Dark Matter Motivated Searches for
Exotic 4th Generation Mirror Quarks

Shufang Su • U. of Arizona

In collaboration with J. Alwall, J.L. Feng, J. Kumar

arXiv: 1002.3366

Exotic 4th Generation Mirror Quarks

S. Su

Exotic 4th Generation Mirror Quarks

chiral under SM gauge group

Exotic 4th Generation Mirror Quarks

chiral under SM gauge group

same charge
opposite chirality

S. Su

Exotic 4th Generation Mirror Quarks

chiral under SM gauge group

charge under
hidden symmetry

same charge
opposite chirality

Outline

- Motivation: general / specific
- WIMPless model
- Constraints
- Simulations and cut analysis
- Exclusion and discovery reach
- Conclusion

Dark matter motivation: general

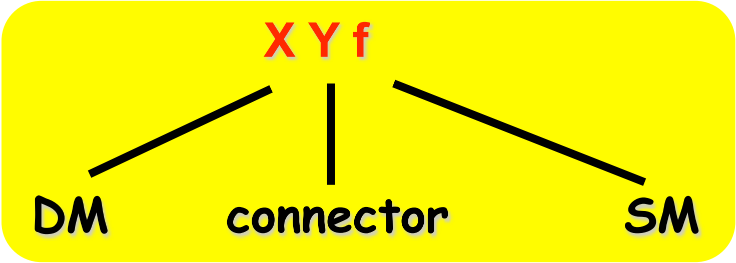
Dark Matter: long-lived on cosmological time scale

Charge under a new unbroken symmetry ⇒ absolutely stable

- have only gravitational interaction with the SM

  can not be discovered at colliders

- couple to SM through connector Y YY production with $y \to f\,X$



Dark matter motivation: general

Dark Matter: long-lived on cosmological time scale

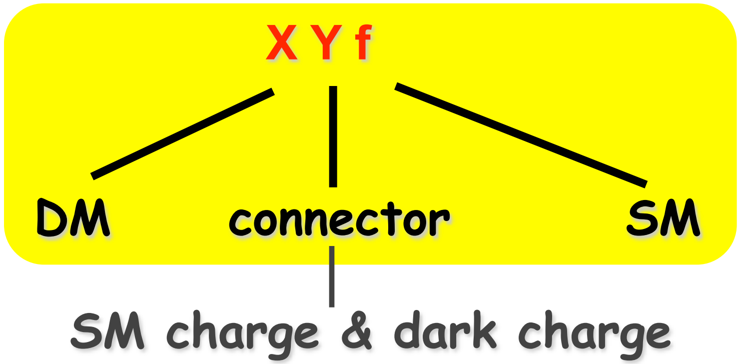
Charge under a new unbroken symmetry ⇒ absolutely stable

- have only gravitational interaction with the SM

can not be discovered at colliders

- couple to SM through connector Y

YY production with $y \to f\,X$



Dark matter motivation: general

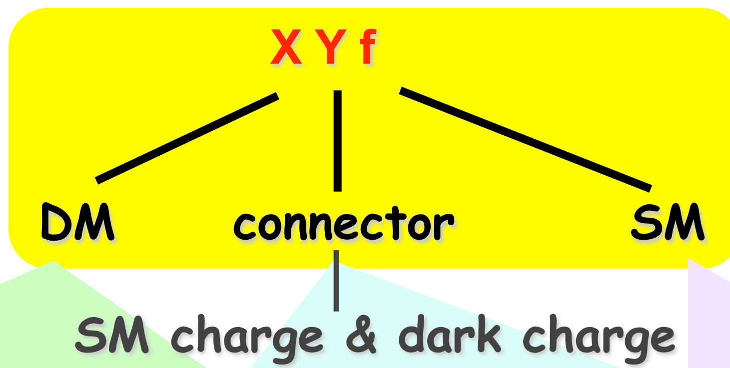
Dark Matter: long-lived on cosmological time scale

Charge under a new unbroken symmetry ⇒ absolutely stable

- have only gravitational interaction with the SM

  can not be discovered at colliders

- couple to SM through connector Y   YY production with y → f X



SUSY	neutralino	squark	quark	R-parity
ExD	KK gauge boson	KK quark	quark	KK-parity
Our study	DM(no SM charge)	exotic quark	quark	dark charge

WIMP miracle

WIMP

- $m_{WIMP} \sim m_{weak}$
- $g \sim g_{weak}$

$$\Omega h^2 \sim \frac{2.6\times 10^{-10}\mathrm{GeV}^{-2}}{\langle\sigma_A v\rangle}$$

$$\langle\sigma_A v\rangle \sim \frac{\alpha^2}{m_{weak}^2} 0.1 \sim 10^{-9}\mathrm{GeV}^{-2}$$

$\Rightarrow \Omega h^2 \sim 0.3$

naturally around the observed value

WIMP miracle

WIMP

- $m_{WIMP} \sim m_{weak}$
- $g \sim g_{weak}$

$$\Omega h^2 \sim \frac{2.6 \times 10^{-10} \mathrm{GeV}^{-2}}{\langle \sigma_A v \rangle}$$

$$\langle \sigma_A v \rangle \sim \frac{\alpha^2}{m_{weak}^2} 0.1 \sim 10^{-9} \mathrm{GeV}^{-2}$$

$\Rightarrow \Omega h^2 \sim 0.3$

naturally around the observed value

WIMPless miracle

$$\Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4}$$

- only fixes one combination of dark matter mass and coupling
- $m_X/g_X^2 \sim m_{weak}/g_{weak}^2$, $\Omega h^2 \sim 0.3$

could have $m_X \neq m_{weak}$ as long as the relation holds

WIMPless DM

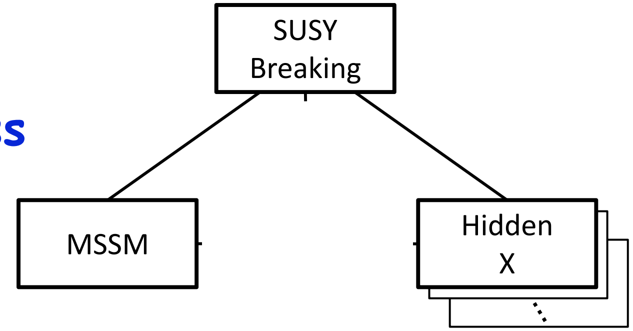
J.L. Feng and J. Kumar, PRL 101, 231301 (2008)

- dark matter: no SM gauge interactions, not WIMP
- naturally obtain right relic density: similar to WIMP

WIMPless model

J.L. Feng and J. Kumar, PRL 101, 231301 (2008)

- Dark matter is hidden no SM interactions
- DM sector has its own particle content, mass m_X, coupling g_X
- Connected to SUSY breaking sector



$$\rightarrow \quad \frac{m_X}{g_X^2} \sim \frac{m}{g^2} \sim \frac{F}{16\pi^2 M} \quad \rightarrow \quad \Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4}$$

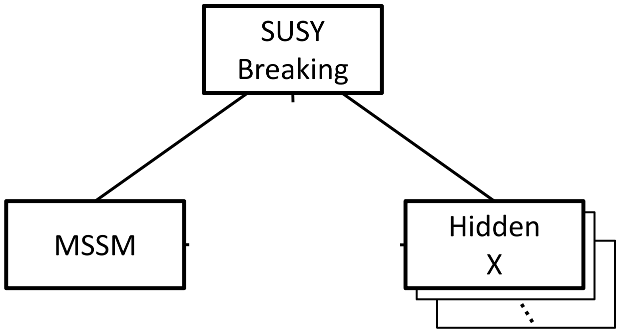
right relic density !
(irrespective of its mass)

J.L. Feng, H. Tu and H. yu, CAP 0810:043,2008

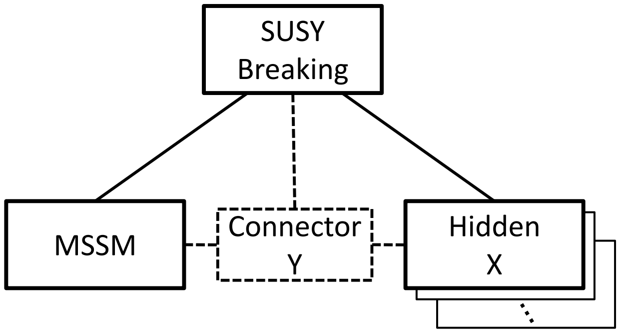
If no direct coupling to SM:

- interact only through gravity
- impact on structure formation
- no direct/indirect/collider signals

WIMPless: not hidden



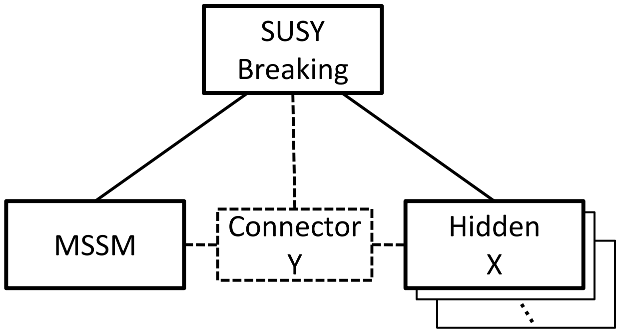
WIMPless: not hidden



$m_Y \sim \max(m_{weak}, m_X)$

interaction λ XYf

WIMPless: not hidden

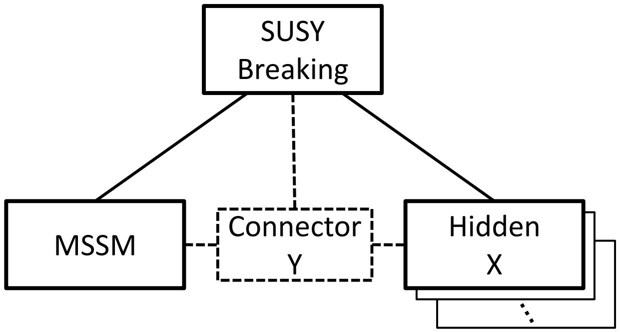


$m_Y \sim \max(m_{weak}, m_X)$

interaction λ XYf

- indirect detection
  XX → ff, YY
- direct detection
  Xf → Xf
- collider: 4th generation fermions

WIMPless: not hidden



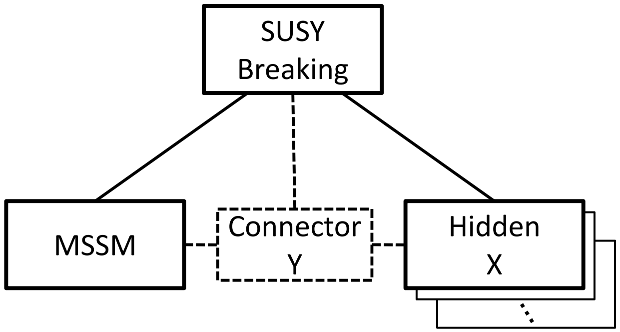
$m_Y \sim \max(m_{weak}, m_X)$

interaction λ XYf

- indirect detection
  $XX \to f\bar{f},\ \gamma\gamma$
- direct detection
  $Xf \to Xf$
- collider: 4th generation fermions

$$10^{-3} \lesssim g_X \lesssim 3$$
$$10\ \mathrm{MeV} \lesssim m_X \lesssim 10\ \mathrm{TeV}$$

WIMPless: not hidden



$m_Y \sim \max(m_{weak}, m_X)$ interaction λ XYf

- indirect detection
  XX → ff, YY
- direct detection
  Xf → Xf
- collider: 4th generation fermions

$$10^{-3} \lesssim g_X \lesssim 3$$
$$10\ \mathrm{MeV} \lesssim m_X \lesssim 10\ \mathrm{TeV}$$

open new possibility for
- DM model parameters
- new experimental search windows

Dark matter motivation: specific

To explain DAMA region: light DM with large σ_{SI}

see talk by T. Schwetz
and related talks by A. Aprile, J. Jochum, P. Belli, G. Gelmini, T. Tait, N. Fornengo, T. Hambye ...

- not generic in typical WIMP **see talk by N. Fornengo**

  σ_{SI} : chirality flip, proportional to Yukawa coupling

  A. Bottino, F. Donato, N. Fornengo and S. Scopel, PRD 68, 043506 (2003); PRD 77, 015002 (2008); PRD 78, 083520 (2008).

- can be easily accommodated in WIMPless model with connector Y

  J.L. Feng, J. Kumar and L.E. Strigari, PLB 670, 37 (2008)

Explaining DAMA: WIMPless

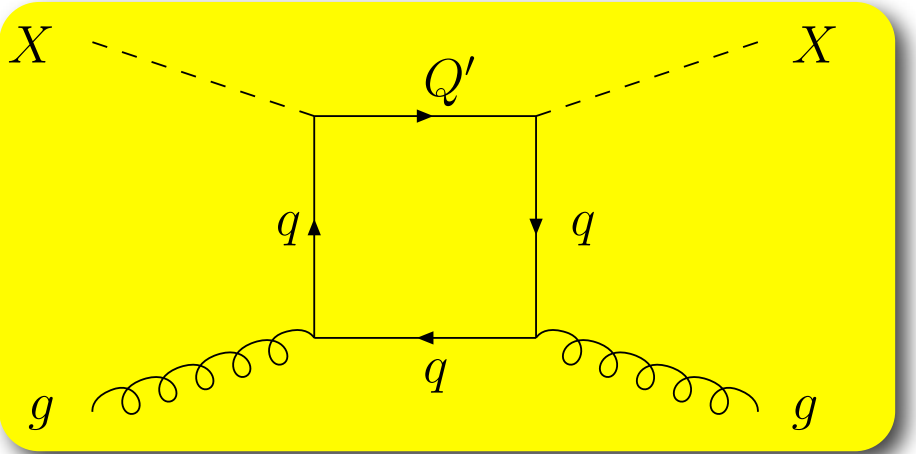
WIMPless model (discrete symmetry)

$$V = \lambda \left[X \bar{Q}'_L q_L + X \bar{B}'_R b_R + X \bar{T}'_R t_R \right]$$

$$\begin{array}{ccl} Q'_L & : & (3, 2, \frac{1}{6}) \\ T'_R & : & (3, 1, \frac{2}{3}) \\ B'_R & : & (3, 1, -\frac{1}{3}) \ . \end{array}$$

scattering: Xq → Q' → Xq, q=b,t, induce coupling to gluon at 1-loop

M. A. Shifman, A. I. Vainshtein and V. I. Zakharov, Phys. Lett. B 78, 443 (1978).



Explaining DAMA: WIMPless

WIMPless model (discrete symmetry)

