Pseudo stransverse mass shining on buried new particles

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Motivation

- **Pair-produced new particle *Y* decaying into visible particles, *V* plus invisible WIMPs, χ .**

$$P + P \rightarrow Y_1 + Y_2 + etc \rightarrow V_1 + \chi_1 \ + \ V_2 + \chi_2 + etc$$

- **Measuring new particle masses is not easy.**

  ✓ **Partonic CM frame ambiguity**
  ✓ **Several missing particles**
  ✓ **Complex event topologies**

- **When the event reconstruction is impossible, measuring kinematic boundaries is a good way to determine new particle masses.**

  ✓ **Transverse mass of W-boson / Invariant mass methods / M_{T2}-kink methods ..**
  ✓ **Observing the endpoints (kinematic boundaries) of the variables is important.**

- **However, in general, identifying a meaningful endpoint is not a trivial task with many sources of systematic uncertainties.**

  - Various kinds of the signal endpoint shape

  - Hard to estimate the backgrounds, especially for jets.

  - Jet combinatorics with hard ISR

  - In many cases, they are irreducible.

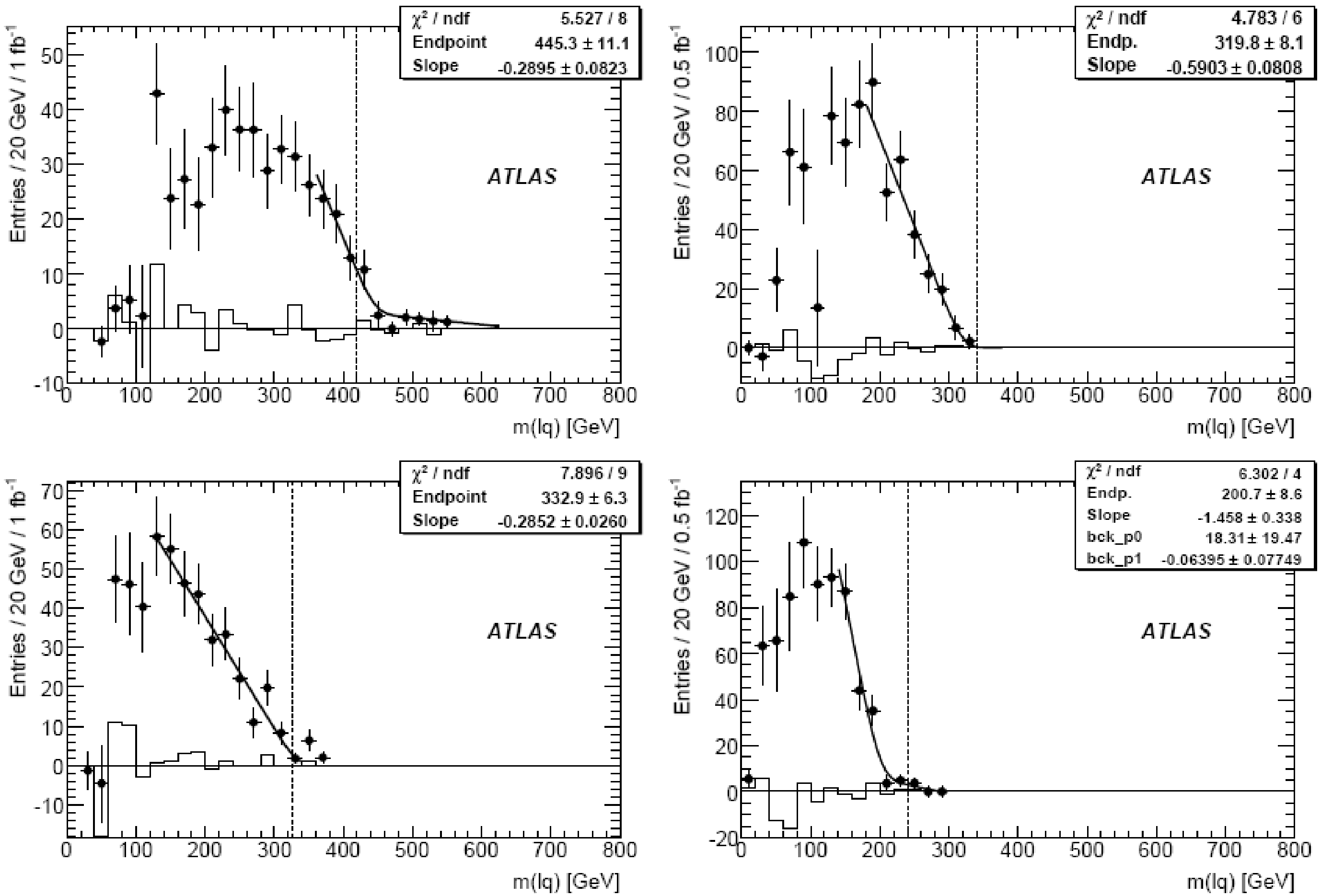
  - Jet E resolution, Finite total decay widths effects.

