Prospects for Off-shell Slepton Search at CEPC

Joint Workshop of the CEPC Physics, Software & New Detector Concept.
Aug 13-18, 2023. Fudan University

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Aug-14, 2023

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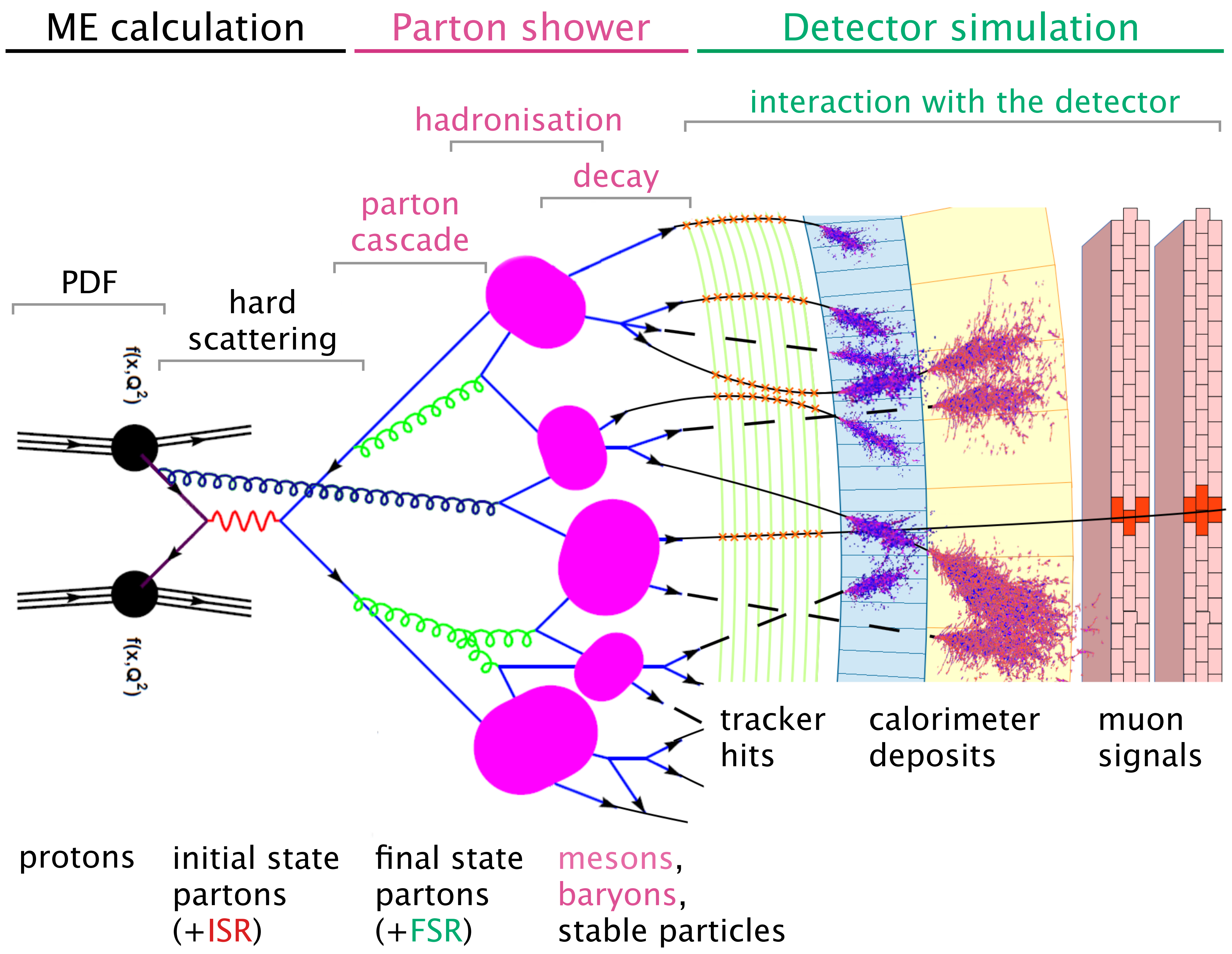
Based on arXiv: 2211.01832

Collider Physics



Hard Scattering Level: (Master Formulae)

$$\sigma = \sum_{a,b} \int_0^1 dx_a dx_b \int f_a^{h1}(x_a, \mu_F)\, f_b^{h2}(x_b, \mu_R)\, d\sigma_{a,b}(\mu_F, \mu_R)$$

- Parton distribution function
- Matrix element
- Initial state radiation

Parton Level

- Parton shower
- Decay
- Final state radiation

Detector Level

- Object reconstruction
- Object Identification
- Electron, muon, jets, photon, tracks

Event Reconstruction Level

- Event number / cross section: σ
- missing energy: p_{miss}
- Kinematic variable distributions: $\frac{d\sigma}{d\mathcal{O}}$

Lepton Collider

Advantages

Conservation laws benefits a lot.

Collision system

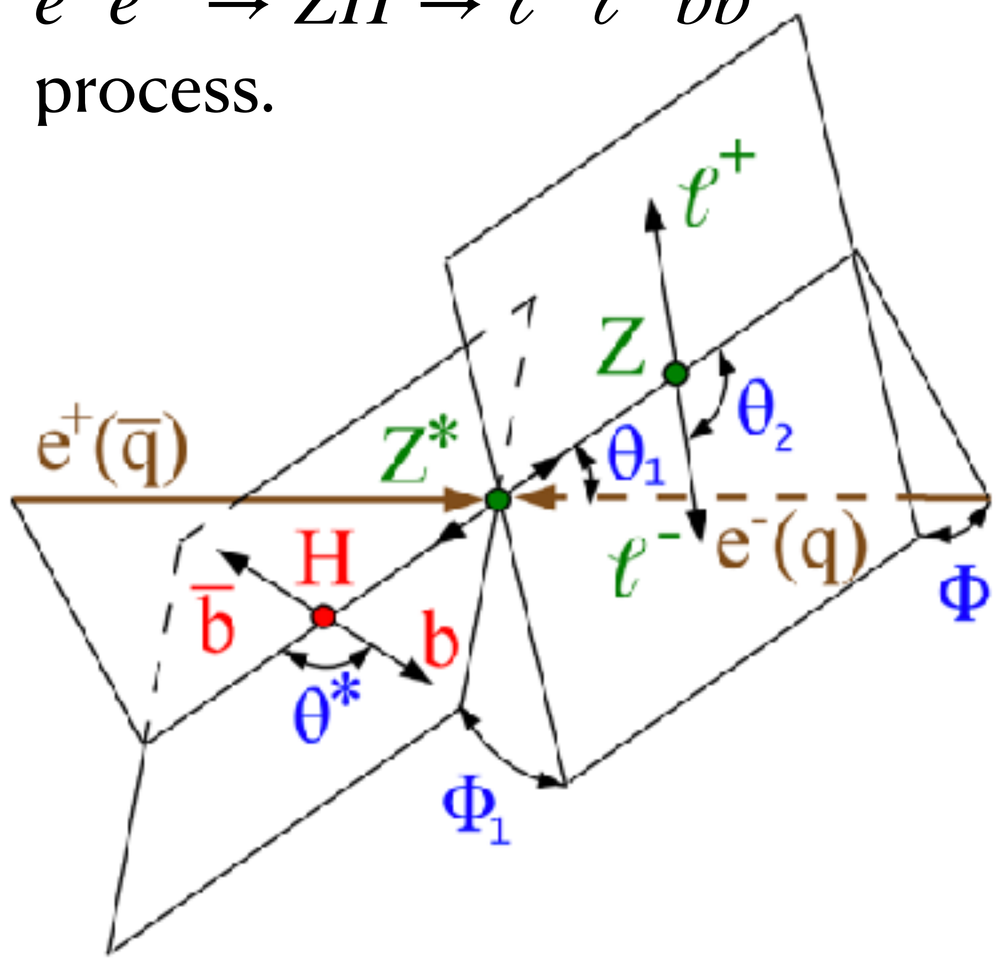
- 0 net charge & 0 lepton number before and after.
    1. Suitable to create new particles after e^+e^- annihilation
- Symmetric beams of e^+e^-.
    2. CM frame ≈ Lab frame;
    3. Total E_{CM} fully exploited to reach highest possible physics threshold.
- Well-understood beam properties.
    4. PDFs are simple, $E_{\mathrm{CM}} = \sqrt{s}$.
    5. ISR from electroweak process.

Detector Level

- Low QCD soft background.
    1. High object identification & reconstruction efficiency.
- High precision four-momentum vector.
    2. Recoil system measurement method.
    3. Lorentz invariant kinematic observables.

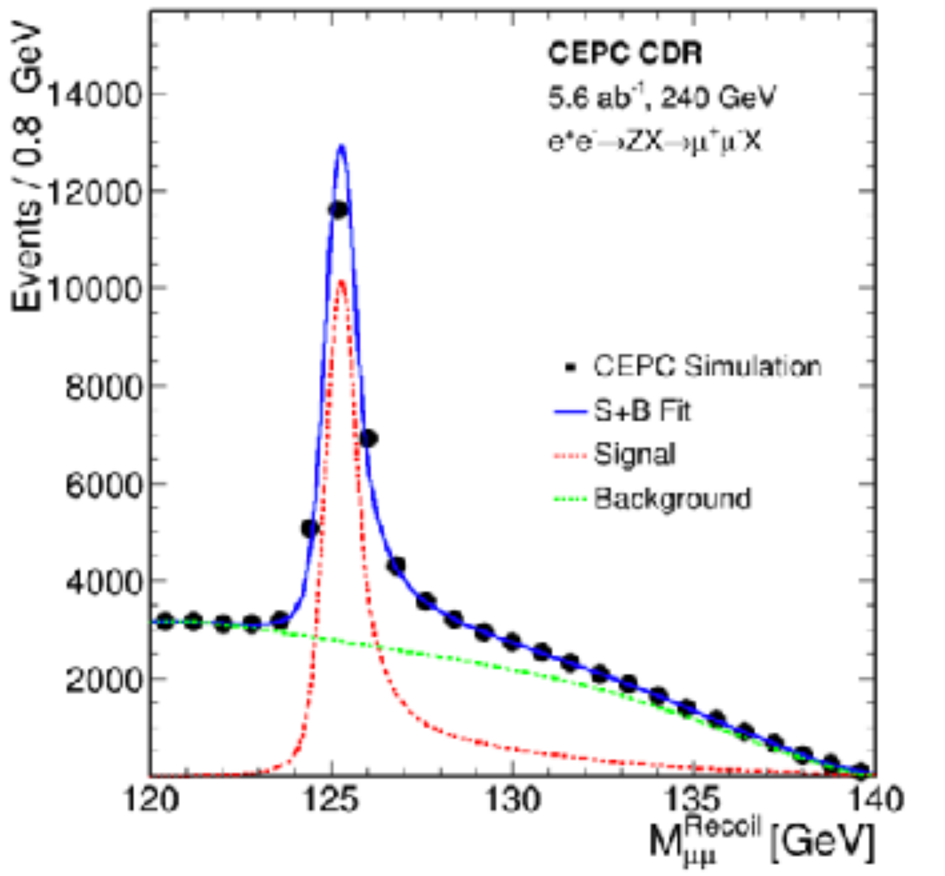
Higgs mass measurement by recoiled Z

Higgs boson production and decay angles of the $e^+e^- \to ZH \to \ell^+\ell^- b\bar{b}$ process.



Recoil mass:

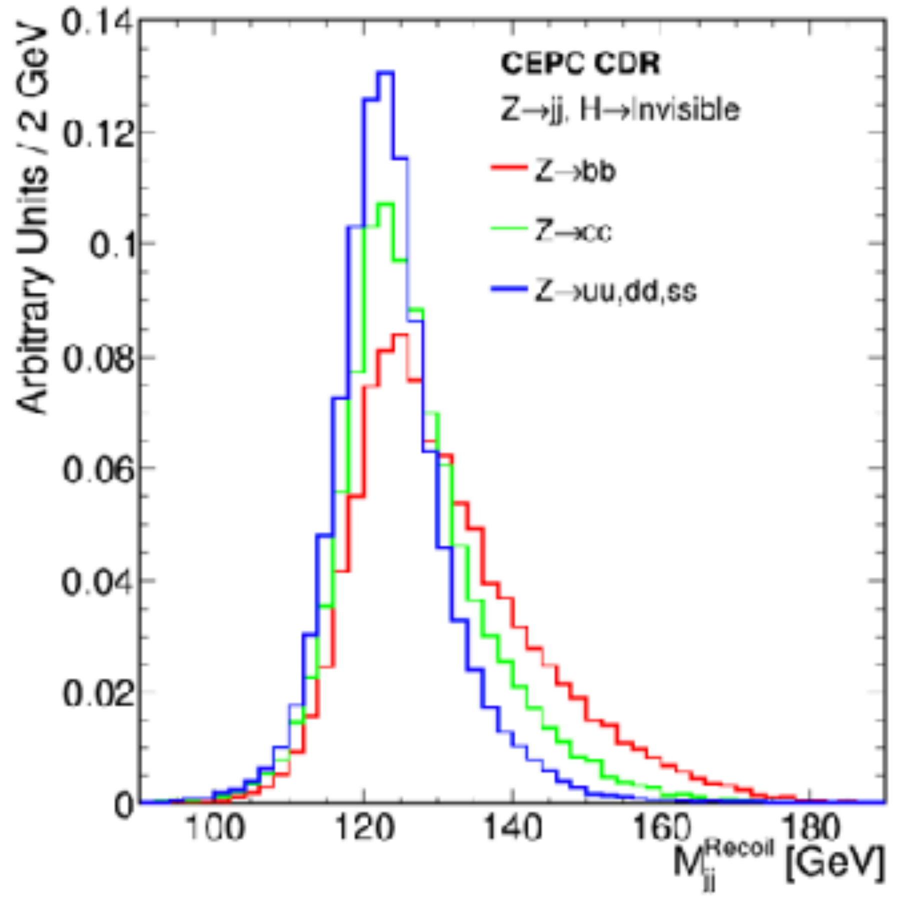
$$m_{\mathrm{recoil}} = \sqrt{(\sqrt{s} - E_{\mu^+\mu^-})^2 - p^2_{\mu^+\mu^-}}$$

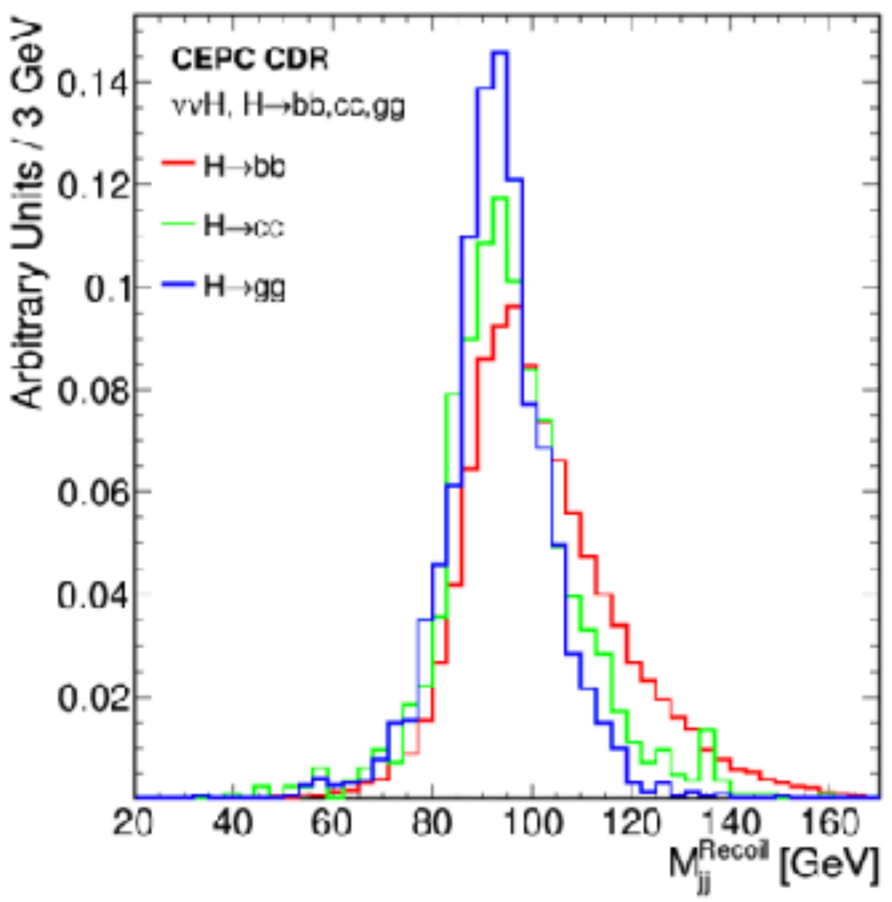


Missing energy and momentum

$$p_\mu^{\mathrm{miss}} = (\sqrt{s}, \vec{0}) - \sum_i p_\mu^i$$

determinations of missing energy and momentum with good precision.

