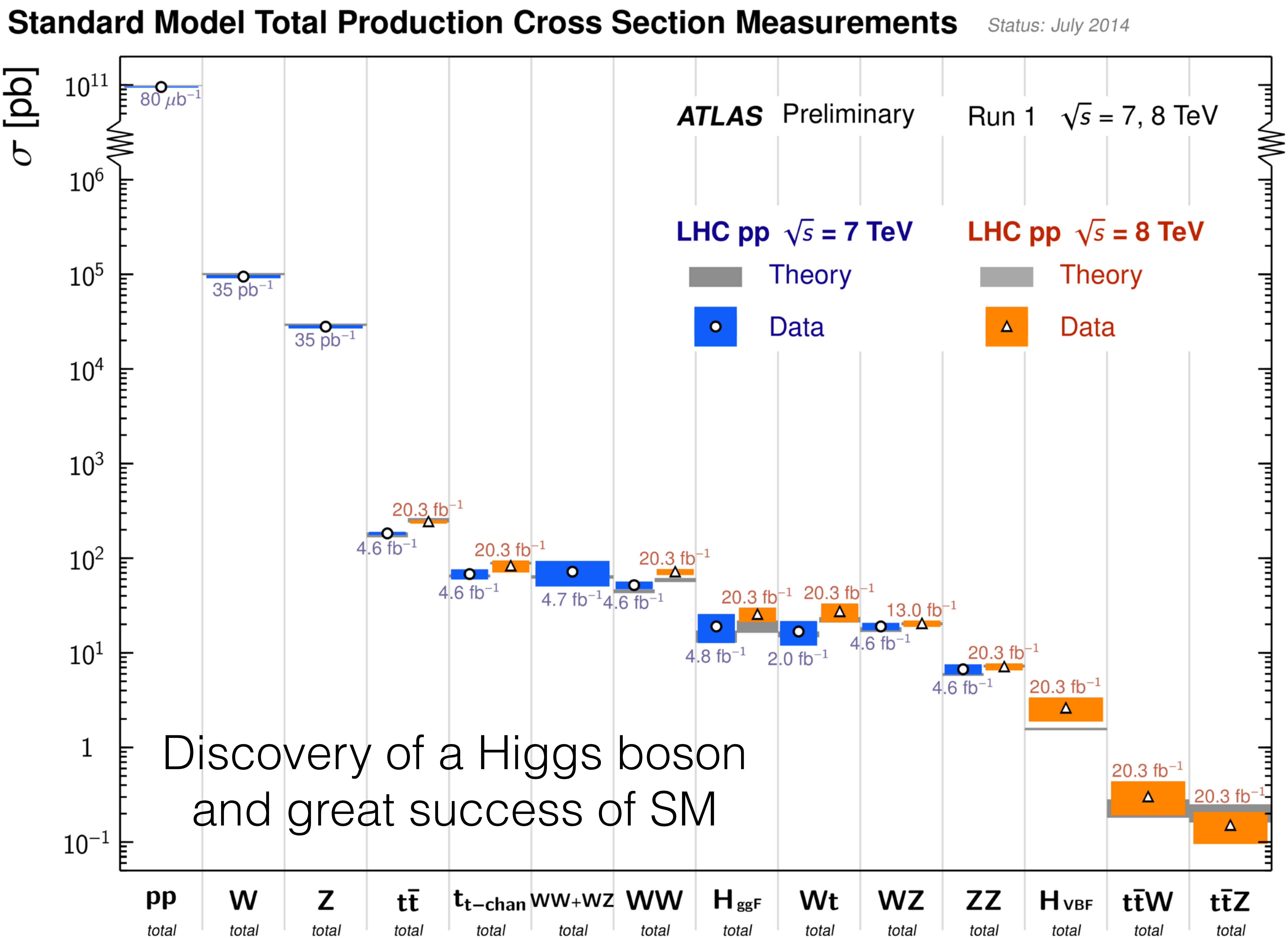
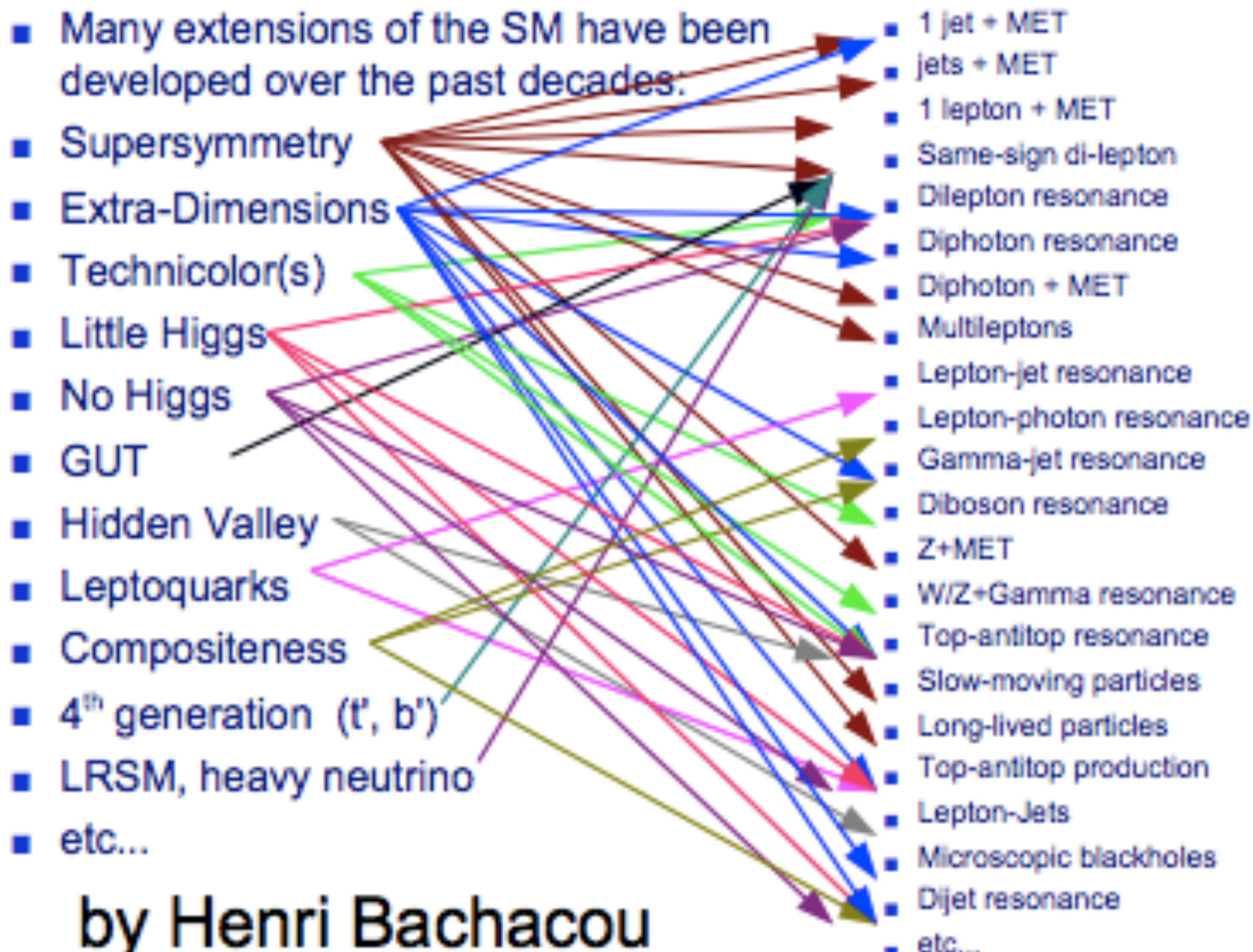
Looking for Resonances under the LHC Lamppost

K.C. Kong
University of Kansas



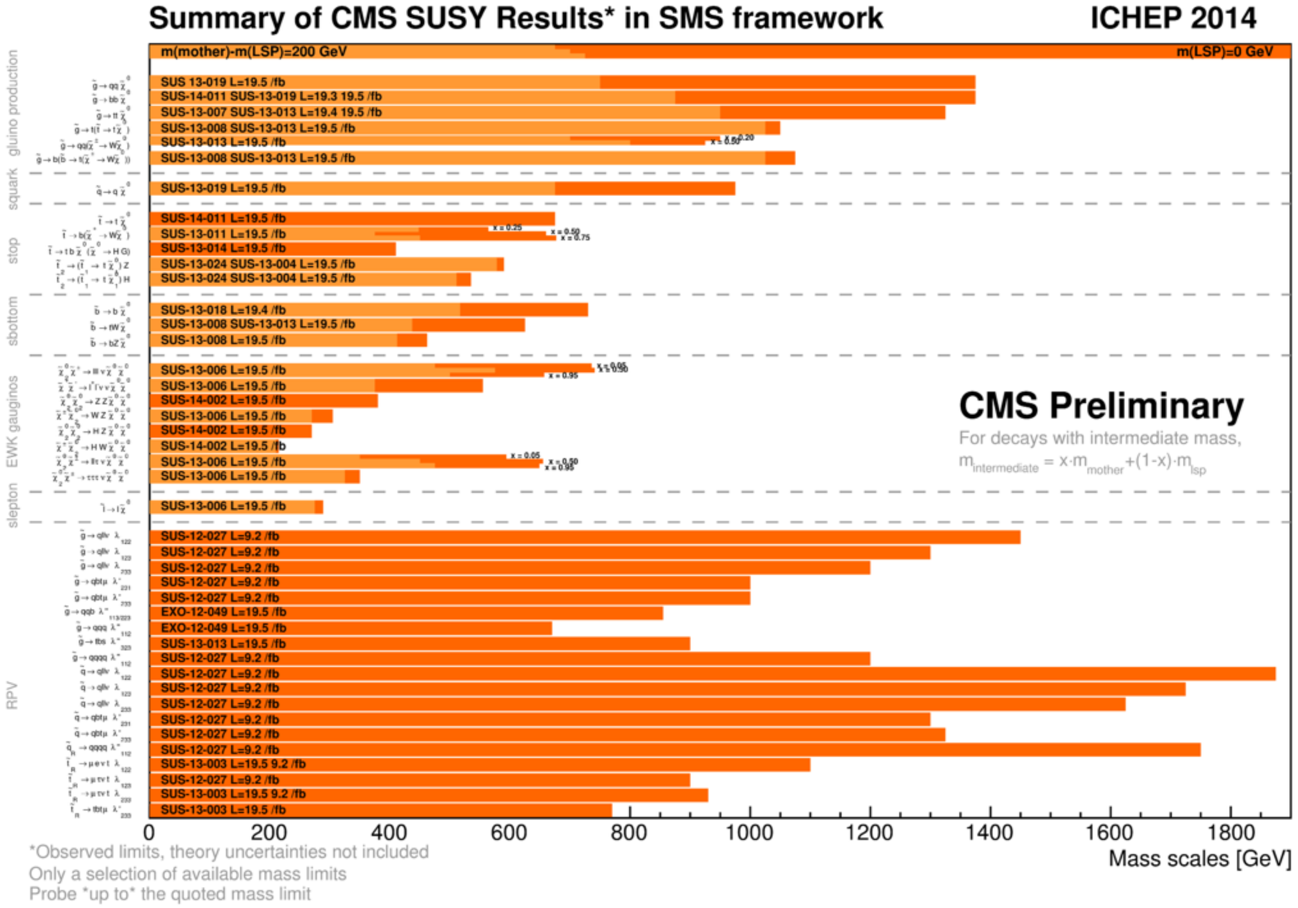
Discovery of a Higgs boson
and great success of SM

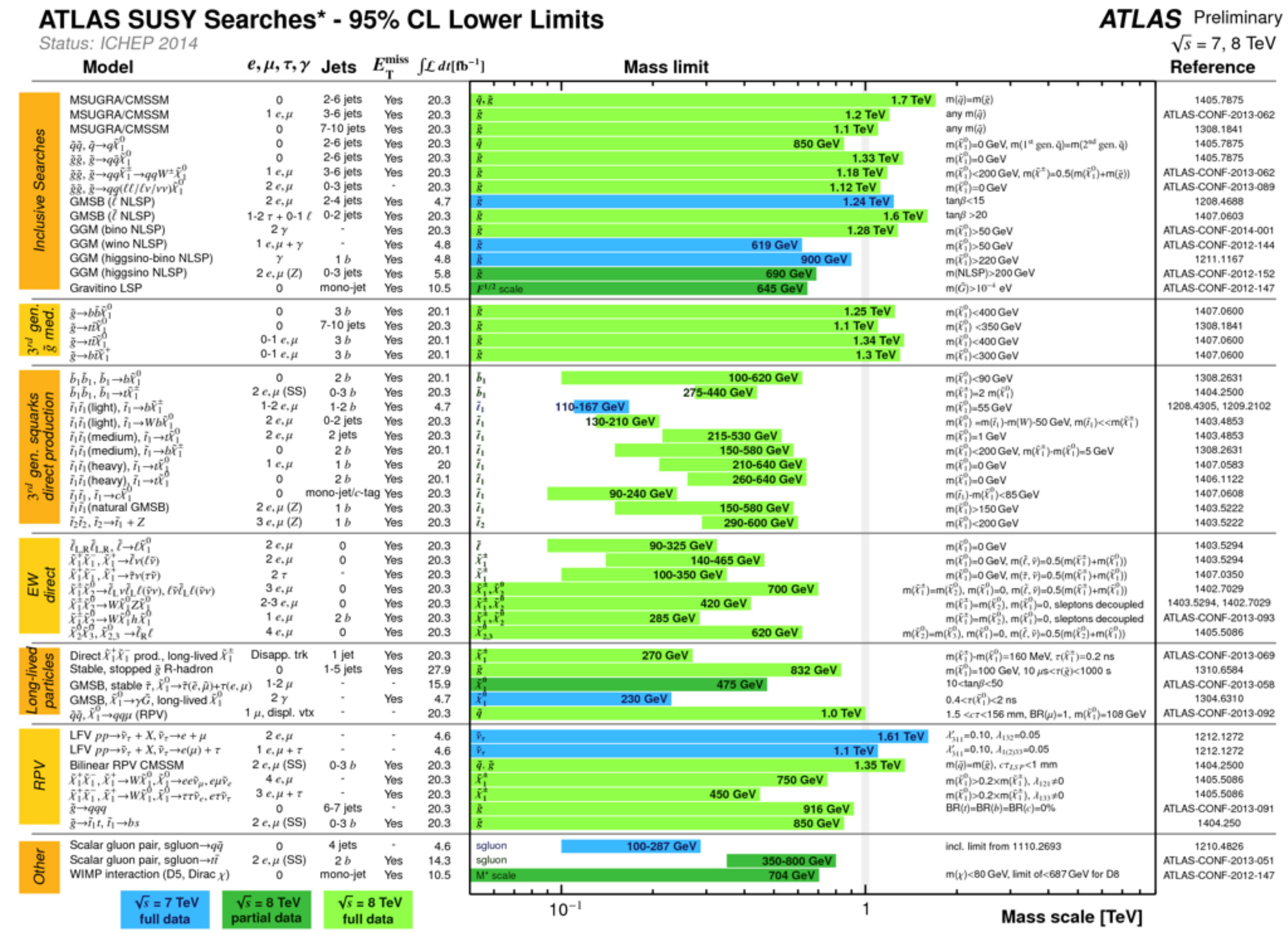
And yes, we are searching for a new phenomena…



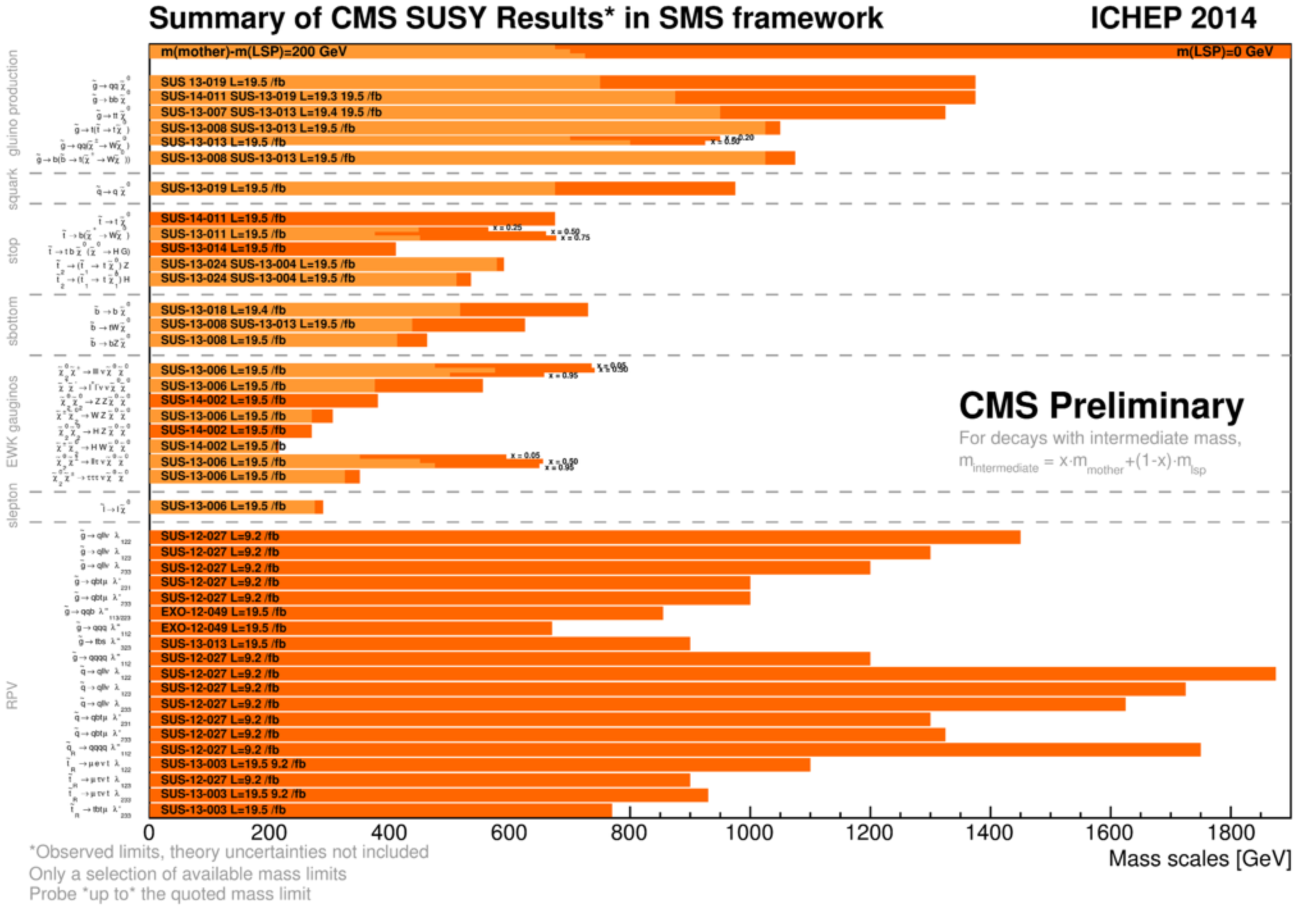
Which BSM model is ‘right’?

- There is no right / wrong as far as hypothetical models are concerned (my subjective opinion).
  - Go to a major conference next year to hear the exact opposite ….. for each model.
- Hopefully the LHC will point us to the right direction.
- Until then, better to keep all options open.
- And that is exactly what experimental collaborations are doing.

