$\sqrt{\hat{s}}_{min}$: a global inclusive variable

for determining the mass scale of new physics in MET events at LHC

HEFTI Workshop on Missing Energy Signals at LHC @ University of California Davis

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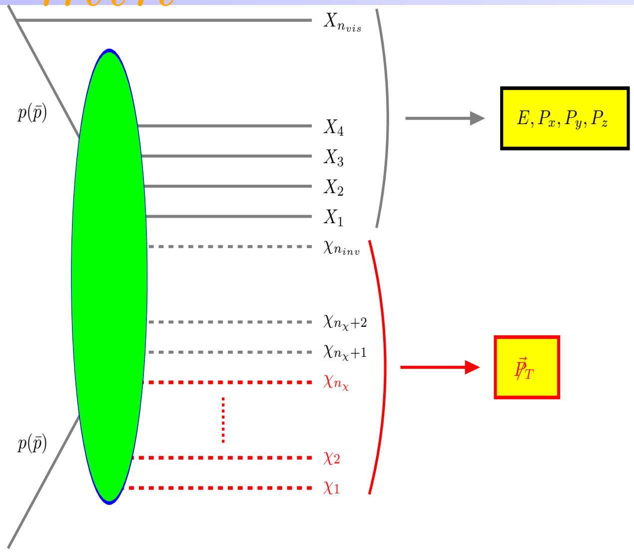
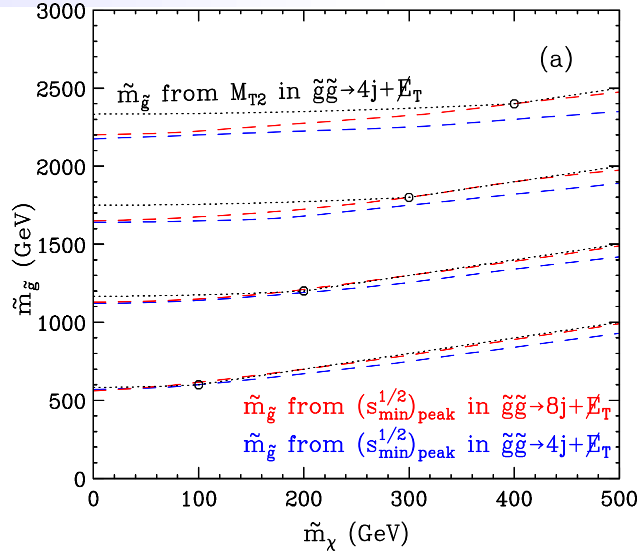
In a work with: K.C.Kong and K.Matchev

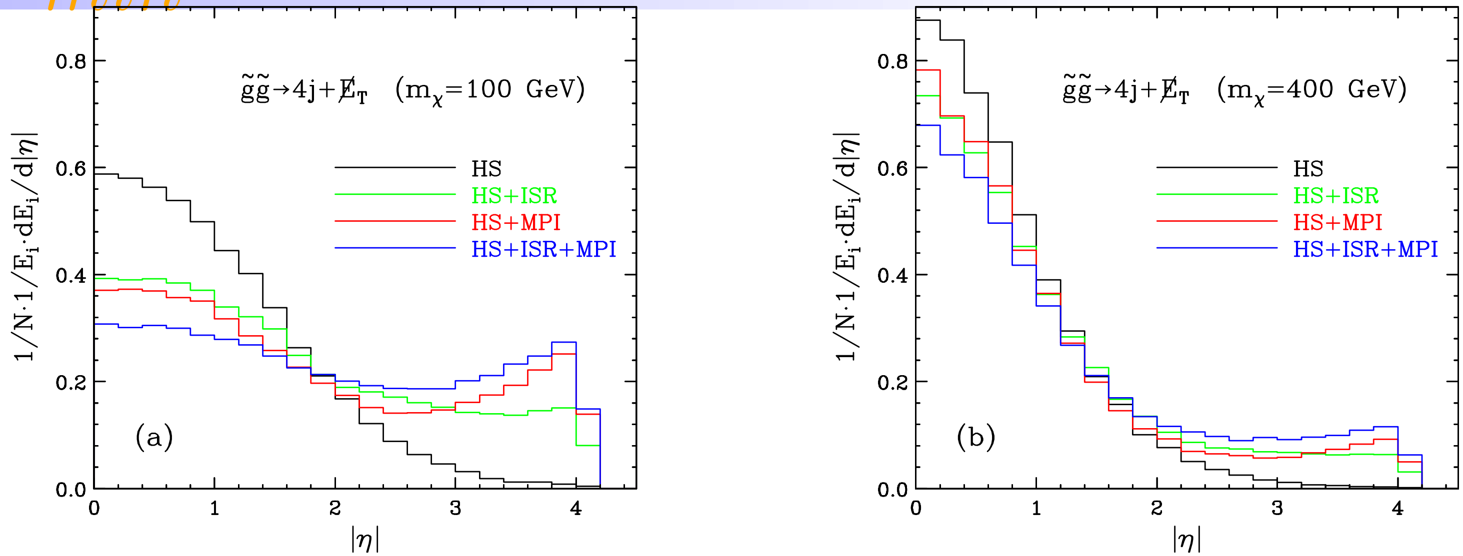
$\sqrt{\hat{s}}_{min}$ and mass scale :ISR effect





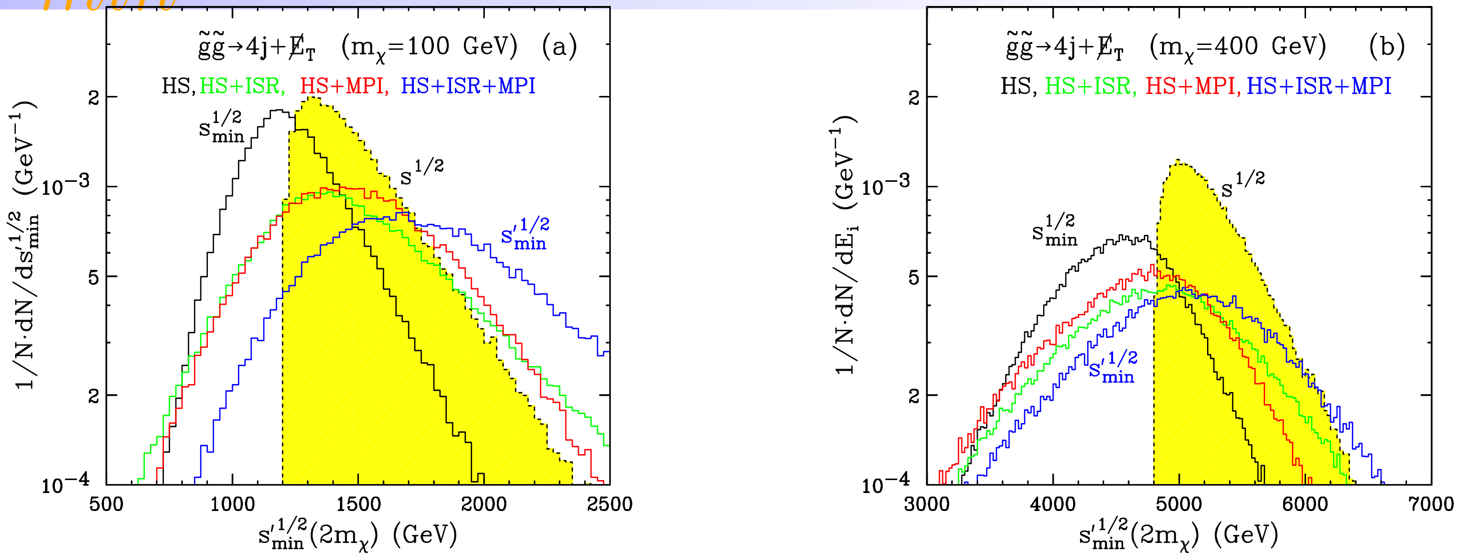
- Ideally, we want to measure $\sqrt{\hat{s}}$ coming from hard scattering.
- $\sqrt{\hat{s}}_{min}$ introduced to deal situation with correlation with new physics mass scale.
- But, Real event can have Initial state radiation (ISR), multiple parton interactions (MPI) and pile-up.
- If not controlled, these extra contributions can increase $\sqrt{\hat{s}}$.
- Easily resolved, when ISR and/or MPI products may be reliably identified and excluded.
- For generic method, we can try to compensate for the ISR/MPI effects by measuring from real data, using well measured Standard Model process.
- Alternatively, we can design and apply cuts which would minimize the ISR and MPI effects.

