Measuring the spectrum of Freeze-In Dark Matter model at the LHC

第十五届TeV物理工作组学术研讨会

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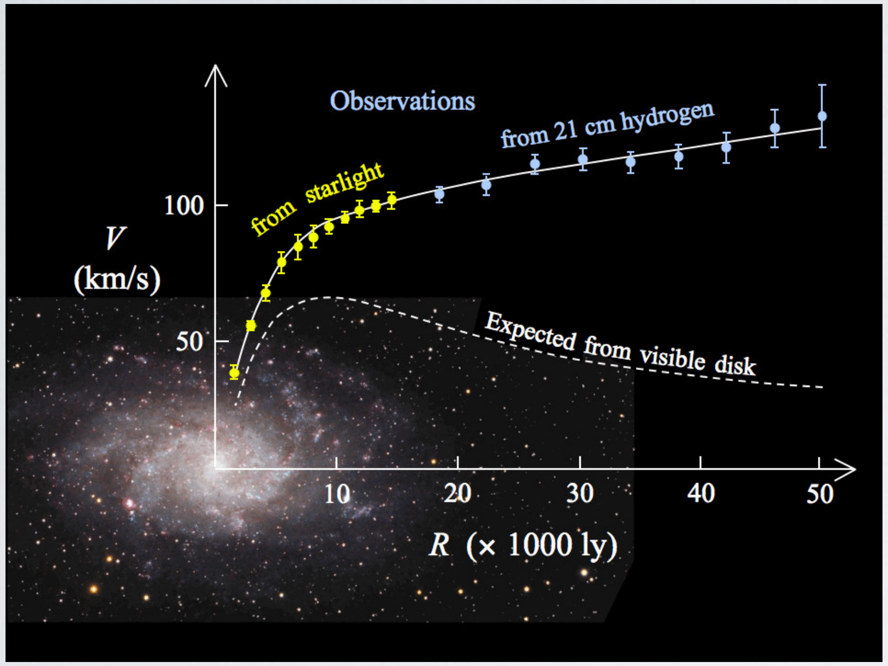
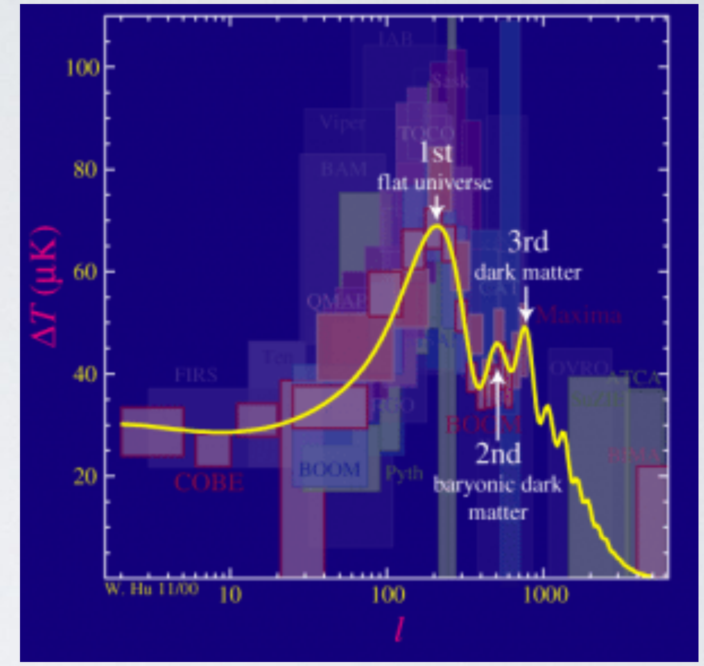
Based on: *Phys.Rev.D* 101 (2020) 11, 115036 (Kyujung Bae, Myeonghun Park, MZ)

There are many evidence of DM

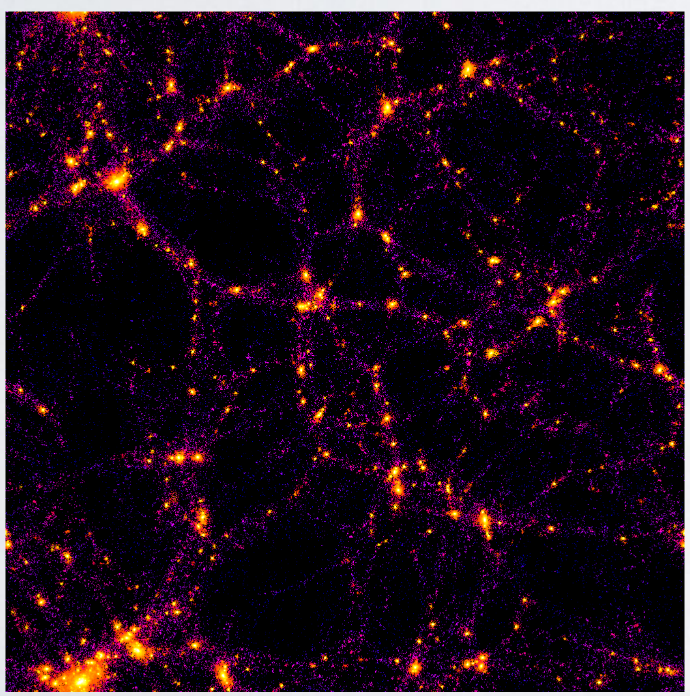


Galaxy rotation curve

Gravity lensing



CMB an-isotropy

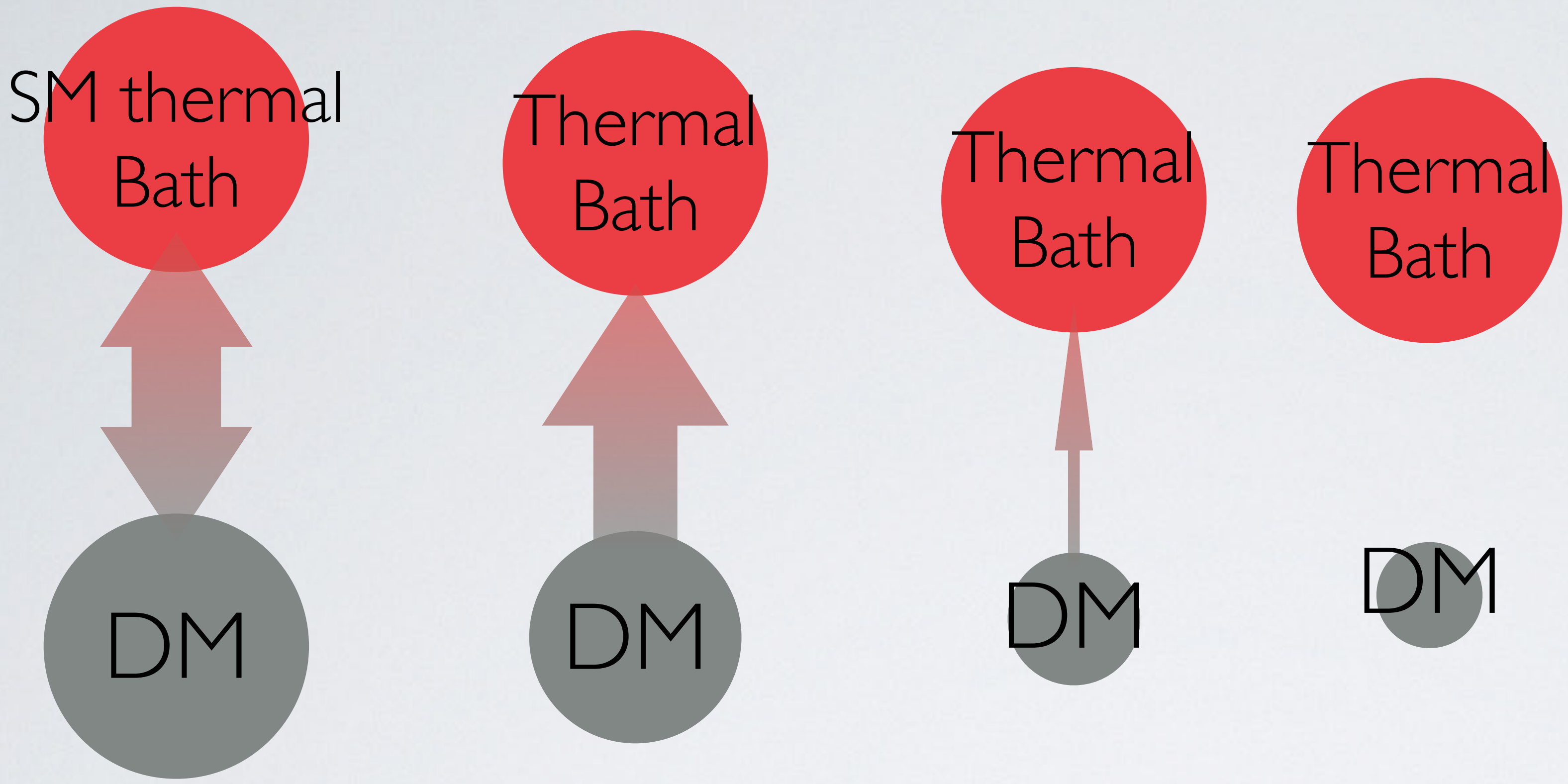


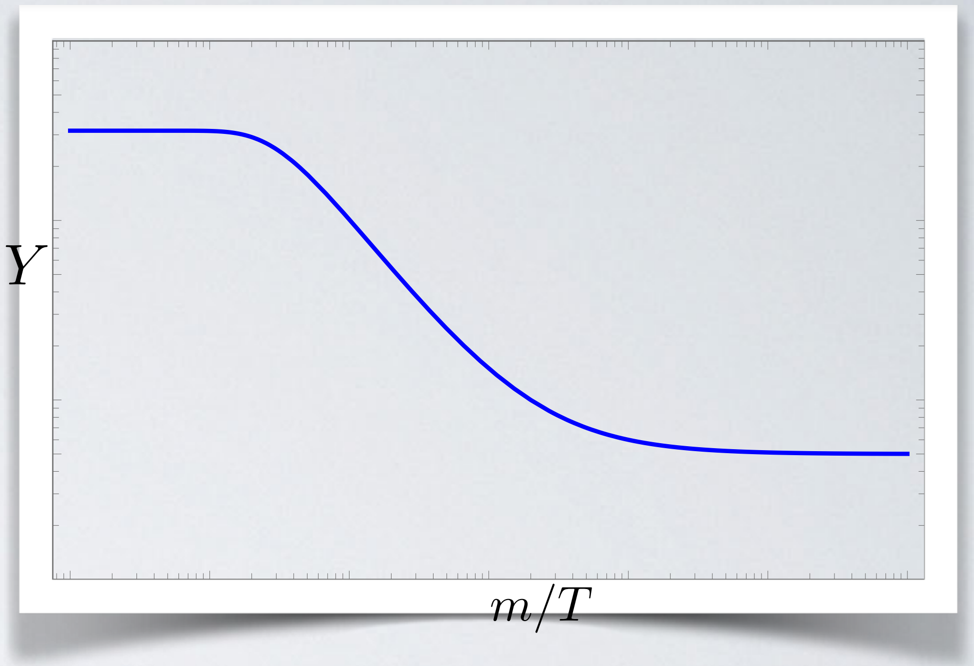
Large scale structure

Bullet cluster

And we know neutrino is too hot and too light to be a DM candidate. New Physics is needed for DM.

