

$\sqrt{\hat{s}}_{\min}$ resurrected

(arXiv:1109.1018)

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Collider signatures of BSM theories

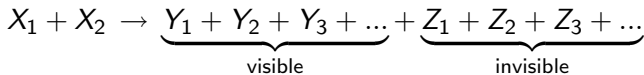
- **generic feature** of any (reasonable) BSM theory:
observable deviations from Standard Model predictions
- ⇒ changed event rates (= modified **cross sections**)
- ⇒ resonances of new particles (= new **mass eigenstates**)
- to fully determine theory at low energy scale:
also need **spins** and **couplings**
- also important: "indirect" measurements through higher order contributions: can give important restrictions
- so far: only collider exclusion limits exist
- ⇒ cf various 2011 conference summary talks...

Why masses ??

- first obvious choice: cross section measurements
- however, depend on knowledge of actual **cm energies**
- **usually "smeared"** (eg bremsstrahlung for ILC)
or **unknown** (LHC), ie only obtainable in form of probability distributions (in form of PDFs)
- furthermore, many experimental issues (calibration of detector, ...)
- variables constructed for **mass measurements**: depend less on overall (experimental and theoretical) normalization uncertainties
- ⇒ construction of Lorentz-invariant mass variables: even cm independent (especially useful for processes at LHC)
- ⇒ ideal candidates for BSM discoveries and measurements
 - spins, couplings: more complicated; next step on the road...

$\sqrt{\hat{s}}_{\min}$: A short historical overview (1)

- $\sqrt{\hat{s}}_{\min}$: suggested by Konar, Kong, Matchev (arXiv:0812.1042)
- motivation: have a **totally inclusive variable**, which does not care about intermediate decay steps/ topology/ ...
- need events of the type:



- requirement: have both **visible and invisible decay products**, as well as energy momentum conservation
- definition: (M_{inv} is input !!)

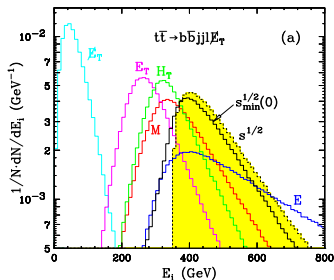
$$\hat{s}_{\min}^{1/2}(M_{\text{inv}}) \equiv \sqrt{E^2 - P_Z^2} + \sqrt{(\not{E}_T)^2 + M_{\text{inv}}^2} \quad (1)$$

- (E, \vec{P}) : total visible fourvector, $\not{E}_T = |P_T|$, $M_{\text{inv}} = \sum_{\text{invisible}} m_i$
- "min": (1) is minimal \sqrt{s} of event compatible with visible/ invisible four momenta

$\sqrt{\hat{s}}_{\min}$: A short historical overview (2)

- original definition **on calorimeter level !!!**
- suppression of **soft background**: cut in pseudorapidity η
- empirical conjecture in original paper: **correlation to hard scale**

$$\sqrt{\hat{s}}_{\min}^{\text{peak}} \sim \sqrt{\hat{s}}_{\text{thr}}^{\text{part}}$$



- tested by Kong ea on various SM and BSM processes
- reminder**: similar conjecture used to exist for M_{eff} , disproved in Conley ea, arXiv:1103.1697

from Konar ea, different kinematic

variables for $t\bar{t} \rightarrow b\bar{b}jjlE_T$

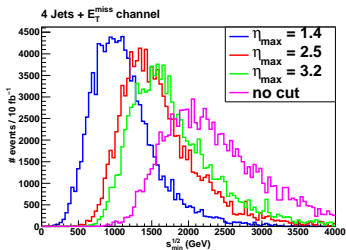
Data from Les Houches 09 mass determination project

