Top Quarks and Jet Substructure at the LHC

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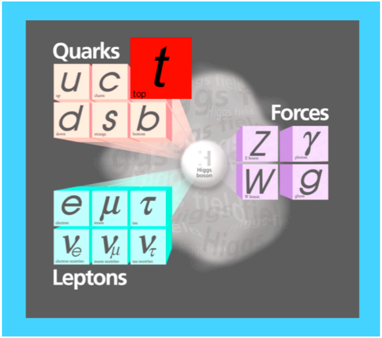
at IPMU, 14th March 2013

What we know

Standard Model: 12 + 4 + 1 particles, SU(3)×SU(2)×U(1)



$$\mathcal{L}_{\rm SM} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}\not{D}\psi + h.c.$$
$$+\bar{\psi}_i y_{ij}\psi_j\phi + h.c.$$
$$+|D_\mu\phi|^2 - V(\phi)$$

$\alpha_1, \alpha_2, \alpha_3, m_i$, mixings, v, λ

17 parameters

Higgs VEV provides all masses

$m_t \sim 173$ GeV (1995)

$m_H \sim 125$ GeV (2012)

Many consistent observations, only a few deviations

Quadratic divergence $\delta m_H \sim \Lambda^2$, $\Lambda \sim M_{pl} = 10^{19}$GeV?

Michihisa
Takeuchi

Introduction

Top at the LHC

Jet substructure

HEPTopTagger

Applications

Summary

Back up

What we know

Existence of dark matter

Rotation curve

Cluster merger

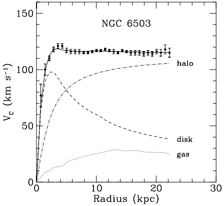
N-body simulation

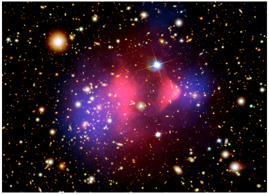
WMAP, BAO etc.

$\Omega_{\rm cdm} h^2 = 0.113$

not possible to explain in SM

all evidence from gravity





– What is dark matter?

WIMP Miracle? (Weakly interacting massive particle)

$\Omega_\chi \sim \frac{0.1\rm pb}{<\sigma_A v>}, <\sigma_A v> \sim \frac{\alpha^2}{m_\chi^2} \sim 10^{-9}{\rm GeV}^{-2},$

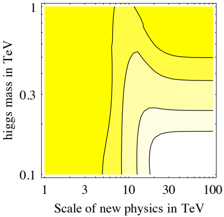
$\alpha_2 \sim 1/30 \rightarrow m_\chi \sim 1$ TeV $\Rightarrow$ something new in TeV?

What we expect

– Estimate for the new physics scale

$\mathcal{L} = \mathcal{L}_{\rm SM} + \sum \frac{c_i}{\Lambda^p} \mathcal{O}_{4+p,i}$

New physics $\Lambda >\sim 10$ TeV



Something new in TeV → some symmetry?

Z_2-parity (DM?), supersymmetry

→ partner particles in TeV?

14 TeV pp-collider LHC can search them

Collider experiments

Directly produce new particles and analyze them

Event rate $\sim |<f|e^{i\int \mathcal{L}}|i>|^2$, various pairs of $|i>, |f>$

Note: most particles decay, $m_q < m_b \ll m_W, m_Z, m_t, m_H$

γ, e, μ, τ and jets (only b-quark flavor)

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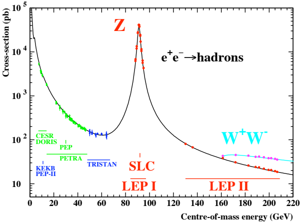

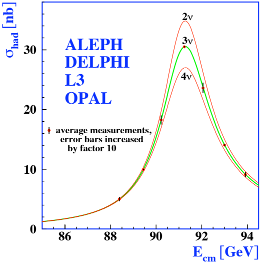

Clear evidence of particles: simple, obvious, convincing

Statistics discriminates models

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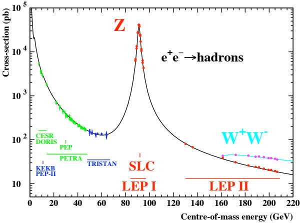

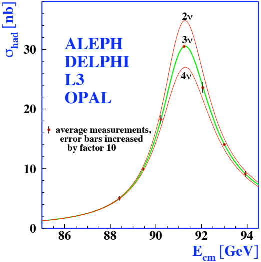

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Statistics discriminates models

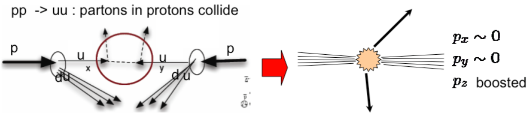
Why not Higgs found at LEP: 209GeV $< m_Z + m_H$

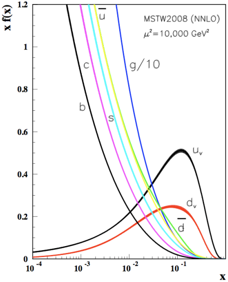
$m_p \sim 2000 m_e$, emission $\propto E/m^2 \Rightarrow$ Hadron Collider: LHC

Hadron Collider

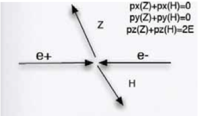
What is the difficulty?

- proton beam: mixed beam of g, u, d, ...
- only p_T conservation





· full reconstruction not possible
  event by event (different from LEP)

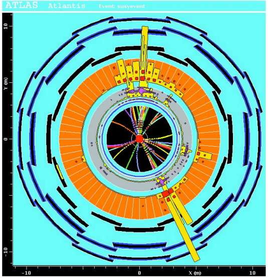


· precision physics possible by statistics

- strong interaction
  jets appear anywhere, initial state radiation etc.

PDF, NLO etc. understanding QCD important

SUSY search



– colored particles produced in pair:

$\tilde{g}$, $\tilde{q}$ expected ~ 1 TeV

– cascade decay $\tilde{g} \rightarrow \tilde{q}q$

$$\tilde{q} \rightarrow q\tilde{\chi}^0(\mathrm{DM})$$

– signal:

multiple jets, missing transverse momentum $\not{E}_T$

– BG:

$W \rightarrow l\nu$

$Z \rightarrow \nu\bar{\nu}$

$t \rightarrow bW \rightarrow bl\nu$

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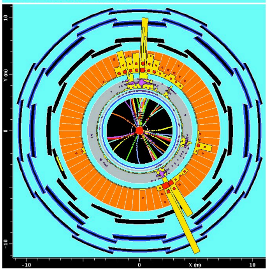

