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

(arXiv:1109.1018, JHEP02(2012)051)

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DEST Theory Workshop 2012

DESY Hamburg

27.9.2012

Collider signatures of BSM theories

- **generic feature** of any (reasonable) BSM theory: **observable** deviations from Standard Model predictions

$\Rightarrow$ changed event rates (= modified **cross sections**)

$\Rightarrow$ 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

$\Rightarrow$ cf various 2012 conference summary talks...

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

$$X_1 + X_2 \;\rightarrow\; \underbrace{Y_1 + Y_2 + Y_3 + \ldots}_{\text{visible}} + \underbrace{Z_1 + Z_2 + Z_3 + \ldots}_{\text{invisible}}$$

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

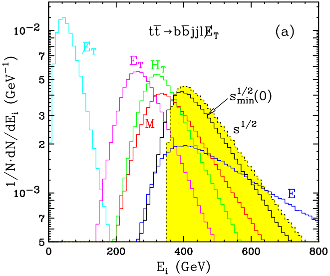
$$\hat{s}^{1/2}_{\min}(M_{\text{inv}}) \equiv \sqrt{E^2 - P_z^2} + \sqrt{(\not{E}_T)^2 + M^2_{\text{inv}}} \qquad (1)$$

- $(E, \overrightarrow{P})$: 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

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



from Konar ea, different kinematic variables for $t\bar{t} \longrightarrow b\bar{b}jjl\not{E}_T$

- 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

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: $\int \mathcal{L} \lesssim 10\,\mathrm{fb}^{-10}$, $\sqrt{s_{\text{hadr}}} = 14\,\mathrm{TeV}$
- point generated: **SPS1a** (this was before its exclusion...)
- generated: **all production channels, all decay channels**

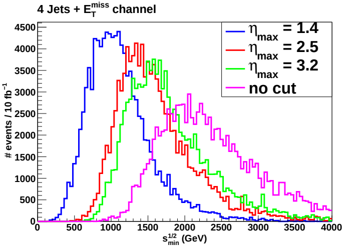
$\Rightarrow$ **samples contain complete signature for this parameter point**

- results: **BSM Les Houches Report 2009** (arXiv:1005.1229)

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

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

- cut in pseudorapidity: strong cut dependence



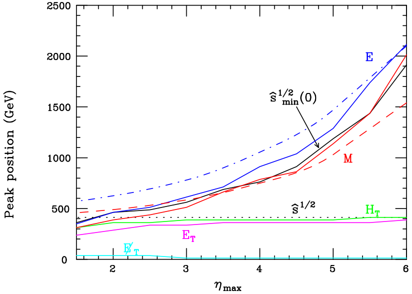
$\hat{s}_{min}^{1/2}(0)$ for different values of η_{cut}

η_{cut} dependence from Les Houches study (J.R. Lessard), using calorimeter level quantitities

- 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, depencence 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 $\sqrt{\hat{s}}_{\rm min}$ definition on several quantities:**

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

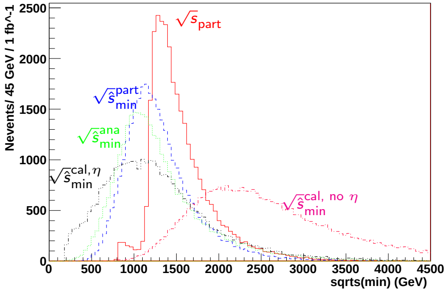
Always:

$$\vec{\not{P}}_T = -\vec{P}_T,\ \not{E}_T = |\vec{\not{P}}_T|$$

(for confusions from differing $\not{E}_T$ definitions:
cf A. Barr ea, "A Storm in a 'T' cup", arXiv:1105.2977)

$\sqrt{\hat{s}}_{\min}$ 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, $\sqrt{\bar{s}_{th}} = 1146\,\mathrm{GeV}$



$\tilde{q}\tilde{q}$, $\tilde{q}\tilde{g}$, , 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) $|\eta| < 1.4$

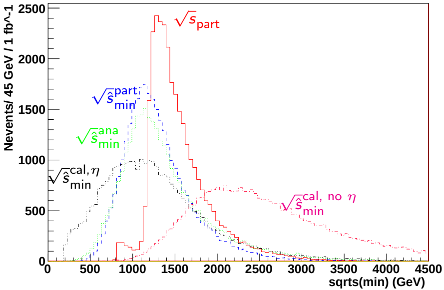
$\Rightarrow$ analysis level definition nicely reproduces parton level

