BeyondtheStandardModel Theory

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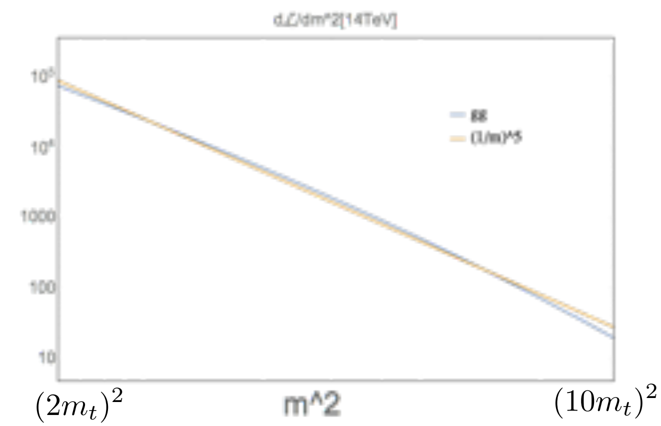
2nd ECFA HL-LHC Workshop

Rationale: high luminosity search strategy, general principle

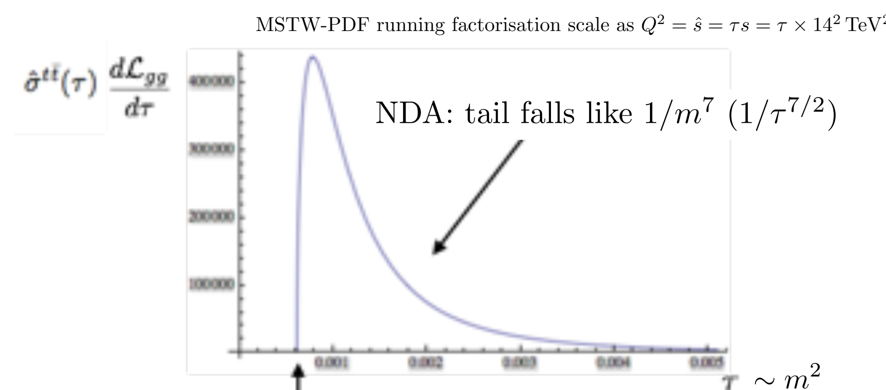
(i) Luminosity functions

are rapidly falling (ex. top phys.):



(ii) Luminosity functions x cross section

fall even faster:



$$\text{Thus, mass reach} \propto (\text{Lumi})^{\frac{1}{7}}$$

See for ex.: Salam-Weiler, http://collider-reach.web.cern.ch/collider-reach/

High luminosity search strategy, general principle

$$\text{mass reach} \propto (\text{Lumi})^{\frac{1}{7}}$$

♦ Slow progress in energy frontier, still conventional searches should push forward. (will be done in any case regardless of what we discuss today…)

More info' e.g: Salam-Weiler, http://collider-reach.web.cern.ch/collider-reach/

$$\text{mass reach} \propto (\text{Lumi})^{1,\frac{1}{2}} \ ?$$

♦ Faster progress in "elusive frontier", not too hard physics scale, relatively weak coupling.

Is it possible to characterise the elusive frontier?

Elusive/weakly coupled/exotic physics

Naturalness

Exotica

what should be our focus?

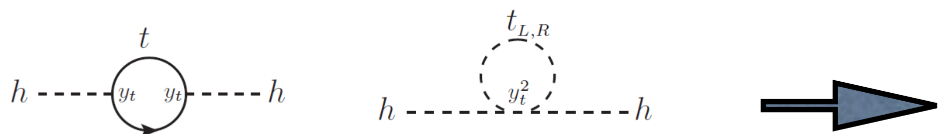
Naturalness, simple motivated concept, learning even if no result

Exotica, signal based (harder to make sys' progress)

Totally subjective & should be view as case study, yet conclusions => quite general

Naturalness => vague scale & states => LHC perspective

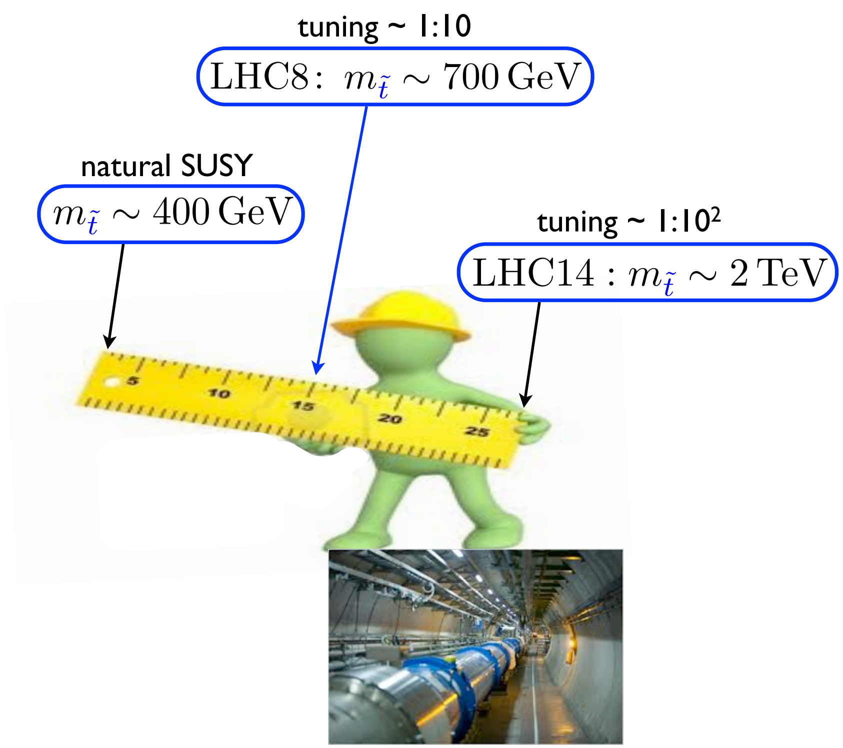
Screening away UV sensitivity => top partners, potentially within the LHC reach.



$$\frac{\delta m_h^2}{m_h^2} \sim \left(\frac{\tilde{m}_t}{400\,\mathrm{GeV}}\right)^2$$

The LHC naturalness ruler:

(~ half way through)



Naturalness & the two top frontiers

tuning ~ 1:10

$\mathrm{LHC8}: \ m_{\tilde{t}} \sim 700\,\mathrm{GeV}$

Elusive regime

Boosted regime

natural SUSY

$m_{\tilde{t}} \sim 400\,\mathrm{GeV}$

tuning ~ 1:10^2

$\mathrm{LHC14}: m_{\tilde{t}} \sim 2\,\mathrm{TeV}$

Shifting fronts, possible status in 3 yrs (lots left behind)

tuning ~ 1:20

$\mathrm{LHC14(100/fb)}: \ m_{\tilde{t}} \sim 1.4$

Elusive regime

Boosted regime

natural SUSY

$m_{\tilde{t}} \sim 400\,\mathrm{GeV}$

tuning ~ 1:10²

$\mathrm{LHC14}: m_{\tilde{t}} \sim 2\,\mathrm{TeV}$

Outline (subjectively focusing on top/top-partner phys.)

- Case #1 pair differential distributions, graduating from bump searches.

- Case #2 elusive naturalness, flavorful naturalness, the top-charm frontier.

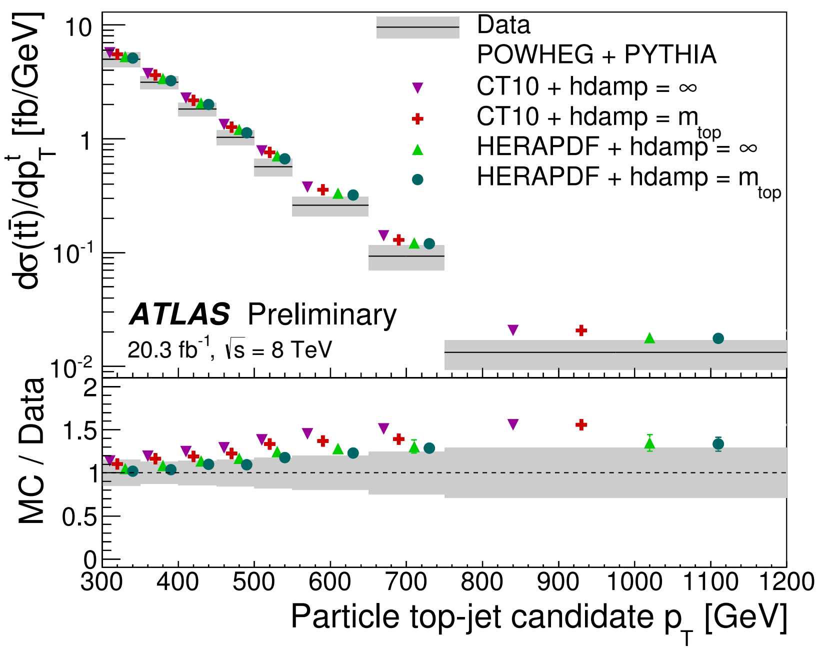
- Case #3 top flavor violation, natural composite H & $t \to cZ/h$. (if time permits)

- Summary.

Case 1: $t\bar{t}$ distributions & TeV new physics (NP)

- Briefly on the state of the art,2 interesting recent measurements:

ATLAS-CONF-2014-057



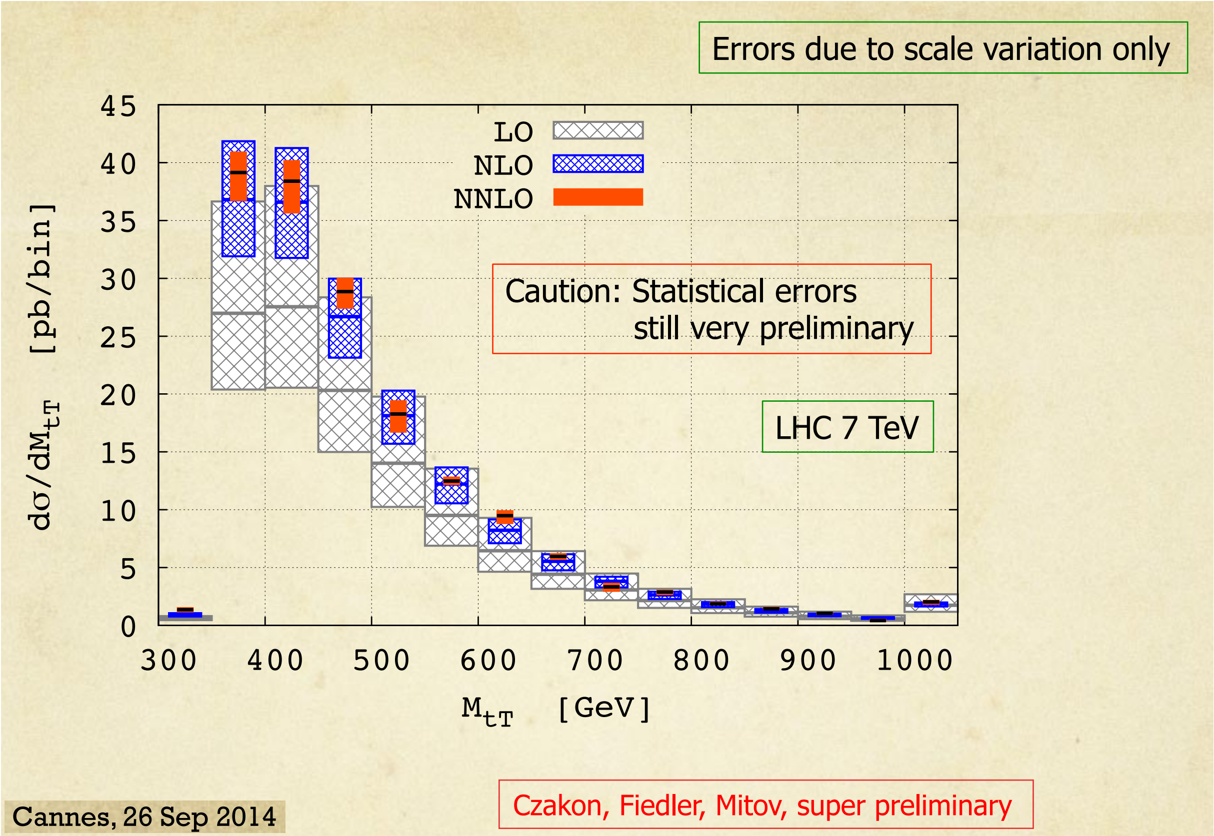
(a) Detector to Particle

CMS 1309.2030

$$\mathcal{S} = \frac{\int_{m_{t\bar{t}}>1\,\mathrm{TeV}/c^2} \frac{d\sigma_{SM+NP}}{dm_{t\bar{t}}} dm_{t\bar{t}}}{\int_{m_{t\bar{t}}>1\,\mathrm{TeV}/c^2} \frac{d\sigma_{SM}}{dm_{t\bar{t}}} dm_{t\bar{t}}} < 1.2 \text{ (95\% CL)}$$

see also talk by Glover.