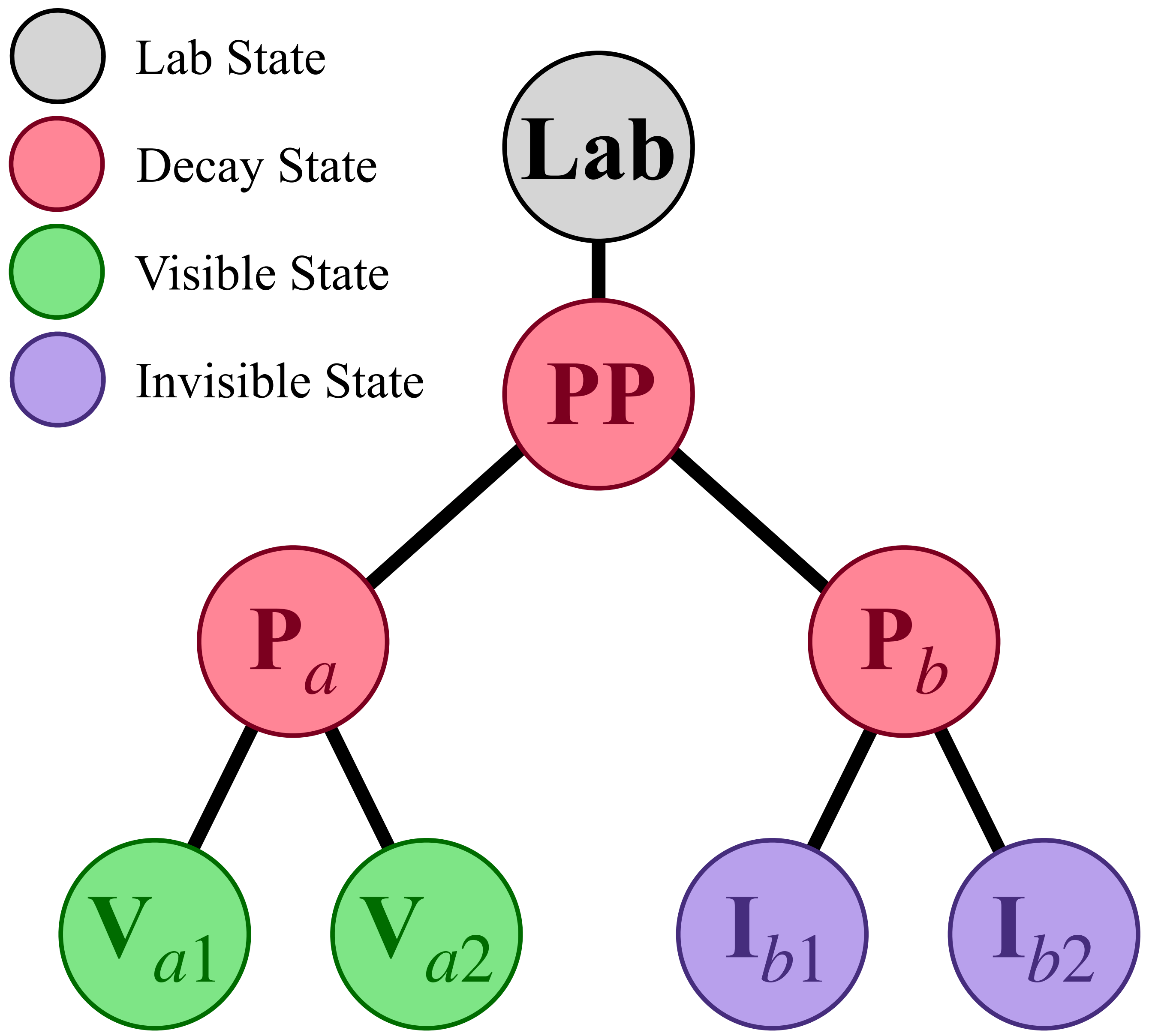


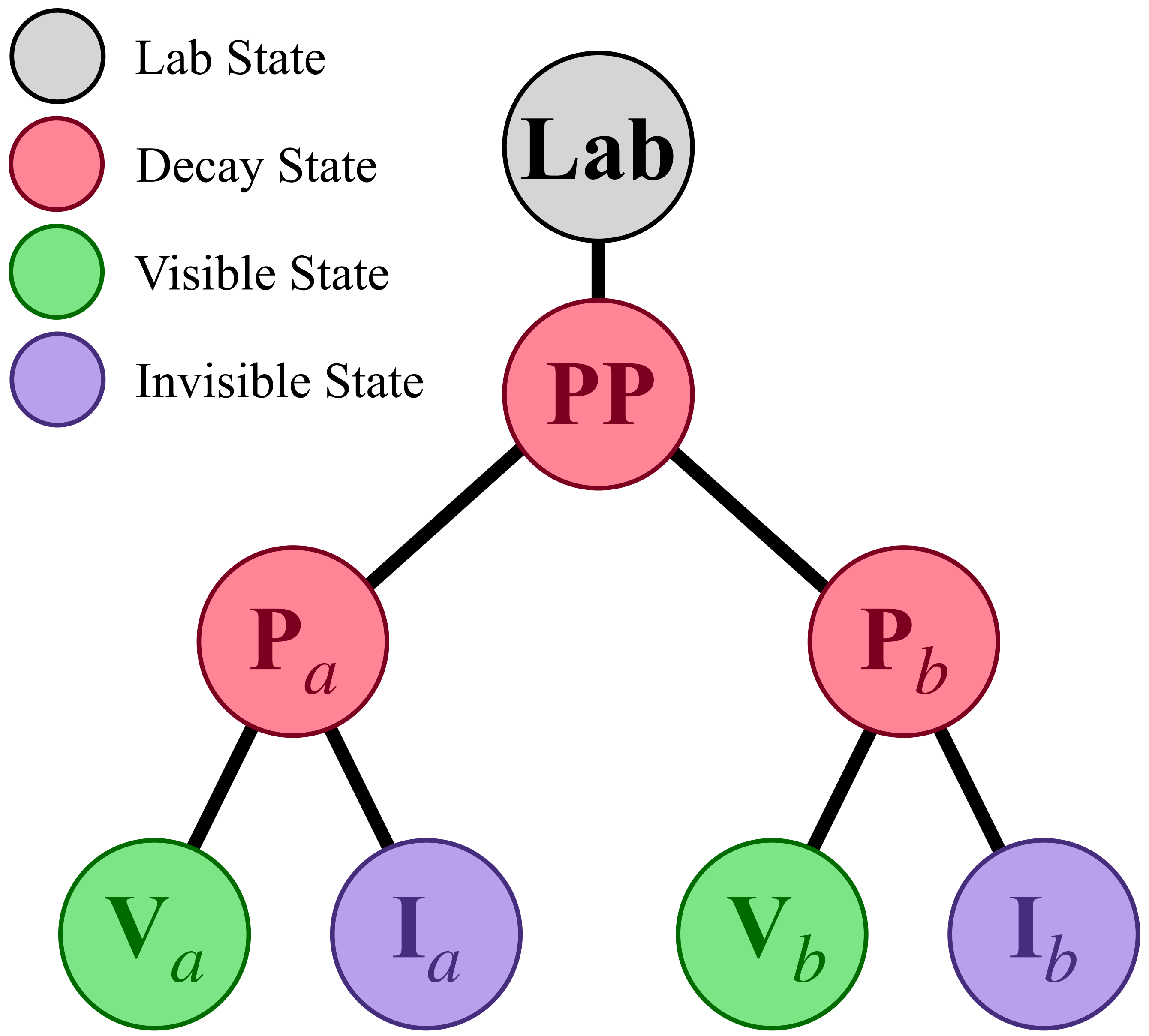


Reconstructing events containing two invisible particle

Lepton Collider

$e^+e^- \to \mathbf{P}_a\mathbf{P}_b$



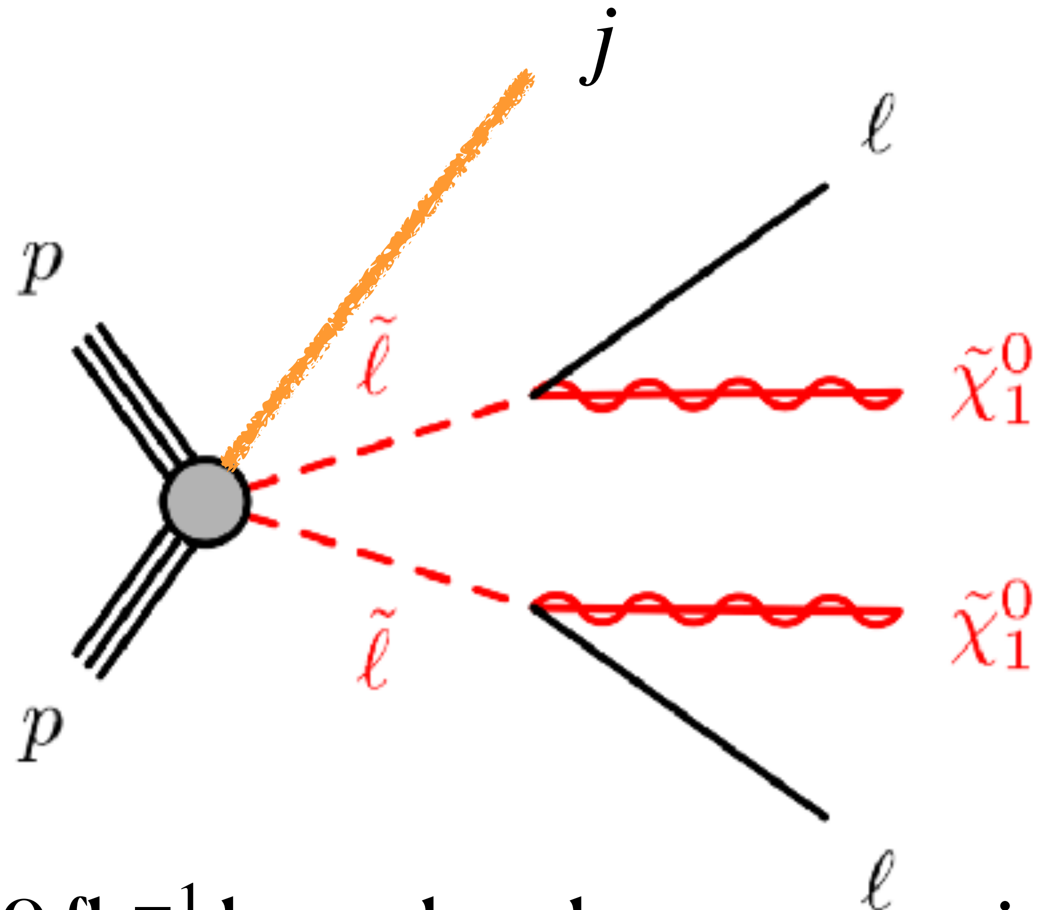


- Investigating the invisible decayed $\mathbf{P}_b$ can be by recoiled system $\mathbf{P}_a$.
- Two Lorentz invariant observable:
  - Invariant mass: $m_{V_{a1}V_{a2}}$
  - Recoil mass: m_{recoil}

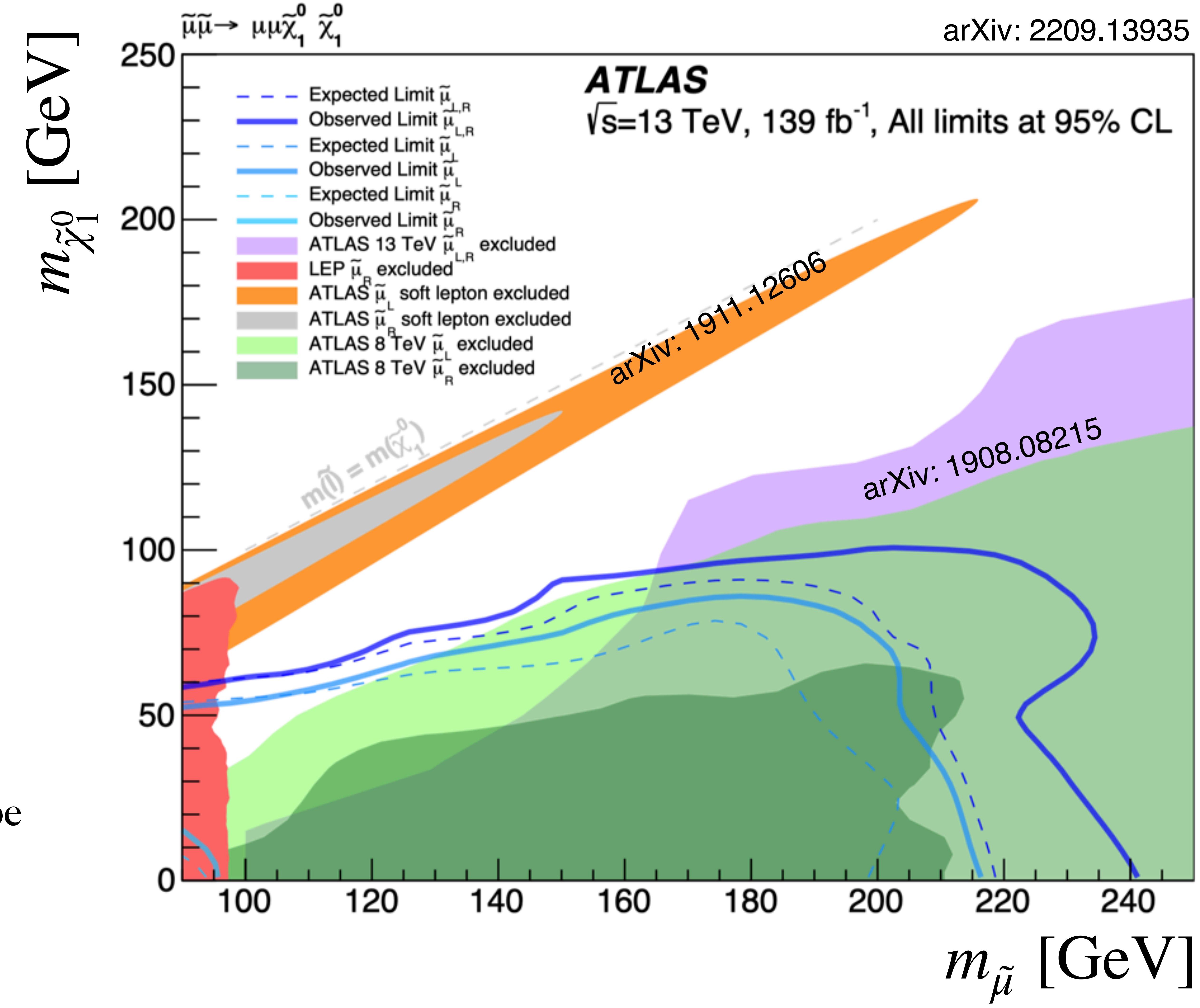
- What for semi-invisible decayed topology?

Almost all new physics theories with dark matter candidates **I** also contain additional particles **P** that are charged not only under new-symmetry but also carry SM charges. At collider, these new particles must be pair produced, and will (cascade) decay into dark matter particle plus one or a group of SM visible particles.

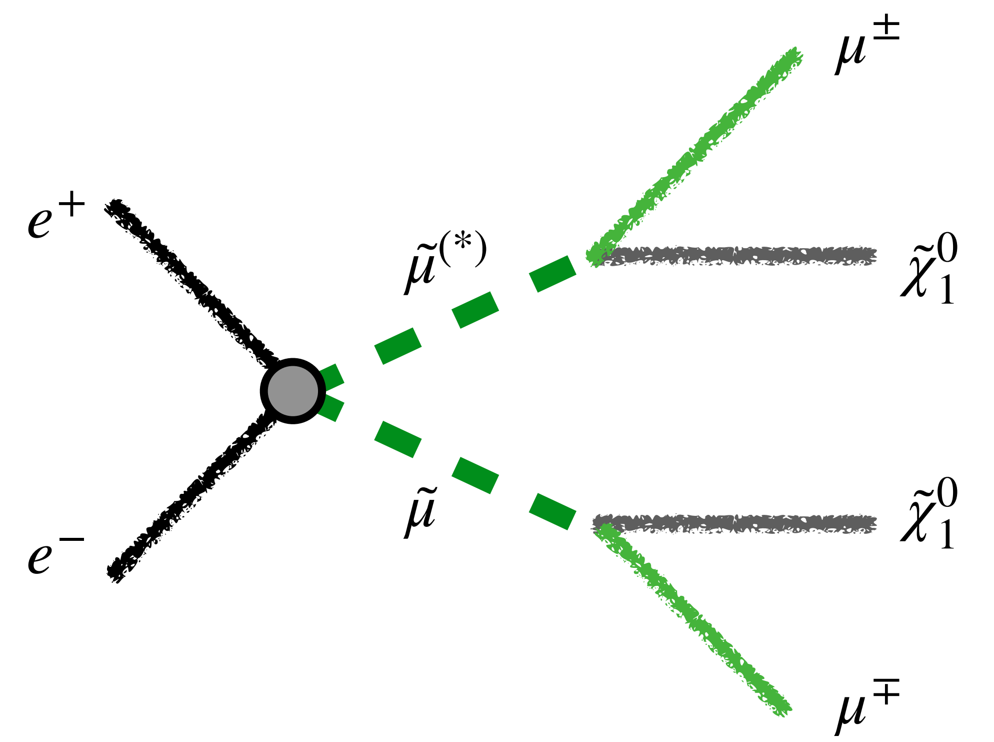
Slepton searches at LHC



- LHC Run-II with 139 fb^{-1} have already set constraints on di-lepton+ $E_{\mathrm{T}}^{\mathrm{miss}}$ final states in searches for slepton pair production.
- Compressed spectrum region can be probed by events with ISR via Recursive Jigsaw Reconstruction(RJR) technique .
- Still a gap uncovered for $m_{\tilde{\ell}}$ at $\mathcal{O}(100)$ GeV.
- A small deviation between the expected limit and observed limit, maybe a statistical fluctuation.



Smuon pair production at lepton collider



arXiv: 2104.06421 provide an idea of searching $\tilde{\mu}$ via pair production process

$$e^+e^- \to \tilde{\mu}\tilde{\mu}^{(*)} \to \mu^+\tilde{\chi}_1^0\mu^-\tilde{\chi}_1^0$$

with one $\tilde{\mu}$ being off-shell.

- On-shell region: $m_{\tilde{\mu}} \leq \sqrt{s}/2$.

  Narrow width approximation (NWA)

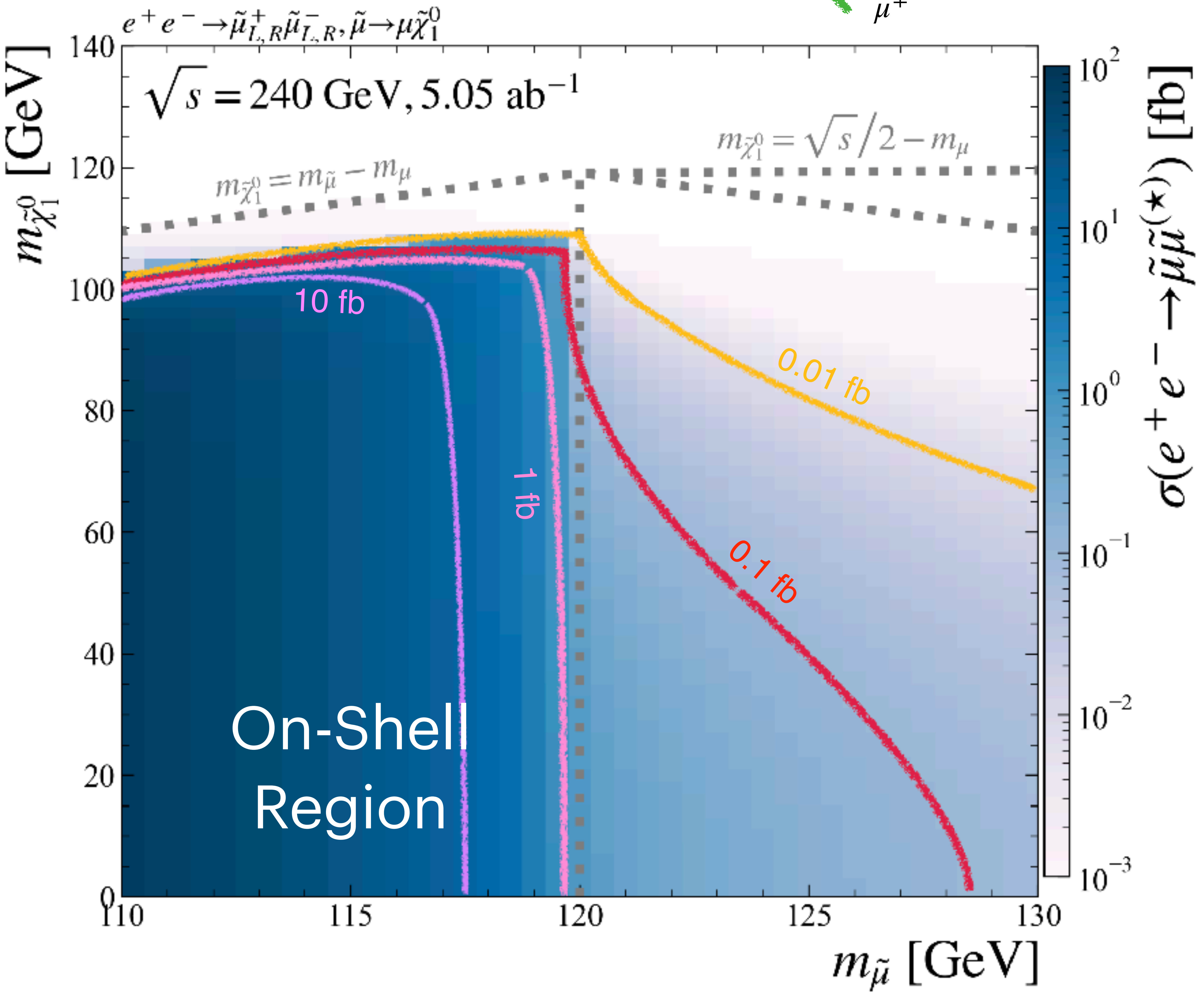
  $$\sigma(e^+e^- \to \mu\mu\tilde{\chi}_1^0\tilde{\chi}_1^0) \approx \sigma(e^+e^- \to \tilde{\mu}\tilde{\mu}) \times \left(\mathrm{BR}(\tilde{\mu} \to \mu\tilde{\chi}_1^0)\right)^2$$

  - NWA is valid in condition: $\sqrt{s}/2 - m_{\tilde{\mu}} \gg \Gamma_{\tilde{\mu}}$
- Off-shell region: $m_{\tilde{\mu}} > \sqrt{s}/2$:

  The cross section of $2 \to 3$ process is smaller than that of $2 \to 2$ process by a factor of $16\pi^2$.

  Assuming $\mathrm{BR}(\tilde{\mu} \to \mu\tilde{\chi}_1^0) = 1$, for 5.05 ab^{-1} data, about 800 signal events can be produced of mass point $(m_{\tilde{\mu}}, m_{\tilde{\chi}_1^0})$ = (140, 0) GeV.