Most popular DM candidate: WIMP





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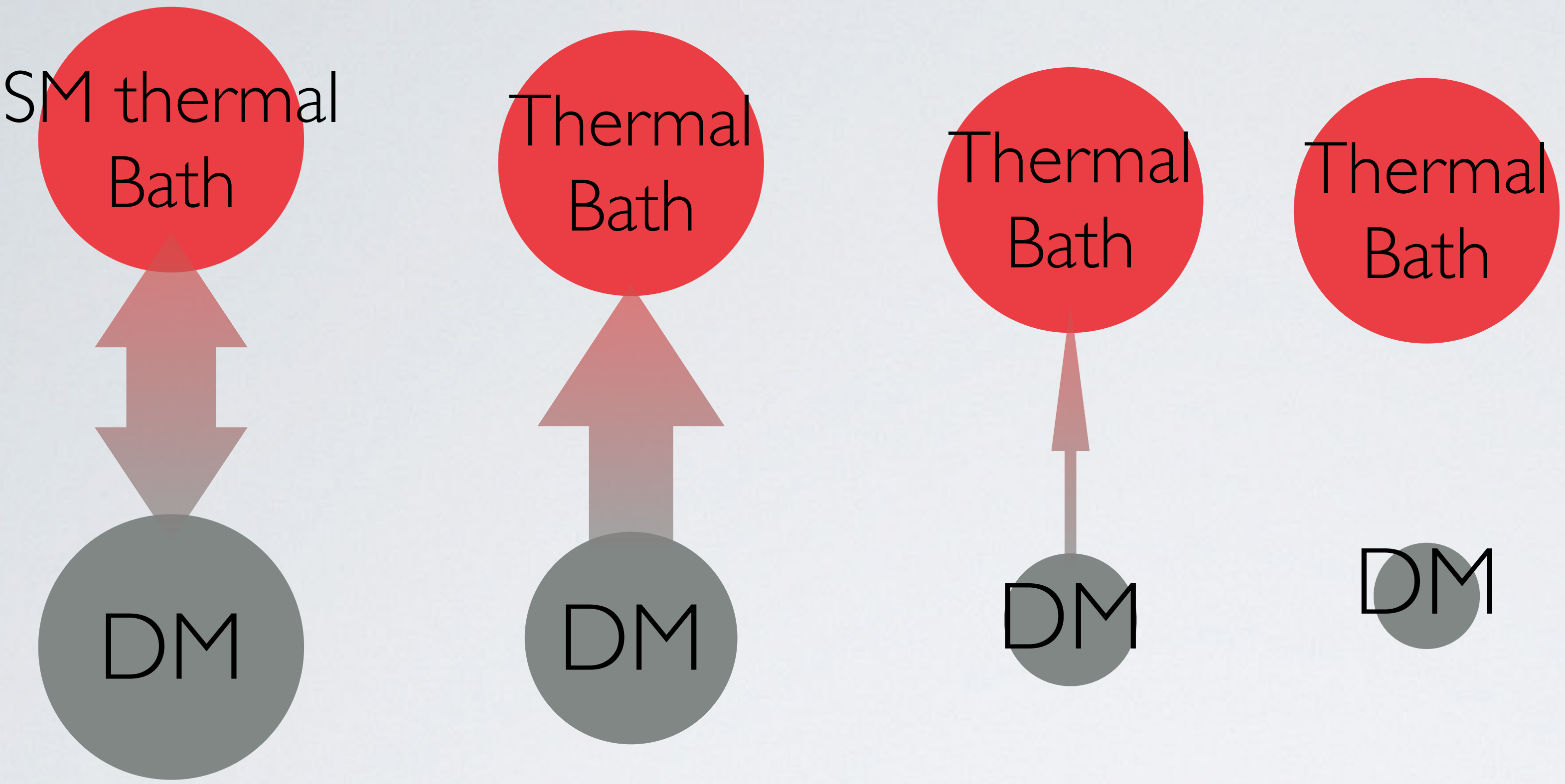
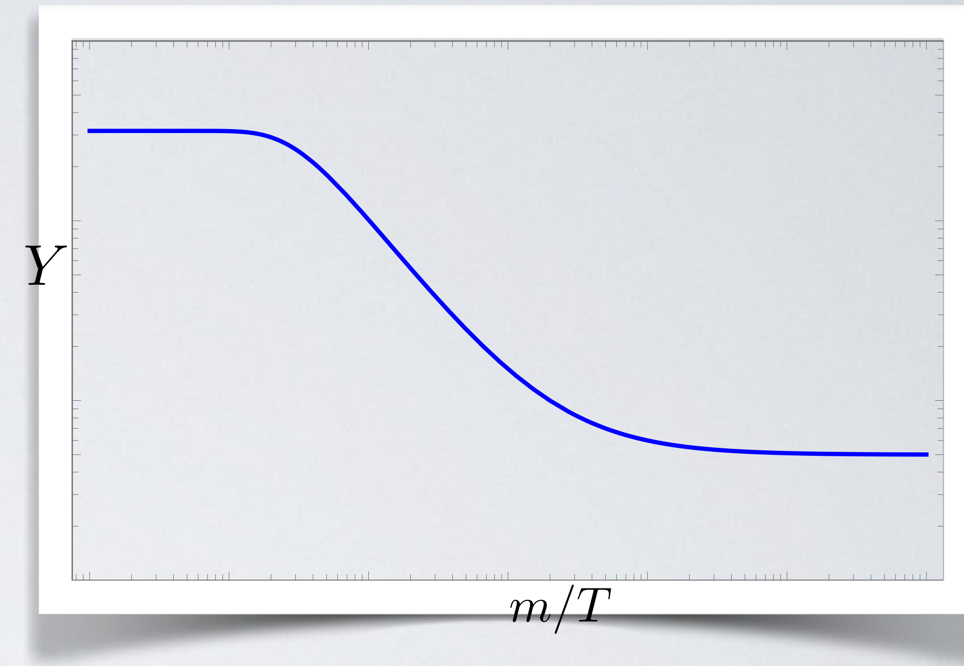
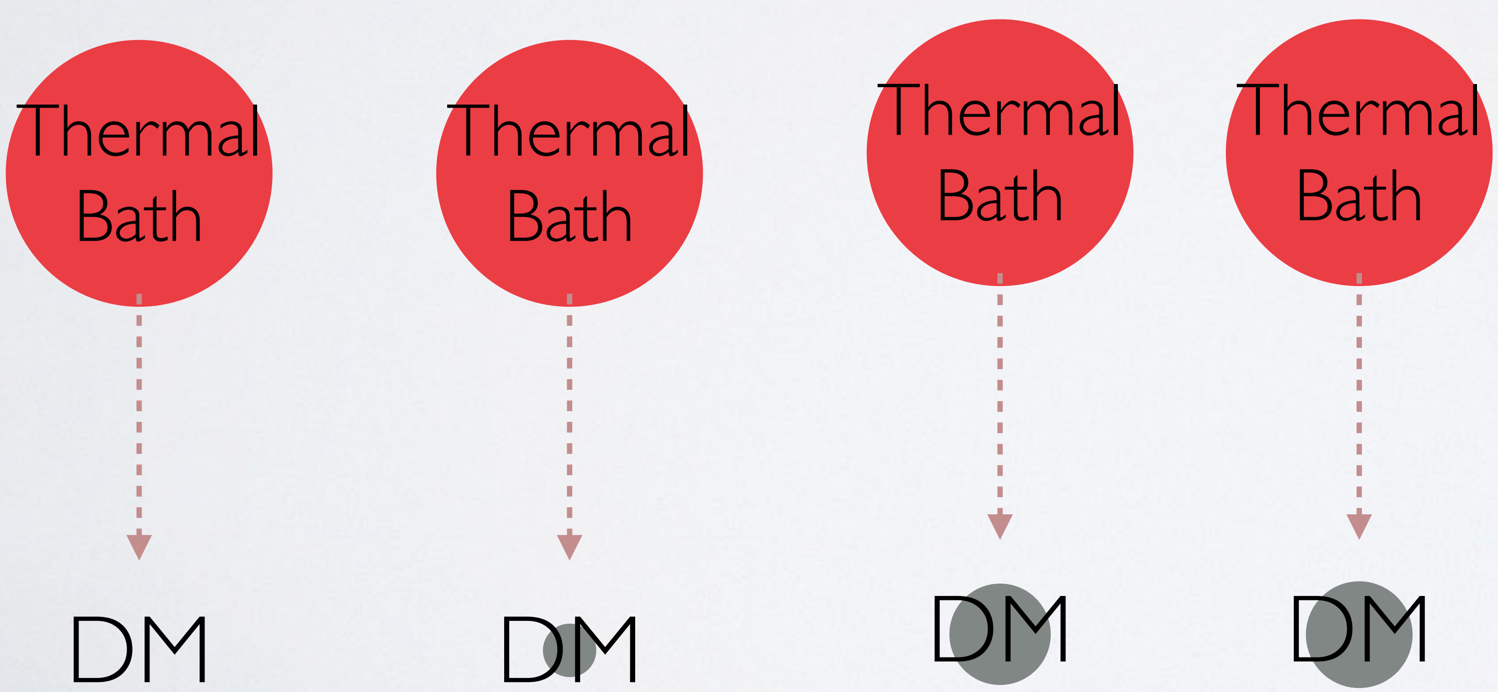




If the coupling between SM and DM is very very small:



For both model, relic density is fixed by CMB: $\Omega h^2 = 0.1199 \pm 0.0022$

But the phase space distribution can be very different.
Freeze-out: thermal distribution
Freeze-in: non-thermal distribution

LSS: Ly-α forest data: $m_{\rm WDM} \gtrsim 5.3$ keV

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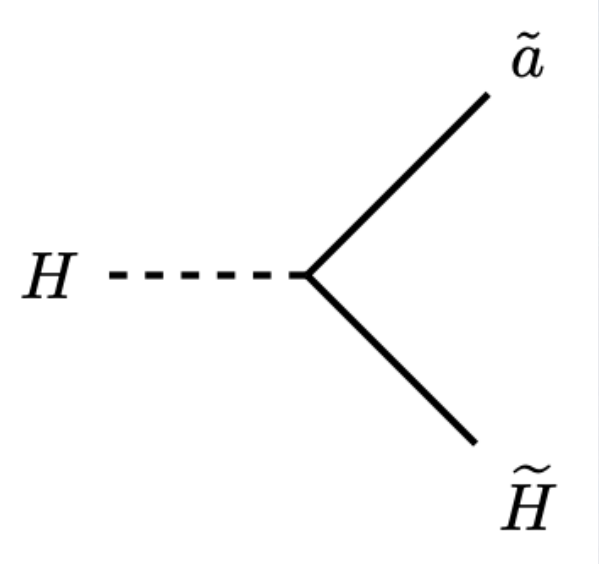
$$\frac{df_{\tilde a}(t,p)}{dt} = \frac{\partial f_{\tilde a}(t,p)}{\partial t} - \frac{\dot R(t)}{R(t)} p \frac{\partial f_{\tilde a}(t,p)}{\partial p} = \frac{1}{E_{\tilde a}} C(t,p)$$



$$\frac{g_{\tilde a}}{E_{\tilde a}} C_{1\to \tilde a+2}(t,p_{\tilde a}) = \pm \frac{T}{16\pi p_{\tilde a} E_{\tilde a}} \sum_{\rm spin} |\mathcal{M}_{1\to\tilde a+2}|^2 \ln \left(\frac{1 \pm e^{-(E_2^- + E_{\tilde a})/T}}{1 \pm e^{-(E_2^+ + E_{\tilde a})/T}} \right)$$

1707.06418

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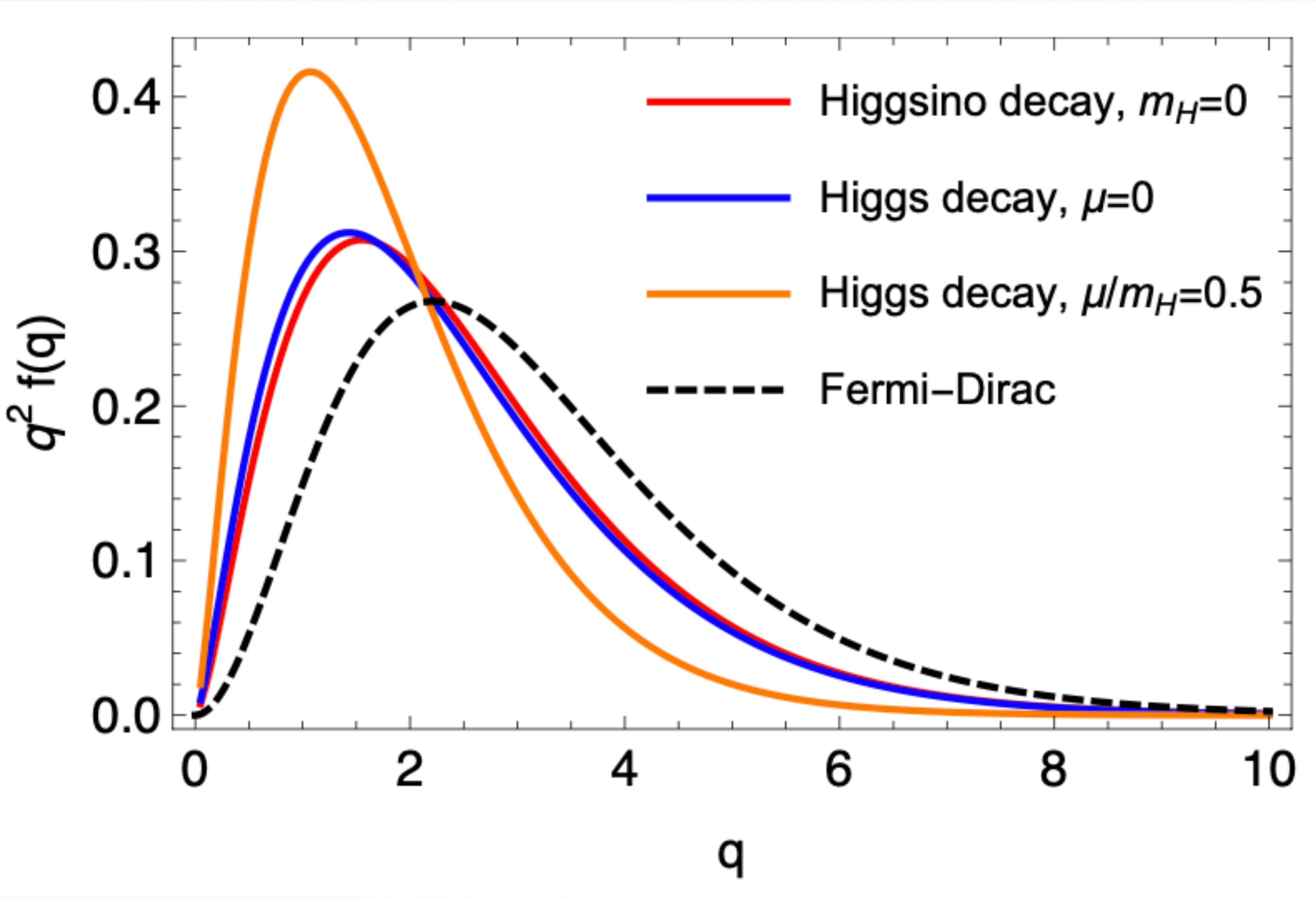
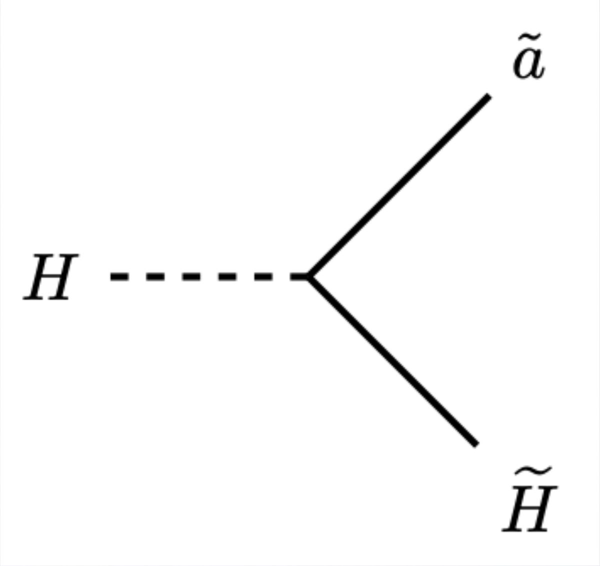




1707.06418

keV FIDM can be "cold"

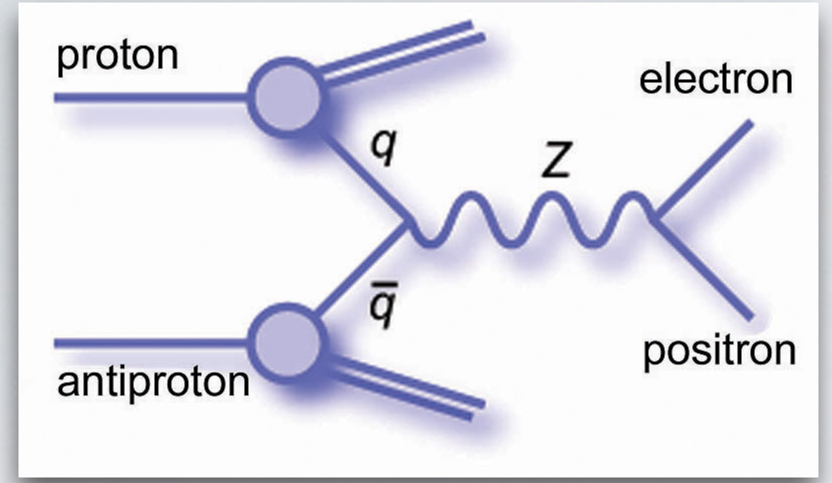
Thus for FIDM, spectrum plays a key role. Q: can we measure it?