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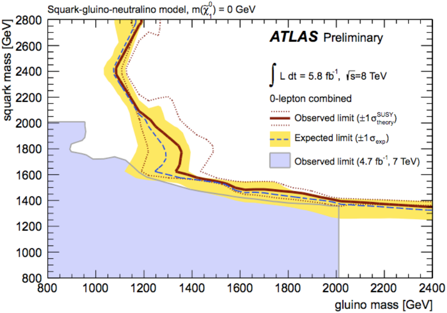
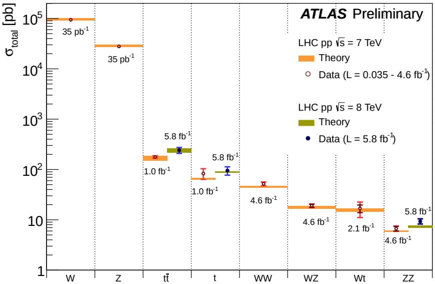
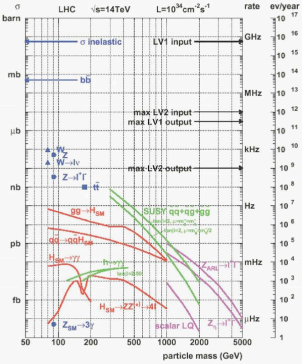


Huge difference among the numbers

– To extract signal need subtract larger contributions

typical signal cross section $\sim$ 1 pb





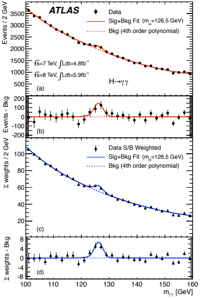
– QCD uncertainty ($\alpha \sim 10\%$), NLO, PDF, jets

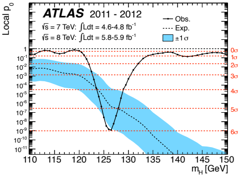
– Theory cannot predict completely $\rightarrow$ data driven estimate

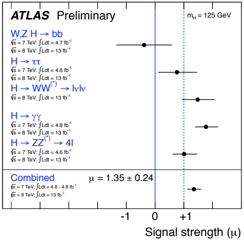
distribution important: ME+PS matching

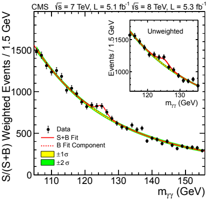
– We know SM but not enough yet to extract new physics

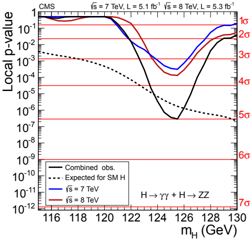
Higgs (like particle) found!

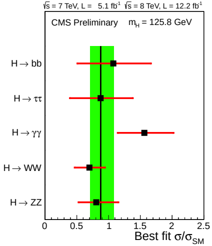












My focus

Top sector

- Only the sector not precisely understood (except higgs)
- LHC: top factory
- Strongly coupled to higgs: key for fine tuning
- Anomalies

Jet substructure

- Fine detector resolution
- state-of-the-art
- use information thrown away before → optimal use of data

Top at the LHC

closest to new physics → probe for new physics

– largest yukawa coupling y_t (need $t\bar{t}H$ measurement)

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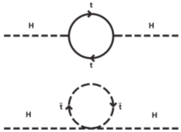

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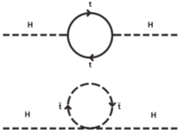
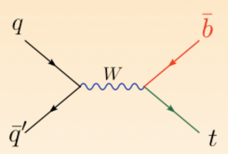
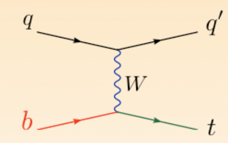
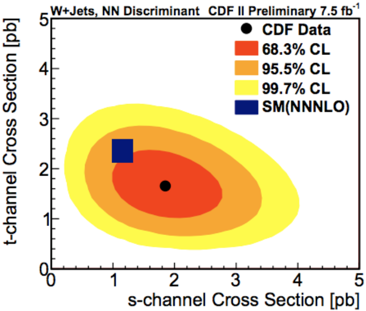


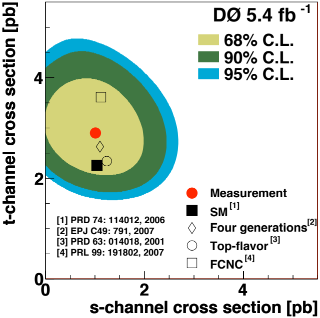
- Tevatron anomalies (A^t_{FB}, single top etc.)

Single tops at Tevatron

s-channel: 

t-channel: 





– 3σ level contradiction between CDF and D0

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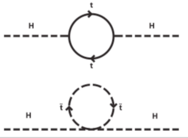

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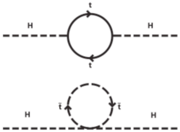
  LHC $\sim 6,000,000\ t\bar{t}$

  Tevatron $\sim 40,000\ t\bar{t}$ → precision physics



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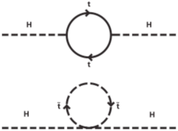
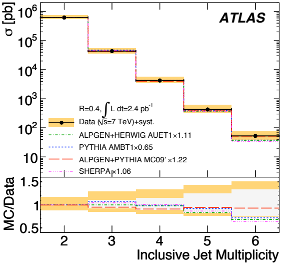
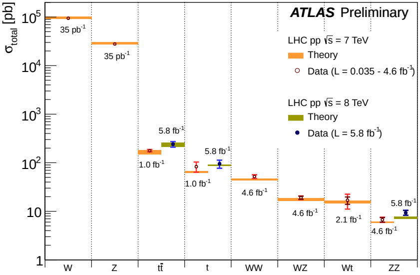


Huge difference among the numbers

SM including pQCD, NLO,... describes data well.





Need subtractions.

Handles:

leptons ℓ

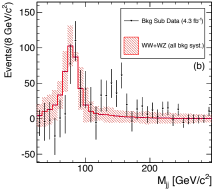
b-tag

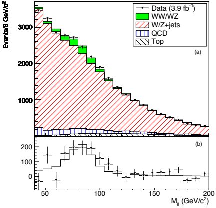
missing momentum $\not{E}_T$ $\quad\rightarrow$ top involves all

Top as background [arXiv:1104.4087 [hep-ph] T. Plehn, MT]

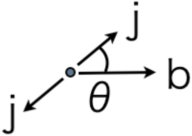
W+jets at CDF: second peak around 150 GeV

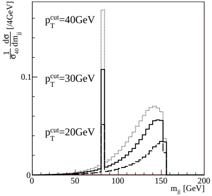
$\sigma(WW + WZ)$
$W \to e\nu$ and $\mu\nu$

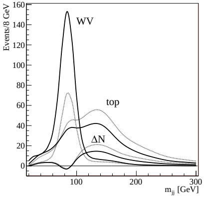




top gives m_{bj} peak around $\sqrt{m_t^2 - m_W^2} \sim 150$ GeV







Need understand top background (also b-tag).

