Time-Information at Colliders

Dong Woo Kang
(Yonsei U.)

In collaboration with
Seong Chan Park and K. C. Kong, Christoper Rogan
To appear soon

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  - Hidden Sector
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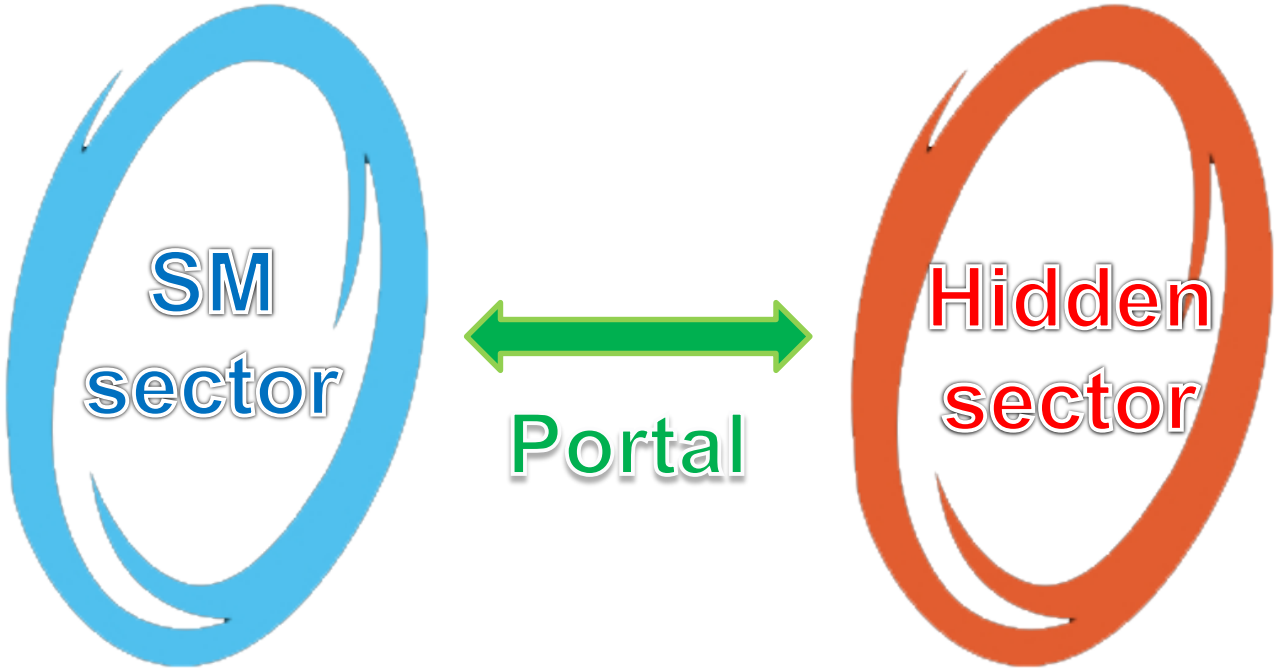
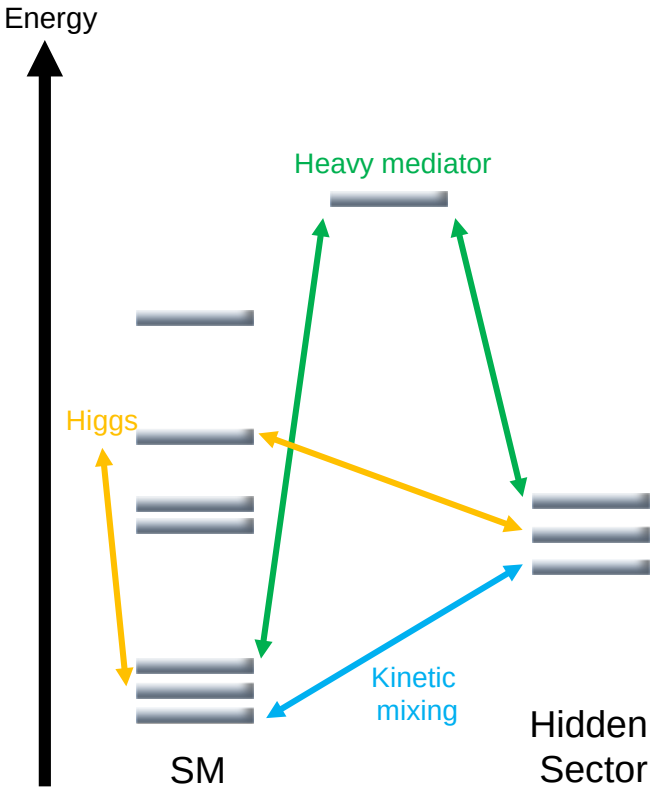
Hidden Sector

- Based on the null result at the LHC, we can guess the new physics particles are live in the hidden sector and they have small couplings with the SM.



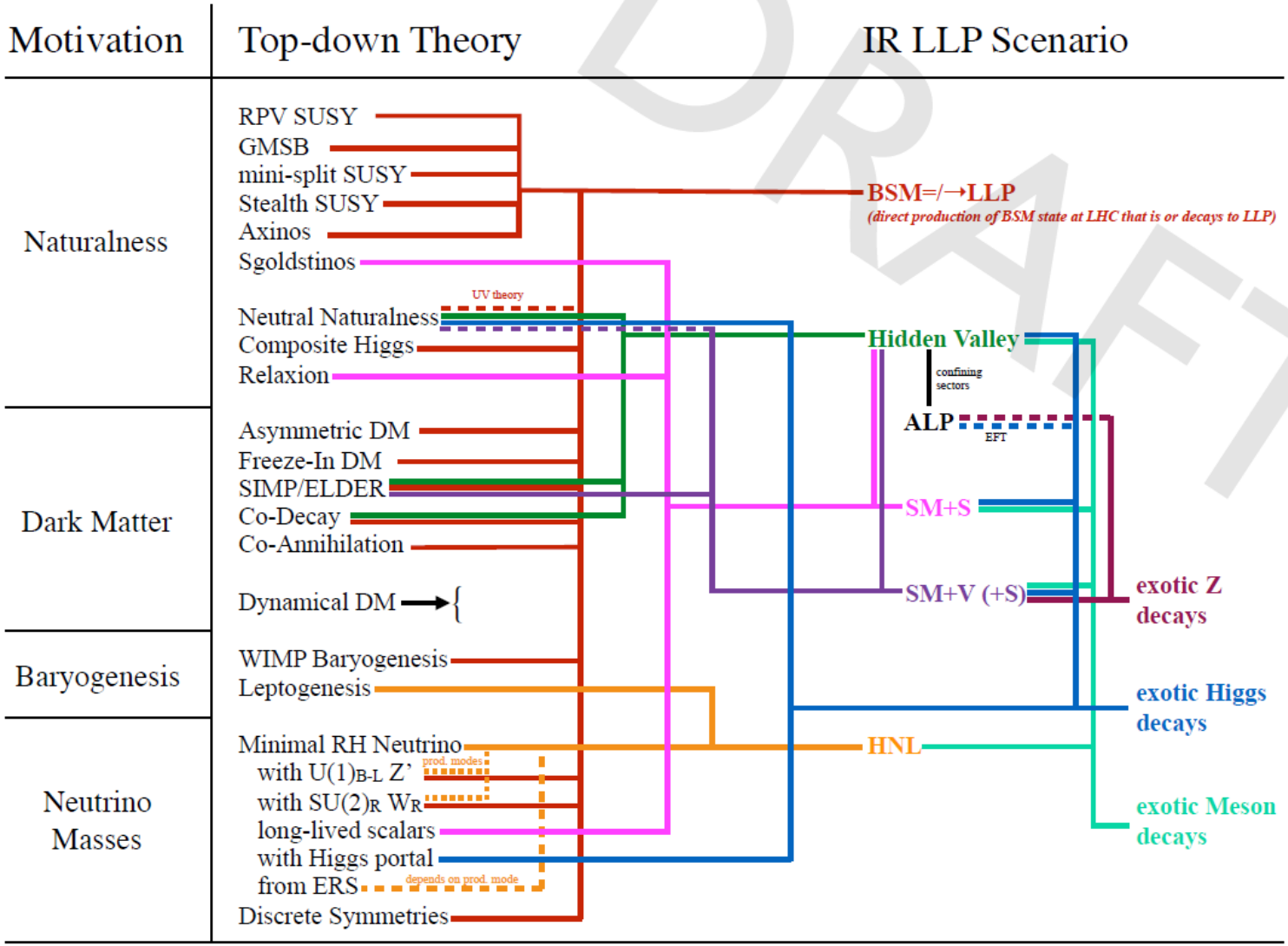
Hidden Sector



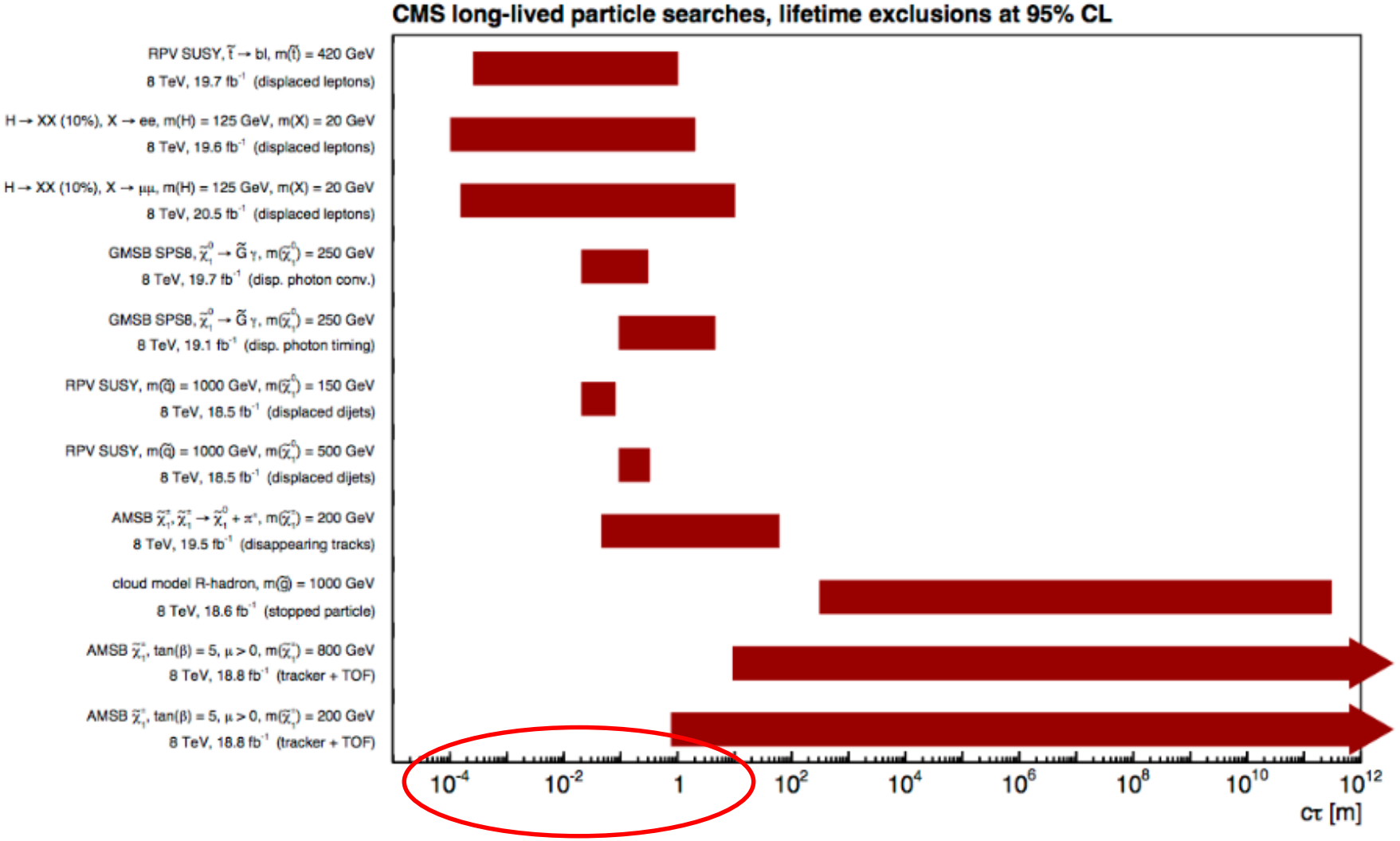
- Hidden sector communicates with the SM sector through portal couplings
- The portal coupling makes hidden sector particles unstable and decay into SM with a relatively long life time
- Once Long Lived Particle (LLP) is produced at colliders and it decay back to the SM after flying some distance (**displaced vertex!**)

$$c\tau \approx \frac{1.2\,\mathrm{fm}}{g^4}\left(\frac{M_{mediator}}{M_{LLP}}\right)^4\left(\frac{1\,\mathrm{TeV}}{M_{LLP}}\right)$$