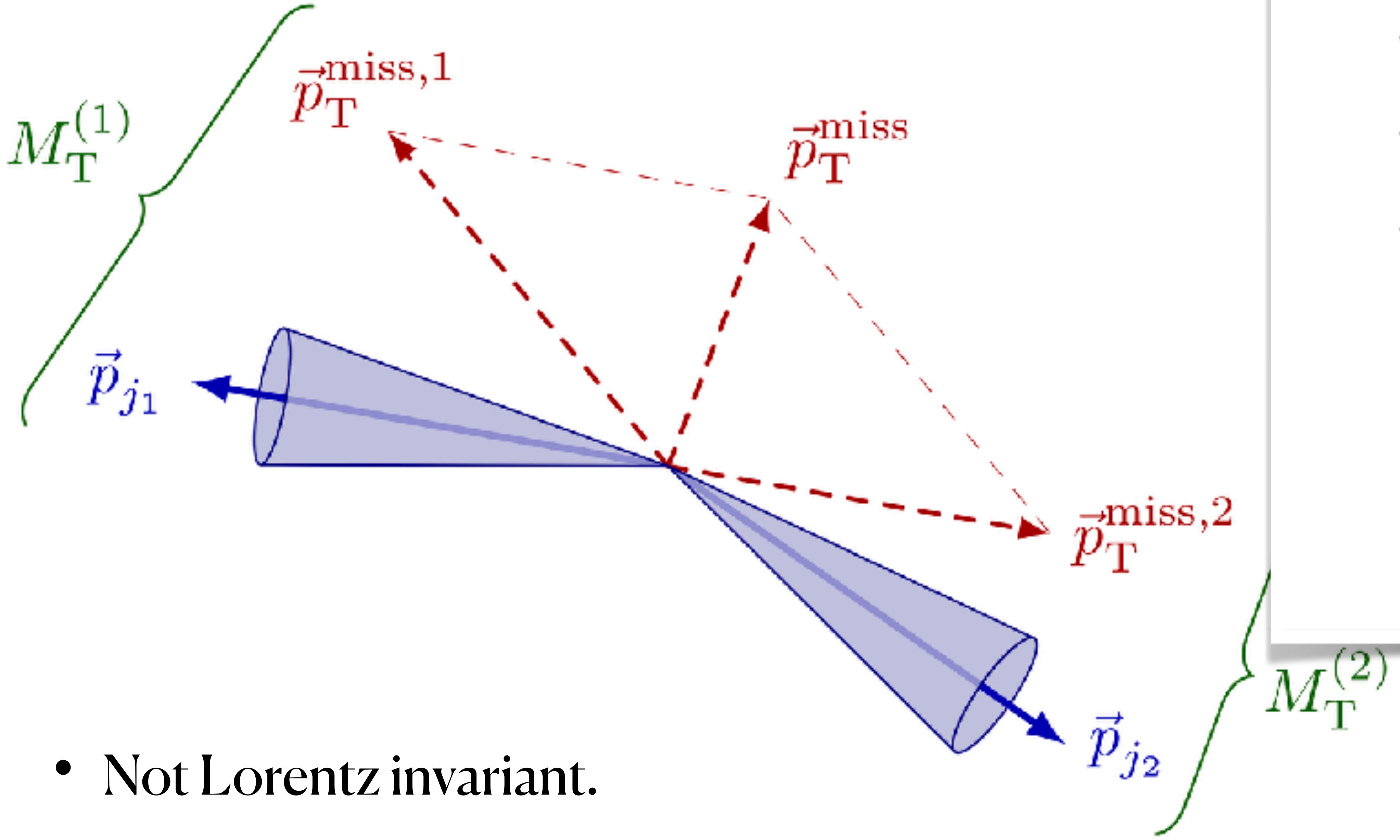
- $(m_{\tilde{\mu}}, m_{\tilde{\chi}_1^0})$ = (115, 0) GeV: 23.6 fb
- $(m_{\tilde{\mu}}, m_{\tilde{\chi}_1^0})$ = (120, 0) GeV: 0.41 fb
- $(m_{\tilde{\mu}}, m_{\tilde{\chi}_1^0})$ = (140, 0) GeV: 0.013 fb

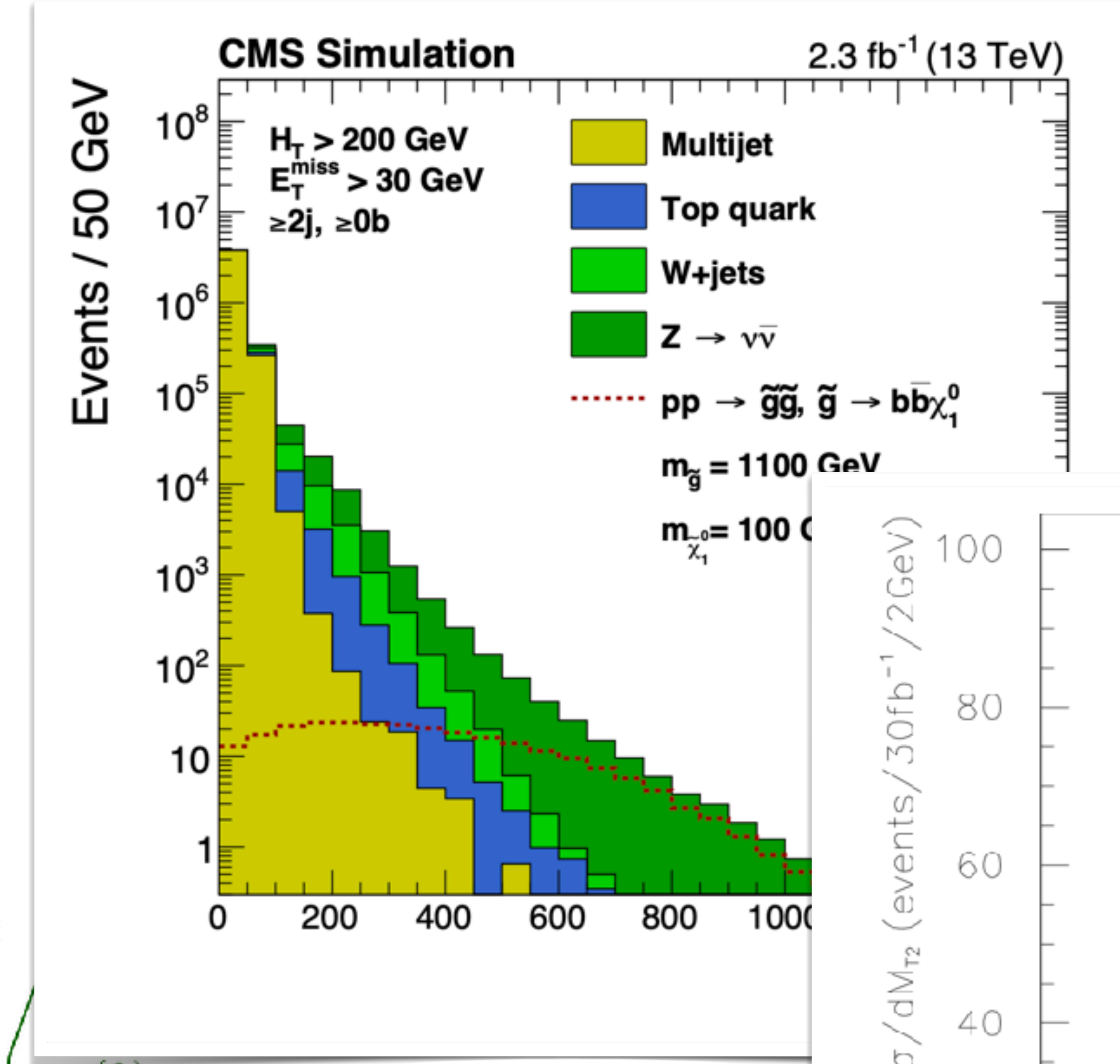


Reconstructing events containing two invisible particle

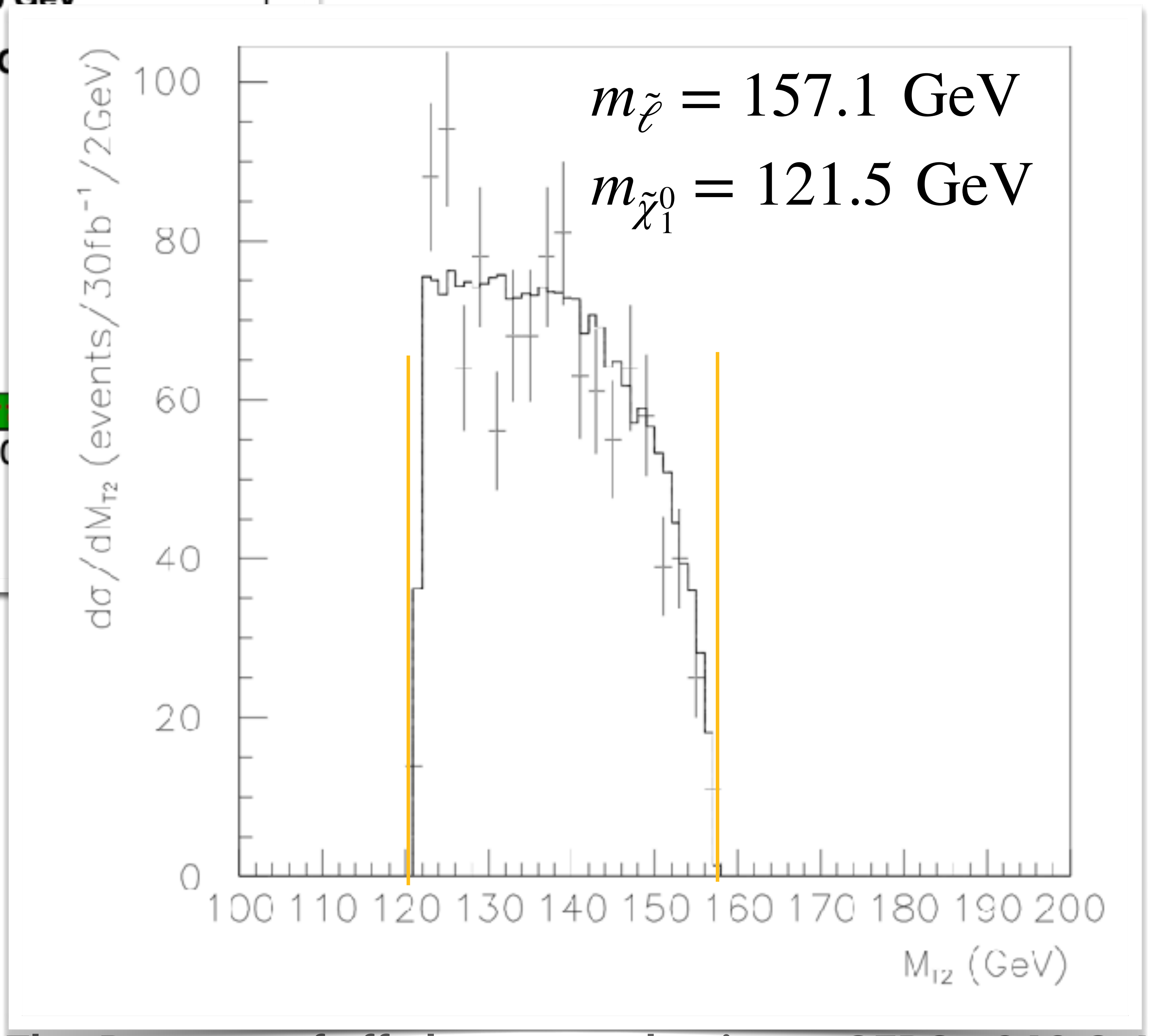
mT2 variable @Hadron Collider

$$m_{\mathrm{T2}} = \min_{p_{\mathrm{T}}^{\mathrm{miss}} = p_{I_a}^{\mathrm{T}} + p_{I_b}^{\mathrm{T}}} \left[\max \left(m_{\mathrm{T}}(p_{V_a}^{\mathrm{T}}, p_{I_a}^{\mathrm{T}}), m_{\mathrm{T}}(p_{V_b}^{\mathrm{T}}, p_{I_b}^{\mathrm{T}}) \right) \right]$$





$$pp \to \tilde{\ell}\tilde{\ell} \to \ell\ell\tilde{\chi}_1^0\tilde{\chi}_1^0$$

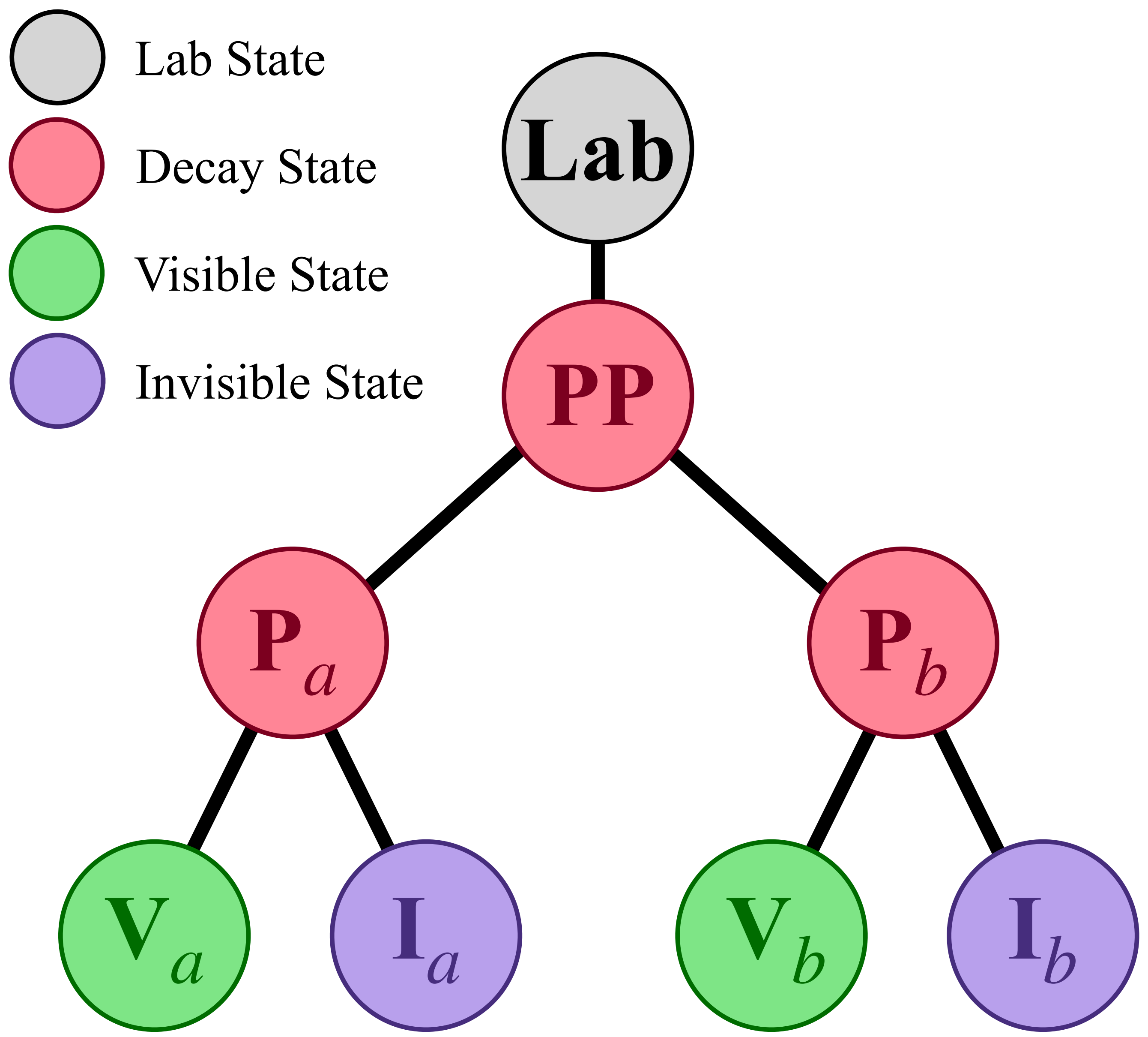


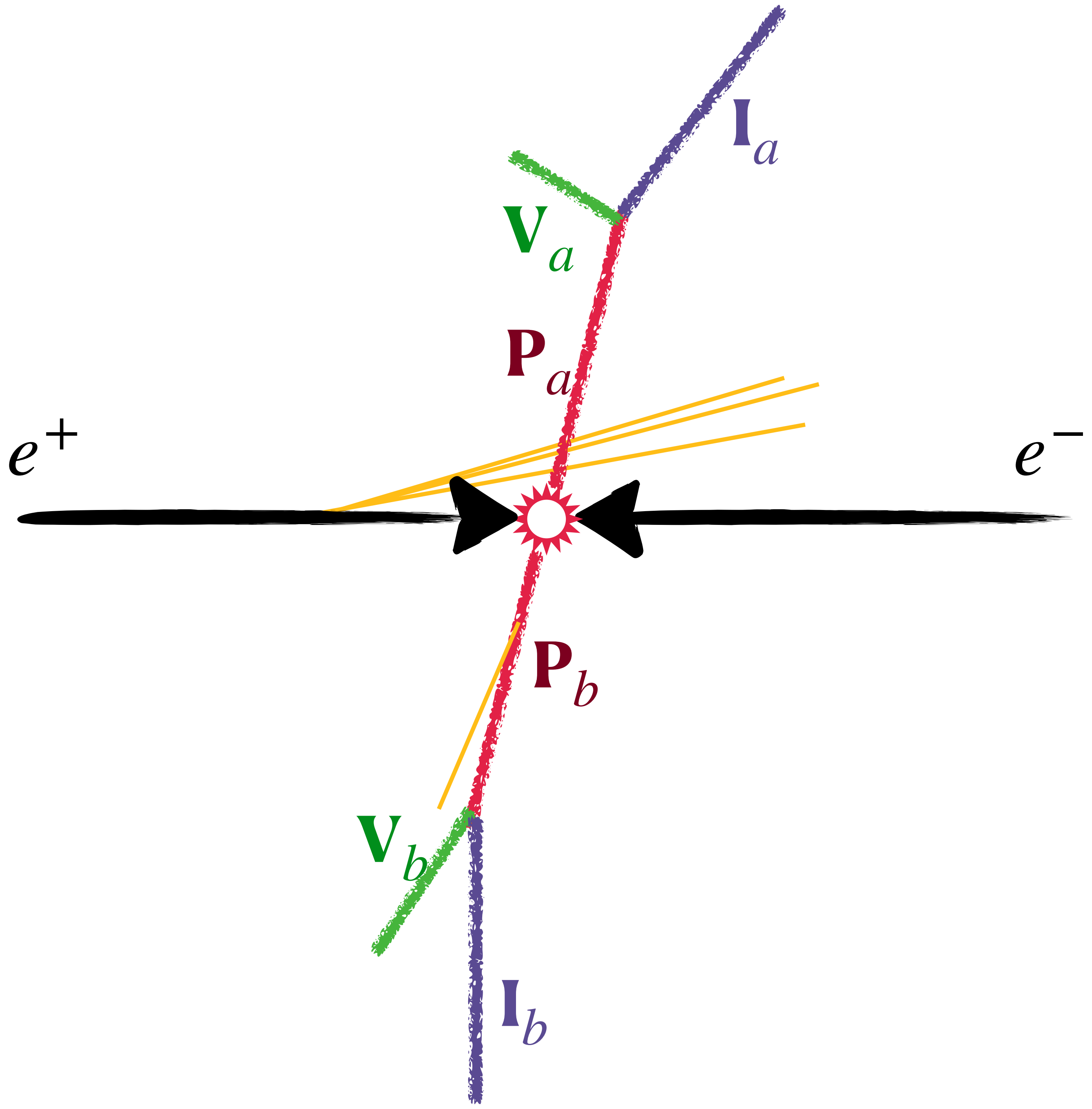
- Not Lorentz invariant.
- But Good "end point" property

Reconstructing events containing two invisible particle

Kinematic reconstruction

$e^+e^- \to \mathbf{P}_a\mathbf{P}_b, \mathbf{P} \to \mathbf{VI}$





What can be reconstructed by detector are:

- $p^\mu_{V_a}$: four-momentum of the visible particle (group) a;
- $p^\mu_{V_b}$: four-momentum of b;
- $p^\mu_{\text{miss}} = p^\mu_{\text{I}_\text{a}} + p^\mu_{\text{I}_\text{b}}$: Vector sum of four-momentum of two invisible particles
- p^μ_{ISR}: four-momentum of anything else

Reconstructing events containing two invisible particle

Physical Constraints (Assumptions)

