Mass and Spin Measurement with M_{T2} and MAOS Momentum

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arXiv:0810.4853 [hep-ph]
arXiv:0711.4526 [hep-ph]
arXiv:0709.0288 [hep-ph]
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arXiv:0908.0079 [hep-ph]

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Outline

1. Motivation: New Physics Events with Missing Transverse Momentum

2. M_{T2}-Kink Method for Mass Measurement

3. M_{T2}-Assisted On-Shell (MAOS) Momentum and its Applications:

   Sparticle Spin and Higgs Mass Determination

4. Summary

Motivations for new physics at the TeV scale:

- Hierarchy Problem

$$\delta m_H^2 \sim \frac{g^2}{8\pi^2}\Lambda_{\rm SM}^2 \sim M_Z^2 \quad \Longrightarrow \quad \Lambda_{\rm SM} \sim 1 \text{ TeV}$$

- Dark Matter

Thermal WIMP with $\Omega_{\rm DM}h^2 \sim \frac{0.1}{g^4}\left(\frac{m_{\rm DM}}{1\text{ TeV}}\right)^2 \sim 0.1$

$\Longrightarrow \quad m_{\rm DM} \sim 1$ TeV

Many new physics models solving the hierarchy problem while providing a DM candidate involve a Z_2-parity symmetry under which the new particles are Z_2-odd, while the SM particles are Z_2-even: SUSY with R-parity, Little Higgs with T-parity, UED with KK-parity, ...

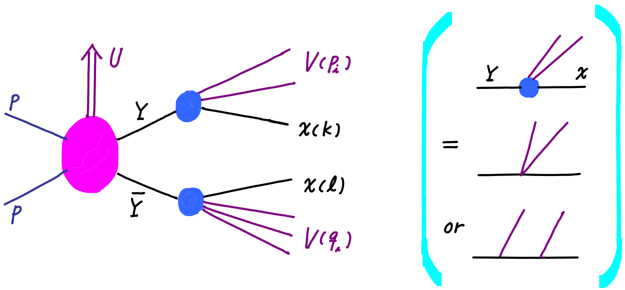
* At colliders, new particles are produced always in pairs.
* Lightest new particle is stable, so a good candidate for WIMP DM.

LHC Signal

Pair-produced new particles $(Y + \bar{Y})$ decaying into visible SM particles (V) plus invisible WIMPs (χ):

$$pp \;\to\; U + Y + \bar{Y} \;\;\to\;\; U + \sum V(p_i) + \chi(k) + \sum V(q_j) + \chi(l)$$

$$\Big(\text{multi-jets} + \text{leptons} + \not{\mathbf{p}}_T\Big)$$



$U \equiv$ Upstream momenta carried by the visible SM particles not from the decay of $Y + \bar{Y}$ ($\bar{Y}$ is not necessarily the antiparticle of Y.)

- Mass measurement of these new particles is quite challenging:

  * Initial parton momenta in the beam-direction are unknown.
  * Each event involves two invisible WIMPs.

  Kinematic methods of mass measurement:

  i) Endpoint Method
  ii) Mass Relation Method
  iii) M_{T2}-Kink Method

- Spin measurement appears to be even more challenging:

  * It often requires a more refined event reconstruction and/or polarized mother particle state.

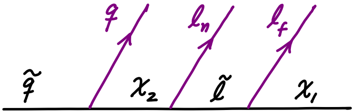
  MAOS momentum provides a systematic approximation to the invisible WIMP momentum, and thus can be useful for spin and mass measurements.

Kinematic Methods of Mass Measurement

i) Endpoint Method Hinchliffe et. al.; Allanach et. al.; Gjelsten et. al.;...

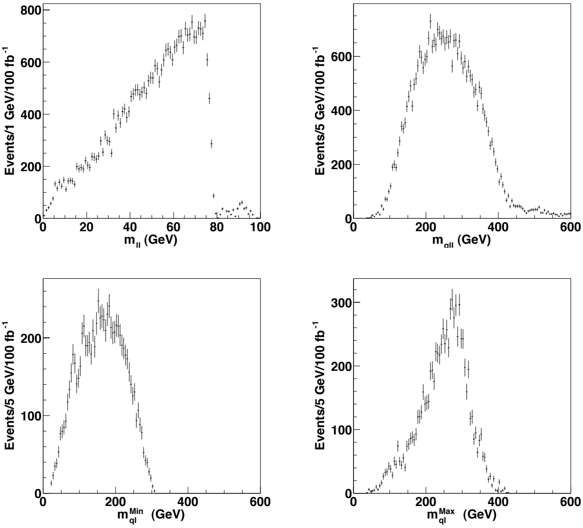
Endpoint value of the invariant mass distribution of visible (SM) decay products depend on the new particle masses.

