New Physics Searches

aside from jets plus missing energy

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Cosener's House, 9/2010

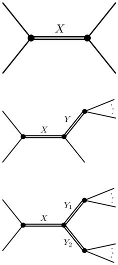
Supermodels

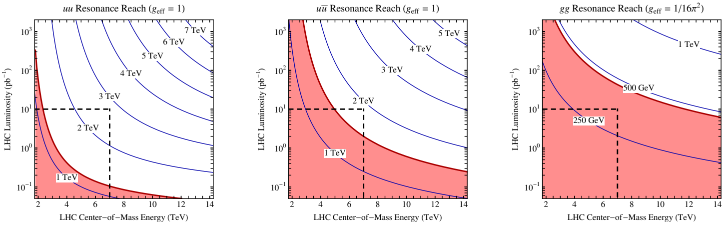
1- General consideration for early LHC [Bauer, Ligeti, Schmaltz, Thaler, Walker]

– models competitive with Tevatron

10 LHC events in 10 pb^{-1}
not ruled out by LEP and flavor physics
not ruled out by Tevatron for 10 fb^{-1} [shaded red]
decay to (leptonic) background-free signatures

– $2 \to 1$ production via $g_\text{eff}^2 G^{\mu\nu} G_{\mu\nu}$ [similar for $q\bar{q}$, qq]





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– Z' or $q\bar{q}$ resonance
decaying to new stable particles [heavy leptons]
decaying to heavy quark pairs $Q \to \ell^+\ell^- q$

– diquarks/lepto-diquarks $uu \to D$, $D \to \ell^- L$, $L \to \ell^+ 2j$

– R parity violating squarks $\tilde{b}^c \to b\,\chi_1$, $\chi_1 \to \ell^+ \tilde{\ell}$, $\tilde{\ell} \to \ell^- 3j$

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$\Rightarrow$ LHC below 100 pb^{-1} a Standard Model machine

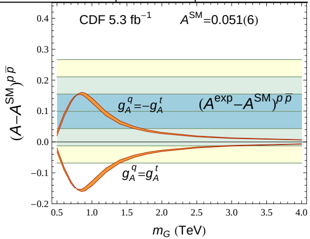
Top asymmetry

2- Lead by experimental anomalies

– forward-backward top asymmetry $A_{FB}^{\text{exp}} = 0.193 > A_{FB}^{\text{SM}} = 0.051$ [Rodrigo; Kühn]

– heavy colored gauge boson
QCD the diagonal of $SU(3)_1 \times SU(3)_2$ [$g_1 \neq g_2$ needed]
candidate model $g_L^t, g_R^q \sim 1 - \cos^2\theta$

$SU(3)_1$			$SU(3)_2$				ΔA_{FB}	
			$(t,b)_L$	q_L	t_R, b_R	q_R	$= 0$	coloron
		q_R	$(t,b)_L$	q_L	t_R, b_R		$= 0$	
	t_R, b_R		$(t,b)_L$	q_L		q_R	$= 0$	
q_L			$(t,b)_L$		t_R, b_R	q_R	$= 0$	
q_L	t_R, b_R		$(t,b)_L$			q_R	> 0	candidate
q_L		q_R	$(t,b)_L$		t_R, b_R		$= 0$	top-color
	t_R, b_R	q_R	$(t,b)_L$	q_L			< 0	axigluon
q_L	t_R, b_R	q_R	$(t,b)_L$				$= 0$	



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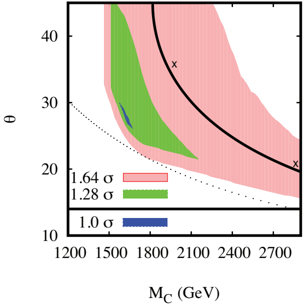
– additional constraints [Framton, Shu, Wang; Chivucula, Simmons, Yuan]
B_d mixing: $M_c \sin 2\theta > 1.8$ TeV [solid]
e-w precision data: $M_c > \cot\theta \times 700$ GeV [dotted]



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  e-w precision data: $M_c > \cot\theta \times 700$ GeV [dotted]
- allowed parameter points: $A_{FB} = 0.04, 0.03$ [$M_C = 2000, 2850$ GeV]
- axigluon interpretation not possible

- alternatives: colored scalars, weak gauge bosons,... [t channel, flavor violating]
  exciting search channel $qq \to tt$