SM expectation (courtesy of informal communication with Alex Mitov)

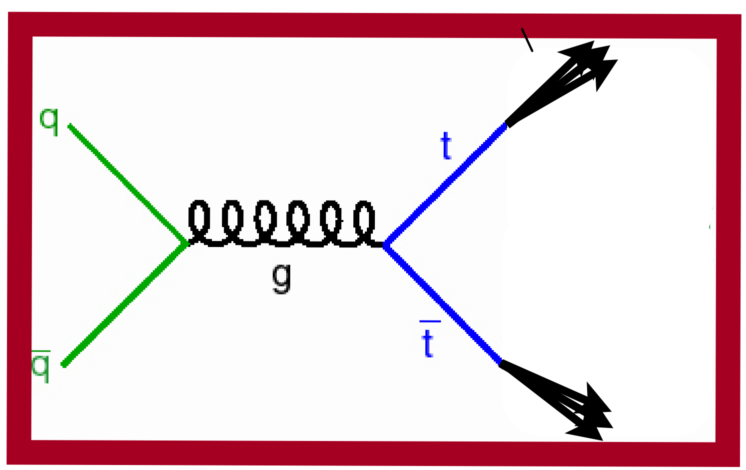


"Statistical integration errors are still too large … we have a bin for M_tT>1TeV at LHC7TeV … totally preliminary: similar to NLO, scale +pdf is no more than 30%"

This, not including errors related to boosted techniques and/or pileup mitigation.

talk by Wells.

Case 1a: trivial weakly coupled broad resonance
&
Ex.: RS/composite resonance (KK gluon)



RS/composite H <=> strong dynamics => broad but weakly produced

Original models had relatively narrow KK's:

$$\frac{g_{\rm RS}^{q\bar{q},l\bar{l}\,G^1}}{g_{\rm SM}} \simeq \xi^{-1} \approx \frac{1}{5}\,, \quad \frac{g_{\rm RS}^{Q3\bar{Q}3G^1}}{g_{\rm SM}} \approx 1\,,$$

$$\frac{g_{\rm RS}^{t_R\bar{t}_R G^1}}{g_{\rm SM}} \simeq \xi \approx 5\,, \quad \frac{g_{\rm RS}^{GGG^1}}{g_{\rm SM}} \approx 0\,, \qquad (1)$$

Agashe, Belyaev, Krupovnickas, GP & Virzi (06); Lillie, Randall & Wang (07).

"KK gluon above 1 TeV has width of MKKG/6"

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"KK gluon above 1 TeV has width of MKKG/6"

Maybe later (depends on time) implicit motivate: (and regardless of motivation …)

$$\frac{g_{\rm RS}^{q\bar q, l\bar l G^1}}{g_{\rm SM}} \simeq 0 \quad , \quad \frac{g_{\rm RS}^{Q3\bar Q3 G^1}}{g_{\rm SM}} \approx \xi \approx 5$$
$$\frac{g_{\rm RS}^{t_R \bar t_R G^1}}{g_{\rm SM}} \simeq \xi \approx 5\,, \quad \frac{g_{\rm RS}^{GGG^1}}{g_{\rm SM}} \approx 0\,,$$

$$\Rightarrow \quad \frac{\Gamma}{M_{\rm KKG}} \sim 50\%!$$

$$\sigma^{14{\rm TeV}}_{2{\rm TeV,\,KKG}} \ll \sigma^{14{\rm TeV}}_{2{\rm TeV,\,SM}\,t\bar t}$$

Case 1b against top-pair resonance searches
&
The “elusive” KK Gluon

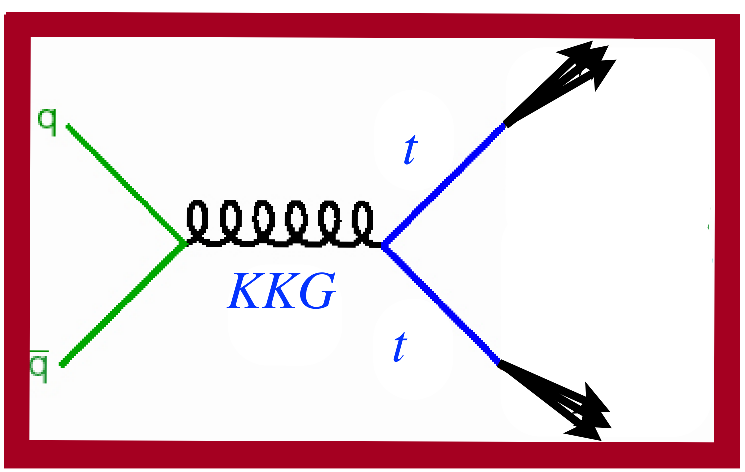
Chala, Juknevich, GP & Santiago, to appear.

Do we search for the right thing?

- The KK gluon is part of the composite sector, it decays to the most composite object allowed by kinematics (t, T).

- S parameter: $m_{KKG} > 3$ TeV; naturalness: $m_T < 1$ TeV.

- Searches: $m_{KKG} > 2.5$ TeV; $m_T > 800$ GeV.



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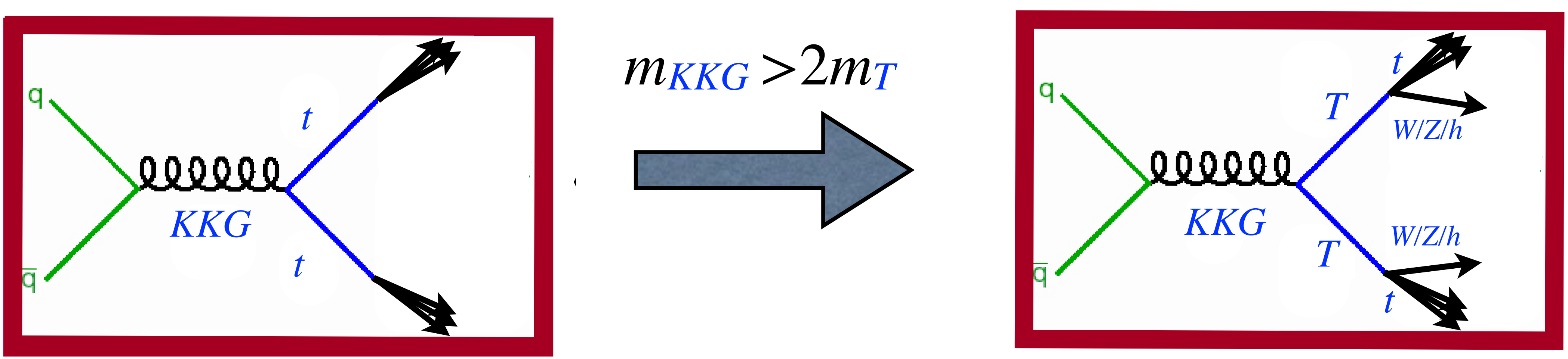
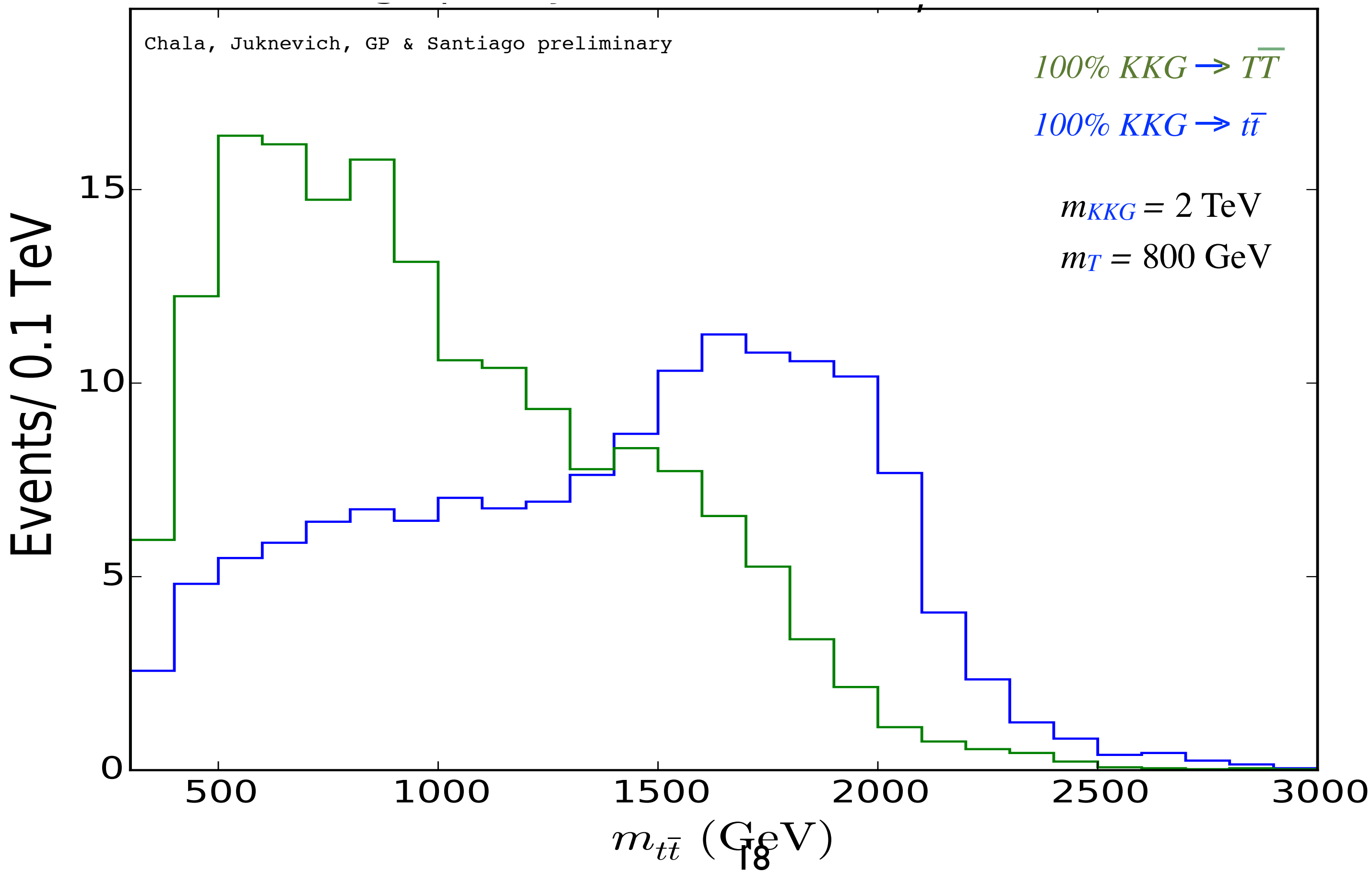


Implications for $KKG \to T\bar{T}$ decay

Chala, Juknevich, GP & Santiago, to appear.