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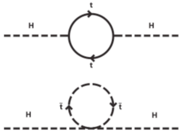

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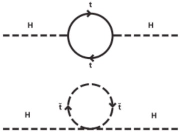

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hadronic top $t \to 3j$

– full momentum reconstruction possible in principle

– top against 10^3 larger QCD, how to identify?

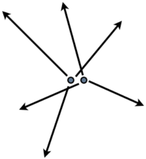
– take 3 jets with simple m_t, m_W condition

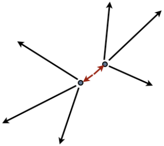
→ large combinatorial BG kill us

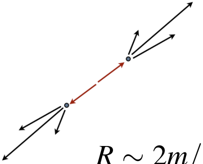
Boosted Tops at the LHC

top looks different

top at rest | moderate boost | highly boosted







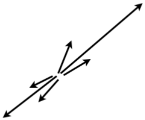
$R \sim 2m/p_T$

separate 3 jets | | massive jet

combinatorics | | QCD jet

QCD jets

- 2 jet topology dominate QCD jets
- substructure: soft-collinear nature (QCD)



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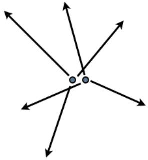

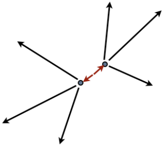

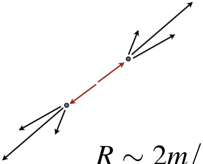

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separate 3 jets | massive jet

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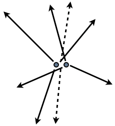
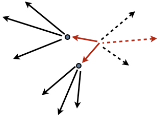
top as a probe

– new physics search with $\not{E}_T$
  $\longrightarrow$ need recoil





· top at rest: not useful

· boosted tops: carry information on dark matter

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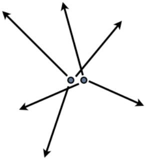
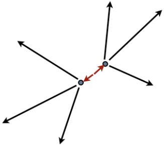
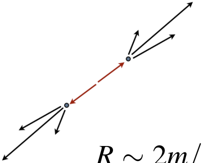






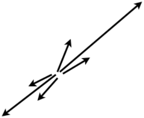
$R \sim 2m/p_T$

separate 3 jets | massive jet

combinatorics | QCD jet

QCD jets

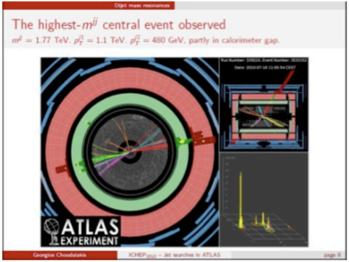
- 2 jet topology dominate QCD jets
- substructure: soft-collinear nature (QCD)

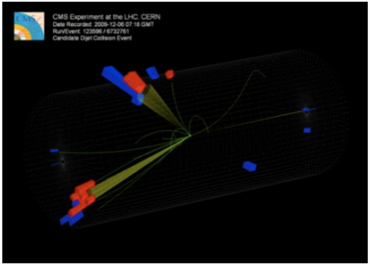


Jet substructure

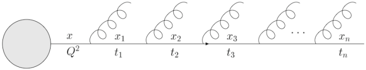
What is a jet?

jet = collimated hadronic activity in the detector





well described by QCD (soft-collinear property)

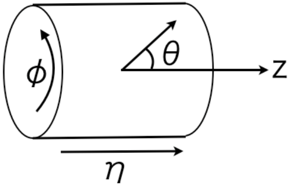


$$\mathcal{M} \sim \frac{1}{t_1}\frac{1}{t_2}\frac{1}{t_3}\cdots$$
$$Q^2 > t_1 > t_2 > \dots$$
$$t = E_1 E_2 (1 - \cos\theta)$$

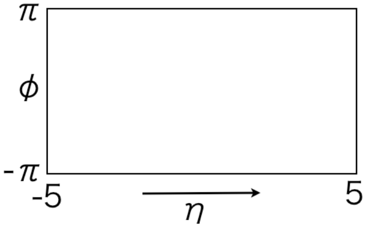
$\longrightarrow$ parton shower $\longrightarrow$

$\longleftarrow$ jet algorithm $\longleftarrow$

(η,ϕ) plane



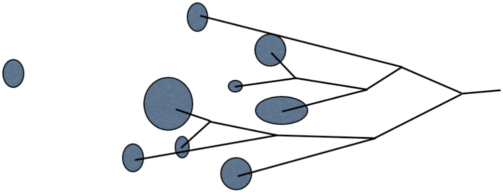
$\eta = -\ln\tan\frac{\theta}{2}$



$\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$

typical size of jet $R = 0.5$

Jet algorithm



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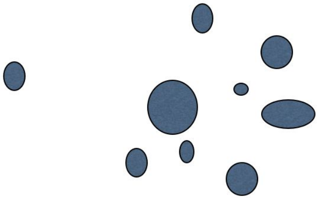

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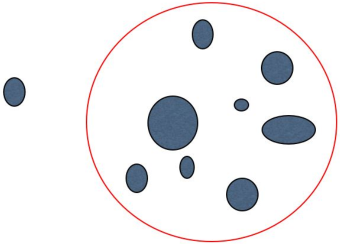

before LHC, cone algorithm, q-momentum reconstructed

Jet algorithm

Clustering algorithm

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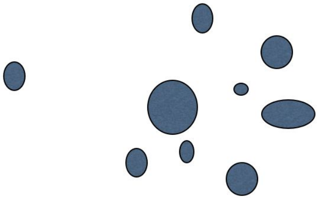

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R: jet size

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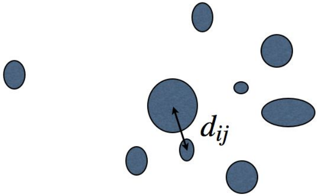

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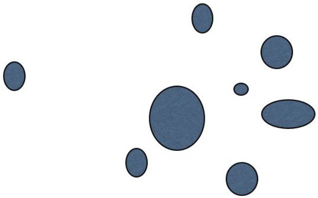

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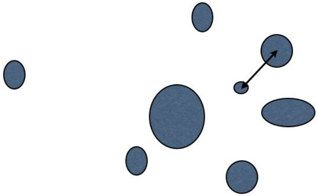

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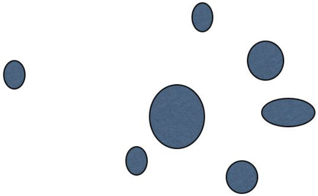

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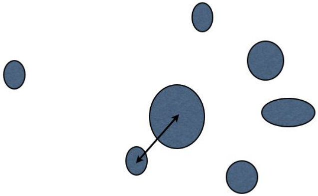