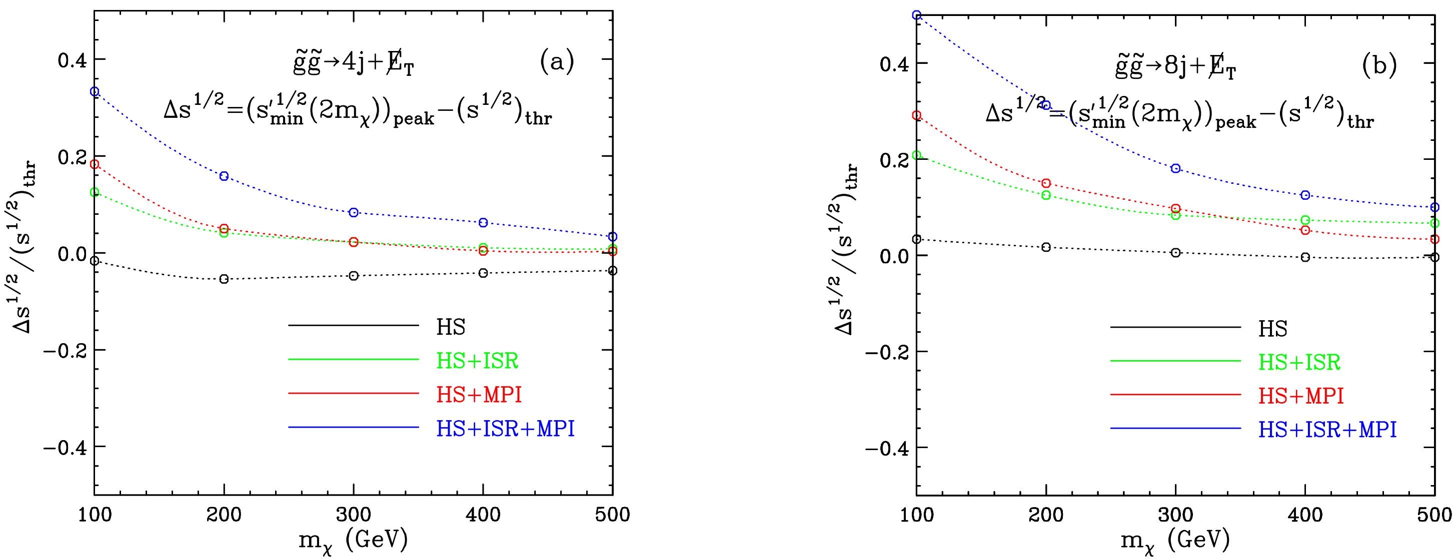
$\sqrt{\hat{s}}_{min}$ and mass scale :ISR effect



- ISR and MPI effect appear mostly in the forward region.
- Reduce their impact by applying a simple $|\eta| < \eta_{max}$ cut.
- Choose $\eta_{max} = 1.4$ at the barrael cal at CMS.
- MPI has a somewhat higher impact than ISR.
- Works better if the new particle spectrum is relatively heavy.

$\sqrt{\hat{s}_{min}}$ and mass scale :ISR effect





Mass measurement in missing energy

- Missing transverse energy BSM signatures are most exciting and well motivated from theoretical perspective.

- Mass measurements are quite challenging task at the hadron collider experiment.
  - BSM (SUSY) events always contain two or more invisible particles.
  - Number of missing particles and their identities are unknown.
  - The masses of invisible particles are a priori unknown.
  - The masses of their parents are also unknown.
  - CM energy and boost along beam direction is unknown.
  - No masses can be reconstructed directly.
- Several methods (and variants) for mass determination

Mass measurement in missing energy

- Endpoint method, Invariant mass edge
  Rely on the kinematic endpoint or shapes of various invariant mass distributions constructed out of visible(SM) decay products in the cascade decay chain. *Hinchliffe, Paige, Bachacou, Allanach, Lester, Parker, Webber, Gjelsten, Miller, Osland..*
- Polynomial method, On shell mass relation
  Attempt to extract event reconstruction using the measured momenta of the visibles and the measured missing transverse momentum. *Nojiri, Polesello, Tovey, Cheng, Gunion, Han, McElrath, Marandella..*
- Cambridge variable method, kink
  Explore the transverse invariant mass variable M_{T2} and the end point of the M_{T2} distribution. *Lester, Summers, Barr, Stephens, Tovey, Cho, Choi, Kim, Park, Kong, Matchev, Park, Burn...*
- Hybrid method
  Combining two or more of these techniques. *Nojiri, Polesello, Tovey, Ross, Serena...*

Mass measurement in missing energy

- Basic characteristics for most of these studies:
  - A particular BSM scenario and investigated its consequences in a rather model-dependent setup.
  - one must attempt at least some partial reconstruction of the events, by assuming a particular production mechanism, and then identifying the decay products from a suitable decay chain.
  - one inevitably encounters a combinatorial problem whose severity depends on the new physics model and the type of discovery signature.

complex event topologies with a large number of visible particles, and/or a large number of jets but few or no leptons, will be rather difficult to decipher, especially in the early data.

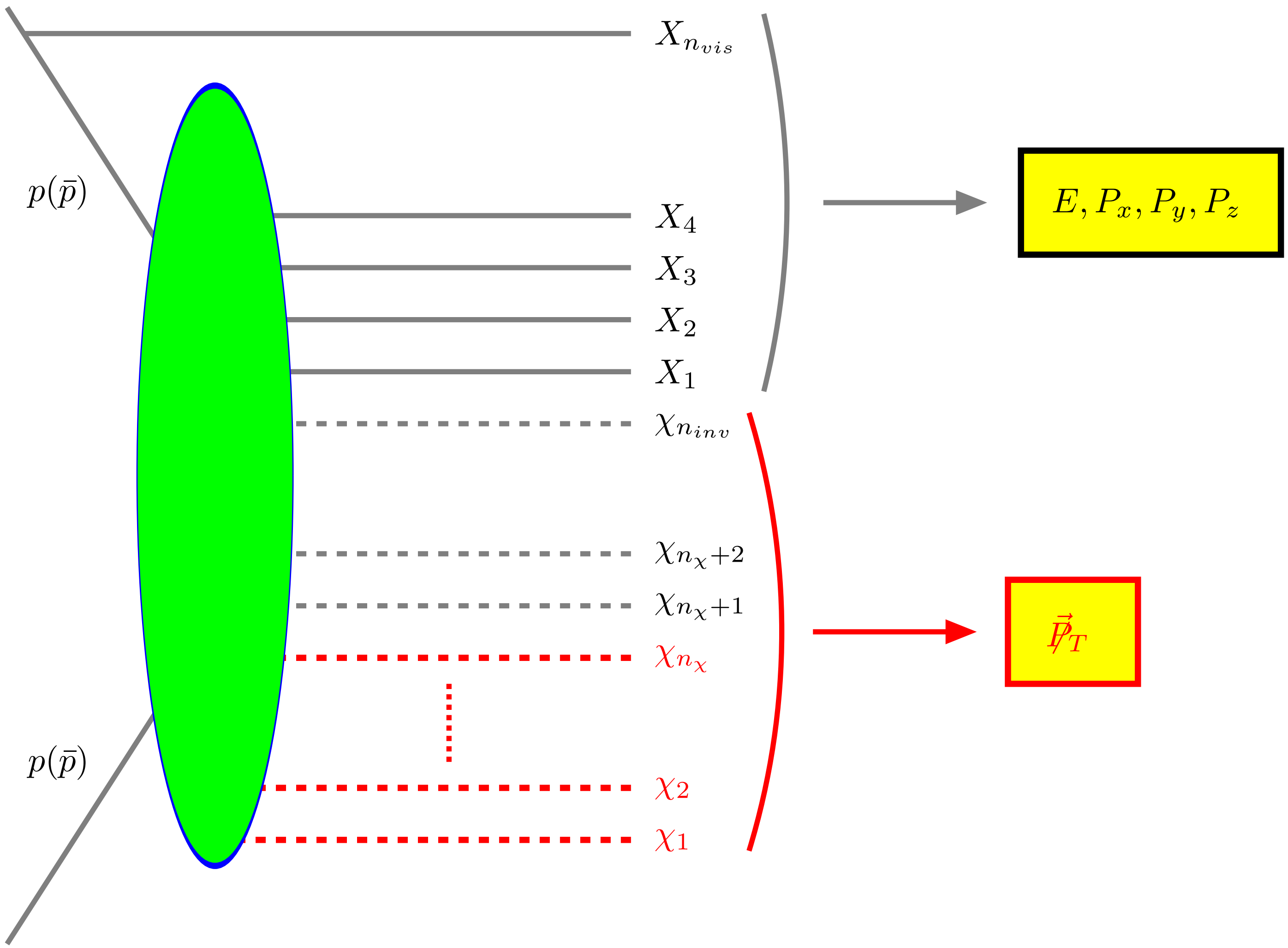
$\sqrt{\hat{s}_{min}}$ – Derivation

Q. whether one can say something about the newly discovered physics and in particular about its mass scale, using only inclusive and global event variables, before attempting any event reconstruction

⊙ General setup : Each event contains

- SM particles - visible to the detectors :
  $\longrightarrow$ reconstructed objects, e.g. jets, photons, electrons and muons.
  $X_i,\ i = 1, 2, \ldots, n_{vis}$
- $\not{E}_T$ from a certain number n_{inv} of stable neutral particles, which are *invisible* in the detector.
  $\chi_i,\ i = 1, 2, \ldots, n_{inv}$
  - BSM particles : n_χ with masses m_i.
  - SM neutrinos :$n_\nu = n_{inv} - n_\chi$ with mass 0.

$\sqrt{\hat{s}_{min}}$ – Derivation



- A global event variable, sensitive to the mass scale of the mother particles that were originally produced in the event, or more generally, to the typical energy scale of the event.

