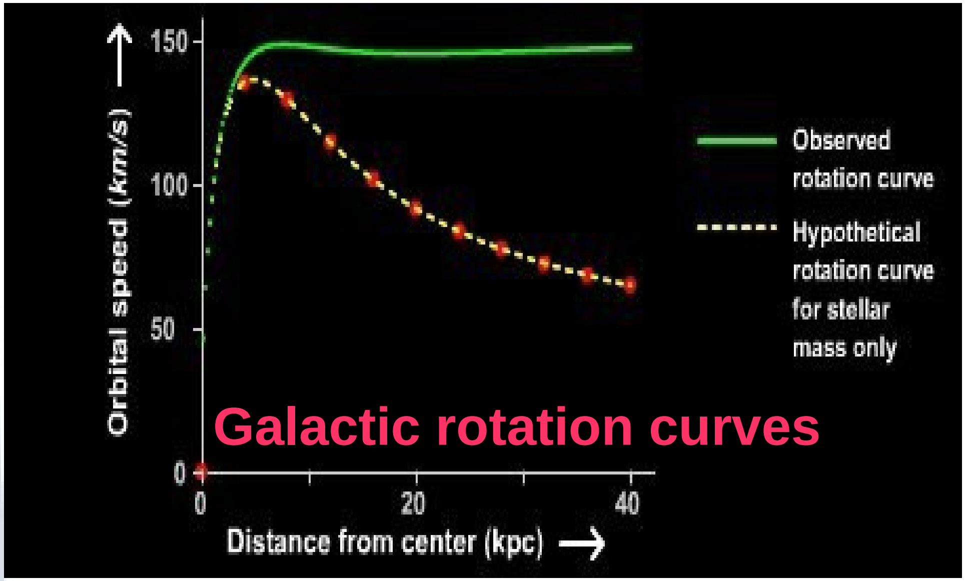
SUSY and alike
Mass Measurements @ LHC

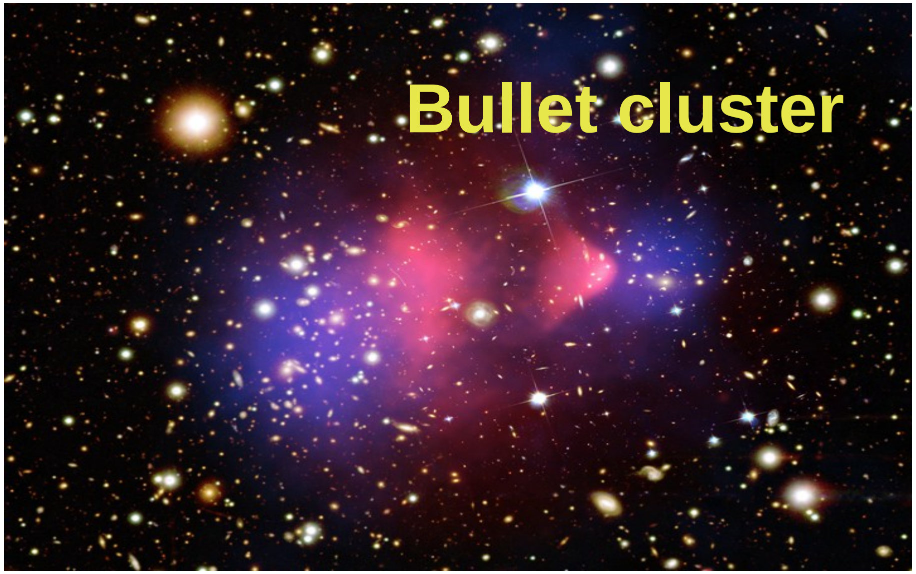
Partha Konar

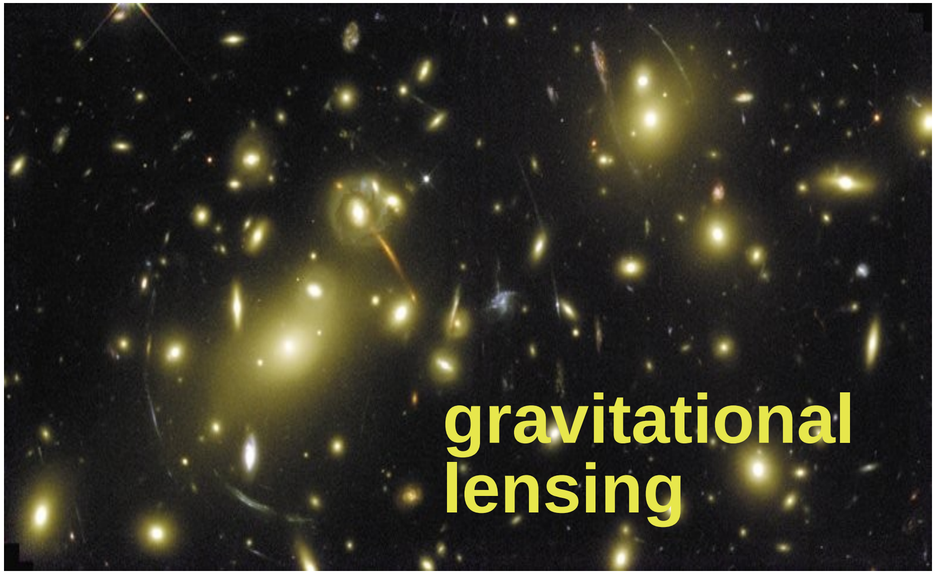
Physical Research Laboratory
Ahmedabad

The 4th KIAS Workshop
on Particle Physics and Cosmology

Evidence of Dark Matter







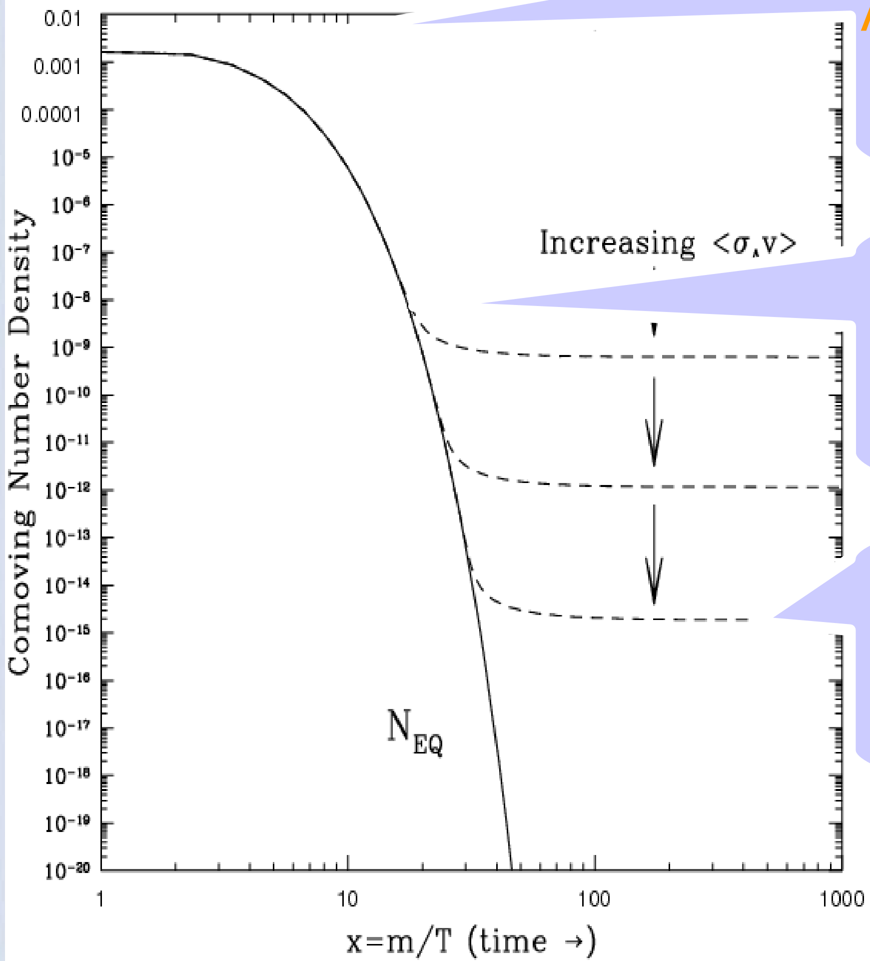
What could dark matter be?

- ✓ Something MASSIVE (cold DM)
- ✓ Interacts via the weak interaction
- ✓ Something different from our known Particles!