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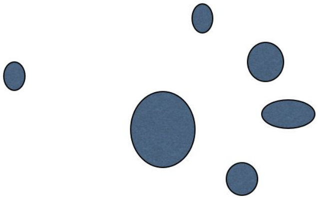

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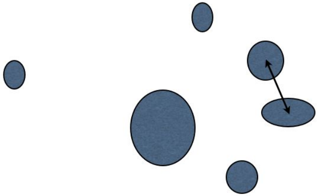

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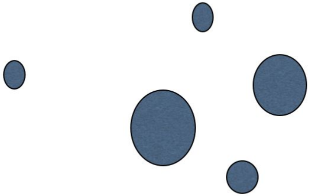

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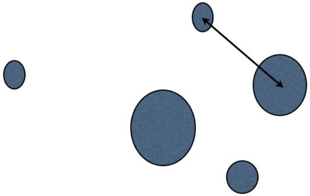

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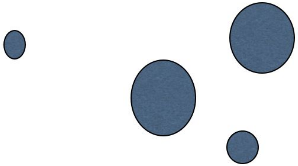

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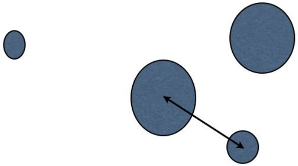

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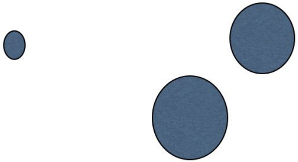

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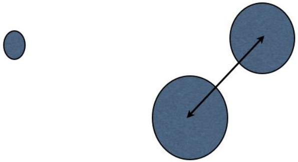

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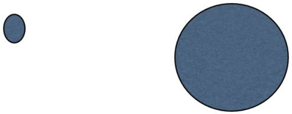

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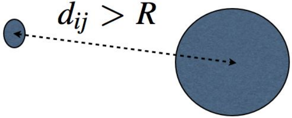

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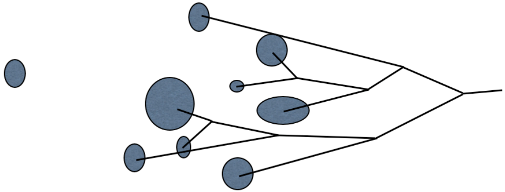

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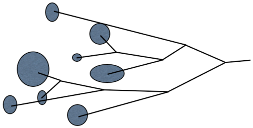
q-momentum reconstructed, additional tree structure.

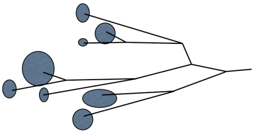
Jet substructure

top or qcd?

– QCD jet → soft-collinear singularity



– top jet → collects collinear decay products by boost



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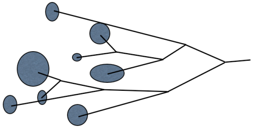

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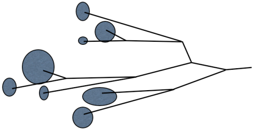


undoing clustering

– expect: clustering history ∼ shower history

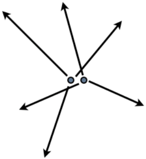
– no soft-collinear singularity for decay of boosted object → mass drop

$$j = j_1 + j_2, \quad \boxed{m_j \gg m_{j1}, m_{j2} \text{ (massive particle)}} \leftrightarrow \boxed{m_j \sim m_{j1} \gg m_{j2} \text{ (QCD)}}$$

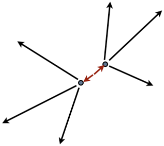
Boosted Tops at the LHC

top looks different

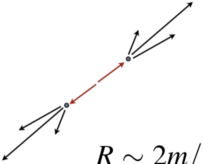
top at rest



moderate boost



highly boosted



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QCD jets

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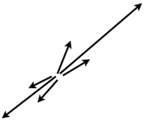


several top taggers available: focus on $p_T > 500$ GeV.

[Kaplan, Rehermann, Schwartz, Tweedie] [Thaler, Wang] [Almeida, Lee, Perez, Sterman, Sung]

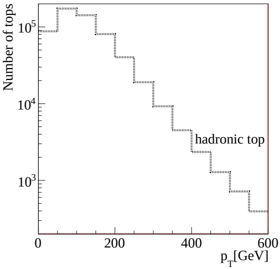
Moderately Boosted Tops at the LHC

top p_T distribution

- $p_T > 500$ GeV: not many in SM

$$\sigma_{>200\mathrm{GeV}} \sim 50\sigma_{>500\mathrm{GeV}}$$

- need top tagger valid down to low p_T range → testable



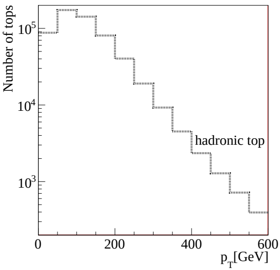
Moderately Boosted Tops at the LHC

top p_T distribution

- $p_T > 500$ GeV: not many in SM

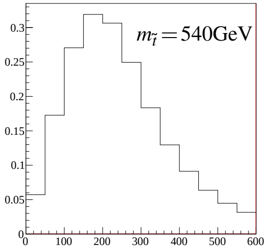
$$\sigma_{>200\text{GeV}} \sim 50\sigma_{>500\text{GeV}}$$

- need top tagger valid down to low p_T range → testable



- light top partners also provide tops in the same range

we focus on $p_T > 200$GeV
→ need fat jet with $R = 1.5$



HEPTopTagger [JHEP 1010:078,2010. arXiv:1006.2833 T. Plehn, M. Spannowsky, D. Zerwas, MT] [Phys.Rev. D85 (2012) 034029, arXiv:1111.5034]

1. fat jets – C/A with $R = 1.5$, $p_T^{\text{fatjet}} > 200$ GeV

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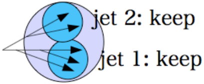
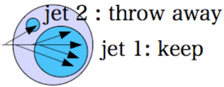
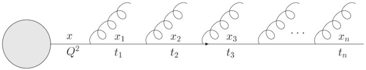
1. **fat jets** – C/A with $R=1.5$, $p_T^{\text{fatjet}} > 200$ GeV
2. **find subjets by mass drop criterion**

$j = j_1 + j_2$

$\boxed{m_j \gg m_{j1}, m_{j2} \text{ (decay)}} \leftrightarrow \boxed{m_j \sim m_{j1} \gg m_{j2} \text{ (QCD)}}$

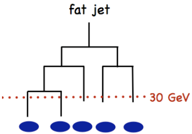






soft-collinear singularity

– keep j_1 and j_2 for $m_{j_1} < 0.8 m_j$ until $m_j < 50$ GeV



Michihisa Takeuchi

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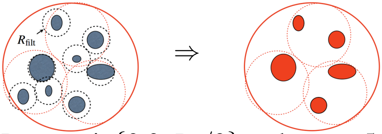
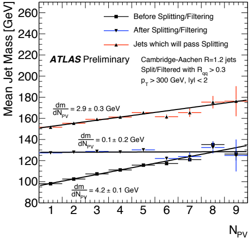
3. **take 3 subjets with best filtered mass**
   – $|m_{jjj}^{\text{filt}} - m_t| < 25$ GeV → top candidate

filtering [Butterworth et al.]