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

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

- "τ corrected": use parton level τs 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: $(1152 \pm 4)\,\mathrm{GeV}$, $(1163 \pm 4)\,\mathrm{GeV}$ ($\checkmark$)

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

- 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 $\sqrt{\hat{s}}_{\text{min}}$

	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
$W+$ jets	254.2	62.53	81.13	48.73	46.73	70.29	42.41	75.89	43.3
$t\bar{t}+$ 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_{vis}, M_{eff} suppress similarly well**

sideremark: $\sqrt{\hat{s}}_{\text{min}}$ used a SM background suppression variable in ATLAS-CONF-2012-070 (light $\tilde{t}$ search); different spectrum...

Instead of Summary: Work in progress[1] (1)

In collaboration w K. Rolbiecki, K. Sakurai

- can we get **generic insight on viability** of $\sqrt{\hat{s}}_{\text{min}}/$ other variables ?
- first **"naive" example: completely invisible final states**, eg
$$e\,e \,\longrightarrow\, Z \,\longrightarrow\, \nu\nu$$
$\sqrt{\hat{s}}_{\text{min}} = 0,\ \hat{s}_{\text{th}} \sim m_Z \Rightarrow$ **complete failure**
(of course no variable works for completely invisible final states...)
- aside: also debateable: definition of "true" M_{inv}, eg in $\tilde{\nu} \longrightarrow \nu\,\tilde{\chi}_1^0$ decays

[1] supported by Fellowship from SFB 676 "Particles, Strings, and the Early Universe"

Work in progress (2): $\sqrt{\hat{s}}_{\min}$ vs M_{eff}

In collaboration w K. Rolbiecki, K. Sakurai

next example: consider $A \rightarrow B_{\textbf{inv}} + c_{\textbf{vis}},\; p_c^2 \,=\, 0$

- remember $\hat{s}_{\min}^{1/2} \equiv \sqrt{E^2 - P_z^2} + \sqrt{\not{E}_T^2 + M_{\text{inv}}^2}$
- consider for comparison $M_{\text{eff}} \,=\, \sum |p_T| + \not{E}_T$

a) large hierarchy, ie $m_A \gg m_B : |p_{B,c}| \sim \frac{m_A}{2}$:

$$\sqrt{\hat{s}}_{\min} \sim M_{\text{eff}} \sim m_A$$

b) degenerate scenario: $m_A \sim m_B : |p_{B,c}| \sim \frac{m_A^2 - m_B^2}{2\, m_A} \ll m_A$:

$$\sqrt{\hat{s}}_{\min} \sim m_A,\, \mathcal{M}_{\text{eff}} \sim 2\,|p_{B,c}| \ll m_A$$

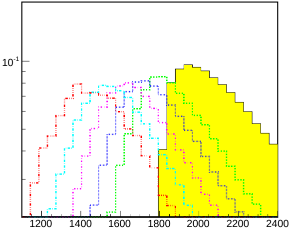
$\Rightarrow$ M_{eff} **fails for degenerate spectra** $\Leftarrow$

(here: only rough order of magnitude estimate, prefactors a la $p_T \,=\, \sin\theta\,|p|$ are neglected)

Work in progress (3): effect of many invisibles

In collaboration w K. Rolbiecki, K. Sakurai

- both $\sqrt{\hat{s}}_{\text{min}}$, M_{eff} depend on $\not{E}_T$
- increased number of invisible final state particles:
  large cancellations in $\not{E}_T = \sum \overrightarrow{p}_{\text{inv,T}}$ possible
  $\Rightarrow$ **effective decrease of peak position** $\Leftarrow$
- example: $\sqrt{\hat{s}}_{\text{min}}$, $\tilde{g}\tilde{g}$ production, with $\tilde{g} \longrightarrow \tilde{\chi}_1^0\, W\; W\, t\, t$,
  Ws decay to qq (no invisibles) or $l\,\nu$ (1 invisible)



$\tilde{g}\tilde{g}$ production and successive decays through W with in total 0,1,2,3,4 invisibles (right to left)

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

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

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

holds: powerful handle on new physics scale !!!

$\Rightarrow$ specified kinematic cases where this is not fulfilled

$\Rightarrow$ further investigation needed

- next step: check for many different spectra, scan underway...

!! Variable not dead yet !!