Conclusion of this work: with the help of displace vertex (common in FIDM), we can measure the spectrum of dark sector through limited signal events.

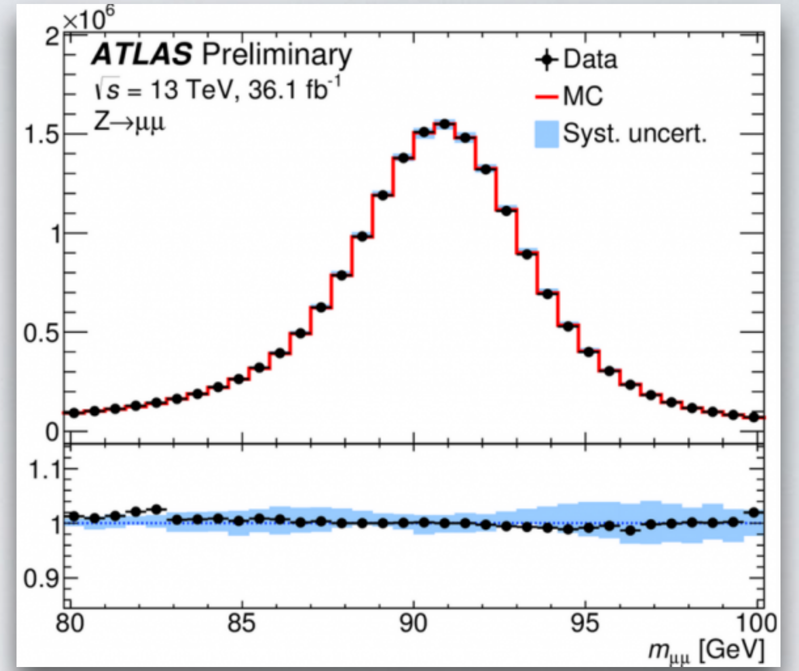
Compared with previous work (1110.1403 & 1801.09671), we clearly pointed out the solvability condition, and did a more realistic analysis(uncertainty+limited signal events).

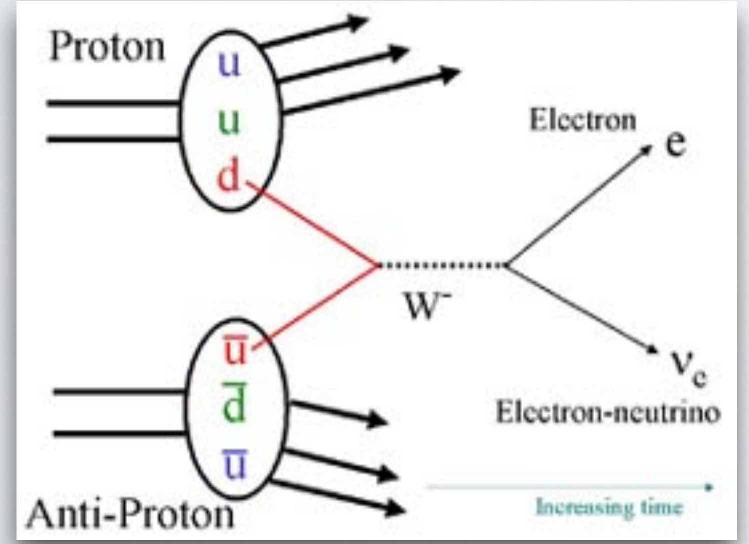
- Motivation: WIMP v.s. FIDM
- **Spectrum measurement at collider**
- More realistic analysis: Uncer. and limited events
- Clean up our data: filtering algorithm

Spectrum measurement

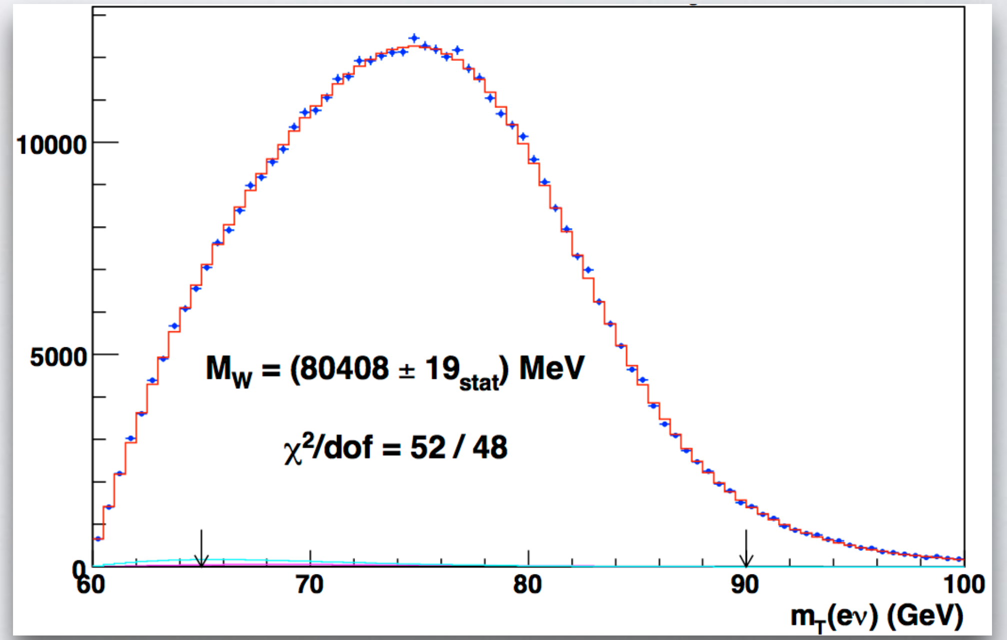


$$m = \sqrt{(p_1 + p_2)^2}$$



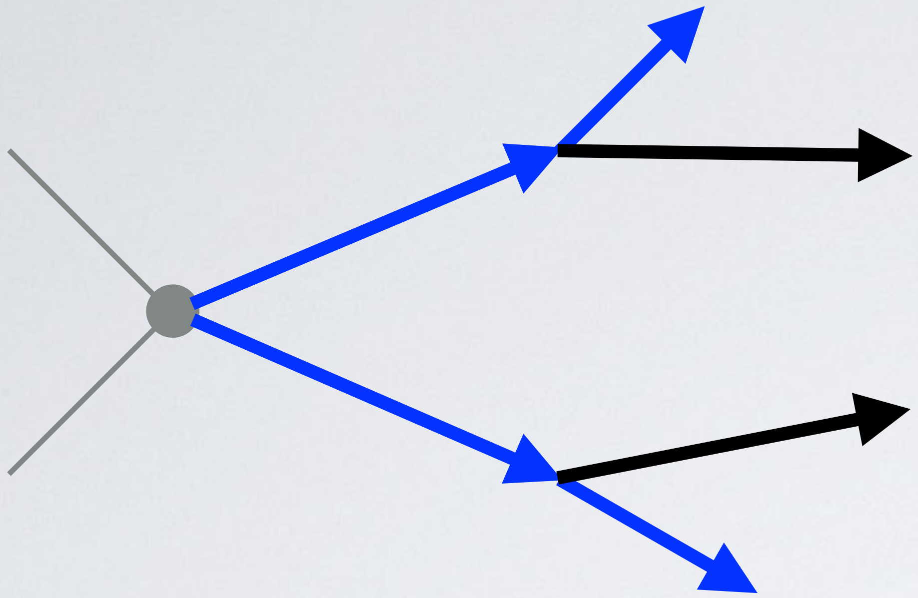


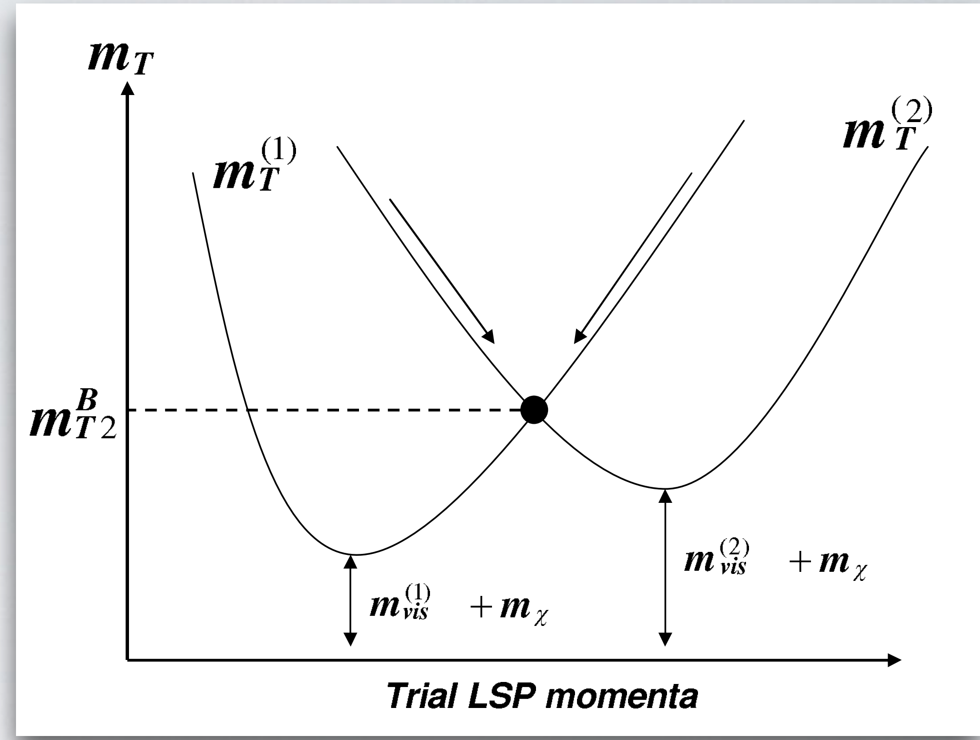
$$m_T^2 = m_l^2 + m_\nu^2 + 2(E_T^l E_T^\nu - \mathbf{p}_T^l \cdot \mathbf{p}_T^\nu)$$



Spectrum measurement

But what if there are 2 inv. particles?





$$m_{T2}(\mathbf{p}_T^{vis(1)}, m_{vis}^{(1)}, \mathbf{p}_T^{vis(2)}, m_{vis}^{(2)}, m_\chi) \equiv \min_{\{\mathbf{p}_T^{\chi(1)}+\mathbf{p}_T^{\chi(2)}=-\mathbf{p}_T^{vis(1)}-\mathbf{p}_T^{vis(2)}\}} \left[\max\{m_T^{(1)}, m_T^{(2)}\}\right]$$

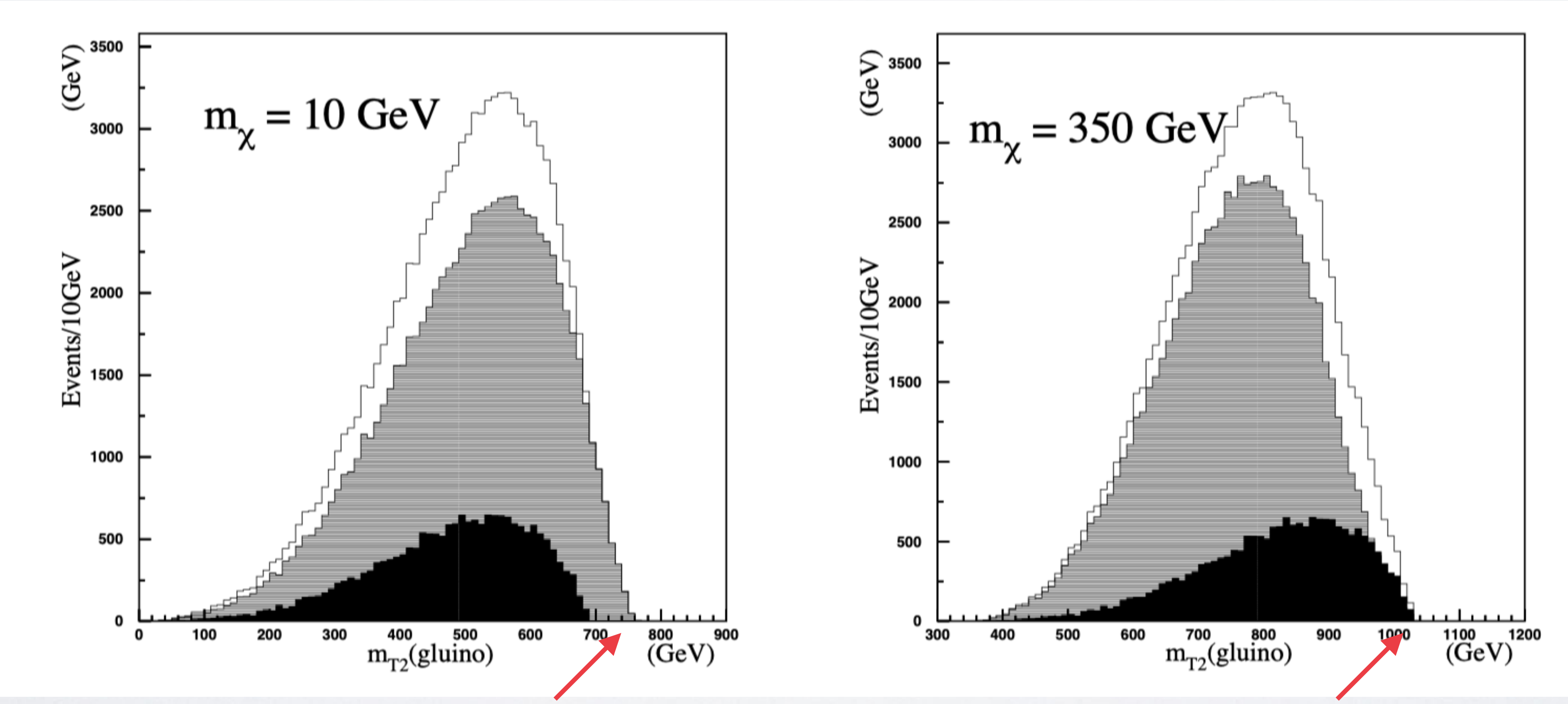
$$\mathbf{p}_T^{\chi(1)} + \mathbf{p}_T^{\chi(2)} = \mathbf{p}_T^{miss}$$

$$m_T^{(i)} = \sqrt{(m_{vis}^{(i)})^2 + m_\chi^2 + 2(E_T^{vis(i)} E_T^{\chi(i)} - \mathbf{p}_T^{vis(i)} \cdot \mathbf{p}_T^{\chi(i)})},$$