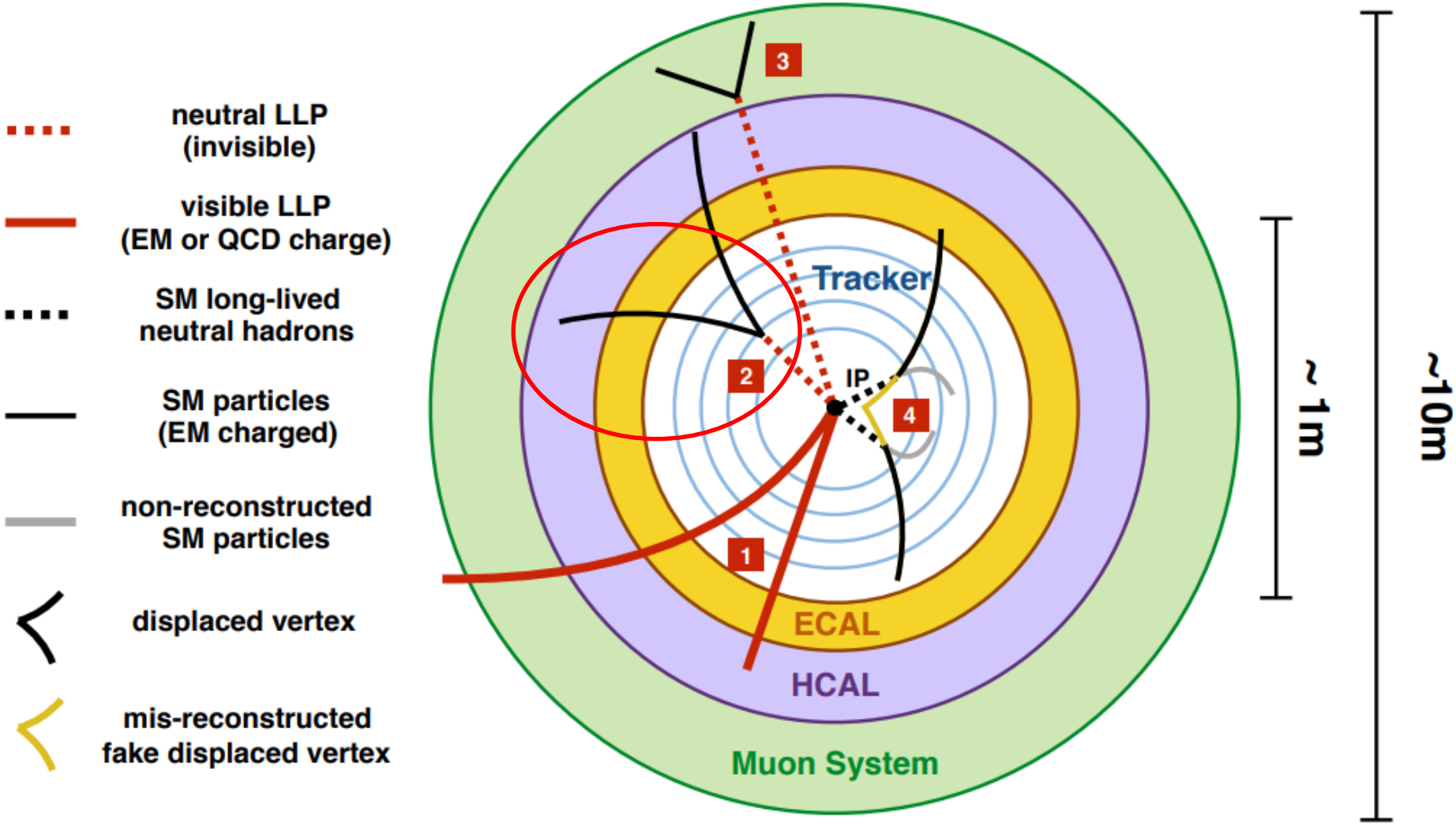
LLP is well motivated



LLP searches at the LHC so far



Signatures at collider



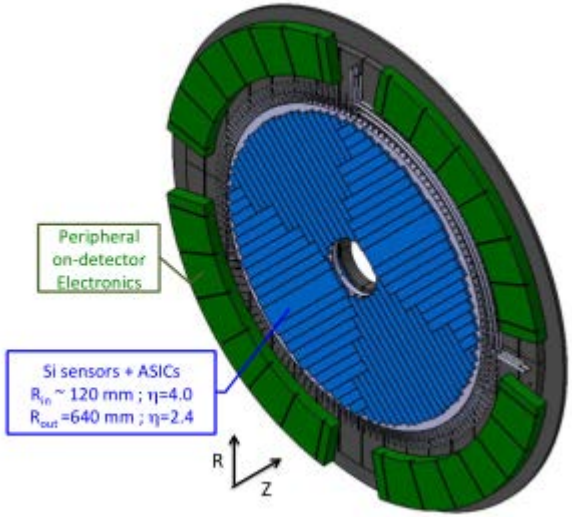
[D. Curtin and R. Sundrum 1702.02524]

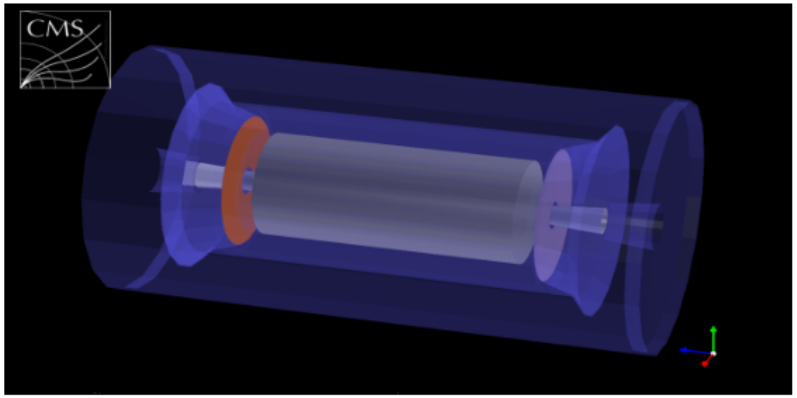
LLP Searches are Challenging

- The LHC is not designed for LLPs.
  - trigger selections are not optimized for the LLP searches
- Relatively small background but hard to estimate it.
- Neutral LLPs have no interaction with the detector
- If the decayed product contains invisible particles, It is hard to reconstruct the event.

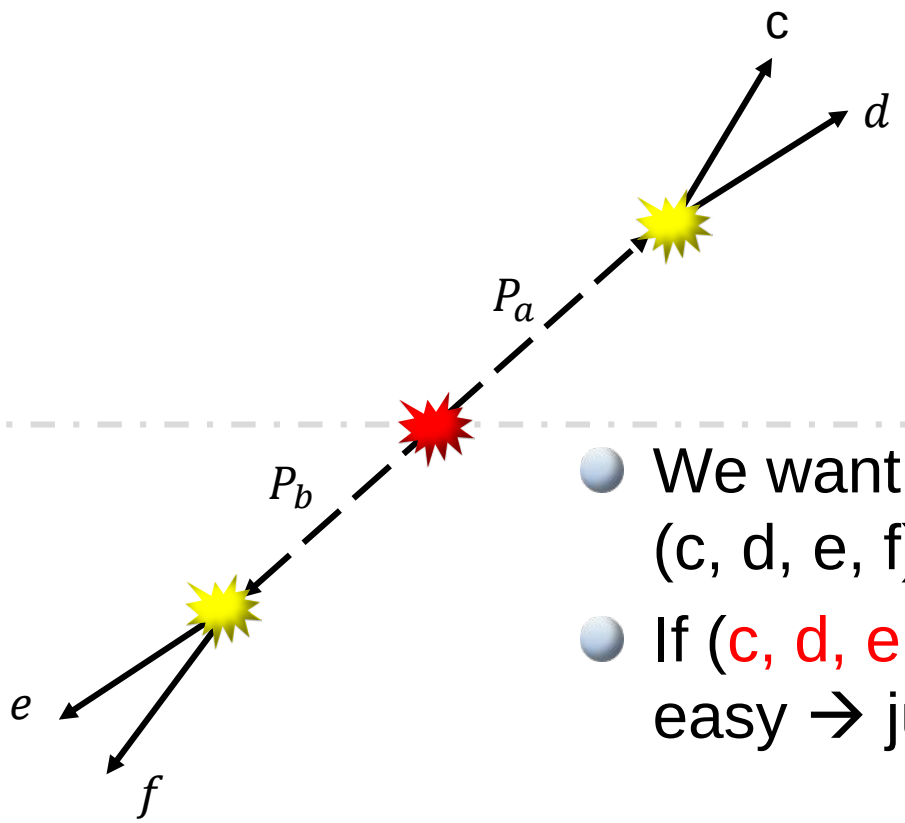
Timing detector @ HL-LHC

- After run-2 both ATLAS and CMS have plan for detector upgrade for HL-LHC
  - ATLAS propose High-Granularity Timing Detector at the endcap region
  - CMS propose the minimum ionizing particles (MIPs) Timing Detector (MTD) between tracker and ECAL
- These effort will open up the **“lifetime frontier”**



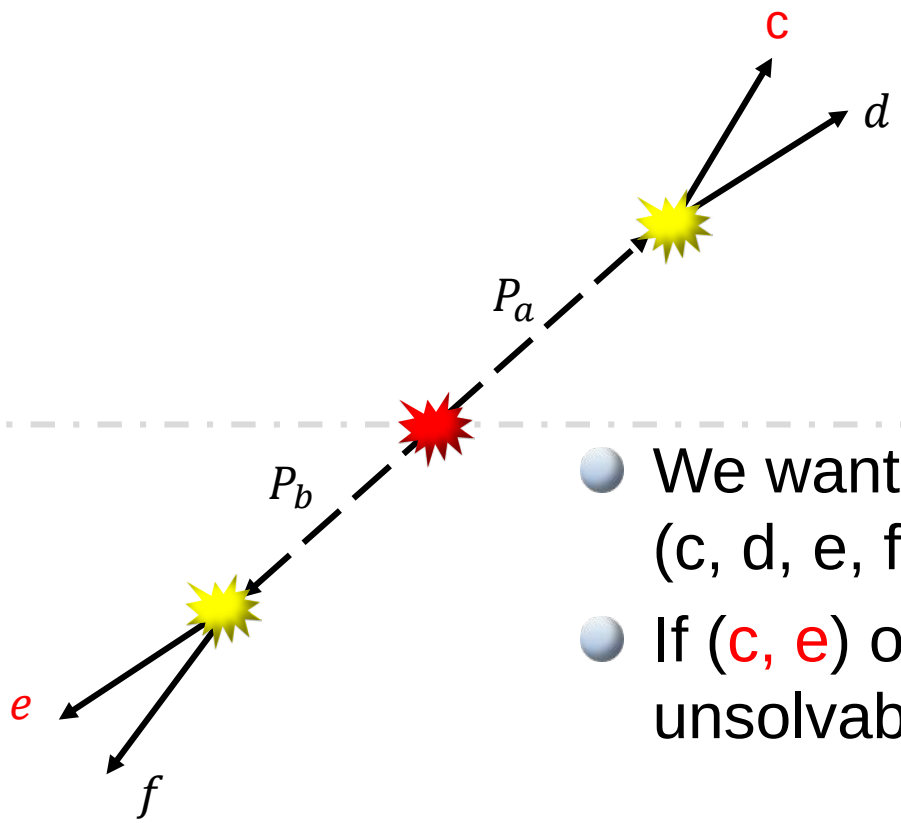


The Problem: easy



- We want to solve “(a, b)” by “measuring” (c, d, e, f)
- If (c, d, e, f) are all visible, the problem is easy → just reconstruct everything!

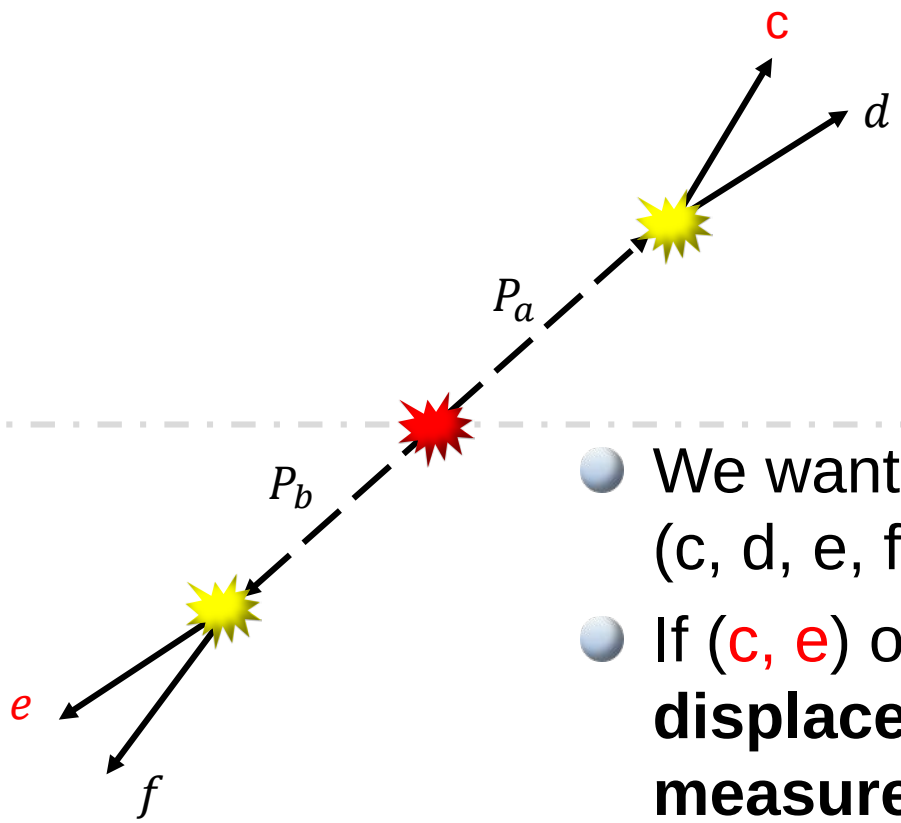
The Problem: unsolved



- We want to solve “(a, b)” by “measuring” (c, d, e, f)
- If (c, e) only are all visible, the problem is unsolvable

