기초과학연구원
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Extracting Dark Matter Information at the LHC

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Signals with Missing Transverse Energy at Colliders

- Motivation : Dark Matter
- We can extract many information of DM once we see a signal excess.
- What kind of information? : DM mass, couplings, interaction type(e.g., s-wave int., p-wave int., whether they can form a bound state, …)

- How? : 1. Theory calculation and fitting

  → applicable for any models, but time consuming

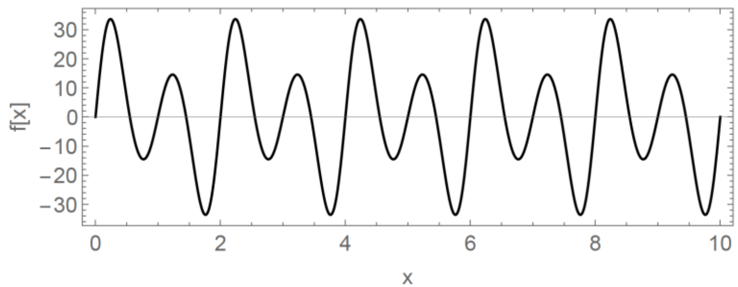
  2. Spectral decomposition

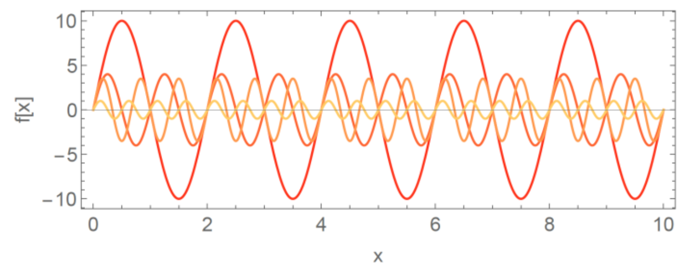
  → applicable only for s-channel mediator models,

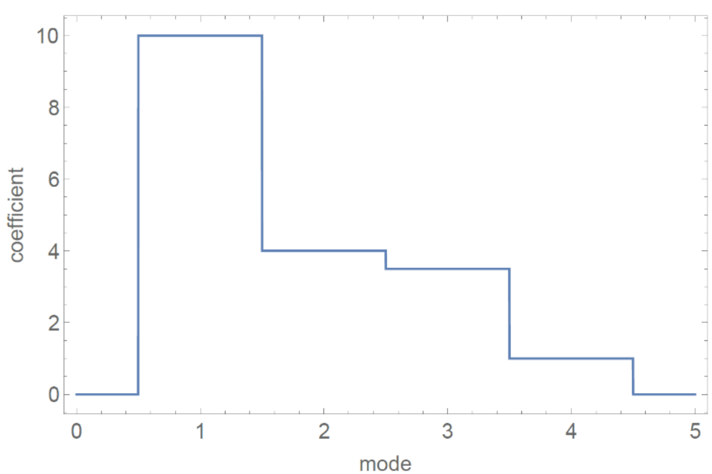
  but efficient and less biased

Spectral Decomposition

- As a classical example, whenever we see a periodic function, ...