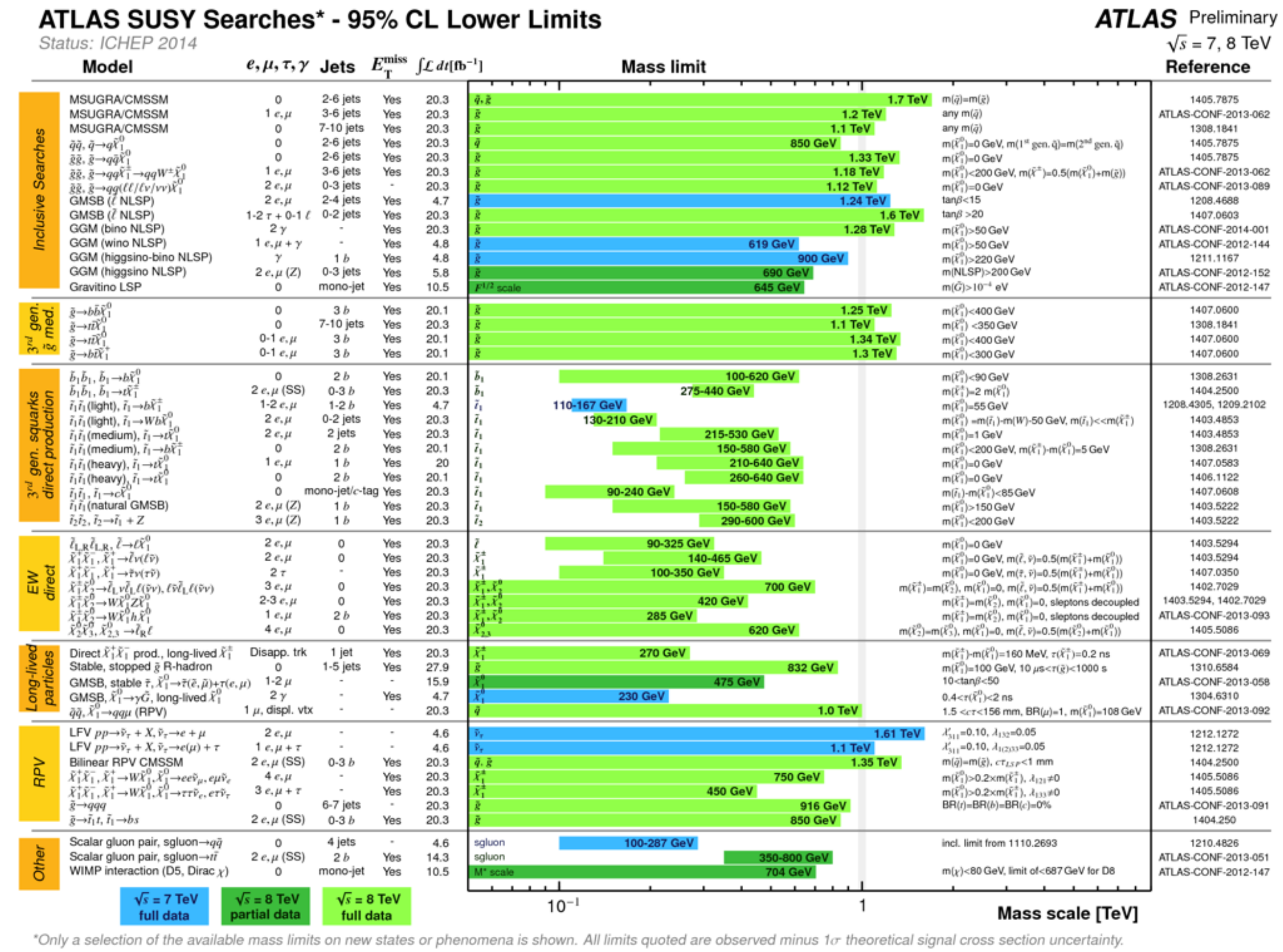




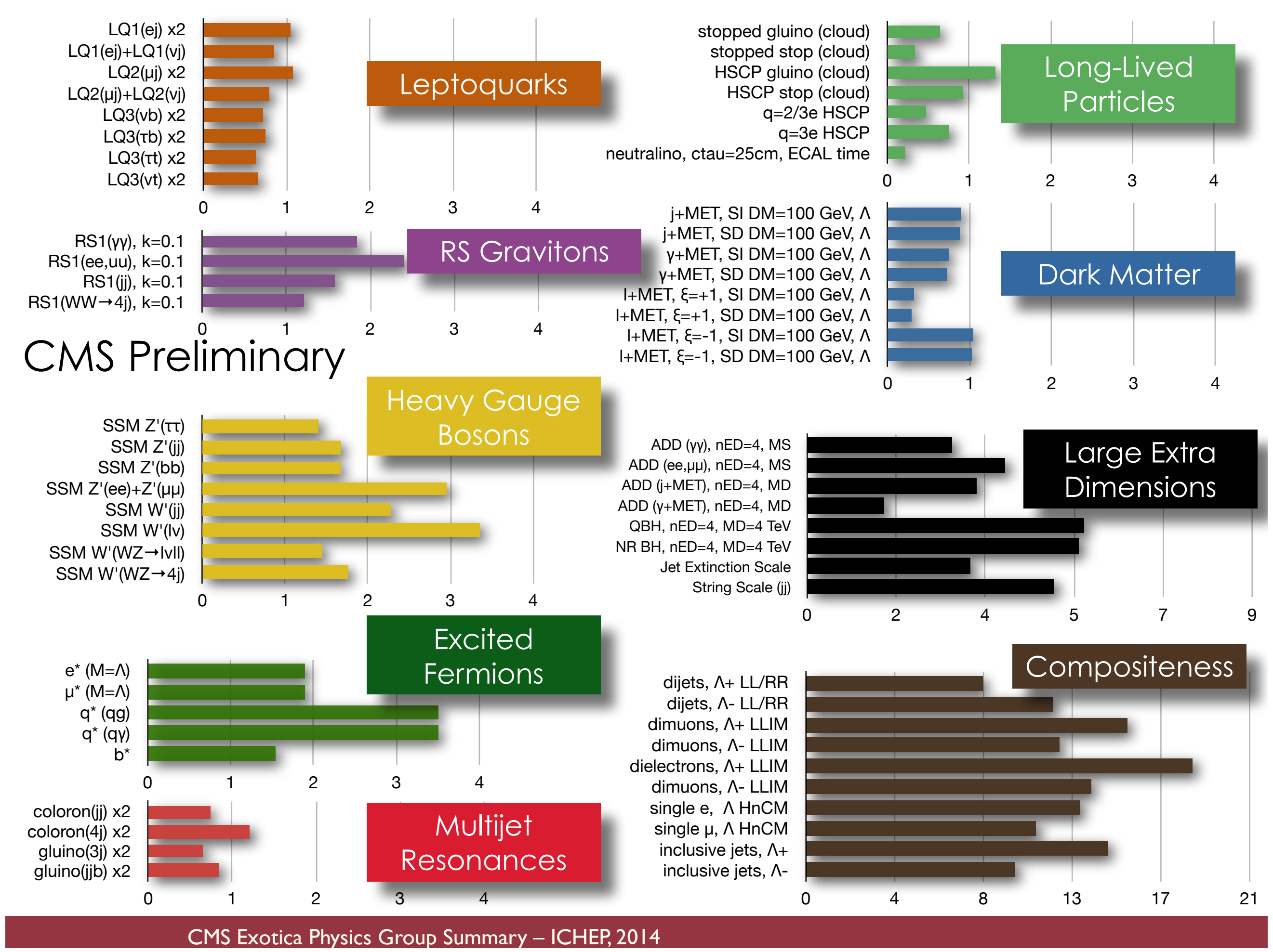
*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.



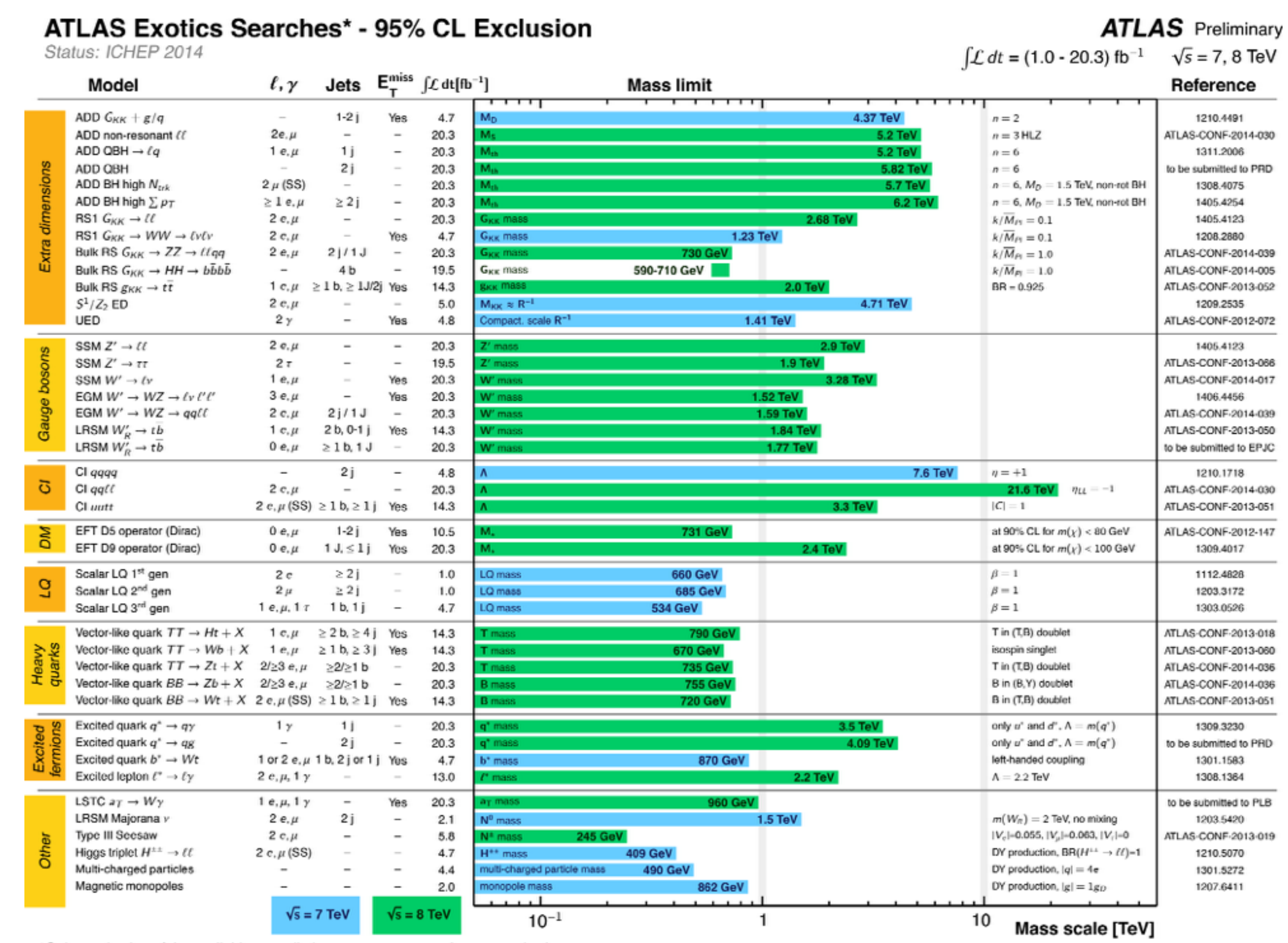
Summary of CMS SUSY Results* in SMS framework
ICHEP 2014
m(mother)-m(LSP)=200 GeV
m(LSP)=0 GeV
gluino production
squark
stop
sbottom
EWK gauginos
slepton
RPV
CMS Preliminary
For decays with intermediate mass,
0 200 400 600 800 1000 1200 1400 1600 1800
Mass scales [GeV]
*Observed limits, theory uncertainties not included
Only a selection of available mass limits
Probe *up to* the quoted mass limit



ATLAS SUSY Searches* - 95% CL Lower Limits
Status: ICHEP 2014
ATLAS Preliminary
$\sqrt{s}$ = 7, 8 TeV
Model
Jets
Mass limit
Reference
Inclusive Searches
EW direct
Long-lived particles
RPV
Other
$\sqrt{s}$ = 7 TeV full data
$\sqrt{s}$ = 8 TeV partial data
$\sqrt{s}$ = 8 TeV full data
Mass scale [TeV]



LQ1(ej) x2
LQ1(ej)+LQ1(νj)
LQ2(μj) x2
LQ2(μj)+LQ2(νj)
LQ3(νb) x2
LQ3(τb) x2
LQ3(ττ) x2
LQ3(νt) x2
Leptoquarks
stopped gluino (cloud)
stopped stop (cloud)
HSCP gluino (cloud)
HSCP stop (cloud)
q=2/3e HSCP
q=3e HSCP
neutralino, ctau=25cm, ECAL time
Long-Lived Particles
RS1(γγ), k=0.1
RS1(ee,uu), k=0.1
RS1(jj), k=0.1
RS1(WW→4j), k=0.1
RS Gravitons
j+MET, SI DM=100 GeV, Λ
j+MET, SD DM=100 GeV, Λ
γ+MET, SI DM=100 GeV, Λ
γ+MET, SD DM=100 GeV, Λ
l+MET, ξ=+1, SI DM=100 GeV, Λ
l+MET, ξ=+1, SD DM=100 GeV, Λ
l+MET, ξ=-1, SI DM=100 GeV, Λ
l+MET, ξ=-1, SD DM=100 GeV, Λ
Dark Matter
CMS Preliminary
SSM Z'(ττ)
SSM Z'(jj)
SSM Z'(bb)
SSM Z'(ee)+Z'(μμ)
SSM W'(jj)
SSM W'(lν)
SSM W'(WZ→lνll)
SSM W'(WZ→4j)
Heavy Gauge Bosons
ADD (γγ), nED=4, MS
ADD (ee,μμ), nED=4, MS
ADD (j+MET), nED=4, MD
ADD (γ+MET), nED=4, MD
QBH, nED=4, MD=4 TeV
NR BH, nED=4, MD=4 TeV
Jet Extinction Scale
String Scale (jj)
Large Extra Dimensions
e* (M=Λ)
μ* (M=Λ)
q* (qg)
q* (qγ)
b*
Excited Fermions
dijets, Λ+ LL/RR
dijets, Λ- LL/RR
dimuons, Λ+ LLIM
dimuons, Λ- LLIM
dielectrons, Λ+ LLIM
dimuons, Λ- LLIM
single e, Λ HnCM
single μ, Λ HnCM
inclusive jets, Λ+
inclusive jets, Λ-
Compositeness
coloron(jj) x2
coloron(4j) x2
gluino(3j) x2
gluino(jjb) x2
Multijet Resonances
CMS Exotica Physics Group Summary – ICHEP, 2014



ATLAS Exotics Searches* - 95% CL Exclusion
Status: ICHEP 2014
ATLAS Preliminary
$\int \mathcal{L}\, dt$ = (1.0 - 20.3) fb^{-1}
$\sqrt{s}$ = 7, 8 TeV
Model
Jets
Mass limit
Reference
Extra dimensions
Gauge bosons
CI
DM
LQ
Heavy quarks
Excited fermions
Other
$\sqrt{s}$ = 7 TeV
$\sqrt{s}$ = 8 TeV
Mass scale [TeV]
*Only a selection of the available mass limits on new states or phenomena is shown.

X → yy summary

Credits: F. Würthwein, ICHEP 2014

Final State	Highest mass event	Highest mass limit
ee	~1.8TeV	2.79TeV
mumu	~1.8TeV	2.53TeV
tautau	~0.7TeV	1.9TeV
dijet	~5.1TeV	5.1TeV
lnu	~2.4TeV	3.4TeV
bb	~4.1TeV	~1.2-1.5TeV
top b	~3.8TeV	2.05TeV
ttbar*	~3.5TeV	1.8TeV

Fermion Pairs

Final State	Highest mass event	Highest mass limit
WZ(3lnu)	~1.1TeV	1.5TeV
VV(jjlnu)	~3.3TeV	2.5TeV
Vq(jj)*	~3.7TeV	3.2TeV
VV(jj)*	~2.7TeV	1.7TeV
ZZ(lljj)	~1.7TeV	0.85TeV
hh(4b)	~1.3TeV	590-710GeV
Wt	~1.8TeV	1.8TeV
γjet	~3TeV	3.5TeV

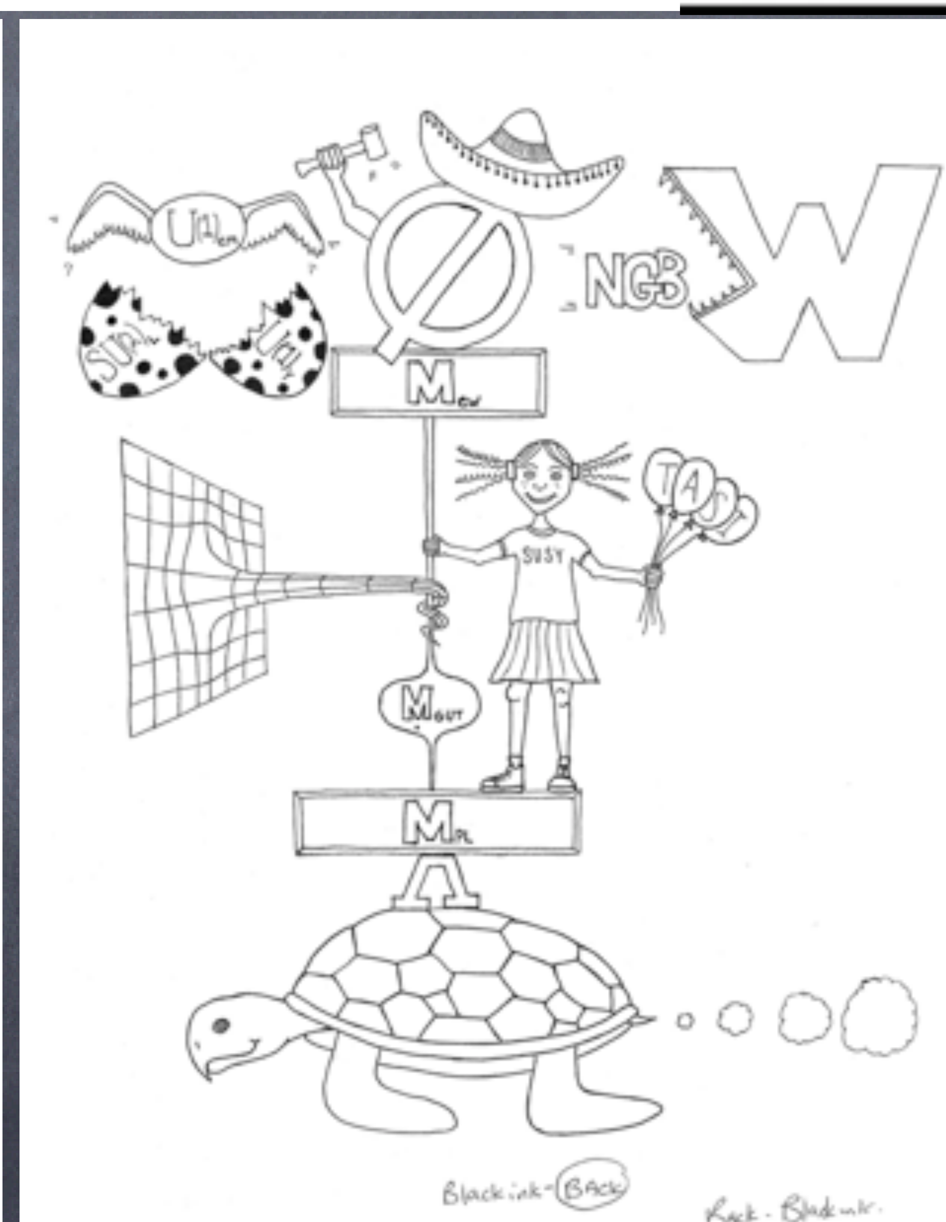
Final states with bosons

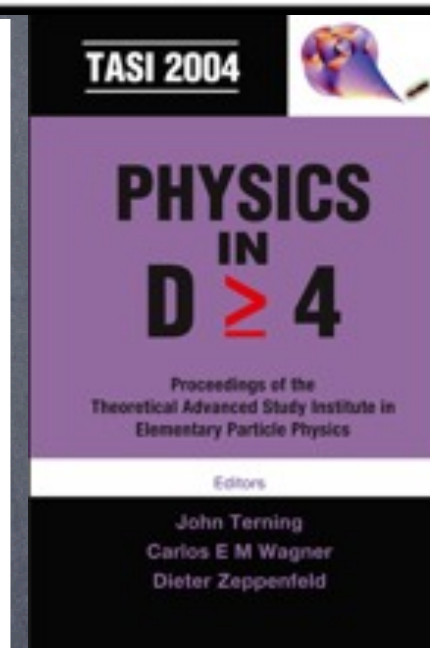
Probe ~1 - 5 TeV scale across a very wide range of fermionic and bosonic final states

- Where is New Physics?

- Hopefully it is just around the conner.

- Where is New Physics?
- Hopefully it is just around the conner.



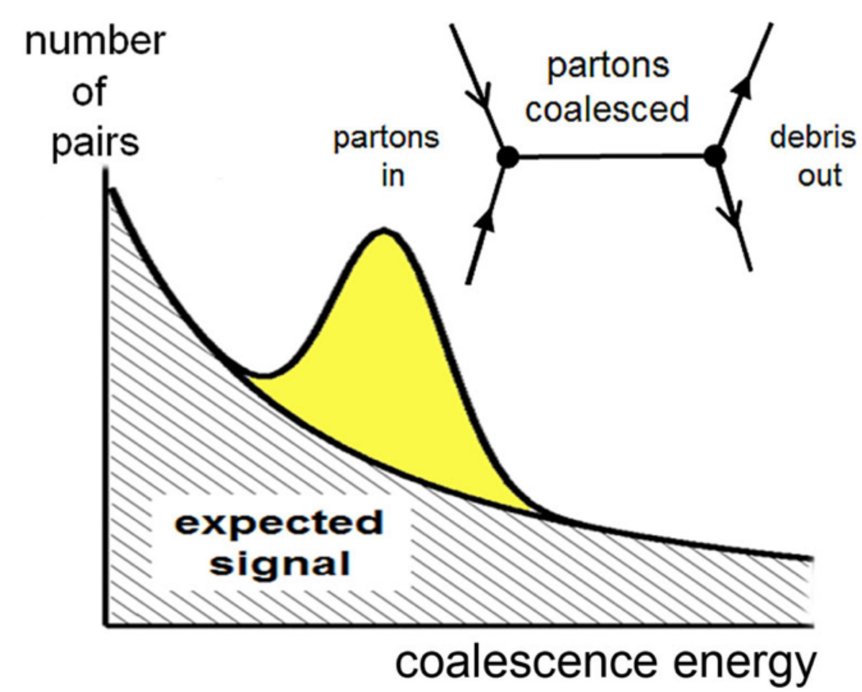


- Where is New Physics?
- Hopefully it is just around the conner.
- Are we sure we covered every single corner?
- Are we digging in the right place?

- Where is New Physics?
- Hopefully it is just around the conner.
- Are we sure we covered every single corner?
- Are we digging in the right place?
- Do we need better tools?


- Where is New Physics?
- Hopefully it is just around the conner.
- Are we sure we covered every single corner?
- Are we digging in the right place?
- Do we need better tools?
- What should we do at Run II?
- Are we prepared?

- Let’s step back and think about a simple physics case (?), such as resonances. (everything can be thought of as a resonance.)
- Relatively easy to find (?). Bump hunting?
- Perhaps we can find a systematic way of thinking about resonances!
- Consider all possible combinations of two reconstructed objects



	γ	$\ell(e,\mu)$	$j(q,b,g)$	τ	t	Z	W	h	$\not\!\!E_T$
γ									
$\ell(e,\mu)$									
j									
τ									
t									
Z									
W									
h									
$\not\!\!E_T$									

Consider all possible objects with two reconstructed objects.
Are covering all spots theoretically and experimentally?

	γ	$\ell(e,\mu)$	$j(q,b,g)$	τ	t	Z	W	h	$\not\!\!E_T$
γ									
$\ell(e,\mu)$									
j									
τ									
t									
Z									
W									
h									
$\not\!\!E_T$									

Table 1: Examples of di-object. F'= 'excited fermion', $\not\!R$= 'R-parity violation', LQ = 'LeptoQuark'. Numbers in subscript indicate that particles have extra dimensional origin. Supersymmetric particles have $\sim$ as usual.

	γ	$\ell(e,\mu)$	$j(q,b,g)$	τ	t	Z	W	h	$\not{E}_T$
γ	G_{KK}, h	F'	F'	F'	F'	h,	W_2	Z_2	$\tilde{\chi}_1^0$, γ_1
$\ell(e,\mu)$		Z'	LQ, $\not{R}$	$\not{R}$	LQ, $\not{R}$	L_2	ν_2		$\tilde{\ell}$
j			Z', W', h	$\not{R}$	$\not{R}$	Q_2, F'	Q_2, F'	$t \to hj$	$\tilde{q}$, q_1
τ				Z'	$\not{R}$	τ_2	ν_2		$\tilde{\tau}$, τ_1
t					RS, G', Z'	T'	$T^{5/3}$	T'	$\tilde{t}$, t_1
Z						h, H	W'	γ_2	
W							h	$H^{\pm}$	$\tilde{\chi}_1^{\pm}$
h								H	
$\not{E}_T$									h

Table 1: Examples of di-object. F'= 'excited fermion', $\not{R}$= 'R-parity violation', LQ = 'Lepto-Quark'. Numbers in subscript indicate that particles have extra dimensional origin. Supersymmetric particles have $\sim$ as usual.