- As T decays to t + $W/Z/h$ but we search only for tops => observed spectrum becomes softer, let us see it in steps:

top pair reconstructed invariant mass (ATLAS reconstruction, ATLAS-CONF-2013-052)



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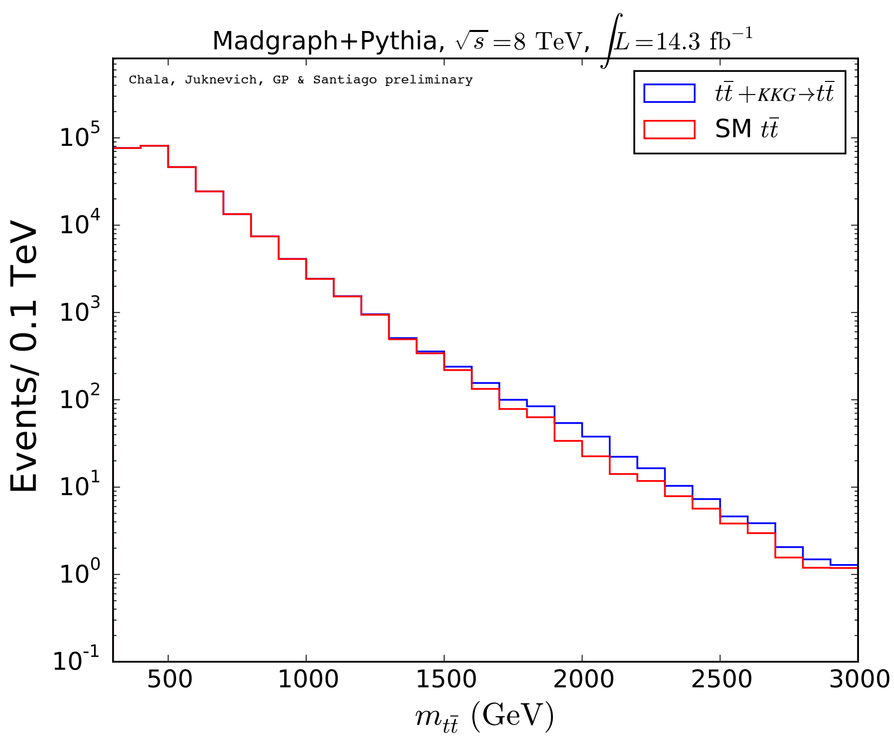
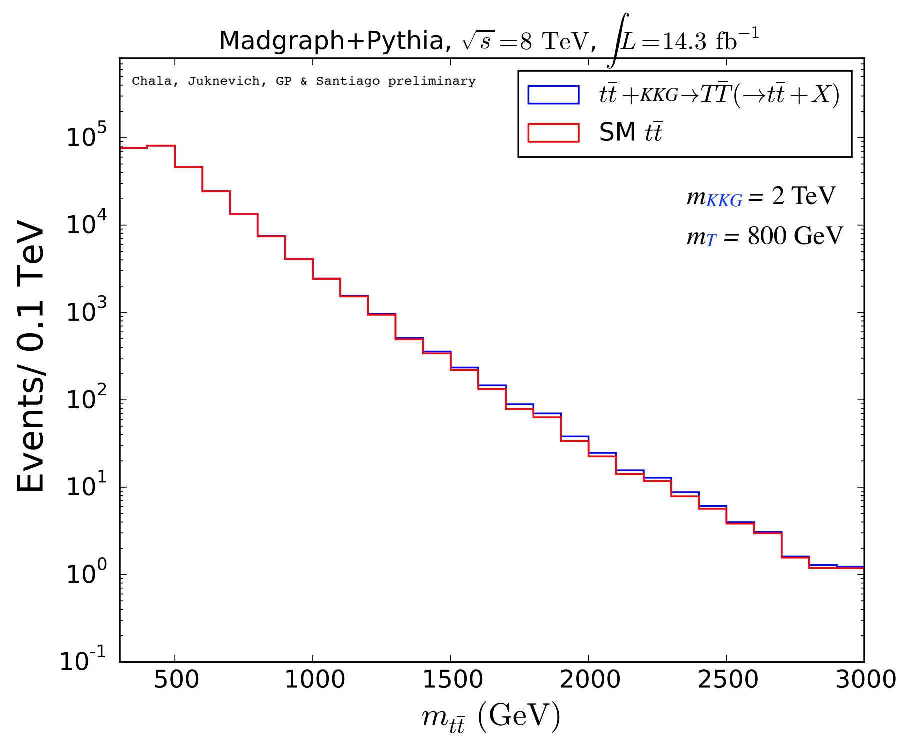
adding SM top pair reconstructed invariant mass

Elusive KKG

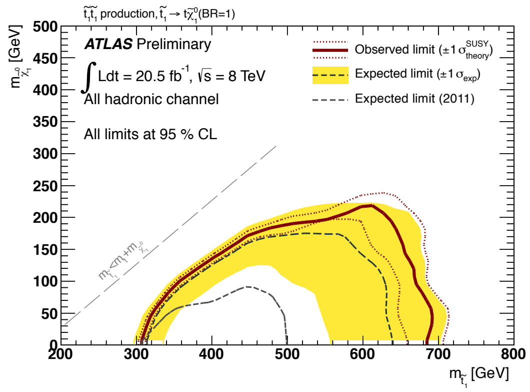




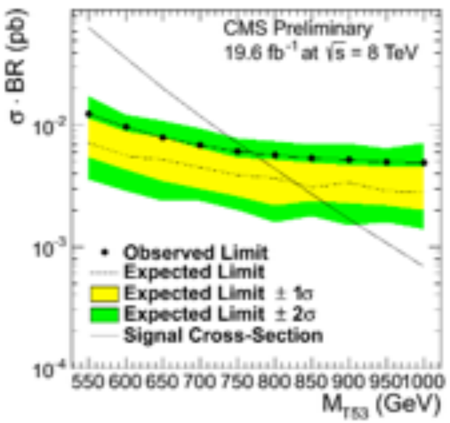
Case 2: Elusive top-partners

Could the stops/t' still be light?

SUSY



composite Higgs



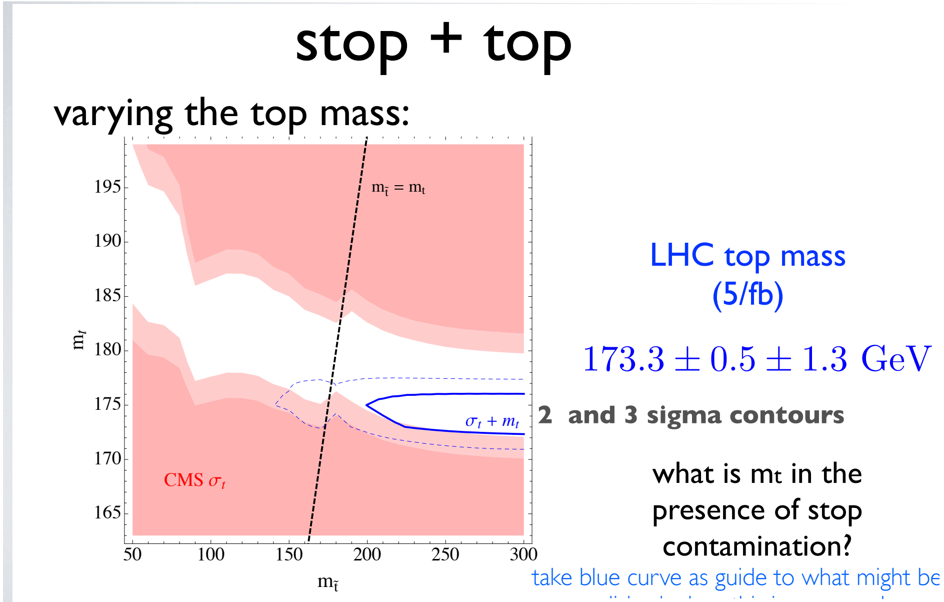
- Almost all approaches have implications to top phys.:

  (i) SUSY, get rid of missing energy in a systematic way:

  RPV, stealth, compressed …   (no time to review it all …)

Could the stops/t' still be light?

Mass & Xsection precision could be helpful:



Czakon, Mitov, Papucci, Ruderman & Weiler (14)

As well as differential distribution (angular), new result from ATLAS.

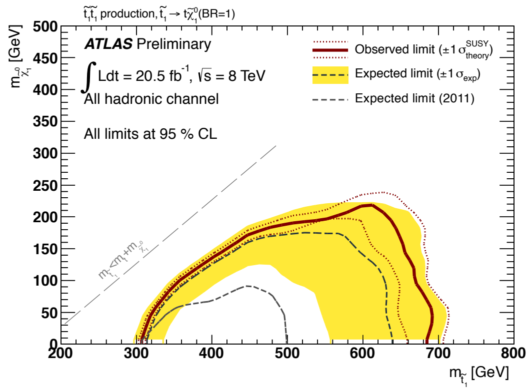
Han, Katz, Krohn and Reece; Belanger, Godbole, Hartgring and Niessen (12); Buckley, Plehn and Ramsey-Musolf (13); Li, Si, Wang, Wang, Zhang and Zhu; Mukhopadhyay, Nojiri and Yanagida (14).

More generically understanding top+jets & thinking about gluinos.

Evans, Kats, Shih and Strassler (13)

Could the stops/*t'* still be light?

SUSY



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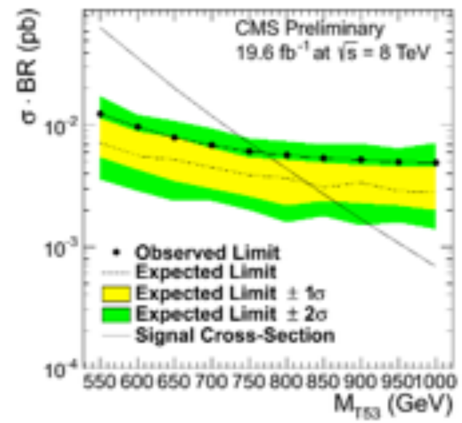


- Almost all approaches have implications to top phys.:

  (i) SUSY, get rid of missing energy in a systematic way:

  RPV, stealth, compressing the spectrum. (no time to review it all …)

  (ii) Get rid of tops in the final state => flavor & connection.

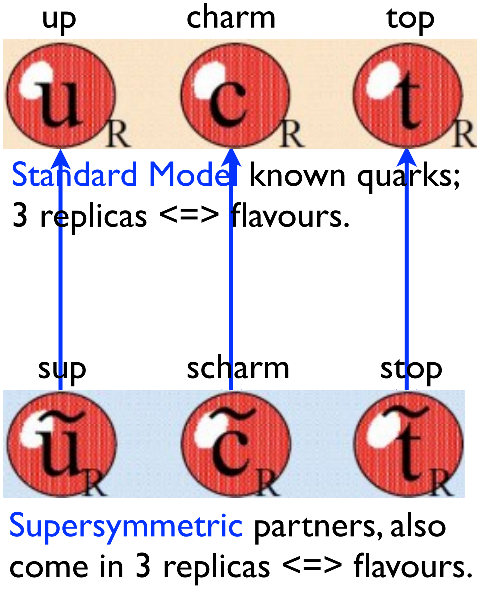
  Applies not only to SUSY.