* 3-step squark cascade decays when $m_{\tilde{q}} > m_{\chi_2} > m_{\tilde{\ell}} > m_{\chi_1}$



$$
\begin{aligned}
m_{\ell\ell}^{\max} &= m_{\chi_2}\sqrt{(1 - m_{\tilde{\ell}}^2/m_{\chi_2}^2)(1 - m_{\chi_1}^2/m_{\tilde{\ell}}^2)} \\
m_{q\ell\ell}^{\max} &= m_{\tilde{q}}\sqrt{(1 - m_{\chi_2}^2/m_{\tilde{q}}^2)(1 - m_{\chi_1}^2/m_{\chi_2}^2)} \\
m_{q\ell(\mathrm{high})}^{\max} &= m_{\tilde{q}}\sqrt{(1 - m_{\tilde{\chi}_2}^2/m_{\tilde{q}}^2)(1 - m_{\chi_1}^2/m_{\tilde{\ell}}^2)} \\
m_{q\ell(\mathrm{low})}^{\max} &= m_{\tilde{q}}\sqrt{(1 - m_{\chi_2}^2/m_{\tilde{q}}^2)(1 - m_{\tilde{\ell}}^2/m_{\chi_2}^2)}
\end{aligned}
$$

Result for SUSY SPS1a Point Weiglein et. al. hep−ph/0410364



Input masses: $(m_{\tilde{q}}, m_{\chi_2}, m_{\tilde{\ell}}, m_{\chi_1}) = (540, 177, 143, 96)$ GeV

Fitted masses: $(543 \pm 13,\ 180 \pm 9,\ 146 \pm 11,\ 98 \pm 9)$ $\quad (\int \mathcal{L} = 100\,\text{fb}^{-1})$

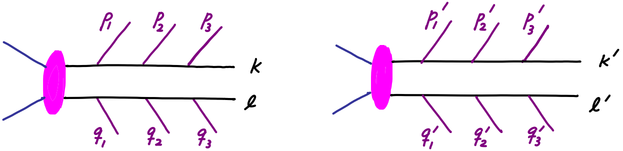
ii) Mass Relation Method

Nojiri, Polesello, Tovey; Cheng et. al.; ...

Reconstruct the missing momenta using all available constraints.

* A pair of symmetric 3-step cascade decays of squark pair

Cheng, Engelhardt, Gunion, Han, McElrath



- 16 unknowns: k^μ, l^μ, k'^μ, l'^μ

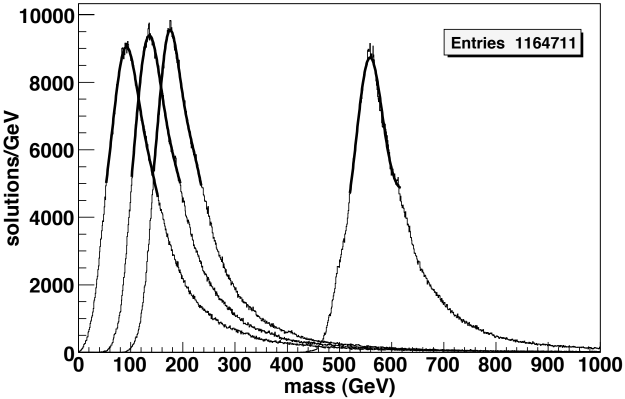
- 12 mass-shell constraints: $k^2 = l^2 = k'^2 = l'^2$,
$(k+p_3)^2 = (l+q_3)^2 = (k'+p'_3)^2 = (l'+q'_3)^2$,
$(k+p_2+p_3)^2 = (l+q_2+q_3)^2 = (k'+p'_2+p'_3)^2 = (l'+q'_2+q'_3)^2$,
$(k+p_1+p_2+p_3)^2 = (l+q_1+q_2+q_3)^2 = (k'+p'_1+p'_2+p'_3)^2$
$= (l'+q'_1+q'_2+q'_3)^2$,

- 4 $\not{\mathbf{p}}_T$-constraints: $\mathbf{k}_T + \mathbf{l}_T = \not{\mathbf{p}}_T$, $\quad \mathbf{k}'_T + \mathbf{l}'_T = \not{\mathbf{p}}'_T$

* 8 (complex) solutions for each event-pair, some of which are real.

* Many wrong solutions from wrong combinatorics.

For given set of event-pairs, number of real solutions shows a peak at the correct masses: Cheng et. al.



Input masses: $(m_{\tilde{q}}, m_{\chi_2}, m_{\tilde{\ell}}, m_{\chi_1}) = (568, 180, 143, 97)$ GeV

Fitted masses: $(562 \pm 4,\ 179 \pm 3,\ 139 \pm 3,\ 94 \pm 3) \quad (\int \mathcal{L} = 300\,\mathrm{fb}^{-1})$

Remarks

- Mass relation method and endpoint method require a long decay chain, at least 3-step chain, to determine the involved new particle masses.