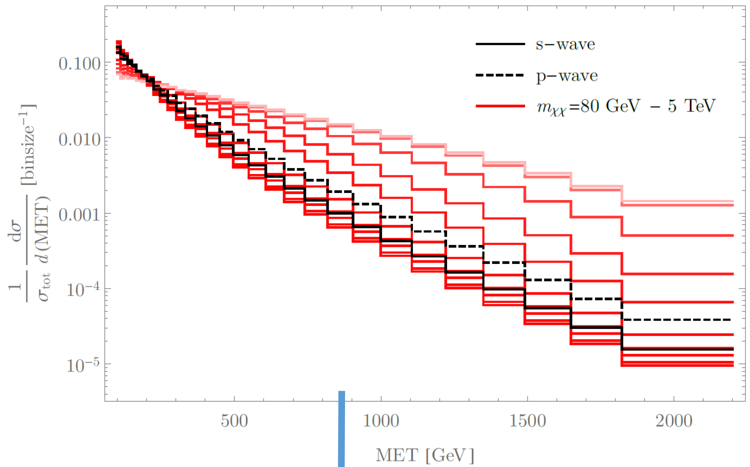


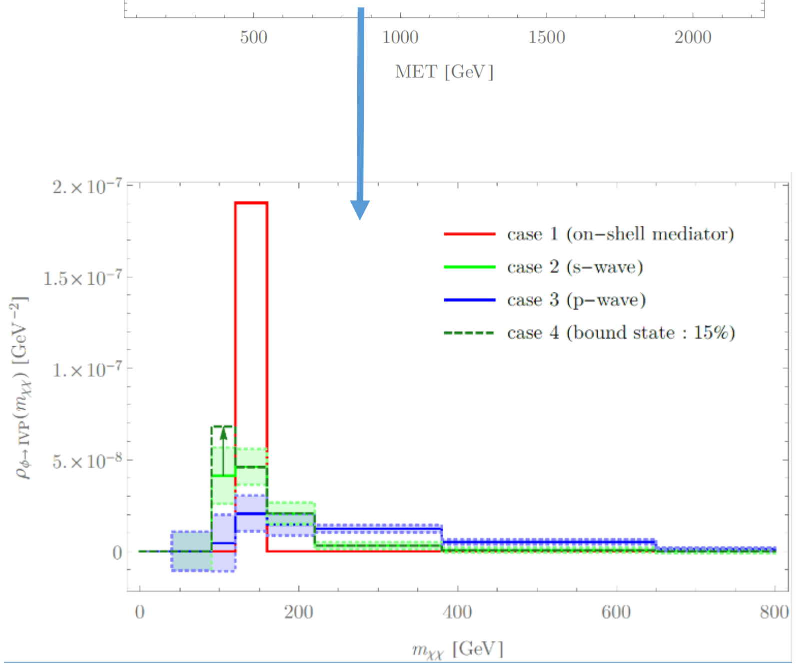


Basis functions : sin(nπx/L) w/ n= integer
Coefficients : amplitude of each mode

Spectral Decomposition

- I am going to do the similar thing to MET distribution.



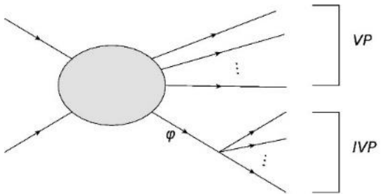


Basis functions in this case?

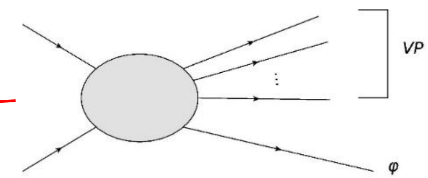
Physical meaning of coefficients?

Spectral Decomposition

- Decomposition is guaranteed by following equations if the mediator is s-channel.



$$
\begin{aligned}
\hat{\sigma}_{\rm full} &= \frac{1}{2s}\int d\Phi_{\rm VP} d\Phi_{\rm IVP}\, |\mathcal{M}_\phi|^2 \left|G_\phi(p_\phi^2, M_\phi^2)\right|^2 |\mathcal{M}_{\phi\to{\rm IVP}}|^2 (2\pi)^4 \delta^{(4)}(\sum_{i\in{\rm ext}} P_i) \\
&\times \int dp_\phi^0 \frac{d^3\vec{p}_\phi}{(2\pi)^3} (2\pi)^3 \delta^{(4)}(p_\phi - \sum_{i\in{\rm IVP}} p_i) \\
&= \int dm_\phi^2\, (\hat{\sigma}_\phi)_{p_\phi^2 = m_\phi^2} |G_\phi(m_\phi^2, M_\phi^2)|^2 \\
&\times \frac{1}{2\pi}\int d\Phi_{\rm IVP}\, |\mathcal{M}_{\phi\to{\rm IVP}}|^2 (2\pi)^4 \delta^{(4)}(p_\phi - \sum_{i\in{\rm IVP}} p_i) \\
&= \int dm_\phi^2\, (\hat{\sigma}_\phi)_{p_\phi^2 = m_\phi^2} |G_\phi(m_\phi^2, M_\phi^2)|^2 \frac{1}{\pi} (-{\rm Im}\Sigma_{\phi\to{\rm IVP}}) \\
&= \int dm_\phi^2\, (\hat{\sigma}_\phi)_{p_\phi^2 = m_\phi^2} \times \rho_{\phi\to{\rm DM}}(S_0, M_\phi^2),
\end{aligned}
$$



Narrow Width Approximation ($\sigma_{\rm full} = \sigma_\phi$ Br.)

