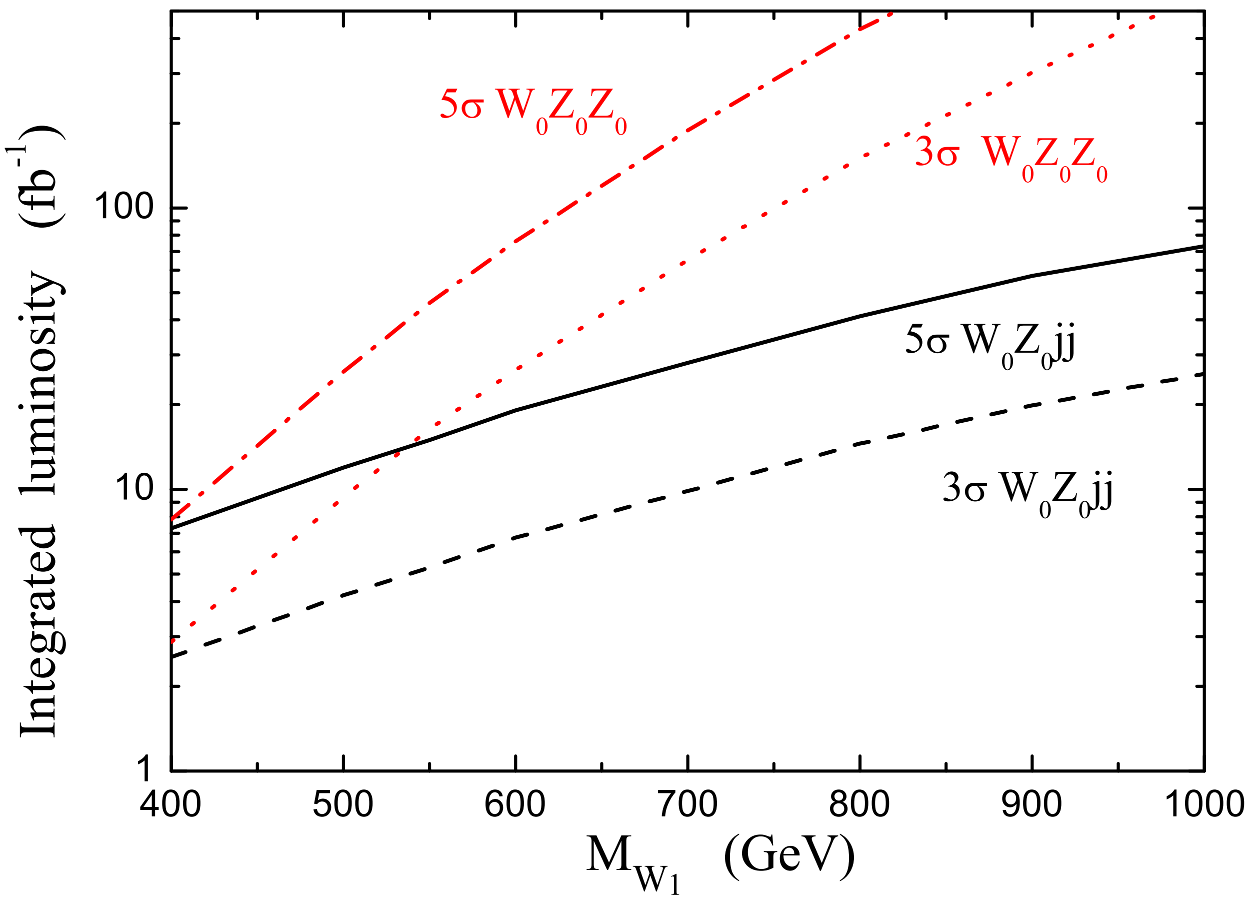
Chivukula, Coleppa, Logan, Martin, Simmons
arXiv:1101.6023 [hep-ph]

LHC Potential for Finding the W'

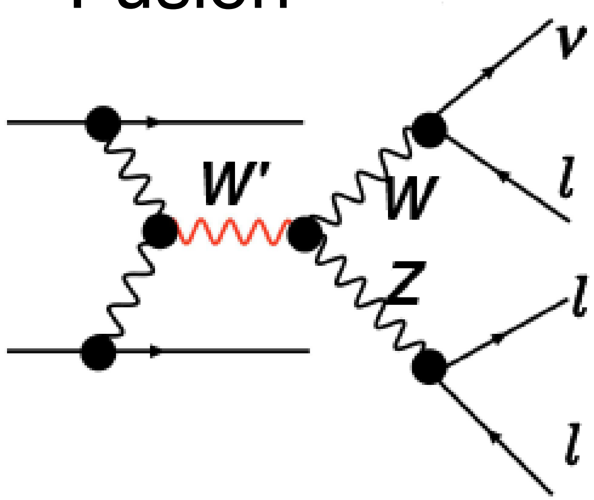
Integrated luminosity needed for 14 TeV LHC discovery of W'