  - …

- **Example of endpoint measurement (1)**

→ **Invariant masses of visible particles in SUSY cascade decay chain**

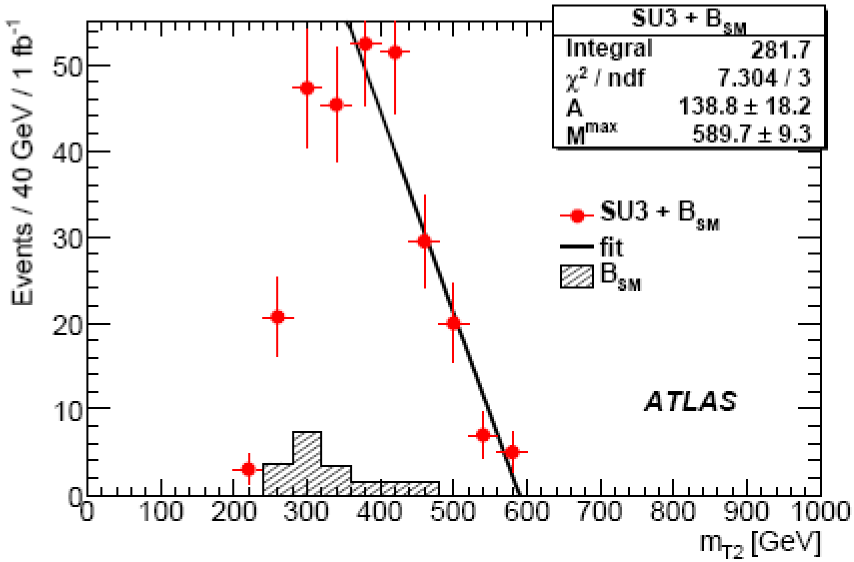
→ **Gaussian smeared linear signal + backgrounds function fits well with 1~10 GeV systematic uncertainty.**



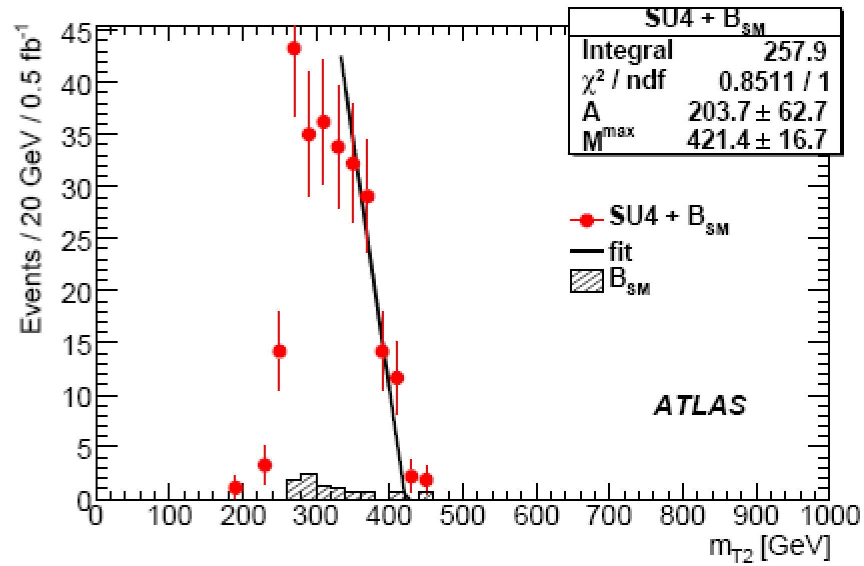
- **Example of endpoint measurement (2)**

M_{T2}^{max} ($\sim q_R \sim q_R \rightarrow q\sim\chi + q\sim\chi$) = RH squark mass, m_x known

ATLAS Technical Design Report 2009



$$m_{\tilde{q}_R} = 611 \text{ GeV}$$



$$m_{\tilde{q}_R} = 406 \text{ GeV}$$

Max of M_{T2} **measurement usually has O(1~10%) systematic uncertainty in fitting process (fitting function, cuts, range …).**

- **In the existence of large systematic uncertainty, extracting the mass parameter using template least chi-square methods or global fit would provide large uncertainty also.**

- **Anyway, even with the bulk distribution with large uncertainty, one can always define the signal endpoint as a breakpoint in the distribution with proper resolution/width effect.**

- **Can we reduce the systematic uncertainty in finding the signal endpoint ?**

- **At least, for M_{T2} endpoint measurement, it's possible!**

$M_{\pi T}$ and $M_{\pi T2}$

- **M_{T2} - An extension of the transverse mass, M_T for the event with two missing particles**

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

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

$\Rightarrow$ Independent of the longditudinal momenta.

