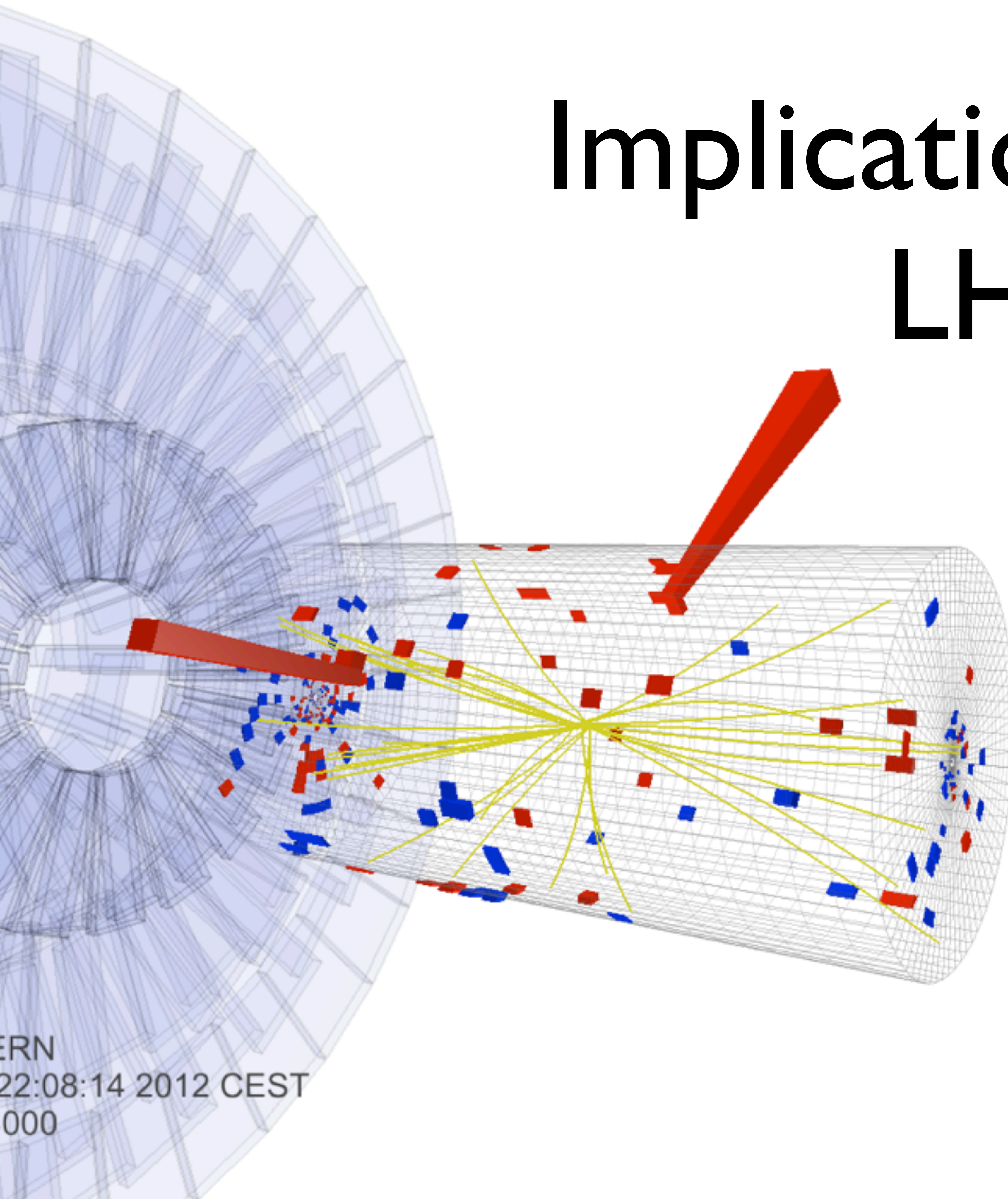


Implications of the LHC results

Andreas Weiler
(DESY)

LEXI meeting
11/10/2012

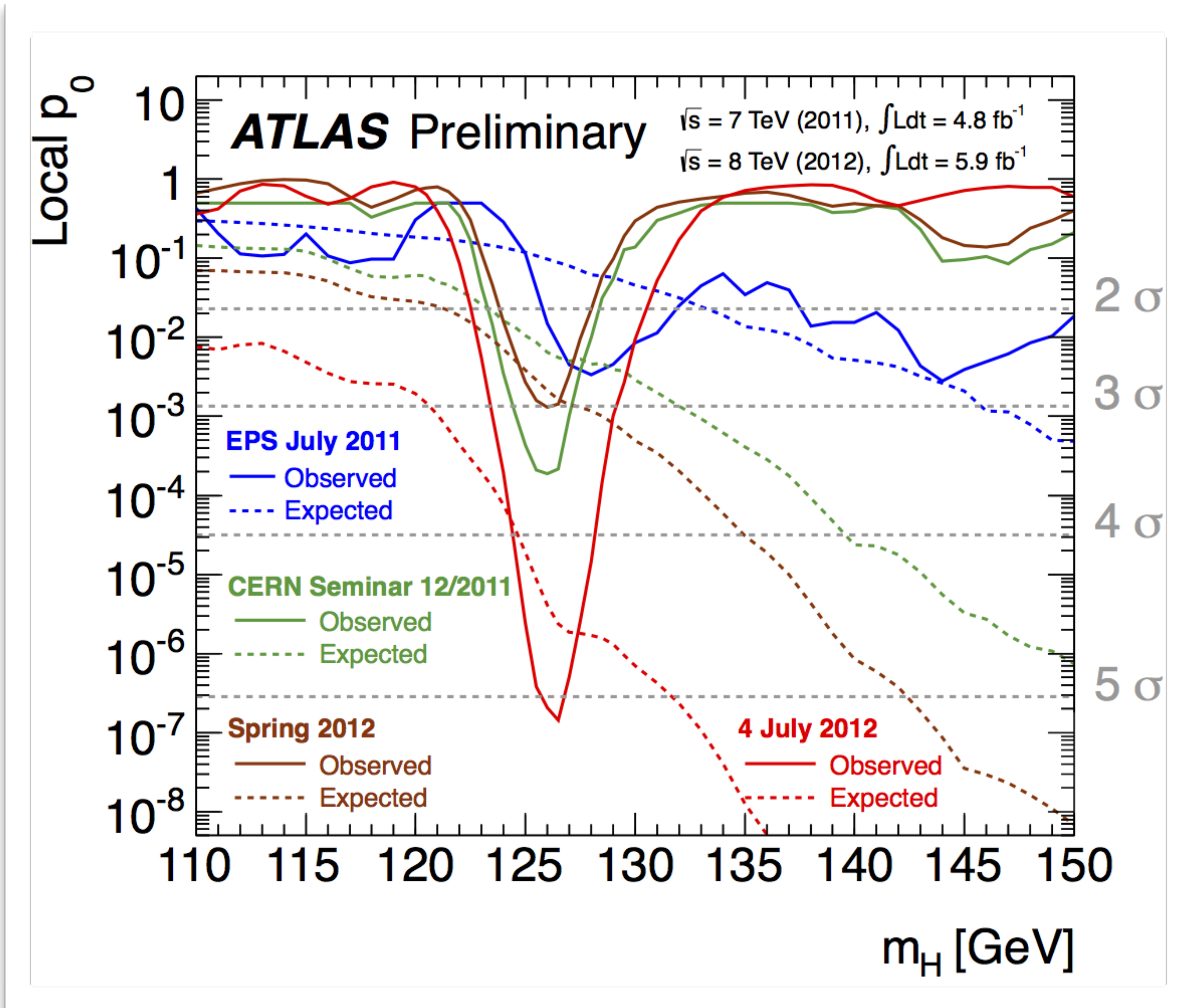
The best of times

- LHC is exceeding expectations
- SM Higgs like state at > 5 σ, 125.5±1 GeV
- 7 & 8 TeV searches beginning to corner the most motivated models
- Early casualties*: 4th generation, fermiophobic Higgs, techni-color, …

*terms and conditions apply

4th July 2012

We have discovered a new particle !



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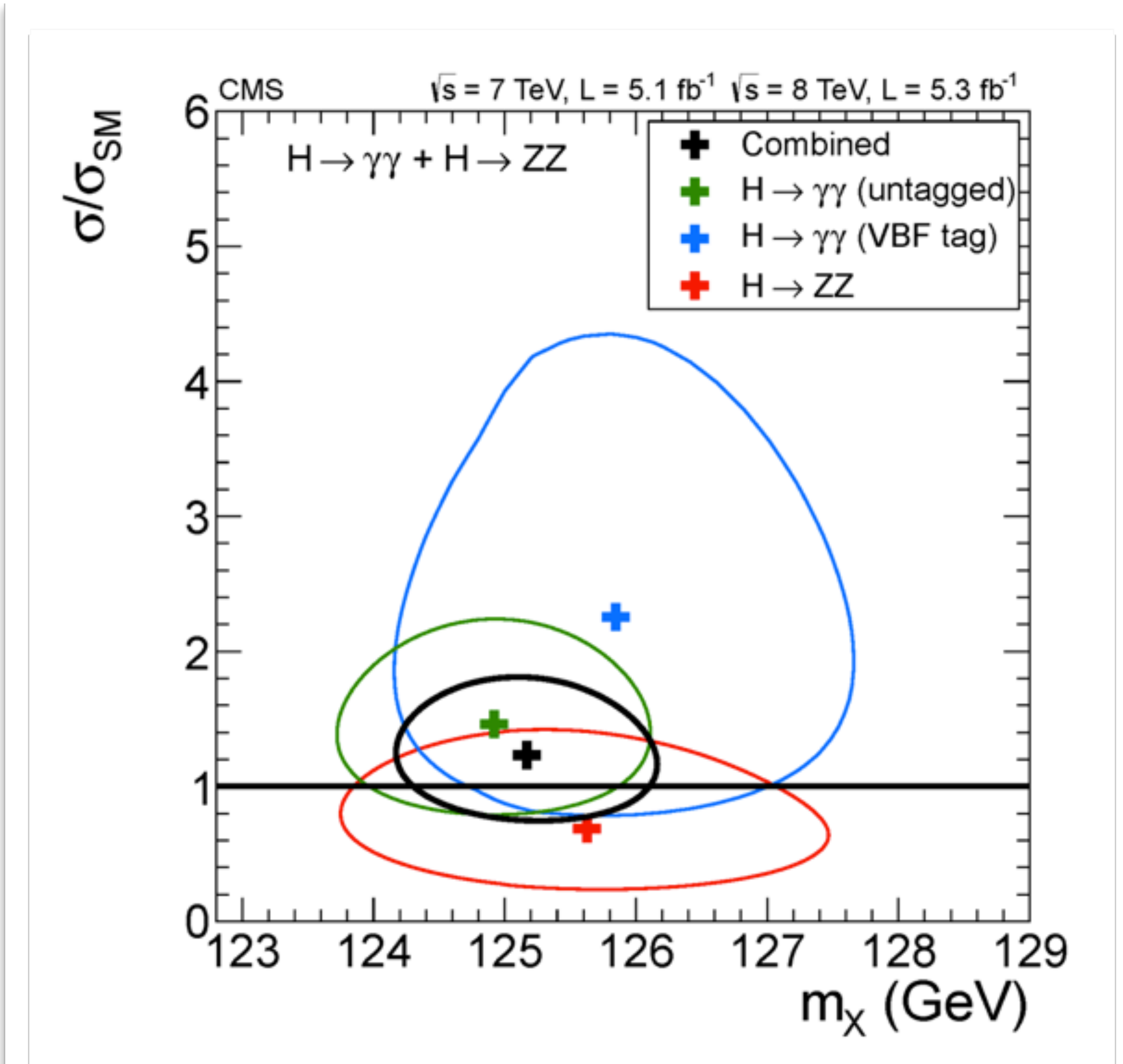


4th July 2012

We have discovered a new particle !

Is it the SM Higgs?

- o Quantum numbers: J^{PC}? *SU(2)xU(1)* charges?
- o Elementary scalar or composite bound state?
- o Part of an extended sector?
- o Portal to SM-neutral new physics?

What screens the quantum corrections to its mass?

Just the SM Higgs

$m_{Higgs} \xrightarrow{\text{extrapolate}} m_{Planck}$

$$V = \lambda(|H|^2 - v^2)^2 \approx \frac{\lambda}{4} h^4$$

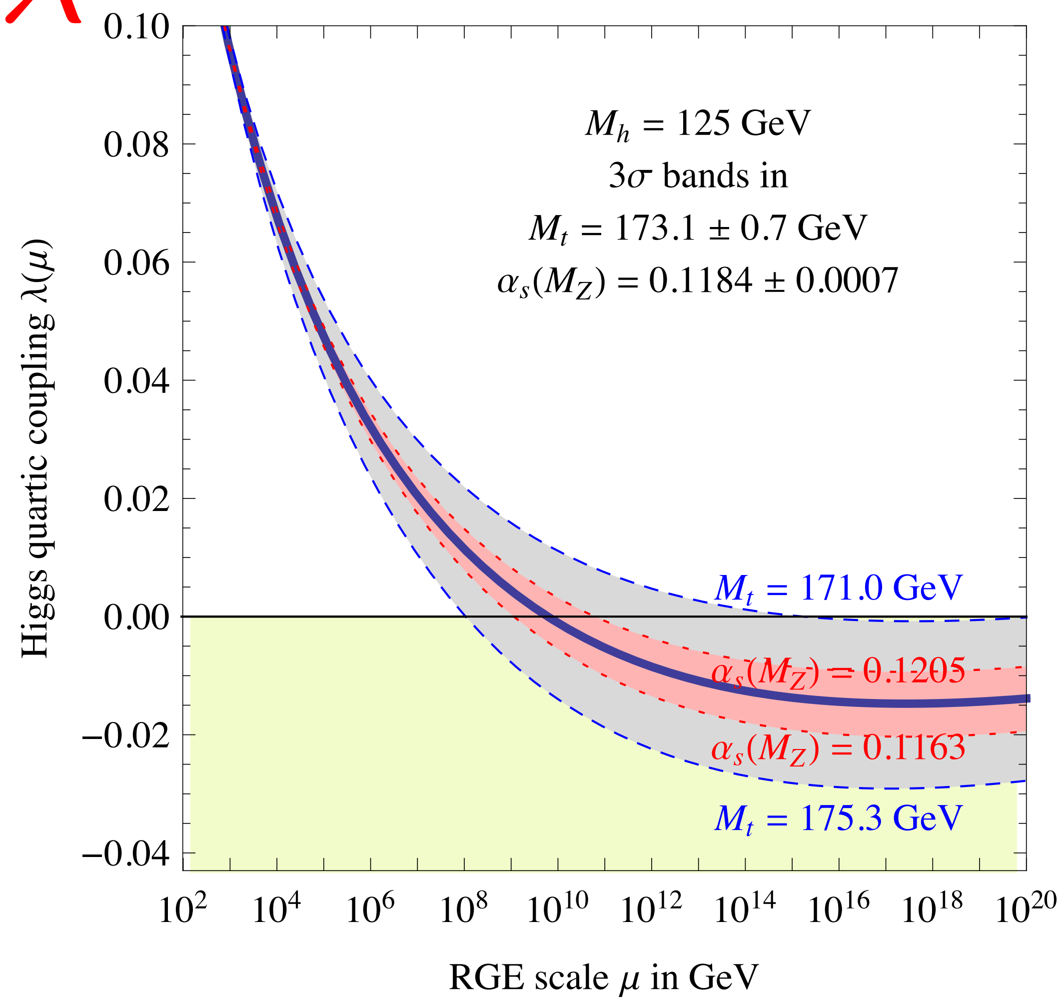
Just the SM Higgs

m_{Higgs} $\longrightarrow$ m_{Planck}

extrapolate

$$V = \lambda(|H|^2 - v^2)^2 \approx \frac{\lambda}{4} h^4$$

Higgs quartic λ



extrapolate SM to this Energy

Just the SM Higgs

m_{Higgs} $\longrightarrow$ m_{Planck}

extrapolate

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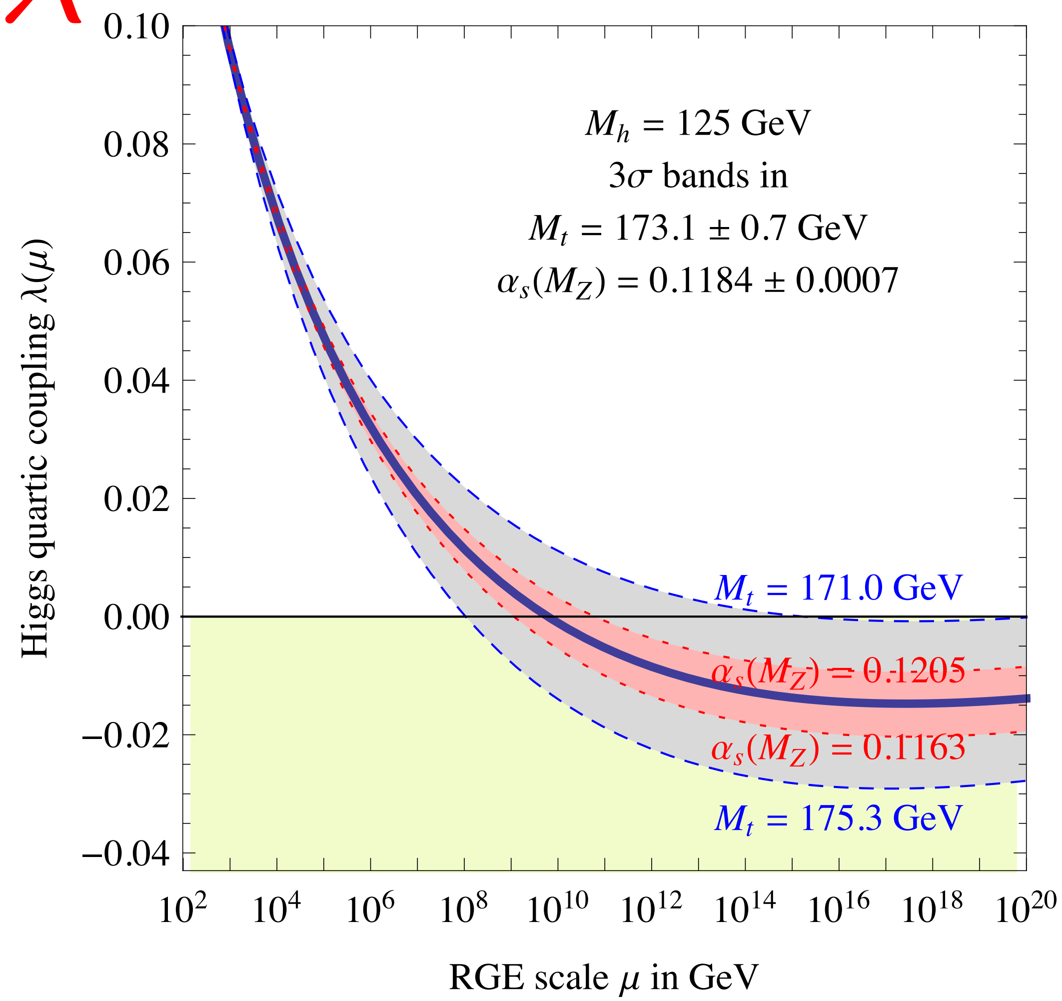
Higgs quartic λ



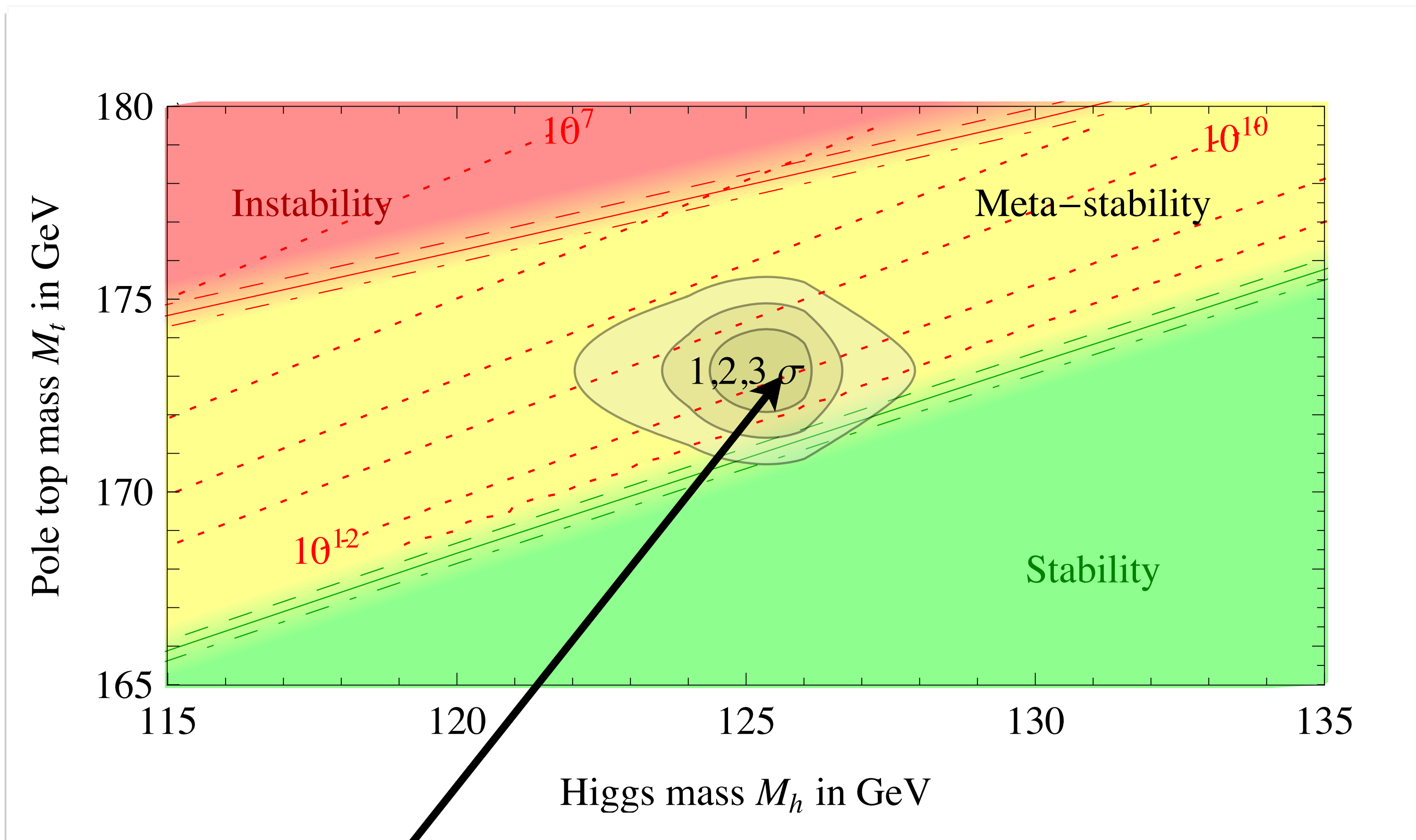
extrapolate SM to this Energy

Curiously close to zero.

Negative values: instability

Just the SM Higgs

Bezrukov et al '12, Degrassi et al '12



- o very likely meta-stable
- o not fully clear if $m_H > m_{stable}$
- o certainly below Landau-pole

meta-stability:
life-time of the SM vacuum is longer than the age of the universe

Example: SM + Dark matter

Cheung '12

SM + $\frac{1}{2}m_S S^2 + m_D D D^c + y_S H S D + y_S^c H^c S D^c$

… think of SM + bino (DM) + higgsino

Example: SM + Dark matter

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$$\text{SM} + \quad \frac{1}{2} m_S S^2 + m_D D D^c + y_S H S D + y_S^c H^c S D^c$$

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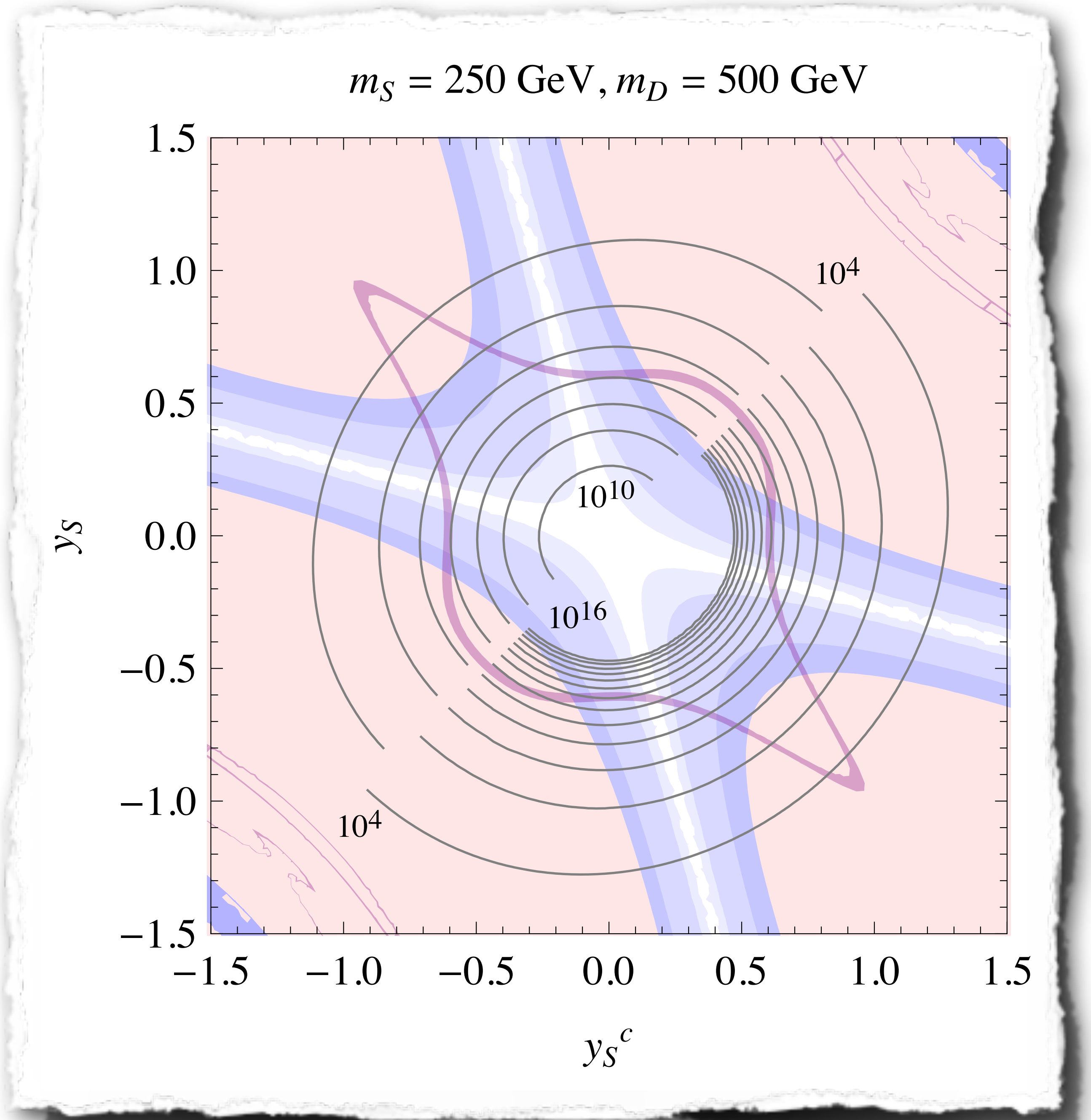

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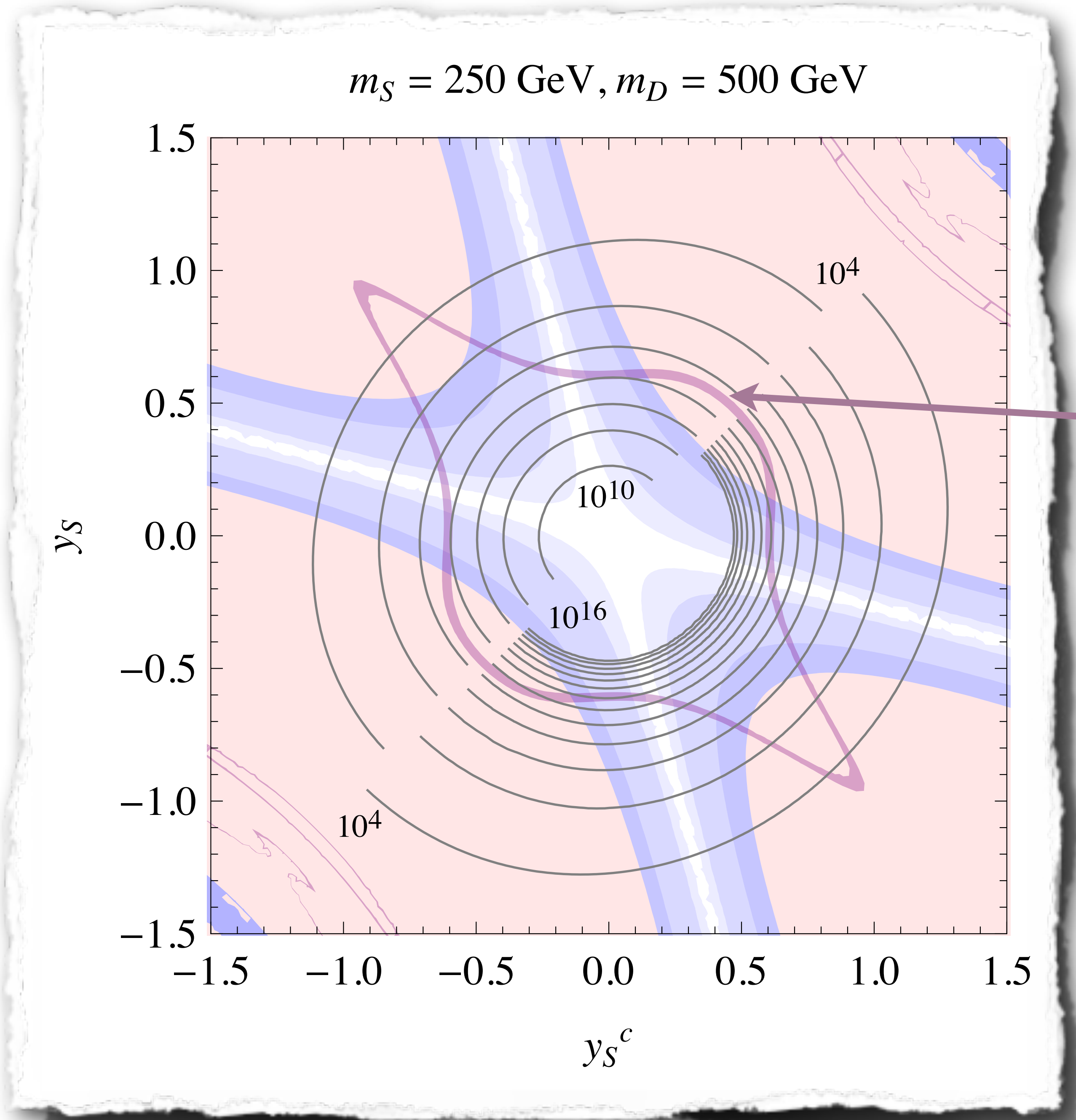

relic abundance ok

Example: SM + Dark matter

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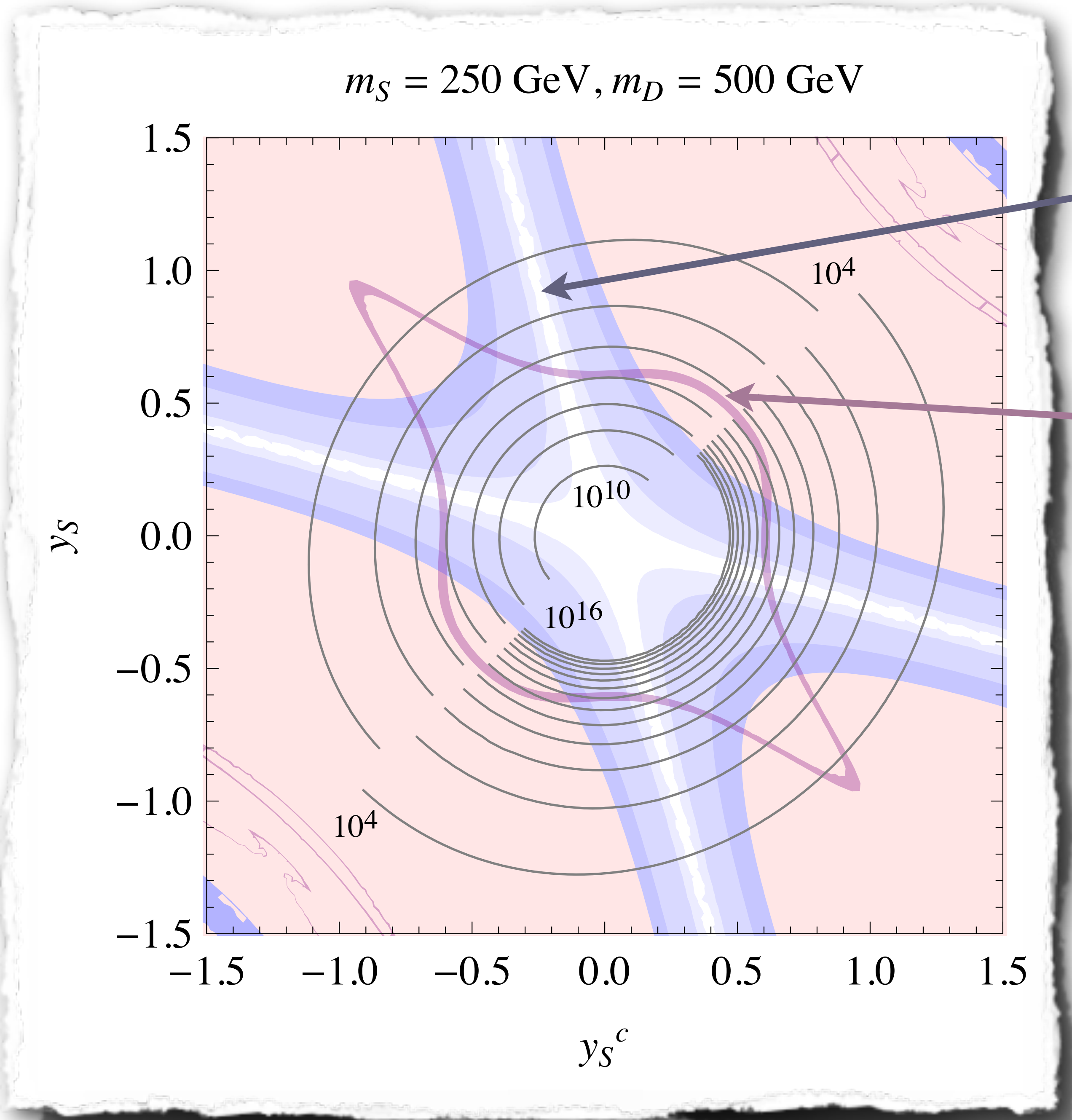

direct searches ok (Xenon100)

relic abundance ok

Example: SM + Dark matter

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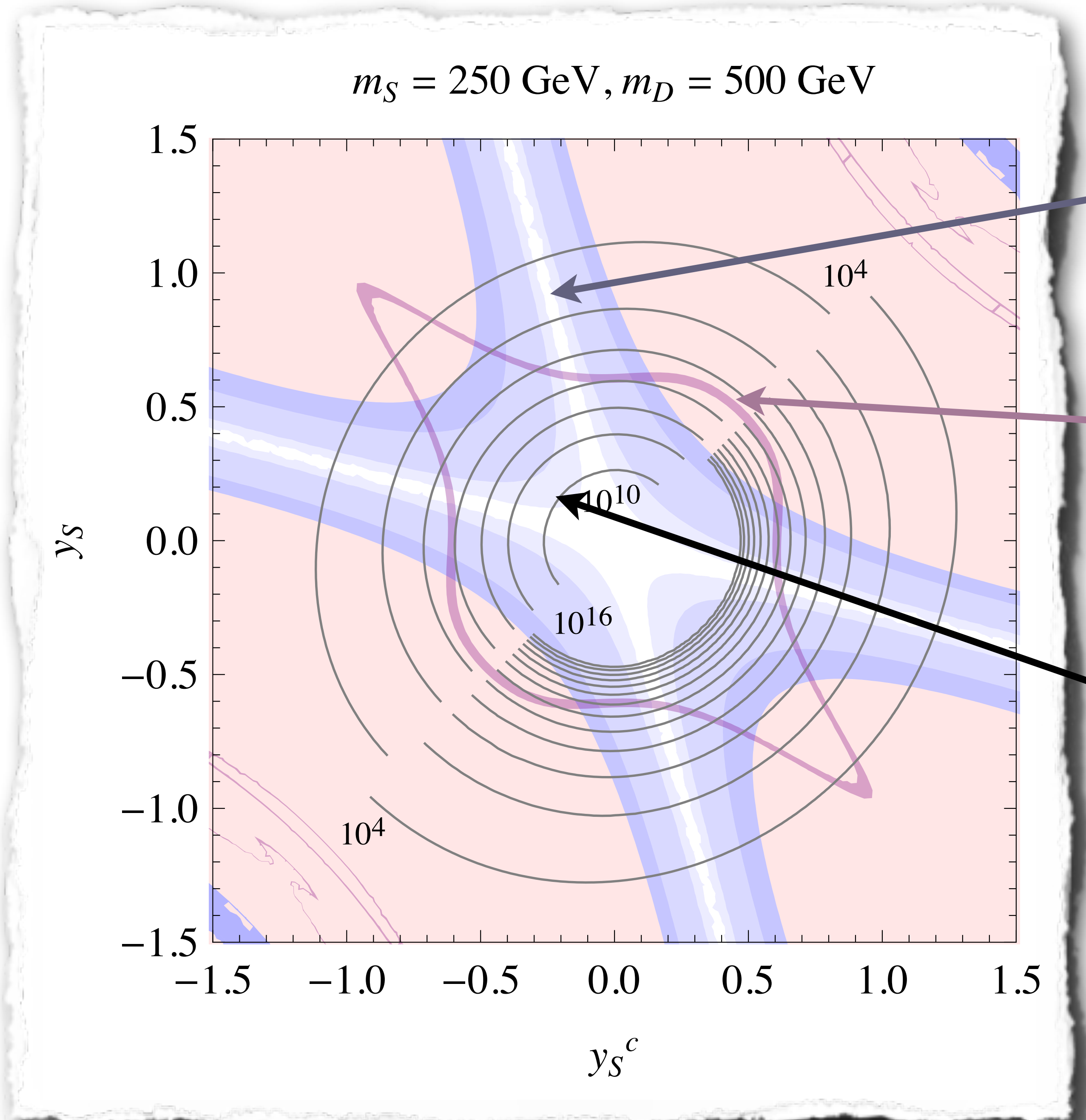

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relic abundance ok

Higgs instability scale

Example: SM + Dark matter

Cheung '12

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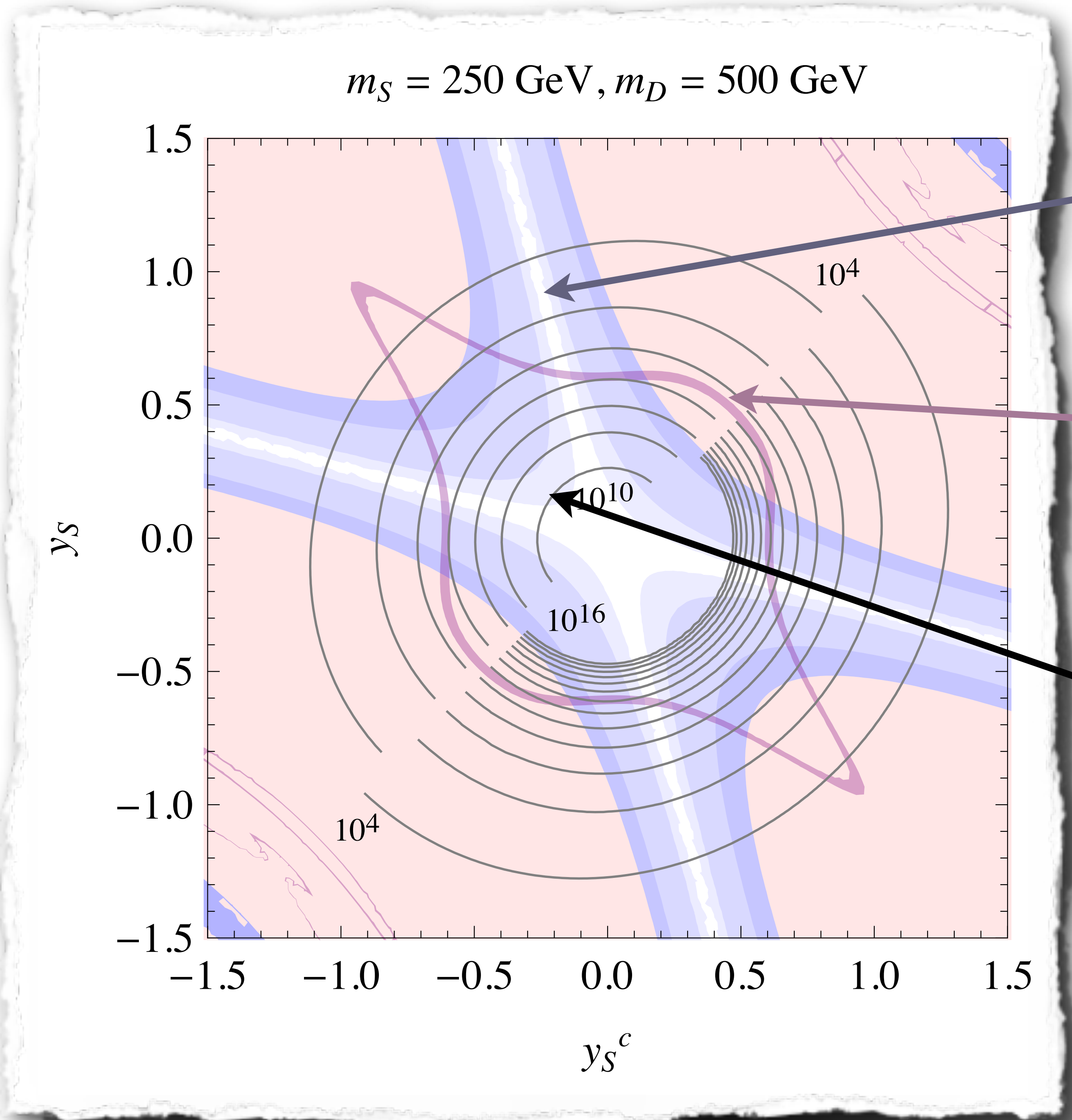


direct searches ok (Xenon100)

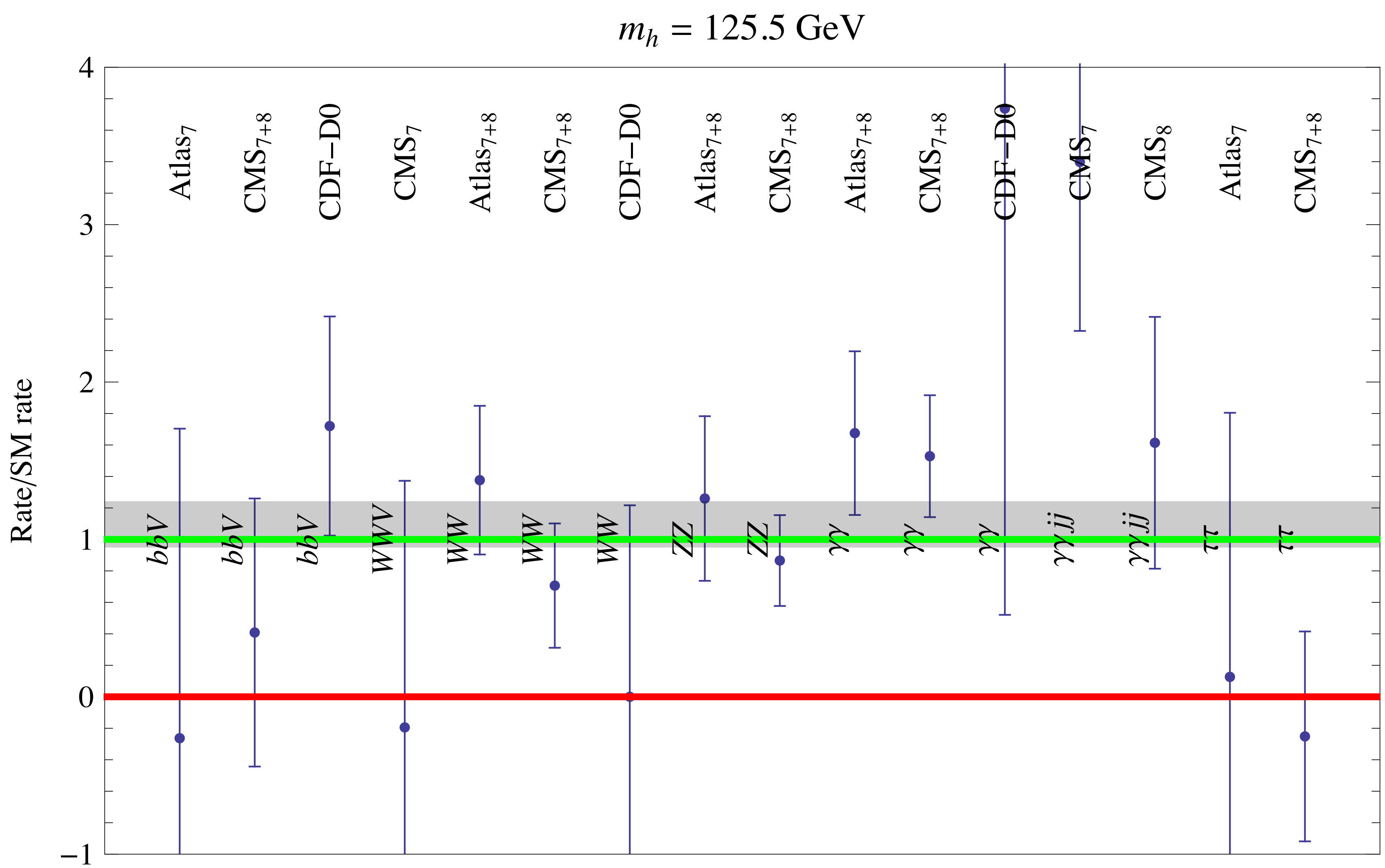
relic abundance ok

Higgs instability scale

... very different

Is it the SM Higgs?