Associated Production



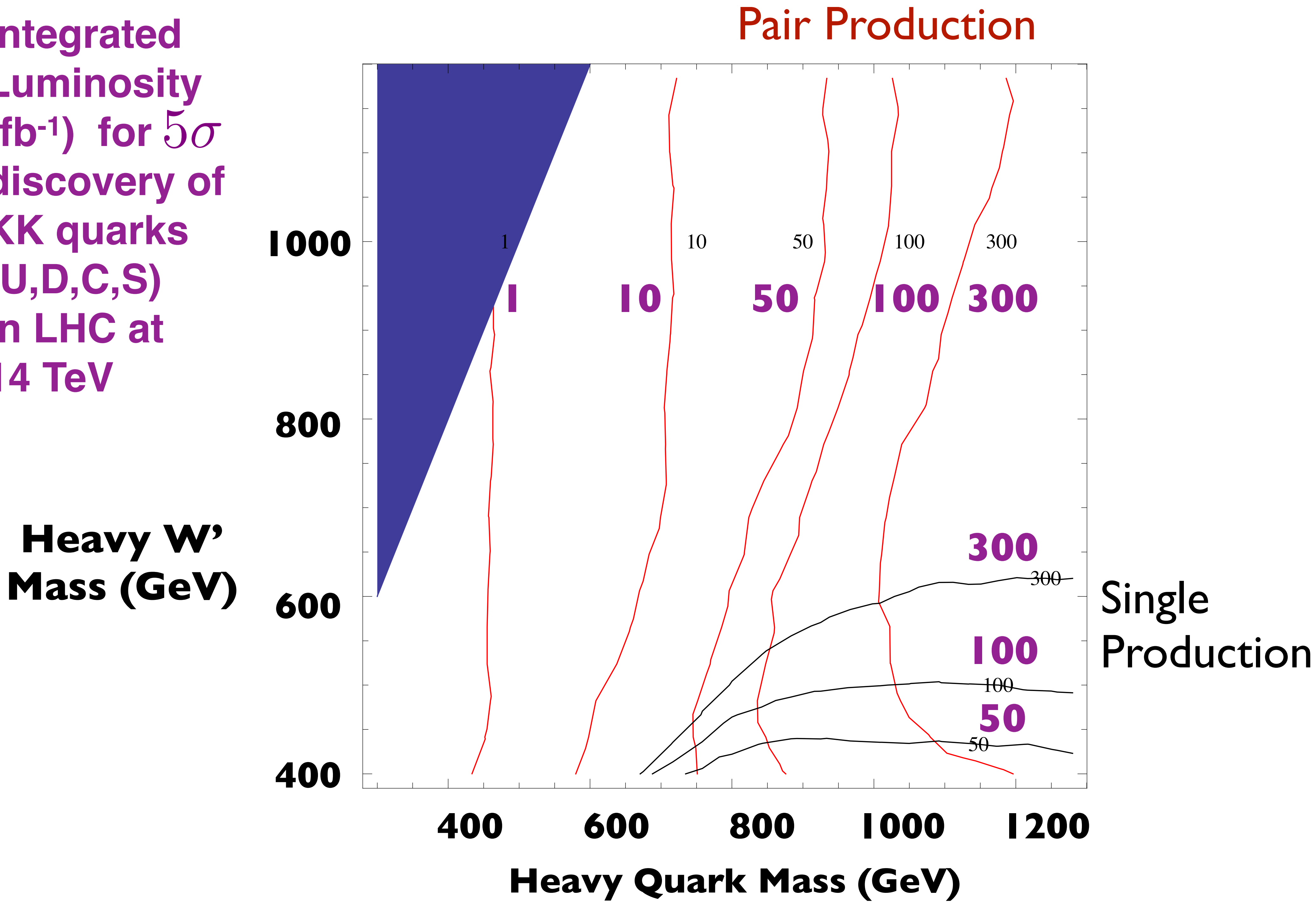


Vector Boson Fusion



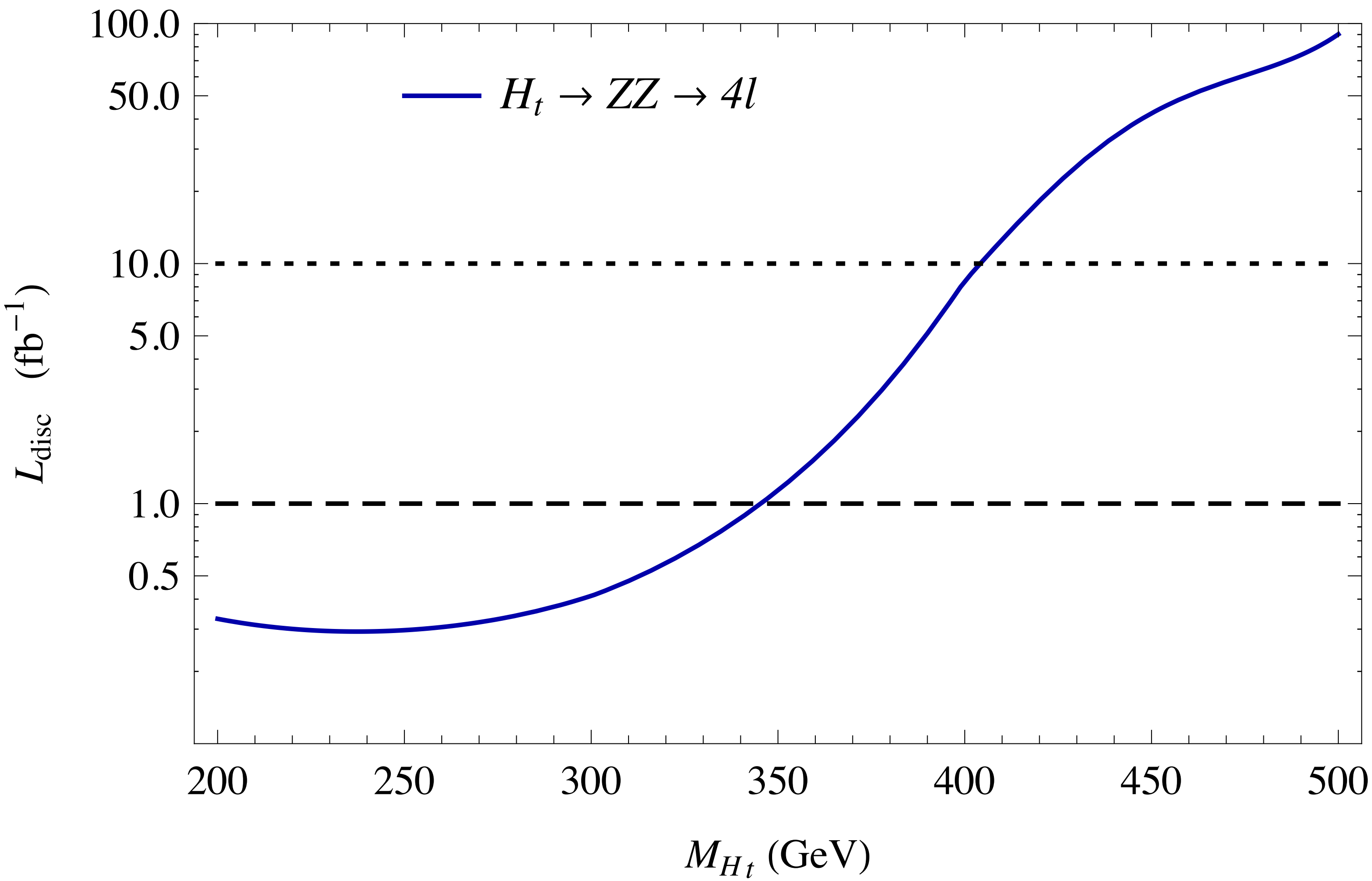
LHC Detection of KK Quarks

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



Top sector at LHC: H_T

Integrated luminosity needed for Top-Higgs discovery in $H_t \rightarrow ZZ$ at 14 TeV LHC is encouragingly low:

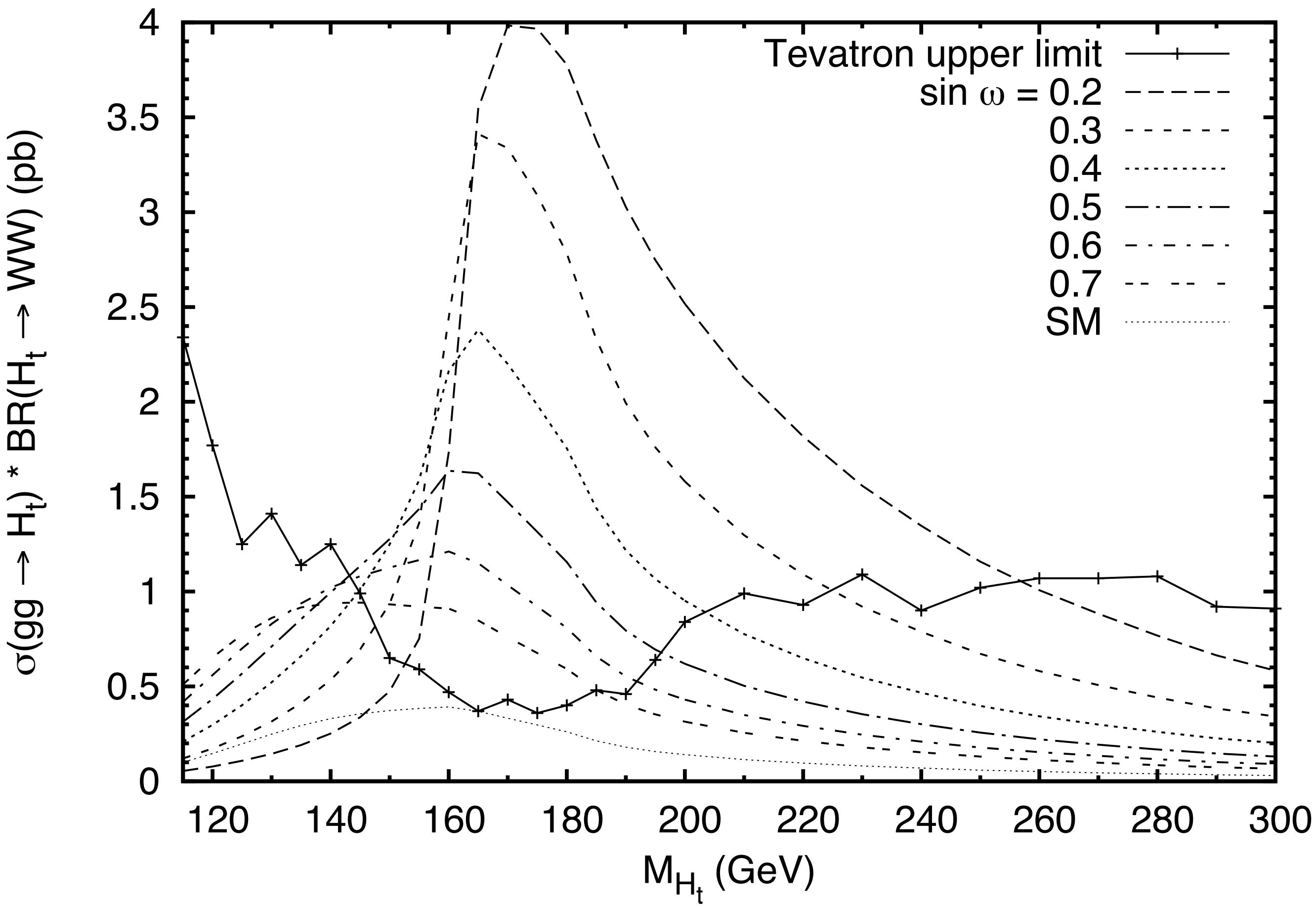


For heavier H_t, the most promising mode is $H_t \rightarrow W\,\Pi_t$

Top sector at LHC: H_T

A top-Higgs of moderate mass would be visible in di-bosons 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

Top sector at LHC

Sample strategy to find states in the top sector and confirm they belong to this kind of Higgsless model:

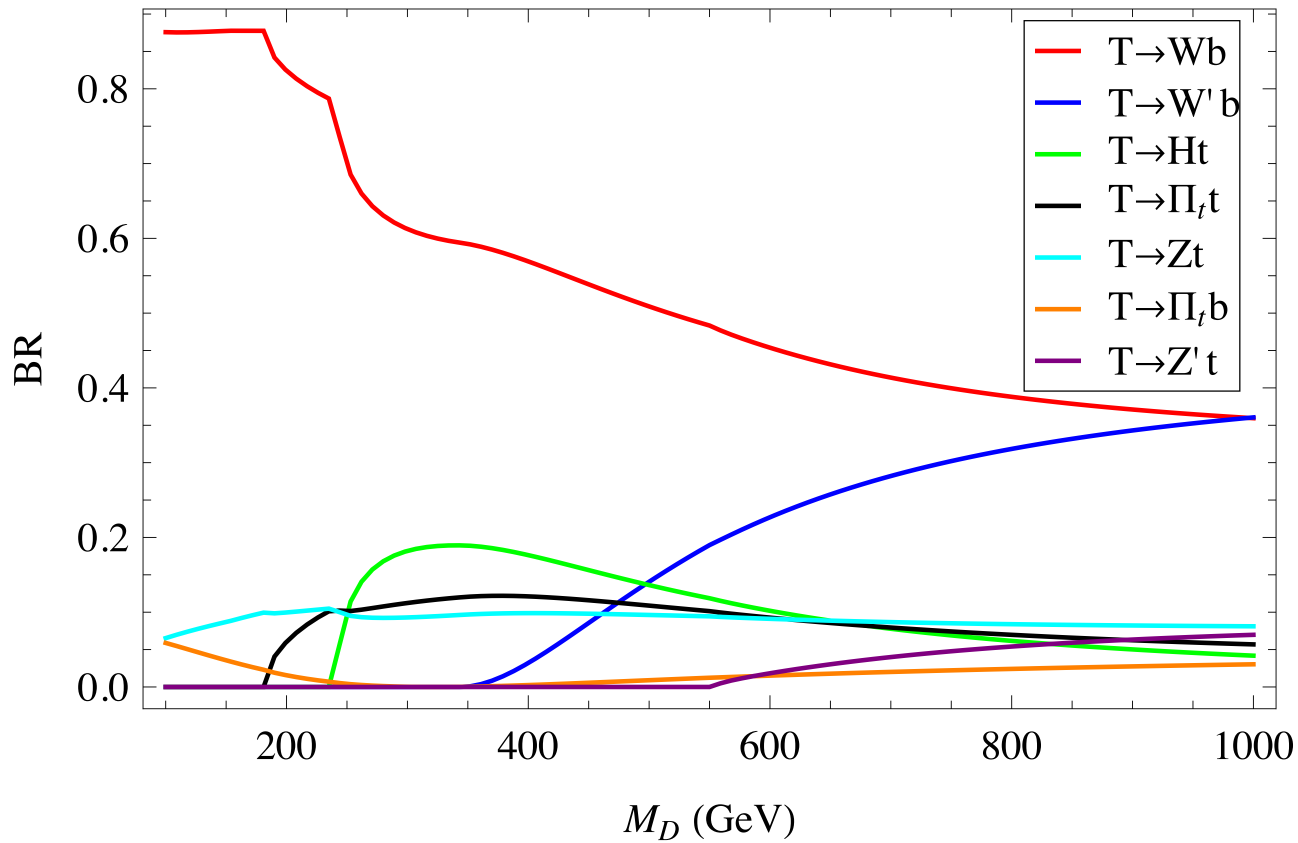
1. With initial LHC data, find $\mathbf{H_t}$ in $\mathbf{H_t} \rightarrow$ **WW, ZZ**; higher-than-SM production rate will indicate that it is exotic
2. As integrated luminosity grows, find top quark's KK partner **T** via its dominant decay to $T \rightarrow Wb$
3. Confirm the $T \rightarrow H_t\, t$ 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

Top sector at LHC: T

Top's KK partner, T, will be most visible in T →Wb.