- WIMPS : Weakly Interacting Massive Particles

Not normal matter at all, but
something entirely exotic and unknown

Thermal history of WIMP



A new (heavy) particle χ in Tharmal equilibrium

$$\chi\chi \Leftarrow\Rightarrow f\bar{f}$$

Universe cooling down

$$\chi\chi \Rightarrow f\bar{f}$$

χ freeze out

$$\chi\chi : f\bar{f}$$

Relic abundance

$$\Omega_{DM} \propto \frac{1}{\sigma_{an}}$$

WIMP miracle or coincidence?

$$\Omega_{DM}^{cosmos} \overset{?}{\Longleftrightarrow} \Omega_{DM}^{wimp}$$

$$\Omega_{CDM} h^2 = 0.110 \pm 0.006$$

$$\simeq 0.1 \times \left(\frac{3 \times 10^{-26}\, cm^3 s^{-1}}{\langle \sigma v \rangle} \right)$$

New physics at weak scale?

$$\langle \sigma v \rangle \simeq 10^{-26}\, cm^3 s^{-1}$$

- Cosmology indicates to explore at weak scale
- BSM independently predicts particle with right density as DM!
- Evidence of new physics? Driving motivation for DM search.

Observed value for the Dark Matter density

Theoretical Wimp density at "freeze-out"

Dark Matter

Cosmology vs Missing particles at Collider

Cosmic Relic Density : $\Omega_\chi h^2 \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_\chi^2}{\alpha^2}$

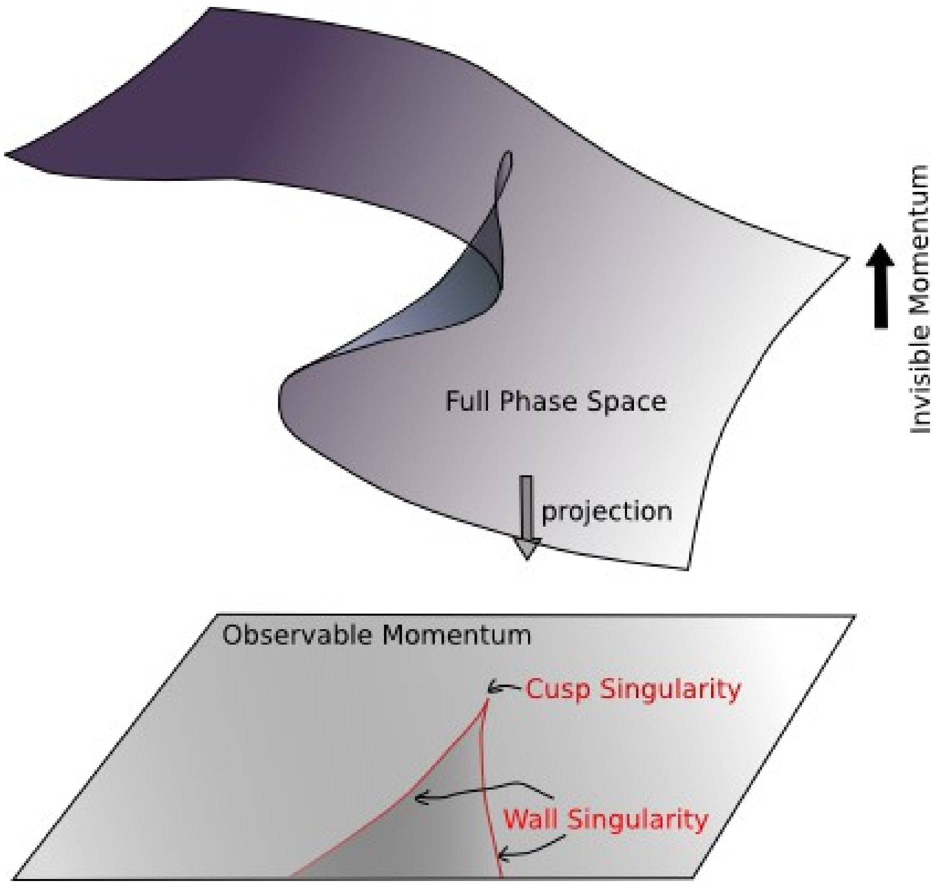
- Crossing: $\chi\chi$ production ~ annihilation ~ scattering.

  ---- *are they same??*

- SM – Neutrino
- BSM – 'Dark matter' at the laboratory
- P_T^{miss} signature at LHC + DM motivated models:

  Difficult to fully reconstruct events and extract masses, couplings of new particles.

Mass measurements : Behind the curtain



- *Global approach:*

  Determine the mass scale of new physics.

- *After NP discovery:*

  Look for specific topology typically with (long) decay chain. Isolate them to extract mass informations.

Singularities in observable phase space?
→ end-point, cusp, kink...

PRL 104, 081601 (2010) PHYSICAL REVIEW LETTERS week ending 26 FEBRUARY 2010

Algebraic Singularity Method for Mass Measurements with Missing Energy

Ian-Woo Kim
Department of Physics, University of Wisconsin, Madison, Wisconsin 53706, USA

Mass measurements : recollection

Mass scale of new physics (No trial mass parameters)

- Transverse variables - $E_T,\ H_T,\ M_{eff}$
- Global inclusive variables- $E\,,M\,,M_{Tgen}^{max}\,,\hat{S}_{min}$

Specific topology + extract mass informations :

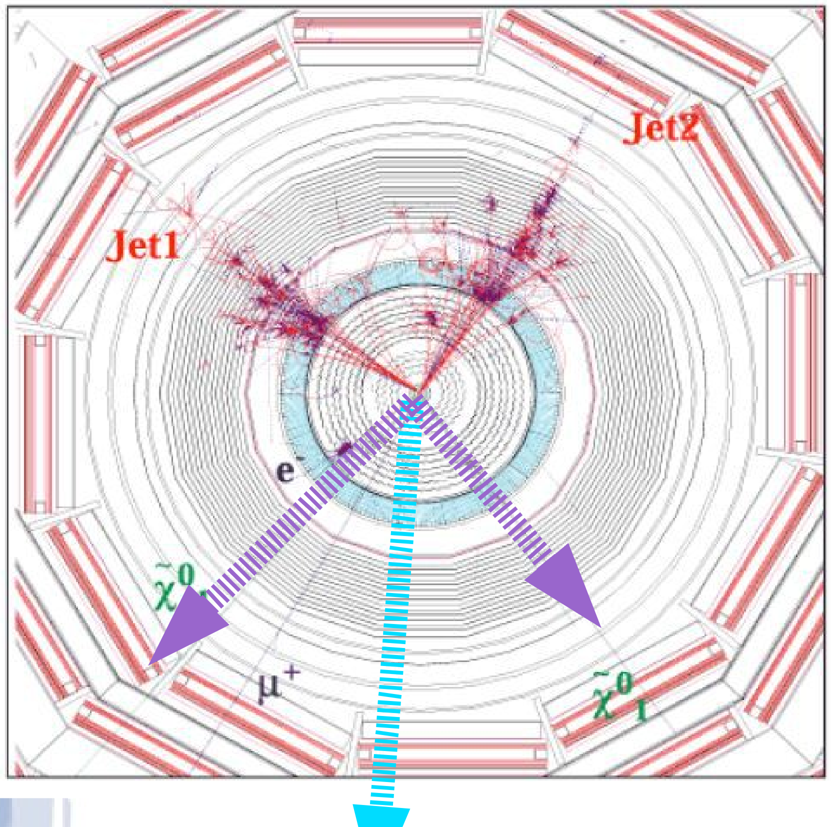
- Invariant mass endpoint boundary line
- Polynomial method
- Transverse mass variables and variants:

$$M_{T2}, M_{CT}, M_{T2}(n,c,p), M_{T2}(perp), M_2$$

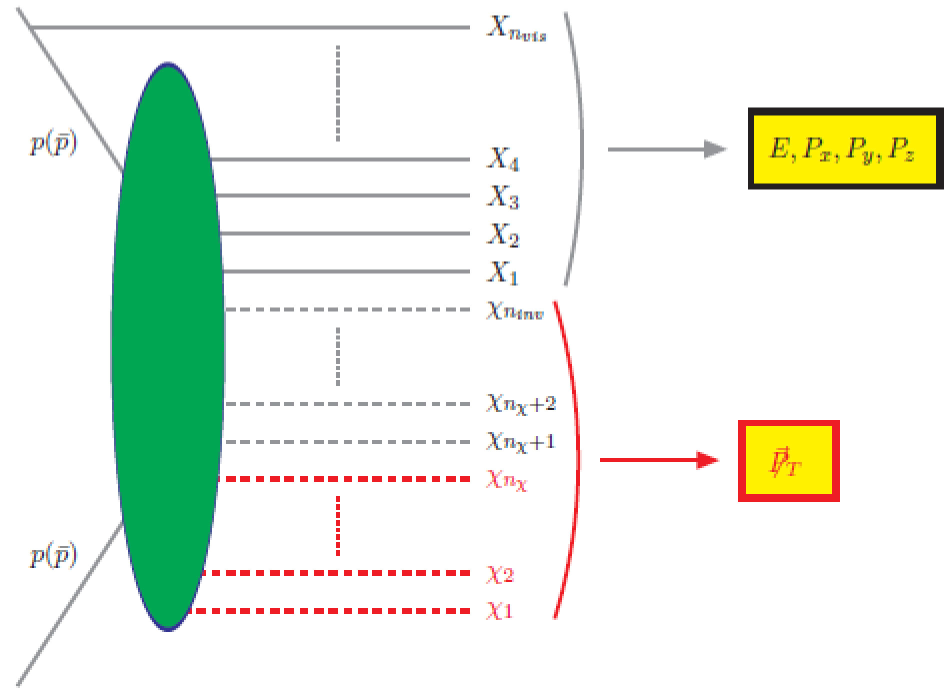
- Hybrid method

Hinchliffe, Paige, Bachacou,Allanach, Lester, Parker, Webber, Gjelsten, Miller, Osland..
Nojiri, Polesello, Tovey, Cheng, Gunion, Han, McElrath, Marandella..
Lester, Summers, Barr, Stephens, Tovey, Cho, Choi, Kim, Park,Kong, Matchev, Park, Burn ..