Giardino '12



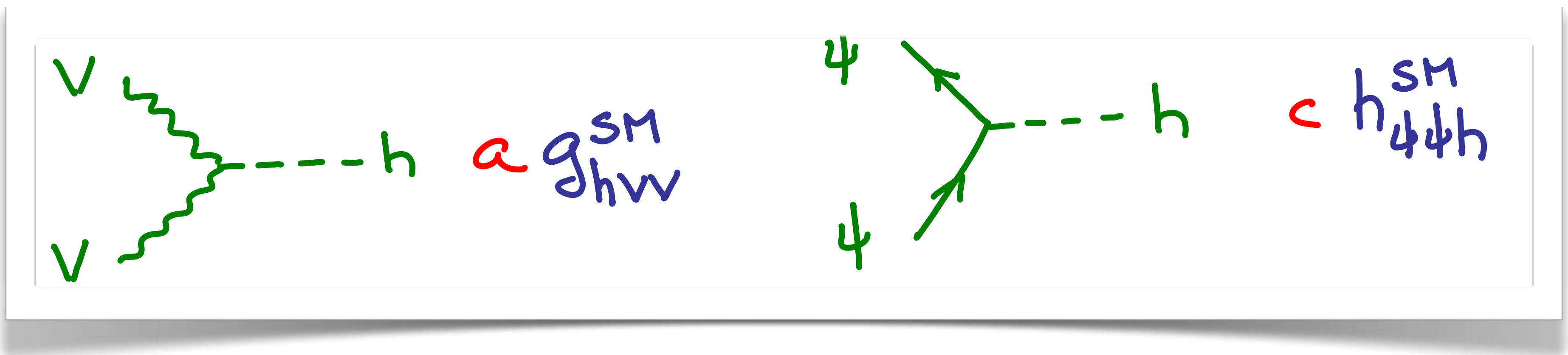
SM rate

Photons are high, taus are low, *WW&ZZ* just about right.

Error bars still sizable. More data is coming in quickly.

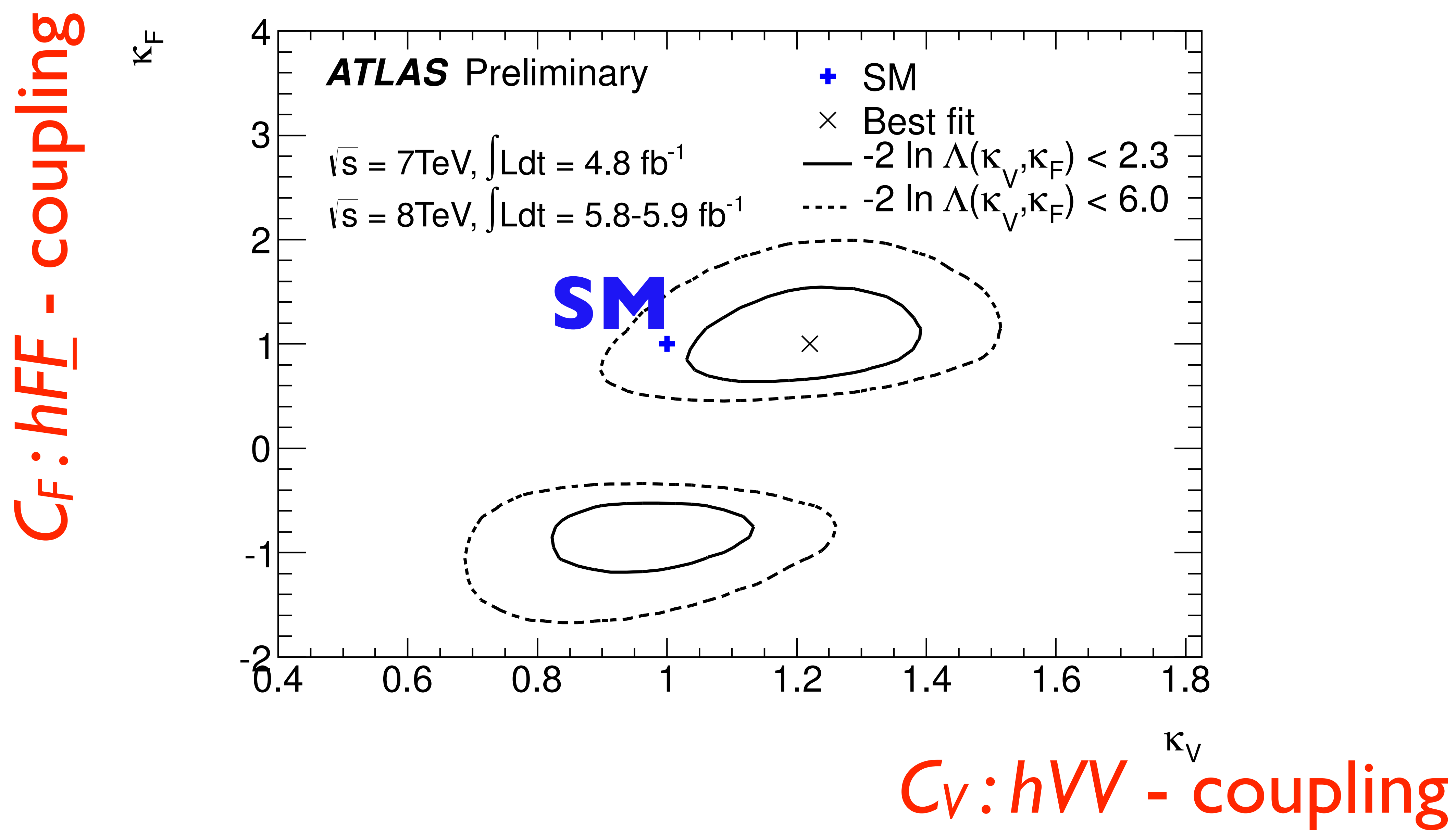
Is it the SM Higgs?

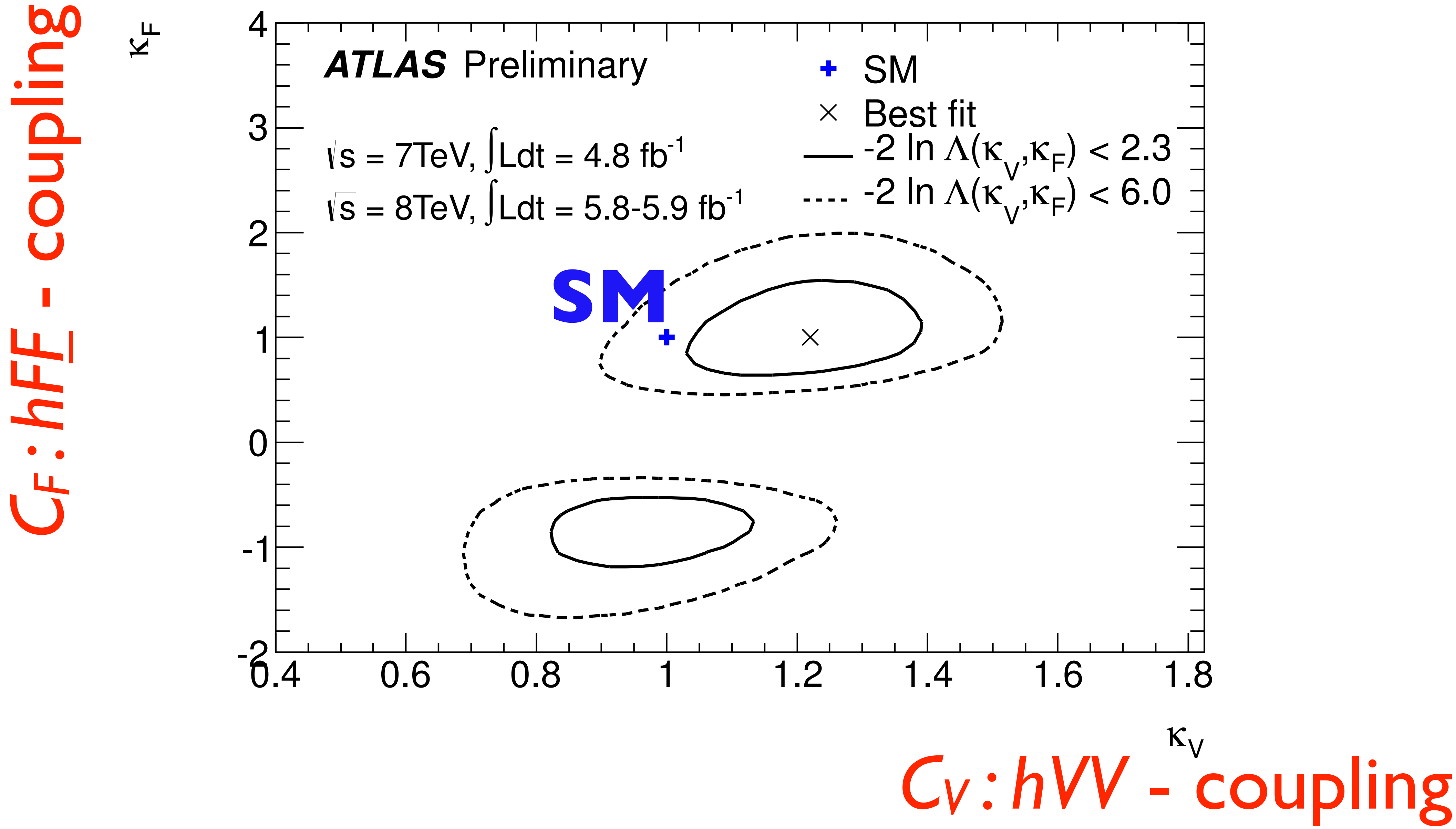
Vary couplings to Vectors + Fermions:



$$\mathcal{L}_{\mathrm{EWSB}} = -m_V^2 V_\mu V^\mu \left(1 + 2a\frac{h}{v}\right) - m_\psi \bar{\psi}\psi \left(1 + c\frac{h}{v}\right)$$

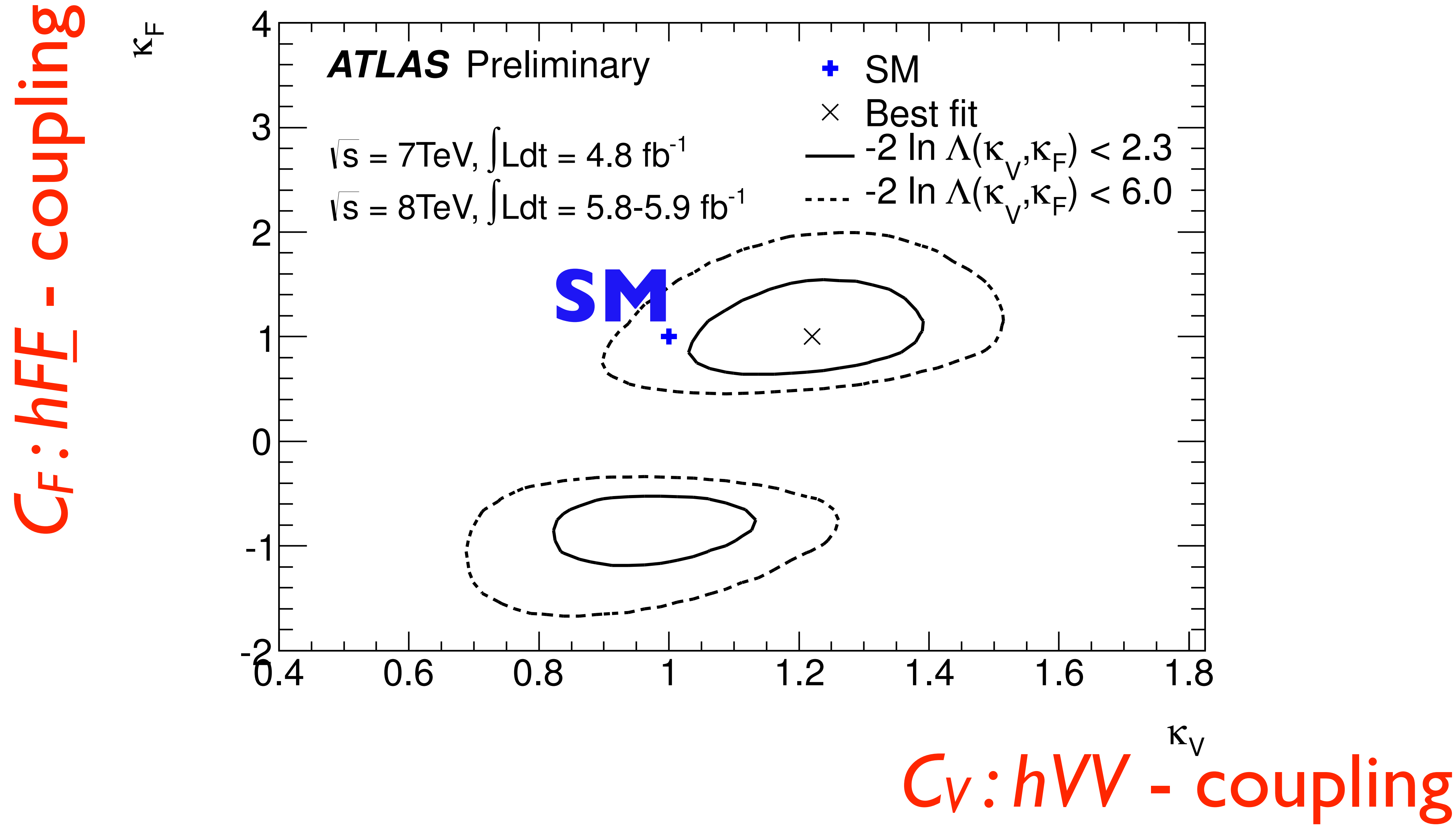
C_V C_F


ATLAS Preliminary
√s = 7TeV, ∫Ldt = 4.8 fb-1
√s = 8TeV, ∫Ldt = 5.8-5.9 fb-1
SM
Best fit
-2 ln Λ(κV,κF) < 2.3
-2 ln Λ(κV,κF) < 6.0
SM
κF
κV
CF : hFF - coupling
CV : hVV - coupling



LHC2TSP - WG1, editors: Heinemeyer, Kado, Mariotti, Weiglein, AW '12

Current sensitivity: 20% on CV and 30% on CF



LHC2TSP - WG1, editors: Heinemeyer, Kado, Mariotti, Weiglein, AW '12

Current sensitivity: 20% on CV and 30% on CF

Future

300/fb @ 14TeV: 5% on CV and 10% on CF

3/ab @ 14TeV: 3% on CV and 5% on CF

A light Higgs is unnatural

$$V(h) = \epsilon \Lambda^2 h^2 + \lambda h^4$$

For $\epsilon = \pm\, \mathcal{O}(1)$ $\quad \langle h \rangle = 0$

$\langle h \rangle = \Lambda$

Need: $\sqrt{\epsilon} \sim m_W / \Lambda$

SM UV sensitivity

$$V_{\rm tree} = \frac{1}{2} m_h^2\, h^2 + \frac{m_h^2}{2v} h^3 + \frac{m_h^2}{8v^2} h^4$$
$$\approx (100\,{\rm GeV})^2\, h^2 + \ldots$$

$$V_{\Lambda^2} \approx (\ \ 15 \ \ - 100 \ \ + \ \ 9.5 \ \ ) \cdot (100\,{\rm GeV})^2 \ h^2$$

SU(2) top higgs

$$\Lambda = 10\,{\rm TeV}$$

SM UV sensitivity

$$V_{\text{tree}} = \frac{1}{2} m_h^2 \, h^2 + \frac{m_h^2}{2v} h^3 + \frac{m_h^2}{8v^2} h^4$$
$$\approx (100\,\text{GeV})^2 \, h^2 + \ldots$$

fine-tuning!

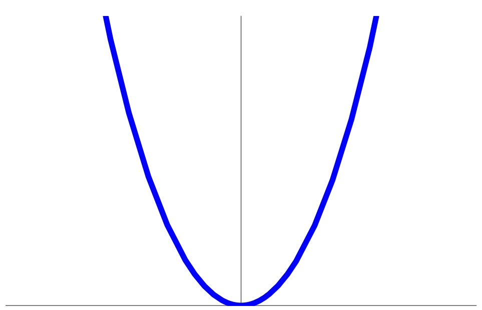
$$V_{\Lambda^2} \approx (\;\; 15 \;\; - 100 \;\; + \;\; 9.5 \;\;) \cdot (100\,\text{GeV})^2 \;\; h^2$$

SU(2) top higgs

$$\Lambda = 10\,\text{TeV}$$

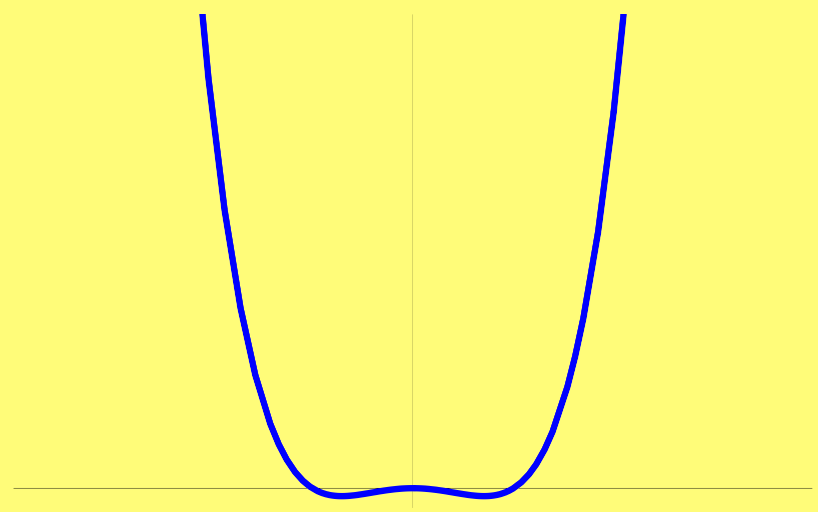
generically

$\epsilon \sim O(1)$



$<H>=0$

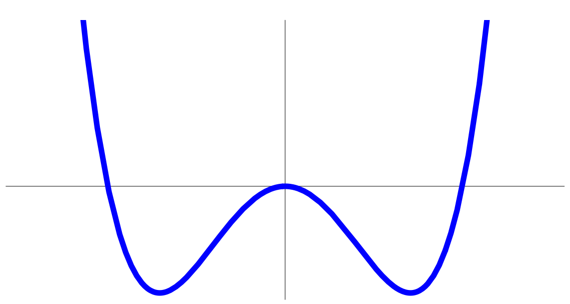
but we need



$\langle H\rangle = \sqrt{\epsilon}\Lambda_{UV}$

$\epsilon \sim 10^{-34}$

$\epsilon \sim -O(1)$



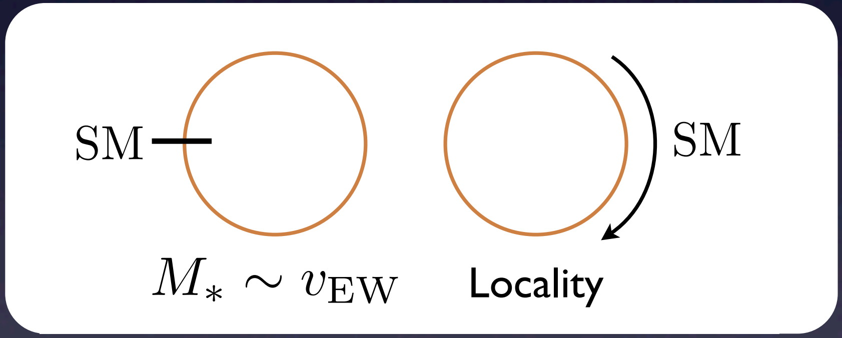
$\langle H\rangle \sim \Lambda_{UV}$

Which principle can stabilize the electro-weak scale?

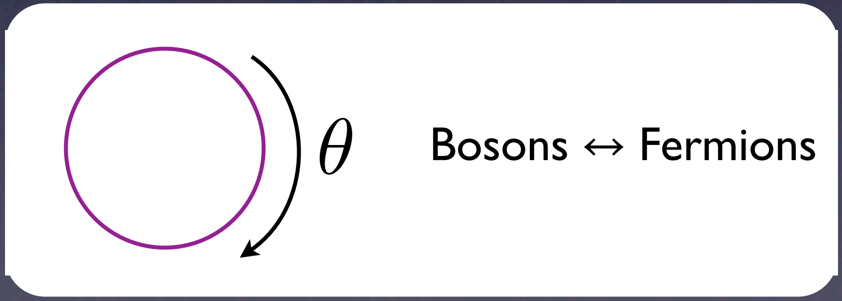
Strong dynamics/ compositeness?

$$\langle \psi \psi^c \rangle \to H \to v_{\mathrm{EW}}$$

Higher Dimensions?



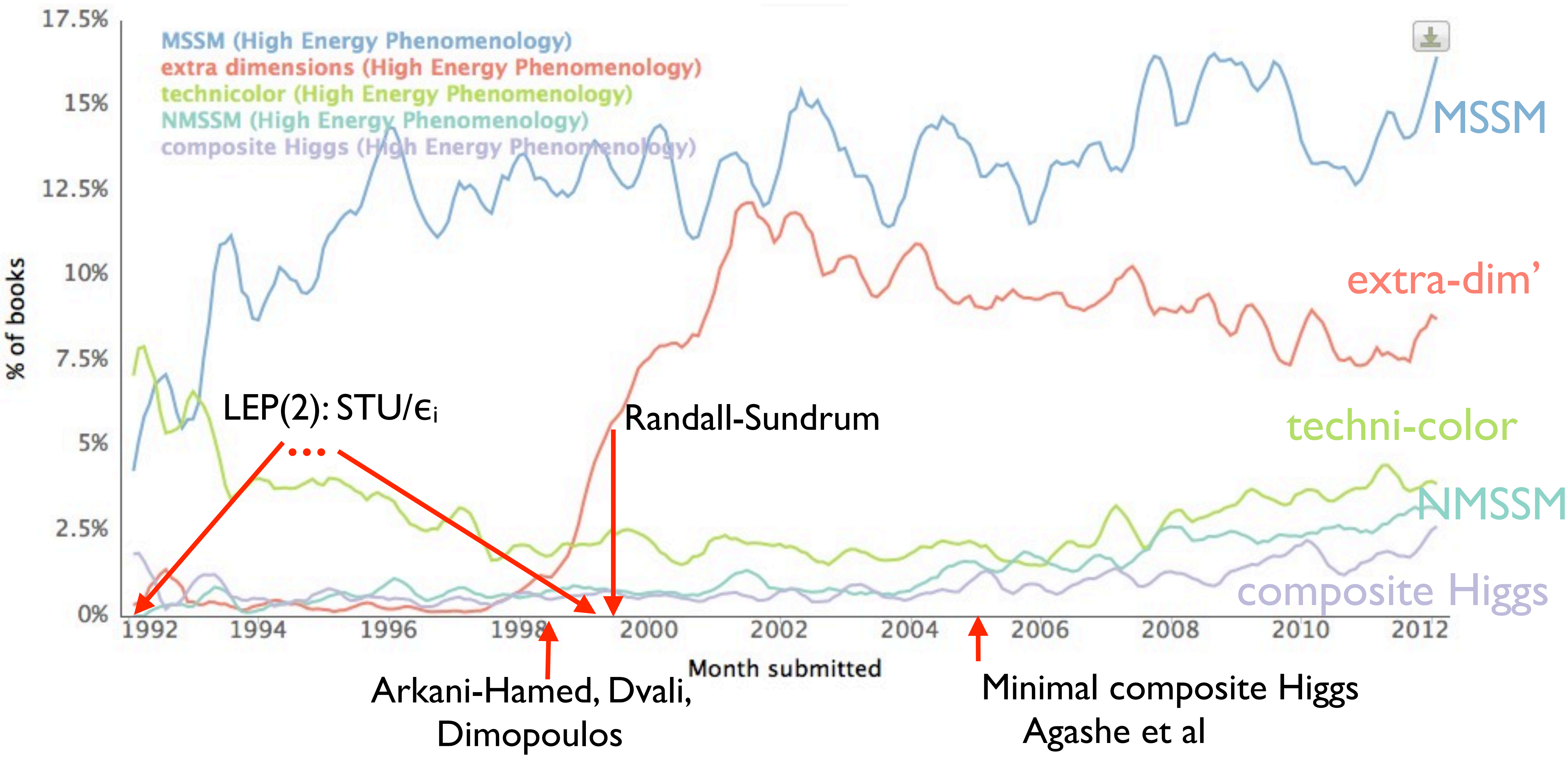
Supersymmetry?



Lack of principles? Anthropic? Non-Wilsonian EFT?

Let’s look at the data

Data pre-LHC

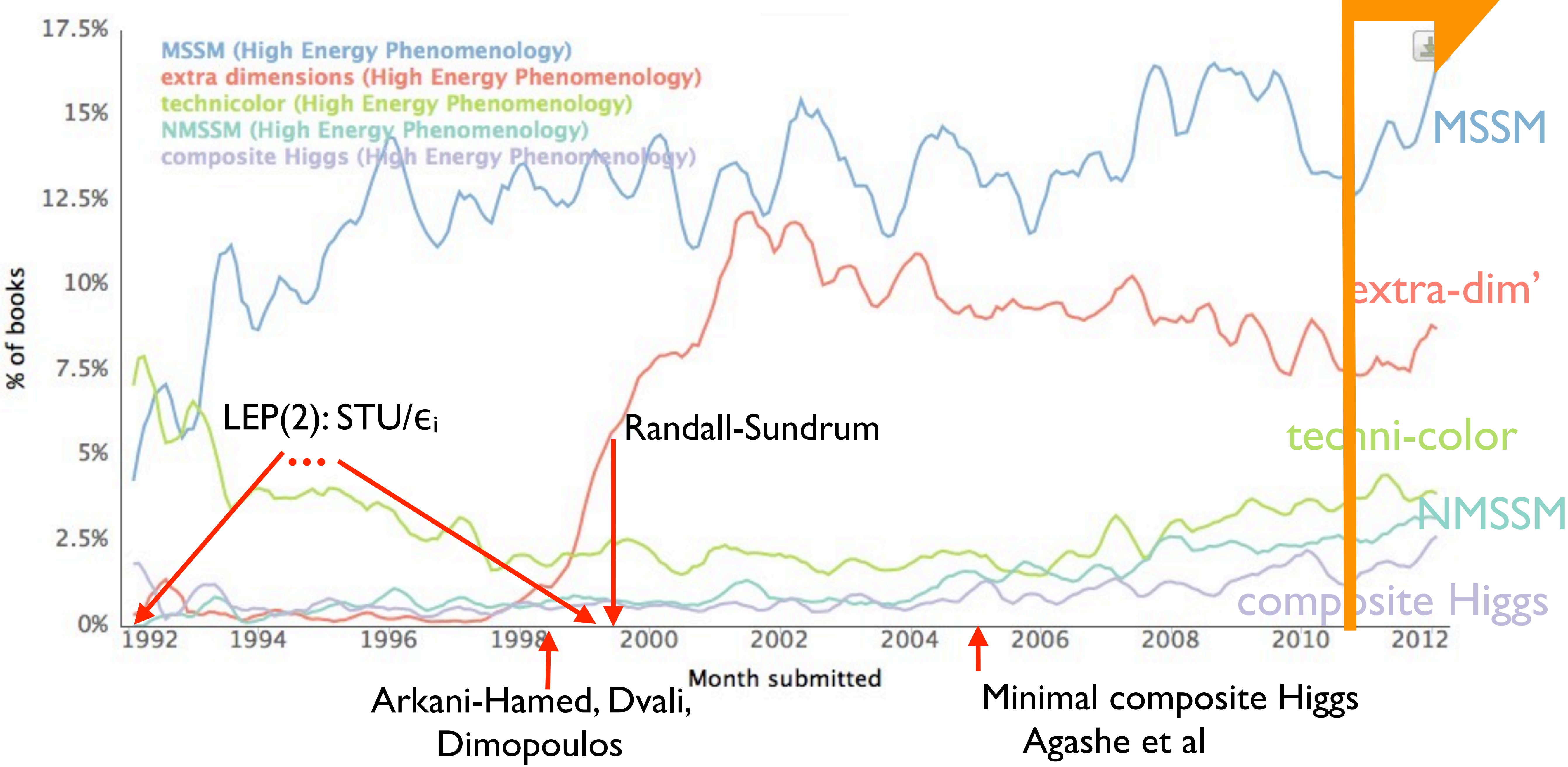


arXiv [hep-ph] mentions

http://arxiv.culturomics.org

new era
starts here

Data pre-LHC



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LHC summary:

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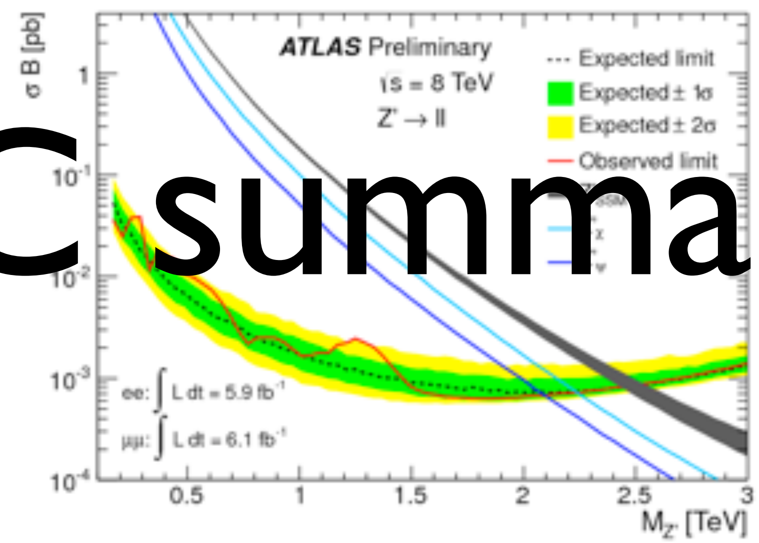
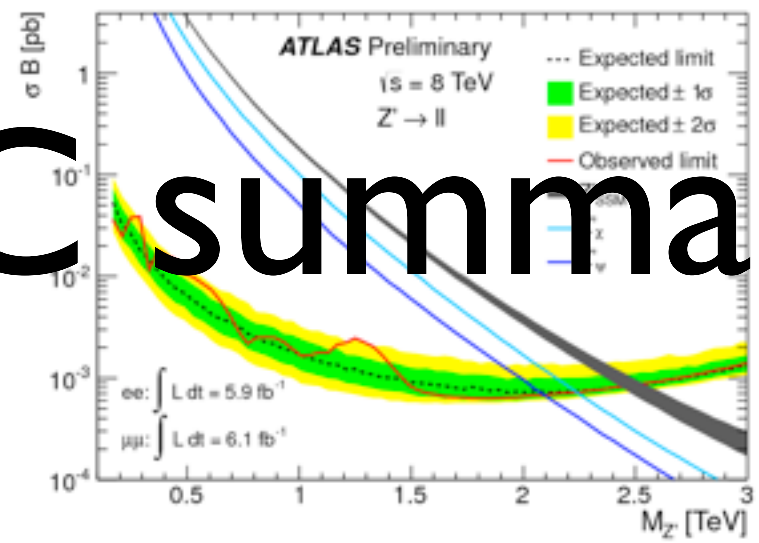

ATLAS Preliminary
√s = 8 TeV
Z' → ll
Expected limit
Expected ± 1σ
Expected ± 2σ
Observed limit
ee: ∫ L dt = 5.9 fb⁻¹
μμ: ∫ L dt = 6.1 fb⁻¹
σ B [pb]
M_Z' [TeV]

LHC summary: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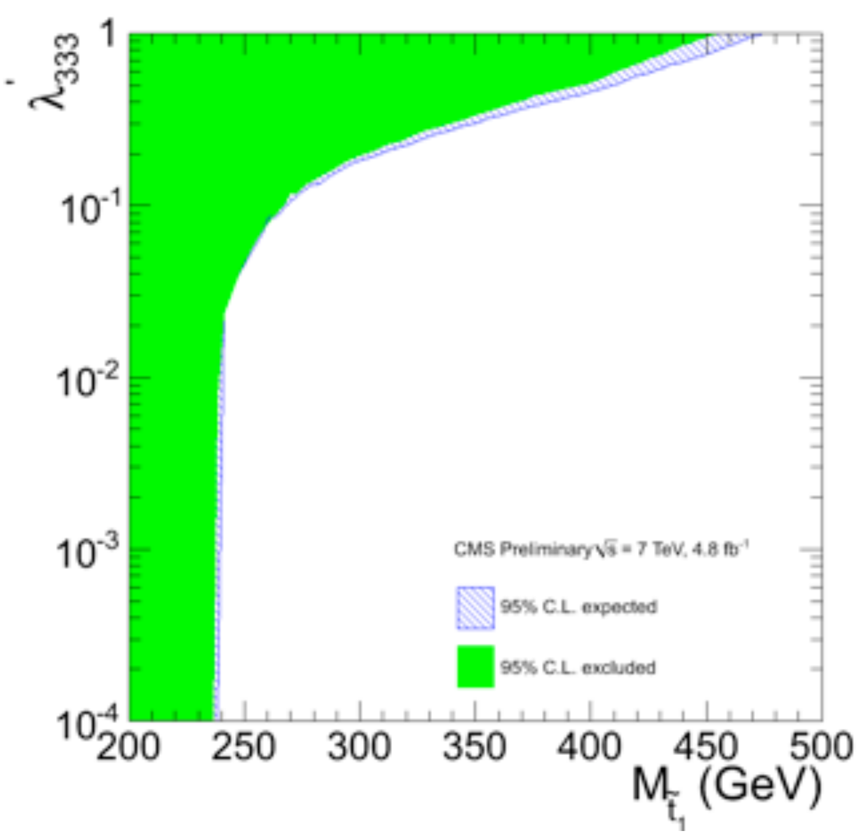
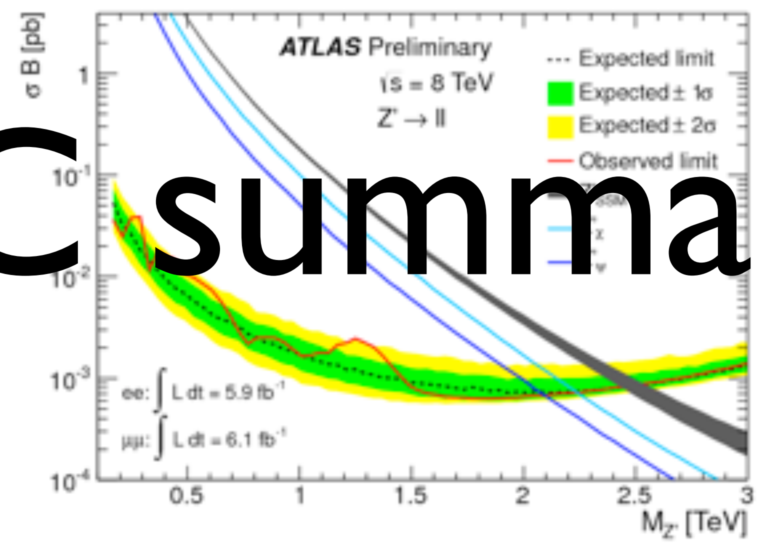

CMS Preliminary √s = 7 TeV, 4.8 fb⁻¹
95% C.L. expected
95% C.L. excluded
λ'_333
M_t̃1 (GeV)

LHC summary: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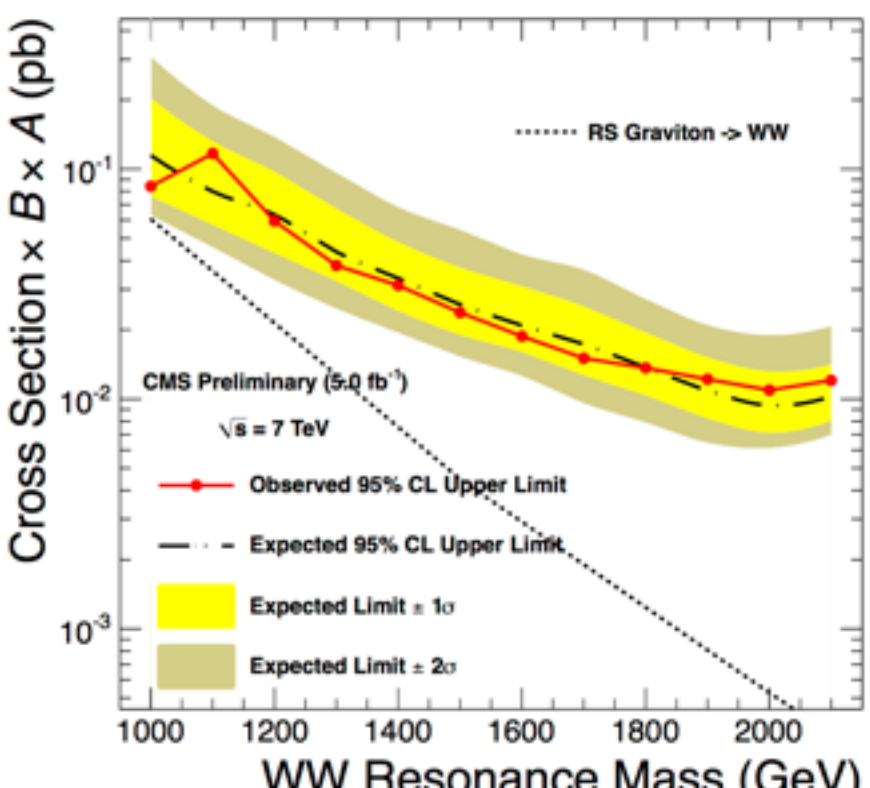
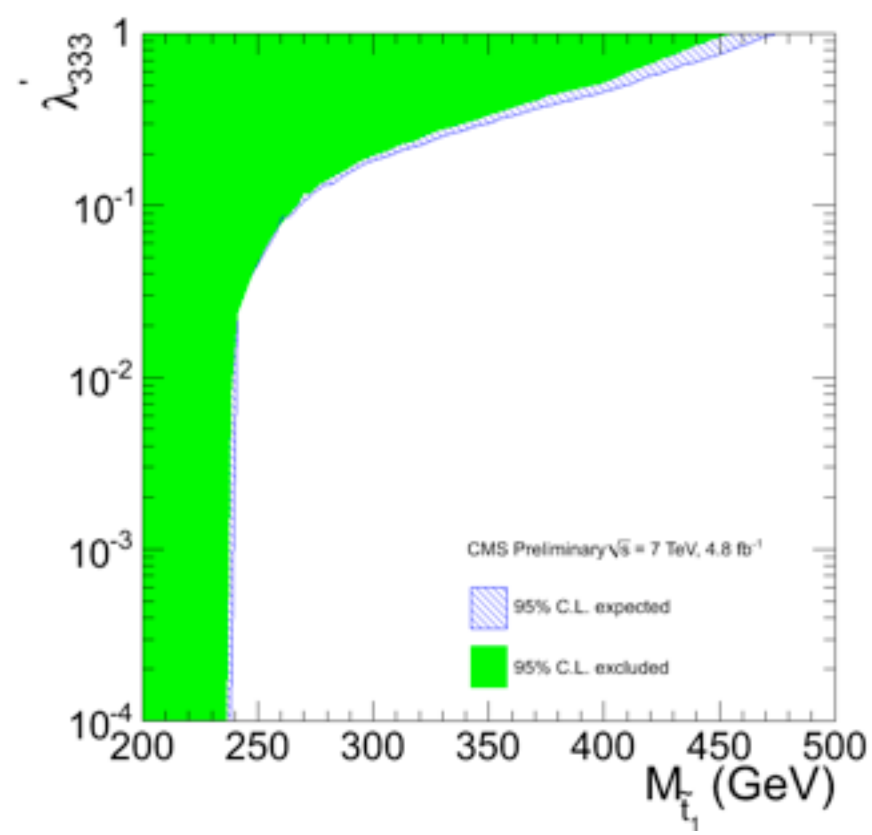

RS Graviton -> WW
CMS Preliminary (5.0 fb⁻¹)
√s = 7 TeV
Observed 95% CL Upper Limit
Expected 95% CL Upper Limit
Expected Limit ± 1σ
Expected Limit ± 2σ
Cross Section × B × A (pb)
WW Resonance Mass (GeV)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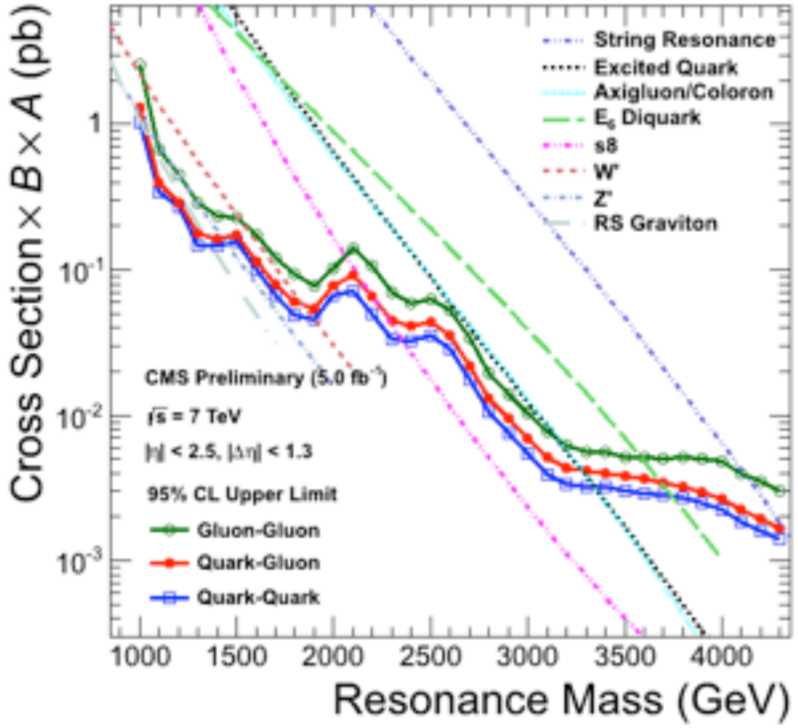
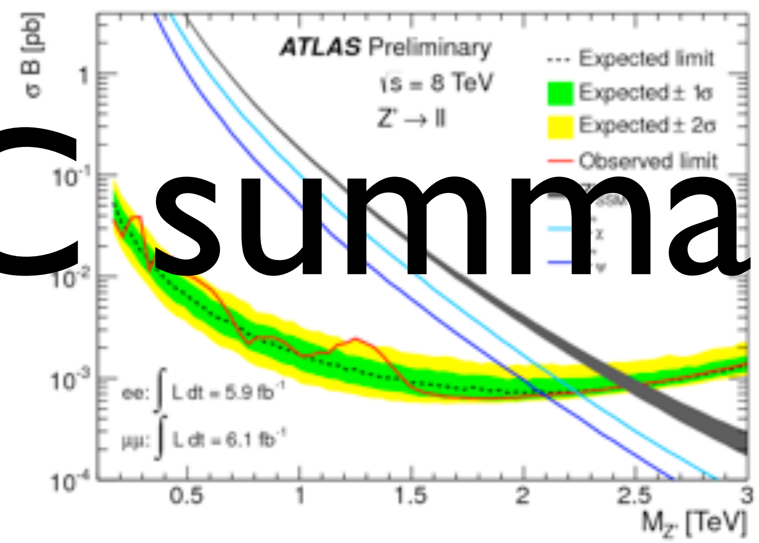

