From Jet Scaling to Jet Vetos

Tilman Plehn

Heidelberg

CMS week, 2/2012

Jet counting

Why count jets

– complete event reconstruction crucial at LHC [Higgs plus 0,1,2 jets; jets plus $\vec{p}_T$]

– utilize tagging and recoil jets in Higgs searches

– identify decay jets in BSM searches

– reduce $t\bar{t}$ and $\tilde{g}\tilde{g}$ backgrounds

$\Rightarrow$ $d\sigma/dn_{\text{jets}}$ just another distribution to cut on (?)

Jet counting

Why count jets

– complete event reconstruction crucial at LHC [Higgs plus 0,1,2 jets; jets plus $\vec{p}_T$]

– utilize tagging and recoil jets in Higgs searches

– identify decay jets in BSM searches

– reduce $t\bar{t}$ and $\tilde{g}\tilde{g}$ backgrounds

$\Rightarrow$ $d\sigma/dn_\text{jets}$ just another distribution to cut on (?)

Why not [intro: arXiv:0910.4182, Springer Lecture Notes]

– remember $qg \to qZ$

– collinear divergence from $g \to q\bar{q}$ splitting [overlapping with soft divergence]

$$\int_{p_T^\text{min}}^{p_T^\text{max}} dp_T^2 \frac{C}{p_T^2} = 2 \int_{p_T^\text{min}}^{p_T^\text{max}} dp_T \; p_T \; \frac{C}{p_T^2} \simeq 2C \int_{p_T^\text{min}}^{p_T^\text{max}} dp_T \frac{1}{p_T} = 2C \; \log \frac{p_T^\text{max}}{p_T^\text{min}}$$

universal form following factorization

$$\sigma_{n+1} = \int \sigma_n \frac{dp_a^2}{p_a^2} dz \; \frac{\alpha_s}{2\pi} \; \hat{P}(z)$$

– universally divergent, fixed order poorly defined

– find object to 'renormalize' [i.e. absorbe universal divergence]

Jet counting

Why count jets

– complete event reconstruction crucial at LHC [Higgs plus 0,1,2 jets; jets plus $\vec{p}_T$]

– utilize tagging and recoil jets in Higgs searches

– identify decay jets in BSM searches

– reduce $t\bar{t}$ and $\tilde{g}\tilde{g}$ backgrounds

$\Rightarrow$ $d\sigma/dn_{\text{jets}}$ just another distribution to cut on (?)

DGLAP equation and jet-inclusive rates

– re-organize perturbation series [sum collinear logs]

$$\sigma_{n+1}(x,\mu) \sim \frac{1}{n!} \left(\frac{1}{2\pi b_0} \log \frac{\alpha_s(\mu_0^2)}{\alpha_s(\mu^2)} \right)^n \int_{x_0}^1 \frac{dx_n}{x_n} \hat{P}\left(\frac{x}{x_n}\right) \cdots \int_{x_0}^1 \frac{dx_1}{x_1} \hat{P}\left(\frac{x_2}{x_1}\right) \sigma_1(x_1,\mu_0)$$

– DGLAP equivalent to ‘infrared RGE’

– factorization scale as inclusive momentum cutoff [vanishing at all orders]

$$\sigma_{\text{tot}}(\mu) = \int_0^1 dx_1 \int_0^1 dx_2 \sum_{ij} f_i(x_1,\mu)\, f_j(x_2,\mu)\, \hat{\sigma}_{ij}(x_1 x_2 S,\mu)$$

– collinear jets automatically included

Poisson scaling

Theory: soft gluon radiation [Peskin & Schroeder Ch 6]

– example: photons off hard electron
only abelian diagrams, successive radiation

– eikonal approximation

$$\mathcal{M}_{n+1} = g_s T^a \, \epsilon^*_\mu(k) \, \bar{u}(q) \frac{q^\mu + \mathcal{O}(\not{k})}{(qk) + \mathcal{O}(k^2)} \, \mathcal{M}_n$$

– factorization of ‘hard process’ and soft radiation factors

– Poisson distribution [normalized pdf for n if $\bar{n}$ expected]

$$\sigma_n = \frac{\bar{n}^n e^{-\bar{n}}}{n!} \qquad \Longleftrightarrow \qquad \boxed{R_{(n+1)/n} = \frac{\sigma_{n+1}}{\sigma_n} = \frac{\bar{n}}{n+1}}$$