$\sqrt{\hat{s}_{min}}$ – Derivation

- Since we are not attempting any event reconstruction $\longrightarrow$ this variable should be defined only in terms of the global event variables describing the visible particles X_i, namely, the *total* energy E in the event, the transverse components P_x and P_y and the longitudinal component P_z of the *total* visible momentum $\vec{P}$ in the event.
- No assumptions about the underlying event structure.
- No usual assumption that the BSM particles are pair produced and, consequently, that there are two and only two BSM decay chains resulting in $n_\chi = 2$ identical dark matter particles with equal masses $m_1 = m_2$.
- No grouping the observed SM objects X_i, $i = 1, 2, \ldots, n_{vis}$, into subsets corresponding to individual decay chains.
- Not to avoid SM neutrinos which could contribute towards the measured MET.

$\sqrt{\hat{s}_{min}}$ – Derivation

- Three-momenta of the invisible particles χ_i, $i = 1, 2, \ldots, n_{inv}$ are $\vec{p}_i$, and masses m_i which are unknown.
- Parton-level Mandelstam variable $\hat{s}$

$$\hat{s} \quad = \quad \left(E + \sum_{i=1}^{n_{inv}} \sqrt{m_i^2 + \vec{p}_i^{\,2}} \right)^2 - \left(\vec{P} + \sum_{i=1}^{n_{inv}} \vec{p}_i \right)^2$$

Subject to the missing energy constraint:

$$\sum_{i=1}^{n_{inv}} \vec{p}_{iT} = \vec{\not{P}}_T = -\vec{P}_T$$

$\sqrt{\hat{s}_{min}}$ – Derivation

$$\hat{s} = \left(E + \sum_{i=1}^{n_{inv}} \sqrt{m_i^2 + \vec{p}_{iT}^{\,2} + p_{iz}^2} \right)^2 - \left(P_z + \sum_{i=1}^{n_{inv}} p_{iz} \right)^2$$

- function of a total of $3.n_{inv}$ variables $\vec{p}_i$
- 2 constraints from missing energy.
- we are missing so much information about the missing momenta $\vec{p}_i$, $\longrightarrow$ No hope of determining $\hat{s}$ *exactly* from experiment.
- The function $\hat{s}$ has an absolute global minimum $\hat{s}_{min}$, when considered as a function of the unknown variables $\vec{p}_i$.
- we choose to approximate the real values of the missing momenta with the values corresponding to the global minimum $\hat{s}_{min}$.

$\sqrt{\hat{s}_{min}}$ – Derivation

The minimization of the function with respect to the variables $\vec{p}_i$, subject to the constraint :

$$\vec{p}_{iT} = \frac{m_i}{M_{inv}} \; \vec{\not{P}}_T$$

$$p_{iz} = \frac{m_i P_z}{\sqrt{E^2 - P_z^2}} \sqrt{1 + \frac{\not{P}_T^2}{M_{inv}^2}}$$

Total invisible mass as:

$$M_{inv} \equiv \sum_{i=1}^{n_{inv}} m_i = \sum_{i=1}^{n_\chi} m_i$$

$\sqrt{\hat{s}_{min}}$ – Derivation

we get the minimum value:

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

$\hat{s}^{1/2}_{min}$ is the *minimum* parton level center-of-mass energy, which is required in order to explain the observed values of E, P_z and $\not{E}_T$.

Feature

- simplicity and Clear physical meaning.
- True for completely general types of events - any number and/or types of missing particles.
- Uses all available informations (not just transverse quantities).
- Model-independent: No need for any event reconstruction.
- $\hat{s}^{1/2}_{min}$ defined in terms of the global and inclusive event quantities E, P_z and $\not{E}_T$.

$\hat{s}_{min}^{1/2}$ and other inclusive variables

- Numerical study with PYTHIA and the PGS detector simulation package
- Without any event reconstruction, summing over all calorimeter towers both HCAL and ECAL energy deposits. Total energy: $E = \sum_\alpha E_\alpha$
- since muons do not deposit significantly in the calorimeters, the measured E_α should first be corrected for the energy of any muons which might be present in the event and happen to pass through the corresponding tower α.
- The three components of the total visible momentum $\vec{P}$ are $P_x = \sum_\alpha E_\alpha \sin\theta_\alpha \cos\varphi_\alpha;$ $P_y = \sum_\alpha E_\alpha \sin\theta_\alpha \sin\varphi_\alpha;$ $P_z = \sum_\alpha E_\alpha \cos\theta_\alpha$
- θ_α and φ_α are correspondingly the azimuthal and polar angular coordinates of the α calorimeter tower.

$\hat{s}^{1/2}_{min}$ and other inclusive variables

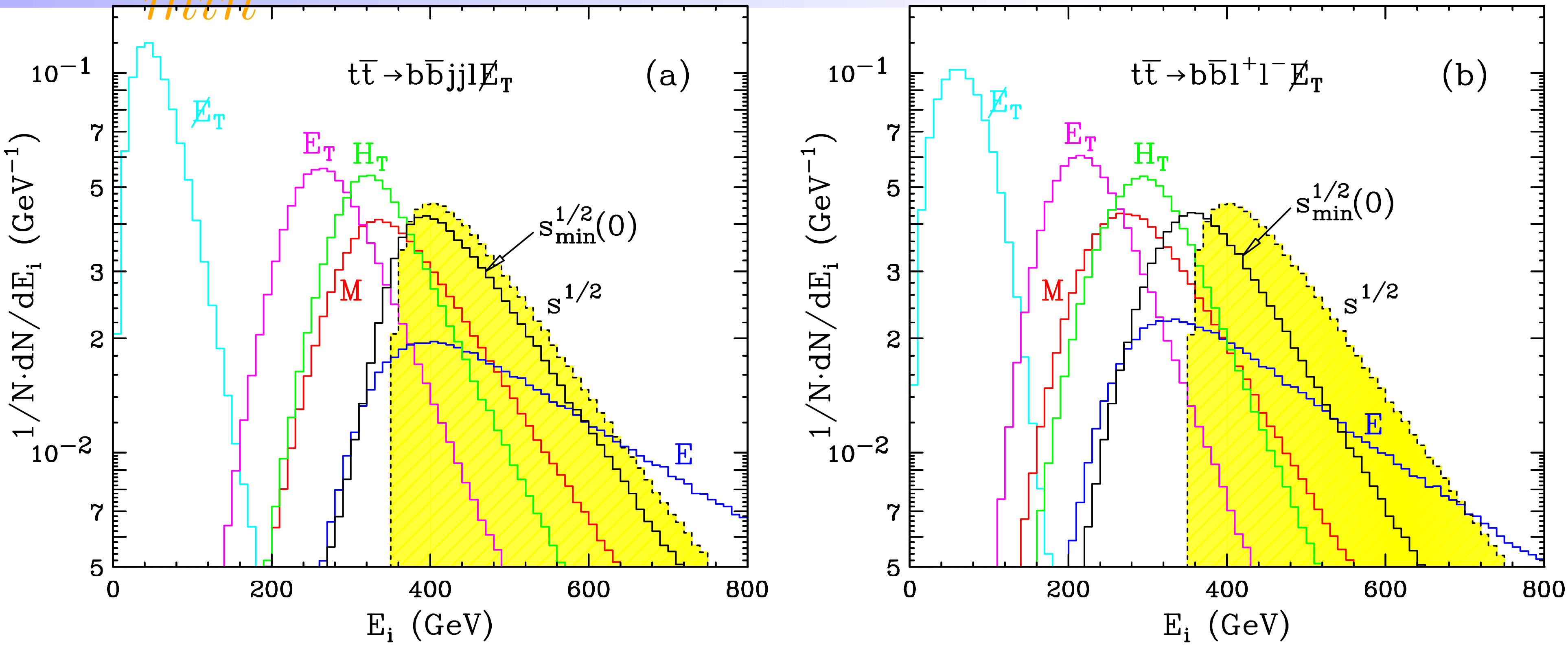
- $$E \equiv \sum_\alpha E_\alpha$$

- $$E_T \equiv \sum_\alpha E_\alpha \sin\theta_\alpha$$

- $$H_T \equiv E_T + \not{E}_T$$

- $$M \equiv \sqrt{E^2 - P_x^2 - P_y^2 - P_z^2} = \sqrt{E^2 - \not{P}_T^2 - P_z^2}$$

$\hat{s}_{min}^{1/2}$ and other inclusive variables



Distributions of the various energy scale variables in (a) single-lepton and (b) dilepton $t\bar{t}$ events.

- An approximate measurement to the true value of $\hat{s}$?
- Better indicator of the relevant energy scale.