String Resonance
Excited Quark
Axigluon/Coloron
E6 Diquark
s8
W'
Z'
RS Graviton
CMS Preliminary (5.0 fb-1)
√s = 7 TeV
|η| < 2.5, |Δη| < 1.3
95% CL Upper Limit
Gluon-Gluon
Quark-Gluon
Quark-Quark
Cross Section × B × A (pb)
Resonance Mass (GeV)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√s = 8 TeV
Z' → ll
Expected limit
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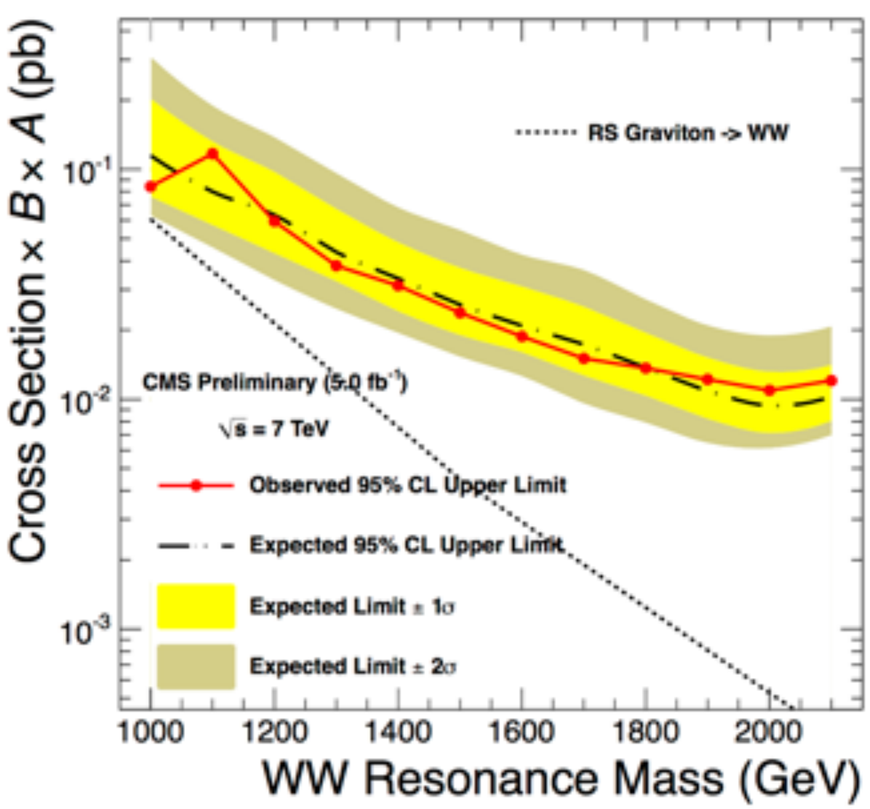
σ B [pb]
M_Z' [TeV]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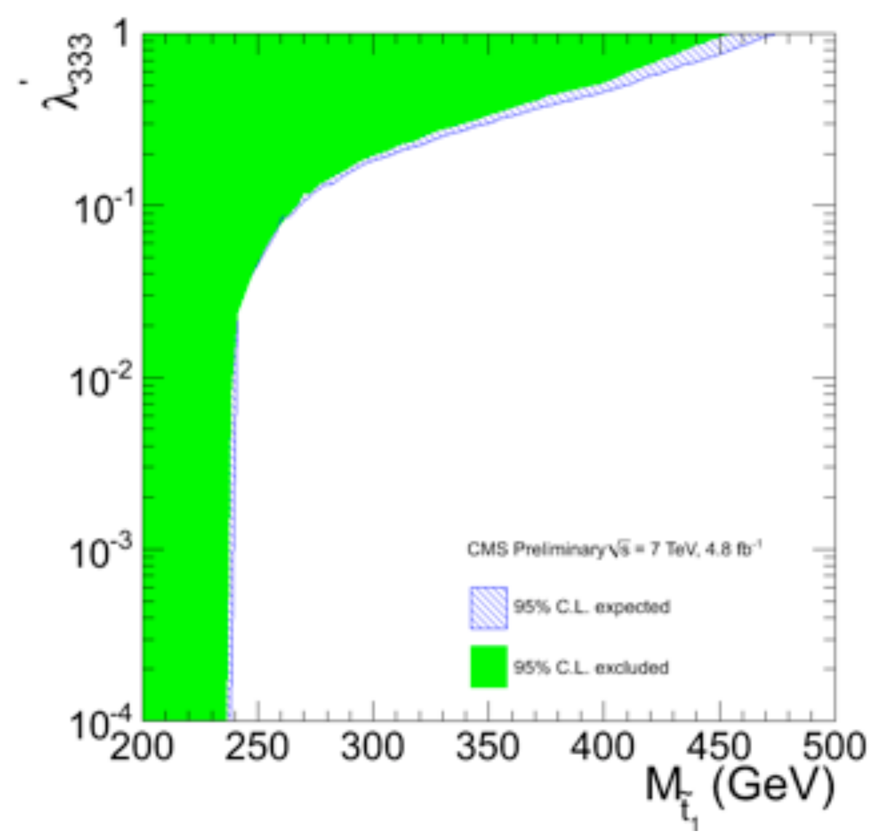
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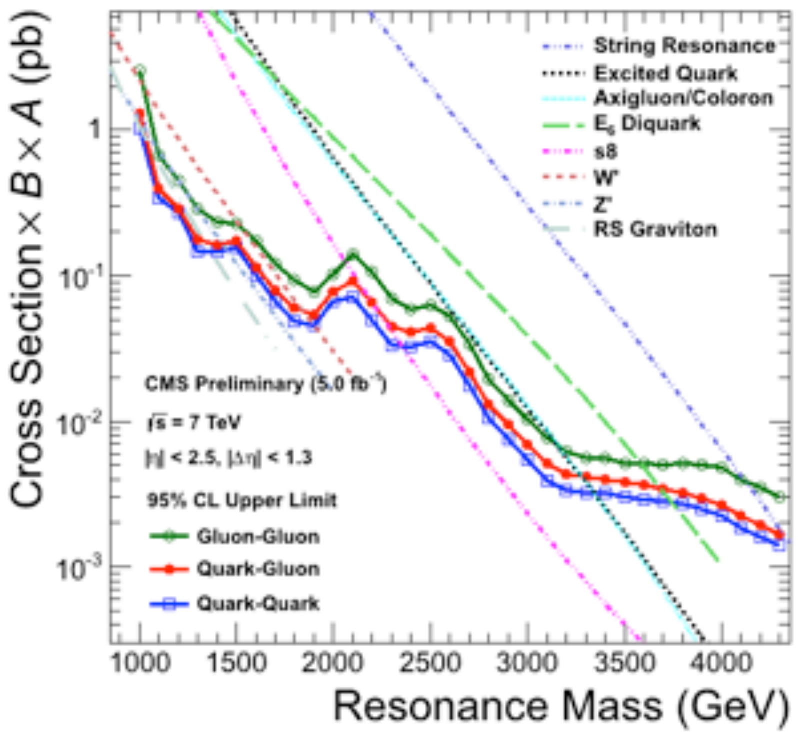

String Resonance
Excited Quark
Axigluon/Coloron
E6 Diquark
s8
W'
Z'
RS Graviton
CMS Preliminary (5.0 fb^{-1})
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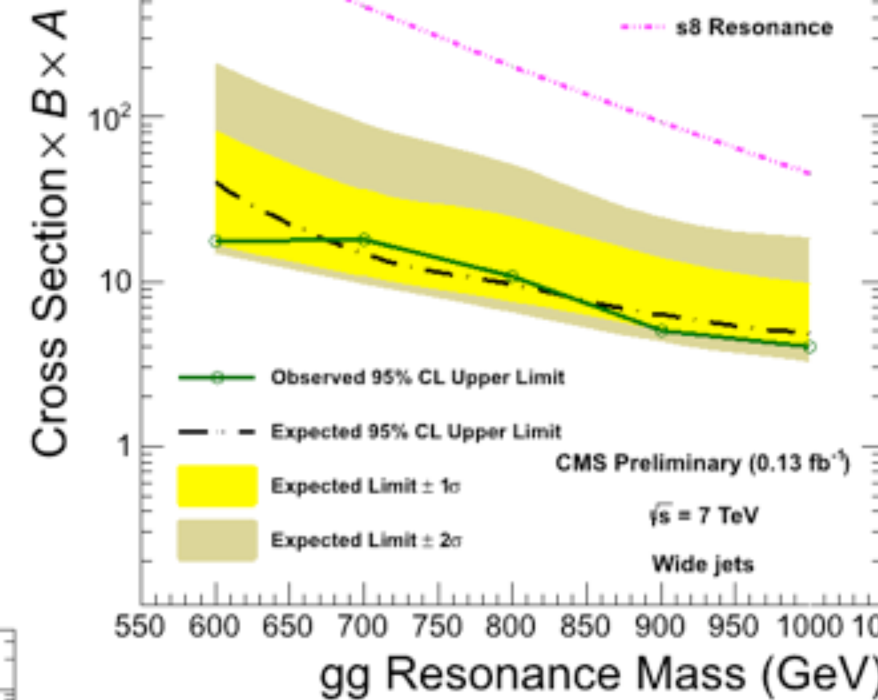
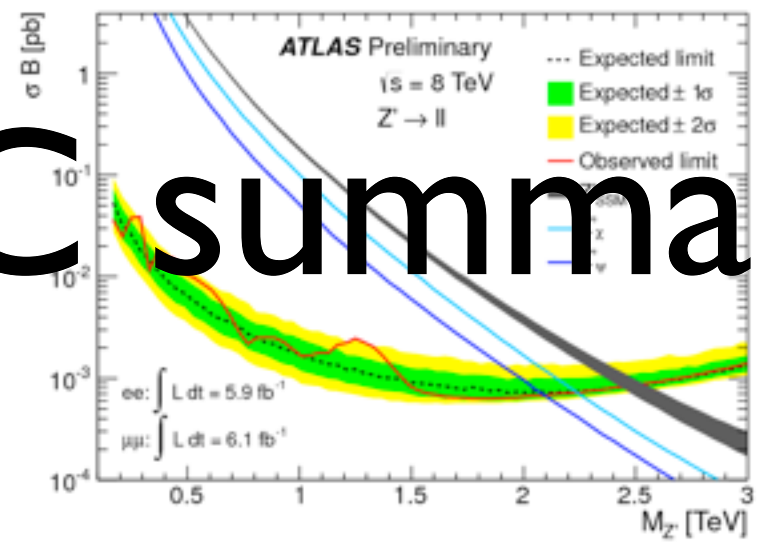
95% CL Upper Limit
Gluon-Gluon
Quark-Gluon
Quark-Quark
Cross Section × B × A (pb)
Resonance Mass (GeV)



s8 Resonance
Observed 95% CL Upper Limit
Expected 95% CL Upper Limit
Expected Limit ± 1σ
Expected Limit ± 2σ
CMS Preliminary (0.13 fb^{-1})
$\sqrt{s}$ = 7 TeV
Wide jets
Cross Section × B × A
gg Resonance Mass (GeV)



ATLAS Preliminary
$\sqrt{s}$ = 8 TeV
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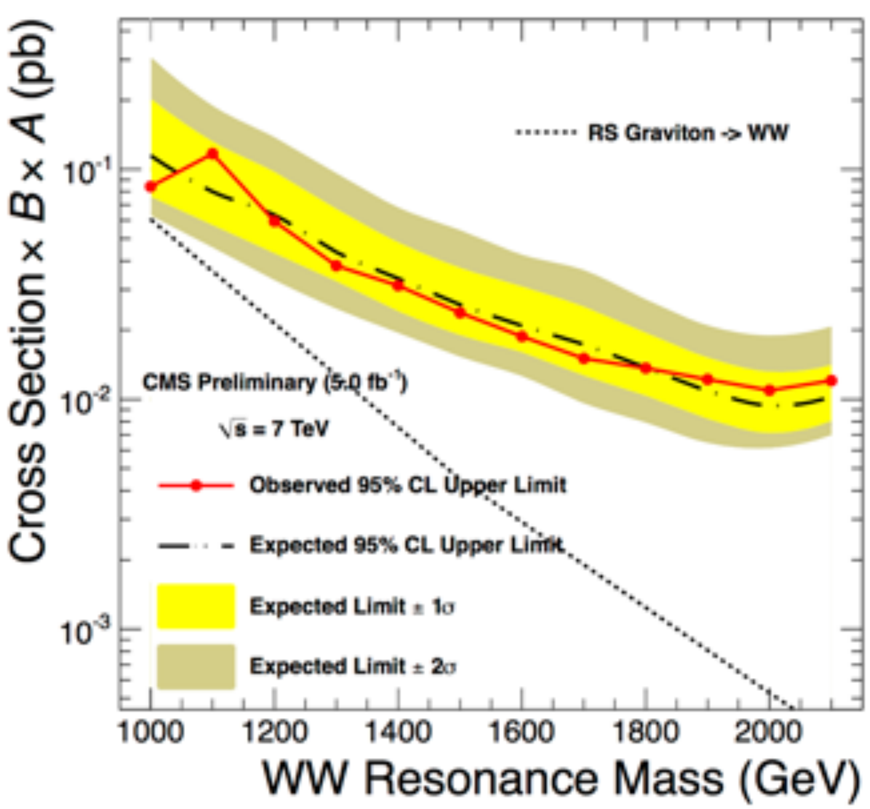
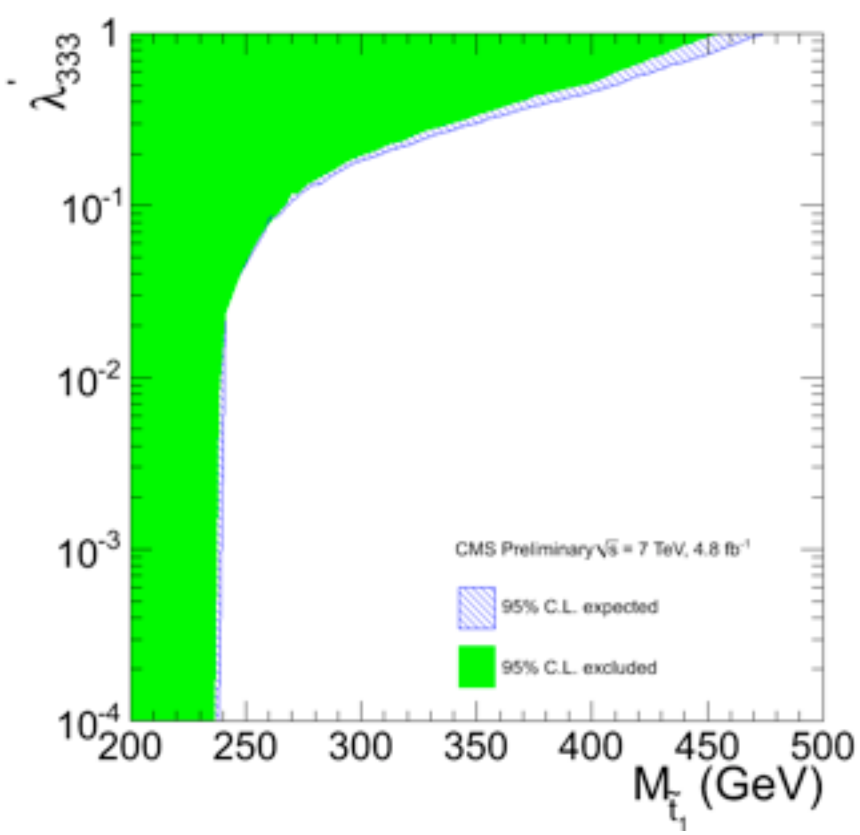
Expected ± 1σ
Expected ± 2σ
Observed limit
σ B [pb]
M$_{Z'}$ [TeV]



RS Graviton -> WW
CMS Preliminary (5.0 fb^{-1})
$\sqrt{s}$ = 7 TeV
Observed 95% CL Upper Limit
Expected 95% CL Upper Limit
Expected Limit ± 1σ
Expected Limit ± 2σ
Cross Section × B × A (pb)
WW Resonance Mass (GeV)



CMS Preliminary $\sqrt{s}$ = 7 TeV, 4.8 fb^{-1}
95% C.L. expected
95% C.L. excluded
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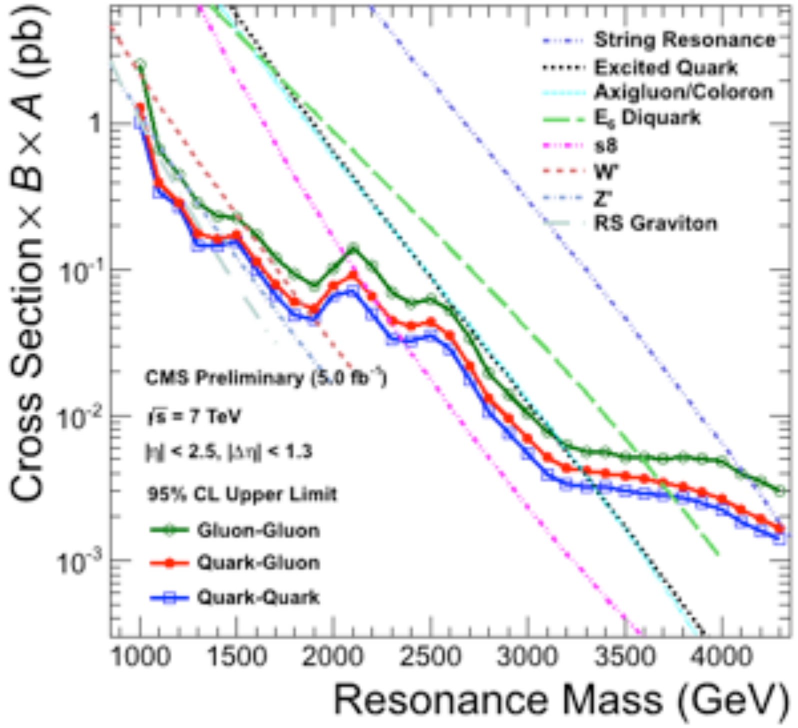
$M_{\tilde{t}_1}$ (GeV)

LHC summary:



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Axigluon/Coloron
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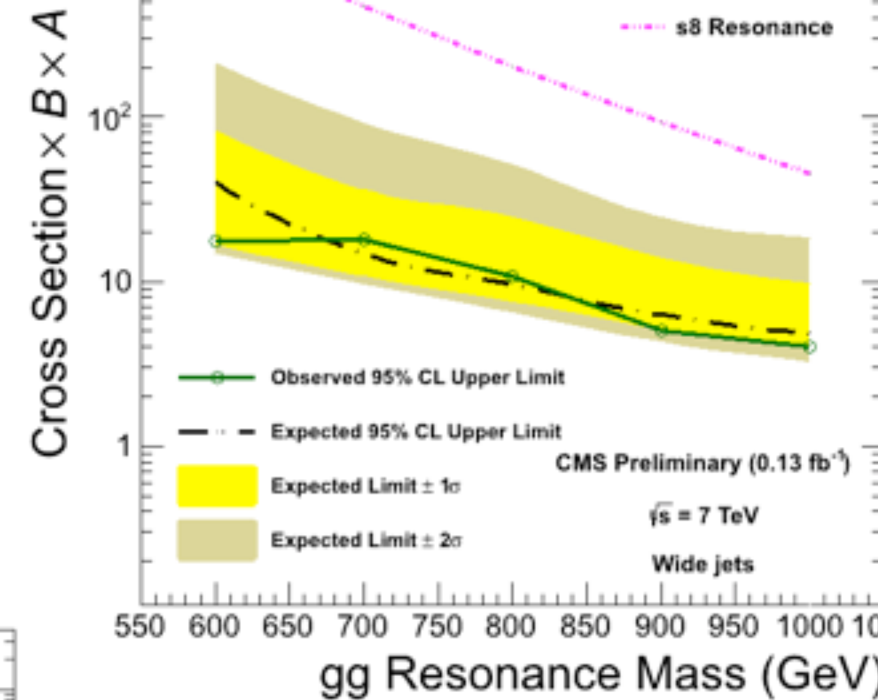
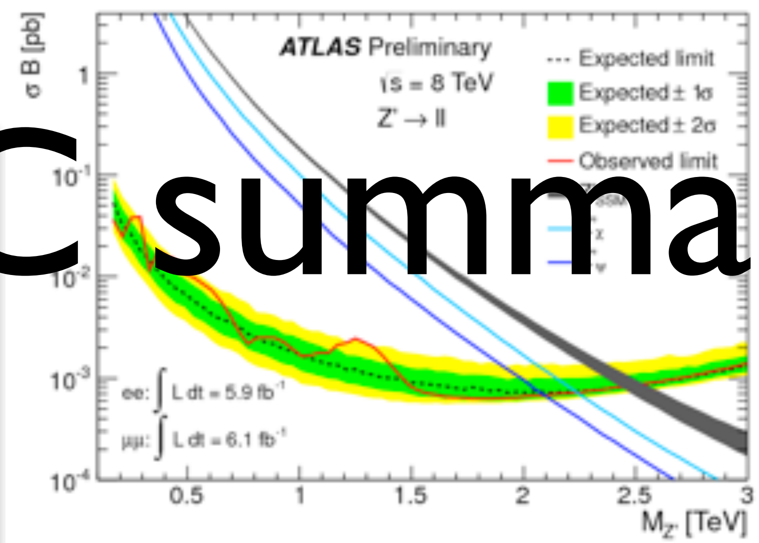


s8 Resonance
Observed 95% CL Upper Limit
Expected 95% CL Upper Limit
Expected Limit ± 1σ
Expected Limit ± 2σ
CMS Preliminary (0.13 fb⁻¹)
√s = 7 TeV
Wide jets
Cross Section × B × A
gg Resonance Mass (GeV)



ATLAS Preliminary
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Z' → ll
Expected limit
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ee: ∫ L dt = 5.9 fb⁻¹
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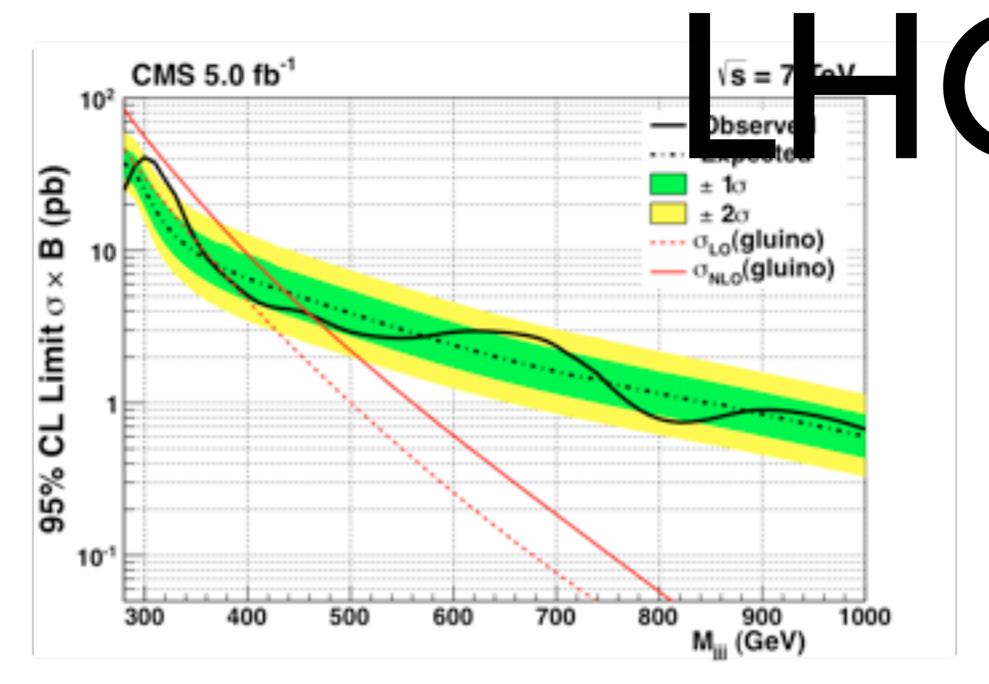
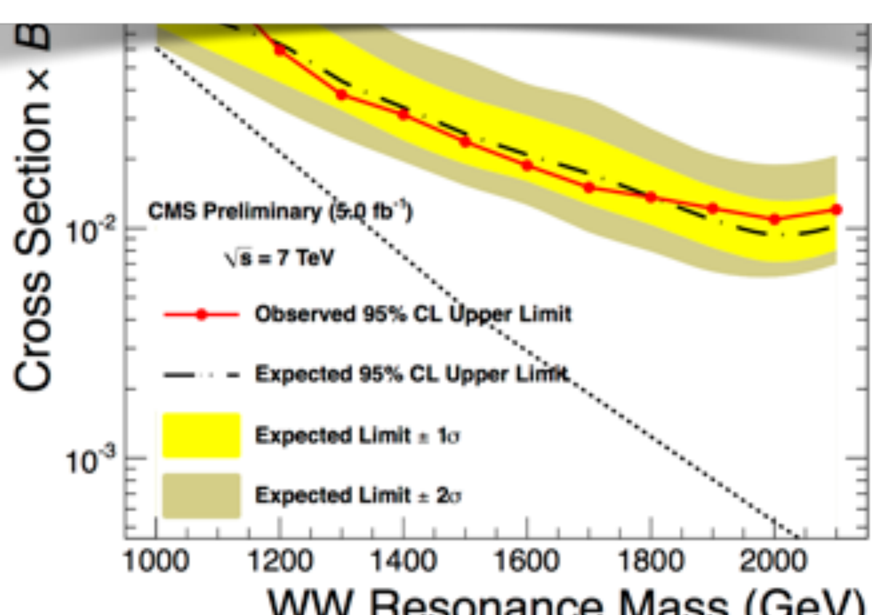
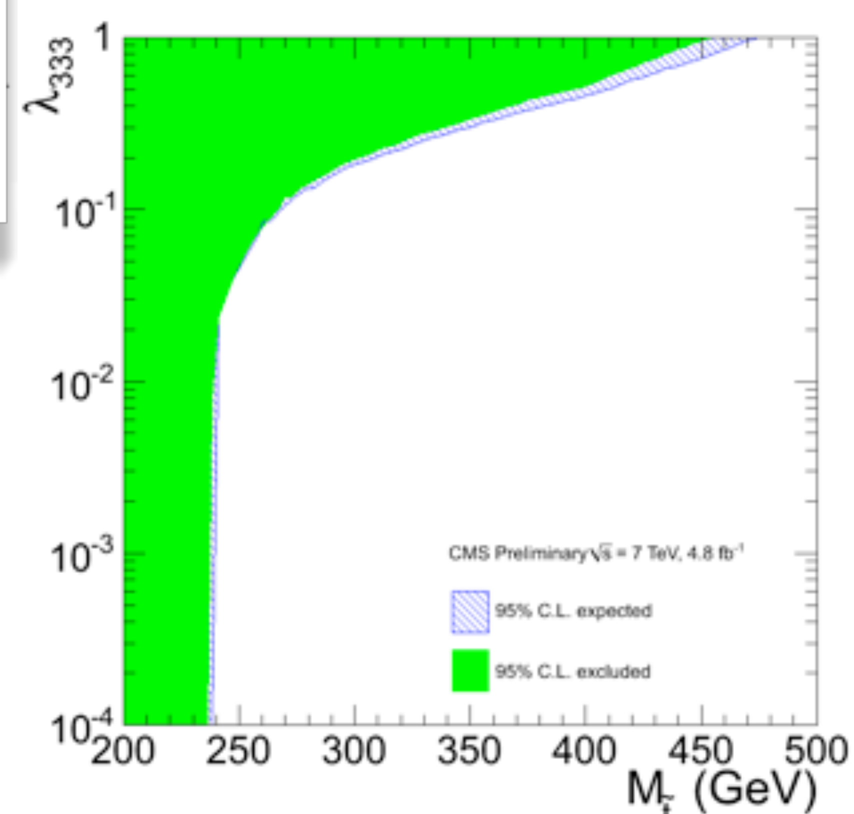
σ B [pb]
M_Z' [TeV]



CMS 5.0 fb⁻¹
± 1σ
± 2σ
σ_LO(gluino)
σ_NLO(gluino)
95% CL Limit σ × B (pb)
M_jjj (GeV)

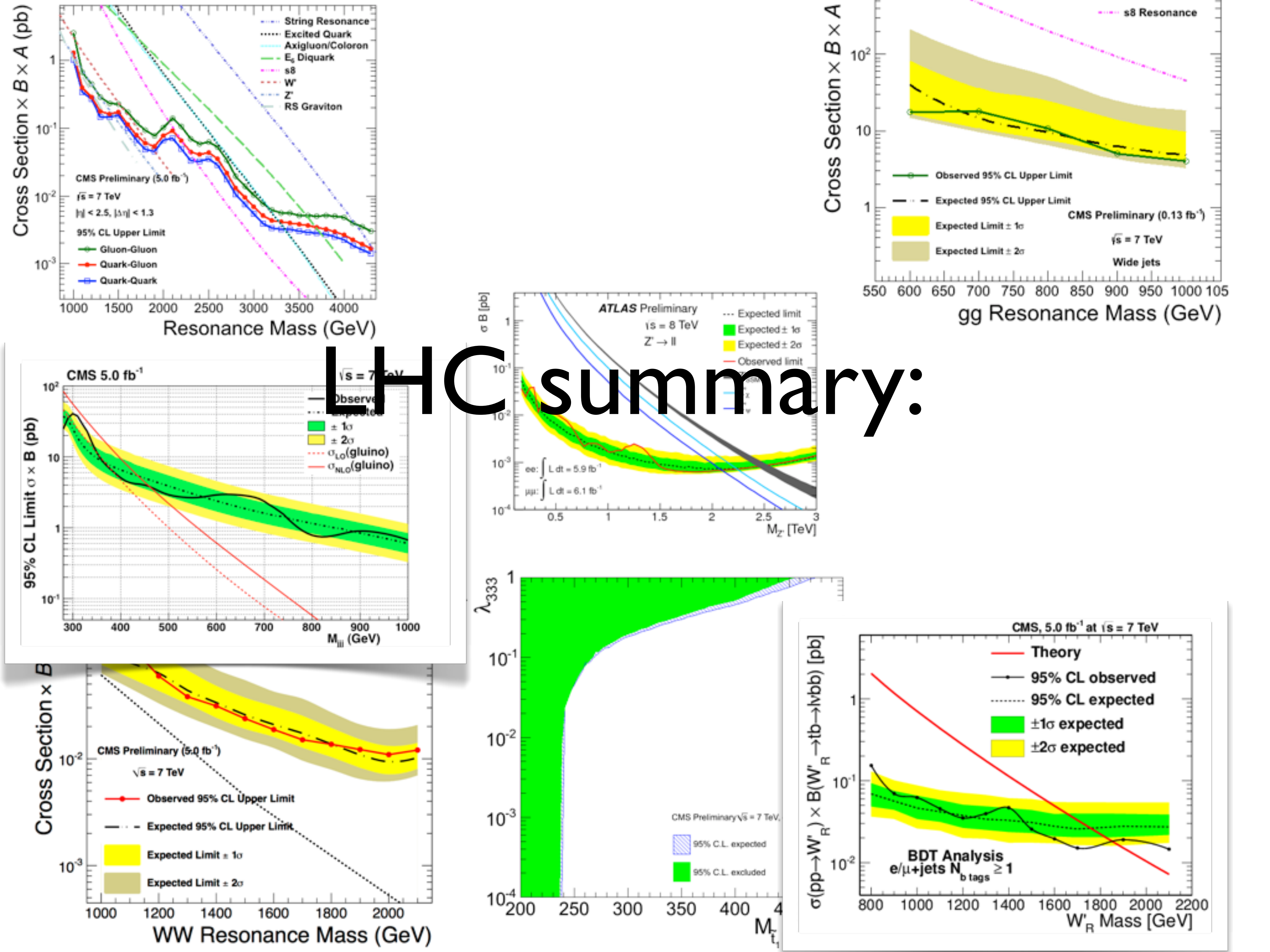


CMS Preliminary (5.0 fb⁻¹)
√s = 7 TeV
Observed 95% CL Upper Limit
Expected 95% CL Upper Limit
Expected Limit ± 1σ
Expected Limit ± 2σ
Cross Section × B
WW Resonance Mass (GeV)



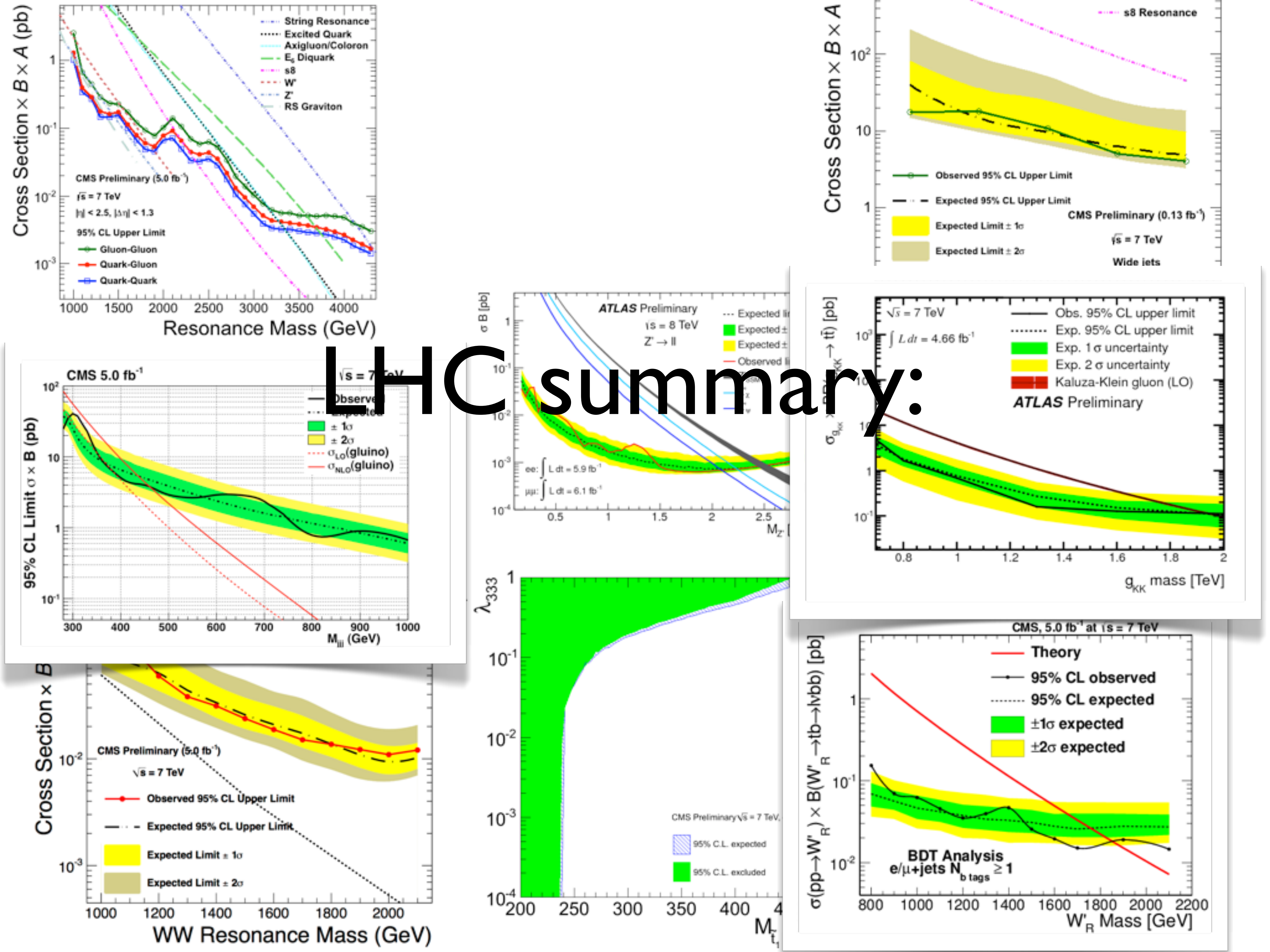
CMS Preliminary √s = 7 TeV, 4.8 fb⁻¹
95% C.L. expected
95% C.L. excluded
λ333
M_t̃1 (GeV)

LHC summary:



String Resonance
Excited Quark
Axigluon/Coloron
E6 Diquark
s8
W'
Z'
RS Graviton
CMS Preliminary (5.0 fb-1)
√s = 7 TeV
|η| < 2.5, |Δη| < 1.3
95% CL Upper Limit
Gluon-Gluon
Quark-Gluon
Quark-Quark
Cross Section × B × A (pb)
Resonance Mass (GeV)
s8 Resonance
Observed 95% CL Upper Limit
Expected 95% CL Upper Limit
Expected Limit ± 1σ
Expected Limit ± 2σ
CMS Preliminary (0.13 fb-1)
√s = 7 TeV
Wide jets
gg Resonance Mass (GeV)
ATLAS Preliminary
√s = 8 TeV
Z' → ll
Expected limit
Expected ± 1σ
Expected ± 2σ
Observed limit
σ B [pb]
M_Z' [TeV]
CMS 5.0 fb-1
95% CL Limit σ × B (pb)
± 1σ
± 2σ
σ_LO(gluino)
σ_NLO(gluino)
M_jjj (GeV)
CMS Preliminary (5.0 fb-1)
√s = 7 TeV
Observed 95% CL Upper Limit
Expected 95% CL Upper Limit
Expected Limit ± 1σ
Expected Limit ± 2σ
Cross Section × B
WW Resonance Mass (GeV)
λ333
CMS Preliminary √s = 7 TeV,
95% C.L. expected
95% C.L. excluded
CMS, 5.0 fb-1 at √s = 7 TeV
Theory
95% CL observed
95% CL expected
±1σ expected
±2σ expected
BDT Analysis
e/μ+jets N_b tags ≥ 1
σ(pp→W'_R) × B(W'_R→tb→lνbb) [pb]
W'_R Mass [GeV]

LHC summary:



String Resonance
Excited Quark
Axigluon/Coloron
E6 Diquark
s8
W'
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RS Graviton
CMS Preliminary (5.0 fb-1)
√s = 7 TeV
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Gluon-Gluon
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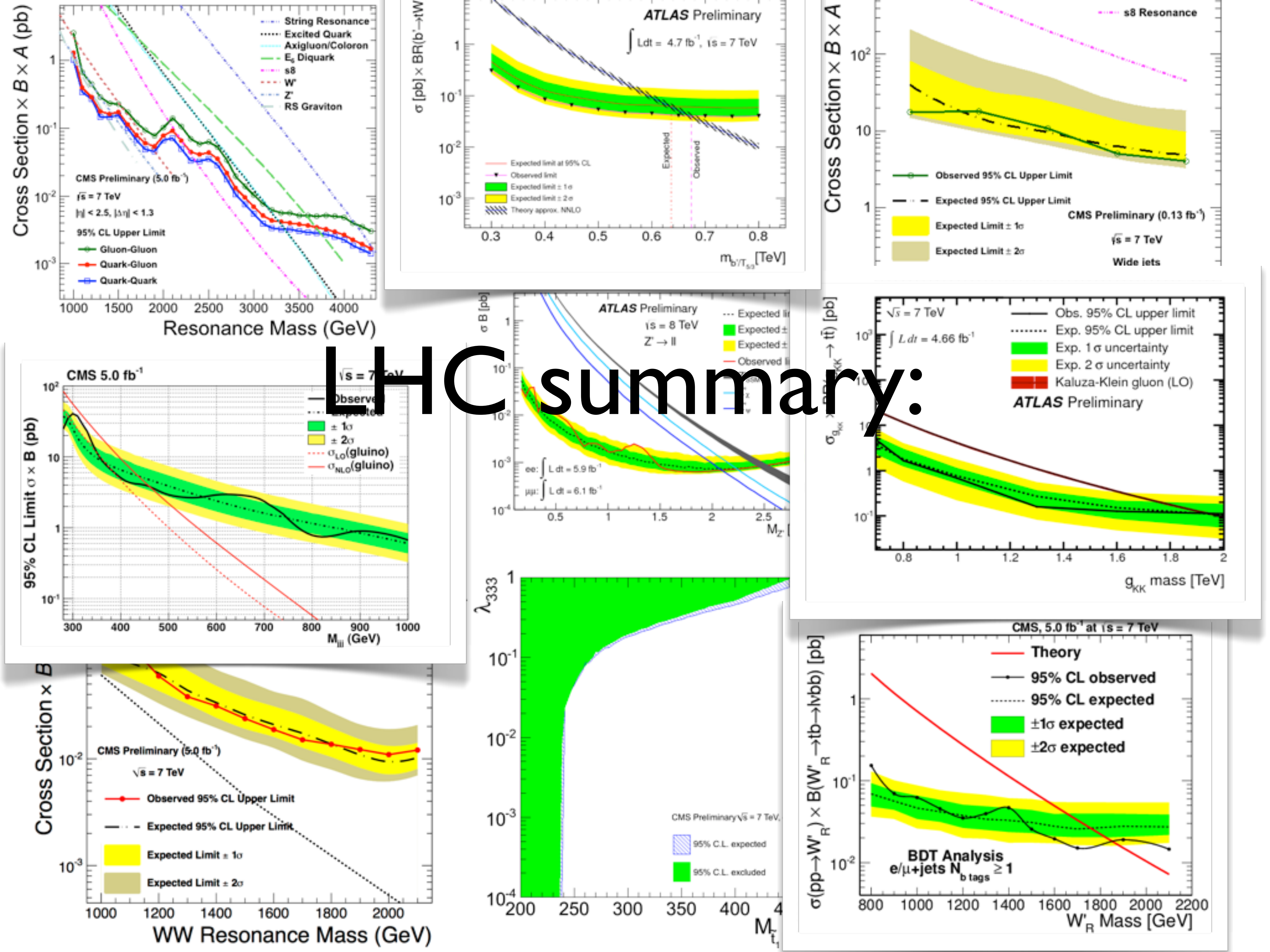
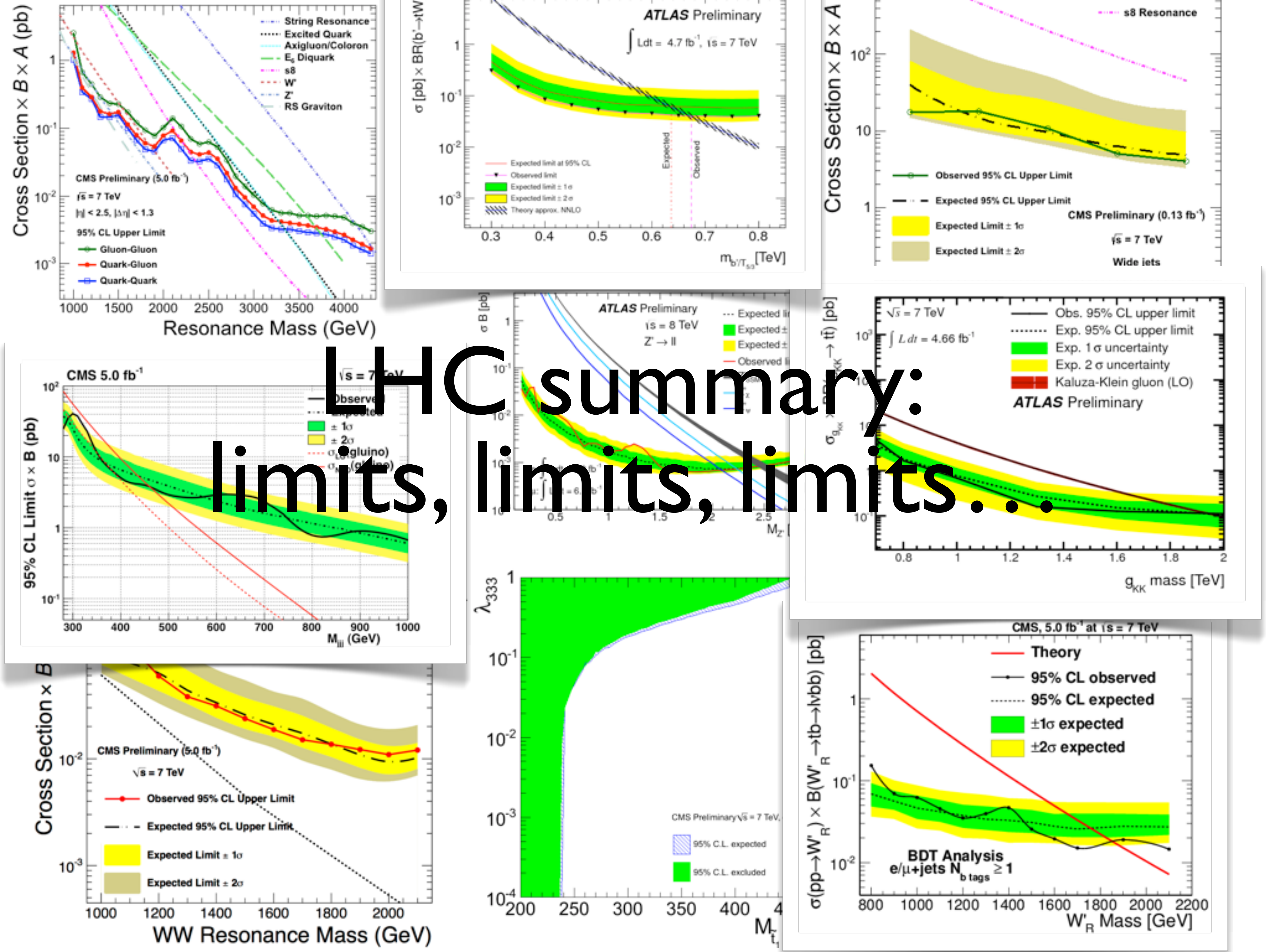
Quark-Quark
Cross Section × B × A (pb)
Resonance Mass (GeV)
s8 Resonance
Observed 95% CL Upper Limit
Expected 95% CL Upper Limit
Expected Limit ± 1σ
Expected Limit ± 2σ
CMS Preliminary (0.13 fb-1)
√s = 7 TeV
Wide jets
Cross Section × B × A
CMS 5.0 fb-1
√s = 7 TeV
95% CL Limit σ × B (pb)
M_jjj (GeV)
ATLAS Preliminary
√s = 8 TeV
Z' → ll
σ B [pb]
√s = 7 TeV
Obs. 95% CL upper limit
Exp. 95% CL upper limit
Exp. 1 σ uncertainty
Exp. 2 σ uncertainty
Kaluza-Klein gluon (LO)
ATLAS Preliminary
g_KK mass [TeV]
CMS Preliminary (5.0 fb-1)
√s = 7 TeV
Observed 95% CL Upper Limit
Expected 95% CL Upper Limit
Expected Limit ± 1σ
Expected Limit ± 2σ
WW Resonance Mass (GeV)
λ333
95% C.L. expected
95% C.L. excluded
CMS, 5.0 fb-1 at √s = 7 TeV
Theory
95% CL observed
95% CL expected
±1σ expected
±2σ expected
BDT Analysis
e/μ+jets N_b tags ≥ 1
W'_R Mass [GeV]

LHC summary:



Cross Section × B × A (pb)
String Resonance
Excited Quark
Axigluon/Coloron
E6 Diquark
s8
W'
Z'
RS Graviton
CMS Preliminary (5.0 fb-1)
√s = 7 TeV
95% CL Upper Limit
Gluon-Gluon
Quark-Gluon
Quark-Quark
Resonance Mass (GeV)
ATLAS Preliminary
∫Ldt = 4.7 fb-1, √s = 7 TeV
Expected limit at 95% CL
Observed limit
Expected limit ± 1σ
Expected limit ± 2σ
Theory approx. NNLO
Expected
Observed
s8 Resonance
Observed 95% CL Upper Limit
Expected 95% CL Upper Limit
CMS Preliminary (0.13 fb-1)
Expected Limit ± 1σ
Expected Limit ± 2σ
Wide jets
√s = 8 TeV
Z' → ll
CMS 5.0 fb-1
95% CL Limit σ × B (pb)
± 1σ
± 2σ
σLO(gluino)
σNLO(gluino)
Mjjj (GeV)
√s = 7 TeV
∫ L dt = 4.66 fb-1
Obs. 95% CL upper limit
Exp. 95% CL upper limit
Exp. 1σ uncertainty
Exp. 2σ uncertainty
Kaluza-Klein gluon (LO)
gKK mass [TeV]
CMS Preliminary (5.0 fb-1)
WW Resonance Mass (GeV)
λ333
95% C.L. expected
95% C.L. excluded
CMS, 5.0 fb-1 at √s = 7 TeV
Theory
95% CL observed
95% CL expected
±1σ expected
±2σ expected
BDT Analysis
W'R Mass [GeV]

LHC summary: limits, limits, limits…



Rules of thumb*

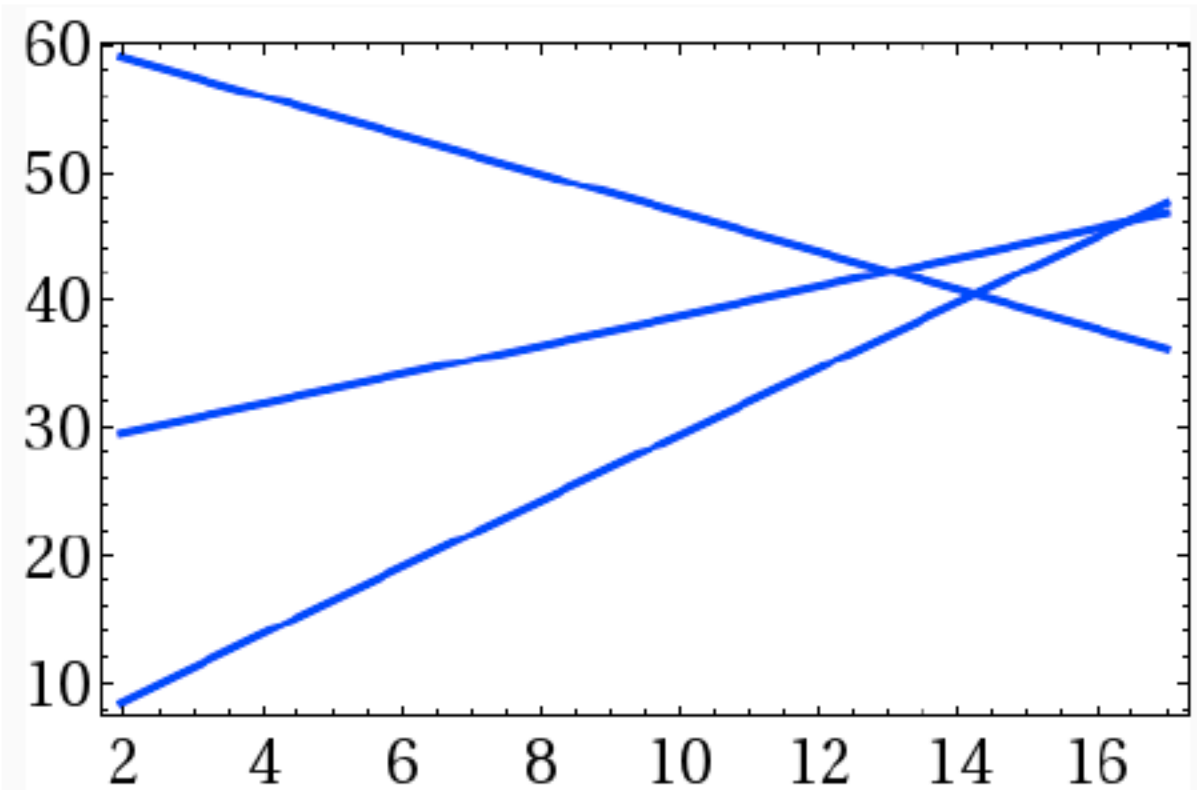
* no MET, mostly w/ SM like couplings

	QCD	EW
Scalar	**> 2.6 TeV** color octet	**> .6 TeV** Higgs-like
Fermion	**> 700 TeV** double prod. (b')	**> 1 TeV** single prod. (vector like, v/m_Q coupl.)
Vector	**> 1.9 TeV** RS KK gluon, $g_{(1)} \to t\underline{t}$	**> 2.5 TeV** W' / Z' → ee,mumu

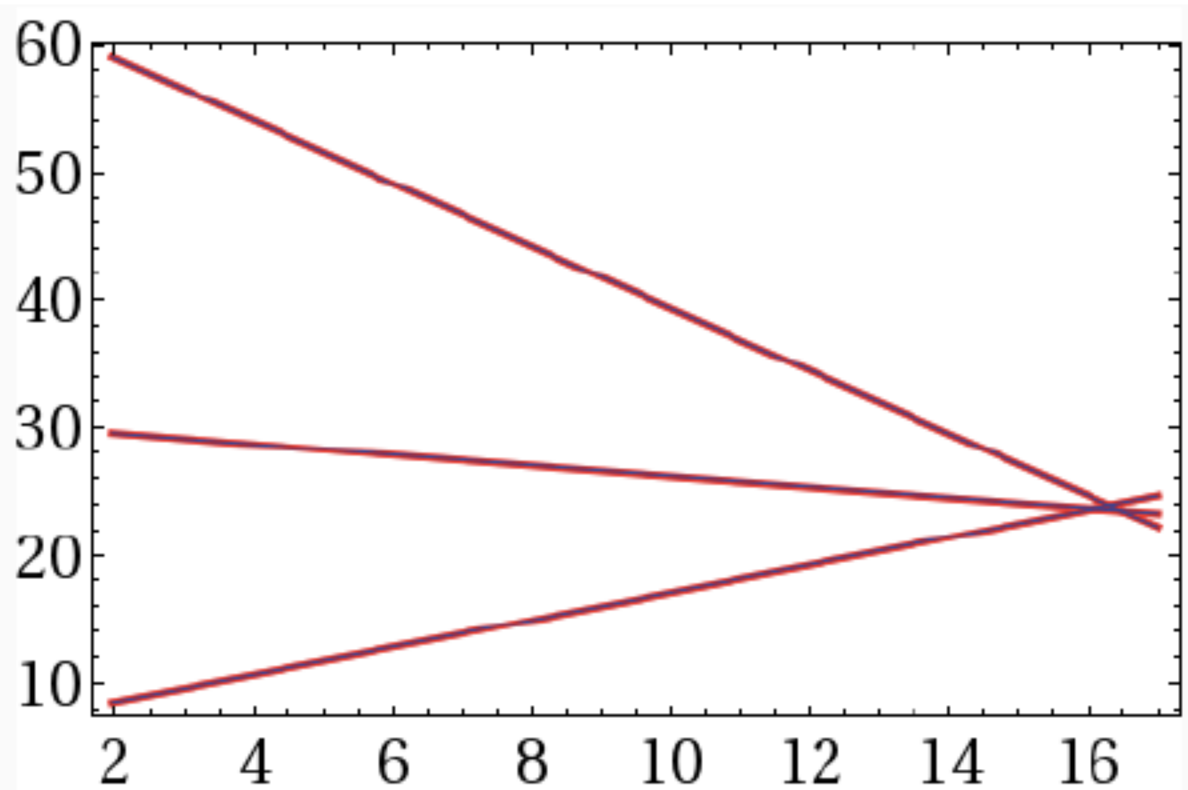
Status of SUSY

A hint?