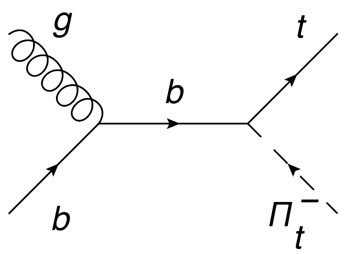
Analysis for other KK quark partners (assuming W→lν) still roughly applies; the channel with one hadronically-decaying W should offer larger signal and full reconstruction of T.

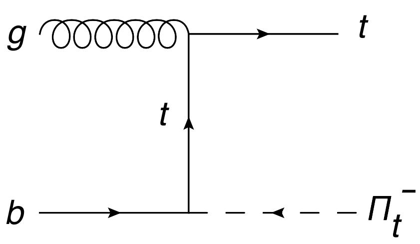
The T →H_t t decays will also be helpful.



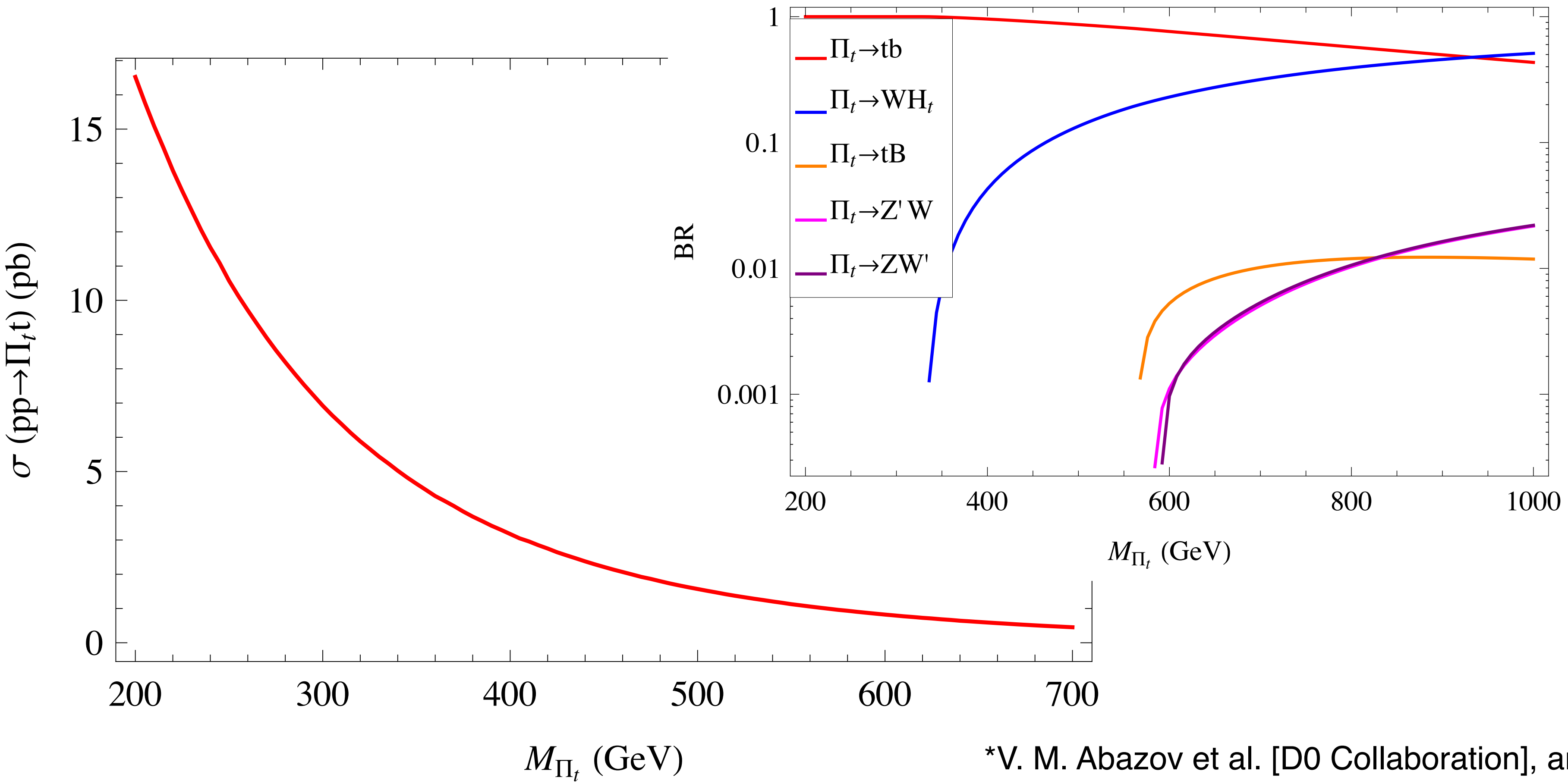
Top sector at LHC: Π_T

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





CMS studies** of $H^{\pm} \to t\,b$ 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.

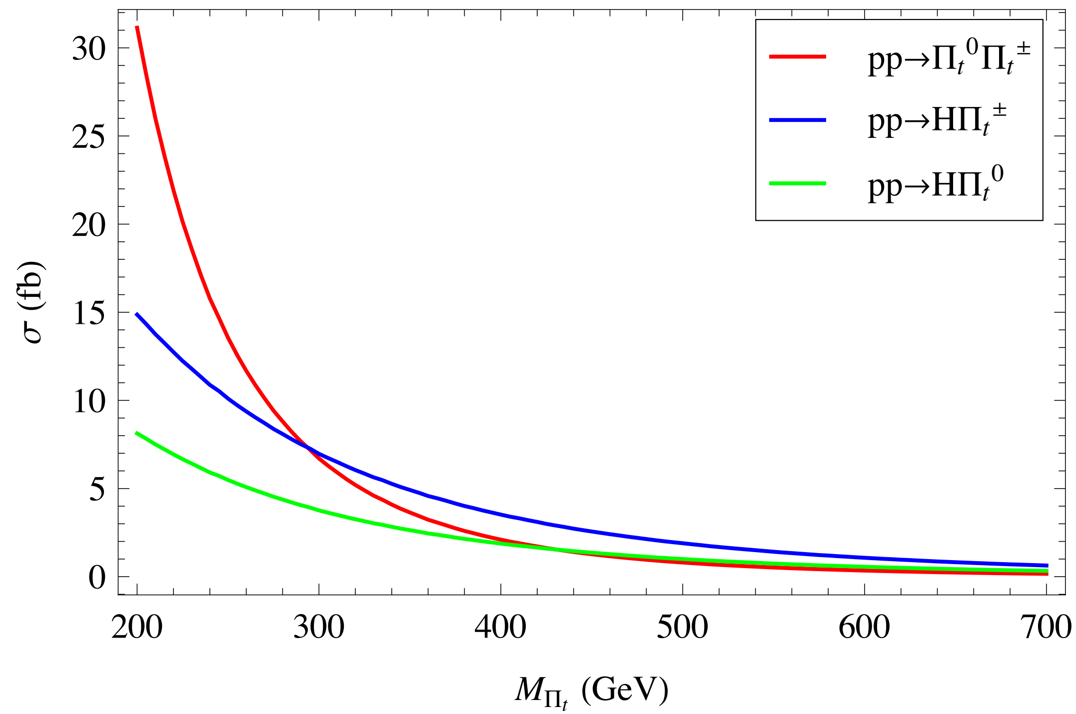
*V. M. Abazov et al. [D0 Collaboration], arXiv:0908.1811

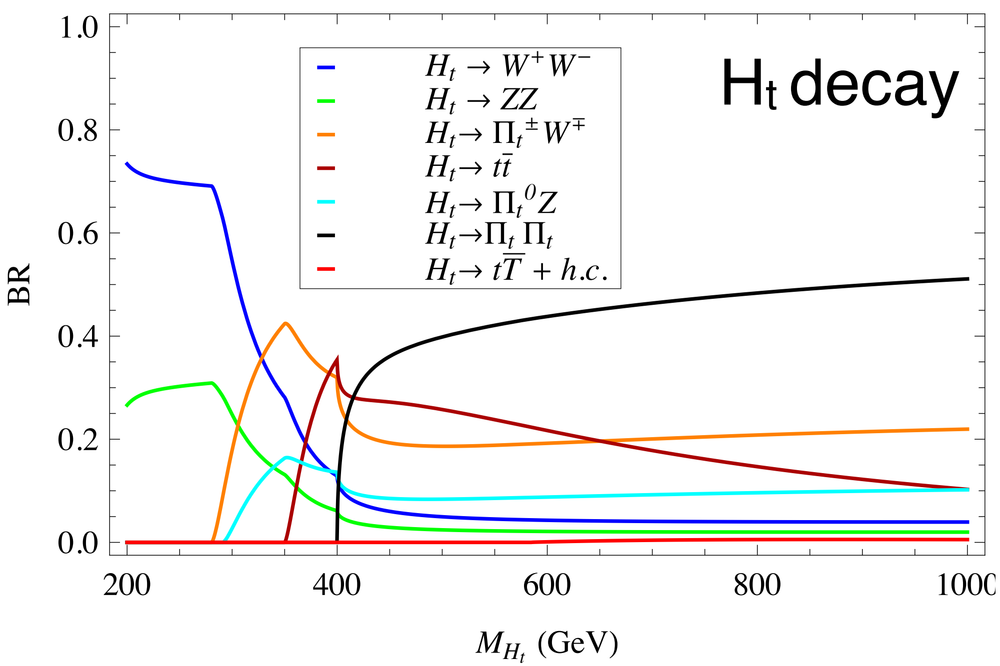
**Lowette, D'Hondt, Vanlaer CERN-CMS-NOTE-2006-109