– effect of pile-up, underlying events

– reduce effective area





– $R_{\text{filt}} = \min\{0.3, R_{ij}/2\}$ and $n_{\text{filt}} = 5$ $(t \to bWg \to bgjjg)$

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4. **check mass ratios**

– 3 subjets: $p_1, p_2, p_3 \rightarrow m_{12}, m_{13}, m_{23}$

– $m_t^2 = m_{123}^2 = m_{12}^2 + m_{13}^2 + m_{23}^2 \rightarrow$ 2D mass ratios

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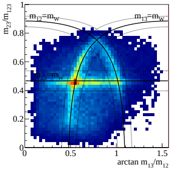
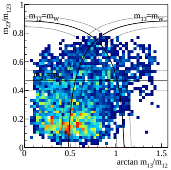
$m_{23} \downarrow 0$

$0 \leftarrow m_{13}$

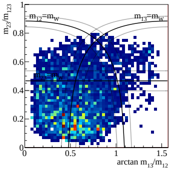
$m_{12} \rightarrow 0$



$t\bar{t}$



W+jets



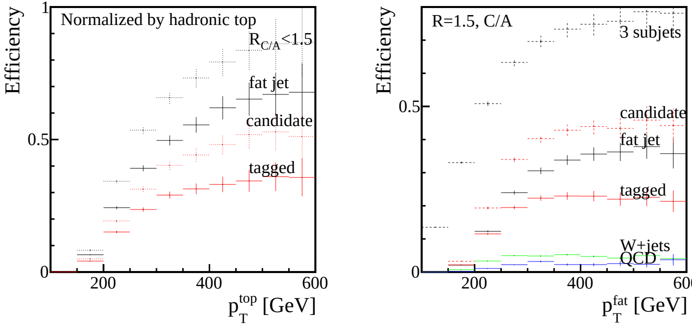
QCD

– W mass condition, soft-collinear cut $\rightarrow$ tagged top

– no b-tag information

HEPTopTagger [JHEP 1010:078,2010. arXiv:1006.2833 T. Plehn, M. Spannowsky, D. Zerwas, MT]

efficiency



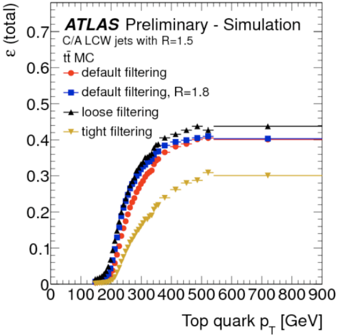
– efficiency $\sim$ 30% for hadronic tops, 2 $\sim$ 4% mis-tag rate

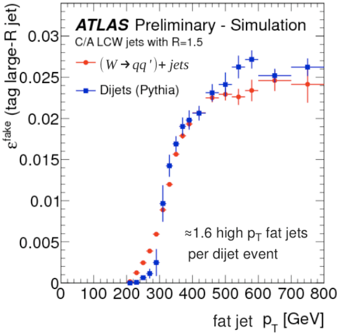
– momentum well reconstructed

– validation with ATLAS experimentalists in Heidelberg

[G. Kasieczka, S. Schätzel, A. Schöning]

Validation by ATLAS [ATLAS-CONF-2012-065]





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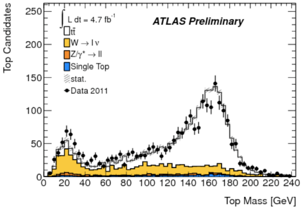
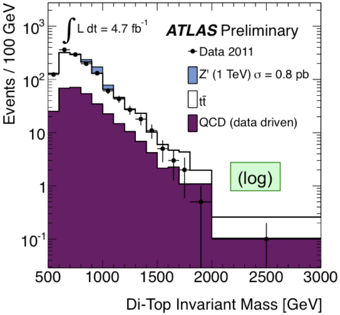
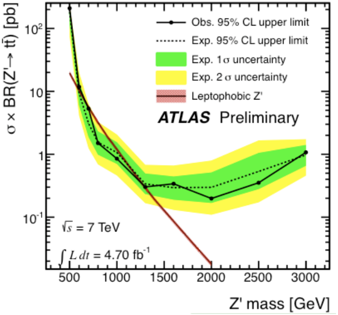
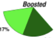
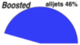
– data well described by MC



Z' search with HEPTopTagger by ATLAS [ATLAS-CONF-2012-065]





	 e+e, μ+μ and e+μ 6.5%	 e+jets 17% μ+jets 17%	 Boosted e+jets 17% μ+jets 17%	 Boosted alljets 46%
Article/ Note	**arXiv: 1205.5371**	**arXiv: 1205.5371**	**arXiv: 1207.2409**	**ATLAS-CONF-2012-102**
Integrated Luminosity	2 fb^{-1}	2 fb^{-1}	2 fb^{-1}	4.7 fb^{-1}
Z' limits $\Gamma/m = 1.2\%$	-	0.5-0.88 TeV	0.6-1.15 TeV	0.7-1.3 TeV
KKG limits $\Gamma/m = 15.3\%$	0.5-1.08 TeV	0.5-1.13 TeV	0.6-1.5 TeV	0.7-1.5 TeV

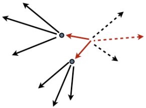
– Extended reach with boosted tops

Applications

Scalar Top Pairs at 14 TeV

hadronic mode [T. Plehn, M. Spannowsky, MT, D. Zerwas]

- $\tilde{t}_1\tilde{t}_1^* \to (t\tilde{\chi}_1^0)(\bar{t}\tilde{\chi}_1^0)$: $m_\chi = 100$ GeV
- main BG: $t\bar{t}$+jets, W+jets and QCD



events in 1 fb^{-1}	$\tilde{t}_1\tilde{t}_1^*$					$t\bar{t}$	QCD	W+jets	Z+jets	S/B	$S/\sqrt{B}_{10\ \mathrm{fb}^{-1}}$
$m_{\tilde{t}}$[GeV]	390	440	490	540	640					390	
$p_{T,j} > 200$ GeV, ℓ veto	447	292	187	124	46	87850	$2.4 \cdot 10^7$	$1.6 \cdot 10^5$	n/a	$\sim 10^{-5}$	
$\not{E}_T > 150$ GeV	234	184	133	93	35	2245	$2.4 \cdot 10^5$	1710	2240	$\sim 10^{-3}$	
first top tag	91	75	57	42	15	743	7590	90	114	0.01	
second top tag	12.4	11	8.4	6.3	2.3	32	129	5.7	1.4	0.07	
b-tag for 1$^{\mathrm{st}}$ top tag	7.4	6.3	5.0	3.8	1.4	19	2.6	$\lesssim 0.2$	$\lesssim 0.05$	0.34	5.0
$m_{T2} > 250$ GeV	5.0	4.9	4.2	3.2	1.2	4.2	$\lesssim 0.6$	$\lesssim 0.1$	$\lesssim 0.03$	1.0	7.1