1. $p^{\mu}_{\mathrm{P_a}} = p^{\mu}_{V_a} + p^{\mu}_{\mathrm{I_a}}$;

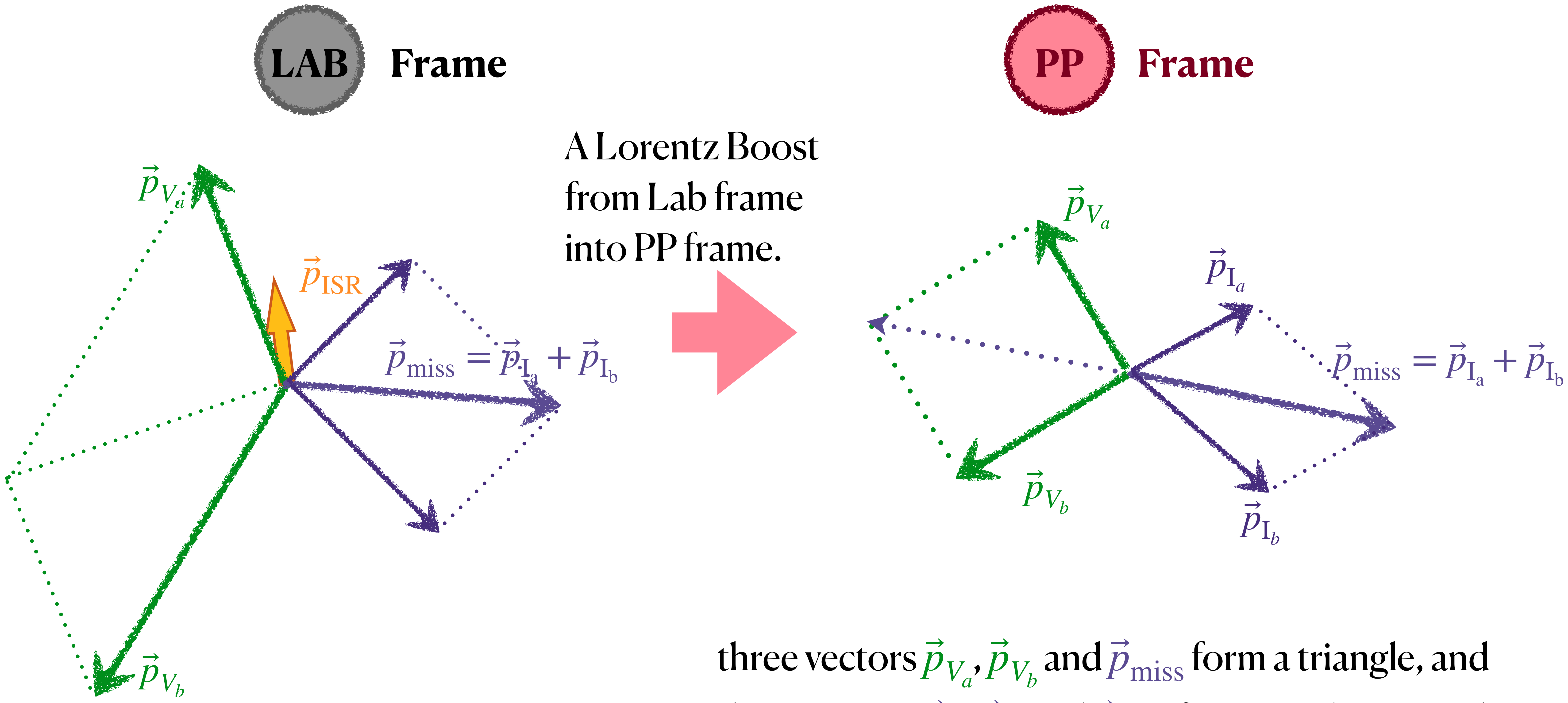
2. $p^{\mu}_{\mathrm{P_b}} = p^{\mu}_{V_b} + p^{\mu}_{\mathrm{I_b}}$;

3. $m_{\mathrm{P}} = m_{\mathrm{P_a}} = m_{\mathrm{P_b}}$;

4. $m_{\mathrm{I}} = m_{\mathrm{I_a}} = m_{\mathrm{I_b}}$;

5. $m_{\mathrm{P}} > 0$;

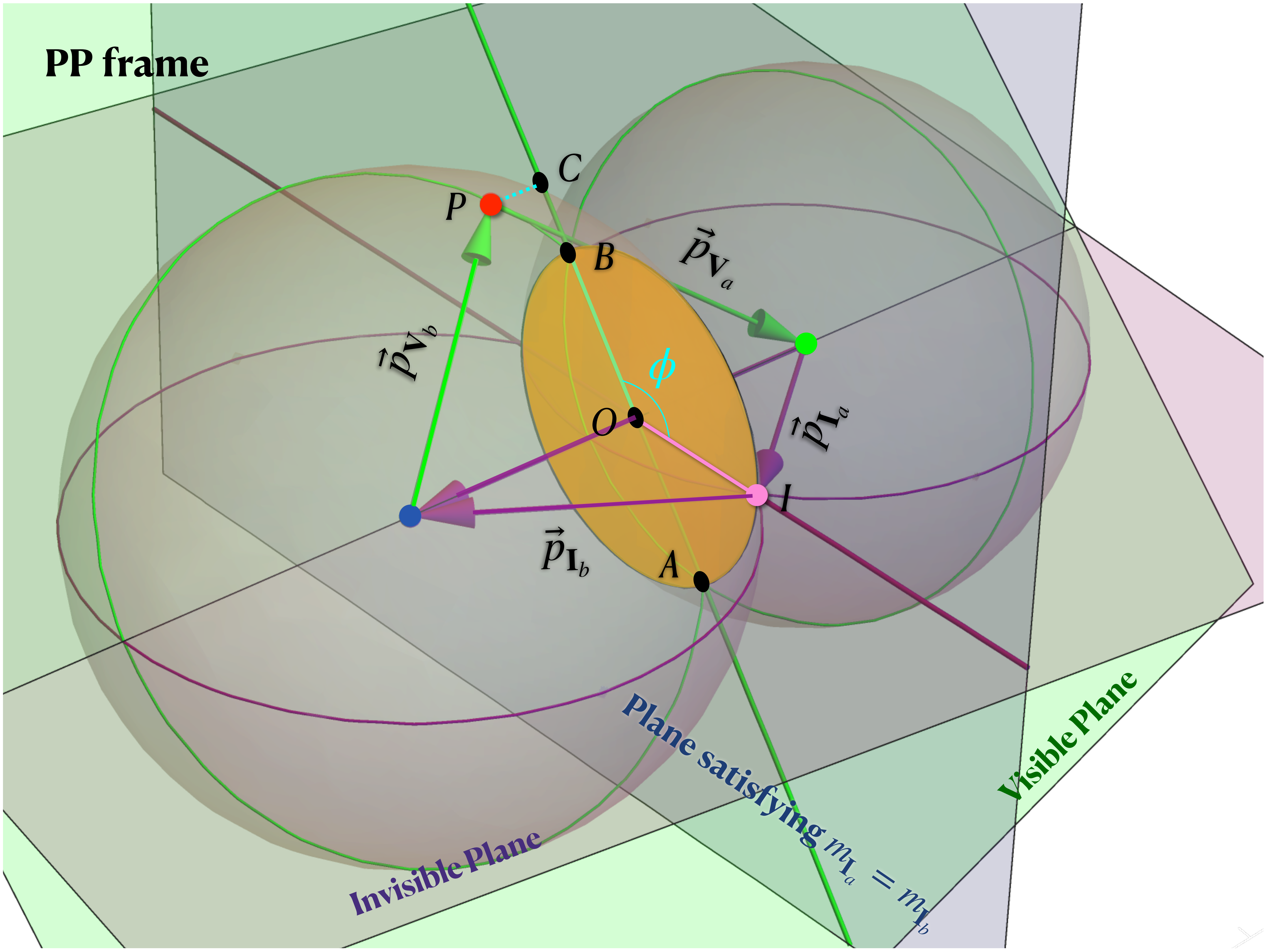
6. $m_{\mathrm{I}} > 0$.



three vectors $\vec{p}_{V_a}, \vec{p}_{V_b}$ and $\vec{p}_{\mathrm{miss}}$ form a triangle, and three vectors $\vec{p}_{\mathrm{I_a}}, \vec{p}_{\mathrm{I_b}}$ and $\vec{p}_{\mathrm{miss}}$ form another triangle.

The mass information are not changed by the Lorentz boost.

Reconstructing events containing two invisible particle



In PP frame,

$$p_{\mathbf{I}_a}^{\mu,\mathrm{PP}} = \left\{ \frac{1}{2}\left(-E_{\mathbf{V}_a}^{\mathrm{PP}} + E_{\mathbf{V}_b}^{\mathrm{PP}} + E_{\mathrm{miss}}^{\mathrm{PP}}\right), \vec{p}_{\mathbf{I}_a}^{\mathrm{PP}} \right\},$$

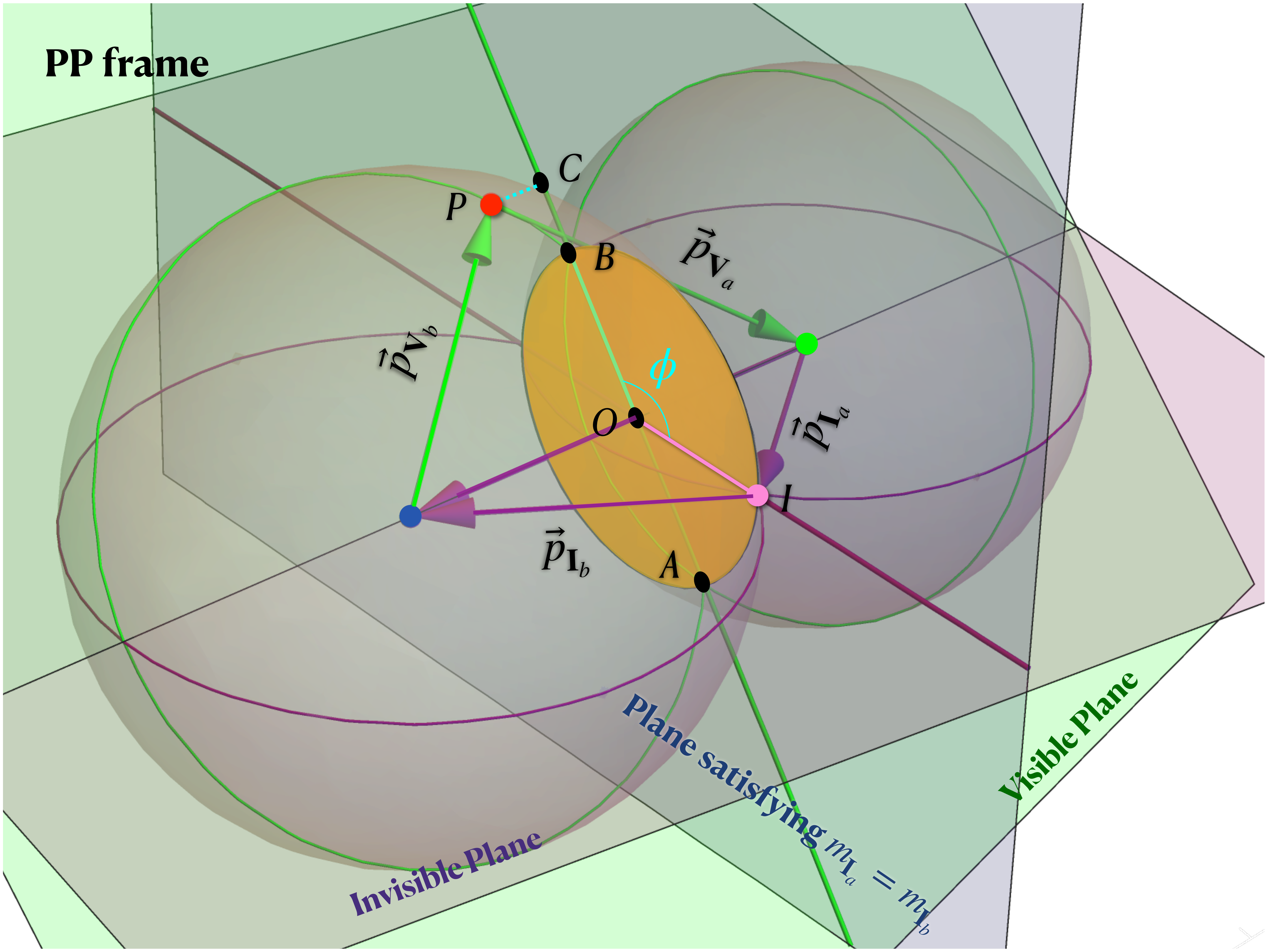
$$p_{\mathbf{P}_a}^{\mu,\mathrm{PP}} = \left\{ \frac{1}{2}\left(E_{\mathbf{V}_a}^{\mathrm{PP}} + E_{\mathbf{V}_b}^{\mathrm{PP}} + E_{\mathrm{miss}}^{\mathrm{PP}}\right), \vec{p}_{\mathbf{V}_a}^{\mathrm{PP}} + \vec{p}_{\mathbf{I}_a}^{\mathrm{PP}} \right\},$$

$$p_{\mathbf{I}_b}^{\mu,\mathrm{PP}} = \left\{ \frac{1}{2}\left(E_{\mathbf{V}_a}^{\mathrm{PP}} - E_{\mathbf{V}_b}^{\mathrm{PP}} + E_{\mathrm{miss}}^{\mathrm{PP}}\right), \vec{p}_{\mathrm{miss}}^{\mathrm{PP}} - \vec{p}_{\mathbf{I}_a}^{\mathrm{PP}} \right\},$$

$$p_{\mathbf{P}_b}^{\mu,\mathrm{PP}} = \left\{ \frac{1}{2}\left(E_{\mathbf{V}_a}^{\mathrm{PP}} + E_{\mathbf{V}_b}^{\mathrm{PP}} + E_{\mathrm{miss}}^{\mathrm{PP}}\right), \vec{p}_{\mathbf{V}_b}^{\mathrm{PP}} + \vec{p}_{\mathrm{miss}}^{\mathrm{PP}} - \vec{p}_{\mathbf{I}_a}^{\mathrm{PP}} \right\}.$$

- $p_{\mathbf{P}_b}^{\mu,\mathrm{PP}} = \left\{ E_{\mathbf{P}_a^{\mathrm{PP}}}, -\vec{p}_{\mathbf{P}_a}^{\mathrm{PP}} \right\}$, so $m_{\mathbf{P}_a} = m_{\mathbf{P}_b}$.

Reconstructing events containing two invisible particle

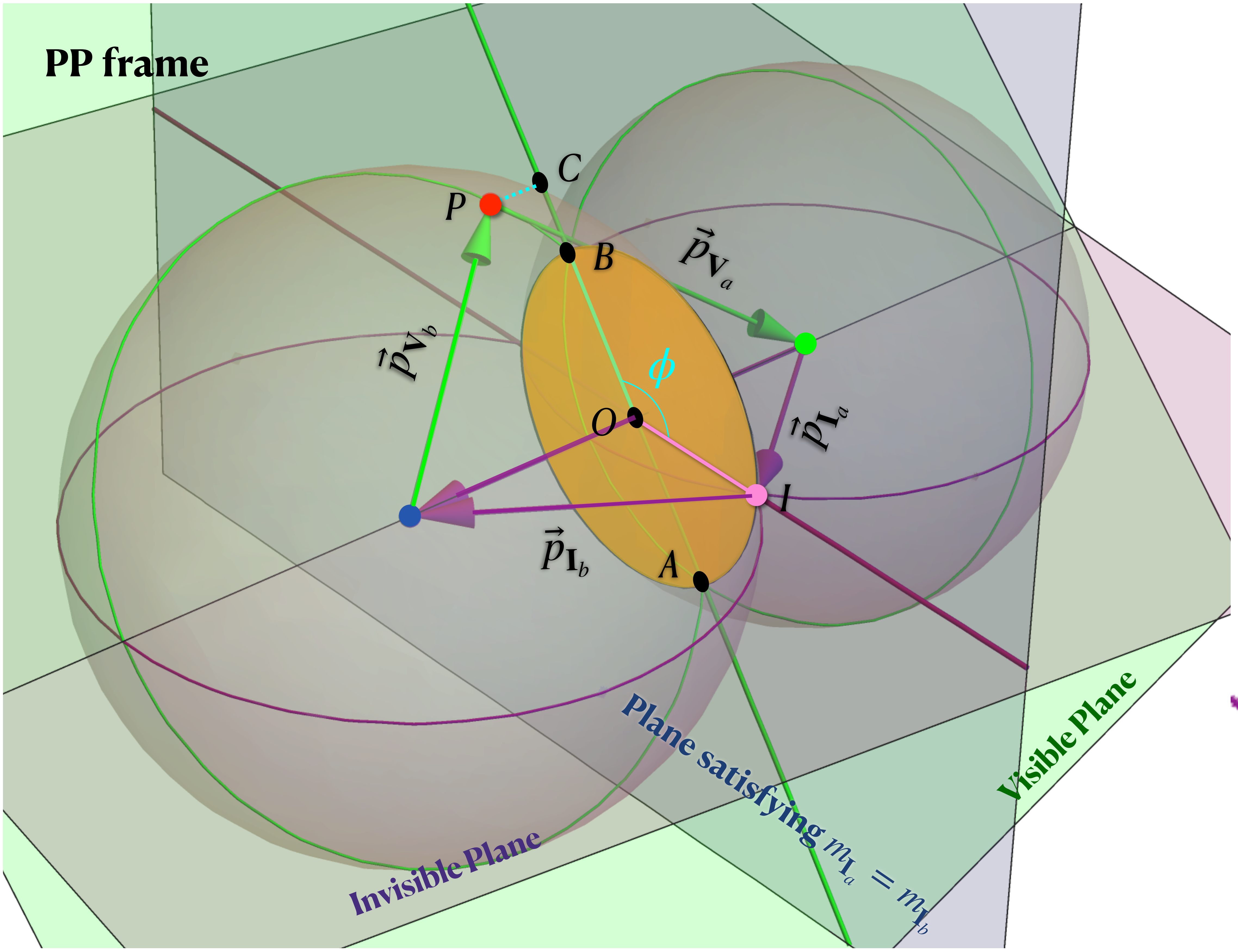


- $m_{\mathbf{I}_a} \geq 0$: The magnitude of $\vec{p}^{\,\mathrm{PP}}_{\mathbf{I}_a}$ must be smaller than $E_{\mathbf{I}_a} = \left(-E^{\mathrm{PP}}_{\mathbf{V}_a} + E^{\mathrm{PP}}_{\mathbf{V}_b} + E^{\mathrm{PP}}_{\mathrm{miss}}\right)/2.$
  Therefore, the point **I** is located in a sphere, where the spherical shell implies $m_{\mathbf{I}_a} = 0.$
- $m_{\mathbf{I}_b} \geq 0$: Similar to the constraint $m_{\mathbf{I}_a} \geq 0.$
- $m_{\mathbf{I}_a} = m_{\mathbf{I}_b} = m_{\mathbf{I}}$: The point **I** is located in a plane vertical to $\vec{p}^{\,\mathrm{PP}}_{\mathrm{miss}}$ (the light blue plane).