(Partial spectral density)

Spectral Decomposition

- Decomposition is guaranteed by following equations if the mediator is s-channel.

Spin = 1 mediator?

$$\hat{\sigma}_{\text{full}} = \frac{1}{2s}\int d\Phi_{\text{VP}} d\Phi_{\text{IVP}} \left|\mathcal{M}_\phi\right|^2 \left|G_\phi(p_\phi^2, M_\phi^2)\right|^2 \left|\mathcal{M}_{\phi\to\text{IVP}}\right|^2 (2\pi)^4 \delta^{(4)}\Big(\sum_{i\in\text{ext}} P_i\Big)$$

$$\times \int dp_\phi^0 \frac{d^3\vec{p}_\phi}{(2\pi)^3} (2\pi)^3 \delta^{(4)}\Big(p_\phi - \sum_{i\in\text{IVP}} p_i\Big)$$

$$G_T(p_\phi^2, M_\phi^2)\left(-g_{\mu\nu} + \frac{p_{\phi\mu}p_{\phi\nu}}{p_\phi^2}\right) + G_L(p_\phi^2, M_\phi^2)\frac{p_{\phi\mu}p_{\phi\nu}}{p_\phi^2}$$

$$G_T(p_\phi^2, M_\phi^2) = -i/(k^2 - M_\phi^2 - \Pi_T) \text{ and } G_L(p_\phi^2, M_\phi^2) = i/(M_\phi^2 + \Pi_L)$$

$$\Pi_{\mu\nu} = \left(-g_{\mu\nu} + \frac{p_{\phi\mu}p_{\phi\nu}}{p_\phi^2}\right)\Pi_T + \frac{p_{\phi\mu}p_{\phi\nu}}{p_\phi^2}\Pi_L$$

Nonzero only when the interaction is axial (involving gamma 5)

$$\left|\mathcal{M}_\phi^\mu G_\phi(p_\phi^2, M_\phi^2)\left(-g_{\mu\nu} + \frac{p_{\phi\mu}p_{\phi\nu}}{p_\phi^2}\right)\mathcal{M}_{\phi\to\text{IVP}}^\nu\right|^2$$

$$= \left|\sum_\lambda \mathcal{M}_\phi^\mu G_\phi(p_\phi^2, M_\phi^2)(\epsilon_{\lambda,\mu}^* \epsilon_{\lambda,\nu})\mathcal{M}_{\phi\to\text{IVP}}^\nu\right|^2$$

$$\to \frac{1}{3}\sum_{\lambda,\lambda'}\left|\left(\mathcal{M}_\phi^\mu \epsilon_{\lambda,\mu}^*\right) G_\phi(p_\phi^2, M_\phi^2)\left(\mathcal{M}_{\phi\to\text{IVP}}^\nu \epsilon_{\lambda',\nu}\right)\right|^2$$

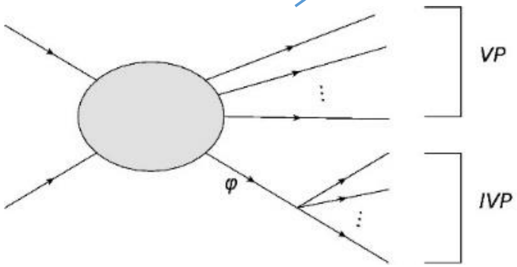
Ref : 0807.4112

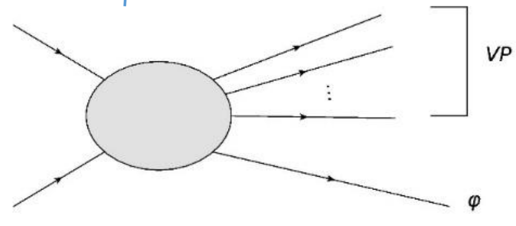
Spectral Decomposition

Kallan-Lehmann Spectral density

$$\hat{\sigma}_{\text{full}} = \int dm_{\chi\chi}^2 \; \hat{\sigma}_\phi(m_{\chi\chi}) \times \rho_{\phi\to\text{IVP}}(m_{\chi\chi}^2, M_\phi^2)$$