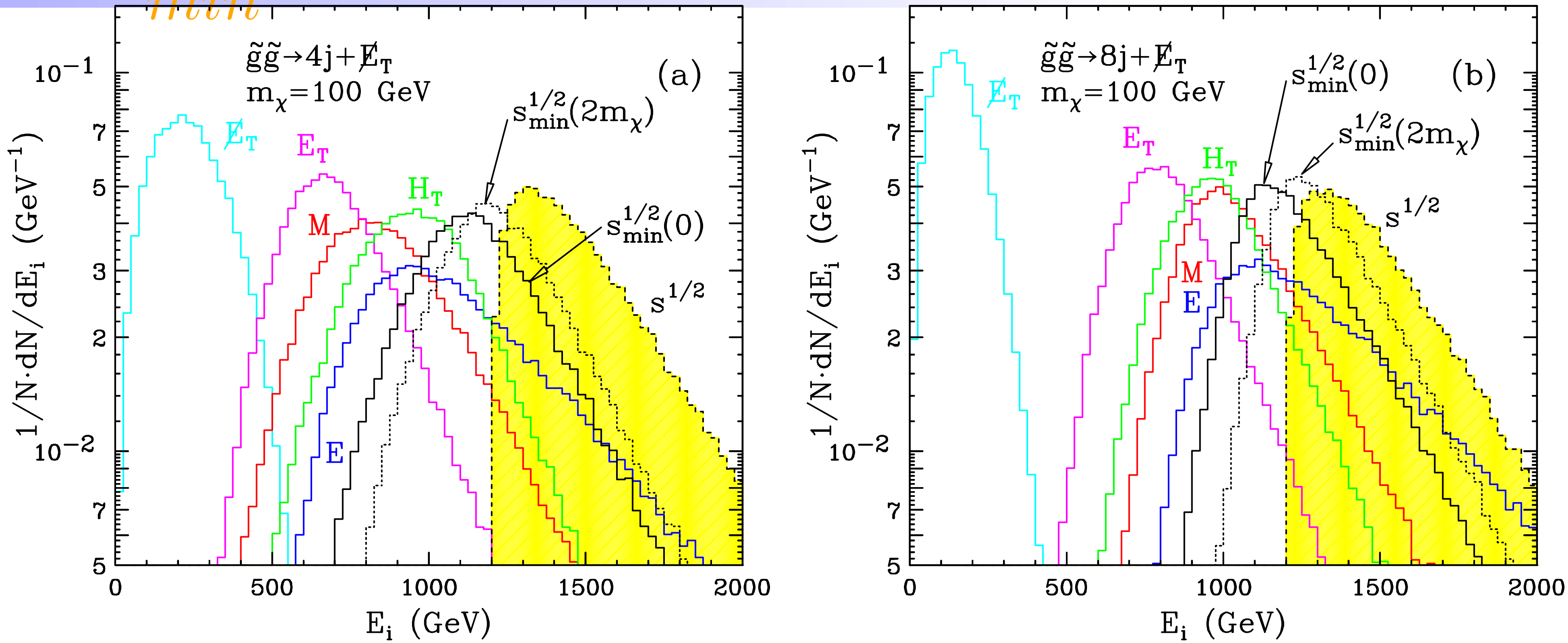
$\hat{s}_{min}^{1/2}$ and other inclusive variables

- Since $\hat{s}_{min}^{1/2}$ was defined through a minimization procedure, it will always underestimate the true $\hat{s}^{1/2}$
- for semi-leptonic events, we are missing a single neutrino, whose transverse momentum is actually measured through $\vec{\not{P}}_T$, so that the only mistake we are making in approximating $\hat{s}^{1/2} \approx \hat{s}_{min}^{1/2}(0)$ is due to the unknown longitudinal component p_{1z}.
- dilepton events, however, there are two missing neutrinos, and thus more unknown degrees of freedom which we have to fix rather ad hoc according to our prescription.
- The dilepton $t\bar{t}$ sample is rather similar to a hypothetical new physics signal due to dark matter particle production: each event has a certain amount of missing energy, which is due to *two* invisible particles escaping the detector.

$\hat{s}_{min}^{1/2}$ and other inclusive variables

- In the case of $t\bar{t}$: approximation $M_{inv} = 0$ is well justified.
- now consider a situation where the observed missing energy signal is due to *massive* neutral stable particles, as opposed to SM neutrinos.
- Typical example of low energy supersymmetry with conserved R-parity.
- Each SUSY event will be initiated by the pair-production of two superpartners
- decay to the lightest supersymmetric particle (LSP);assume, lightest neutralino $\tilde{\chi}_1^0$.
- there are two SUSY cascades per event, there will be two LSP particles in the final state
- $n_{inv} = n_\chi = 2$ and $m_1 = m_2 \equiv m_\chi$.
- we construct our variable: $\hat{s}_{min}^{1/2}(M_{inv}) = \hat{s}_{min}^{1/2}(2m_\chi)$

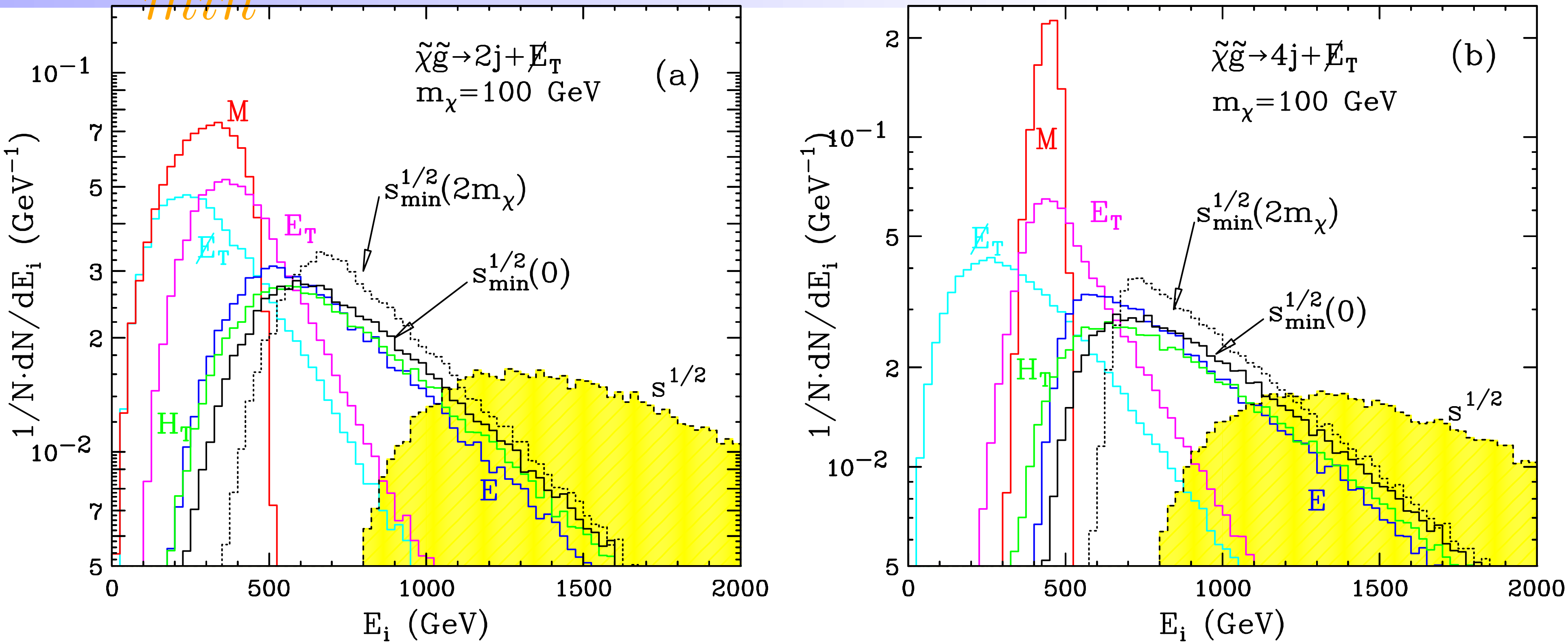
$\hat{s}_{min}^{1/2}$ and other inclusive variables



gluino pair production events with (a) 2-jet gluino decays and (b) 4-jet gluino decays.

- A difficult signature — lots of jets plus $\not{E}_T$, for which all other proposed methods for mass determination are bound to face significant challenges.

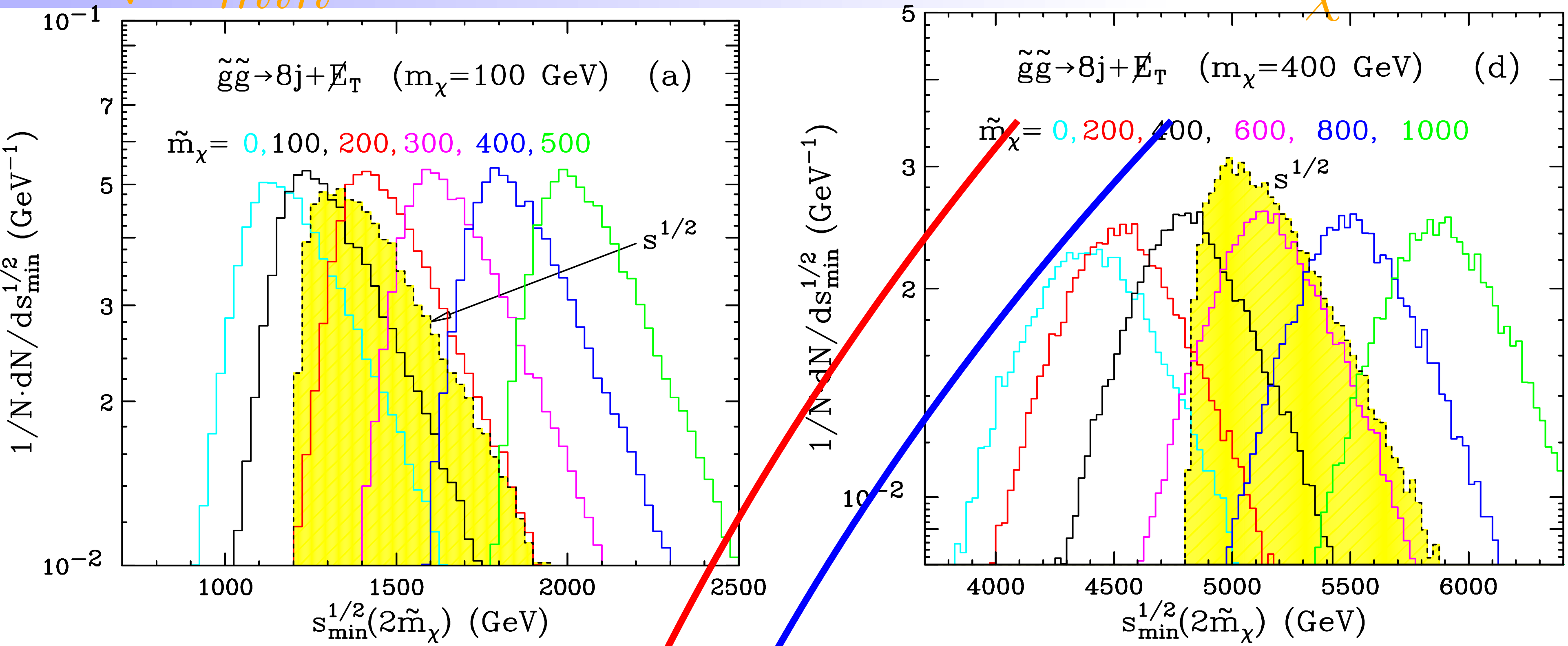
$\hat{s}_{min}^{1/2}$ and other inclusive variables