Spectrum measurement

Benchmark point: $m_{\tilde{g}} = 780 \text{ GeV}, \quad m_{\tilde{\chi}_1^0} = 98 \text{ GeV}$

You don't know the real mass of LSP, you need to try:



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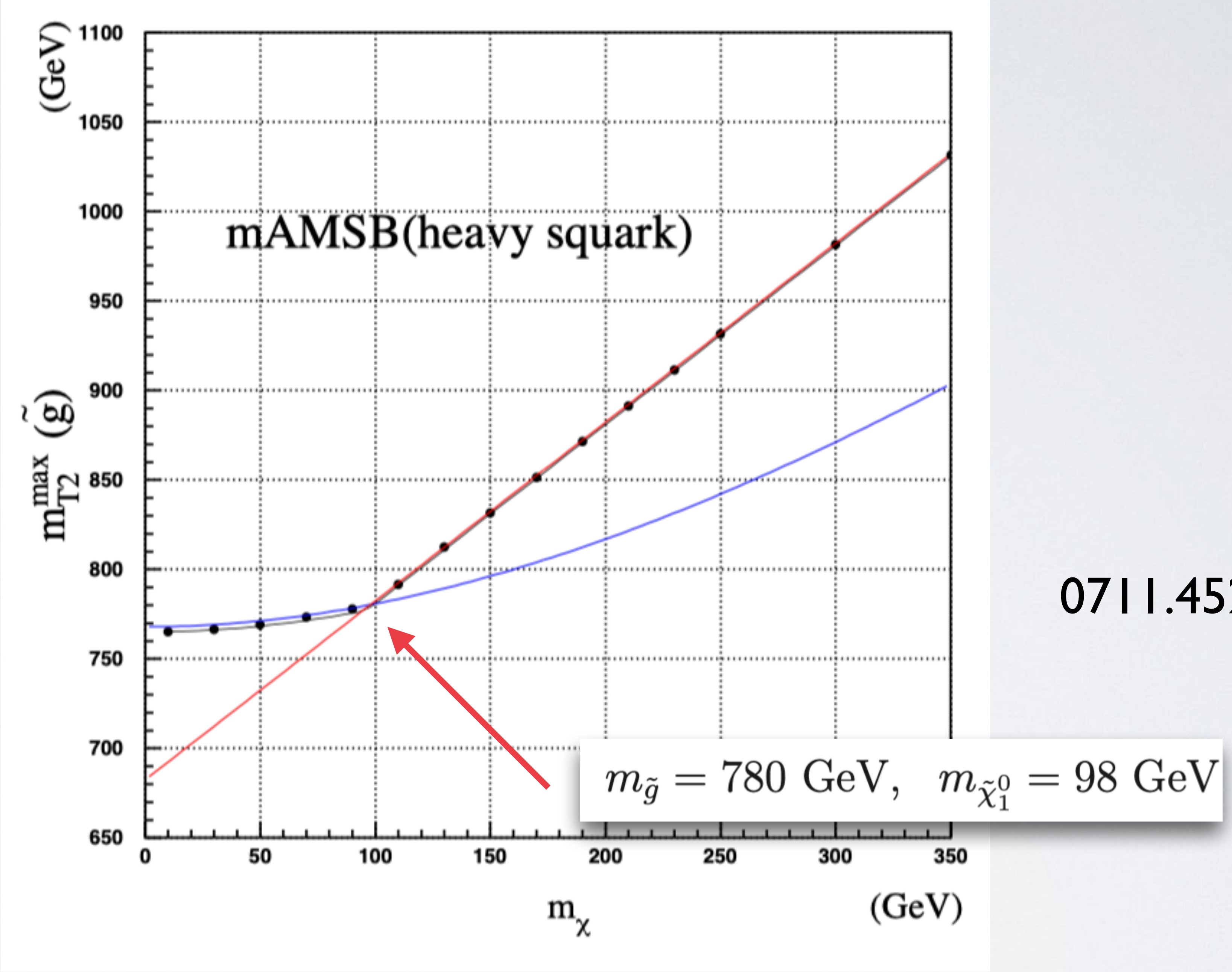
Kink!



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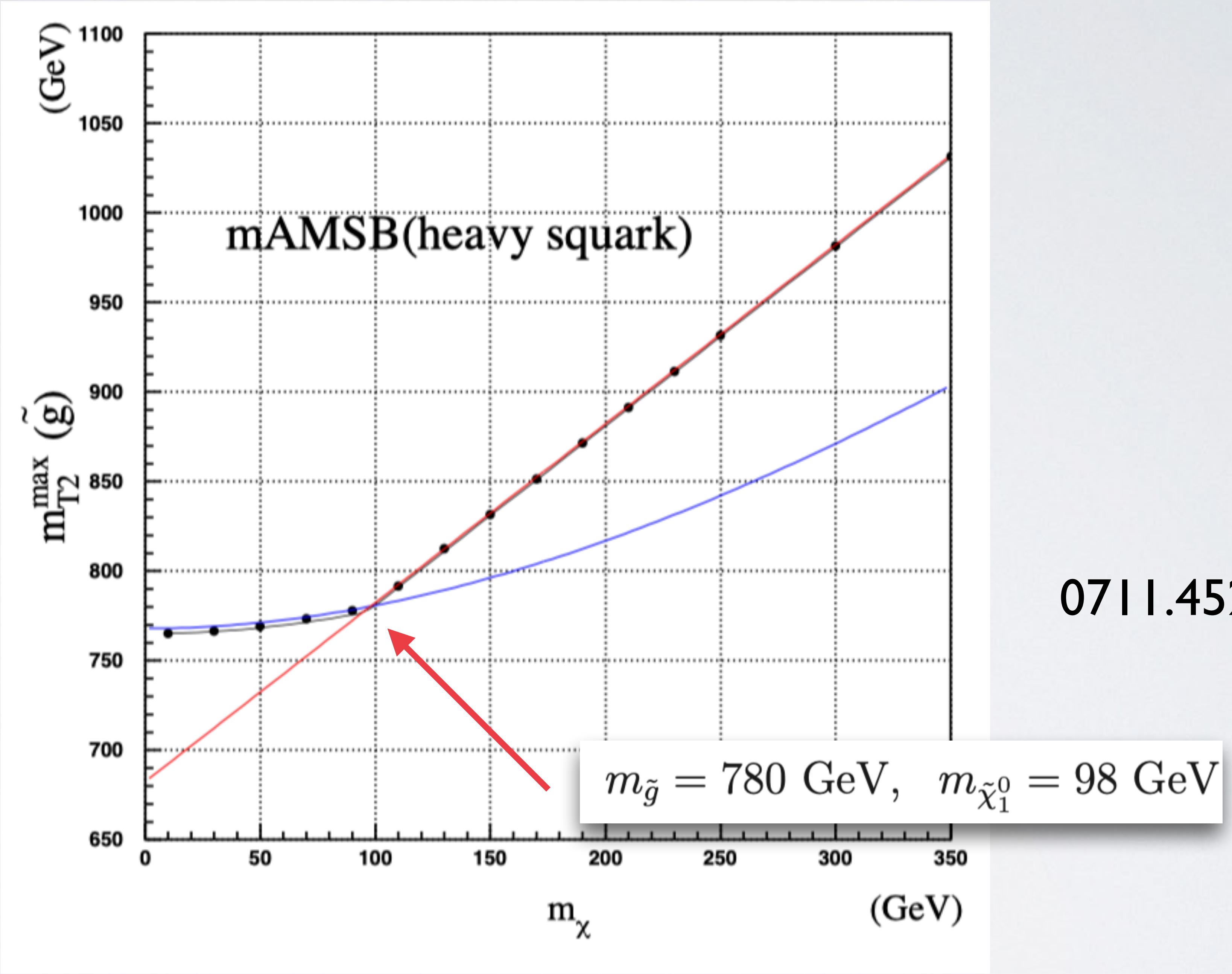

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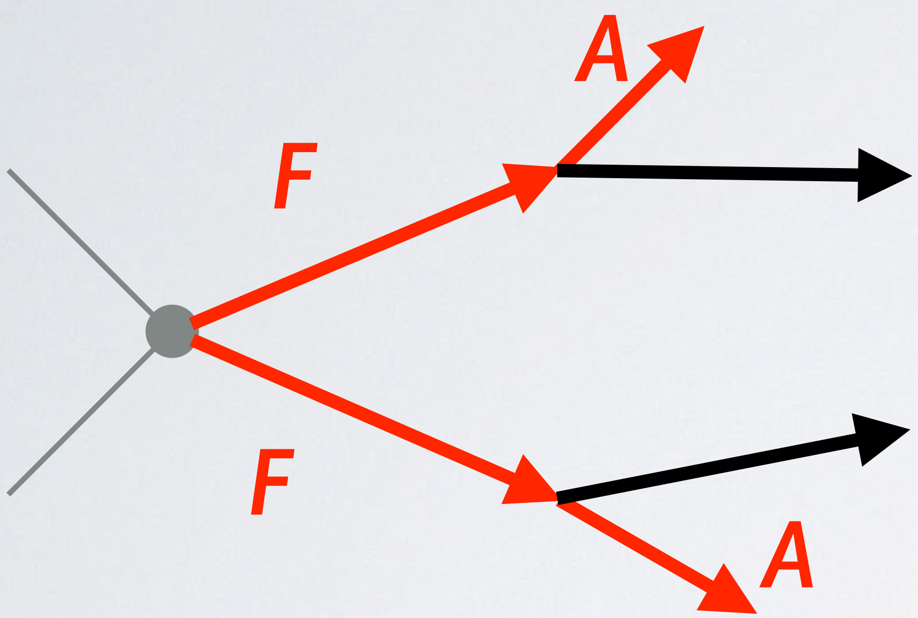
But you need numerous signal events to utilize MT2!

In "LHC friendly" FIDM model, mother particles are long-lived, can we get something new?

("LHC friendly",1811.05478)

$$\frac{1}{\Gamma_F} \approx 50 \text{ cm} \times \left(\frac{10^{-8}}{\lambda}\right)^2 \left(\frac{200 \text{ GeV}}{m_F}\right)$$

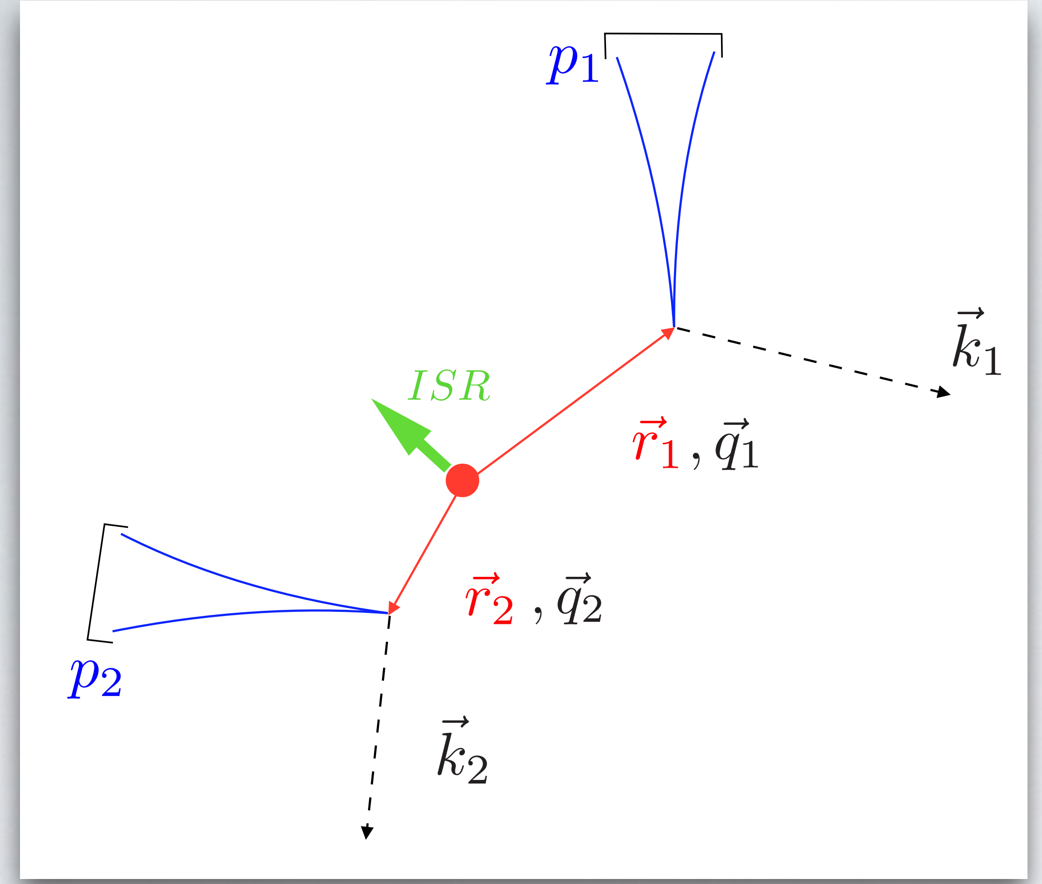


Long-lived F $\rightarrow$ displaced vertex $\rightarrow$ direction of F

There are some new information!

I will show you:
If there are two displaced vertex (DV) and initial state radiation (ISR), you can obtain the mass of F and DM by only one event.

This is the process we consider



Things we can directly measure:

- 4-momentum of two visible daughter particles, p_1 and p_2.
- missing transverse momentum, $\vec{\not{p}}_T$.
- position of 2 DVs, $\vec{r}_1$ and $\vec{r}_2$.