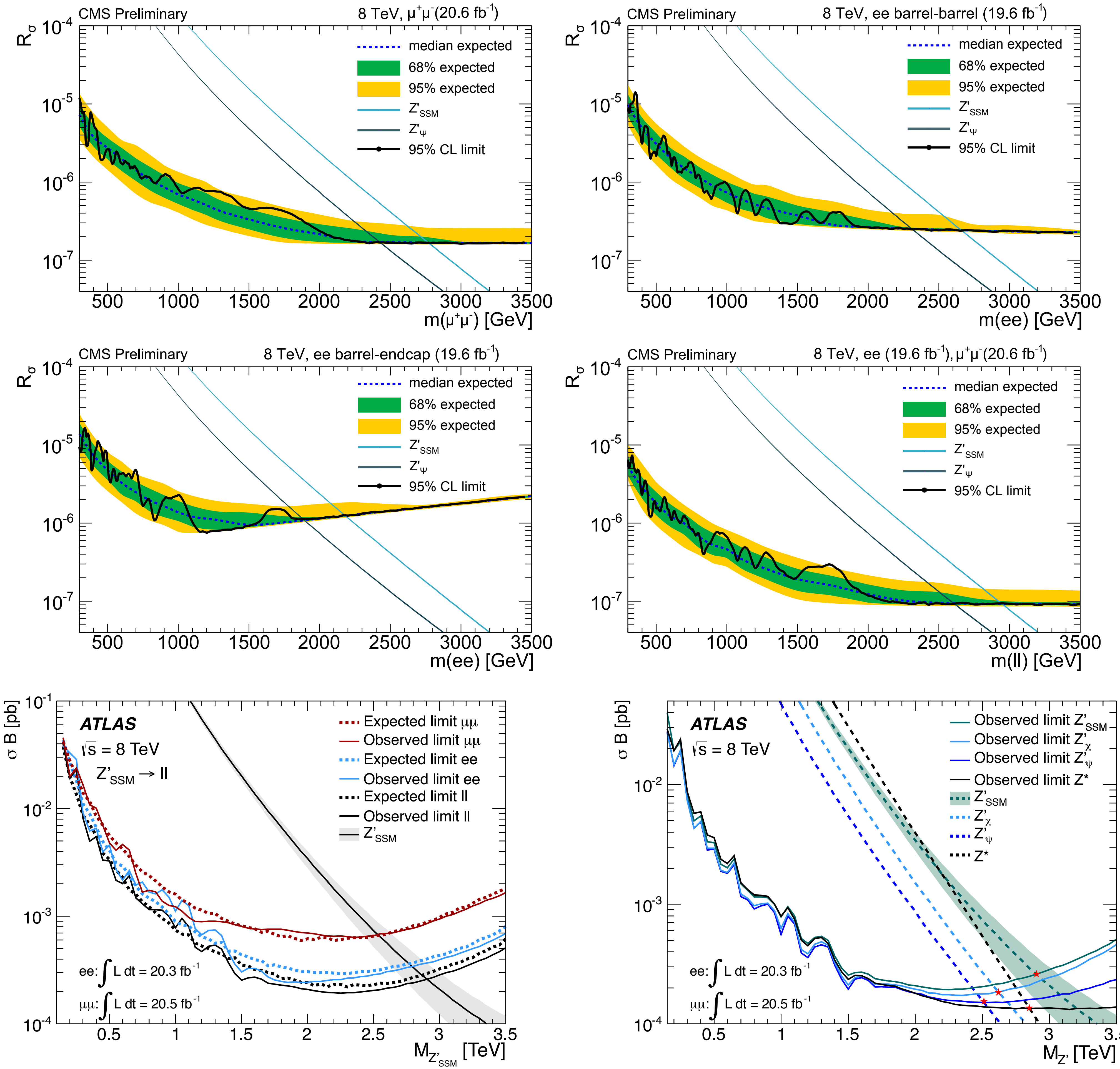
This is NOT a complete list at all!

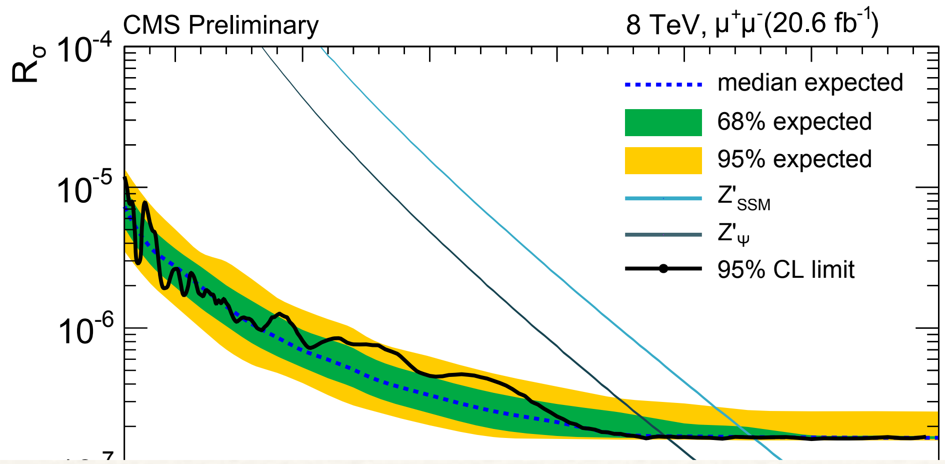
A few comments

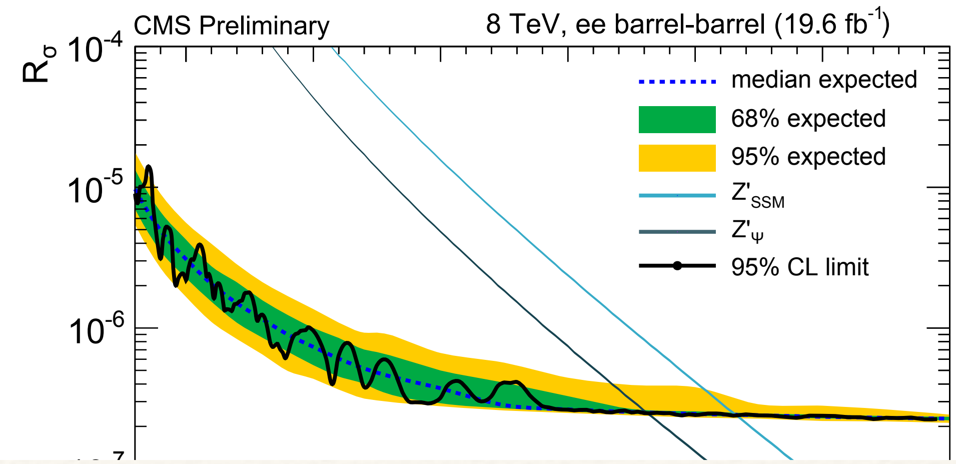
- Table tells us how a di-object decays. No information on its production.
- Search strategy can be different depending on the mass scale and details of each model.
- One can further classify
  - in terms of electric charge (SS/DS), color charge (single, triplet, octet, sextet etc), Lorentz symmetry (scalar/fermion/vector)
  - e and mu are different. tau is special. Gluon and quarks are different.
- Table can be extended with THREE reconstructed objects.
- Reconstruction of a resonance in MET channel is challenging.
  - Various ideas exist: MT2, M2 etc. (See Doojin's talk)

- Certainly the table is not complete and can be improved. Nevertheless we are covering these boxes pretty well.
- In fact, almost all spots are considered at least in theory.
- Some channels are looked at experimentally and some are not.
- However, we always have to remember what assumptions are made behind each analysis.
- We cover final states reasonably but we make strong assumptions on their production.
- We will take a look at three examples of resonances with non-standard production mechanism that might escape current analysis.
    - dilepton, dijet and ttbar resonances.

dilepton resonance


CMS Preliminary
8 TeV, μ+μ- (20.6 fb-1)
Rσ
median expected
68% expected
95% expected
Z'SSM
Z'ψ
95% CL limit
m(μ+μ-) [GeV]
CMS Preliminary
8 TeV, ee barrel-barrel (19.6 fb-1)
m(ee) [GeV]
CMS Preliminary
8 TeV, ee barrel-endcap (19.6 fb-1)
m(ee) [GeV]
CMS Preliminary
8 TeV, ee (19.6 fb-1), μ+μ- (20.6 fb-1)
m(ll) [GeV]
ATLAS
√s = 8 TeV
Z'SSM → ll
σ B [pb]
Expected limit μμ
Observed limit μμ
Expected limit ee
Observed limit ee
Expected limit ll
Observed limit ll
Z'SSM
ee: ∫L dt = 20.3 fb-1
μμ: ∫L dt = 20.5 fb-1
MZ'SSM [TeV]
ATLAS
√s = 8 TeV
Observed limit Z'SSM
Observed limit Z'χ
Observed limit Z'ψ
Observed limit Z*
Z'SSM
Z'χ
Z'ψ
Z*
ee: ∫L dt = 20.3 fb-1
μμ: ∫L dt = 20.5 fb-1
MZ' [TeV]





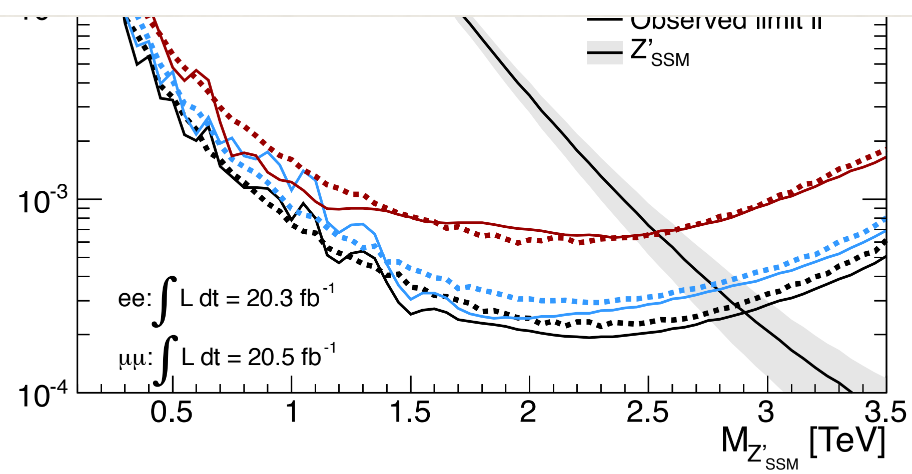
Credits: F. Würthwein, ICHEP 2014

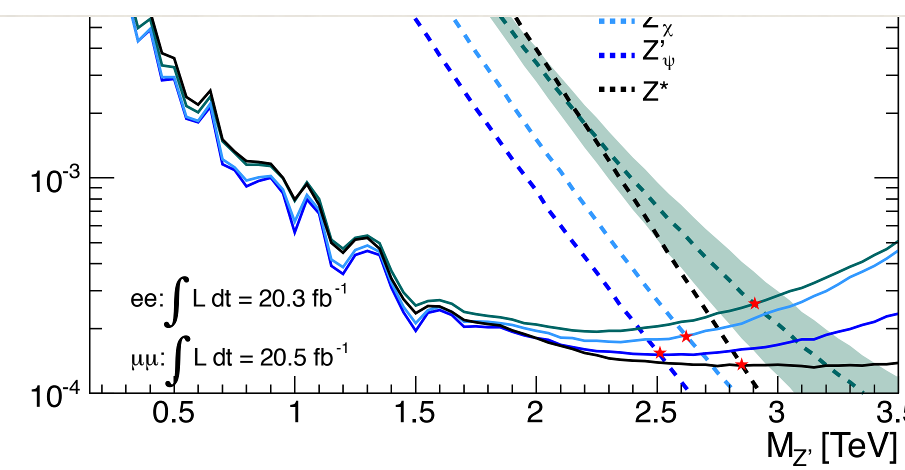
Final State	Highest mass event	Highest mass limit
ee	~1.8TeV	2.79TeV
mumu	~1.8TeV	2.53TeV
tautau	~0.7TeV	1.9TeV
dijet	~5.1TeV	5.1TeV
lnu	~2.4TeV	3.4TeV
bb	~4.1TeV	~1.2-1.5TeV
top b	~3.8TeV	2.05TeV
ttbar*	~3.5TeV	1.8TeV

Fermion Pairs

Final State	Highest mass event	Highest mass limit
WZ(3lnu)	~1.1TeV	1.5TeV
VV(jjlnu)	~3.3TeV	2.5TeV
Vq(jj)*	~3.7TeV	3.2TeV
VV(jj)*	~2.7TeV	1.7TeV
ZZ(lljj)	~1.7TeV	0.85TeV
hh(4b)	~1.3TeV	590-710GeV
Wt	~1.8TeV	1.8TeV
γjet	~3TeV	3.5TeV

Final states with bosons



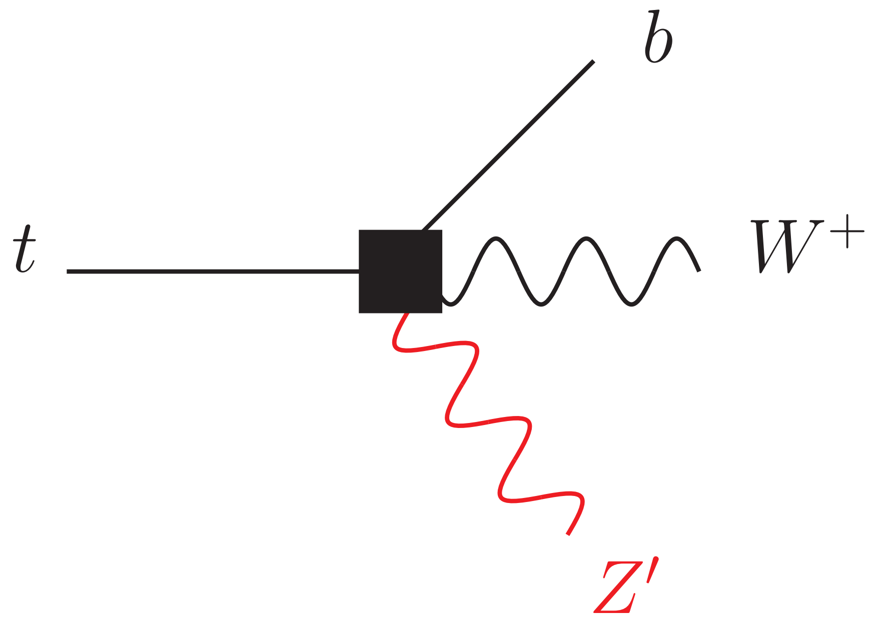


Is a very light dilepton resonance searched for?

Perhaps dilepton resonance exists in the low mass region (not in the high mass side).

Perhaps we were going in the wrong direction.

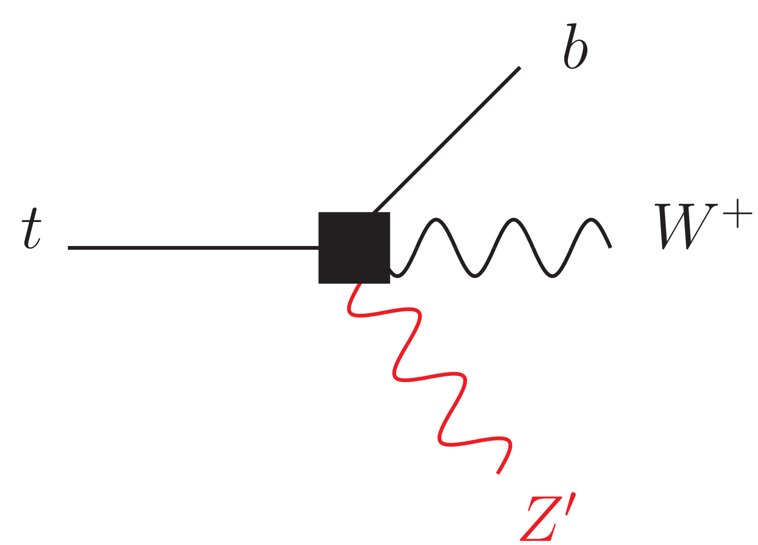
Maybe dilepton resonance is produced via top quark, not from qqbar annihilation.



- MZprime ~ O(1-10) GeV

Charged Higgs + Z'

- Dark Z + 2HDM (type I)
- Charged Higgs: H+/H-   (mW < mH+ < mtop)
- Neutral Higgses: h, H   and A
- Dark Z: Zd of mass O(1-10) GeV (1, 2 and 5 GeV)



Dark Zprime (Zd)

- A gauge boson of a new dark U(1).
- Light Zd with weak couplings to SM may address various anomalies such as positron data, muon g-2 etc.
- Zd has no direct couplings to SM. It couples to SM via kinetic mixing + extra mass mixing.
- Exact couplings depend on details of model, especially on higgs sector.
- It opens up exotic Higgs decays and provides interesting collider signatures!

$$\begin{aligned}\mathcal{L}_{\text{dark }Z} &= -\left(\varepsilon e J^{\mu}_{em} + \varepsilon_Z g_Z J^{\mu}_{\text{NC}}\right) Z'_{\mu} \\ &= \bar{f}\left(g_V \gamma^{\mu} - g_A \gamma^{\mu}\gamma^5\right) f Z'_{\mu}\end{aligned}$$

$$\begin{aligned}g_V &= -\varepsilon e Q_f - \varepsilon_Z g_Z \left(\frac{1}{2}T_{3f} - Q_f \sin^2\theta_W\right) \\ g_A &= -\varepsilon_Z g_Z \left(\frac{1}{2}T_{3f}\right),\end{aligned}$$

$$|\varepsilon| \lesssim 10^{-2} \qquad \varepsilon_Z \equiv \delta \, \frac{m_{Z'}}{m_Z}$$

$$|\delta| \lesssim 10^{-2}$$

Charged Higgs + Zd

- In 2HDM, FCNC constraints can be addressed by a new U(1), under which Higgs doublets carry different charges.

- Such a scenario may introduce tree-level HWZprime coupling.

- For a light “dark” Z model (with mass < 10 GeV), charged Higgs may decay dominantly into W + Zd (for mass < mtop)

- For a Zd with O(1) GeV mass, BR into leptons is large.

- At LHC, such a Zd can be boosted, and two leptons from Zd decay appear as a Lepton-Jet.

Davoudiasl, Marciano, Ramos, Sher, 2014

Kong, Lee, Park, 2014

Charged Higgs (H+) decay

- For MH+ < mtop, dominant decays are into cs and tau-neutrino in usual 2HDM.
- For (i), the lighter Higgs boson is SM-like. H+W-Zd coupling is small but H+ Br to WZd can be large.
- For (ii), the charged Higgs can decay to the lighter Higgs. In the decoupling limit (alpha=pi/2 or -pi/2), the heavier Higgs is SM-like.
- Br(h -> Zd Zd) ~ 1, since h does not couple to SM fermions. (Type I)
- In both (i) and (ii), over much of parameter space, Y~1. Whether (i) or (ii) dominates depends on the mass of Higgs boson, especially mass of non-SM Higgs.
- In principle, $t \to qZ'$ (with $q = u, c$) is possible.

$$\Gamma(H^+ \to \nu\tau^+) \simeq \frac{m_{H^\pm}}{8\pi v^2}\frac{m_\tau^2}{\tan^2\beta}$$

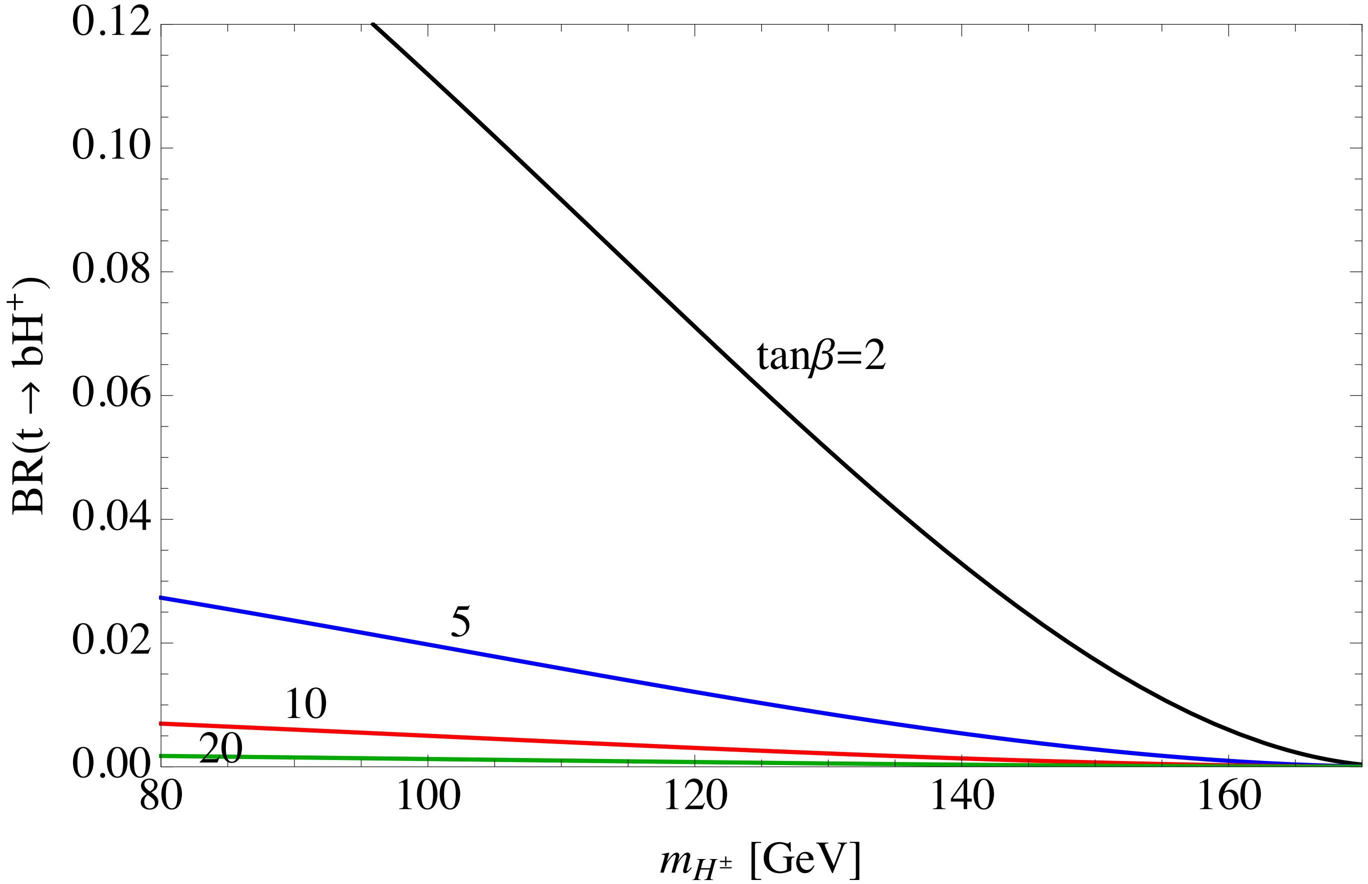
$$\Gamma(H^\pm \to WZ') \simeq \frac{m_{H^\pm}^3}{16\pi v^2}(\sin\beta\cos\beta_d)^2\left(1-\frac{m_W^2}{m_{H^\pm}^2}\right)^3$$

$$\Gamma(H^\pm \to Wh) \simeq \frac{\sin^2\beta}{16\pi v^2}\frac{1}{m_{H^\pm}^3}\lambda^{3/2}(m_{H^\pm}^2, m_W^2, m_h^2)$$

$$Y \equiv \mathrm{BR}(H^\pm \to W + Z'\mathrm{s}),$$

(i) $t \to bH^+ \to bW + Z'$
(through $H^\pm W^\mp Z'$ coupling),
(ii) $t \to bH^+ \to bW + h \to bW + Z'Z'$
(with a light non-SM Higgs boson h),
(iii) $t \to bW^* \to bW + Z'$
(through $Z'WW$ coupling),
(iv) $t \to bW^* \to bW + h \to bW + Z'Z'$
(through hWW coupling).