Flavourful naturalness

- Standard model: 3 copies (flavours) of quarks; same holds for new physics. (say supersymmetry)

- "Hardwired" assumption: top partner (stop) is mass eigenstate.

  Dine, Leigh & Kagan, Phys.Rev. D48 (93); Dimopoulos & Giudice (95); Cohen, Kaplan & Nelson (96)



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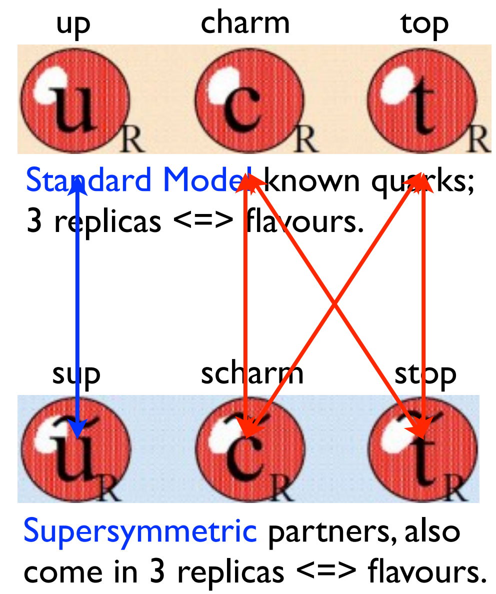
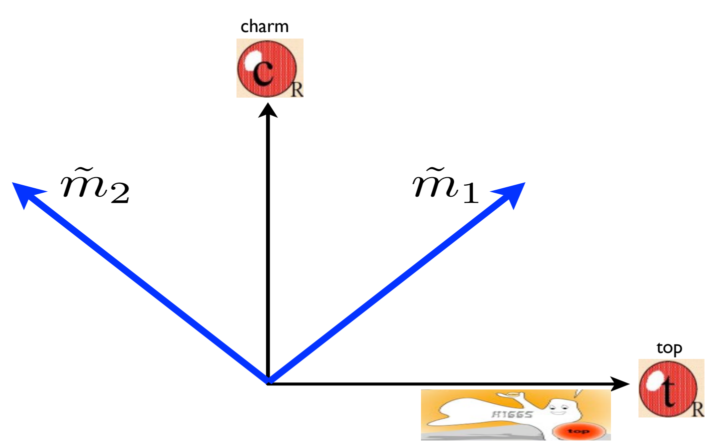


- This need not be the case, top-partner => “stop-scharm” admixture.



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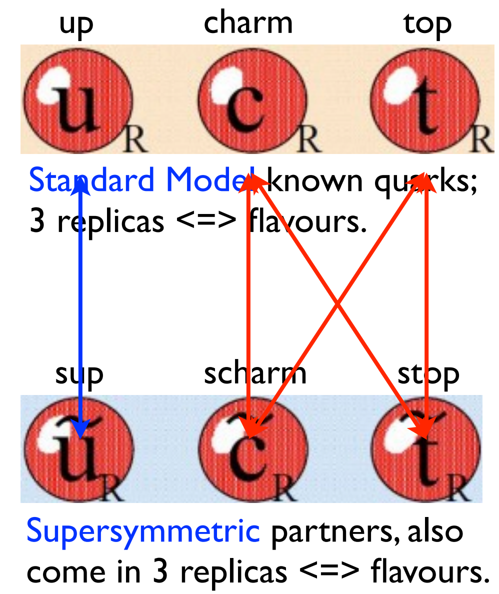

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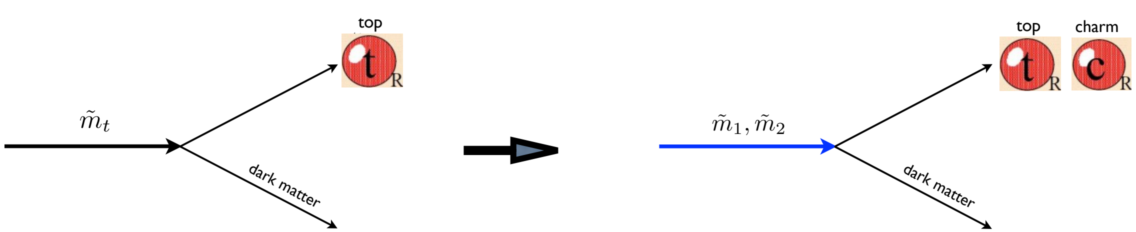

Flavorful naturalness, ameliorating stops bounds

- The relevant parameters to constrain are: Blanke, Giudice, Paride, GP & Zupan (13)

Define relative tuning measure: $\xi = \frac{\tilde{m}_1^2 c^2 + \tilde{m}_2^2 s^2}{m_0^2}$, $\quad (m_0 = 570\,\text{GeV})$

stop,scharm like squark mass, $m_{1,2}$ & $C \equiv \cos\theta_{23}^{RR}$

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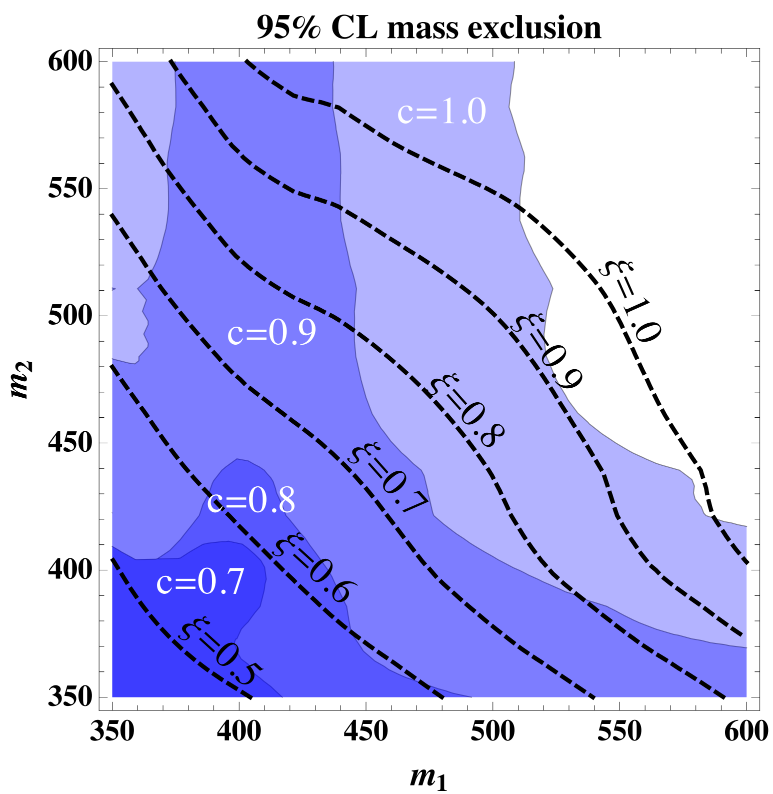
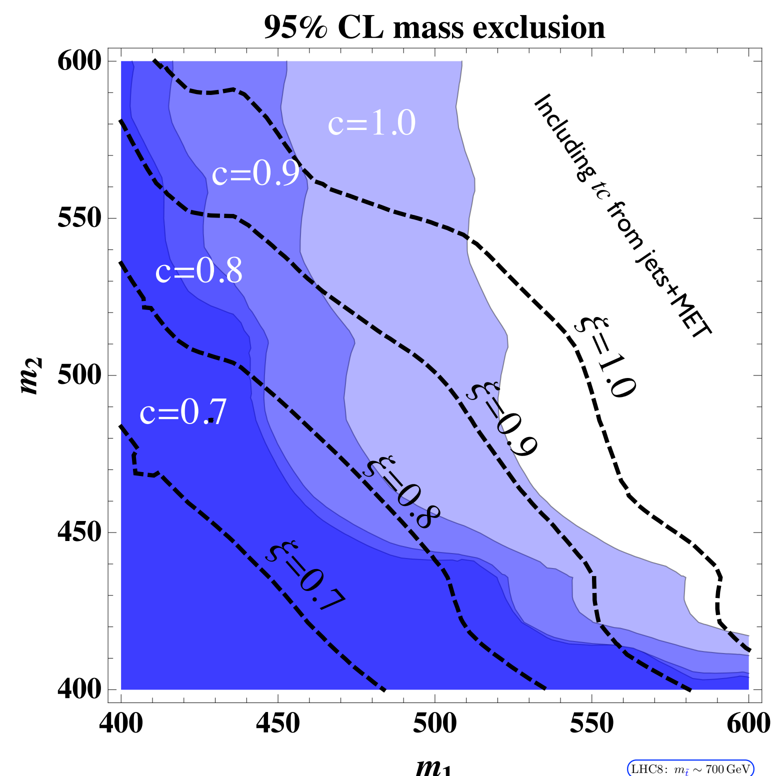
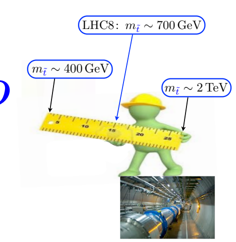




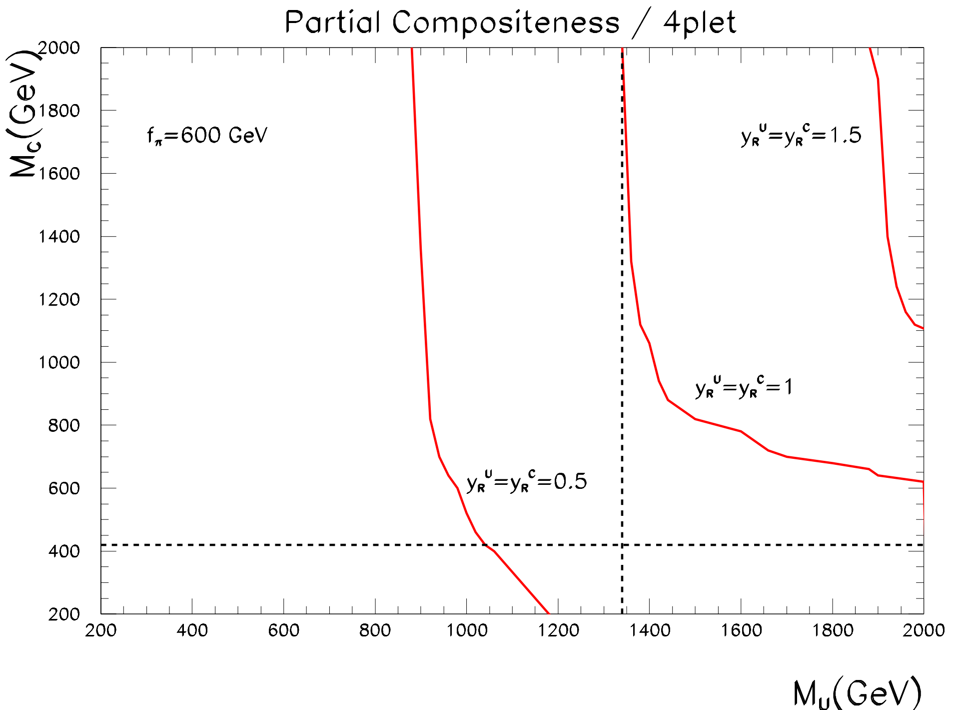
Can get $\xi \sim 0.5 - 0.8$ for $\theta_{23}^{RR} \sim 45^o$