- project started at the **Les Houches 2009 BSM session**
 - generate generic BSM data samples, including **all background**, use **parton showers** and **detector simulation**
 - use this data to check several (new/ old) mass determination methods/ proposals
 - relative low luminosity: $\int \mathcal{L} \lesssim 10 \text{ fb}^{-10}$, $\sqrt{s}_{\text{hadr}} = 14 \text{ TeV}$
 - point generated: **SPS1a** (this was before its exclusion...)
 - generated: **all production channels, all decay channels**
- ⇒ **samples contain complete signature for this parameter point**
- results: **BSM Les Houches Report 2009** (arXiv:1005.1229)

$\sqrt{\hat{s}}_{\min}$ and soft background (1)

First test: **apply calorimeter-based variable** (J.R. Lessard, LH09 mass study)

- cut in pseudorapidity: **strong cut dependence**



η_{cut} dependence

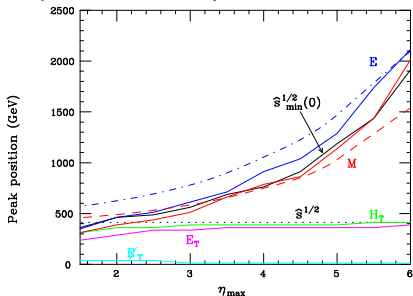
from Les Houches study (J.R. Lessard), using **calorimeter level quantities**

$\hat{s}_{\min}^{1/2}(0)$ for different values of η_{cut}

- **analytic proof of peak shift:** Papaefstathiou, Webber, 09/10

$\sqrt{\hat{s}_{\min}}$ and soft background (2)

- analytic proof of peak shift: Papaefstathiou, Webber, 09/10



peak of $\sqrt{\hat{s}_{\min}}$ distribution for $t\bar{t}$ decay, dependence on η cut, resummation approach

A.Papaefstathiou, B. Webber, arXiv:0903.2013

- solution: define $\sqrt{\hat{s}_{\min}}$ on reconstruction level (Matchev ea, 11)
- however: many people esteem damage done, variable lost... is this true ??

A more thorough analysis on the Les Houches 09 sample

In the following: **apply $\sqrt{\hat{s}}_{\min}$ definition on several quantities:**

- $\sqrt{\hat{s}}_{\min}^{\text{part}}$: apply definition in **parton level quantity** (= "perfect reconstruction"), mainly for behaviour checks
- $\sqrt{\hat{s}}_{\min}^{\text{ana}}$: apply on **analysis level objects after detector simulation** (experimental object definitions through p_T, η , isolation cuts)
- $\sqrt{\hat{s}}_{\min}^{\text{cal}}$: apply definition on **calorimeter quantities** (original suggestion)
- $\sqrt{\hat{s}}_{\min}^{\text{cal},\eta}$: apply definition on **calorimeter quantities, with $|\eta| < 1.4$**

Always:

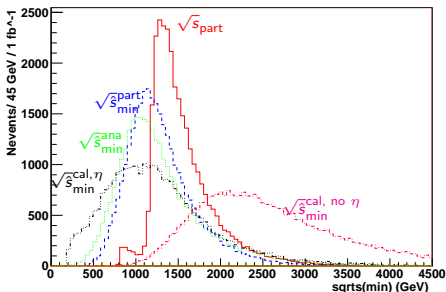
$$\vec{\cancel{p}}_T = -\vec{P}_T, \cancel{E}_T = |\vec{\cancel{p}}_T|$$

(for confusions from differing \cancel{E}_T definitions:

cf A. Barr ea, "A Storm in a 'T' cup", arXiv:1108.5182)

$\sqrt{\hat{s}}_{\min}$ on the Les Houches 09 sample

- apply different definitions of $\sqrt{\hat{s}}_{\min}$ on Les Houches sample
- fully inclusive \Rightarrow include all final states, $\sqrt{\bar{s}}_{\text{th}} = 1146 \text{ GeV}$