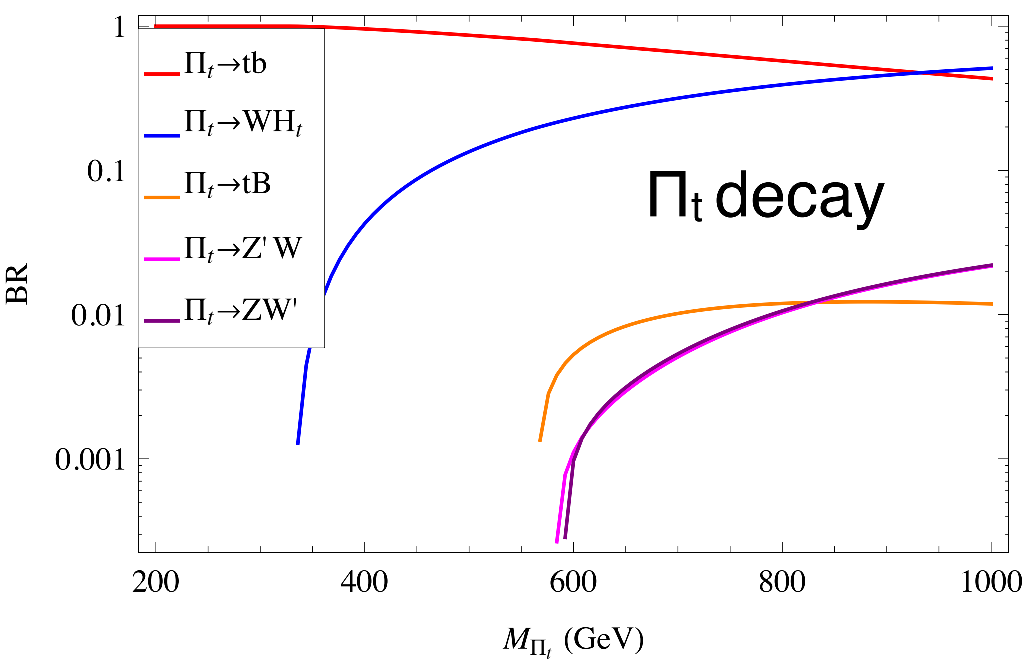
Top sector at LHC: Π_T

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 $H_t \to W\Pi_t$ or $\Pi_t \to WH_t$ would be similarly informative.



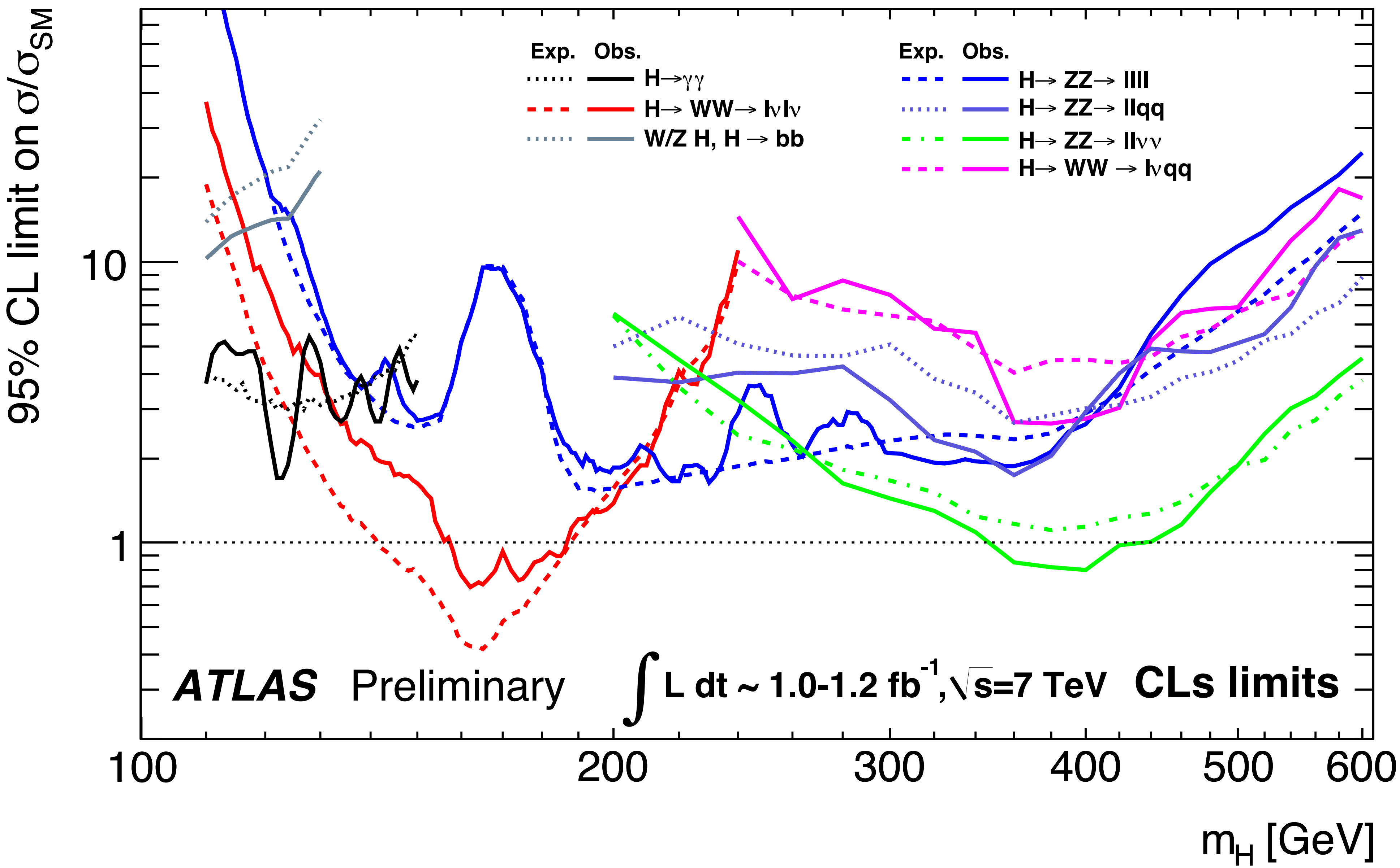




What the LHC Has (NOT) Seen

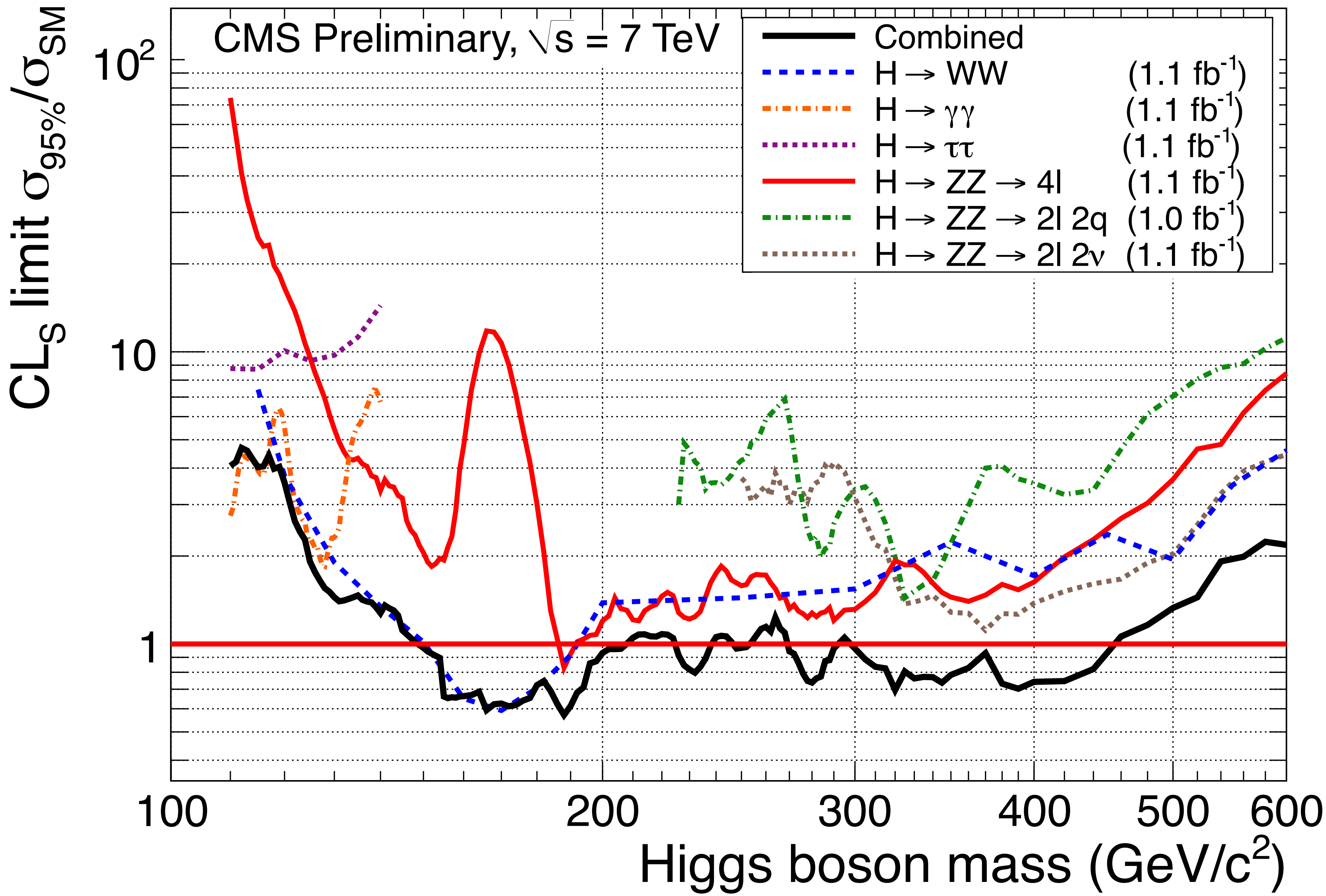
Chivukula, Coleppa, Logan, Martin, Simmons
arXiv: 1108.4000 [hep-ph]