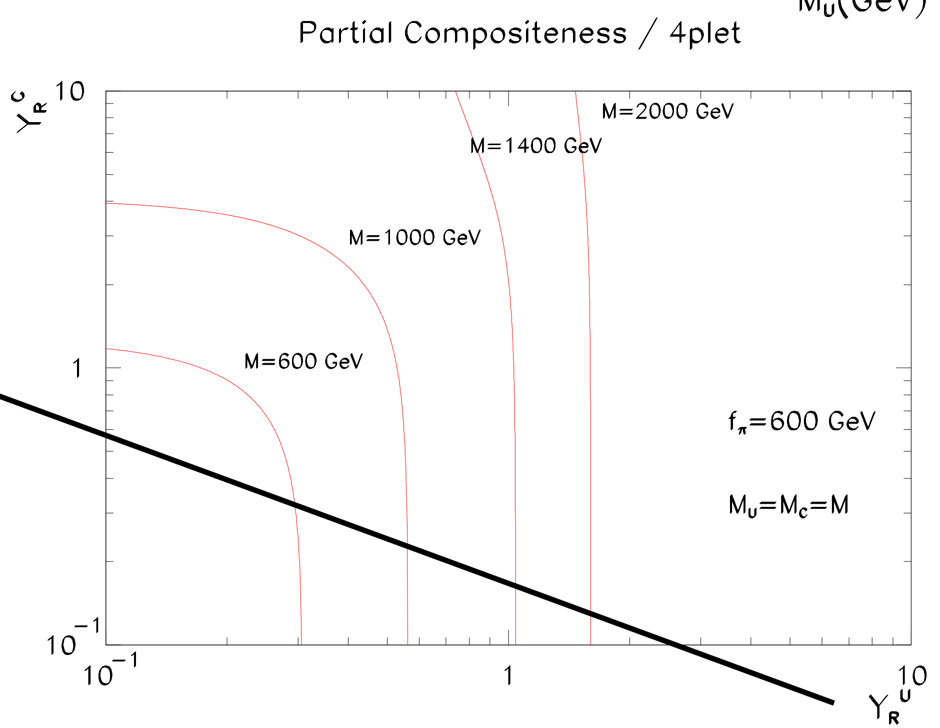
Compositeness: split 2 gen' LHC bounds (similar to SUSY case)

Delaunay, Fraille, Flacke, Lee, Panico & GP (13).

$$M_c \ll M_U$$



$$y_c \gg y_u$$



Composite natural $t \to cZ$

- $t \to cZ$ null test of the SM.
- $t \to cZ$ in composite models could be large.

Agashe GP & Soni (06)

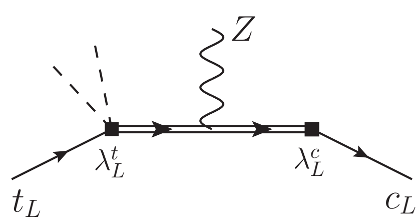
- $t \to cZ$ in custodial composite models could be small.

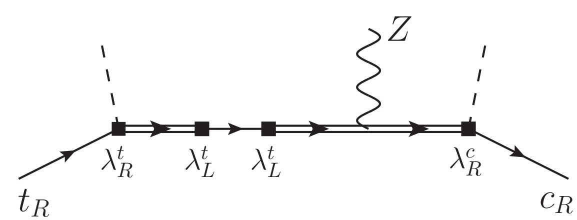
Agashe, Contino, Da Rold & Pomarol (06)

- $t \to cZ$ in natural custodial composite models should be large.

As both LH & RH tops needs to be composite, Azatov, Panico GP & Soreq (14)

$$\mathrm{BR}(t \to cZ) \sim 10^{-5} \left(\frac{700}{M_*}\right)^4 .$$



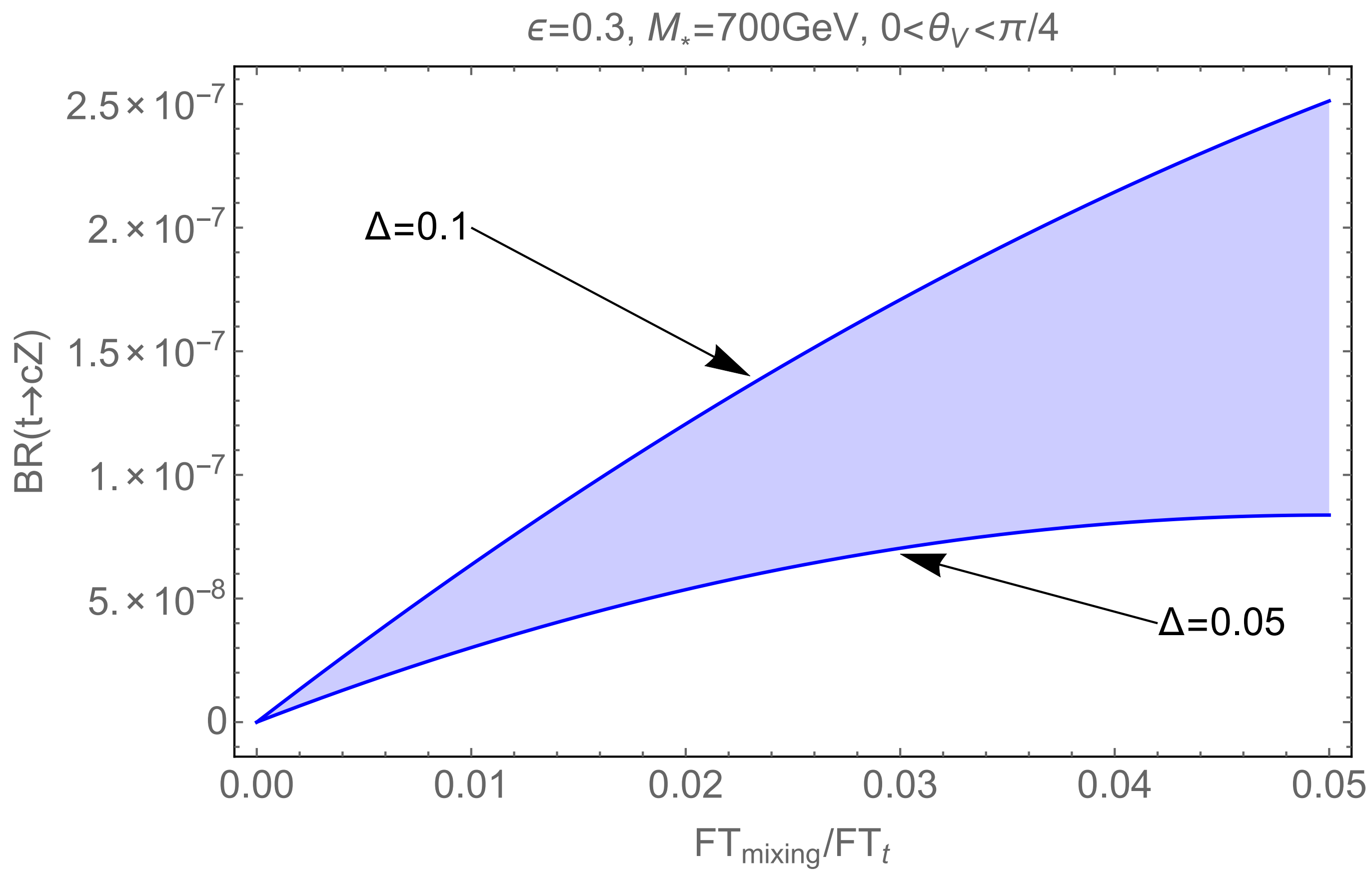


- One extra prediction tops should be RH polarized.

Azatov, Panico, GP & Soreq (14)

BR($t \to cZ$) vs. tuning

Azatov, Panico, GP & Soreq (14)

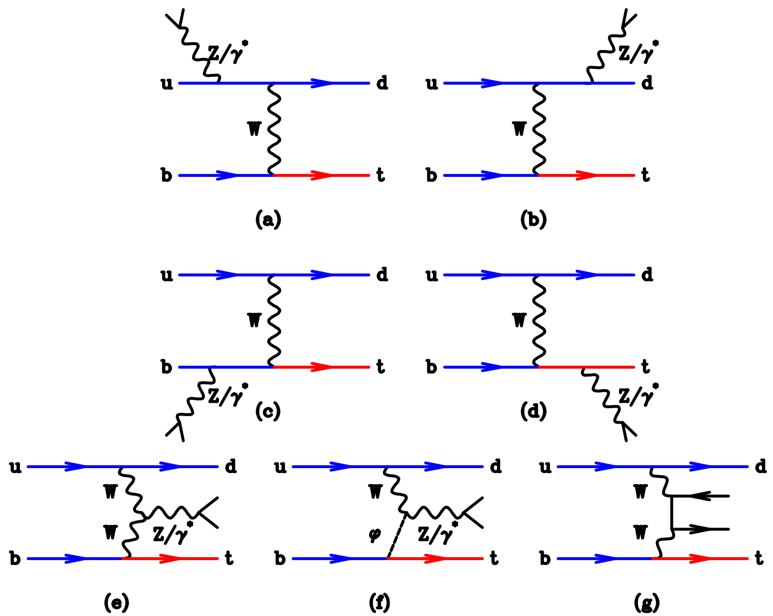


The correlation between BR(t → cZ) and the additional fine-tuning of the model FT_{mixing}/FT_t .

The SM semi-irreducible background

- tZj in the SM is important once BR($t \rightarrow cZ$) < 10^{-5} is reached.

Campbell, Ellis & Rontsch (13)



- Current bound is BR($t \rightarrow cZ$)~ 5x10^{-4} , more serious studies required before the experimentalists actually go below 10^{-4} …

Conclusions

♦ High Lumi' => moderate gain for E-frontier, large gain for elusive frontier.

♦ Many searches, due to elusive nature <=> improve control on SM dist'.

♦ Two frontiers of the (top) battle of naturalness at the LHC (run II) -

(i) "mini-energy" frontier of hard phys. keep pushing, no conceptual change.

(ii) "mini-intensity" precision frontier of new physics; more demanding searches, require closer contact \w SM groups both for TH & EXP.

♦ Tried to discuss several different searches that would potential gain -

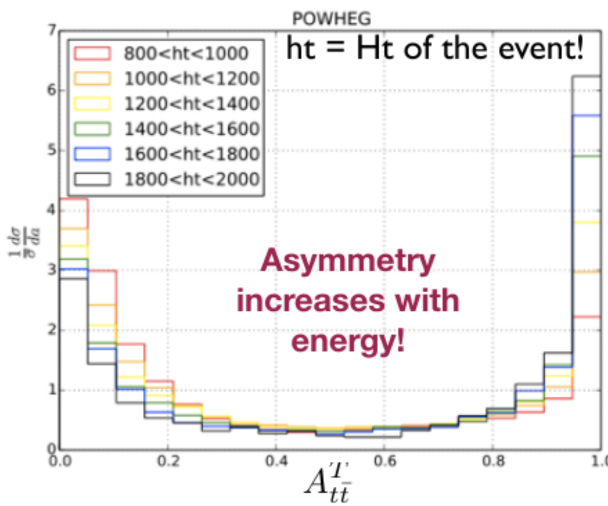
(i) top-pair distributions; (ii) top-charm frontier; (iii) top flavor violation.

