

# MAOS Momentum: A New Collider Variable for Mass and Spin Measurements

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arXiv:0810.4853 [hep-ph];

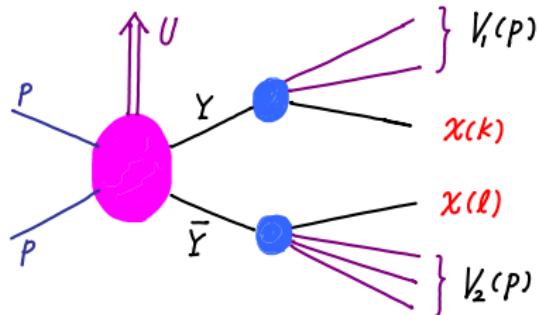
K. Choi, S. Choi, J.S. Lee, C.B. Park,  
arXiv:0908.0079 [hep-ph]

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SM and BSM Physics at the LHC, CERN, August 2009

## Mass and spin measurements with two invisible particles

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



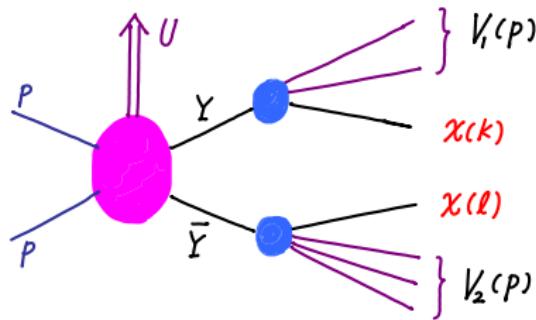
(  $V_{1,2}$  = visible particles,     $\chi$  = invisible particle )

- New physics events with dark matter particle  $\chi$ :  
SUSY with  $R_P$ , UED with  $KK_P$ , Little Higgs with  $T_P$ , ...
- Some SM processes:  
 $H \rightarrow W W \rightarrow \ell \bar{\nu} \bar{\ell} \nu$ ,    $t \bar{t} \rightarrow b W^+ \bar{b} W^- \rightarrow b \bar{\ell} \nu \bar{b} \ell \bar{\nu}$

## M<sub>T2</sub>-Assisted-On-Shell (MAOS) Momentum:

A systematic approximation to the invisible particle momenta in an event involving two invisible particles

- M<sub>T2</sub>: Lester and Summers

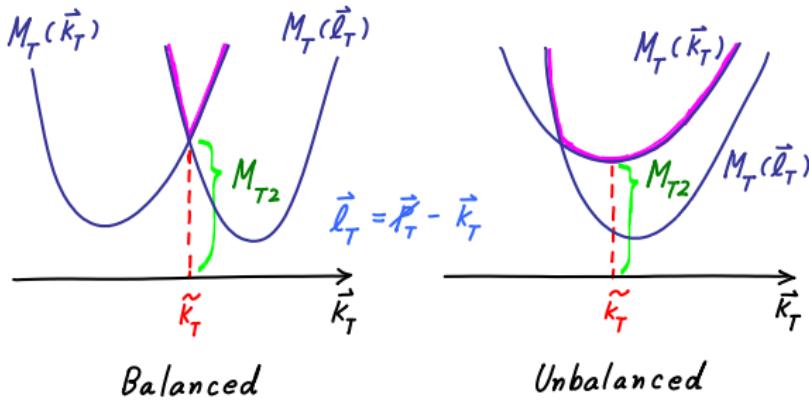


$$M_{T2}(m_{V_1}, \mathbf{p}_T, m_{V_2}, \mathbf{q}_T, \not{\mathbf{p}}_T; m_\chi) = \min_{\mathbf{k}_T + \mathbf{l}_T = \not{\mathbf{p}}_T} \left[ \max \left( M_T(m_{V_1}, \mathbf{p}_T, m_\chi, \mathbf{k}_T), M_T(m_{V_2}, \mathbf{q}_T, m_\chi, \mathbf{l}_T) \right) \right]$$

