Top signals at the LHC

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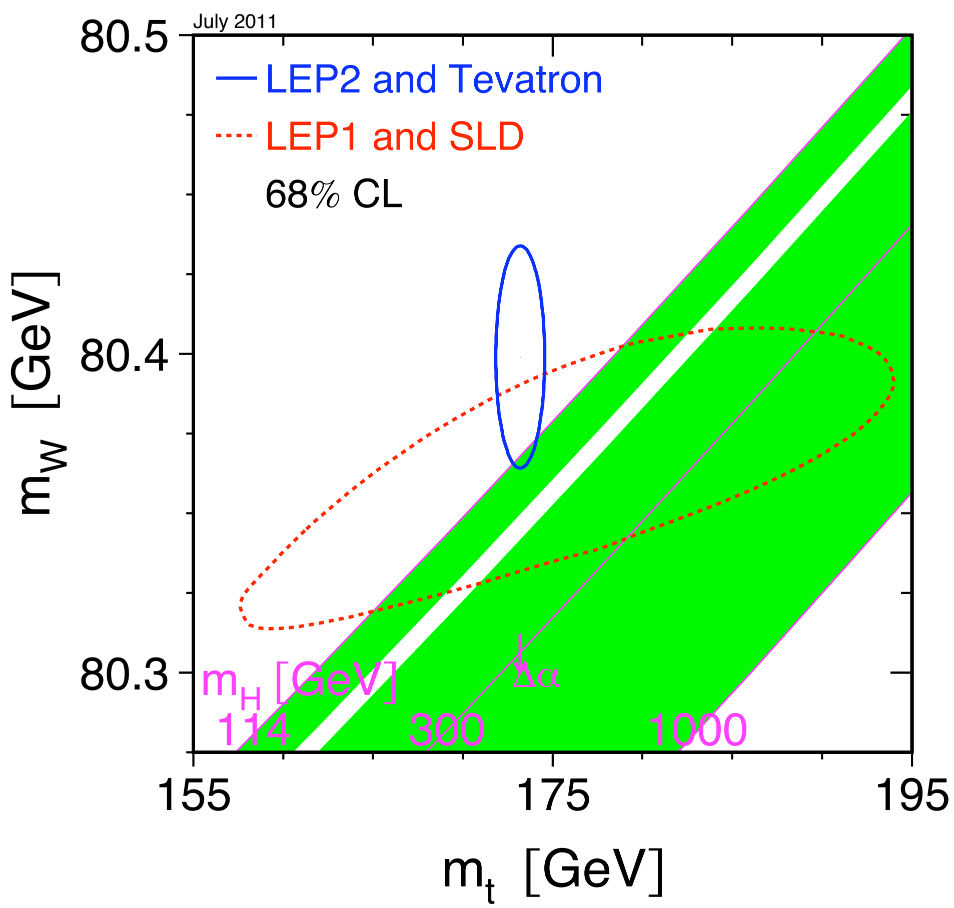
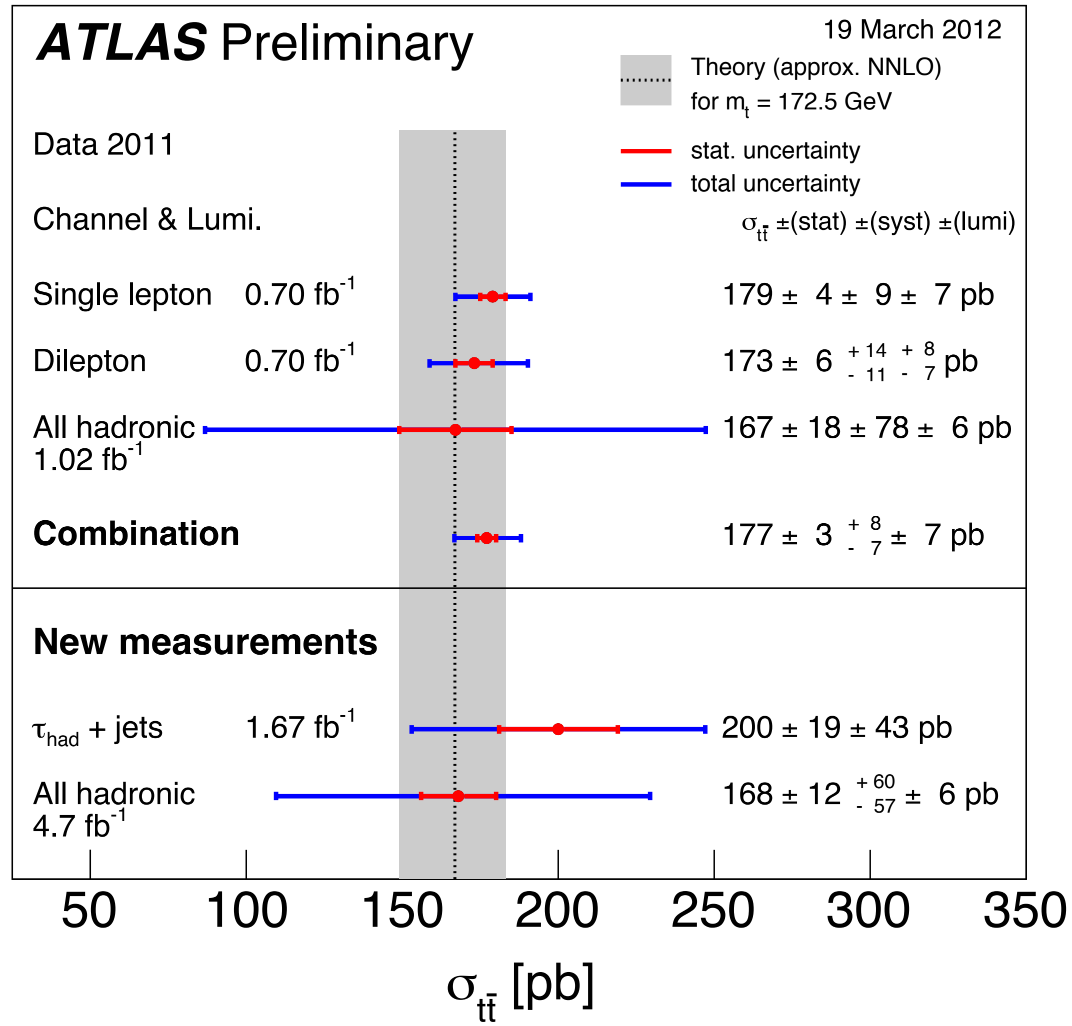
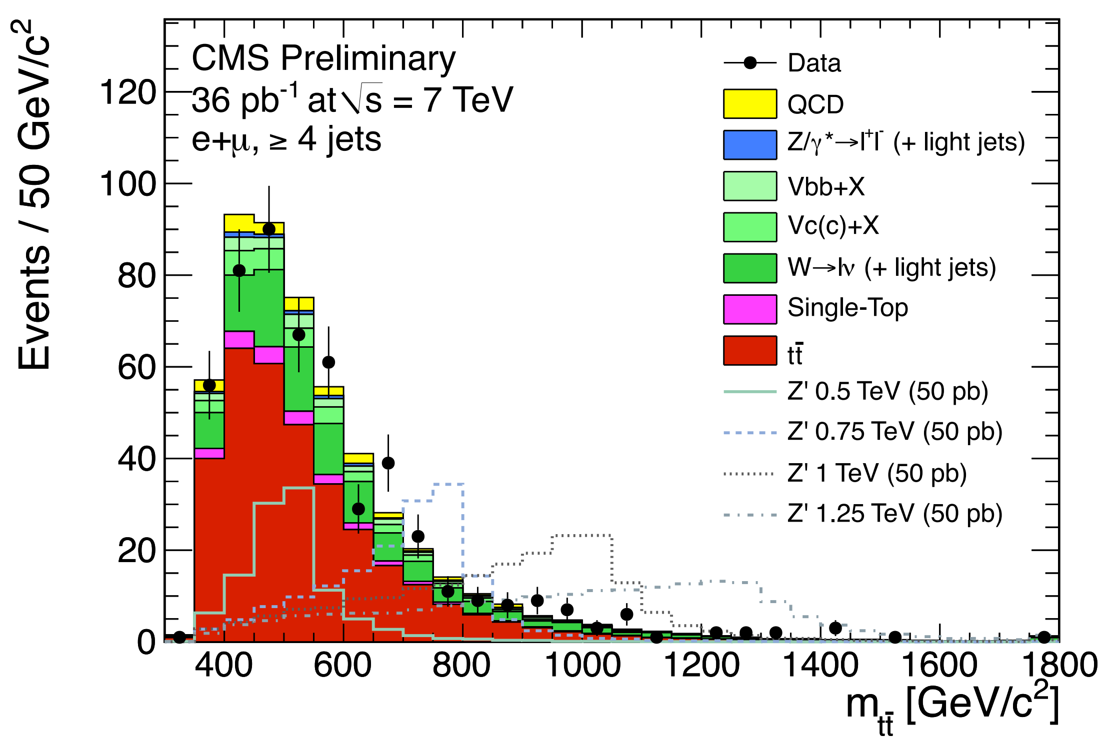
Main message

- Top (bottom) rich channels are the most likely places for new physics to show up.
- It is definitely worth while to exhaust every possibilities.
- I will remind you the main motivations and give a (very partial and sketchy) list of possibilities.
  - Highlights a few new developments.

Measuring the top







- Rare decay, spin correlation, W helicity...

Top is special

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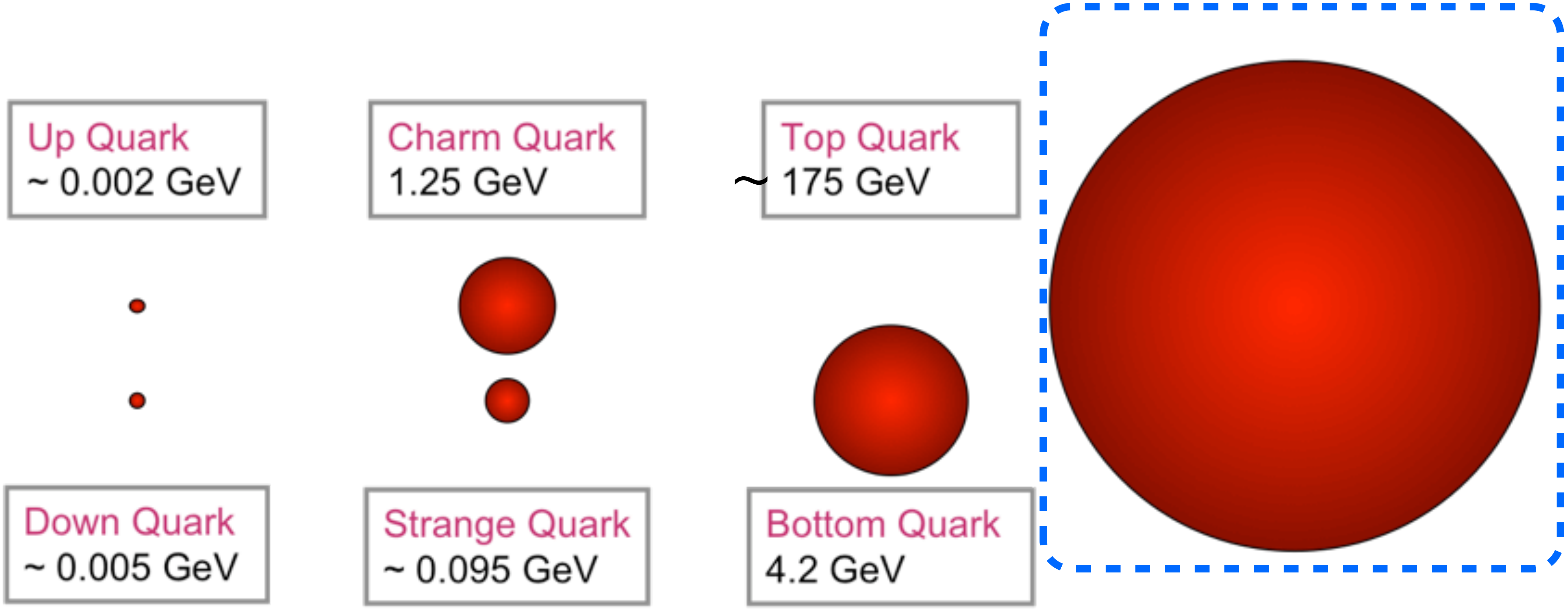


- $m_{top} \gg m_{u,d,c,s,b}$.

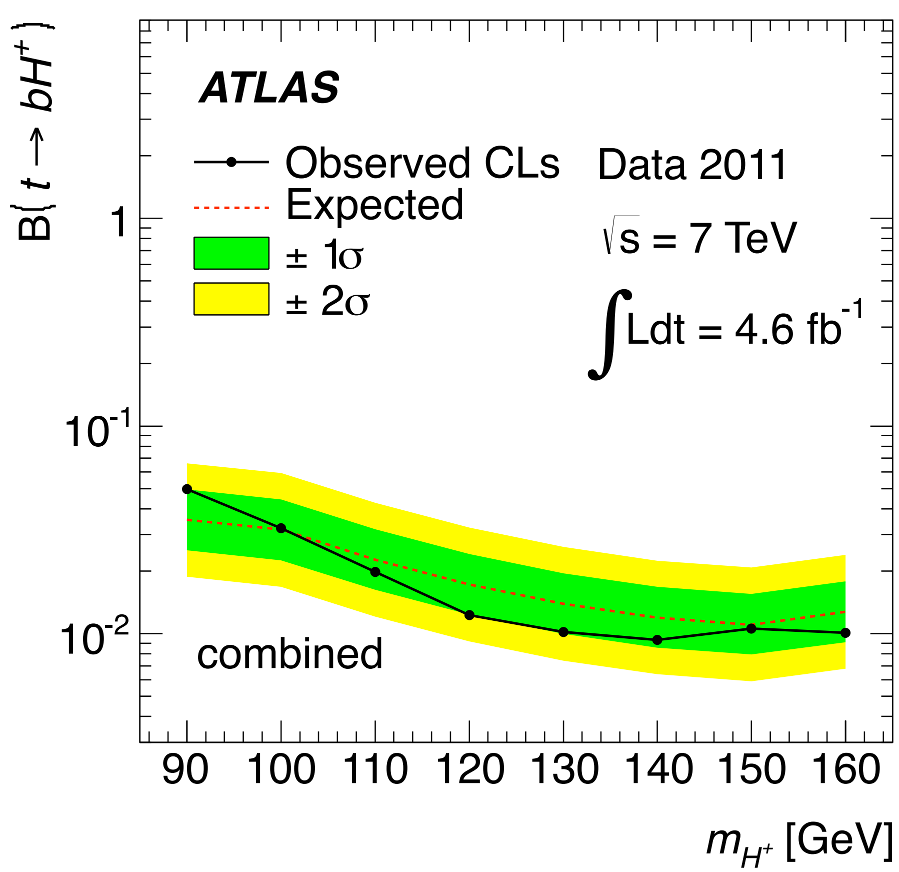
Tight connection with EWSB.