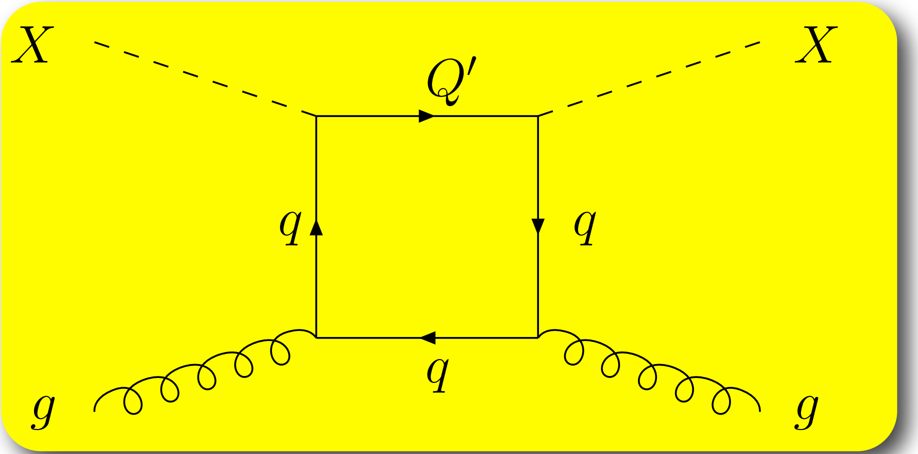
$$V = \lambda \left[X \bar{Q}'_L q_L + X \bar{B}'_R b_R + X \bar{T}'_R t_R \right]$$

not chirality
opposite chirality
of SM quark

$$\begin{array}{lcl} Q'_L & : & (3, 2, \frac{1}{6}) \\ T'_R & : & (3, 1, \frac{2}{3}) \\ B'_R & : & (3, 1, -\frac{1}{3}) \ . \end{array}$$

scattering: Xq → Q' → Xq, q=b,t, induce coupling to gluon at 1-loop

M. A. Shifman, A. I. Vainshtein and V. I. Zakharov, Phys. Lett. B 78, 443 (1978).



Explaining DAMA: WIMPless

WIMPless model (discrete symmetry)

$$V = \lambda \left[X \bar{Q}'_L q_L + X \bar{B}'_R b_R + X \bar{T}'_R t_R \right]$$

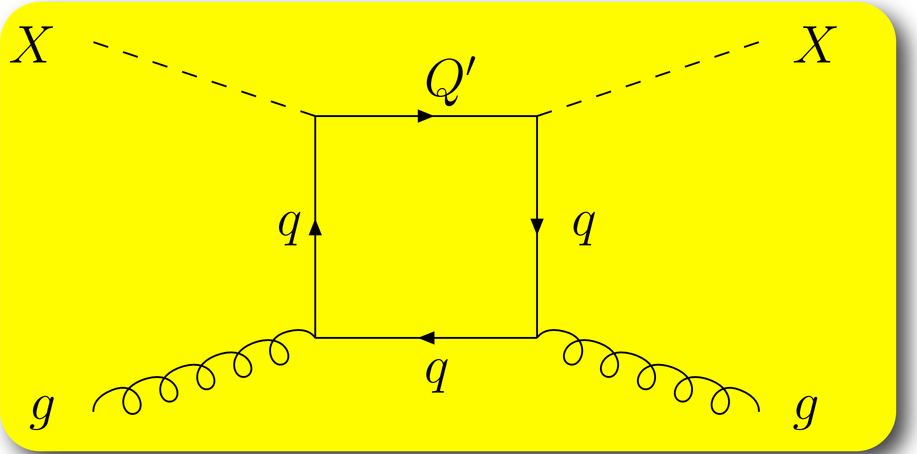
not chirality
opposite chirality
of SM quark

$$\begin{array}{lcl} Q'_L & : & (3, 2, \frac{1}{6}) \\ T'_R & : & (3, 1, \frac{2}{3}) \\ B'_R & : & (3, 1, -\frac{1}{3}) \ . \end{array}$$

Exotic 4th-generation
mirror quarks

scattering: Xq → Q' → Xq, q=b,t, induce coupling to gluon at 1-loop

M. A. Shifman, A. I. Vainshtein and V. I. Zakharov, Phys. Lett. B 78, 443 (1978).

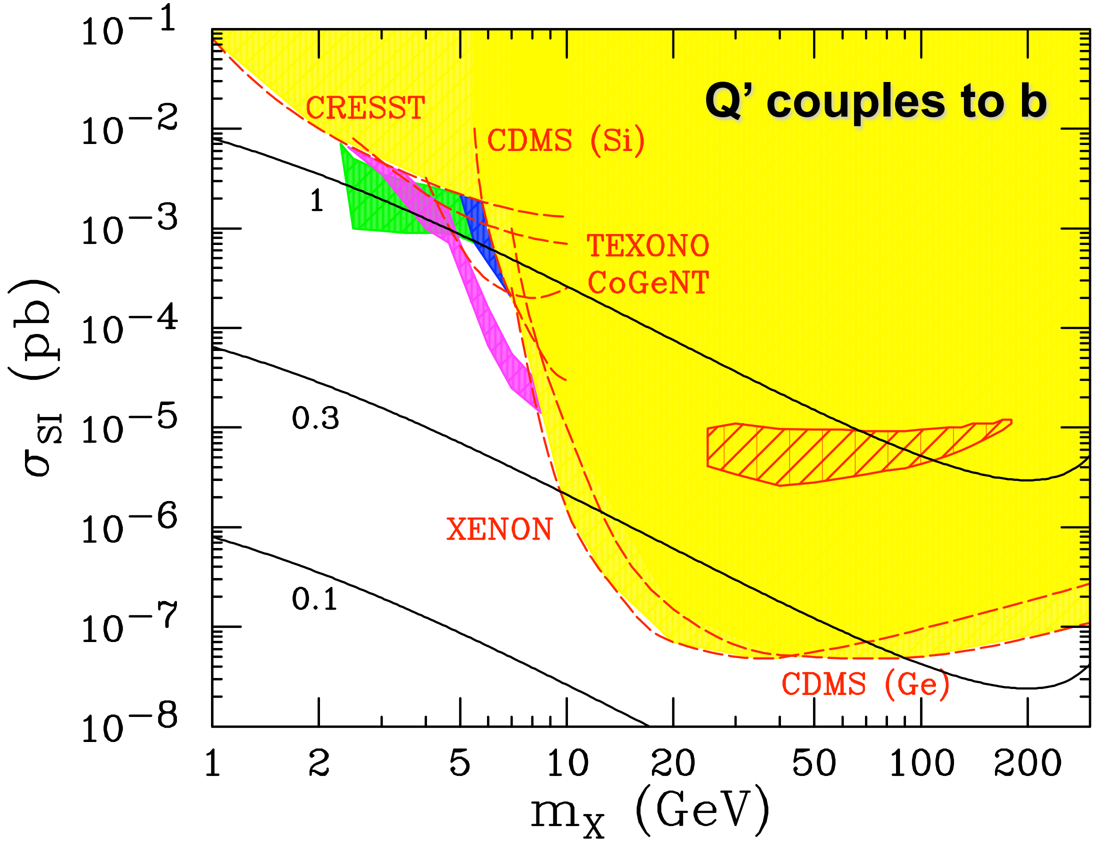


Explaining DAMA: WIMPless

WIMPless model

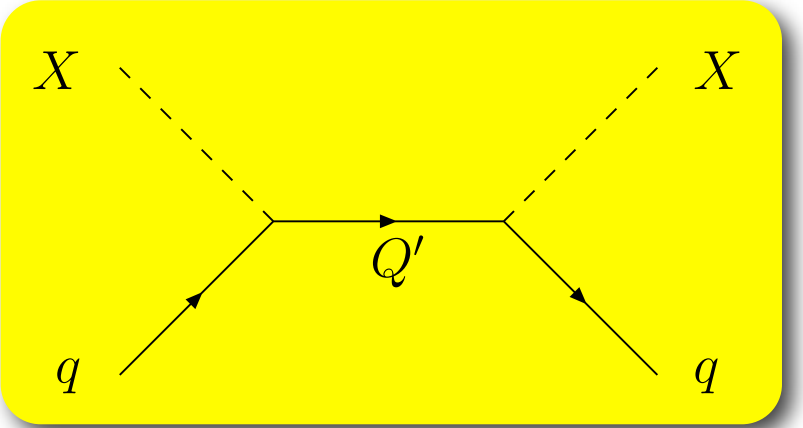
$m_X \sim$ 1-10 GeV, $m_{Q'} \sim$300-500 GeV, $\lambda \sim$ 0.3-1, σ_{SI} in right range

J.L. Feng, J. Kumar and L.E. Strigari, PLB 670, 37 (2008)



3rd generation vs. the first two

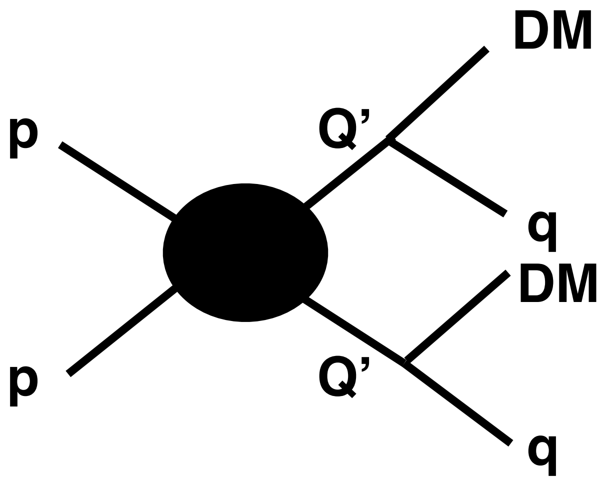
- first two generations, tree level scattering $\Rightarrow \lambda \sim 0.03$



- third generation
  - loop level scattering, $\lambda \sim 0.3$-1, more natural
  - less constrained by FCNC

Collider Signature: exotic quarks

Y particle appears as exotic 4th generation mirror quarks Q'



Collider Signal

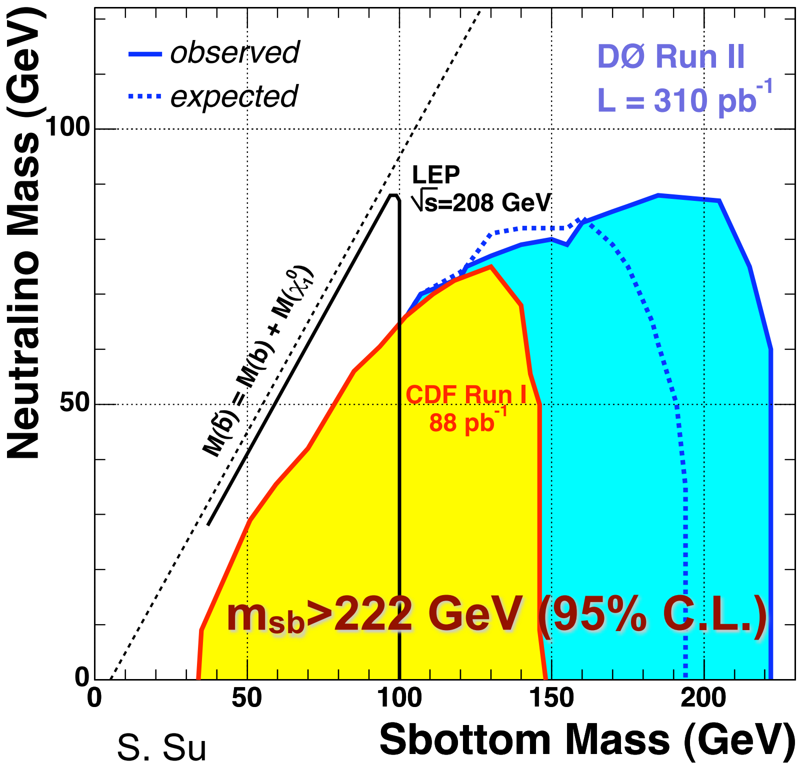
T'T'→ttXX, B'B' →bbXX

- differ from SUSY searches: cascade decay
- differ from usual 4th generation quark T' → Wb, B' → Wt
- appears in a general set of new physics scenarios
  - little Higgs with T-parity   H.C. Cheng and I. Low, JHEP 0408, 061 (2004)
  - baryon and lepton number as gauge symmetry   P. Fileviez Perez and M. B. Wise, arXiv: 1002.1754
  - ...