$\Rightarrow$ One may use an arbitrary trial WIMP mass m_χ to define M_T

(True WIMP mass = m_χ^{true})

Stransverse mass of $Y_1\ Y_2 \to (V_1(p_1) + \chi_1(k_1)) + (V_2(p_2) + \chi_2(k_2))$

$$M_{T2}^{\,2} = \min[\max\{M_T(Y_1), M_T(Y_2)\}]$$

$\Rightarrow$ *Minimization* over all possible WIMP transverse momenta

- **For all events, $M_{T\,\&T2}(m_\chi = m_\chi^{true}) \le m_Y^{true}$**

- **The mass constraint from M_{T2} : p_0**
  [Cho,Choi,Kim,Park : arXiv-0709.0288/arXiv-0711.4526]

$$\mathbf{M_{T2}^{max}(x) = p^0 + \sqrt{p^{0\,2} + x^2}},$$

x = trial WIMP mass , Visible particle mass ~ 0

$p^0 = \dfrac{m_Y^{\ 2} - m_x^{\ 2}}{2m_Y}$, the momentum of v & χ in the rest frame of Y

- **It's an interesting result of M_{T2} kinematics *because each of the two mother particles is not at rest in LAB frame!***

(!) It is only valid when total transverse momentum of 2 mother particle system is zero. $(p_T(Y_1) + p_T(Y_2) = 0)$

M_{π} and $M_{\pi T}$

Transverse mass(M_T) & invariant mass(M) ***of*** $Y \rightarrow V(p) + \chi(k)$

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

$\Rightarrow$ Defined in **any frame** with fixed endpoint, M

Pseudo transverse mass($M_{\pi T}$) & pseudo invariant mass(M_π)

$$M_{\pi T}^{\,2} = m_V^{\,2} + m_\chi^{\,2} + 2\sqrt{m_V^{\,2} + |\mathbf{p}_\mathbf{T}^0|^2}\sqrt{m_\chi^{\,2} + |\mathbf{p}_\mathbf{T}^0|^2} - 2(\mathbf{R}(\pi)\mathbf{p}_\mathbf{T}^0)\cdot(-)\mathbf{p}_\mathbf{T}^0$$

$$\le M_\pi^{\,2}(= m_V^{\,2} + m_\chi^{\,2} + 2\sqrt{m_V^{\,2} + |\mathbf{p}_\mathbf{T}^0|^2}\sqrt{m_\chi^{\,2} + |\mathbf{p}_\mathbf{T}^0|^2}\,Cosh\Delta\eta - 2(\mathbf{R}(\pi)\mathbf{p}_\mathbf{T}^0)\cdot(-)\mathbf{p}_\mathbf{T}^0$$

R(π) is the rotation in transverse plain by anlge, π

$\Delta\eta =$ rapidity difference between the visible and invisible particles

$\Rightarrow$ Defined in **the rest frame of Y** with fixed $M_{\pi T}$ endpoint, M_π

$\Rightarrow$ Endpoint useful only for a **mother particle with $P_T = 0$**

(*) The way of combininig momenta constituents for $M_{\pi T}$ is exactly same with the collider variable, M_{CT} [Tovey, arXiv:0802.2879]

If it is possible, then the pseudo transverse mass endpoint will also provide us the P^0

$$M_{\pi T}^{\max 2}(x) = m_V^2 + x^2 + 2\sqrt{m_V^2 + |\mathbf{p^0}|^2}\sqrt{x^2 + |\mathbf{p^0}|^2} - |\mathbf{p^0}|^2$$

$x =$ trial WIMP mass

→ *How about the new mother particle pair, each with nonzero P_T?*

Pseudo - stransverse mass ($M_{\pi T2}$) for

$$Y_1 \; Y_2 \rightarrow (V_1(p_1) + \chi_1(k_1)) + (V_2(p_2) + \chi_2(k_2))$$

$$M_{\pi T2}{}^2 \equiv \min[\max\{M_{\pi T}(Y_1), M_{\pi T}(Y_2)\}]$$

$$M_{\pi T} \equiv m_V{}^2 + m_\chi{}^2 + 2\sqrt{m_V{}^2 + |\mathbf{p_T}|^2}\sqrt{m_\chi{}^2 + |\mathbf{k_T}|^2} - 2(\mathbf{R}(\pi)\mathbf{p_T}) \cdot \mathbf{k_T},$$

$\mathbf{p_T}$ s' are visible transverse momenta ***in the LAB frame***

min&max over all possible invisible momentum $\mathbf{k_T}$

- ***$M_{\pi T}$* endpoint can be realized using *$M_{\pi T2}$ (pseudo-stransverse mass) variable* *defined in the LAB frame* for the pair of mother particles with total P_T=0 !**

- **Then, the endpoint behavior in trial WIMP mass, x, also provides the P^0**

$$M_{\pi T2}^{\max 2}(x) = m_V^{\ 2} + x^2 + 2\sqrt{m_V^{\ 2} + |\mathbf{p^0}|^2}\sqrt{x^{\ 2} + |\mathbf{p^0}|^2} - |\mathbf{p^0}|^2$$