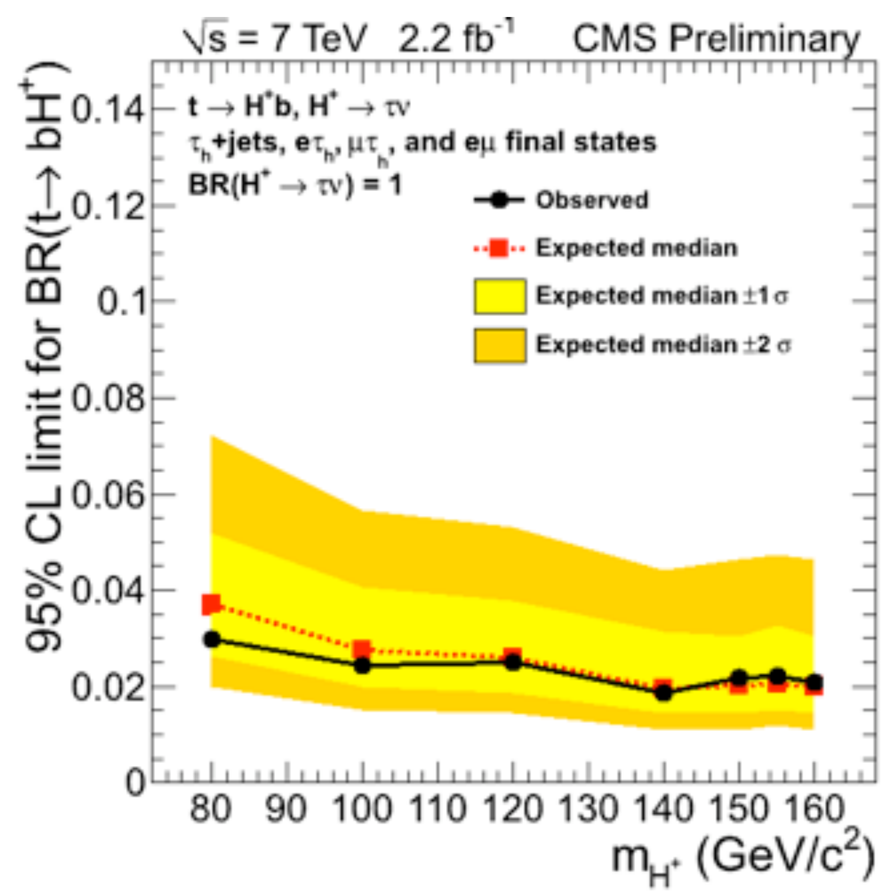
- SM is chiral. Fermions only get mass after Electroweak symmetry breaking.
- (very) Heavy top → top couples strongly to the mechanism of electroweak symmetry breaking.
  - e.g. large Yukawa coupling $y_t h t_L t_R$ to the Higgs

Top knows more about the Higgs sector.

- Is there an extended Higgs sector? (likely!)

$$t \longrightarrow H^+ b$$





For heavier H^+, $H^+ \rightarrow t\, b$

ttbar resonances.

- Special dynamics (new force) → heavy top.
  - New dynamics will create new resonances.
  - Such new resonances couples strongly to the tops.
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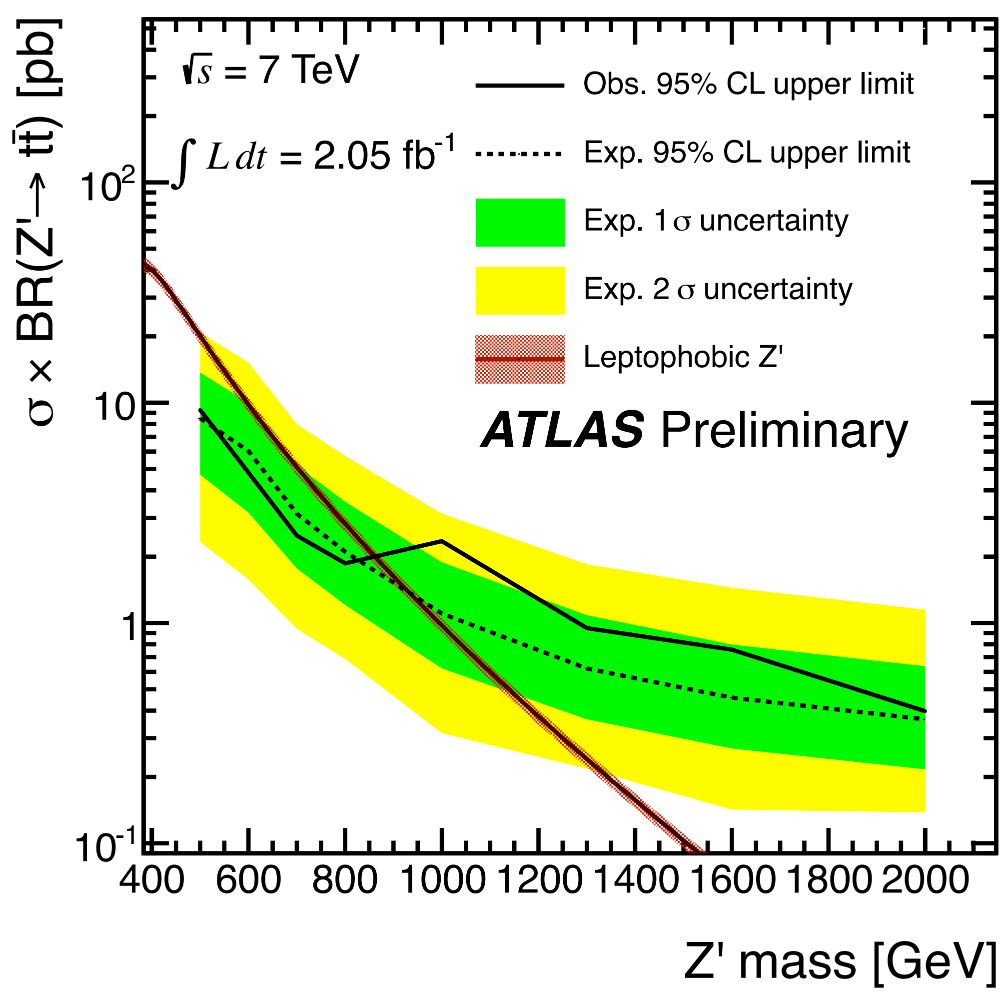
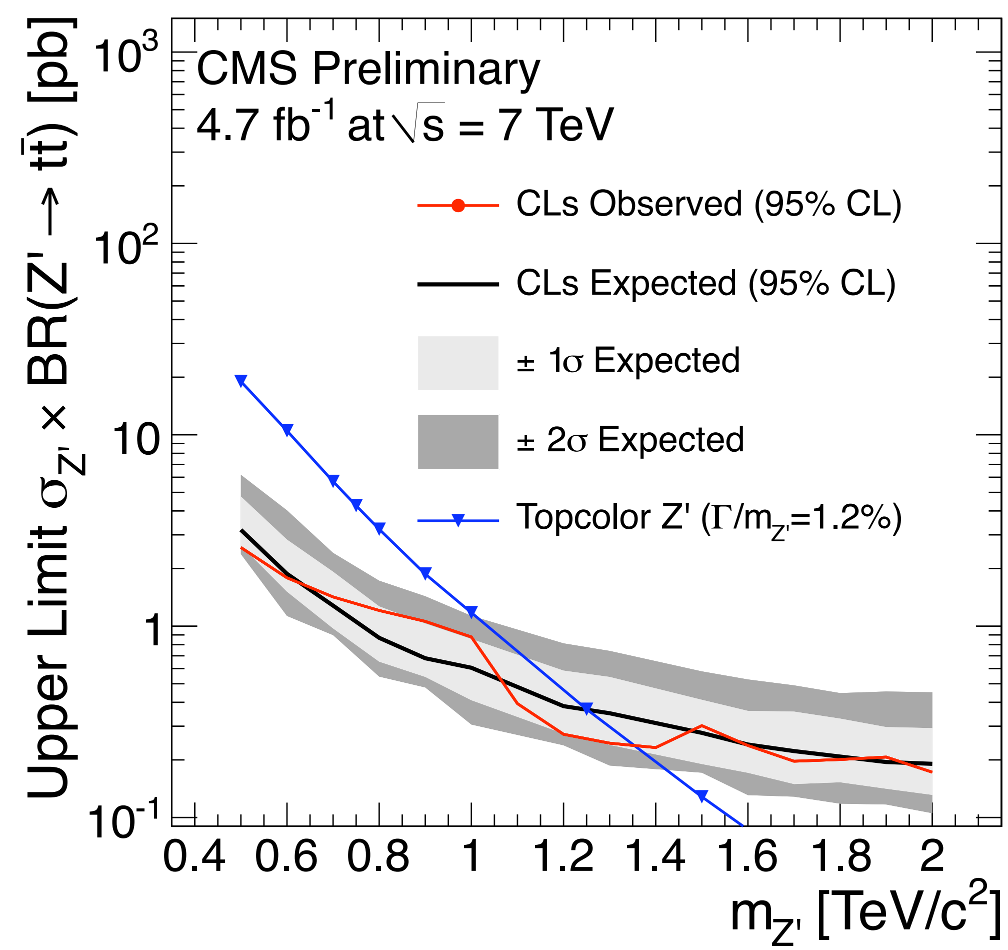
a.k.a, anything other than SUSY.

Search for ttbar resonance.



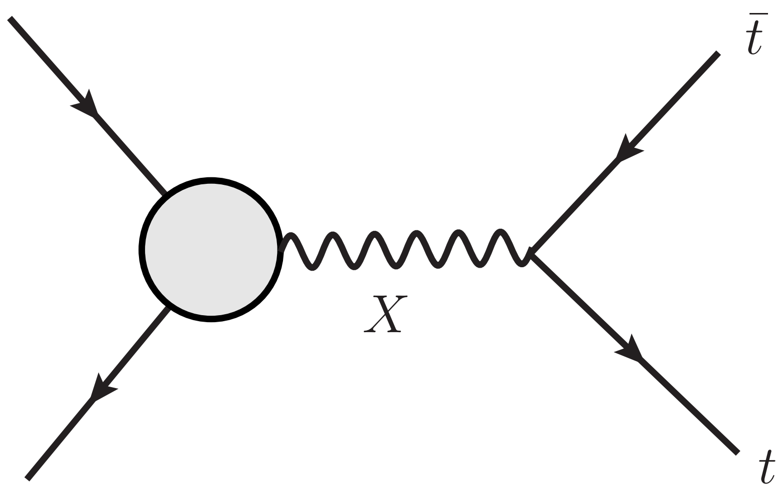


- Generic resonance could also be spin-0, or spin-2.

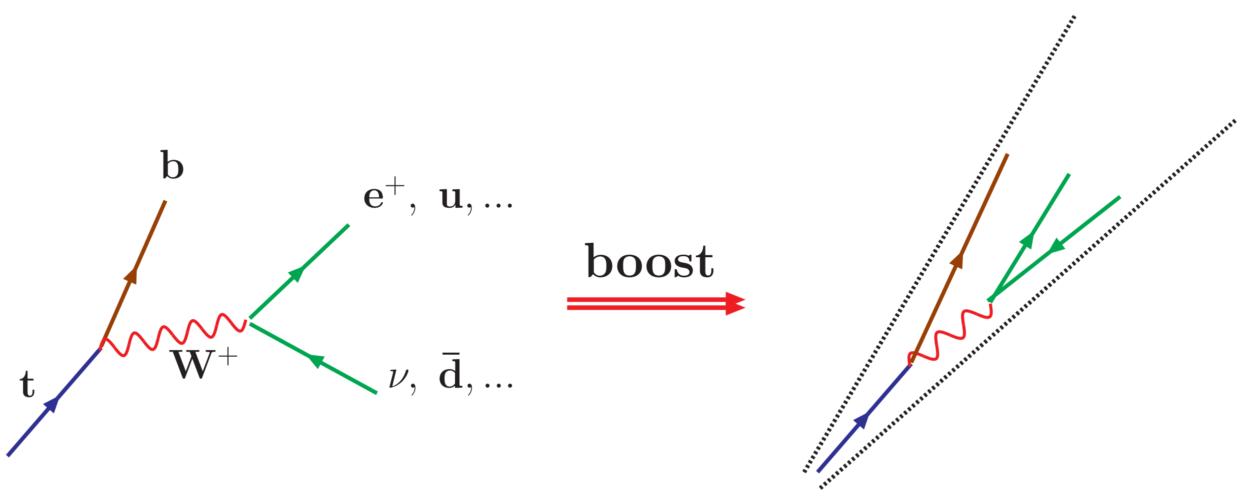
- Can be broad. Need careful modeling.

Boosted top is also hard to identify.

- Heavy resonance decay.