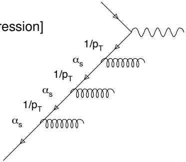
Ingredients of Poisson distribution

1– radiation matrix element $\bar{n}^n$:
abelian fine, non-abelian a little tricky [ISR-FSR, see Ioffe, Fadin, Lipatov]

2– phase space factor $1/n!$:
only combinatorics, matrix element ordered [angular ordering, color suppression]

3– normalization factor $e^{-\bar{n}}$

– similar to parton shower for collinear regime



Staircase scaling

Experiment: from UA1 to ATLAS/CMS [Steve Ellis, Kleiss, Stirling]

Volume 154B, number 5,6 PHYSICS LETTERS 9 May 1985

W's, Z's AND JETS

S.D. ELLIS [1,2], R. KLEISS and W.J. STIRLING

CERN, CH 1211 Geneva 23, Switzerland

Received 24 January 1985

The process $p + \bar{p} \to W^{\pm}, Z^0$ plus 2 jets is discussed in the context of perturbative QCD. The magnitude of the expected rate for this process and the correlations anticipated between the jets are presented.

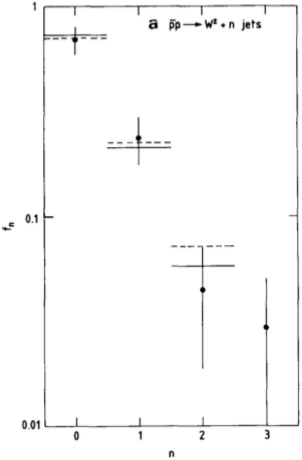
Staircase scaling

Experiment: from UA1 to ATLAS/CMS [Steve Ellis, Kleiss, Stirling]

– W/Z+jets production

– many equivalent descriptions

$$R_{(n+1)/n} = \frac{\sigma_{n+1}}{\sigma_n} = \text{const}$$



Staircase scaling

Experiment: from UA1 to ATLAS/CMS [Steve Ellis, Kleiss, Stirling]

– W/Z+jets production
– many equivalent descriptions

$$\boxed{R_{(n+1)/n} = \frac{\sigma_{n+1}}{\sigma_n} = \text{const}}$$

– same for inclusive and exclusive rates [Blackhat-Sherpa]

$$R^{\text{incl}}_{(n+1)/n} = \frac{\sum_{j=n+1}^{\infty} \sigma_j^{(\text{excl})}}{\sigma_n^{(\text{excl})} + \sum_{j=n+1}^{\infty} \sigma_j^{(\text{excl})}} = R^{\text{excl}}_{(n+1)/n}$$

Staircase scaling

Experiment: from UA1 to ATLAS/CMS [Steve Ellis, Kleiss, Stirling]

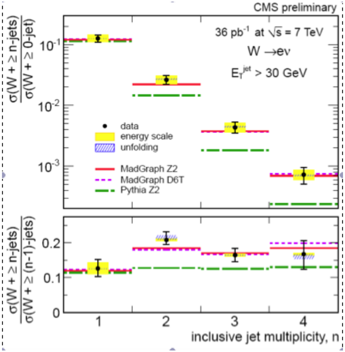
– W/Z+jets production
– many equivalent descriptions

$$R_{(n+1)/n} = \frac{\sigma_{n+1}}{\sigma_n} = \text{const}$$

– same for inclusive and exclusive rates [Blackhat-Sherpa]

$$R^{\text{incl}}_{(n+1)/n} = \frac{\sum_{j=n+1}^{\infty} \sigma_j^{(\text{excl})}}{\sigma_n^{(\text{excl})} + \sum_{j=n+1}^{\infty} \sigma_j^{(\text{excl})}} = R^{\text{excl}}_{(n+1)/n}$$

– confirmed by CMS



Staircase scaling

Experiment: from UA1 to ATLAS/CMS [Steve Ellis, Kleiss, Stirling]