- Transverse MAOS momenta:

$$M_{T2} = M_T(p^2, \mathbf{p}_T, m_\chi, \mathbf{k}_T^{\text{maos}}) \geq M_T(q^2, \mathbf{q}_T, m_\chi, \mathbf{l}_T^{\text{maos}})$$

$$\left( \mathbf{p}'_T = \mathbf{k}_T^{\text{maos}} + \mathbf{l}_T^{\text{maos}} \right)$$



- **Longitudinal and Energy Components:**

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

### 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:

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

\* If  $m_\chi$  and  $m_Y$  are unknown, one can simply use

$$m_\chi = 0, \quad m_Y = M_{T2}^{\max}(m_\chi = 0),$$

which still provides a good approximation when  $m_\chi^2/m_Y^2 \ll 1$ .

\* Scheme 2 works well even when the intermediate particles ( $Y, \bar{Y}$ ) are in off-shell, e.g.  $H \rightarrow W W \rightarrow \ell \nu \ell \nu$  for  $m_H < 2M_W$ .

**Efficiency of the MAOS approximation:**  $\frac{\Delta \mathbf{k}}{\mathbf{k}} \equiv \frac{k_{\text{maos}}^\mu - k_{\text{true}}^\mu}{k_{\text{true}}^\mu}$

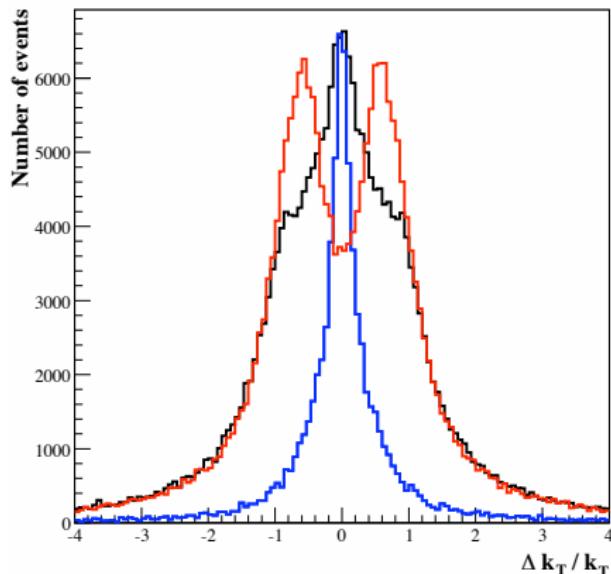
- $k_{\text{maos}}^\mu = k_{\text{true}}^\mu$  for the endpoint events with  $M_{T2} = M_{T2}^{\max}$ , when constructed with correct  $m_\chi$  and  $m_Y$ .
- In most cases, a significant fraction of events are near the  $M_{T2}$  endpoint, so even for generic event the MAOS momenta provide a reasonably good approximation to the true invisible momenta.
- For unknown  $m_\chi$  and  $m_Y$ , the MAOS momenta constructed with  $m_\chi = 0$  and  $m_Y = M_{T2}^{\max}(m_\chi = 0)$  can be good enough to distinguish different spin correlations, if the true masses satisfy  $m_\chi^2/m_Y^2 \ll 1$ .
- MAOS approximation can be systematically improved by selecting the near endpoint events of  $M_{T2}$ .

$$\frac{\Delta \mathbf{k}_T}{\mathbf{k}_T} = \frac{\tilde{\mathbf{k}}_T - \mathbf{k}_T^{\text{true}}}{\mathbf{k}_T^{\text{true}}} \text{ distribution for } \tilde{q}\tilde{q}^* \rightarrow q\chi\bar{q}\chi :$$

$$\tilde{\mathbf{k}}_T = \frac{1}{2}\mathbf{p}_T \quad (\tilde{\mathbf{k}}_T + \tilde{\mathbf{l}}_T = \mathbf{p}_T)$$