- However, there are many cases (including a large fraction of popular scenarios) that such a long decay chain is not available:

  A simple example: mSUGRA with $m_0^2 > 0.6\,M_{1/2}^2 \;\Rightarrow\; m_{\tilde{\ell}} > m_{\chi_2}$

- SUSY with $m_{\rm sfermion} \gg m_{\rm gaugino}$:

  (Focus point scenario, Loop-split SUSY, Some string moduli-mediation, ...)

* Mass relation method simply can not be applied.

* Endpoint method determines only the gaugino mass differences.

* M_{T2}-kink method can determine the full gaugino mass spectrum.

iii) M_{T2}-Kink Method Cho, Choi, Kim, Park; Barr, Gripaios, Lester

M_{T2} is a generalization of the transverse mass to an event producing two invisible particles with the same mass.

Transverse mass **of** $Y \to V(p) + \chi(k)$:

$$M_T^2 = m_V^2 + m_\chi^2 + 2\sqrt{m_V^2 + |\mathbf{p}_T|^2}\sqrt{m_\chi^2 + |\mathbf{k}_T|^2} - 2\mathbf{p}_T \cdot \mathbf{k}_T$$

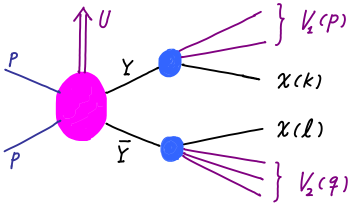
* Invariant Mass: $M^2 = m_V^2 + m_\chi^2 + 2\sqrt{m_V^2 + |\mathbf{p}|^2}\sqrt{m_\chi^2 + |\mathbf{k}|^2} - 2\mathbf{p} \cdot \mathbf{k}$

$$= m_V^2 + m_\chi^2 + 2\sqrt{m_V^2 + |\mathbf{p}_T|^2}\sqrt{m_\chi^2 + |\mathbf{k}_T|^2}\cosh(\eta_V - \eta_\chi) - 2\mathbf{p}_T \cdot \mathbf{k}_T \geq M_T^2$$

One can use an arbitrary trial WIMP mass m_χ to define M_T. (True WIMP mass $= m_\chi^{\rm true}$).

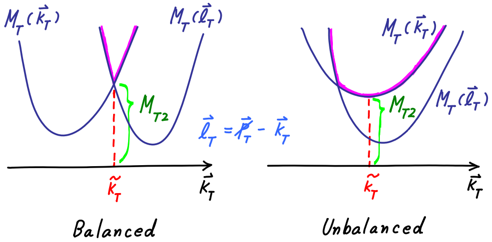
* For each event, M_T is an increasing function of m_χ.
* For all events, $M_T(m_\chi = m_\chi^{\rm true}) \leq m_Y^{\rm true}$ in the zero width limit.

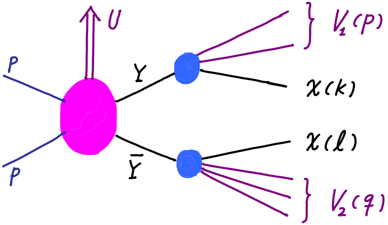
M_{T2} Lester and Summers; Barr, Lester and Stephens



$$M_{T2}(\text{event}; m_\chi) \quad \left(\{\text{event}\} = \{m_{V_1}, \mathbf{p}_T, m_{V_2}, \mathbf{q}_T, \not{\mathbf{p}}_T\}\right)$$

$$= \min_{\mathbf{k}_T + \mathbf{l}_T = \not{\mathbf{p}}_T} \left[\max\Big(M_T(\mathbf{p}_T, m_{V_1}, \mathbf{k}_T, m_\chi), M_T(\mathbf{q}_T, m_{V_2}, \mathbf{l}_T, m_\chi) \Big) \right]$$





$$M_{T2}(\text{event}; m_\chi) \quad \Big(\{\text{event}\} = \{m_{V_1}, \mathbf{p}_T, m_{V_2}, \mathbf{q}_T, \not{\mathbf{p}}_T\}\Big)$$

$$= \min_{\mathbf{k}_T + \mathbf{l}_T = \not{\mathbf{p}}_T} \Big[\max\Big(M_T(\mathbf{p}_T, m_{V_1}, \mathbf{k}_T, m_\chi), M_T(\mathbf{q}_T, m_{V_2}, \mathbf{l}_T, m_\chi)\Big) \Big]$$

$$(\not{\mathbf{p}}_T = -\mathbf{p}_T - \mathbf{q}_T - \mathbf{u}_T)$$

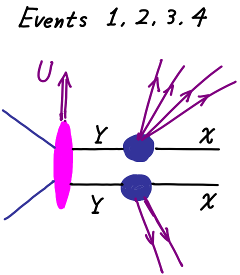
* For each event, M_{T2} is an increasing function of m_χ.
* For all events, $M_{T2}(m_\chi = m_\chi^{\text{true}}) \leq m_Y^{\text{true}}$ in the zero width limit.