– W/Z+jets production

– many equivalent descriptions

$$R_{(n+1)/n} = \frac{\sigma_{n+1}}{\sigma_n} = \text{const}$$

– same for inclusive and exclusive rates [Blackhat-Sherpa]

$$R^{\text{incl}}_{(n+1)/n} = \frac{\sum_{j=n+1}^{\infty} \sigma_j^{(\text{excl})}}{\sigma_n^{(\text{excl})} + \sum_{j=n+1}^{\infty} \sigma_j^{(\text{excl})}} = R^{\text{excl}}_{(n+1)/n}$$

– confirmed by CMS

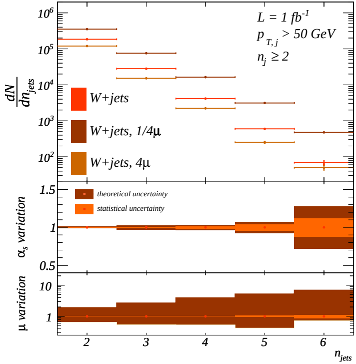
Theoretical studies [Englert, TP, Schichtel, Schumann]

– CKKW/MLM merging [we used Sherpa]

– phase space effects? $\to$ moderate

– α_s uncertainties? $\to$ small

– scale uncertainties? $\to$ tuning parameter?



Staircase scaling

Experiment: from UA1 to ATLAS/CMS [Steve Ellis, Kleiss, Stirling]

– W/Z+jets production

– many equivalent descriptions

$$R_{(n+1)/n} = \frac{\sigma_{n+1}}{\sigma_n} = \text{const}$$

– same for inclusive and exclusive rates [Blackhat-Sherpa]

$$R^{\text{incl}}_{(n+1)/n} = \frac{\sum_{j=n+1}^{\infty} \sigma_j^{(\text{excl})}}{\sigma_n^{(\text{excl})} + \sum_{j=n+1}^{\infty} \sigma_j^{(\text{excl})}} = R^{\text{excl}}_{(n+1)/n}$$

– confirmed by CMS

Theoretical studies [Englert, TP, Schichtel, Schumann]

– CKKW/MLM merging [we used Sherpa]

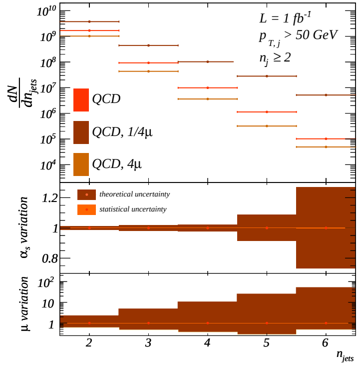
– phase space effects? → moderate

– α_s uncertainties? → small

– scale uncertainties? → tuning parameter?

– same for QCD jets

– correctly described by ME-PS merging!?



Interpolating scaling patterns

Scaling for photon plus jets [Englert, TP, Schichtel, Schumann]

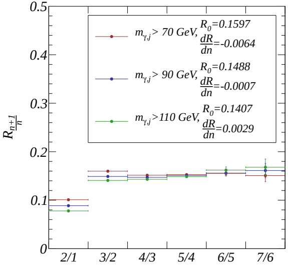
– naively, no scaling at all [Alex Tapper, private complaint]

– after appropriate cuts, great playground

1– staircase

democratic γ and jet acceptance
large γ-jet separation [m or ΔR, no large logs]
no reason for ordered emission [$1/n!$ in Poisson form]

dominant: non-abelian splitting of ISR gluon
helping: pdf effect shifting to high-n_{jets}



Interpolating scaling patterns

Scaling for photon plus jets [Englert, TP, Schichtel, Schumann]

– naively, no scaling at all [Alex Tapper, private complaint]

– after appropriate cuts, great playground

1– staircase

democratic γ and jet acceptance
large γ-jet separation [m or ΔR, no large logs]
no reason for ordered emission [$1/n!$ in Poisson form]

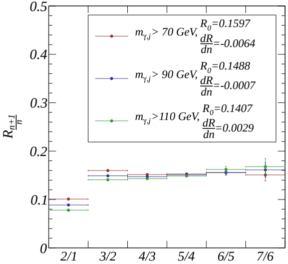
dominant: non-abelian splitting of ISR gluon
helping: pdf effect shifting to high-n_jets

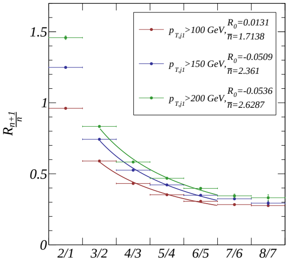
2– Poisson

generate 'hard process' [m, p_T, ΔR, ...]
lower general p_T^min for soft-collinear logarithm
rely on lot-enhanced radiation

dominant: successive ordered ISR
remaining: high-n staircase tail

$\Rightarrow$ staircase–Poisson transition tunable!