Thanks for listening

Appendix

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, ...) $\Rightarrow$ getting better and better though...
- variables constructed for **mass measurements**: depend less on overall (experimental and theoretical) normalization uncertainties

$\Rightarrow$ construction of Lorentz-invariant mass variables: even cm independent (especially useful for processes at LHC)

$\Rightarrow$ ideal candidates for BSM discoveries and measurements

- spins, couplings: more complicated; next step on the road...

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.
$\widetilde{\chi}_1^-$	181.7	$\widetilde{\chi}_2^-$	380.0	$\widetilde{\chi}_1^0$	96.7	$\widetilde{\chi}_2^0$	181.1	$\lvert\widetilde{\chi}_3^0\rvert$	363.8	$\widetilde{\chi}_4^0$	381.7	$\tilde{g}$	607.

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

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

Production cross sections in pb for $p\,p \to X_1\,X_2$, for a cm energy of 14 TeV. CTEQ6L1 PDFs were used. $2 \to 3$ sample includes explicitly generated hard jet, where hard is defined by $p_{T,\mathrm{jet}} > 40\,\mathrm{GeV}$.

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

- **SUSY spectrum**: generated using **SoftSusy** (B. Allanach, hep-ph/0104145)
- $2 \to 2$ and $2 \to 3$ **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

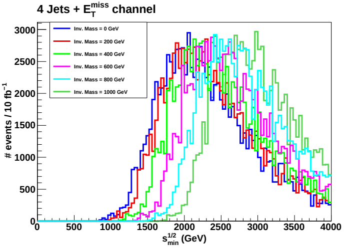
(L.Basso, T. Lari, J.-R. Lessard)

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

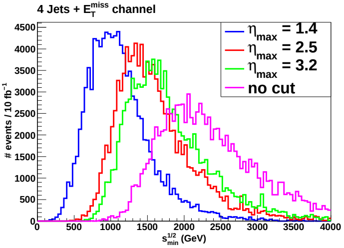
$\sqrt{\hat{s}}_{\min}$ (J.-R. Lessard)

- $\sqrt{\hat{s}}_{\min}$: determine scale of new physics by threshold scan
- **however:** requires mass of invisible final state particle as input
- definition: $\hat{s}^{1/2}_{\min}(M_{\rm inv}) \equiv \sqrt{E^2 - P_z^2} + \sqrt{(E_T^{\rm miss})^2 + M^2_{\rm inv}}$

— high sensitivity to ISR; solution: cut in jet pseudorapidity



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



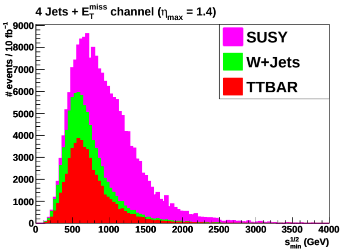
$\hat{s}^{1/2}_{\min}(0)$ for different values of $\eta_{\rm cut}$

large dependence on η cut !!

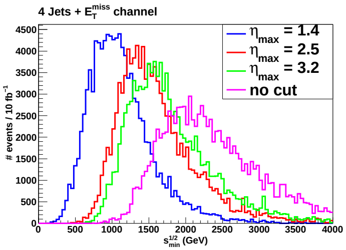
also: large effects when resummation is included;

(Papaefstathiou ea, arXiv:1002.4375, 1004.4762; Konar ea, 1006.0653)