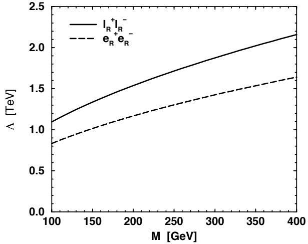
Dark matter

2- Only historical value? Dirac dark matter to explain PAMELA [Harnik & Kribs; Benakli]

– interacting via higher-dimensional operators [SUSY: $\Lambda = m_{\tilde{f}}$; no coupling to Z]

$$\mathcal{O}_{D5} = \frac{1}{\Lambda} \overline{D} D H^\dagger H \qquad \mathcal{O}_{D6} = \frac{c_L}{\Lambda^2} \overline{D} \gamma^\mu D \, \bar{f} \gamma_\mu P_L f \qquad \mathcal{O}_{D6} = \frac{c_R}{\Lambda^2} \overline{D} \gamma^\mu D \, \bar{f} \gamma_\mu P_R f$$

– annihilation rate $\langle \sigma v \rangle \sim \sum_f c_{L,R}^2 / \Lambda^4$
  Dirac bino: dominated by leptons $c \sim (Y g')^2$ [R-symmetric MSSM]



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Effective theory analysis of dark matter [Goodman, Ibe, Rajaraman, Sheperd, Tait, Yu]

– complex/real scalars, Majorana/Dirac fermions coupling to Standard Model fields

– list of operators

	Operator	Coefficient
C1	$\chi^\dagger \chi \bar{q} q$	m_q / Λ^2
C2	$\chi^\dagger \chi \bar{q} \gamma^5 q$	$i m_q / \Lambda^2$
C3	$\chi^\dagger \partial_\mu \chi \bar{q} \gamma^\mu q$	$1 / \Lambda^2$
C4	$\chi^\dagger \partial_\mu \chi \bar{q} \gamma^\mu \gamma^5 q$	$1 / \Lambda^2$
C5	$\chi^\dagger \chi G_{\mu\nu} G^{\mu\nu}$	$\alpha_s / 4\Lambda^2$
C6	$\chi^\dagger \chi G_{\mu\nu} \tilde{G}^{\mu\nu}$	$i \alpha_s / 4\Lambda^2$
R1	$\chi^2 \bar{q} q$	$m_q / 2\Lambda^2$
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R3	$\chi^2 G_{\mu\nu} G^{\mu\nu}$	$\alpha_s / 8\Lambda^2$
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D7	$\bar{\chi} \gamma^\mu \chi \bar{q} \gamma_\mu \gamma^5 q$	$1 / \Lambda^2$
D8	$\bar{\chi} \gamma^\mu \gamma^5 \chi \bar{q} \gamma_\mu \gamma^5 q$	$1 / \Lambda^2$
D9	$\bar{\chi} \sigma^{\mu\nu} \chi \bar{q} \sigma_{\mu\nu} q$	$1 / \Lambda^2$
D10	$\bar{\chi} \sigma_{\mu\nu} \gamma^5 \chi \bar{q} \sigma_{\alpha\beta} q$	i / Λ^2
D11	$\bar{\chi} \chi G_{\mu\nu} G^{\mu\nu}$	$\alpha_s / 4\Lambda^3$
D12	$\bar{\chi} \gamma^5 \chi G_{\mu\nu} G^{\mu\nu}$	$i \alpha_s / 4\Lambda^3$
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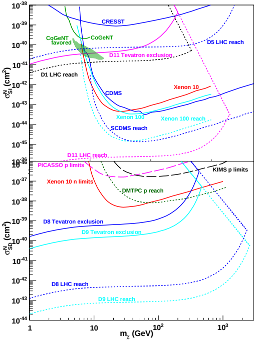
– complex/real scalars, Majorana/Dirac fermions coupling to Standard Model fields

– WIMP-nucleon cross section [direct detection]
compared to Tevatron/LHC reach $\chi\chi$+jets

$\Rightarrow$ and what does it mean?



MRSSM

3- Opposite of anomaly: understand 6×6 squark mass matrix?

– flavor violation: K-$\overline{K}$ mixing, $b \to s\gamma$, etc

– CP violation in flavor sector, electric dipole moments...