SM



MSSM

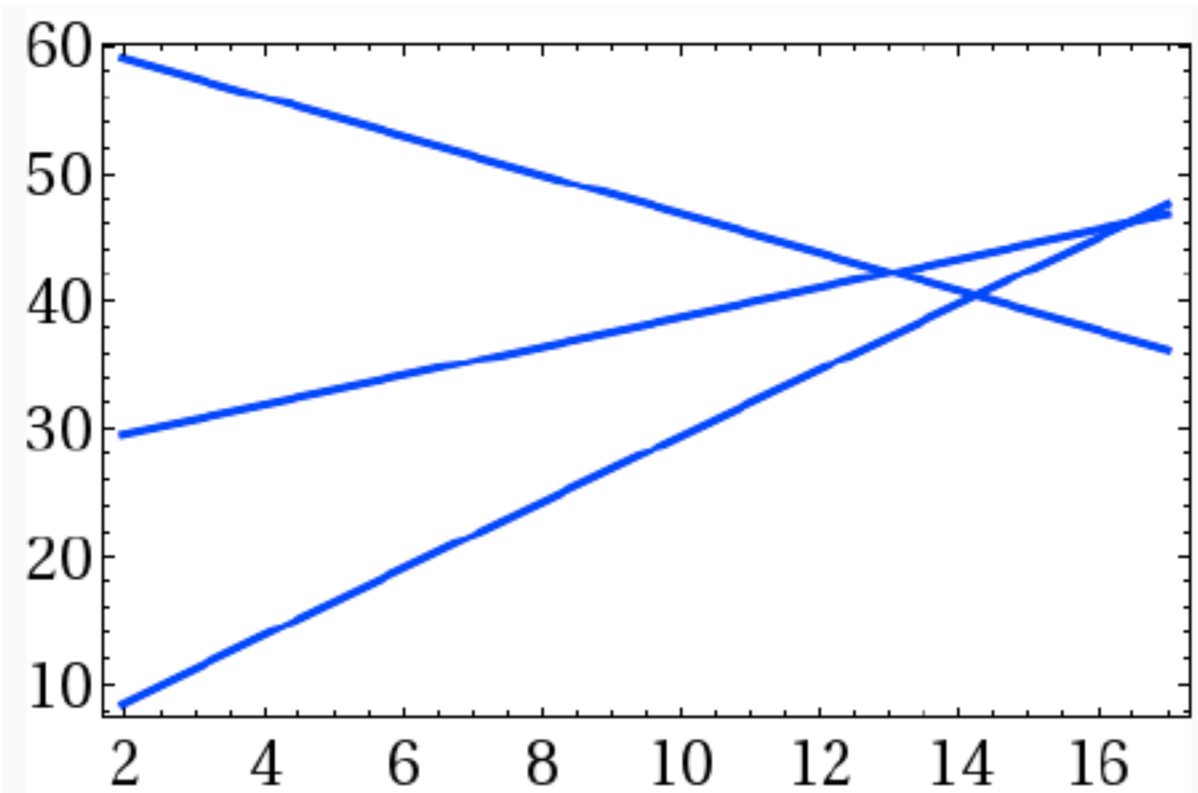


Gauge Coupling running at two loops

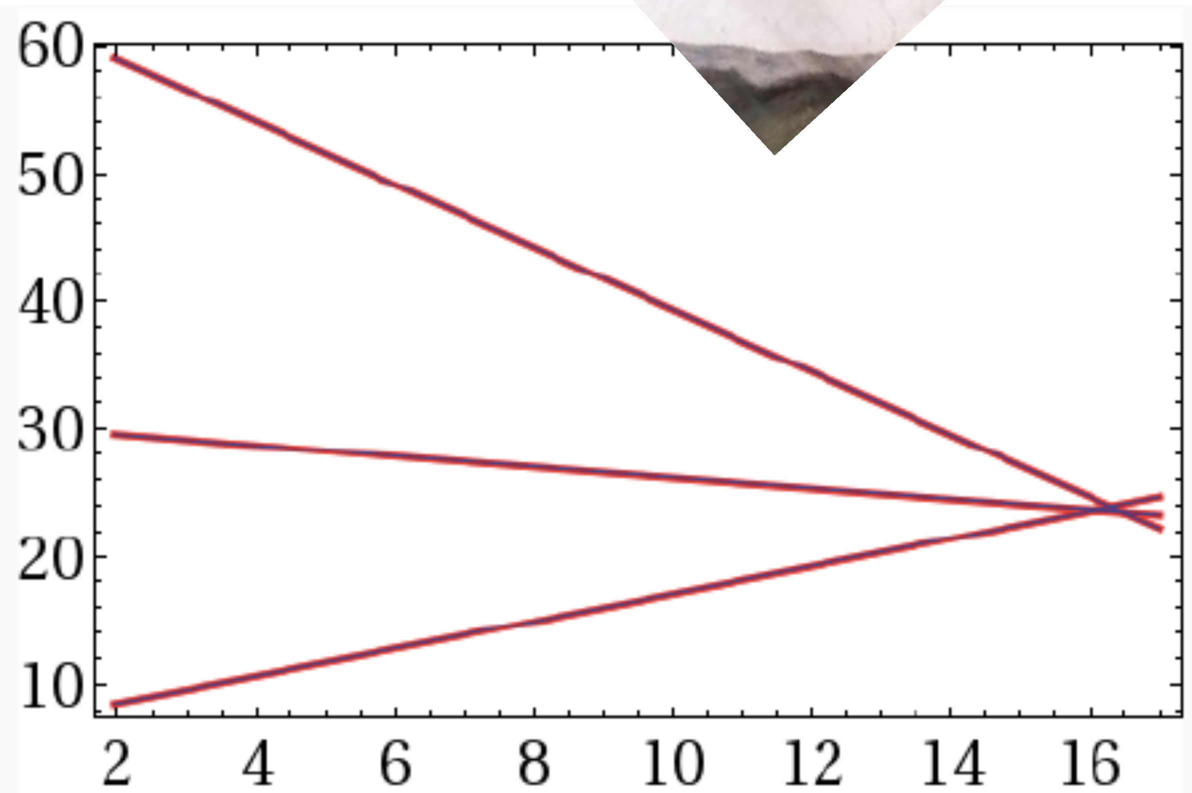
Note, still works with M_{SUSY} = 100 TeV.

A hint?

SM



MSSM



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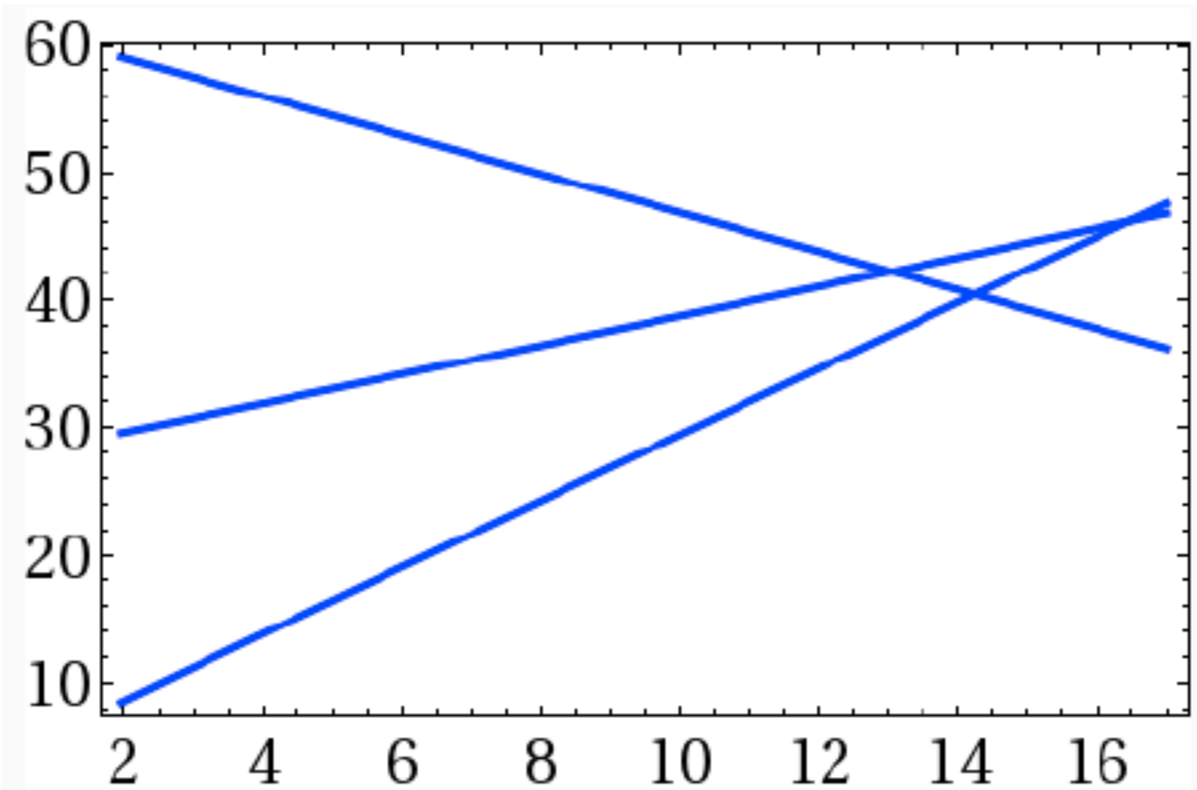
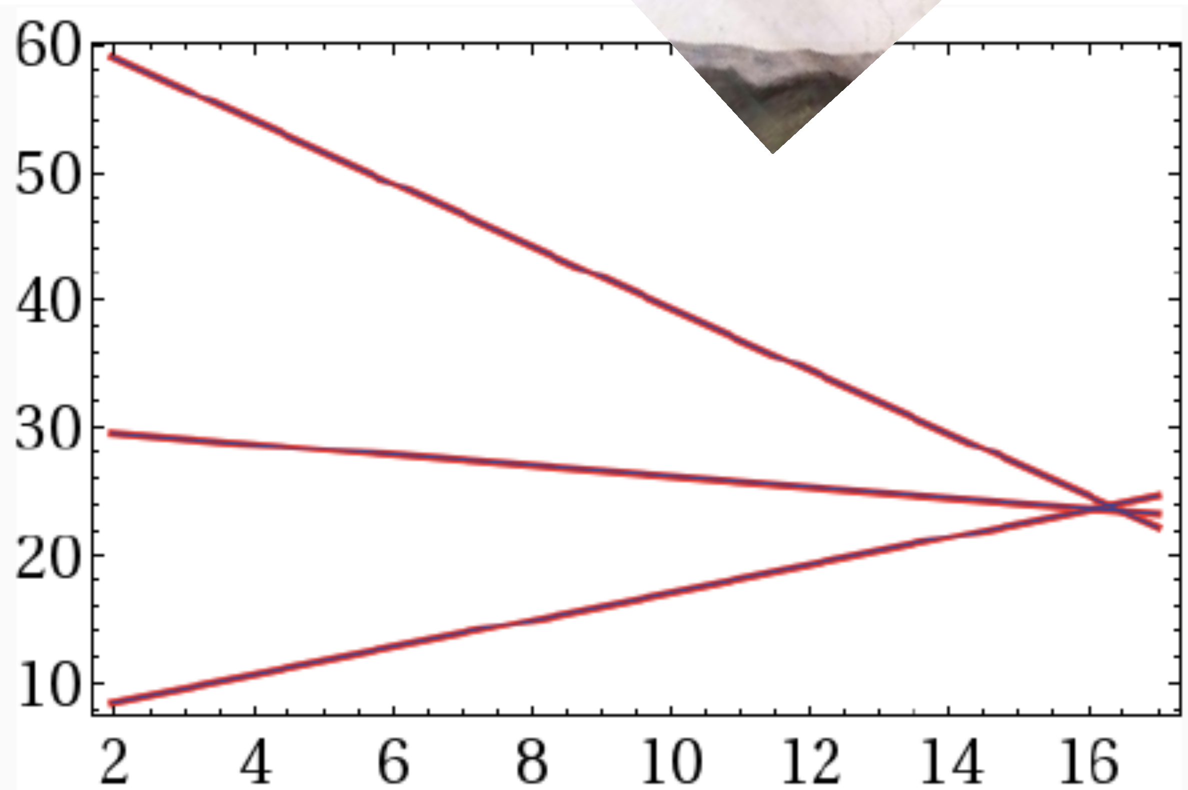
A hint?

SM



MSSM



Gauge Coupling running at two loops

Note, still works with M_{SUSY} = 100 TeV.

MSSM and the 125 GeV Higgs

$\tilde{t}$ $\tilde{t}$

MSSM:

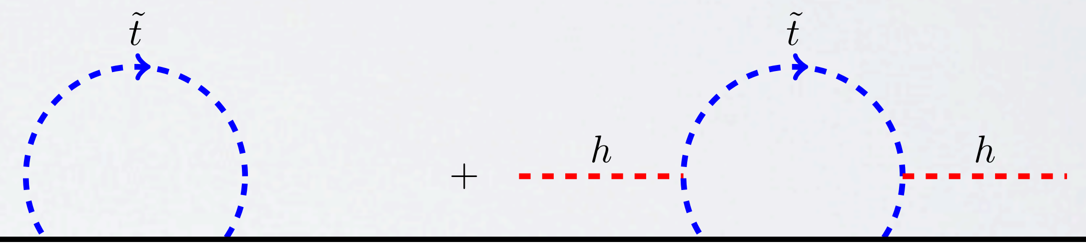
tree-level bound < M_Z

Haber, Hempfling '91

$$m_h^2 = \boxed{m_Z^2 c_{2\beta}^2} + \frac{3m_t^4}{4\pi^2 v^2}\left(\log\left(\frac{M_S^2}{m_t^2}\right) + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12M_S^2}\right)\right)$$

MSSM and the 125 GeV Higgs

MSSM:



Logarithmic growth with M$_{\text{SUSY}}$

$$m_h^2 = m_Z^2 c_{2\beta}^2 \quad \ldots \quad 91$$

$$+ \frac{3m_t^4}{4\pi^2 v^2}\left(\boxed{\log\left(\frac{M_S^2}{m_t^2}\right)} + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12M_S^2}\right)\right)$$

MSSM and the 125 GeV Higgs

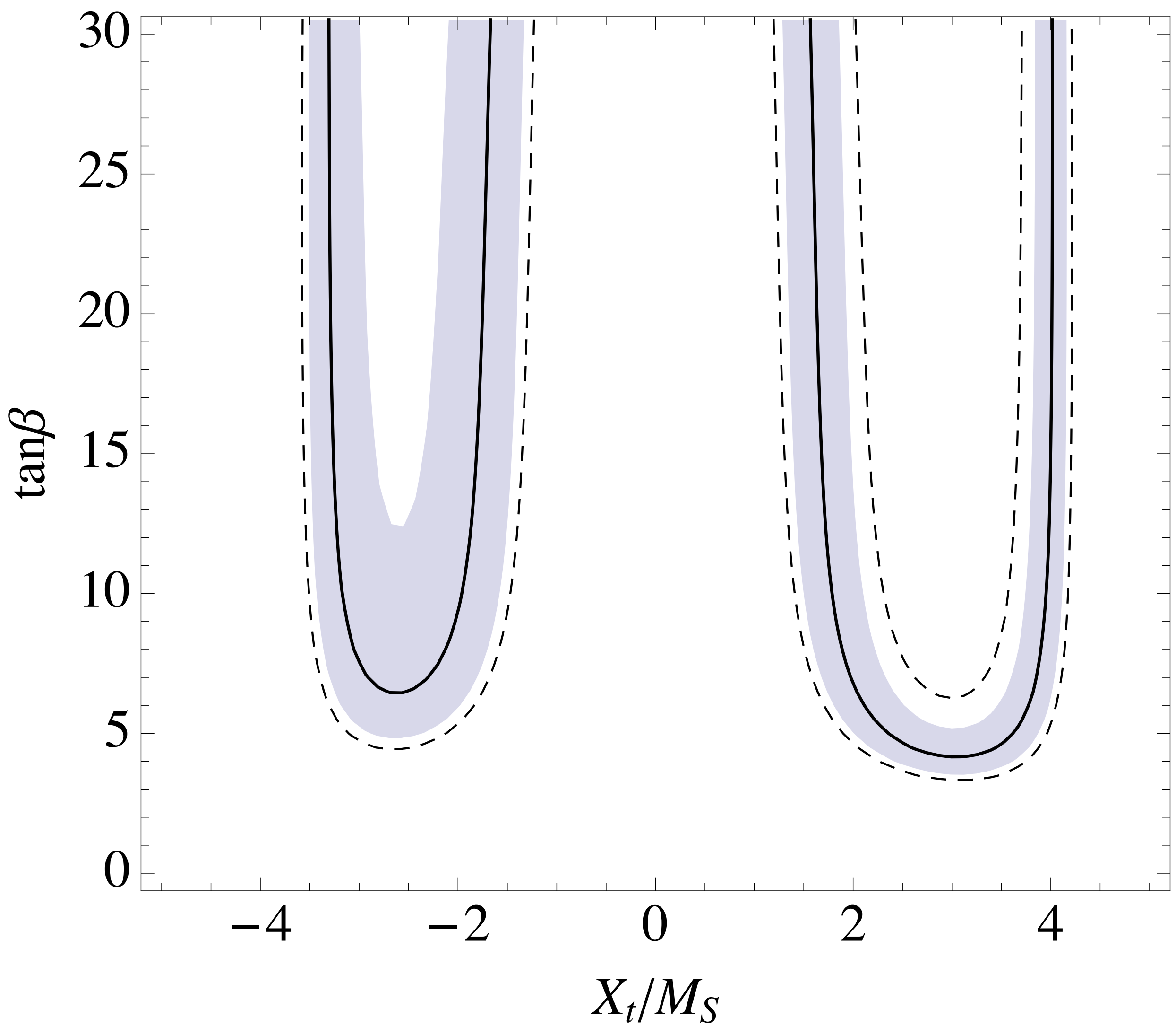
MSSM:

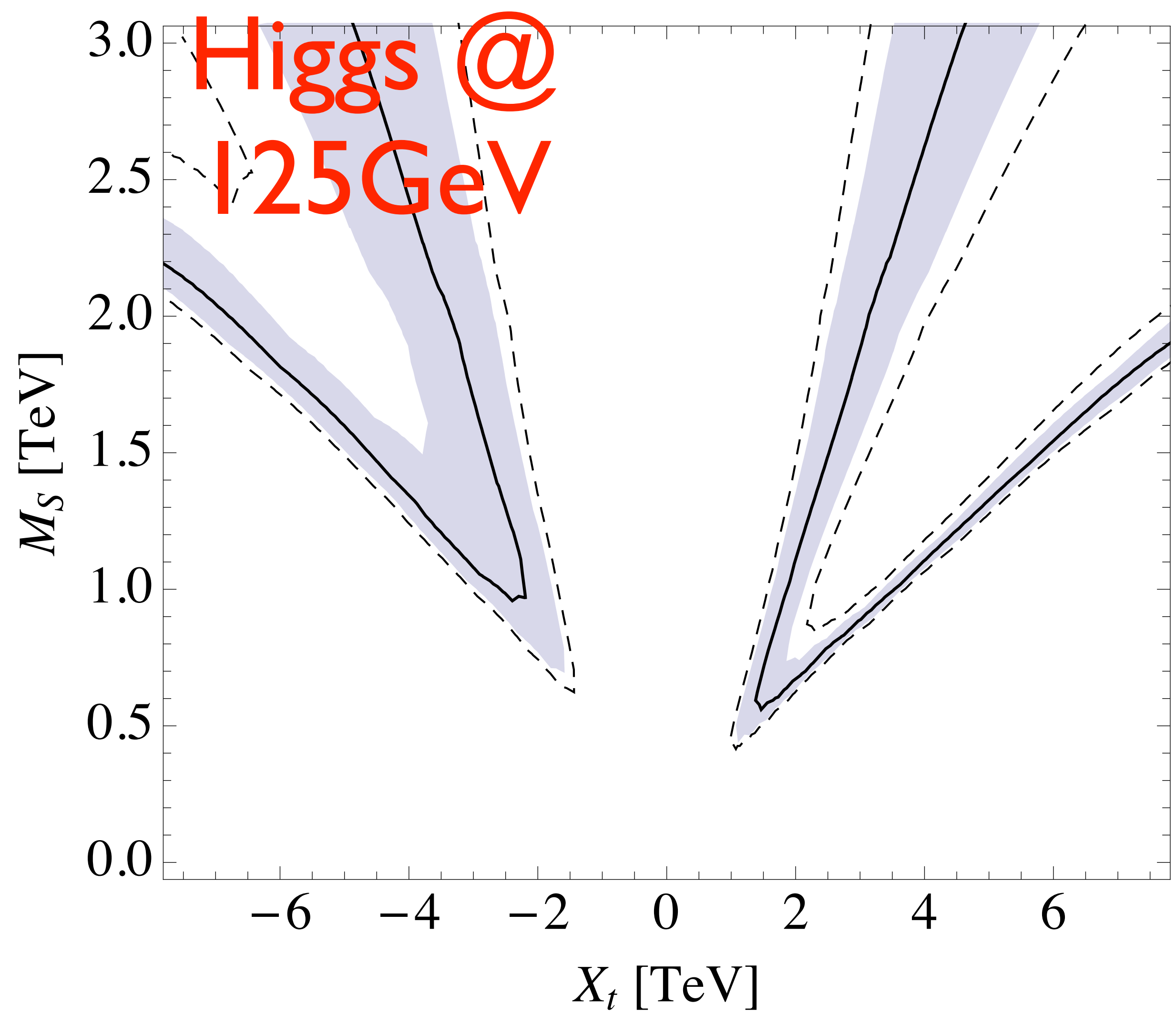
Quadratic term from stop mixing

$$m_h^2 = m_Z^2 c_{2\beta}^2 + \frac{3m_t^4}{4\pi^2 v^2}\left(\log\left(\frac{M_S^2}{m_t^2}\right) + \boxed{\frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12M_S^2}\right)}\right)$$

more: Haber, Hempfling, Hoang, Ellis, Ridolfi, Zwirner, Casas, Espinosa, Quiros, Riotto, Carena, Wagner, Degrassi, Heinemeyer, Hollik, Slavich, Weiglein

MSSM vs. m_H =125 GeV

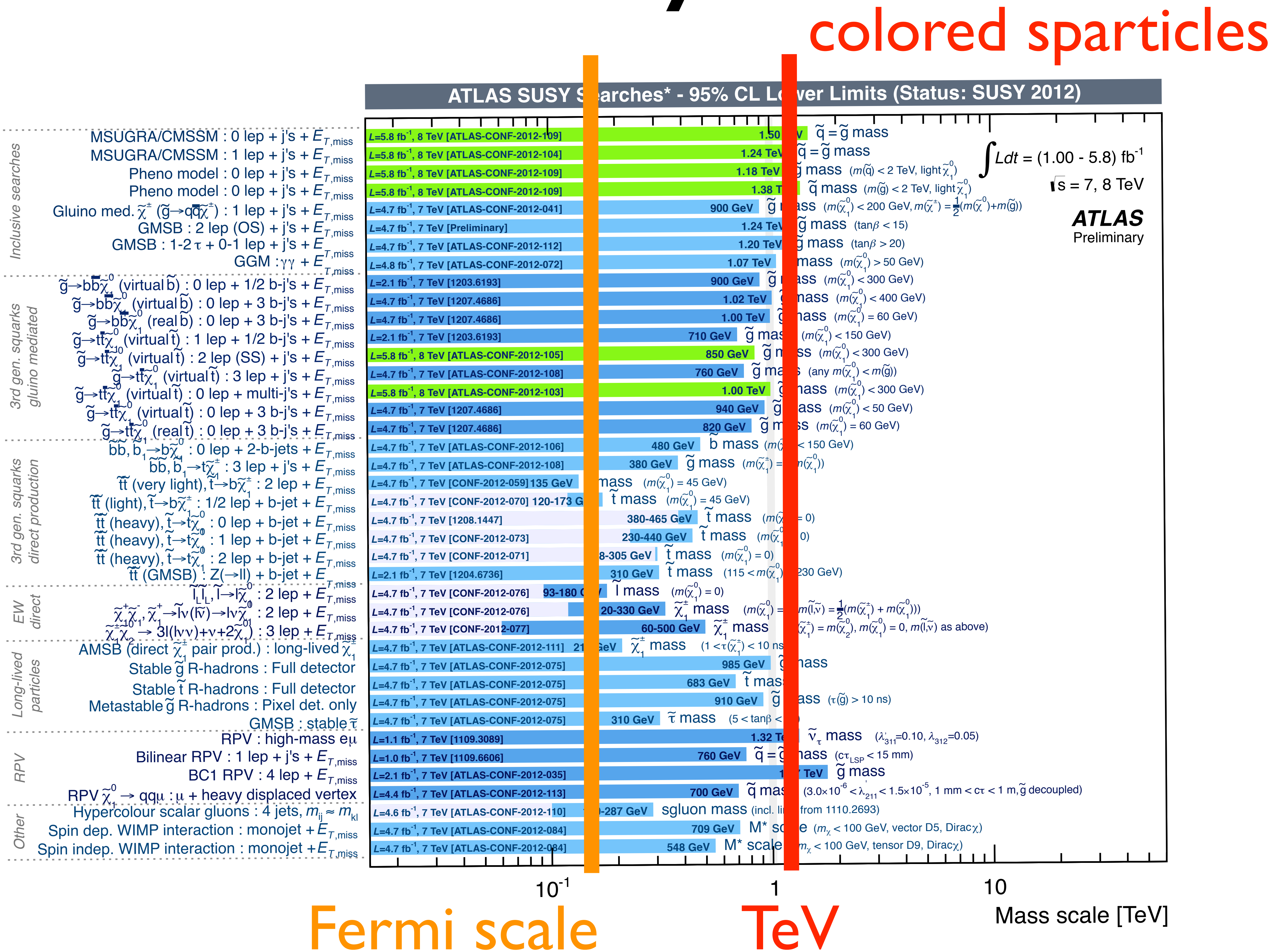




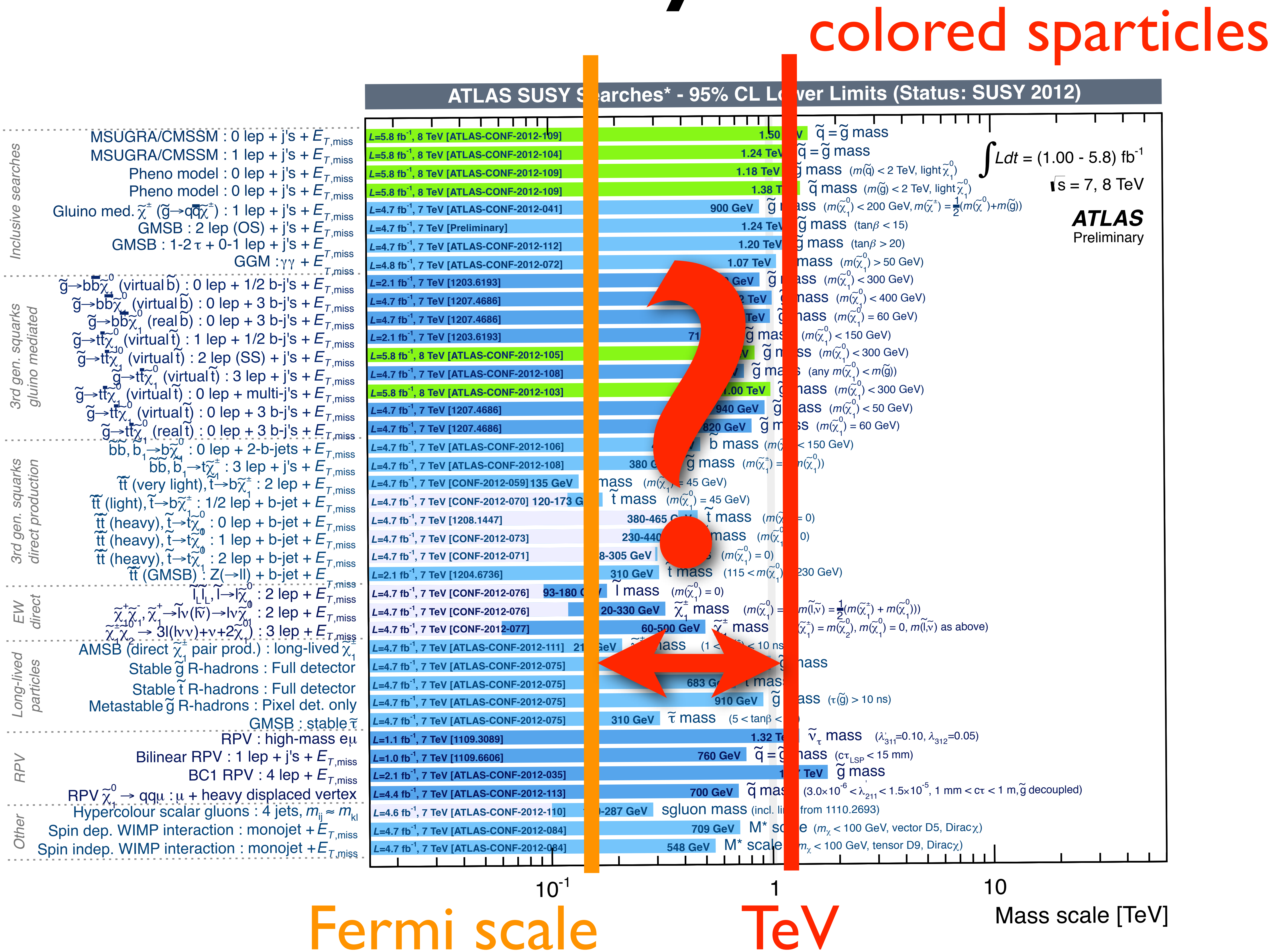
$\tan\beta \gtrsim 3.5$ $\qquad \frac{X_t}{M_S} \approx -3, \; -1.7, \; 1.5, \; \text{or} \; 3.5$ $\qquad M_S \gtrsim 500$ GeV

More conservative error treatment, see Heinemeyer et al '12

Colored Susy > TeV ?



Colored Susy > TeV ?



Where's susy hiding?

- Compressed spectra (→ Tattersall)
- R-parity violation (→ Hajer)
- Natural Susy
- …

Where's susy hiding?

- Compressed spectra (→ Tattersall)
- R-parity violation (→ Hajer)
- ~~Natural~~ Ascetic Susy
- …

Natural EWSB & SUSY *

* valid for MSSM,NMSSM, …

Do not want tuning in (Higgs mass)^2

$$\frac{m_{Higgs}^2}{2} = -|\mu|^2 + \ldots + \delta m_H^2$$

Dimopoulos,
Giudice/

Natural EWSB & SUSY*

* valid for MSSM,NMSSM, …

Do not want tuning in (Higgs mass)^2

$$\frac{m^2_{Higgs}}{2} = -\boxed{|\mu|^2} + \ldots + \delta m^2_H$$

Higgsinos

Dimopoulos, Giudice/

Natural EWSB & SUSY *

* valid for MSSM,NMSSM, ...

Do not want tuning in (Higgs mass)^2

$$\frac{m^2_{Higgs}}{2} = -|\mu|^2 + \ldots + \delta m^2_H$$

Higgsinos

1loop $\quad \delta m^2_H|_{stop} = -\frac{3}{8\pi^2} y_t^2 \left(\underline{m^2_{U_3} + m^2_{Q_3} + |A_t|^2} \right) \log\left(\frac{\Lambda}{\mathrm{TeV}}\right)$

stops, sbottom$_L$

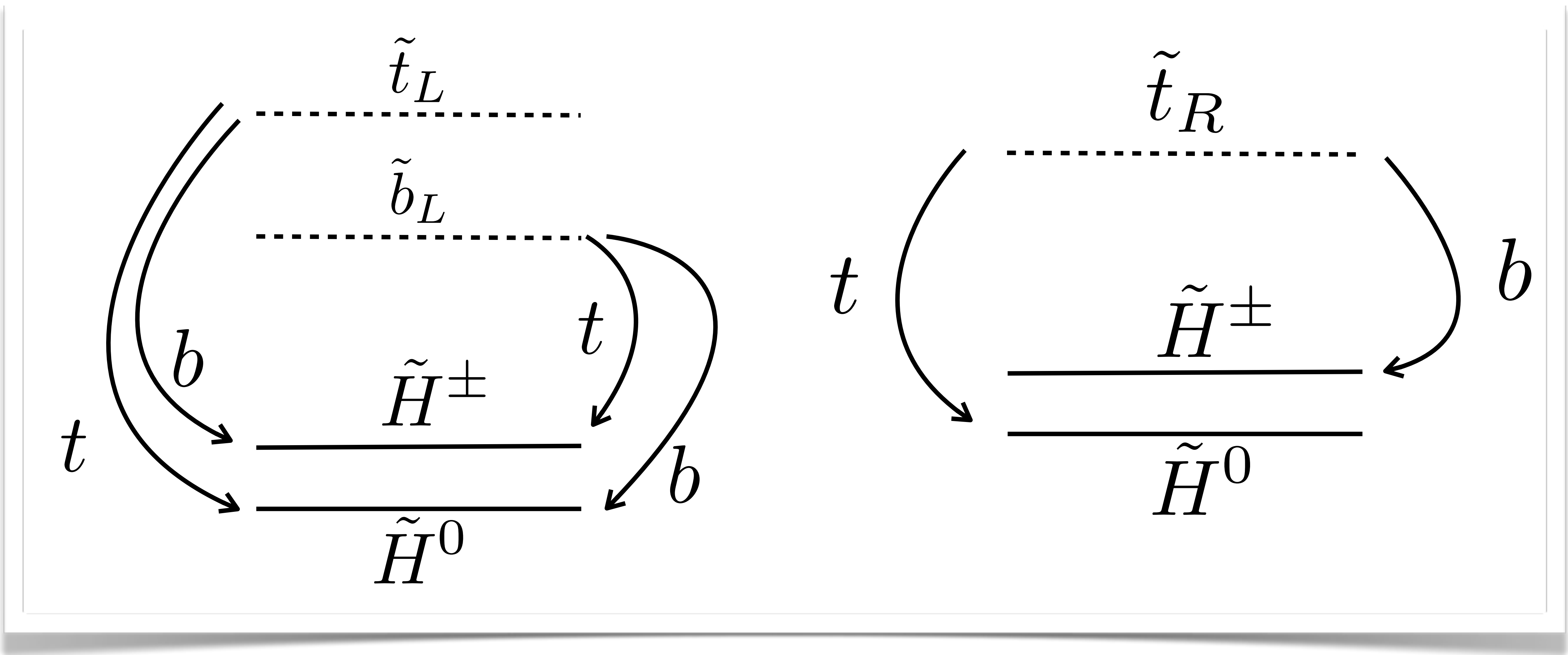
2loop $\quad \delta m^2_H|_{gluino} = -\frac{2}{\pi^2} y_t^2 \left(\frac{\alpha_s}{\pi}\right) \underline{|M_3|^2} \log^2\left(\frac{\Lambda}{\mathrm{TeV}}\right)$

gluino

Dimopoulos, Giudice/

Stops (sbottom) + Higgsinos

M. Papucci, J. Ruderman, AW

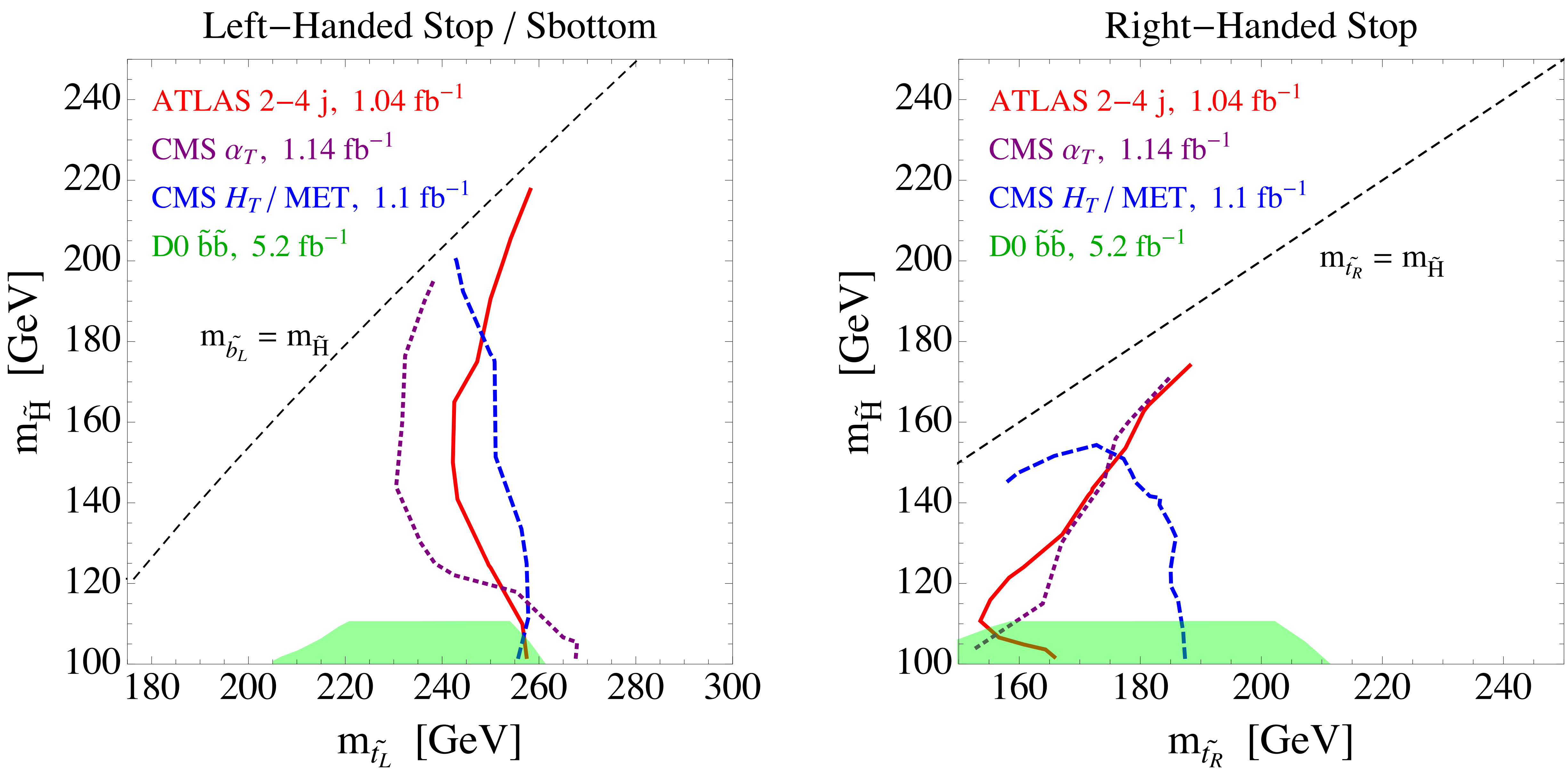


Stops can act as "sbottom" (bjet+χ) !