Top decay into Zd via H+



- For numerical analysis, we focus on

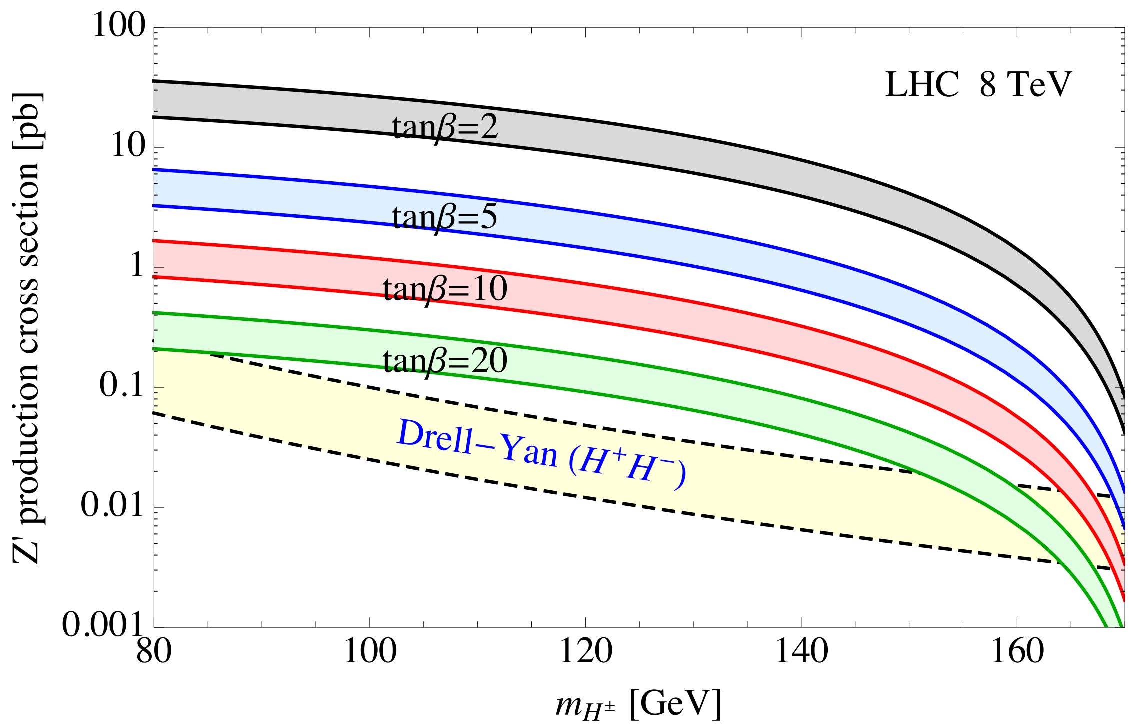
  (i) $t \to bH^+ \to bW + Z'$
  (through $H^\pm W^\mp Z'$ coupling)

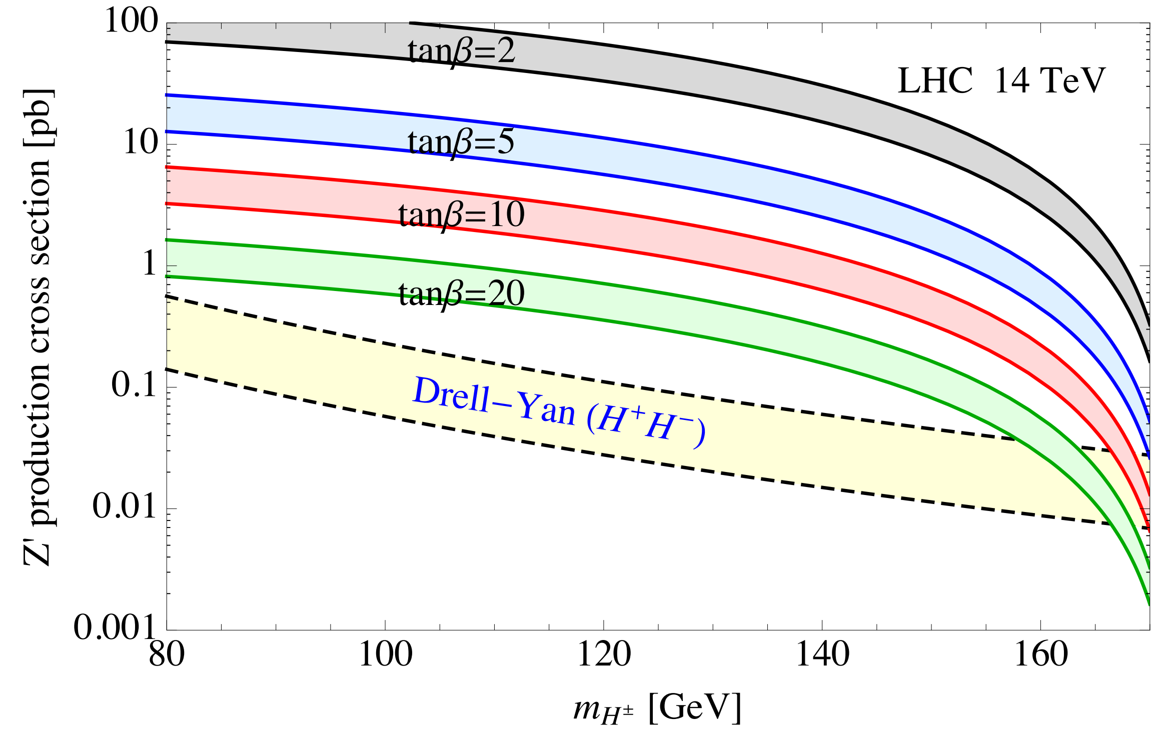
- Higher BR for lower tan(beta).

- Current limit allows O(1)% branching fraction.

$$\mathrm{BR}(t \to bH^+) \simeq \frac{\Gamma_{t\to bH^+}}{\Gamma_{t\to bW} + \Gamma_{t\to bH^+}}$$
$$\approx \left(\frac{m_t^2 - m_{H^\pm}^2}{m_t^2 - m_W^2}\right)^2 \frac{1/\tan^2\beta}{1 + 2m_W^2/m_t^2}$$

Production of Zd





- Zd production in DY ($pp \to H^+H^- \to WW + Z'Z'$) and top pair production,

$$\sigma(pp \to bW\,\bar{b}W + Z'\mathrm{s}) \simeq \sigma_{t\bar{t}}\,2X \quad X = \mathrm{BR}(t \to bH^+)\,Y$$

- The band indicates BR(H+ -> W Zd)=0.5-1 range. $Y = \mathrm{BR}(H^\pm \to WZ') = 0.5 - 1$
- Cross section at 14 TeV is about 4 times larger than that at 8 TeV.
- For a low tan(beta), top quark production is important.

Lepton Pair from Zd decay

- Light Zd cannot be reconstructed with the usual lepton tagging.
- $\Delta R \simeq \Delta\eta$ since $\Delta\phi$ is peaked at 0.

$$\begin{aligned} m^2_{\ell^+\ell^-} &= 2P_{T_1}P_{T_2}\left(\cosh\Delta\eta - 1\right) \\ &\simeq 2P_{T_1}P_{T_2}\left(\cosh\Delta R - 1\right) \end{aligned}$$

- For a moderate lepton tagging efficiency, most analysis require

$$P^{\rm min}_{T(e)} = 10\ {\rm GeV}, \quad P^{\rm min}_{T(\mu)} = 5\ {\rm GeV}.$$

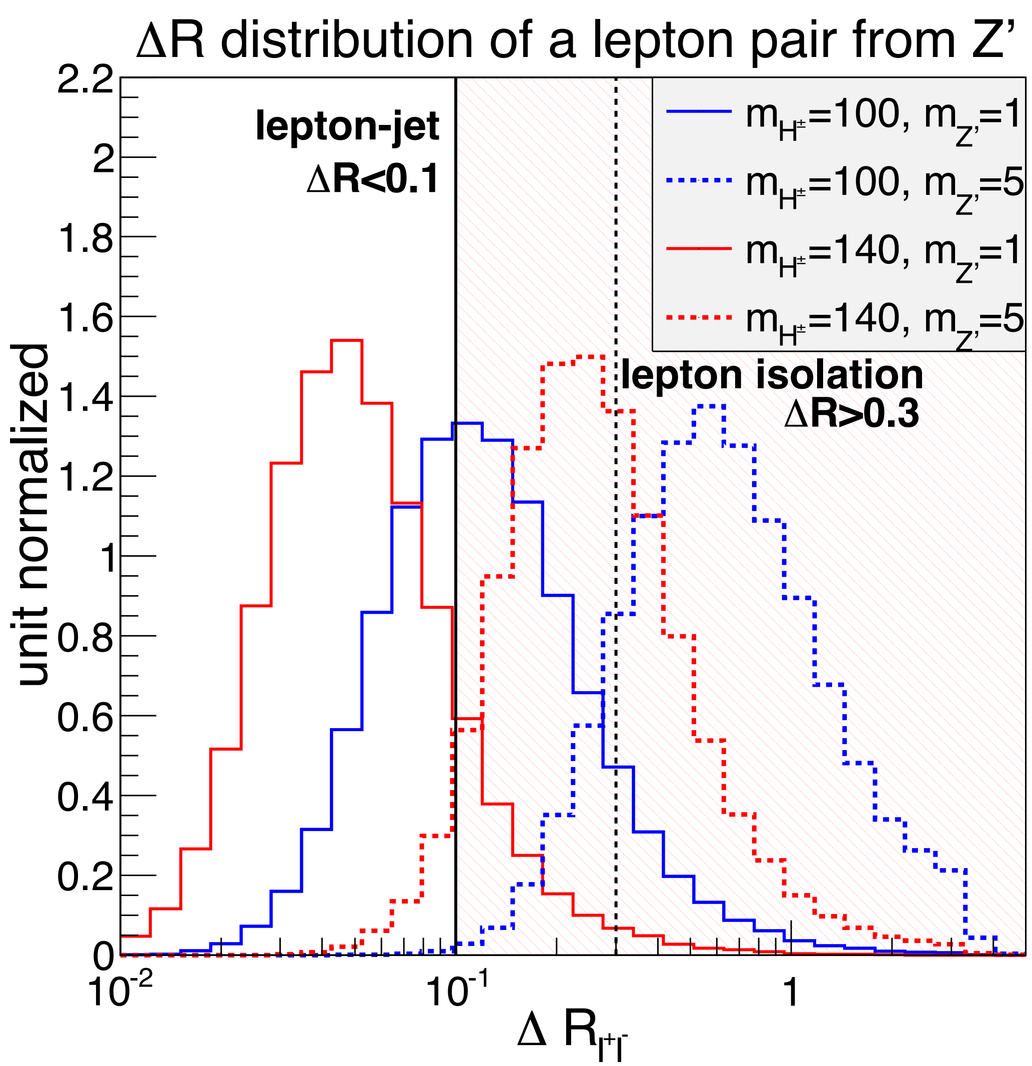
- With an isolation requirement of $\Delta R > 0.3$,

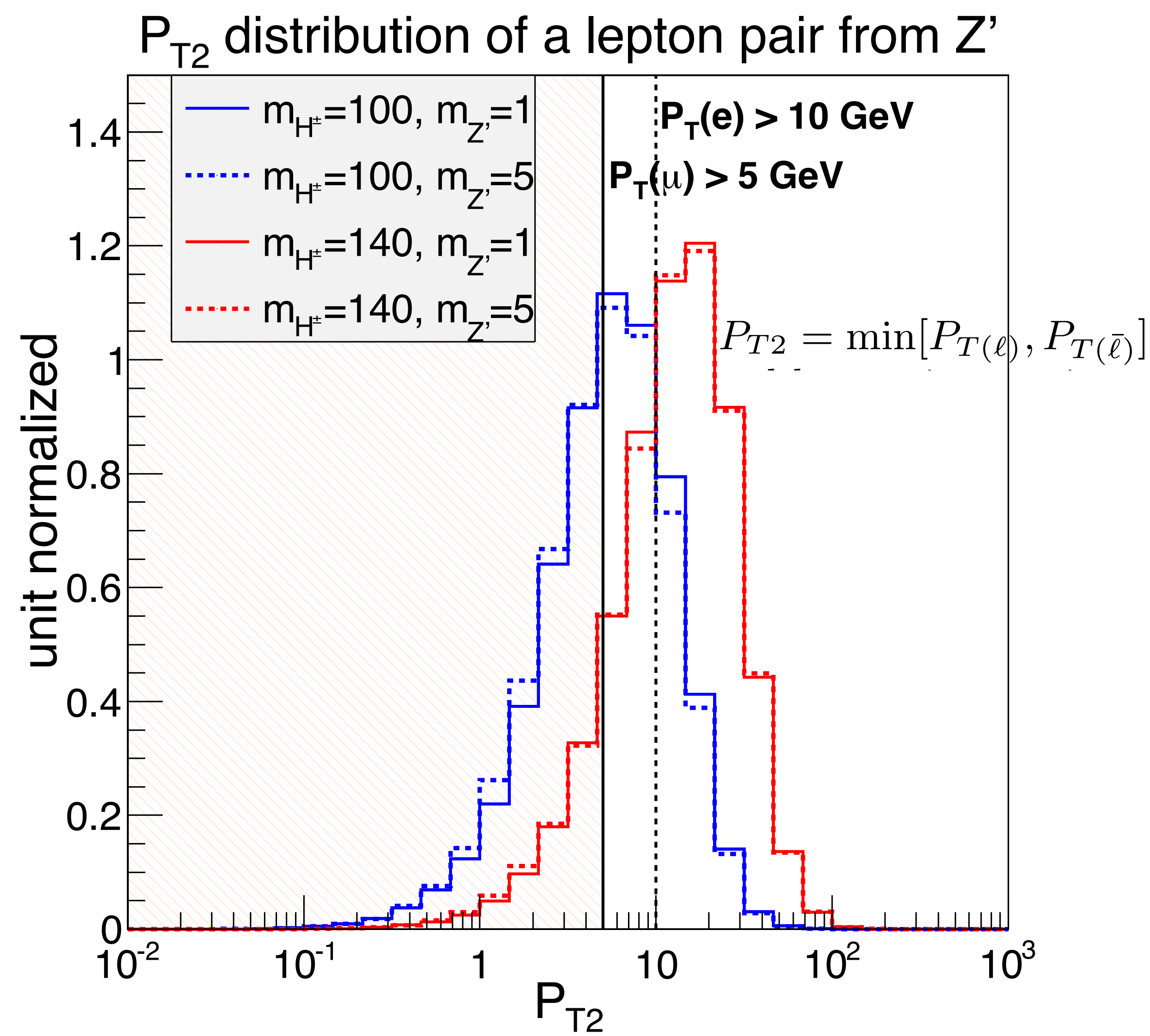
$$m_{ee} > \sqrt{2P^{\rm min}_{T(e)}P^{\rm min}_{T(e)}(\cosh(0.3)-1)} \simeq 3\ {\rm GeV},$$
$$m_{\mu\mu} > \sqrt{2P^{\rm min}_{T(\mu)}P^{\rm min}_{T(\mu)}(\cosh(0.3)-1)} \simeq 1.5\ {\rm GeV}.$$

- Conventional analysis would miss Zd lighter than 3 (1.5) GeV in the dielectron (dimuon) channel.

Lepton Pair from Zd decay

- Light Zd cannot be reconstructed with the usual lepton tagging.





$$\Delta R^{(\text{peak})} \sim \cosh^{-1}\left(\frac{2m_{Z'}^2}{(E_\ell^{(\text{cusp})})^2}+1\right)$$

$$\eta_{H^\pm} = \cosh^{-1}\left(\frac{m_t^2+m_{H^\pm}^2-m_b^2}{2m_t m_{H^\pm}}\right),$$

$$\eta_{Z'} = \cosh^{-1}\left(\frac{m_{H^\pm}^2+m_{Z'}^2-m_W^2}{2m_{Z'} m_{H^\pm}}\right).$$

$$E_\ell^{(\max)} = \frac{m_{Z'}}{2}e^{(\eta_{Z'}+\eta_{H^\pm})}$$

$$E_\ell^{(\text{cusp})} \equiv \frac{m_{Z'}}{2}e^{|\eta_{Z'}-\eta_{H^\pm}|}$$

$$P_T^{\text{peak}} \equiv \frac{1}{2}E_\ell^{(\text{cusp})}$$

Kong, Lee, Park, 2014

Improved Lepton Selection

1. At least two same flavor leptons with $P_T > 10$ GeV (electron), 5 GeV (muon) and in a cone of $\Delta R < 0.1$.
2. Isolation: Hadronic and leptonic isolation of $\sum P_T < 3$ GeV in $0.1 < \Delta R < 0.4$.
3. Invariant mass cut on lepton-jet: $|m_{\mathrm{LJ}} - m_{Z'}| < 0.2 \times m_{Z'}$.

- For our study, we use FeynRules, MG4, PYTHIA, and Delphes.
- 60%-75% of b-tagging efficiency, depending on PT and ETA, following CMS CSVM tagging.

- We make minor changes in the Delphes module to include the non-zero muon mass in the original routine.
- We add the lepton-jet class in the Delphes, following above definitions.
- Use anti-kt with DeltaR < 0.5. Require at least one b-tagged jet and above LJ conditions.
- For numerical study, we use $X = 0.001$ and $\mathrm{BR}(Z' \to \ell^+\ell^-) = 0.2$

$$\sigma(pp \to bW\,\bar{b}W + Z'\mathrm{s}) \simeq \sigma_{t\bar{t}}\,2X \quad X = \mathrm{BR}(t \to bH^+)\,Y$$

Signal and Backgrounds

- Dilepton channel
  - pt < 20 GeV, eta < 2.5 for electron   and   pt > 20 GeV, eta < 2.1 for muon
  - veto OSSF with mll < 20 GeV and | MZd - mll | < 15 GeV,   met > 40 GeV
  - at least two jets with pt > 30 GeV, eta < 2.5
- Semileptonic channel
  - pt > 30 GeV, eta < 2.5 for electron   and   pt > 26 GeV, eta < 2.1 for muon
  - at least four jets with pt1, pt2 > 45 GeV, pt3, pt4 > 35 GeV.
- Hadronic channel
  - at least 6 jets, pt > 30 GeV, eta < 2.4.
  - CMS requires pt1, pt2, pt3, pt4 > 60 GeV, pt5 > 50 GeV, pt6 > 30 GeV, and additional constrains for two b-tagged jets and a kinematic for mass reconstruction of tops and W.
- Backgrounds: ttbar + dilepton   with Kbknd=2. (Ksig=1.74 (1.84) at 8 (14) TeV.)

LJ Tagging Efficiencies

LHC [TeV]	$m_{Z'}$ [GeV]	$\epsilon_{\rm LJ}(\epsilon_{\rm (LJ+CMS)})$ [%] for signal $m_{H^\pm} = 100$ GeV	$m_{H^\pm} = 140$ GeV	$m_{H^\pm} = 160$ GeV	Mass range of $m_{\ell^+\ell^-}$ [GeV]	$\sigma^{\rm LO}_{\rm bkg}$ [pb]	$\epsilon_{\rm LJ}(\epsilon_{\rm (LJ+CMS)})$ [%] for background
8	1	16.37 (4.18/2.07)	46.77 (10.96/4.51)	52.04 (9.40/3.04)	$0.5 - 1.5$	0.617	2.05 (0.61/0.28)
	2	3.07 (0.92/0.43)	31.01 (7.64/3.13)	40.74 (7.57/2.50)	$1.0 - 3.0$	0.157	0.53 (0.19/0.08)
	5	0.02 (0.00/0.00)	2.24 (0.64/0.26)	5.55 (1.25/0.48)	$3.0 - 5.0$	0.0175	0.32 (0.10/0.04)
14	1	16.38 (4.28/2.02)	44.28 (10.73/4.37)	50.54 (9.44/3.13)	$0.5 - 1.5$	2.536	2.18 (0.60/0.30)
	2	3.33 (1.11/0.49)	29.73 (7.52/3.13)	39.31 (7.64/2.51)	$1.0 - 3.0$	0.640	0.57 (0.23/0.11)
	5	0.03 (0.01/0.00)	2.57 (0.76/0.28)	5.90 (1.40/0.47)	$3.0 - 5.0$	0.0706	0.34 (0.15/0.08)

TABLE III: Lepton-jet tagging efficiency $\epsilon_{\rm LJ}$ (%) in $pp \to bW\bar{b}W + \ell^+\ell^-$ for signal (for given $m_{H^\pm}$ and $m_{Z'}$) and background (from virtual photon and virtual Z boson) at the 8 and 14 TeV LHC. The numbers in parentheses ($\epsilon_{\rm (LJ+CMS[1b])}/\epsilon_{\rm (LJ+CMS[2b])}$) are the efficiencies when we require additional selection cuts, requiring one b-tagged or two b-tagged jets as described in Appendix A 2. Coupling structure of Z' to the lepton does not give a significant effect on the tagging efficiency. In the above table, we take axial coupling as an example. For backgrounds, we set the trigger of a $m_{\ell^+\ell^-}$ mass window as in the table to enlarge statistics.

Kong, Lee, Park, 2014

Signal and Backgrounds

$m_{Z'}$ [GeV]	$m_{H^\pm}$ 100 GeV	140 GeV	160 GeV	BKG
1	40.0	86.2	58.1	69.6
2	8.2	59.9	47.8	5.0
5	0.1	5.0	9.1	0.3

TABLE I: Expected number of events in each lepton-jet bin (20% window of the Z' mass) with two b-tagging in 8 TeV LHC 20 fb^{-1}. We set $X = 0.001$ and $\mathrm{BR}(Z' \to \ell^-\ell^+) = 0.2$. Signal events were obtained with high order $\sigma_{t\bar{t}}$ with branching ratio, and the background events were obtained with tree-level simulation with $K_{\rm bkg} = 2$.

$m_{Z'}$ [GeV]	$m_{H^\pm}$ 100 GeV	140 GeV	160 GeV
1	$7.8\,\mathrm{fb}^{-1}$	$1.9\,\mathrm{fb}^{-1}$	$3.4\,\mathrm{fb}^{-1}$
2	$14.5\,\mathrm{fb}^{-1}$	$0.7\,\mathrm{fb}^{-1}$	$1.0\,\mathrm{fb}^{-1}$
5	-	$7.3\,\mathrm{fb}^{-1}$	$3.5\,\mathrm{fb}^{-1}$

TABLE II: Required luminosity for 14 TeV LHC to see the likelihood ratio $S_{\rm cL} = 5$ (corresponding to 5σ discovery). Basically the same method as Table I is used.