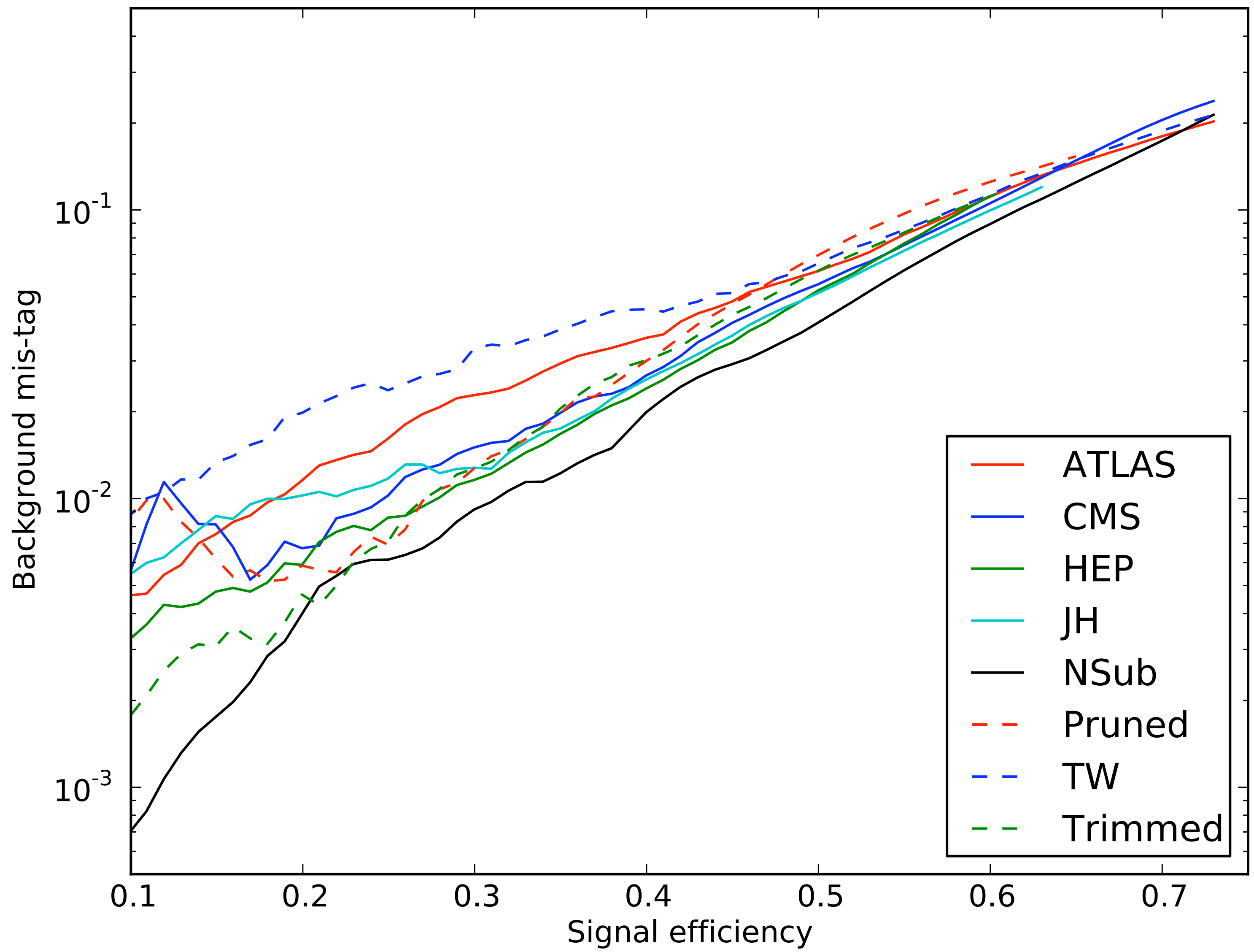
$$E_{\text{top}} \simeq \frac{M_X}{2}$$



No isolated objects

B. Lillie, L. Randall, and LTW, hep-ph/0701166

boosted top taggers

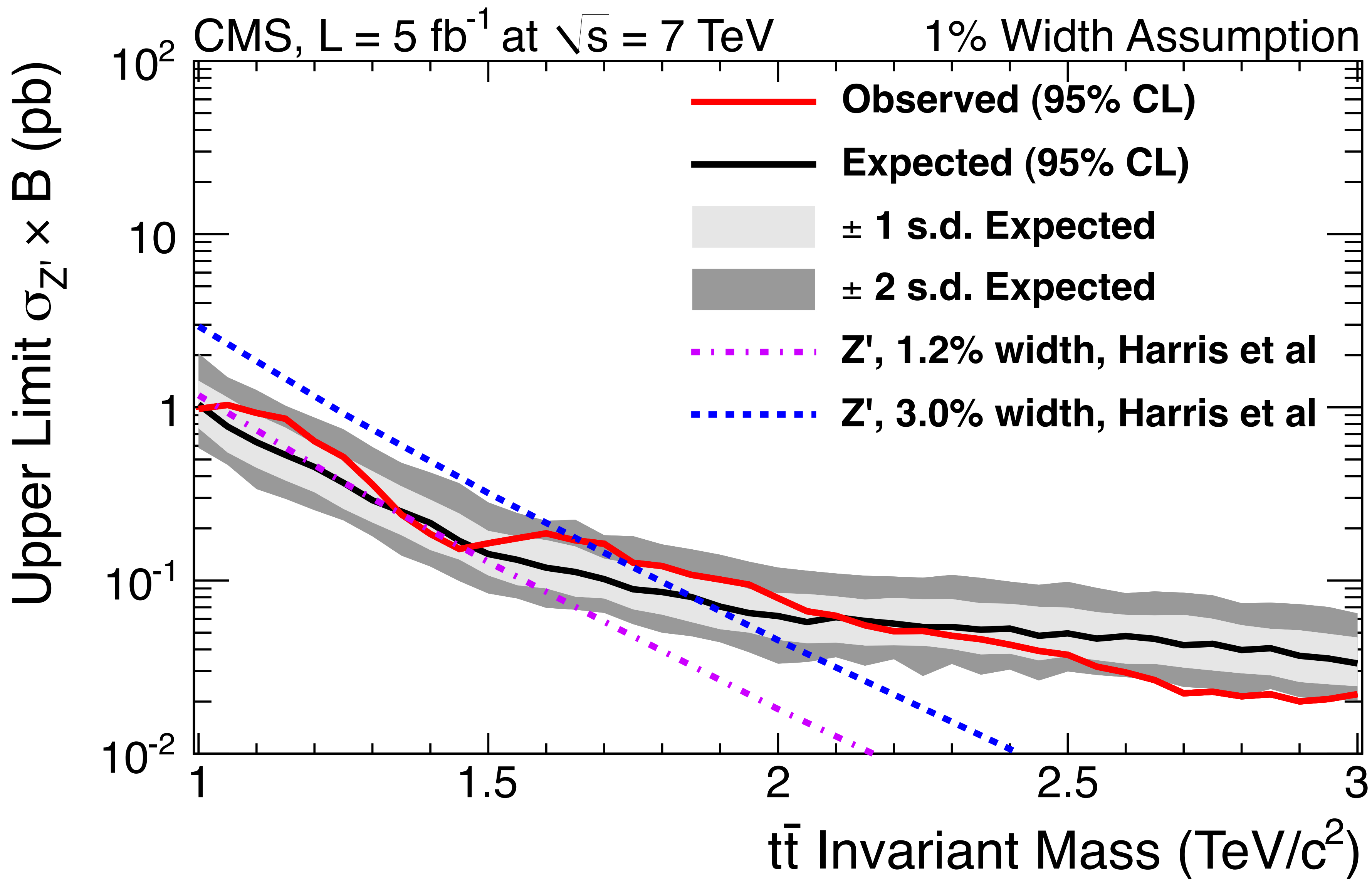


1201.0008

- Jet substructure.

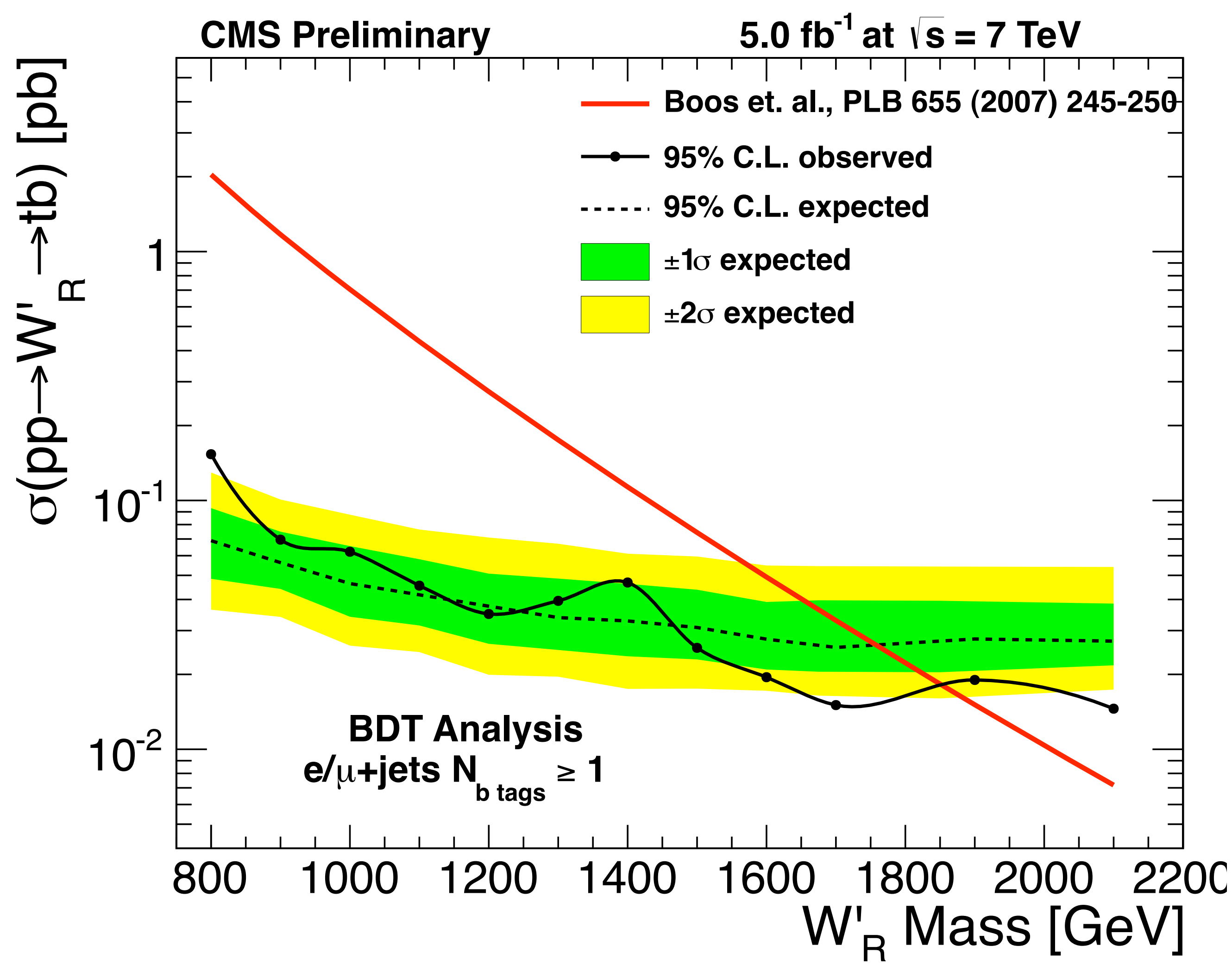
- "Grooming techniques"

Talks by Miller, Rappoccio and Krohn



- Expectation: resonance mass ~ TeVs.

W′→ tb

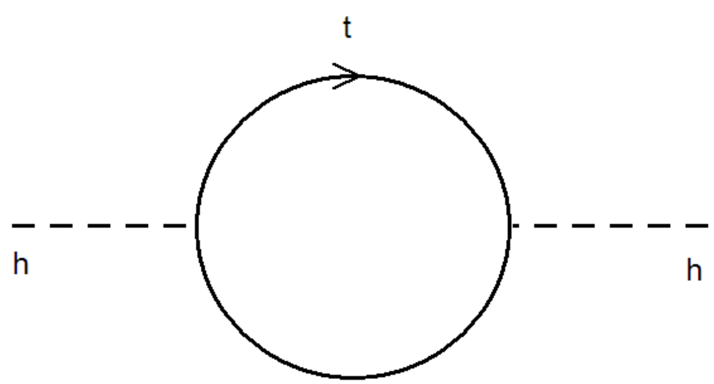


- Almost as generic as the X → ttbar channel.
  - New physics typically comes in with non-trivial SU(2) representation.

Top partner

Top partner

- Heavy top → largest coupling to the Higgs.
  - Biggest contribution to its mass.



$$\delta m_h^2 = -\frac{3}{8\pi^2} y_t^2 \Lambda^2$$

- This is the essential piece of the so-called naturalness or hierarchy problem.

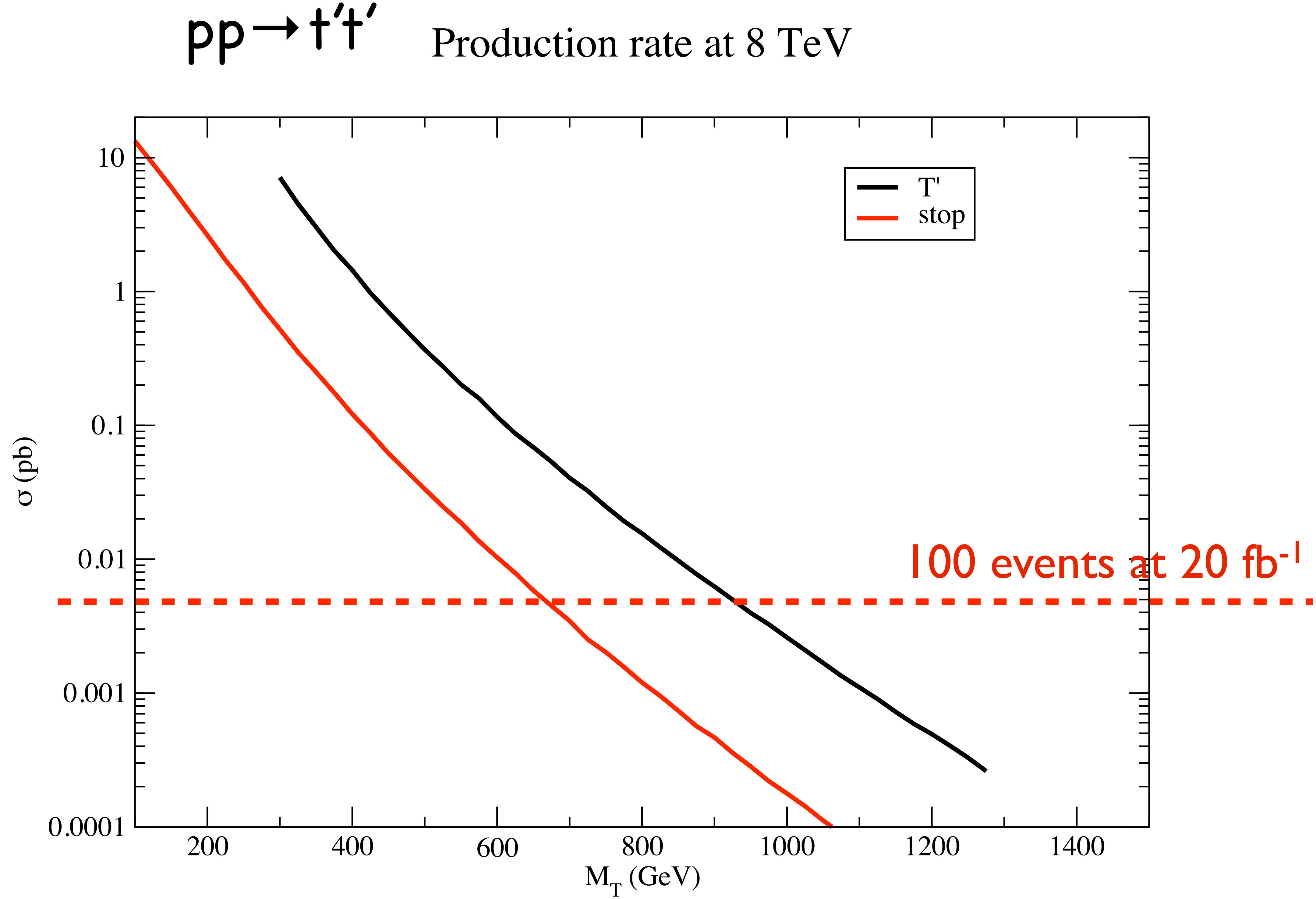
- Any natural theory must introduce top partner.
  - Most anticipated new physics particle.

Top partners.

- Introducing top partners.
  - stop in SUSY, T' in little Higgs, etc.
  - top like states in extra-dim models.
- Another "standard" feature: a discrete parity (Z_2)
  - Good for precision test, flavor, CP.
    - R-parity, KK parity, T parity...
  - Dark matter candidate, lightest stable neutral NP state.

