Making the Most of MET

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(now in LAPTh)

1301.0345 & Phys.Rev. D

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Prelude

Q: How can we discover X in

$$\begin{array}{c}\text{incoming particles} \\ \downarrow \\ \text{whatever} + X \\ \downarrow \\ \text{whatever} + 1 + 2 + \ldots + i + \ldots \quad ?\end{array}$$

A: $\mathrm{mass}(\sum_{\mathrm{i}} \mathrm{p}_{\mathrm{i}}^{\mu})$

Missing Momenta

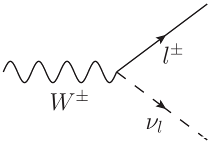
One or two invisible particles χ leaving the detector:

	lepton collider	hadron collider
1χ	3 unknowns: $\mathbf{p}_\chi$ 3 measurements: $\not{\mathbf{p}}$	3 unknowns: $\mathbf{p}_\chi$ 2 measurements: $\not{\mathbf{p}}_T$
2χ	6 unknowns: $\mathbf{p}_{\chi_a}, \mathbf{p}_{\chi_b}$ 3 measurements: $\not{\mathbf{p}}$	6 unknowns: $\mathbf{p}_{\chi_a}, \mathbf{p}_{\chi_b}$ 2 measurements: $\not{\mathbf{p}}_T$

(assuming m_χ is known).

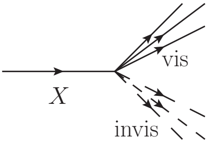
2χ at hadron colliders – e.g. $\mathbb{Z}_2$-symmetric dark matter at the LHC.

One Decaying Particle At A *Hadron* Collider: m_T



$$
\begin{aligned}
m_W^2 &= (E_l + E_\nu)^2 - (\mathbf{p}_l + \mathbf{p}_\nu)^2 \\
&= m_l^2 + m_\nu^2 + 2(E_{T,l}E_{T,\nu}\cosh(\Delta y_{l\nu}) - \mathbf{p}_{T,l}\cdot\mathbf{p}_{T,\nu}) \\
m_T^2 &\equiv (E_{T,l} + E_{T,\nu})^2 - (\mathbf{p}_{T,l} + \mathbf{p}_{T,\nu})^2 \\
&= m_l^2 + m_\nu^2 + 2(E_{T,l}E_{T,\nu} \qquad\qquad - \mathbf{p}_{T,l}\cdot\mathbf{p}_{T,\nu})
\end{aligned}
$$

$$\therefore\ m_T \le m_W$$

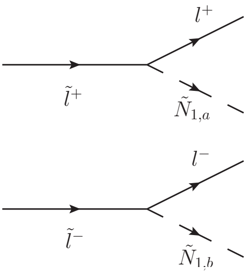


$$m_T^2 \equiv (E_{T,\text{vis}} + E_{T,\text{invis}})^2 - (\mathbf{p}_{T,\text{vis}} + \mathbf{p}_{T,\text{invis}})^2$$

$$\therefore\ m_T \le m_X$$

* *must approximate* $m_{\text{invis}} \approx 0$

Two Decaying Particles At A *Hadron* Collider: M_{T2}



$$\max\{\mathrm{m}_\mathrm{T}^2(\mathbf{p}_{\mathrm{T},\mathrm{l}^+}, \mathbf{p}_{\mathrm{T},\tilde{\mathrm{N}}_{1,\mathrm{a}}}), \\ m_T^2(\mathbf{p}_{T,l^-}, \mathbf{p}_{T,\tilde{N}_{1,b}})\} \leq m_{\tilde{l}}^2,$$

but we don't know the decomposition

$$\not{\mathbf{p}}_T = \mathbf{p}_{T,\tilde{N}_{1,a}} + \mathbf{p}_{T,\tilde{N}_{1,a}}$$

$\implies$ try all decompositions & take the most conservative:

$$M_{T2}^2 \equiv \min_{\not{\mathbf{p}}_1 + \not{\mathbf{p}}_2 = \not{\mathbf{p}}_T} \left(\max\{\mathrm{m}_\mathrm{T}^2(\mathbf{p}_{\mathrm{T},\mathrm{l}^+}, \not{\mathbf{p}}_1), \mathrm{m}_\mathrm{T}^2(\mathbf{p}_{\mathrm{T},\mathrm{l}^-}, \not{\mathbf{p}}_2)\} \right) \leq m_{\tilde{l}}^2$$

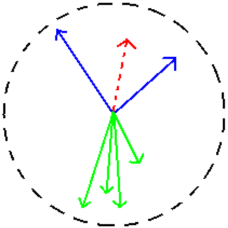
9906349 Lester, Summers

The Massless Collinear Approximation

Aim for $\mathrm{mass}(\sum_\mathrm{i} \mathrm{p}_\mathrm{i}^\mu)$.
To constrain the kinematics we must have a prejudice about the directions of χ_a and χ_b.
e.g. both are parallel to visible particles, due to boosted decays.