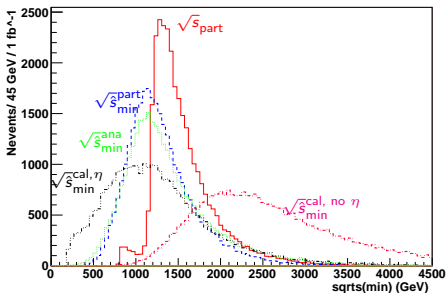
$\tilde{q}\tilde{q}$, $\tilde{q}\tilde{g}$, and $\tilde{g}\tilde{g}$ initial states, true \sqrt{s} , parton level $\sqrt{\hat{s}}_{\min}$, analysis level $\sqrt{\hat{s}}_{\min}$, \sqrt{s}_{\min} using calorimeters with (without) $|\eta| < 1.4$

\Rightarrow analysis level definition nicely reproduces parton level

- peaks using Gaussian fit: $(1152 \pm 4) \text{ GeV}$, $(1083 \pm 4) \text{ GeV}$

$\sqrt{\hat{s}}_{\min}$ on the Les Houches 09 sample: τ corrected

- " τ corrected": use parton level τ s on analysis level
- "cheaty" (=theorists) way to assess effects of tau reconstruction



$\tilde{q}\tilde{q}$, $\tilde{q}\tilde{g}$, and $\tilde{g}\tilde{g}$ initial states, true \sqrt{s} , parton level $\sqrt{\hat{s}}_{\min}$, analysis level $\sqrt{\hat{s}}_{\min}$, \sqrt{s}_{\min} using calorimeters with (without) $|\eta| < 1.4$

peaks using Gaussian fit: $(1152 \pm 4) \text{ GeV}$, $(1163 \pm 4) \text{ GeV}$ (✓)

Peak position of $\sqrt{\hat{s}_{\min}}$

- is there a **rigorous analytic proof of $\sqrt{\hat{s}_{\min}^{\text{peak}}} \sim \sqrt{\hat{s}_{\text{thr}}^{\text{part}}}$??**
- **quite complicated:** need "effective" description in terms of $P_{\text{vis}}^{\mu}, P_{\text{invis}}^{\mu}$
- one complication: onshell condition $P^2 = m^2 \rightarrow$ distribution $f(m^2)$
- first steps: **2 \rightarrow 2 process, massless final state, unit matrix element, unit PDF**

- then:

$$\frac{d\sigma}{d\sqrt{\hat{s}_{\min}}} \sim \int_{\hat{s}_{\min}/S}^1 dy \frac{\sqrt{\hat{s}_{\min}}}{S^2 y^{3/2} \sqrt{y - \frac{\hat{s}_{\min}}{S}}} f(y)$$

with $f(y) = 0$ for $y < \max\left\{\frac{s_{\text{th}}}{S}; \frac{\hat{s}_{\min}}{S}\right\}$

- leads to **constant rise (fall) for $\hat{s}_{\min} < s_{\text{th}}$ ($\hat{s}_{\min} > s_{\text{th}}$)**
- complete proof: **long way to go...** (really worth it ??)

SM suppression using $\sqrt{\hat{s}}_{\min}$

- got nice results for **analysis level peak positions**
- **however**, depends on $M_{\text{inv}} = \sum_{\text{invis}} m_i$!! what if wrong guess ??
- can at least check **SM suppression power** of $\sqrt{\hat{s}}_{\min}$

	no cut	$M_{\text{inv}} =$ $2 m_{\tilde{\chi}_1^0}$	0	400	10^3	$M_{\text{vis, min}}$ 400	500	$M_{\text{eff, min}}$ 400	500
$W + \text{jets}$	254.2	62.53	81.13	48.73	46.73	70.29	42.41	75.89	43.3
$t\bar{t} + \text{jets}$	151.4	52.99	64.67	51.77	50.14	64.63	46.3	63.98	40.12
BSM	31.05	28.82	29.82	28.42	27.80	27.07	24.43	29.99	28.72

units are pb and GeV. $\sqrt{\hat{s}}_{\text{min, cut}} = M_{\text{inv}} + 500\text{GeV}$.