$\Rightarrow$ flavor symmetries required

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Solution [Kribs, Poppitz, Weiner]

– start from well-known R parity [proton decay, dark matter,...]
expand to continuous, global symmetry [Hall & Randall]

– forbidden soft-breaking terms $\phi^3, \phi^* \phi^2, \tilde{\lambda}\tilde{\lambda}$

– no Majorana masses, no A, μ, δ_{LR} terms [Majorana neutrino okay]

– squark mixing hardly constrained
gluino Dirac mass via additional state [chiral superfield with sgluon]

$\Rightarrow$ sgluon/color octet [TP & Tait]

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Close relatives

– axigluons: strong coupling to quarks [Bagger, Schmidt, King, 1988]

– supersoft SUSY breaking: sgluon not relevant for pheno [Fox, Nelson, Weiner]

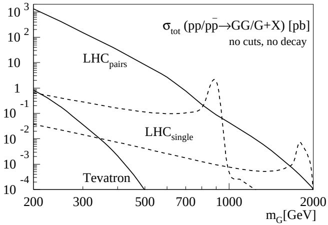
– $N = 2$ hybrid: minimal flavor violation [Popenda et al]

– colorons: boosted tops discussed later [Cilic, Schumann, Sundrum]

Color octets/sgluons

Production easy [TP & Tait, Popenda et al]

– pair production via SUSY-QCD
– single production at one-loop
– like stop pairs with new color factor



New Physics

Tilman Plehn

Early running

Anomalies

Models

Fat jets

Top tagging

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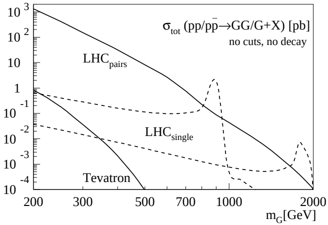
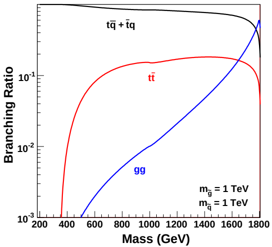


Decays with flavor structure

- $\Gamma(G \to gg) \propto m_{\tilde{g}}^2$
  $\Gamma(G \to t\bar{q} + \bar{t}q) \propto (m_t m_{\tilde{g}})^2$
  $G \to gg$ dominant for very large m_G
- SUSY decays possible
  $G \to t\bar{t}$ useful with MFV
  off-shell channels $<$ one-loop channels
- single production background-burdened

$\Rightarrow$ like-sign tops plus jets



Hidden valleys and portals

Skipping, ask me over coffee...

Chiral 4th Generation

3- Open questions

- why three generations? [review: Framton, Hung, Sher]
- anomaly cancellation?
  light neutrinos and LEP?
  Majorana neutrinos in neutrinoless double beta decay?
  electroweak precision data?
  flavor constraints?

⇒ none of the constraints convincing [Peccei: 'Why there should not be a fourth generation']

- strongly interacting theory? [Holdom; Burdman & De Rold]
  electroweak baryogenesis? [Fok & Kribs]
  dark matter?

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The model [old story]

- complete additional generation $[Q_4 \, , \, U_4 \, , \, D_4 \, , \, L_4 \, , \, e_4 \, , \, \nu_4]$
- masses from Yukawas
- representations as Standard Model: no FCNC
- charged currents: (4×4) fermion–mixing matrices [single-top (D0) $V_{bt} \gtrsim 0.68$]
- neutrino mass: $\mathcal{L} \sim y_4 \, \tilde{H} \bar{L}_4 \nu_{4R} + M \, \bar{\nu}^c_{4R} \nu_{4R}/2$

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Just as the 3rd generation... [Holdom; Vysotsky,...; Kribs, TP, Spannowsky, Tait]

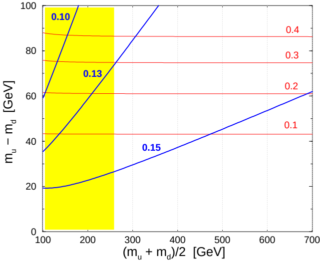
– okay, got it, some people prefer a Z'
let's be honest for a change...