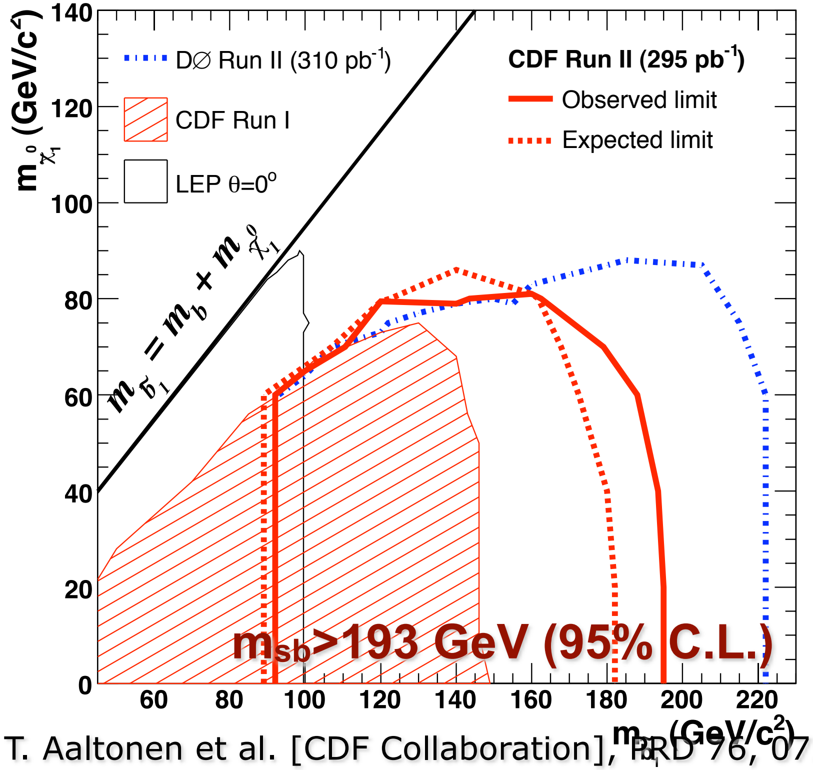
Constraints

- perturbativity constraints: $m_{Q'} = y_{Q'} v$, $m_{Q'} \leq 600$ GeV
- precision electroweak data: $|m_{T'} - m_{B'}| \sim 50$ GeV
- direct searches limits

B'B'→bbXX, similar to sbottom pair production with $\tilde{b} \to b\tilde{\chi}_1^0$



S. Su



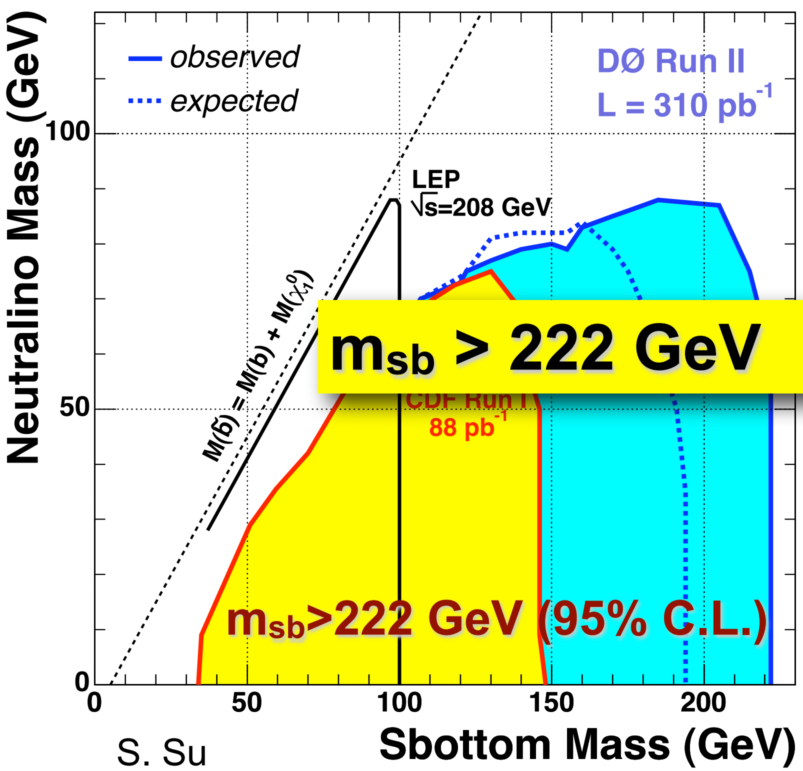
T. Aaltonen et al. [CDF Collaboration], PRD 76, 072010 (200

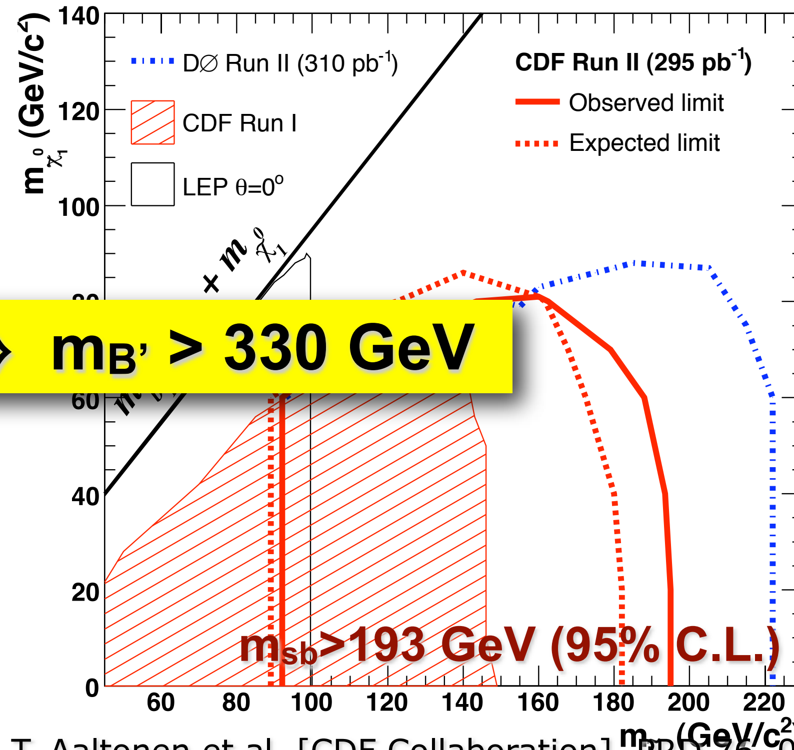
V. M. Abazov et al. [D0 Collaboration], PRL 97, 171806 (2006).

Constraints

- perturbativity constraints: $m_{Q'} = y_{Q'}\, v$, $m_{Q'} \leq 600$ GeV
- precision electroweak data: $|m_{T'} - m_{B'}| \sim 50$ GeV
- direct searches limits

B'B'→bbXX, similar to sbottom pair production with $\tilde{b} \rightarrow b\tilde{\chi}_1^0$





$m_{sb} > 222$ GeV (95% C.L.) $\qquad m_{sb} > 193$ GeV (95% C.L.)

$m_{sb} > 222$ GeV ⇒ $m_{B'} > 330$ GeV

S. Su

T. Aaltonen et al. [CDF Collaboration], PRD 76, 072010 (200

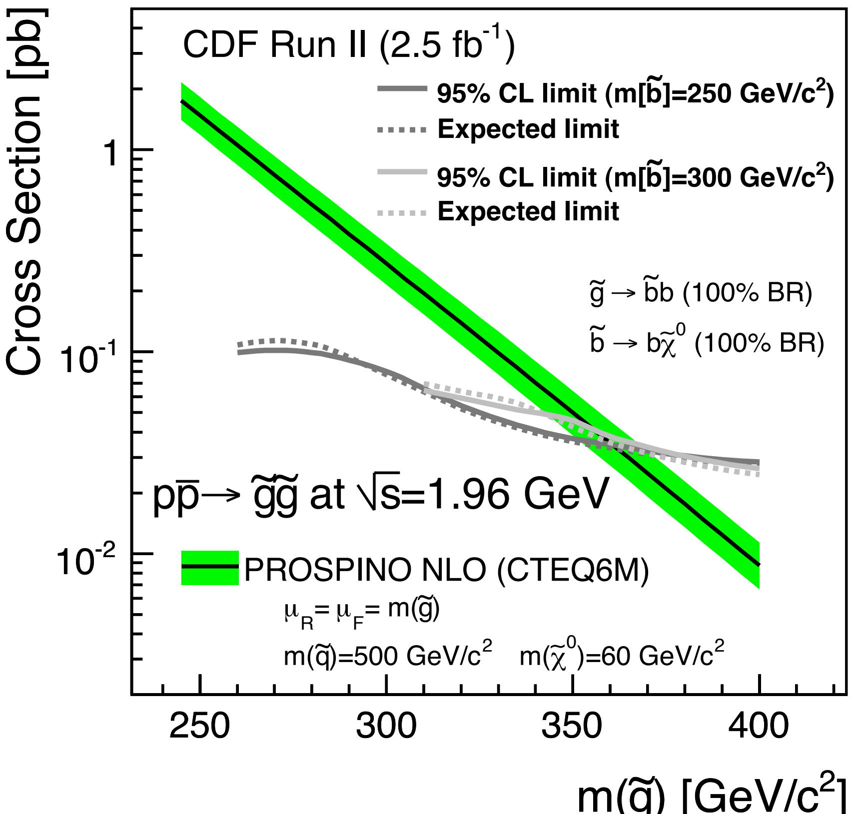
V. M. Abazov et al. [D0 Collaboration], PRL 97, 171806 (2006).

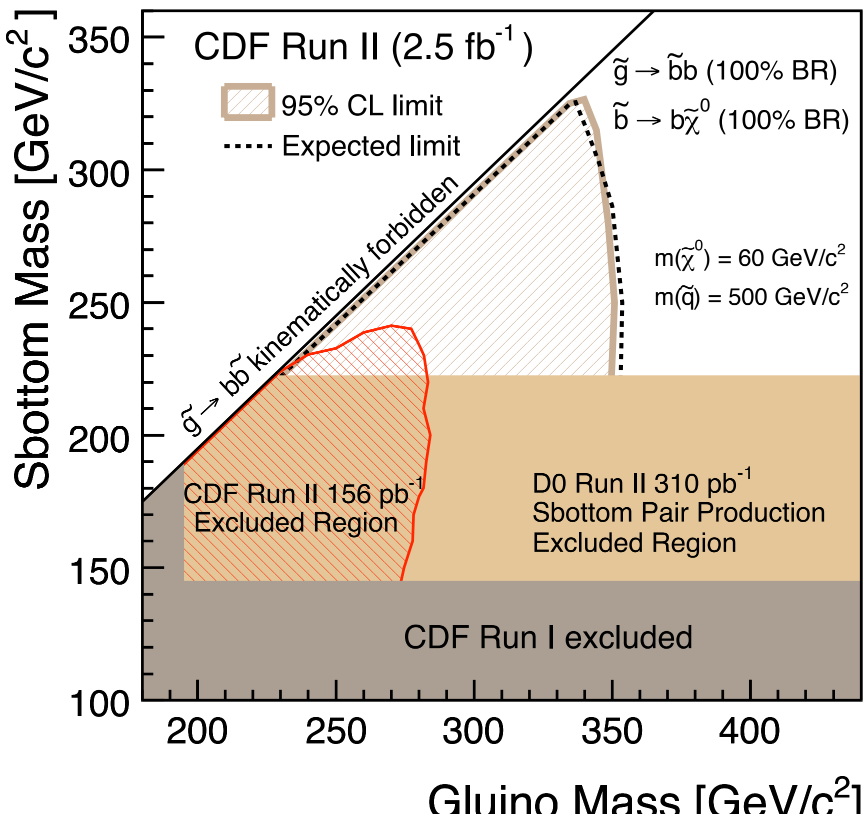
Constraints: direct search

CDF, Run II, 2.5 fb^{-1}, gluino pair production, $\tilde{g} \to b\tilde{b} \quad \tilde{b} \to b\tilde{\chi}^0_1$

two or more jets, large MET, 2b-tagging

T. Aaltonen et al. [CDF Collaboration], PRL 102, 221801 (2009).



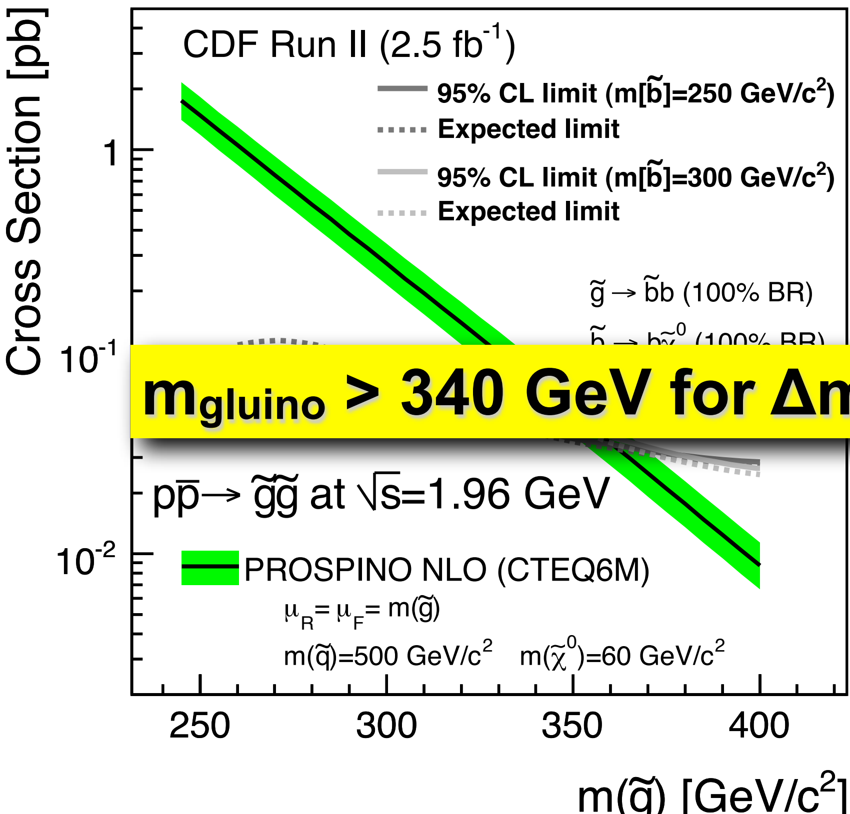


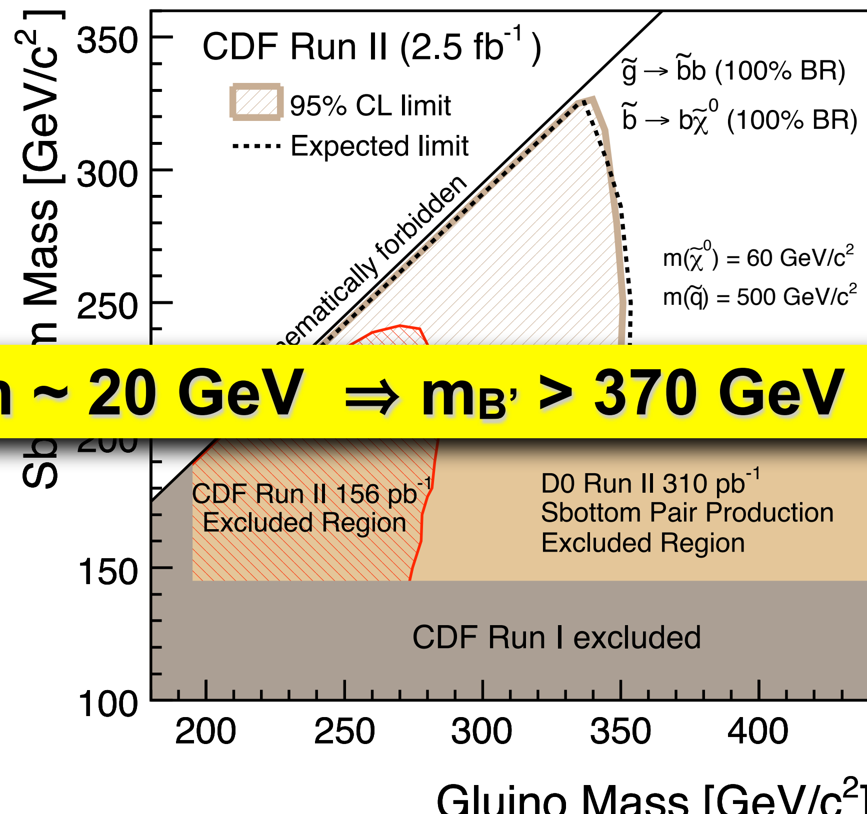
Constraints: direct search

CDF, Run II, 2.5 fb^{-1}, gluino pair production, $\tilde{g} \rightarrow b\tilde{b} \quad \tilde{b} \rightarrow b\tilde{\chi}_1^0$