# of unknown > # of independent relations

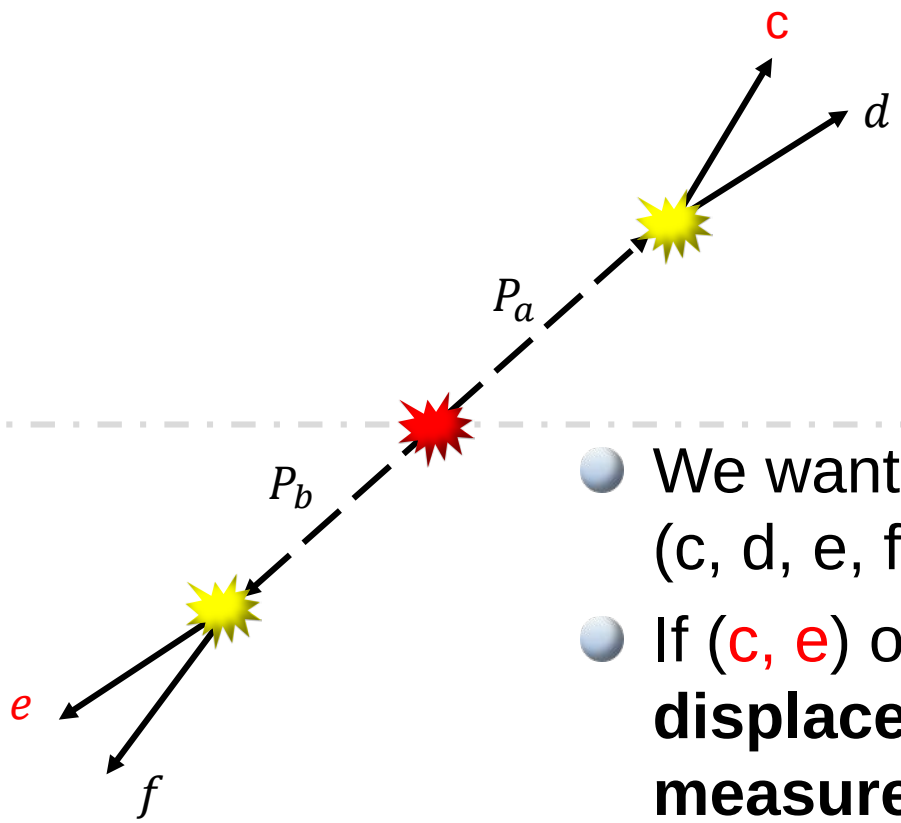
The Problem: partly solvable



- We want to solve “(a, b)” by “measuring” (c, d, e, f)
- If (c, e) only are all visible, **and the displaced vertices of (a, b) are measured**
- Solvable (often) with multiple solutions only when a, b are same particle and d, f also are the same particle.

  # of unknown = # of independent relations

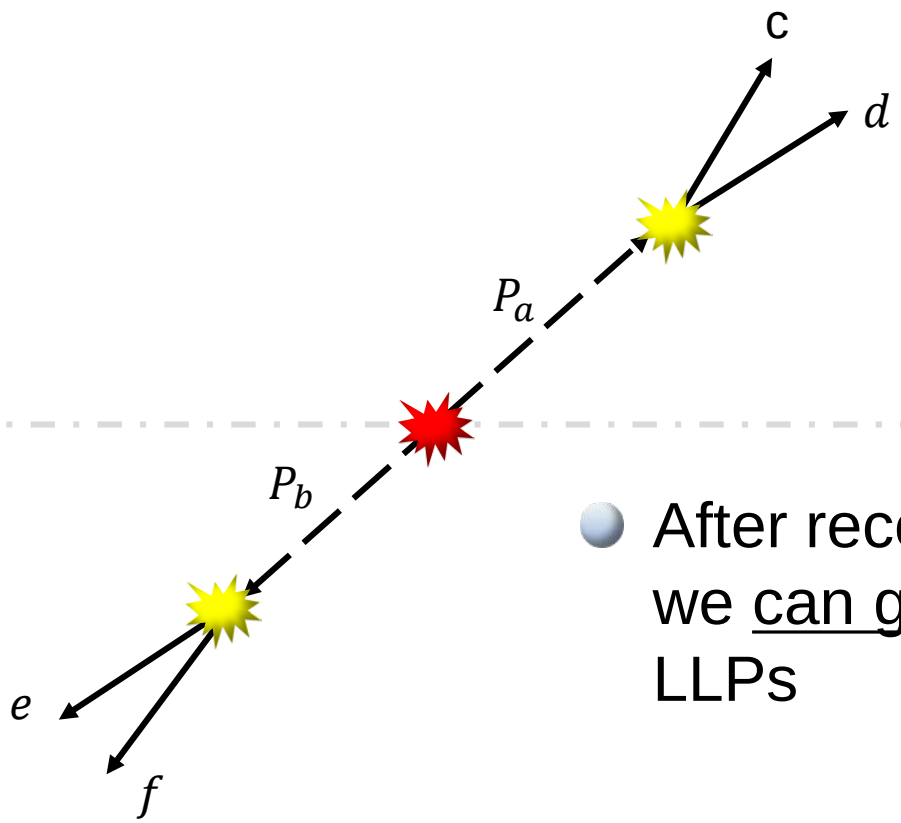
The Problem: completely solvable



- We want to solve “(a, b)” by “measuring” (c, d, e, f)
- If (c, e) only are all visible, **and the displaced vertices of (a, b) are measured & timing information of (a, b) are measured**
- **Solvable!**

  # of unknown = # of independent relations

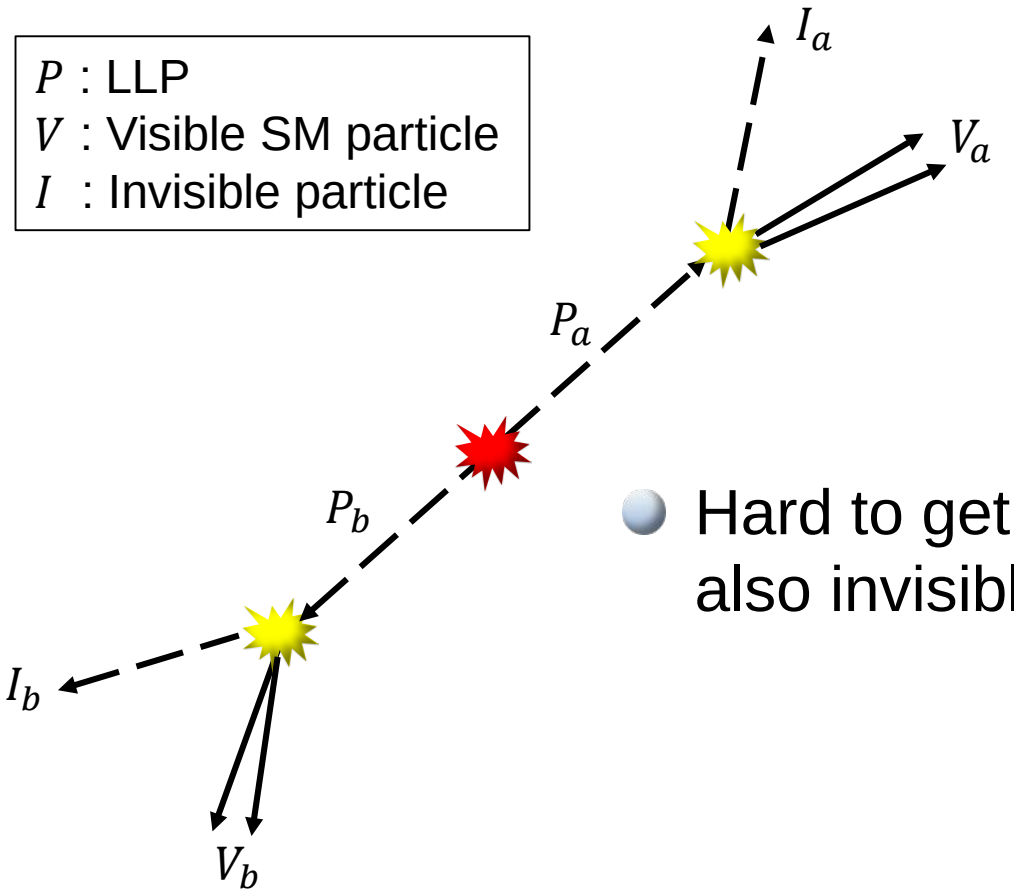
LLP decay to visible particles



- After reconstruct the displaced vertex, we can get 4-momentum information of LLPs

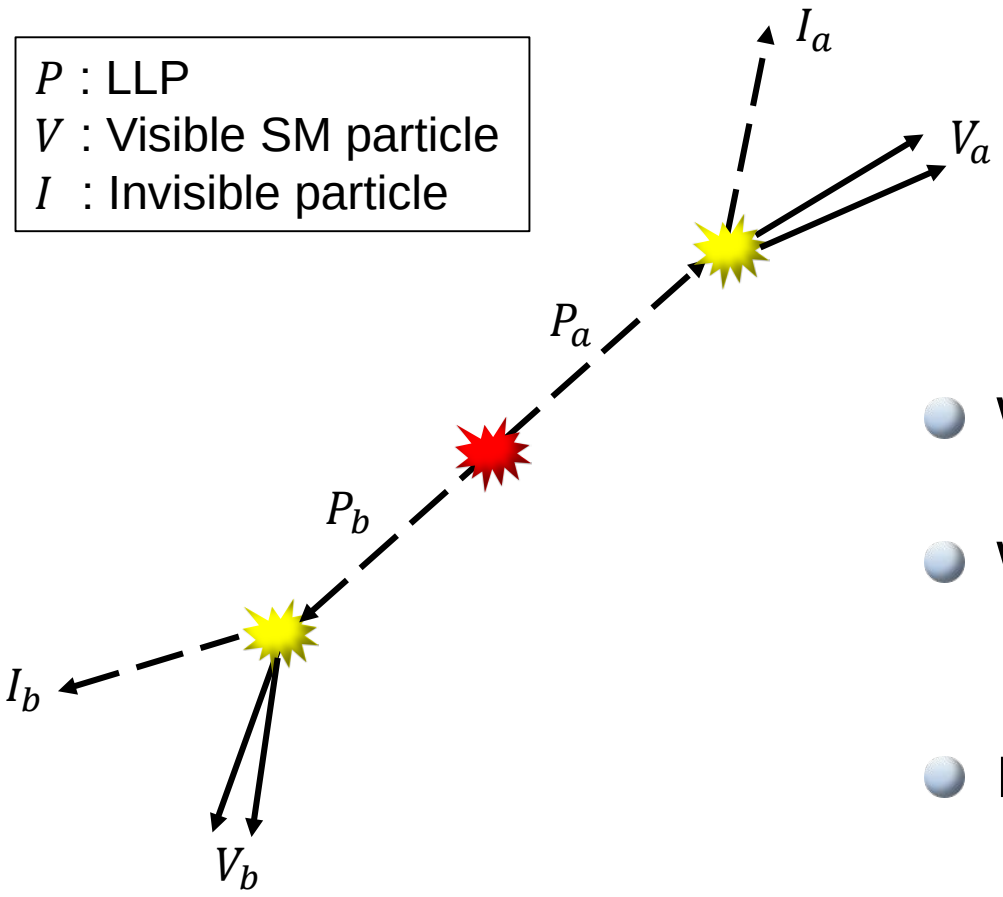
LLP decay semi-visibly

P : LLP
V : Visible SM particle
I : Invisible particle



- Hard to get the information of LLPs and also invisible particles.

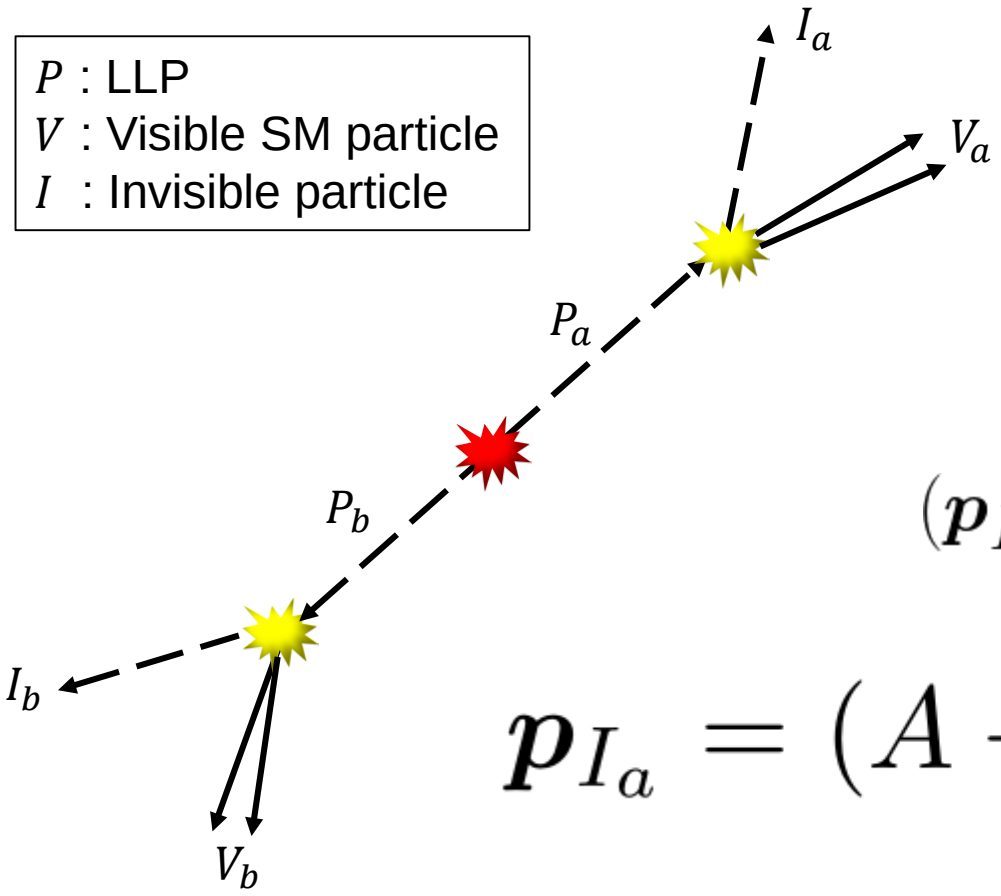
LLP Event reconstruction



- We want to know
  - P_a, P_b 4-momentum 4*2 d.o.f
- We can measure
  - $\hat{r}_a$, $\hat{r}_b$ 2*2 d.o.f
  - p_T^{miss} 2 d.o.f
- Futher assumptions
  - $M_a = M_b$
  - $M_{I_a} = M_{I_b}$