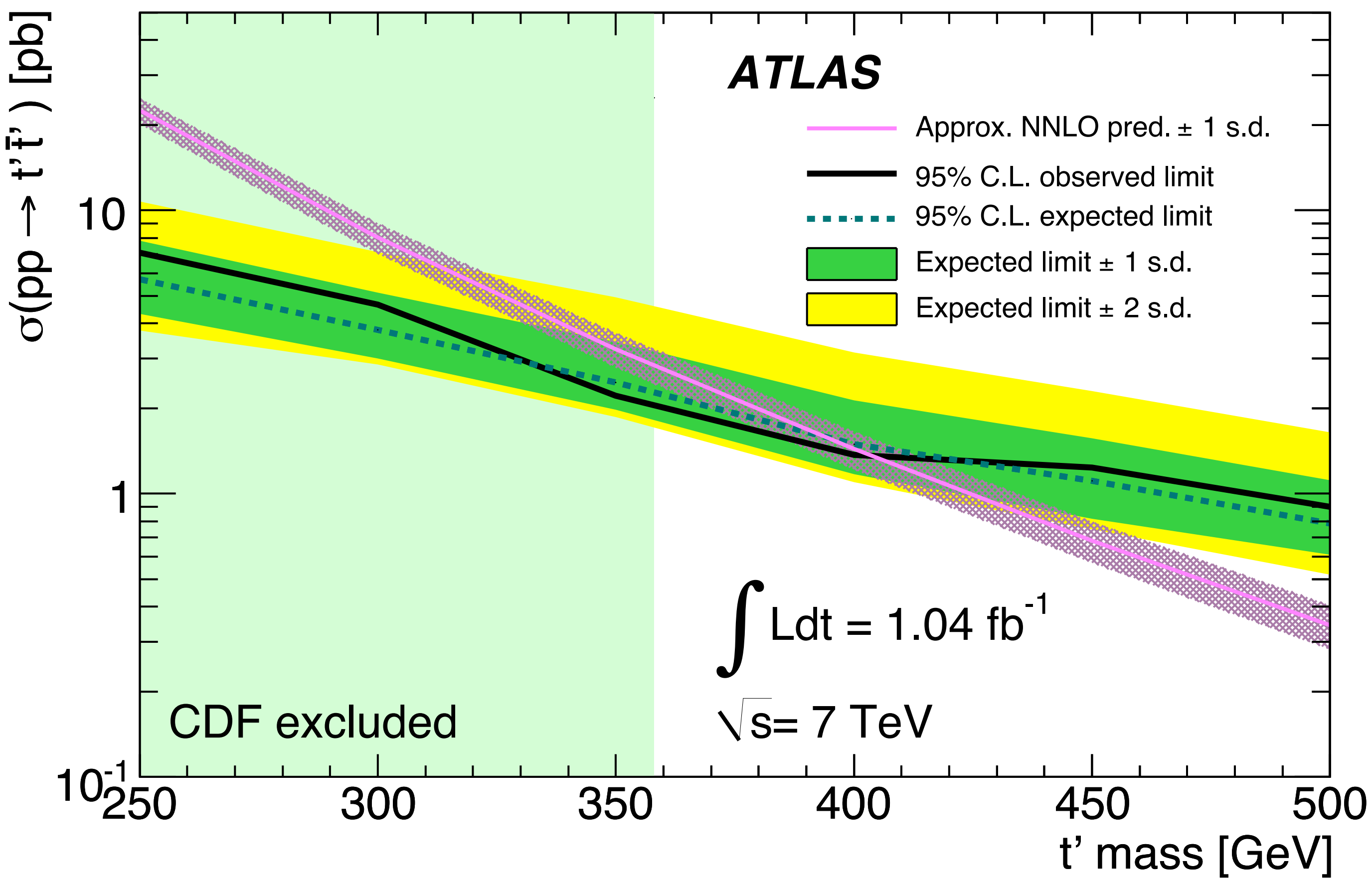
Top partner production at 8 TeV

$pp \to t't'$



PYTHIA parton level

Signal of top partner (without parity).



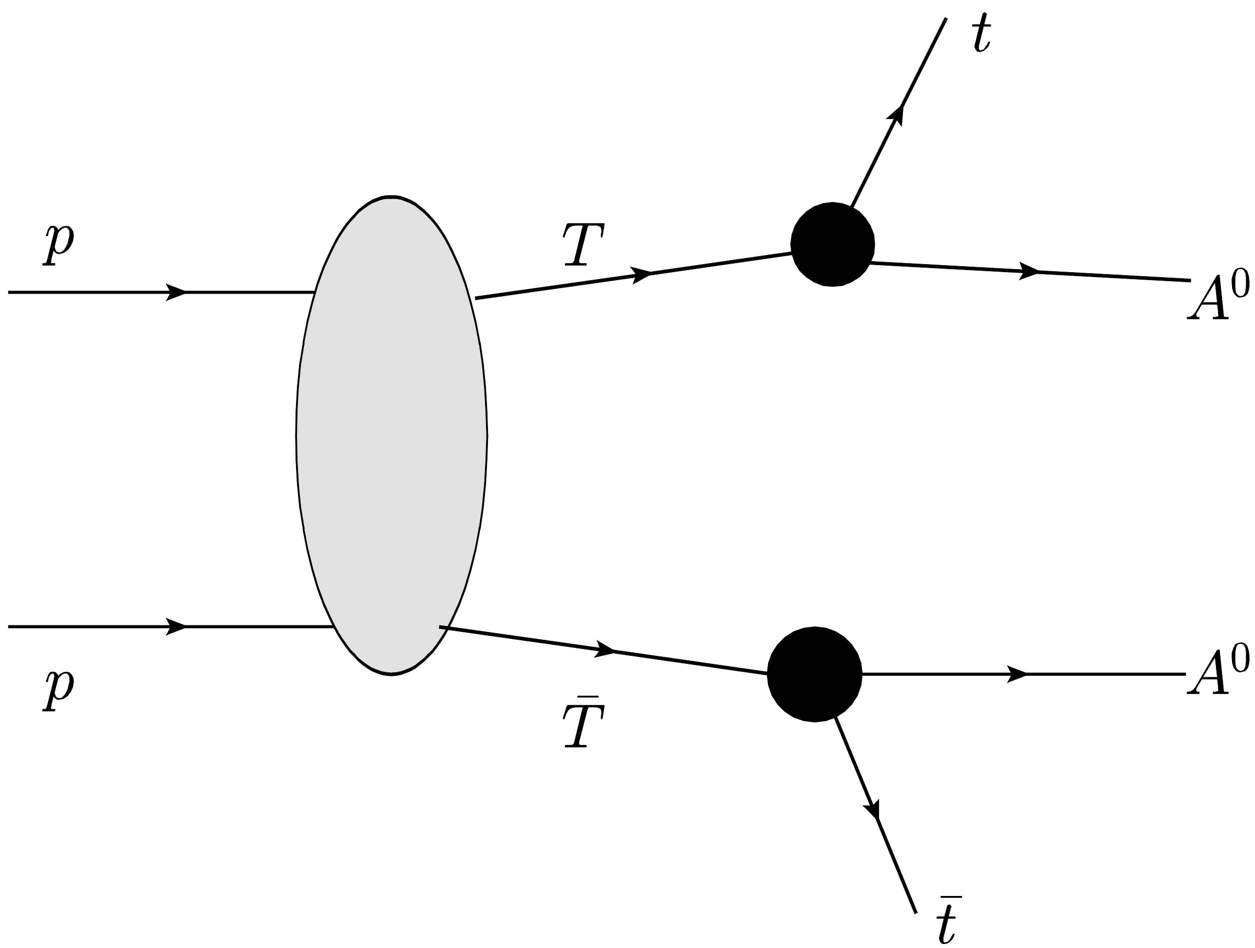
- Pair production of t′ followed by
- t′→ Wb, "heavy top"

Signal of top partner (without parity).

- What about the tZ and th_0 channels?
- Expected to be there.
  - $t' \to Wb:tZ:th_0 \approx 2:1:1$ (Goldstone equivalence theorem)

    Perelstein, Peskin, Pierce, 0310039
  - top-like or b-rich signal.

Signal of top partner, with Z_2 parity.



$$t\ \bar{t} + \not{E}_T$$

$T(\bar{T})$ top partner : $\tilde{t},\ t^{\rm KK},\ t^{\rm T},\ ...$

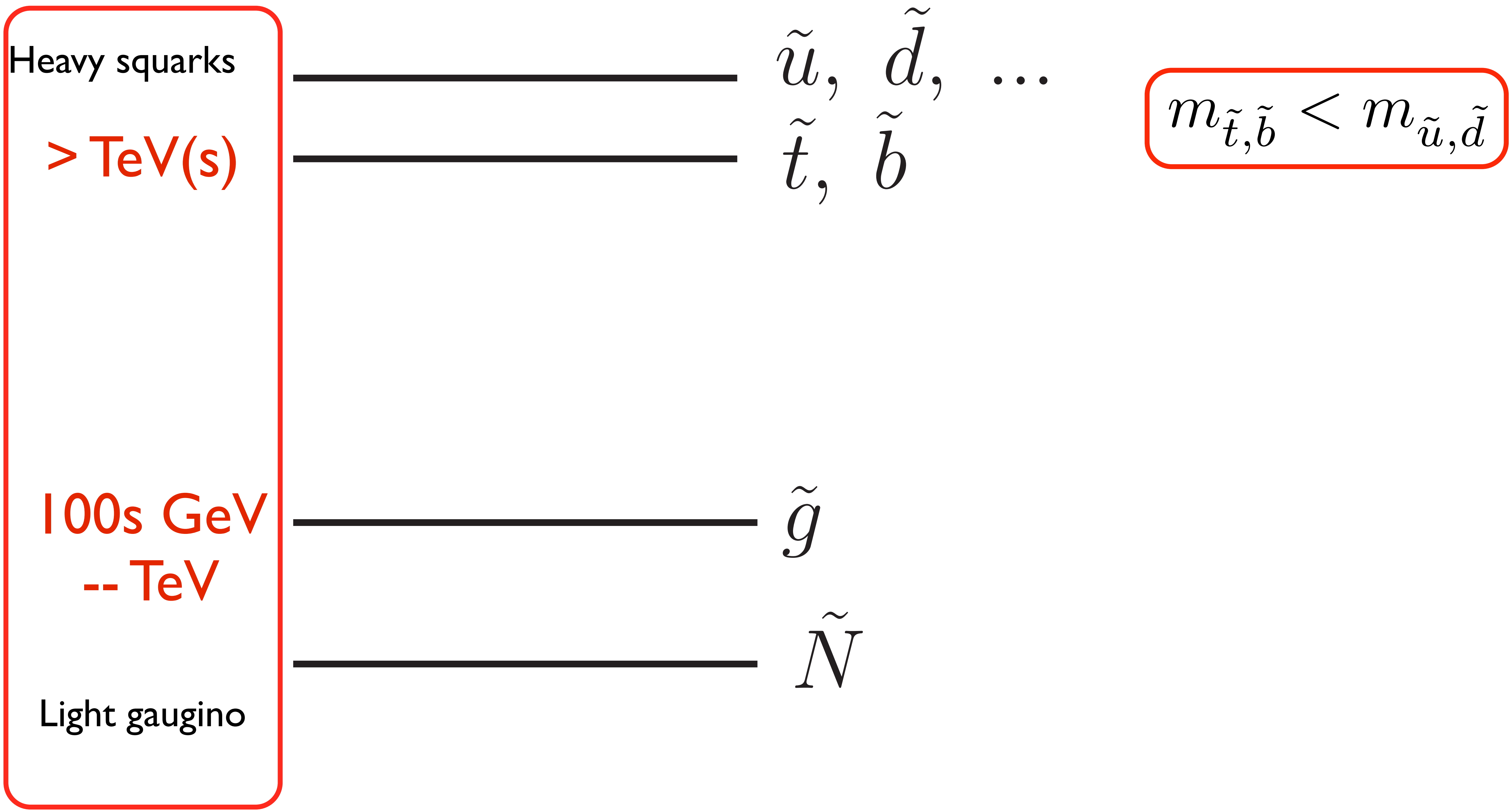
A^0 missing neutral particle : LSP, LKP, LTP, ...

Top partner can have spin 0, 1/2, 1

Difficult due to: limited rate, similar to SM ttbar

Many recent studies. Talk by Reece

A promising scenario.



Why considering heavy scalars?

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- On general round, scalar tends to be heavier.
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  - R-symmetry tends to protect gaugino mass terms.
- Examples: F-term SUSY breaking.
  - With R-symmetry broken. But gauginos are sequestered (geometry, etc.) at tree level.
  - Gaugino mass from AMSB.

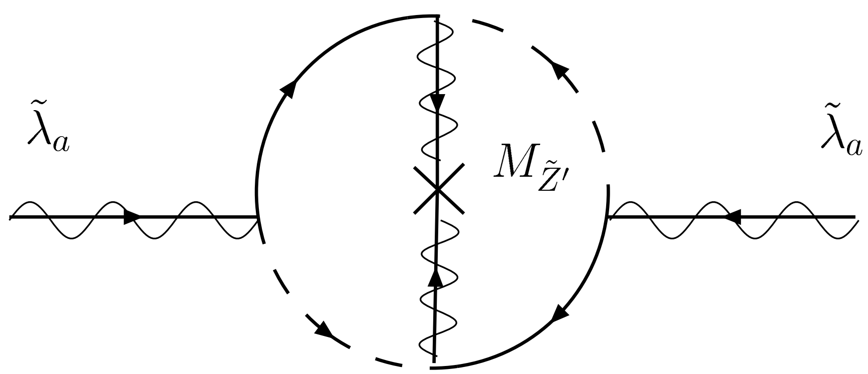
$$m_{\tilde{q},\tilde{\ell}} \sim m_{2/3}, \quad m_{1/2} \sim \frac{1}{16\pi^2} m_{2/3}$$

Zprime-ino mediation.

- Gaugino mediation through an extra U(1)′

$$\int d^2\theta \frac{X}{M} W_{Z'} W_{Z'} \to m_{\tilde{Z}'} = \frac{F_X}{M}$$

$$m^2_{\tilde{q},\tilde{\ell}} \sim \frac{g^2_{Z'}}{16\pi^2}\frac{F_X^2}{M^2}, \quad m_{1/2}^{\rm MSSM} \sim \frac{g^2 g'^2_Z}{(16\pi^2)^2}\frac{F_X}{M}$$



$$\frac{m_{\rm scalar}}{m_{\rm MSSM\ gaugino}} \sim (4\pi)^3$$

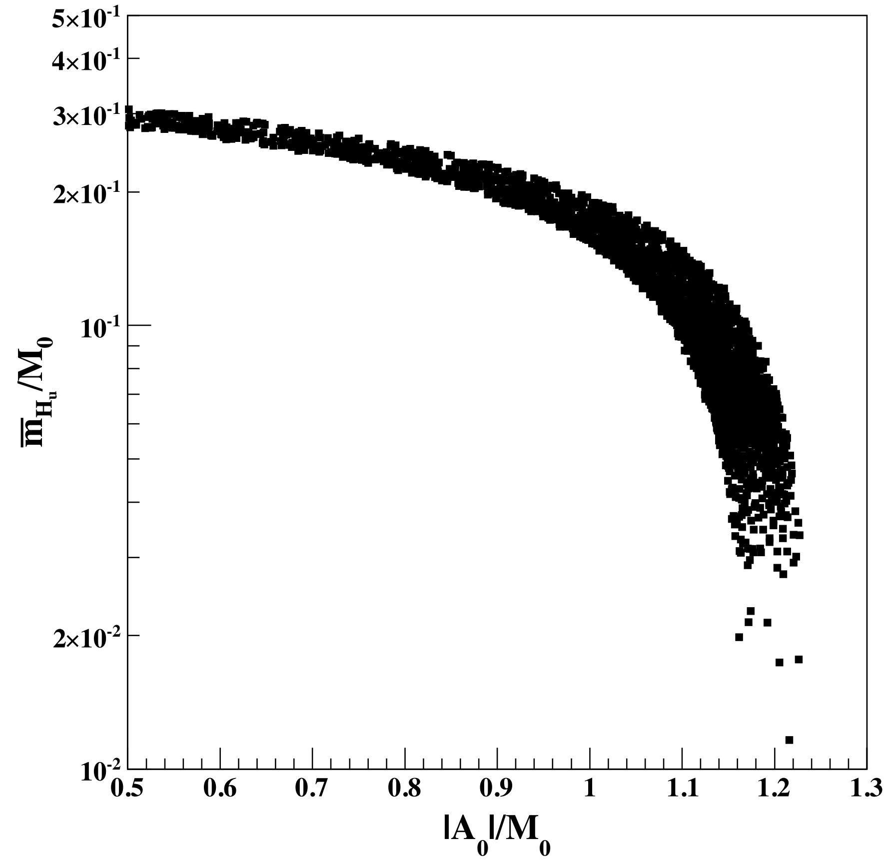
Langacker, Paz, LTW, Yavin, 0710.1632,
Verlinde, LTW, Wijnholt, Yavin, 0711.3214

Heavy scalar benefits.