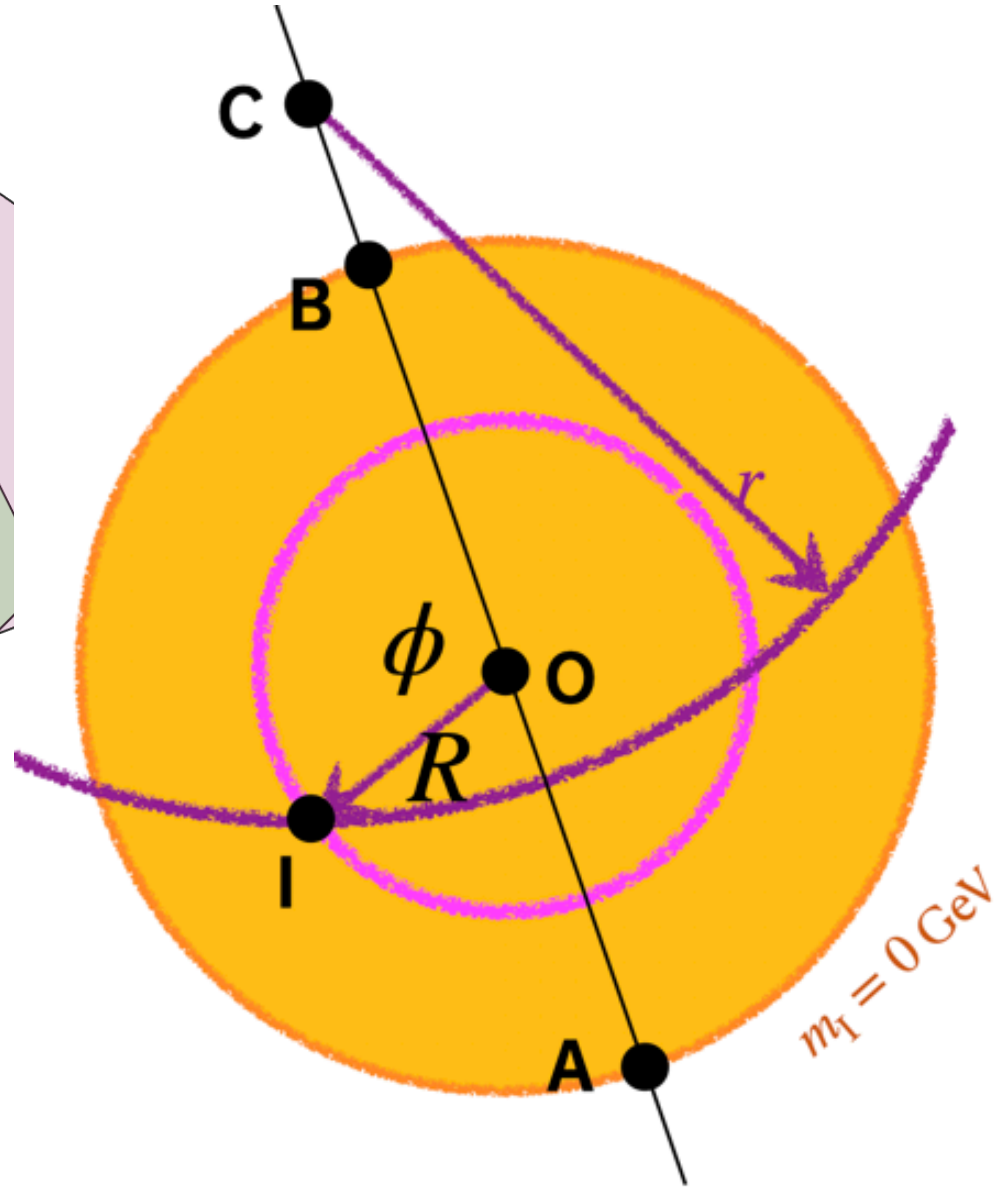
$$\vec{p}^{\,\mathrm{PP}}_{\mathbf{I}_a} \cdot \vec{p}^{\,\mathrm{PP}}_{\mathrm{miss}} - D = 0,$$

$$D = \frac{1}{2}\left(E^{\mathrm{PP}2}_{\mathbf{V}_a} - E^{\mathrm{PP}2}_{\mathbf{V}_b} + E^{\mathrm{PP}}_{\mathbf{PP}}(E^{\mathrm{PP}}_{\mathbf{V}_b} - E^{\mathrm{PP}}_{\mathbf{V}_a}) + \left|\vec{p}^{\,\mathrm{PP}}_{\mathrm{miss}}\right|^2\right)$$

Reconstructing events containing two invisible particle



What unknown is the location of the pink dot, but it must satisfy the physical assumptions, i.e. it must located in the yellow round plane.

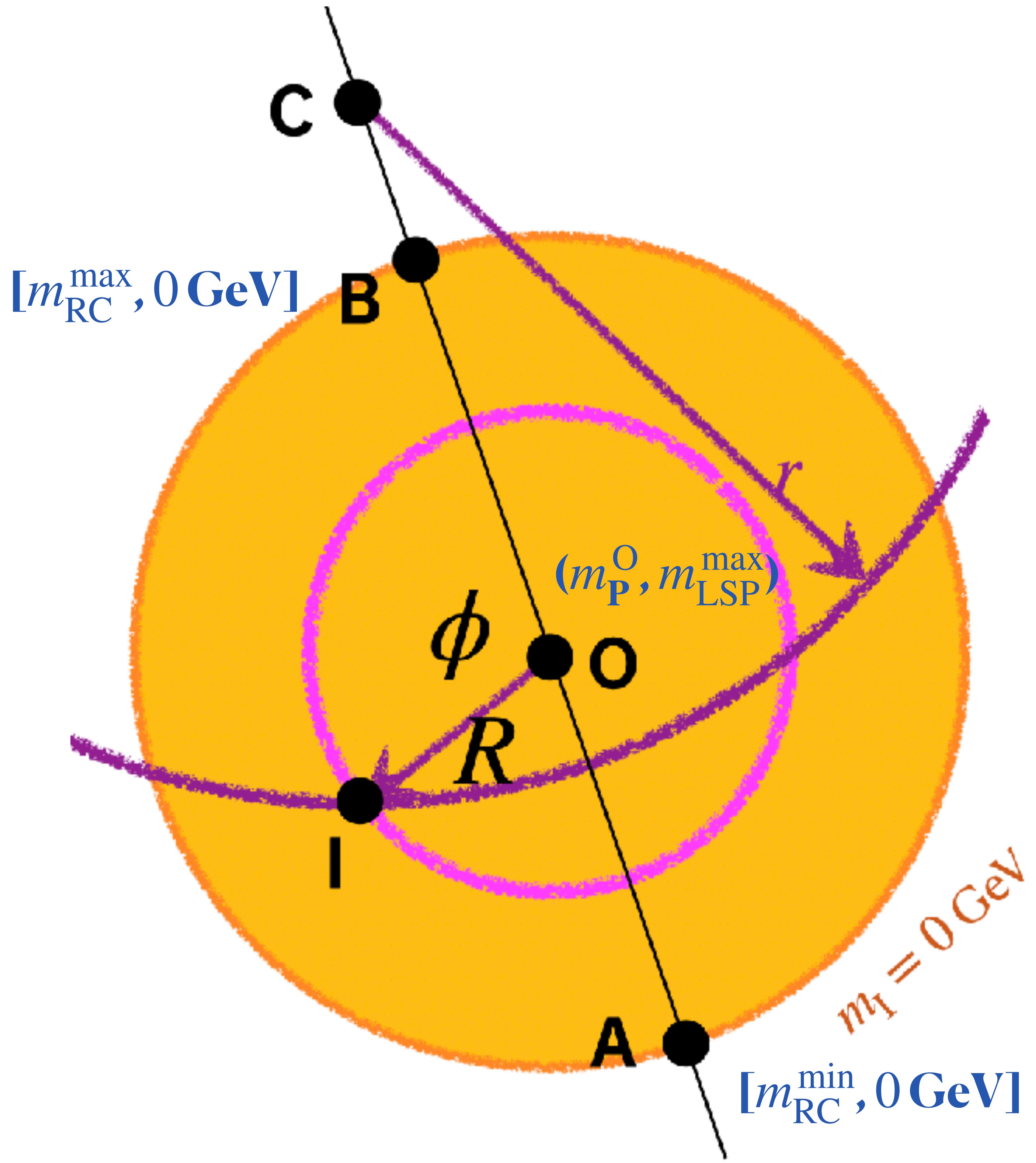


There are two independent degree to determine the location of the pink dot:

- ϕ: the angle between visible vector plane and invisible plane.
- R: the distance between the pink dot and the center of yellow round plane.

The boundary means $m_{\mathrm{I}} = 0$ GeV.

Reconstructing events containing two invisible particle



Given a pink dot, we can solve a set of (m_{P}, m_{I}):

- For the point in the circle of fixed R (pink circle), the m_{I} is the same.
- For the point in the purple circle (fixed r), the m_{P} is the same.

So the geometric property of the disk(physical region) implies the kinetic information of the semi-invisibly decayed events, which can be represented as three "reconstructed-mass" variables:

$m_{\mathrm{RC}}^{\mathrm{min}}$: the m_{P} by choosing pink dot located in point A.

$m_{\mathrm{RC}}^{\mathrm{max}}$: the m_{P} by choosing pink dot located in point B

(or point C, if C is inside the disc).

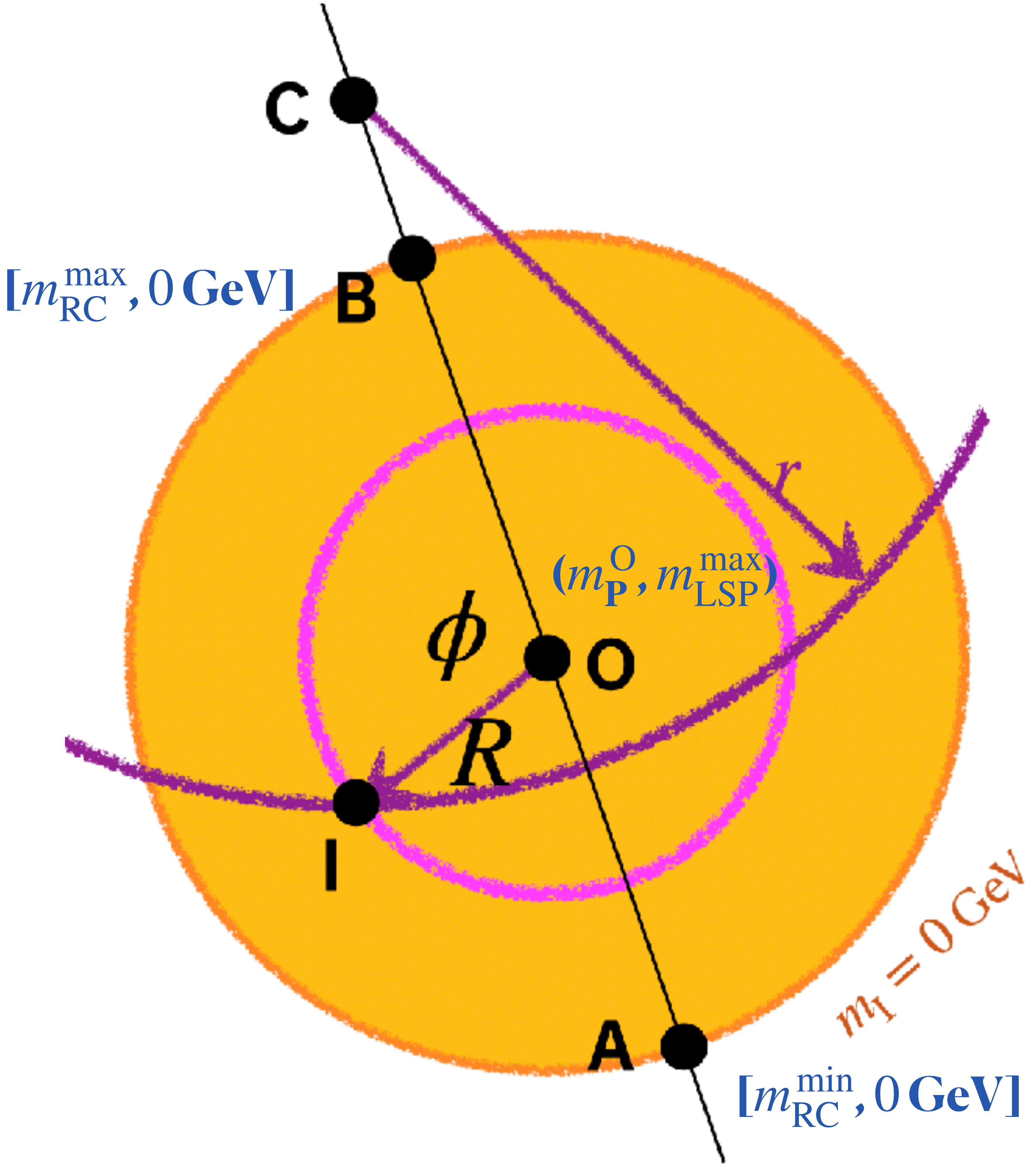
$m_{\mathrm{LSP}}^{\mathrm{max}}$: the m_{I} by choosing pink dot located in center point O.

It is easy to say that:

$$0 < m_{\mathrm{RC}}^{\mathrm{min}} \le m_{\mathrm{P}}^{\mathrm{true}} \le m_{\mathrm{RC}}^{\mathrm{max}} < \sqrt{s}\,/2$$

$$0 \le m_{\mathrm{I}}^{\mathrm{ture}} \le m_{\mathrm{LSP}}^{\mathrm{max}}$$

Reconstructing events containing two invisible particle



The problem of "how massive the intermediate particle is" is transformed into a geometric problem:

$$m_{\mathrm{RC}}^{\min} = \sqrt{\frac{E_{\mathbf{PP}}^2}{4} - |PC|^2 - \left(|OC| + |OA|\right)^2},$$

$$m_{\mathrm{RC}}^{\max} = \sqrt{\frac{E_{\mathbf{PP}}^2}{4} - |PC|^2 - \left(|OC| - |OB|\right)^2}, \text{ if } |OC| > |OB|,$$

$$m_{\mathrm{RC}}^{\max} = \sqrt{\frac{E_{\mathbf{PP}}^2}{4} - |PC|^2}, \qquad \text{if } |OC| \leq |OB|;$$

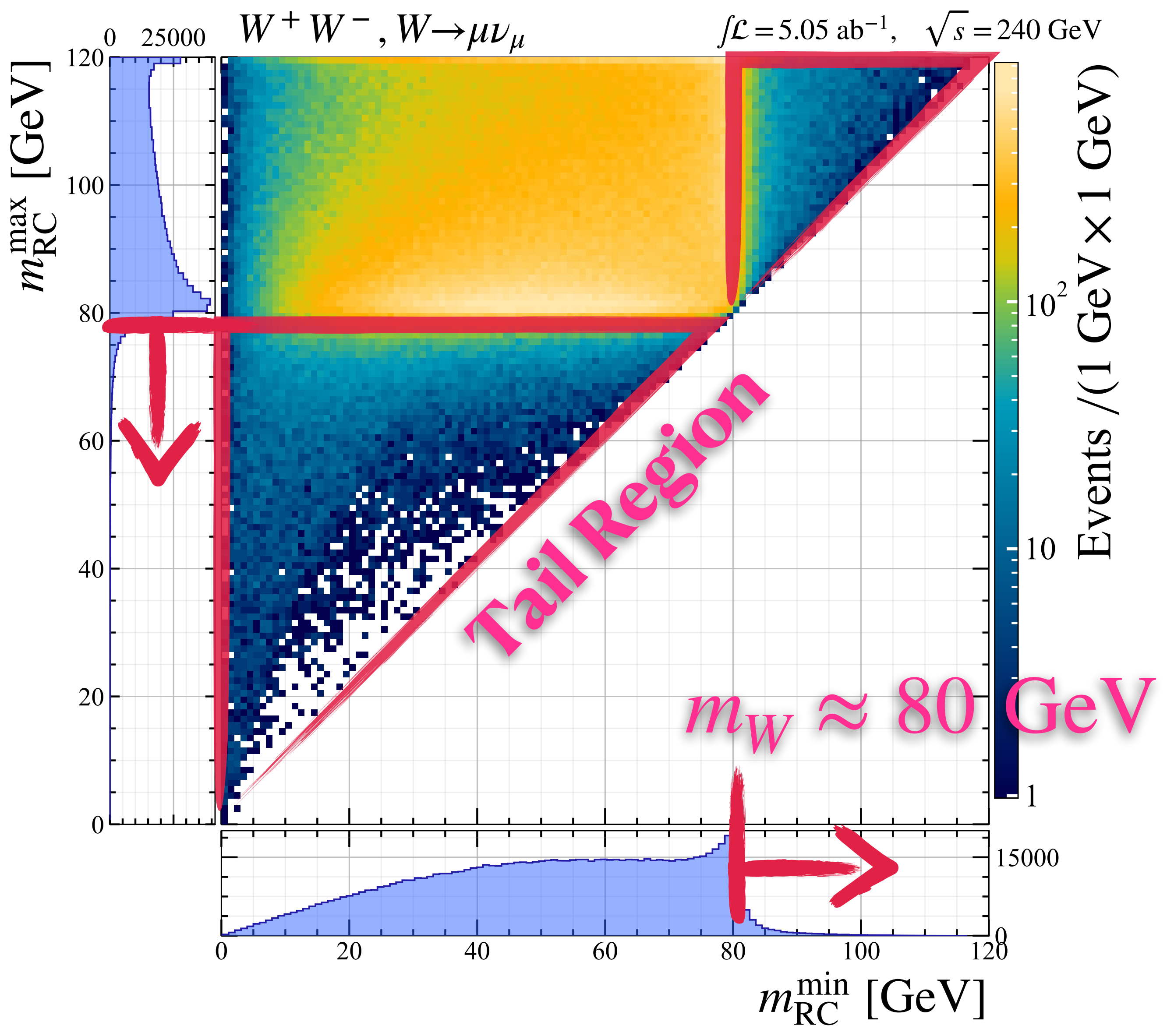
$$m_{\mathrm{LSP}}^{\max} = \sqrt{E_{\mathbf{I}_a}^2 - \frac{1}{4\,|\vec{p}_{\mathrm{miss}}|^2}\left(|\vec{p}_{\mathrm{miss}}|^2 + E_{\mathbf{I}_a}^2 - E_{\mathbf{I}_b}^2\right)^2}.$$

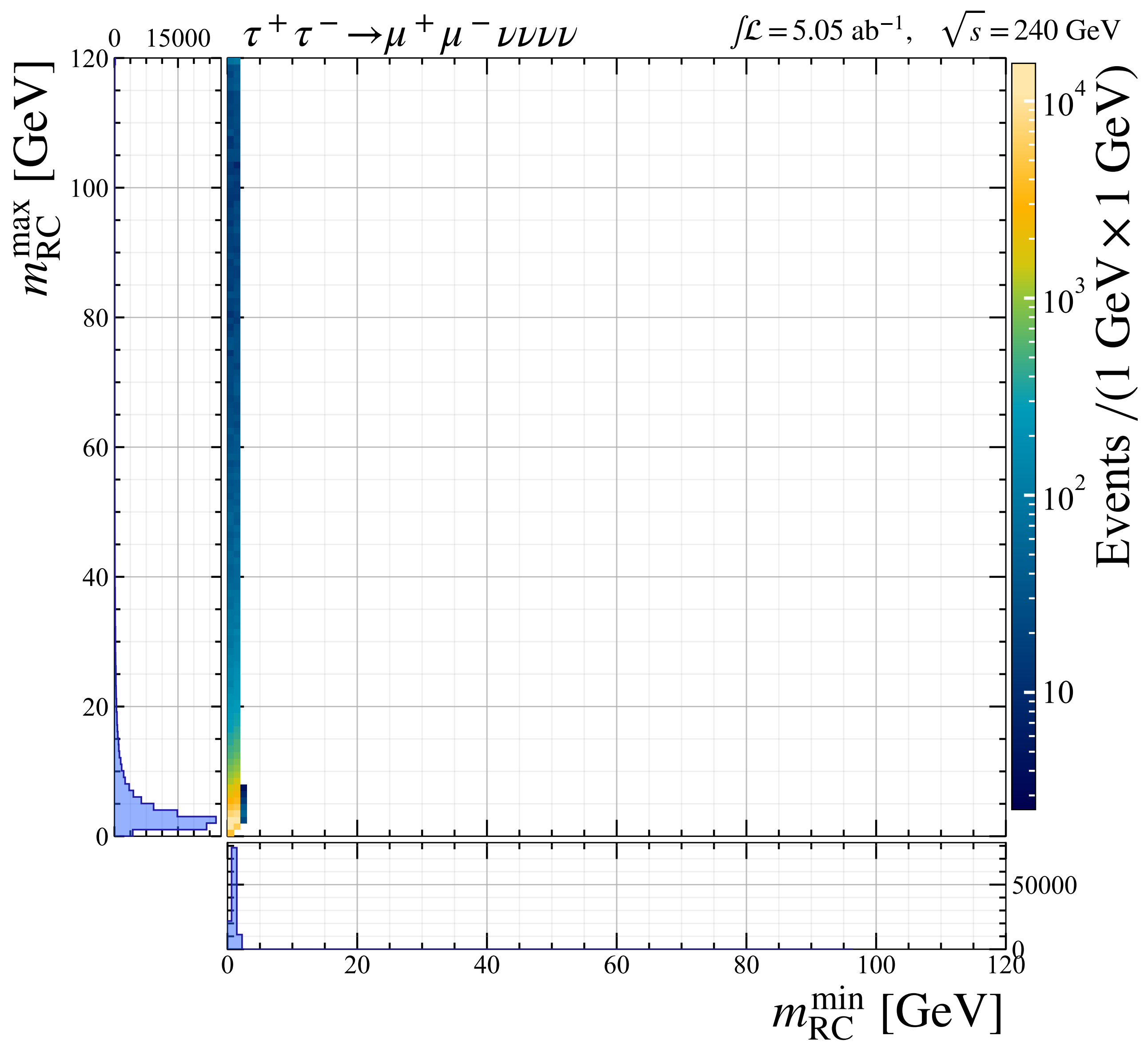
$$|PC| = \frac{1}{2\,|\vec{p}_{\mathrm{miss}}|}\left(-E_{\mathbf{I}_a}^2 + E_{\mathbf{I}_b}^2 + |\vec{p}_{\mathbf{V}_a}|^2 - |\vec{p}_{\mathbf{V}_b}|^2\right),$$

$$|OC| = \frac{1}{2\,|\vec{p}_{\mathrm{miss}}|}\left[-|\vec{p}_{\mathrm{miss}}|^4 - \left(|\vec{p}_{\mathbf{V}_a}|^2 - |\vec{p}_{\mathbf{V}_b}|^2\right)^2 + 2\,|\vec{p}_{\mathrm{miss}}|^2\left(|\vec{p}_{\mathbf{V}_a}|^2 + |\vec{p}_{\mathbf{V}_b}|^2\right)\right]^{\frac{1}{2}},$$