LLP Event reconstruction

P : LLP
V : Visible SM particle
I : Invisible particle



[Giovanna Cottin 1801.09671]

$$(\boldsymbol{p}_{I_a})_{||P_a} = (\boldsymbol{p}_{I_a} \cdot \hat{r}_a)\hat{r}_a$$
$$(\boldsymbol{p}_{V_a})_{||P_a} = (\boldsymbol{p}_{V_a} \cdot \hat{r}_a)\hat{r}_a$$
$$(\boldsymbol{p}_{I_a})_{\perp P_a} = \boldsymbol{p}_{I_a} - (\boldsymbol{p}_{I_a} \cdot \hat{r}_a)\hat{r}_a$$
$$(\boldsymbol{p}_{V_a})_{\perp P_a} = \boldsymbol{p}_{V_a} - (\boldsymbol{p}_{V_a} \cdot \hat{r}_a)\hat{r}_a$$

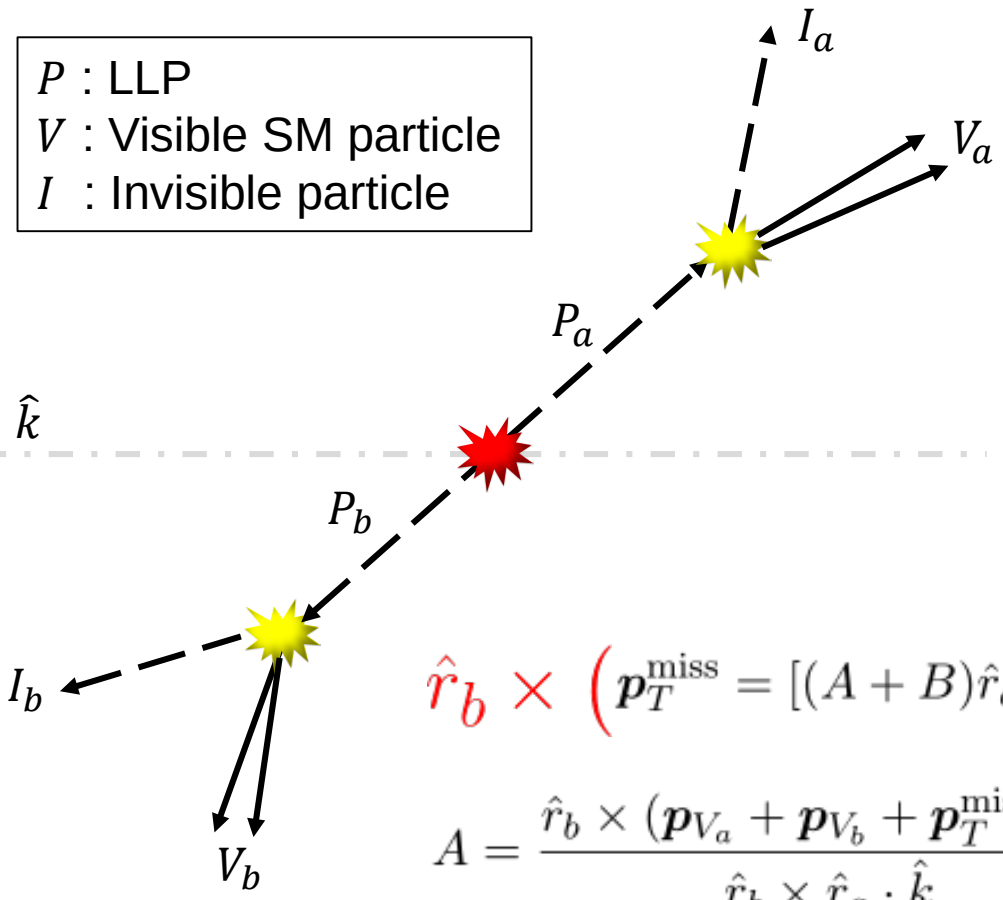
$$(\boldsymbol{p}_{I_a})_{\perp P_a} = -(\boldsymbol{p}_{V_a})_{\perp P_a}$$

$$\boldsymbol{p}_{I_a} = (A + B)\hat{r}_a - \boldsymbol{p}_{V_a}$$

$$A \equiv (\boldsymbol{p}_{I_a} \cdot \hat{r}_a)$$
$$B \equiv (\boldsymbol{p}_{V_a} \cdot \hat{r}_a)$$

LLP Event reconstruction

P : LLP
V : Visible SM particle
I : Invisible particle



$$A \equiv (\boldsymbol{p}_{I_a} \cdot \hat{r}_a)$$
$$B \equiv (\boldsymbol{p}_{V_a} \cdot \hat{r}_a)$$
$$C \equiv (\boldsymbol{p}_{I_b} \cdot \hat{r}_a)$$
$$D \equiv (\boldsymbol{p}_{V_b} \cdot \hat{r}_a)$$

$$\boldsymbol{p}_{I_a} = (A+B)\hat{r}_a - \boldsymbol{p}_{V_a}$$
$$\boldsymbol{p}_{I_b} = (C+D)\hat{r}_b - \boldsymbol{p}_{V_b}$$

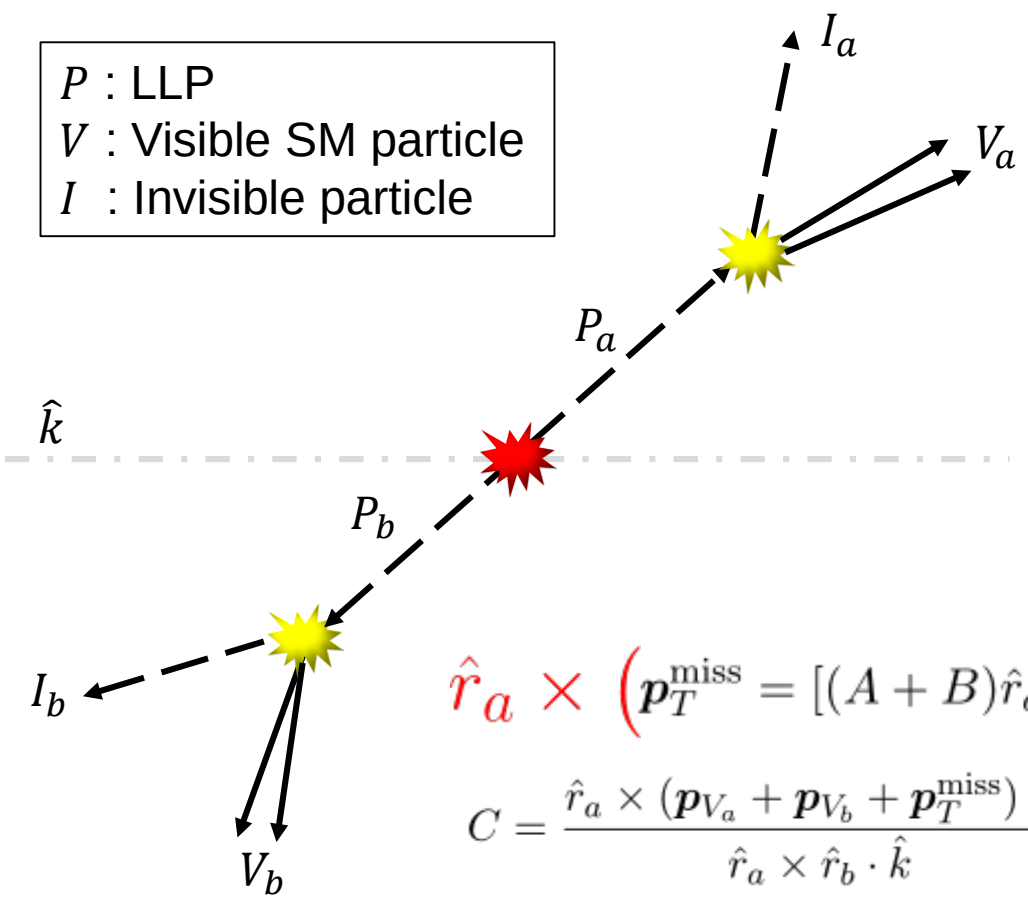
$$\hat{r}_b \times \left(\boldsymbol{p}_T^{\text{miss}} = [(A+B)\hat{r}_a - \boldsymbol{p}_{V_a} + (C+D)\hat{r}_b - \boldsymbol{p}_{V_b}]_\perp \right) \cdot \hat{k}$$

$$A = \frac{\hat{r}_b \times (\boldsymbol{p}_{V_a} + \boldsymbol{p}_{V_b} + \boldsymbol{p}_T^{\text{miss}}) \cdot \hat{k}}{\hat{r}_b \times \hat{r}_a \cdot \hat{k}} - B$$

$$\boldsymbol{p}_{I_a} = \left(\frac{\hat{r}_b \times (\boldsymbol{p}_{V_a} + \boldsymbol{p}_{V_b} + \boldsymbol{p}_T^{\text{miss}}) \cdot \hat{k}}{\hat{r}_b \times \hat{r}_a \cdot \hat{k}} \right) \hat{r}_a - \boldsymbol{p}_{V_a}$$

LLP Event reconstruction

P : LLP
V : Visible SM particle
I : Invisible particle



$$A \equiv (\boldsymbol{p}_{I_a} \cdot \hat{r}_a)$$
$$B \equiv (\boldsymbol{p}_{V_a} \cdot \hat{r}_a)$$
$$C \equiv (\boldsymbol{p}_{I_b} \cdot \hat{r}_a)$$
$$D \equiv (\boldsymbol{p}_{V_b} \cdot \hat{r}_a)$$

$$\boldsymbol{p}_{I_a} = (A+B)\hat{r}_a - \boldsymbol{p}_{V_a}$$
$$\boldsymbol{p}_{I_b} = (C+D)\hat{r}_b - \boldsymbol{p}_{V_b}$$

$$\hat{r}_a \times \left(\boldsymbol{p}_T^{\text{miss}} = [(A+B)\hat{r}_a - \boldsymbol{p}_{V_a} + (C+D)\hat{r}_b - \boldsymbol{p}_{V_b}]_\perp\right) \cdot \hat{k}$$

$$C = \frac{\hat{r}_a \times (\boldsymbol{p}_{V_a} + \boldsymbol{p}_{V_b} + \boldsymbol{p}_T^{\text{miss}}) \cdot \hat{k}}{\hat{r}_a \times \hat{r}_b \cdot \hat{k}} - D$$

$$\boldsymbol{p}_{I_b} = \left(\frac{\hat{r}_a \times (\boldsymbol{p}_{V_a} + \boldsymbol{p}_{V_b} + \boldsymbol{p}_T^{\text{miss}}) \cdot \hat{k}}{\hat{r}_a \times \hat{r}_b \cdot \hat{k}}\right) \hat{r}_b - \boldsymbol{p}_{V_b}$$

LLP Event reconstruction

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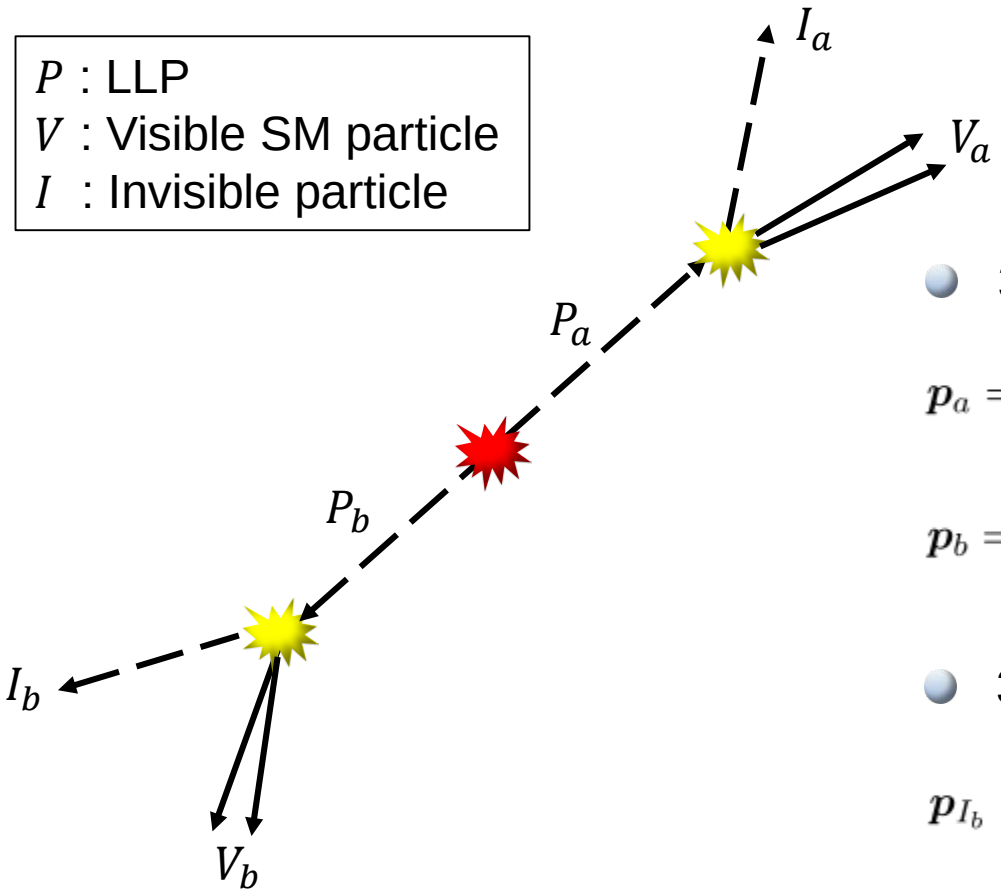
I : Invisible particle