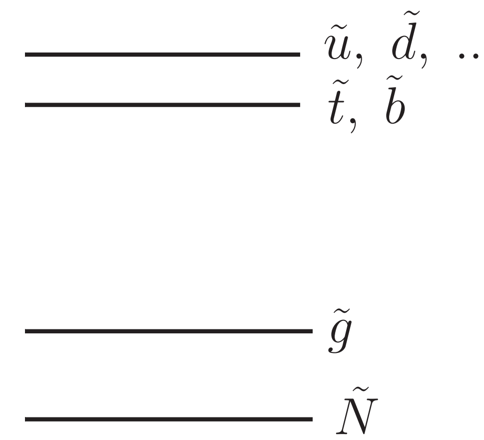
- Better consistency with constraints:
  - flavor, CP: $\propto 1/(16\pi^2\, m^2_{squark})$
  - Higgs mass (125?) in MSSM: $\approx m_Z^2 + 3/(2\pi^2)\, |y_t\, m_t|^2 \log[(m_{stop})/m_t]$

- Fine with EWSB.

Feldman, Kane, Kuflik, Lu, 1105.3765



3rd vs first two generations



- RGE.

$$\frac{dm^2_{\tilde{t},\tilde{b}}}{dt} = \frac{1}{16\pi^2}|y_{t,b}|^2(m^2_{H_{u,d}} + m^2_{Q_3} + m^2_{\tilde{t}_R,\tilde{b}_R}) + ...$$

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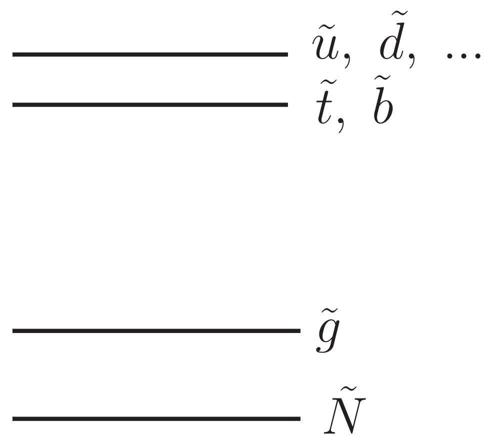

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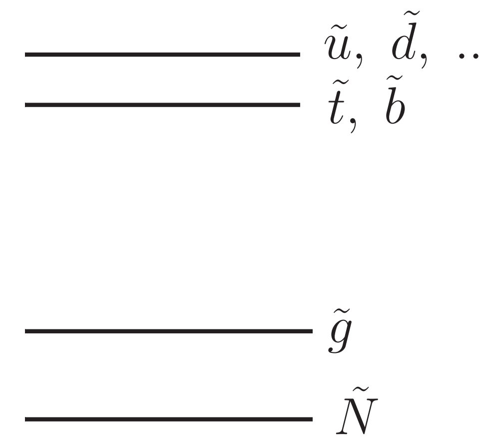

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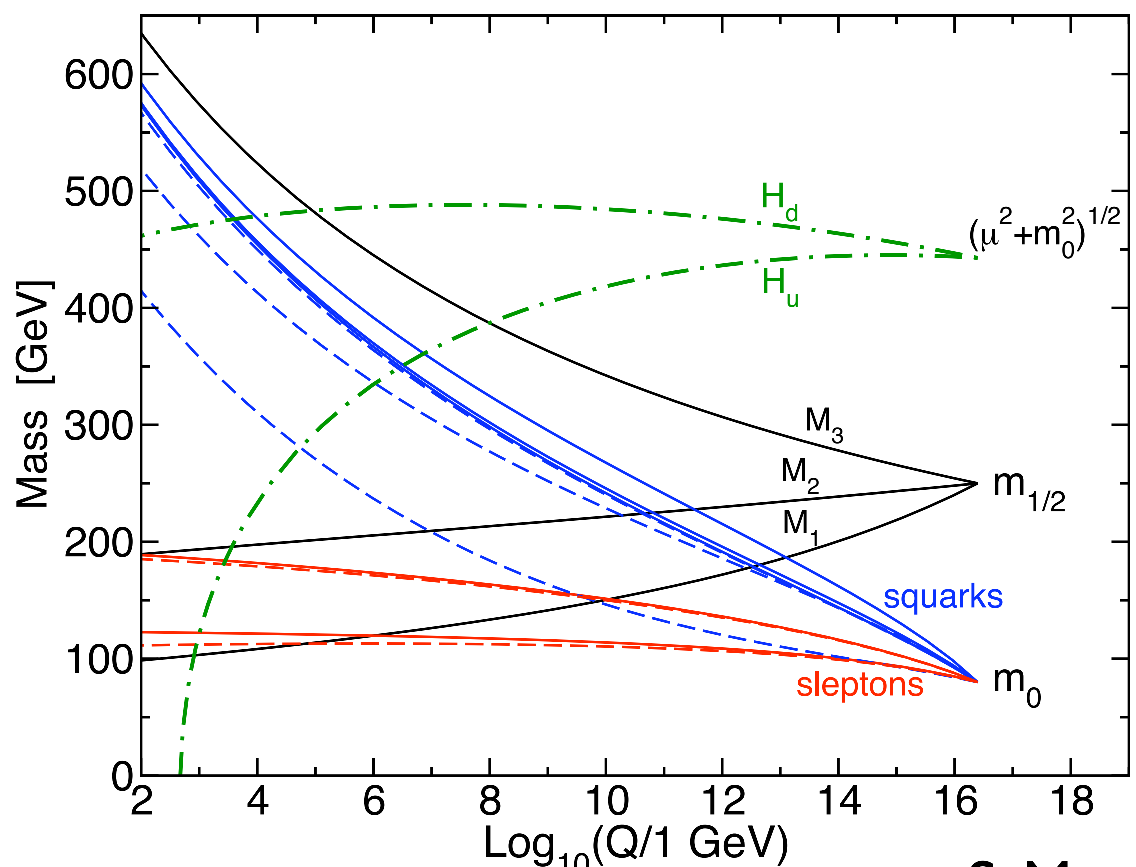

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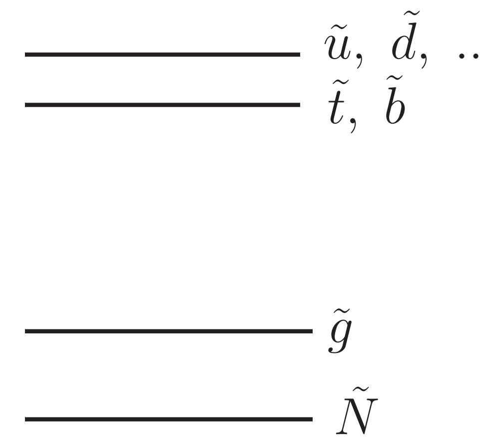

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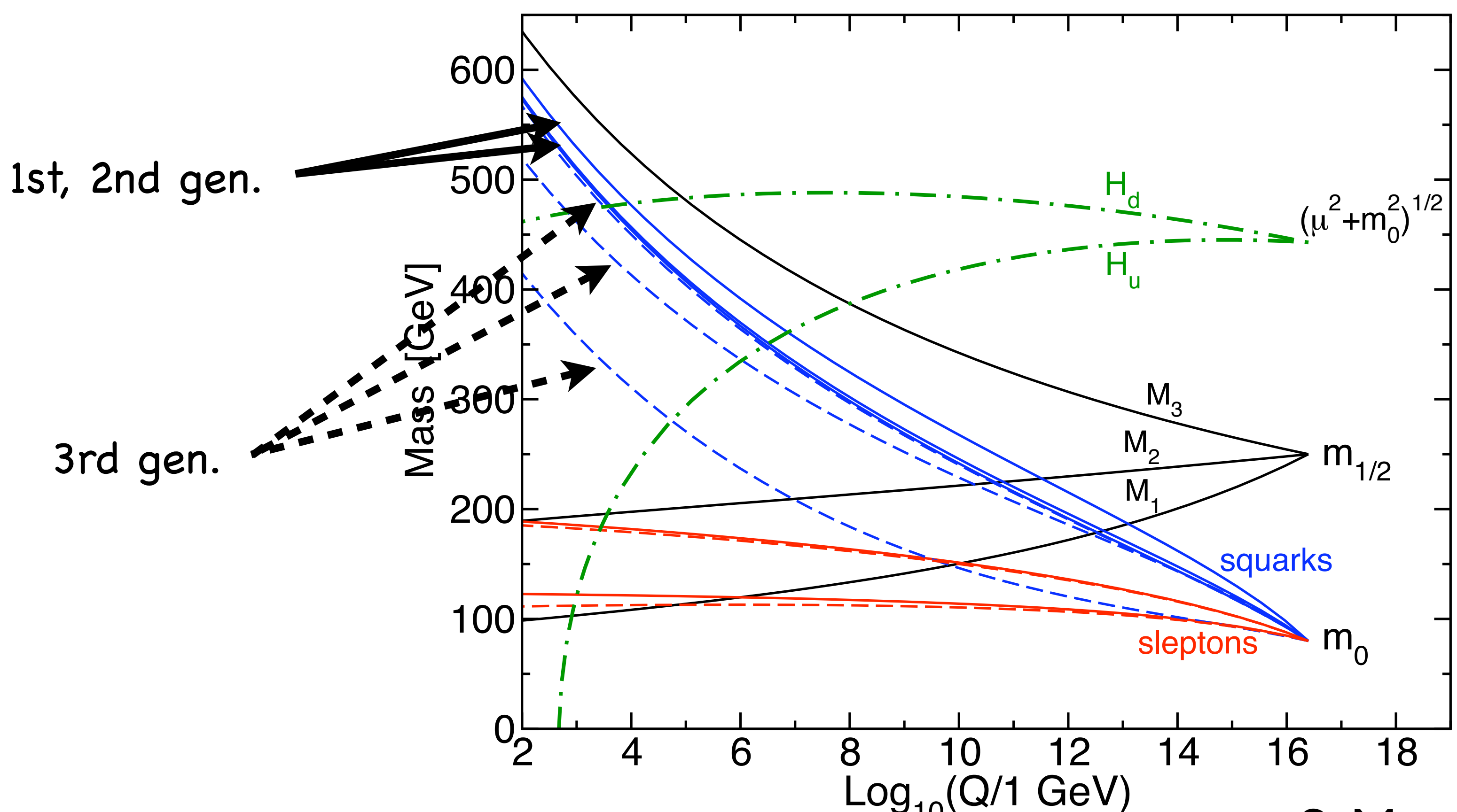

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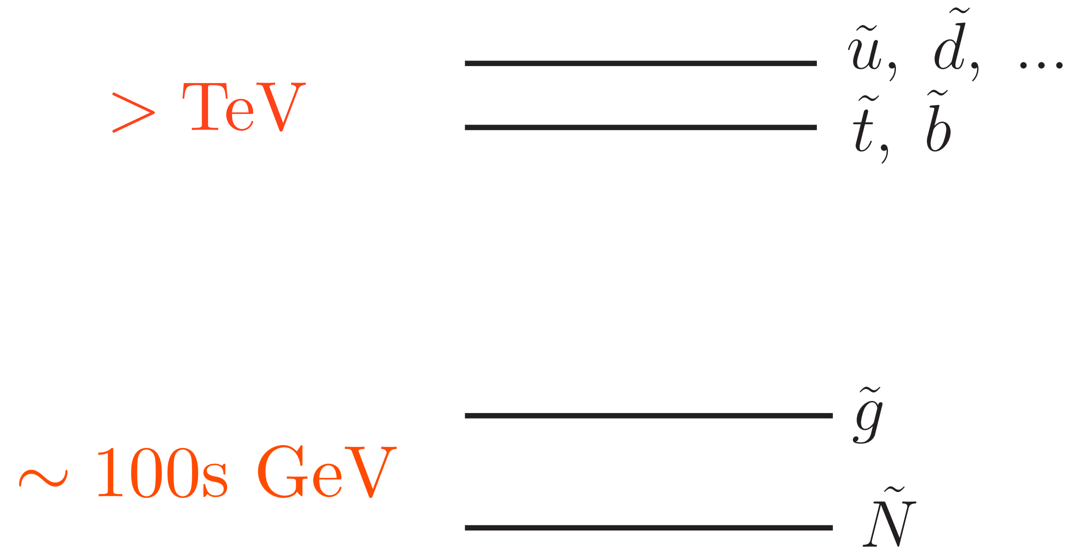
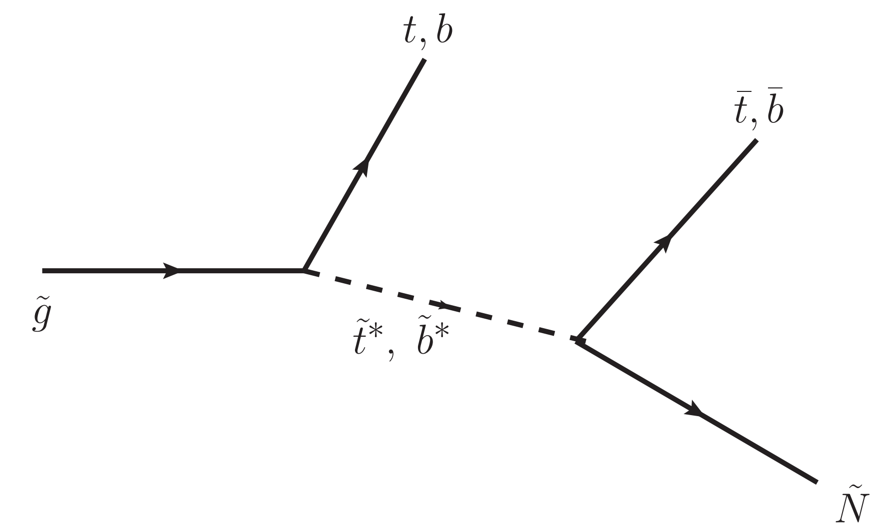
Recent Models (partial list)

- Langacker, Paz, LTW, Yavin, 0710.1632
- Verlinde, LTW, Wijnholt, Yavin, 0711.3214
- Acharya, Bobkov, Kane, Kumar, 0801.0478
- Nakamura, Okumura, Yamaguchi, 0803.3725
- Everett, Kim, Ouyang, Zurek, 0806.2330
- Hackman, Vafa, 0809.3452
- Sundrum, 0909.5430
- Barbieri, Bertuzzo, Farina, Lodone, Rappadopulo, 1004.2256

A promising, and complicated, scenario.

Kane, Kuflik, Lu and LTW, 1101.1963





The Dominant channel

$$p\,p \to \tilde{g}\tilde{g} \to t\bar{t}t\bar{t}(\text{or } t\bar{t}b\bar{b},\ t\bar{t}t\bar{b}\ \ldots)$$

$$\tilde{g} \to t\bar{t}(b\bar{b}) + \tilde{N},\ \text{or}\ \ t\bar{b} + \tilde{C}^- \quad t \to b\ell^+\nu$$

- Multiple b, multiple lepton final state.
  - Good early discovery potential.
  - Challenging to interpret: top reconstruction difficult.