So we know the direction of F's momentum:

$$\hat{\vec{r}}_1 = (\ \sin\theta_1 \cos\phi_1\ ,\ \sin\theta_1 \sin\phi_1\ ,\ \cos\theta_1\ )$$
$$\hat{\vec{r}}_2 = (\ \sin\theta_2 \cos\phi_2\ ,\ \sin\theta_2 \sin\phi_2\ ,\ \cos\theta_2\ )$$

and

$$\vec{q}_1 = |\vec{q}_1|\hat{\vec{r}}_1\ ,\ \vec{q}_2 = |\vec{q}_2|\hat{\vec{r}}_2$$

By using 3-momentum conservation, 3-momentum of DM are:

$$\vec{k}_1 = |\vec{q}_1|\hat{\vec{r}}_1 - \vec{p}_1\ ,\ \vec{k}_2 = |\vec{q}_2|\hat{\vec{r}}_2 - \vec{p}_2$$

Missing transverse momentum comes from DM pair:

$$\vec{\not{p}}_T = \left\{\vec{k}_1 + \vec{k}_2\right\}_T = \left\{|\vec{q}_1|\hat{\vec{r}}_1 + |\vec{q}_2|\hat{\vec{r}}_2 - \vec{p}_1 - \vec{p}_2\right\}_T$$

Thus we obtain two linear equations for two unknown variables $|\vec{q}_1|$ and $|\vec{q}_2|$:

$$\begin{cases} \sin\theta_1\cos\phi_1|\vec{q}_1| + \sin\theta_2\cos\phi_2|\vec{q}_2| = \left(\vec{p}\!\!/_T + \vec{p}_1 + \vec{p}_2\right)_x, \\ \sin\theta_1\sin\phi_1|\vec{q}_1| + \sin\theta_2\sin\phi_2|\vec{q}_2| = \left(\vec{p}\!\!/_T + \vec{p}_1 + \vec{p}_2\right)_y \end{cases}$$

$|\vec{q}_1|$ and $|\vec{q}_2|$ are absolute values of F's momentum.

Direction of 2 DVs gives us a chance to obtain mother particles' momentum. But this equation system is not always solvable. If 2 F are back-to-back on transverse plane:

$$\phi_1 = \phi_2 + \pi$$

Then the determinant of this equations system is:

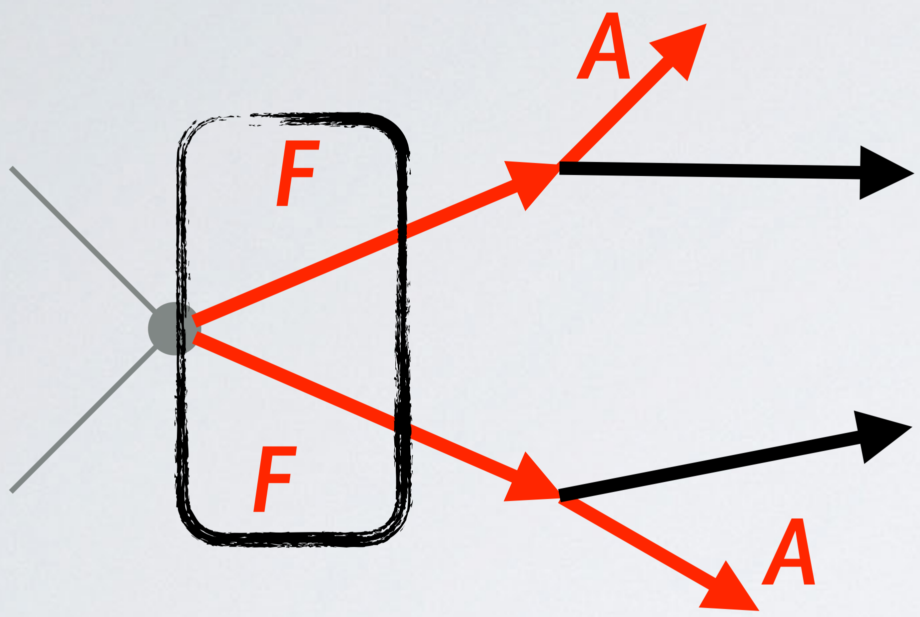
$$\begin{vmatrix} \sin\theta_1\cos\phi_1 & \sin\theta_2\cos\phi_2 \\ \sin\theta_1\sin\phi_1 & \sin\theta_2\sin\phi_2 \end{vmatrix} = \begin{vmatrix} -\sin\theta_1\cos\phi_2 & \sin\theta_2\cos\phi_2 \\ -\sin\theta_1\sin\phi_2 & \sin\theta_2\sin\phi_2 \end{vmatrix} = 0$$

This is why we need an ISR! Because without ISR, 2 F are back-to-back and we can get nothing. But for hadron collider it's not a problem, ISR is always there.

Let's continue.

By solving the equations system, we obtain 3-momentum of 2 DM and 2 F.

But, we only got 3-momentums of F and DM, their mass are still unknown. We need more equations!



Long-lived mediator particles are on-shell!

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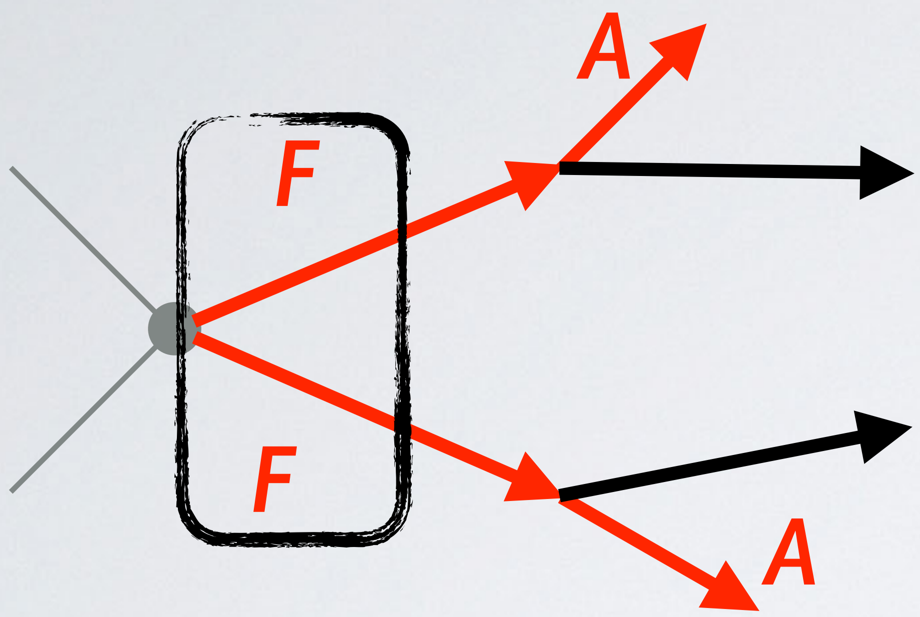


Long-lived mediator particles are on-shell!

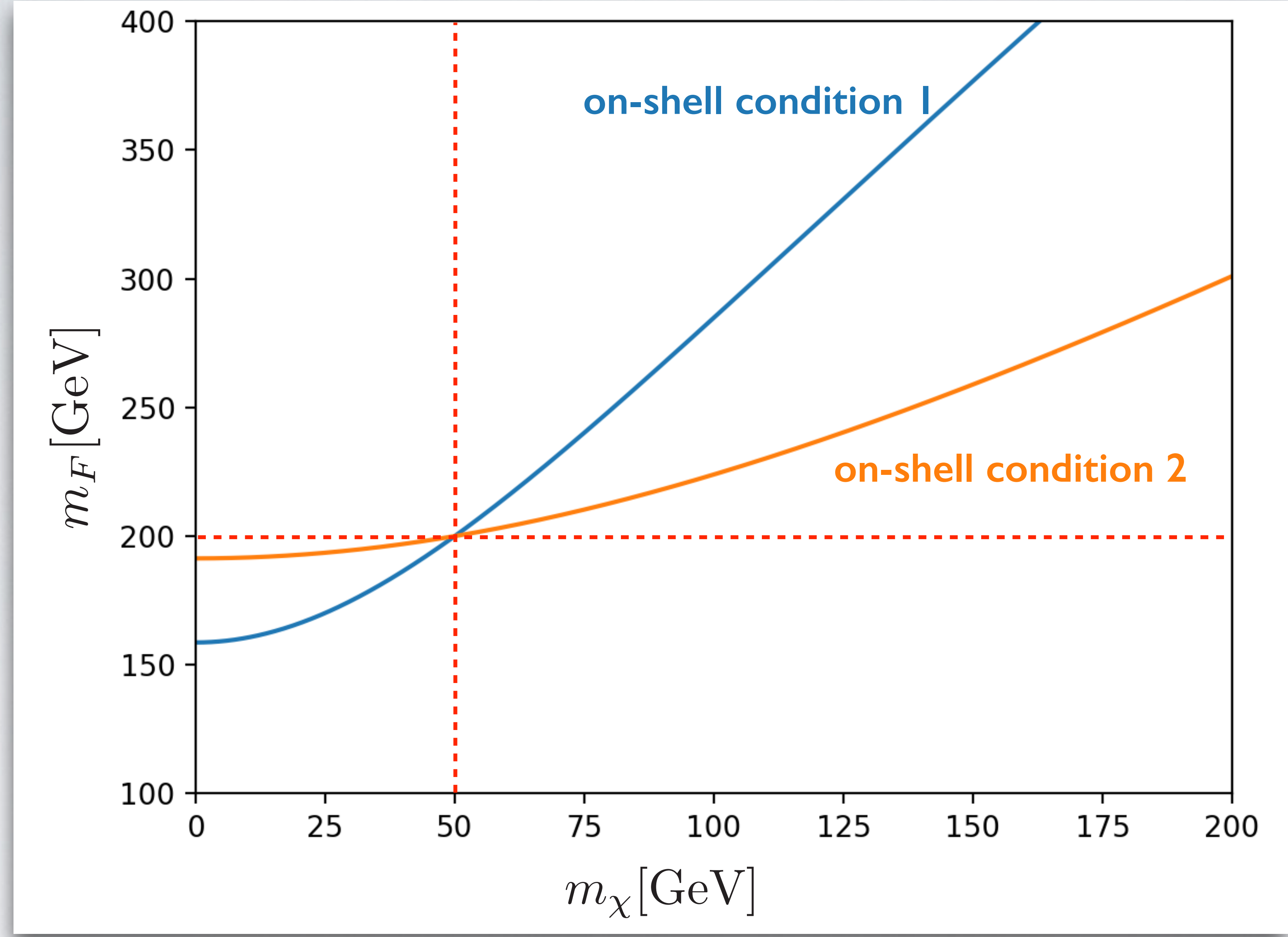
This is the last thing we need, on-shell condition.

$$\text{Branch 1: } m_F = \sqrt{\left(p_1^0 + \sqrt{|\vec{k}_1|^2 + m_\chi^2}\right)^2 - |\vec{q}_1|^2},$$

$$\text{Branch 2: } m_F = \sqrt{\left(p_2^0 + \sqrt{|\vec{k}_2|^2 + m_\chi^2}\right)^2 - |\vec{q}_2|^2}$$

F mass are functions of DM mass, and we have 2 such functions, so….

True spectrum: $m_\chi = 50$ GeV, $m_F = 200$ GeV



If there are two displaced vertex (DV) and initial state radiation (ISR), you can obtain the mass of F and DM by only one event.

- Motivation: WIMP v.s. FIDM
- Spectrum measurement at collider
- **More realistic analysis: Uncer. and limited events**
- Clean up our data: filtering algorithm

Looks perfect, but, in a **real** experiment, things can't not be so good.

First, uncertainty.

Our input:

- 4-momentum of two visible daughter particles, p_1 and p_2.
- missing transverse momentum, $\vec{\not{p}}_T$.
- position of 2 DVs, $\vec{r}_1$ and $\vec{r}_2$.

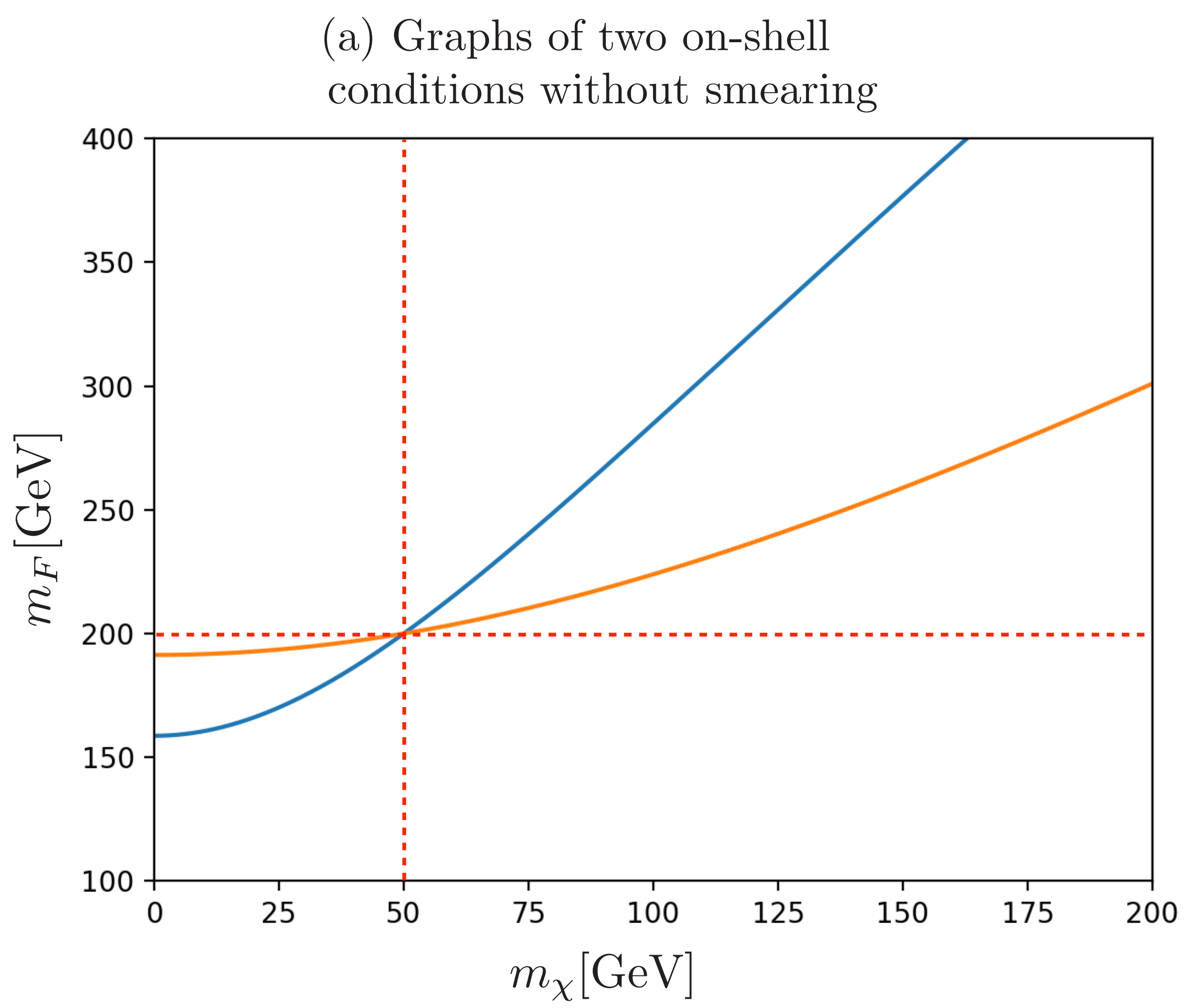
Their uncertainty:

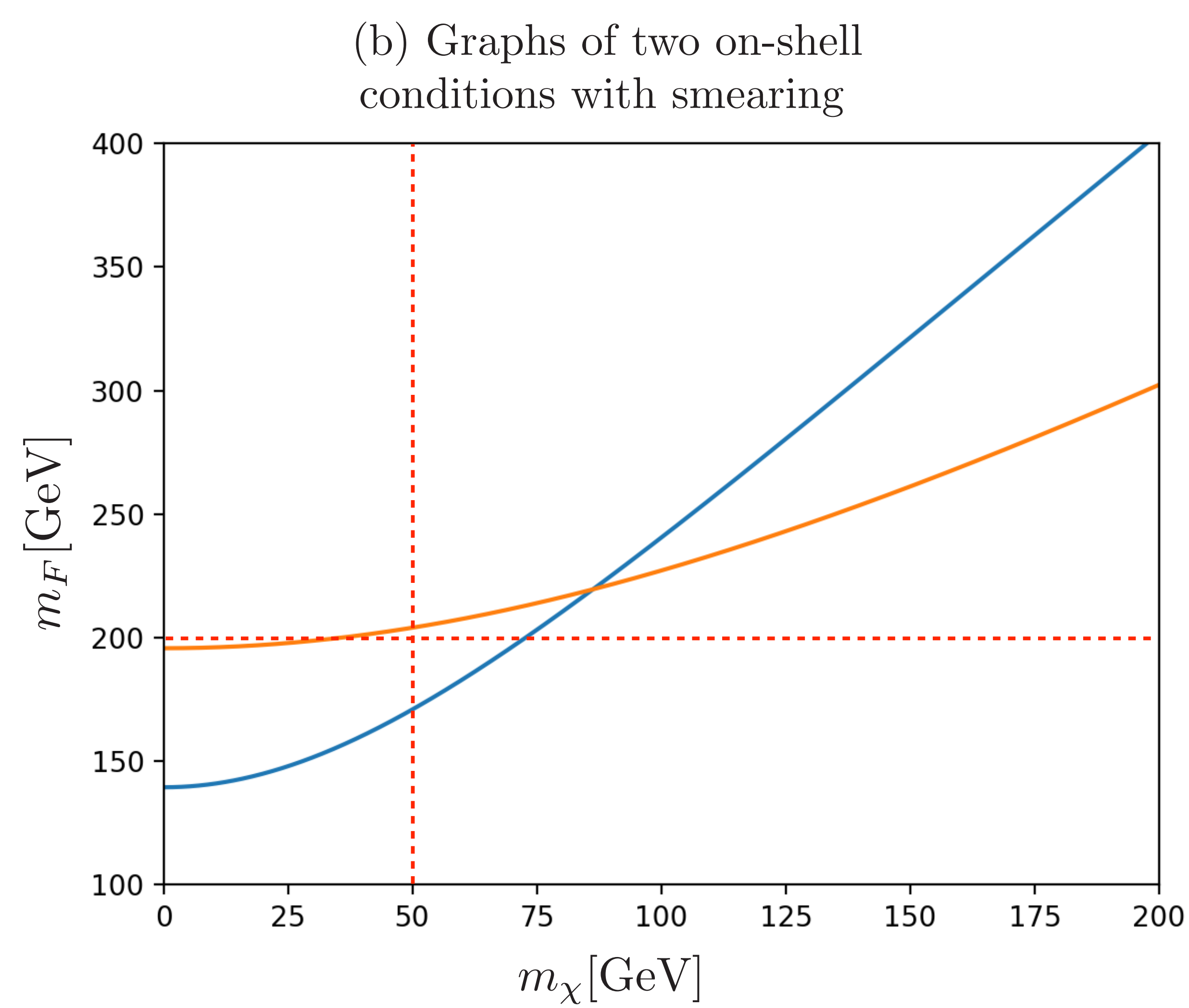
1~2%, for lepton

10%, if > 200GeV

0.2~0.5mm, inside inner detector

What will happen if we include uncertainty?





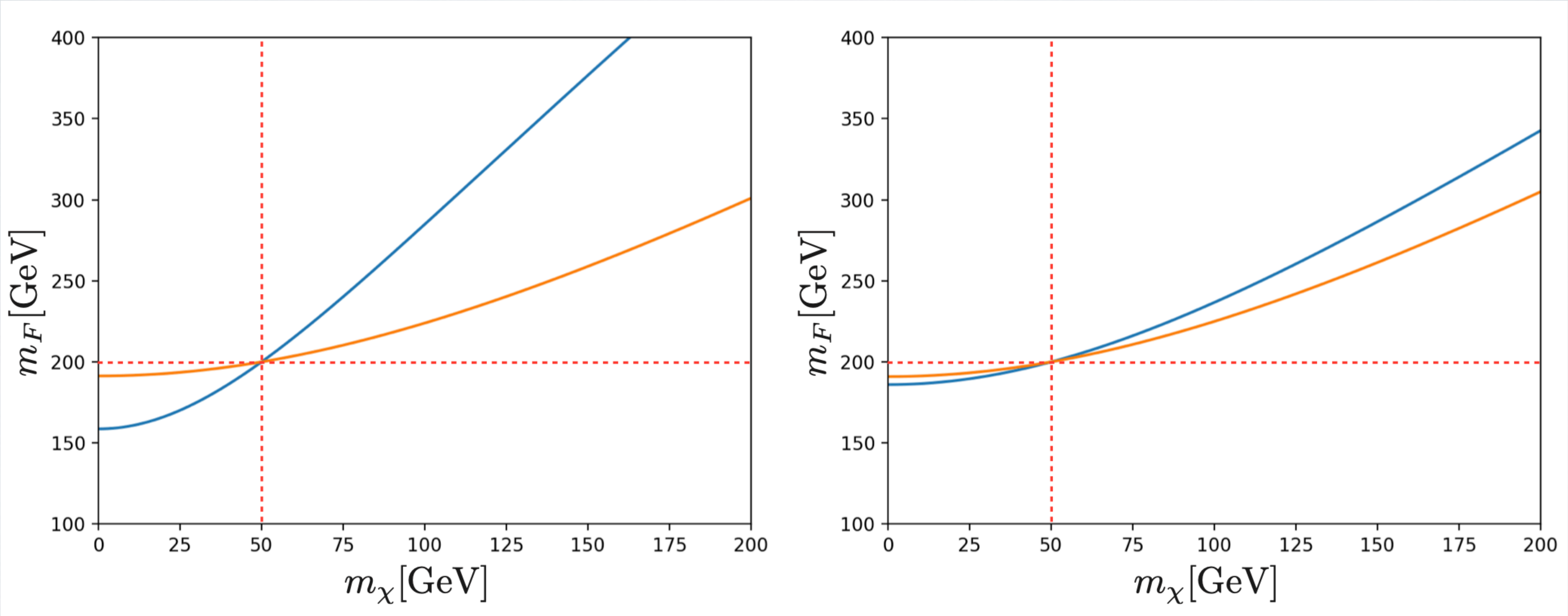
Deviation of input

Deviation of on-shell conditions

Deviation of cross-point

For some events, uncertainty can be amplified.

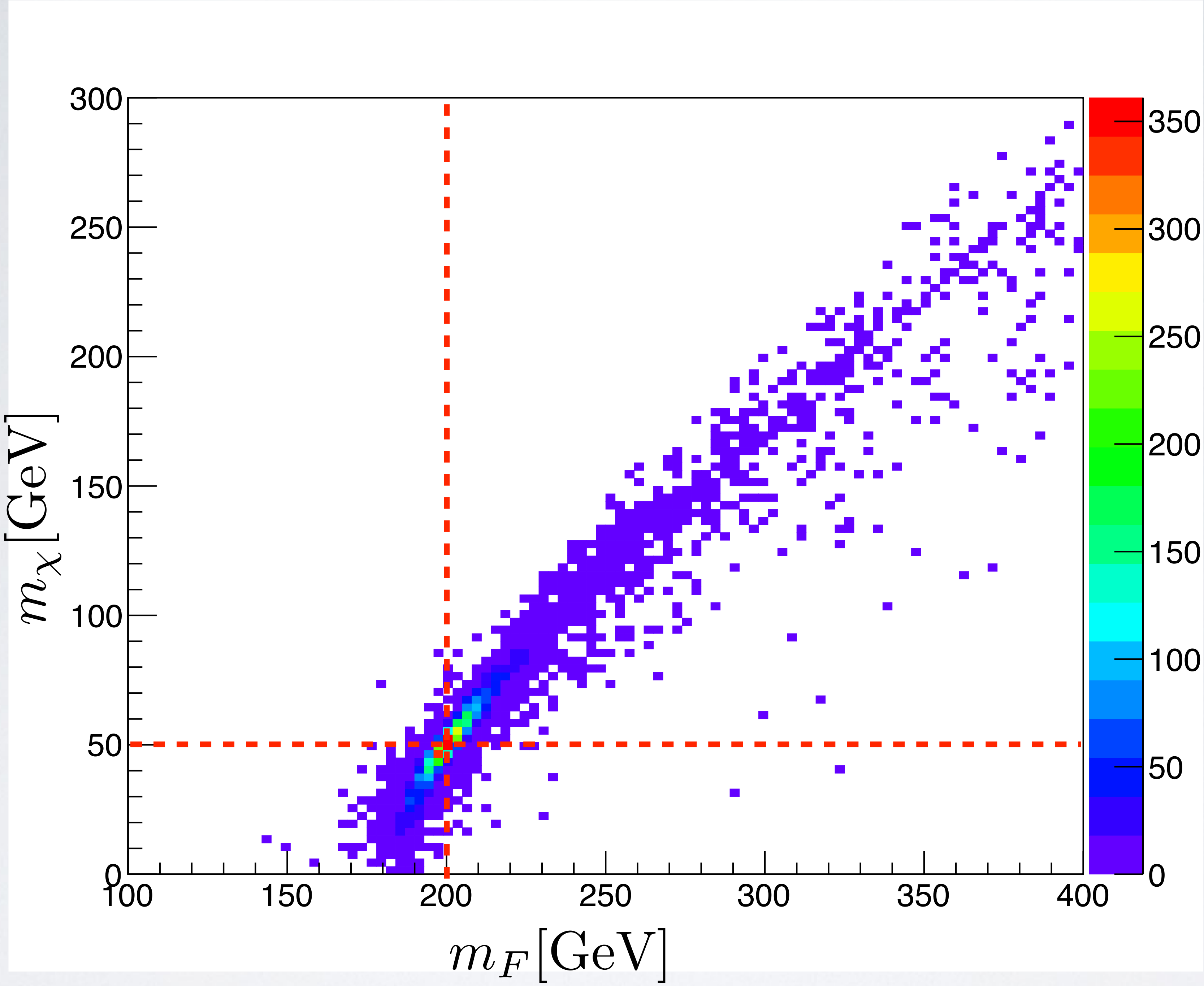
Some events could be very sensitive to Uncer.



Robust Fragile

Related to mediator boost and decay direction, out of my control.

For 10k events, the distribution is like:



It’s fine, I can just choose the peak point.

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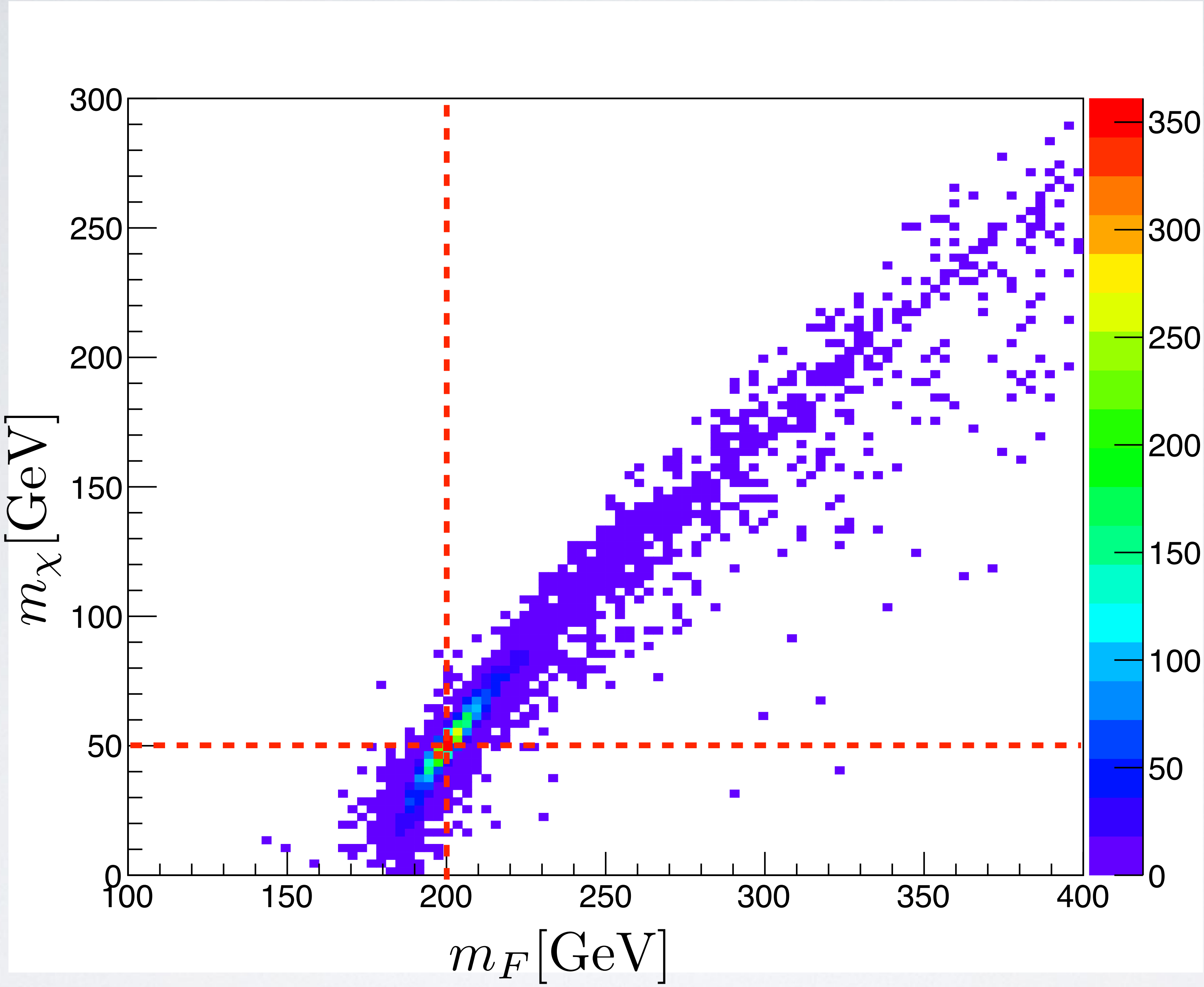