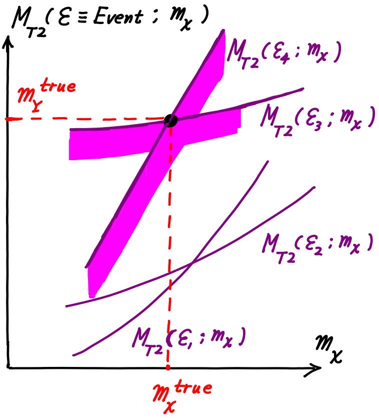
$\mathbf{M_{T2}}$-Kink

If the event set has a certain variety, which is in fact quite generic,

$$M_{T2}^{\max}(m_\chi) = \max_{\{\text{all events}\}} \Big[M_{T2}(\text{event}; m_\chi) \Big]$$

has a kink-structure at $m_\chi = m_\chi^{\text{true}}$ with $M_{T2}^{\max}(m_\chi = m_\chi^{\text{true}}) = m_Y^{\text{true}}$.





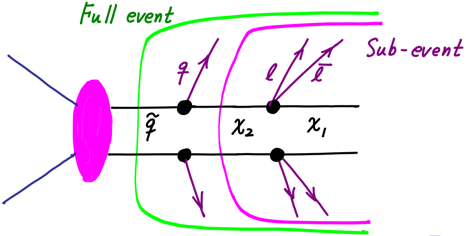
Kink (due to different slopes) appears if

- The visible decay products of $Y \to V + \chi$ have a sizable range of invariant mass m_V, which would be the case if V is a multi-particle state. Cho, Choi, Kim, Park

- There are events with a sizable range of upstream transverse momentum $\mathbf{u}_T$, which would the case if Y is produced with a sizable ISR or produced through the decay of heavier particle. Gripaios

* **Kink is a fixed point (or a point of enhanced symmetry) at $m_\chi = m_\chi^{\rm true}$ under the variation of m_V and $\mathbf{u}_T$.**

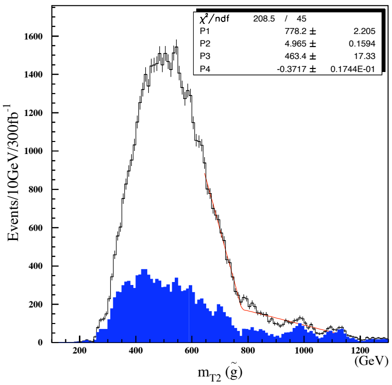
* **For cascade decays, M_{T2}-kink method can be applied to various sub-events:**

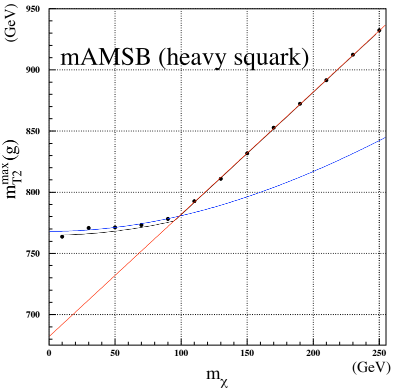


Gluino M_{T2}-Kink in heavy sfermion scenario

Cho, Choi, Kim, Park

M_{T2} of hard 4-jets (no b, no ℓ) which are mostly generated by the gluino-pair 3-body decay: $\tilde{g}\tilde{g} \to q\bar{q}\chi q\bar{q}\chi$, where $m_{\tilde{g}} \lesssim 1$ TeV and $m_{\tilde{q}} \sim$ few TeV.





Input masses: $(m_{\tilde{g}},\, m_{\chi_1}) = (780\,\text{GeV},\;\; 98\,\text{GeV})$ (Wino-like χ_1)

Fitted masses: $(776 \pm \text{few},\; 97 \pm \text{few}))$ $(\int \mathcal{L} = 300\,\text{fb}^{-1})$

Kink itself is quite generic, but often it might not be sharp enough to be visible in the real analysis.

Related methods which might be useful:

- Number of real solutions for M_{T2}-assisted on-shell (MAOS) momenta, which is expressed as a function of m_χ, might show a sharper kink at $m_\chi = m_\chi^{\text{true}}$. Cheng and Han; arXiv:0810.5178

- M_{T2}-kink is a fixed point under $\partial/\partial m_V$, $\partial/\partial u_T$:

$$\Longrightarrow \quad \left(\frac{\partial}{\partial m_V}, \frac{\partial}{\partial u_T}\right) \left\{ M_{T2}^{\max}(m_\chi^{\text{trial}} = 0),\ M_{CT}^{\max},\ ... \right\}$$

can provide information which would allow mass determination in the absence of long decay chain. Torvey: arXiv:0802.2879
Konar, Kong, Matchev and Park: arXiv:0910.3679

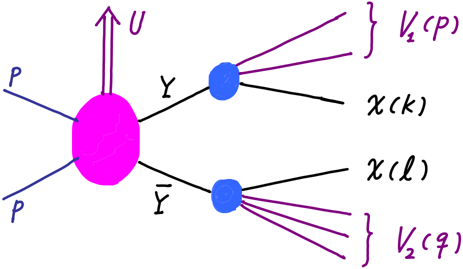
- Algebraic singularity method: I.W.Kim: arXiv:0910.1149

More general and systematic method to find a variable (= singularity coordinate) most sensitive to the singularity structure providing information on the unknown masses in missing energy events.