associated gluino-LSP production events with (a) 2-jet gluino decays and (b) 4-jet gluino decays.

- An extreme case of asymmetric events, where the parent particles are very different. All visible decay products are from one leg.

$\sqrt{\hat{s}}_{min}$ and unknown masses $\tilde{m}_\chi$



distributions of the $\hat{s}^{1/2}_{min}(M_{inv})$ variable for several different SUSY mass spectra

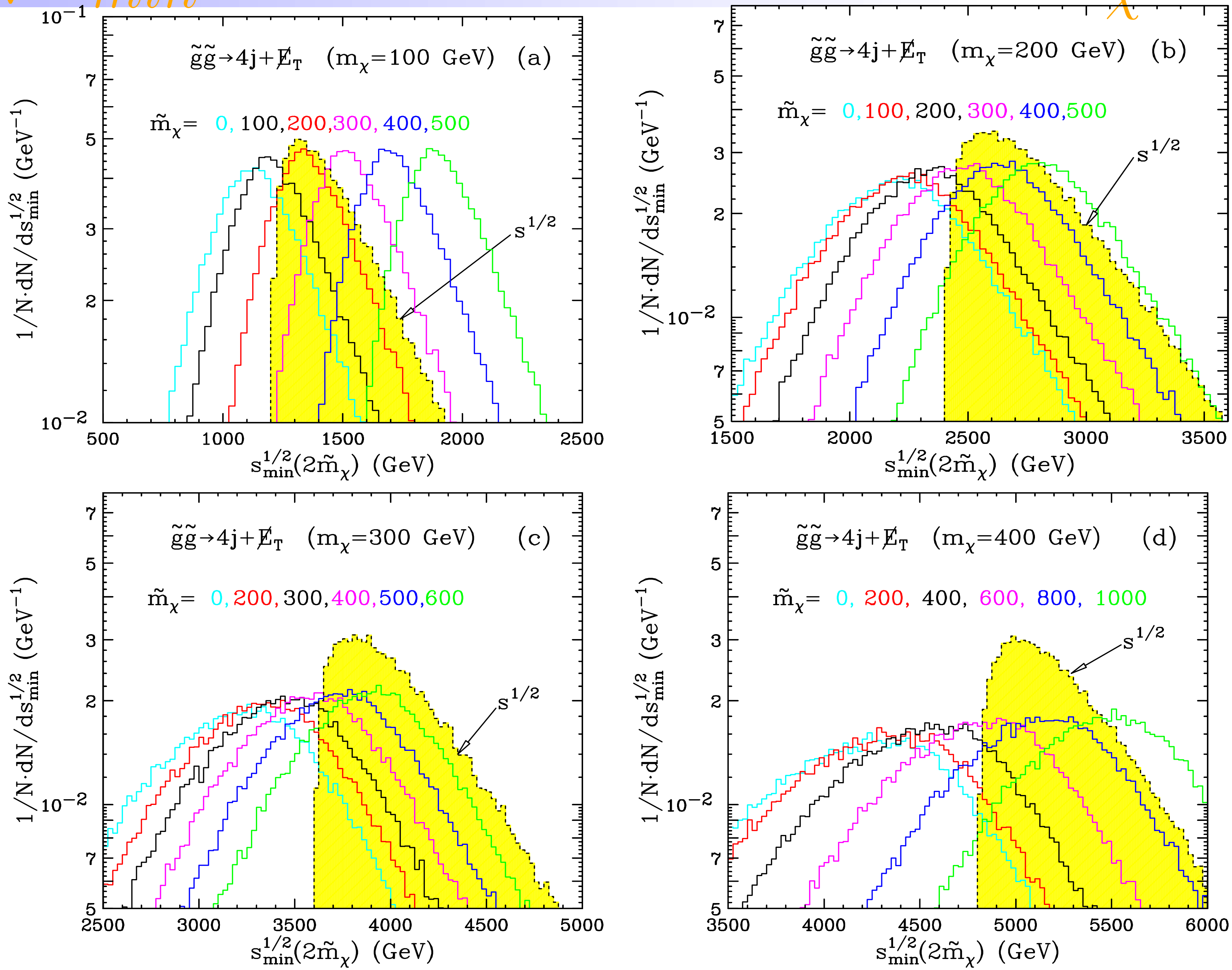
True mass

Trial mass

- Can one measure SUSY masses in terms of LSP mass ?

$$\left(\hat{s}^{1/2}\right)_{thr} \approx \left(\hat{s}^{1/2}_{min}(2m_\chi)\right)_{peak}$$

$\sqrt{\hat{s}}_{min}$ and unknown masses $\tilde{m}_\chi$



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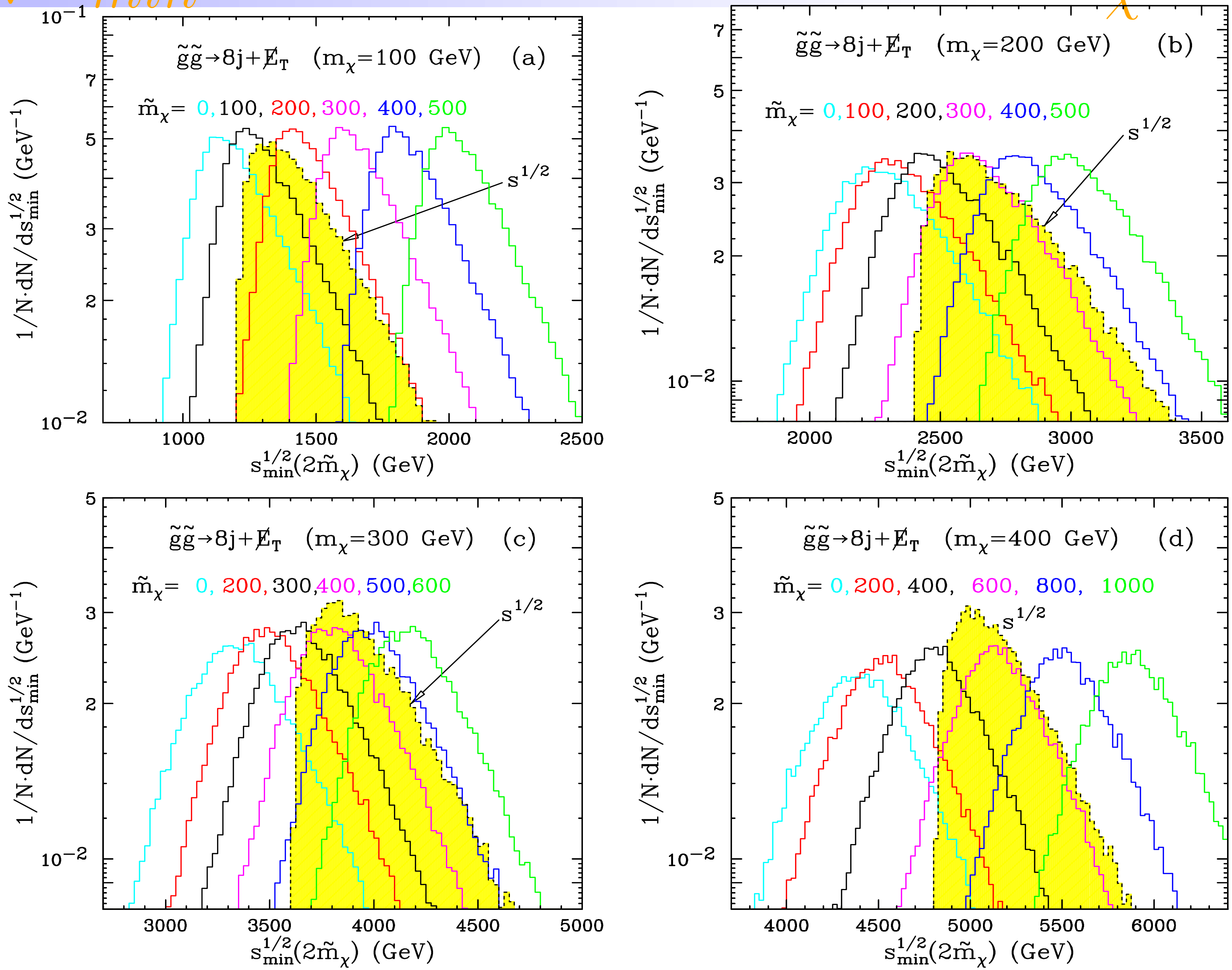