$x =$ trial WIMP mass

- **Condition for PST endpoint :**

$$\delta_T \equiv |P_T(Y_1 + Y_2)| = 0$$

$M_{\pi T2}$ solution for an event with $\delta_T = 0$

(For single visible particle in each decay chain)

$$M_{\pi T2}^{\ \ 2}(m_v^{(i)}, \vec{P}_T^{\,v(i)}, \chi) = \chi^2 - A_T$$

$$+\sqrt{[1 + \frac{4\chi^2}{(2A_T - m_v^{(1)\,2} - m_v^{(2)\,2})}][A_T^{\ 2} - (m_v^{(1)} m_v^{(2)})^2]}$$

$$A_T = E_T^{\ v(1)} E_T^{\ v(2)} + \vec{P}_T^{\ v(1)} \cdot \vec{P}_T^{\ v(2)}$$

- **Properties of *$M_{\pi T2}(x)$ distribution***

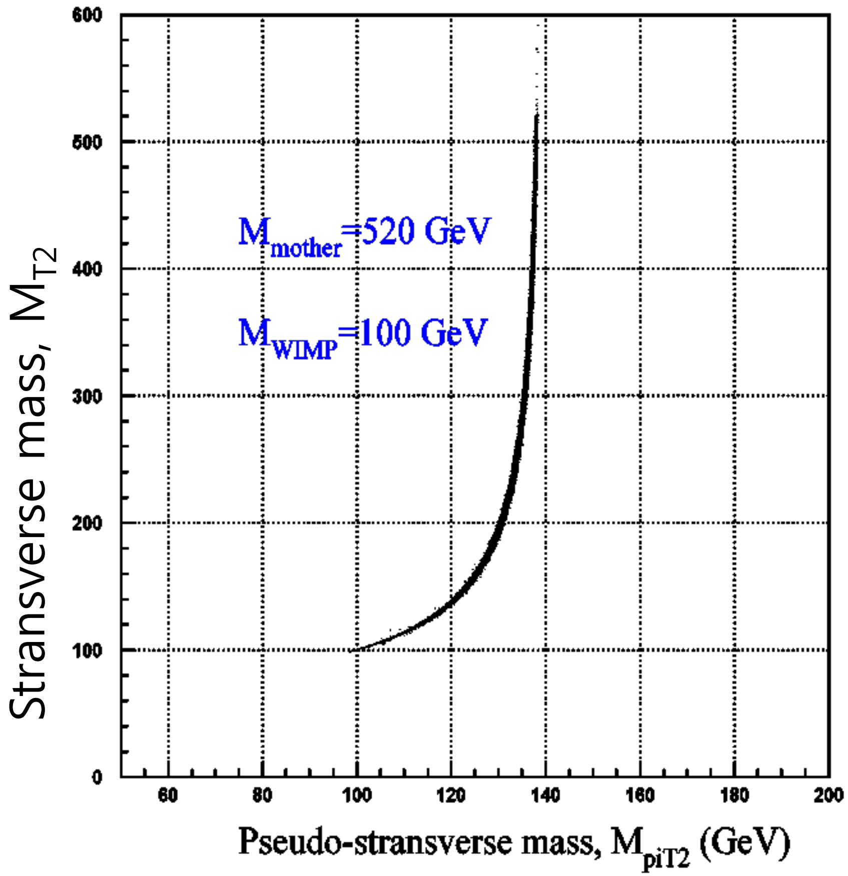
  - If $m_{vis}\sim 0$, $M_{\pi T2}(x)$ projection of events has *amplified endpoint structure with proper value of trial WIMP mass, x* originated from Jacobian factor between M_T and $M_{\pi T}$

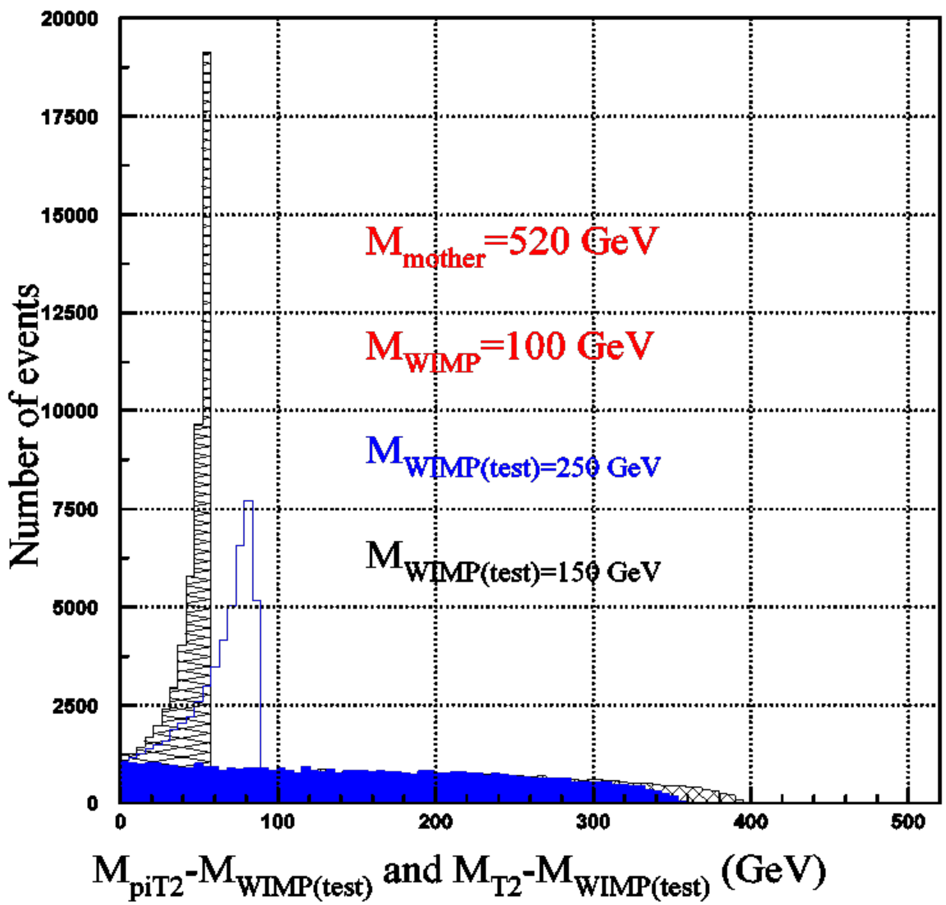
$$\sigma^{-1}\frac{d\sigma}{dM_{\pi T}(x)} \sim J(M_{\pi T}(x), M_{\pi T}(x))\sigma^{-1}\frac{d\sigma}{dM_T(x)}$$