two or more jets, large MET, 2b-tagging

T. Aaltonen et al. [CDF Collaboration], PRL 102, 221801 (2009).





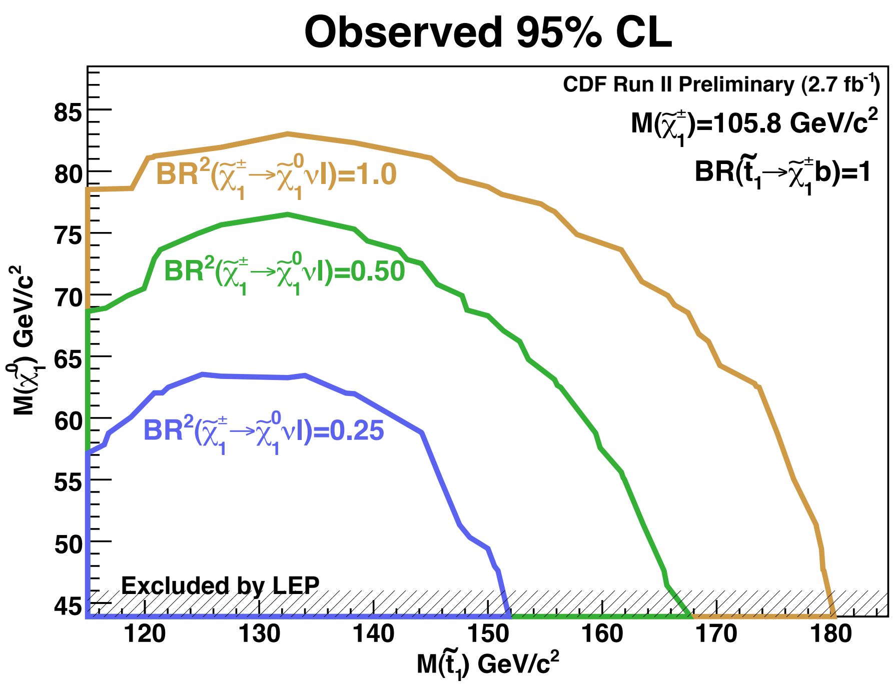
m_{gluino} > 340 GeV for Δm ~ 20 GeV ⇒ $m_{B'}$ > 370 GeV

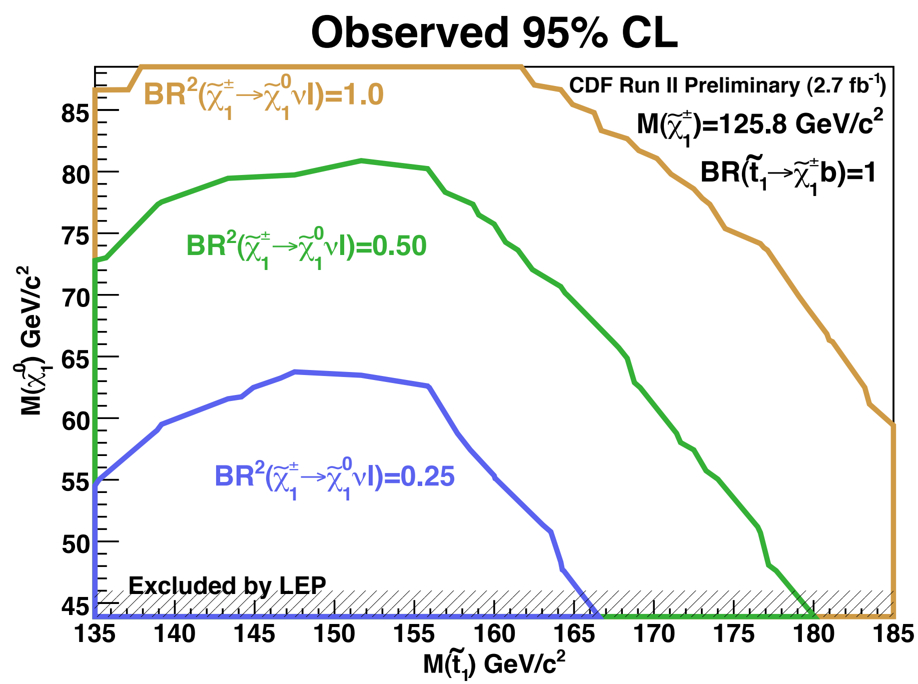
S. Su

Constraints: direct search

CDF, Run II, 2.7 fb^{-1}, stop pair production, $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^{\pm} \rightarrow b\tilde{\chi}_1^0 l\nu$

m_{st} > 150 - 185 GeV, weaker than sbottom limit





A. G. Ivanov [CDF Collaboration], arXiv:0811.0788 [hep-ex].

Simulation

MadGraph - Pythia - PGS

Signal: $T'\bar{T}' \to t^{(*)} X \bar{t}^{(*)} X \to bW^+ X \bar{b} W^- X$

- hadronic channel: large cross section
  - SM backgrounds, tt, W, have MET with lepton
  - irreducible background: Z→ νν + jets
- semi-leptonic channel: isolated lepton, suppress QCD background
- purely leptonic channel: suppressed cross section

Similar analyses in the literature

- semileptonic mode, high mass, large luminosity

  T. Han, R. Mahbubani, D. G. E. Walker and L. T. E. Wang, JHEP 0905, 117 (2009)

- hadronic mode, spin and mass determination

  P. Meade and M. Reece, Phys. Rev. D 74, 015010 (2006).

Simulation

MadGraph - Pythia - PGS

Signal: $T'\bar{T}' \to t^{(*)}X\bar{t}^{(*)}X \to bW^+X\bar{b}W^-X$

- hadronic channel: large cross section
  - SM backgrounds, tt, W, have MET with lepton
  - irreducible background: Z→ νν + jets
- semi-leptonic channel: isolated lepton, suppress QCD background
- purely leptonic channel: suppressed cross section

Similar analyses in the literature

- semileptonic mode, high mass, large luminosity

  T. Han, R. Mahbubani, D. G. E. Walker and L. T. E. Wang, JHEP 0905, 117 (2009)

- hadronic mode, spin and mass determination

  P. Meade and M. Reece, Phys. Rev. D 74, 015010 (2006).

Simulation

MadGraph - Pythia - PGS

Signal: $T'\bar{T}' \to t^{(*)} X \bar{t}^{(*)} X \to bW^+ X \bar{b} W^- X$

- hadronic channel: large cross section
  - SM backgrounds, tt, W, have MET with lepton
  - irreducible background: Z→ vv + jets
- semi-leptonic channel: isolated lepton, suppress QCD background
- purely leptonic channel: suppressed cross section

Similar analyses in the literature

- semileptonic mode, high mass, large luminosity

  T. Han, R. Mahbubani, D. G. E. Walker and L. T. E. Wang, JHEP 0905, 117 (2009)

- hadronic mode, spin and mass determination

  P. Meade and M. Reece, Phys. Rev. D 74, 015010 (2006).

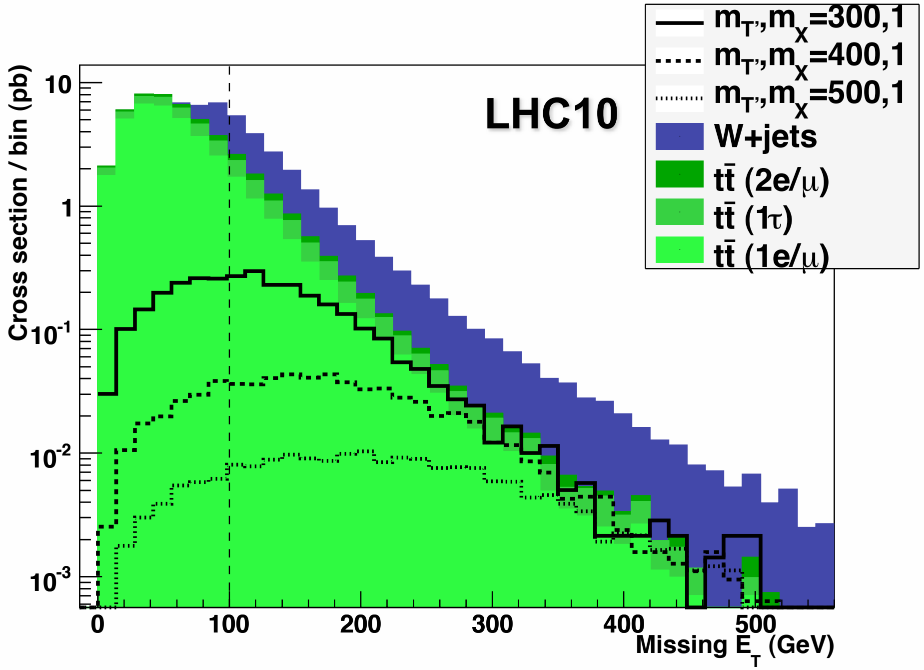
Semileptonic channel: precuts

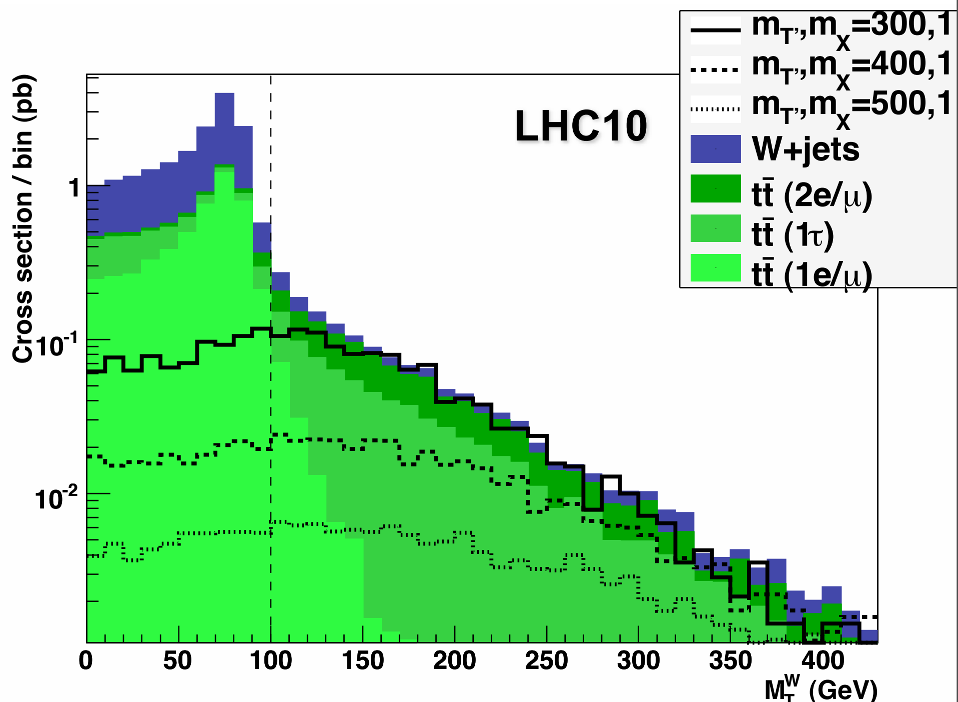
Signal: T'T' → ttXX → bbjj l + MET

Precuts

- one isolated electron or muon
- large MET
- large m_T^W

$$m_T^W \equiv m_T(p_T^l, \not{p}_T) = \sqrt{2|p_T^l||\not{p}_T|\cos(\Delta\phi(p_T^l, \not{p}_T))}$$