M_{T2}-Assisted-On-Shell (MAOS) Momentum

arXiv:0810.4853[hep-ph]; arXiv:0908.0079[hep-ph]

MAOS momentum is a collider event variable designed to approximate systematically the invisible particle momentum for an event set producing two invisible particles with the same mass.



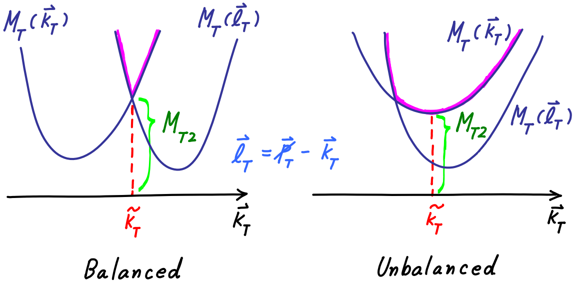
Construction of the MAOS WIMP momenta $\mathbf{k}_\mu^{\rm maos}$ and $\mathbf{l}_\mu^{\rm maos}$

i) Choose appropriate trial WIMP and mother particle masses: m_χ, m_Y.

ii) Determine the transverse MAOS momenta with M_{T2}:

$$M_{T2} = M_T(p^2, \mathbf{p}_T, m_\chi, \mathbf{k}_T^{\rm maos}) \geq M_T(q^2, \mathbf{q}_T, m_\chi, \mathbf{l}_T^{\rm maos})$$
$$\left(\not{\mathbf{p}}_T = \mathbf{k}_T^{\rm maos} + \mathbf{l}_T^{\rm maos} \right)$$

* M_{T2} selects unique $\mathbf{k}_T^{\rm maos}$ and $\mathbf{l}_T^{\rm maos}$:



iii) Two possible schemes for the longitudinal and energy components:

$$Y(p+k)\,\bar{Y}(q+l) \;\rightarrow\; V_1(p) + \chi(k) + V_2(q) + \chi(l)$$

Scheme 1:

$$k_{\text{maos}}^2 = l_{\text{maos}}^2 = m_\chi^2, \quad (k_{\text{maos}} + p)^2 = (l_{\text{maos}} + q)^2 = m_Y^2$$

Scheme 2:

$$k_{\text{maos}}^2 = l_{\text{maos}}^2 = m_\chi^2, \quad \frac{k_z^{\text{maos}}}{k_0^{\text{maos}}} = \frac{p_z}{p_0}, \quad \frac{l_z^{\text{maos}}}{l_0^{\text{maos}}} = \frac{q_z^{\text{maos}}}{q_0^{\text{maos}}}$$

(Scheme 2 can work even when $Y + \bar{Y}$ are in off-shell.)

The MAOS constructions are designed to have $\mathbf{k}_{\text{maos}}^\mu = \mathbf{k}_{\text{true}}^\mu$ for the M_{T2} endpoint events when $m_\chi = m_\chi^{\text{true}}$ and $m_Y = m_Y^{\text{true}}$.

$\Longrightarrow$ **One can systematically reduce $\Delta\mathbf{k}/\mathbf{k} \equiv (\mathbf{k}_{\text{maos}}^\mu - \mathbf{k}_{\text{true}}^\mu)/\mathbf{k}_{\text{true}}^\mu$ with an M_{T2}-cut selecting the near endpoint events.**

- For each event, MAOS momenta obtained in the scheme 1 are real iff $m_Y \geq M_{T2}(\text{event}; m_\chi)$.

$\Longrightarrow$ MAOS momenta are real for all events if

$$m_Y \geq M_{T2}^{\max}(m_\chi) \equiv \max_{\{\text{events}\}} \Big[M_{T2}(\text{event}; m_\chi) \Big] \quad \left(m_Y^{\text{true}} = M_{T2}^{\max}(m_\chi^{\text{true}}) \right)$$

* If m_χ^{true} and m_Y^{true} are known, use $m_\chi = m_\chi^{\text{true}}$ and $m_Y = m_Y^{\text{true}}$.

* Unless, one can use $m_\chi = 0$ and $m_Y = M_{T2}^{\max}(0)$.