New ATLAS limits on Higgs Production



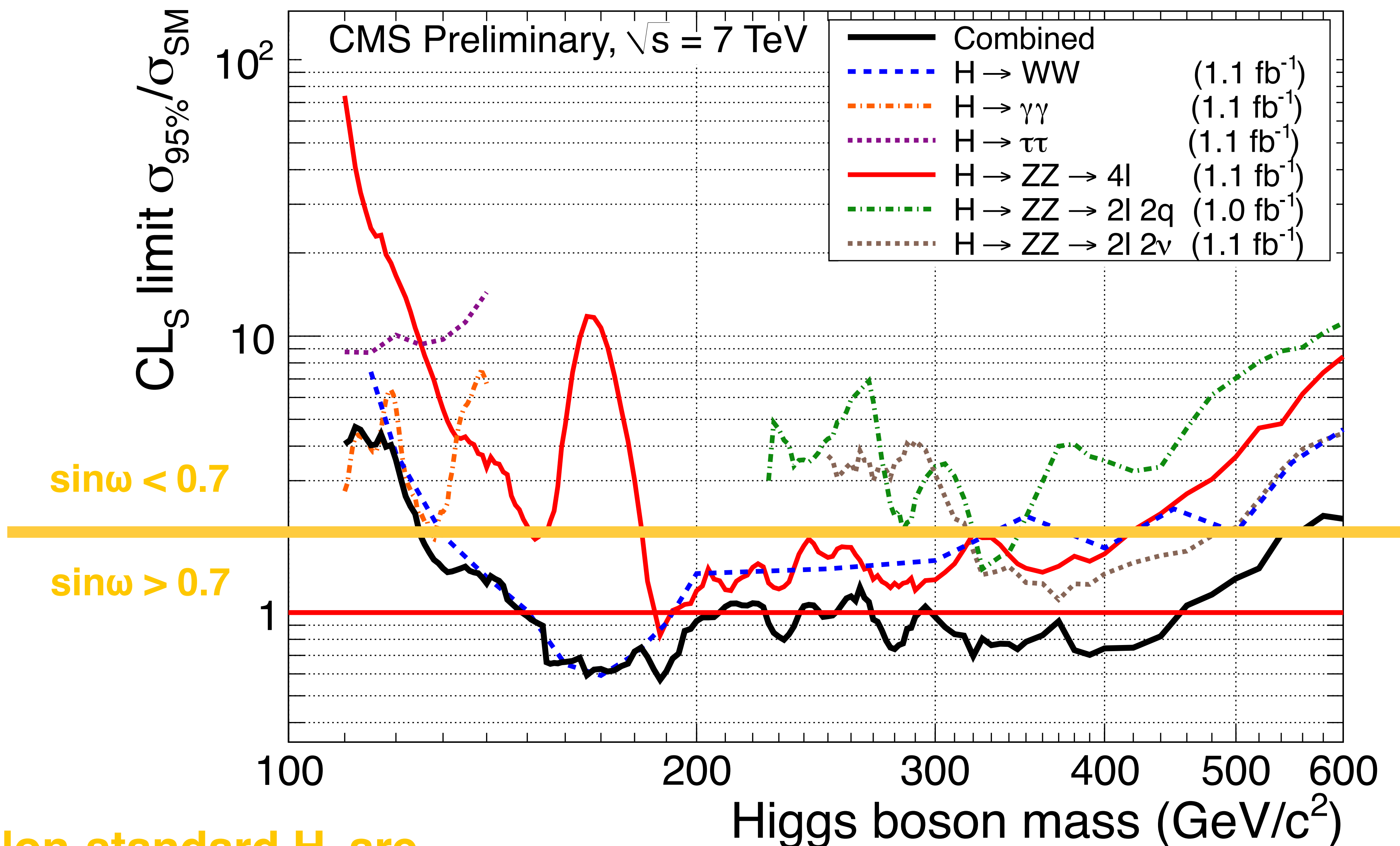
ATLAS-CONF-2011-112

New CMS limits on Higgs Production



CMS PAS HIG-11-011

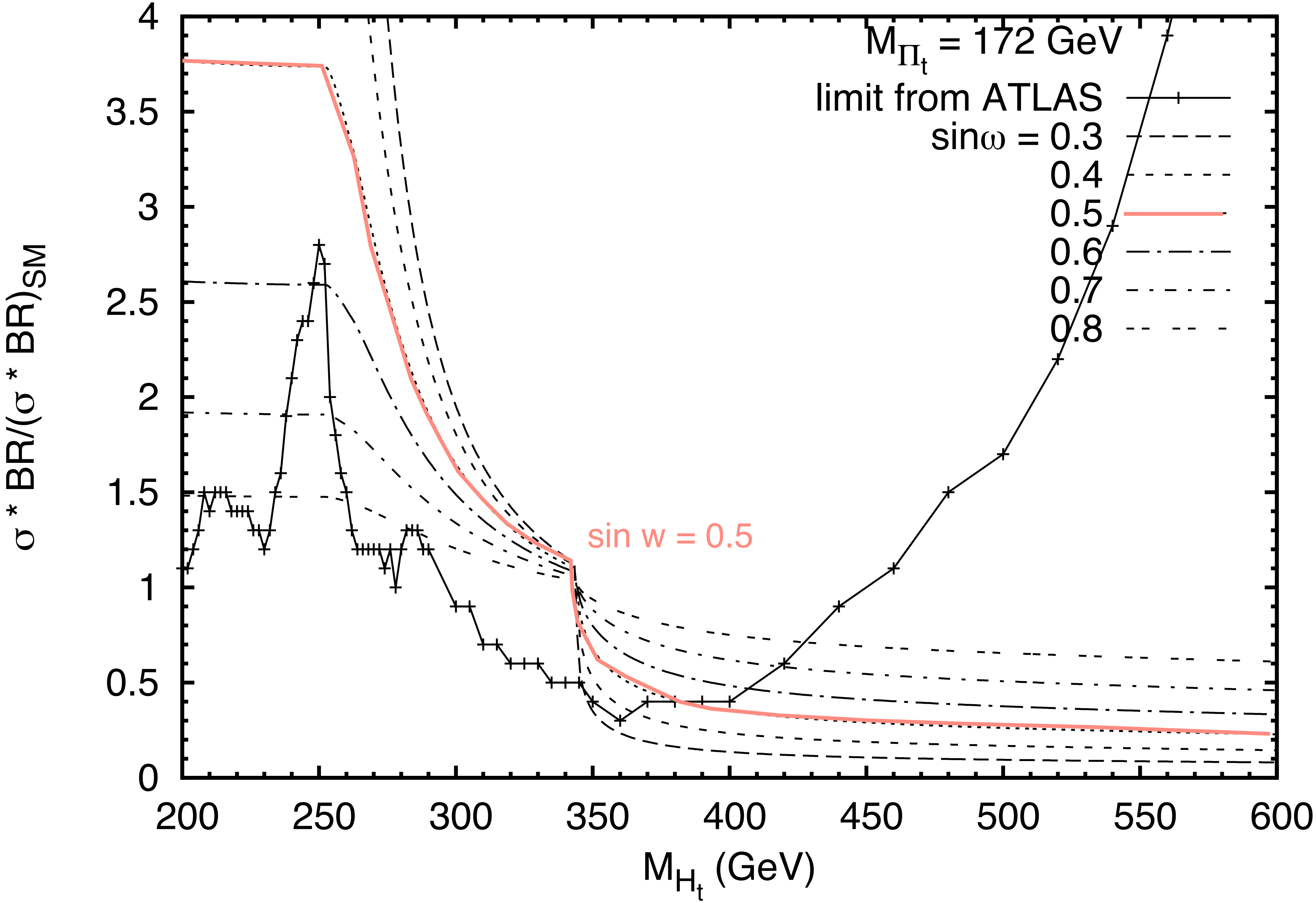
NEW CMS LIMITS ON HIGGS PRODUCTION



Non-standard H_t are tightly constrained

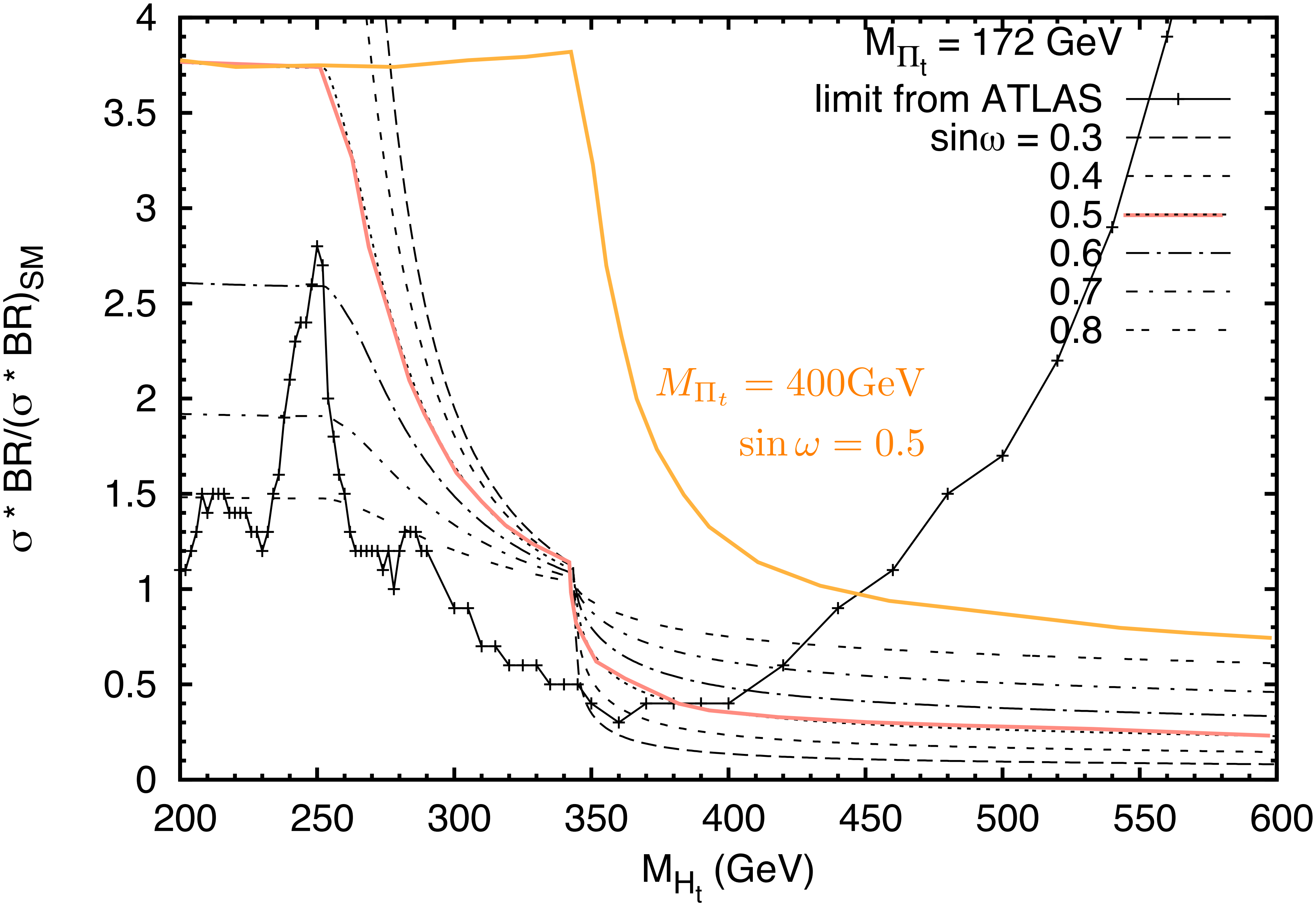
CMS PAS HIG-11-011

ATLAS vs H_T (light top-pion)