Chargino-neutralino splitting irrelevant for present searches

M. Papucci, J. Ruderman, AW

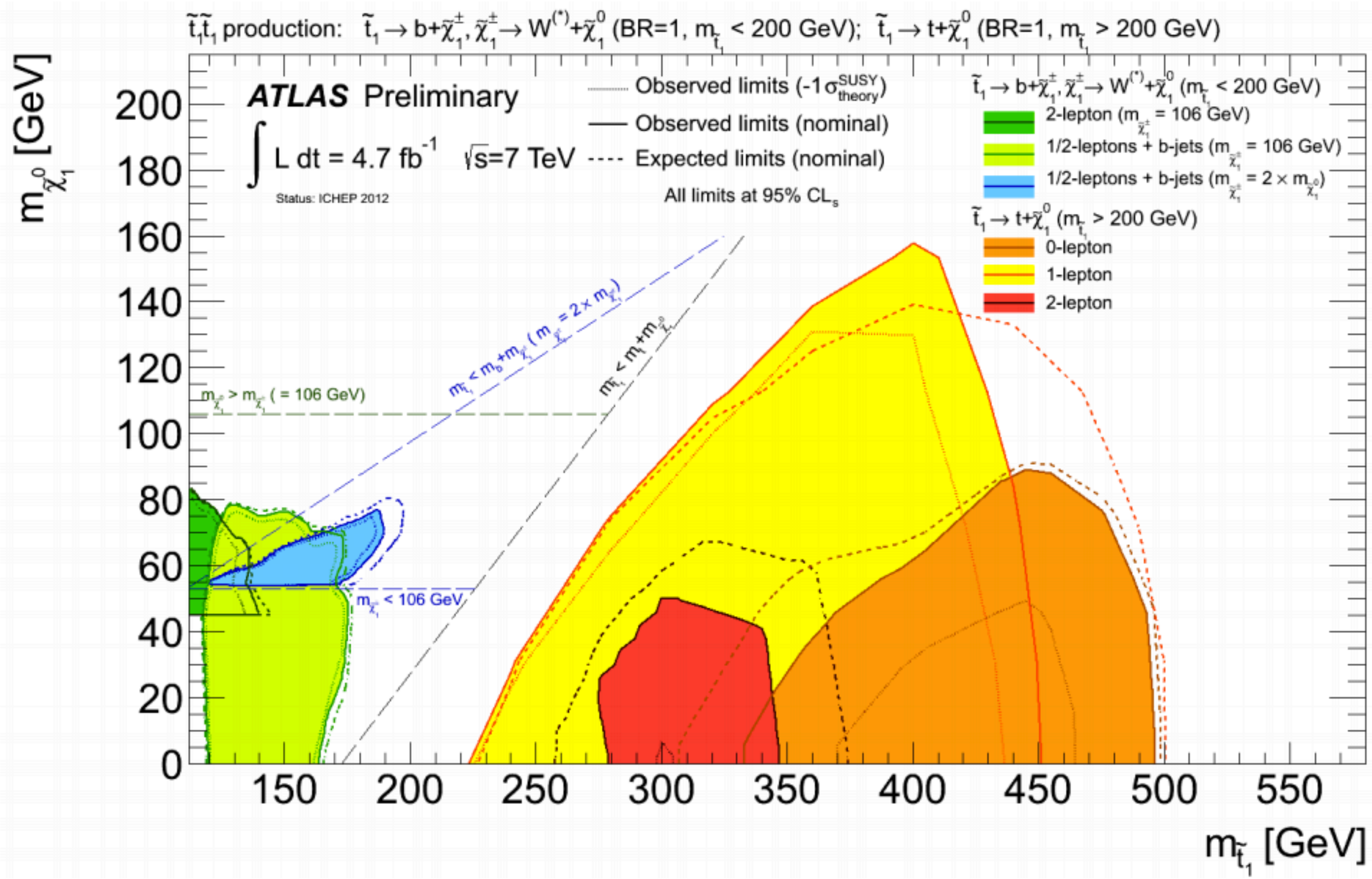
Stops (sbottom) + Higgsinos



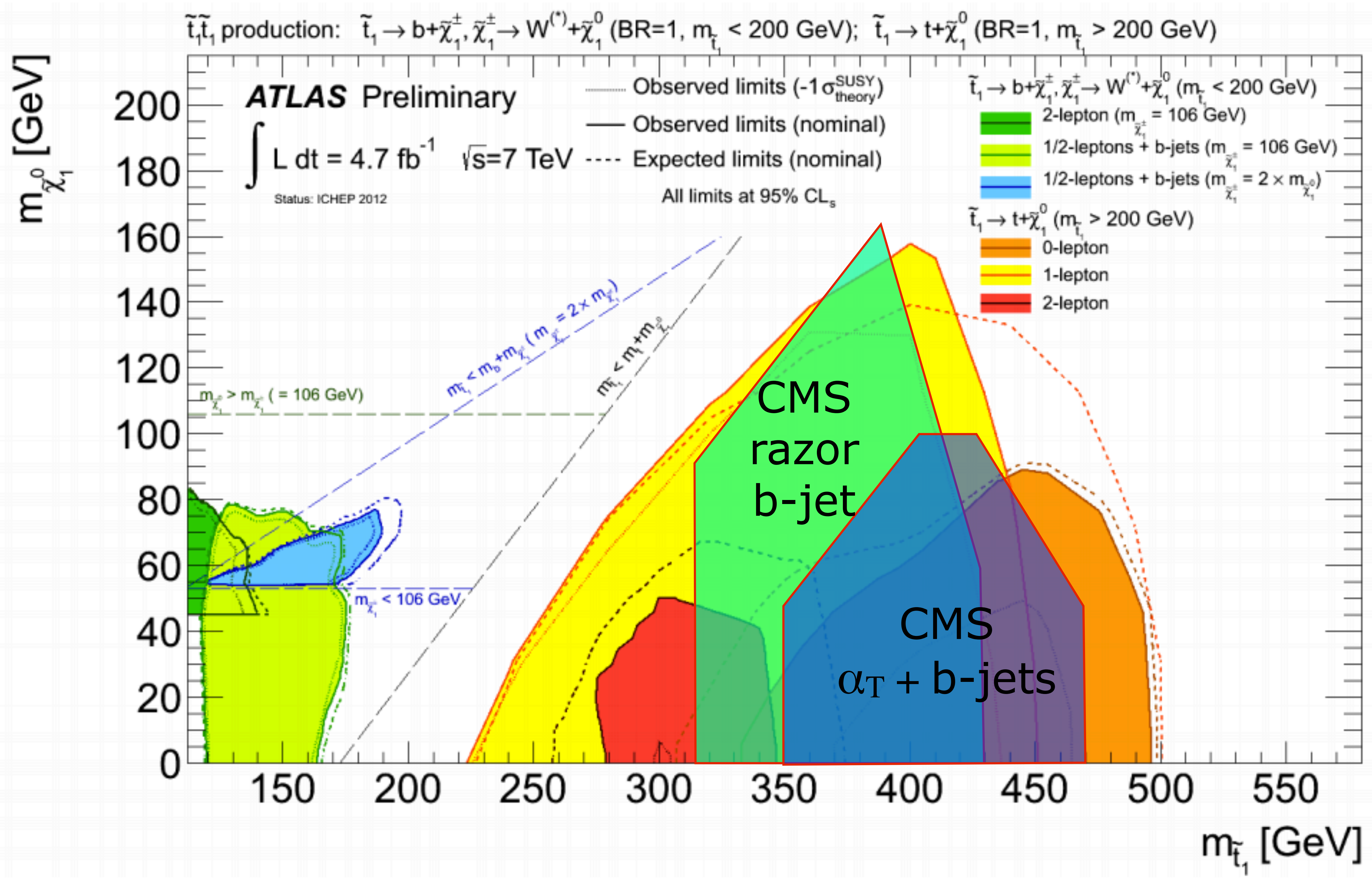
LHC surpasses Tevatron:

Strongest bounds from jets + MET

First Results for Direct Stop Production



First Results for Direct Stop Production



The near Future (according to theorists)

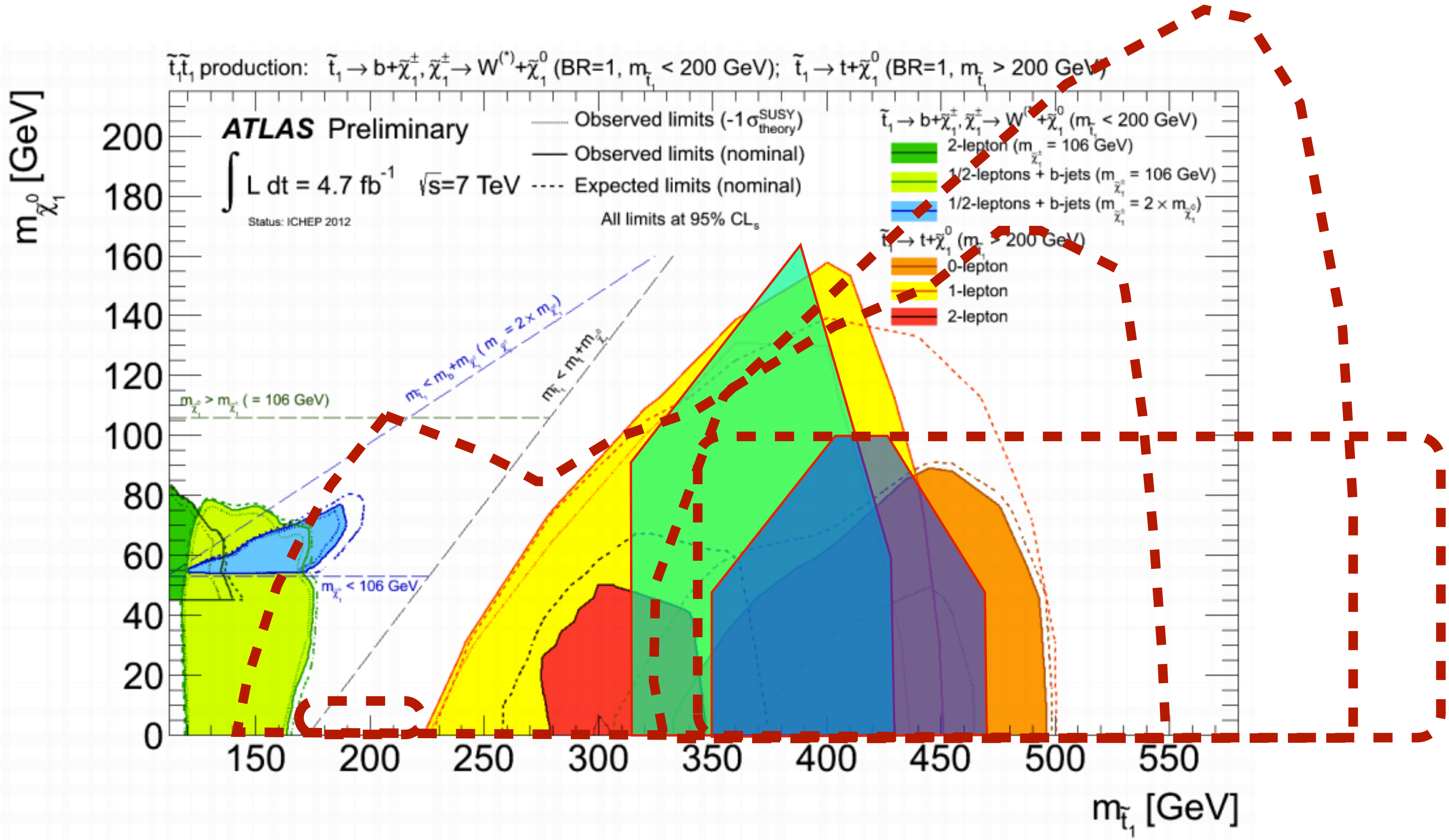
kinematic variables with endpoints for background
arXiv:1203.4813 Bai, Cheng, Gallicchio, Gu

Spin correlations and rapidity gaps
arXiv:1205.5808 Han, Katz, Krohn, Reece

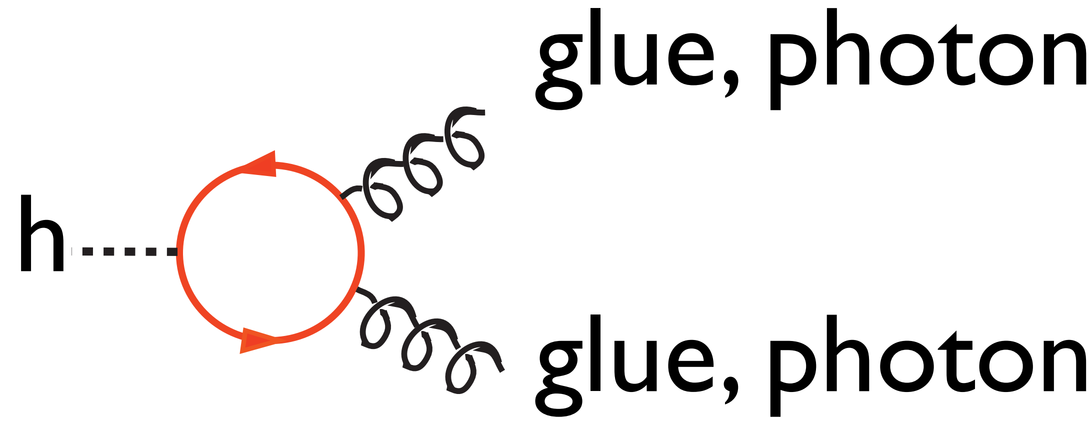
Top-tagging boosted tops from stop decays
arXiv:1205.5816 Kaplan, Rehermann, Stolarski
arXiv:1205.2696 Plehn, Spannowsky, Takeuchi

MET and M_T shapes
arXiv:1205.5805 Alves, Buckley, Fox, Lykken, Yu

estimated reach with 20/fb @ 8 TeV

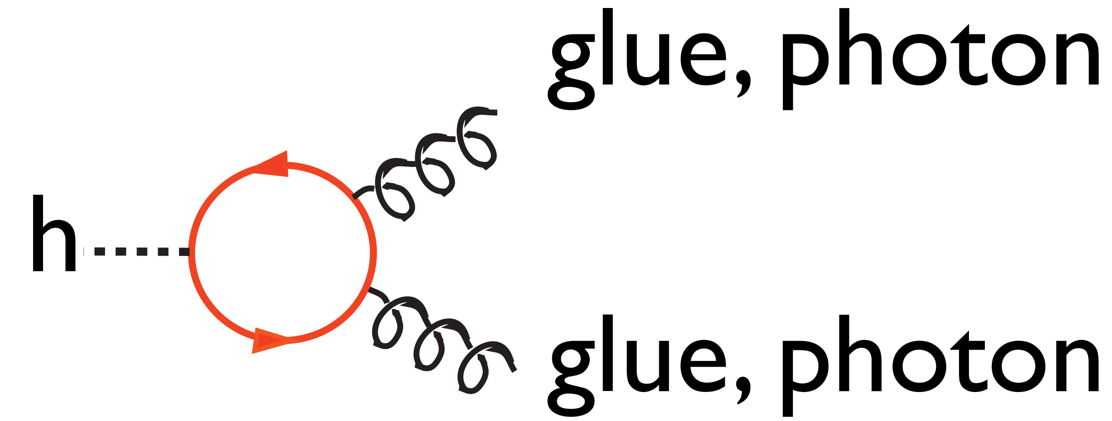


Higgs precision impact



stop contribution

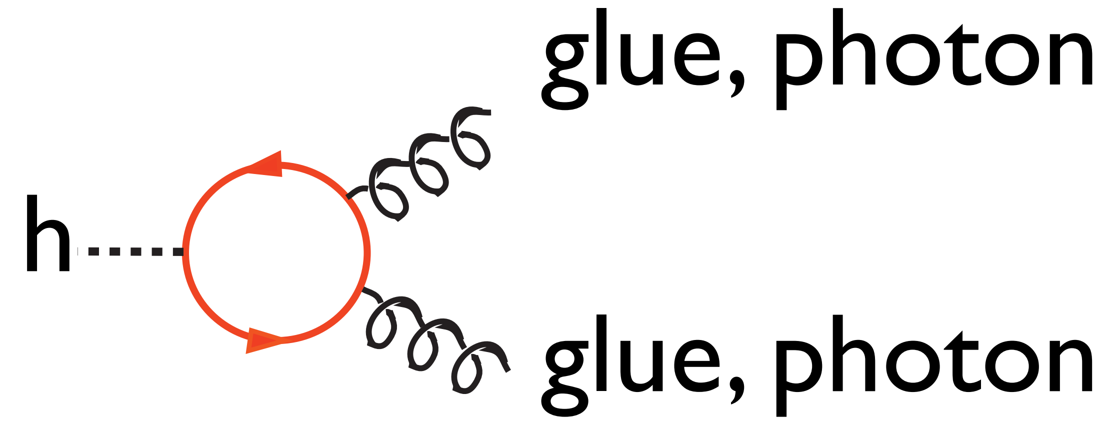
Higgs precision impact



stop contribution

$$\mathcal{L}_{HD} = -\frac{c_g\, g_3^2}{2\,\Lambda}\, h\, G^A_{\mu\,\nu} G^{A\,\mu\,\nu} - \frac{c_\gamma\,(2\,\pi\,\alpha)}{\Lambda}\, h\, F_{\mu\,\nu} F^{\mu\,\nu}$$

Higgs precision impact

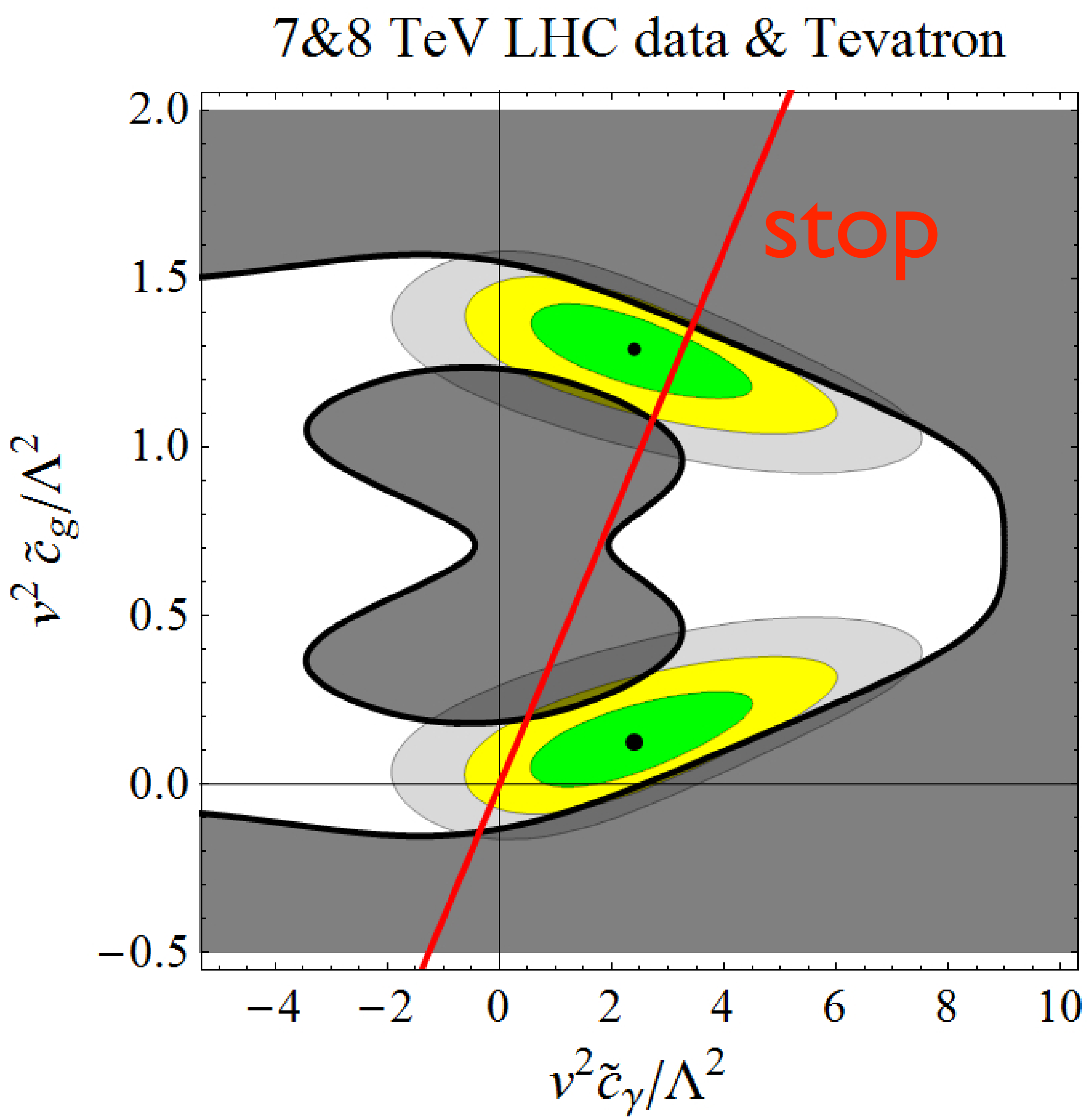


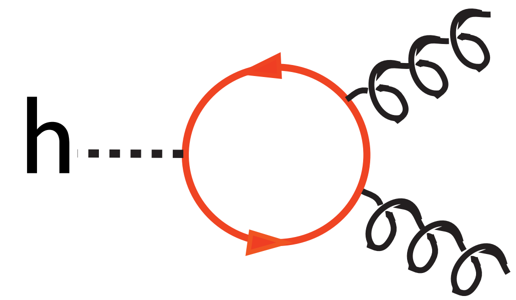
stop contribution

$$\frac{\tilde{c}_g}{\tilde{c}_\gamma} = \frac{1}{2 N_c Q_{\tilde{t}}^2} \frac{C_g(\alpha_s)}{C_\gamma(\alpha_s)} = \frac{3}{8} \left(1 + \frac{3\,\alpha_s}{2\,\pi}\right)$$

$$\mathcal{L}_{HD} = -\frac{c_g\, g_3^2}{2\,\Lambda}\, h\, G^A_{\mu\,\nu} G^{A\,\mu\,\nu} - \frac{c_\gamma\,(2\,\pi\,\alpha)}{\Lambda}\, h\, F_{\mu\,\nu} F^{\mu\,\nu}$$

Higgs precision impact





stop contribution

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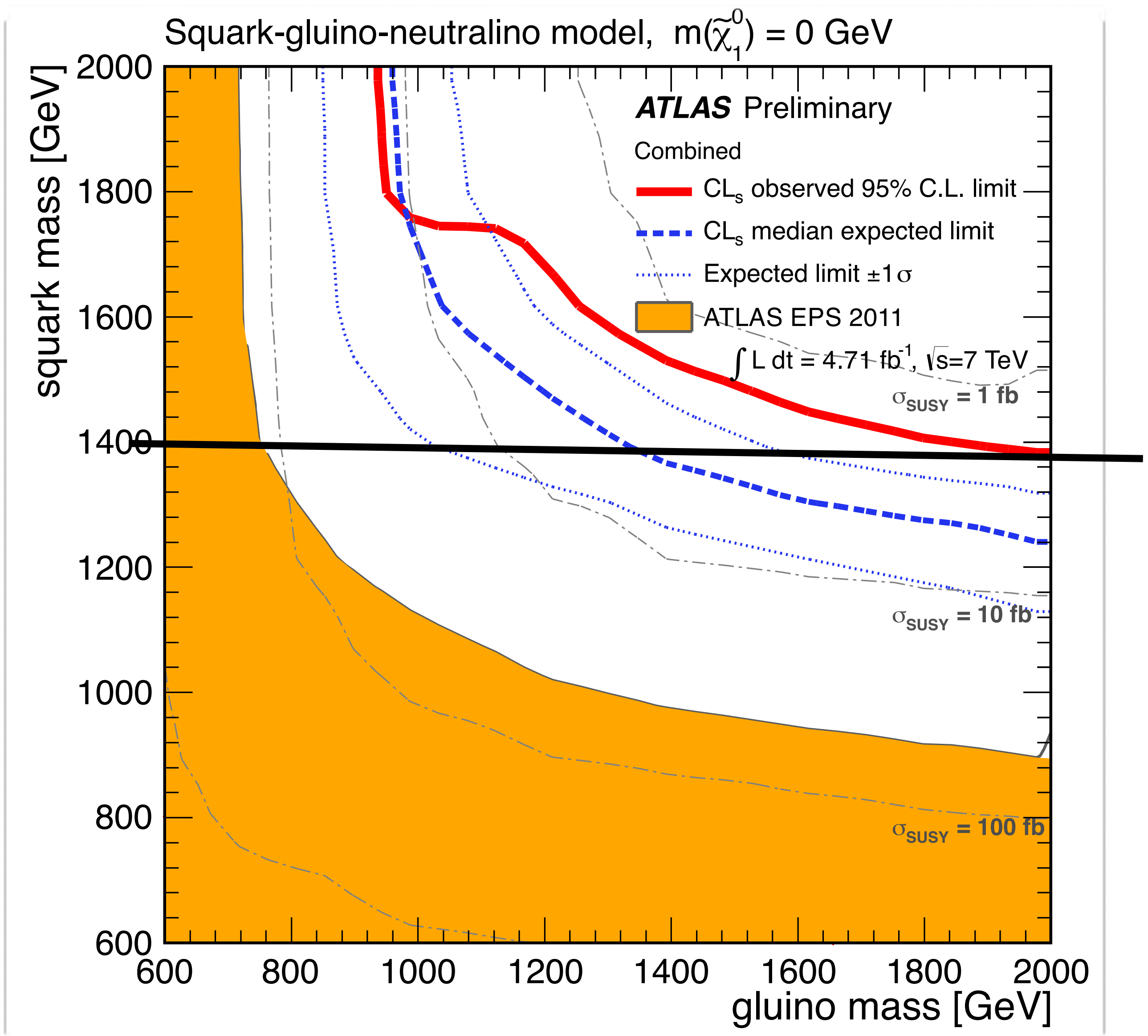
$$\mathcal{L}_{HD} = -\frac{c_g\, g_3^2}{2\,\Lambda}\, h\, G^A_{\mu\nu} G^{A\,\mu\,\nu} - \frac{c_\gamma\,(2\,\pi\,\alpha)}{\Lambda}\, h\, F_{\mu\,\nu} F^{\mu\,\nu}$$

Degenerate squarks?

to appear soon with

M. Papucci, J. Ruderman (LBL Berkely)
G. Perez, R. Mahbubani (CERN)



Do the 1st & 2nd gen' squarks have to be degenerate?

M

8 dof

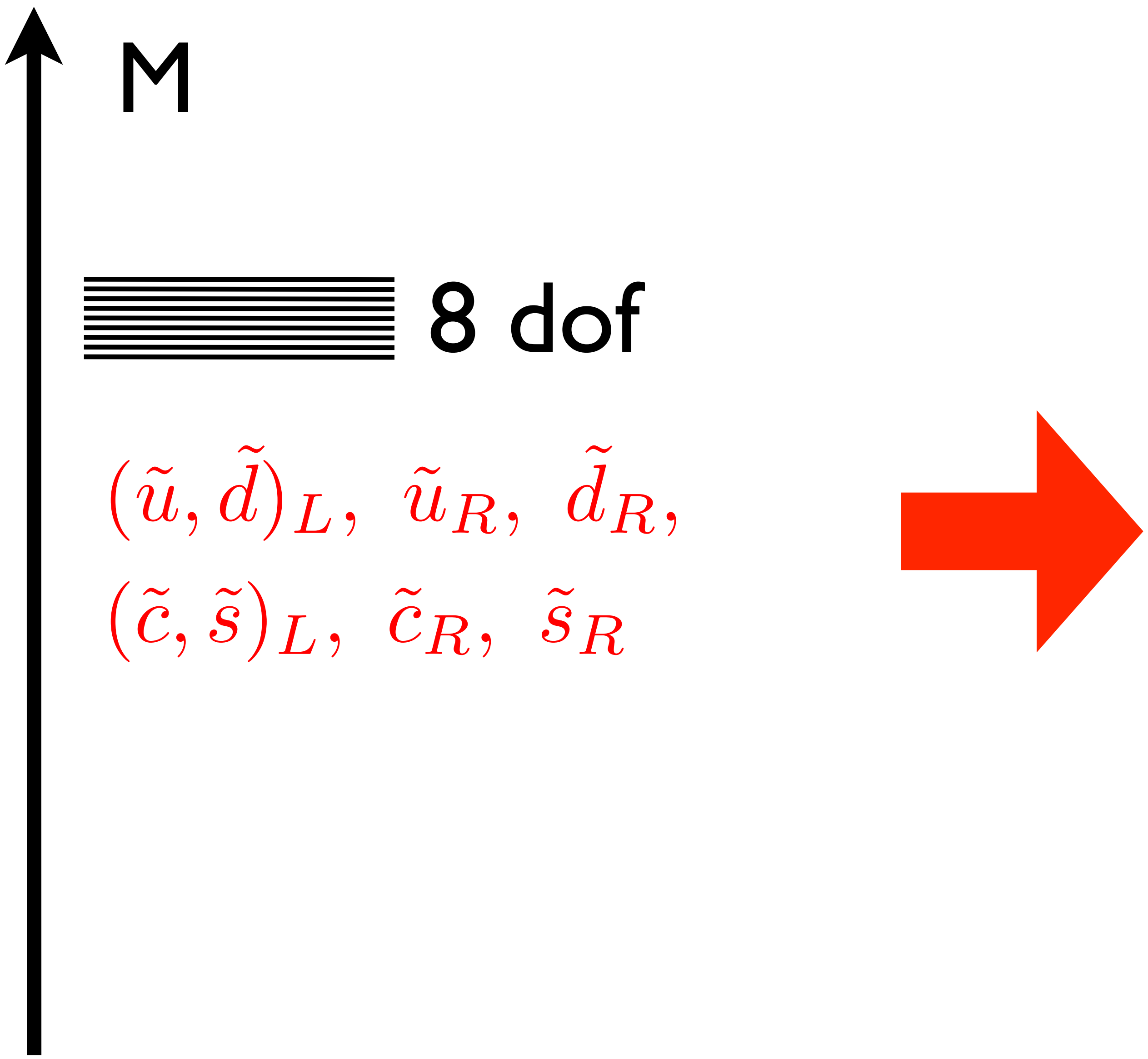
$(\tilde{u}, \tilde{d})_L, \;\; \tilde{u}_R, \;\; \tilde{d}_R,$

$(\tilde{c}, \tilde{s})_L, \;\; \tilde{c}_R, \;\; \tilde{s}_R$

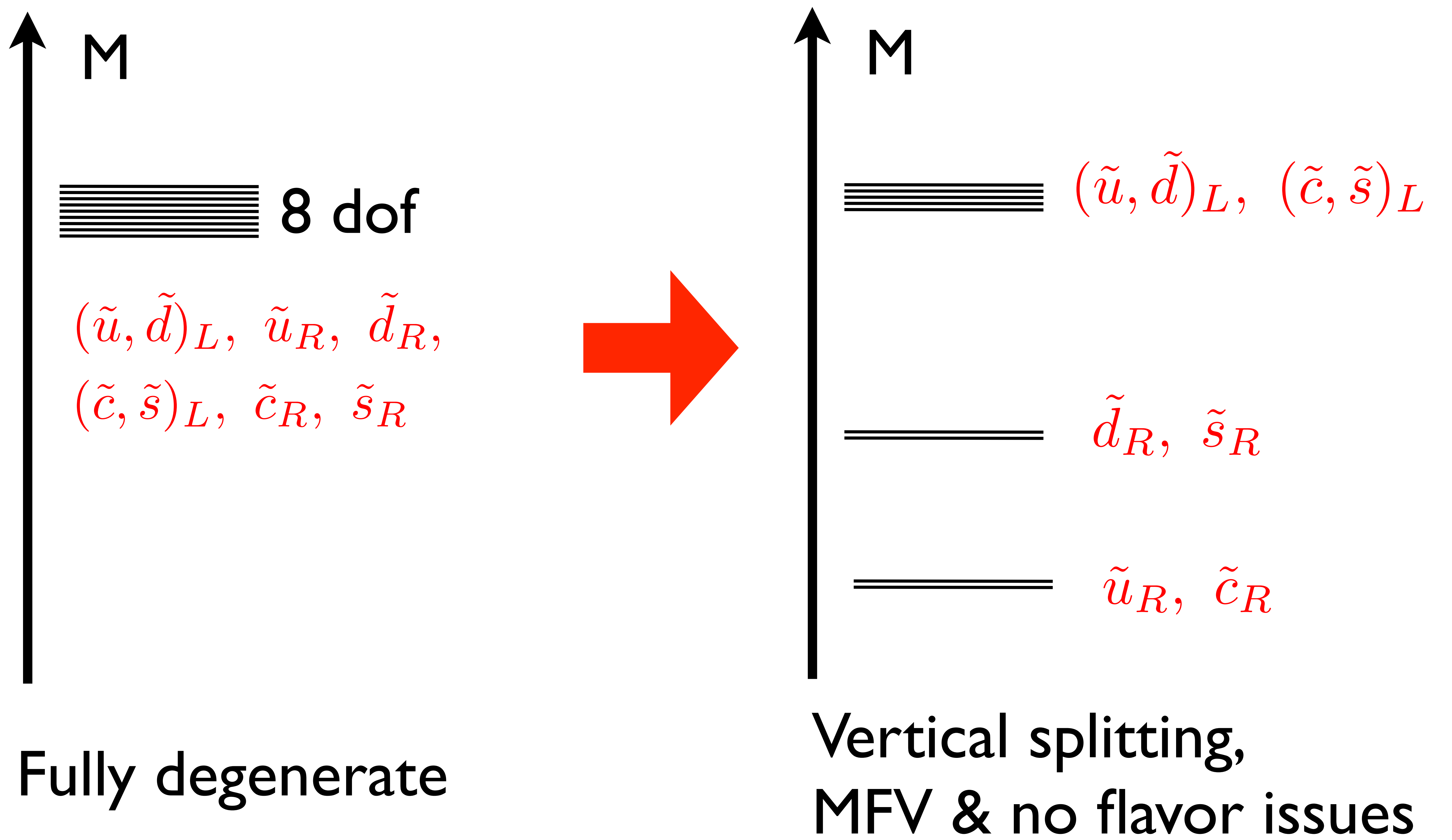
$(3,2)_{1/6} \;\; (3,1)_{2/3} \;\; (3,1)_{-1/3}$

- Because of flavor constraints? Not really.

Assumed spectrum in ATLAS/CMS plots

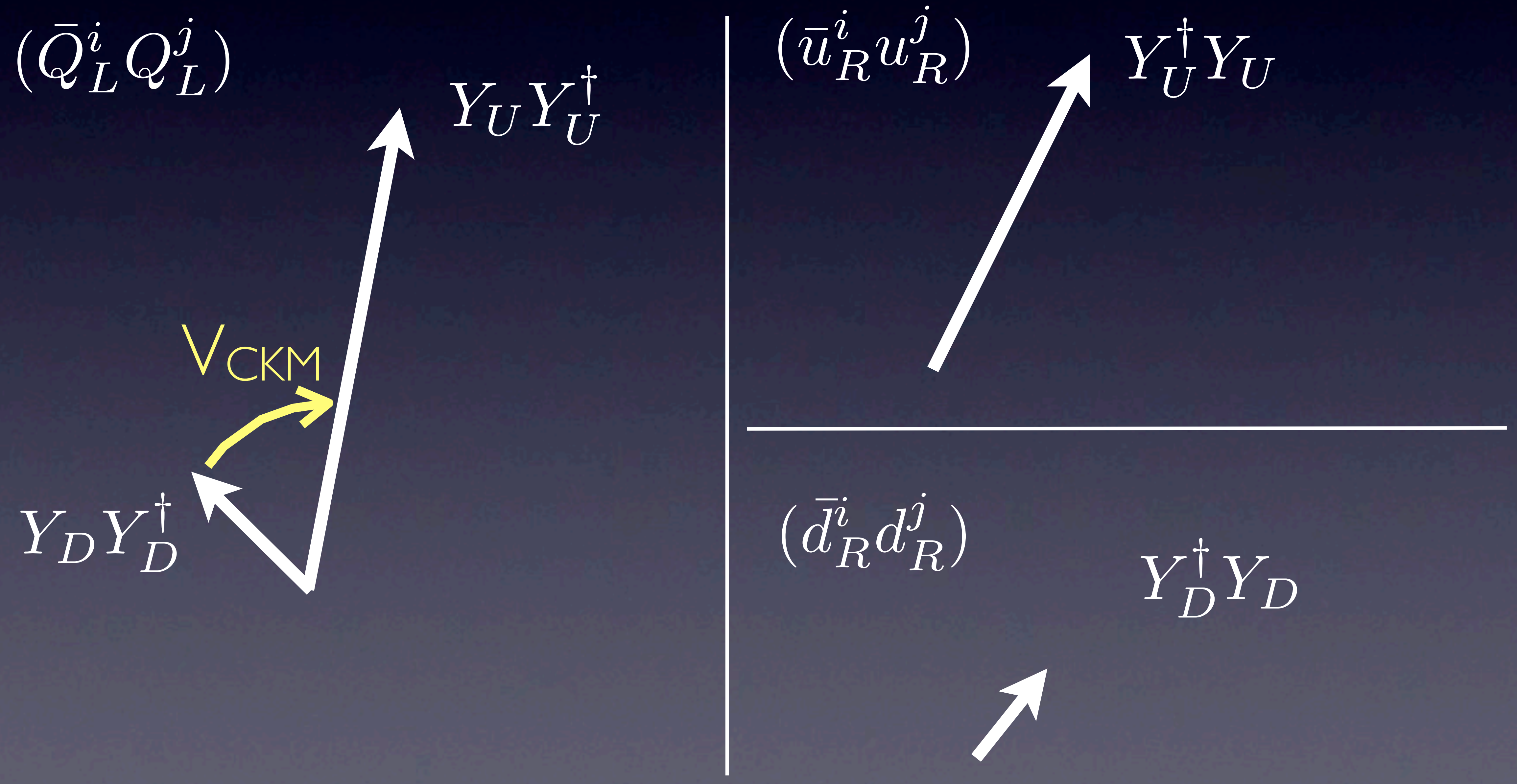


Fully degenerate


M
8 dof
$(\tilde{u},\tilde{d})_L,\ \tilde{u}_R,\ \tilde{d}_R,$
$(\tilde{c},\tilde{s})_L,\ \tilde{c}_R,\ \tilde{s}_R$
Fully degenerate
M
$(\tilde{u},\tilde{d})_L,\ (\tilde{c},\tilde{s})_L$
$\tilde{d}_R,\ \tilde{s}_R$
$\tilde{u}_R,\ \tilde{c}_R$
Vertical splitting,
MFV & no flavor issues

Flavor dynamics: alignment

Dynamics (e.g. $U(1)_{horiz.}$) generates hierarchies in masses & mixings. Consequence: partial alignment with SM



+ LR, RL

Flavor dynamics: alignment

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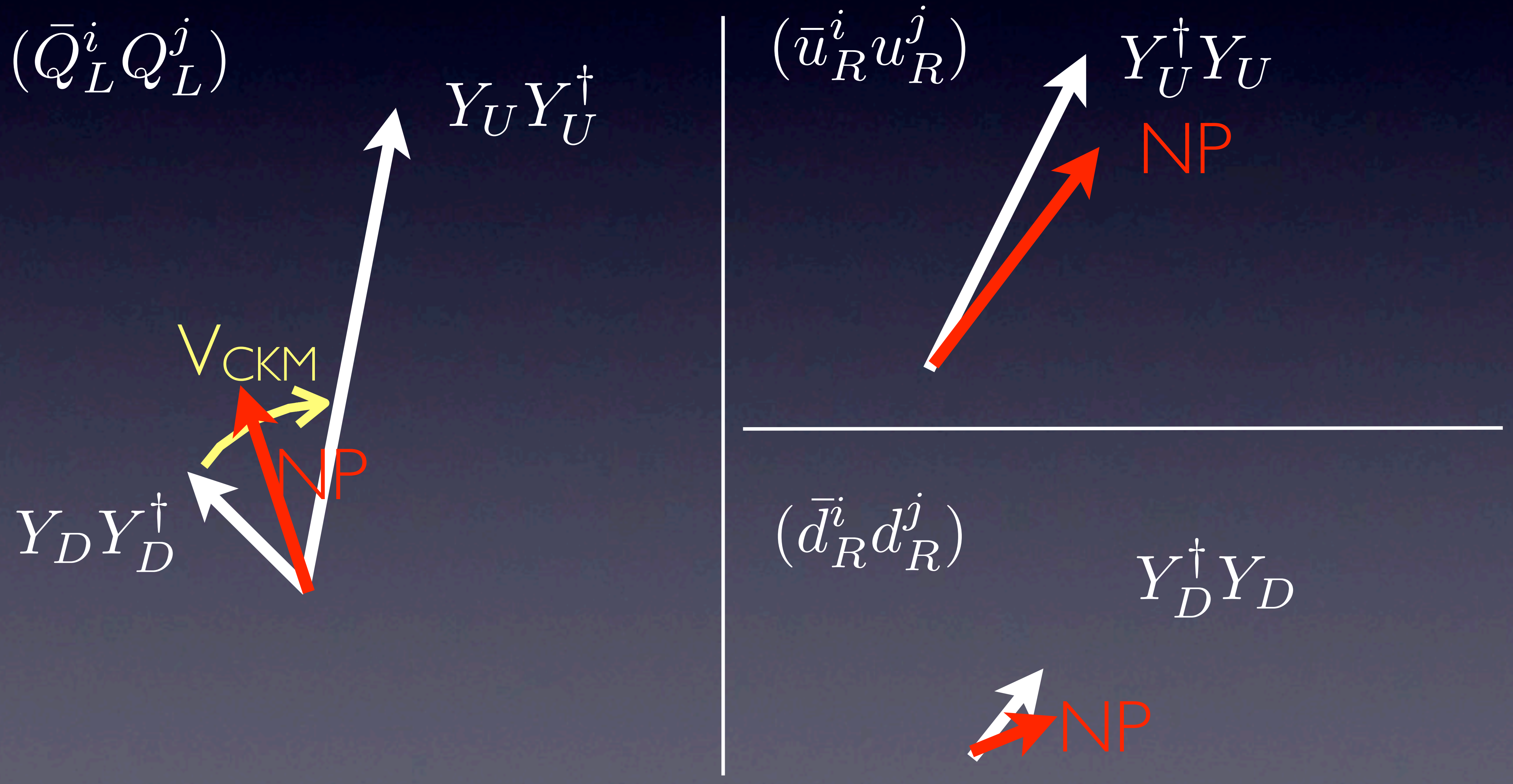
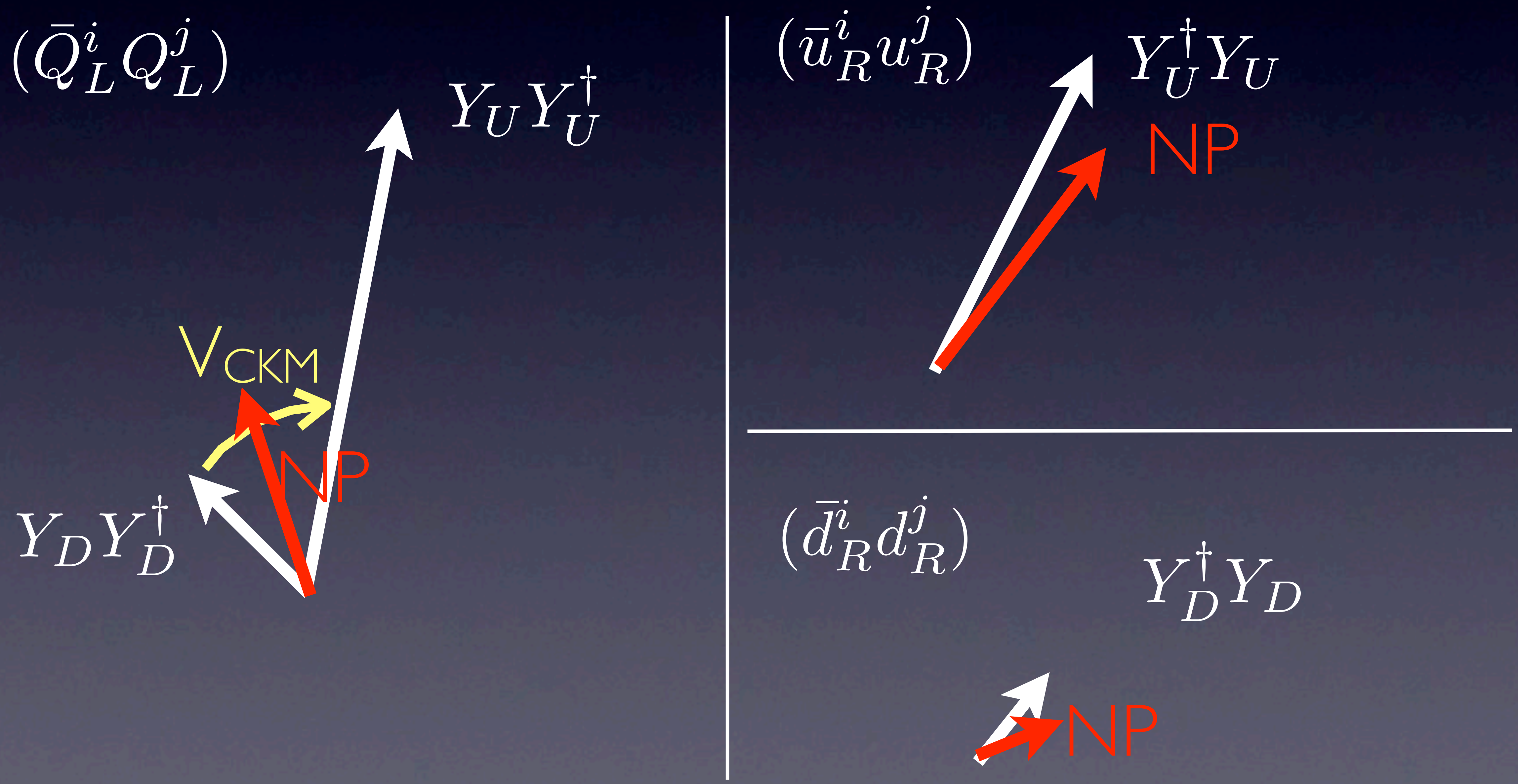


+ LR, RL

Left-handed (Q_L): either aligned with up or downs

Right-handed (u_R, d_R): can be fully aligned



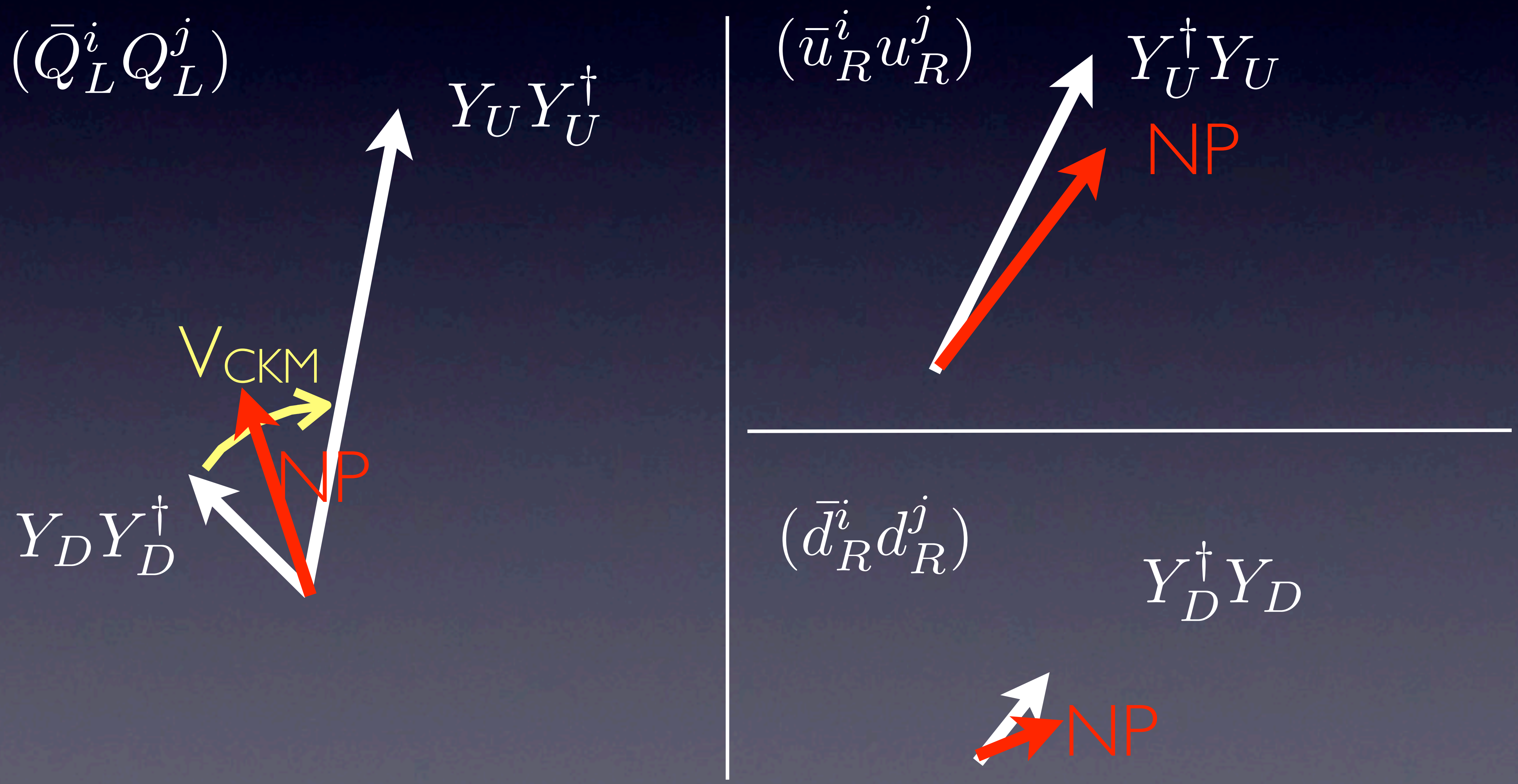
+ LR, RL

Left-handed (Q_L): either aligned with up or downs

→ **limited splitting**

Right-handed (u_R, d_R): can be fully aligned

→ **any splitting**



+ LR, RL

Back of the envelope estimate

Cross-sections roughly scale like ~1/m^6.