- At 8 TeV, top pair production cross section ~239 pb.
- For mH+ = 140 GeV, MZd=2 GeV,

$$N_{\rm sig} = \sigma_{t\bar{t}}\, 2X\, \mathrm{BR}(Z' \to \ell^+\ell^-)\, \epsilon_{\rm sig}\, L \approx 60$$

$$N_{\rm bkg} = \sigma_{\rm bkg}\, \epsilon_{\rm bkg}\, L \approx 5$$

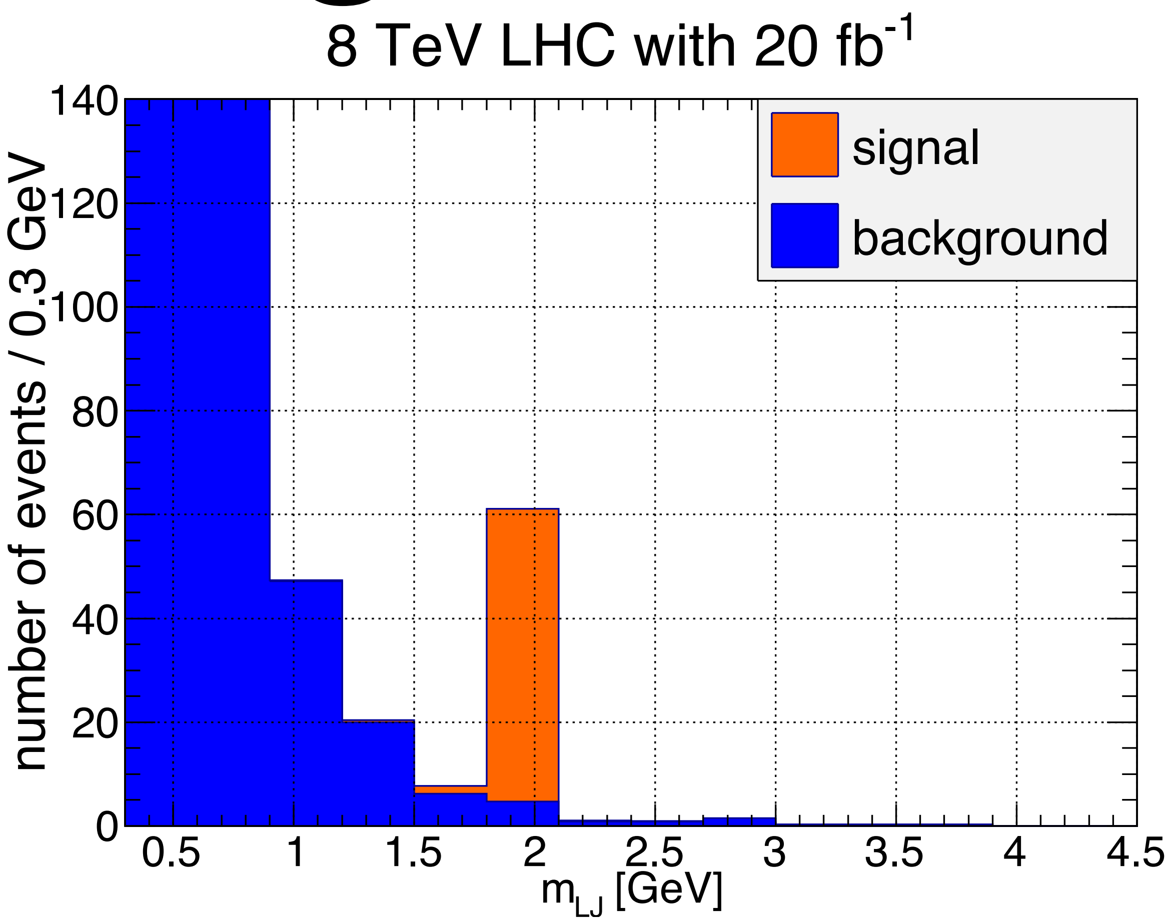
$$N_{\rm obs} = N_{\rm sig} + N_{\rm bkg}$$

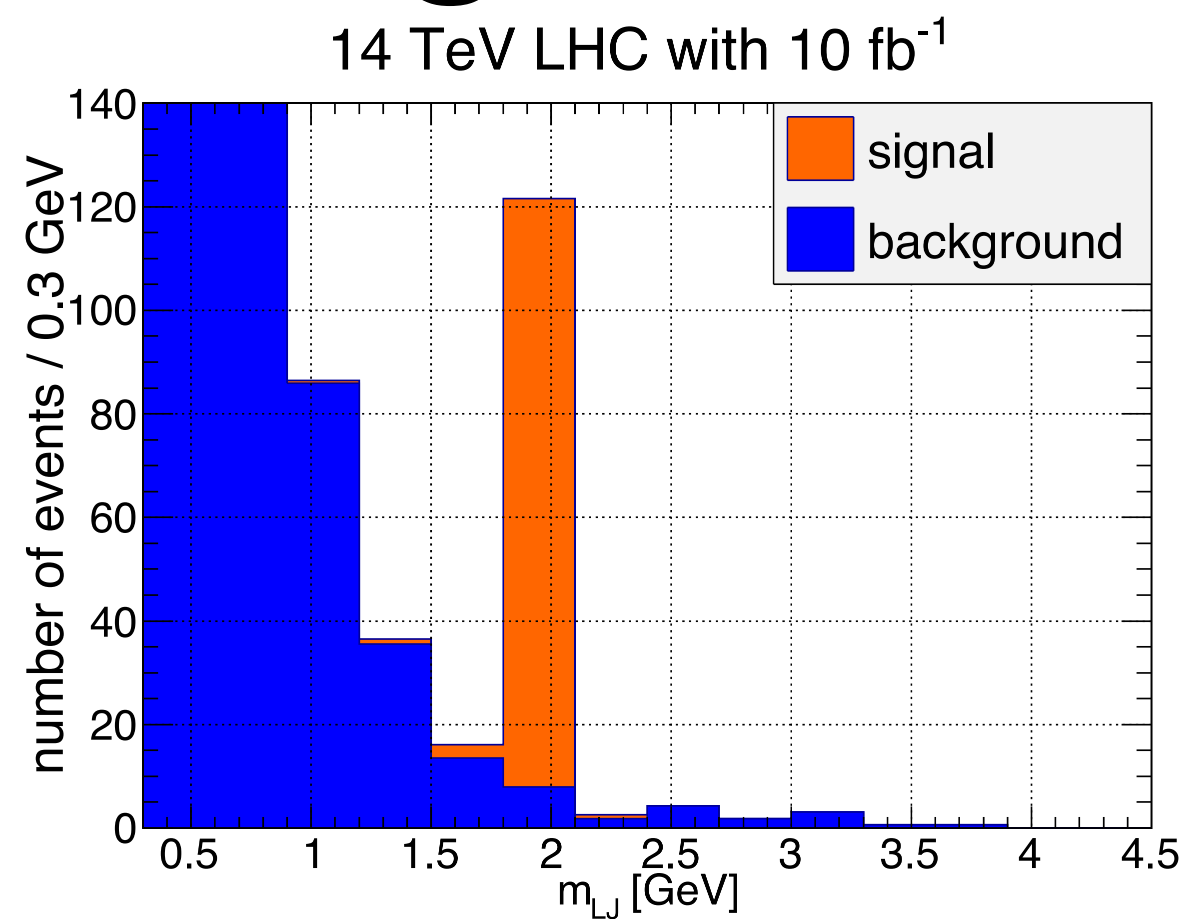
$$S_{\rm cL} = \sqrt{2N_{\rm obs}\log\left(1 + N_{\rm sig}/N_{\rm bkg}\right) - 2N_{\rm sig}} \simeq 14.6$$

- Conventional search gives Nsig~ 4 with eff=0.71%, and signal is buried in background uncertainty, which is 591.
- $N_{\rm bkg} \simeq 1.7 \times 10^4$ results in ScL=0.03.
- Good sensitivity for LHC Run II.

Kong, Lee, Park, 2014

Signal and Backgrounds





- At 8 TeV, top pair production cross section ~239 pb.
- For mH+ = 140 GeV, MZd=2 GeV,

$$N_{\rm sig} = \sigma_{t\bar{t}}\, 2X\, {\rm BR}(Z' \to \ell^+\ell^-)\, \epsilon_{\rm sig}\, L \approx 60$$

$$N_{\rm bkg} = \sigma_{\rm bkg}\, \epsilon_{\rm bkg}\, L \approx 5$$

$$N_{\rm obs} = N_{\rm sig} + N_{\rm bkg}$$

$$S_{\rm cL} = \sqrt{2N_{\rm obs}\log\left(1 + N_{\rm sig}/N_{\rm bkg}\right) - 2N_{\rm sig}} \simeq 14.6$$

- Conventional search gives Nsig~ 4 with eff=0.71%, and signal is buried in background uncertainty, which is 591.
- $N_{\rm bkg} \simeq 1.7 \times 10^4$ results in ScL=0.03.
- Good sensitivity for LHC Run II.

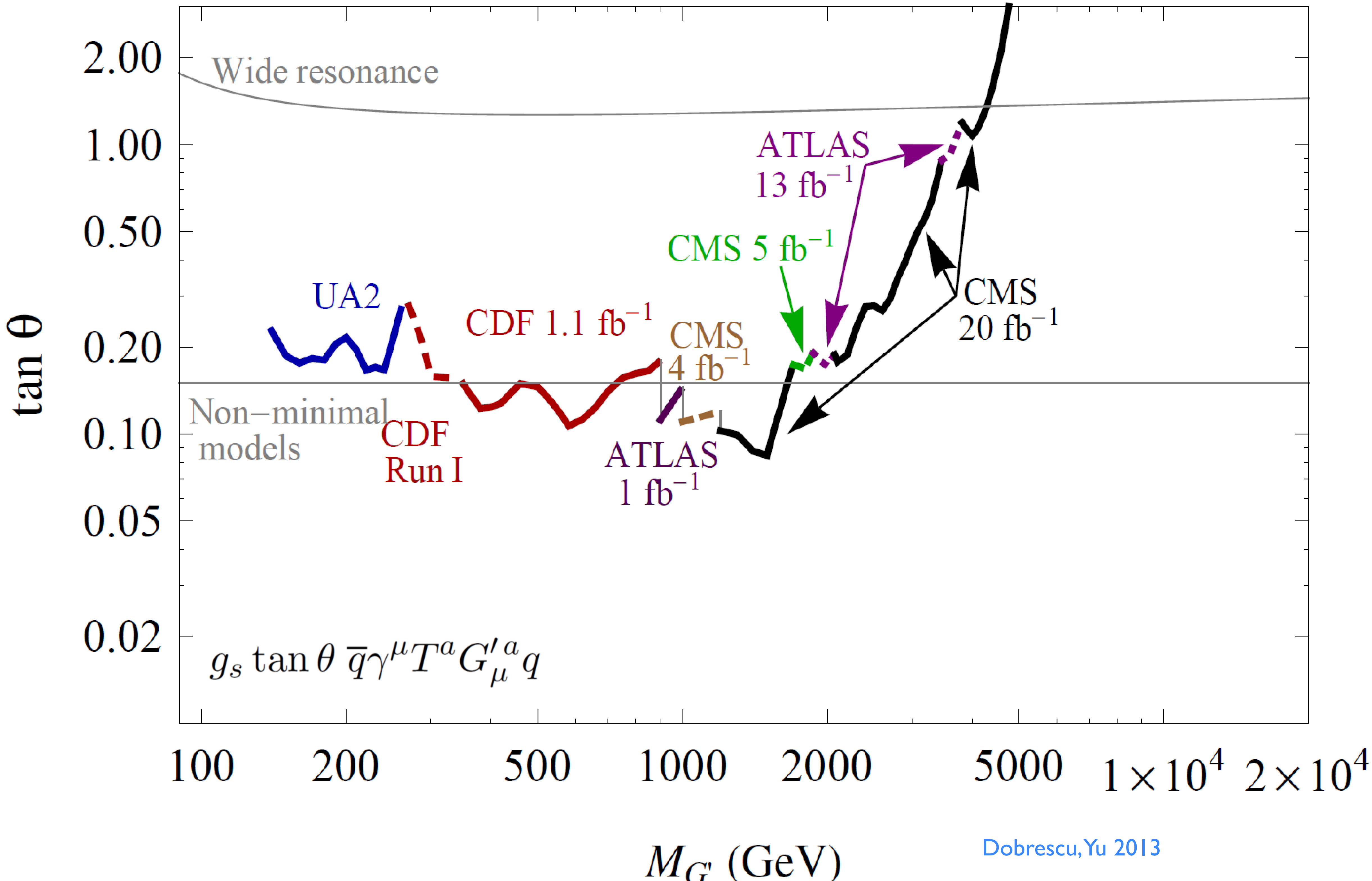
Kong, Lee, Park, 2014

A Light Dilepton resonance

- A light Zprime is well motivated and its search is very active at low energy experimental facilities.
- It also provides interesting collider signatures.
- It may be produced via top quark production.
- It decays to a collimated lepton pair, which may be missed by conventional searches.
- 8 TeV already rules out some parameter space.
- Exciting opportunity at LHC run II.

dijet resonance

Coupling vs. mass **current limits:** G'



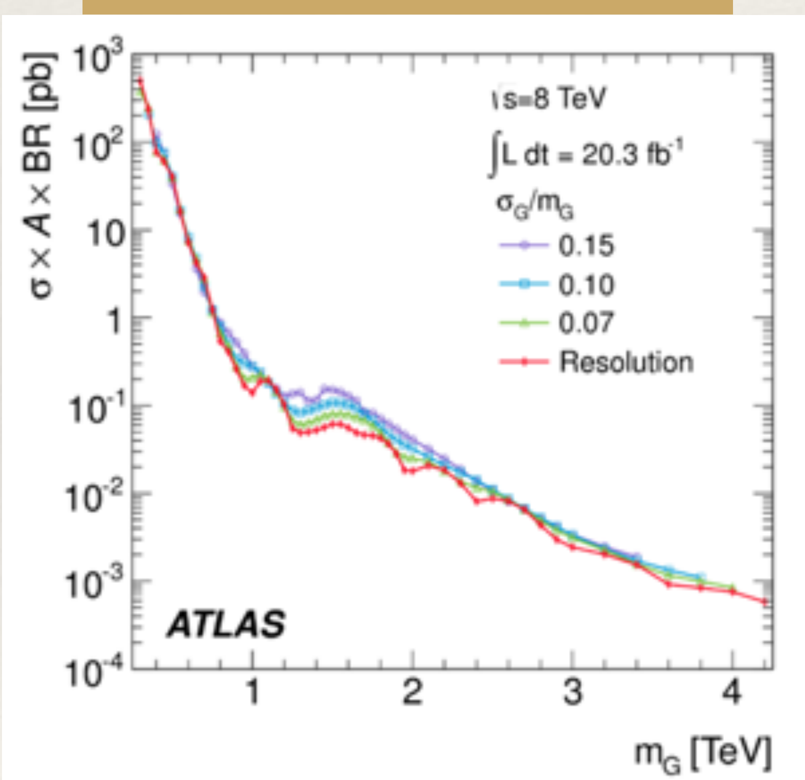
Dobrescu, Yu 2013

taken from Felix's talk

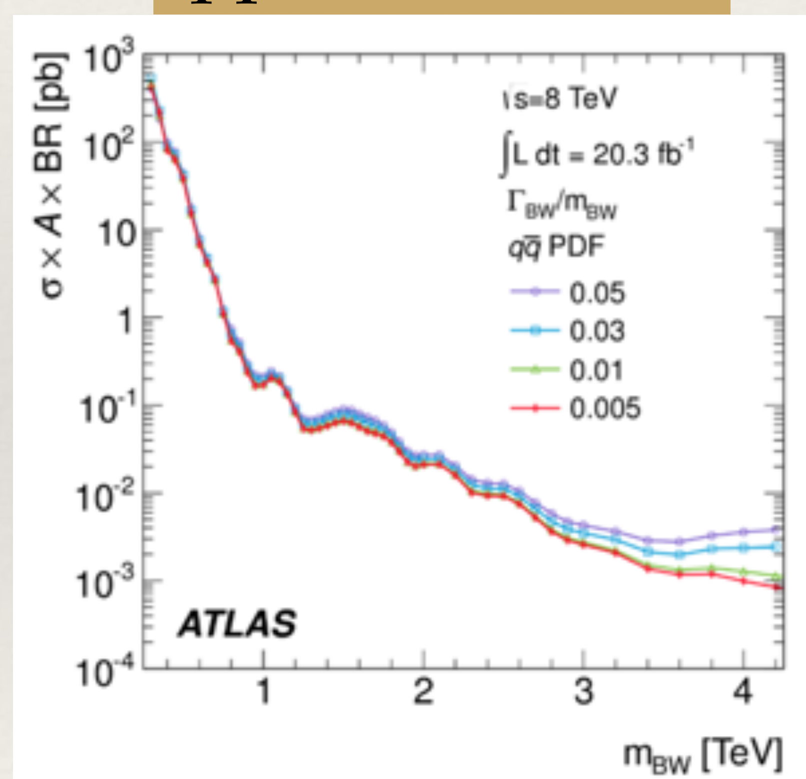
Dijet Resonances: pushing to low masses

- Model independent limits on $\sigma \times A$ for masses between 0.2 and ~4 TeV

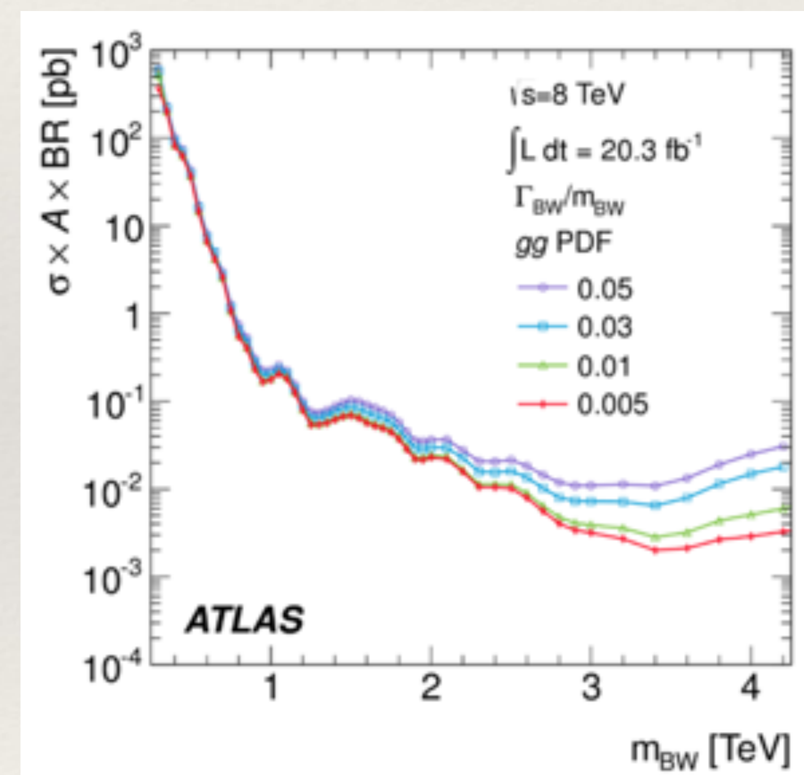
Generic Gaussian



qq induced BW

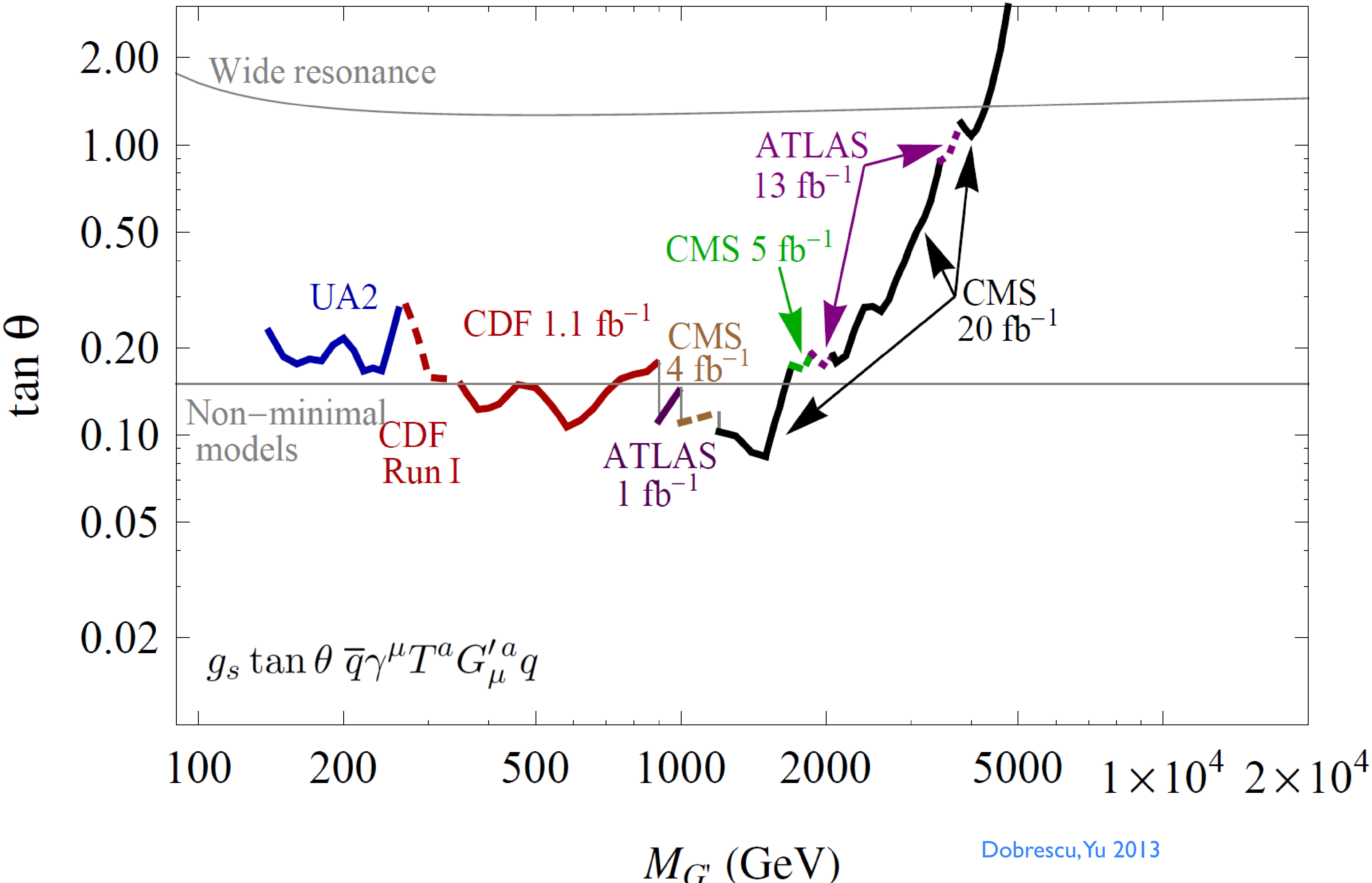


gg induced BW



Similar results from CMS but m > 1 TeV

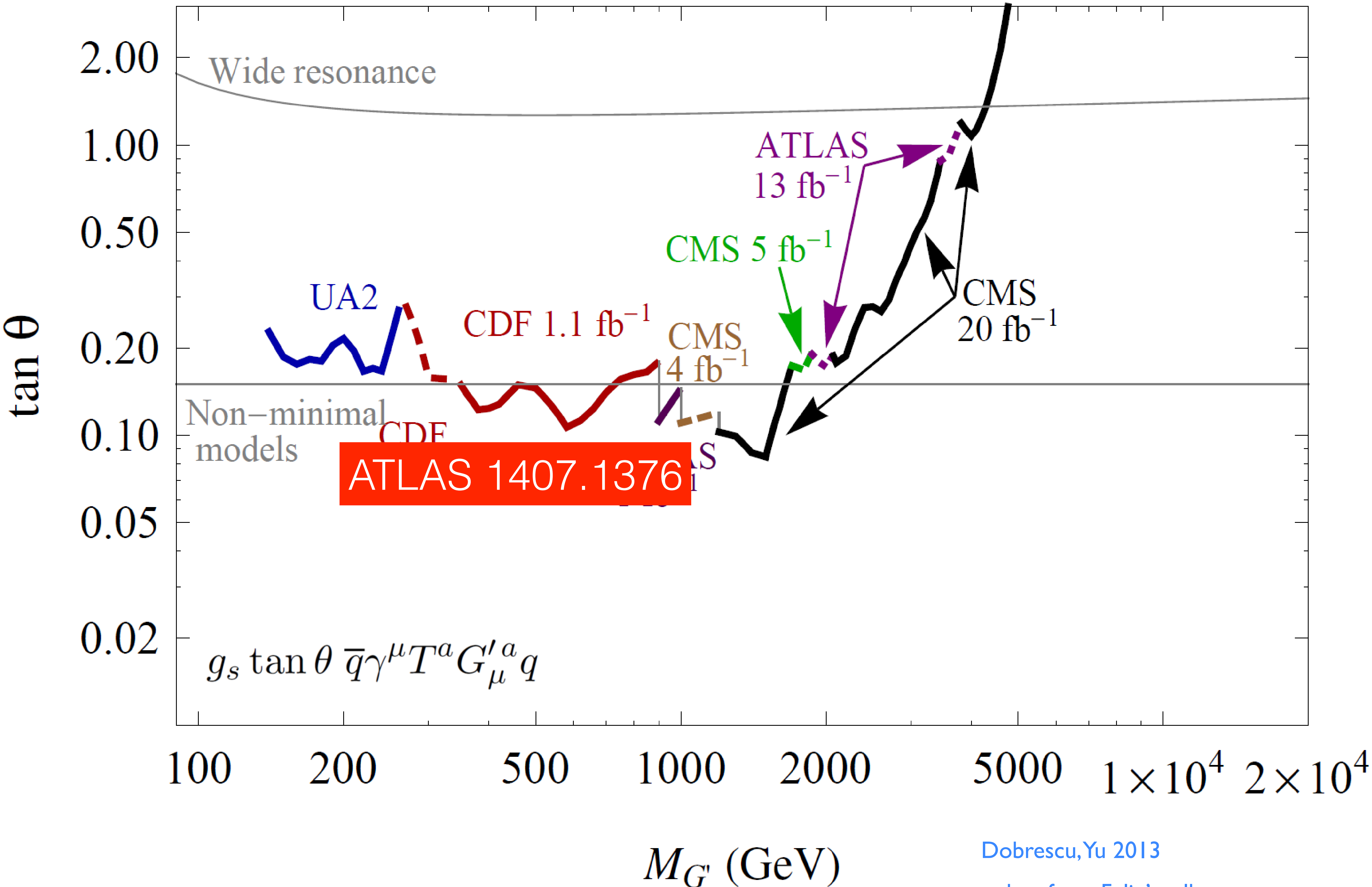
Coupling vs. mass **current limits: G'**



Dobrescu, Yu 2013

taken from Felix's talk

Coupling vs. mass **current limits**: G'



Dobrescu, Yu 2013

taken from Felix's talk

How do we look for a dijet resonance,
when diquark coupling is small?