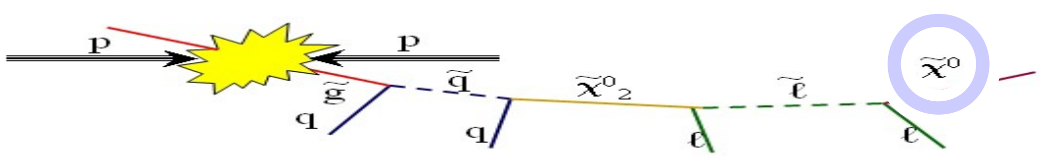
P_T^{miss} Events@LHC: Different viewpoint



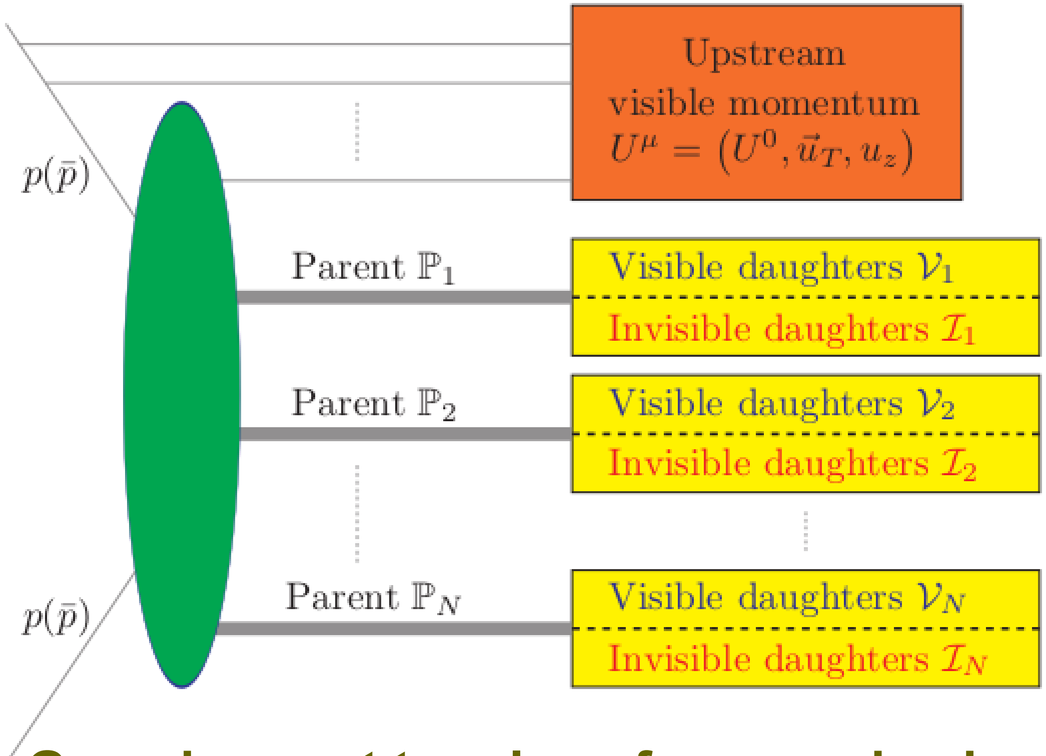
Missing PT



Dark matter candidate



Event Partitioning



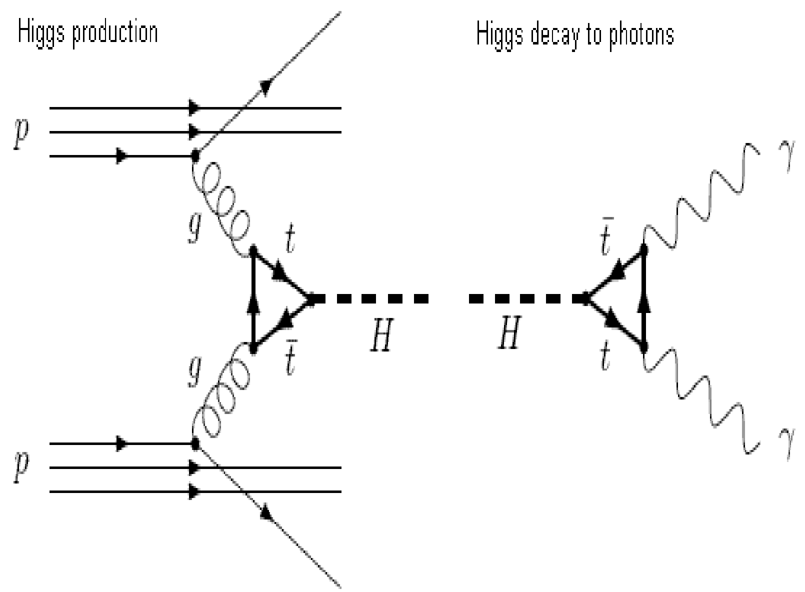
Generic event topology for new physics

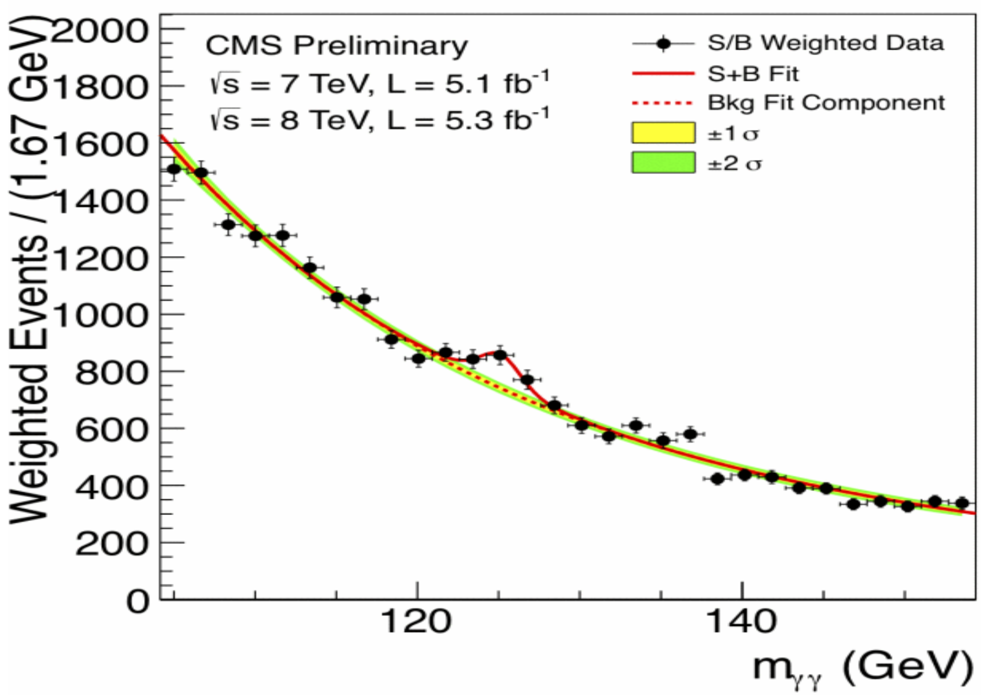
Constraint in Transverse Projection

$$\sum_{i=1}^{N_{\mathcal{I}}} \vec{q}_{iT} = \not{\vec{p}}_T \equiv -\vec{u}_T - \sum_{i=1}^{N_{\mathcal{V}}} \vec{p}_{iT}.$$