Example: 8 light squarks → 2 light squarks

Shift limit only by $\sim 4^{1/6} - 1 \approx 25\%$

→ too naive!

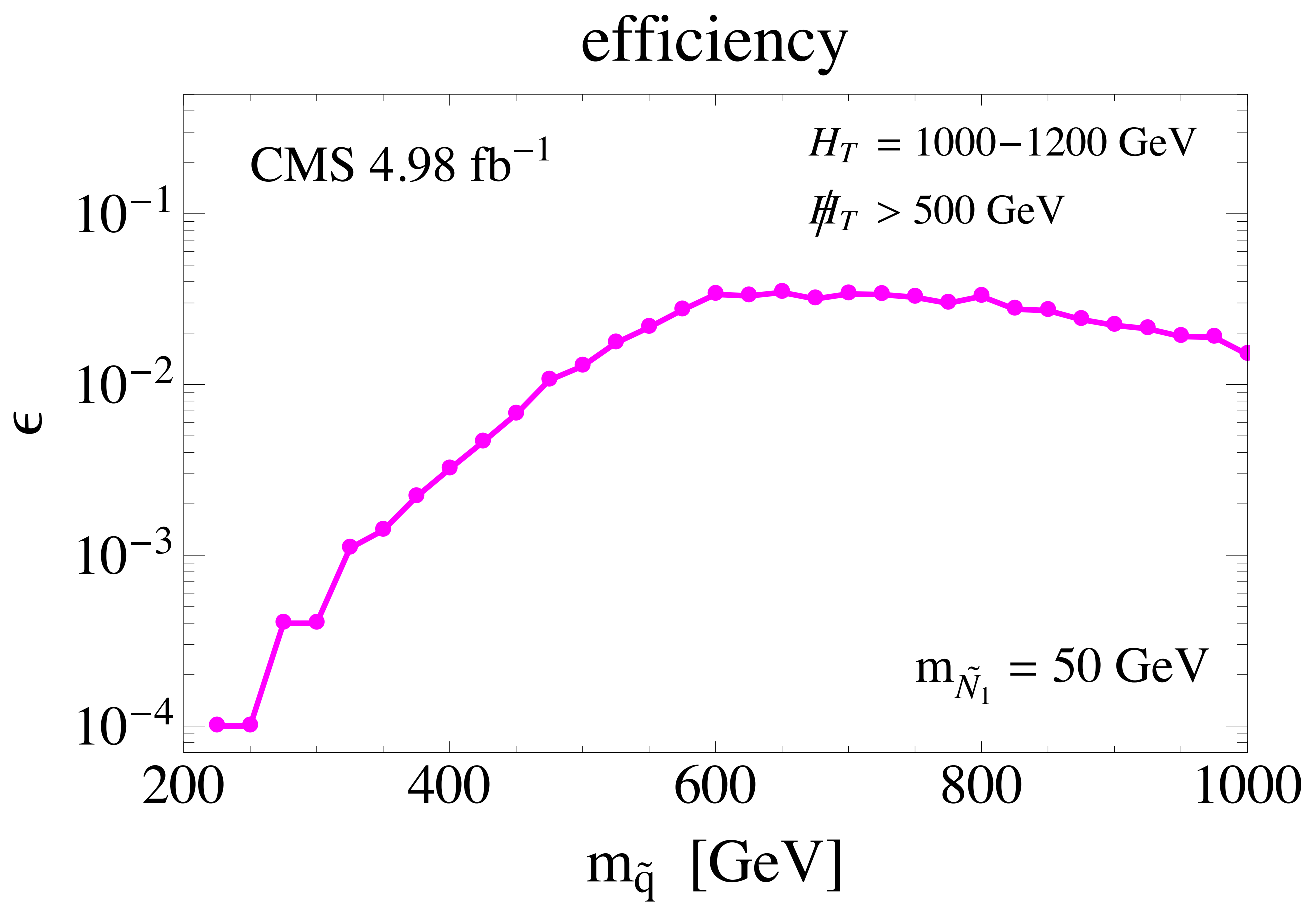
Dedicated study needed

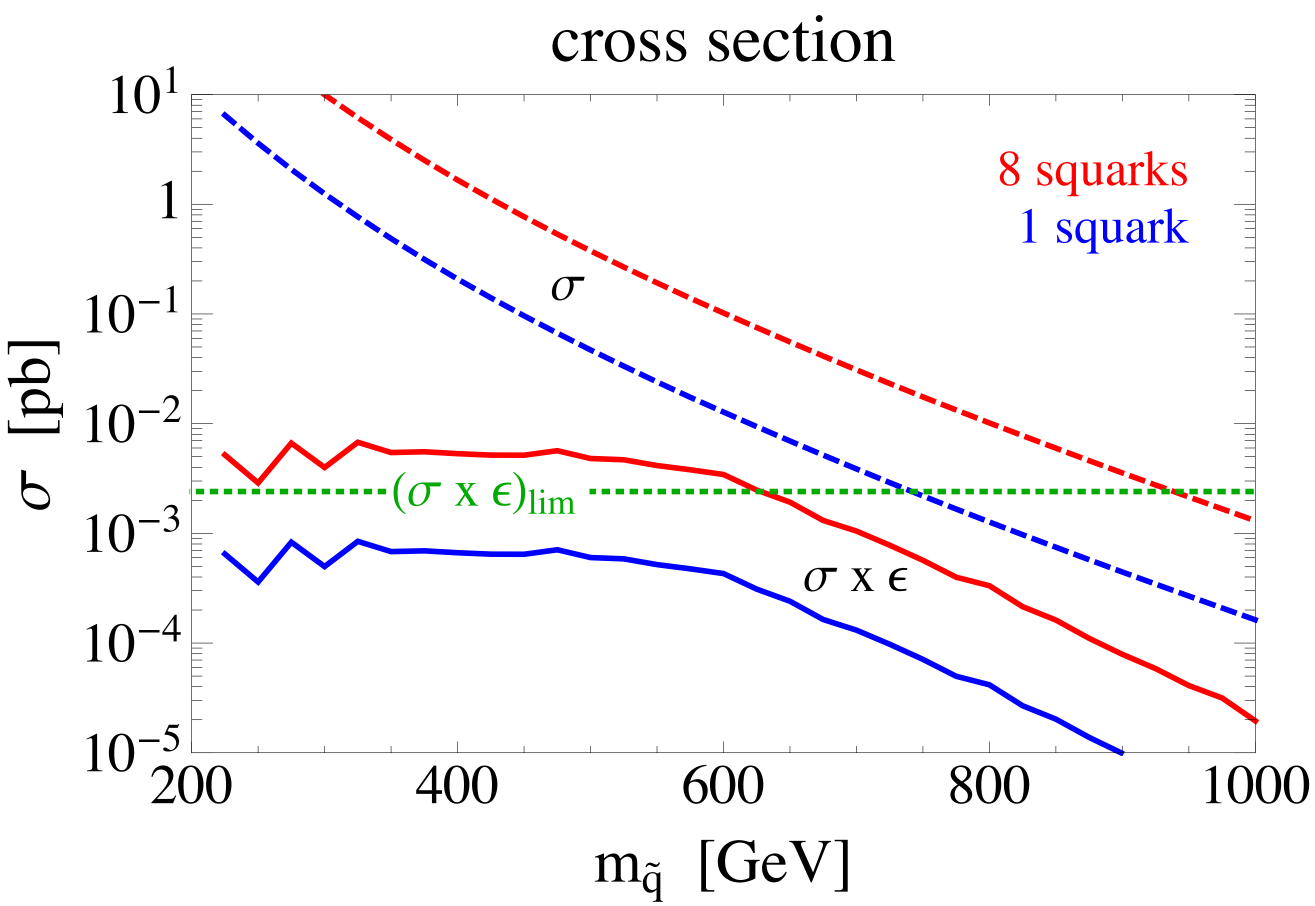
- Production cross-section can be flavor dependent if gluino is not fully decoupled through p.d.f's (u vs. d, sea vs. valence)
- Experimental efficiencies for light squarks efficiencies have thresholds and current limits are on the thresholds

Squark searches

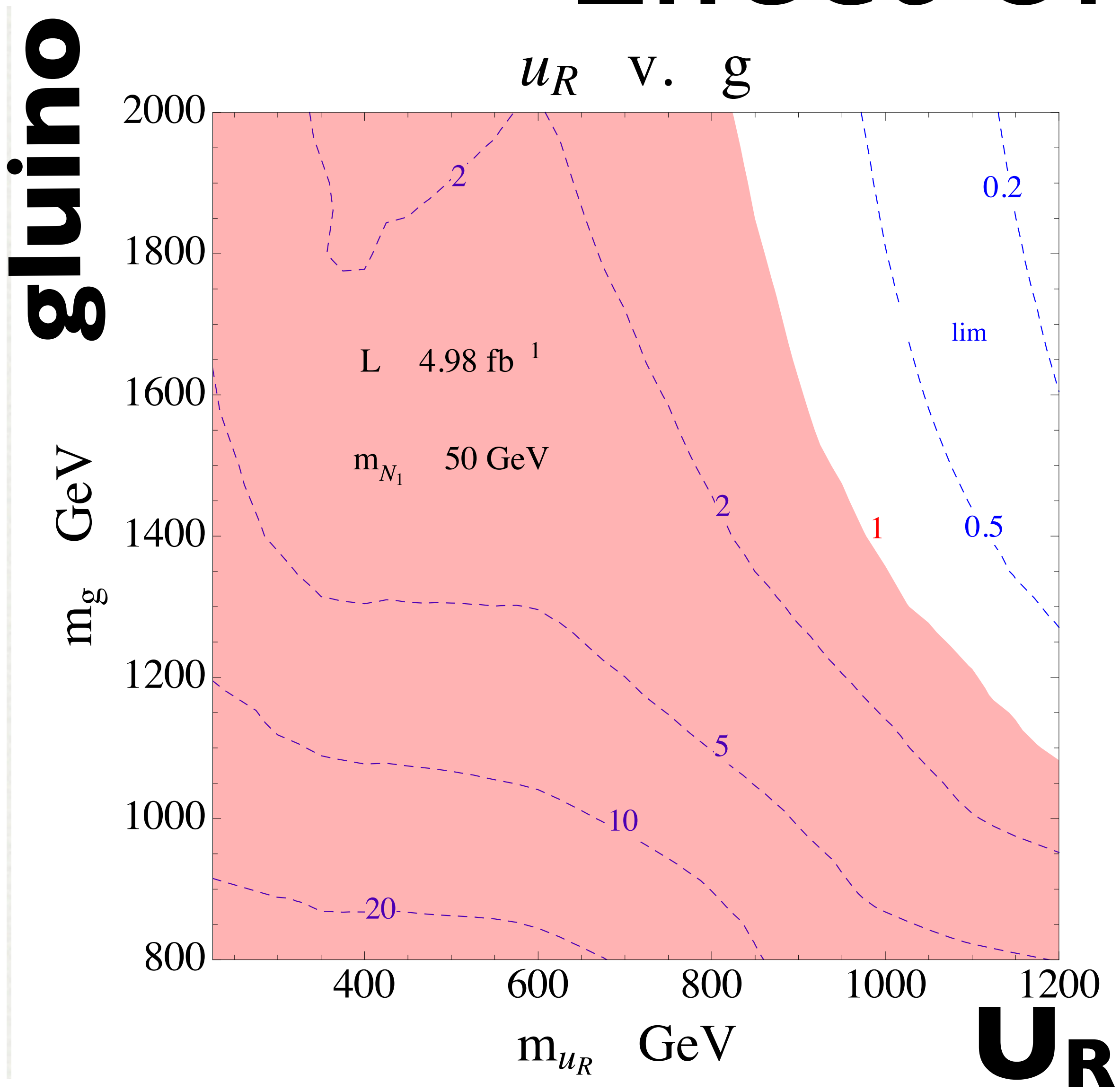
M. Papucci, J. Ruderman
G. Perez, R. Mahbubani, AW

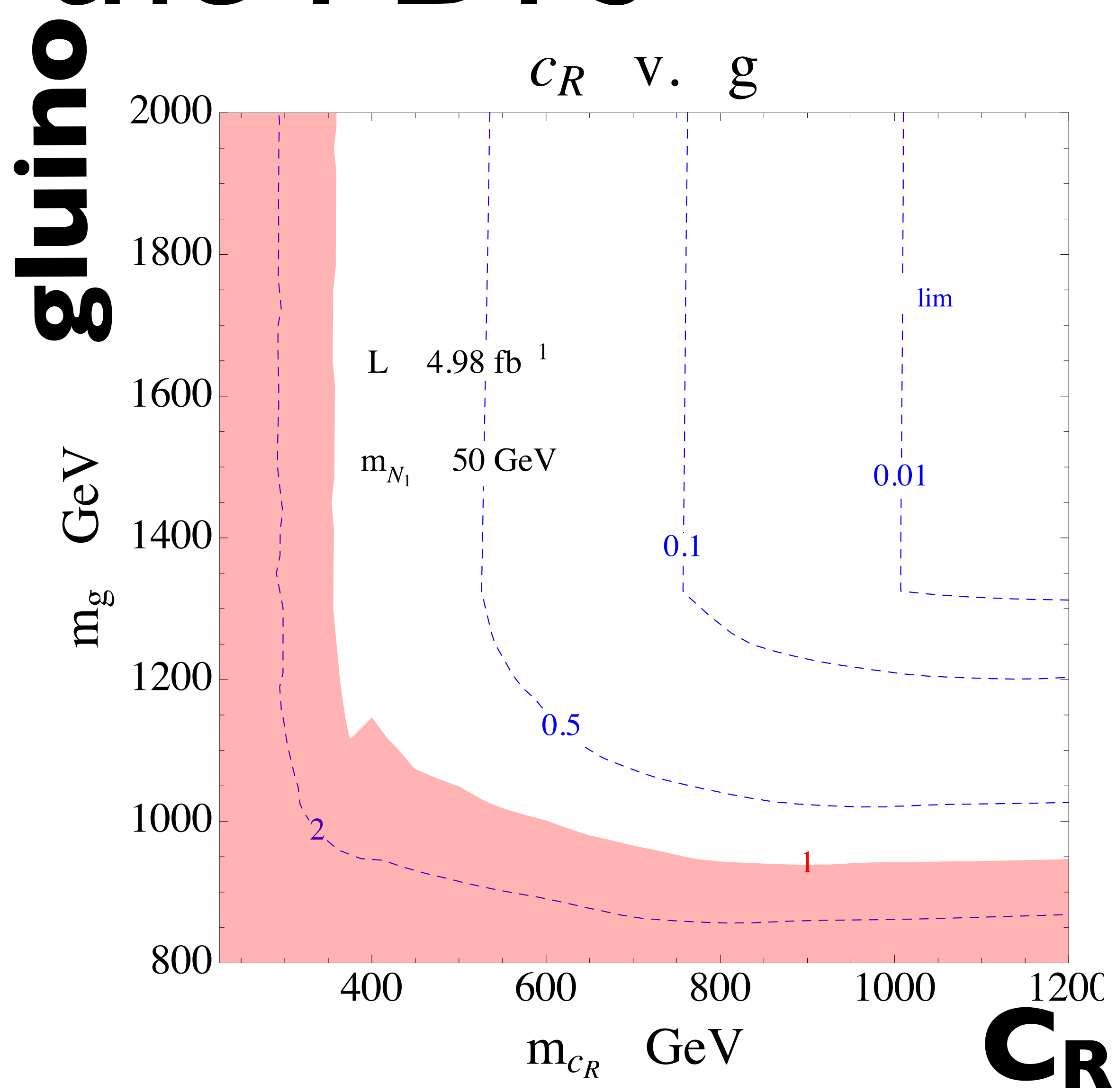
Effect of the efficiency threshold:



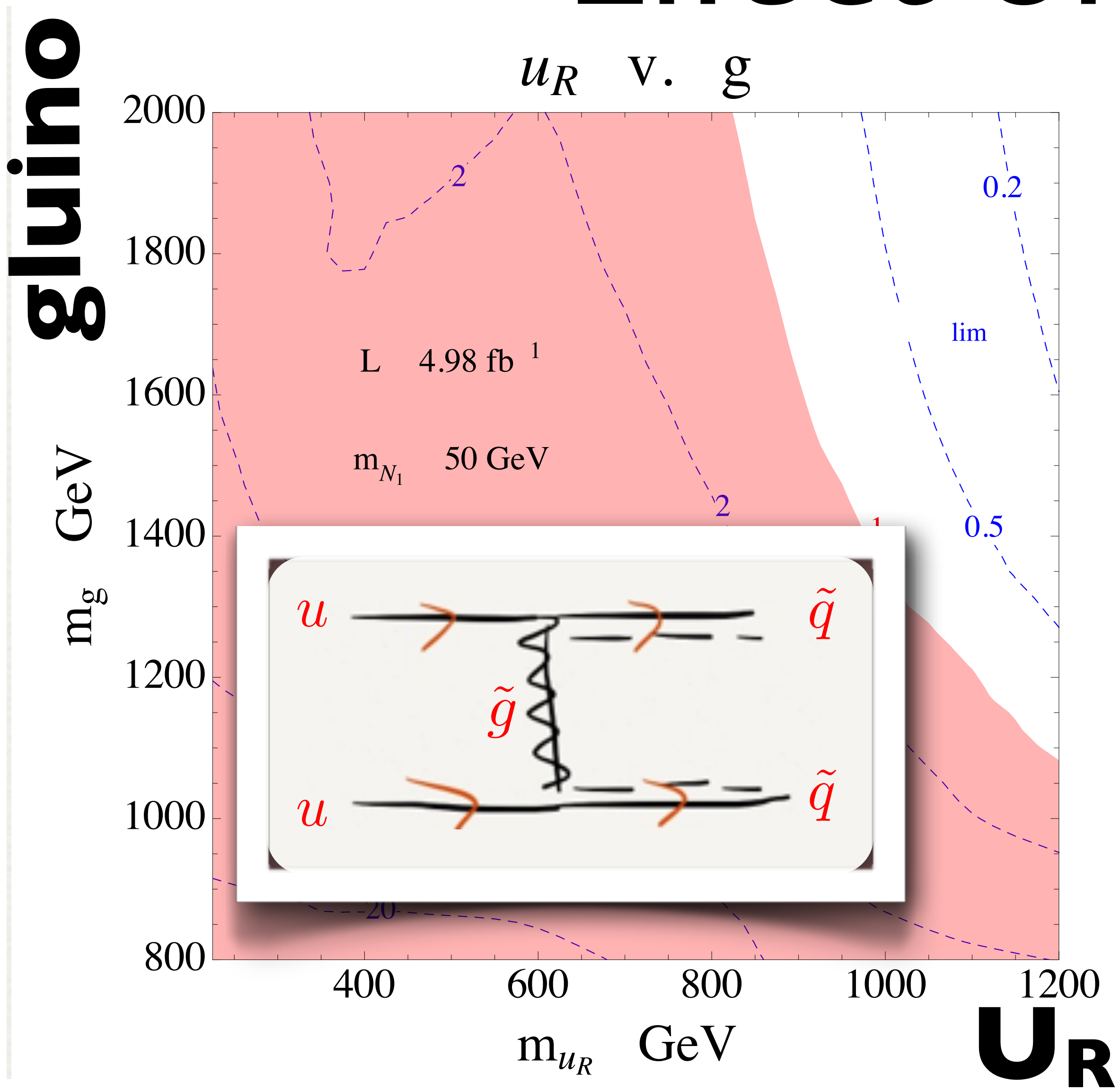


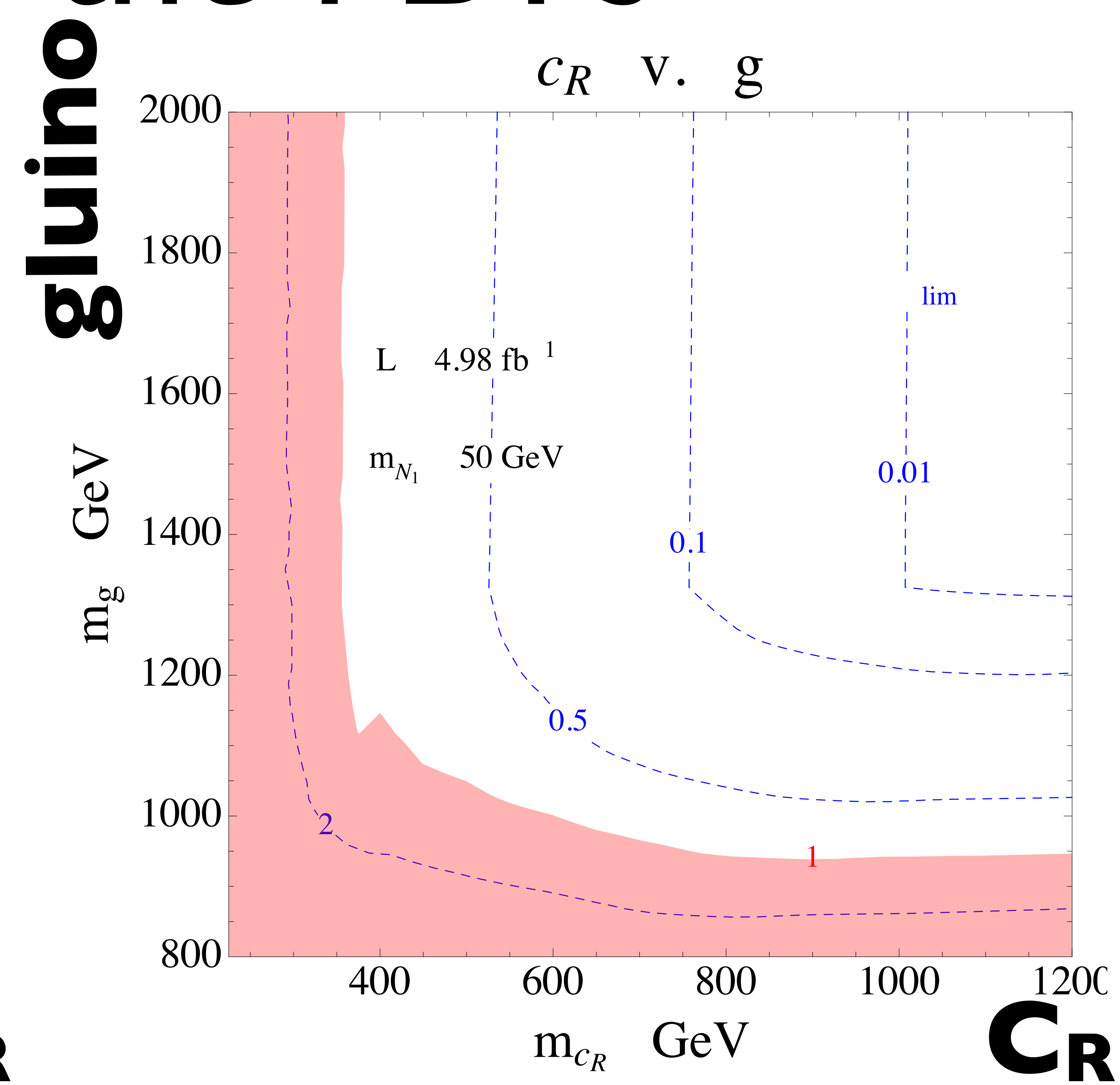
Effect of the PDFs





Effect of the PDFs



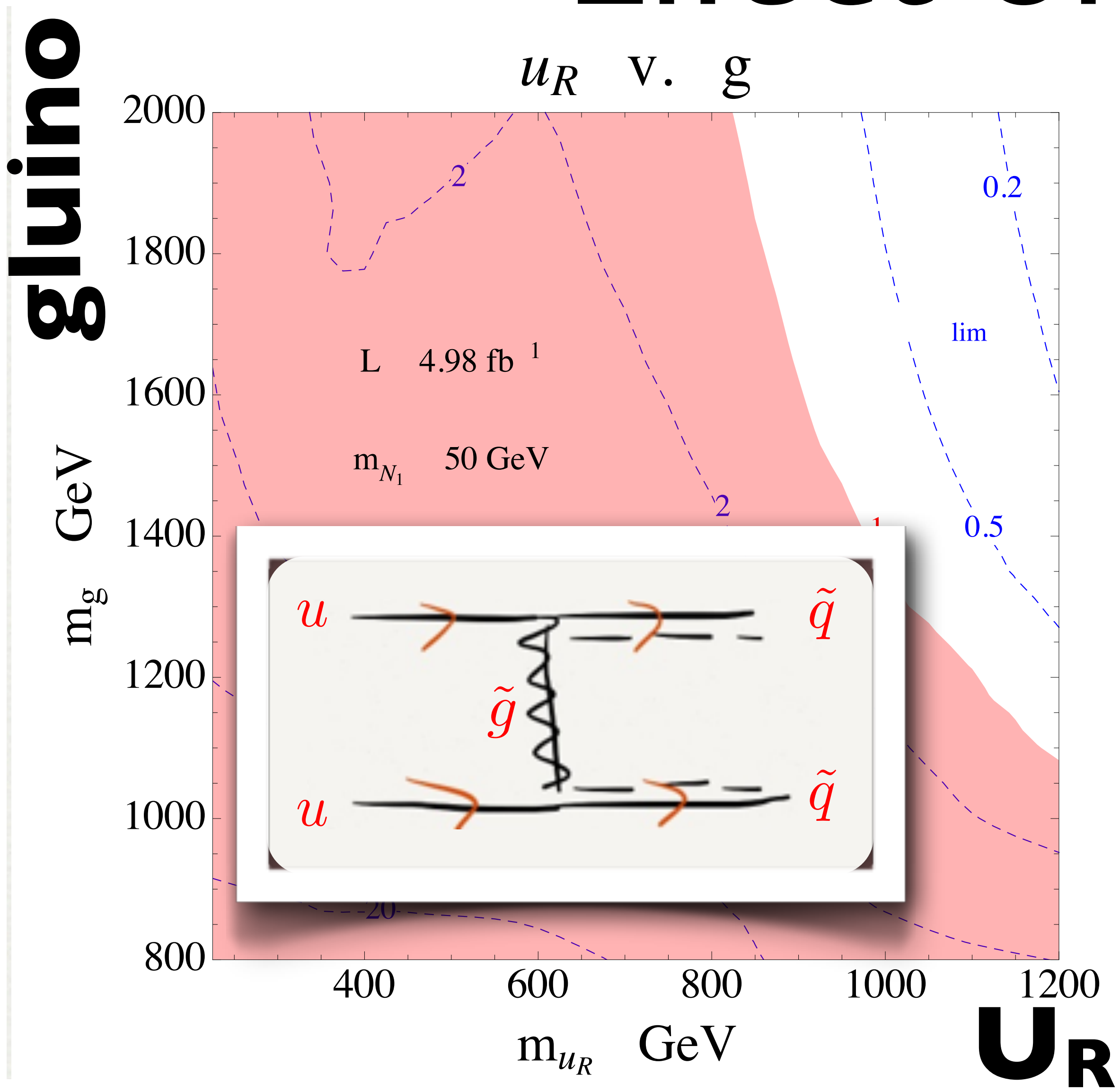


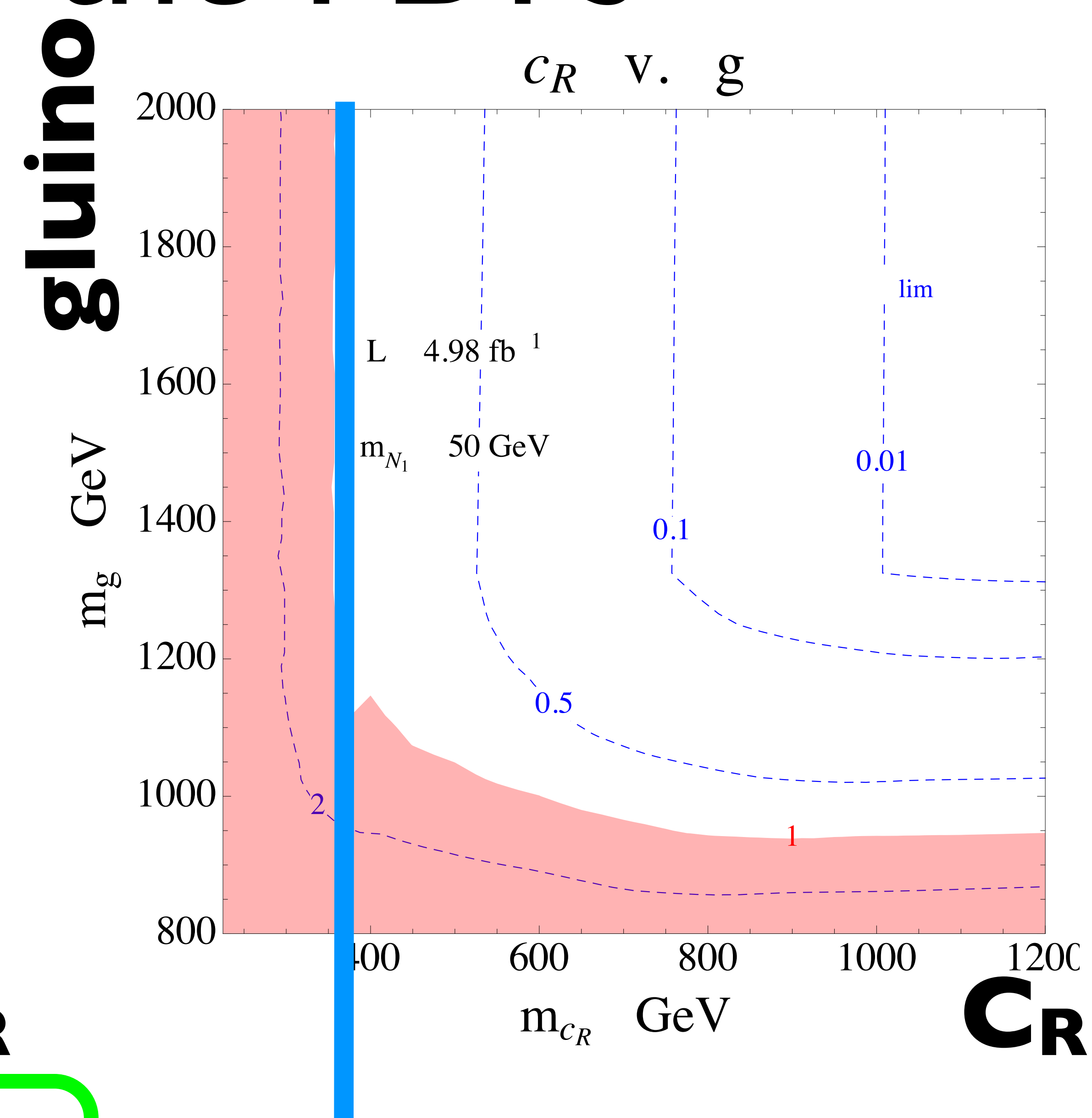
$$\frac{1}{m_{\tilde{g}}}\tilde{q}\tilde{q}\,u_R u_R$$ dim5 op.

$$\rightarrow \quad \sigma \sim 1/m_{\tilde{g}}^2$$

slow decoupling

Effect of the PDFs





$$\frac{1}{m_{\tilde{g}}}\tilde{q}\tilde{q}\,u_R u_R$$ dim5 op.

$$\rightarrow \quad \sigma \sim 1/m_{\tilde{g}}^2$$

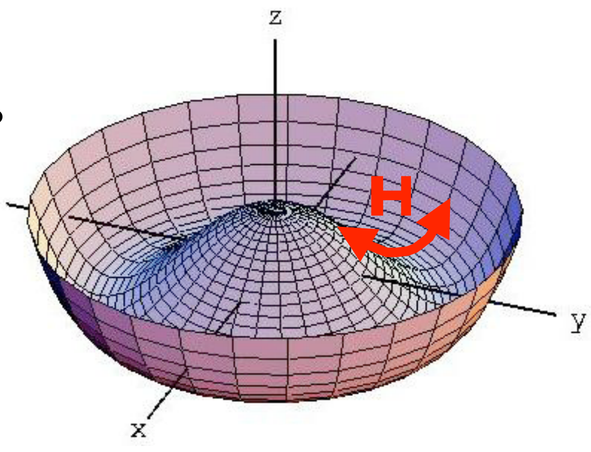
slow decoupling

Valence squarks can still be < 400 GeV

Motivation to go beyond SUSY?

1) Take anomalies (charm, top A_{FB}, B→Kpi…) at face value and run with it.

2) Strong EWSB vs. the hierarchy problem: composite Higgs, TC, Randall-Sundrum,…



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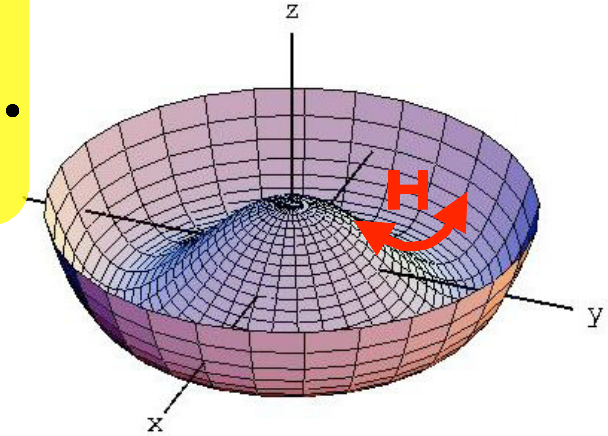
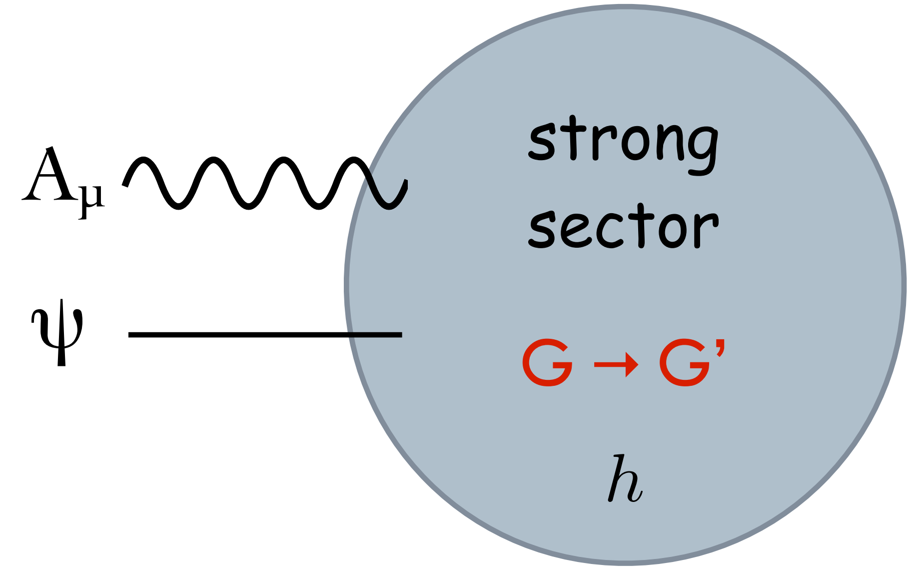


Why is the Higgs light?

Kaplan; Agashe et. al

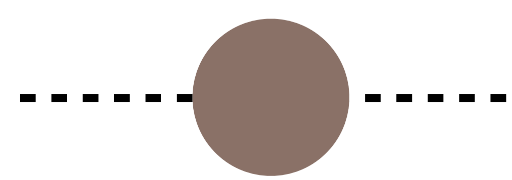


Higgs as a pNGB

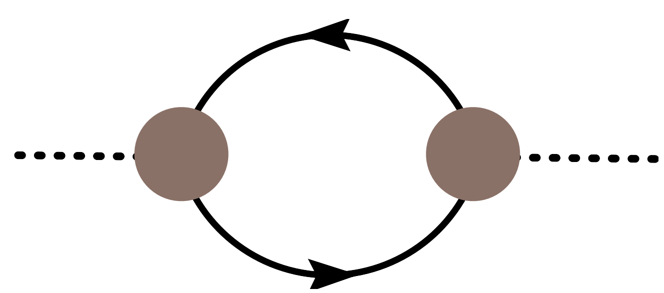
minimal example

SO(5) → SO(4) ~ SU(2)$_L$ x SU(2)$_R$

No pure composite effects,
vanish due to NG symmetry

 = 0

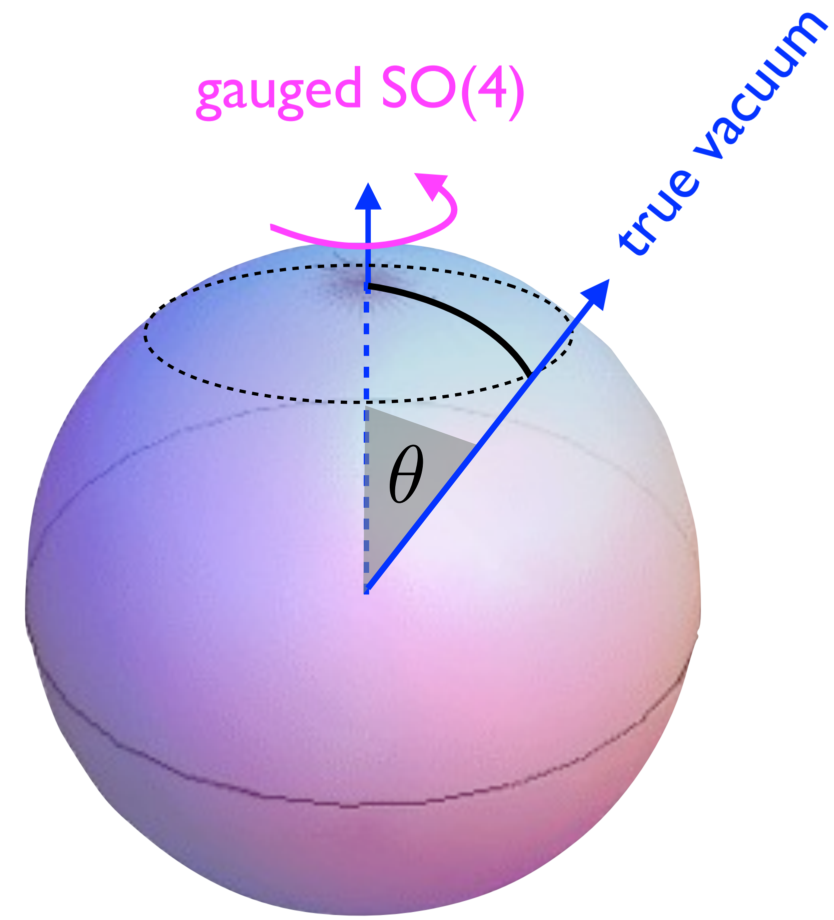
NG symmetry broken by
elementary-composite couplings:



$$m_h^2 \sim \frac{\lambda^2}{16\pi^2}\Lambda_{comp}^2$$

$$\lambda \ll 4\pi$$

θ: misalignment between gauged SO(4) and SO(4)' preserved in the quantum corrected vacuum



Tree level: gauge SO(4) aligned

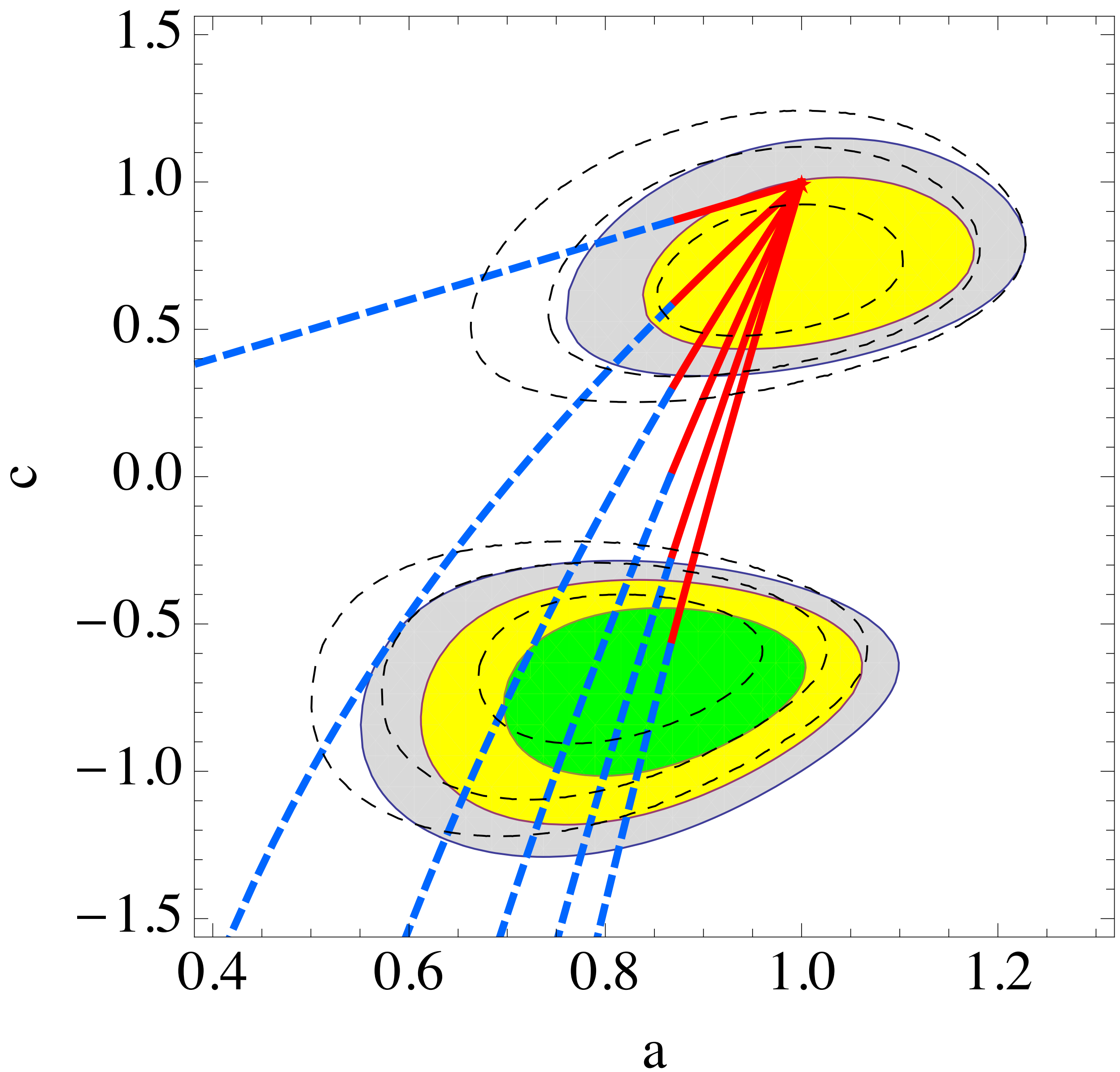
Higgs

$$\phi = e^{i\pi^{\hat{a}}T^{\hat{a}}/f}\begin{pmatrix}0\\0\\0\\0\\1\end{pmatrix} = \begin{pmatrix}\sin(\pi/f)\times\begin{pmatrix}\hat{\pi}^1\\\hat{\pi}^2\\\hat{\pi}^3\\\hat{\pi}^4\end{pmatrix}\\ \cos(\pi/f)\end{pmatrix} = \begin{pmatrix}\sin(\theta+h(x)/f)\;\; e^{i\chi^i(x)A^i/v}\begin{pmatrix}0\\0\\0\\1\end{pmatrix}\\ \cos(\theta+h(x)/f)\end{pmatrix}$$

@ 1-loop <pi> = θ * f

eaten by W_L, Z_L

Higgs fit ATLAS/CMS/Tevatron

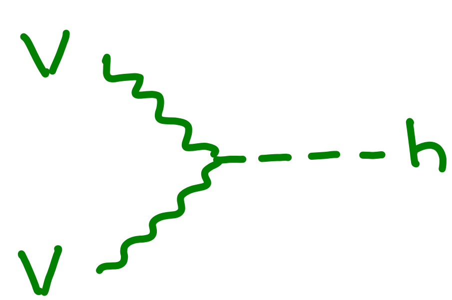


$$a = \sqrt{1-\xi}$$

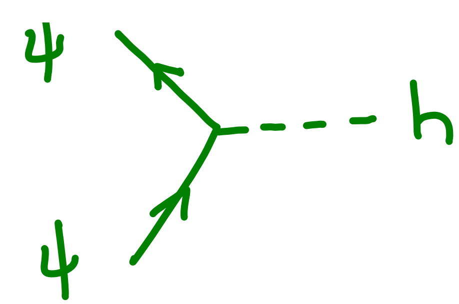
$$c_f = \frac{1-(1+n)\xi}{1-\xi}$$

Montull/Riva

see also: Espinosa et al, Carmi et al, Azatov et al, ...