$\tilde{\mathbf{k}}_T = \mathbf{k}_T^{\text{maos}}$  for the full events

$\tilde{\mathbf{k}}_T = \mathbf{k}_T^{\text{maos}}$  for the top 10% of the near-endpoint events of  $M_{T2}$

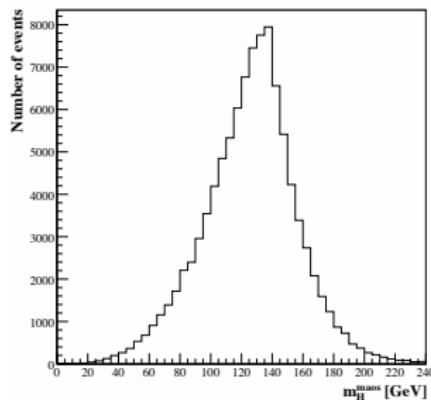


# Higgs mass determination: arXiv:0908.0079[hep-ph]

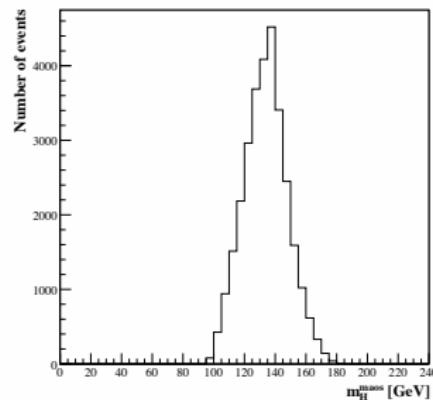
$$H \rightarrow WW \rightarrow \ell(p) \nu(k) \ell(q) \nu(l)$$

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**  
 $(m_H = 140 \text{ GeV})$

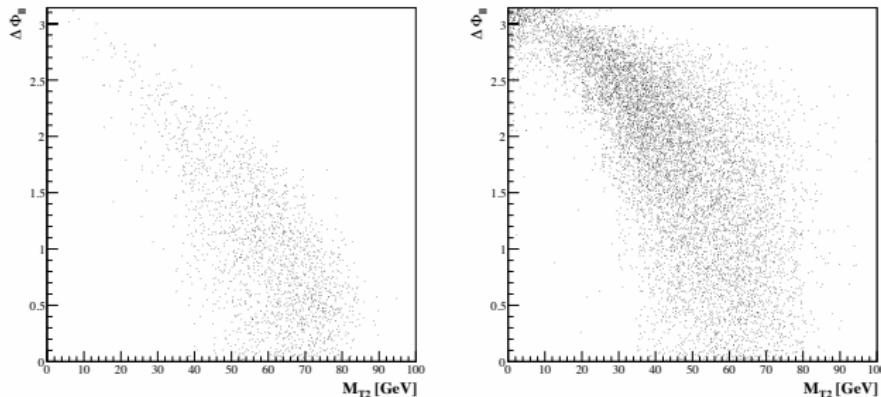


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## Correlation between $\Delta\Phi_{ll} = \frac{\mathbf{p}_T \cdot \mathbf{q}_T}{|\mathbf{p}_T| |\mathbf{q}_T|}$ and $M_{T2}$ :

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

Even with ISR, such correlation persists:

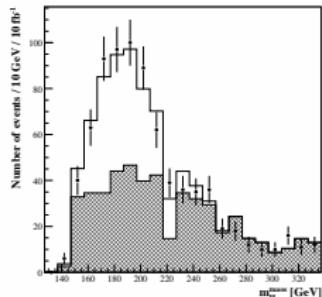
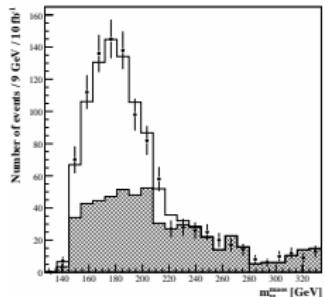
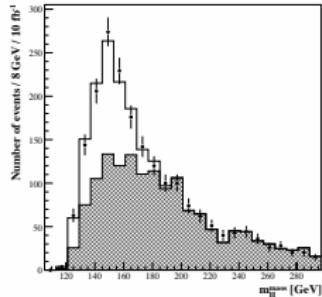
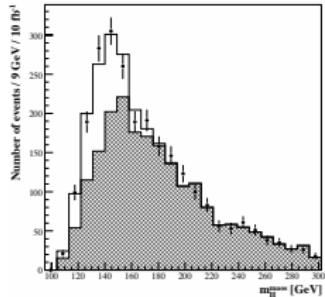


$$H \rightarrow WW \rightarrow \ell\nu\ell\nu$$

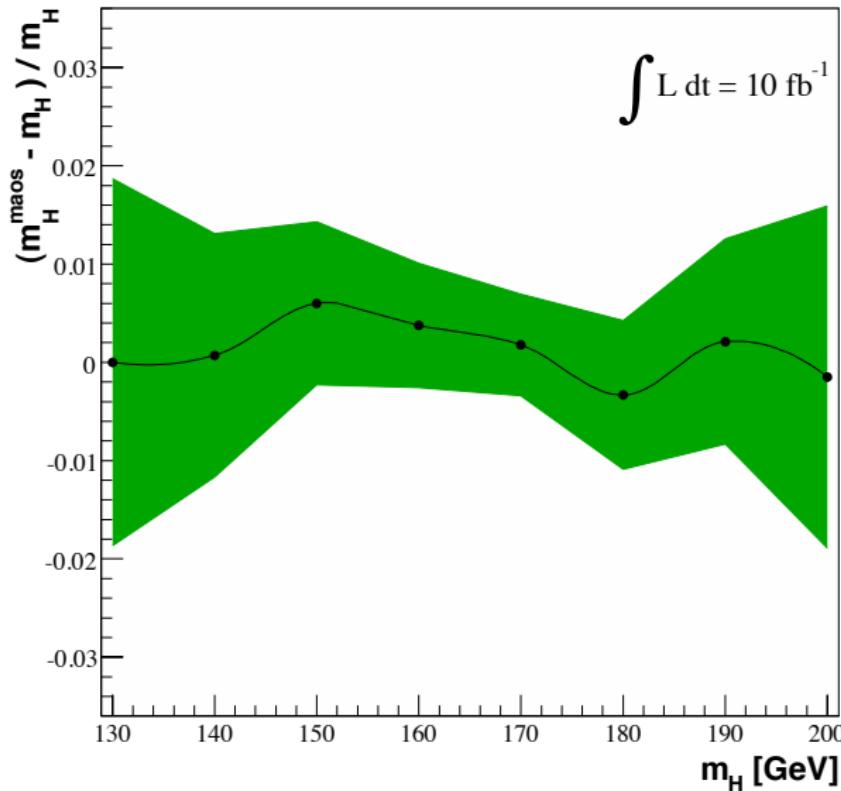
$$q\bar{q} \rightarrow WW \rightarrow \ell\nu\ell\nu$$

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



$1-\sigma$  error of  $m_H$  from the likelihood fit to the  $m_H^{\text{maos}}$  distribution