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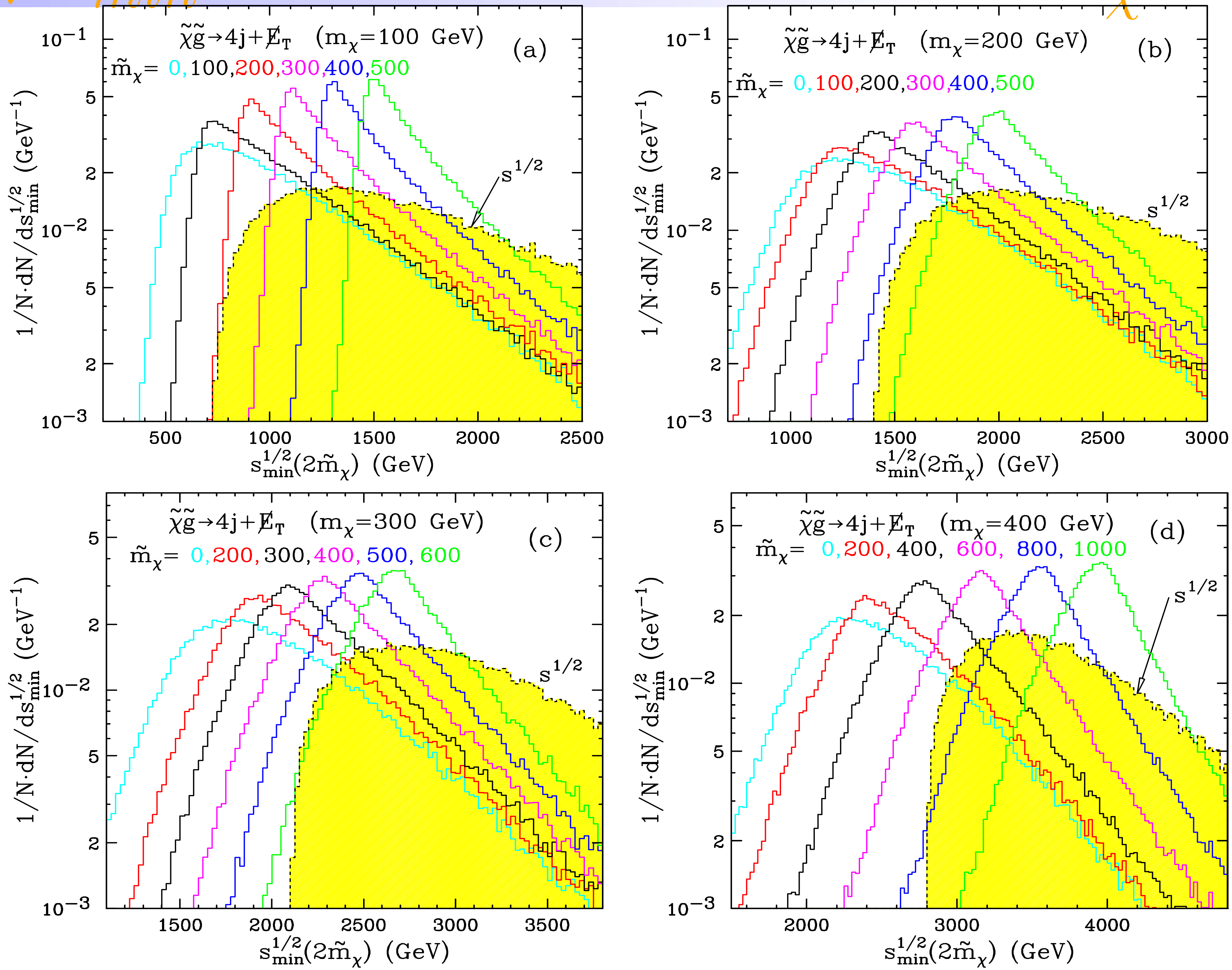

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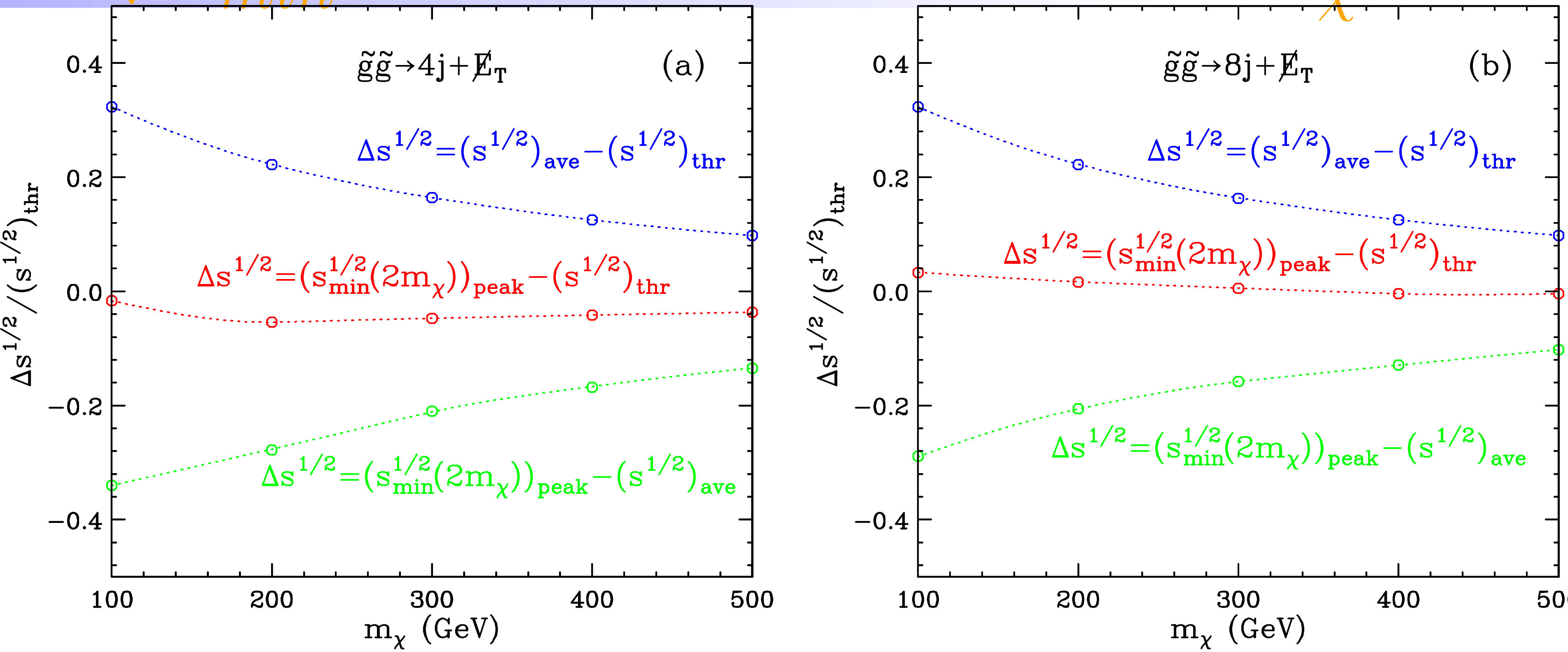