$$\mathrm{J}=\frac{M_{\pi}(x)}{M(x)}\left(\frac{E_x+P_o}{E_x-P_0}\right)^2$$

$$\rightarrow \begin{cases} M_T \text{ max region, } \mathrm{J}_{\max} \rightarrow \infty \text{, when } x \text{ is small} \\ M_T \text{ min region, } \mathrm{J}_{\min} \rightarrow 1 \end{cases}$$

- **In result of very different compression rate, most of the large M_{T2} events are accumulated in narrow $M_{\pi T2}$ endpoint region**





- **A faint breakpoint(e.g. signal endpoint) with small slope difference, $\Delta a \rightarrow \Delta a` = J^2 \Delta a$ by the amplification in $M_{\pi T2}$ projection.**

  With the salient breakpoint structure, the fitting scheme(function/range) can be elaborated, and it reduces the sysmematic uncertainties in extracting the position of the breakpoint.

Error analysis with histogram : $(x_i, y_i \pm \sigma_i)$

$\sigma_i =$ statistical error of the i-th bin

Statistical error for breakpoint(BP)

(using Least Square methods)

$$\delta_{BP}{}^2 \sim \frac{\sigma^2}{\Delta a^2} \rightarrow \frac{J^2\sigma^2}{J^4\Delta a^2} \sim \frac{1}{J^2}\delta_{BP}{}^2$$

$$\therefore \delta_{BP}{}^{(stat)}(M_{\pi T2}) \sim \frac{1}{J}\delta_{BP}{}^{(stat)}(M_{T2})$$

However, the error propagation factor ~ J for getting p^0,

$\delta_{p^0}{}^{(stat)}(M_{\pi T2}) \sim \delta_{p^0}{}^{(stat)}(M_{T2})$: No advantage for statistical errors.

Systematic error for BP using Segmented Linear Regression:

$(x_i, y_i) \to$ Find the BP with maximal "Coefficient of Explanation"

$$\delta_{BP}{}^2 \sim \frac{\sum \varepsilon^2}{\Delta a^2} \to \frac{\sum \varepsilon'^2}{J^4 \Delta a^2} \sim \frac{1}{J^4} \delta_{BP}{}^2$$

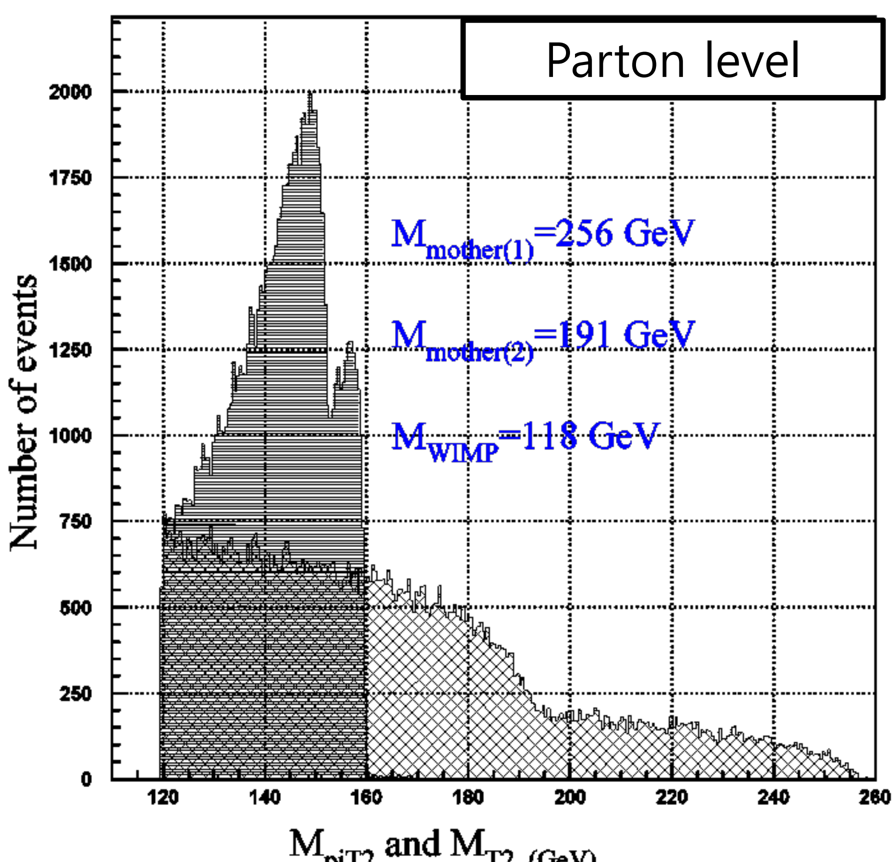
($\sum \varepsilon'^2 \sim \sum \varepsilon^2$, similar square sum of residuals after maximization *with* elaborated fitting functions)