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



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

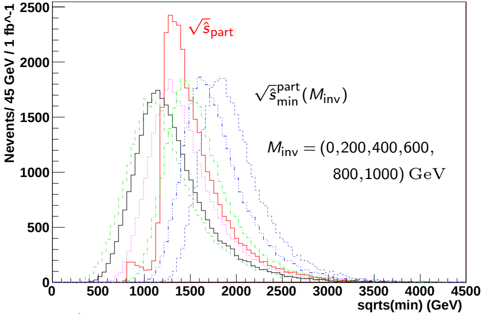


$\hat{s}_{min}^{1/2}(0)$ for different values of η_{cut}

✓ peaked at value different from SM background

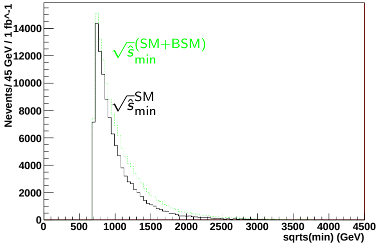
⇒ **useful for BSM discovery**

$\sqrt{\hat{s}}_{\text{min}}$: dependence on M_{inv}

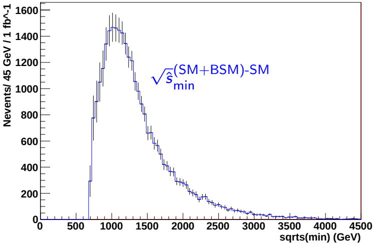


- peaks shuffle $\sim \frac{1}{2}\Delta M_{\text{inv}}$ (max bin analysis)
- same functional dependence for $\not{P}_T$: can use this for estimate of fake P_T from soft physics
- typical values: (Gaussian fits) $\sqrt{\hat{s}}_{\text{min}}^{\text{peak}}(\Delta P_T^{\text{fake}} = 10\,\text{GeV})$: $(1082 \pm 4)\,\text{GeV}$, $\sqrt{\hat{s}}_{\text{min}}^{\text{peak}}(\Delta P_T^{\text{fake}} = 100\,\text{GeV})$: $(1093 \pm 4)\,\text{GeV}$

SM Background



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



BSM = (SM+BSM) -(SM)

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

Derivation of $\sqrt{\hat{s}}_{\text{min}}$: Minimization

- **start with**

$$\hat{s}_{(\vec{P}_T = -\vec{\not{p}}_T)} = \left(E + \sum_j E_j\right)^2 - \left(P_Z + \sum_j p_{jz}\right)^2 \qquad (2)$$

- Introduce **additional constraint** $\sum_j p_{jT} = \not{p}_T$ using Lagrange multipliers, ie **minimize**

$$\mathcal{L} = \hat{s} - \lambda \left(\sum_j p_{jT} - \not{p}_T\right),$$

- **solutions**:

$$p_{iT} = \frac{\not{p}_T}{M_{\text{inv}}}\, m_i, \; p_{iz} = \frac{P_z\, m_i}{\sqrt{E^2 - P_z^2}} \sqrt{1 + \frac{\not{p}_T^2}{M_{\text{inv}}^2}}.$$

- put back in Eq. (2): **obtain**

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

!!! purely kinematic minimization !!! (eg for $m_i = 0,\; p_i = 0$)

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

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

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

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

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

Easy example in more detail (1): analytic approximation

process: $A \rightarrow B_{\mathbf{inv}} + c_{\mathbf{vis}},\; p_c^2 = 0$

$$|p_{B,c}| = \frac{m_A^2 - m_B^2}{2\, m_A},\; m_A \gg m_B : |p_{B,c}| \sim \frac{m_A}{2}$$

$$p_T = \sin\theta\, |p|,\; \langle p_T \rangle = \frac{\pi}{4} |p|$$

- hierarchy: $\langle \sqrt{\hat{s}}_{\mathbf{min}} \rangle \approx \langle M_{\mathbf{eff}} \rangle \approx 0.8\, m_A$
- degeneracy: $\sqrt{\hat{s}}_{\mathbf{min}} \approx m_B,\; \langle M_{\mathbf{eff}} \rangle \approx \frac{\pi}{4} \frac{m_A^2 - m_B^2}{2\, m_A} \ll m_A$

!! Average values, not peak positions !!

Easy example in more detail (2): plots

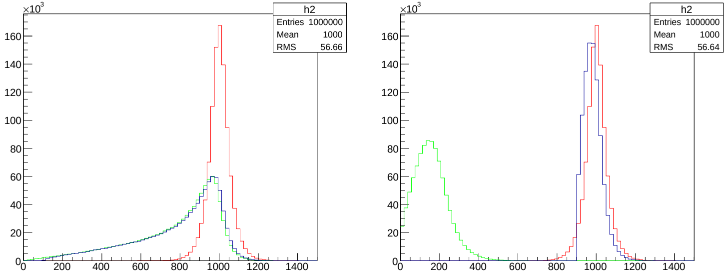


Figure: True m_A (red), M_{eff} (green), and $\sqrt{\hat{s}}_{\text{min}}$ (blue) for $m_B = 0.1\, m_{A0}$ (left) and $m_B = 0.9\, m_{A0}$ (right) where the visible decay product is massless. As expected, the peak of $\sqrt{\hat{s}}_{\text{min}}$ is around the true value m_A, while M_{eff} fails for degenerate scenarios.