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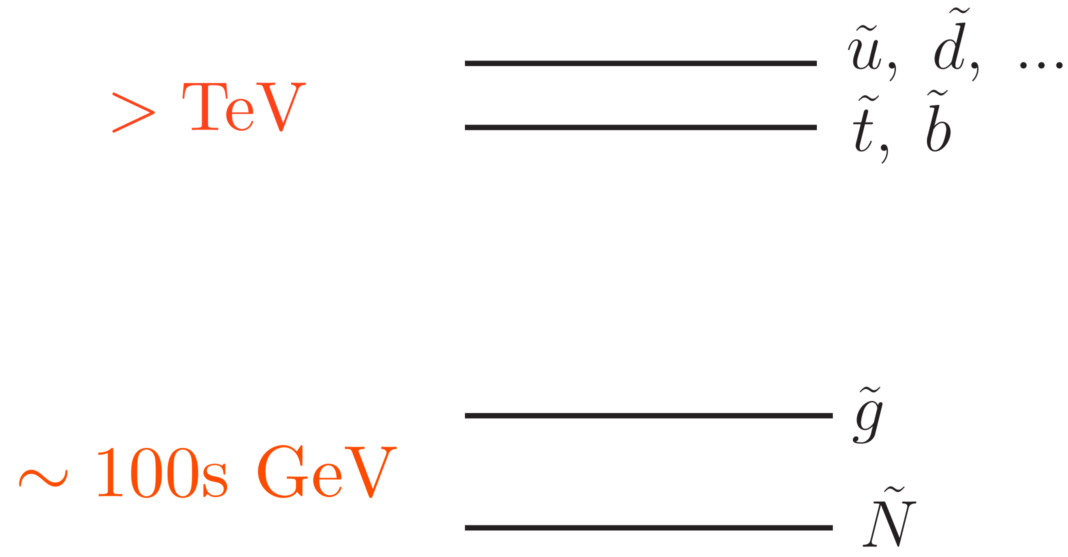

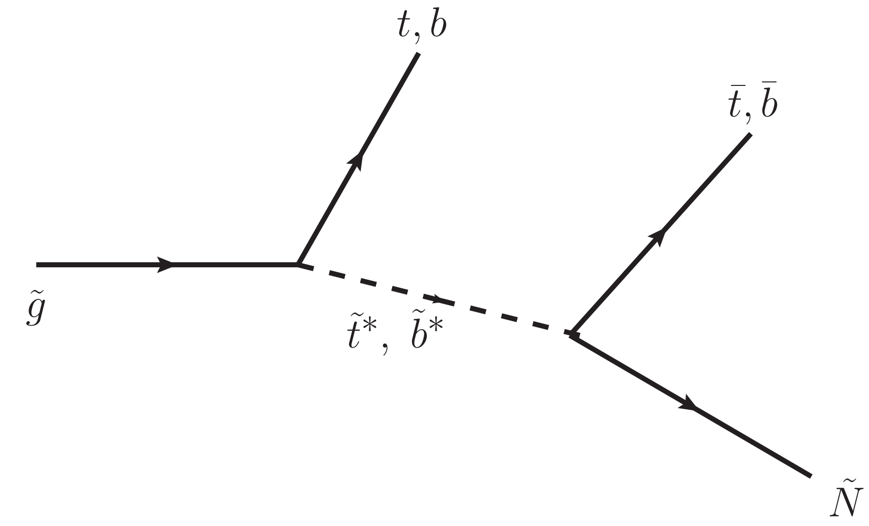

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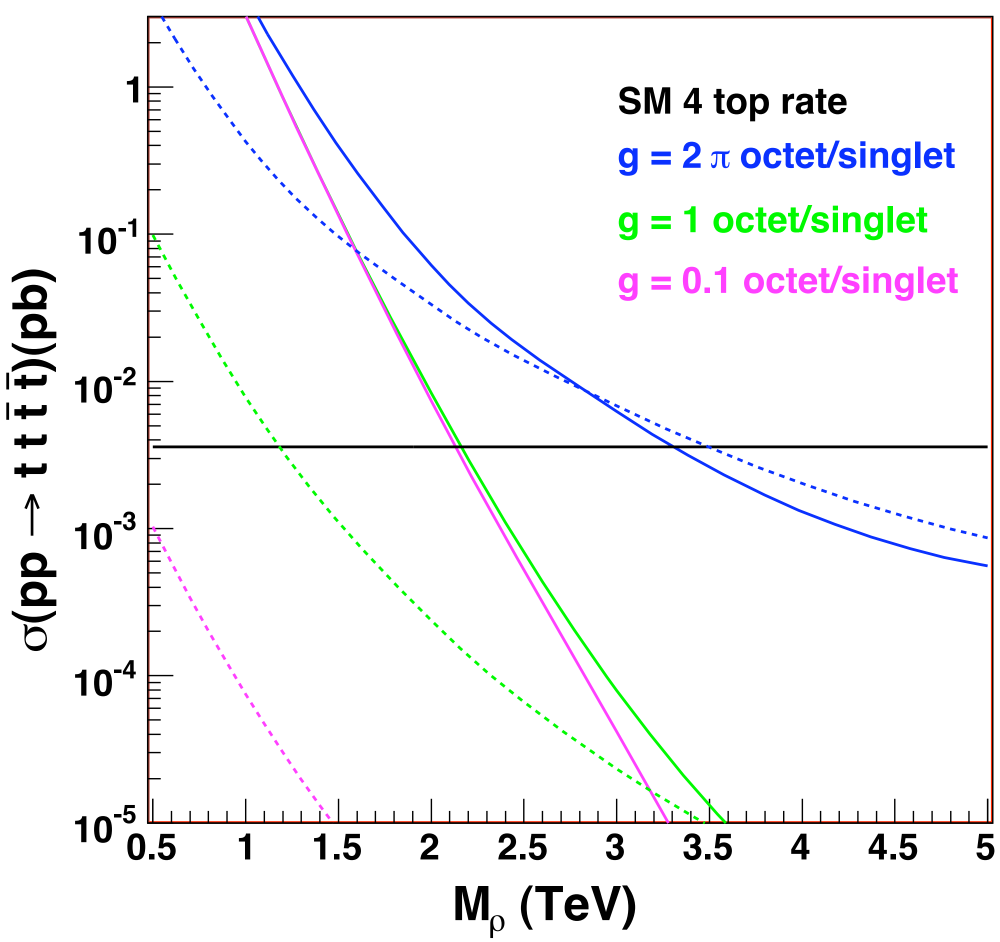
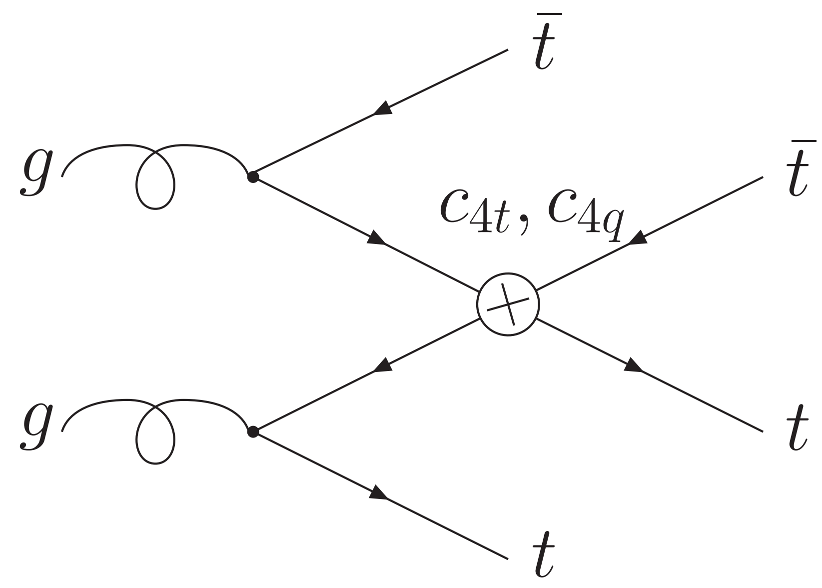
Quite a few recent searches

Signal similar to [gluino→on-shell stop], talk by Reece

Another multi-top signal: top compositeness





Lillie, Shu, Tait, 0712.3057

Pomarol, Serra, 0806.3247

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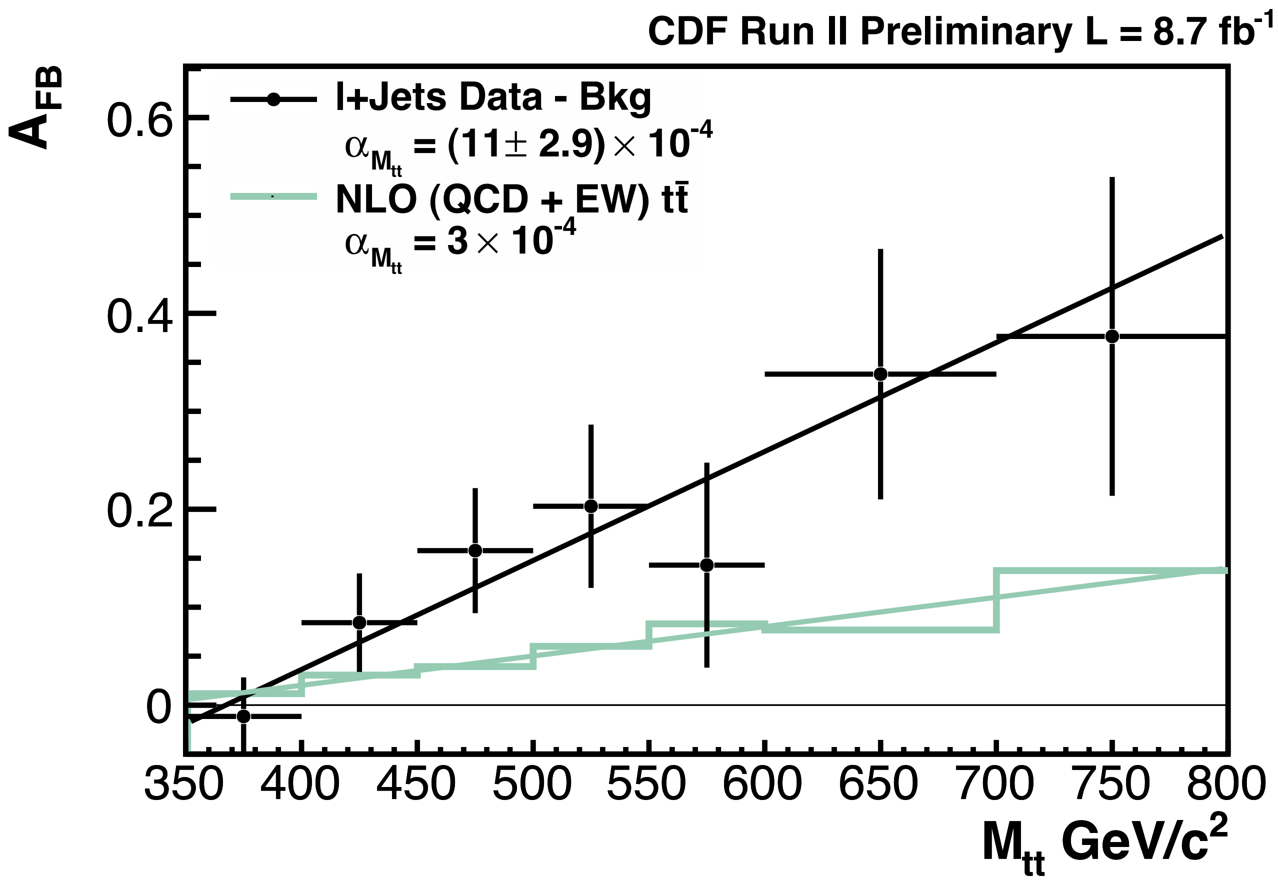
- 4th generation (motivated by the first 3).

Top can give us surprises.

It is the least tested sector

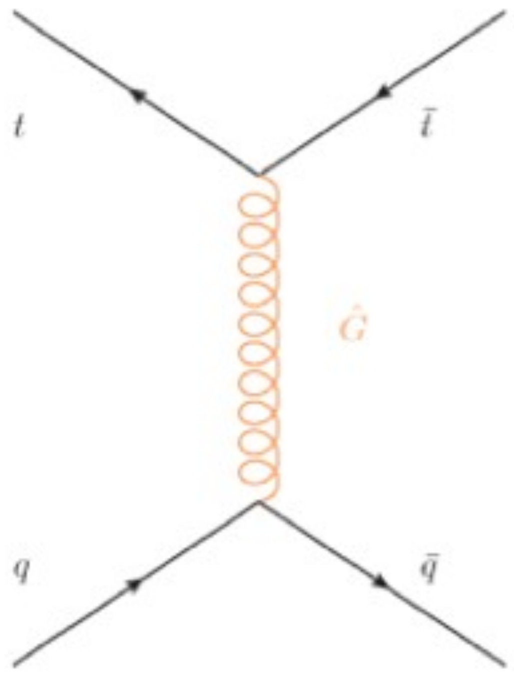
For example: Top AFB

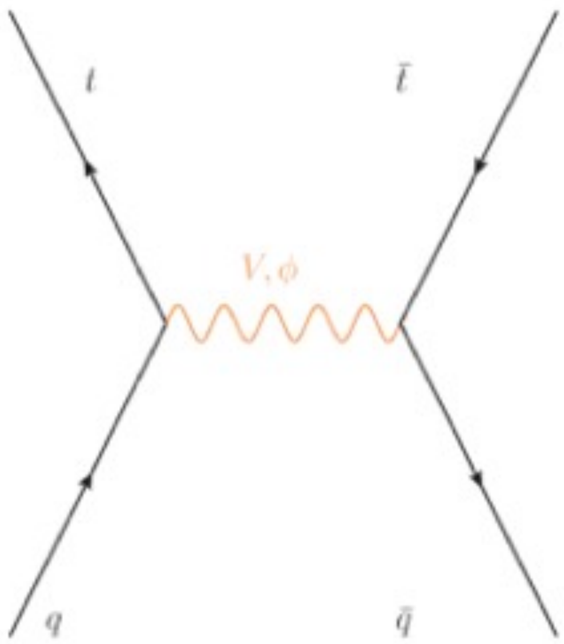
- Motivated by potential experimental evidence.



- Many studies and models.

Two classes of Models.





- S-channel. Large couplings. “work”s.
- G: 1-2 TeV or 400 GeV.
- ttbar resonance search.

- t-channel. Large couplings. “work”s. Flavor “structure”.
- $O(10^2)$s GeV mediator.
- tqq resonances.

At the LHC.

- AFB measurement less direct, but possible.
- However,
  - All models are designed to give large AFB and barely consistent with other Tevatron ttbar data.
    - Surprising if nature works this way.
  - At the LHC, with the large increase of E_{cm}, can not stay hidden anymore.
  - Current LHC data should already give strong constraints.

Various tests of models

- New resonance searches (Kim, Gresham, Zurek (2011); Hewett, Shelton et al (2011))
- Same sign top pair production: t-channel Z' model (Berger et. al. (2011))
- Excesses in ttbar and single t production (Aguilar-Saavedra, Perez-Victoria (2011); Gedalia et al (2011); Degrande et al (2011))
- Top polarization: measure chiral structure (D. Krohn, Tao Liu, J. Shelton, LTW (2011); Godbole et. al.; Choudhury et. al. (2010); V. Barger et. al (2011))
- Non-SM spin-correlation of top pair: distinguish s- and t-channel models (D. Krohn, Tao Liu, J. Shelton, LTW (2011))

Will be covered later in the workshop: talk by Zupan

Top polarization as a probe of NP.

- New physics typically gives different top polarizations.
  - e.g. some AFB model prefers right-handed couplings.
- Direct measurement of polarization after accurate reconstruction.
  - Powerful, probably need larger statistics.