virtual mass of the mediator





$$\frac{d\sigma_{\text{full}}}{d\not{E}_T} = \int_0^{m_{\text{max}}^2} dm_{\chi\chi}^2 \; \frac{d\sigma_\phi(m_{\chi\chi})}{d\not{E}_T} \times \rho_{\phi\to\text{IVP}}(m_{\chi\chi}, M_\phi^2)$$

$$\frac{d\sigma_{\text{full}}}{d\not{E}_T} \simeq \sum_{i=1}^{N} c_i \; \frac{\Delta m_{\chi\chi}^{(i)}}{m_{\chi\chi}^{(i)}} \frac{d\sigma_\phi(m_{\chi\chi}^{(i)})}{d\not{E}_T}$$

coefficient

basis function

(Mediator model dependent)

Spectral Decomposition

Obtained by fitting

$$\frac{d\sigma_{\text{full}}}{d\not{E}_T} \simeq \sum_{i=1}^{N} c_i \frac{\Delta m_{\chi\chi}^{(i)}}{m_{\chi\chi}^{(i)}} \frac{d\sigma_\phi(m_{\chi\chi}^{(i)})}{d\not{E}_T}$$

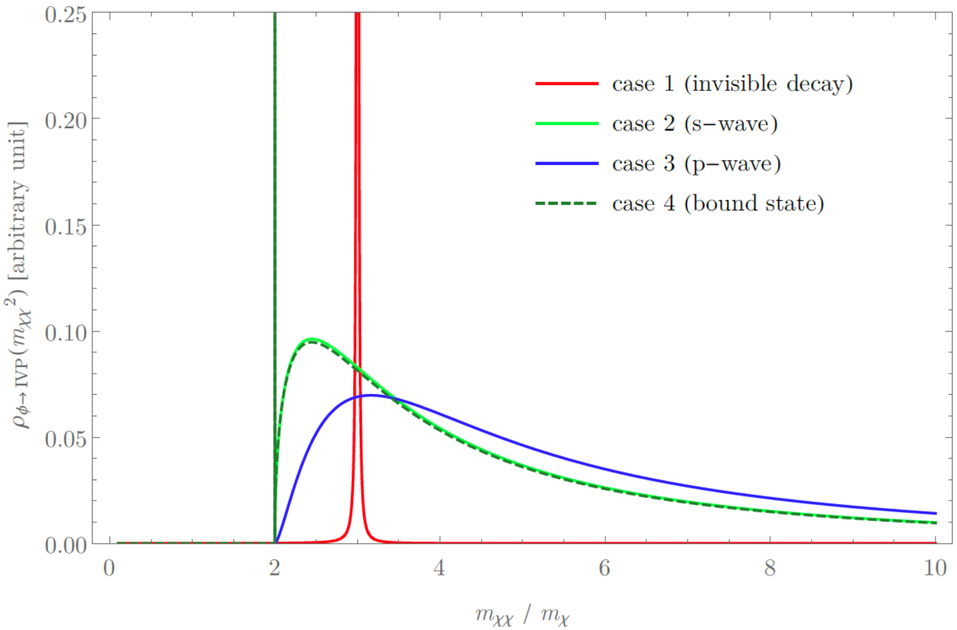
Signal Data

Calculation from given Mediator Model

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{Med}-\text{SM}} + \mathcal{L}_{\text{Mediator}} + \mathcal{L}_{\text{Med}-\text{DM}} + \mathcal{L}_{\text{DM}}$$

Physical meaning of coefficients = spectral density

	Mediator	Interaction
Case 1	On-shell($M_\phi > 2m_\chi$)	Resonance
Case 2	Off-shell($M_\phi < 2m_\chi$)	S-wave
Case 3	Off-shell($M_\phi < 2m_\chi$)	P-wave
Case 4	Off-shell($M_\phi < 2m_\chi$)	S-wave & bound state (long range force)