Z or h – mass measurements

The "Standard signals": **All visible decay**



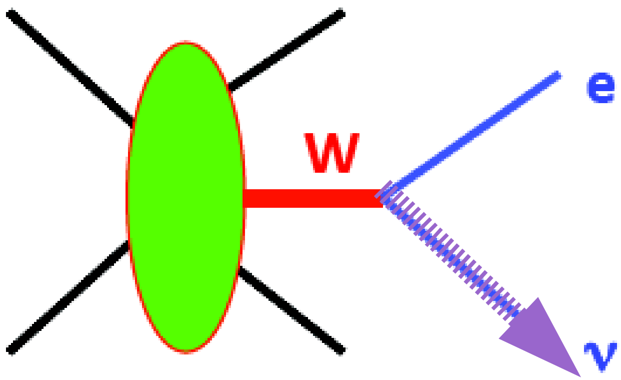


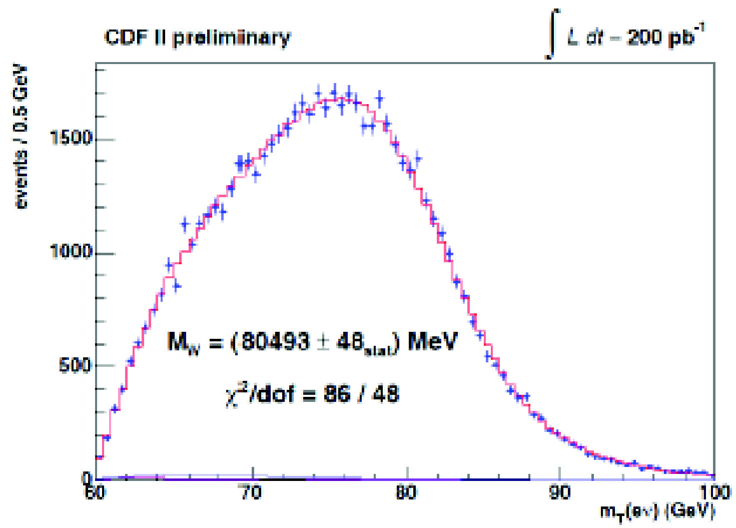
Invariant Mass (M)

$$M_h^2 = M^2(\gamma,\gamma) \equiv (|\vec{P}_1|+|\vec{p}_2|)^2-(\vec{P}_1+\vec{p}_2)^2$$

W – mass measurements

The "Standard signals": **single Semi-invisible decay**





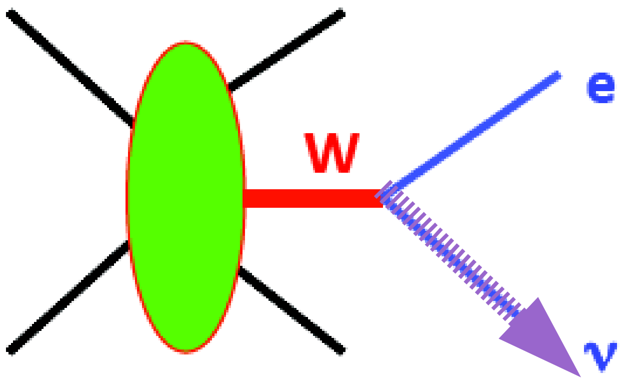
Transverse Mass (MT) ~ massless neutrino

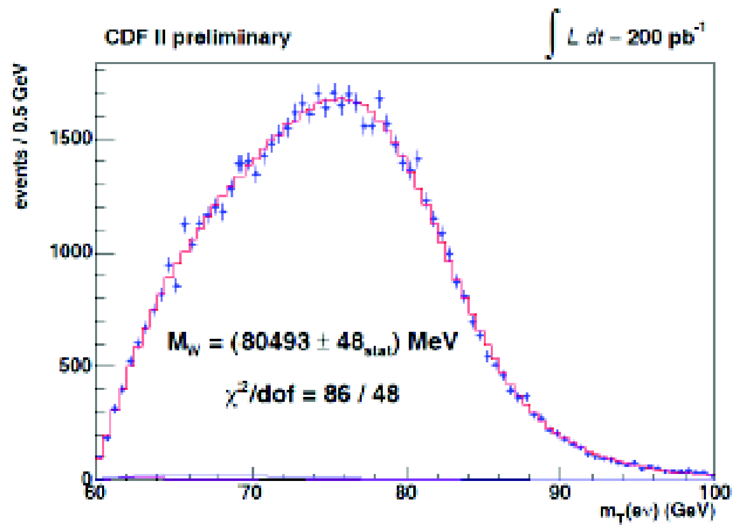
$$M_w^2 \geq M_T^2(l,\nu) \equiv (|\vec{P}_T^l| + |\vec{q}_T^\nu|)^2 - (\vec{P}_T^l + \vec{q}_T^\nu)^2$$

Kinemetic end point over many points

W – mass measurements

The "Standard signals": **singleSemi-invisible decay**





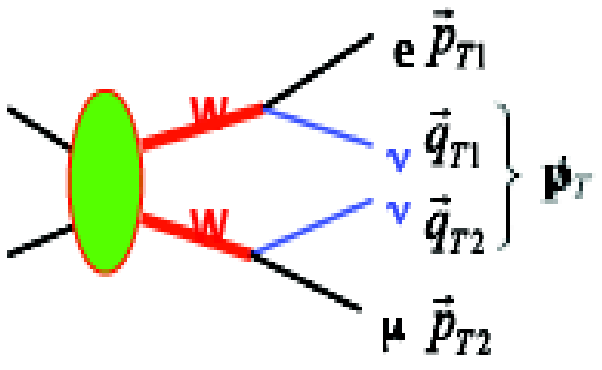
Transverse Mass (MT)

~ massless neutrino

$$M_w^2 \geq M_T^2(l,\nu) \equiv (|\vec{P}_T^l| + |\vec{q}_T^{\nu}|)^2 - (\vec{P}_T^l + \vec{q}_T^{\nu})^2$$

Kinemetic end point over many points

If there are two invisibles?



$$M_T \rightarrow M_{T2}$$

- If we could have measured q's!
- For each leg $M_w^2 \geq M_T^2(l,\nu) \equiv (|\overrightarrow{P_T^l}|+|\overrightarrow{q_T^\nu}|)^2-(\overrightarrow{P_T^l}+\overrightarrow{q_T^\nu})^2$

$$M_w \geq \max\{m_T(\vec{p}_{T1},\vec{q}_{T1}), m_T(\vec{p}_{T2},\vec{q}_{T2})\}$$

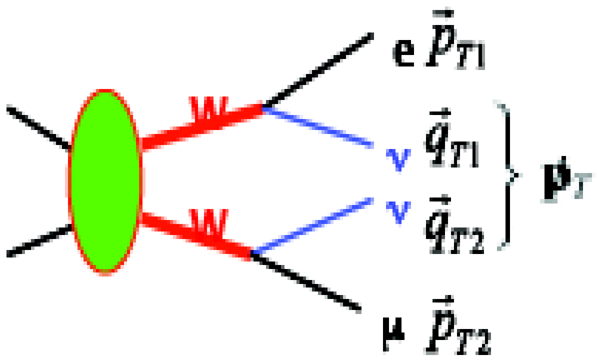
- Without having transverse momentum of each missing one:

$$M_W \geq M_{T2} = \min_{\vec{q}_{T1}+\vec{q}_{T2}=\not{E}_T} [\max\{m_T(\vec{p}_{T1},\vec{q}_{T1}), m_T(\vec{p}_{T2},\vec{q}_{T2})\}]$$

- Minimization over all possible 'trial' q-momentum.

Lester,Summers,Barr..

If there are two of them?



- If we could measure q's!
- For each leg $M_w^2 \ge M_T^2(l,\nu) \equiv (|\vec{P}_T^l|+|\vec{q}_T^\nu|)^2 - (\vec{P}_T^l+\vec{q}_T^\nu)^2$

$$M_w \ge \max\{m_T(\vec{p}_{T1},\vec{q}_{T1}), m_T(\vec{p}_{T2},\vec{q}_{T2})\}$$

- Without having transverse momentum of each missing one:

$$M_W \ge M_{T2} = \min_{\vec{q}_{T1}+\vec{q}_{T2}=\not{E}_T} [\max\{m_T(\vec{p}_{T1},\vec{q}_{T1}),\ m_T(\vec{p}_{T2},\vec{q}_{T2})\}]$$

$$M_T \rightarrow M_{T2}$$

$$M_{T2}^{max} \rightarrow M_w$$

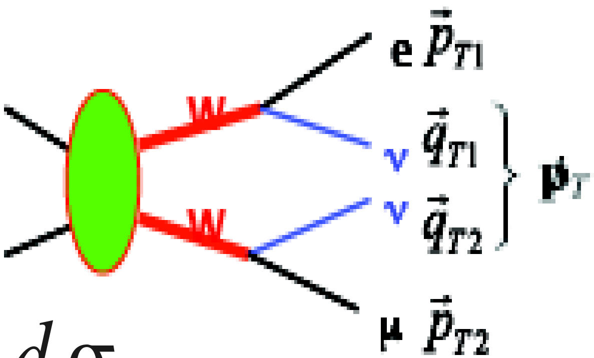
{Over all events}

- Minimization over all possible 'trial' q-momentum.