Preliminary

ATLAS vs H_T (heavier top-pion)

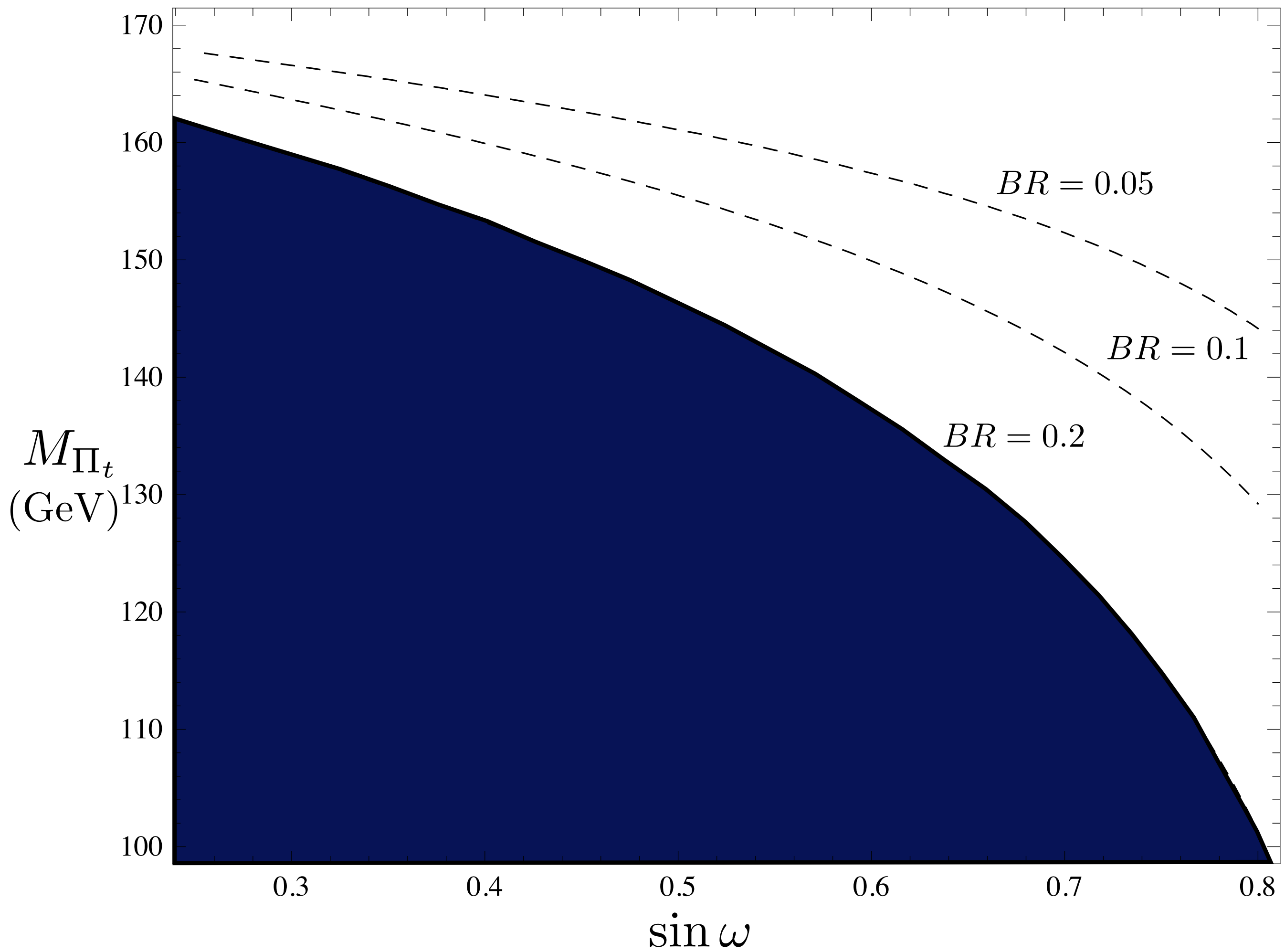


Preliminary

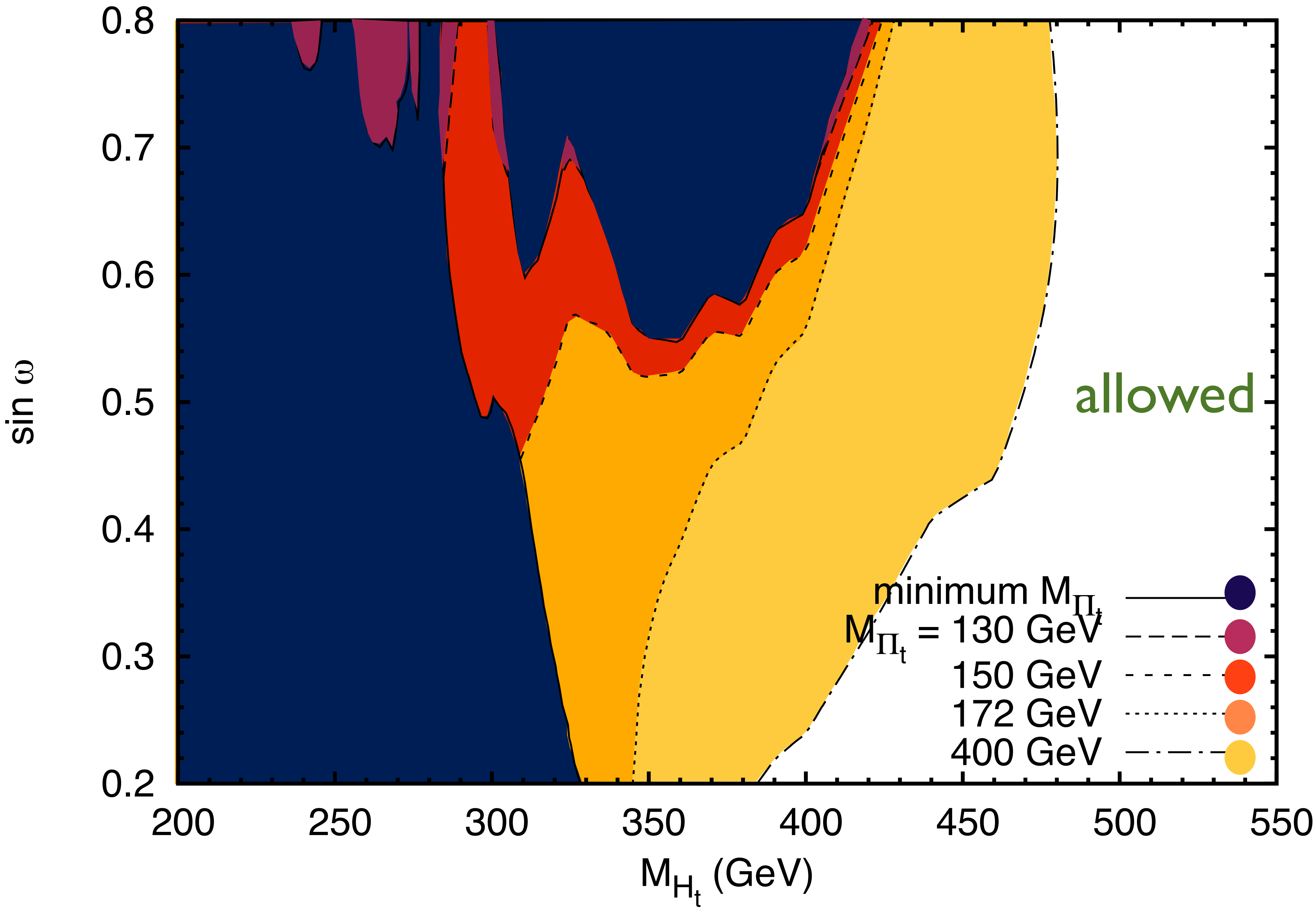
Impact of Top-Pion Mass

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)