Example : Mono-jet channel w/ Simplified Model

1. Simplified model

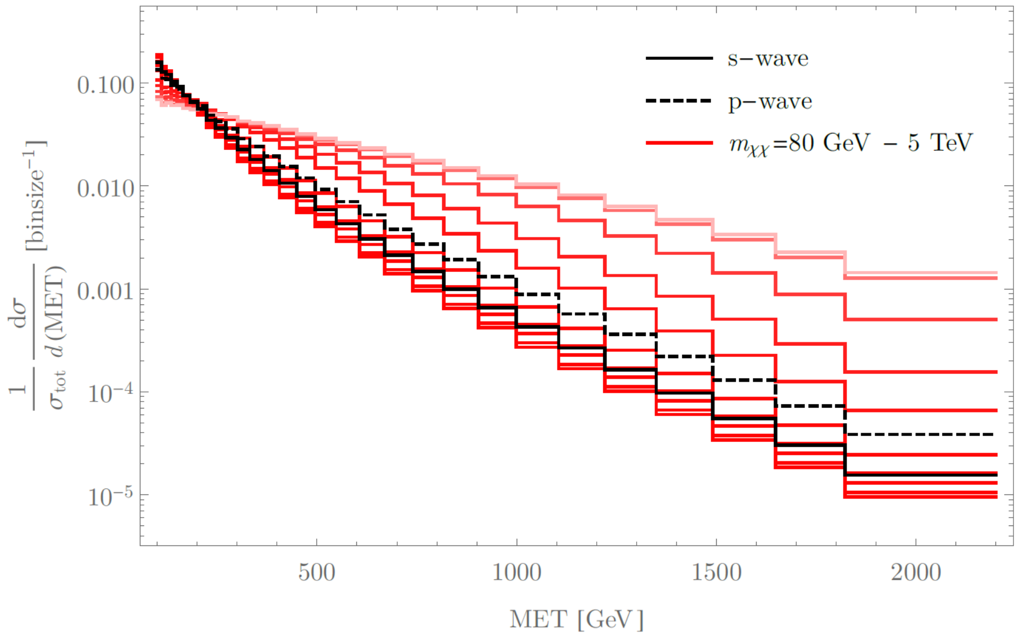
$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2}\partial^\mu\phi\partial_\mu\phi - \frac{1}{2}m_\phi^2\phi^2 + \frac{k}{\Lambda}\phi G^{a\mu\nu}G^a_{\mu\nu}$$
$$+ \mathcal{L}_{1/2-{\rm DM}} + \mathcal{L}_{0-{\rm DM}}$$
$$\mathcal{L}_{1/2-{\rm DM}} = \bar\chi(i\partial\!\!\!/ - m_\chi)\chi + y_\chi\phi\bar\chi\chi$$
$$\mathcal{L}_{0-{\rm DM}} = \frac{1}{2}\partial^\mu s\partial_\mu s - \frac{1}{2}m_s^2 s^2 + \frac{1}{2}m_s g_s\phi s^2$$

2. Parton level

3. Tree level

$$\frac{d\sigma_{\rm full}}{d\not\!\!E_T} \simeq \sum_{i=1}^{N} c_i\,\frac{\Delta m_{\chi\chi}^{(i)}}{m_{\chi\chi}^{(i)}}\,\frac{d\sigma_\phi(m_{\chi\chi}^{(i)})}{d\not\!\!E_T}$$