S. Su

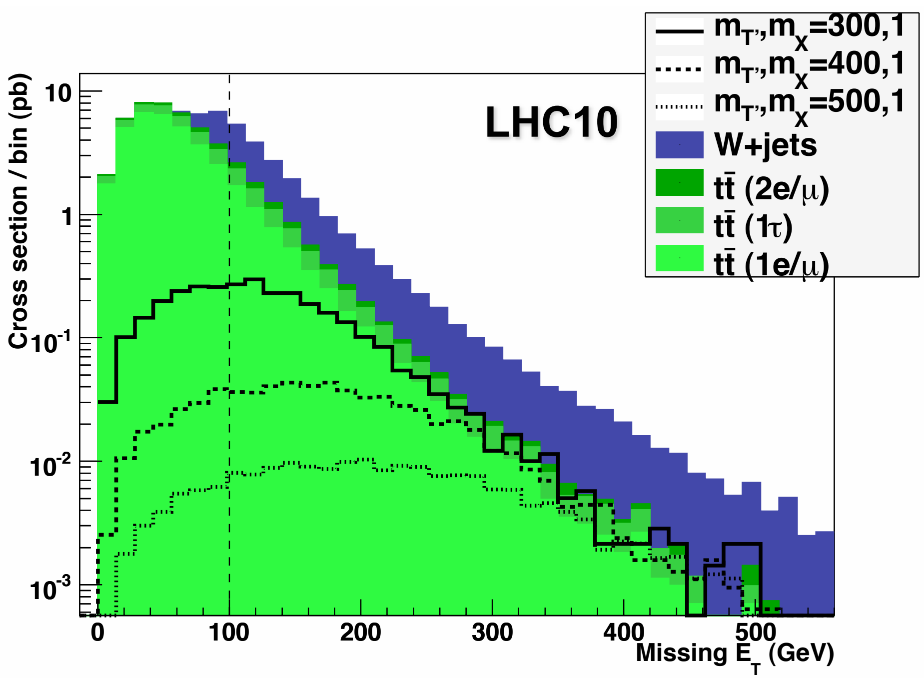
Semileptonic channel: precuts

Signal: T'T' → ttXX → bbjj l + MET

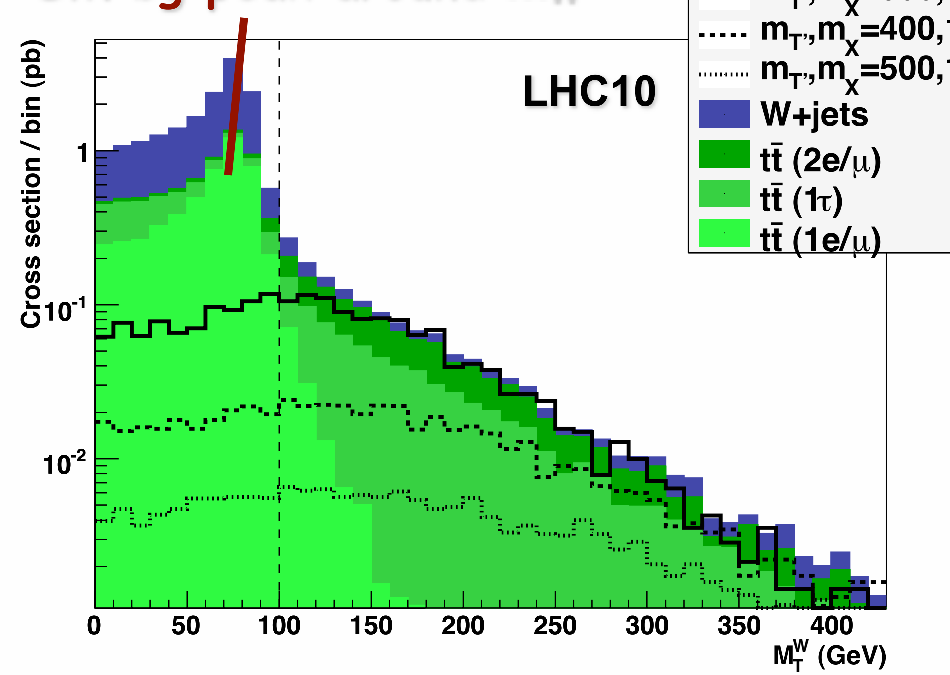
Precuts

- one isolated electron or muon
- large MET
- large m_T^W

$$m_T^W \equiv m_T(p_T^l, \not{p}_T) = \sqrt{2|p_T^l||\not{p}_T|\cos(\Delta\phi(p_T^l, \not{p}_T))}$$



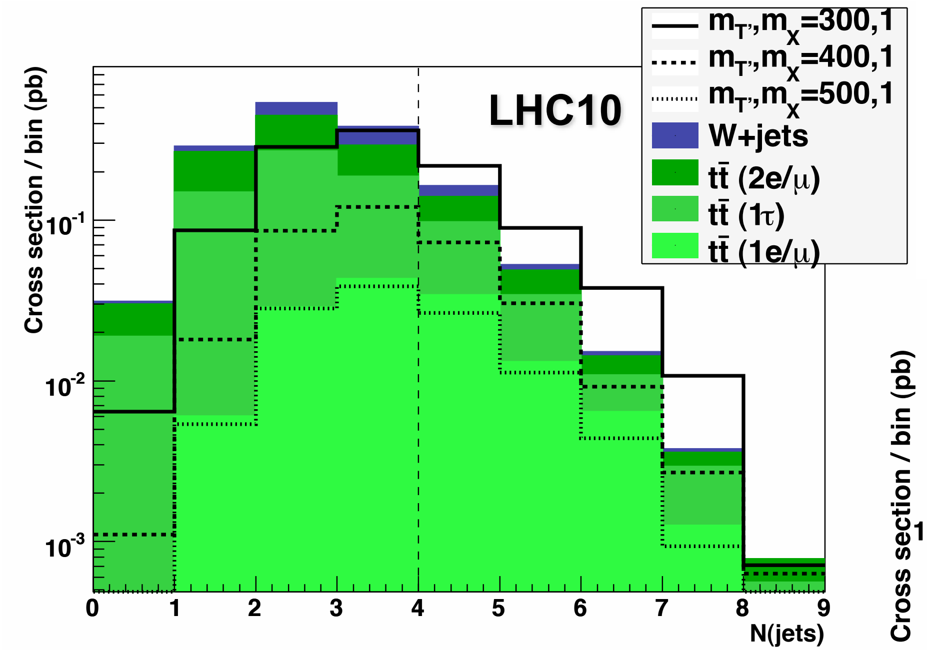
SM bg peak around m_W



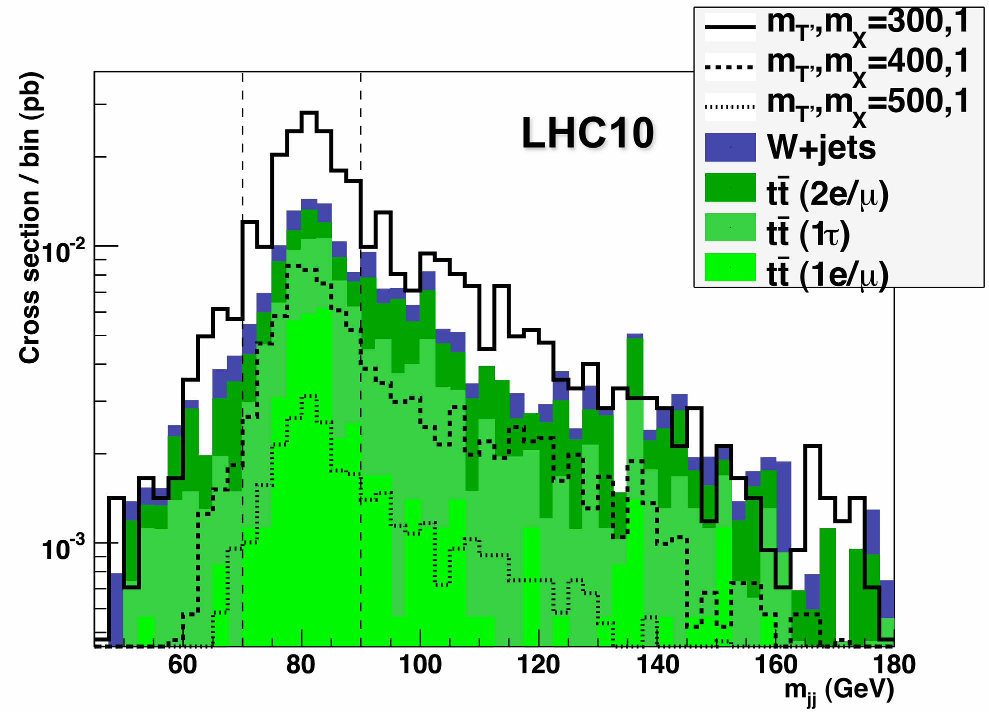
S. Su

Semileptonic channel: precuts

- $N_{jet} \geq 4$



- second, hadronically decay W



Semileptonic channel: Tevatron

Additional cuts: **MET, m_T^W, H_T**

Tevatron: semileptonic

Cut	T' (300)	T' (400)	T' (500)	$t\bar{t}$	W+jets
No cut	203.2	16.33	1.11	5619	(5179)
1 μ/e, no τ	36.1	2.88	0.194	1041	(2060)
$\not{E}_T > 100$ GeV	17.7	2.00	0.157	107.2	(728.8)
$m_T^W > 100$ GeV	10.7	1.38	0.114	22.6	(36.62)
≥ 4 jets	4.81	0.64	0.062	2.6	0.30
$\lvert m_{jj} - m_W \rvert < 10$ GeV	4.13	0.51	0.049	2.2	0.19
All precuts	4.13	0.51	0.049	2.19	0.19
$m_T^W > 150$ GeV	1.93	0.325	0.036	0.62	0.035
$\not{E}_T > 150$ GeV	1.75	0.367	0.041	0.281	0.035
$H_T > 300$ GeV	1.93	0.353	0.042	1.18	0.07
$\not{E}_T > 150,\ H_T > 300$	1.04	0.279	0.037	0.056	0.017

2.4 fb

Semileptonic channel: LHC10

Additional cuts: MET, m_T^W, H_T

LHC10: semileptonic

Cut	T' (300)	T' (400)	T' (500)	$t\bar{t}$ (1 e/μ)	$t\bar{t}$ (1 τ)	$t\bar{t}$ (2 e/μ)	W+jets
No cut	14.89	3.16	0.922	66.67	43.96	10.62	(42.28)
1 μ/e, no τ	3.2	0.669	0.193	36.45	8.15	3.18	(15.74)
$\not{E}_T > 100$ GeV	1.92	0.52	0.165	5.05	2.07	0.888	(10.33)
$m_T^W > 100$ GeV	1.1	0.342	0.116	0.134	0.638	0.471	(0.235)
≥ 4 jets	0.357	0.116	0.043	0.056	0.091	0.062	0.028
$\lvert m_{jj} - m_W \rvert < 10$ GeV	0.165	0.049	0.016	0.026	0.03	0.014	0.01
All precuts	0.165	0.049	0.016	0.027	0.031	0.014	0.01

82 fb

- Additional m_T^W cut: $m_T^W > 150, 200$ GeV
- Additional $\not{E}_T$ cuts: $\not{E}_T > 150,\ 200,\ 250$ GeV.
- $H_T = \sum_{i=1}^{4} |p_T^j|_i + |p_T^l|$ cuts: $H_T > 400,\ 500$ GeV.
- Combinations of the cuts above.

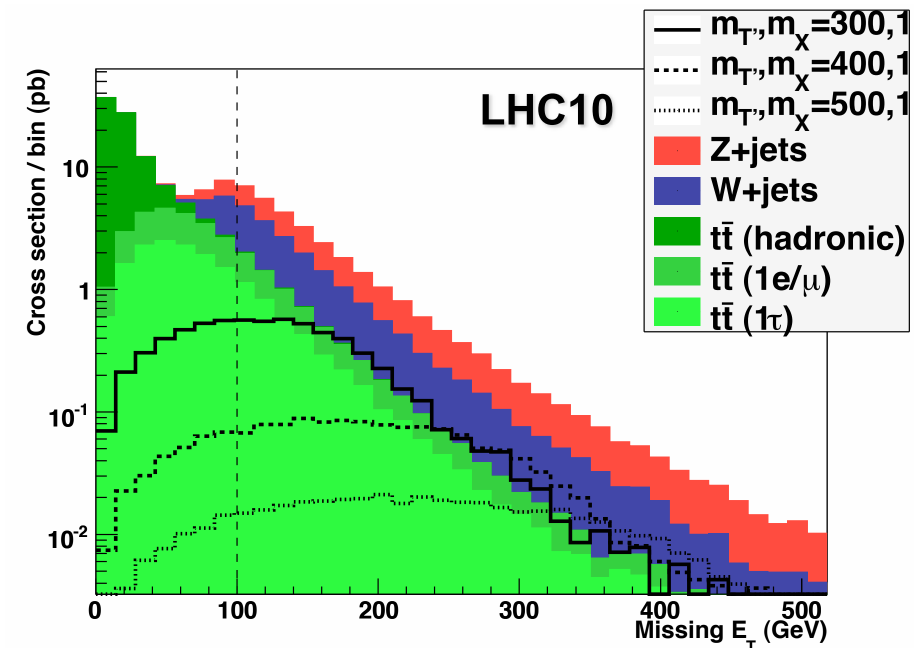
Hadronic channel: precuts

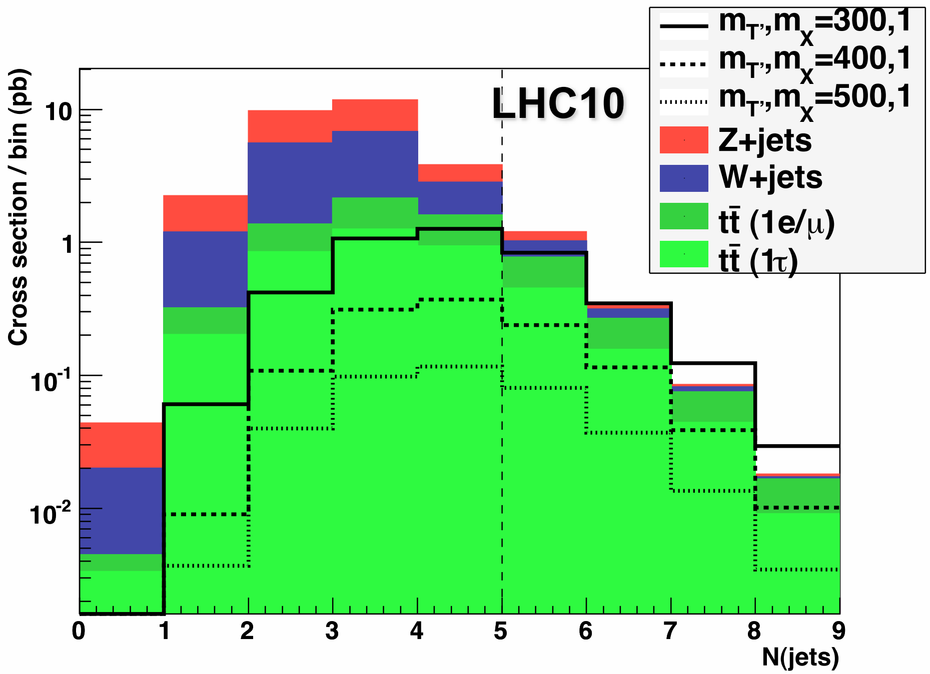
Signal: T'T' → ttXX → bbjjjj + MET

Background:
- leptonic W decay with lepton missed
- tau lepton mistagged as jets
- Z→νν + jets