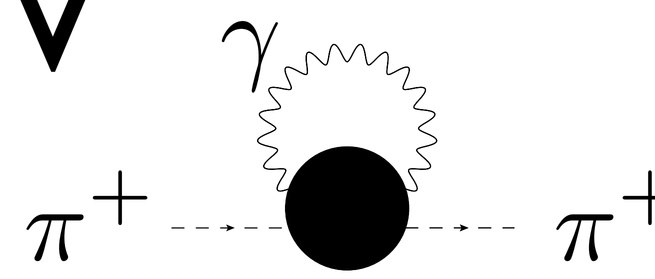


$a\, g^{SM}_{hVV}$



$c\, h^{SM}_{\psi\psi h}$

Implications of m_H = 125 GeV



Das et al '67

Agashe et. al

Coleman-Weinberg potential

$$V_{gauge}(h) = \frac{9}{2}\int \frac{d^4p}{(2\pi)^4}\log\left(\Pi_0(p) + \frac{s_h^2}{4}\Pi_1(p)\right) \qquad s_h \equiv \sin h/f$$

$$\Pi_0(p) = \frac{p^2}{g^2} + \Pi_a(p)\ , \qquad \Pi_1(p) = 2\left[\Pi_{\hat{a}}(p) - \Pi_a(p)\right]$$

$\int d^4p\, \Pi_1(p)/\Pi_0(p)$ **< ∞**

require Higgs dependent term to be UV finite

Pomarol et al; Marzocca

Implications of m_H = 125 GeV

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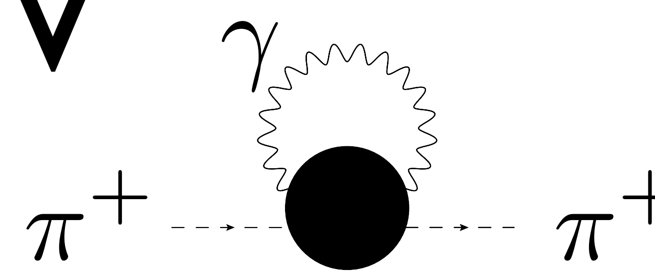

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$\int d^4p\, \Pi_1(p)/\Pi_0(p)$ **< ∞**

require Higgs dependent term to be UV finite

'Weinberg sum rules'

Pomarol et al; Marzocca

$$\lim_{p^2\to\infty} \Pi_1(p) = 0\ , \qquad \lim_{p^2\to\infty} p^2\Pi_1(p) = 0$$

Minimal contribution (need at least two resonances)

$$\Pi_1(p) = \frac{f^2 m_\rho^2 m_{a_1}^2}{(p^2 + m_\rho^2)(p^2 + m_{a_1}^2)}$$

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$$\Pi_1(p) = \frac{f^2 m_\rho^2 m_{a_1}^2}{(p^2 + m_\rho^2)(p^2 + m_{a_1}^2)}$$

Analogously for SO(5) fermionic contribution

Pomarol et al; Marzocca

$$m_h^2 \simeq \frac{N_c}{\pi^2}\left[\frac{m_t^2}{f^2}\frac{m_{Q_4}^2 m_{Q_1}^2}{m_{Q_1}^2 - m_{Q_4}^2}\log\left(\frac{m_{Q_1}^2}{m_{Q_4}^2}\right)\right]$$

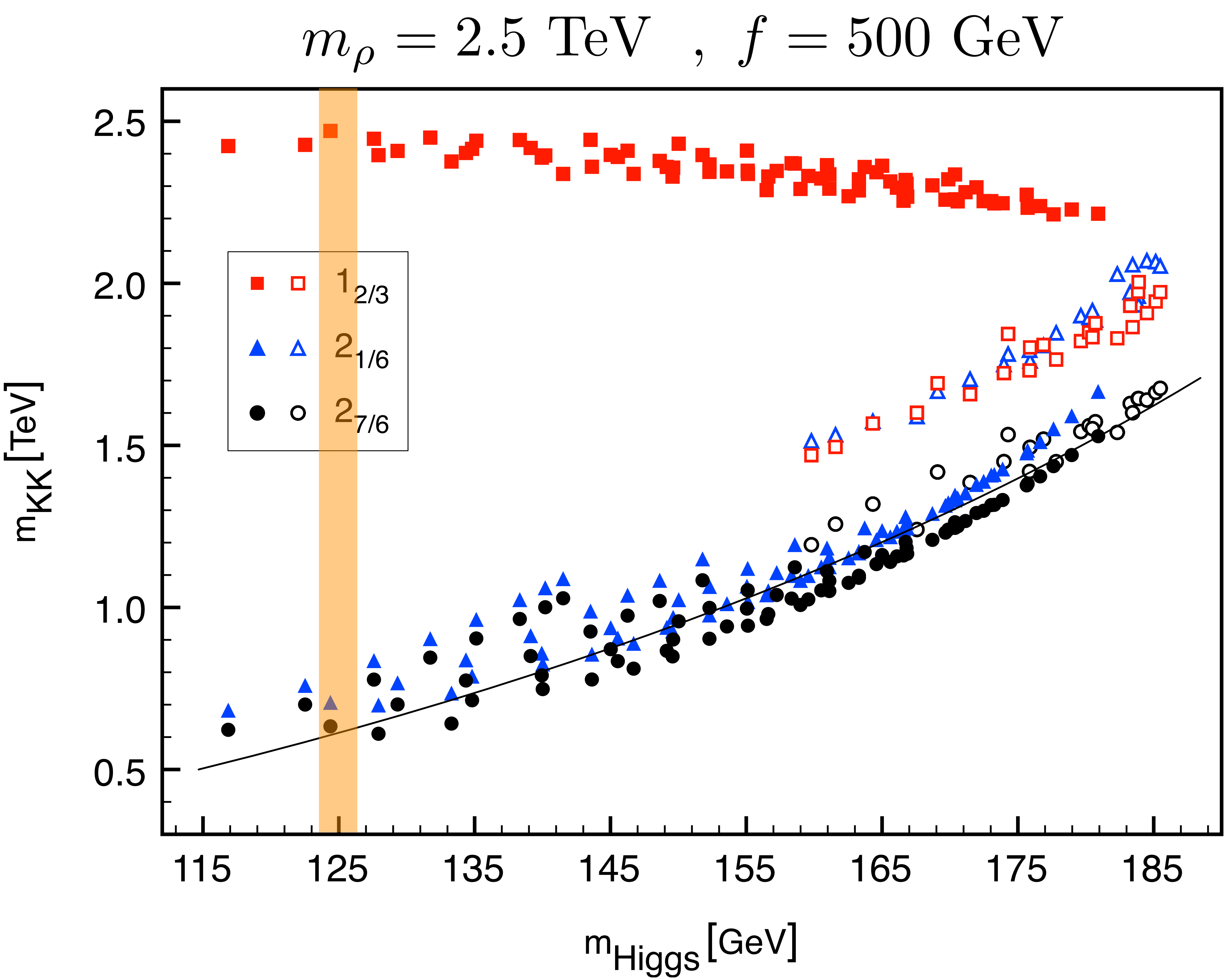
similar result in deconstruction:
Matsedonskyi et al; Redi et al

$5 = 4 + 1$ with EM charges 5/3, 2/3,-1/3

Q_4 Q_1

→ solve for m_h = 125 GeV

Light Higgs implies light fermionic top partners



Contino et al 07, Matsedonskyi, et al '12 ; Redi,Tesi 12; Marzocca et al ; Pomarol, Riva 12

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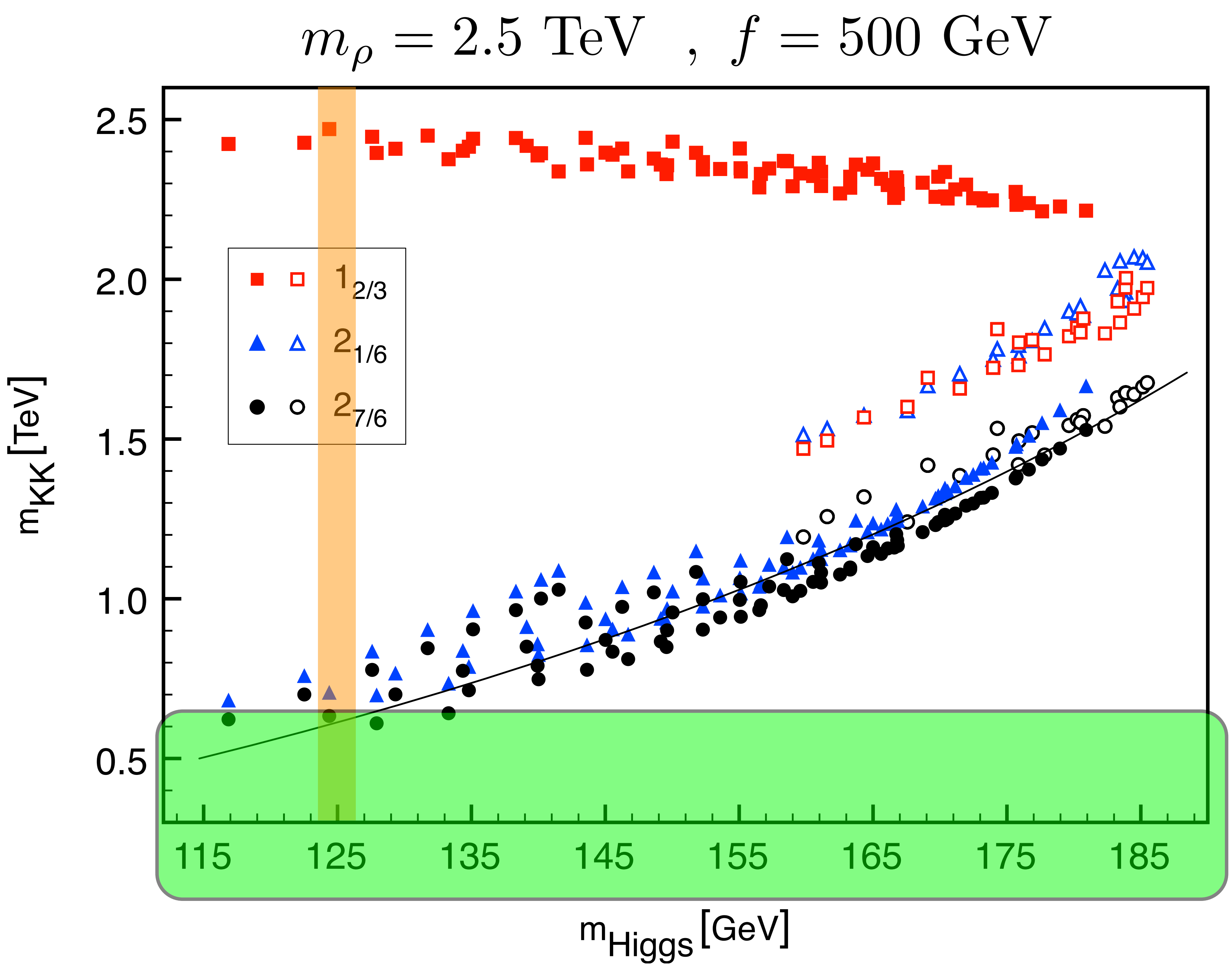


ATLAS: $T_{5/3}$

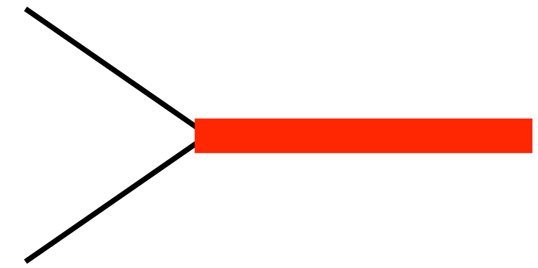
4.7 1/fb, 7 TeV

Contino et al 07, Matsedonskyi, et al '12 ; Redi,Tesi 12; Marzocca et al ; Pomarol, Riva 12

Three ways to flavor

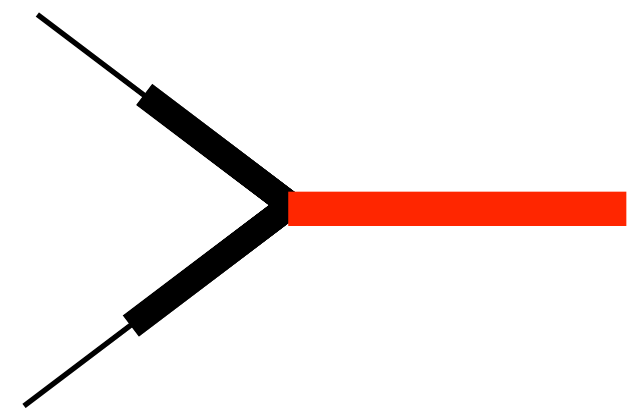
Bilinear: ETC, conformalTC

Dimopoulos, Susskind
Holdom
....
Luty, Okui



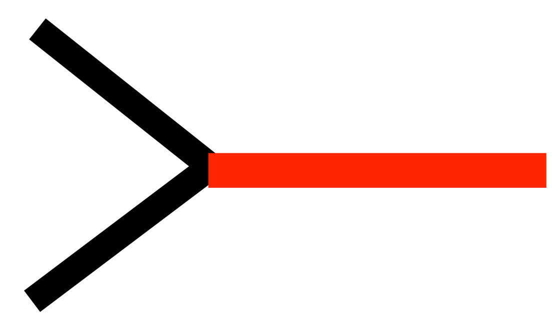
Linear: partial compositeness

D.B. Kaplan
....
Huber
RS with bulk fermions
Agashe, Perez, Soni, ...



Total compositeness

ex: minimal RS
Rattazzi-Zaffaroni



from R.Rattazzi

Three ways to flavor

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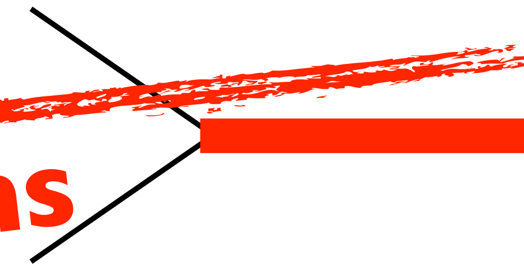

disfavored by CFT theorems

Rychkov et al '08

Linear: partial compositeness

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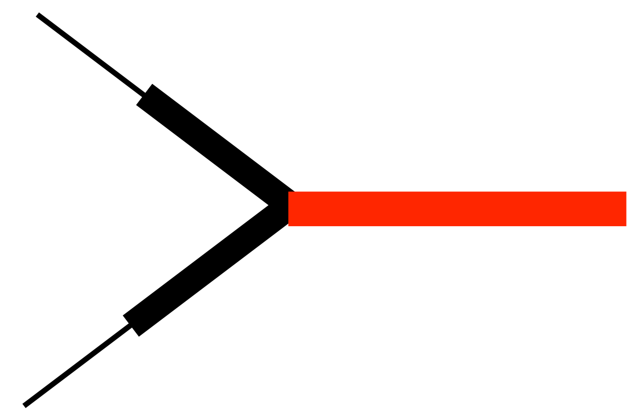

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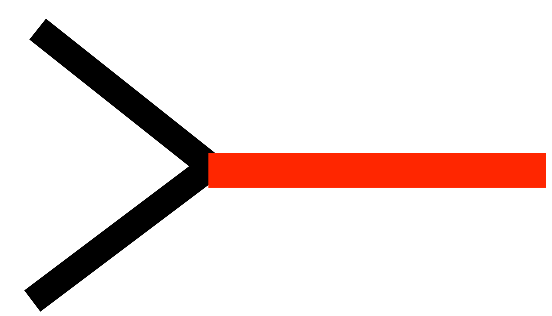

from R.Rattazzi

Three ways to flavor

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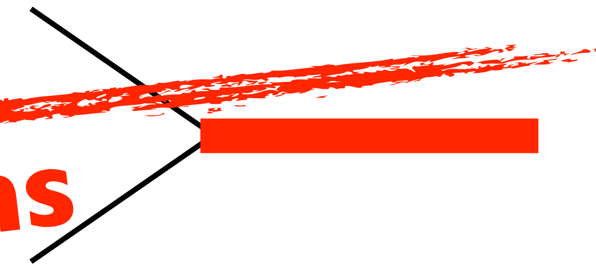
~~....~~
~~Luty, Okui~~



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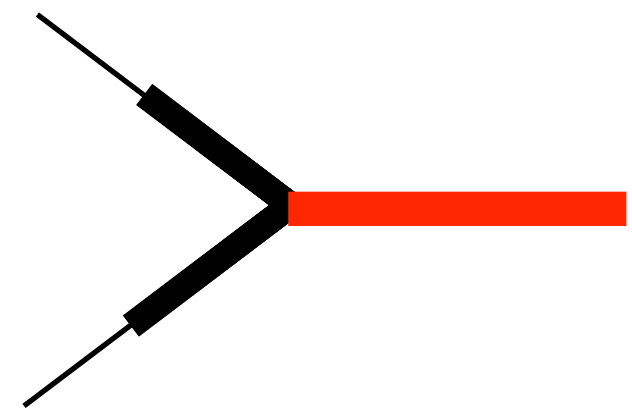

~~Total compositeness~~

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~~Rattazzi-Zaffaroni~~

ruled out by LEP

from R.Rattazzi

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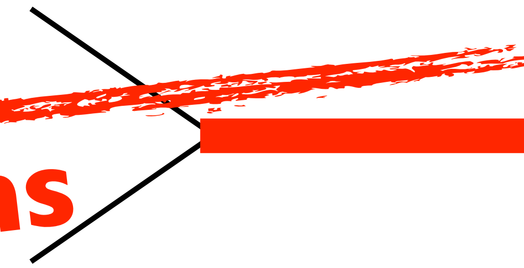

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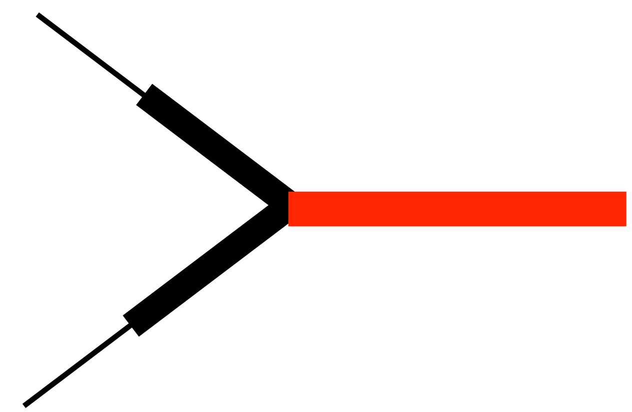


Total compositeness

ex: minimal RS

Rattazzi-Zaffaroni

ruled out by LEP

from R.Rattazzi

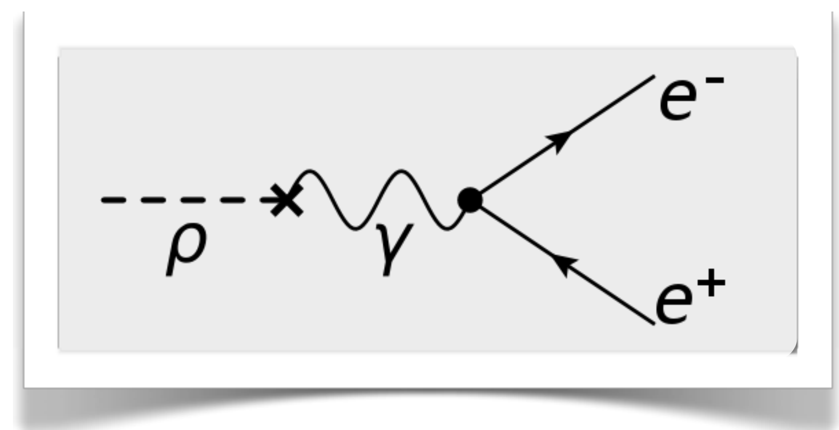
Partial compositeness

vector-like
composite fermion

Fermionic operators can excite composite fermions at low energy:

$$\langle 0|\mathcal{O}|\chi\rangle = \lambda\, f$$

Analogous to photon-rho mixing
Br(rho → e+e-) ~ 10^{-5}



Linear couplings imply mass mixings:

$$\mathcal{L} = \bar\psi\, i\partial\!\!\!/\, \psi + \bar\chi(\, i\partial\!\!\!/ - m_*)\chi + \lambda f\, \bar\psi\chi + h.c.$$

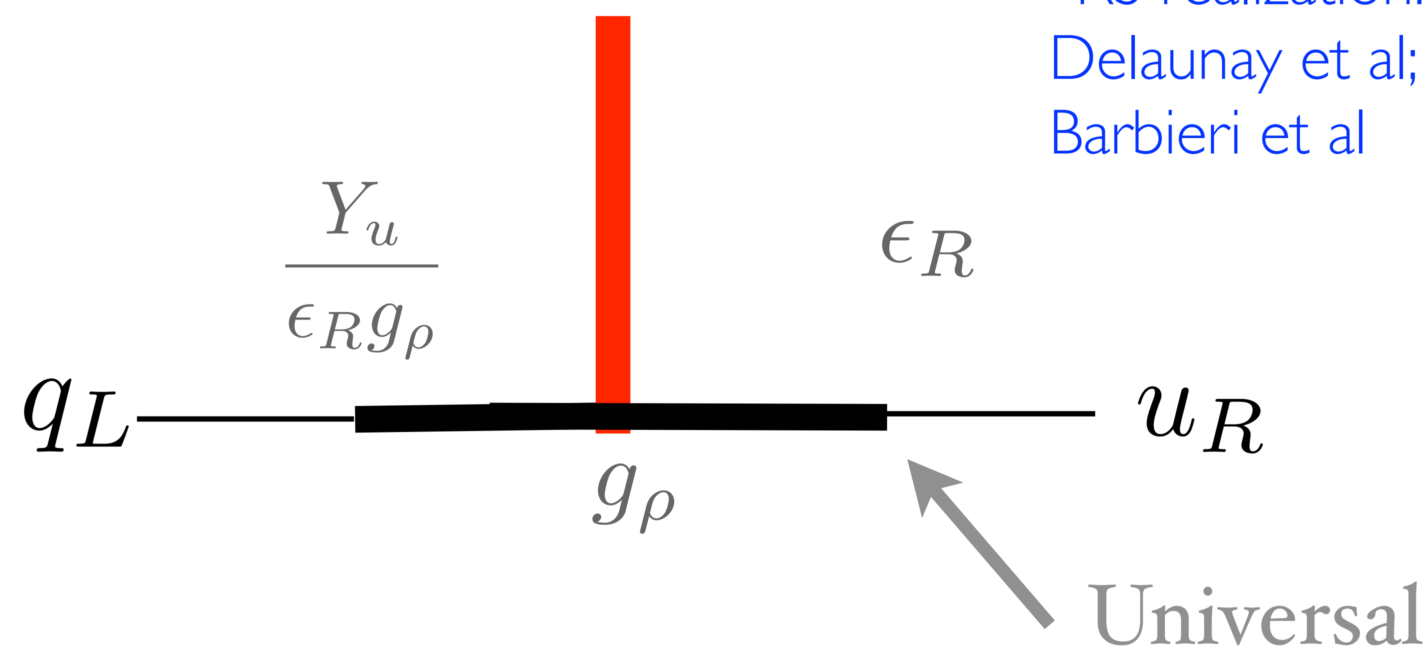
rotating to mass eigenbasis:

$$\begin{pmatrix}\psi\\ \chi\end{pmatrix} \to \begin{pmatrix}\cos\varphi & \sin\varphi\\ \sin\varphi & \cos\varphi\end{pmatrix}\begin{pmatrix}\psi\\ \chi\end{pmatrix} \qquad \tan\varphi = \frac{\lambda\, f}{m_*}$$

It makes sense to invoke MFV

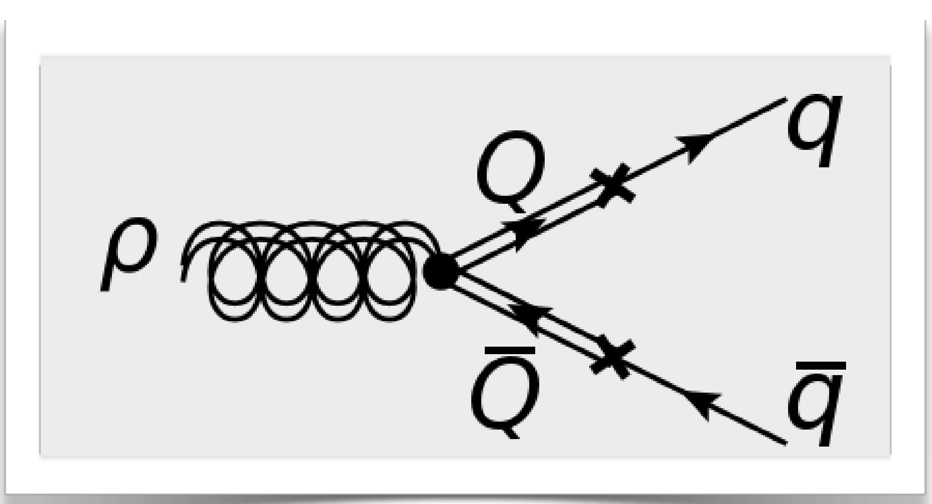
Redi/AW

RS realization: Csaki,AW et al; Delaunay et al; da Rold; see also Barbieri et al



Observed m_t $\Longrightarrow$ $\epsilon_R \gtrsim \frac{1}{g_\rho} > 0.1$

Predict sizeable effects in right handed quarks of all generations

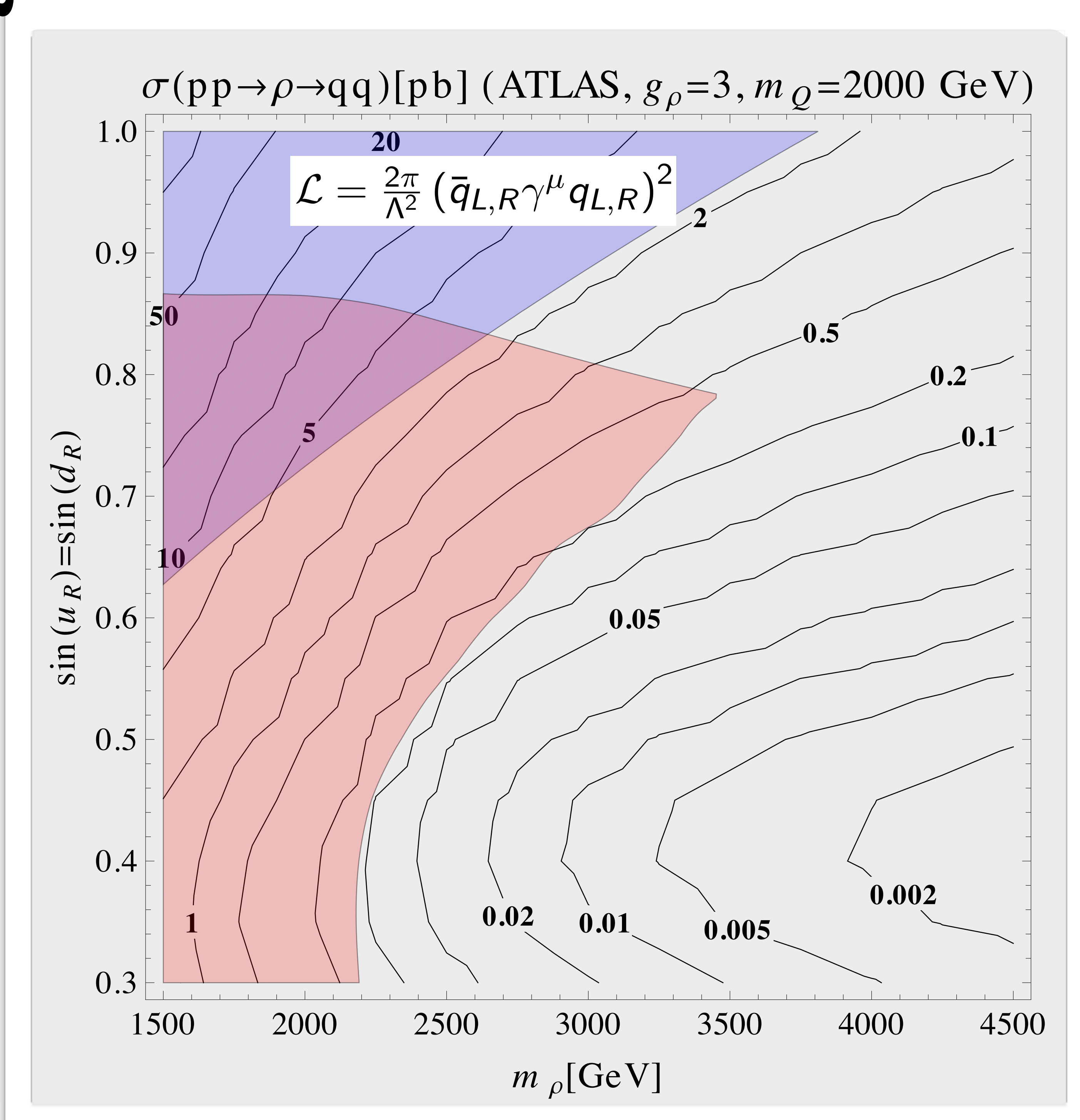


all possible resonances (Ex. massive gluon)

LHC14 will tell

de Vries, Redi, Sanz, AW, in prep.

Mixing



ATLAS dijet angular searches [ATLAS-CONF-2012-038]

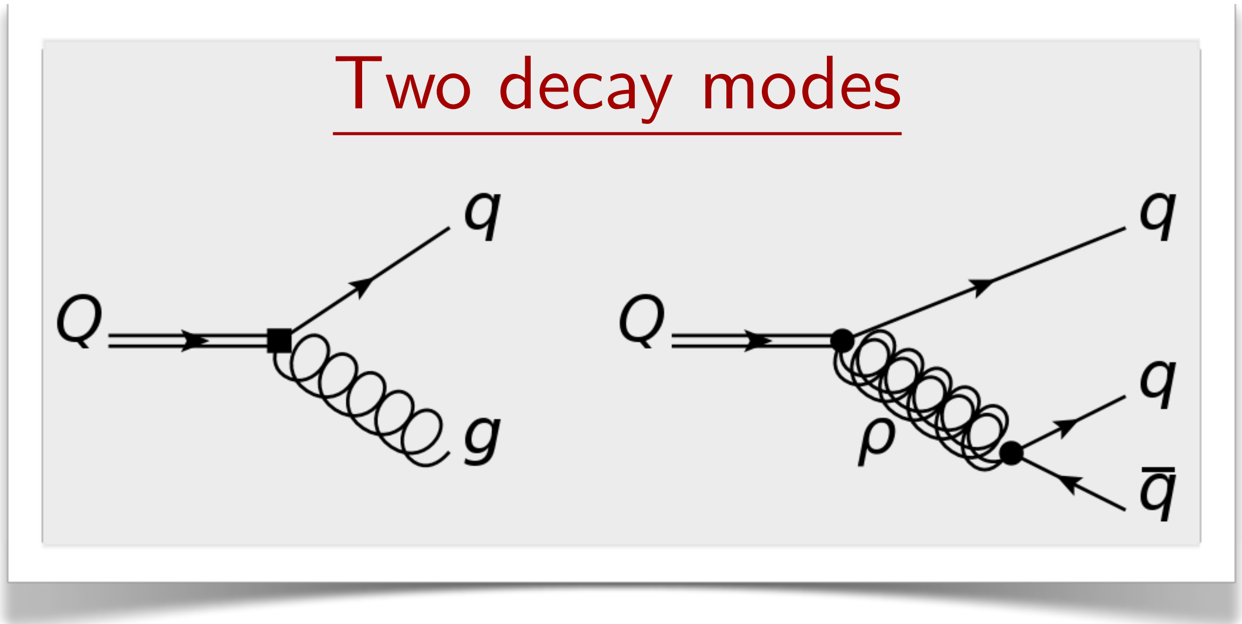
Dijet resonance search bounds ATLAS 8 TeV 5.8 fb−1 [ATLAS-CONF-2012-088]

Vector resonance mass

similar plot from CMS

Light Fermionic Partners

deVries, Redi, Sanz, AW, in prep.



$$\mathcal{L} = \frac{g_s \kappa}{m_Q} \bar{Q} \sigma^{\mu\nu} T^a q G^a_{\mu\nu}$$

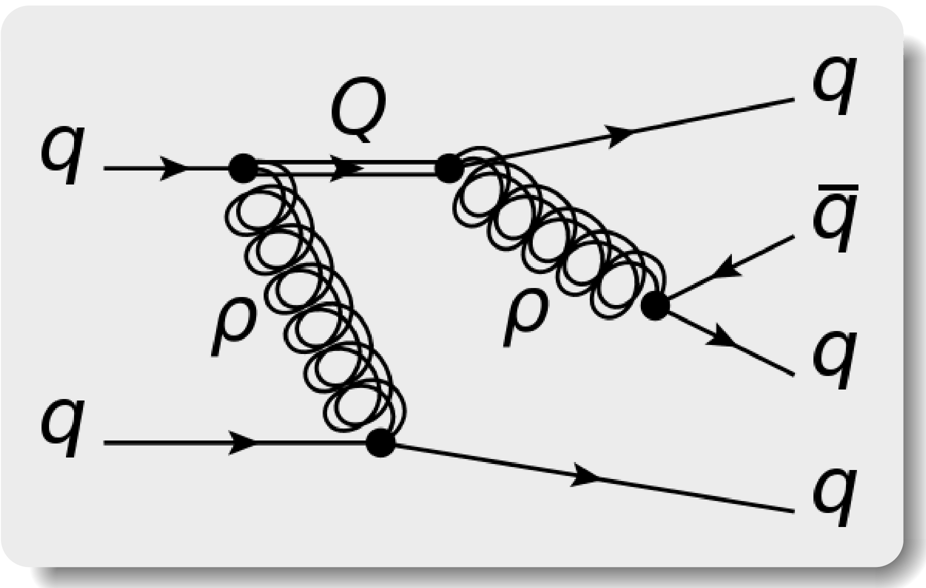
three-body

chromo-magnetic (loop)

Both decay modes suppressed
and result in a narrow width

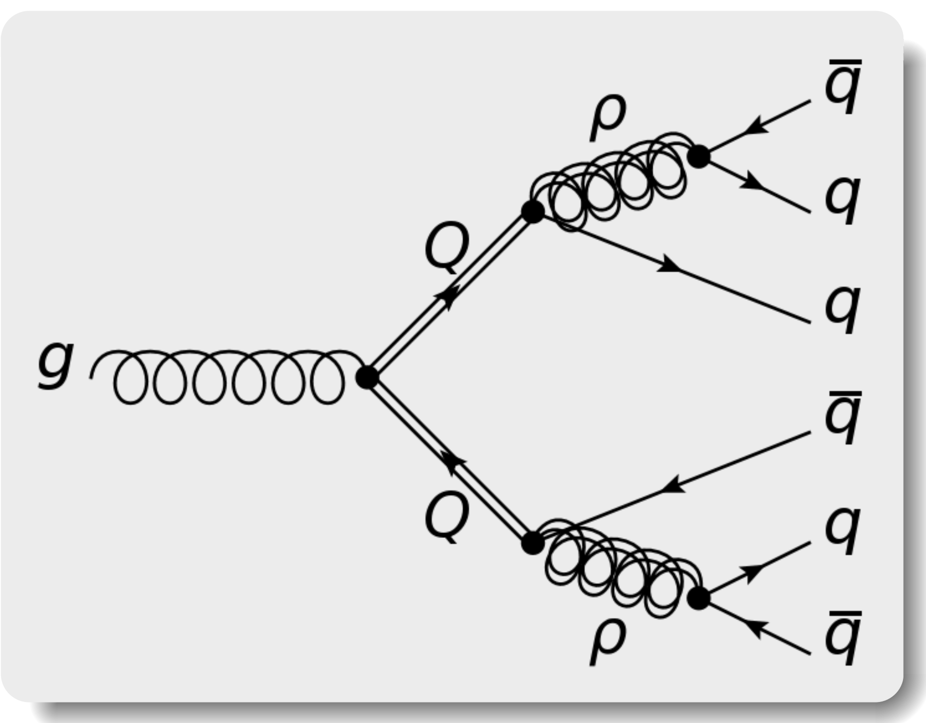
Search strategies

deVries, Redi, Sanz, AW, in prep.



Four jet analysis CMS 7 TeV 2.2 fb−1
[CMS PAS EXO-11-016]

optimized for pair production of two heavy resonances



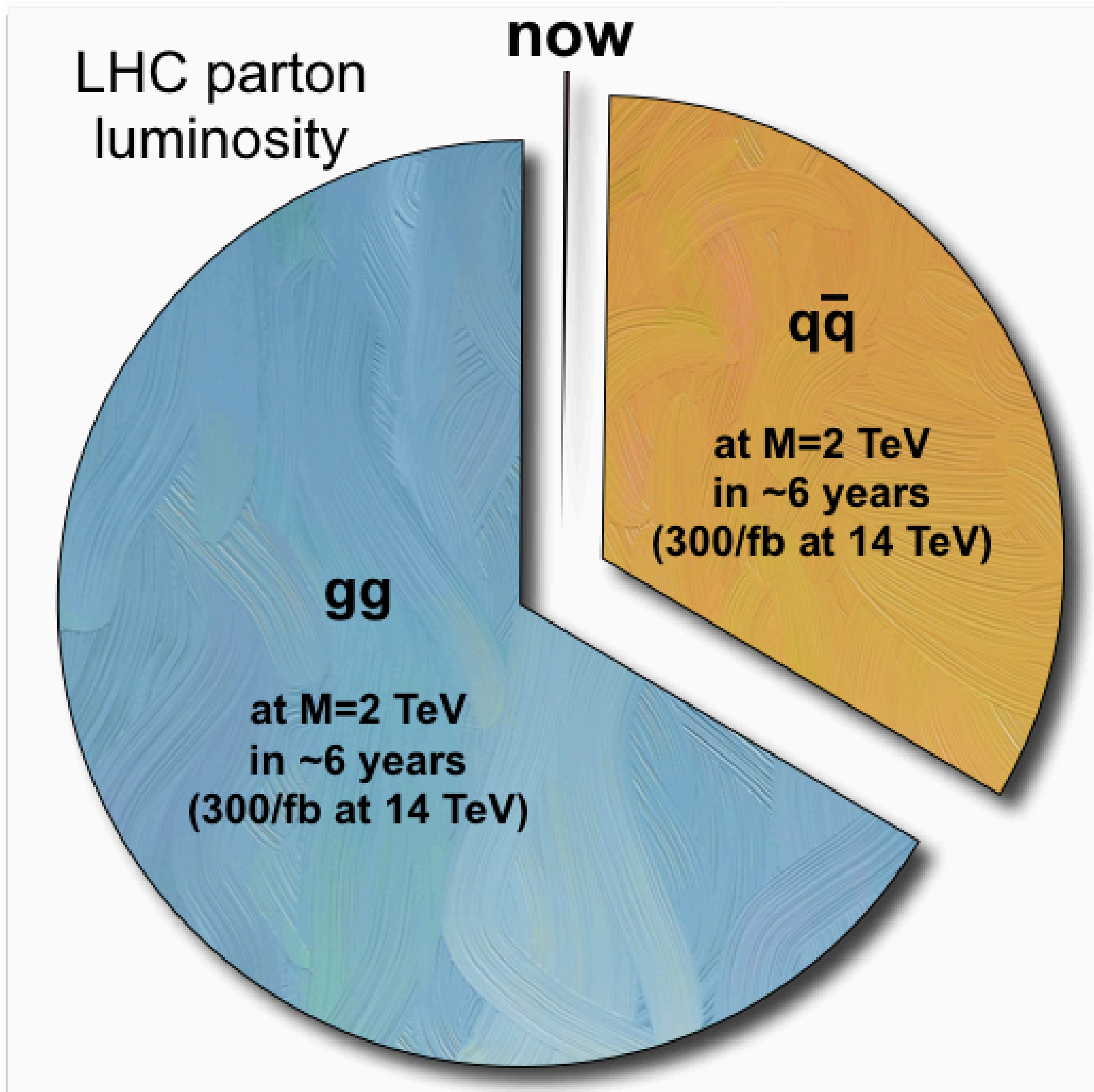
Six jet analysis CMS 7 TeV 5.0 fb−1
[CMS-EXO-11-060]

Currently recasting analysis & designing dedicated search

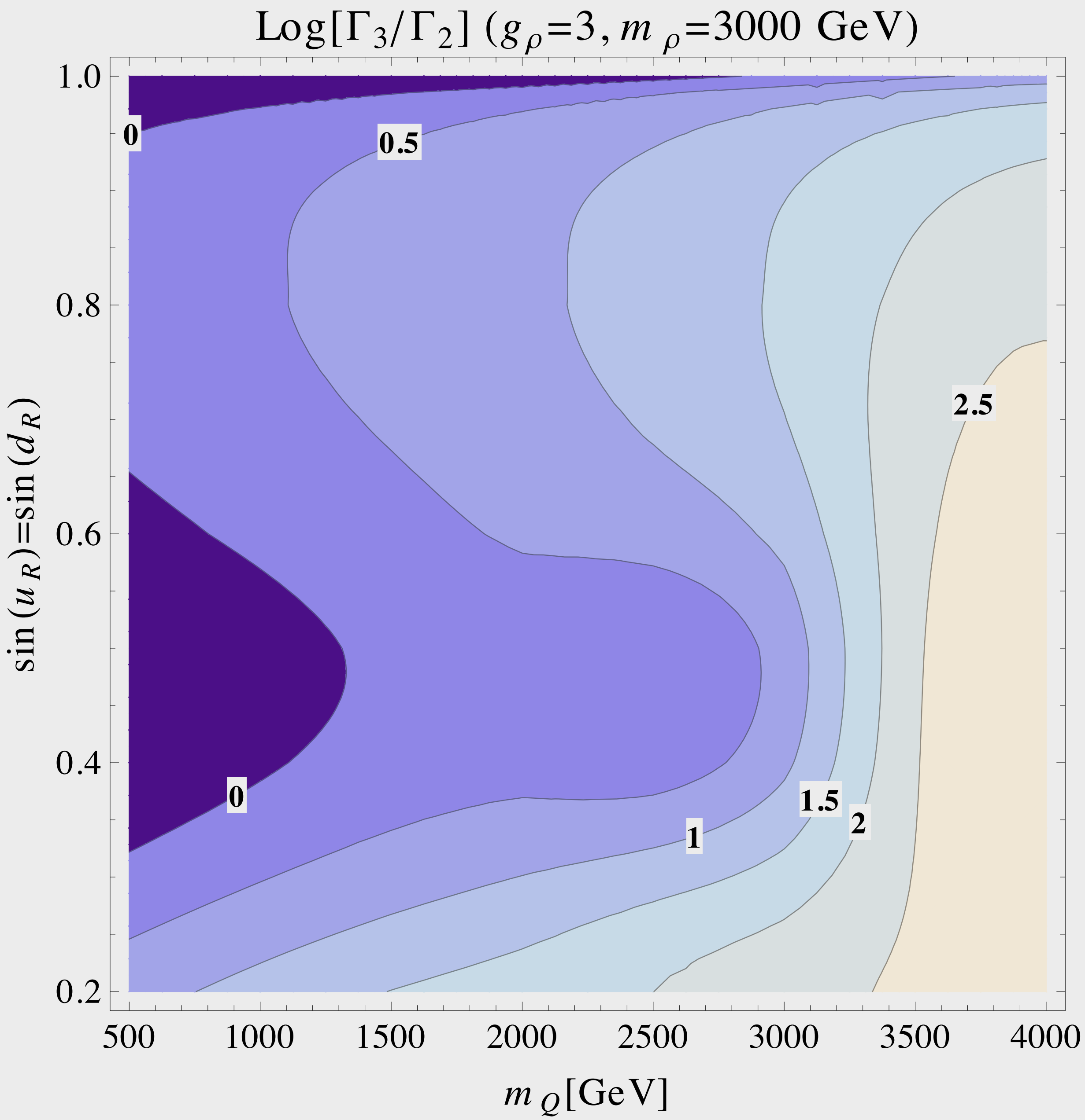
Conclusions

- Three main options after Higgs discovery: 1) SM 2) SUSY 3) Composite pGB Higgs
- In the next years, naturalness is on trial: stops or fermionic top partners?
- Flavor trivial composite Higgs is very visible, survives EWPT with large compositeness: expect discovery/exclusion by LHC14