W+jets, Z+jets negligible with 2 top tag

QCD negligible with additional b-tag

$t\bar{t}$ reduced with m_{T2} cut

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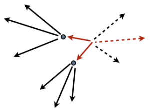

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QCD negligible with additional b

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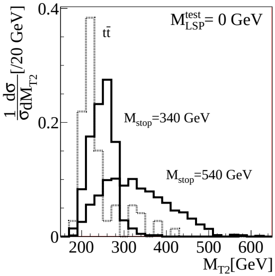

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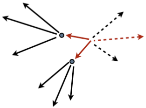

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– stop mass from $m_{T2}(m_{\tilde{\chi}_1^0})$ endpoint [C. G. Lester, D. J. Summers]

like sleptons or sbottoms

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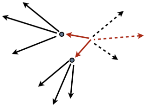

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  like sleptons or sbottoms

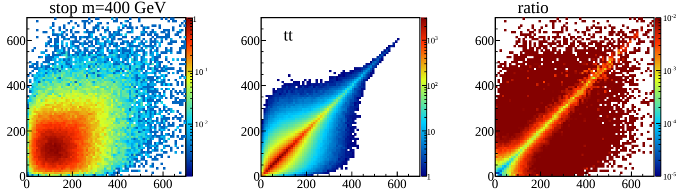
semi-leptonic mode [JHEP 1105 (2011) 135 [arXiv:1102.0557], T. Plehn, M. Spannowsky, MT]

boosted leptonic top $\boxed{S/B \sim 2, S/\sqrt{B} > 5 \text{ at 14 TeV with } 10\text{fb}^{-1}}$

Scalar Top Pairs at 8TeV

[arXiv:1205.2696 T. Plehn, M. Spannowsky, MT]

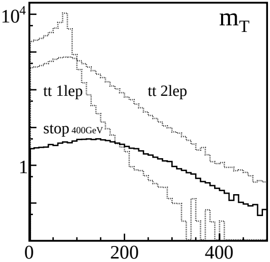
- $\sigma^{8\mathrm{TeV}} \sim \frac{1}{10}\sigma^{14\mathrm{TeV}}$: both for $t\bar{t}$ and $\tilde{t}_1\tilde{t}_1^*$
- 2 boosted tops: not enough signal left
  $S/B \sim 0.8, S/\sqrt{B} \sim 1.5$ (two top tag)
- $t\bar{t}$: dominant background at the end



- 1 boosted top and 1 non-boosted top
  - hadronic mode: 1 hadronic top-tag + b-jet + $\not{E}_T$
  - semi-leptonic mode: 1 hadronic top-tag + ℓ, $\not{E}_T$

Scalar Top Pairs at 8TeV [arXiv:1205.2696 T. Plehn, M. Spannowsky, MT]

– semi-leptonic mode: 1 hadronic top-tag + $\ell, \not{E}_T$



$t\bar{t} \to t_h + b\ell\nu$

negligible with $m_T(\ell, \not{E}_T) > 150$ GeV

$t\bar{t} \to b\bar{b} + \tau_h\ell + 2\nu$

fake hadronic top tag with ISR or τ_h

$\to$ subjet id: b-tag, τ_h rejection.

$\sqrt{s} = 8$ TeV, $R = 1.5$	$\tilde{t}1\tilde{t}1^*$						$t\bar{t}$	S/B	$S/\sqrt{B}_{10\text{fb}^{-1}}$
$m_{\tilde{t}}$[GeV]	350	400	450	500	600	700		400	
cross section [fb]	760	337	160	80.5	23.0	7.19	$2.34 \cdot 10^5$		
$n_\ell = 1$, $\not{E}_T > 100$ GeV, $n_{\text{fat}} \geq 1$	104.37	61.49	34.81	19.54	6.28	2.11	5631		
$n_{\text{tag}} = 1$	13.09	9.02	5.80	3.60	1.33	0.50	788.79		
$m_T > 150$ GeV	4.63	4.27	3.25	2.19	0.94	0.38	3.28	1.0	6.5
$j_b = b$	1.47	1.38	1.06	0.70	0.31	0.13	0.63	2.1	5.4
$(j_b, j_{W1}, j_{W2}) = (b, j, j)$	1.33	1.27	0.96	0.65	0.29	0.12	0.50	2.4	5.5
$(j_b, j_{W1}, j_{W2}) = (b, j, j)$, reject τ_h	1.20	1.16	0.88	0.60	0.27	0.11	0.25	4.1	6.9

Scalar Top Pairs at 8TeV [arXiv:1205.2696 T. Plehn, M. Spannowsky, MT]

For scalar top mass 400 GeV for 10 fb^{-1}

– fully hadronic mode: statistically limited
 $S/B \sim 0.8, S/\sqrt{B} \sim 1.5$ (two top tag)
 $S/B \sim 1, S/\sqrt{B} \sim 3$ (one top tag)

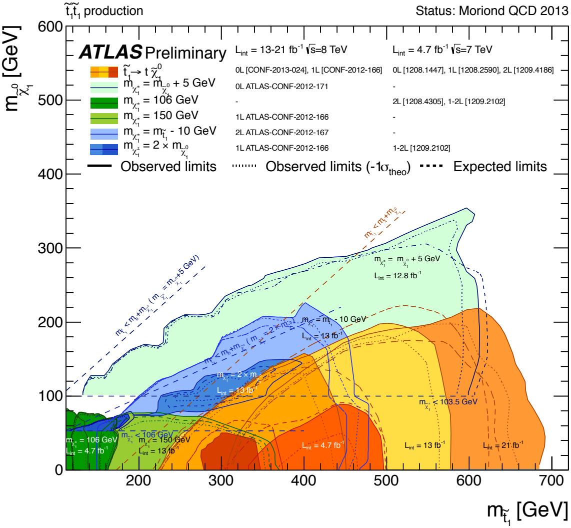
– semi-leptonic mode:
 $S/B \sim 4, S/\sqrt{B} \sim 7$

– di-lepton mode: not conclusive
 $S/B \sim 6, S/\sqrt{B} \sim 16$
 95% C.L. exclusion up to ~ 600 GeV

Scalar Top Pairs at 8TeV

[arXiv:1205.2696 T. Plehn, M. Spannowsky, MT]

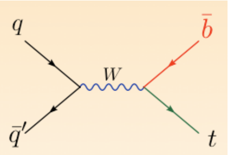
2013 Moriond: up to 660 GeV excluded 95% C.L.