- 6 d.o.f become two 3-momenta
  - $\hat{r}_a, \hat{r}_b$ 2*2 d.o.f
  - p_T^{miss} 2 d.o.f

- 3-momenta of LLPs

$$\boldsymbol{p}_a = \left(\frac{\hat{r}_b \times (\boldsymbol{p}_{V_a} + \boldsymbol{p}_{V_b} + \boldsymbol{p}_T^{\text{miss}}) \cdot \hat{k}}{\hat{r}_b \times \hat{r}_a \cdot \hat{k}} \right) \hat{r}_a$$

$$\boldsymbol{p}_b = \left(\frac{\hat{r}_a \times (\boldsymbol{p}_{V_a} + \boldsymbol{p}_{V_b} + \boldsymbol{p}_T^{\text{miss}}) \cdot \hat{k}}{\hat{r}_a \times \hat{r}_b \cdot \hat{k}} \right) \hat{r}_b$$

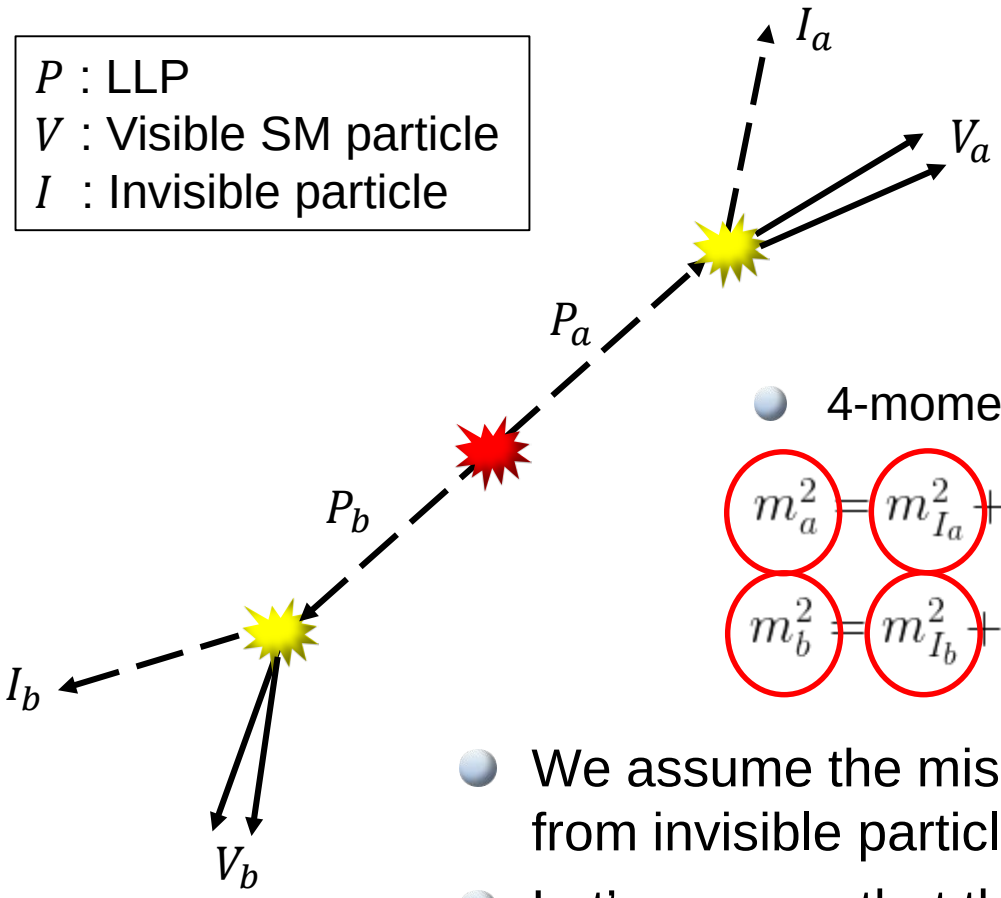
- 3-momenta of invisible particles

$$\boldsymbol{p}_{I_b} = \left(\frac{\hat{r}_a \times (\boldsymbol{p}_{V_a} + \boldsymbol{p}_{V_b} + \boldsymbol{p}_T^{\text{miss}}) \cdot \hat{k}}{\hat{r}_a \times \hat{r}_b \cdot \hat{k}} \right) \hat{r}_b - \boldsymbol{p}_{V_b}$$

$$\boldsymbol{p}_{I_a} = \left(\frac{\hat{r}_b \times (\boldsymbol{p}_{V_a} + \boldsymbol{p}_{V_b} + \boldsymbol{p}_T^{\text{miss}}) \cdot \hat{k}}{\hat{r}_b \times \hat{r}_a \cdot \hat{k}} \right) \hat{r}_a - \boldsymbol{p}_{V_a}$$

LLP Event reconstruction

P : LLP
V : Visible SM particle
I : Invisible particle



- 4-momentum conservation

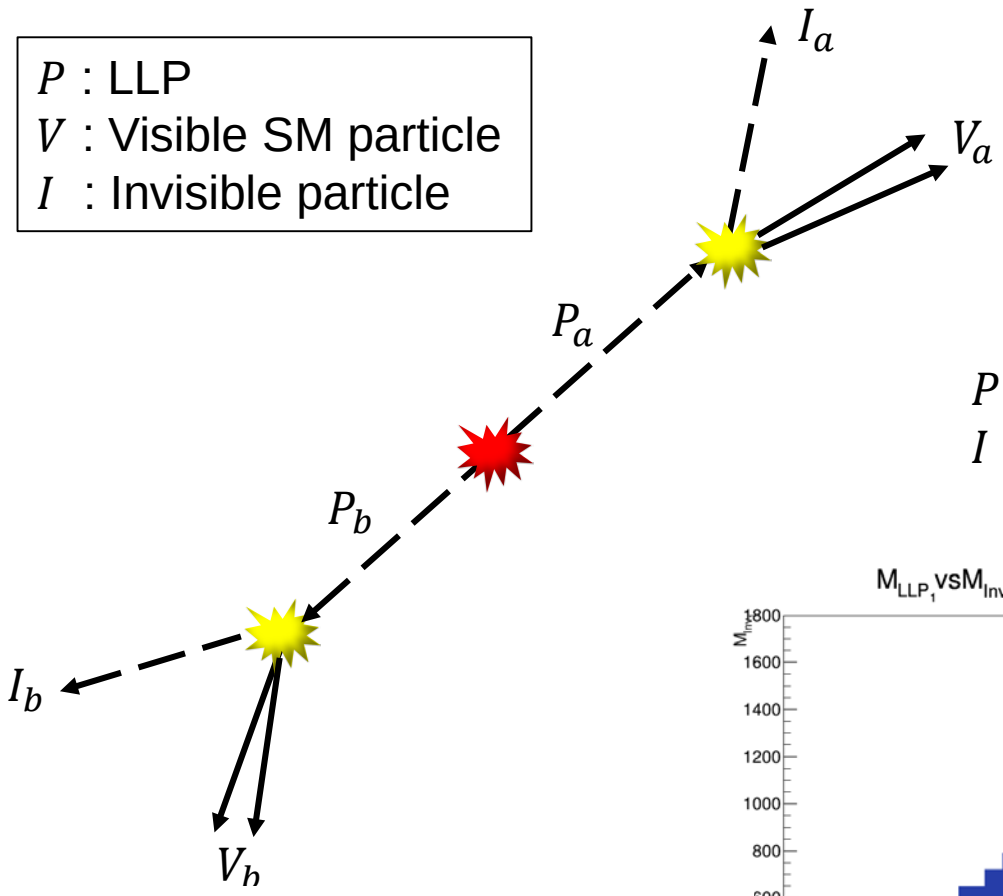
$$m_a^2 = m_{I_a}^2 + m_{V_a}^2 + 2E_{V_a}\sqrt{m_{I_a}^2 + |\boldsymbol{p}_{I_a}|^2} - 2\boldsymbol{p}_{V_a}\cdot\boldsymbol{p}_{I_a}$$

$$m_b^2 = m_{I_b}^2 + m_{V_b}^2 + 2E_{V_b}\sqrt{m_{I_b}^2 + |\boldsymbol{p}_{I_b}|^2} - 2\boldsymbol{p}_{V_b}\cdot\boldsymbol{p}_{I_b}$$

- We assume the missing transverse energy solely coms from invisible particles
- Let's assume that the mass of LLPs are same and also mass of invisible particle are same.
- We can find 1 or 2 positive mass pairs

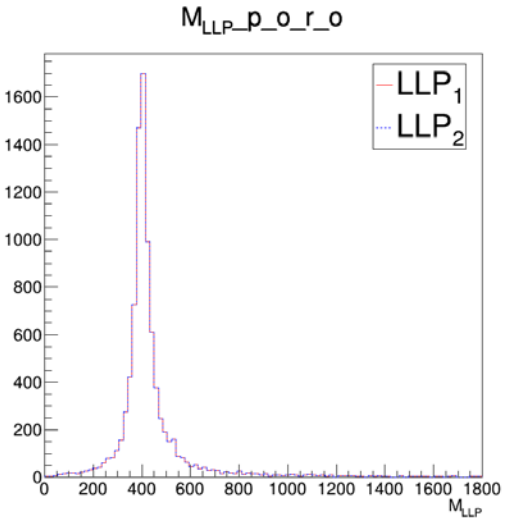
LLP Event reconstruction

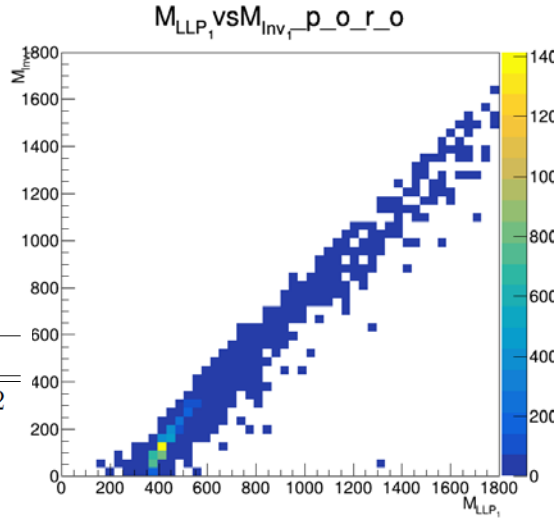
P : LLP
V : Visible SM particle
I : Invisible particle

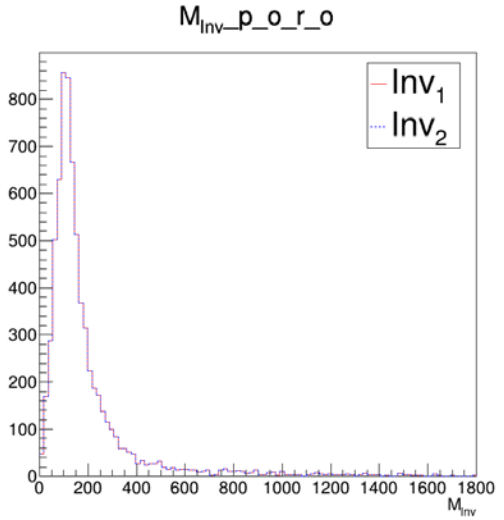


P : 400 GeV
I : 100 GeV

		m_{LLP_1}	m_{LLP_2}	m_{I_1}	m_{I_2}
Case 1	no timing	404.654	404.654	123.542	123.542

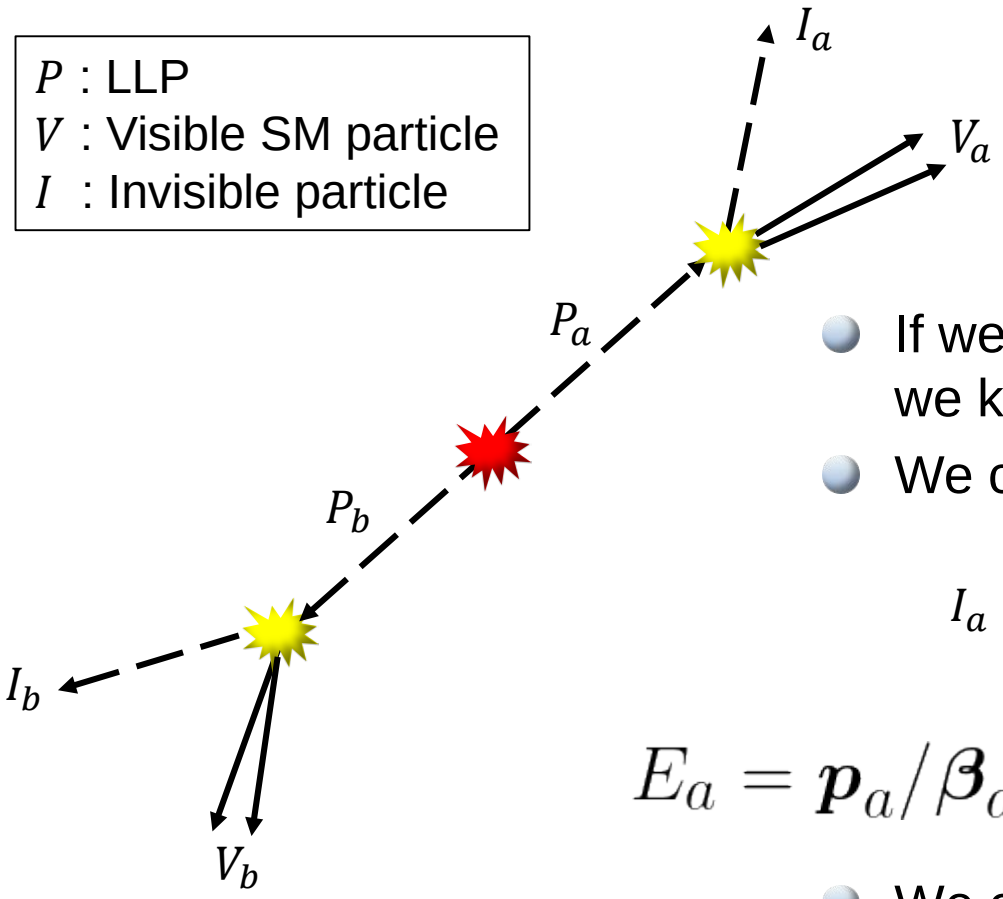




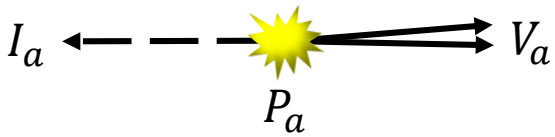


Timing reconstruction

P : LLP
V : Visible SM particle
I : Invisible particle



- If we can also measure the time-of-flight, we know the velocity β_a
- We can boost to LLP rest frame