Pair Production of Color Octet

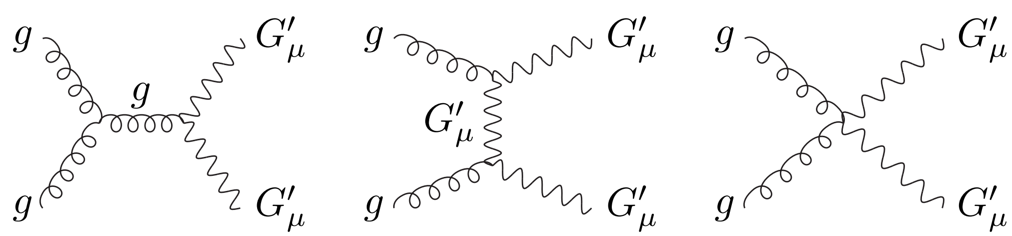
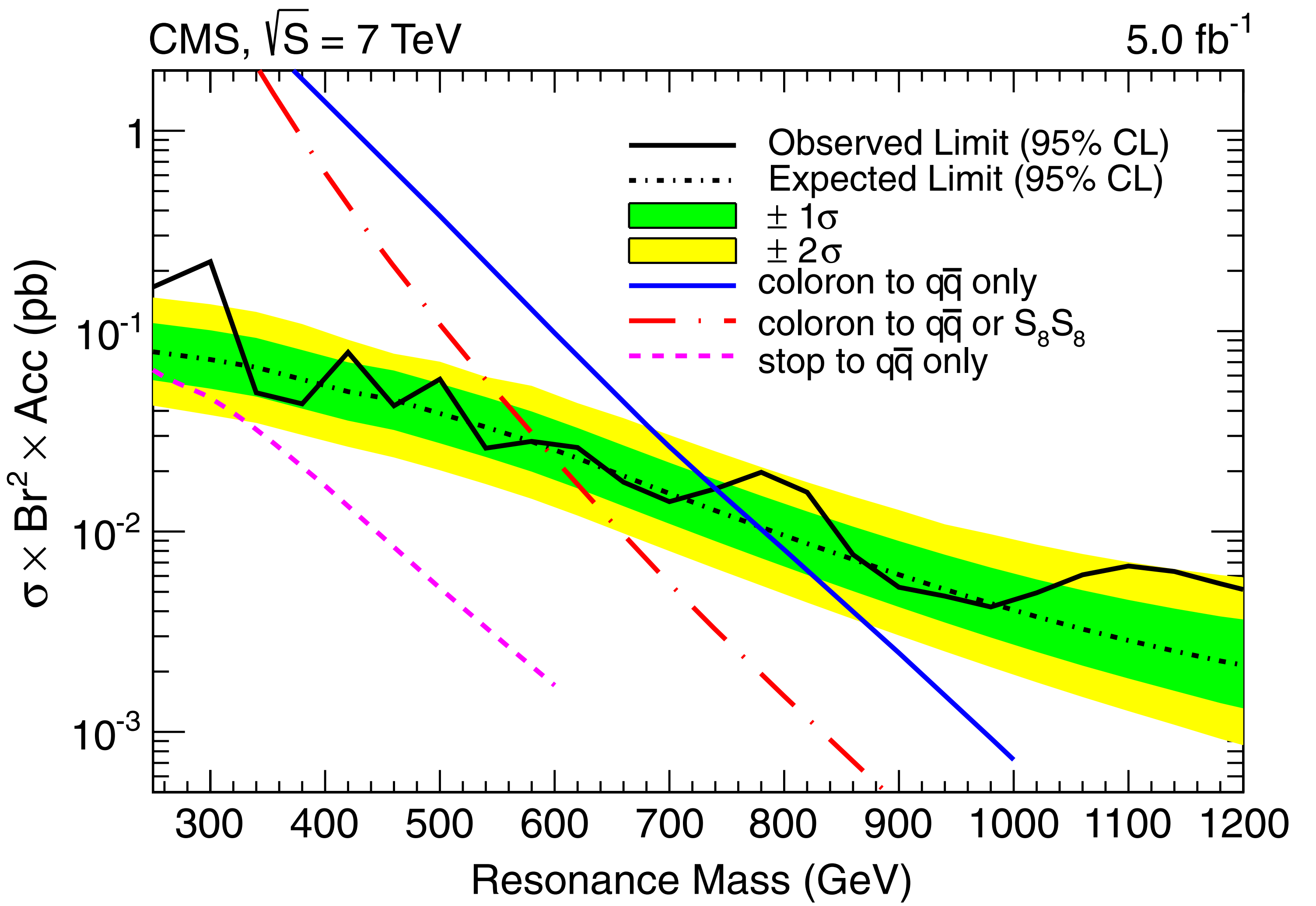


Figure 1: $G'_\mu G'_\mu$ production from gg initial state (u-channel G'_μ exchange is not shown). Curly lines represent gluons, while wavy lines represent massive vector octets.

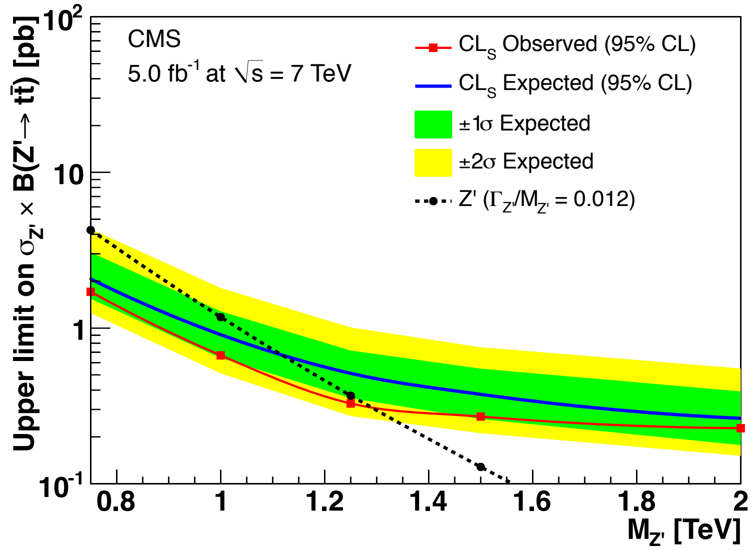
$$\frac{g_s^2}{2} f^{abc} f^{ade}\, G'^{\mu b} \left[G^{\nu d} \left(G'^{c}_{\nu} G^{e}_{\mu} + G'^{e}_{\mu} G^{c}_{\nu} \right) + G'^{e}_{\nu} G^{\nu c} G^{d}_{\mu} \right]$$
$$+ g_s f^{abc} G'^{a}_{\mu} \left[\left(\partial^\mu G'^{\nu b} - \partial^\nu G'^{\mu b} \right) G^{c}_{\nu} - G'^{b}_{\nu}\, \partial^\mu G^{\nu c} \right] \ .$$

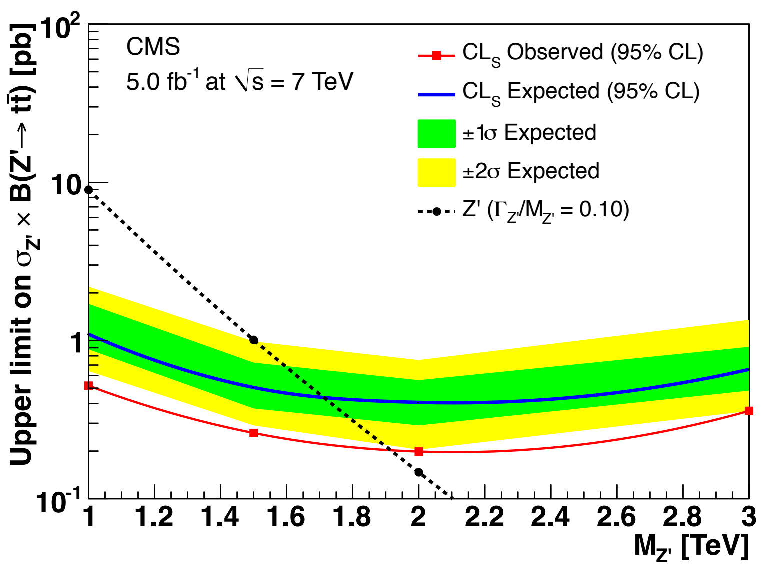
$$\sigma(gg \to G'_\mu G'_\mu) \;=\; \frac{9\pi\alpha_s^2}{16\hat{s}^3} \left[\beta\hat{s} \left(\frac{8\hat{s}^2}{M_G^2} + 13\hat{s} + 34M_G^2 \right) \right.$$
$$\left. -\ 8\left(\hat{s}^2 + 3M_G^2\hat{s} - 3M_G^4\right) \ln\left(\frac{1+\beta}{1-\beta}\right) \right] \ , \quad (3)$$

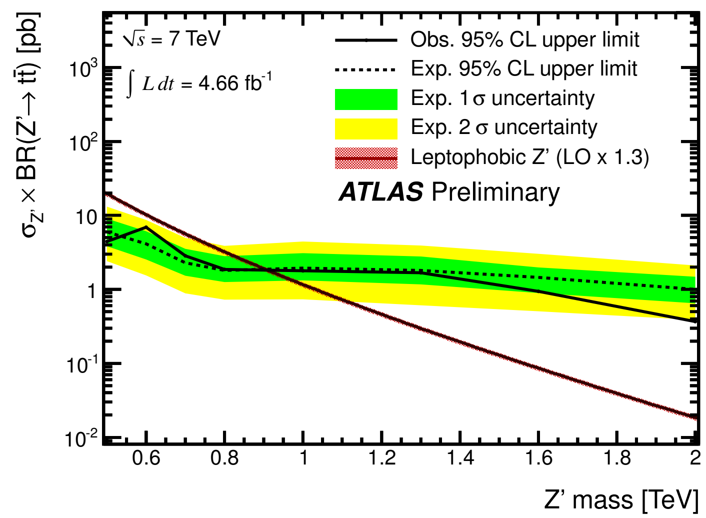


Dobrescu, Kong, Mahbubani 2007

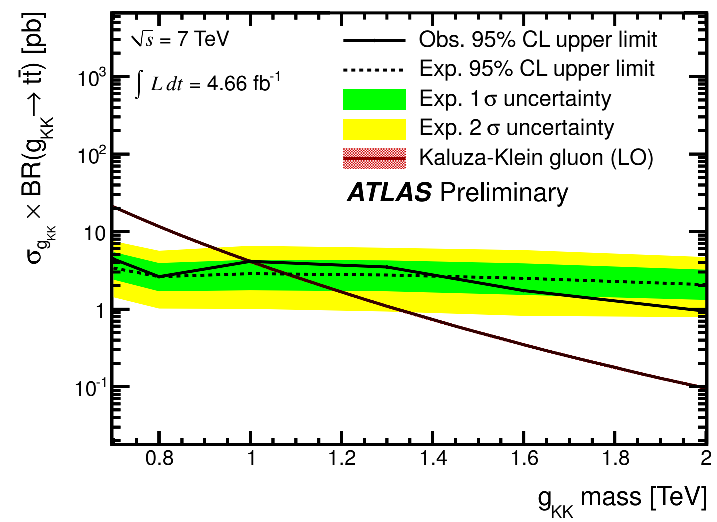
ttbar resonance



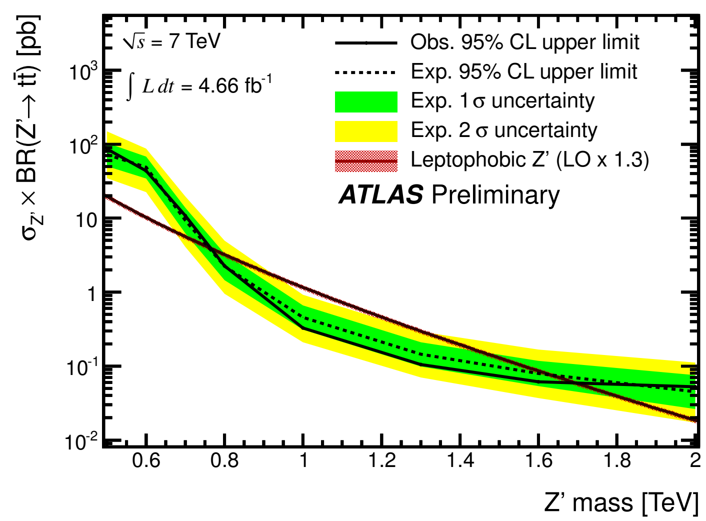




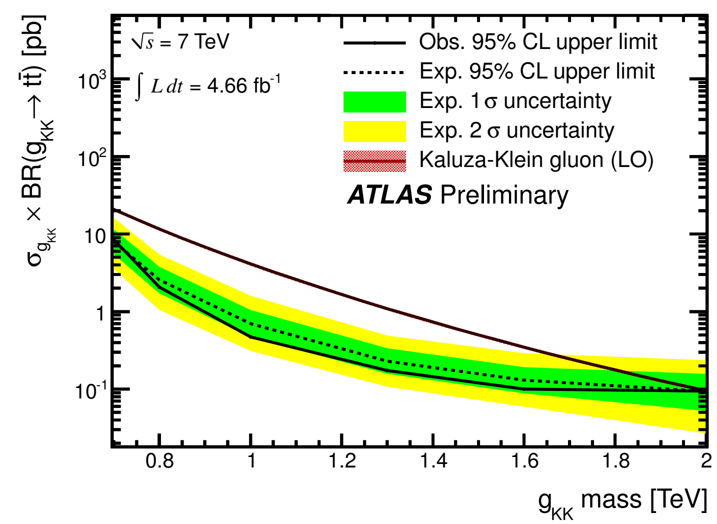
(a) Z', resolved selection.



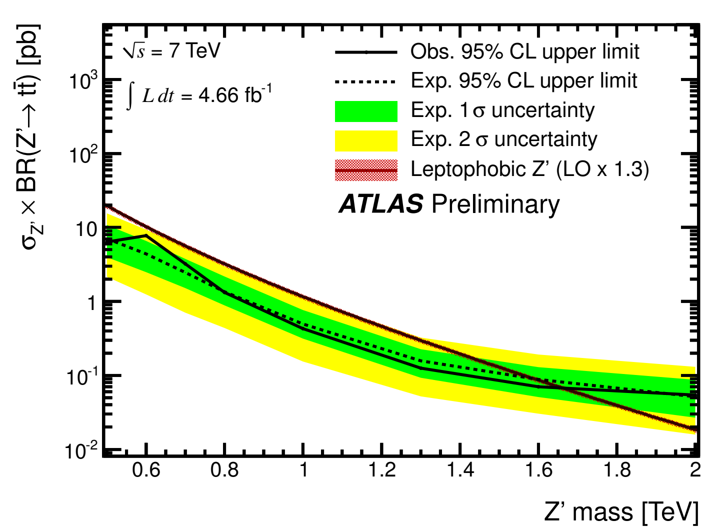
(b) g_{KK}, resolved selection.



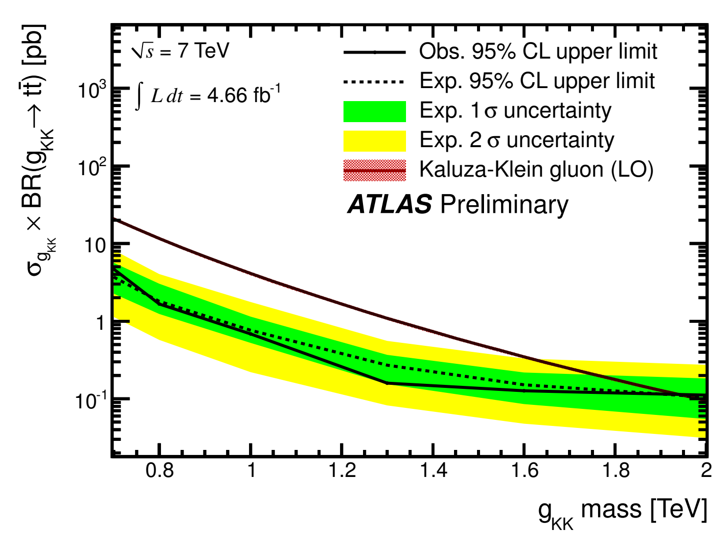
(c) Z', boosted selection.



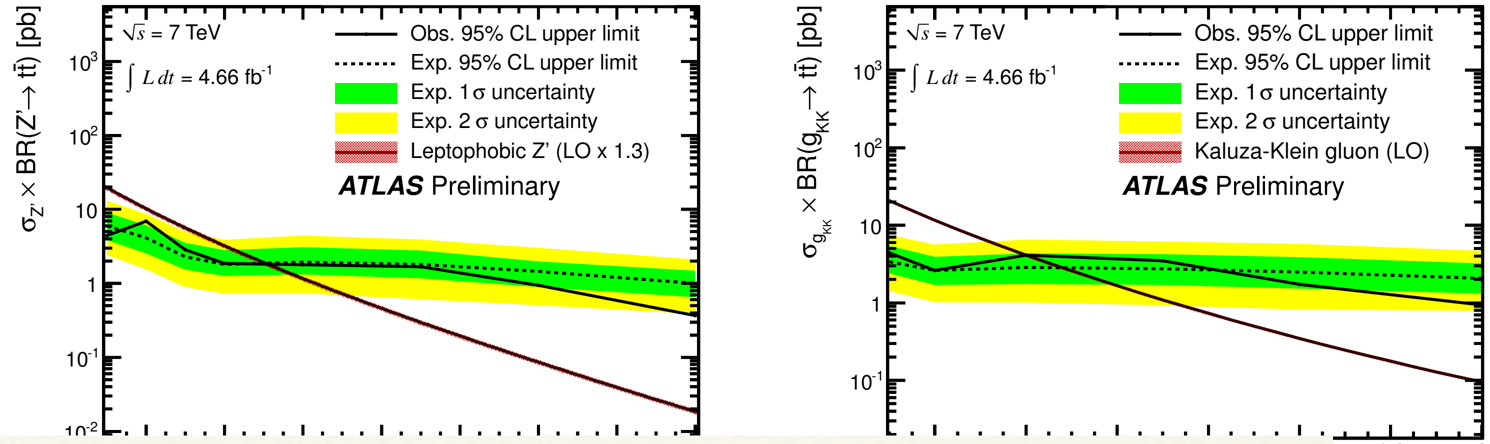
(d) g_{KK}, boosted selection.

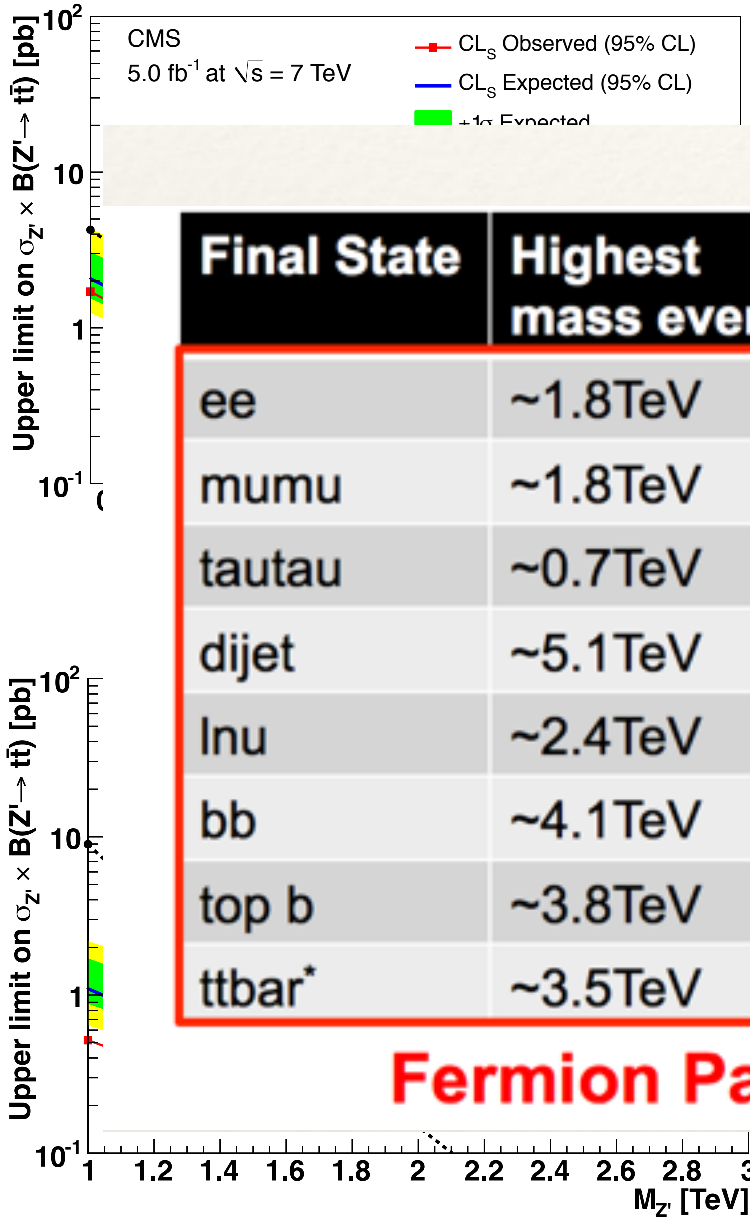


(e) Z', resolved and boosted combination.