- Precise knowledge of m_χ^{true} and m_Y^{true} might not be essential if $(m_\chi^{\text{true}}/m_Y^{\text{true}})^2 \ll 1$:

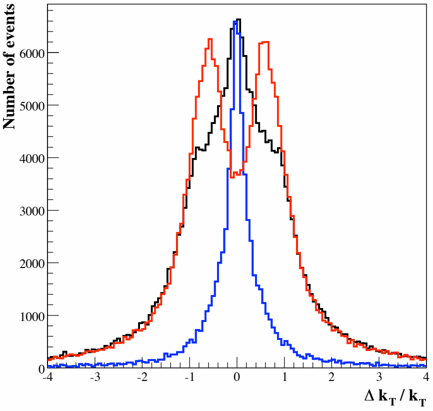
$$\left(\frac{\Delta \mathbf{k}}{\mathbf{k}}\right)_{m_\chi^{\text{true}},\, m_Y^{\text{true}}} - \left(\frac{\Delta \mathbf{k}}{\mathbf{k}}\right)_{m_Y = M_{T2}^{\max}(0)} = \mathcal{O}\left(\left(\frac{m_\chi^{\text{true}}}{m_Y^{\text{true}}}\right)^2\right),$$

$$\frac{\Delta \mathbf{k_T}}{\mathbf{k_T}} = \frac{\tilde{\mathbf{k}}_\mathbf{T} - \mathbf{k}_\mathbf{T}^{\rm true}}{\mathbf{k}_\mathbf{T}^{\rm true}}$$ **distribution for** $\tilde{q}\tilde{q}^* \to q\chi\bar{q}\chi$:

$\tilde{\mathbf{k}}_\mathbf{T} = \frac{1}{2}\not{\mathbf{p}}_\mathbf{T} \quad (\tilde{\mathbf{k}}_\mathbf{T} + \tilde{\mathbf{l}}_\mathbf{T} = \not{\mathbf{p}}_\mathbf{T})$

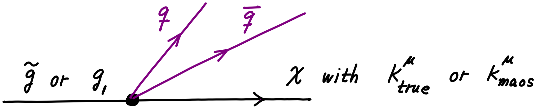
$\tilde{\mathbf{k}}_\mathbf{T} = \mathbf{k}_\mathbf{T}^{\rm maos}$ for full events

$\tilde{\mathbf{k}}_\mathbf{T} = \mathbf{k}_\mathbf{T}^{\rm maos}$ for the top 10 % of near endpoint events



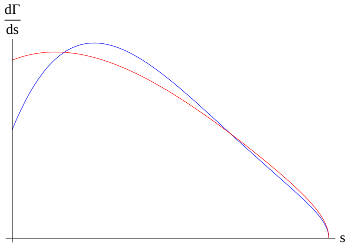
MAOS Momentum and Spin Measurement

Example 1: Gluino/KK-gluon 3-body decay for SPS2 point and its UED equivalent:



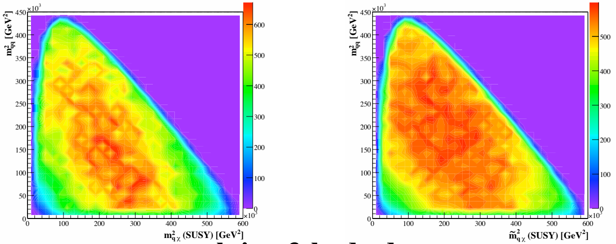
$$\mathbf{s} = (p_q + p_{\bar{q}})^2, \quad \mathbf{t}_{\text{true}} = (p_{q(\bar{q})} + k_{\text{true}})^2, \quad \mathbf{t}_{\text{maos}} = (p_{q(\bar{q})} + k^{\pm}_{\text{maos}})^2$$

Without $\mathbf{k}^{\mu}_{\text{maos}}$, one may consider **the s-distribution** to distinguish **gluino** from **KK-gluon**: Csaki, Heinonen, Perelstein

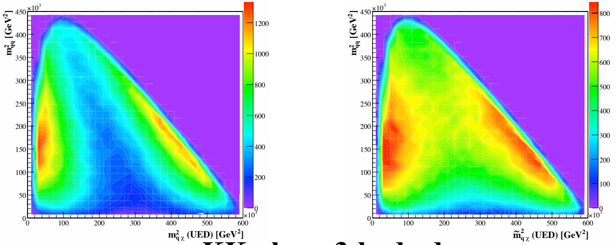


With $k^{\mu}_{\rm maos}$ (scheme 1), one can use **the s-t$_{\rm maos}$ distribution** clearly distinguishing the gluino from the KK-gluon: arXiv:0810.4853[hep-ph]

$$\frac{d\Gamma}{ds\,d\mathbf{t}_{\rm true}} \qquad \frac{d\Gamma}{ds\,d\mathbf{t}_{\rm maos}} \quad (\text{no } M_{T2} \text{ cut})$$