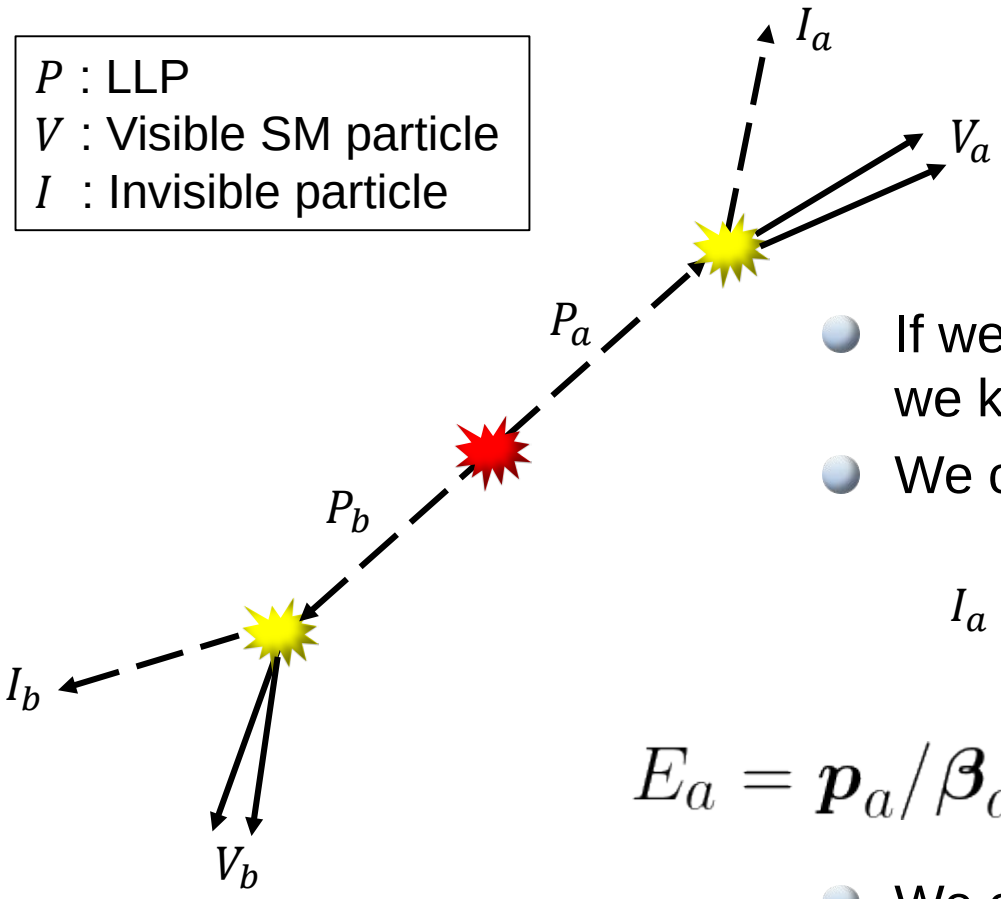


$$E_a = \boldsymbol{p}_a / \boldsymbol{\beta}_a \qquad \boldsymbol{p}_a = \left(\frac{\hat{r}_b \times (\boldsymbol{p}_{V_a} + \boldsymbol{p}_{V_b} + \boldsymbol{p}_T^{\text{miss}}) \cdot \hat{k}}{\hat{r}_b \times \hat{r}_a \cdot \hat{k}} \right) \hat{r}_a$$

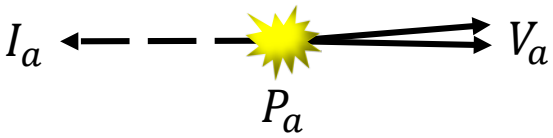
- We can find 4-momentum of the LLPs without any presumable assumptions
- The solution is unique

Timing reconstruction

P : LLP
V : Visible SM particle
I : Invisible particle



- If we can also measure the time-of-flight, we know the velocity β_a
- We can boost to LLP rest frame

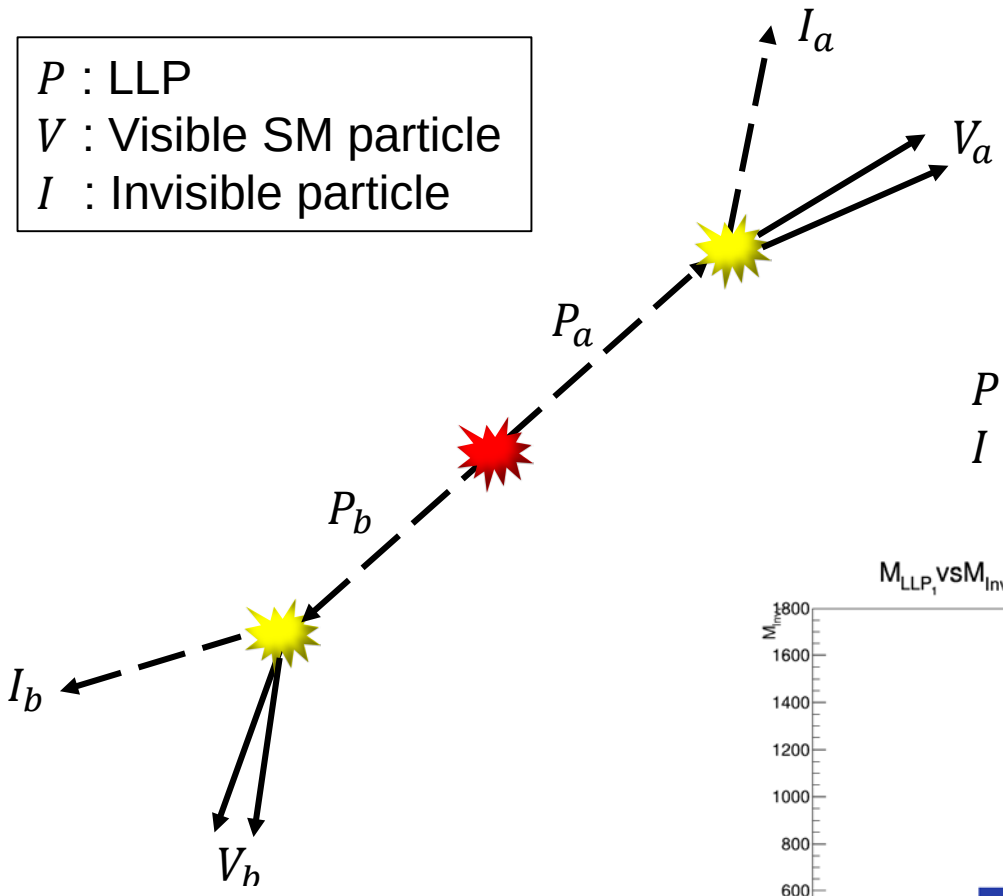


$$E_a = \boldsymbol{p}_a / \boldsymbol{\beta}_a \quad \boldsymbol{p}_a = \left(\frac{\boldsymbol{\beta}_b \times (\boldsymbol{p}_{V_a} + \boldsymbol{p}_{V_b} + \boldsymbol{p}_T^{\text{miss}}) \cdot \hat{k}}{\boldsymbol{\beta}_b \times \boldsymbol{\beta}_a \cdot \hat{k}} \right) \boldsymbol{\beta}_a$$

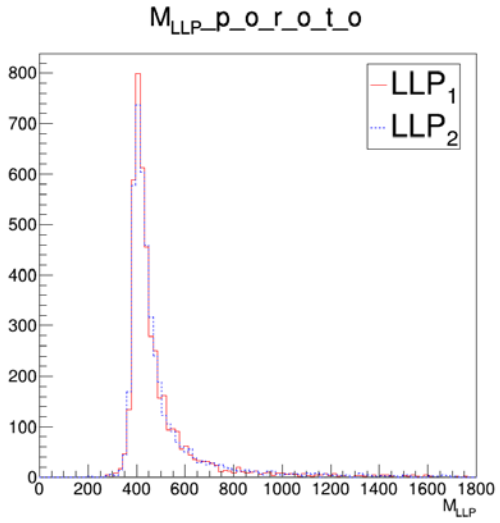
- We can find 4-momentum of the LLPs without any presumable assumptions
- The solution is unique

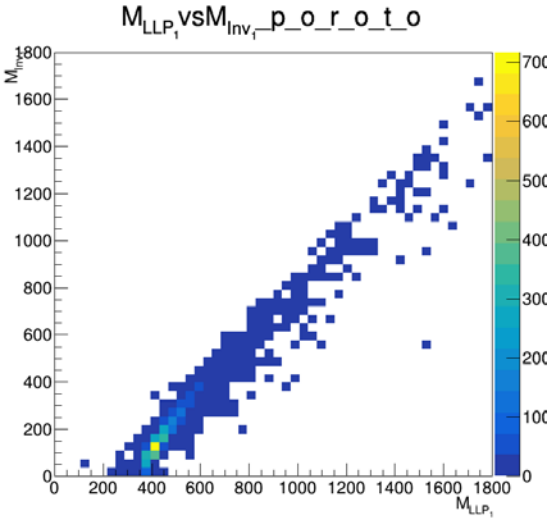
Timing reconstruction

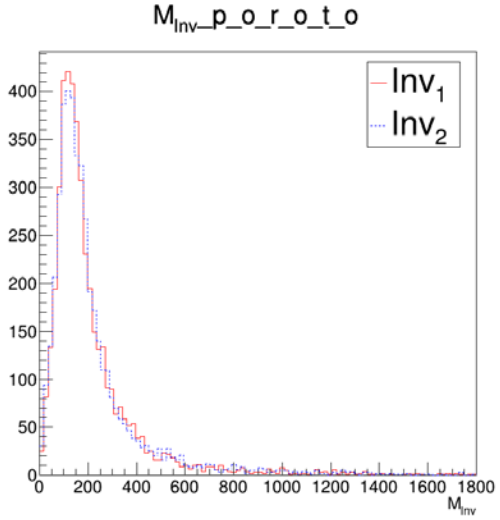
P : LLP
V : Visible SM particle
I : Invisible particle



P : 400 GeV
I : 100 GeV



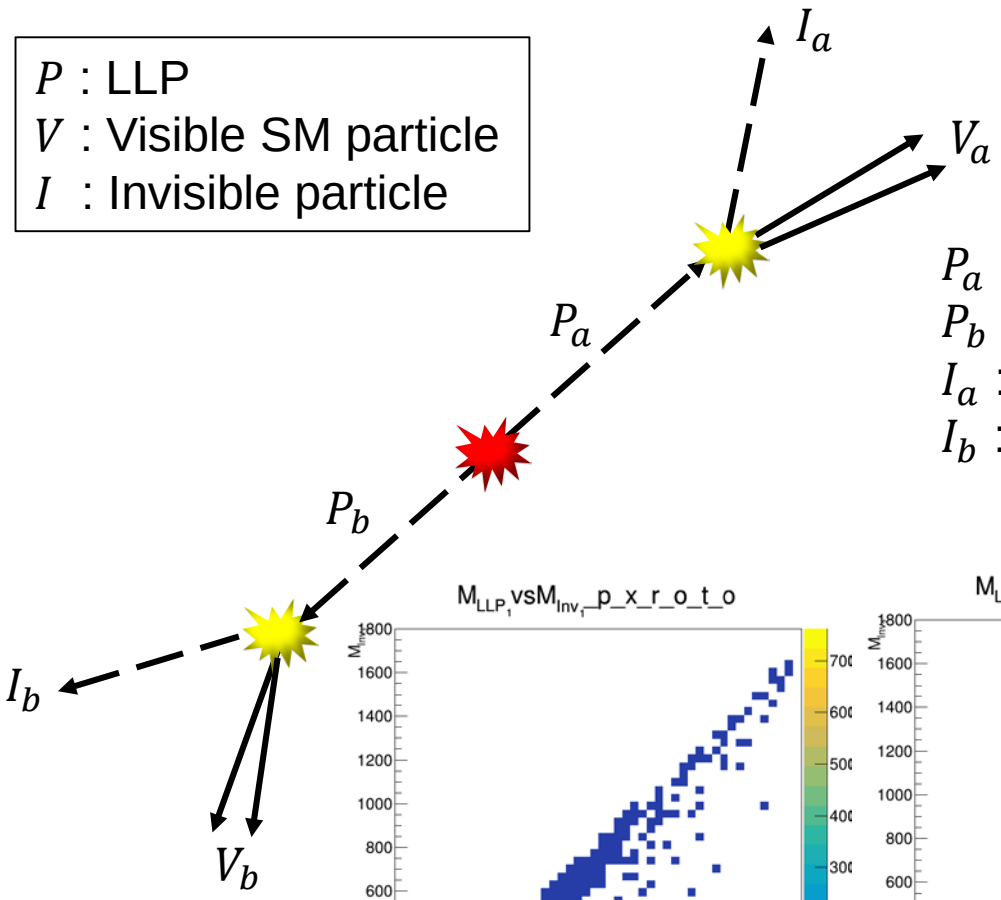




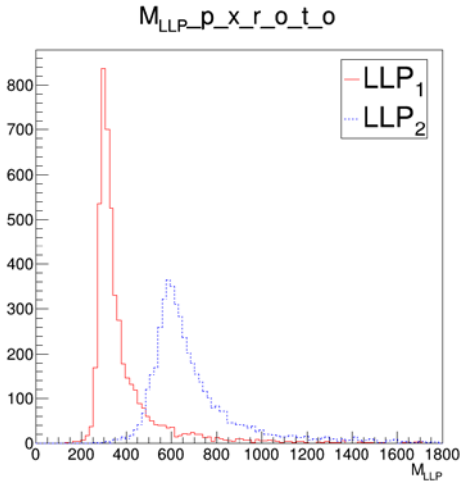
		m_{LLP_1}	m_{LLP_2}	m_{I_1}	m_{I_2}
Case 1	no timing	404.654	404.654	123.542	123.542
	timing	412.481	413.735	148.353	155.783