$\Rightarrow \sqrt{\hat{s}}_{\text{min}}, M_{\text{vis}}, M_{\text{eff}}$ **suppress similarly well**

$\sqrt{\hat{s}}_{\min}$: Summary and Outlook

- **if** correlation between threshold and maximum of $\sqrt{\hat{s}}_{\min}$

$$\sqrt{\hat{s}}_{\min}^{\text{peak}} \sim \sqrt{\hat{s}}_{\text{thr}}^{\text{part}}$$

holds: **powerful handle on new physics scale !!!**

- however, **only empirically shown** for several cases
- analytic proof **far from trivial !!**
- aside: analysis level objects **always implicitly dependent on cuts**
(η, p_T, \dots)
- first step: **check for many different spectra**
(\Rightarrow SUSY without prejudice ??)

!! Variable not dead yet !!
Thanks for listening

Appendix

SPS1a mass spectrum and cross sections

\tilde{d}_L	568.4	\tilde{d}_R	545.2	\tilde{u}_L	561.1	\tilde{u}_R	549.3	\tilde{b}_1	513.1	\tilde{b}_2	543.7	\tilde{t}_1	399
\tilde{l}_L	202.9	\tilde{l}_R	144.1	$\tilde{\tau}_1$	134.5	$\tilde{\tau}_2$	206.9	$\tilde{\nu}_l$	185.3	$\tilde{\nu}_\tau$	184.7	\tilde{t}_2	585
$\tilde{\chi}_1^-$	181.7	$\tilde{\chi}_2^-$	380.0	$\tilde{\chi}_1^0$	96.7	$\tilde{\chi}_2^0$	181.1	$ \tilde{\chi}_3^0 $	363.8	$\tilde{\chi}_4^0$	381.7	\tilde{g}	607

Relevant masses for SPS1a in GeV. $u = (u, c)$, $d = (d, s)$, $l = (e, \mu)$.

$X_1 X_2$	$2 \rightarrow 2$	$2 \rightarrow 3$
$\tilde{q}\tilde{q}(j)$	6.56	7.83
$\tilde{q}\tilde{g}(j)$	19.52	21.75
$\tilde{g}\tilde{g}(j)$	4.53	5.47
$\tilde{\chi}\tilde{\chi}(j)$	1.97	4.89

Production cross sections in pb for $pp \rightarrow X_1 X_2$, for a cm energy of 14 TeV.

CTEQ6L1 PDFs were used. $2 \rightarrow 3$ sample includes explicitly generated hard jet,

where hard is defined by $p_{T,\text{jet}} > 40$ GeV.

Details on data generation (R. Brunelière, T. Lari, S. Sekmen)

- **SUSY spectrum**: generated using **SoftSusy**
(B. Allanach, hep-ph/0104145)
- $2 \rightarrow 2$ and $2 \rightarrow 3$ **matrix element generation**: **Madgraph**
(T. Stelzer, W. Long, hep-ph/9401258; F. Maltoni, T. Stelzer, hep-ph/0208156)
- **generation of decay chains**: **Bridge**
(P. Meade, M. Reece, hep-ph/0703031)
- **parton shower generation**: **Pythia** (in **Madgraph**)
(T.Sjostrand, S.Mrenna, P. Skands, hep-ph/0603175)
- **matching** of samples with different jet multiplicities: **MLM matching algorithm** in **Madgraph** (J.Alwall ea, hep-ph/0706.2569; J.Alwall, S. de Visscher, F. Maltoni, hep-ph/0810.5350)
- **detector simulation**: **Delphes**
(S. Ovyn, X. Rouby, V. Lemaitre, hep-ph/0903.2225)
- **data analysis**: **ROOT** (<http://root.cern.ch>)

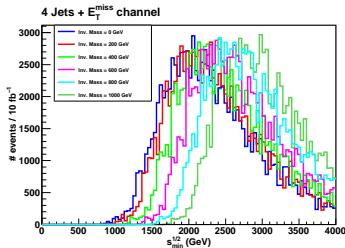
Delphes pre cuts and analysis object definitions

(L.Basso, T. Lari, J.-R. Lessard)