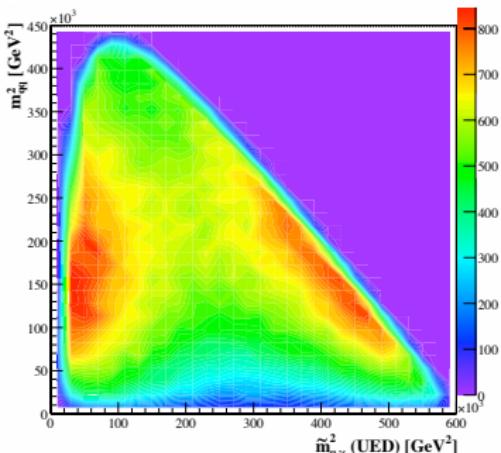
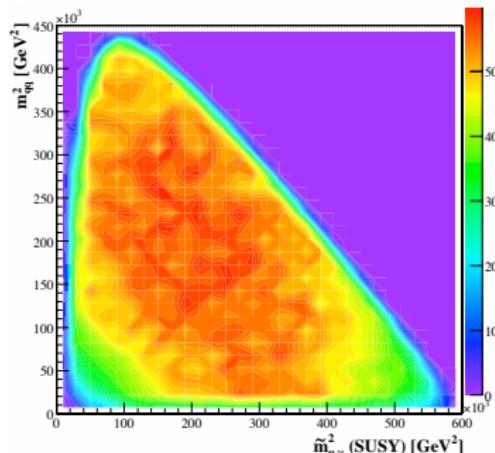
3-body decay of gluino ( $\tilde{g}$ ) or KK gluon ( $g_{KK}$ ):

$$\tilde{g} \rightarrow q(p_1)\bar{q}(p_2)\chi(k), \quad g_{KK} \rightarrow q(p_1)\bar{q}(p_2)\gamma_{KK}(k)$$

$$s = (p_1 + p_2)^2, \quad t_{\text{maos}} = (p_1 + k_{\text{maos}})^2 \text{ or } (p_2 + k_{\text{maos}})^2$$

$$\left( \frac{d\Gamma}{ds dt_{\text{maos}}} \right)_{\text{gluino}}$$

$$\left( \frac{d\Gamma}{ds dt_{\text{maos}}} \right)_{\text{KKgluon}}$$

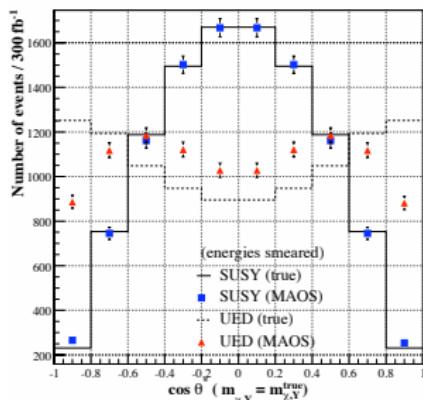


Drell-Yan pair production of slepton ( $\tilde{\ell}$ ) or KK-lepton ( $\ell_{KK}$ )

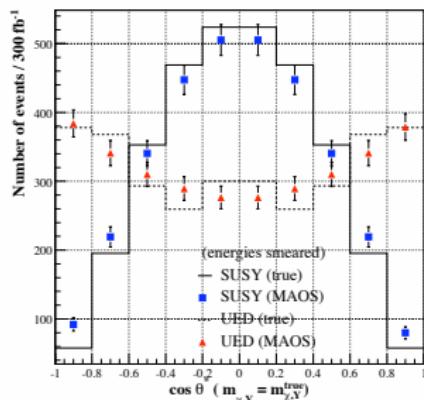
$$q\bar{q} \rightarrow Z^0/\gamma \rightarrow Y(p+k) \bar{Y}(q+l) \rightarrow \ell(p) X(k) \bar{\ell}(q) X(k)$$

$$(Y = \tilde{\ell} \text{ or } \ell_{KK}, \quad X = \chi \text{ or } \gamma_{KK})$$

**MAOS angle distribution:**  $\cos \theta_{\text{maos}} = \frac{(\mathbf{p} + \mathbf{k}_{\text{maos}}) \cdot \mathbf{p}_{\text{beam}}}{|\mathbf{p} + \mathbf{k}_{\text{maos}}| |\mathbf{p}_{\text{beam}}|}$



full event



top 30%