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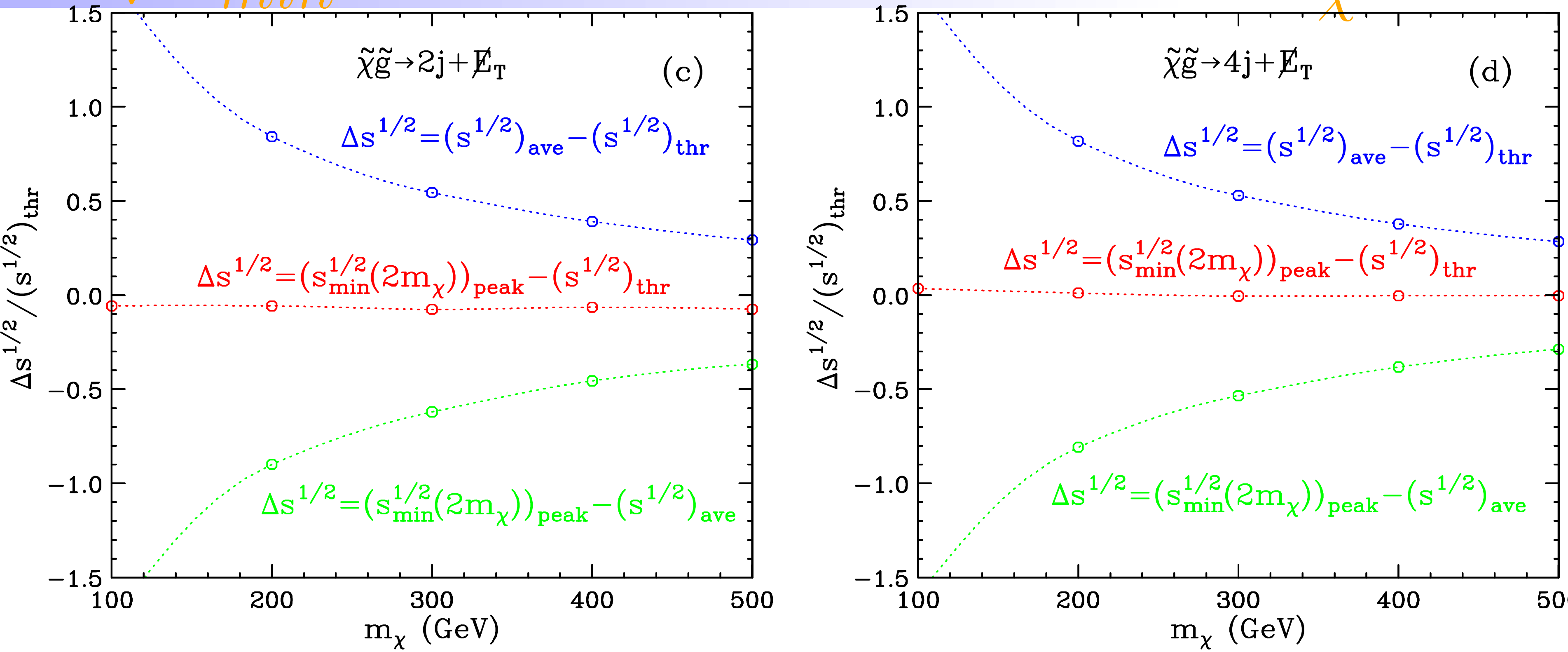

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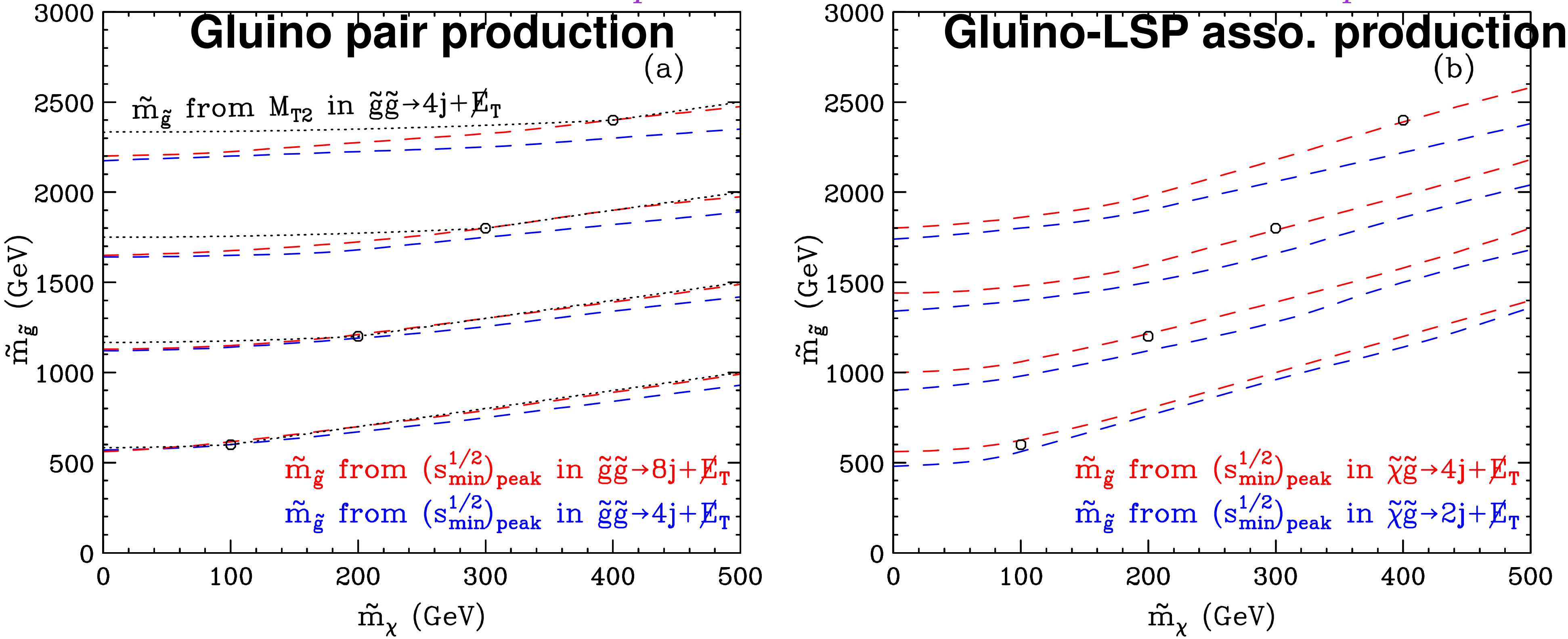
$\sqrt{\hat{s}_{min}}$ and mother mass :Correlation

$$\tilde{m}_{\tilde{g}}(\tilde{m}_\chi) \approx \frac{1}{2}\left(\hat{s}^{1/2}_{min}(2\tilde{m}_\chi)\right)_{peak} \qquad \tilde{m}_{\tilde{g}}(\tilde{m}_\chi) \approx \left(\hat{s}^{1/2}_{min}(2\tilde{m}_\chi)\right)_{peak} - \tilde{m}_\chi$$



The correlation between the test LSP mass $\tilde{m}_\chi$ and the corresponding gluino mass $\tilde{m}_{\tilde{g}}$

- black dotted lines are theoretically derived correlation from an ideal M_{T2} endpoint analysis, i.e. assuming perfect resolution of the jet combinatorial ambiguity and ignoring any detector resolution effects.

$\sqrt{\hat{s}}_{min}$ and mother mass :ISR effect

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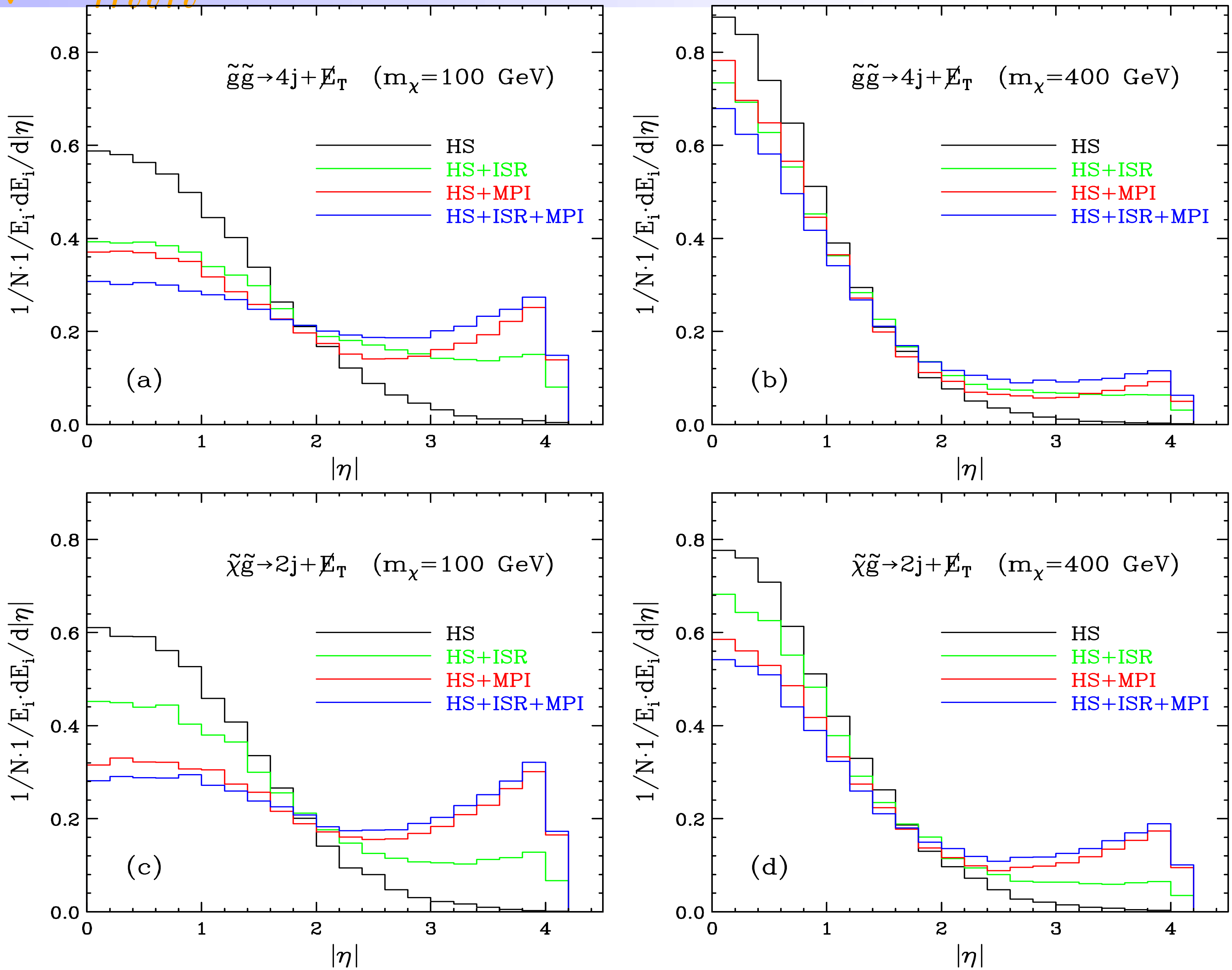