Jet veto in Higgs searches

Jet veto in Higgs analyses [Barger, Phillips, Zeppenfeld; Rainwater]

– particularly useful for WBF signals [remove $t\bar{t}$ and Z+jets backgrounds]

– veto central (semi-hard) jets
estimate P_{veto}
apply as ‘efficiency factor’

Table C.1: Summary of veto survival probabilities for $p_T^{veto} = 20$ GeV used in Chapters 3-5.

search	Hjj	$t\bar{t}$	$t\bar{t}j$, $t\bar{t}jj$	QCD $V(V)jj$	EW $V(V)jj$	QCD $Wjjj$	QCD $b\bar{b}jj$	DPS $\gamma\gamma jj$
$\gamma\gamma jj$	0.89	-	-	0.30	0.75	-	-	0.30
$W^{(*)}W^{(*)}jj$	0.89	0.46	0.29	0.29	0.75	-	-	-
$\tau\tau jj$	0.87	-	-	0.28	0.80	0.28	0.28	-

Jet veto in Higgs searches

Jet veto in Higgs analyses [Barger, Phillips, Zeppenfeld; Rainwater]

– particularly useful for WBF signals [remove $t\bar{t}$ and Z+jets backgrounds]

– veto central (semi-hard) jets
estimate P_{veto}
apply as 'efficiency factor'

– implicit in LHC Higgs searches
individual searches for exclusive fixed n_{jets}

– problem in Higgs phenomenology

Jet veto in Higgs searches

Jet veto in Higgs analyses [Barger, Phillips, Zeppenfeld; Rainwater]

- particularly useful for WBF signals [remove $t\bar{t}$ and Z+jets backgrounds]
- veto central (semi-hard) jets
  estimate P_{veto}
  apply as 'efficiency factor'
- implicit in LHC Higgs searches
  individual searches for exclusive fixed n_{jets}
- problem in Higgs phenomenology

In terms of jet counting [Gerwick, TP, Schumann]

- avoid P_{veto} as one number
- study exclusive n_{jets} distribution:

1– understand basic features:
  staircase for inclusive samples
  Poisson for hard processes
2– predict from theory [including error]
3– validate simulation
4– extrapolate to regimes/processes

Jet veto in Higgs searches

Jet veto in Higgs analyses [Barger, Phillips, Zeppenfeld; Rainwater]

– particularly useful for WBF signals [remove $t\bar{t}$ and Z+jets backgrounds]

– veto central (semi-hard) jets
estimate P_{veto}
apply as 'efficiency factor'

– implicit in LHC Higgs searches
individual searches for exclusive fixed n_{jets}

– problem in Higgs phenomenology

In terms of jet counting [Gerwick, TP, Schumann]

– avoid P_{veto} as one number

– study exclusive n_{jets} distribution:

1– understand basic features:
staircase for inclusive samples
Poisson for hard processes
2– predict from theory [including error]
3– validate simulation
4– extrapolate to regimes/processes

	staircase scaling	Poisson scaling
σ_n	$\sigma_0\, e^{-bn}$	$\sigma_{\text{tot}}\, \dfrac{e^{-\bar{n}}\bar{n}^n}{n!}$
$R^{\text{excl}}_{(n+1)/n}$	e^{-b}	$\dfrac{\bar{n}}{n+1}$
$R^{\text{incl}}_{(n+1)/n}$	e^{-b}	$\left(\dfrac{(n+1)\, e^{-\bar{n}}\, \bar{n}^{-(n+1)}}{\Gamma(n+1) - n\Gamma(n,\bar{n})} + 1\right)^{-1}$
$\langle n_{\text{jets}} \rangle$	$\dfrac{1}{2}\, \dfrac{1}{\cosh b - 1}$	$\bar{n}$
P_{veto}	$1 - e^{-b}$	$e^{-\bar{n}}$