$\rightarrow$

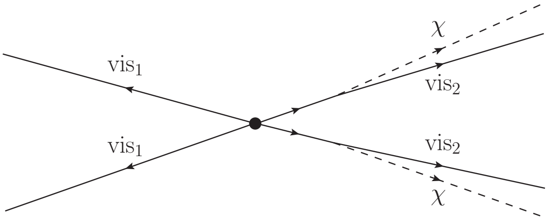
- unique decomposition $\not{\mathbf{p}}_T = \mathbf{p}_{T,\chi_a} + \mathbf{p}_{T,\chi_b}$
- unique $p_{z,\chi_a},\ p_{z,\chi_b}$
- if χ is 'light', set $m_\chi = 0$



In the transverse plane:
$\not{\mathbf{p}}_T$ (which is $\mathbf{p}_{T,\chi_a} + \mathbf{p}_{T,\chi_b}$)
Two visible particles $\parallel$ to χ_a and χ_b
Other stuff

c.f. $H \rightarrow \tau\tau$ by Ellis, Hinchliffe, Soldate, Van Der Bij '88

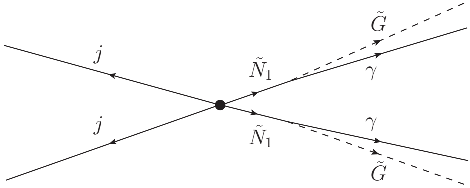
A Pair Of Boosted Semi-invisible Decays



e.g. $2\tilde{q} \to 2q + 2\tilde{N}_1$; $\tilde{N}_1$ could decay to

- a gravitino $\tilde{G}$ — *1110.6444 Kats, Meade, Reece, Shih*
- a pseudo-goldstino $\tilde{G}'$ — *1002.1967 Cheung, Nomura, Thaler, 1112.5058 Argurio et al*
- a singlino $\tilde{S}$ — *e.g. 1202.5244 Das, Ellwanger, Teixeira*
- a new photino' $\tilde{\gamma}'$ — *e.g. 1206.0751 Baryakhtar, Craig, Van Tilburg*

e.g. Gauge Mediation $\tilde{N}_1 \to \gamma + \tilde{G}$



Aforementioned steps reconstruct (massless) $p^{\mu}_{\tilde{N}_{1;a,b}}$.

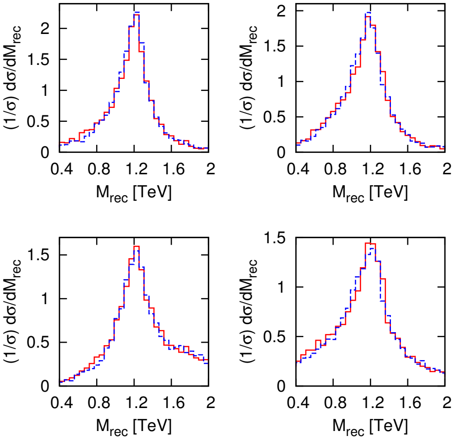
How to pair $\tilde{N}_{1,a}, \tilde{N}_{1,b}$ with the 'correct' j_a, j_b?

criterion α: $-\left(\mathbf{p}_{\tilde{N}_{1,a}}.\mathbf{p}_{j_a} + \mathbf{p}_{\tilde{N}_{1,b}}.\mathbf{p}_{j_b}\right)$ maximal

criterion β: $\left|(p^{\mu}_{\tilde{N}_{1,a}} + p^{\mu}_{j_a})^2 - (p^{\mu}_{\tilde{N}_{1,b}} + p^{\mu}_{j_b})^2\right|$ minimal

Mass Reconstruction

$$M^2_{\mathrm{rec};a,b} = (p^\mu_{\tilde{N}_{1;a,b}} + p^\mu_{j_{a,b}})^2$$



$$pp \to 2\tilde{q} \to$$
$$2q + 2(\tilde{N}_1) \to$$
$$2q + 2(\tilde{G} + \gamma)$$

Herwig++,

MadGraph-PYTHIA-PGS

$$m_{\tilde{q}} = 1.2 \text{ TeV}$$
$$m_{\tilde{N}_1} = 100 \text{ GeV}$$
$$m_{\tilde{G}} = 1 \text{ eV}$$

Accuracy

$$\begin{array}{ccccccc} & \nearrow & \text{sample of 100} & \to & \text{one } M \text{ value} & \searrow & \\ \text{many signal events} & \to & \text{sample of 100} & \to & \text{one } M \text{ value} & \to & P(M)dM \\ & \searrow & \text{sample of 100} & \to & \text{one } M \text{ value} & \nearrow & \\ & & \vdots & & \vdots & & \end{array}$$