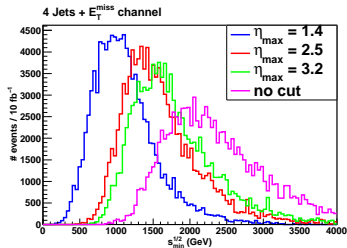
<i>object</i>	<i>Delphes predefinition</i>	<i>additional requirement</i>
electron/ position	$ \eta < 2.5$ in tracker, $p_T > 10$ GeV	isolated
muon	$ \eta < 2.4$ in tracker, $p_T > 10$ GeV	isolated
lepton isolation criteria	no track with $p_T > 2$ GeV in a cone with $dR = 0.5$ around the considered lepton	no track with $p_T > 6$ GeV in a cone with $dR = 0.5$ around the considered lepton
n leptons	—	exactly n isolated leptons at detector level
taujet	$p_T > 10$ GeV	—
jet	$p_T > 20$ GeV CDF jet cluster algorithm, $R = 0.7$	$p_{T,jet} > 50$ GeV, $ \eta _{jet} < 3$
Missing transverse energy	—	$E_T^{miss} > 100$ GeV

$\sqrt{\hat{s}}_{\min}$ (J.-R. Lessard)

- $\sqrt{\hat{s}}_{\min}$: determine scale of new physics by threshold scan
- **however:** requires mass of invisible final state particle as input
- definition: $\hat{s}_{\min}^{1/2}(M_{\text{inv}}) \equiv \sqrt{E^2 - P_z^2} + \sqrt{(E_T^{\text{miss}})^2 + M_{\text{inv}}^2}$
- high sensitivity to ISR; solution: cut in jet pseudorapidity



$\hat{s}_{\min}^{1/2}$, different values of M_{inv} , no η cut



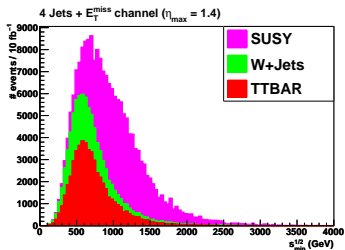
$\hat{s}_{\min}^{1/2}(0)$ for different values of η_{cut}

large dependence on η cut !!

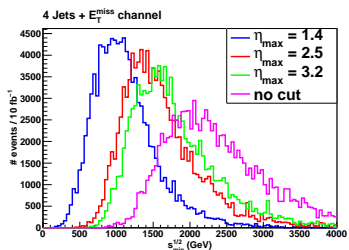
also: large effects when resummation is included;

(Papaefstathiou et al, arXiv:1002.4375, 1004.4762; Konar et al, 1006.0653)

$\sqrt{\hat{s}}_{\min}$: including SM background (J.-R. Lessard)



$\sqrt{\hat{s}}_{\min}(0)$, 4 jet channel, SUSY + SM
background

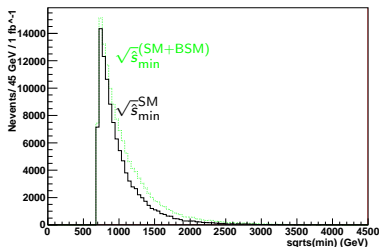


$\hat{s}_{\min}^{1/2}(0)$ for different values of η_{cut}

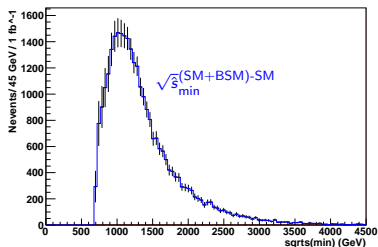
✓ peaked at value different from SM background

⇒ **useful for BSM discovery**

SM Background



SM+BSM (136834 events),
SM only (108017 events)



BSM = (SM+BSM) - (SM)

Analysis level $\sqrt{\hat{s}}_{\min}$ after a cut $\sqrt{\hat{s}}_{\min} > 700$ GeV.

SM background: $(W + 2j, W + 3j, W + 4j, t\bar{t}, t\bar{t} + 1j, t\bar{t} + 2j)$.

- peak disappears after addition of (some) background
- after background subtraction (data driven or other): peak reappears