Example : Mono-jet channel w/ Simplified Model

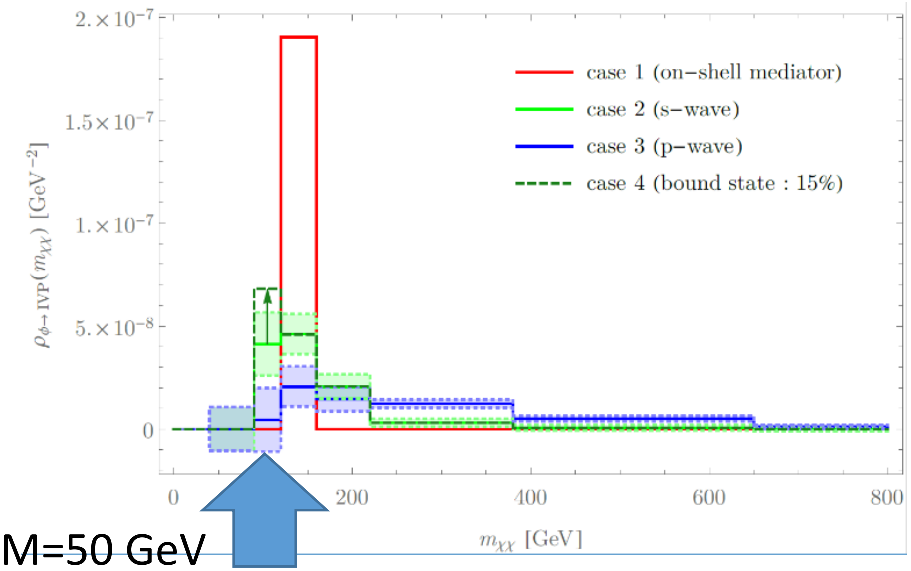


Lessons

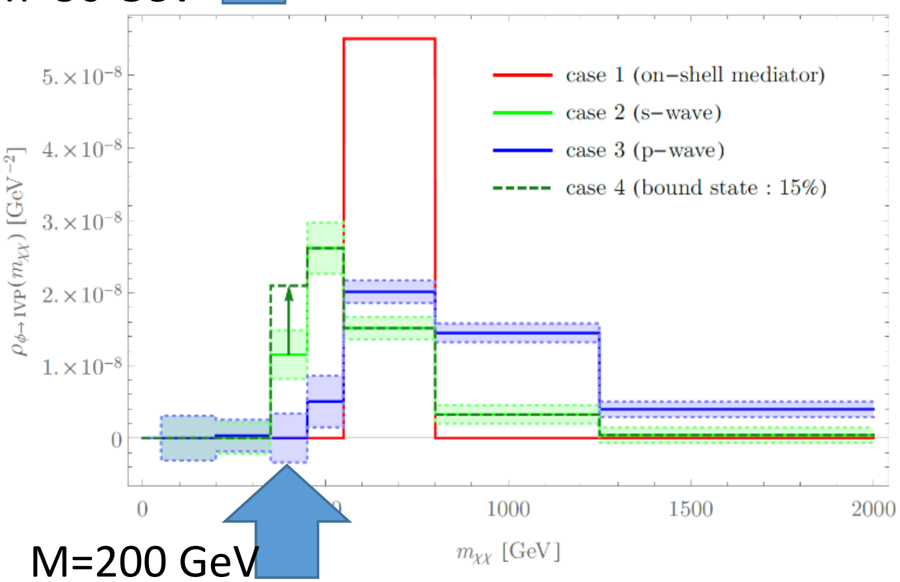
1. As m_ϕ increases, events are more distributed at hard MET (PT of jet) region.

2. At hard PT region, m_ϕ dependence of the slope becomes weaker.
(, but S/B ratio becomes bigger. => some balance on PT cut)

Example : Mono-jet channel w/ Simplified Model



M=50 GeV



M=200 GeV

L=3 ab^{-1} , $S/\sqrt{S+B} = 10$

(If the current significance ~ 1,
then probably it would be 10 for HL-LHC)

Summary

1. Spectral decomposition approach is suggested as a method to extract information of dark matter.

2. We applied it to the monojet channel with simplified model. It can be applied to any other channels, but only with

   s-channel mediator models.

   And you can play with other kinematics, as well.

Thank you!

Back Up

luminosity function

$$\sigma_\phi = \sum_{i,j} \int dx_1 dx_2 P_i(x_1) P_j(x_2) \hat{\sigma}_\phi^{(ij)}$$

$$= \sum_{i,j} \int dm_{ij} dy \frac{dL_{ij}}{dm_{ij} dy} \hat{\sigma}_\phi^{(ij)}$$

$$\frac{dL_{ij}}{dm_{ij}dy} = \frac{2m_{ij}}{S} P_i(\frac{m_{ij}}{\sqrt{S}} e^y) P_j(\frac{m_{ij}}{\sqrt{S}} e^{-y})$$

$$\frac{d\sigma_\phi}{d\not{p}_T} = \sum_{i,j} \int_{\not{p}_T + \sqrt{\not{p}_T^2 + m_\phi^2}}^{\sqrt{S}} dm_{ij} f_{ij}(m_{ij}) \frac{d\hat{\sigma}_\phi^{(ij)}}{d\not{p}_T}$$

$$\frac{\frac{d\sigma_\phi}{d\not{p}_T}(\not{p}_T, m_{ij}, m_\phi)}{\frac{d\sigma_\phi}{d\not{p}_T}(0, m_{ij}, m_\phi)} \sim \frac{f_{ij}(\not{p}_T + \sqrt{\not{p}_T^2 + m_\phi^2})}{f_{ij}(m_\phi)}$$