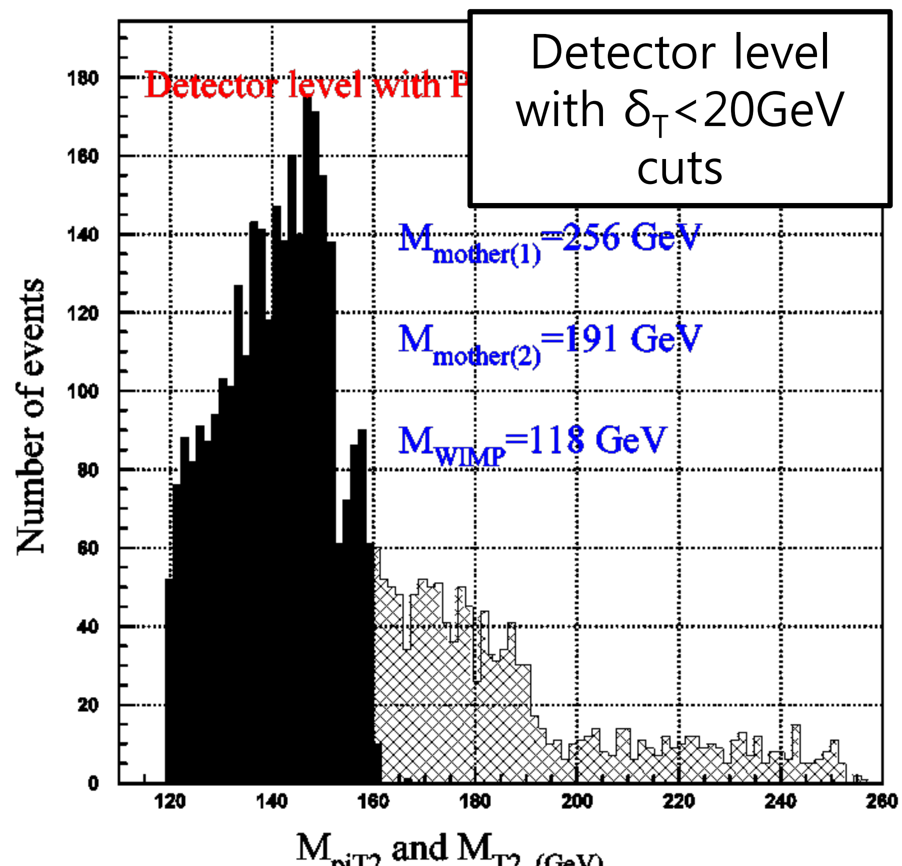
$$\therefore \delta_{BP}{}^{(sys)}(M_{\pi T2}) \sim \frac{1}{J^2} \delta_{BP}{}^{(sys)}(M_{T2})$$

Taking into account the error propagation factor,

$\delta_{p^0}{}^{(sys)}(M_{\pi T2}) \sim \frac{1}{J} \delta_{p^0}{}^{(sys)}(M_{T2})$: O(1/J) reduction is expected!

- **Shining on buried new particle endpoints (1)**
  - **2 signal endpoints from same signature (*2lepton+ MET*)**
  - **Measurement of mass differences precisely with small systematic fit errors**
  - **Example (1)** ***LH or RH slepton pair production → 2l + 2chi10***