– for our purpose: leading S and T [$\Delta U \sim 0$ as in SM]

– remember doublet: $\Delta S = N_f/(6\pi)(1 - 2Y \log m_u^2/m_d^2)$

(1) keep ΔS and ΔT small

[ΔS_q blue; ΔT_q red]



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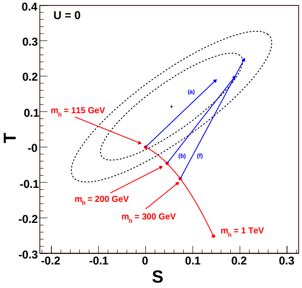
Electroweak precision data [LEPEWWG]

(2) old trick: compensate $\Delta S \sim \Delta T > 0$ [Hill...]
small m_H: $\Delta T \sim \Delta S \sim 0.2$
large m_H: $\Delta T \sim \Delta S + 0.2 \sim 0.3$

– allowed parameter points [$m_{\nu_4} = 100$ GeV, $m_{\ell_4} = 155$ GeV]

m_{u_4}	m_{d_4}	m_H	ΔS_{tot}	ΔT_{tot}
310	260	115	0.15	0.19
320	260	200	0.19	0.20
330	260	300	0.21	0.22
400	350	115	0.15	0.19
400	340	200	0.19	0.20
400	325	300	0.21	0.25



– generic $m_{u_4} > m_{d_4}$ allows for $u_4 \to d_4 W$

Chiral 4th Generation

Dimension-5 Higgs couplings [e.g. SFitter-Higgs; got a hacked HDecay]

– loop effects of new particles [Arik, Arik, Cetin, Conca, Mailov, Sultansoy; Kribs, TP, Spannowsky, Tait]
– chiral fermions without Appelquist-Carazone decoupling

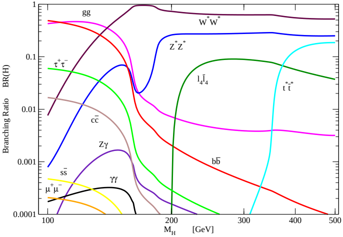
$$\Gamma_{H\to\gamma\gamma} = \frac{G_\mu \alpha^2 m_H^3}{128\sqrt{2}\pi^3} \left| \sum_f N_c Q_f^2 A_f(\tau_f) + A_W(\tau_W) \right|^2$$

$$\Gamma_{H\to gg} = \frac{G_\mu \alpha_s^2 m_H^3}{36\sqrt{2}\pi^3} \left| \frac{3}{4} \sum_f A_f(\tau_f) \right|^2 \qquad \text{with} \quad \tau_i = \frac{m_H^2}{4 m_i^2}$$

$$A_f(\tau) = \frac{2}{\tau^2} \left[\tau + (\tau - 1) f(\tau)\right]$$

$$A_W(\tau) = -\frac{1}{\tau^2} \left[2\tau^2 + 3\tau + 3(2\tau - 1) f(\tau)\right] \qquad \text{with} \quad f(\tau \to 0) \to \tau$$

(1) increase $g_{ggH} \to 3 \times g_{ggH}$
decrease $g_{\gamma\gamma H} \to 1/3 \times g_{\gamma\gamma H}$



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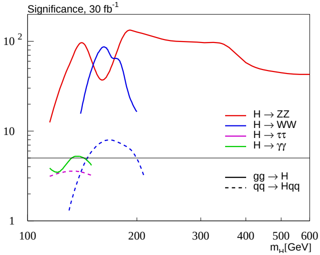
(1) increase $g_{ggH} \to 3 \times g_{ggH}$
decrease $g_{\gamma\gamma H} \to 1/3 \times g_{\gamma\gamma H}$

(2) factor 9 enhancement of $gg \to H$ [Tevatron!?]
$\sigma_{gg}\,\text{BR}_{\gamma\gamma} \to \sigma_{gg}\,\text{BR}_{\gamma\gamma}$
$\sigma_{gg}\,\text{BR}_{ZZ} \to (5 \cdots 8)\ \sigma_{gg}\,\text{BR}_{ZZ}$



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Dimension-5 Higgs couplings [e.g. SFitter-Higgs; got a hacked HDecay]

– loop effects of new particles [Arik, Arik, Cetin, Conca, Mailov, Sultansoy; Kribs, TP, Spannowsky, Tait]

– chiral fermions without Appelquist-Carazone decoupling

$$\Gamma_{H\to\gamma\gamma} = \frac{G_\mu \alpha^2 m_H^3}{128\sqrt{2}\pi^3} \left| \sum_f N_c Q_f^2 A_f(\tau_f) + A_W(\tau_W) \right|^2$$

$$\Gamma_{H\to gg} = \frac{G_\mu \alpha_s^2 m_H^3}{36\sqrt{2}\pi^3} \left| \frac{3}{4} \sum_f A_f(\tau_f) \right|^2 \qquad \text{with} \quad \tau_i = \frac{m_H^2}{4m_i^2}$$

$$A_f(\tau) = \frac{2}{\tau^2} \left[\tau + (\tau - 1) f(\tau)\right]$$

$$A_W(\tau) = -\frac{1}{\tau^2} \left[2\tau^2 + 3\tau + 3(2\tau - 1) f(\tau)\right] \qquad \text{with} \quad f(\tau \to 0) \to \tau$$