(f) g_{KK}, resolved and boosted combination.





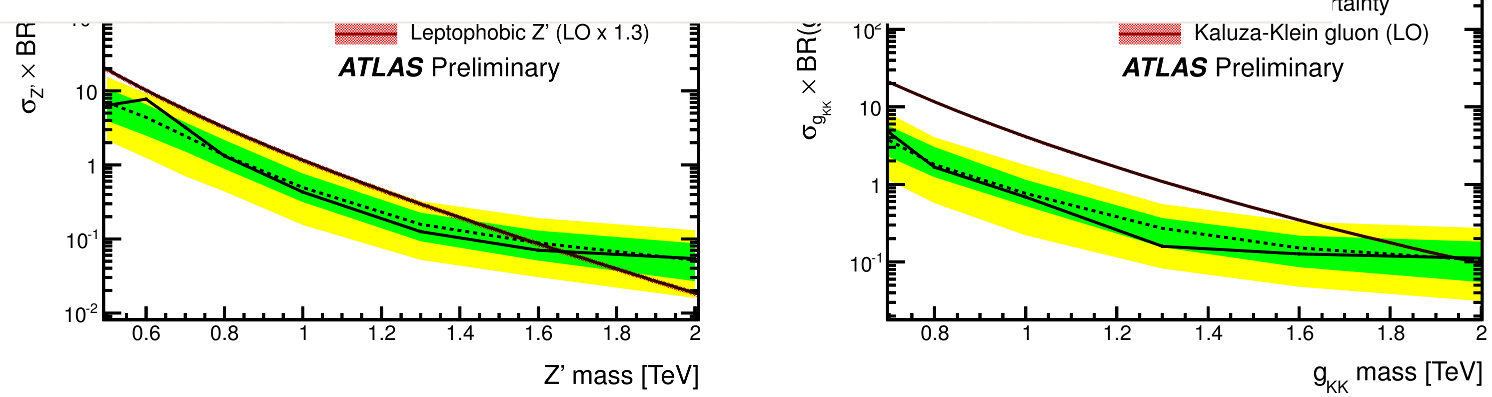
Credits: F. Würthwein, ICHEP 2014

Final State	Highest mass event	Highest mass limit
ee	~1.8TeV	2.79TeV
mumu	~1.8TeV	2.53TeV
tautau	~0.7TeV	1.9TeV
dijet	~5.1TeV	5.1TeV
lnu	~2.4TeV	3.4TeV
bb	~4.1TeV	~1.2-1.5TeV
top b	~3.8TeV	2.05TeV
ttbar*	~3.5TeV	1.8TeV

Fermion Pairs

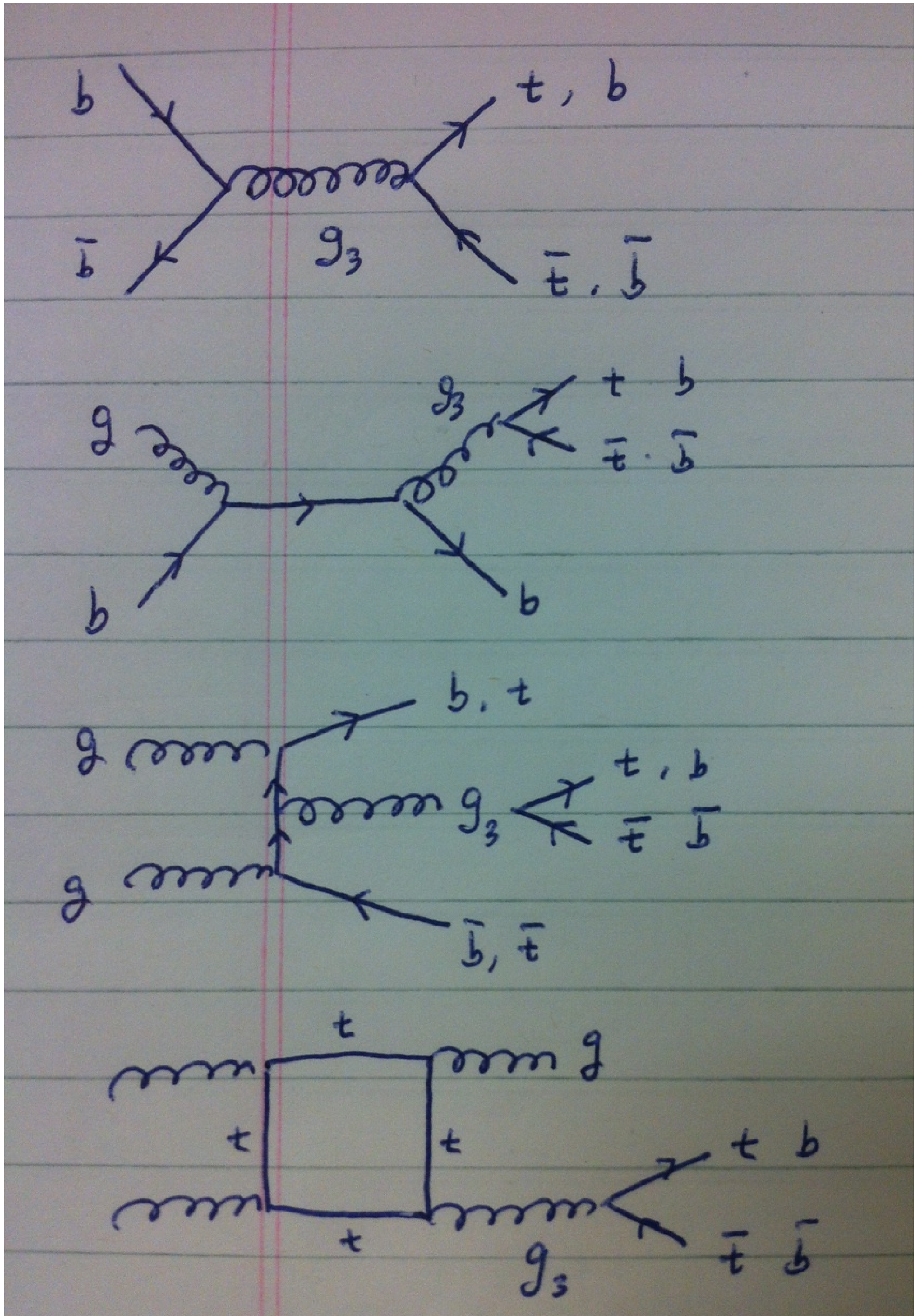
Final State	Highest mass event	Highest mass limit
WZ(3lnu)	~1.1TeV	1.5TeV
VV(jjlnu)	~3.3TeV	2.5TeV
Vq(jj)*	~3.7TeV	3.2TeV
VV(jj)*	~2.7TeV	1.7TeV
ZZ(lljj)	~1.7TeV	0.85TeV
hh(4b)	~1.3TeV	590-710GeV
Wt	~1.8TeV	1.8TeV
γjet	~3TeV	3.5TeV

Final states with bosons



(e) Z', resolved and boosted combination.

(f) g_{KK}, resolved and boosted combination.



How do we look for a ttbar (vector) resonance, if it does not couple to light quarks?
(we call it 'g3' resonance)

It is not produced by qqbar annihilation.

Perhaps we should be looking at different final states to look for such a ttbar resonance.

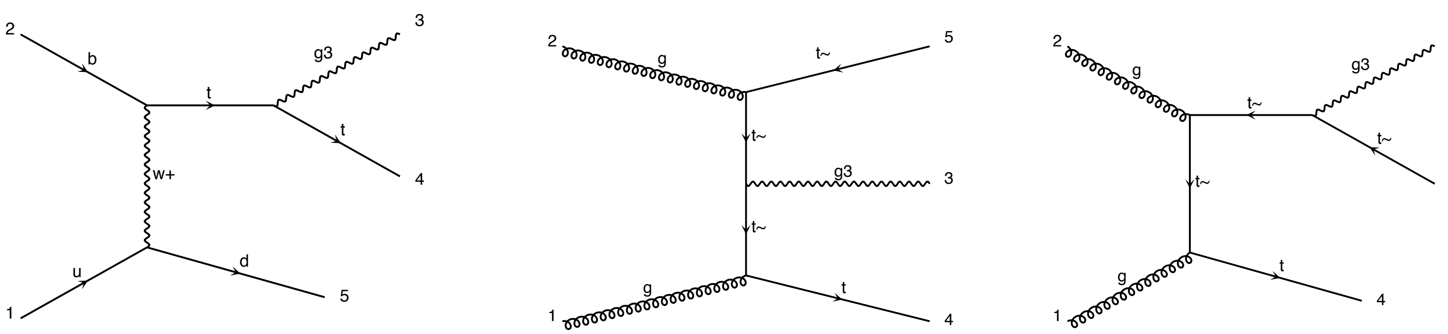
Production of Top-Philic Resonance

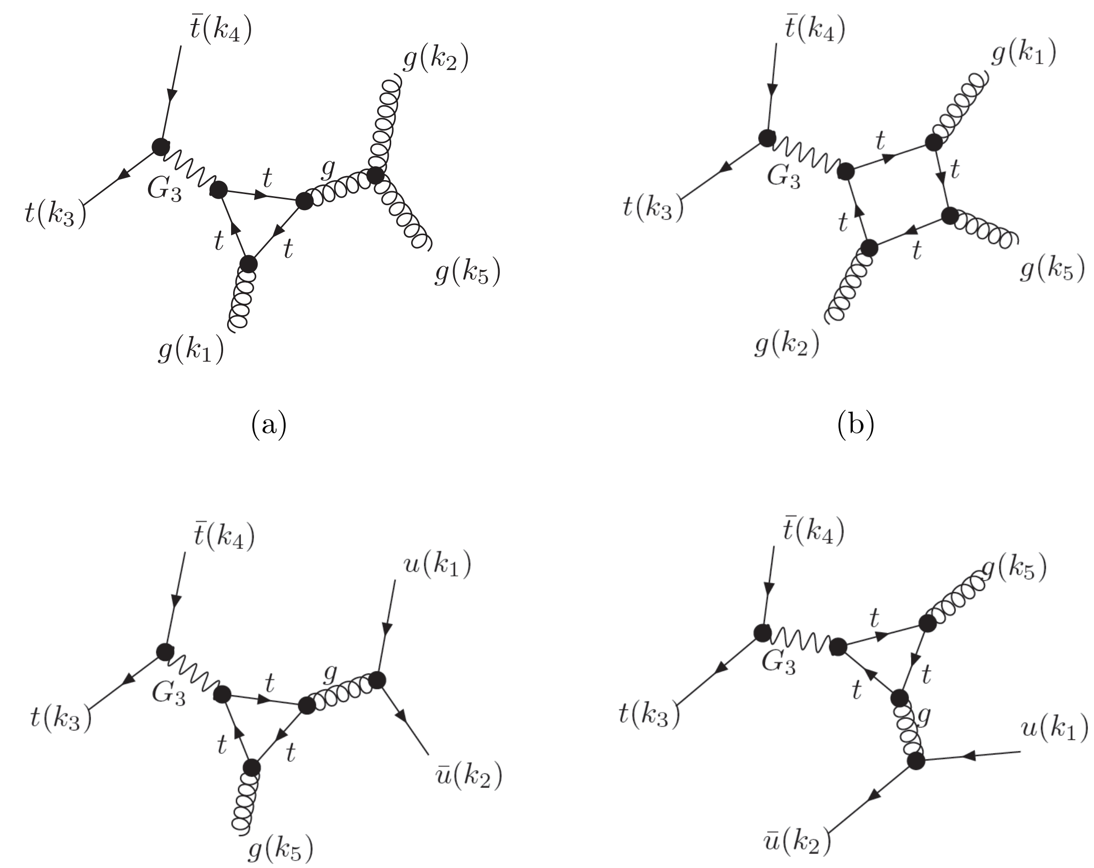
$$\mathcal{L} = \bar{t}\,\gamma_\mu\Big(c_L P_L + c_R P_R\Big) t\, G_3^\mu\,,$$
$$= c_t \bar{t}\,\gamma_\mu\Big(\cos\theta P_L + \sin\theta P_R\Big) t\, G_3^\mu$$

(a) four top-quark channel: $pp \to G_3 + t\bar{t} \to t\bar{t} + t\bar{t}$

(b) single top mode : $pp \to G_3 + t(\bar{t}) + j \to t\bar{t} + t(\bar{t}) + j$

(c) single top mode : $pp \to G_3 + t(\bar{t}) + W^\pm \to t\bar{t} + t(\bar{t}) + W^\pm$





(a) (b) (c) (d)

(a) loop induced $t\bar{t}j$: $pp \to G_3 + j \to t\bar{t} + j$

(b) loop induced $t\bar{t}$: $pp \to G_3 \to t\bar{t}$ (off-shell)

Greiner, Kong, Park, Winter, preliminary

Production of Top-Philic Resonance

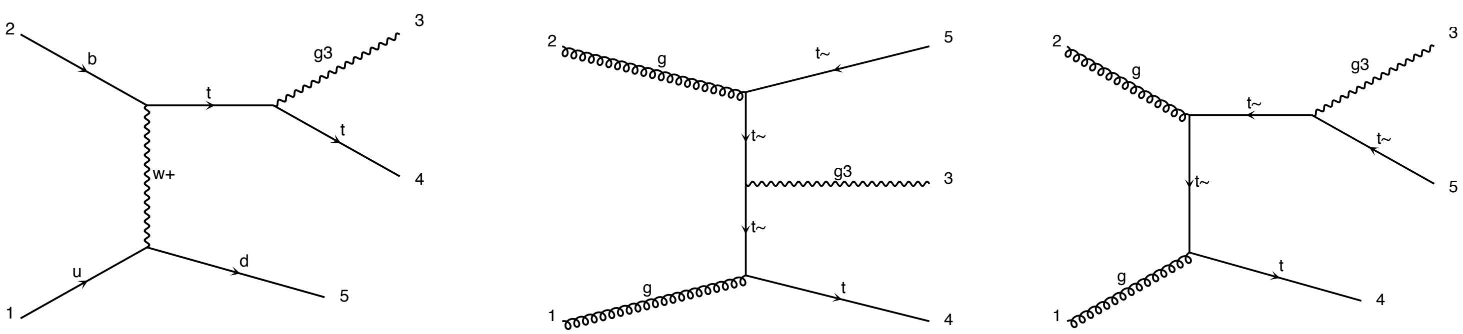
- At tree level

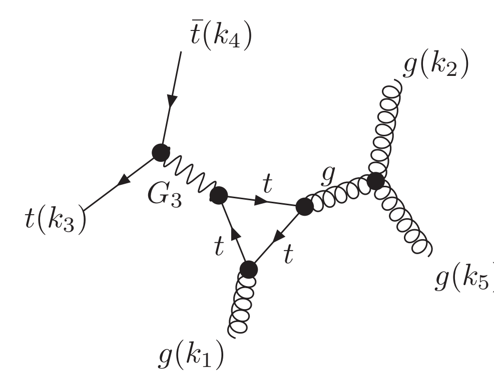
$$\mathcal{L} = \bar{t}\,\gamma_\mu\Big(c_L P_L + c_R P_R\Big)t\,G_3^\mu\,,$$
$$= c_t\bar{t}\,\gamma_\mu\Big(\cos\theta P_L + \sin\theta P_R\Big)t\,G_3^\mu$$

(a) four top-quark channel: $pp \to G_3 + t\bar{t} \to t\bar{t} + t\bar{t}$

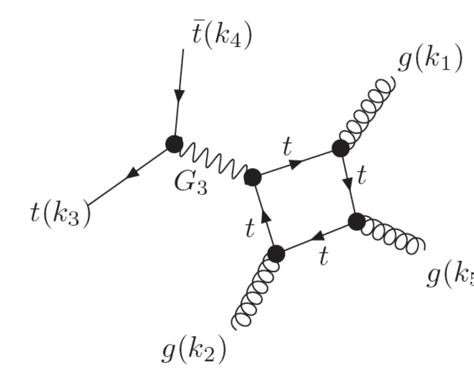
(b) single top mode : $pp \to G_3 + t(\bar{t}) + j \to t\bar{t} + t(\bar{t}) + j$

(c) single top mode : $pp \to G_3 + t(\bar{t}) + W^\pm \to t\bar{t} + t(\bar{t}) + W^\pm$





(a)

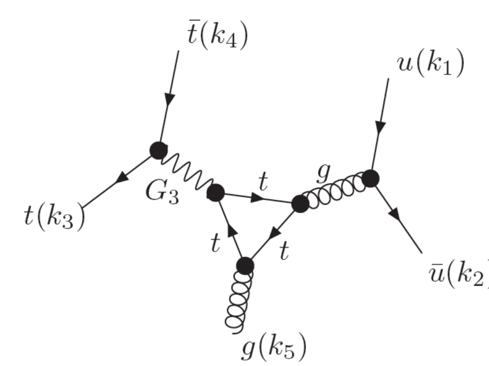


(b)

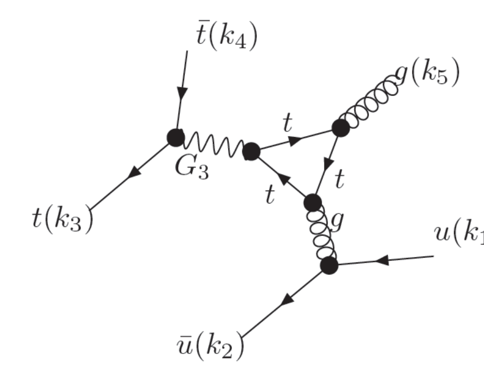
- At one loop

(a) loop induced $t\bar{t}j$: $pp \to G_3 + j \to t\bar{t} + j$

(b) loop induced $t\bar{t}$: $pp \to G_3 \to t\bar{t}$ (off-shell)



(c)

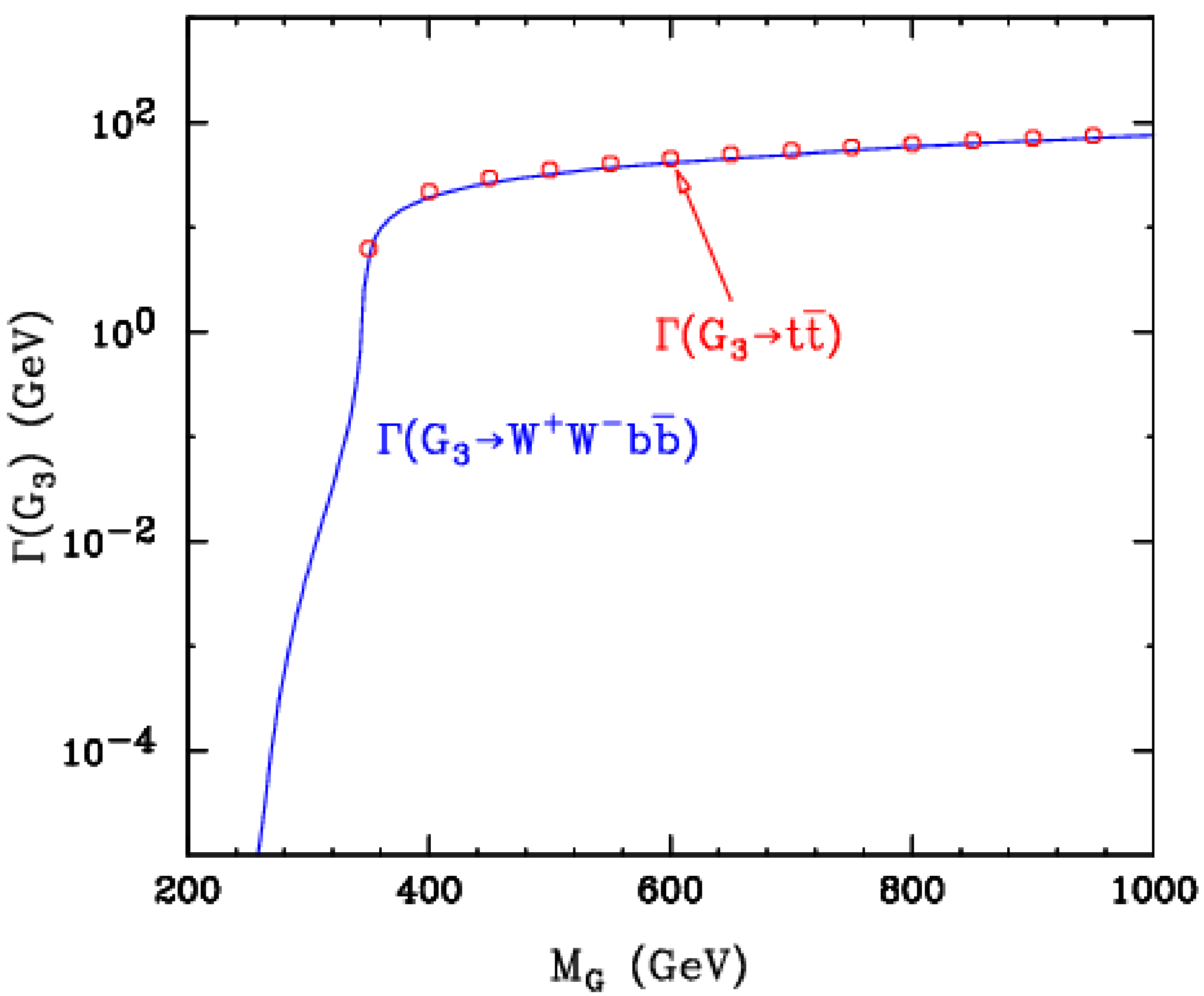


(d)

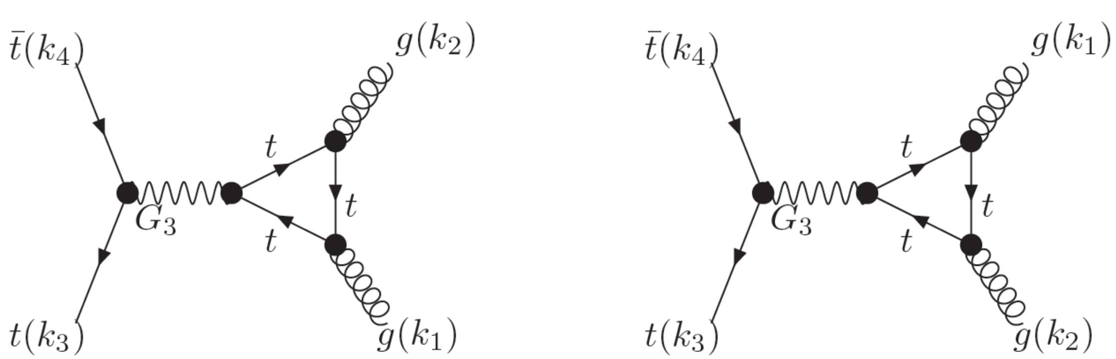
Greiner, Kong, Park, Winter, preliminary