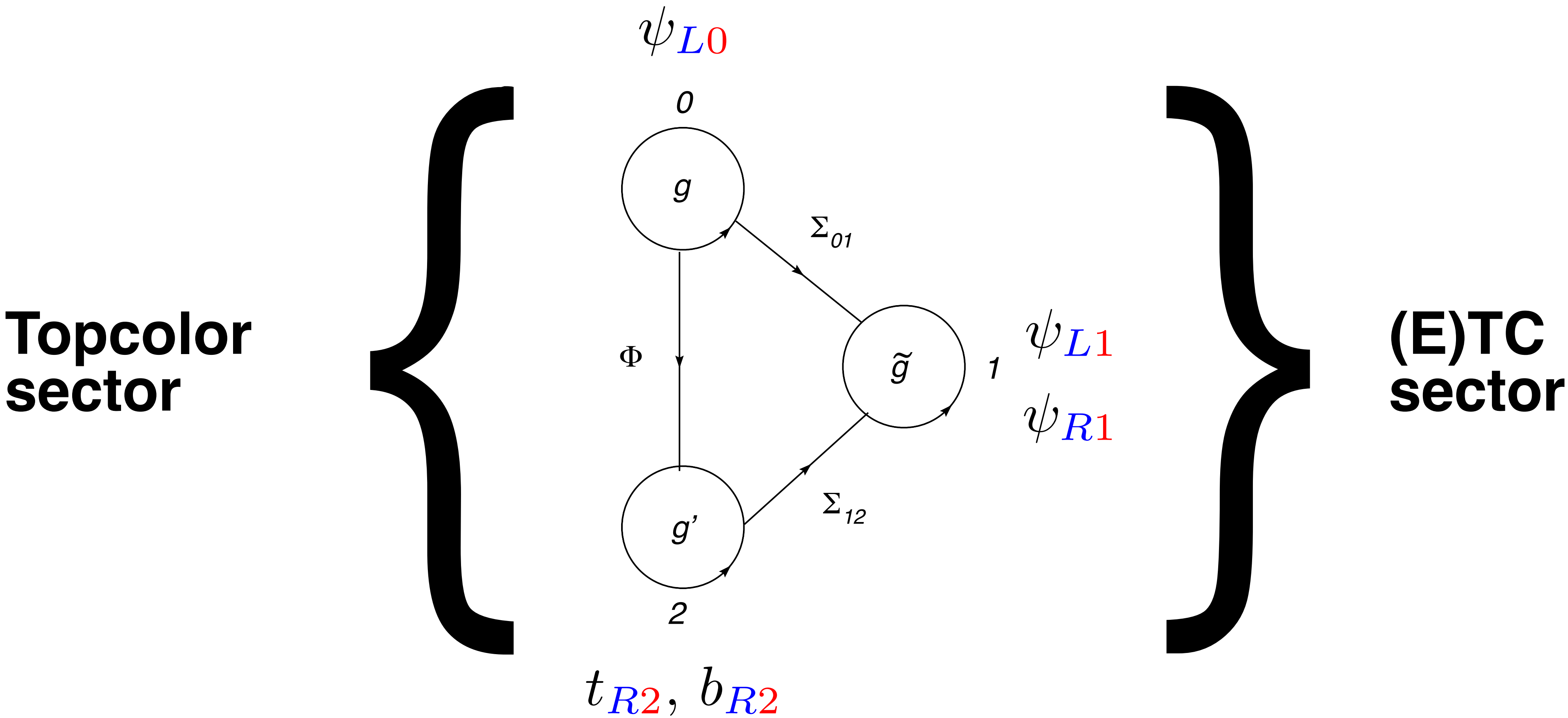
Implications of What the LHC Has (NOT) Seen

LHC limits on the top-Higgs in models with strong top quark dynamics

Chivukula, Coleppa, Logan, Martin, Simmons

arXiv:1108.4000 [hep-ph]

Triangle Moose and Topcolor-Assisted TC



TC2 Dynamics

Consider the top triangle moose as a deconstructed version of topcolor-assisted technicolor (TC2):

- 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 $M_{H_t} \lesssim 2m_{t,dyn}$

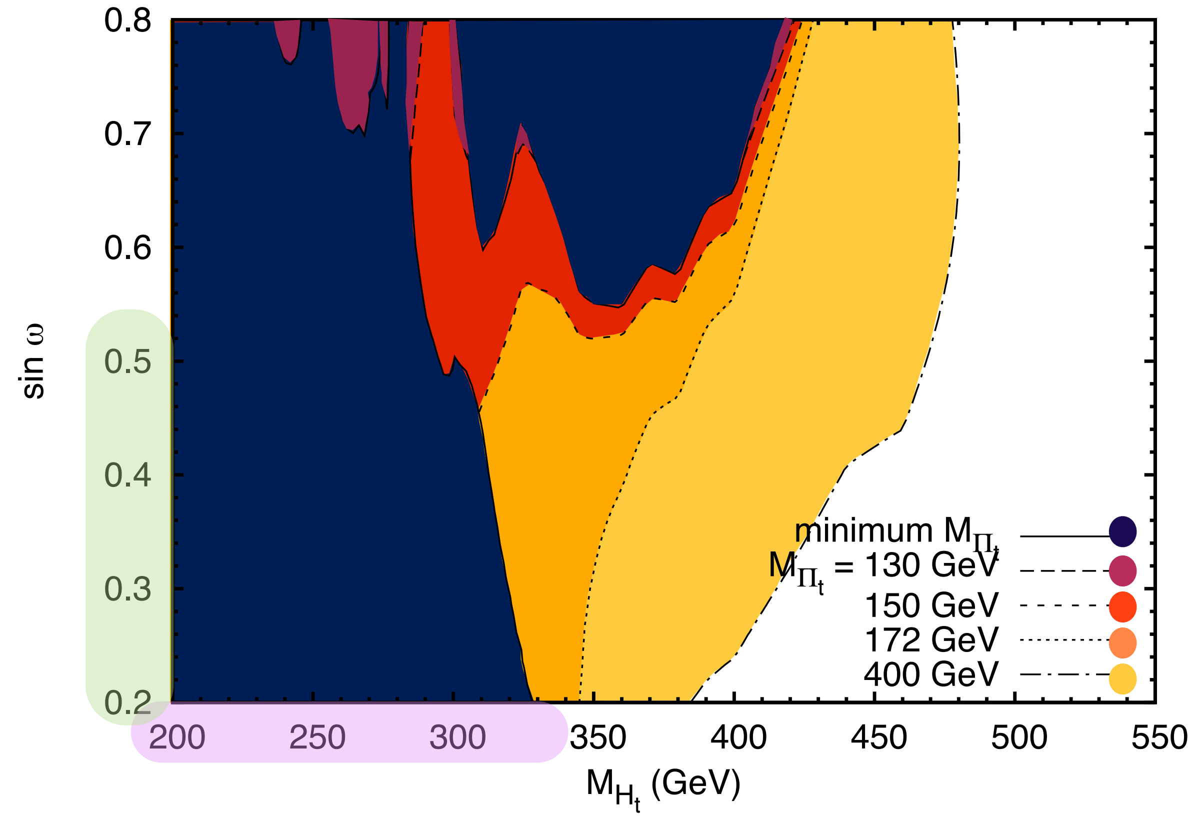
TC2 Parameter Range at LHC

Considering the top triangle moose as a low-energy effective theory for TC2, one would then expect the 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 new LHC data appears to exclude precisely this region.

Conclusions

Conclusions and Next Steps

- Avoiding large weak isospin violation is a challenge for dynamical models of EWSB and fermion masses.

- The top triangle moose is a useful effective theory for studying a range of models where a topcolor-like mechanism generates the top quark mass (such as TC2).

- In this scenario, the heavy partner (KK) quarks are light enough to produce at LHC and the top sector includes T, H_t and Π_t states. Interplay among these states would signal that top dynamics plays a role in EWSB.

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

What the LHC Can See (detail)

<u>W' searches:</u>

Belyaev, et al., arXiv:0708.2588

<u>KK quarks:</u>

Chivukula, Christensen, Coleppa, Simmons arXiv:0906.5667

<u>KK top quark, top-Higgs, and top-Pions</u>

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

<u>related work:</u>

3-site: Ohl, Speckner arXiv:0809.0023

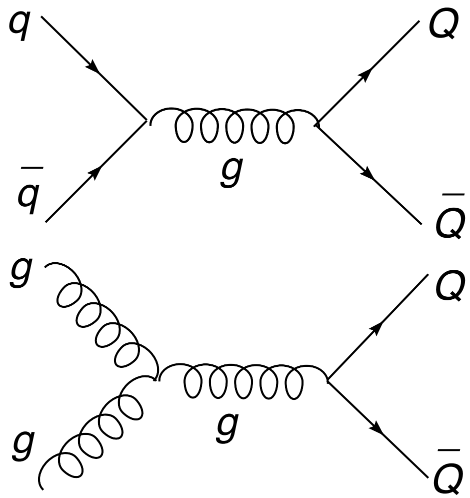
4-site: Hirn, Martin, Sanz arXiv:0712.3783

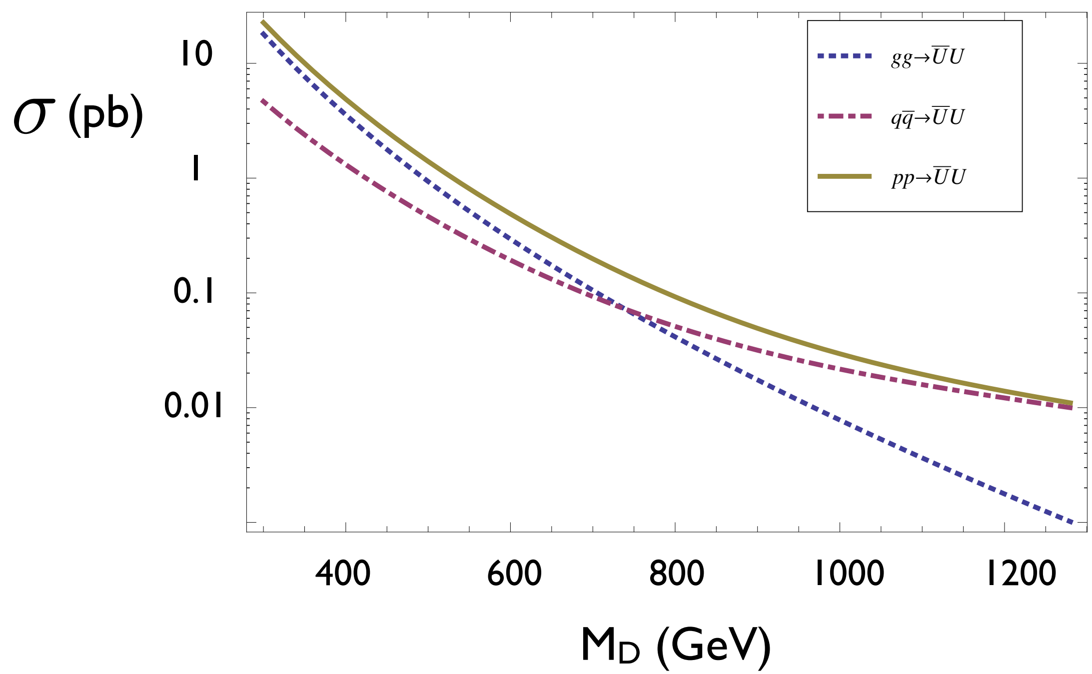
4-site: Accomando et al. arXiv:0807.5051