(1) increase $g_{ggH} \to 3 \times g_{ggH}$
decrease $g_{\gamma\gamma H} \to 1/3 \times g_{\gamma\gamma H}$

(2) factor 9 enhancement of $gg \to H$ [Tevatron!?]
$\sigma_{gg}\,\text{BR}_{\gamma\gamma} \to \sigma_{gg}\,\text{BR}_{\gamma\gamma}$
$\sigma_{gg}\,\text{BR}_{ZZ} \to (5\cdots 8)\;\sigma_{gg}\,\text{BR}_{ZZ}$

(3) Higgs pair production the winner [Baur, TP, Rainwater]

$\Rightarrow$ if nothing else — what a great straw man!

New physics searches at the LHC

	missing energy (p.89)	cascade decays (p.91)	mono-jets/photon (p.15)	lepton resnce (p.109)	di-jet resnce (p.109)	top resnce (p.120)	WW/ZZ resnce (p.15)	W' resnce (p.93)	top partner (p.116)	charged tracks (p.123)	displ. vertex (p.123)	multi-photons (p.29)	spherical events (p.47,76)
SUSY (heavy grav.) (p.17,26)	✓✓	✓✓							✓				
SUSY (light grav.) (p.17,27)	✓	✓	✓						✓	✓	✓		
large extra dim (p.39)	✓✓		✓✓										✓
universal extra dim (p.47)	✓✓	✓✓		✓	✓	✓	✓	✓	✓				
technicolor (vanilla) (p.51)				✓	✓	✓	✓	✓✓					
topcolor/top seesaw (p.53,54)					✓	✓✓	✓						
little Higgs (w/o T) (p.55,58)				✓	✓	✓	✓	✓					
little Higgs (w T) (p.55,58)	✓✓	✓✓	✓	✓	✓	✓	✓	✓	✓				
warped extra dim (IR SM) (p.61,63)				✓	✓	✓	✓						
warped extra dim (bulk SM) (p.61,64)				✓	✓	✓✓	✓	✓					
Higgsless/comp. Higgs (p.69,73)				✓	✓	✓✓	✓✓						
hidden valleys (p.75)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

[arXiv:0912.3259, Morrissey, TP, Tait]

Boosted W bosons

Why fat jets?

1. decay products too collinear to resolve
2. automatic reduction of signal combinatorics
3. improved resonance mass reconstruction

Boosted particles at LHC

1994 boosted $W \to 2$ jets from heavy Higgs [Seymour]

1994 boosted $t \to 3$ jets [Seymour]

2002 boosted $W \to 2$ jets from strongly interacting WW [Butterworth, Cox, Forshaw]

2006 boosted $t \to 3$ jets from heavy resonances [Agashe, Belyaev, Krupovnickas, Perez, Virzi]

2007 boosted $\tilde{\chi}_1^0 \to 3$ jets in R parity violating SUSY [Butterworth, Ellis, Raklev]

2008 boosted $H \to b\bar{b}$ [Butterworth, Davison, Rubin, Salam]

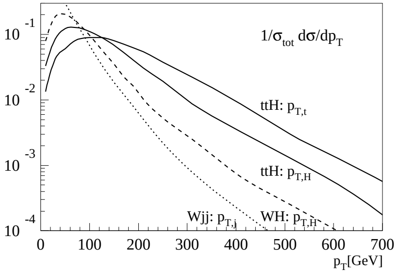
2009 boosted $t \to 3$ jets from top partners [TP, Salam, Spannowsky, Takeuchi]

...