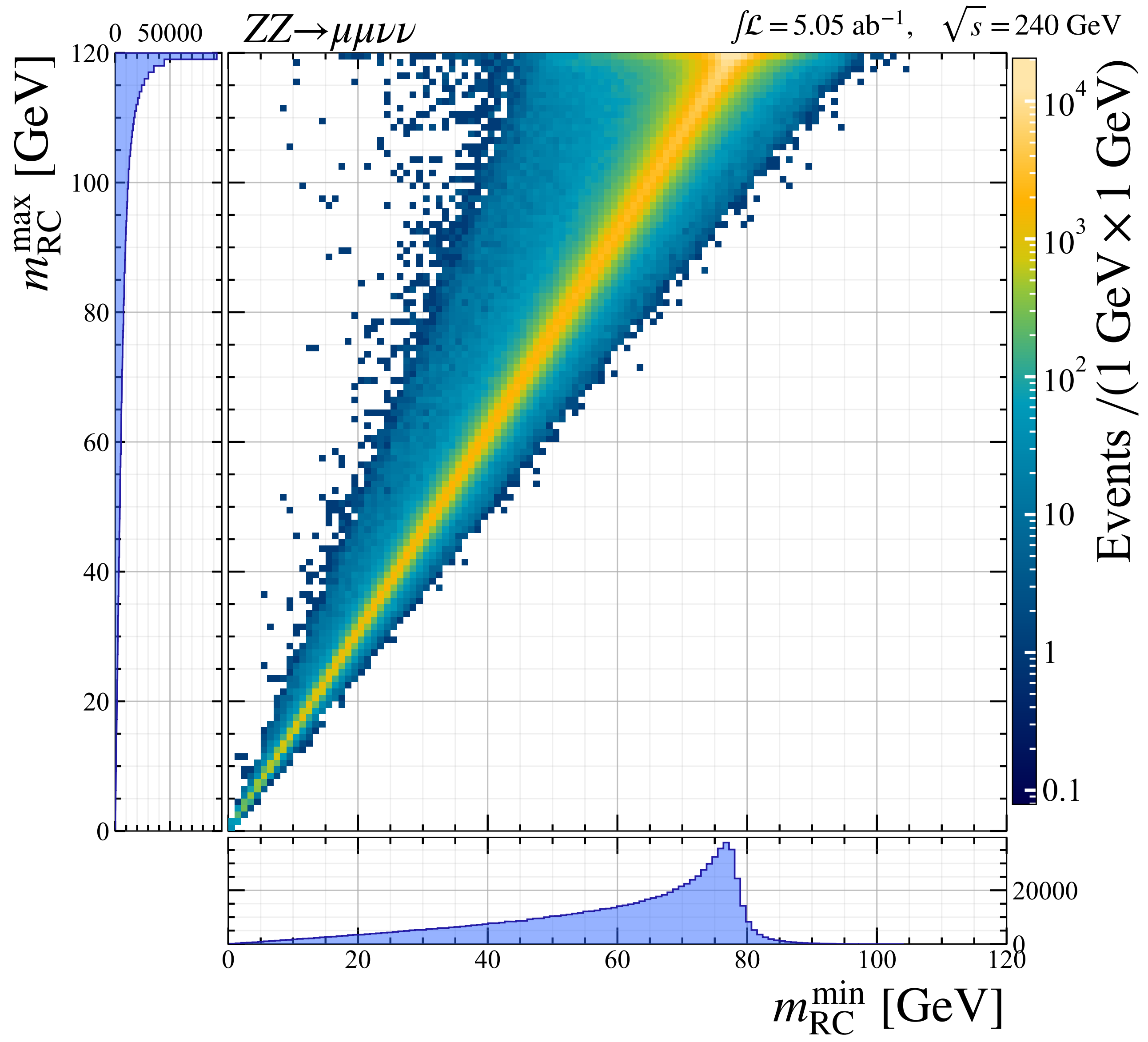
$$|OA| = \frac{1}{2\,|\vec{p}_{\mathrm{miss}}|}\left[-E_{\mathbf{I}_a}^4 - \left(E_{\mathbf{I}_b}^2 - |\vec{p}_{\mathrm{miss}}|^2\right)^2 + 2E_{\mathbf{I}_a}^2\left(E_{\mathbf{I}_b}^2 + |\vec{p}_{\mathrm{miss}}|^2\right)\right]^{\frac{1}{2}}.$$

Reconstructed mass variables: $m_{\mathrm{RC}}^{\mathrm{min}}$ vs $m_{\mathrm{RC}}^{\mathrm{max}}$





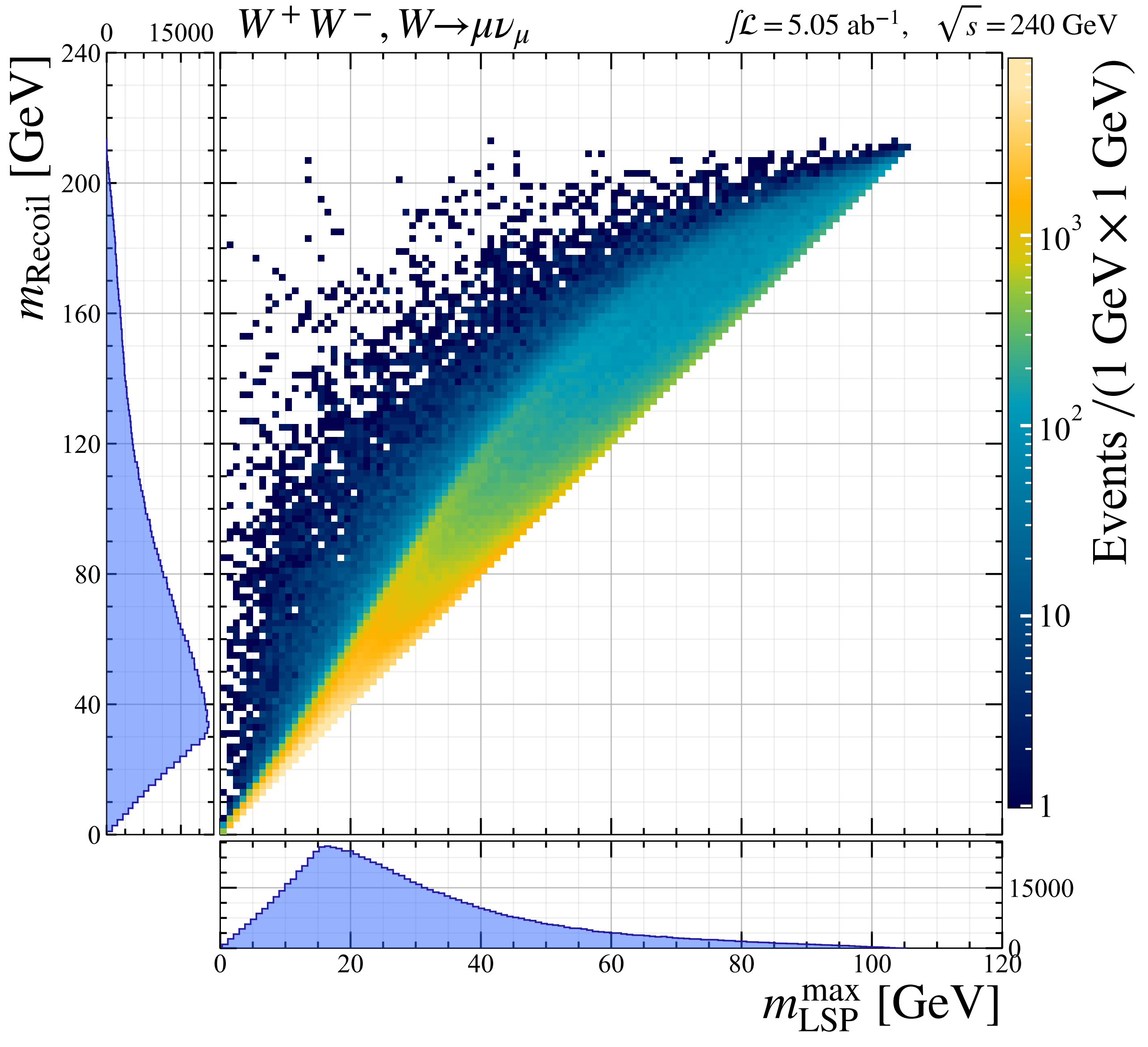
- The calculation is decay topology independent. For example, Z boson in ZZ events is not semi-invisibly decayed.
- A linear relation between $m_{\mathrm{RC}}^{\mathrm{min}}$ and $m_{\mathrm{RC}}^{\mathrm{max}}$ of ZZ event.

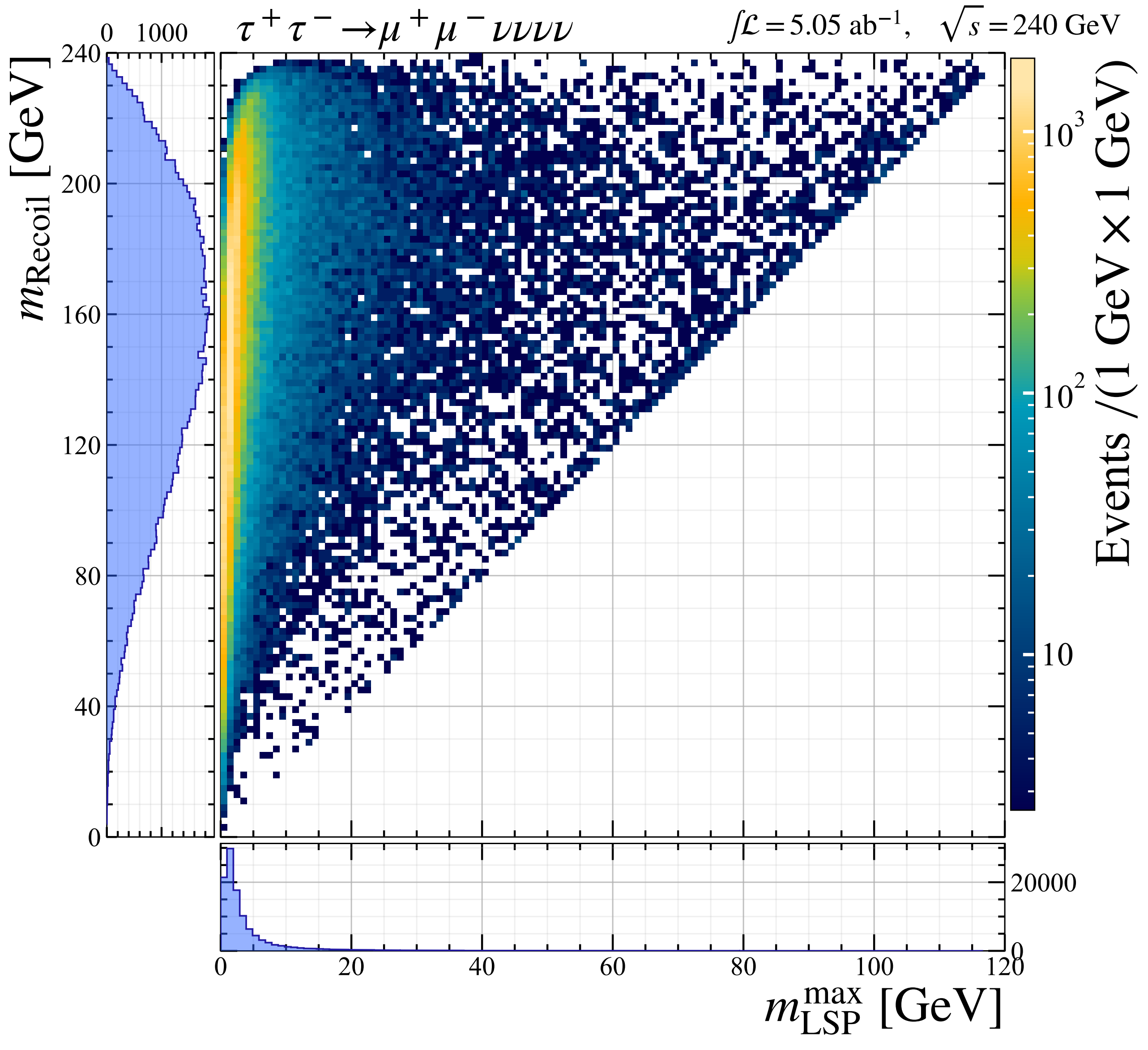


- Both distributions of $m_{\mathrm{RC}}^{\mathrm{min}}$ and $m_{\mathrm{RC}}^{\mathrm{max}}$ have the "end-point"s and the peaks at $m_{\mathbf{P}}$.
- The tails of $m_{\mathrm{RC}}^{\mathrm{min}}$ and $m_{\mathrm{RC}}^{\mathrm{max}}$ (tail region) are caused by that the muon (bare-level muons used in the calculation) in final state losing energy through photon radiation.

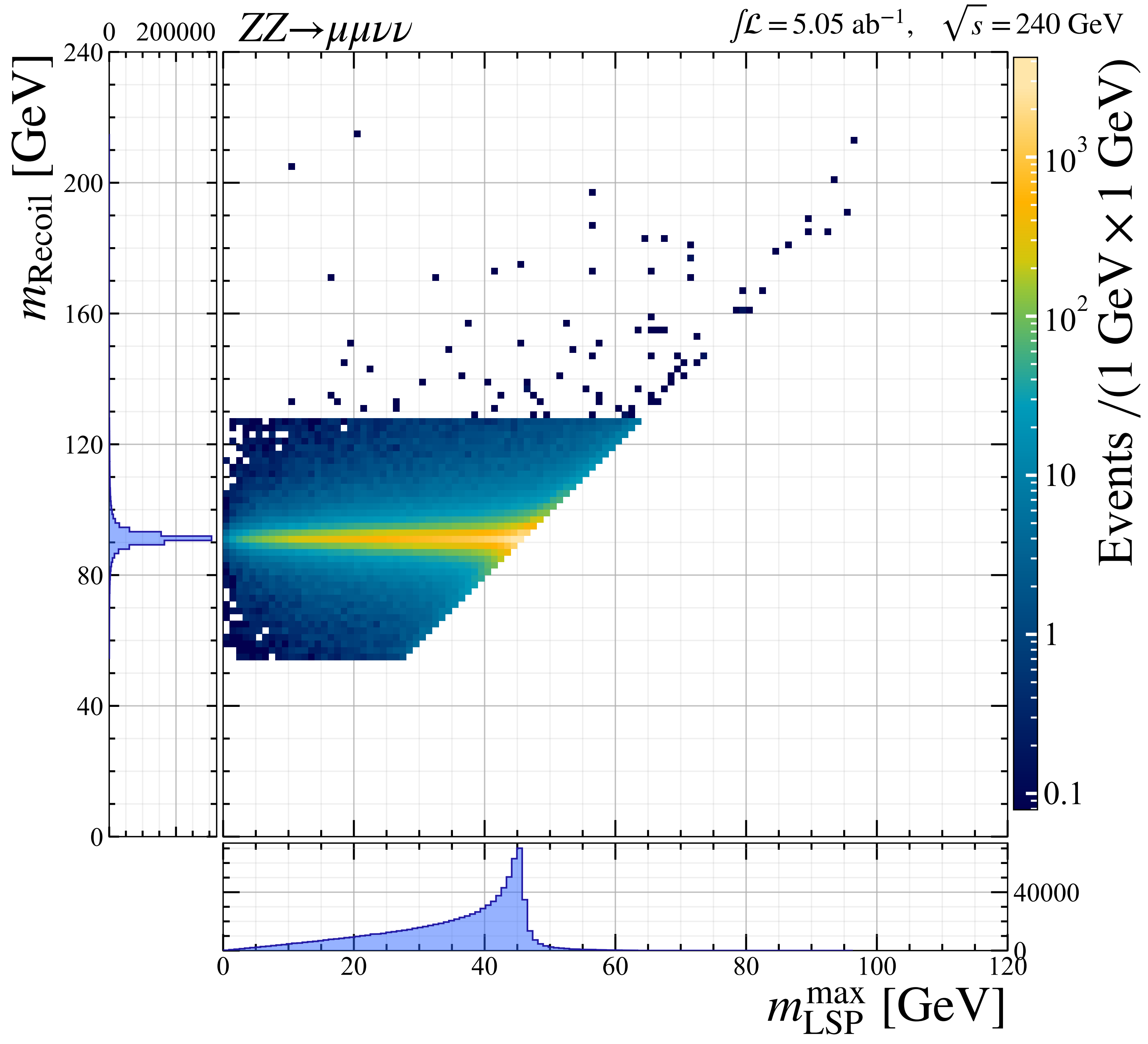
- The distribution of WW, ZZ and $\tau\tau$ events in same final state $\mu^+\mu^- + E_{\mathrm{miss}}$ are much different.
- $\tau\tau$ events' shape are also show the τ mass.