Precuts

- No isolated electron, muon, tau-tagged jets
- large MET
- $N_{jet} \geq 5$

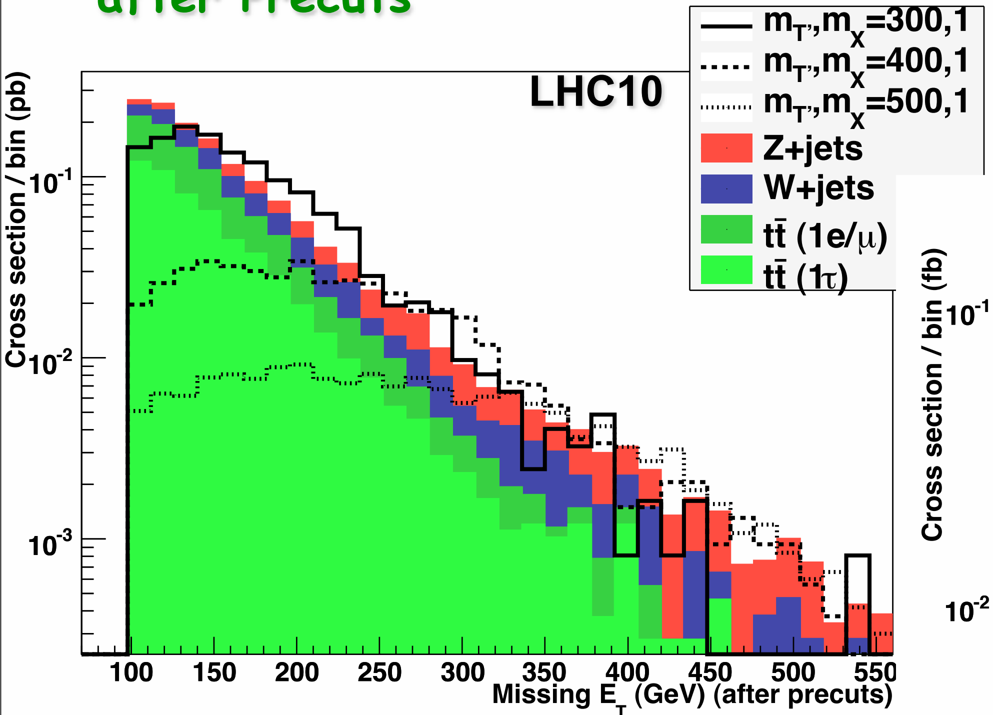




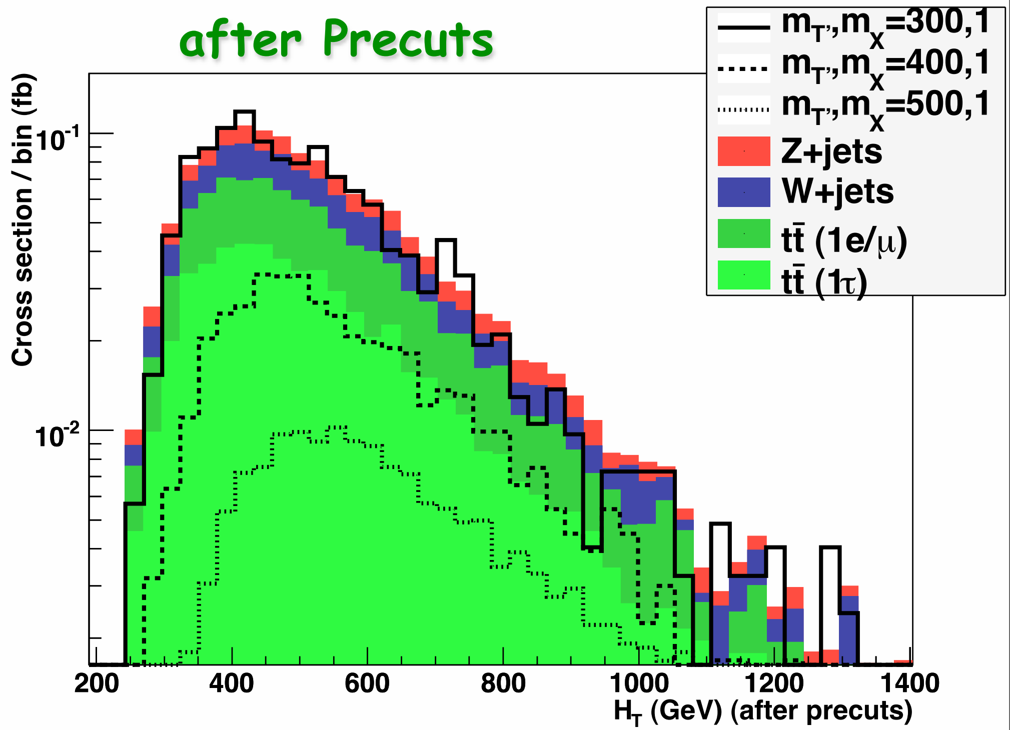
Hadronic channel: precuts

- $\Delta\phi(\not{p}_T, p_T^j)$ suppress QCD bg

after Precuts



after Precuts



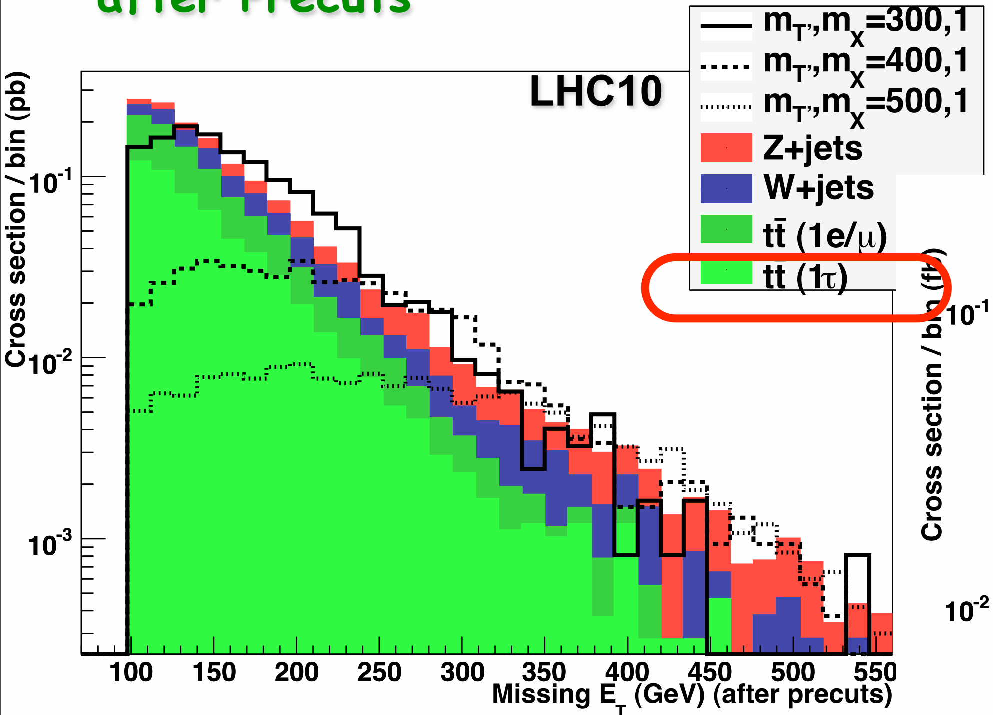
S. Su

Hadronic channel: precuts

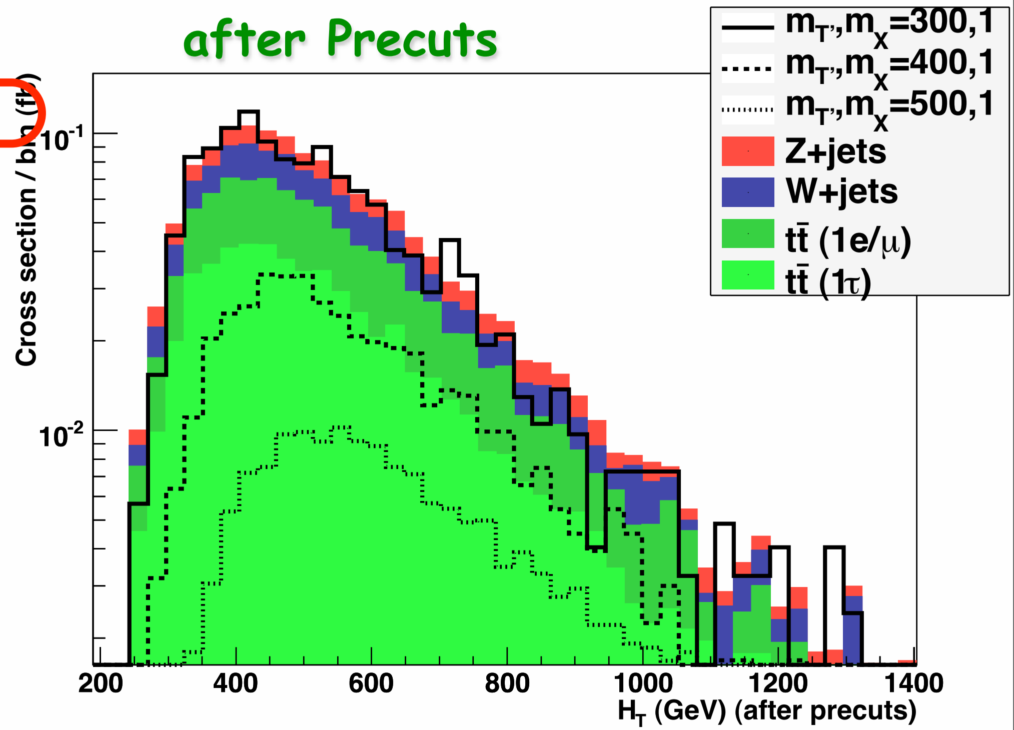
- $\Delta\phi(\not{p}_T, p_T^j)$ suppress QCD bg

tau background: important for new physics with jets and MET.

after Precuts



after Precuts



S. Su

Hadronic channel: Tevatron

Additional cuts: **MET, H_T, N_{jet}**

Tevatron: hadronic

Cut	T' (300)	T' (400)	T' (500)	$t\bar{t}$	W+jets	Z+jets
No cut	203.24	16.33	1.11	5619.1	(5179.06)	(3030.09)
0 isolated leptons	82.88	6.97	0.499	2265.54	(1756.96)	(2545.12)
$\not{E}_T > 100$ GeV	42.86	5.28	0.422	125.93	(663.5)	(1219.22)
≥ 5 jets	22.64	3.07	0.273	22.11	3.3	2.6
$\Delta\phi$ cuts	19.0	2.74	0.245	15.8	2.8	2.2
All precuts	19	2.74	0.245	15.8	2.8	2.2

21 fb

- Additional $\not{E}_T$ cuts: $\not{E}_T > 150, 200, 250$ GeV.
- $H_T = \sum_{i=1}^{5} |p_T^j|_i$ cuts: $H_T > 300, 350, 400$ GeV.
- At least 6 jets with $|p_T^j| > 20$ GeV.
- Combinations of the cuts above.

Hadronic channel: LHC10

Additional cuts: MET, H_T, N_{jet}

LHC10: hadronic

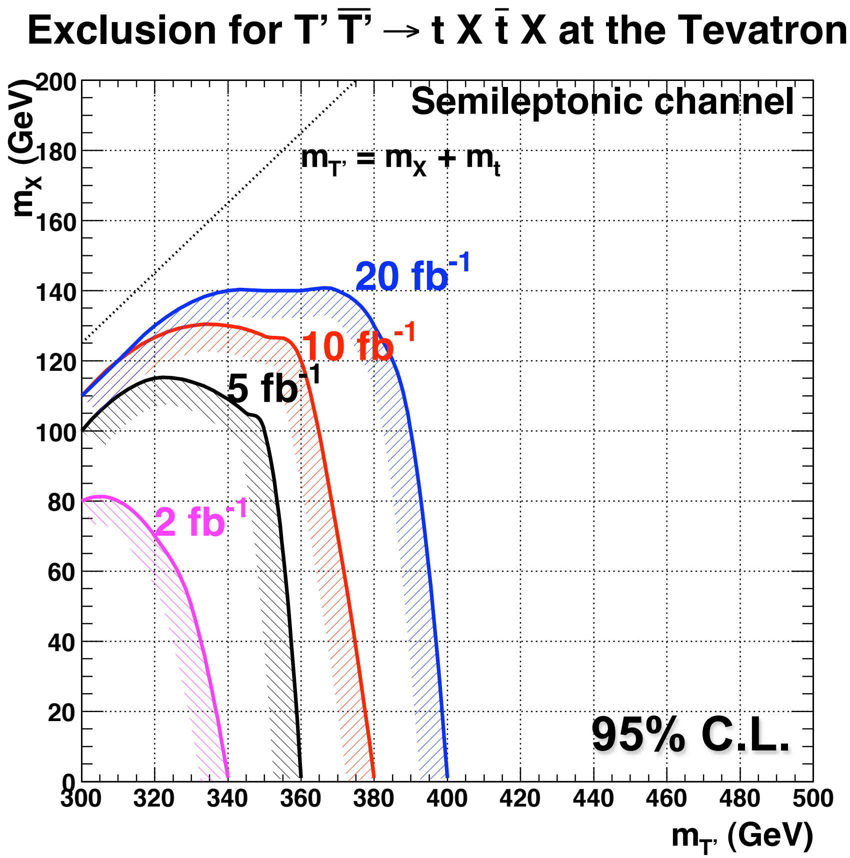
Cut	T' (300)	T' (400)	T' (500)	$t\bar{t}$ (1 τ)	$t\bar{t}$ (1 e/μ)	$t\bar{t}$ (had)	W+jets	Z+jets
No cut	14.89	3.16	0.922	43.96	66.67	104.59	(42.28)	(18.86)
0 isolated leptons	6.75	1.5	0.45	16.88	13.11	72.29	(16.8)	(15.71)
$\not{E}_T > 100$ GeV	4.15	1.21	0.394	3.91	2.67	0.097	(11.25)	(11.48)
≥ 5 jets	1.34	0.406	0.135	0.664	0.47	0.031	0.305	0.212
$\Delta\phi$ cuts	1.19	0.374	0.125	0.56	0.41	0.01	0.265	0.187
All precuts	1.19	0.374	0.125	0.56	0.41	0.01	0.265	0.187