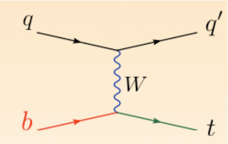
Single tops at 8TeV

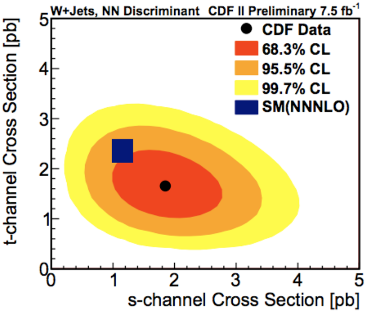
[arXiv:1207.4787 F. Kling, T. Plehn, MT]

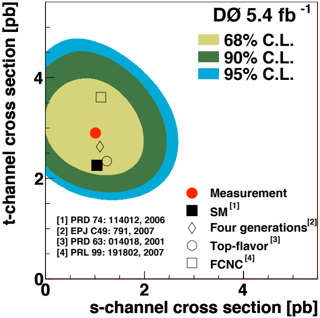
s-channel:



t-channel:



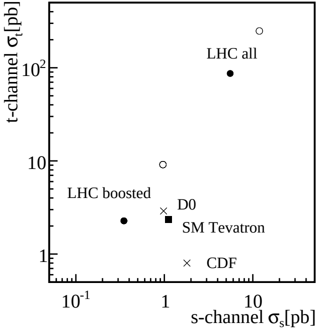


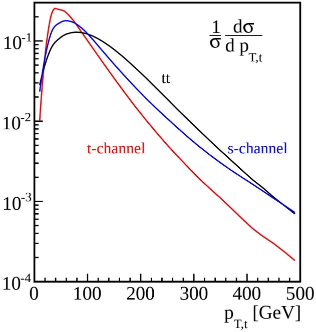


– 3σ level contradiction between CDF and D0

Single tops at 8TeV

[arXiv:1207.4787 F. Kling, T. Plehn, MT]





– small $\bar{q}$ and large $g \to b\bar{b}$

$\to \sigma_t \sim 16\sigma_s$ at LHC

8 TeV: $p_{T,t}^{\min}$	0	100	200	300	400	500
σ_s [fb]	5548	1784	349	86.4	26.5	9.54
σ_t [fb]	86829	18167	2273	409.2	95.7	26.0
$\sigma_{t\bar{t}}$ [fb]	234731	137274	34640	7560	1850	519
$\sigma_s/\sigma_t(\%)$	6.4	9.8	15.4	21.1	27.7	36.7
$\sigma_s/\sigma_{t\bar{t}}(\%)$	2.36	1.29	1.00	1.14	1.43	1.83

σ_s/σ_t improves

in boosted regime

$\to$ top tagger

Single tops at 8TeV [arXiv:1207.4787 F. Kling, T. Plehn, MT]

– no lepton, 2 fat jets

– one top tag

– Δm^{prune}, b-tag in top tag

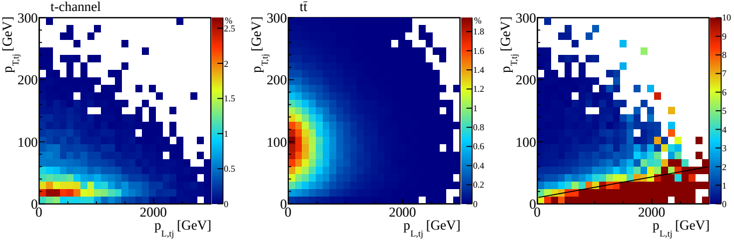
$\rightarrow t\bar{t}$ becomes main BG

8 TeV: rates in fb	t-ch.	s-ch.	$t\bar{t}$	tW	QCD	W+jets	S/B	$S/\sqrt{B}$
0. cross section	$8.72\cdot10^4$	$5.55\cdot10^3$	$2.34\cdot10^5$	$4.06\cdot10^4$	$6.58\cdot10^8$	$1.57\cdot10^6$	–	–
1. $n_\ell = 0$, 2 fat-j	$1.57\cdot10^3$	230	$1.88\cdot10^4$	$1.63\cdot10^3$	$6.67\cdot10^6$	$4.81\cdot10^4$	0.0002	1.9
2. one top tag	204	28.2	3070	227	$6.38\cdot10^4$	1297	0.003	2.5
3. Δm^{prune} cut	110	13.9	1421	102	$9.71\cdot10^3$	530	0.009	3.2
4. b-tag in top tag	44.3	5.29	524	37.4	97.1	5.30	0.07	5.4

Single tops at 8TeV

[arXiv:1207.4787 F. Kling, T. Plehn, MT]

– tj-system momentum ($\leftarrow t\bar{t}$ not balanced)



$$p_{T,tj} < \frac{p_{L,tj}}{60} + 10 \ \ \text{GeV} \quad \text{to reduce } t\bar{t}$$

8 TeV: rates in fb	t-ch.	s-ch.	$t\bar{t}$	tW	QCD	W+jets	S/B	$S/\sqrt{B}$
0. cross section	$8.72\cdot10^4$	$5.55\cdot10^3$	$2.34\cdot10^5$	$4.06\cdot10^4$	$6.58\cdot10^8$	$1.57\cdot10^6$	–	–
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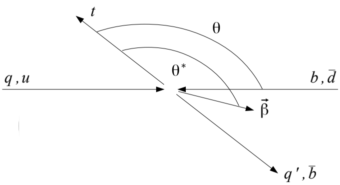
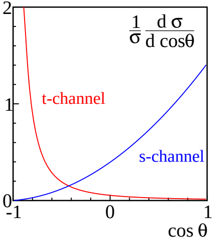
4. b-tag in top tag	44.3	5.29	524	37.4	97.1	5.30	0.07	5.4
5. p_{tj} cut	15.3	1.34	11.1	1.12	12.4	1.27	0.57	9.3

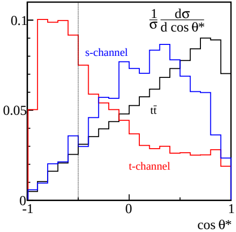
Single tops at 8TeV

[arXiv:1207.4787 F. Kling, T. Plehn, MT]