Lester,Summers,Barr..

In place of 'neutrinos' something massive!!

- Take a trial ν mass $\rightarrow \widetilde{m}_0$
- Look for $M_{T2}(\widetilde{m}_0)$ distribution

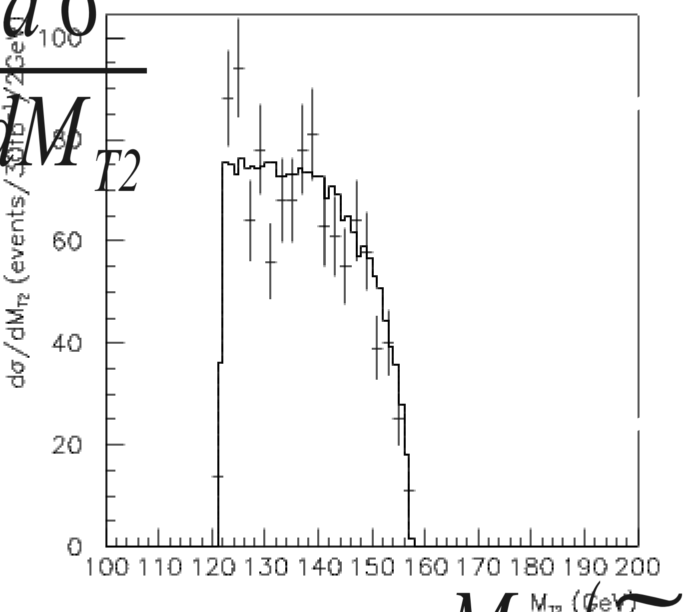


Find $M_{T2}^{max}(\widetilde{m}_0)$

$$pp \rightarrow X + \tilde{l}_R^+ \tilde{l}_R^- \rightarrow X + l^+ l^- \tilde{\chi}_1^0 \tilde{\chi}_1^0$$

$$m_{\tilde{l}_R} = 157.1\,\mathrm{GeV}, \quad m_{\tilde{\chi}_1^0} = 121.5\,\mathrm{GeV}.$$

$$\frac{d\sigma}{dM_{T2}}$$



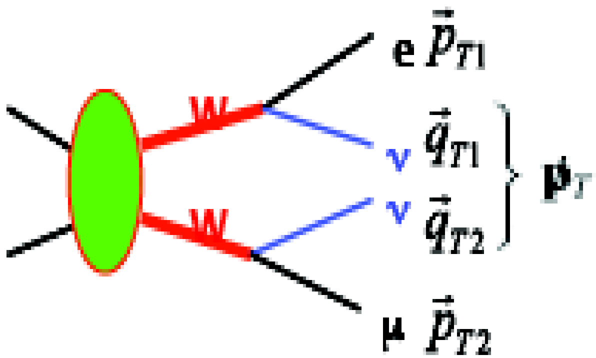
$$M_{T2}(\widetilde{m}_0)$$

$$m_{T2}^{\max} \simeq 157\ \mathrm{GeV} \quad \rightarrow \widetilde{m}_1$$

(with $m_{\tilde{\chi}_1^0} = 121.5$ GeV) $\rightarrow \widetilde{m}_0$

Lester,Summers'99

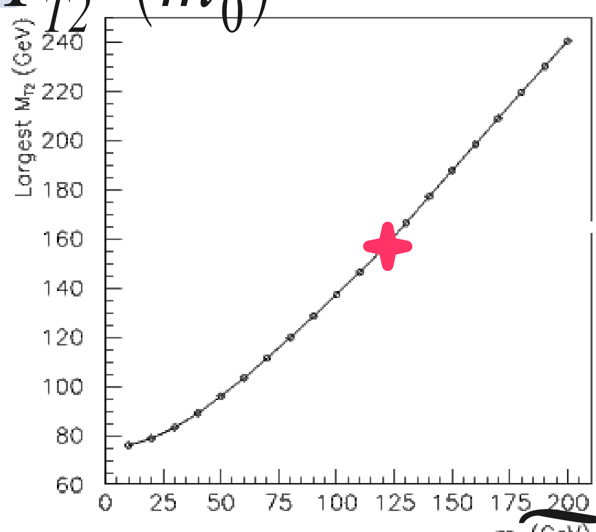
If 'neutrinos' were massive!!



- Take a trial ν mass $\rightarrow \widetilde{m}_0$
- Look for $M_{T2}(\widetilde{m}_0)$ distribution

Find $M_{T2}^{max}(\widetilde{m}_0)$

$M_{T2}^{max}(\widetilde{m}_0)$



$\rightarrow \widetilde{m}_0$

$$pp \rightarrow X + \tilde{l}_R^+ \tilde{l}_R^- \rightarrow X + l^+ l^- \tilde{\chi}_1^0 \tilde{\chi}_1^0$$

Role of trial mass

$$m_{\tilde{l}_R} = 157.1\,\text{GeV}, \quad m_{\tilde{\chi}_1^0} = 121.5\,\text{GeV}.$$

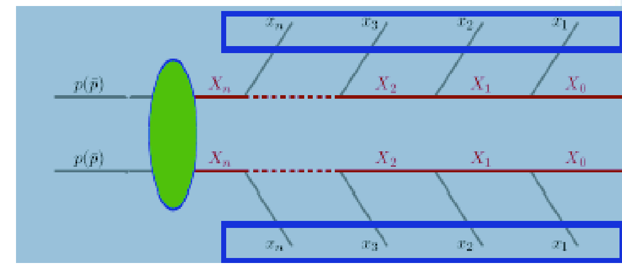
$$m_{T2}^{\max} \simeq 157\ \text{GeV} \quad \rightarrow \widetilde{m}_1$$

(with $m_{\tilde{\chi}_1^0} = 121.5$ GeV) $\rightarrow \widetilde{m}_0$

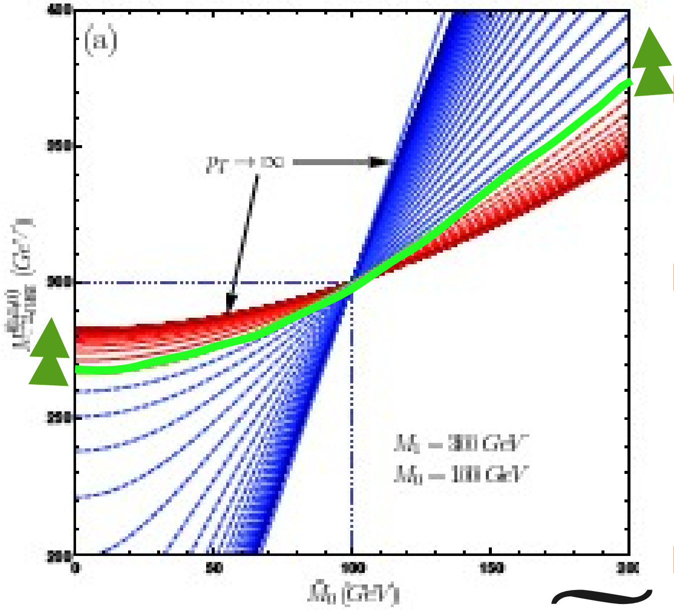
Lester,Summers'99

Magic Kink !