Reconstructed mass variables: $m_{\mathrm{LSP}}^{\max}$ (compared to m_{Recoil})





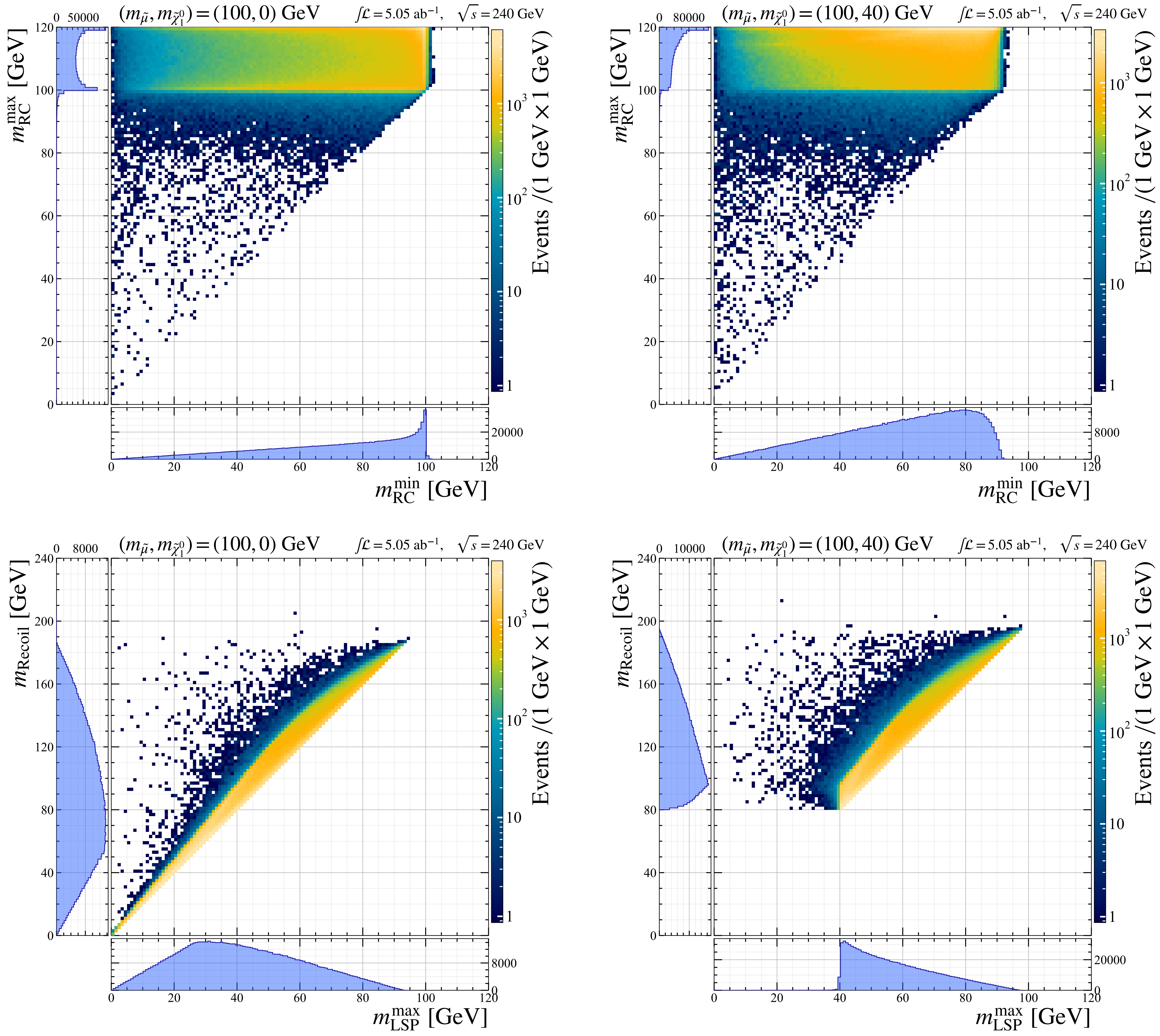
- For invisibly recoiled events, like ZZ events, the recoil mass is more physical.



- $m_{\mathrm{LSP}}^{\max} \leqslant \frac{1}{2} m_{\mathrm{Recoil}}$.
- For WW events, the shape of $m_{\mathrm{LSP}}^{\max}$ is much similar to that of m_{Recoil}.

- For $\tau\tau$ events, $m_{\mathrm{LSP}}^{\max}$ distributed in the small value region. But m_{Recoil} distributed more flat.
- For semi-invisible decay topology event, $m_{\mathrm{LSP}}^{\max}$ is better than m_{Recoil}.

Reconstructed mass variables: Smuon pair production

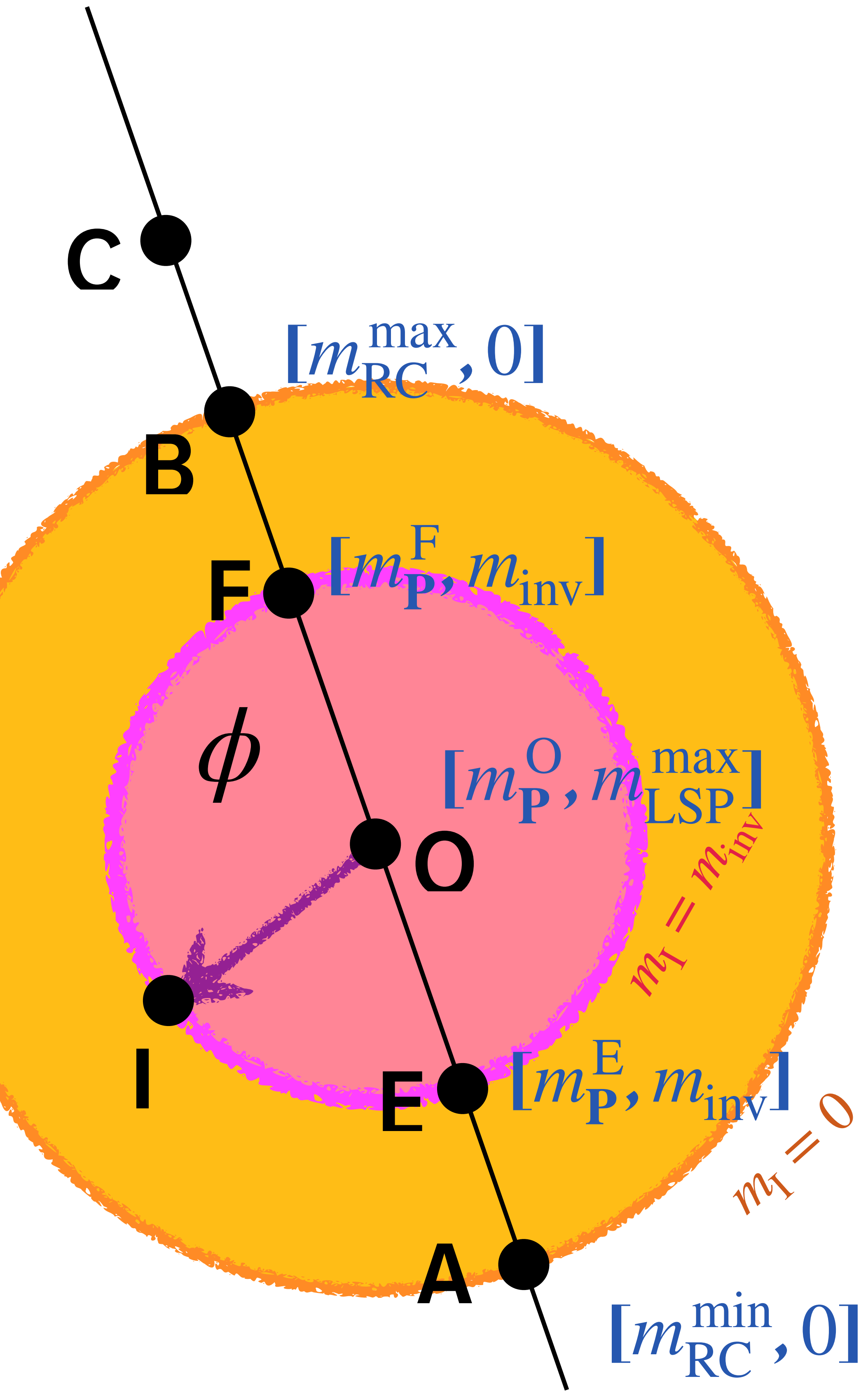


- For massless LSP, both m_{RC}^{min} and m_{RC}^{max} have significant peaks at $m_{\tilde{\mu}}$ and also an obvious truncation at $m_{\tilde{\mu}}$.
- For massive LSP, the truncations of m_{RC}^{min} and m_{RC}^{max} are disappearing, and the range $[m_{RC}^{min}, m_{RC}^{max}]$ gets bigger with $m_{\tilde{\chi}_1^0}$ increase.
- The end-point of m_{LSP}^{max} at $m_{\tilde{\chi}_1^0}$ are much obvious.

$$0 < m_{RC}^{min} \leq m_{P}^{true} \leq m_{RC}^{max} < \sqrt{s}\,/2$$

$$0 \leq m_{I}^{ture} \leq m_{LSP}^{max} \leq m_{Recoil}/2$$

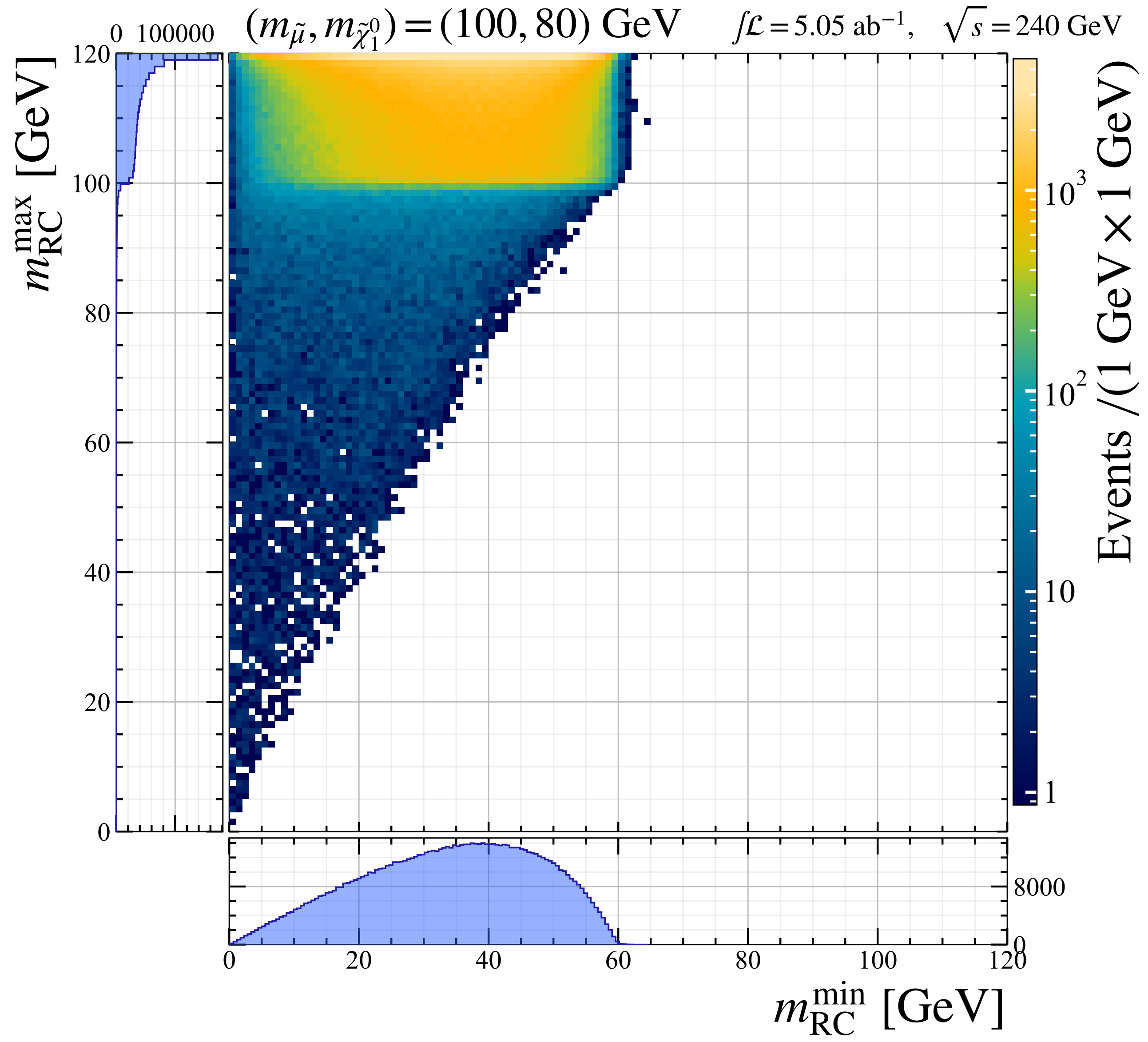
Reconstructed mass variables: Smuon pair production

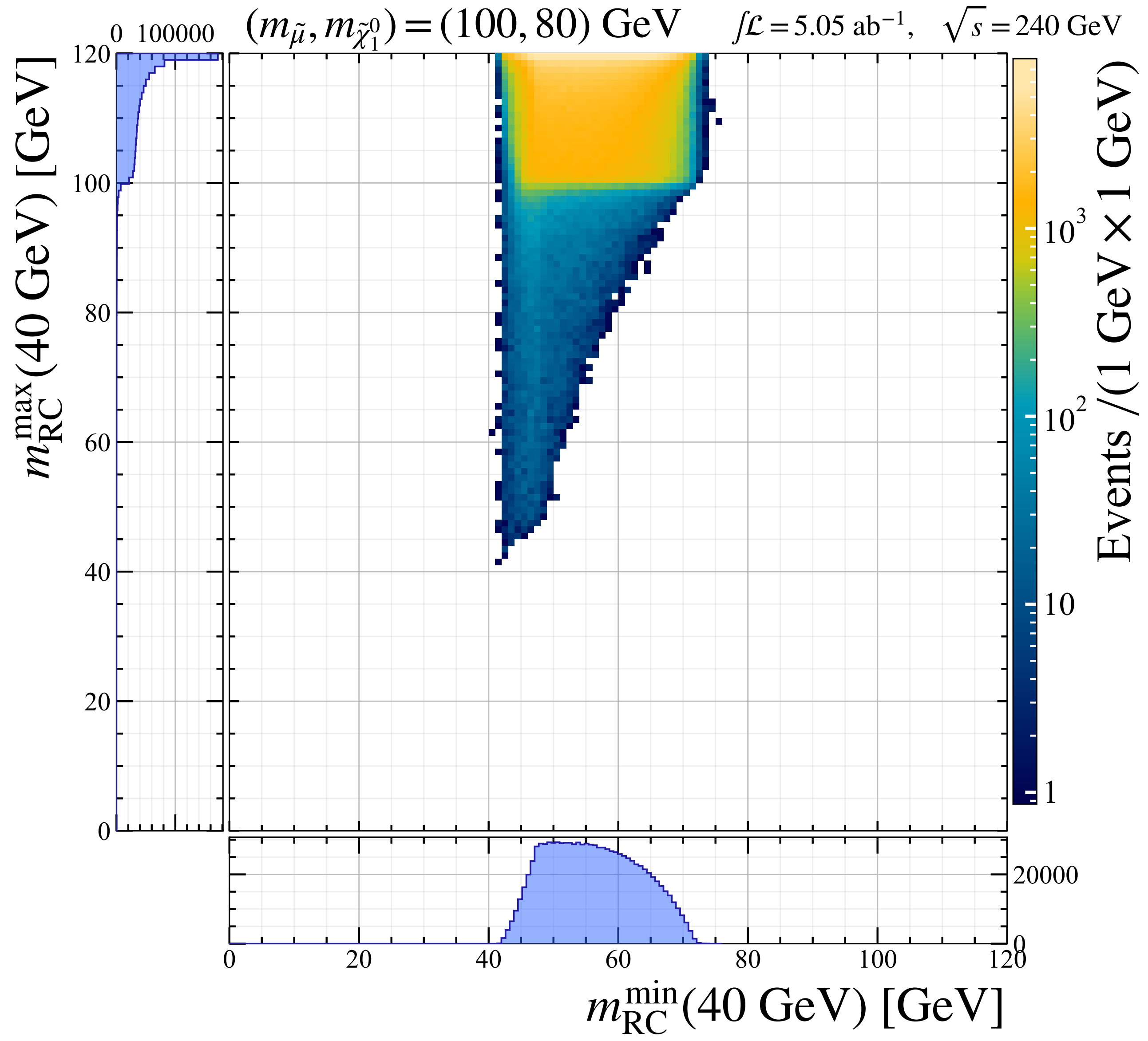


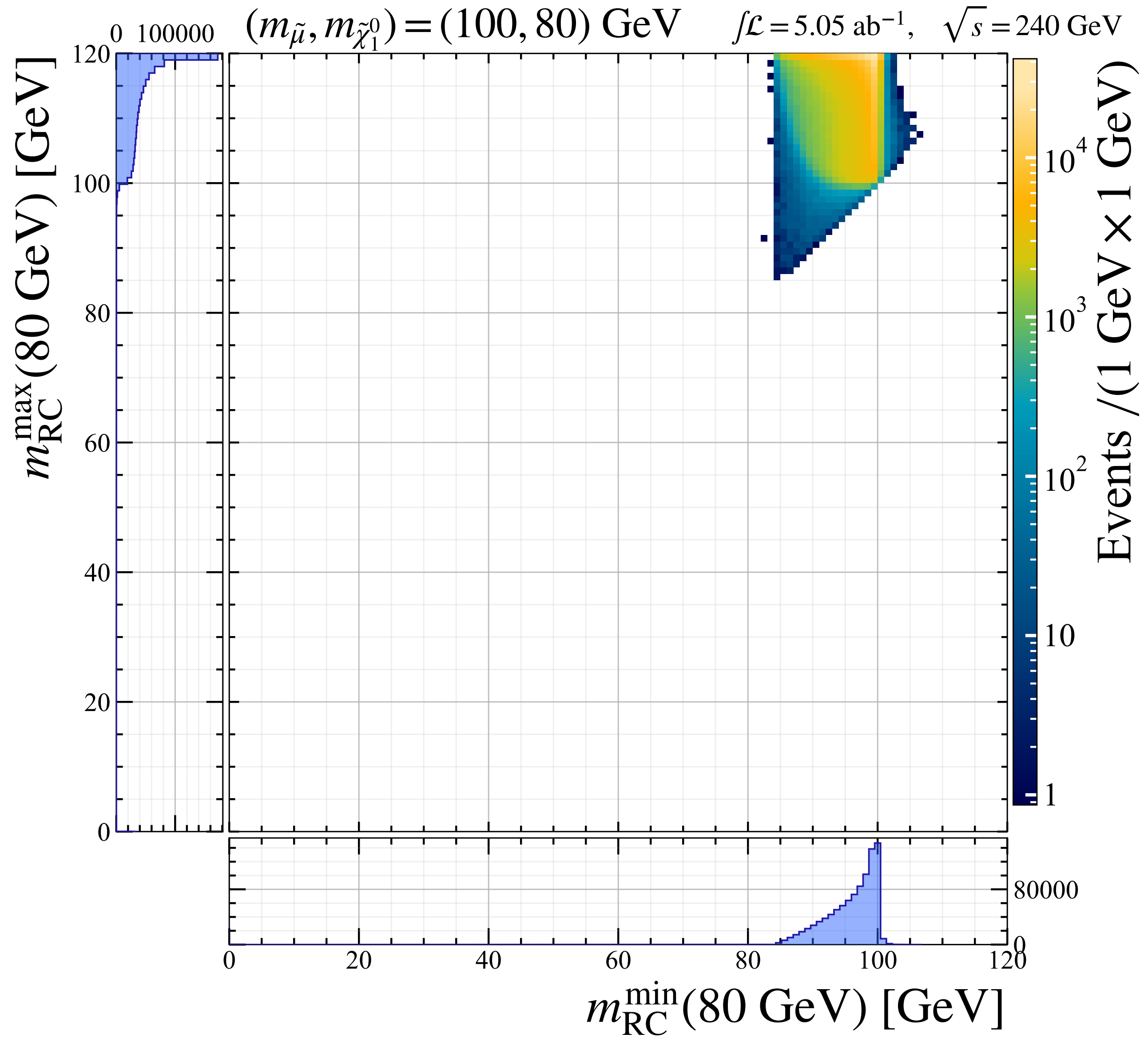
- If given an assumed value of LSP, m_{inv}. A new group variable can be defined
  - $m_{RC}^{min}(m_{inv}) \equiv m_{\mathbf{P}}^{E}$ & $m_{RC}^{max}(m_{inv}) \equiv m_{\mathbf{P}}^{F}$
- The truncation re-appearing in the distributions of $m_{RC}^{min}(m_{inv})$ and $m_{RC}^{max}(m_{inv})$.

$$0 < m_{RC}^{min} \le m_{RC}^{min}(m_{inv}) \le m_{P}^{true} \le m_{RC}^{max}(m_{inv}) \le m_{RC}^{max} < \sqrt{s}/2$$