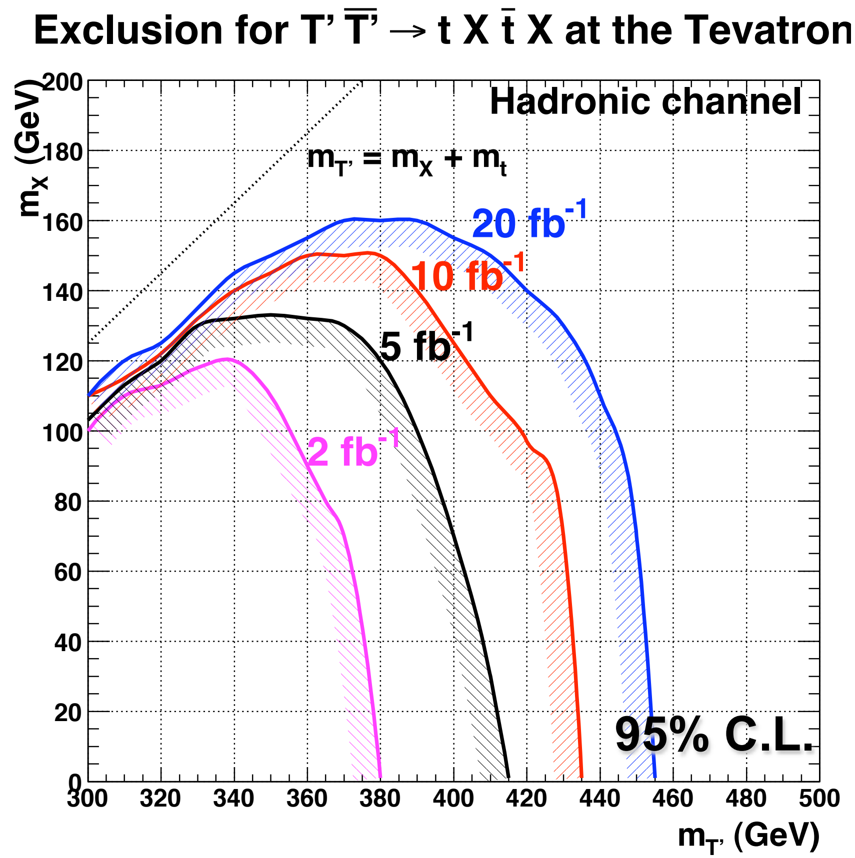
1.4 pb

- Additional $\not{E}_T$ cuts: $\not{E}_T > 150, 200, 250, 300$ GeV.
- $H_T = \sum_{i=1}^{5} |p_T^j|_i$ cuts: $H_T > 400, 500$ GeV.
- At least 6 jets with $|p_T^j| > 40$ GeV.
- Combinations of the cuts above.

Tevatron exclusion

- optimal cuts (after precuts)
- S/B > 0.1, more than 2 events
- Poisson statistics

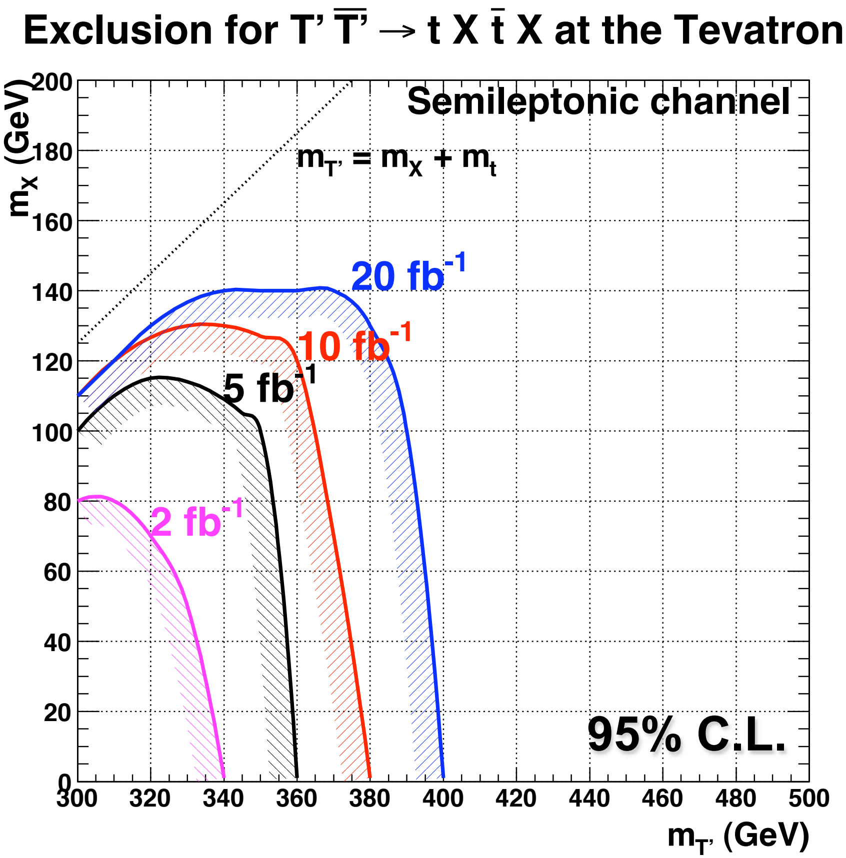


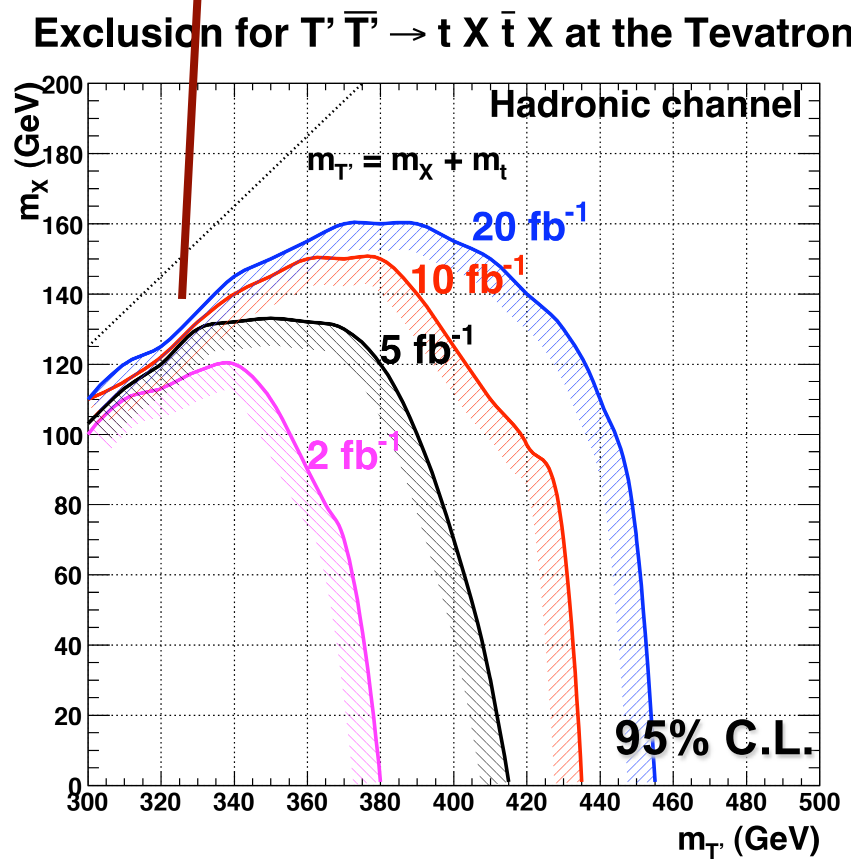


Tevatron exclusion

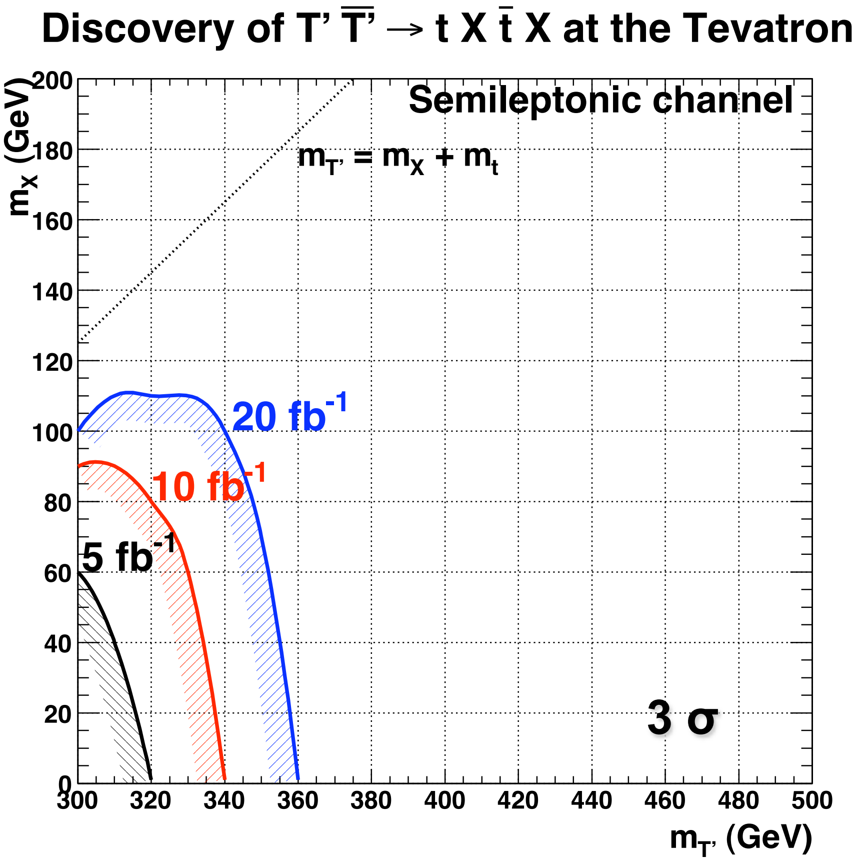
- optimal cuts (after precuts)
- S/B > 0.1, more than 2 events
- Poisson statistics