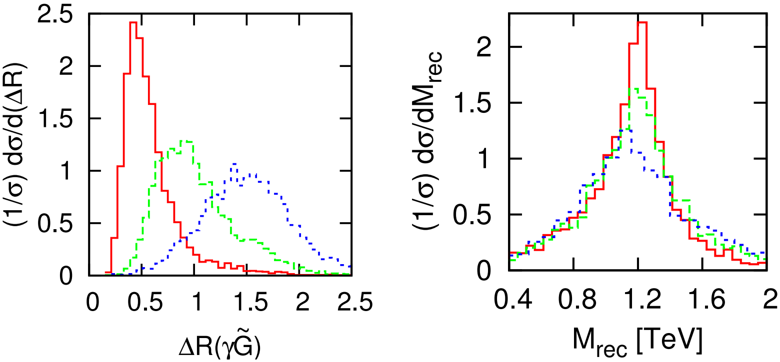
$$\Longrightarrow \text{ root-mean-square}(M - M_{\rm true}) = \mathbf{5\%}\ M_{\rm true}$$

from 100 events

c.f. (with large pinch of salt!) ATLAS Technical Design Report, squark mass from kinks:

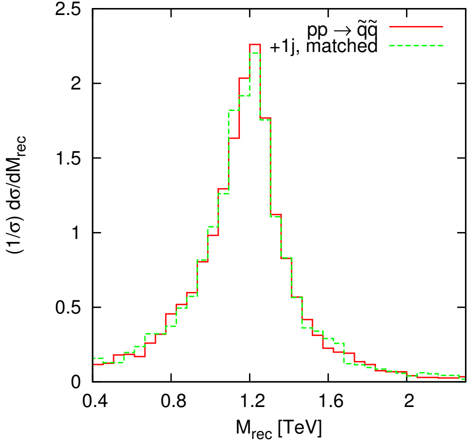
3% after one **million** signal events

Dependence On Boostedness



$m_{\tilde{q}} = 1.2$ TeV, $\quad m_{\tilde{N}_1} = 100, 200, 400$ GeV

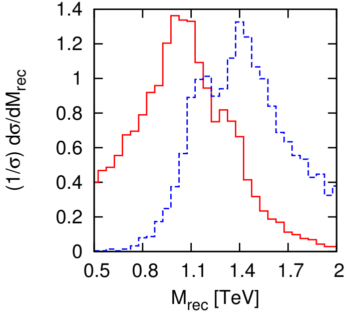
Additional Radiation

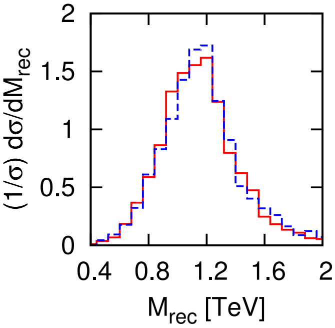


Comparison of $pp \to \tilde{q}\tilde{q}$
with $pp \to \tilde{q}\tilde{q}(+1j)$, MLM matched*

*0706.2569 Mangano *et al.*

Non-degenerate Squarks; Gluinos





$m_{\tilde{q}} = 1.1, 1.4$ TeV

smaller mass,

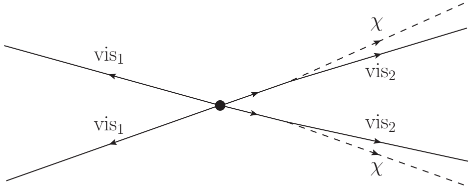
larger mass

$m_{\tilde{g}} = 1.2$ TeV

Herwig++,

MG5-PYTHIA-PGS

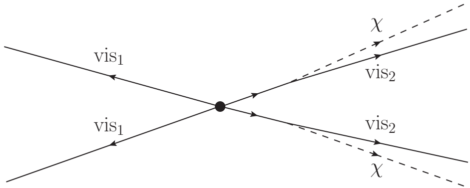
Other Generalisations



- vis_1 = more than one particle,
- vis_2 = more than one particle,
- $\mathrm{vis}_1 = \mathrm{vis}_2$,
- 3χ,

see 1301.0345.

Wish List



Theorists: see if your model has boosted semi-invisible decays, tell experimentalists these final states are motivated.

Experimentalists: search for resonances thusly in any clean final state – $\mathrm{vis}_{1,2} = \mathrm{l}, \gamma, \mathrm{j};\ \mathrm{vis}_{1,2} \neq \mathrm{b}, \mathrm{t}$? Unexpected bumps?

`PGS`/HepMC output $\rightarrow$ peak-finding code at
`www.ippp.dur.ac.uk/~hndv85/`