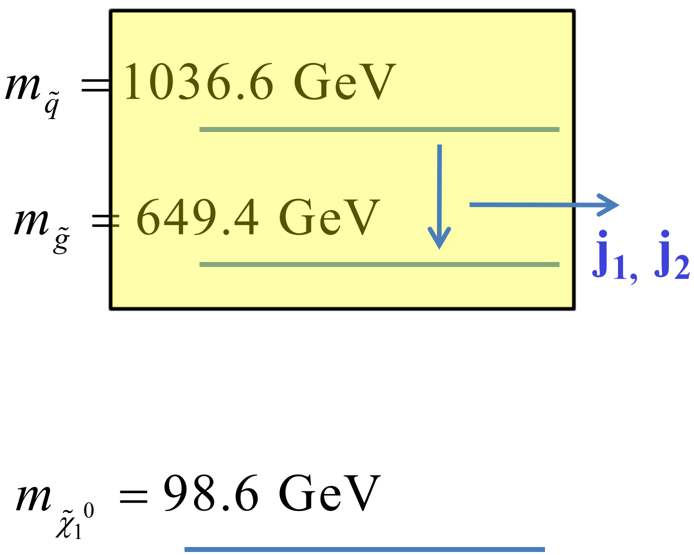


• Shining on buried new particle endpoints (2)

- Amplifying & identifying the correct 2 jet signal endpoint from squark decays to gluino.

(~q~q → j_1 ~g j_2 ~g → j_1 $j_3 j_5$ χ + j2 $j_4 j_6$χ) using >6 jets events.

- SUSY spectrum



$$\sigma(\tilde{q}\tilde{q}) = 0.5 \text{ pb},\ \sigma(\tilde{g}\tilde{q}) \sim \sigma(\tilde{g}\tilde{g}) = 3 \text{ pb}$$

The spectrum is properly separated so that the jets from squark decay and gluino decay are hard to be distinguished by any cuts.

We want to get the mass constraint, p^0

$$p^0 = \frac{m_{\tilde{q}}^2 - m_{\tilde{g}}^2}{2m_{\tilde{q}}}$$

by construction of subsystem $M_{\pi T2}$ using j_1, j_2 with gluino pair as effective missing particles.

• *E*vent and jet selection scheme for subsystem $M_{\pi T2}$

1. At least 6 jets with $P_T \geq 30\,\mathrm{GeV}$
2. No leptons, no b-jets
3. $\delta_T (\equiv |\not{\mathbf{e}}_T + \sum_{i=1..6} \mathbf{p}_T^i|) \leq 30\,\mathrm{GeV}$

P$_T$ of 6jet system

Sum of the P$_T$ of hardest 6 jets

- No particular 2-jet selection scheme.

- For signal processes, there exist 15 jet-paring combinations.

- Also there exists many background processes with gluino+squark / gluino+gluino production with hard ISR jets / ...

- We just consider all the hardest 6 jets and constructed all possible subsystem $\boldsymbol{M_{\pi T2}}^{(n=1..15)}$ *as follows*

Trial gluino mass

$$M_{\pi T2}^{(n)}(\chi) = \min_{\mathbf{k}_{1T}+\mathbf{k}_{2T}=\not{\mathbf{e}}_T^{(n)}} [\max \{M_{\pi T}^{(n,1)}, M_{\pi T}^{(n,2)}\}]$$

$$M_{\pi T}^{(n,i)}(\chi)^2 = \chi^2 + m_i^{(n)2} + 2(e_i^{(n)} e_{\chi_i} + \mathbf{p}_{iT}^{(n)'}(\pi) \cdot \mathbf{k}_{iT})$$