Asymmetric $t\bar{t}$ events and top tagging

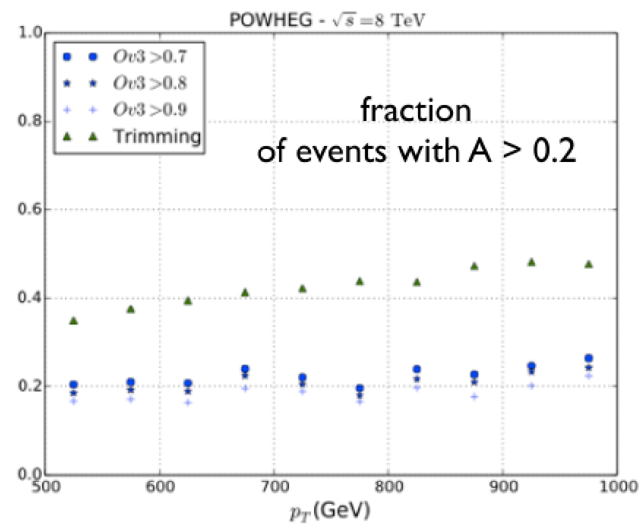
Backovic, JJ, Perez, Soreq

We define an asymmetry for truth level tops to quantify the p_T imbalance in $t\bar{t}$ events

$$A_{t\bar{t}}^{SV} = \frac{|\vec{p}_{T,t} + \vec{p}_{T,\bar{t}}|}{p_{T,t} + p_{T,\bar{t}}}$$



Asymmetric events are also a background to $t\bar{t}$ resonance searches



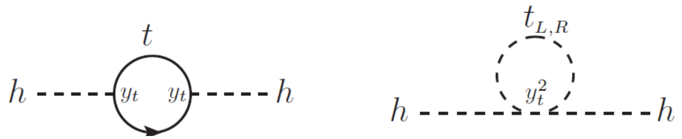
Top template tagger can remove more asymmetric events than d_{12} + mass cut

What is the impact of stop-flavor-violation on tuning ? (flavored naturalness)

- Flavor: only $\tilde{t}_R - \tilde{u}_R$ or $\tilde{t}_R - \tilde{c}_R$ sizable mixing is allowed.

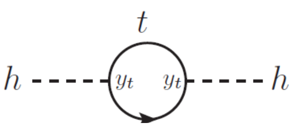
- Naively sounds crazy ...

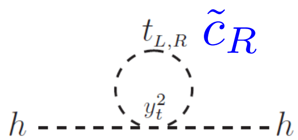
Dine, Leigh & Kagan (93); Dimopoulos & Giudice (95).



What is the impact of adding flavor violation on stop searches ? (flavorful naturalness)

- Flavor: only $\tilde{t}_R - \tilde{u}_R$ or $\tilde{t}_R - \tilde{c}_R$ sizable mixing is allowed.
- Naively sounds crazy as worsening the fine tuning problem.





$$\delta m^2_{Hu} = -\frac{3y_t^2}{8\pi^2}\left(m^2_{\tilde{t}_L} + \cos^2\theta^{RR}_{23} m_1^2 + \sin^2\theta^{RR}_{23} m_2^2\right)$$

- However, as you'll see soon the scharm can be light...
- The $"\tilde{t}_R\, \tilde{t}^*_R" \to t_R\, t^*_R$ production is suppressed by $\left(\cos\theta^R_{23}\right)^4$.

↓

Potentially: new hole in searches, possibly improve naturalness

Constraining (RH) flavorful naturalness

- RH stops & naturalness, $m_{\tilde{t}_R} \gtrsim m_0 = 570\,\mathrm{GeV}$

Analysis applies for ATLAS (12); now new bounds from ATLAS and CMS around 670 GeV.

- To constrain, look for: tt, cc & tc + MET (very qualitative).

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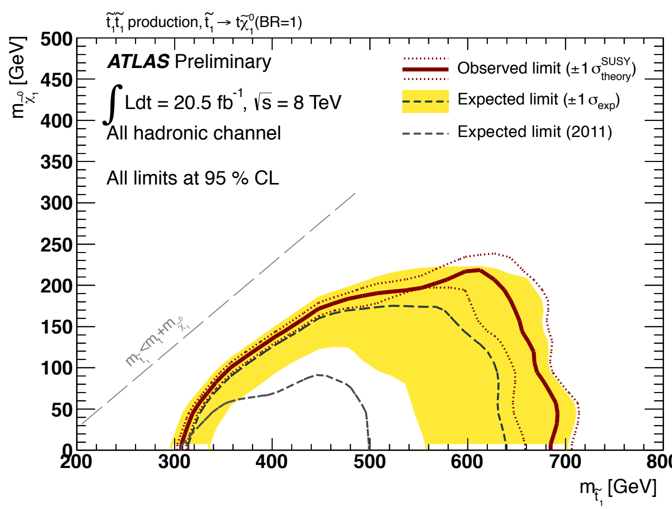

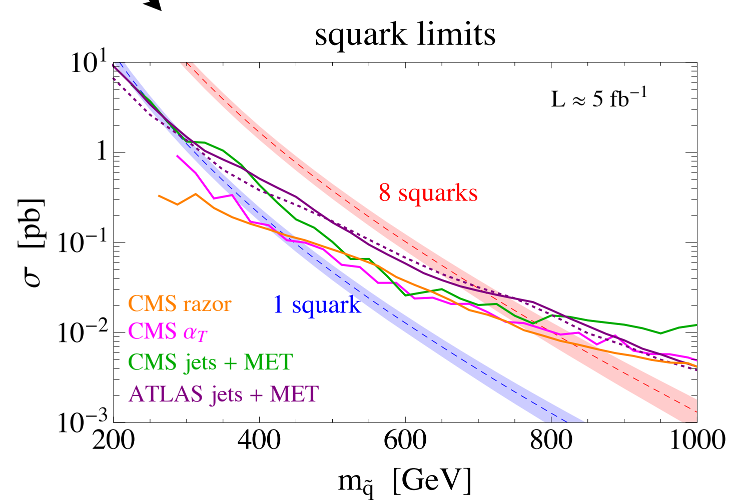

Mahbubani, Papucci, GP, Ruderman & Weiler (12).

Constraining (RH) flavorful naturalness

- RH stops & naturalness, $m_{\tilde{t}_R} \gtrsim m_0 = 570\,\mathrm{GeV}$

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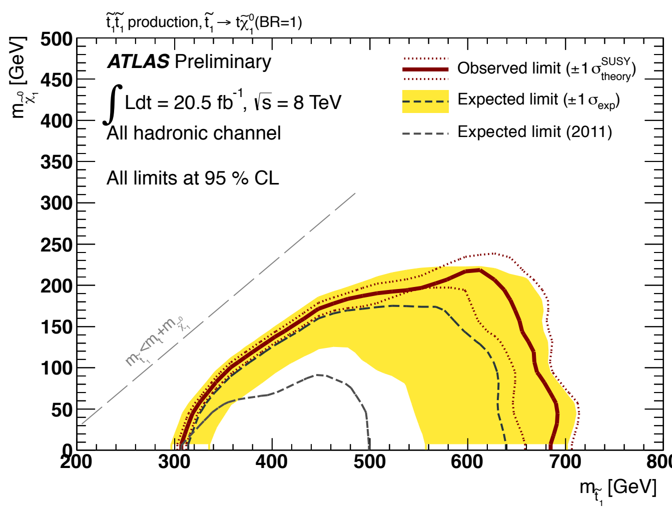

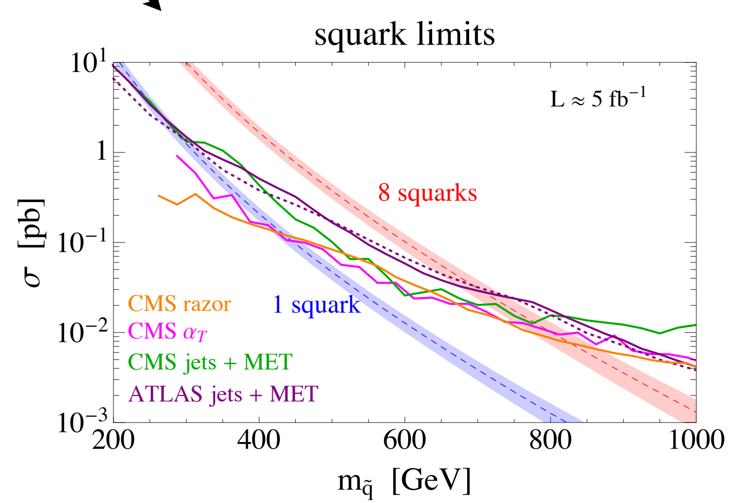

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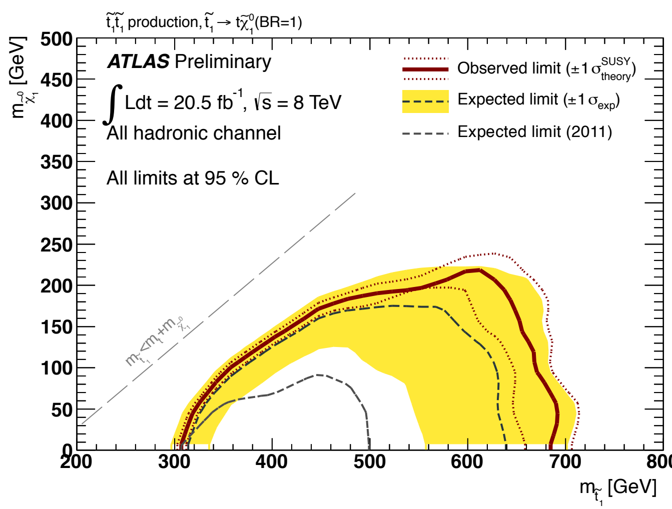
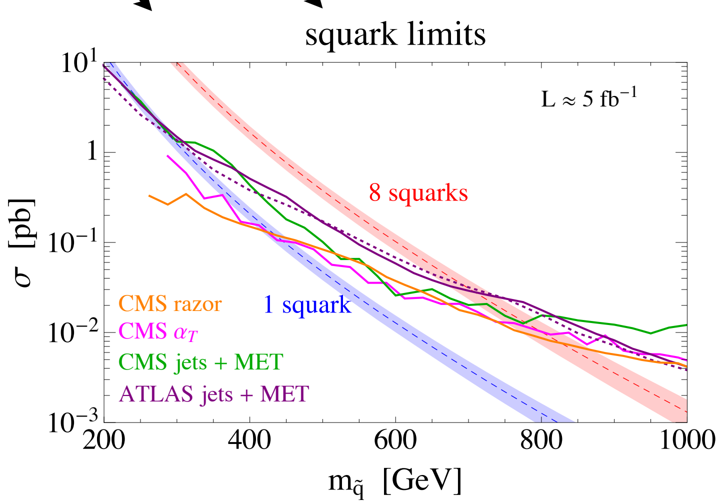
compromise





Mahbubani, Papucci, GP, Ruderman & Weiler (12).

Conclusions

♦ Subjective: despite entering the “boosted” era (not in Higgs) the “jet-substructure” field is behind the rest of the PQCD one.

♦ More energy => about to enter “hybrid-boosted” era.