(semi)Lepton asymmetry

$$\mathcal{A}^{\ell}_{FB} = \frac{N(q_\ell y_\ell > 0) - N(q_\ell y_\ell < 0)}{N(q_\ell y_\ell > 0) + N(q_\ell y_\ell < 0)}$$

	frame and mass range	$t\bar{t}$ asymmetry	Lepton asymmetry	stat. sig. (5.3 fb^{-1})
G_A	lab, sel. cuts	9 %	4 %	1.1
	lab, $m_{t\bar{t}} > 450$ GeV	17 %	9 %	1.9
	CM, sel. cuts	12 %	6 %	1.7
	CM, $m_{t\bar{t}} > 450$ GeV	19 %	12 %	2.4
G_L	lab, sel. cuts	7 %	-3 %	0.9
	lab, $m_{t\bar{t}} > 450$ GeV	14 %	-1 %	0.2
	CM, sel. cuts	13 %	-4 %	1.4
	CM, $m_{t\bar{t}} > 450$ GeV	20%	-3 %	0.6
G_R	lab, sel. cuts	9 %	12 %	3.9
	lab, $m_{t\bar{t}} > 450$ GeV	14 %	18 %	5.0
	CM, sel. cuts	9 %	16 %	3.5
	CM, $m_{t\bar{t}} > 450$ GeV	15 %	22 %	4.4
W'	lab, sel. cuts	15 %	13 %	3.9
	lab, $m_{t\bar{t}} > 450$ GeV	26 %	22 %	4.9
	CM, sel. cuts	20 %	16 %	4.4
	CM, $m_{t\bar{t}} > 450$ GeV	31 %	26 %	5.3

- Nice performance on G_R and W' .
- CM frame asym. better, but lab frame asym. already useful.
- G_L, G_A models are more difficult. But can improve with full data set.

D. Krohn, Tao Liu, J. Shelton, LTW (2011)

Conclusions.

- Top rich final states are well motivated in search for BSM NP.
  - I would argue it is the place to look for NP.
- In this talk
  - Top - Higgs connection
  - ttbar resonances.
  - Top partner.
  - ttbar AFB.
- More possibilities. Can have surprises.

extras

Benchmark models

- Reference models.

Model	M [TeV]	Γ [TeV]	g_1^A	g_1^V	g_3^A	g_3^V	g^A	g^V
G_A	2.0	1.40	-2.3	0.0	3.35	0.0	/	/
G_L	2.0	1.40	-2.3	0.0	3.35	3.35	/	/
G_R	2.0	1.40	-2.3	0.0	3.35	-3.35	/	/
W'	0.40	0.04	/	/	/	/	-0.90	0.90

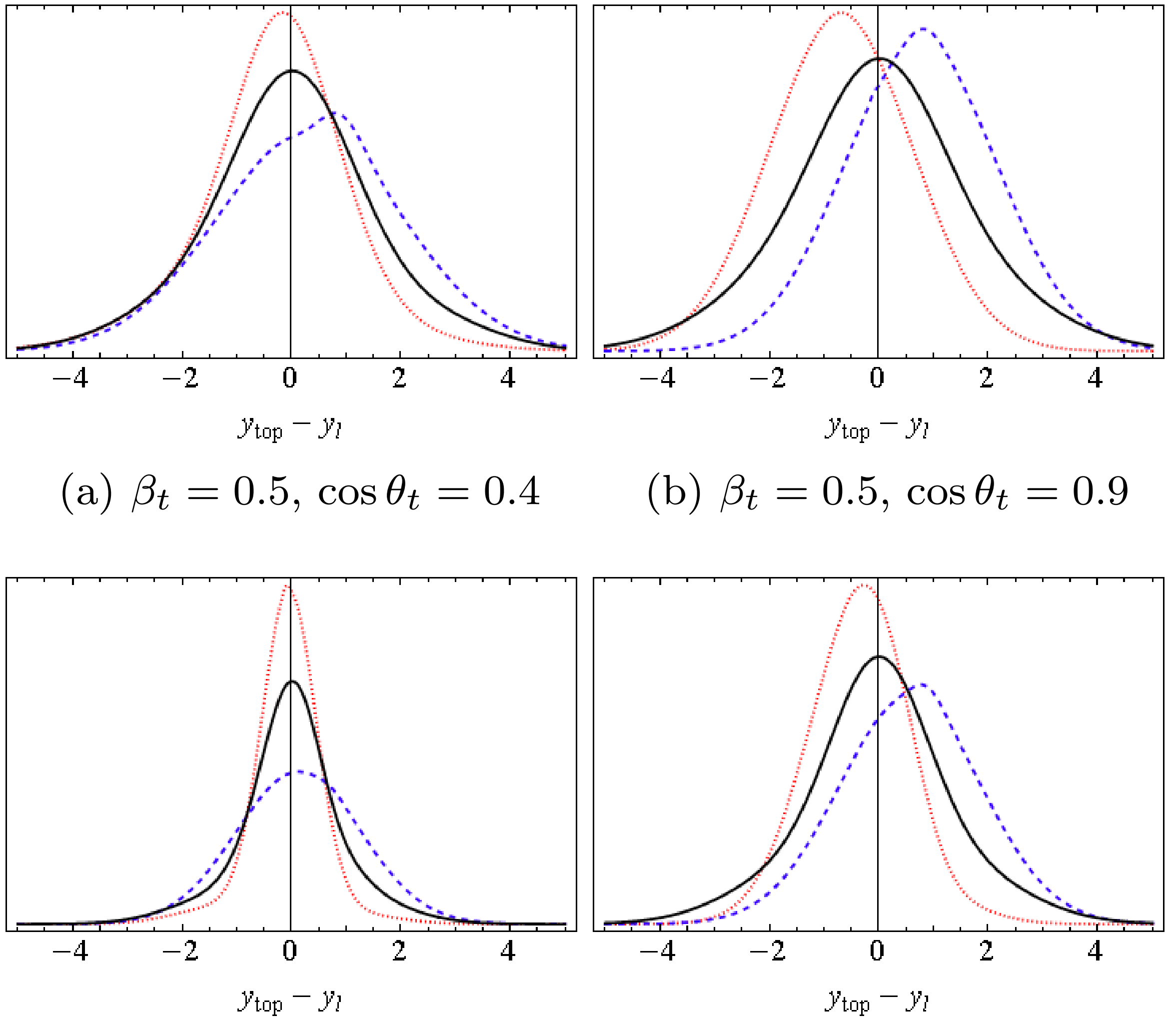
Model	$\sigma_{tt}^{\text{Tevatron}}$[pb]	σ_{tt}^{LHC}[pb]	A_{fb}^{Tevatron}
SM	5.6	89	0%
G_A	5.8	91	14%
G_L	6.1	95	13%
G_R	6.1	95	13%
W'	7.3	123	24%

- Our simulation
  - Madgraph + Pythia + PGS.

Using leptons

red: RH, blue: LH, black: SM

- Charge leptons "follows" the direction of top. Probes AFB.
- (left) right-polarized top leads to (anti)boosted leptons. Probes chiral coupling.



(a) $\beta_t = 0.5,\ \cos\theta_t = 0.4$ (b) $\beta_t = 0.5,\ \cos\theta_t = 0.9$

(c) $\beta_t = 0.9,\ \cos\theta_t = 0.4$ (d) $\beta_t = 0.9,\ \cos\theta_t = 0.9$

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_{i,n}} = \frac{1}{2}(1 + \mathcal{P}_n \kappa_i \cos\theta_{i,n})$$

$$\kappa_{\text{lepton}} = 1$$

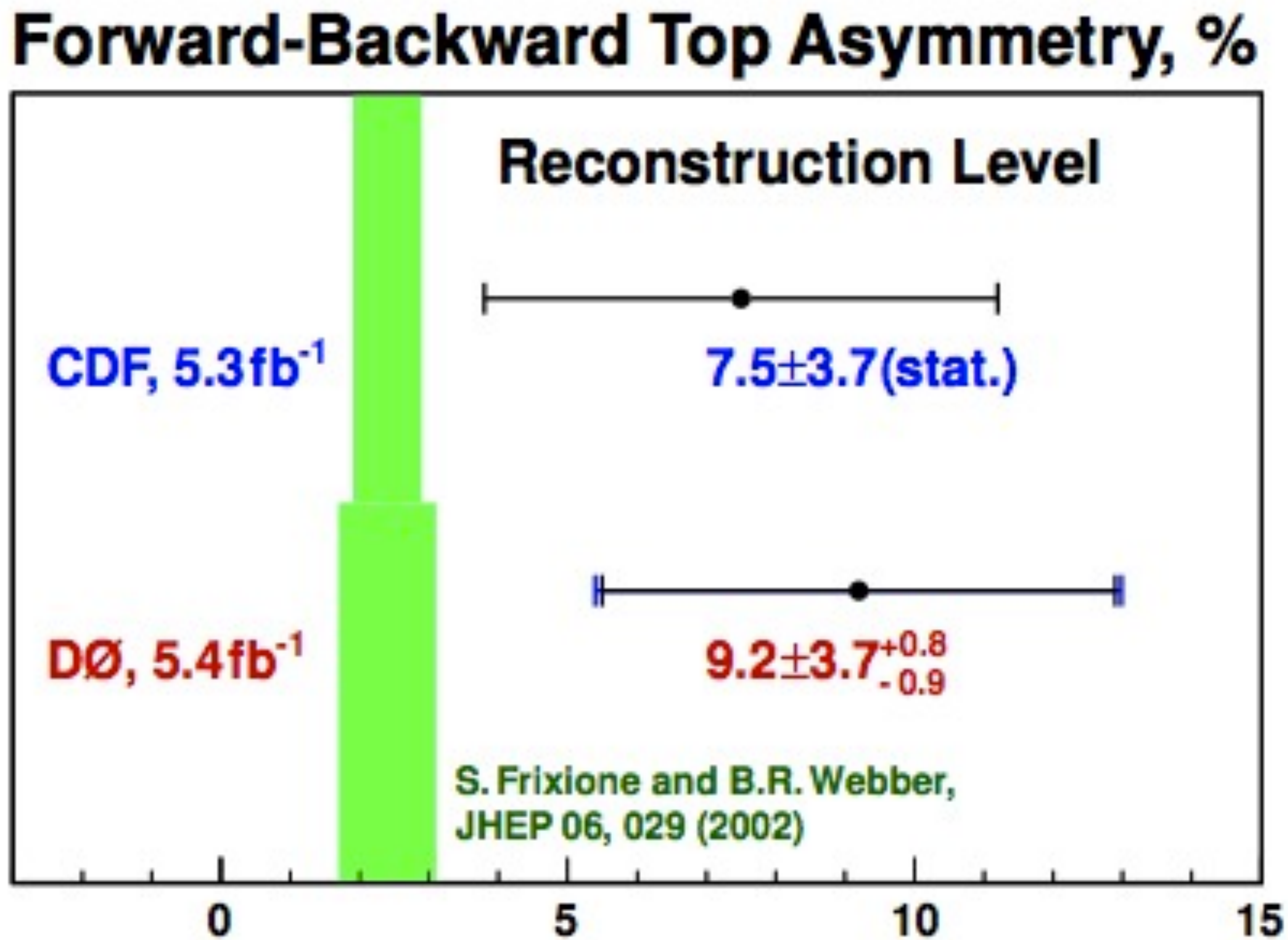
$$\mathcal{P}_n = 1(-1),\ \text{right(left)-handed}$$

(di)leptonic asymmetry

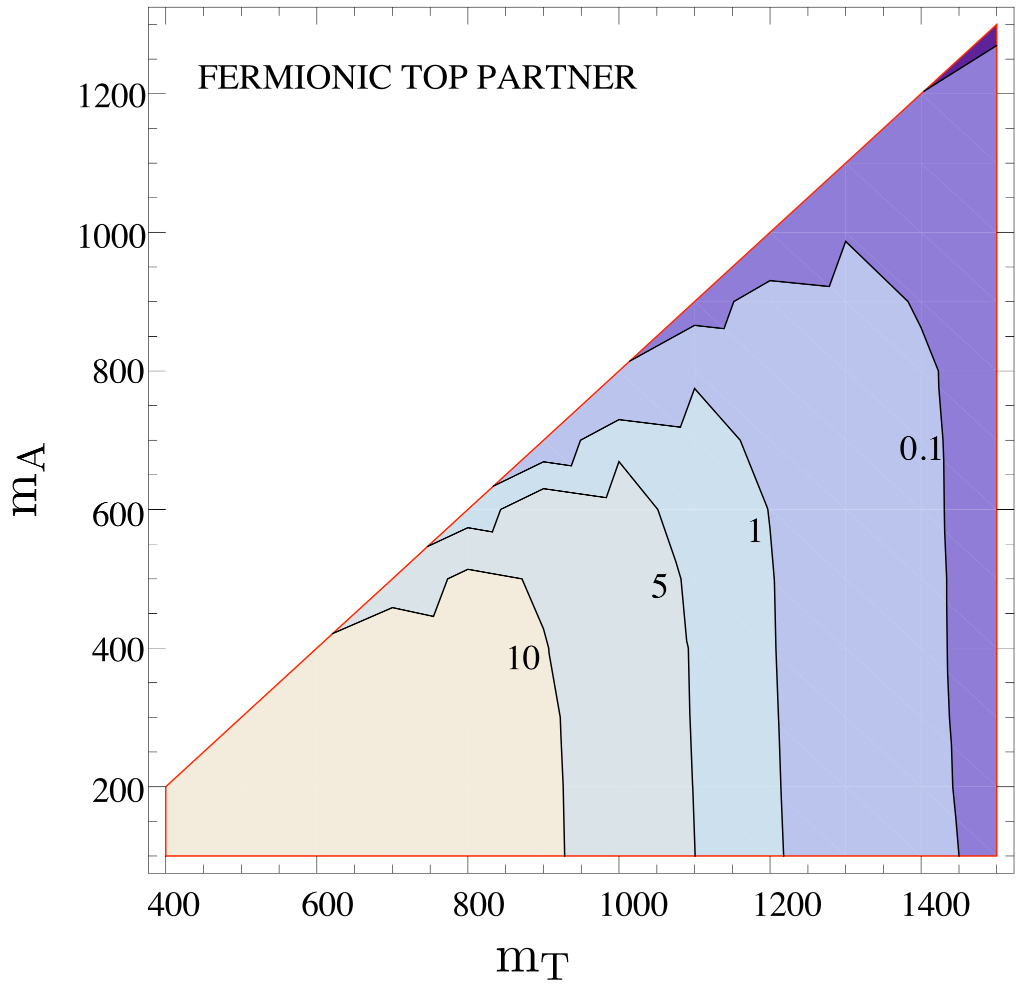
$$\mathcal{A}_{FB}^{\Delta\ell} = \frac{N((y_{\ell^+} - y_{\ell^-}) > 0) - N((y_{\ell^+} - y_{\ell^-}) < 0)}{N((y_{\ell^+} - y_{\ell^-}) > 0) + N((y_{\ell^+} - y_{\ell^-}) < 0)}$$