gluino 3-body decay



KK-gluon 3-body decay

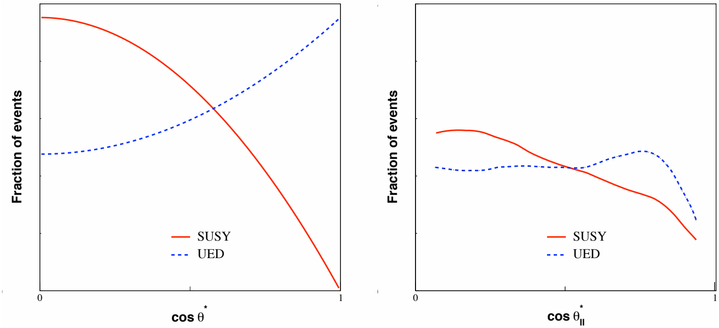
Example 2: Drell-Yan pair production of **slepton** or **KK-lepton** for SUSY SPS1a point and its UED equivalent: Barr

$$\frac{d\Gamma}{d\cos\theta_Y} \text{ and } \frac{d\Gamma}{d\cos\theta_\ell} \quad \text{of} \quad q\bar{q} \to Z^0/\gamma \to Y\bar{Y} \to \ell\chi\bar{\ell}\chi$$

$Y =$ slepton or KK-lepton, $\quad \chi =$ LSP or KK-photon,

$\cos\theta_Y = \hat{p}_Y \cdot \hat{p}_{\text{beam}}$ in the CM frame of $Y\bar{Y}$,

$\cos\theta_\ell = \hat{p}_\ell \cdot \hat{p}_{\text{beam}}$ in the CR(rapidity) frame of $\ell\bar{\ell}$



Without MAOS, one may look at the lepton angle ($\cos\theta_\ell$) distribution to distinguish the slepton pair production from the KK-lepton pair production: Barr

With MAOS momentum (scheme 1), the mother particle production angle ($\cos\theta_Y$) can be reconstructed: Cho, Choi, Kim, Park

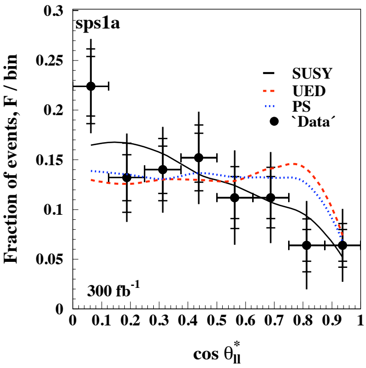
$$Y(p+k^{\pm}_{\rm maos})\bar{Y}(q+l^{\pm}_{\rm maos}) \rightarrow \ell(p)\chi(k^{\pm}_{\rm maos})\bar{\ell}(q)\chi(l^{\pm}_{\rm maos})$$

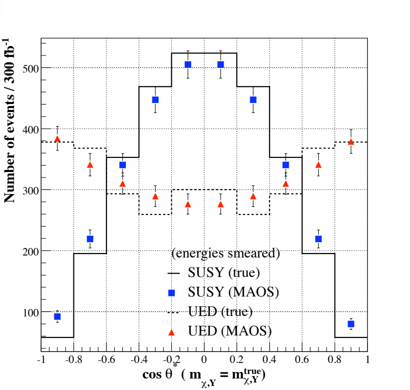
$$\frac{d\Gamma}{d\cos\theta_Y^{\rm maos}} \equiv \sum_{\alpha=\pm,}\sum_{\beta=\pm}\frac{d\Gamma}{d\cos\theta_{\alpha\beta}}$$

$$(\cos\theta_{\pm\pm} = \hat{p}_Y\cdot\hat{p}_{\rm beam} \text{ for } k^{\pm}_{\rm maos} \text{ and } l^{\pm}_{\rm maos})$$

$$\frac{d\Gamma}{d\cos\theta_\ell} \quad \text{vs} \quad \frac{d\Gamma}{d\cos\theta_Y^{\rm maos}}$$

with appropriate event cut ($\ni$ the M_{T2}-cut selecting the top 30 %) while including the detector smearing effect for SUSY SPS1a and its UED equivalent: (Knowledge of the mass is not essential.)





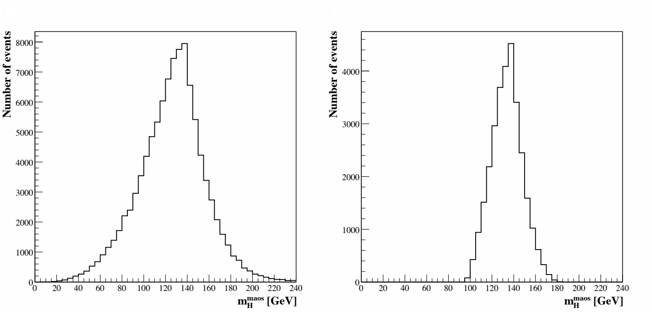
MAOS Momentum and Higgs Mass Measurement

arXiv:0908.0079[hep-ph]

$$H \to W\, W \to \ell(p)\, \nu(k)\, \ell(q)\, \nu(l)$$

Use the scheme 2 which approximates well the neutrino momenta even when W-bosons are in off-shell.