- Kink can arise from

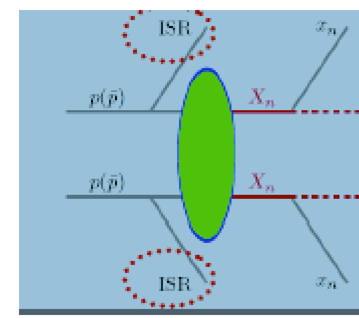


$$M_{T2}^{max}(\widetilde{m}_0)$$



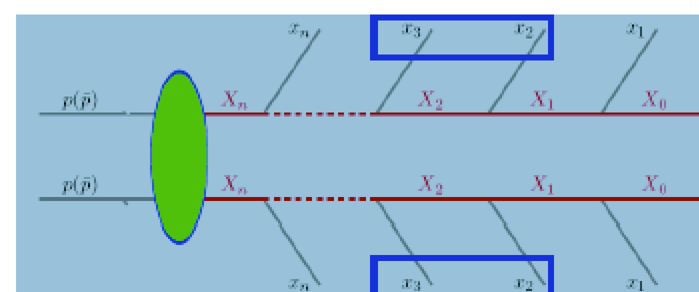
$$\rightarrow \widetilde{m}_0$$

- Composite particle each side
  Cho, Choi, Kim, Park '07



- ISR effect
  Barr, Gripaios, Lester '07
  Burns, Kong, Matchev, Park '08

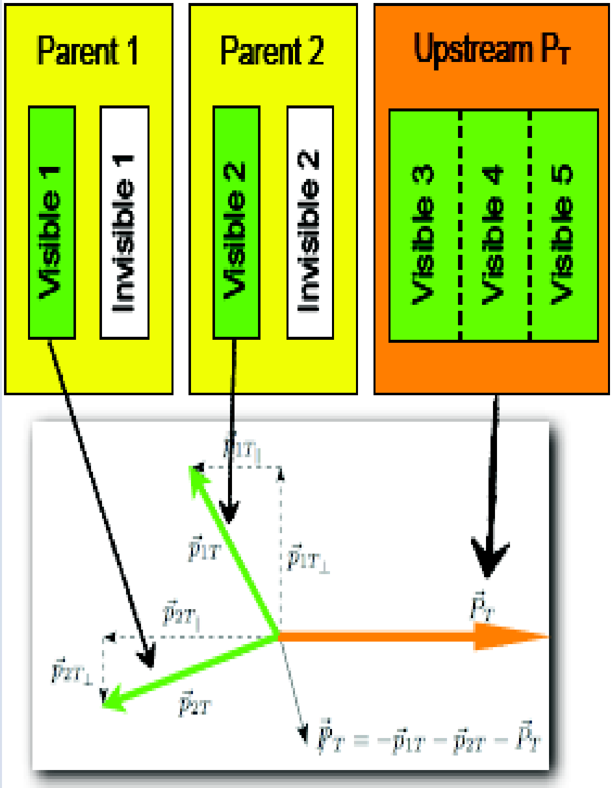
- Subsystem



Burns, Kong, Matchev, Park'08

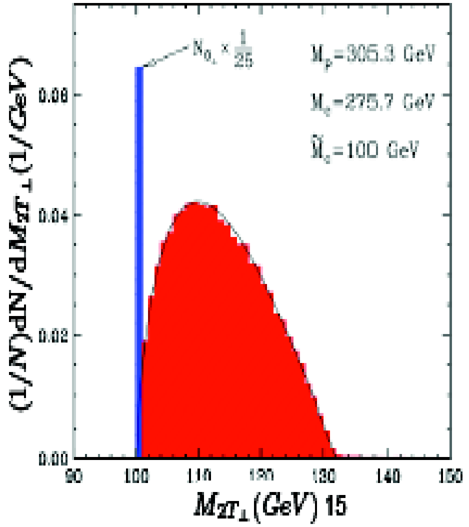
Second Transversification

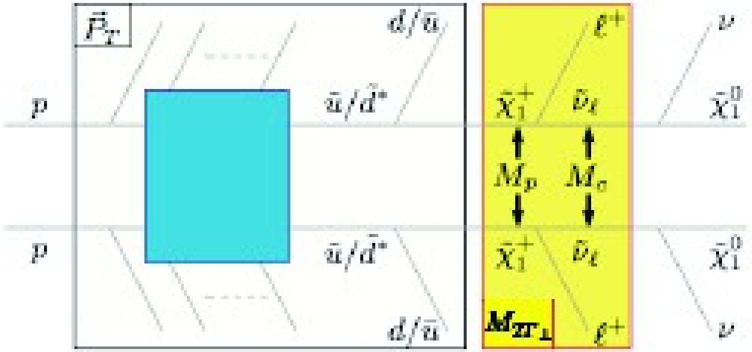
- Having projected on the transverse plane, one can additionally project on the direction of Upstream P_T:



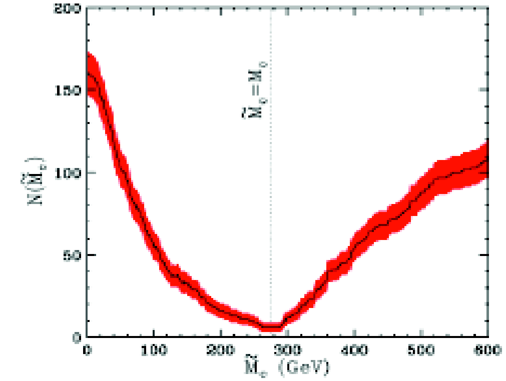
- The endpoints of "perp" distributions are stable against P_T variations

Konar,Kong,KM,Park 2009





$$N(\tilde{M}_c) = \sum_{all\ events} H(M_{2T}(\tilde{M}_c) - M_{2T\perp}^{max}(\tilde{M}_c))$$



pk,Kong,Matchev,Park'09

Global inclusive variables

- Mass scale of new physics.
- Make use of all observed momenta including Z-component, without hypothesising any particular topology or final states.
  - Total visible energy : E
  - Total visible inv. Mass : M
  - Oxbridge variable: M_{Tgen}^{max}
  - Gator variable: $\sqrt{\hat{s}_{min}}$

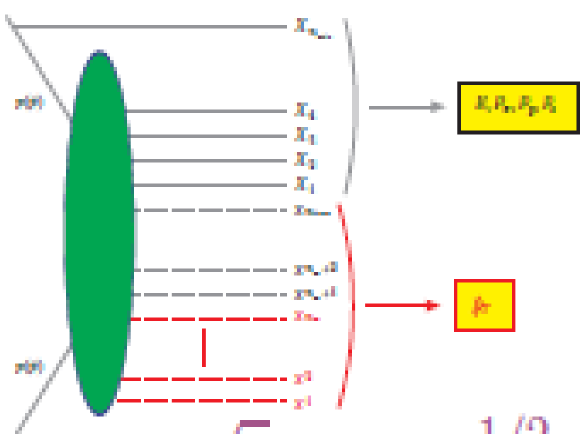
Mass scale measurement

- Depend on both M_{SUSY} and M_χ OR don't!

→ $M_{\rm susy}^{\rm eff} = \left(M_{\rm susy} - \frac{M_\chi^2}{M_{\rm susy}} \right)$ $H_T \equiv E_T + \not{E}_T$ $E_T \equiv \sum_\alpha E_\alpha \sin\theta_\alpha$ $M_{\rm eff} = \not{E}_T + \sum_{{\rm jets}\ j} p_{Tj}$

→ Oxbridge variant : $m_{Tgen}^{max}(m_\chi) = M_{SUSY}$

→ Gator variable $S_{min}(m_\chi) = (2 M_{SUSY})^2$



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

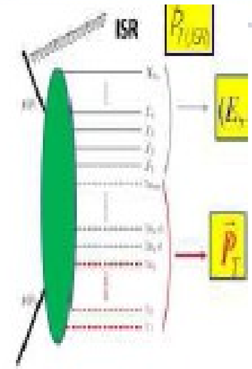
Find: The *minimum value* of the Mandelstam variable *consistent* with the measured values of the *total energy E, total visible momentum (Px,Py,Pz) and Missing* $\not{E}_T$!