Boosted Higgs bosons

Hadronic Higgs decays [Butterworth, Davison, Rubin, Salam]

- S: large m_{bb}, boost-dependent R_{bb}
  B: large m_{bb} only for large R_{bb}
  S/B: large m_{bb} and small R_{bb}, so boosted Higgs
- fat Higgs jet $R_{bb} \sim 2m_H/p_T < 1$



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$\Rightarrow$ non-trivial challenge to jet algorithms

	σ_S/fb	σ_B/fb	$S/\sqrt{B}_{30}$
C/A, $R = 1.2$, MD-F	0.57	0.51	4.4
$k_\perp$, $R = 1.0$, y_{cut}	0.19	0.74	1.2
SISCone, $R = 0.8$	0.49	1.33	2.3

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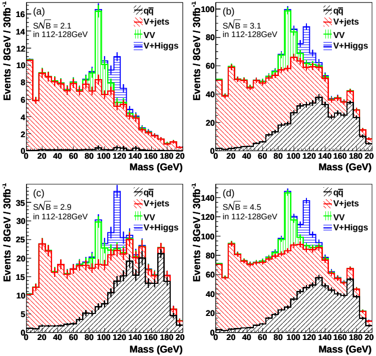
WH/ZH productionm $H \to b\bar{b}$

- combined channels $V \to \ell\ell, \nu\nu, \ell\nu$
- Z peak as sanity check
- confirmed to 20% [ATLAS: Piquadio]
  subjet b tag excellent [70%/1%]
  charm rejection challenging
  $m_H \pm 8$ GeV tough
- improvements possible [Soper, Spannowsky]

$\Rightarrow$ crucial to understand Higgs sector



More boosted Higgs bosons

Long death of $t\bar{t}H$, $H \to b\bar{b}$ [Cammin & Schumacher, CMS-TDR and Atlas-CSC worse]

– trigger: $t \to bW^+ \to b\ell^+\nu$
  reconstruction and rate: $\bar{t} \to \bar{b}W^- \to \bar{b}jj$

– not a chance:
  1– combinatorics: m_H in $pp \to 4b_{tag}\ 2j\ \ell\nu$
  2– kinematics: peak-on-peak with $t\bar{t}b\bar{b}$, $t\bar{t}jj$
  3– systematics: $S/B \sim 1/9$ [$S/\sqrt{B}$ irrelevant]

Higgs tagger for $t\bar{t}H$ [TP, Salam, Spannowsky]

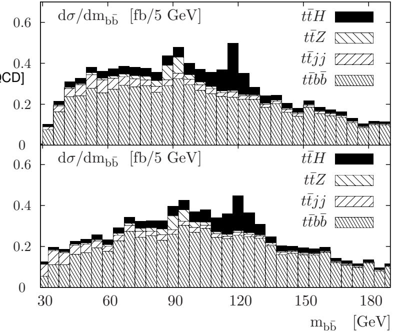
– tagged top and tagged Higgs
  trigger on lepton

– add'l continuum b tag [remove $t_\ell \to b$ plus QCD]

– side bin in continuum $t\bar{t}b\bar{b}$

– promising, but 100 fb^{-1}

m_H	S	S/B	$S/\sqrt{B}$
115	57	1/2.1	5.2 (5.7)
120	48	1/2.4	4.5 (5.1)
130	29	1/3.6	2.9 (3.0)



Boosted top quarks

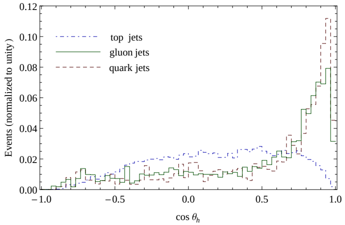
Highly boosted top quarks [Kaplan, Rehermann, Schwartz, Tweedie; Princeton, Seattle...]

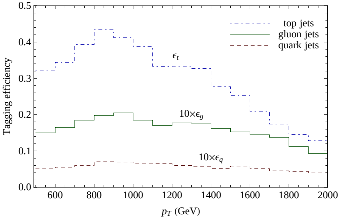
– identify hadronic tops with $p_T \gtrsim 800$ GeV
  isolation and b tagging challenging

– C/A algorithm with p_T drop criterion
  all top decay jets identified
  3 kinematic constraints: $m_W, m_t, \cos\theta_{\text{hel}}$ [no b tag]

– top mass included, no sidebins

– improvement $S/B \to 15 \times S/B$





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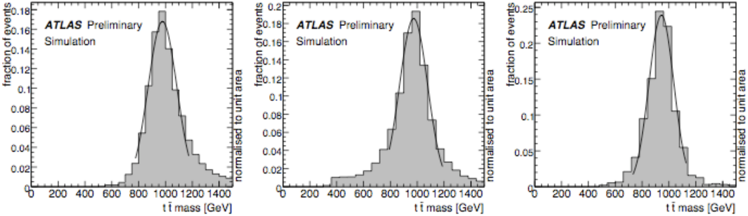
– ATLAS studies on semi-leptonic channel promsing