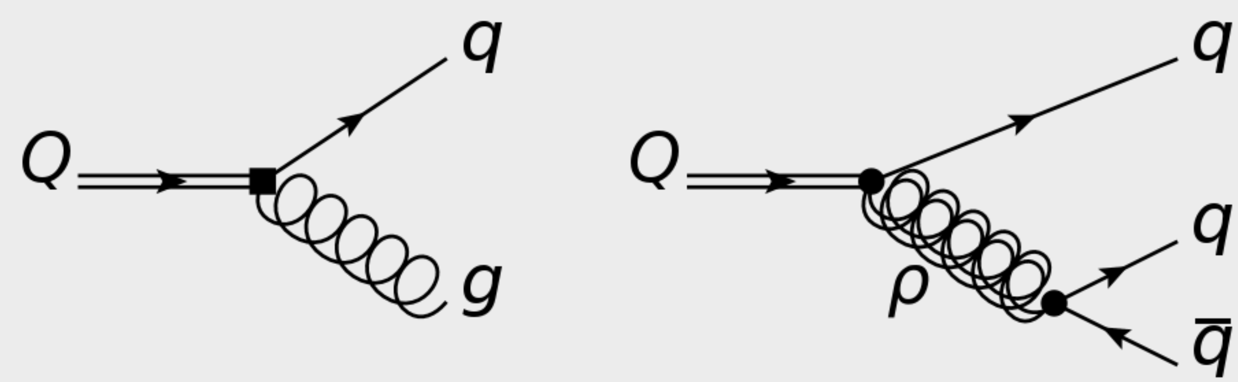
Outlook



G. Rolandi, private comm.

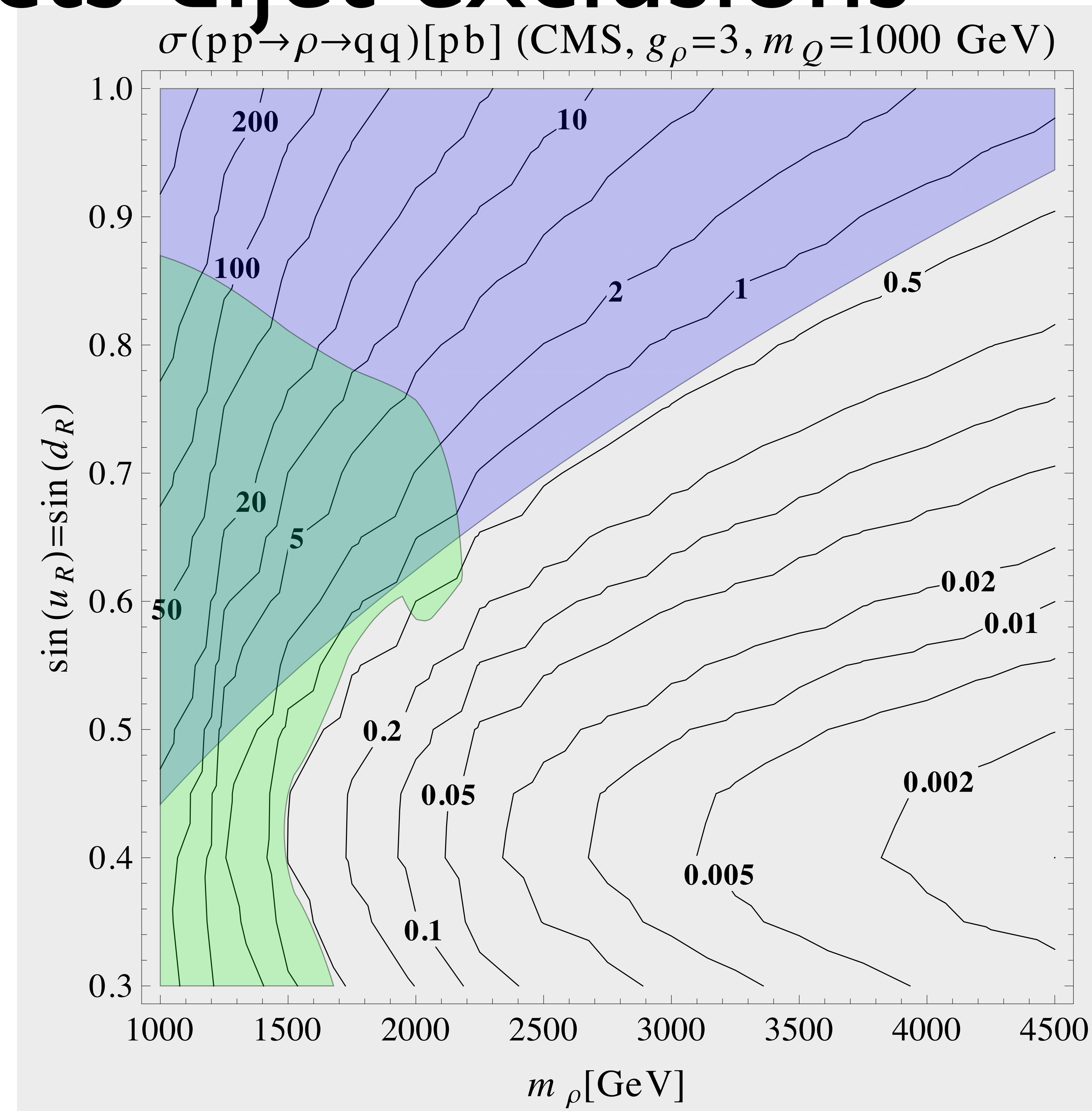


Heavy Fermion Decay Modes



- Three body decay dominant almost everywhere
- $\Gamma_2 > \Gamma_3$ only in small region of low m_Q

Light Fermionic Partners affects dijet exclusions



Flavor transparent strong sector

w/ Michele Redi

arxiv:1106.6357[hep-ph]

See also:

Rattazzi-Zaffaroni '01

Cacciapaglia, Csaki, Galloway, Marandella, Terning, AW. '07

Barbieri, Isidori, Pappadopulo '08

Delaunay, Gedalia, Lee, Perez, Ponton '11

Rattazzi-Zaffaroni Model:

JHEP 0104 (2001) 021

$$SU(3)_L \otimes SU(3)_u \otimes SU(3)_d$$

$q_L = (3, 1, 1)$ $\quad$ $u_R = (1, 3, 1)$ $\quad$ $d_R = (1, 1, 3)$

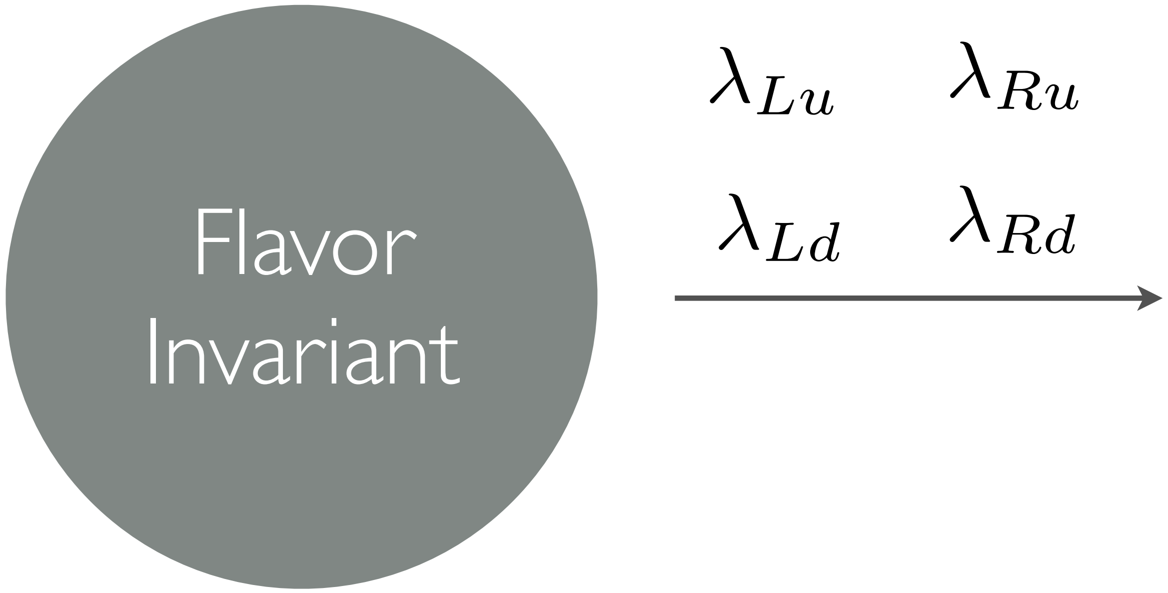
MFV realized if flavor symmetry is broken by two bifundamentals:

$Y_u = (3, \bar{3}, 1)$ $\quad$ $Y_d = (3, 1, \bar{3})$

All quarks are composite, severe constraint:

$$m_\rho > 5 g_\rho \, \mathrm{TeV}$$

Composite sector is trivial w.r.t flavor

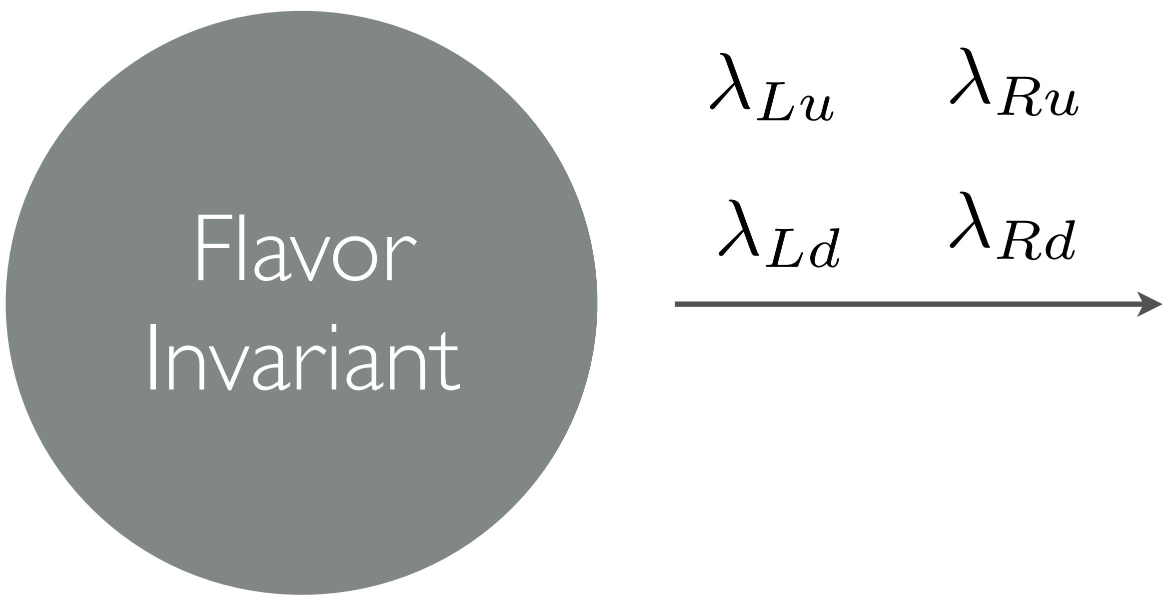


All flavor violation comes from the external mixings.

$$y_u \propto \lambda_{Lu}\lambda_{Ru}$$

$$y_d \propto \lambda_{Ld}\lambda_{Rd}$$

Composite sector is trivial w.r.t flavor



All flavor violation comes from the external mixings.

$$y_u \propto \lambda_{Lu}\lambda_{Ru}$$

$$y_d \propto \lambda_{Ld}\lambda_{Rd}$$

Simple realization of Minimal Flavor Violation:

mixings ~ SM Yukawas

- Left-handed compositeness:

$$\lambda_{Lu} \propto Id\,, \qquad \lambda_{Ld} \propto Id$$
$$\lambda_{Ru} \propto y_u\,, \qquad \lambda_{Rd} \propto y_d$$

$$+ \qquad SU(3)_F$$
$$L_U\,, L_D\,, U\,, D \in 3_F$$

- Right-handed compositeness:

$$\lambda_{Lu} \propto y_u\,, \qquad \lambda_{Ld} \propto y_d$$
$$\lambda_{Ru} \propto Id\,, \qquad \lambda_{Rd} \propto Id$$

$$+ \qquad SU(3)_U \otimes SU(3)_D$$
$$L_U\,, U \in (3,1) \qquad L_D\,, D \in (1,3)$$

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$$+ \qquad \begin{array}{c} SU(3)_U \otimes SU(3)_D \\ L_U\,, U \in (3,1) \quad L_D\,, D \in (1,3) \end{array}$$

MFV $\longrightarrow$ Mixing of one chirality of light quarks is large.

Flavor bounds are automatically satisfied.
No EDMs are generated to leading order.

LEP bounds,

$$R_b = \frac{\Gamma(Z \to b\bar{b})}{\Gamma(Z \to q\bar{q})} = .21629 \pm .00066$$

$$R_h = \frac{\Gamma(Z \to q\bar{q})}{\Gamma(Z \to \mu\bar{\mu})} = 20.767 \pm .025$$

Modified couplings strongly constrained

$$\frac{\delta R_h}{R_h} \approx .57\frac{\delta g_{Lu}}{g_{Lu}} + .11\frac{\delta g_{Ru}}{g_{Ru}} + 1.28\frac{\delta g_{Ld}}{g_{Ld}} + .04\frac{\delta g_{Rd}}{g_{Rd}}$$

$$\frac{\delta g_{Lu}}{g_{Lu}} < .002 \qquad \frac{\delta g_{Ru}}{g_{Ru}} < .01 \qquad \frac{\delta g_{Ld}}{g_{Ld}} < .001 \qquad \frac{\delta g_{Rd}}{g_{Rd}} < .02$$

Flavor bounds are automatically satisfied.
No EDMs are generated to leading order.

LEP bounds,

$$R_b = \frac{\Gamma(Z \to b\bar{b})}{\Gamma(Z \to q\bar{q})} = .21629 \pm .00066$$

$$R_h = \frac{\Gamma(Z \to q\bar{q})}{\Gamma(Z \to \mu\bar{\mu})} = 20.767 \pm .025$$

Modified couplings strongly constrained

$$\frac{\delta R_h}{R_h} \approx .57 \frac{\delta g_{Lu}}{g_{Lu}} + .11 \frac{\delta g_{Ru}}{g_{Ru}} + 1.28 \frac{\delta g_{Ld}}{g_{Ld}} + .04 \frac{\delta g_{Rd}}{g_{Rd}}$$

$$\frac{\delta g_{Lu}}{g_{Lu}} < .002 \qquad \xcancel{\frac{\delta g_{Ru}}{g_{Ru}} < .01} \qquad \xcancel{\frac{\delta g_{Ld}}{g_{Ld}} < .001} \qquad \xcancel{\frac{\delta g_{Rd}}{g_{Rd}} < .02}$$

protected reps

Similar bound is found from unitarity of CKM

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 \approx 1 - .7\,\frac{\delta g_{Lu}}{g_{Lu}}$$

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = .9999 \pm .0012$$

LH COMPOSITENESS:

$$\delta g \sim \frac{Y^2 v^2}{2\, m_\rho^2} \sin\varphi_q^2$$

$$\frac{\delta g_{Lu}}{g_{Lu}} < .002 \xrightarrow{\quad m_t \quad} \sin\varphi_{t_R} \geq 35 \frac{m_t}{m_\rho}$$

Strongly constrained and only possible if tR is composite.

RH COMPOSITENESS:

No bounds from LEP!

Main constraint from recent di-jet searches,

$$\mathcal{L}_{4-Fermi} = \frac{2\pi}{\Lambda^2}\left(\bar{q}_L \gamma^\mu q_L\right)^2$$

LHC: $\Lambda > 6\,\mathrm{TeV}$

$$\frac{g_\rho^2}{4\,m_\rho^2}\sin^4\varphi_{q_R}\left(\bar{q}^i_{R\alpha}\gamma^\mu q^i_{R\beta}\bar{q}^j_{R\beta}\gamma_\mu q^j_{R\alpha}\right) \xrightarrow{\text{COMPOSITENESS}} \sin^2\varphi_{q_R} \leq \frac{2}{g_\rho}\left(\frac{m_\rho}{3\,\mathrm{TeV}}\right)$$

Large or full compositeness is still allowed with $m_\rho = 3\ \mathrm{TeV}$

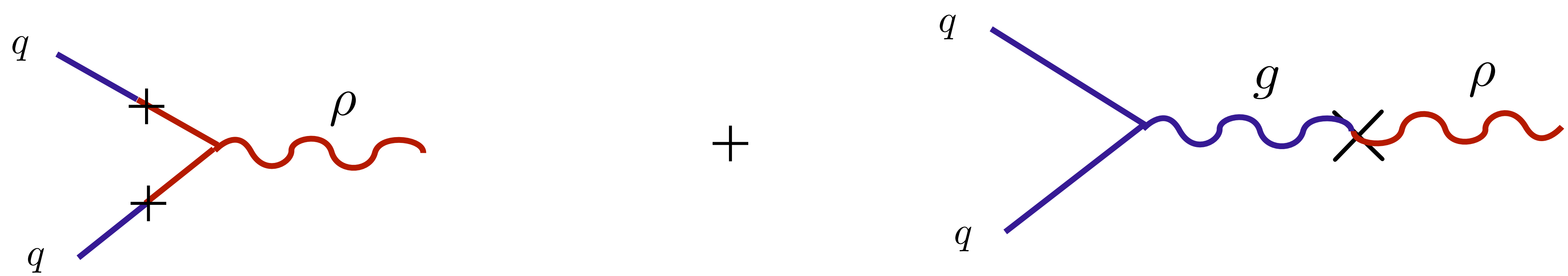
If RH quarks are fully composite: MFV follows automatically from the flavor symmetry.

(Only two possible mixings with strong sector).

LHC phenomenology

1) Proton is 1/2 composite!
2) Decay patter˙n change

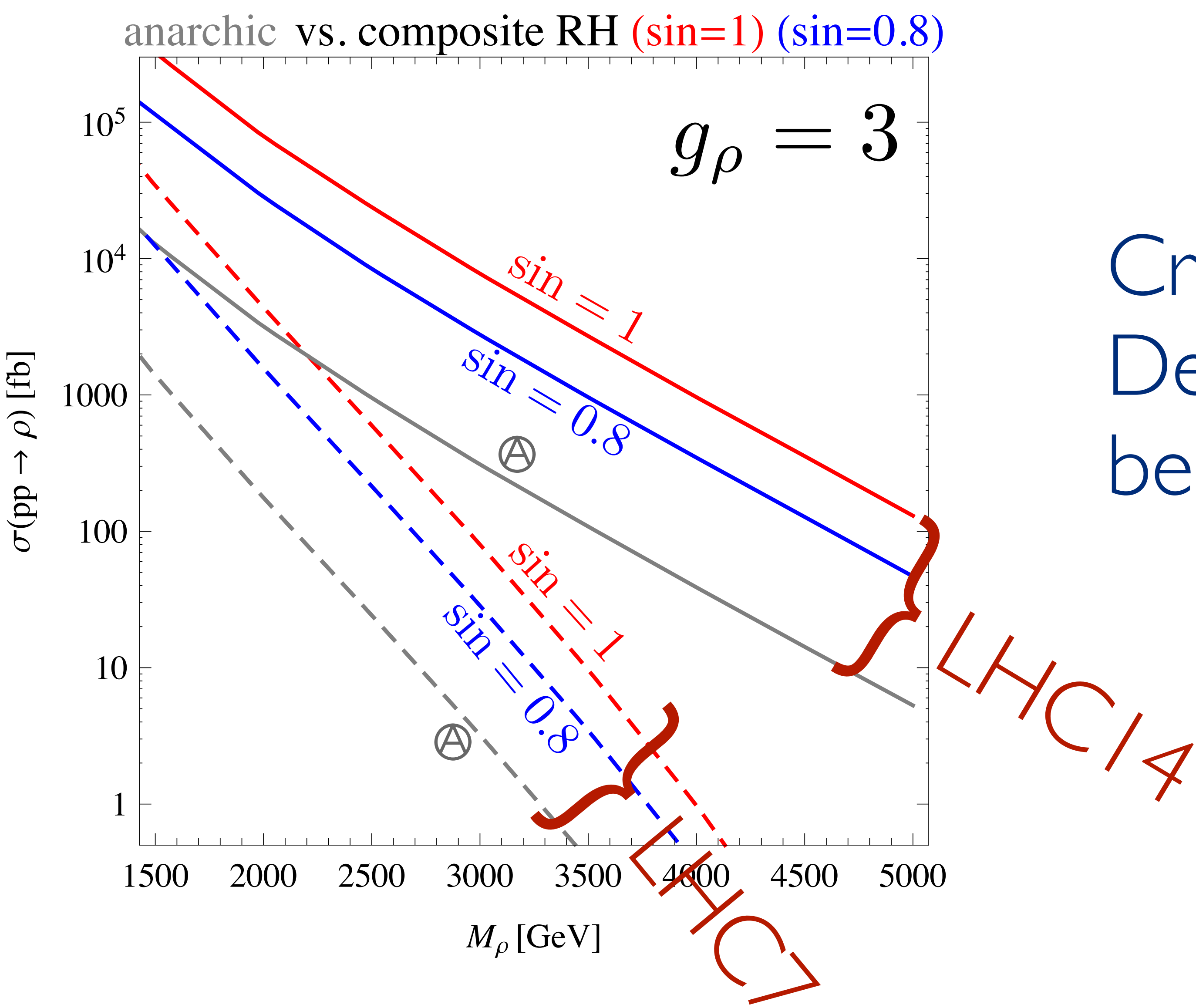
Spin-1: gluon, electro-weak, flavor resonances



$$g_{\rho\bar{q}q} = g(\sin^2\varphi\cot\theta - \cos^2\varphi\tan\theta)$$

First term easily dominates for RH compositeness.

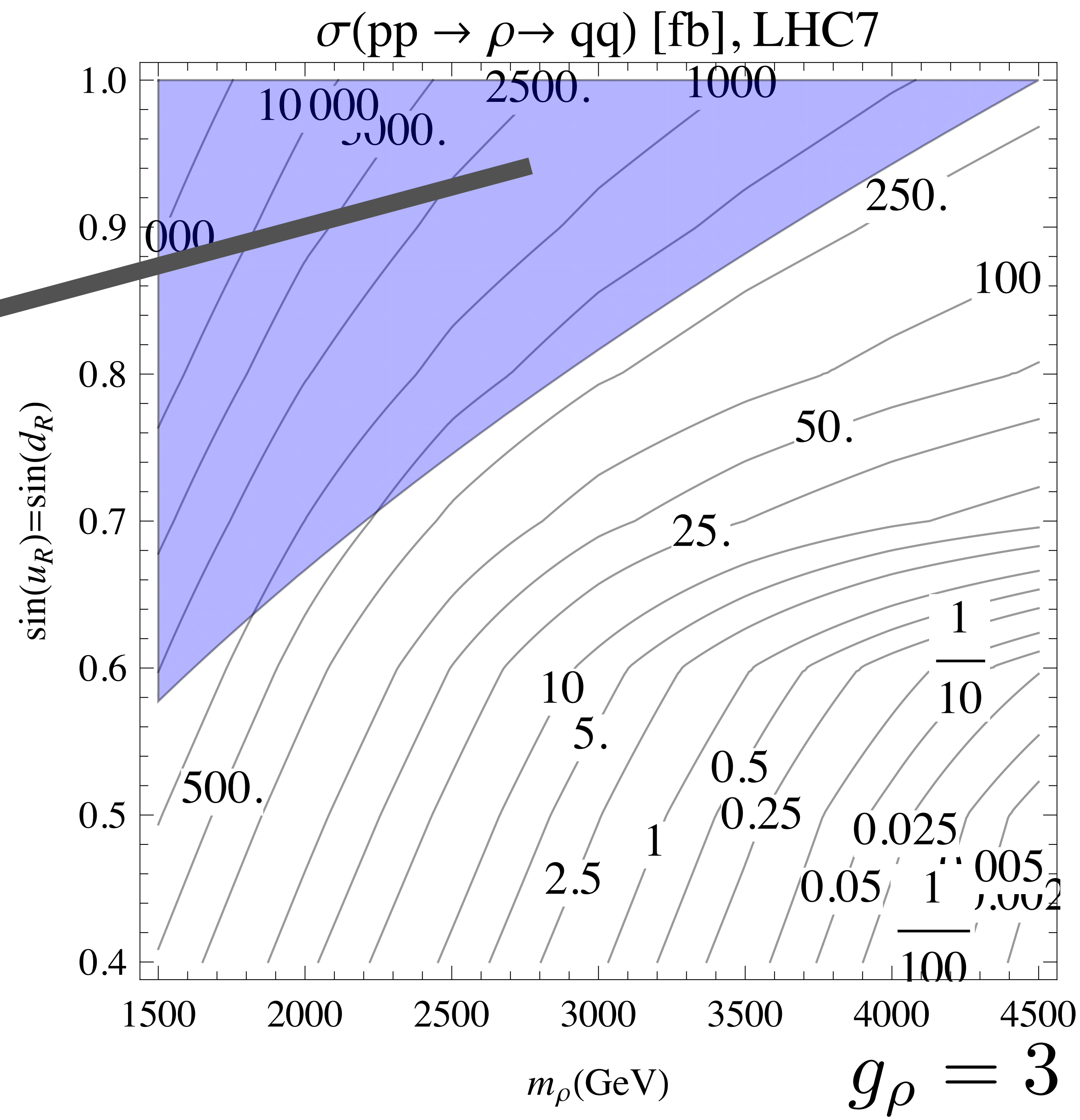
Gluon resonances:



Cross-sections > O(10) larger.
Decay into light generation can be important.

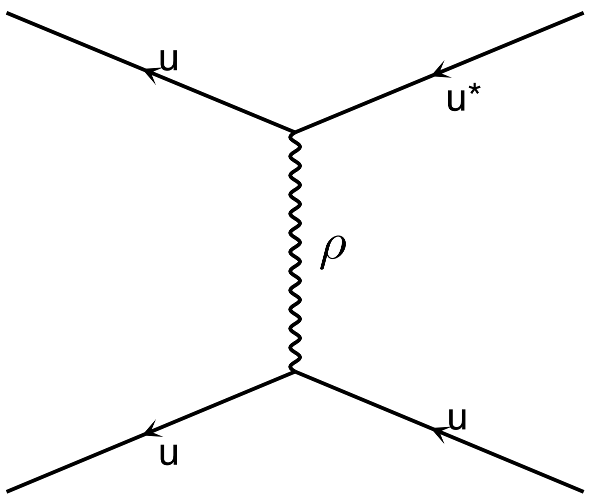
LHC7 bounds already relevant:

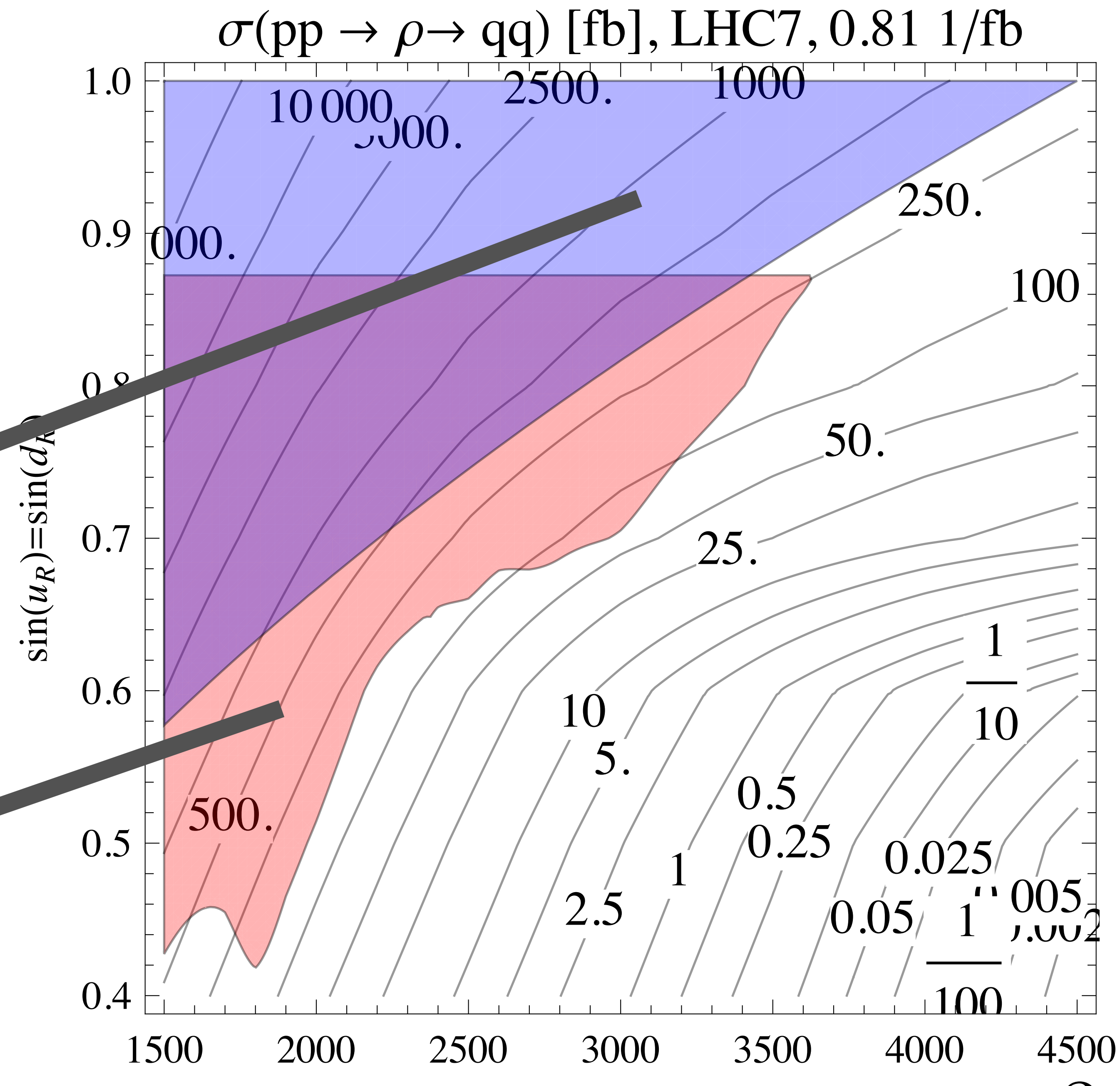
Di-jet bounds 35/pb
Compositeness



$g_\rho = 3$

LHC7 bounds already relevant:





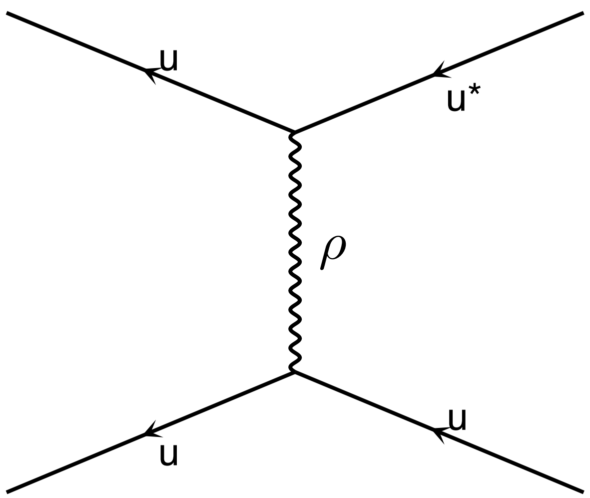
$g_\rho = 3$

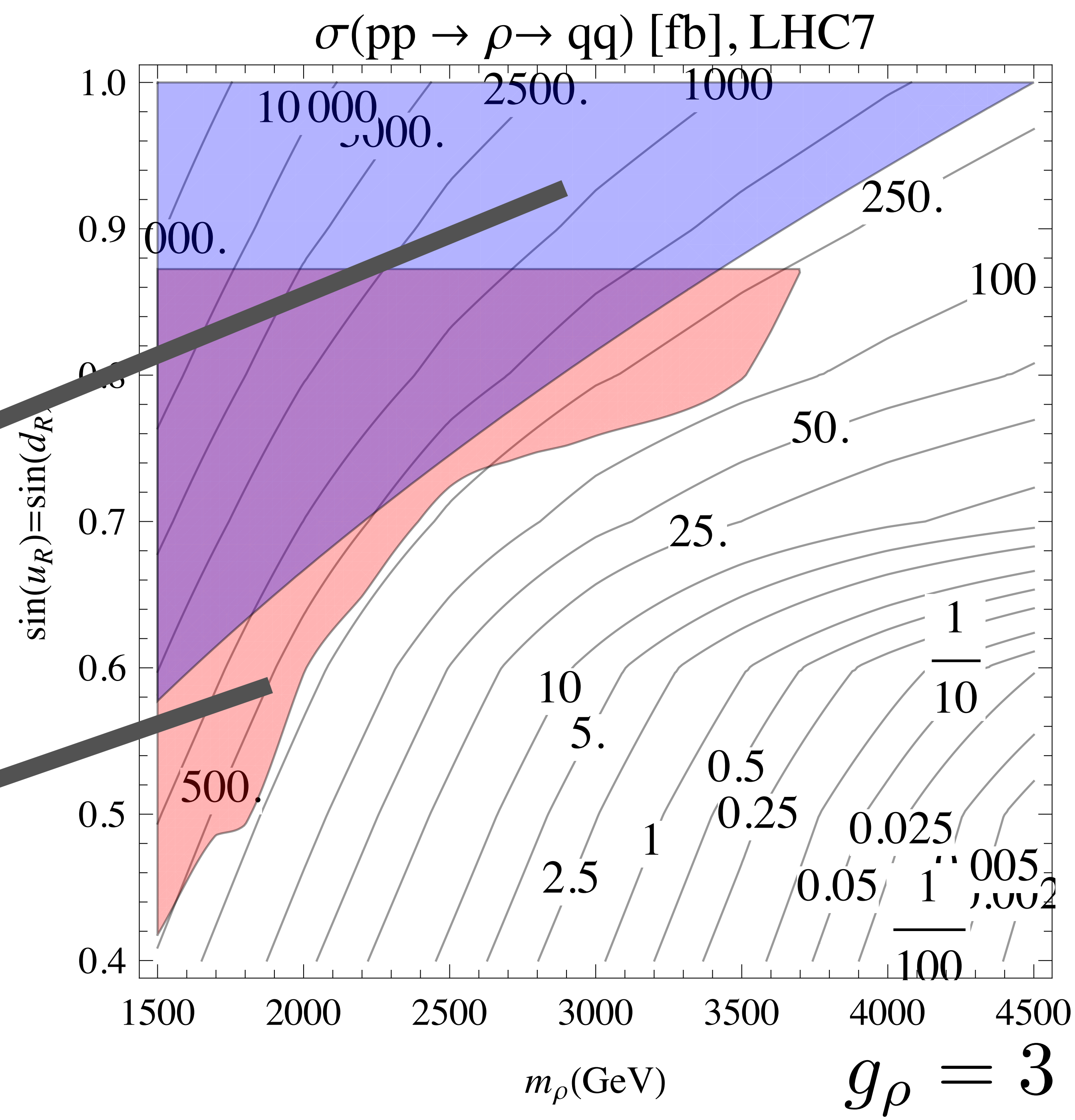
Di-jet bounds 35/pb
compositeness

Atlas-Conf-2011-081
Bump search 810/pb

Expected signals in di-jet.

LHC7 bounds already relevant:

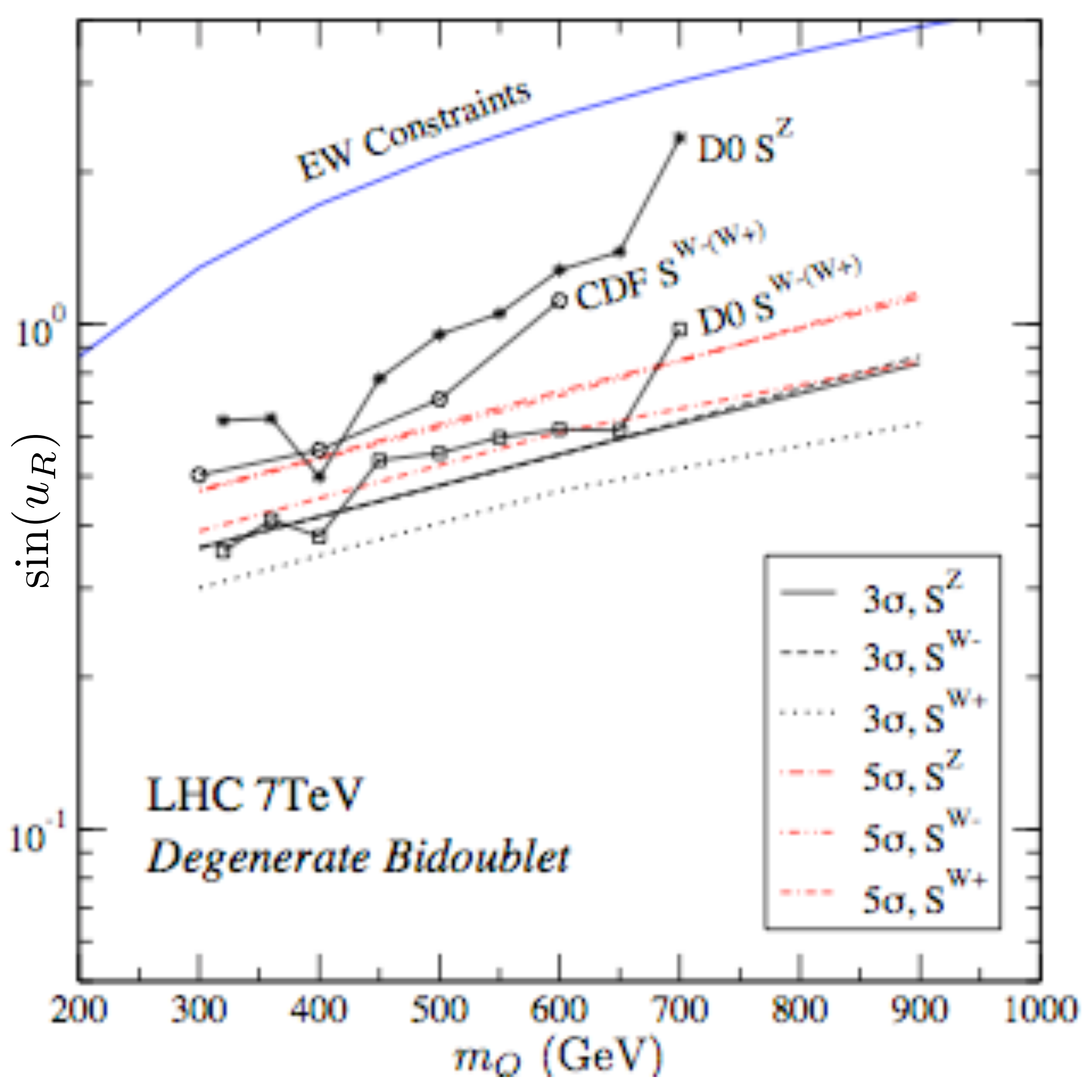


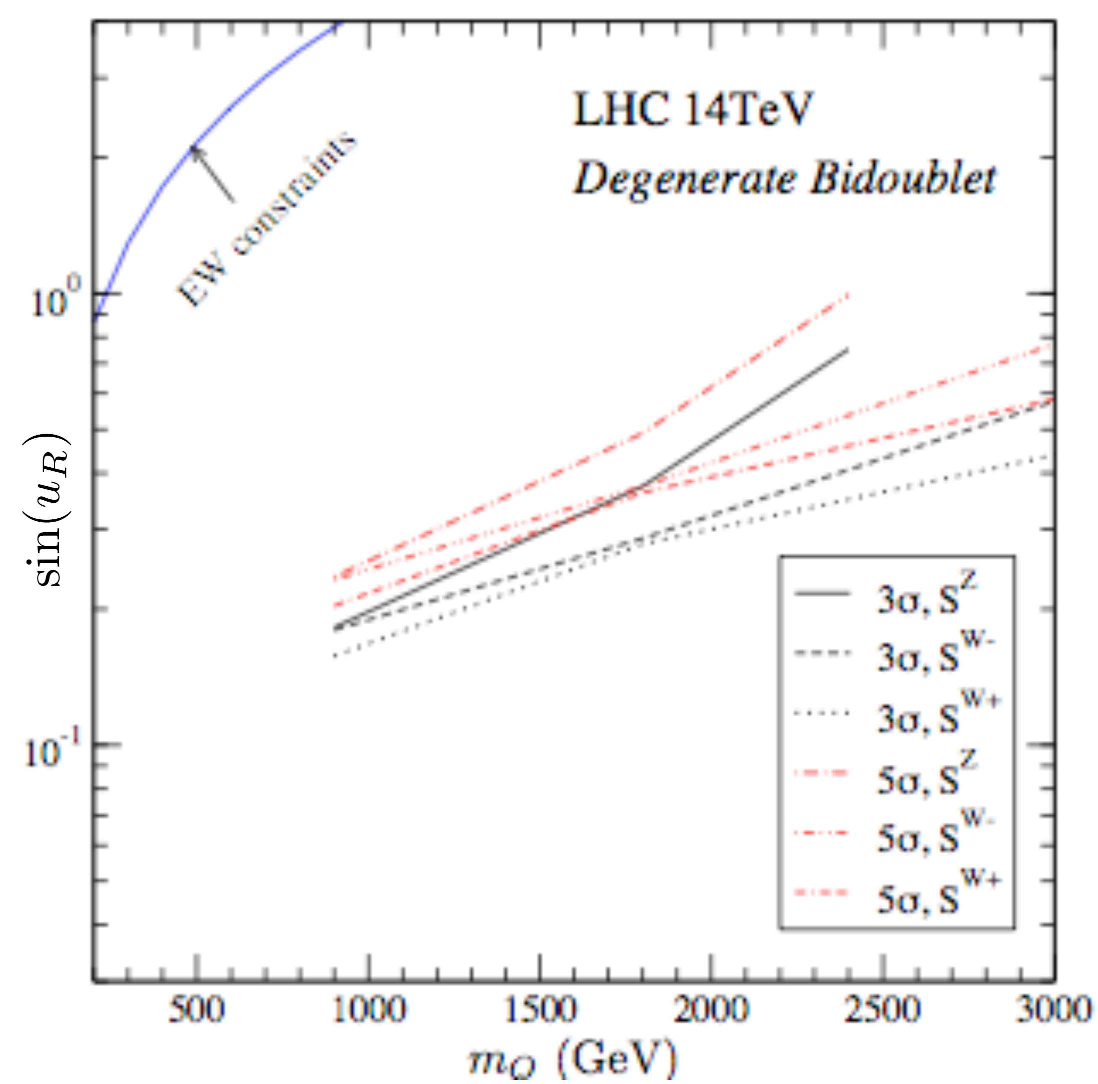


Di-jet bounds 35/pb

CMS-EXO-11-015
1/fb

Expected signals in di-jet.

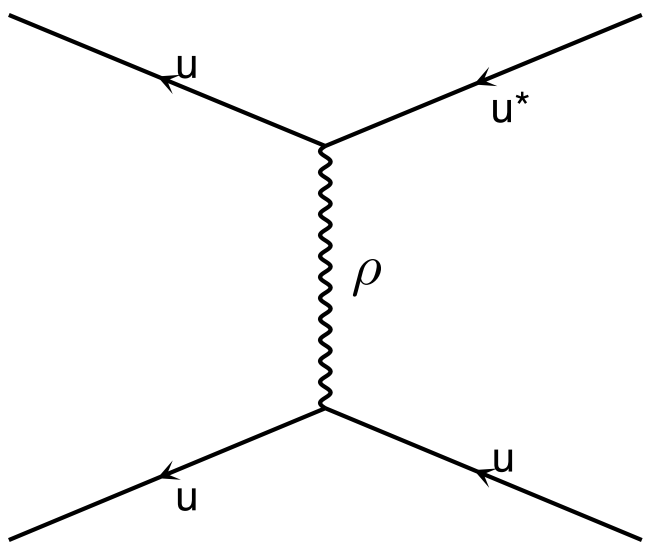


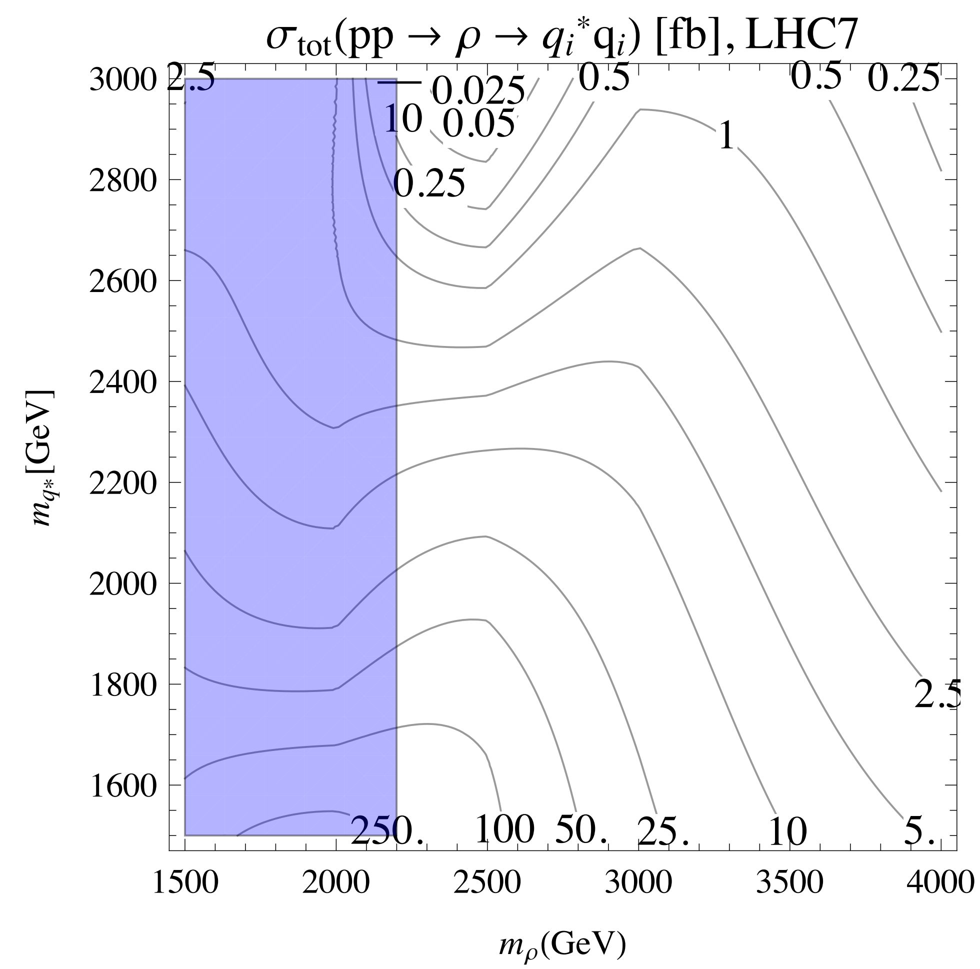


Atre, Azuelos, Carena, Han,
Ozcan, Santiago, Unel '11

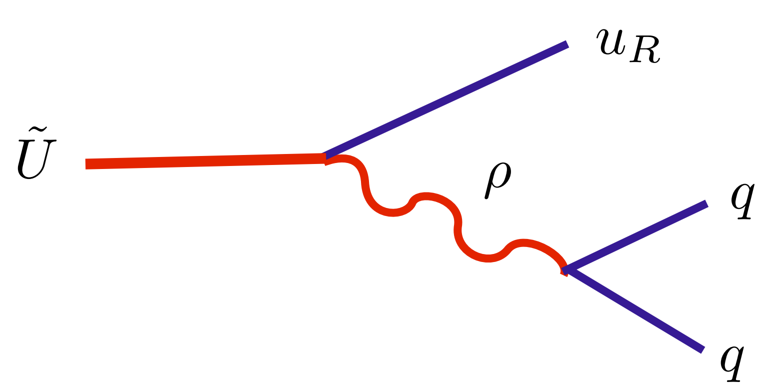
LHC searches could probe fermions up to 1 TeV.
LHC14 will either discover or exclude the model.

Right quark partners produced by resonance exchange.





$$g_\rho = 3\,, \sin\varphi_{u_R} = .7\,, \sin\varphi_{d_R} = 1/6$$



MR, Sanz, Weiler, in progress

3-4 jet final states.