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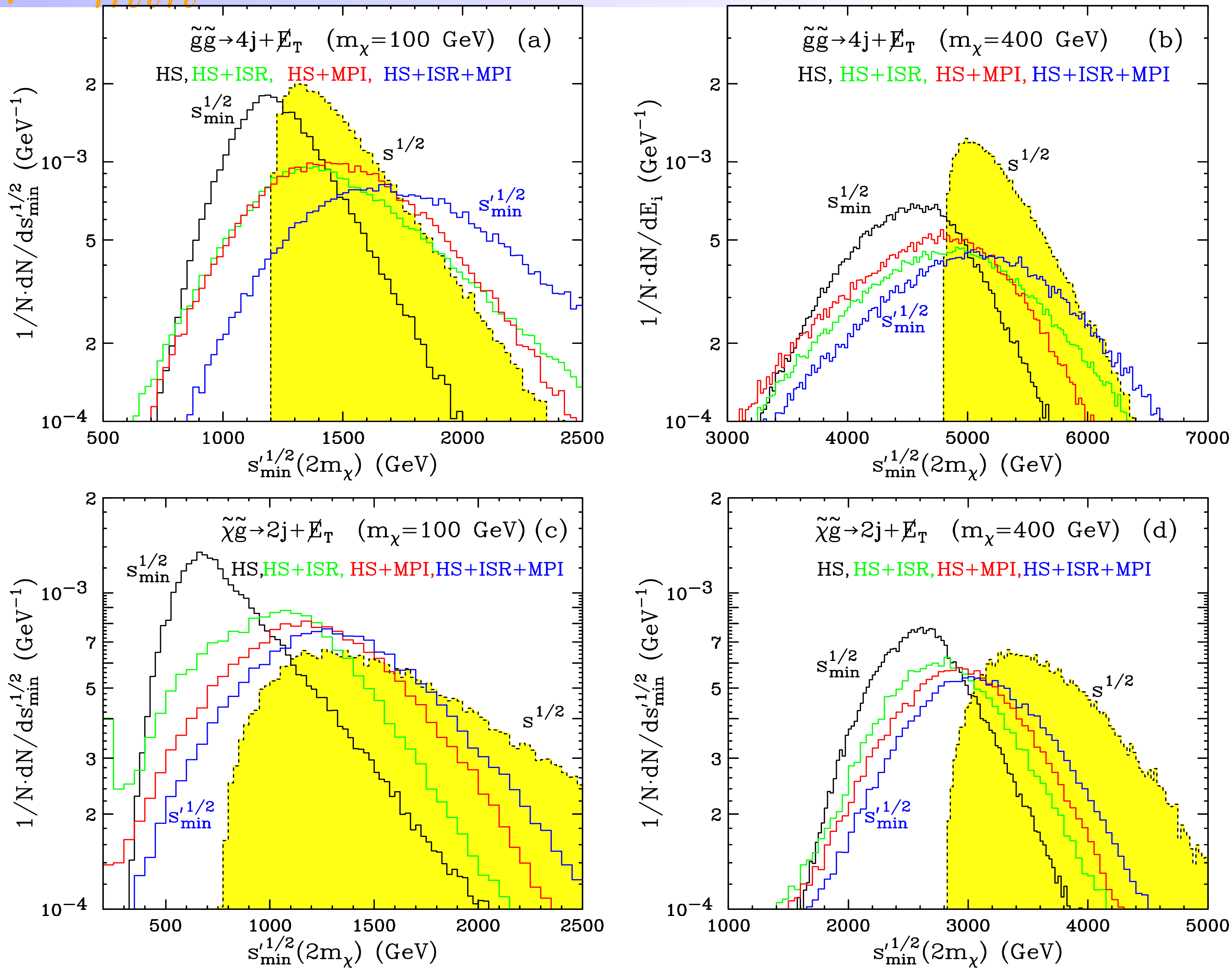

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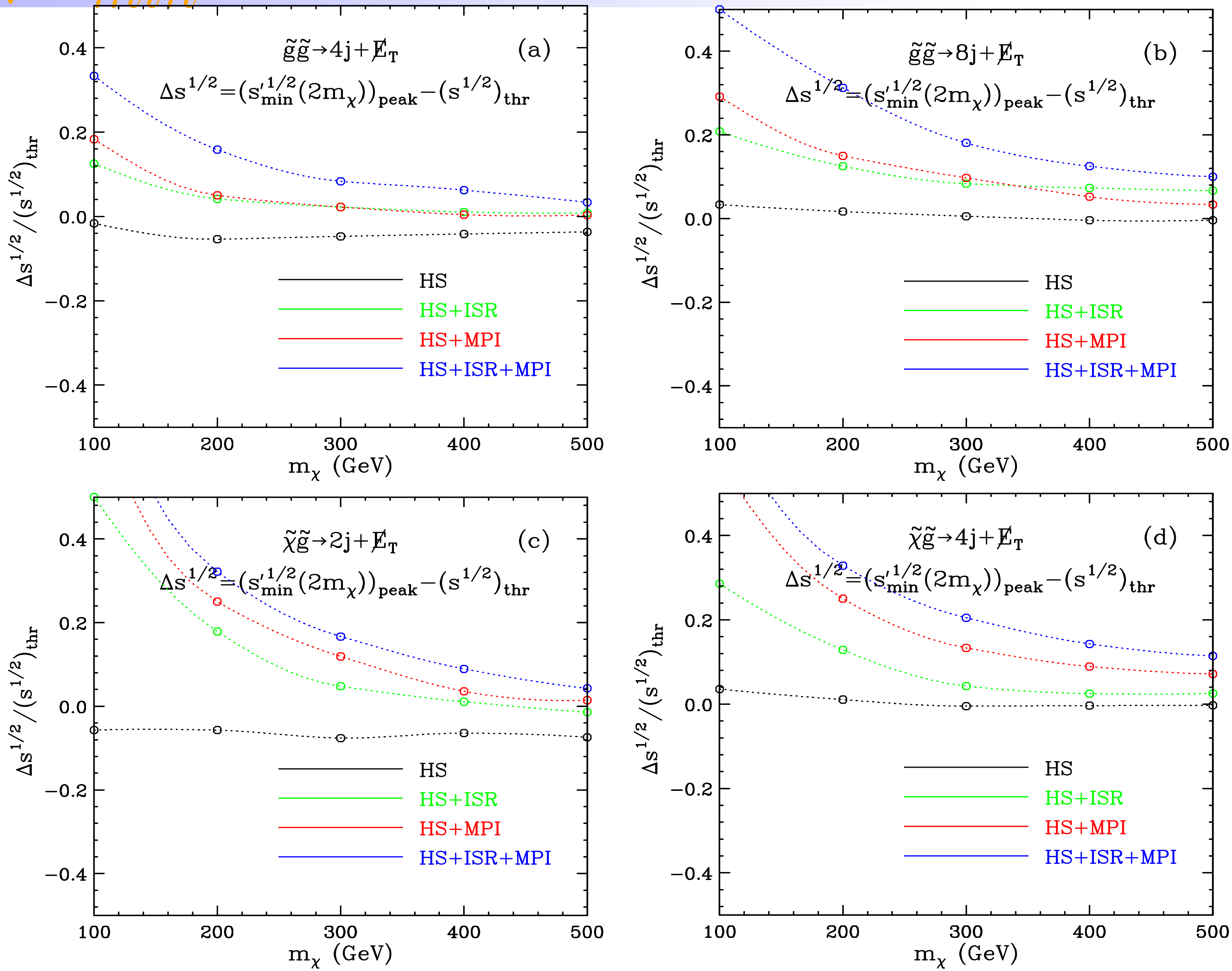

$\sqrt{\hat{s}_{min}}$ @ LHC – Summary

- Expect an early discovery of a missing energy signal at LHC.
- May involve a signal topology which is too complex for a successful and immediate exclusive event reconstruction
- $\hat{s}_{min}^{1/2}$ is a new global and inclusive variable.
- it is the minimum required center-of-mass energy, given the measured values of the total calorimeter energy E, total visible momentum $\vec{P}$, and/or missing transverse energy $\not{E}_T$ in the event.
- completely general, and is valid for any generic event with an arbitrary number and/or types of missing particles - symmetric or asymmetric.
- its shape matches the true $\hat{s}^{1/2}$ distribution better than any of the other global inclusive quantities $\rightarrow$ identifying the scale of the hard scattering.

$\sqrt{\hat{s}_{min}}$ @ LHC – Summary

- $\hat{s}^{1/2}(M_{inv})$ distribution with the true value of the invisible mass M_{inv}, its peak is very close to the mass threshold of the parent particles originally produced in the event.
- Possibility of measuring the mass scale of the new physics within the level of 10%.
- $\hat{s}^{1/2}_{min}(0)$ can already be used for background rejection and increasing signal to noise, just like $M_{T2}(0)$
- Farther possibility to use it at the trigger level.

Thank You