(a) minimal (b) full reconstruction (c) mono-jet

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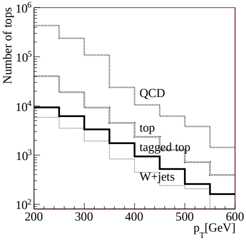
Standard Model: HEPTopTagger [TP, Salam, Spannowsky, Takeuchi]

– extend reach to $p_T \gtrsim 250$ GeV

– start like Higgs tagger [mass drop, $R = 1.5$]
kinematic selection: $m_{jjj}, m_{jj}^{(1)}, m_{jj}^{(2)}$ [no b tag, filtered]

– no id of top decay products
no boost



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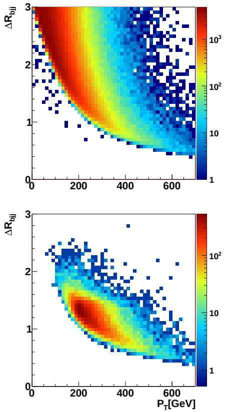

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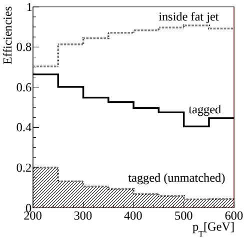
  kinematic selection: $m_{jjj}, m_{jj}^{(1)}, m_{jj}^{(2)}$ [no b tag, filtered]
- no id of top decay products
  no boost
- realistic for $t\bar{t}$ in SM
- top reconstruction possible [hadronic top tag almost like b tag]
- waiting to be tested: Tevatron/LHC



Stops

Stop pairs [TP, Spannowsky, Takeuchi, Zerwas]

– top partner most important particle in MSSM [hierarchy problem]
comparison to other top partners [Meade & Reece]

– dark matter difficult for semi-leptonic channel

– purely hadronic: $\tilde{t}\tilde{t}^* \to t\tilde{\chi}_1^0\, \bar{t}\tilde{\chi}_1^0$ [CMS-TDR: leptons as life guards]

events in 1 fb^{-1}	$\tilde{t}_1\tilde{t}_1^*$						$t\bar{t}$	QCD	W+jets	Z+jets	S/B	$S/\sqrt{B}_{10\,\text{fb}^{-1}}$
$m_{\tilde{t}}$[GeV]	340	390	440	490	540	640					340	
$p_{T,j} > 200$ GeV, ℓ veto	728	447	292	187	124	46	87850	$2.4 \cdot 10^7$	$1.6 \cdot 10^5$	n/a	$3.0 \cdot 10^{-5}$	
$\not{E}_T > 150$ GeV	283	234	184	133	93	35	2245	$2.4 \cdot 10^5$	1710	2240	$1.2 \cdot 10^{-3}$	
first top tag	100	91	75	57	42	15	743	7590	90	114	$1.2 \cdot 10^{-2}$	
second top tag	15	12.4	11	8.4	6.3	2.3	32	129	5.7	1.4	$8.3 \cdot 10^{-2}$	
b tag	8.7	7.4	6.3	5.0	3.8	1.4	19	2.6	$\lesssim 0.2$	$\lesssim 0.05$	0.40	5.9
$m_{T2} > 250$ GeV	4.3	5.0	4.9	4.2	3.2	1.2	4.2	$\lesssim 0.6$	$\lesssim 0.1$	$\lesssim 0.03$	0.88	6.1

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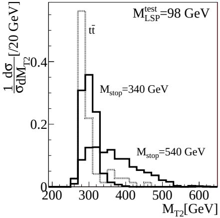
– stop mass from m_{T2} endpoint [like slepton pairs]

– not even a hard analysis with tested top tagger



Outlook

Watching Tevatron and LHC

– new physics only starting towards 1 fb^{-1}

– anomalies either unexplainable or unconvincing

– little happening in model space [arXiv:0912.3259, Morrissey, TP, Tait]

$\Rightarrow$ time for helpful phenomenology

– parton shower/matrix element merging [CKKW, MLM, MC@NLO, POWHEG, CKKW@NLO]

– automized higher order calculations [SM & BSM]

– new physics interfaces in event generators [FeynRules]

– effective theories of new physics [useful?]

– personally: boosted heavy particles

$\Rightarrow$ time to test tools on Tevatron/LHC data [HEPTopTagger]