$$\not{\mathbf{e}}_T^{(n)} \equiv \not{\mathbf{e}}_T + \mathbf{q}_T^{(n)}.$$

Effective MET corresponding as if gluino P$_T$ sum

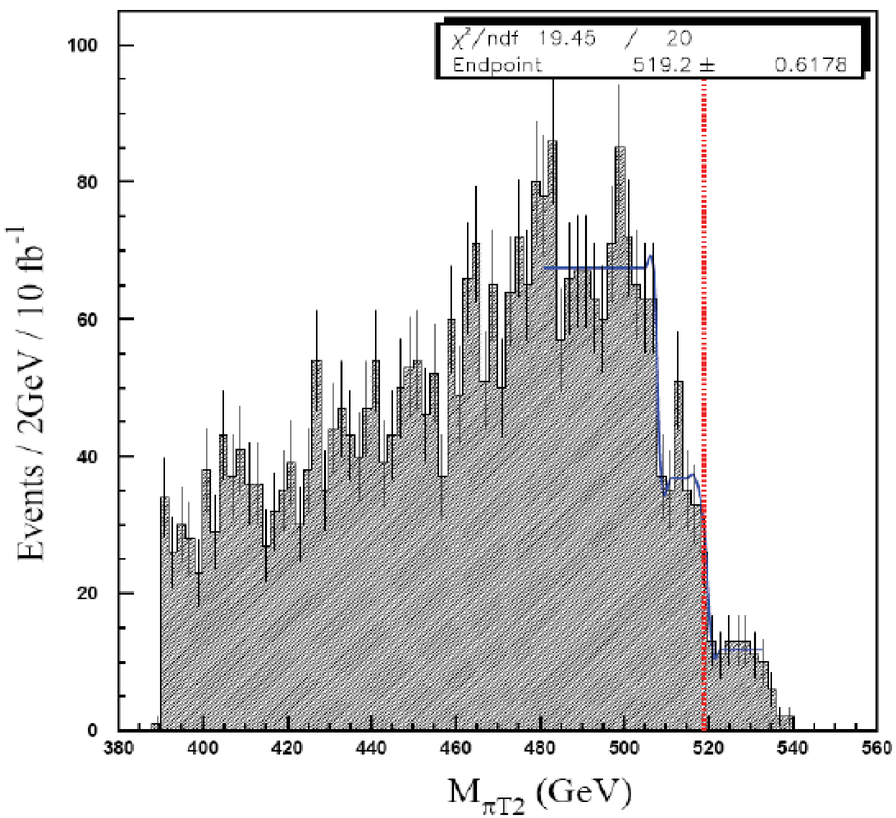
Total MET

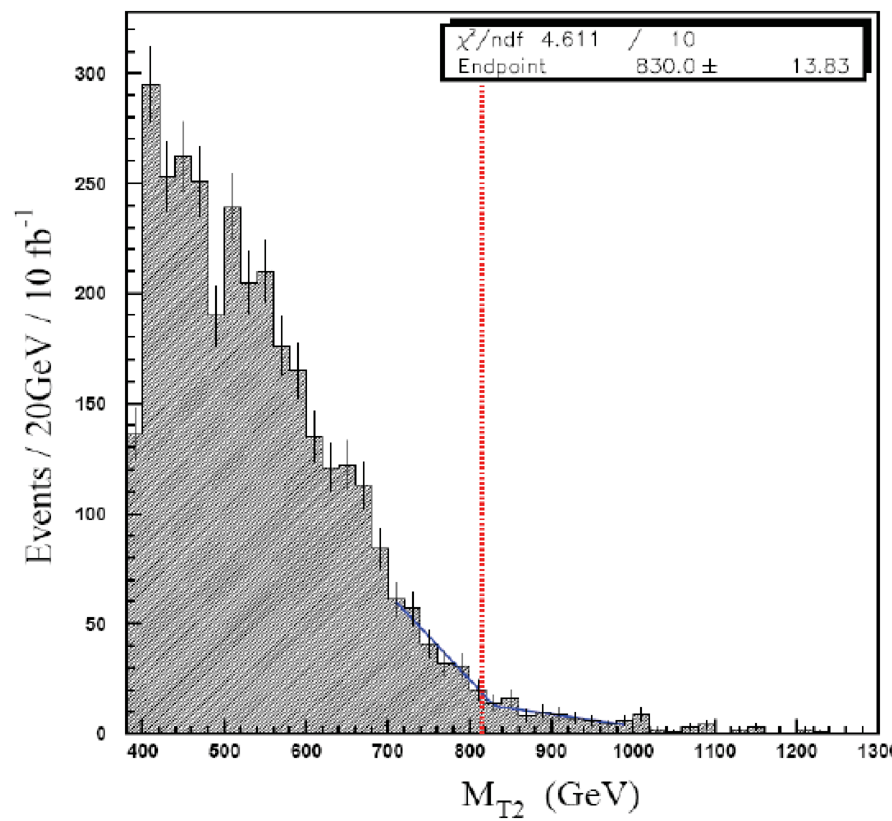
Sum of the P$_T$ of 4 jets, not selected as 2 squark jet candidate

- Histogram of all the subsystem $M_{\pi T2}$ *and* M_{T2}
- Expecting the correct tagged values (<1/15) consistently contribute to a slight slope discontinuity in M_{T2}
- Then, see the breakpoint enhancement in $M_{\pi T2}$ projection!

- Trial gluino mass = 1.24 p^0 = 389.7GeV → J =12.2
- Expected endpoint : ***$M_{\pi T2}$=519.5, M_{T2}=814.8 GeV***
- *Bin size in selected as best one among 10×(1,2,2.5) GeV*
- Model fitting function : Gaussian smeared step func / G. S. linear functions
- Mean values of measured endpoint & Systematic uncertainty in fitting (varying ranges, widths, while keeping $\chi^2/n < 2.$)

$M_{\pi T2}{}^{exp}$=519.4±0.2 GeV, $M_{T2}{}^{exp}$=797±20 GeV → ***$\delta M_{\pi T2}/\ \delta M_{\pi T2} \sim 1/J^2$***





- **Simulation :**

PYTHIA(~q~q, ~g~g, ~q~g production)(fully showered and hadronized)

→ PGS 4.0

- $\Delta E/E = 0.6/E$ in hadronic calorimeter

- Jets were reconstructed using cone algorithm, $\Delta R = 0.5$

- We ignored the jet invariant masses in constructing M_{T2} and $M_{\pi T2}$ (It was effective for reducing the jet energy res. effects in identifying the endpoint at the expected position.)

Conclusion

- $M_{\pi T2}$ **distribution has very impressive endpoint structure enhancement with respect to varying trial WIMP mass,x**

- **Small slope discontinuities are amplified by J(x)^2, enlightening the breakpoint structures clearly**

- **It might give us a chance to measure the *mass constraints* with reduced systematic uncertainties, even in the case with irreducible heavy jet combinatoric backgrounds.**