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

pk,Kong,Matchev'08

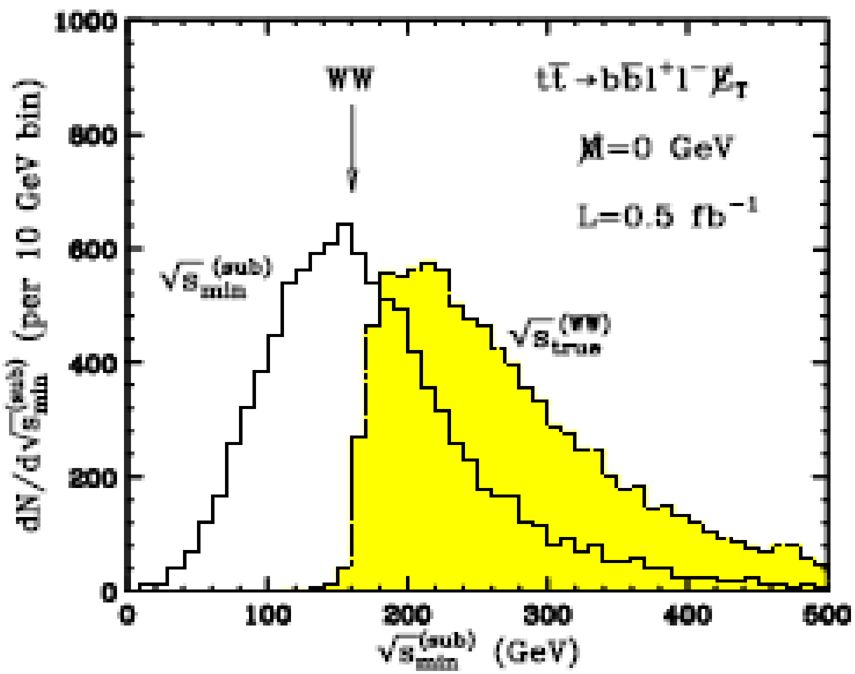
$\sqrt{\hat{s}_{min}}$: Subsystem

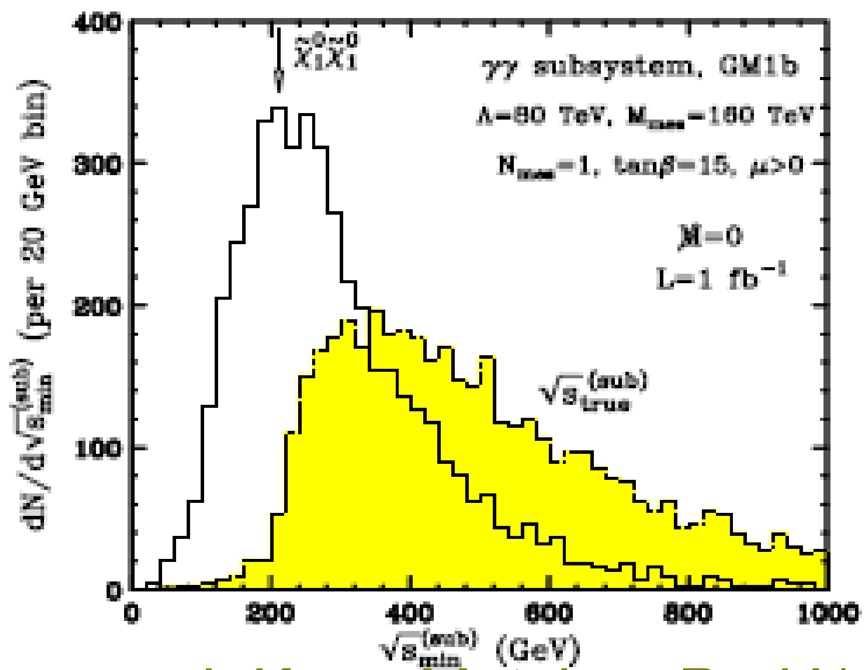
- $\sqrt{\hat{s}_{min}} = \sqrt{\left(\sqrt{E^2 - P_z^2} + \sqrt{\not{P}_T^2 + M_{inv}^2}\right)^2 - \vec{P}_{T(ISR)}^2}$



- tt-bar events
  - identify the WW threshold from the 2 lepton subsystem

- GMSB SUSY events
  - identify the N_1N_1 threshold from the 2 photon subsystem

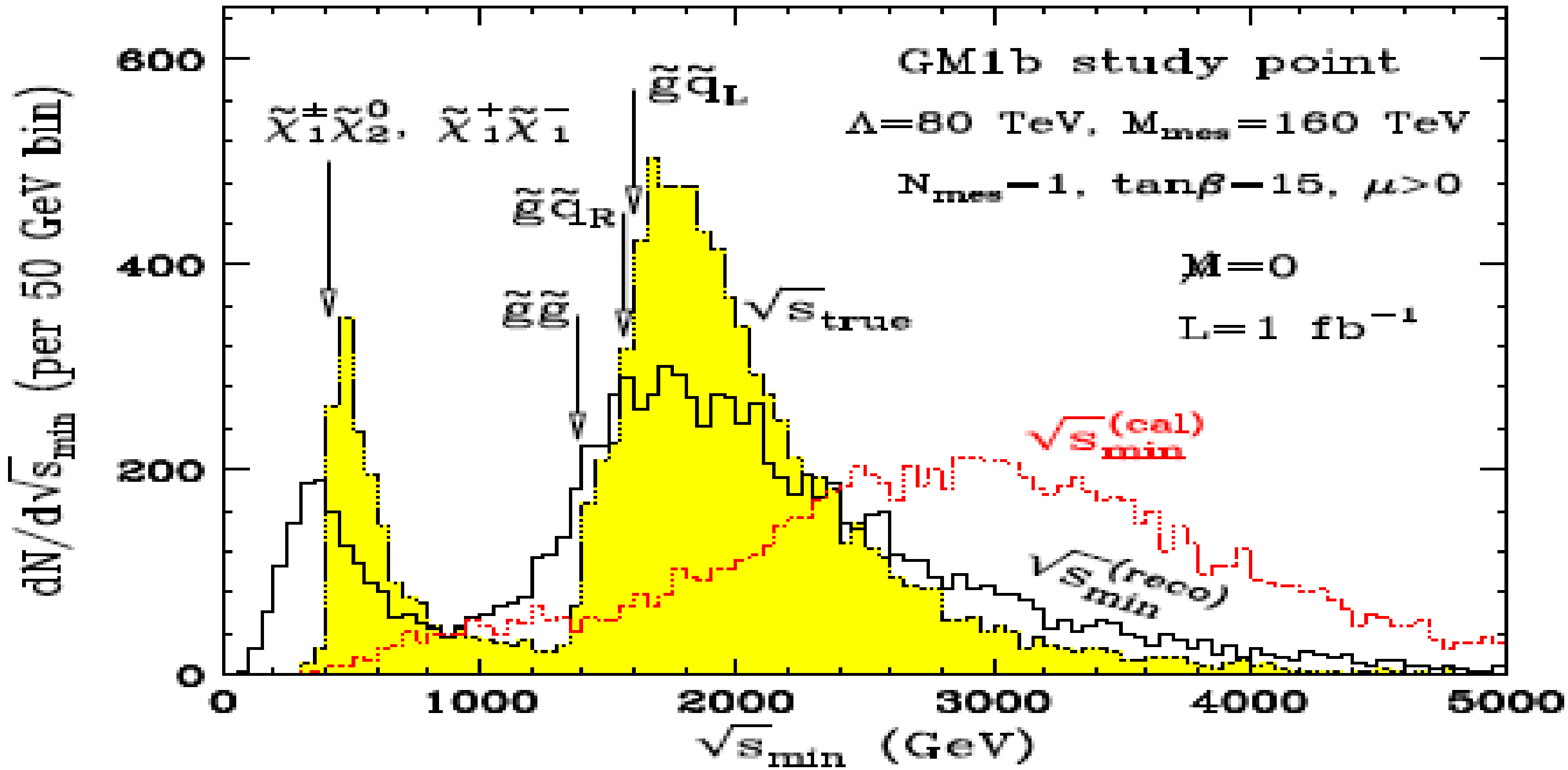




pk,Kong,Matchev,Park'10

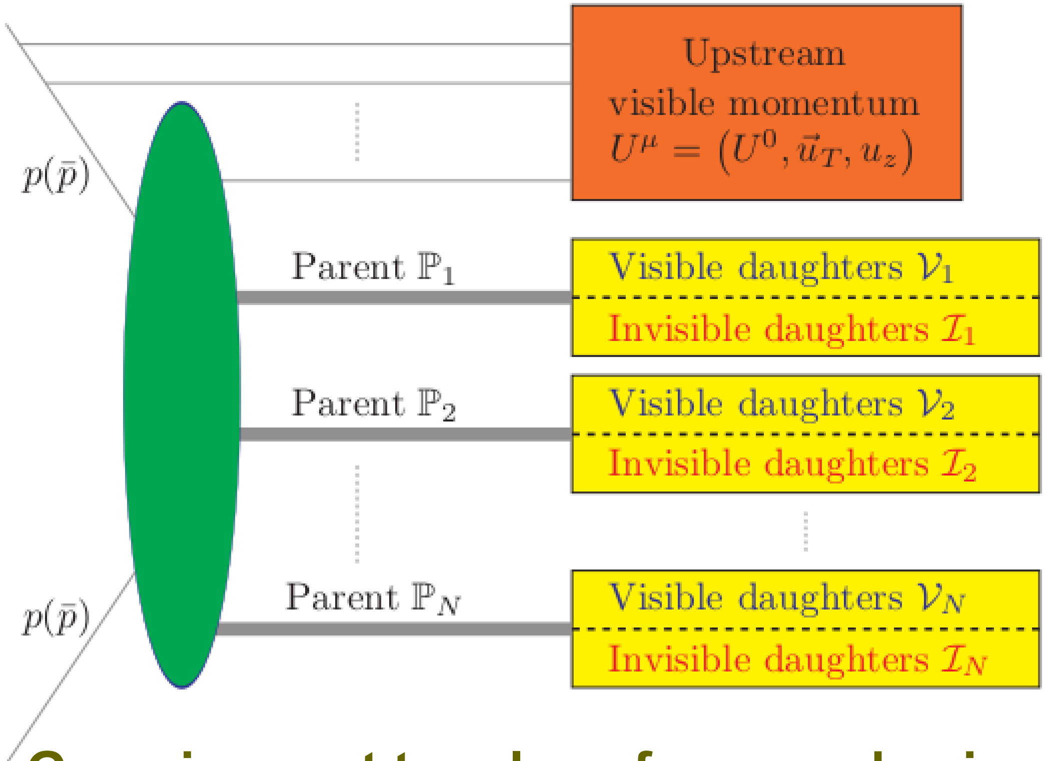
$\sqrt{\hat{s}_{min}}$:Inclusive SUSY production

- The peak of $\sqrt{\hat{s}_{min}}$ locate the thresholds for individual dominant production sub-process
- GMSB study-point - GM1b : EW and strong productions



pk,Kong,Matchev,Park'10

Event Partitioning



Generic event topology for new physics

Constraint in Transverse Projection

$$\sum_{i=1}^{N_{\mathcal{I}}} \vec{q}_{iT} = \vec{\not{p}}_T \equiv -\vec{u}_T - \sum_{i=1}^{N_{\mathcal{V}}} \vec{p}_{iT}.$$

A Storm in a 'T' Cup

Refine Transversification

Separate operations:

1. Partitioning & Summation of the mom-vec of the daughters [N]
2. Projecting into the transverse plane.
3. 2nd projection in to the transverse plane?
4. Minimisation at the end

Transverse Projection : Which way?