Width

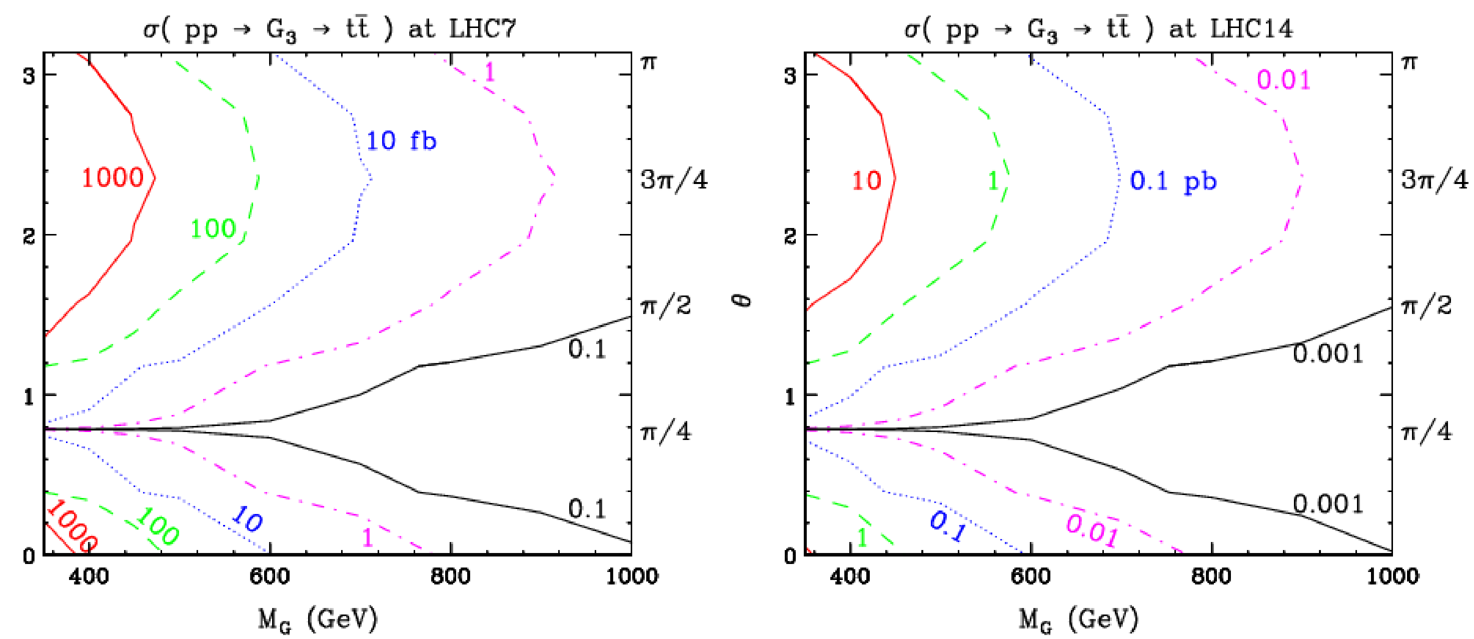
$$\Gamma\Big(G_3 \to t\bar{t}\Big) = \frac{c_t^2 M_G}{8\pi}\sqrt{1-\frac{4M_t^2}{M_G^2}}\Big[1+\frac{M_t^2}{M_G^2}\big(3\sin 2\theta - 1\big)\Big]$$
$$\approx \frac{c_t^2 M_G}{8\pi} \qquad \text{for } M_t \ll M_G\,.$$



Off-Shell Production

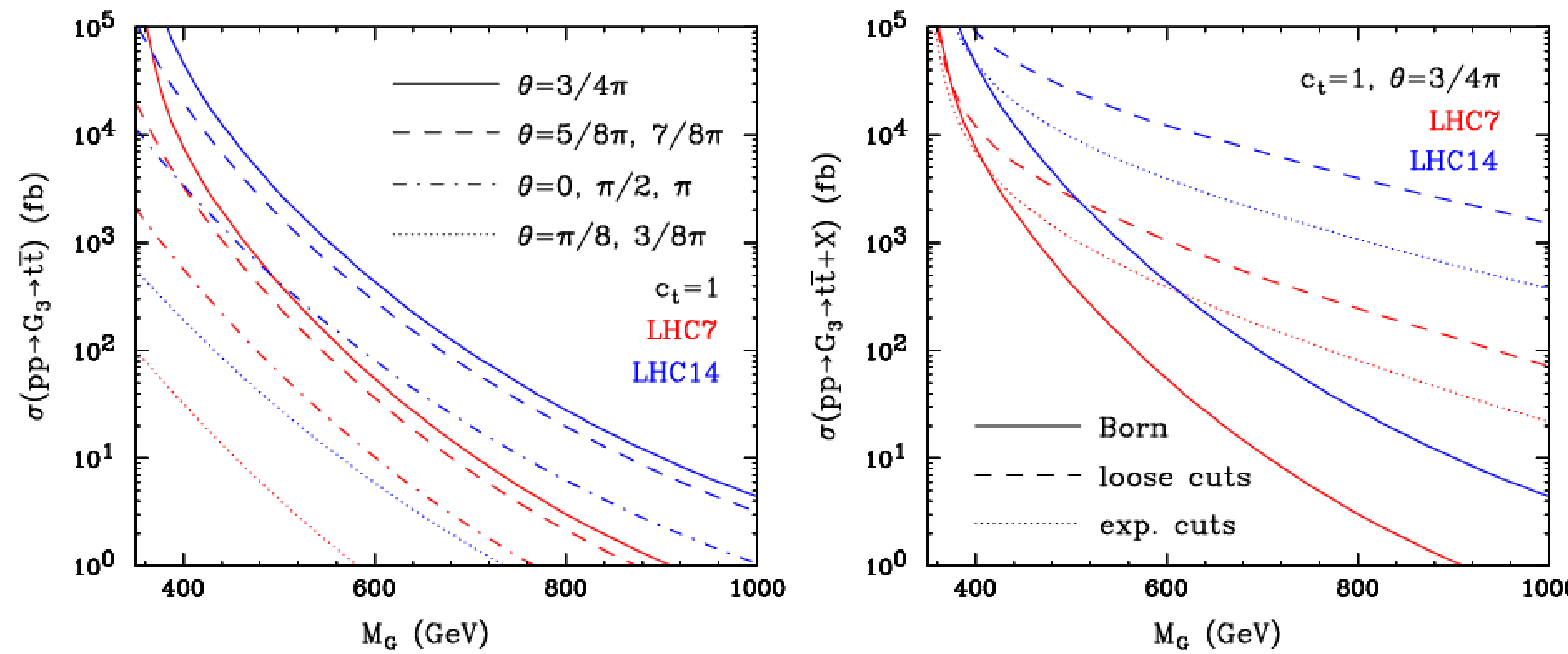


Greiner, Kong, Park, Winter, preliminary



(a)

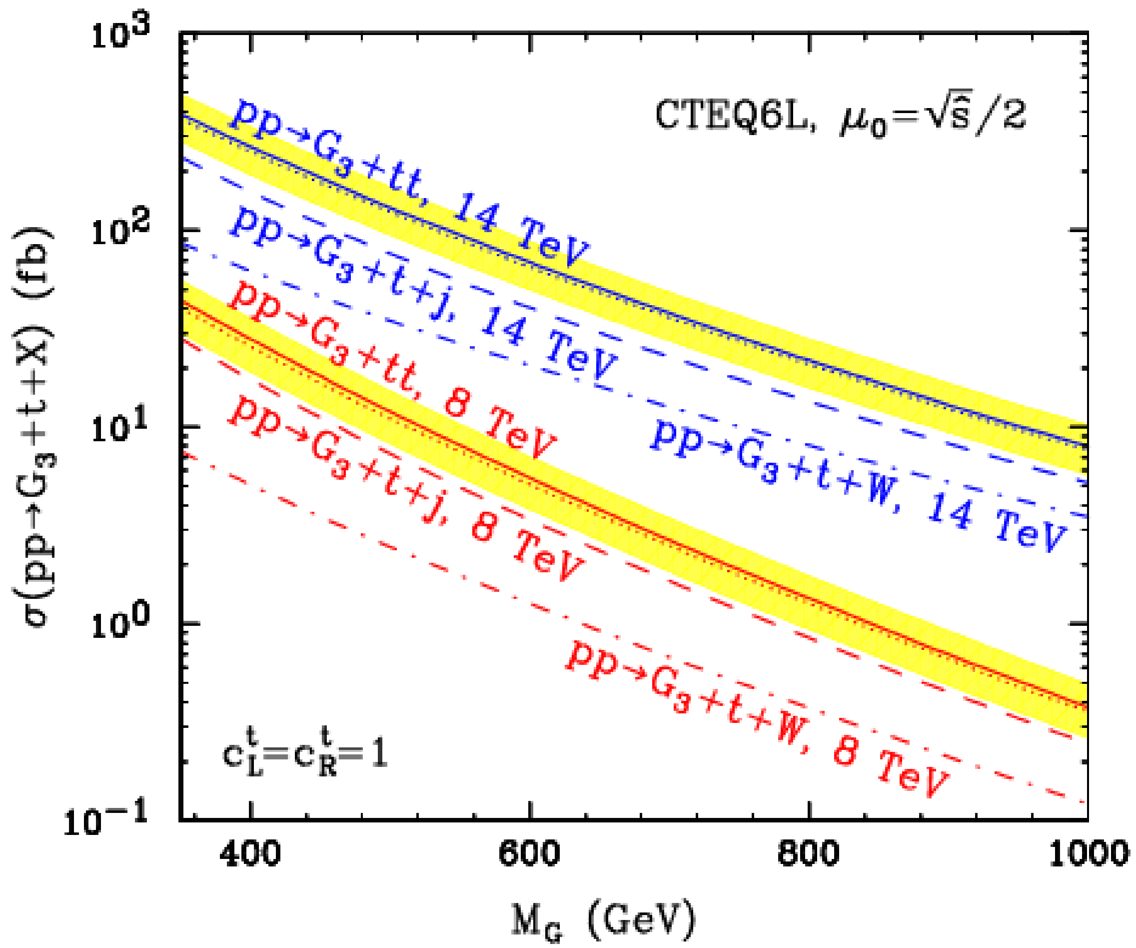
(b)

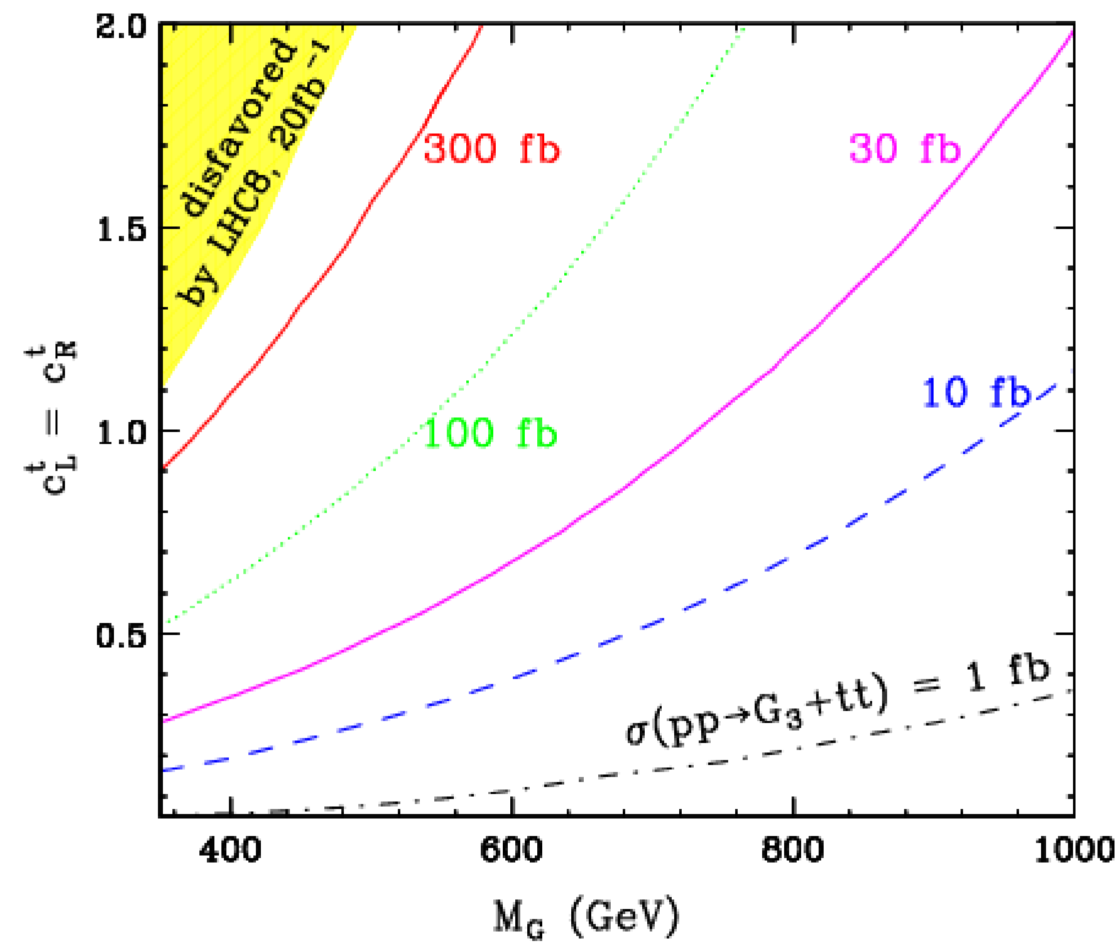


(a)

(b)

Cross Sections at Tree



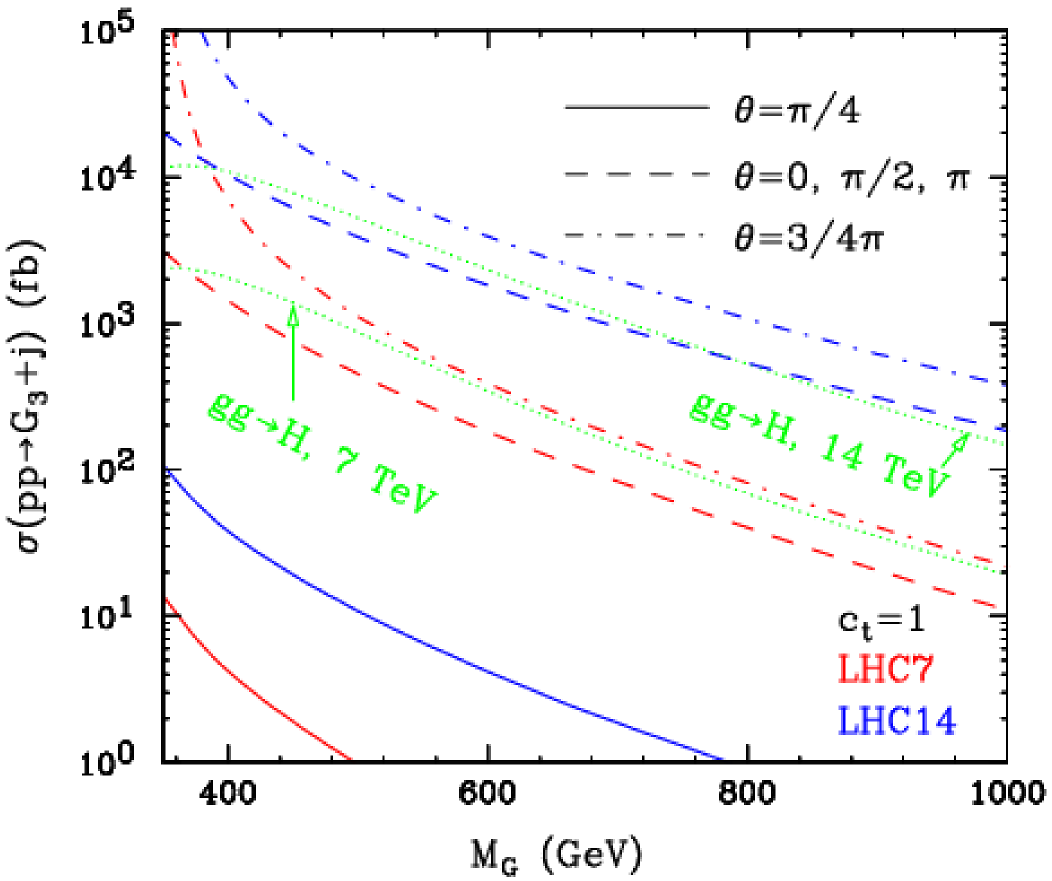


Collider	Category:	I0	I1	E0	E1
Tevatron 1.96 TeV		0.41			
LHC 7 TeV		10	26	$8\ldots9$	12
LHC 8 TeV		13			

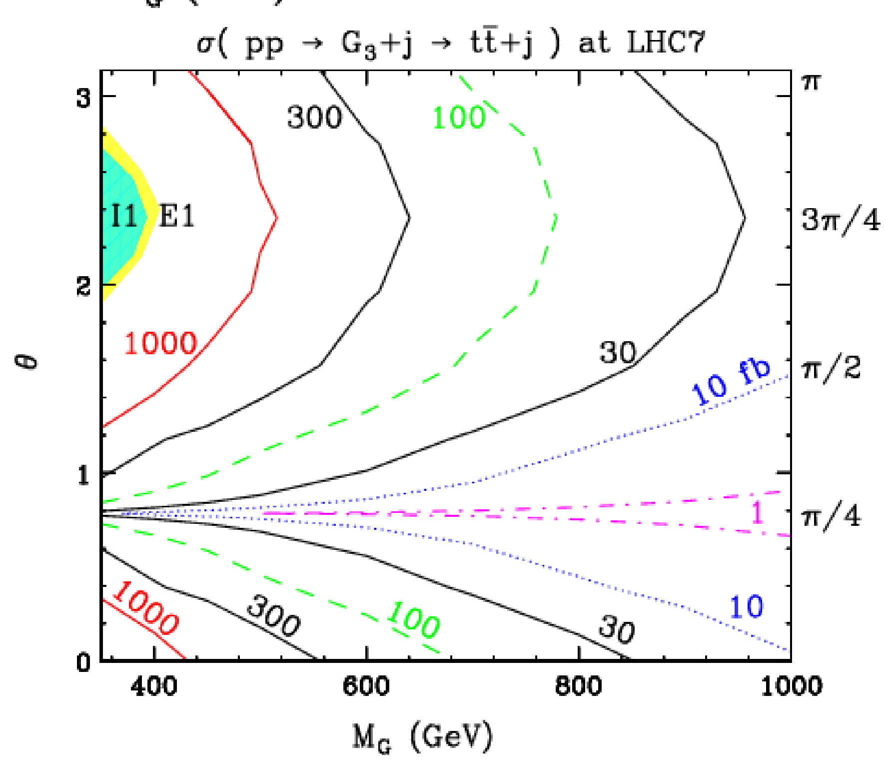
Table 1: Overview of the $\Delta\sigma_{t\bar{t}}$ quantities, in pb, for the different limit categories concerning current inclusive (IX) and exclusive (EX) cross section measurements for $t\bar{t}$ production in association with $X = 0, 1$ jets.

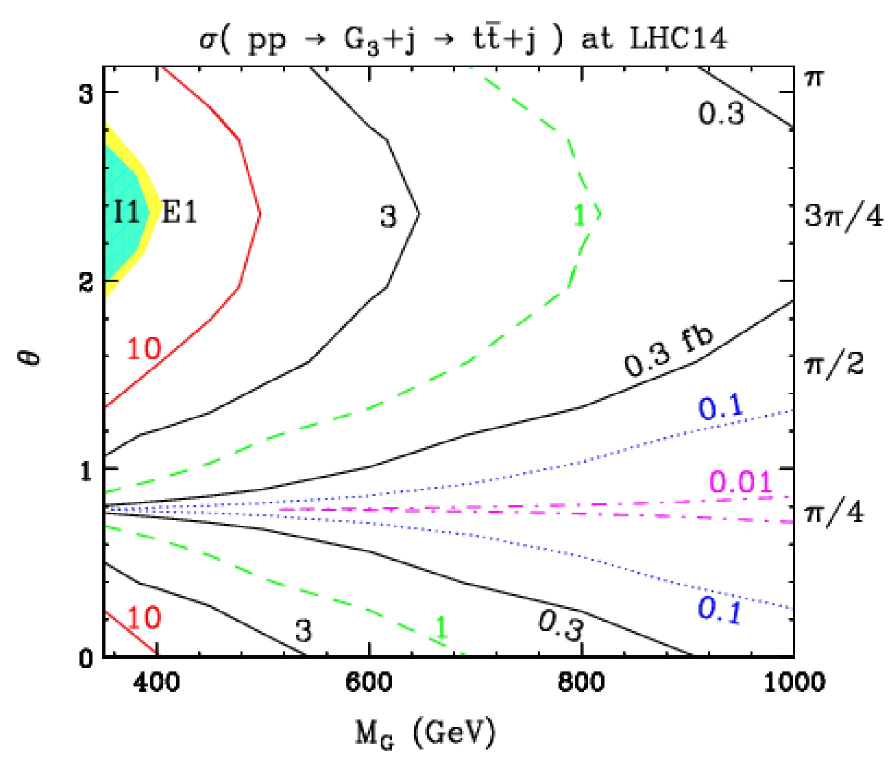
Greiner, Kong, Park, Winter, preliminary

Cross Section at One Loop



We should look at ttbar plus one jet instead of ttbar, to search for a top-philic resonance.





To Compute One Loop Cross Section….

The virtual amplitudes at one loop have been generated with GoSam [8, 9], a publicly available package for the automated generation of one-loop amplitudes. It is based on a Feynman diagrammatic approach using QGRAF [10] and FORM [11] for the diagram generation, and Spinney [12], Haggies [13] and FORM to write an optimized Fortran output. For the reduction of the tensor integrals we used Ninja [14, 15], an automated package for the integrand reduction via Laurent expansion. This package is a part of GoSam and therefore no further work is required to use it. Alternatively one can use other reduction techniques such as integrand reduction using the OPP method [16–18] as implemented in Samurai [19] or using methods of tensor reduction as contained in Golem95 [20–22]. The remaining scalar integrals have been evaluated using OneLoop [23].

To Compute One Loop Cross Section….

The virtual amplitudes at one loop have been generated with GoSam [8, 9], a publicly available package for the automated generation of one-loop amplitudes. It is based on a Feynman diagrammatic approach using QGRAF [10] and FORM [11] for the diagram generation, and Spinney [12], Haggies [13] and FORM to write an optimized Fortran output. For the reduction of the tensor integrals we used Ninja [14, 15], an automated package for the integrand reduction via Laurent expansion. This package is a part of GoSam and therefore no further work is required to use it. Alternatively one can use other reduction techniques such as integrand reduction using the OPP method [16–18] as implemented in Samurai [19] or using methods of tensor reduction as contained in Golem95 [20–22]. The remaining scalar integrals have been evaluated using OneLoop [23].

- MG5_aMC@NLO will allow this computation much easier.
- These tools help to expedite early discovery!

Summary

- Exciting Opportunities at Run II in 2015.
- Continue with both ‘model-dependent’ and ‘model-independent’ searches but also think of new topologies and new channels that have not been searched for.
- Might need more systematic approaches to look for resonances.
- Eliminate common assumptions one by one.
- Nature could be more exotic than we expect!