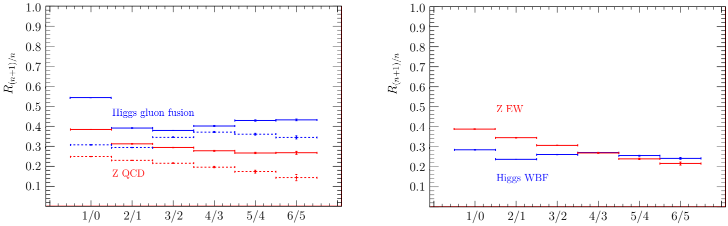
Jet veto in Higgs searches

Example: WBF $H \to \tau\tau$ [Gerwick, TP, Schumann]

– staircase scaling before WBF cuts [QCD and e-w processes]

– first emission sensitive to cuts

– e-w *Zjj* production with too many structures



Jet veto in Higgs searches

Example: WBF $H \to \tau\tau$ [Gerwick, TP, Schumann]

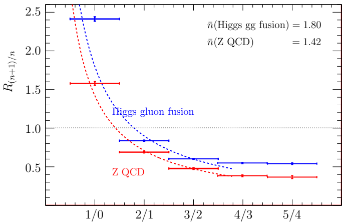
- staircase scaling before WBF cuts [QCD and e-w processes]
- first emission sensitive to cuts
- e-w *Zjj* production with too many structures

WBF cuts: two forward tagging jets

- count add'l jets to reduce backgrounds

$$p_T^{\text{veto}} > 20\ \text{GeV} \qquad \min y_{1,2} < y^{\text{veto}} < \max y_{1,2}$$

- Poisson for QCD processes ['radiation' pattern]



Jet veto in Higgs searches

Example: WBF $H \to \tau\tau$ [Gerwick, TP, Schumann]

– staircase scaling before WBF cuts [QCD and e-w processes]

– first emission sensitive to cuts

– e-w *Zjj* production with too many structures

WBF cuts: two forward tagging jets

– count add'l jets to reduce backgrounds

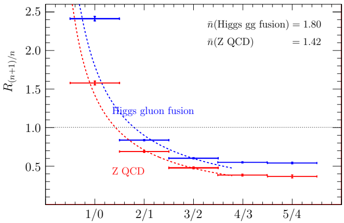
$$p_T^{\text{veto}} > 20 \text{ GeV} \qquad \min y_{1,2} < y^{\text{veto}} < \max y_{1,2}$$

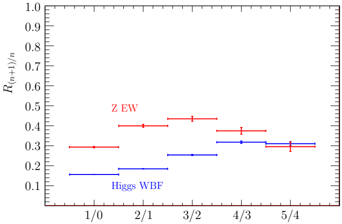
– Poisson for QCD processes ['radiation' pattern]

– staircase-like for e-w processes [generic]

– features of n_{jets} distributions understood

$\Rightarrow$ cut on n_{jets} fine, your job now





Jet veto in Higgs searches

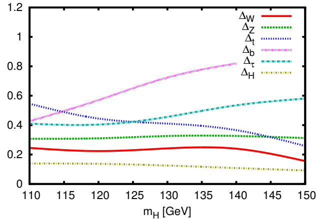
Example: WBF $H \to \tau\tau$ [Gerwick, TP, Schumann]

- staircase scaling before WBF cuts [QCD and e-w processes]
- first emission sensitive to cuts
- e-w *Zjj* production with too many structures

Why we need the veto probabilities [SFitter: Lafaye, TP, Rauch, Zerwas]

- extraction of Higgs couplings [with error bars]
- including associated Higgs-jet channels [WBF eventually crucial]
- general fit of all couplings [Michael Rauch in Moriond 2012]

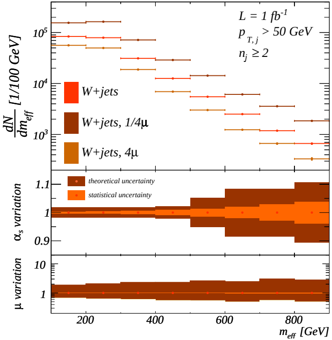
$$g_{jjH} = g_{jjH}^{\text{SM}} \left(1 + \Delta_j\right)$$