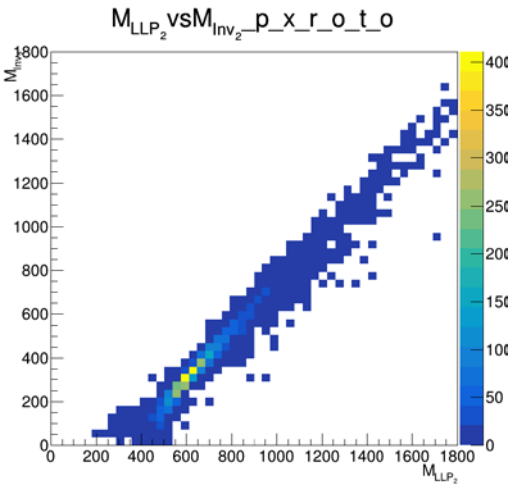
Timing reconstruction

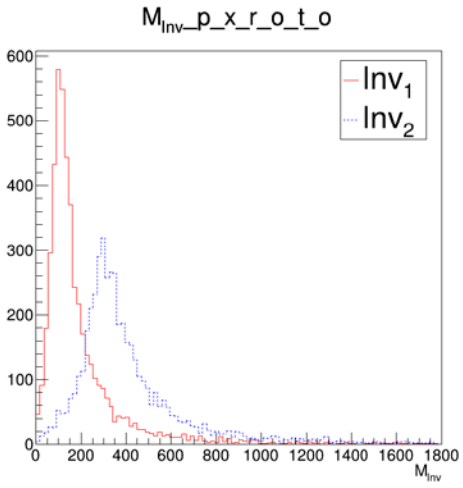
P : LLP
V : Visible SM particle
I : Invisible particle



P_a : 300 GeV
P_b : 600 GeV
I_a : 100 GeV
I_b : 300 GeV

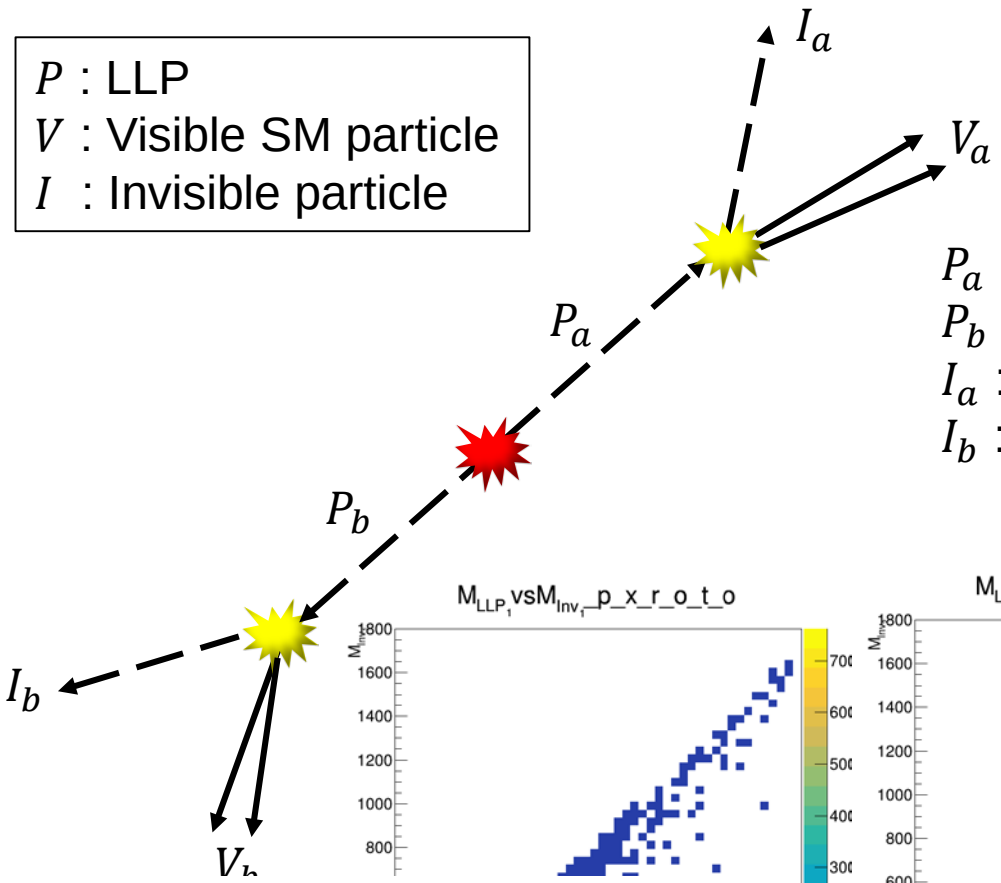




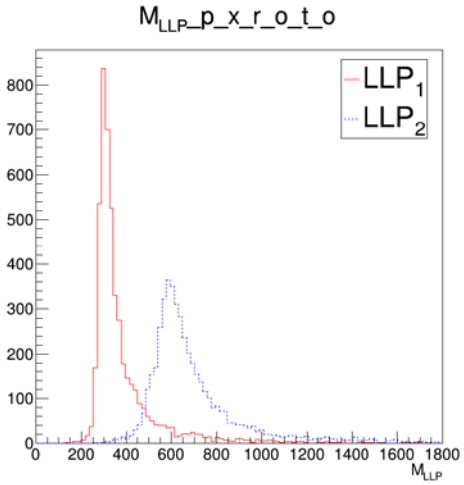


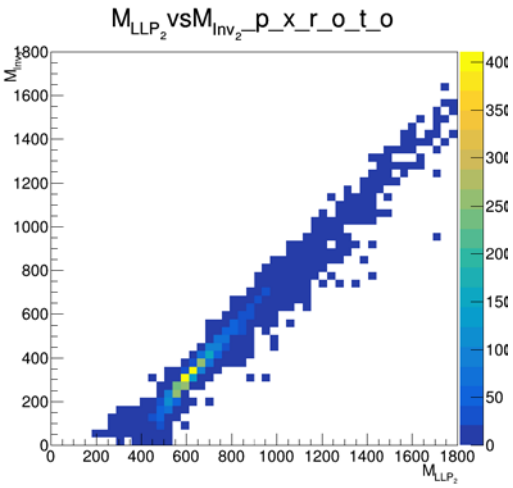
Timing reconstruction

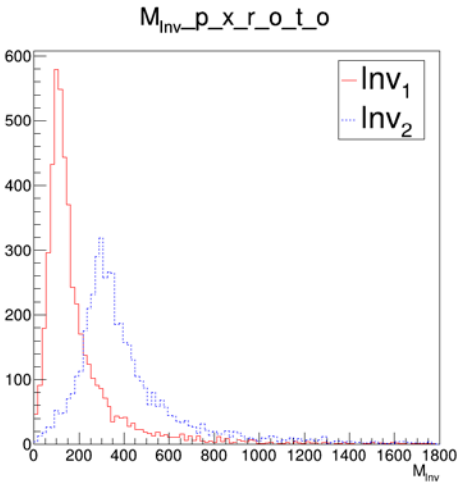
P : LLP
V : Visible SM particle
I : Invisible particle



P_a : 300 GeV
P_b : 600 GeV
I_a : 100 GeV
I_b : 300 GeV



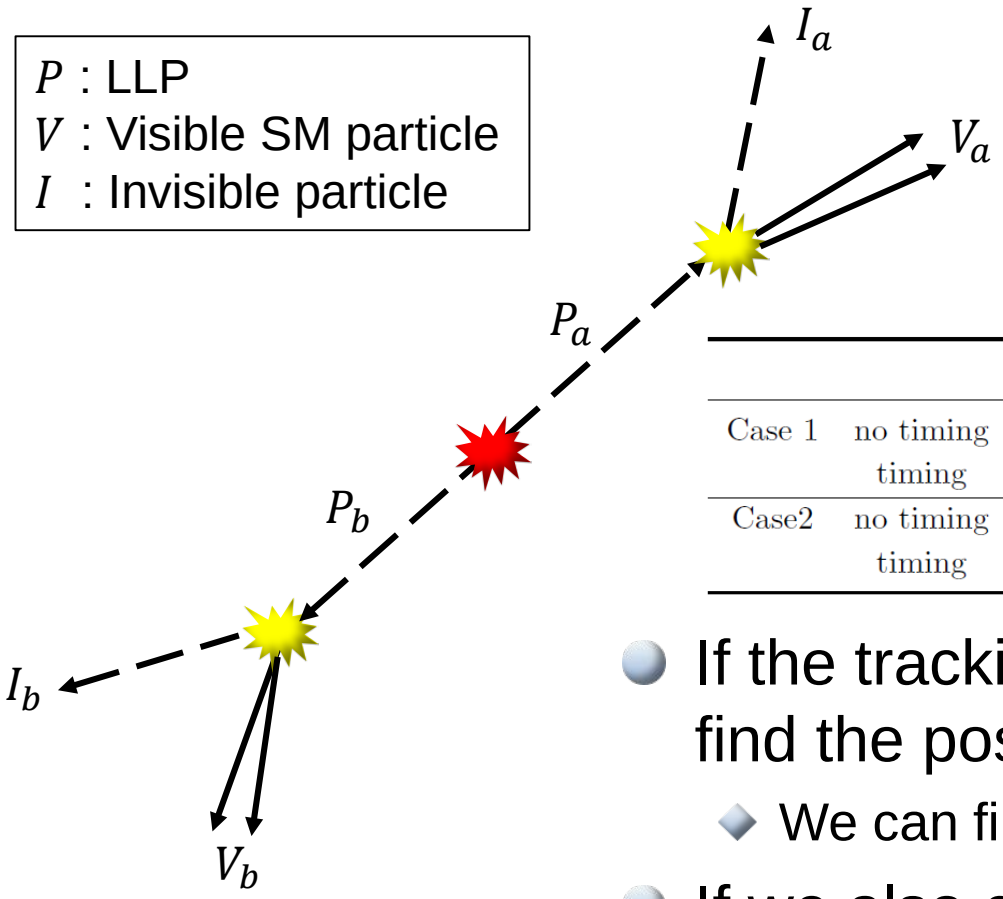




		m_{LLP_1}	m_{LLP_2}	m_{I_1}	m_{I_2}
Case 1	no timing	404.654	404.654	123.542	123.542
	timing	412.481	413.735	148.353	155.783
Case2	no timing	-	-	-	-
	timing	306.582	616.64	108.639	314.348

Summary of Event reconstruction

P : LLP
V : Visible SM particle
I : Invisible particle



		m_{LLP_1}	m_{LLP_2}	m_{I_1}	m_{I_2}	$\boldsymbol{p}_{LLP_1}$	$\boldsymbol{p}_{LLP_2}$	$\boldsymbol{p}_{I_1}$	$\boldsymbol{p}_{I_2}$
Case 1	no timing	△	△	△	△	○	○	○	○
	timing	○	○	○	○	○	○	○	○
Case2	no timing	×	×	×	×	○	○	○	○
	timing	○	○	○	○	○	○	○	○

- If the tracking system is perfect, we can find the position of the LLP decay
  - We can find the 3-momentums of the event
- If we also can measure the time-of-flight of the LLP
  - We can reconstruct the whole event.