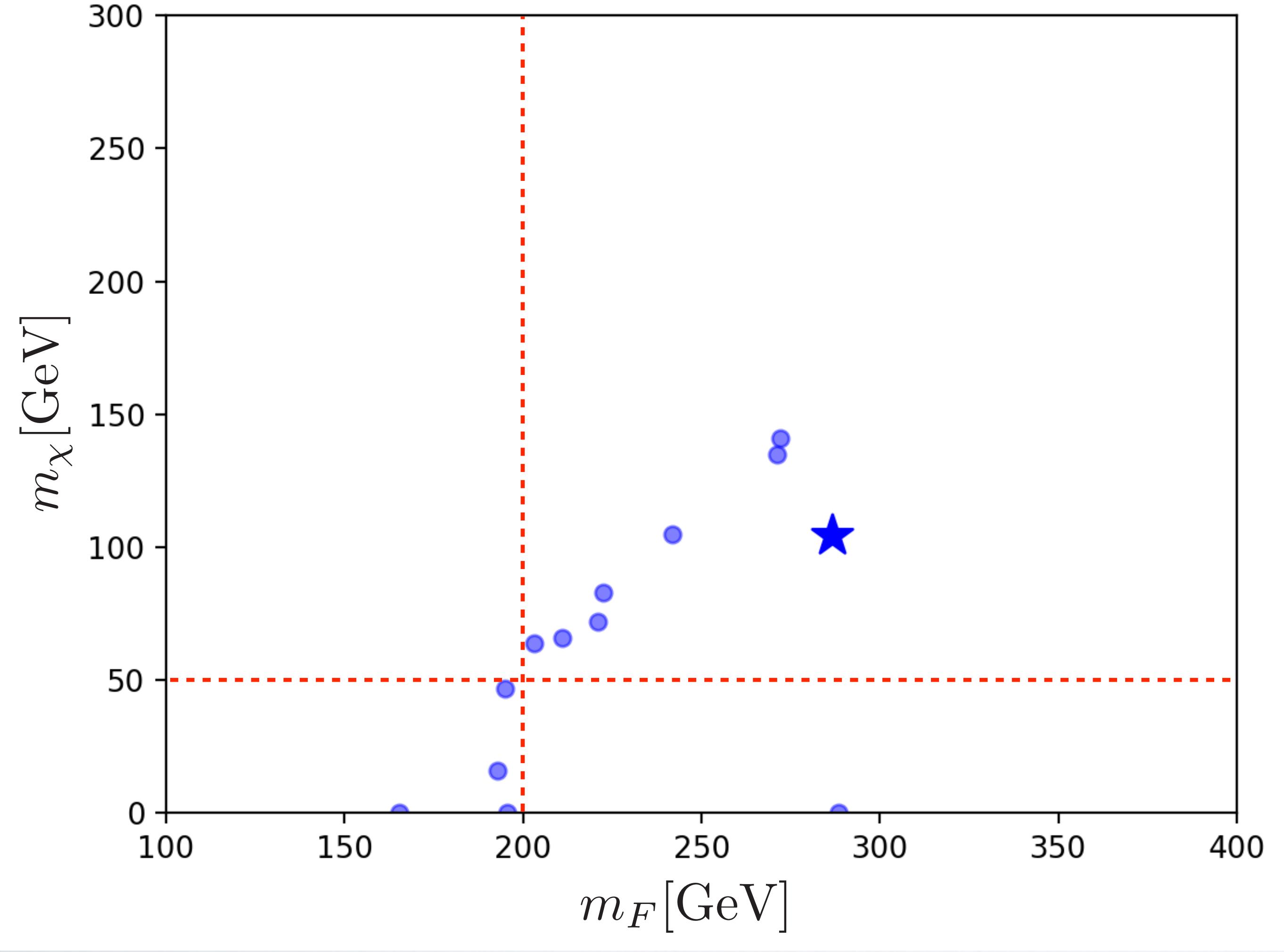
It's fine, I can just choose the peak point.

No! You can't observe so many events!

So at which collider you can observe 10k events? HL-LHC? If you can observe 10k DV at HL-LHC, then we should have already seen it now!

If you consider limits from current DV search, at HL-LHC, you can only observe 20~30 single events.

So the real distribution is like….



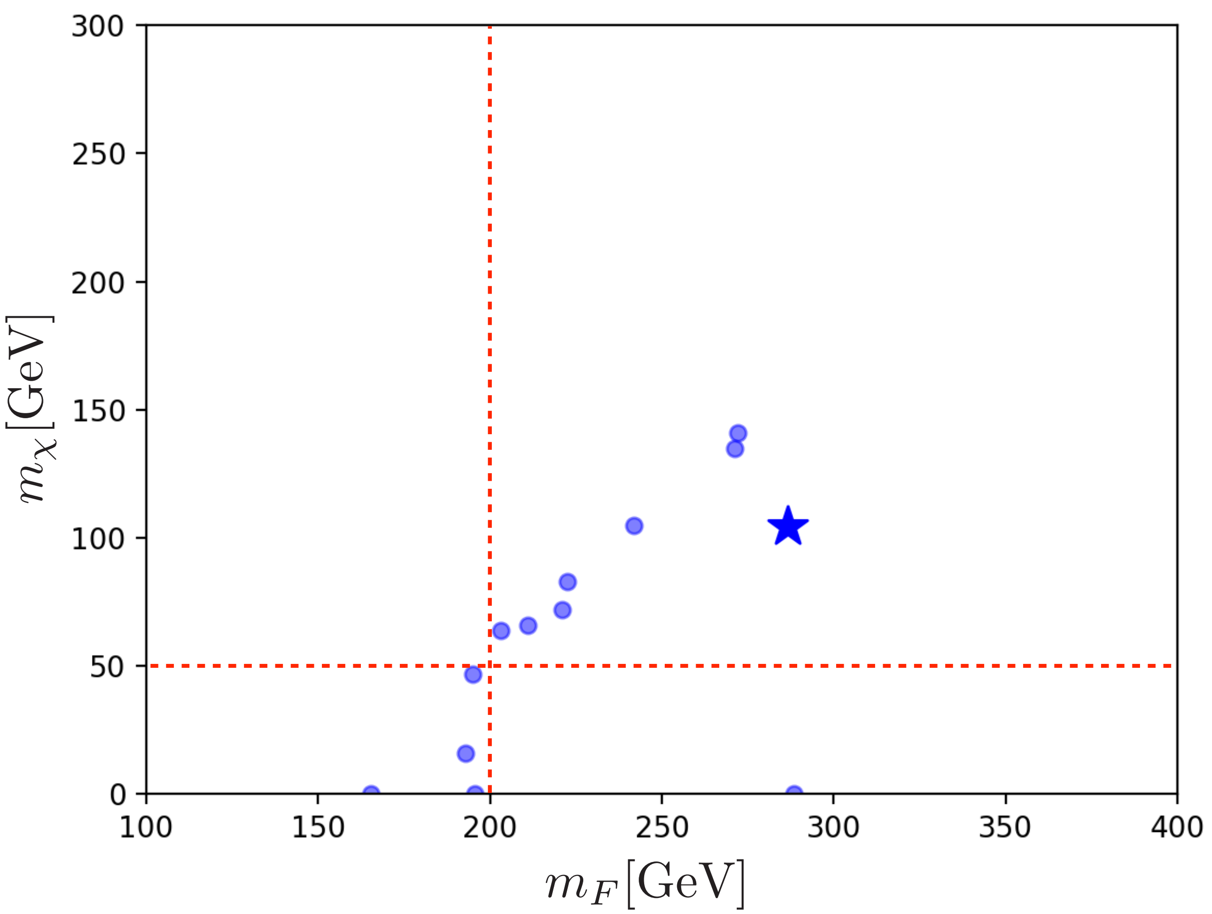
Peak value is ill-defined.

Fitting? too little amount of events.

Only mean value is well-defined. But mean value is far from true value.

We need to “wash” our data.
We propose a “filtering algorithm” to do it.
(similar to jet-clustering)

(a) Measured masses in a pseudo-experiment before filtering



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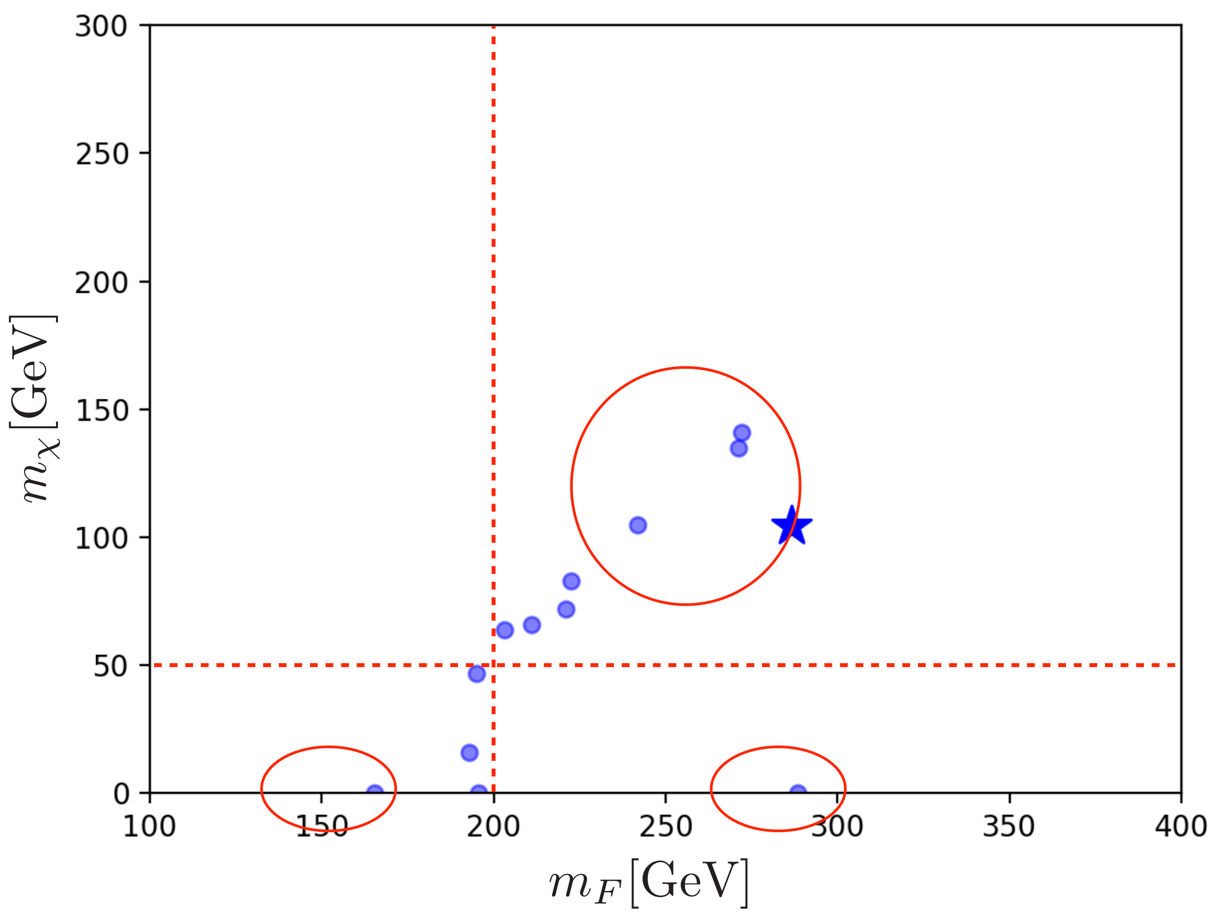