New physics

Effective mass [Englert, TP, Schichtel, Schumann]

- obviously sensitive to new physics masses but awful variable, after theory uncertainty
- correlation $m_{\text{eff}} \sim \langle p_T \rangle \times n_{\text{jets}}$
- use merged sample for m_{eff} estimate scale and α_s uncertainties



New physics

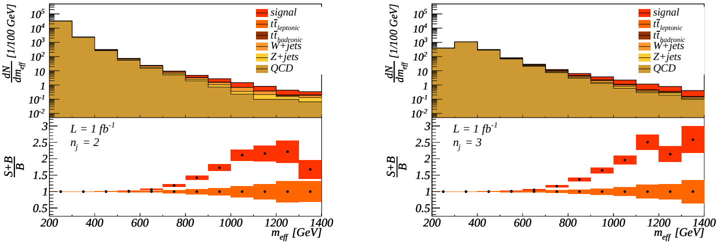
Effective mass [Englert, TP, Schichtel, Schumann]

– obviously sensitive to new physics masses
  but awful variable, after theory uncertainty

– correlation $m_{\text{eff}} \sim \langle p_T \rangle \times n_{\text{jets}}$

– use merged sample for m_{eff}
  estimate scale and α_s uncertainties

– estimate SUSY significance as function of m_{eff}



New physics

Effective mass [Englert, TP, Schichtel, Schumann]

– obviously sensitive to new physics masses
  but awful variable, after theory uncertainty
– correlation $m_{\text{eff}} \sim \langle p_T \rangle \times n_{\text{jets}}$
– use merged sample for m_{eff}
  estimate scale and α_s uncertainties
– estimate SUSY significance as function of m_{eff}
– multijet studies establishing m_{eff}

New physics

Effective mass [Englert, TP, Schichtel, Schumann]

– obviously sensitive to new physics masses
  but awful variable, after theory uncertainty

– correlation $m_\text{eff} \sim \langle p_T \rangle \times n_\text{jets}$

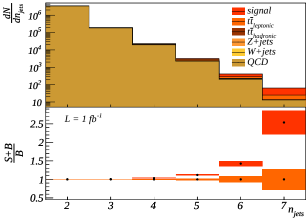
– use merged sample for m_eff
  estimate scale and α_s uncertainties

– estimate SUSY significance as function of m_eff

– multijet studies establishing m_eff

Mass vs color charge

– now, significance as function of n_jets



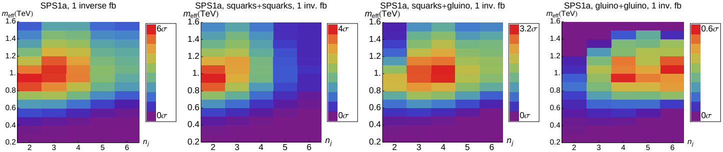
New physics

Effective mass [Englert, TP, Schichtel, Schumann]

- obviously sensitive to new physics masses
  but awful variable, after theory uncertainty
- correlation $m_\text{eff} \sim \langle p_T \rangle \times n_\text{jets}$
- use merged sample for m_eff
  estimate scale and α_s uncertainties
- estimate SUSY significance as function of m_eff
- multijet studies establishing m_eff

Mass vs color charge

- now, significance as function of n_jets
- representing new physics color charge [gluino does not decay via gluon]
- exclusive 2D likelihood including all information



Exclusive jet counting

staircase (non-abelian) vs Poisson (ordered)

- start by measuring $d\sigma/dn_{\text{jets}}$
- test both regimes in photon+jets
- described by ME-PS merging [CKKW/MLM, unchanged by NLO]
- key to jet vetos
- key to SUSY searches

Understanding Jet Scaling and Jet Vetos in Higgs Searches
E Gerwick, TP, S Schumann
PRL 108 (2012)

Establishing Jet Scaling Patterns with a Photon
C Englert, TP, P Schichtel, S Schumann
arXiv:1108.5473, JHEP in print

Jets plus Missing Energy with an Autofocus
C Englert, TP, P Schichtel, S Schumann
PRD83 (2011)

Much of this work was funded by the BMBF Theorie-Verbund which is ideal for hard and relevant LHC work

Bundesministerium
für Bildung
und Forschung

New physics 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]