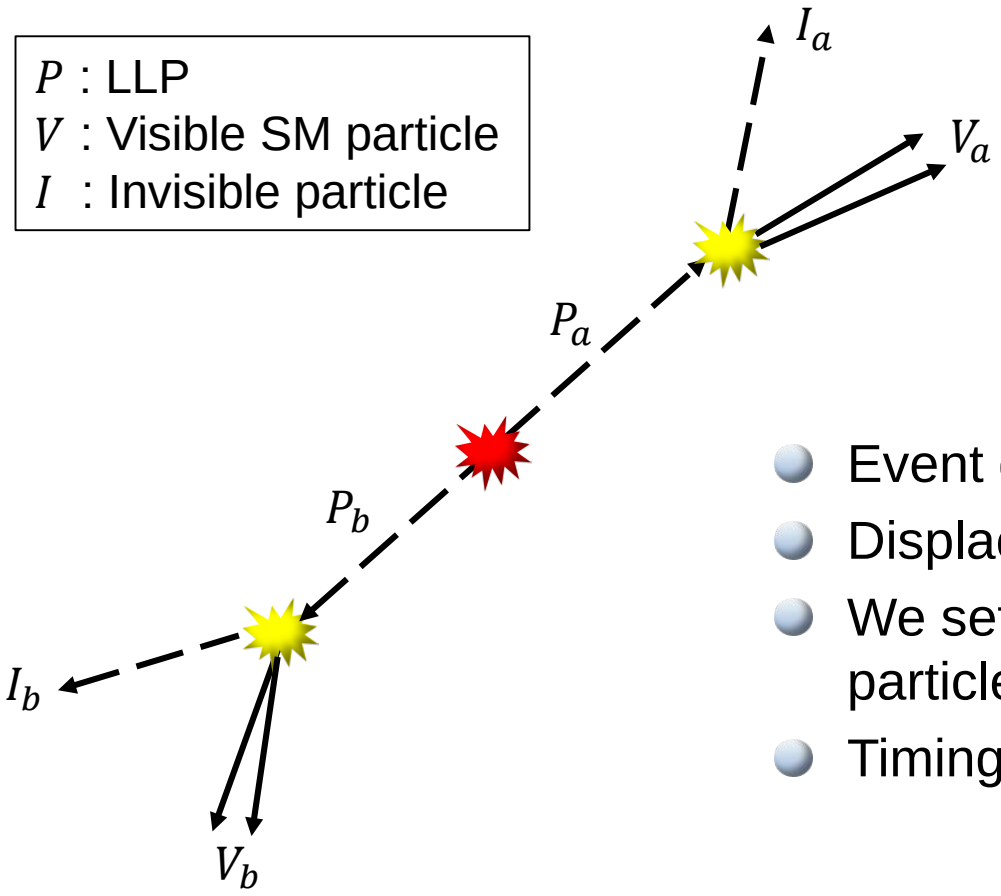
Conclusion

- New physics may buried in the hidden sector
- The timing detectors will flash the hidden sector where we have overlooked before.
- Using the time-of-flight information, we can fully reconstruct the events
- Lifetime frontier is just started, we need to develop more concrete program

backup

LLP Event reconstruction

P : LLP
V : Visible SM particle
I : Invisible particle

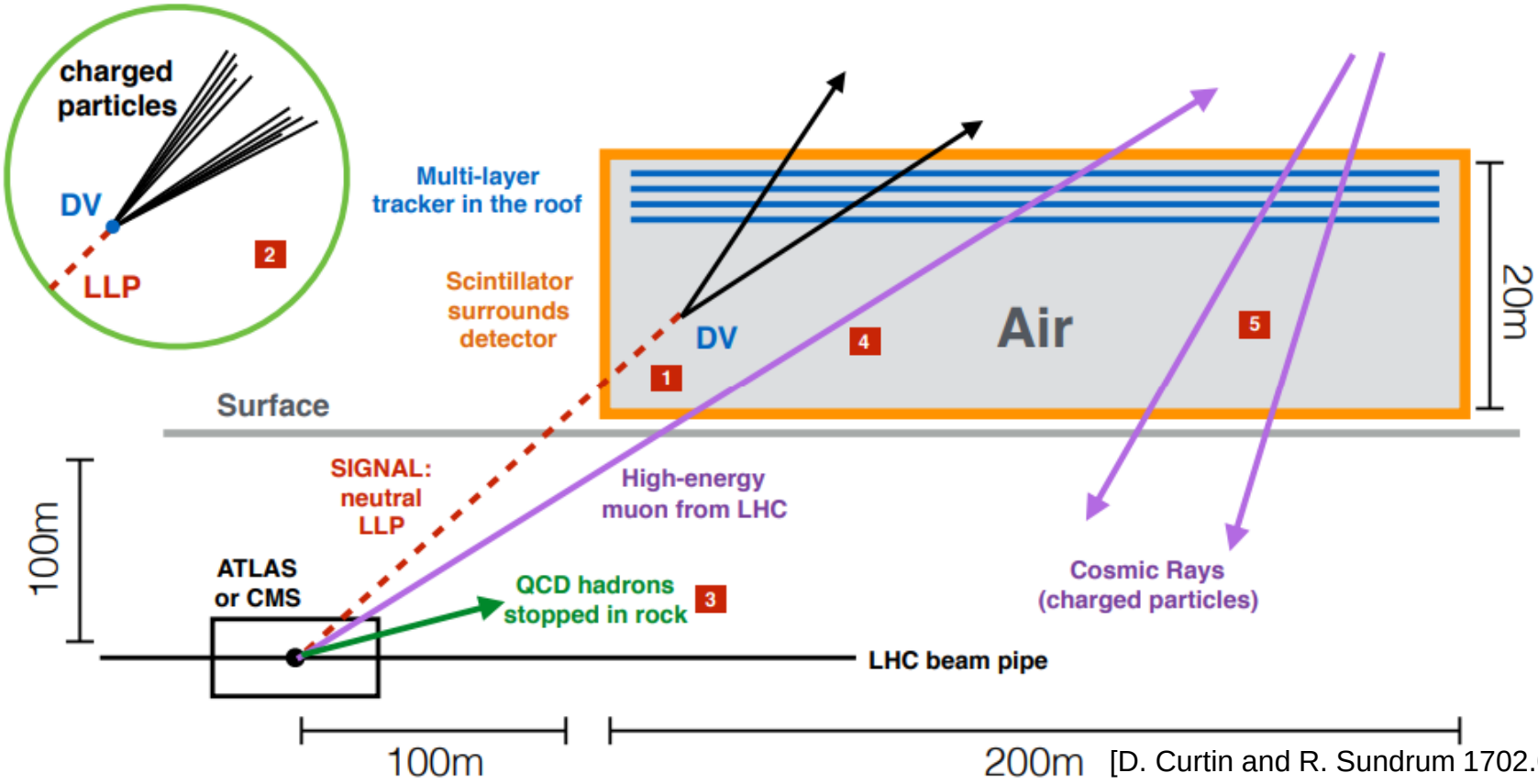


- Event generation is done by MadGraph5
- Displaced decay in PYTHIA8
- We set LLP mass 400 GeV and invisible particles mass is 100 GeV
- Timing resolution assumes 30 ps

MATHUSLA

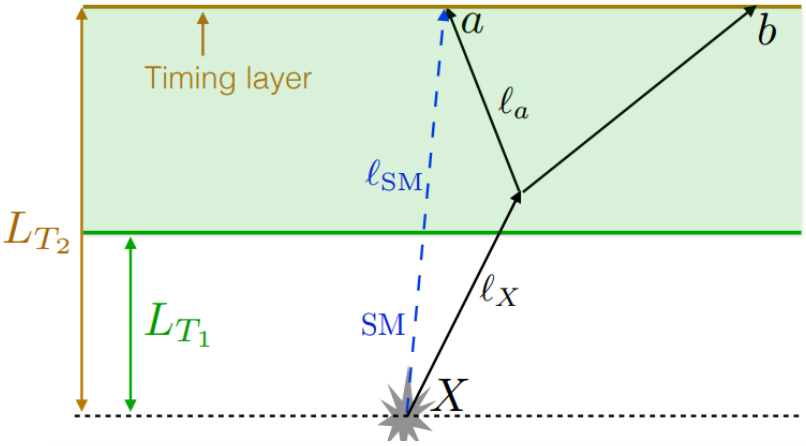
[J. P. Chou, D. Curtin, H. J. Lubatti 1606.06298]

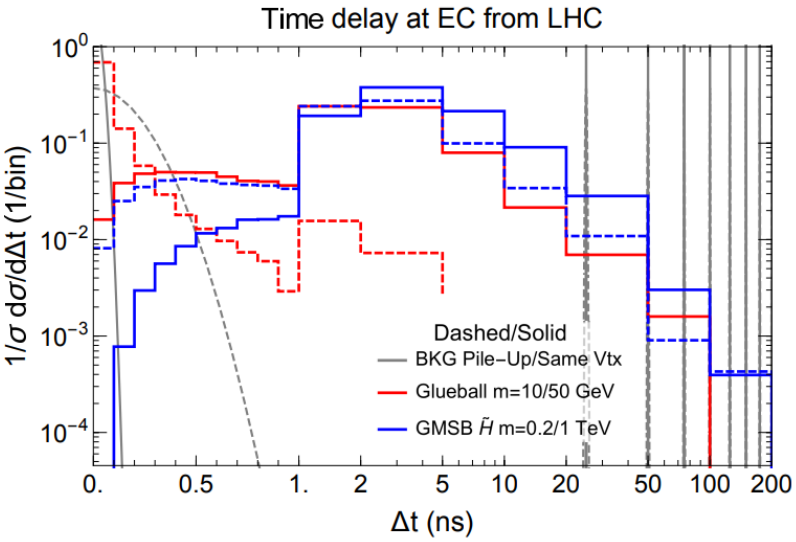
- MAssive Timing Hodoscope for Ultra-Stable neutraL pArticles

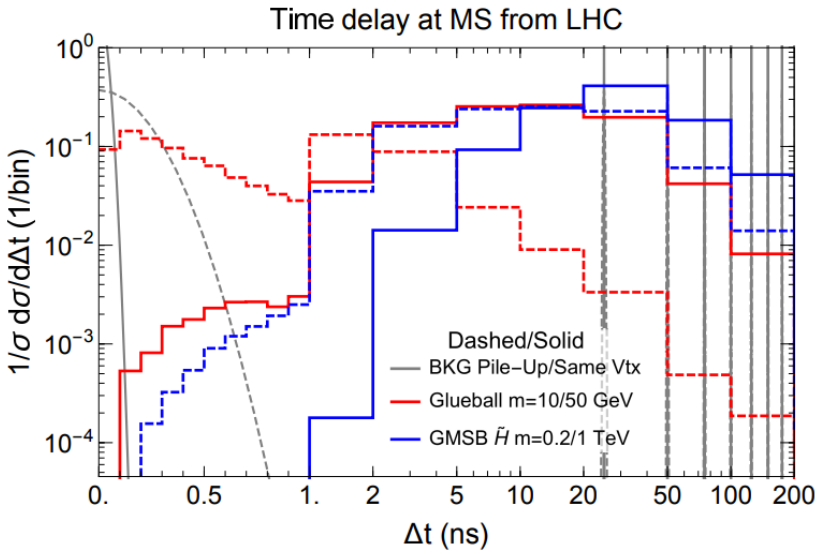


[D. Curtin and R. Sundrum 1702.02524]

Lian-Tao's paper



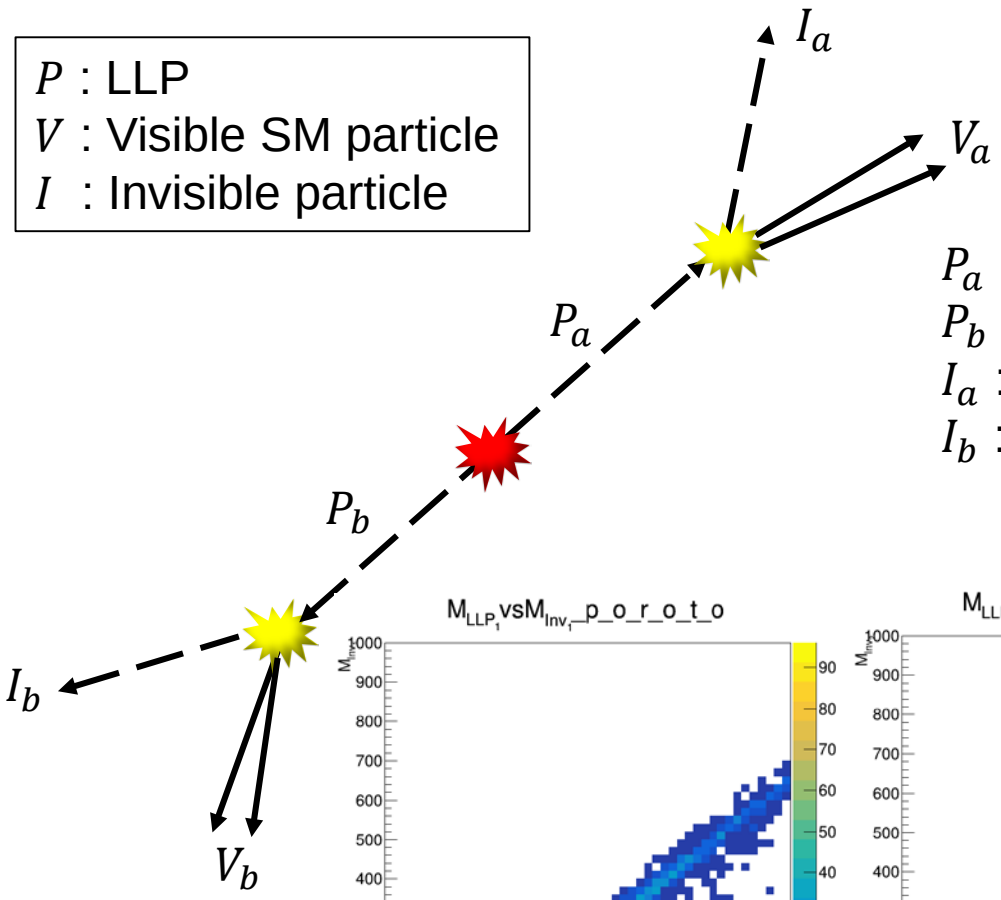




[J. Liu, Z. Liu and L. Wang 1805.05957]

Timing reconstruction (p Smeared)

P : LLP
V : Visible SM particle
I : Invisible particle



P_a : 300 GeV
P_b : 600 GeV
I_a : 100 GeV
I_b : 300 GeV