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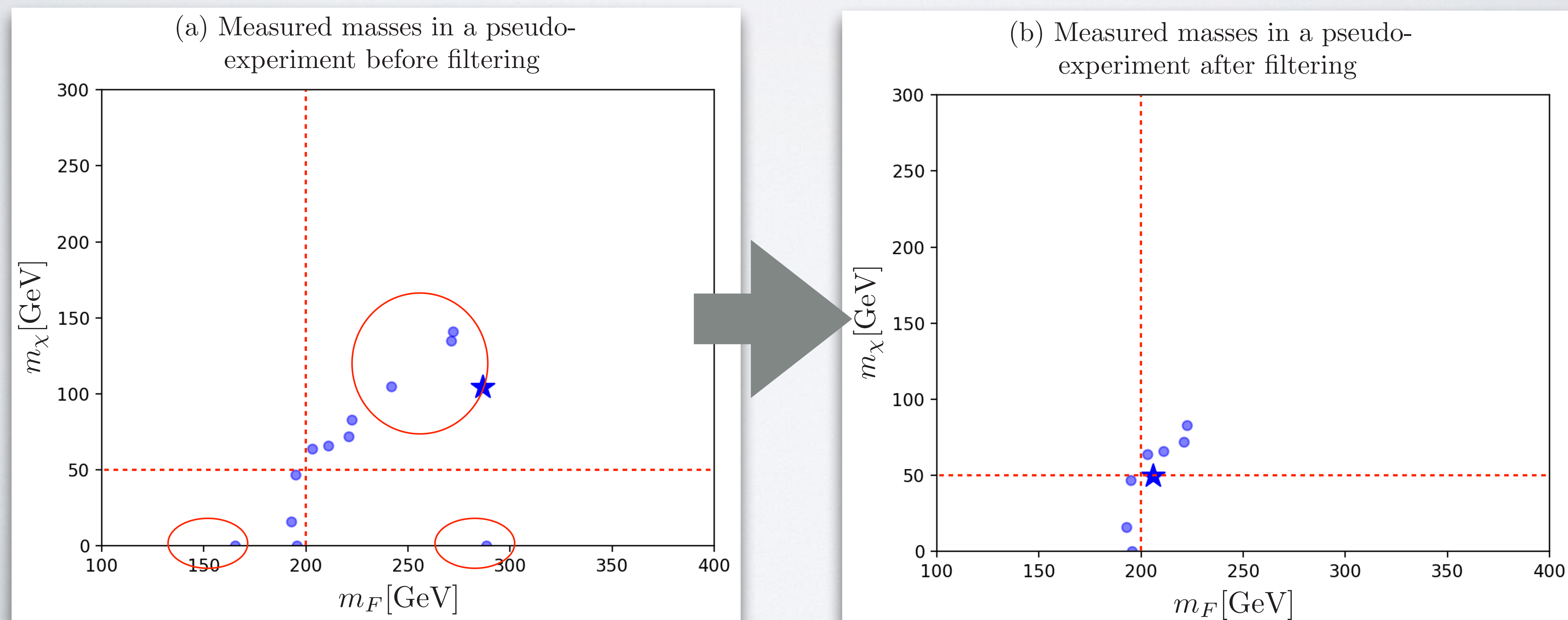
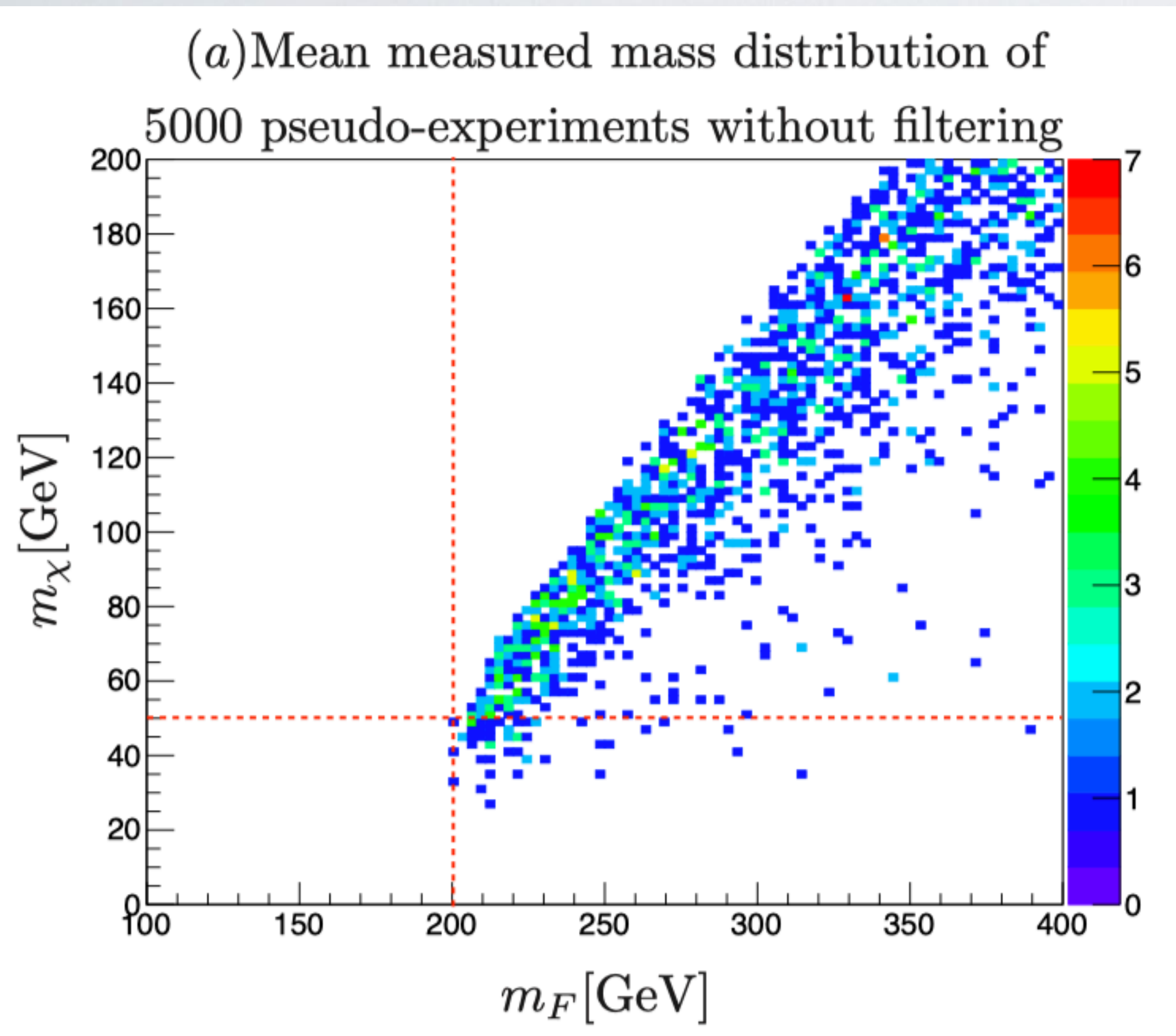
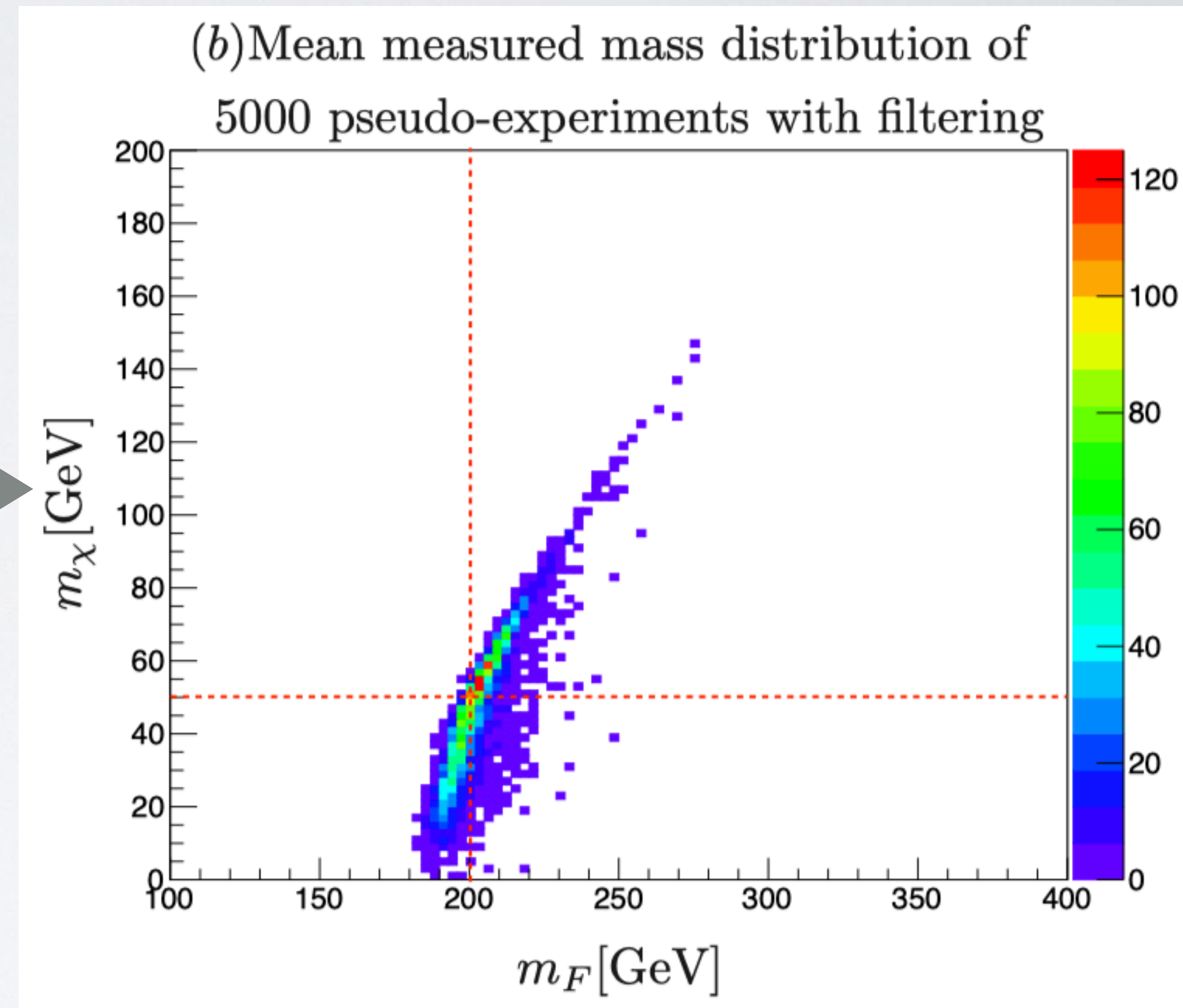


It works well~

20 events for each pseudo-experiment





Conclusion

Due to a feeble interaction between DM and SM, FIDM model is naturally related to long-lived particle, and displaced object search at collider.

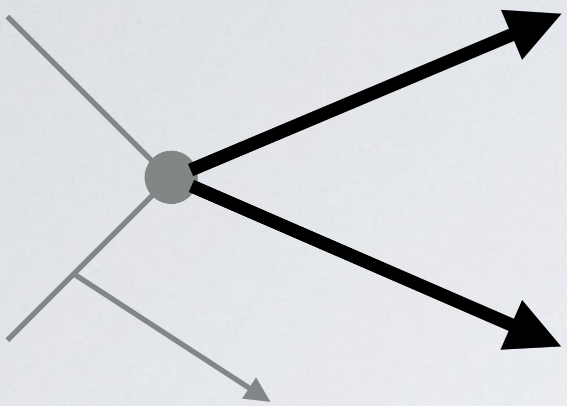
By using the position information of DV, we can measure the spectrum of dark sector easily.

Uncertainty and limited signal events makes measurement difficult, we propose a “filtering algorithm” to deal with this issue.

Backup

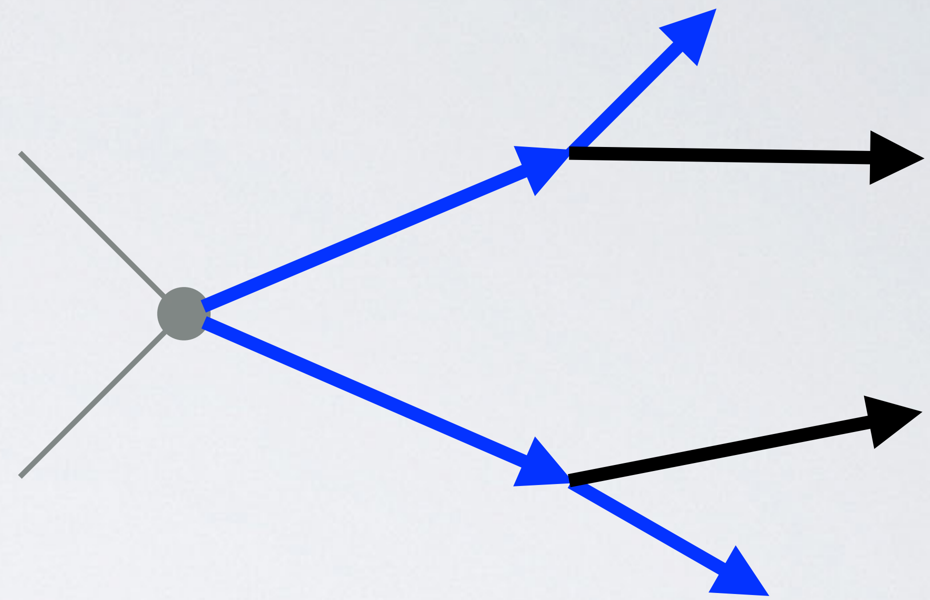
WIMP search at collider

From Freeze-out , we have:



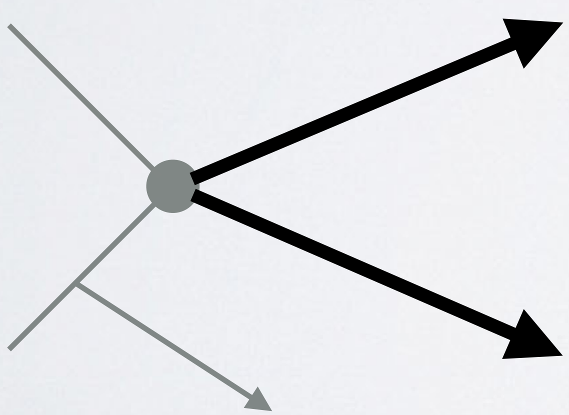
Mono-X: Simple and Robust

If WIMP is embedded in SUSY,
we can consider:



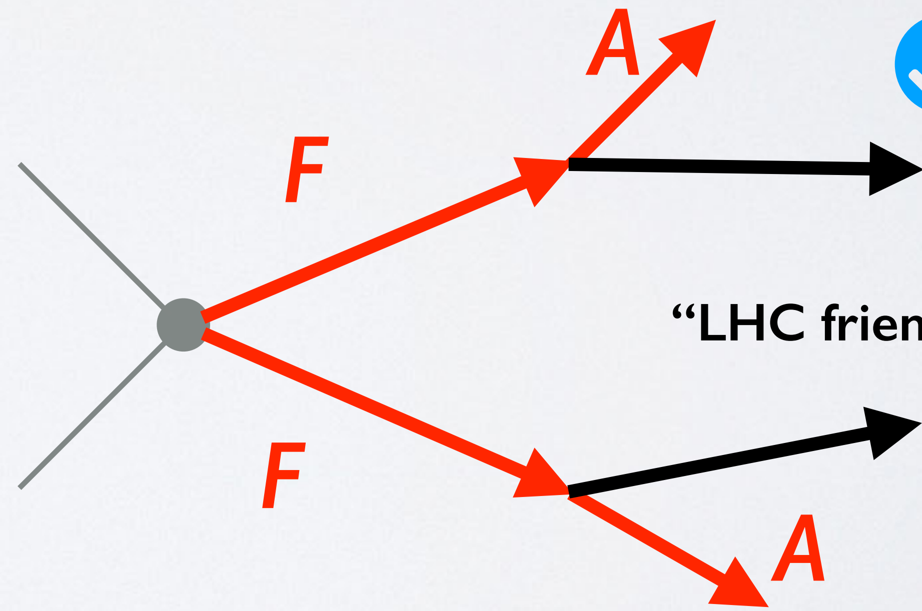
FIDM search at collider

A simple idea:



Interaction is very small!!

$BR(F \to A\ DM) = 1$



"LHC friendly"1811.05478

Very small coupling ➡ F is long-lived