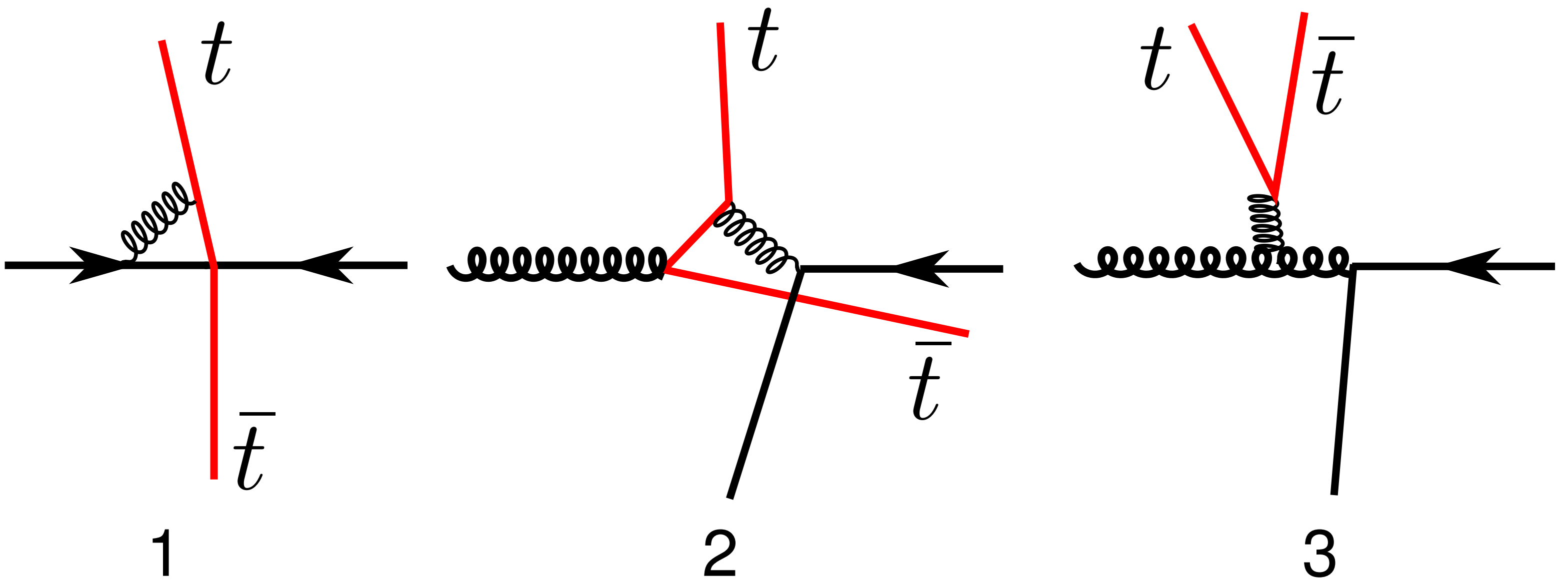
♦ Elusive: light (non-”sups”) squarks/partners maybe buried.

♦ Stop-scharm mixing might lead to improve naturalness.

♦ Ask for new type of searches, charm tagging important, linked to CPV in D mixing, soon to be tested at LHCb.

Next-to-leading order effects

Are top pairs in high-p_T events always back to back?



How do 2 and 3 change distributions?

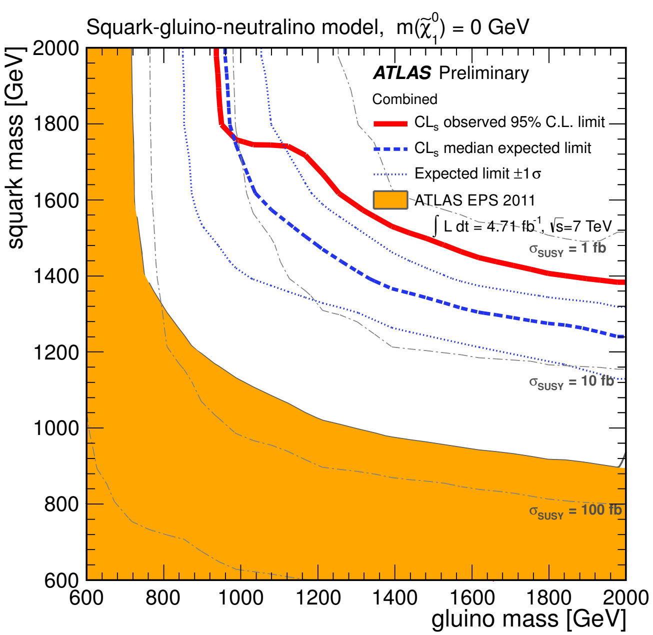
Salam, '13, ATLAS Top WG

`Backovic, Gabizon, Juknevich, GP & Soreq (13)`

Light scharms at the LHC

Putting stops aside, what are the bounds on first 2-generation "light" squarks?

Summer bounds from ATLAS & CMS :



Light squarks > 1.4 TeV?

What drives the experimental limits?

- Squark multiplicity;
- Signal efficiencies;
- Production rate, PDFs.

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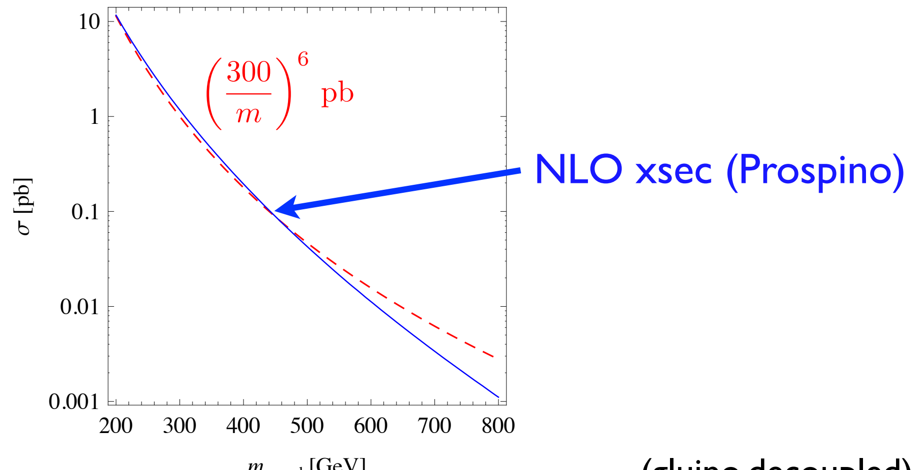
Multiplicity: how bound changes when one doublet is made lighter ?

Cross-sections vs. mass

$$\sigma(pp \to \tilde{u}_R \tilde{u}_R^*) \propto \frac{1}{m^6}$$ (roughly)



(gluino decoupled)

$$8/m^6 = 6/m_H^6 + 2/m_L^6$$

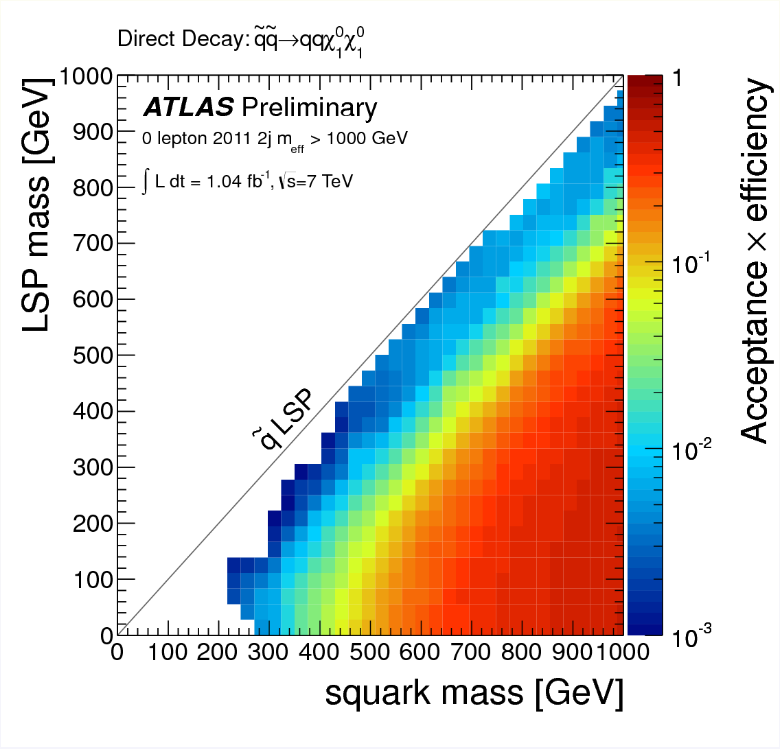
$$(m_L/m_H) = (1/4)^{1/6} \sim 0.8$$

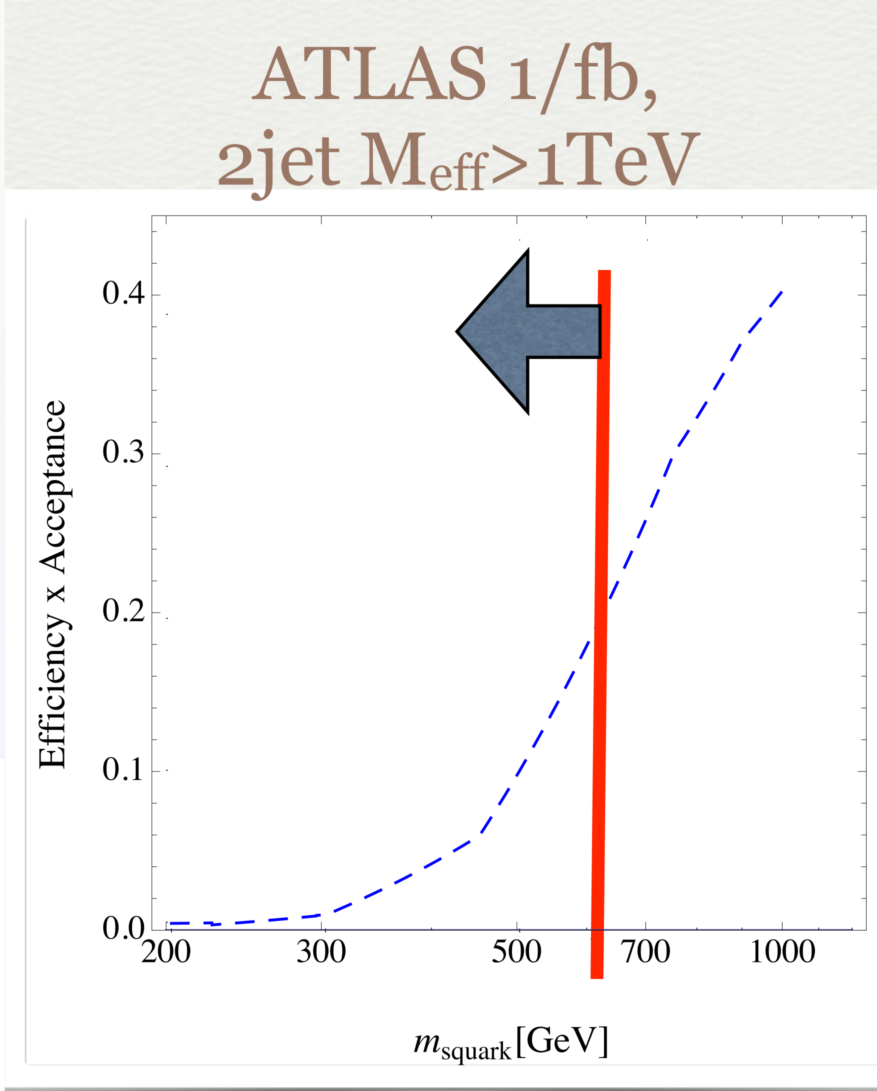
gain is marginal

Efficiencies, strong mass dependence!