KK Quark Production at LHC

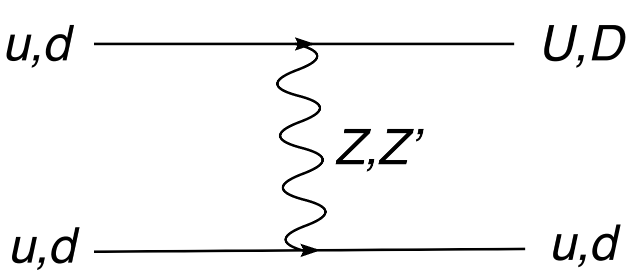
(triangle moose model)

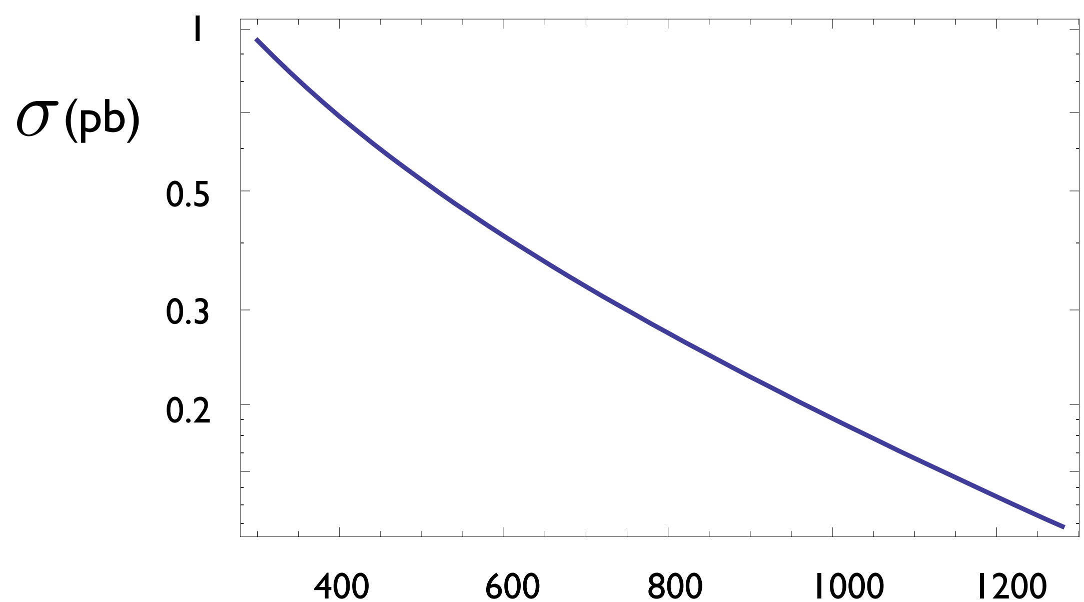
Pair Production





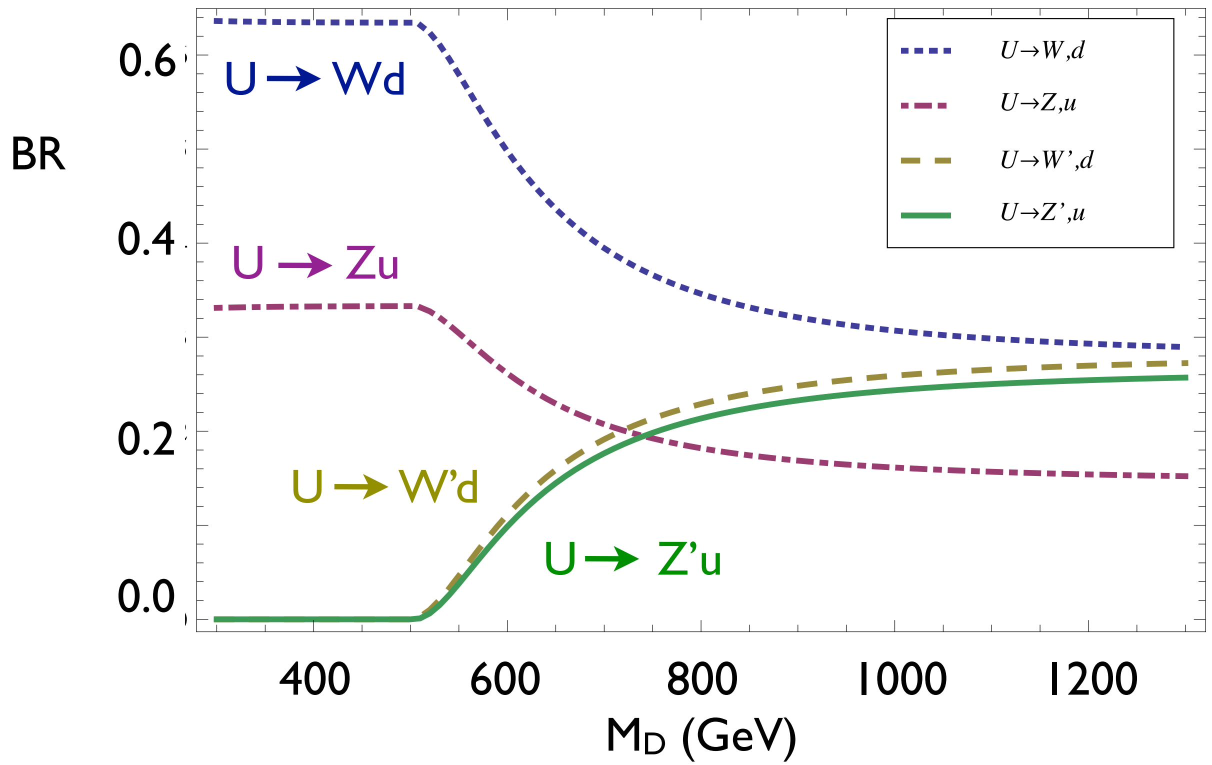
Single Production





KK Quark Decay and Detection

KK fermion decay modes



$M_{Z'}$ = 500 GeV

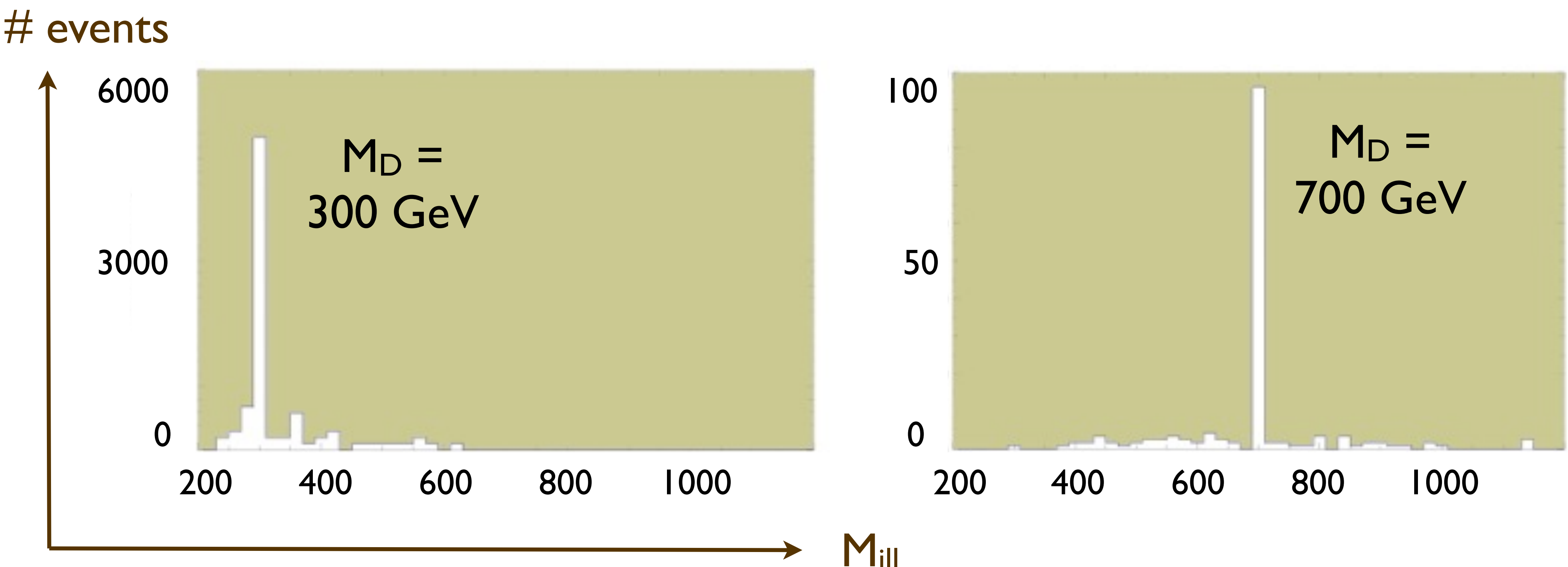
QQ signature: $pp \to Q\bar{Q} \to WZqq \to \ell\ell\ell\, jj\, \not{E}_T$

Qq signature: $pp \to Qq \to W'qq \to WZqq \to \ell\ell\ell\, jj\, \not{E}_T$

KK Quark Pair Production

With basic identification and separation cuts on jets and leptons, **a hard jet p_T cut removes nearly all SM background**

Variable	Cut
p_{Tj}	$>$100 GeV
p_{Tl}	$>$15 GeV
Missing E_T	$>$15 GeV
$\lvert\eta_j\rvert$	$<$ 2.5
$\lvert\eta_l\rvert$	$<$ 2.5
ΔR_{jj}	$>$0.4
ΔR_{jl}	$>$0.4
M_{ll}	89 GeV$< M_{ll} <$ 93 GeV



KK Quark Single Production

Identification and separation cuts on jets and leptons, **a hard jet p_T cut, and jet & lepton rapidity cuts control the SM background**

Variable	Cut
p_{Tj} hard	>200 GeV
p_{Tj} soft	>15 GeV
p_{Tl}	>15 GeV
Missing E_T	>15 GeV
$\|\eta_j$ hard$\|$	< 2.5
$\|\eta_j$ soft$\|$	$2< \|\eta\| < 4$
$\|\eta_l\|$	< 2.5
ΔR_{jj}	>0.4
ΔR_{jl}	>0.4