– top production angle distribution







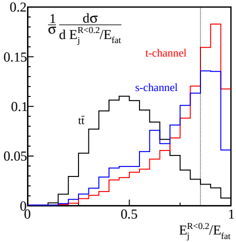
8 TeV: rates in fb	t-ch.	s-ch.	$t\bar{t}$	tW	QCD	W+jets	S/B	$S/\sqrt{B}$
0. cross section	$8.72\cdot10^4$	$5.55\cdot10^3$	$2.34\cdot10^5$	$4.06\cdot10^4$	$6.58\cdot10^8$	$1.57\cdot10^6$	–	–
1. $n_\ell = 0$, 2 fat-j	$1.57\cdot10^3$	230	$1.88\cdot10^4$	$1.63\cdot10^3$	$6.67\cdot10^6$	$4.81\cdot10^4$	0.0002	1.9
2. one top tag	204	28.2	3070	227	$6.38\cdot10^4$	1297	0.003	2.5
3. Δm^{prune} cut	110	13.9	1421	102	$9.71\cdot10^3$	530	0.009	3.2
4. b-tag in top tag	44.3	5.29	524	37.4	97.1	5.30	0.07	5.4
5. p_{tj} cut	15.3	1.34	11.1	1.12	12.4	1.27	0.57	9.3
6. $\cos\theta^* < -0.5$	8.6	0.07	1.58	0.14	3.3	0.21	1.62	11.8

t-channel $\rightarrow S/B > 1,\ S/\sqrt{B} > 10$ for 10fb^{-1}

Single tops at 8TeV [arXiv:1207.4787 F. Kling, T. Plehn, MT]

s-channel: need additional cuts for recoil jet

- $\cos\theta^* > -0.5$
- b-tag in recoil jet
- $E_j^{R<0.2}/E_{\rm fat} > 0.85$ and $m_j < 65$ GeV
- $\not{p}_T < 40$ GeV



8 TeV: rates in fb	t-ch.	s-ch.	$t\bar{t}$	tW	QCD	W+jets	S/B	$S/\sqrt{B}$
1-5. one top tag, b-tag, p_{tj} cut	15.3	1.34	11.1	1.12	12.4	1.27	–	–
6. $\cos\theta^* > -0.5$	6.75	1.27	9.52	0.97	9.06	1.06	0.05	1.2
7. b-tag in recoil jet	0.07	0.64	1.94	0.18	0.09	0.01	0.28	2.1
8. $E_j^{R<0.2}/E_{\rm fat}$, $m_j < 65$ GeV	0.04	0.35	0.11	0.02	0.03	–	1.75	3.9
9. $\not{p}_T < 40$ GeV	0.04	0.32	0.07	0.02	0.03	–	2.00	4.0

s-channel $\rightarrow S/B = 2$, $S/\sqrt{B} = 4$ for 25fb^{-1}

Summary

HEPTopTagger available on http://www.thphys.uni-heidelberg.de/∼plehn/

- top closest to new physics
- moderate p_T tops (> 200GeV) $\rightarrow$ testable in SM
- fat jets kill combinatorics
- jet substructure
  information thrown away $\rightarrow$ use all available infomation
- momentum well reconstructed
- general idea: tops at LHC identified just like bottoms

Applications

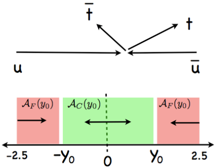
- stop pairs at 14 TeV (2 boosted tops)
- stop pairs at 8 TeV
- single tops at 8 TeV
- A^t_{FB}

Top forward backward asymmetry A^t_{FB}

[Phys.Rev. D84 (2011) 054005 arXiv:1103.4618, J. L. Hewett, J. Shelton, M. Spannowsky, T.M.P. Tait, MT]

- QCD A^t_{FB}: small NLO effect ($\sim 6\%$)
- D0 and CDF observed anomalously large A^t_{FB} especially in large m_{tt}
- LHC (pp collider):

  charge asymmetry in forward-central region



anti-tops are more central

$$\mathcal{A}_C(y_0) = \frac{N_t(|y|<y_0) - N_{\bar{t}}(|y|<y_0)}{N_t(|y|<y_0) + N_{\bar{t}}(|y|<y_0)} < 0$$

$$\mathcal{A}_F(y_0) = \frac{N_t(|y|>y_0) - N_{\bar{t}}(|y|>y_0)}{N_t(|y|>y_0) + N_{\bar{t}}(|y|>y_0)} > 0$$

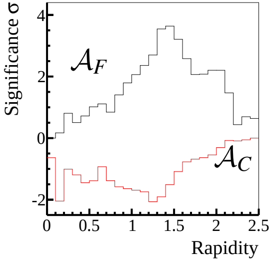
Top forward backward asymmetry A^t_{FB}

[Phys.Rev. D84 (2011) 054005 arXiv:1103.4618, J. L. Hewett, J. Shelton, M. Spannowsky, T.M.P. Tait, MT]

- semi-leptonic mode: $t\bar{t} \to (bjj)(bl\nu)$
  - one isolated lepton & one hadronic top tag
  - b-tag in top tag $\to$ W+jets negligible
  - top charge determined by lepton

$$\mathcal{A}_C(y_0) = \frac{N_t(|y|<y_0) - N_{\bar{t}}(|y|<y_0)}{N_t(|y|<y_0) + N_{\bar{t}}(|y|<y_0)} < 0$$

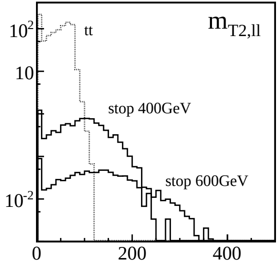
$$\mathcal{A}_F(y_0) = \frac{N_t(|y|>y_0) - N_{\bar{t}}(|y|>y_0)}{N_t(|y|>y_0) + N_{\bar{t}}(|y|>y_0)} > 0$$



- SM: 5σ after 60fb^{-1}(14TeV)
- BSM: with 4 quark contact interactions for Tevatron
  5σ after 2fb^{-1}(14TeV)
  2.8σ after 10fb^{-1} (7TeV)

Scalar Top Pairs at 8TeV [arXiv:1205.2696 T. Plehn, M. Spannowsky, MT]

– di-lepton mode



$t\bar{t} \to b\bar{b} + \ell\ell + 2\nu$

negligible with $m_{T2}^{\ell\ell} > 100$ GeV

$$m_{T2} = \min_{\not{E}_T\ split} \left[\max\{m_T^{\ell_1}, m_T^{\ell_2}\} \right]$$

$\sqrt{s} = 8$ TeV	$\tilde{t}1\tilde{t}1^*$						$t\bar{t}$	$t\bar{t}Z$	S/B	$S/\sqrt{B}_{10\text{fb}^{-1}}$
$m_{\tilde{t}}$[GeV]	350	400	450	500	600	700			400	
$n_\ell = 2$	30.98	14.27	7.07	3.58	1.04	0.33	7650.88	n.a.		
$\not{E}_T > 100$GeV	19.04	9.99	5.40	2.94	0.91	0.30	1312.74	0.35		
$m_{T2}^{\ell\ell} > 100$ GeV	6.05	4.30	2.70	1.65	0.56	0.20	0.65	0.09	5.8	16
$m_{T2}^{\ell\ell} > 150$ GeV	0.81	1.21	1.06	0.81	0.34	0.14	0.00	0.02	60	27