Signal efficiency falls very rapidly with decreasing squark mass

Below $\sim$ 600 GeV $\epsilon\sigma = 1$

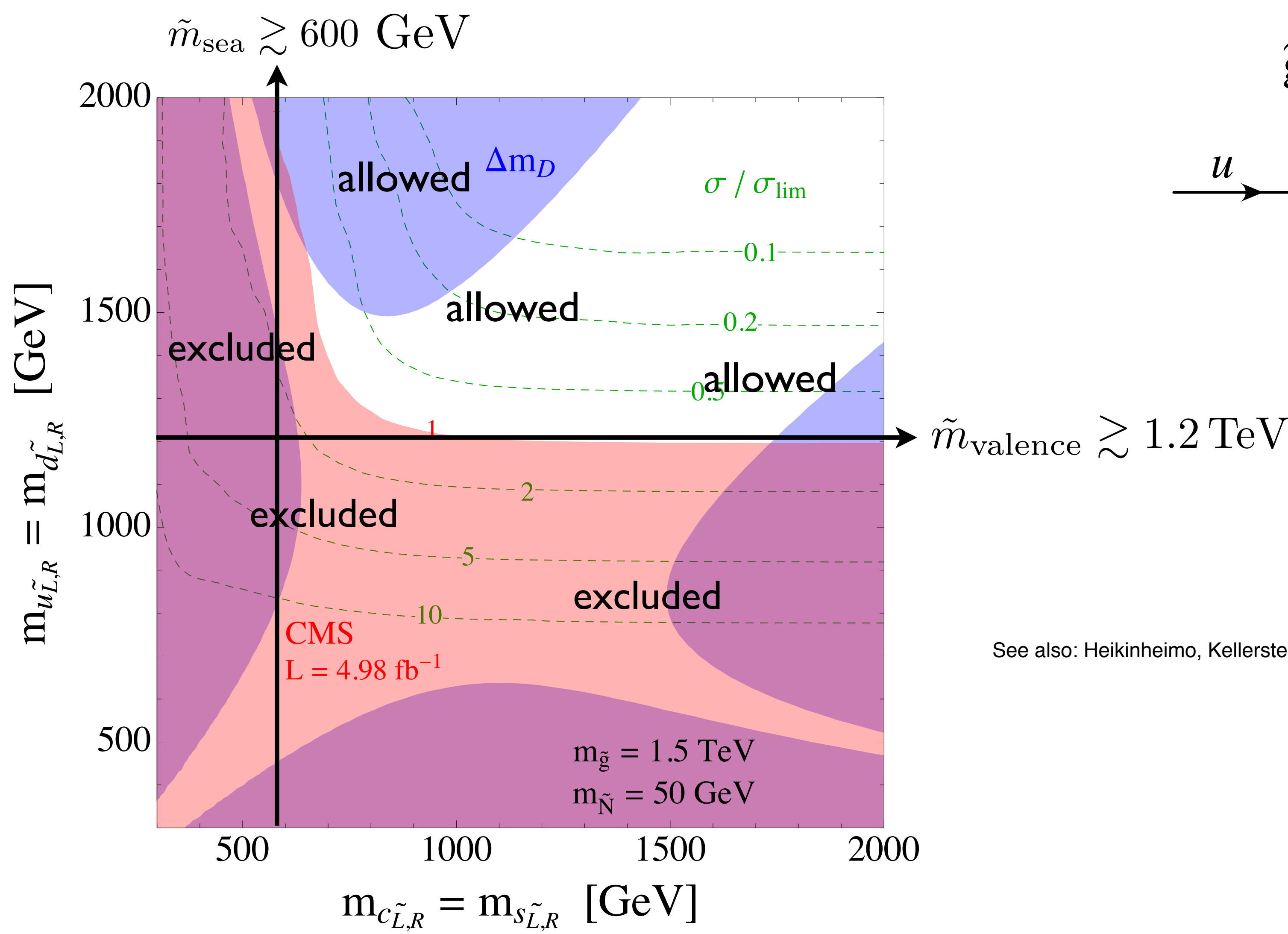


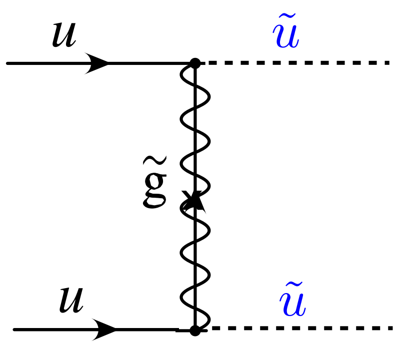


meff is the scalar sum of transverse momenta of the leading N jets with Emiss.

PDFs: all 4 flavor "sea" squarks can be light!

sea vs. valence

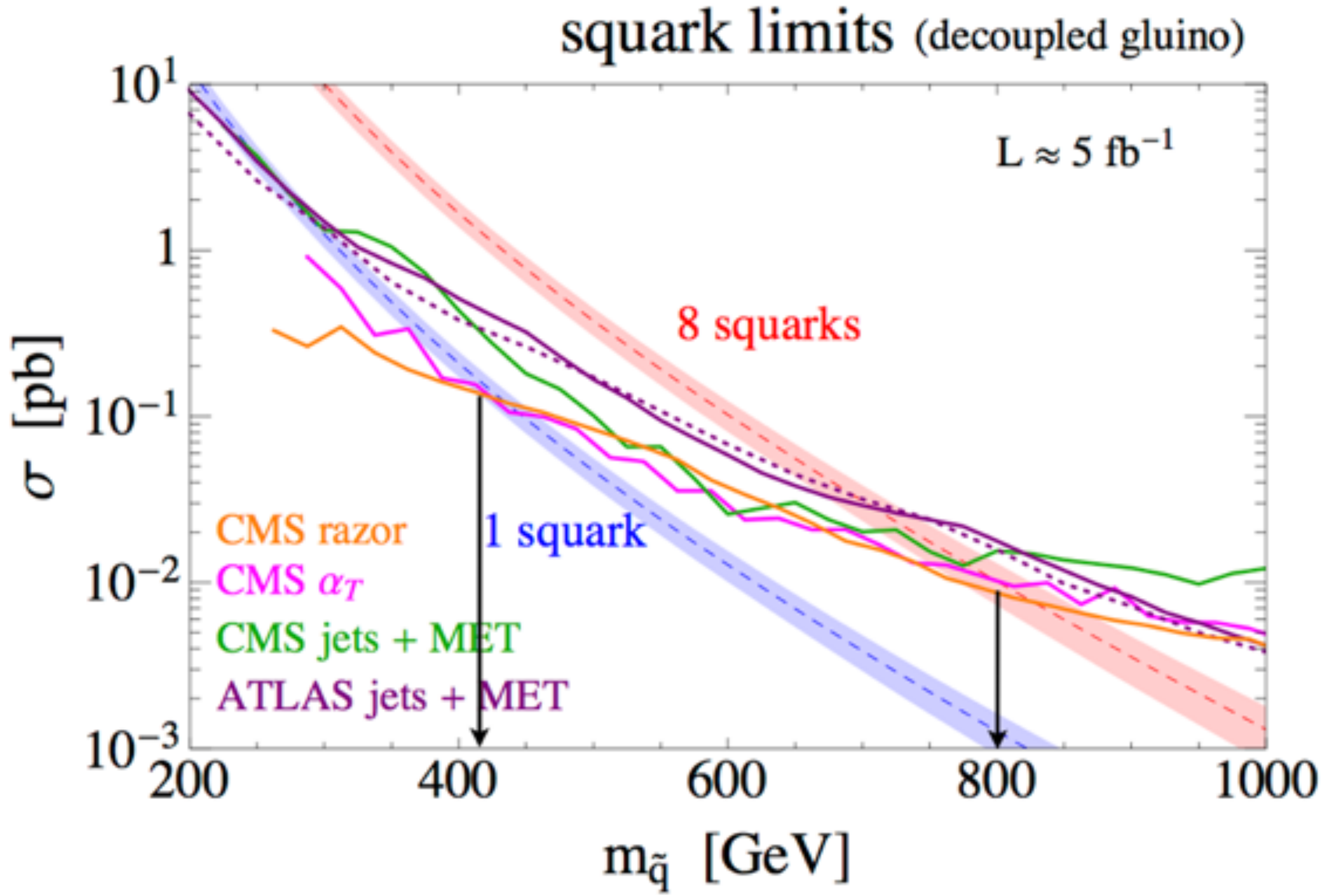




See also: Heikinheimo, Kellerstein & Sanz (11); Kribs & Martin (12),

Mahbubani, Papucci, GP, Ruderman & Weiler (12).

Single squark can be as light as 400-500 GeV!



Mahbubani, Papucci, GP, Ruderman & Weiler (12).

Open parenthesis

Charm tagging at the LHC ATLAS EPS 2013

- In new ATLAS search for stop decay to charm + neutralino ($\tilde{t} \to c + \chi^0$) charm jet tagging has been employed for the first time at LHC

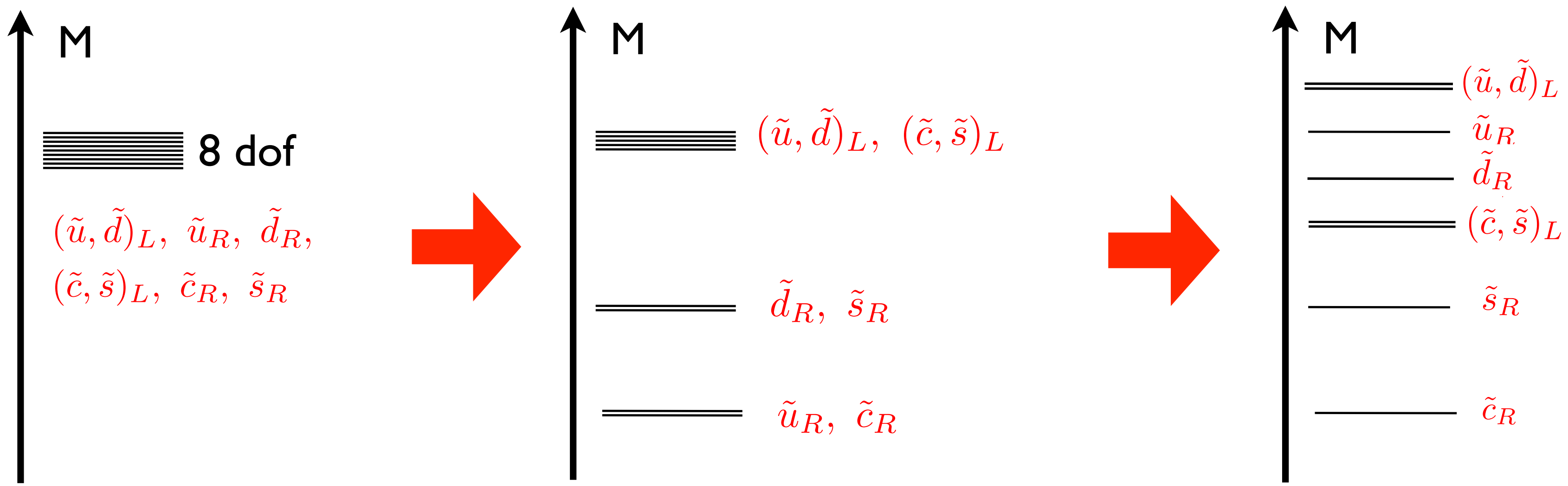
ATLAS-CONF-2013-068

- charm jets identified by combining "information from the impact parameters of displaced tracks and topological properties of secondary and tertiary decay vertices" using multivariate techniques

- 'medium' operating point: c-tagging efficiency = 20%, rejection factor of 5 for b jets, 140 for light jets. #'s obtained for simulated $t\bar{t}$ events for jets with $30 < p_T < 200$, and calibrated with data

Spectrum of flavorful natural models

Mahbubani, Papucci, GP, Ruderman & Weiler (12).



Everything degenerate

Split, but MFV

Anarchy!

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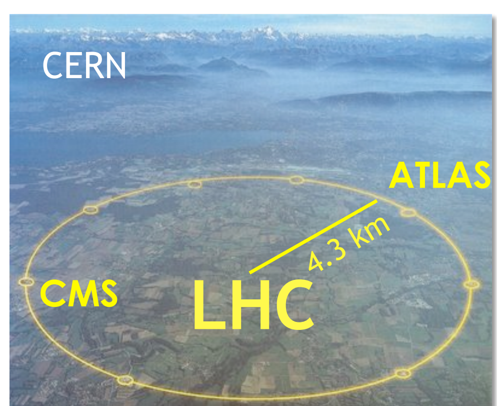

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