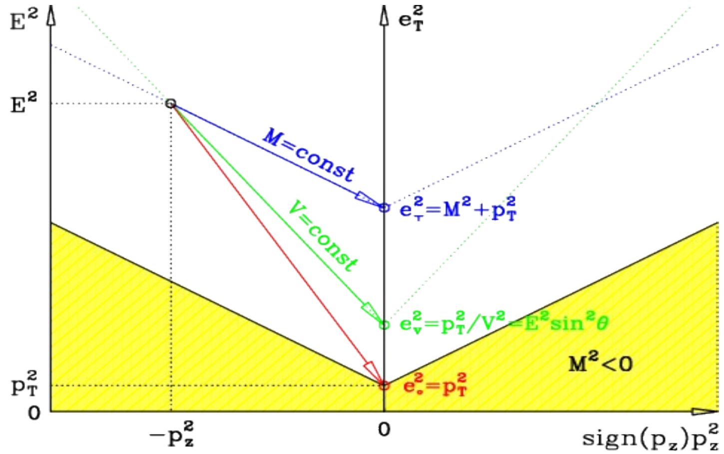
Mass-preserving "T"	Speed-preserving "V"	Massless "o"

Hierarchy:

$$M = m_{\mathsf{T}} \geq m_{\mathsf{V}} \geq m_{\circ} = 0.$$

&

$$E \geq e_{\mathsf{T}} \geq e_{\mathsf{V}} \geq e_{\circ} = p_T.$$



Q. Separate operations: when and how ?

- (Partitioning & Summing) over visible momentums :

  When and Which way – N = 1, 2, … ?
- Projecting into transverse plane : Y/N

  If Y: When and Which way – T, V, o ?
- Second Projection : Y/N

  If Y: Which way – T, V, o ?
- Minimization at the end. $\sum_{i=1}^{N_{\mathcal{I}}} \vec{q}_{iT} = \vec{p}\!\!/_T \equiv -\vec{u}_T - \sum_{i=1}^{N_{\mathcal{V}}} \vec{p}_{iT}.$

$$M_N, \quad M_{NT}, M_{NV}, M_{N0}, \quad M_{TN}, M_{VN}, M_{0N},$$

$$M_{NT\tau} : 27\left(3 \text{ for N} \times 3 \textit{ types of } T \times 3 \textit{ types of } \tau\right)$$

How existing variables fit into

Existing variable	$N=1$				$N=2$	
	$M_1(\not{M}_1) = M_{1T}(\not{M}_1)$	$M_{T1}(\not{M}_1)$	$M_{\circ 1}$	$M_{1\circ}$	$M_2(\not{M}_a) = M_{2T}(\not{M}_a)$	$M_{2T\perp}(\not{M}_a)$
$2\not{p}_T = 2\not{E}_T$				$u_T \to 0$		
m_{eff}		$\not{M}_1 \to 0, u_T \to 0$	$u_T \to 0$			
$\sqrt{\hat{s}}^{(sub)}_{min}(\not{M}_1)$	√					
$\sqrt{\hat{s}}_{min}(\not{M}_1)$	$u_T \to 0$					
$m_{Te\nu}(M_e, M_\nu)$	√	√	$M_e, M_\nu \to 0$	$M_e, M_\nu \to 0$		
$M_{T,ZZ}(M_Z)$	√	√				
$M_{C,WW}$	$\not{M}_1 \to 0$					
m_T^{true}	$\not{M}_1 \to 0$					
$m_{T2}(\not{M}_a)$					√	
$m_{T2\perp}(\not{M}_a)$						√

PHYSICAL REVIEW D **84,** 095031 (2011)

Guide to transverse projections and mass-constraining variables

A. J. Barr,[1] T. J. Khoo,[2] P. Konar,[3] K. Kong,[4] C. G. Lester,[2] K. T. Matchev,[5] and M. Park[5]

Some more recent works

M2 variables, utility and topology

Cho,Gainer,Kim,Matchev,Moortgat,Pape,Park '14

- Analogue to M_{T2} :

$$M_2(\tilde{m}) \equiv \min_{\vec{q}_1,\vec{q}_2} \{\max [M_{P_1}(\vec{q}_1,\tilde{m}),\ M_{P_2}(\vec{q}_2,\tilde{m})]\}$$

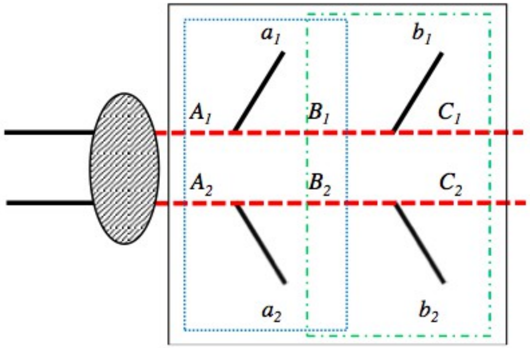
$$\vec{q}_{1T} + \vec{q}_{2T} = \vec{\not{P}}_T$$

- Based on different subsystem and

  using additional constraints from equality of “mother”, “Relative”

  variables like M_{2xx} , M_{2cx} , $M_{\mathbf{2xc}}$,M_{2cc} are created

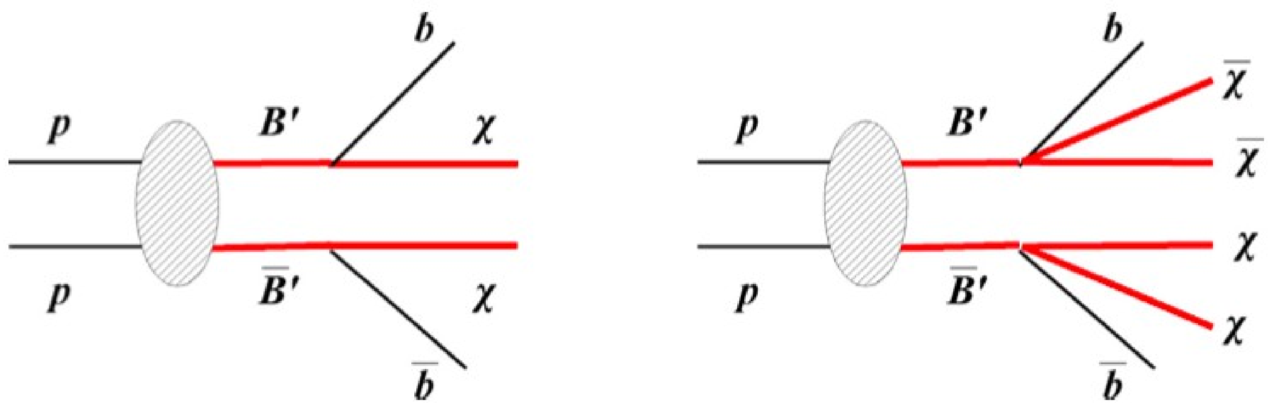
- Minimization over all components of “q”
- Sharper end point and test on topology informations.



Some more recent works

- Dark Matter stabilization symmetry & Counting DM particles
  Agashe etal, '12, '13; Giudice,Gripaios,Mahbubani '12

- Peak of “visible” energy distribution, M_T and M_{T2} distribution.



- Significance Variables *Nachmana, Lester '13*
- Includes the event by event resolution of kinematic variable
- Used to improve the analysis using M_T and M_{T2} as discrimination variable
- Apology that I could not add many more interesting works.

Summary

- Exciting time to cross-check the effectiveness new techniques with large amount LHC data.
- Compelling evidence for cold dark matter – turn for collider to find one.
- Motivates new model building : WIMP – our best bet.
- Mass (and spin) measurement one important step with signatures of new physics (and SM).
- Ideas and techniques developing fast for more generalised but precise measurements. CMS and ATLAS working closely to implement some of these ideas.
- Stay tuned with latest tricks in studying missing energy events.

Thank You