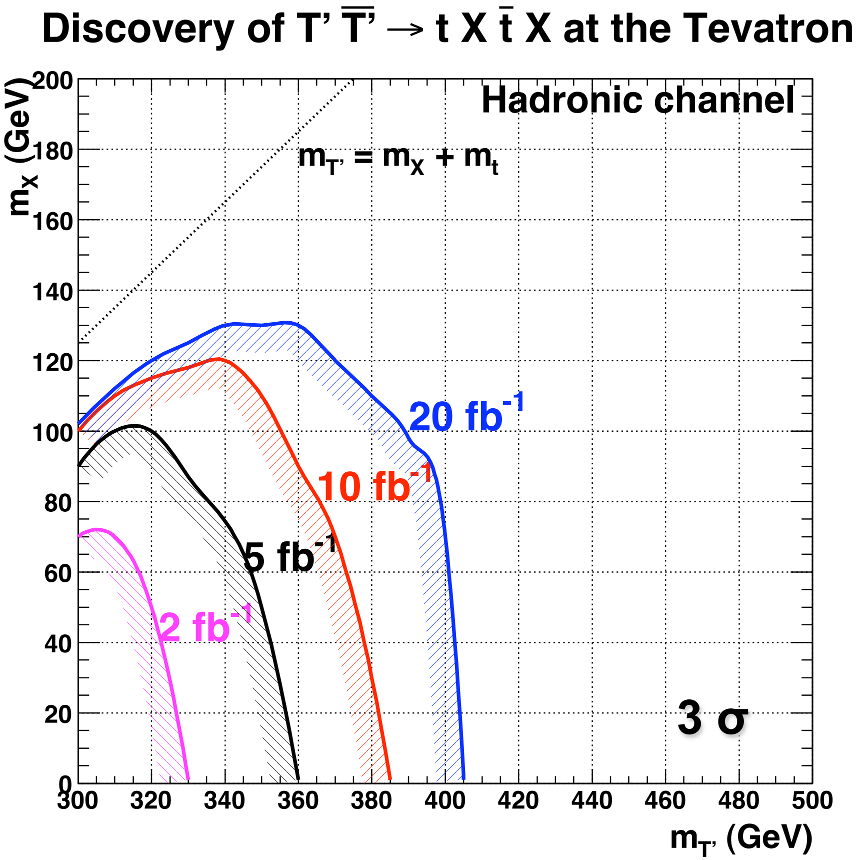
soft decay products



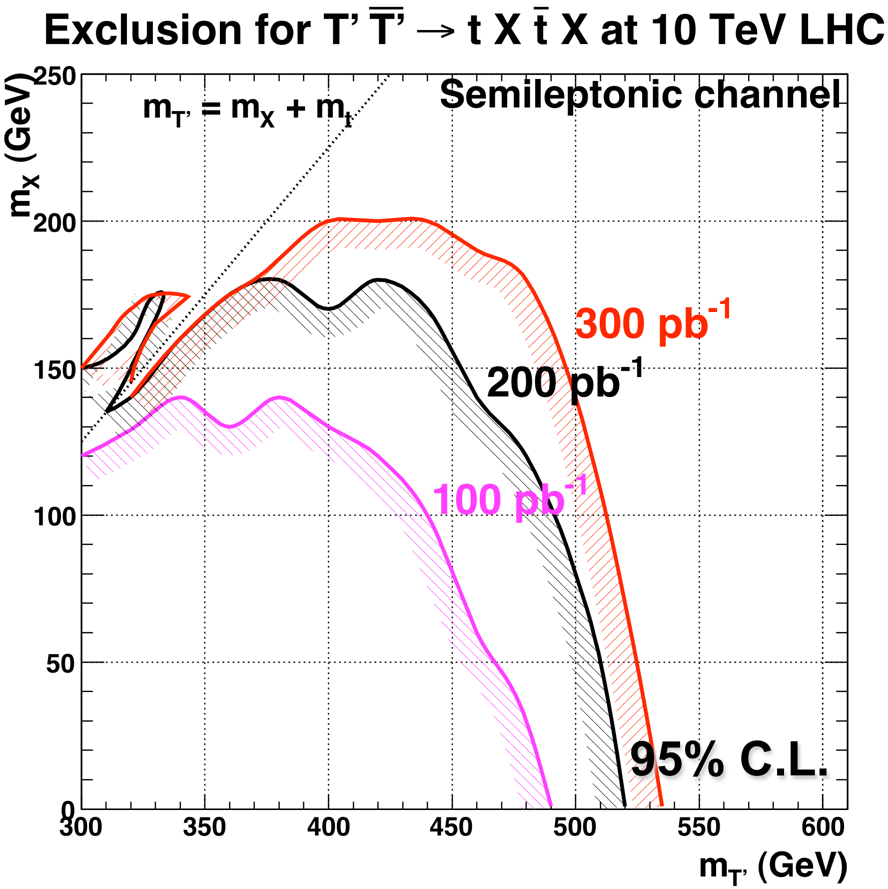


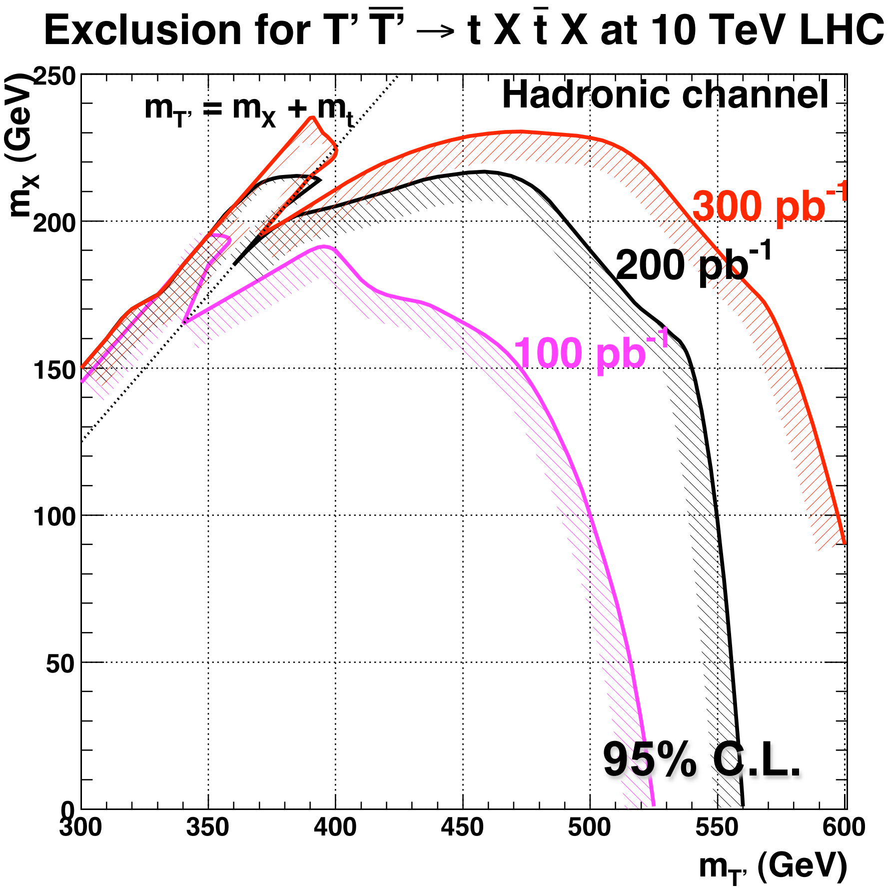
Tevatron discovery





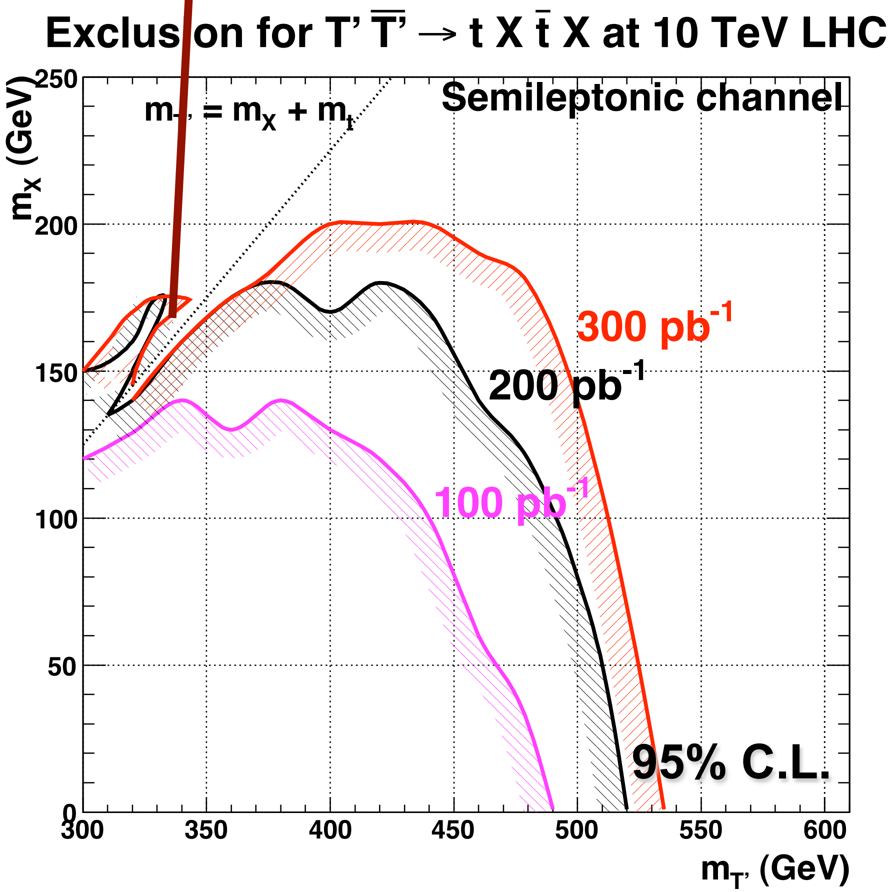
LHC 10 exclusion

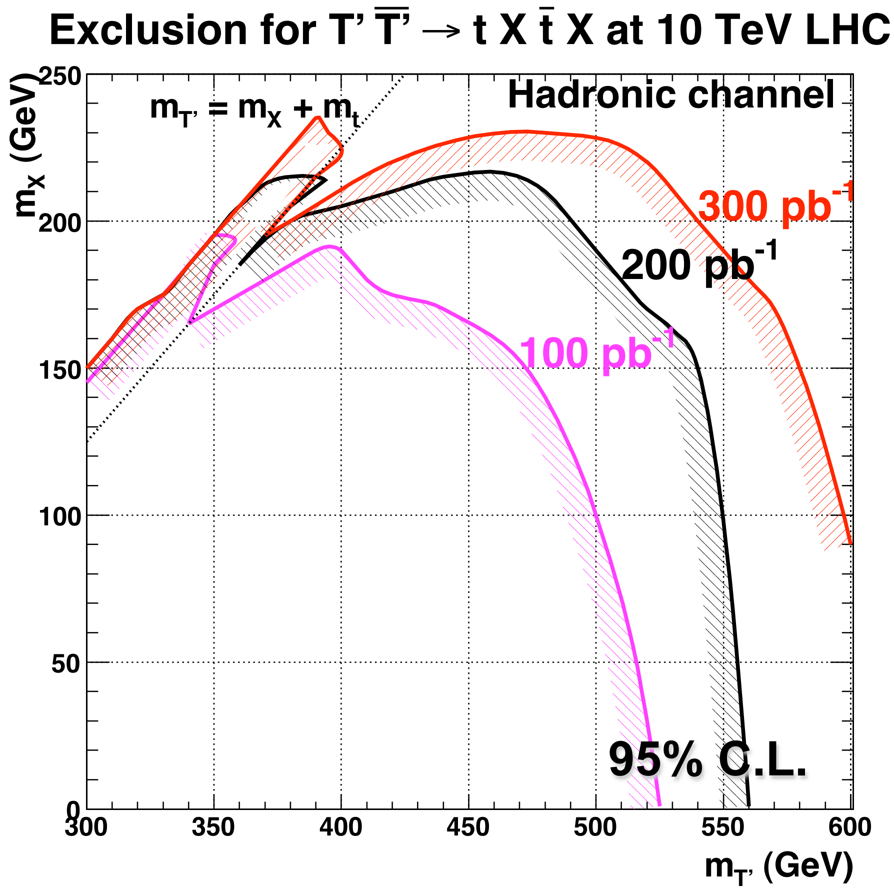




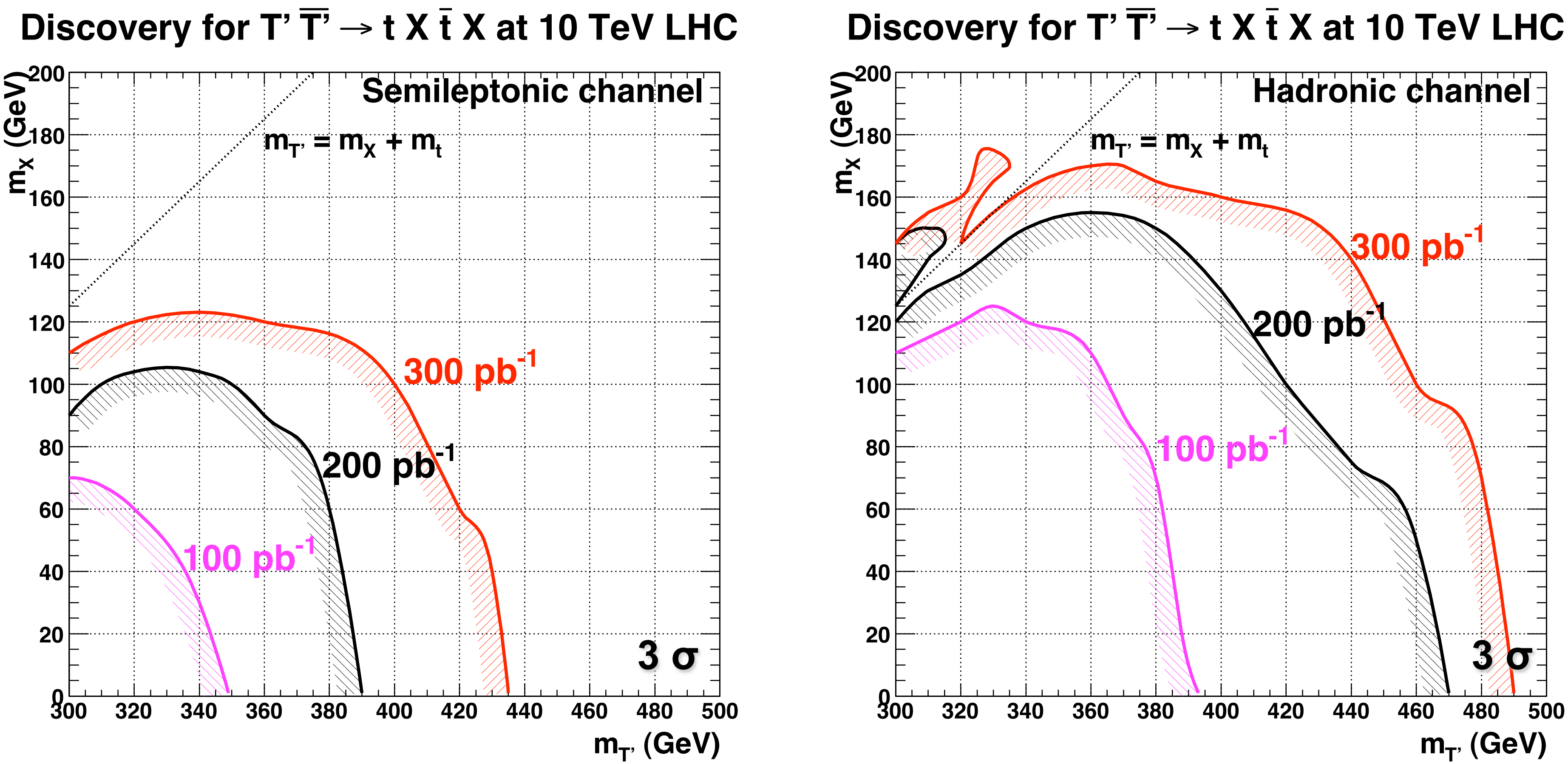
LHC 10 exclusion

off-shell top





LHC10 discovery



LHC @7TeV, multiply lumonisity by a factor of 3.

Conclusions

- Pair production of exotic quarks → DM + SM particles

  DM motivated, WIMPless scenario

  - natural obtain the right relic density
  - explain DAMA results: light DM, large σ_{SI}

- $T'\bar{T}' \to t\bar{t}XX$ semileptonic mode and hadronic mode
- Exclusion: LHC @ 10 TeV, 300 pb^{-1}
- Discovery:

  m_X<130 GeV, $m_{T'}$ < 405 GeV for Tevatron 20 fb^{-1}

  m_X<170 GeV, $m_{T'}$ < 490 GeV for LHC10 300 pb^{-1}

Conclusions

- identify signal as $T'\bar{T}' \to t\bar{t}XX$, comparing with SUSY $\tilde{t}\tilde{t}^* \to t\bar{t}\tilde{\chi}_1^0\tilde{\chi}_1^0$
- complementary between collider studies and DM searches
  - small λ, DM searches unsuccessful
  - displaced vertex at collider