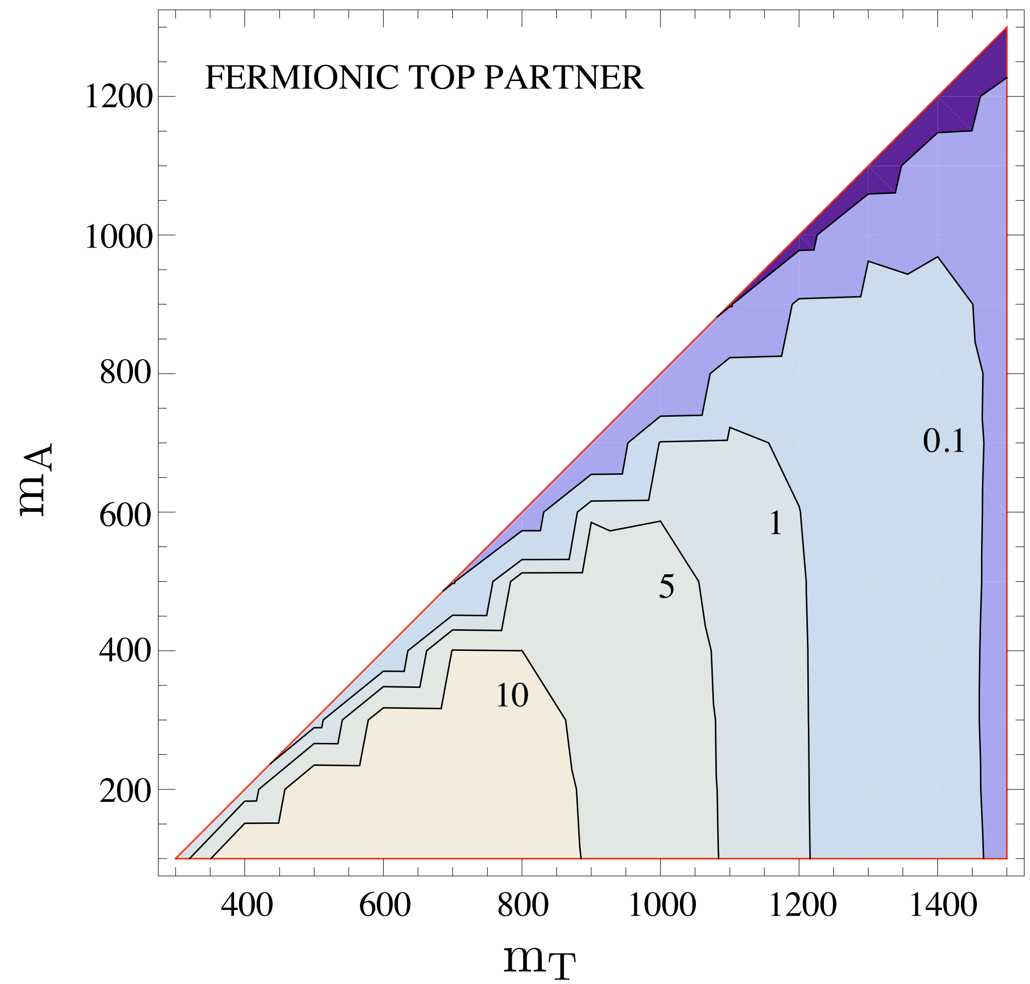
	mass range	asymmetry (5.1 fb^{-1})	stat. sig.
G_A	sel. cuts	8 %	1.2
	$m_{t\bar{t}} > 450$ GeV	14 %	1.4
G_L	sel. cuts	-4 %	0.5
	$m_{t\bar{t}} > 450$ GeV	1 %	0
G_R	sel. cuts	15 %	2.4
	$m_{t\bar{t}} > 450$ GeV	20 %	2.1
W'	sel. cuts	15 %	2.3
	$m_{t\bar{t}} > 450$ GeV	24 %	2.6

- Useful and complementary to the semileptonic mode, especially with the full data set.


Forward-Backward Top Asymmetry, %
Reconstruction Level
CDF, 5.3fb-1
7.5±3.7(stat.)
DØ, 5.4fb-1
9.2±3.7+0.8 -0.9
S. Frixione and B.R. Webber,
JHEP 06, 029 (2002)
0
5
10
15

Top partner reach, 14 TeV, 100 fb^{-1}





Polarization: LHC

$$\mathcal{P}_n = \frac{N(\cos\theta_{\ell,n} > 0) - N(\cos\theta_{\ell,n} < 0))}{N(\cos\theta_{\ell,n} > 0) + N(\cos\theta_{\ell,n} < 0))}$$

- Select helicity basis as the polarization axis

	$G_A(\%)$	$G_L(\%)$	$G_R(\%)$	$W'(\%)$	SM(%)
Selection cuts	1	-1	4	18	1 (±1.2)
$m_{t\bar{t}} > 450$ GeV	2	-2	6	26	0 (±1.7)
$\lvert y(t) + y(\bar{t})\rvert > 2$	0	-4	3	19	-2 (±3.2)

- Select beam basis as the polarization axis

	$G_A(\%)$	$G_L(\%)$	$G_R(\%)$	$W'(\%)$	SM(%)
Selection cuts	4	-1	5	9	2 (±1.2)
$m_{t\bar{t}} > 450$ GeV	1	-4	4	11	0 (±1.7)
$\lvert y(t) + y(\bar{t})\rvert > 2$	2	-5	7	15	1 (±3.2)

- The GR and W' models can be distinguished from the SM at a C.L. > 3 sigma in the helicity basis
- The left- chiral, right-chiral models and the SM can be distinguished from each other at a C.L. > 2 sigma in the beam basis

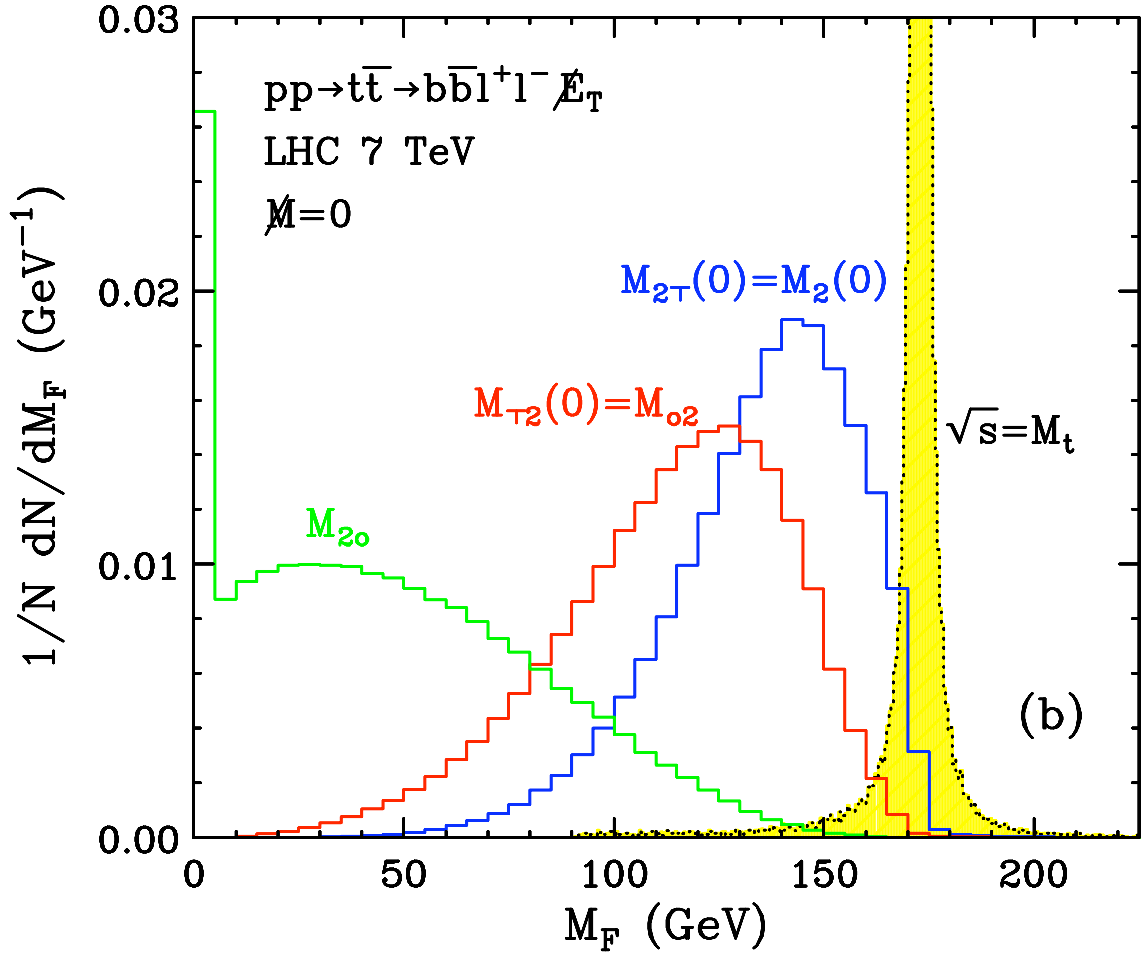
See our paper for more details

Top as testing ground.

- Top is heavy, gives new physics-like signals.
  - With high multiplicity final state.
  - With jets, lepton and MET.
- Headache for new physics discovery.
  - Important to understand it very well.
- Good testing ground for many kinematical variables, reconstruction techniques.
  - M_{T2} and its descendants

A recent example

Barr, Konar, Kong, Lester, Matchev, Park1108.5182

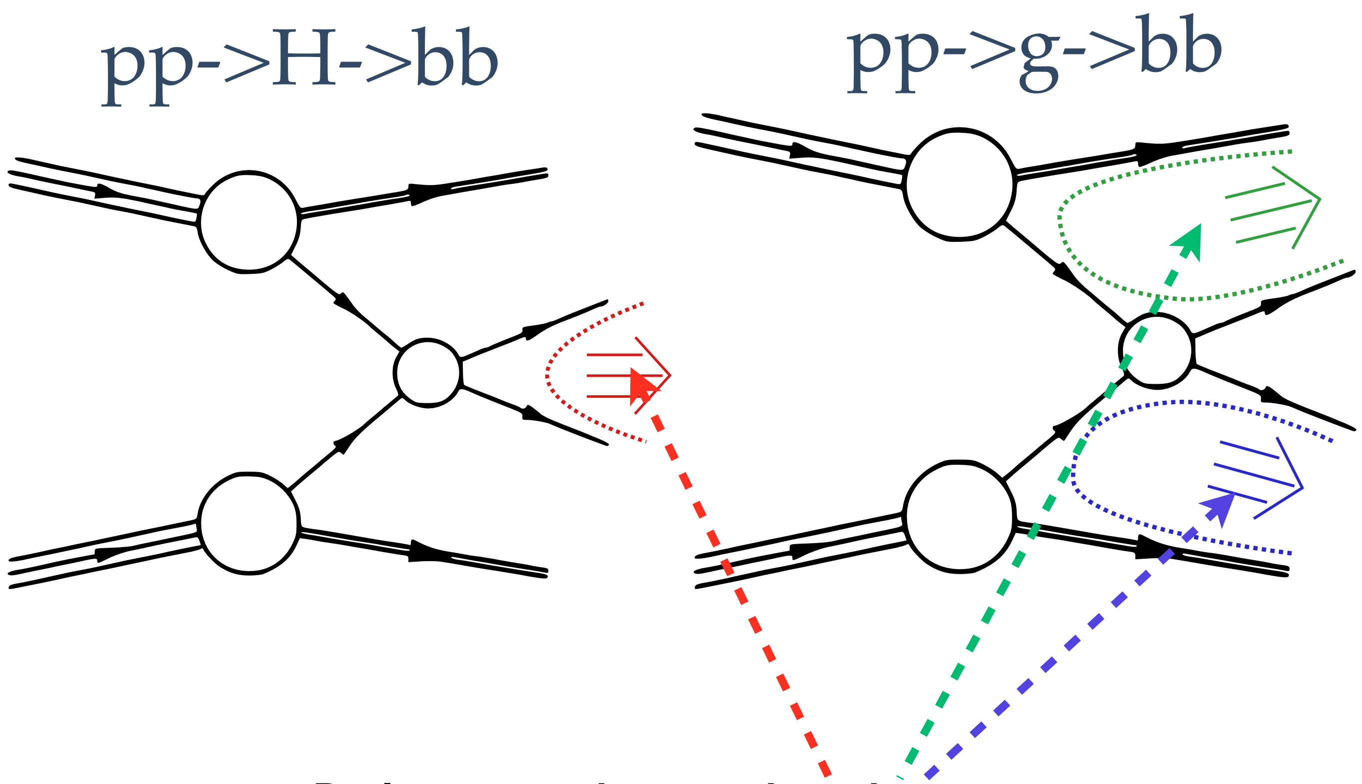


- Such variables are crucial in discovery and reconstruction of NP.

- They can be affected by additional radiation, etc.
  - More tests.

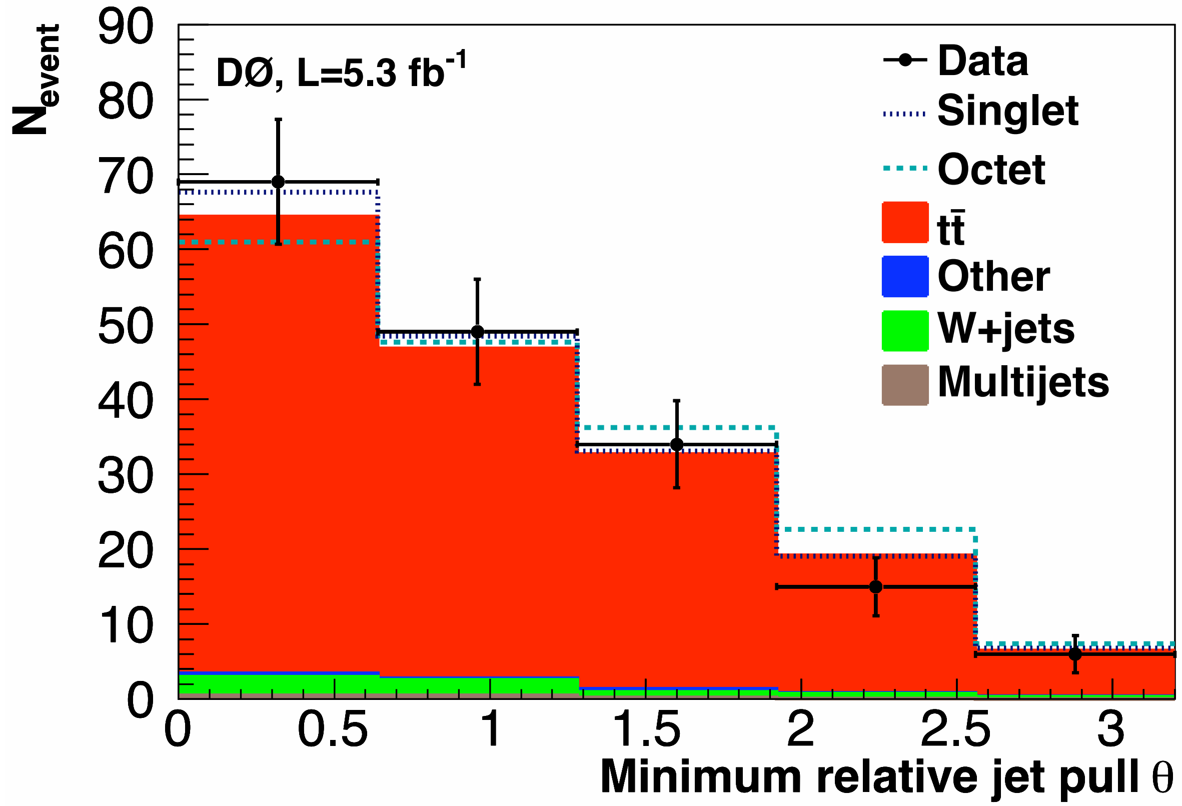
Superstructure

Gallicchio, Schwartz, 1001.5027



- Using more global information.
- Applications to other channels as well.
- Not very well modeled by MC, exp. test crucial.

W→ jets in ttbar



- part of ttbar events
  - Good (statistics) sample of singlet→dijet.
- Sensitive to higher level of pile-up.

Examples.

- F-term breaking, with R-symmetry preserved.

$$W = \mu^2 X + ..., \quad K = XX^\dagger + \frac{(XX^\dagger)^2}{M^2} + ...$$

$$R[X] = 2, \quad F_X = \mu^2, \quad \langle X \rangle = 0$$

$$\int d^4\theta \frac{XX^\dagger}{M^2} Q^\dagger Q \rightarrow m_{\tilde{Q}}^2 = \frac{\mu^4}{M^2}$$

$$\int d^4\theta \frac{XX^\dagger}{M^3} W_\alpha W^\alpha r \rightarrow m_{1/2} = \frac{\mu^4}{M^3} r$$

r: additional R-symm breaking spurion

- Similar story for D-term breaking.