$$m_H^{\text{maos}} = (p + q + k^{\text{maos}} + l^{\text{maos}})^2$$



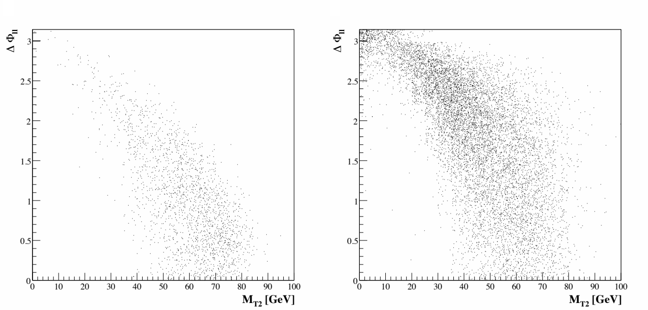
full event **top 30%**

($m_H = 140$ GeV)

Correlation between $\Delta\Phi_{ll} = \frac{\mathbf{p}_T \cdot \mathbf{q}_T}{|\mathbf{p}_T||\mathbf{q}_T|}$ and M_{T2}:

In the limit of vanishing ISR, $M_{T2}^2 = 2|\mathbf{p}_T||\mathbf{q}_T|\left(1 + \cos\Delta\Phi_{ll}\right)$

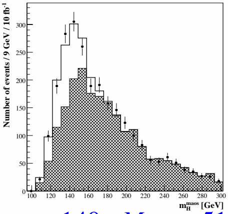
Even with ISR, such correlation persists:



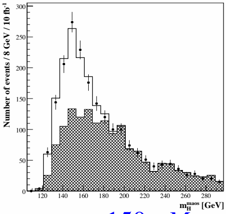
$H \to WW \to \ell\nu\ell\nu$ $\qquad$ $q\bar{q} \to WW \to \ell\nu\ell\nu$

Using $\Delta\Phi_{ll}$ and M_{T2} for the event selection, both the signal to background ratio and the efficiency of the MAOS approximation can be enhanced together.

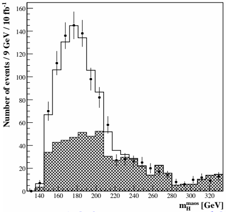
- Event generation with PYTHIA6.4 with $\int L\,dt = 10\ \mathrm{fb}^{-1}$
- Detector simulation with PGS4
- Include $q\bar{q}, gg \to WW$ and $t\bar{t}$ backgrounds
- Event selection including the optimal cut of M_{T2} and $\Delta\Phi_{ll}$



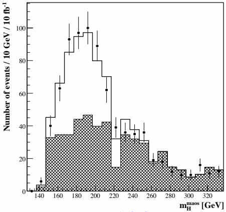
$m_H = 140,\ M_{T2} > 51$



$m_H = 150,\ M_{T2} > 57$

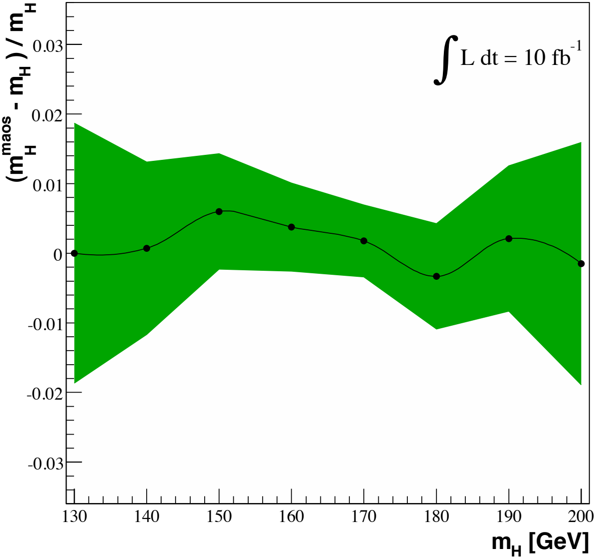


$m_H = 180,\ M_{T2} > 68$



$m_H = 190,\ M_{T2} > 70$

1-σ error of m_H from the likelihood fit to the m_H^{maos} distribution



Summary

- M_{T2}-kink method (or related methods) might be able to determine new particle masses with missing energy events, even when a long decay chain is not available.
- MAOS momenta provide a systematic approximation to the invisible particle momenta in missing energy events, which can be useful for a spin measurement of new particle.
- MAOS momenta can be useful also for some SM processes with two missing neutrinos, particularly for probing the properties of the Higgs boson and top quark with

  * $H \to W^+W^- \to \ell^+\nu\ell\bar{\nu}$,
  * $t\bar{t} \to bW^+\bar{b}W^- \to b\ell^+\nu\bar{b}\ell\bar{\nu}$.