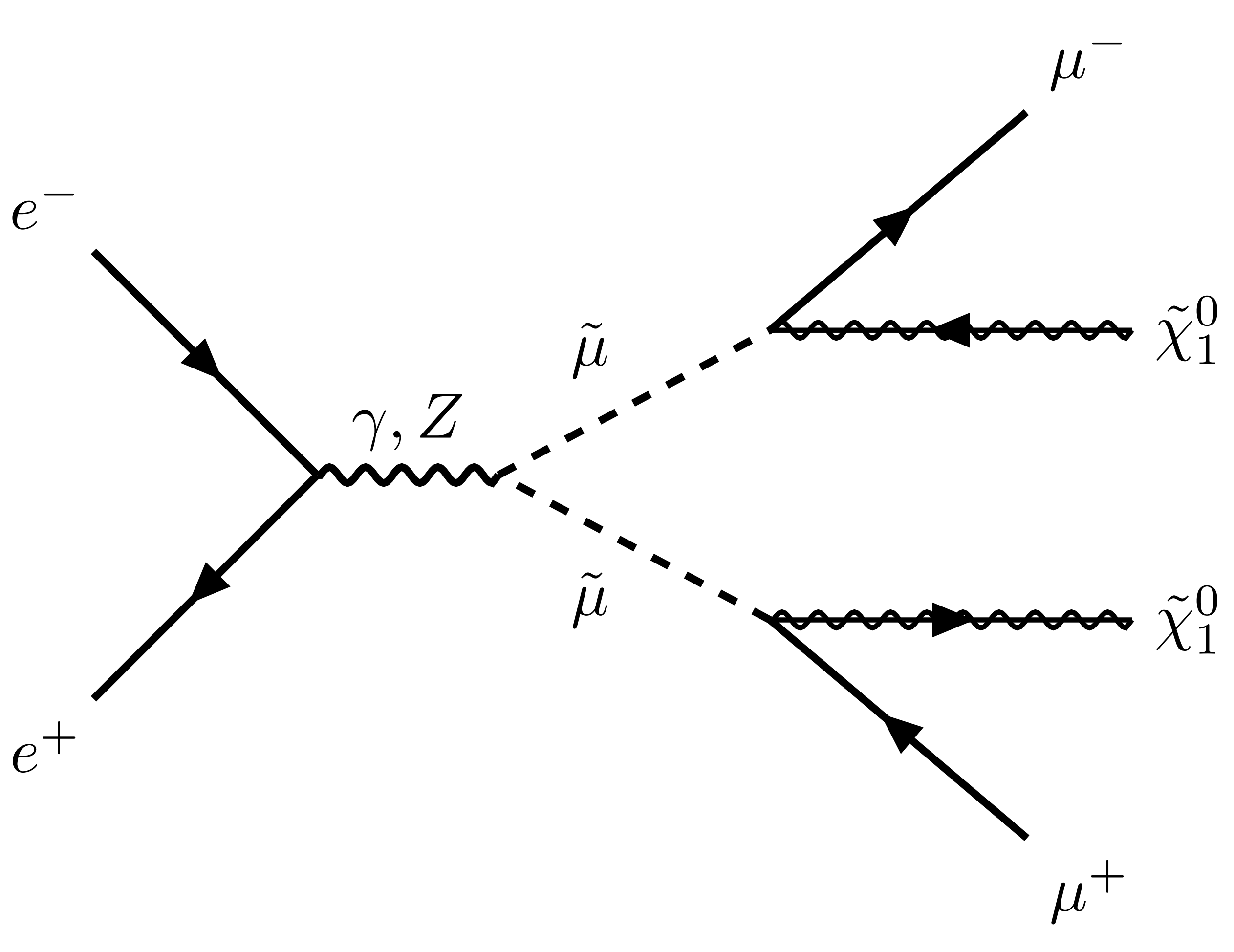
$$0 \le m_{I}^{ture} \le m_{LSP}^{max} \le m_{Recoil}/2$$

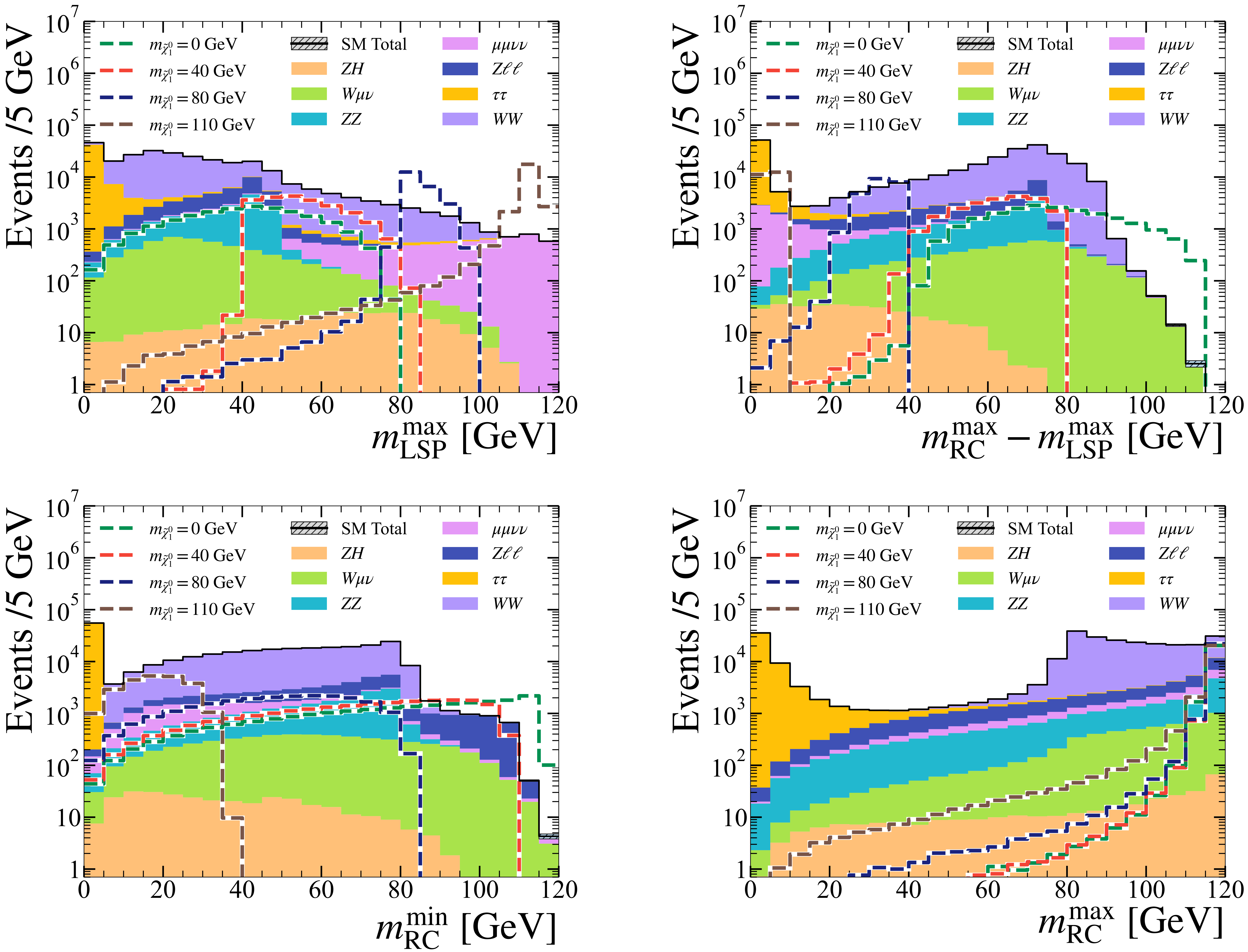






Prospect of smuon pair production at CEPC





- Degenerate left-handed and right-handed smuon mass, bino-like LSP.
- The distributions closely related to the $m_{\tilde{\mu}}$ and $m_{\tilde{\chi}_1^0}$
- Three similar SRs to 2203.10580.

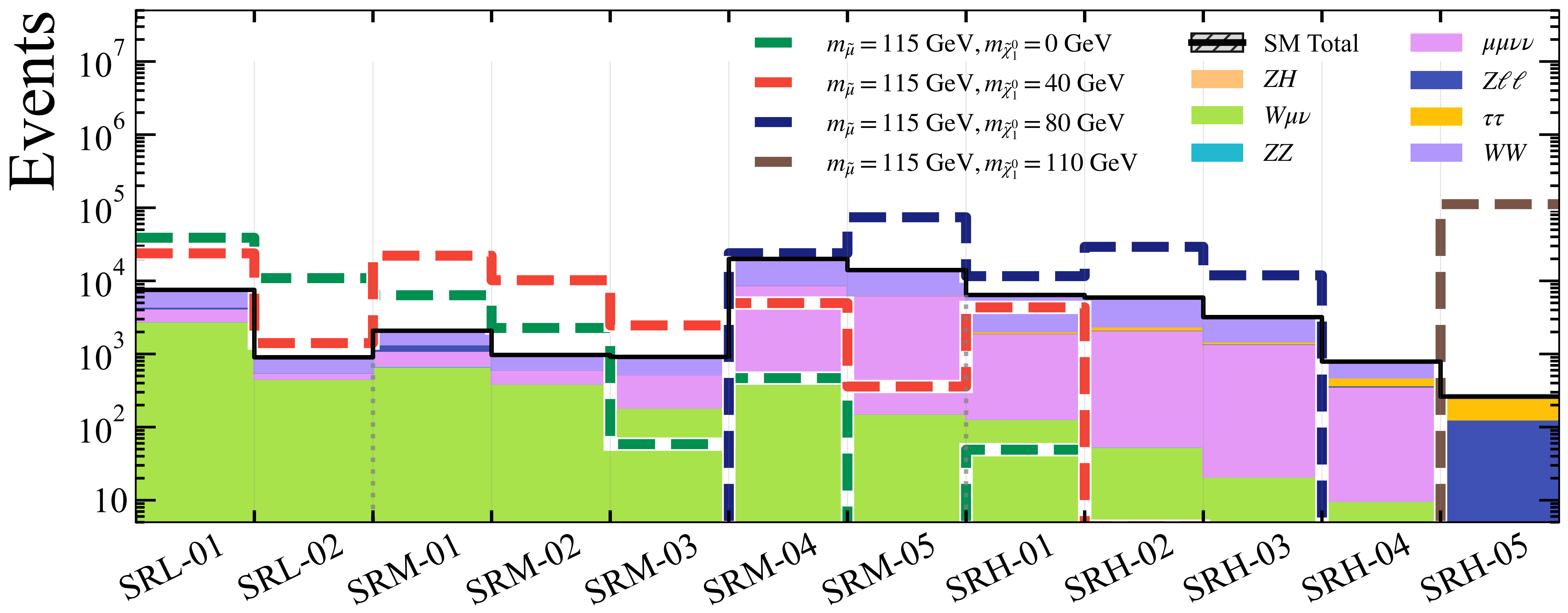
Prospect of smuon pair production at CEPC

- Preselection Criteria: OS muon pair, $E_{\mathrm{T}}^{\mathrm{miss}} > 1$ GeV, $E_{\mu} > 1$ GeV, $\left|\eta^{\ell}\right| < 3, m_{\mathrm{RC}}^{\max} > 115$ GeV.
- 12 SRs defined due to the distributions are much shape and closed related to the sparticle masses.
- Very good signal noise ratio are reached.
- For $m_{\tilde{\mu}} = 115$ GeV, about 110K smuon events can be generated at CPEC @ 240 GeV, 5 fb^{-1}.
- More than 10K event can be kept in the most sensitive SR.

SR	SRL-01	SRL-02	SRM-01	SRM-02
	$m_{\mathrm{RC}}^{\min} > 85$	$m_{\mathrm{RC}}^{\max} > 117$ $m_{\mathrm{RC}}^{\min} > 95$ $E_{\mu^{\pm}} \in [50, 70]$	$m_{\mathrm{RC}}^{\min} > 85$ $m_{\mathrm{LSP}}^{\max} \in [40, 60]$ $m_{\mathrm{RC}}^{\max}(40) > 110$	$m_{\mathrm{LSP}}^{\max} \in [50, 70]$ $m_{\mathrm{RC}}^{\max}(40) > 110$ $m_{\mathrm{RC}}^{\min}(40) > 100$
BKG	7532 ± 86	900 ± 30	2079 ± 45	970 ± 31
SGN(0)	38900	10900	6360	2270
SGN(40)	23800	1410	22100	10200
SGN(80)	0	0	0	0
SGN(110)	0	0	0	0

SR	SRM-03	SRM-04	SRM-05	SRH-01
	$m_{\mathrm{LSP}}^{\max} \in [60, 80]$ $m_{\mathrm{RC}}^{\min}(40) > 95$	$m_{\mathrm{LSP}}^{\max} \in [70, 85]$ $m_{\mathrm{RC}}^{\min}(70) > 100$	$m_{\mathrm{LSP}}^{\max} \in [80, 95]$ $m_{\mathrm{RC}}^{\min}(80) > 105$	$E_{\mu^{\pm}} \in [34, 44]$ $\Delta m^{\max} \in [35, 50]$
BKG	912 ± 30	19941 ± 141	14039 ± 118	6412 ± 80
SGN(0)	59	468	0	49
SGN(40)	2460	4970	359	4340
SGN(80)	0	23900	74100	11600
SGN(110)	0	0	0	0

SR	SRH-02	SRH-03	SRH-04	SRH-05
	$E_{\mu^{\pm}} \in [28, 37]$ $\Delta m^{\max} \in [25, 40]$	$E_{\mu^{\pm}} \in [22, 28]$ $\Delta m^{\max} \in [15, 30]$	$E_{\mu^{\pm}} \in [15, 18]$ $\Delta m^{\max} \in [0, 20]$	$\Delta m^{\max} \in [0, 10]$
BKG	5913 ± 76	3190 ± 56	786 ± 28	262 ± 12
SGN(0)	0	0	0	0
SGN(40)	5	0	0	0
SGN(80)	29200	11900	0	0
SGN(110)	0	0	0	112000



Prospect of smuon pair production at CEPC

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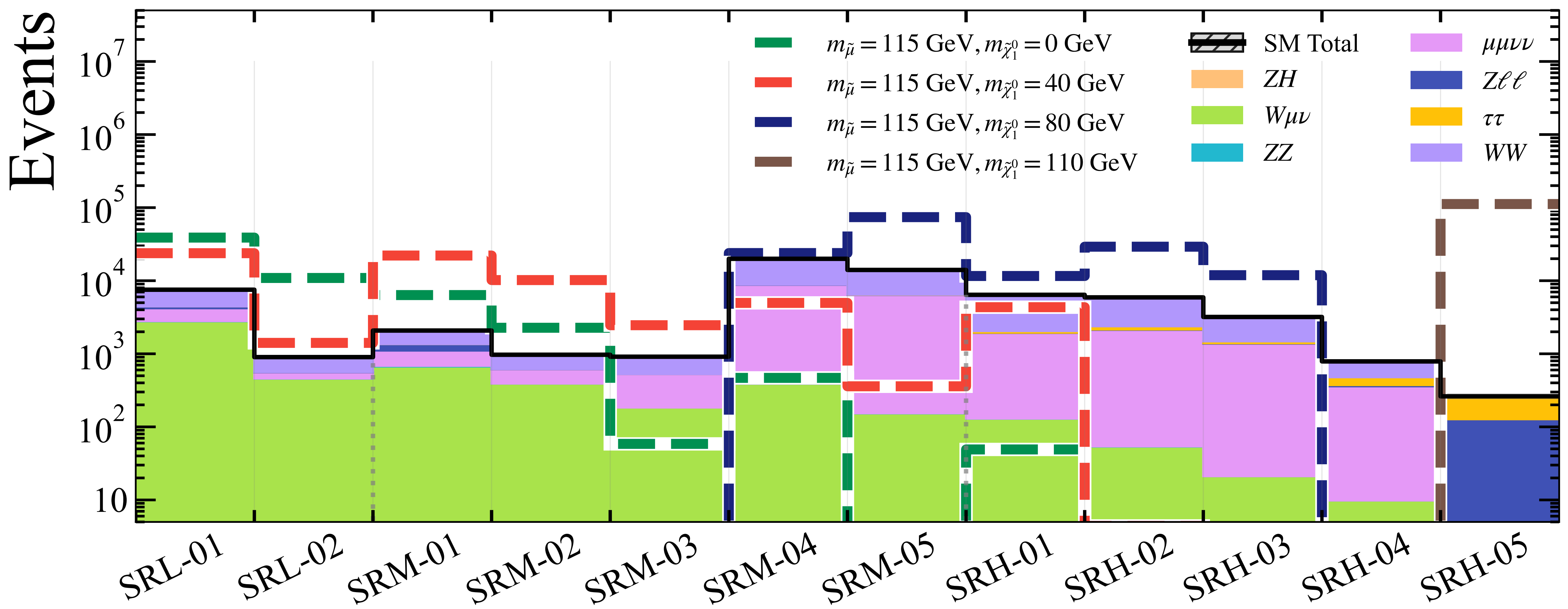
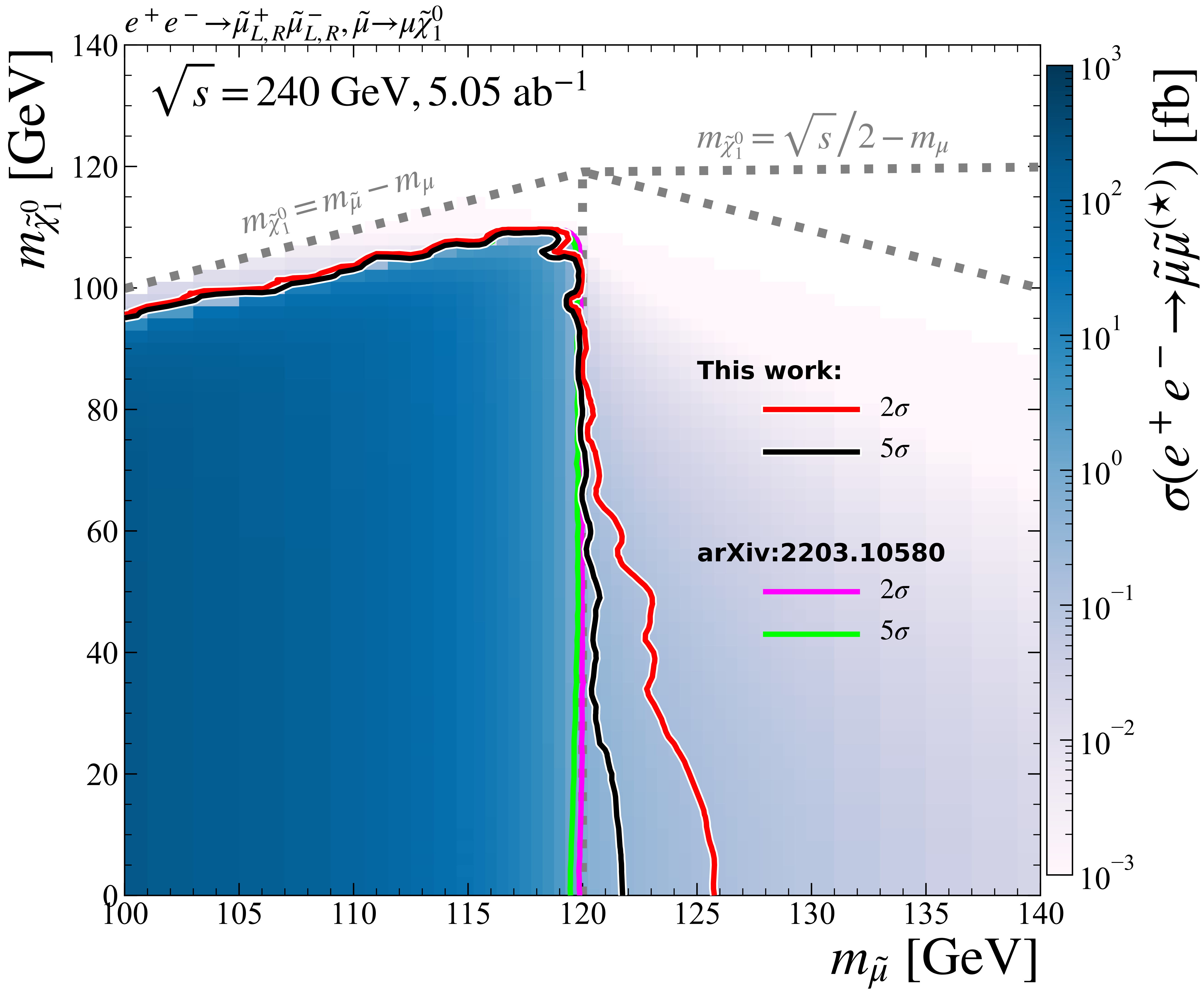
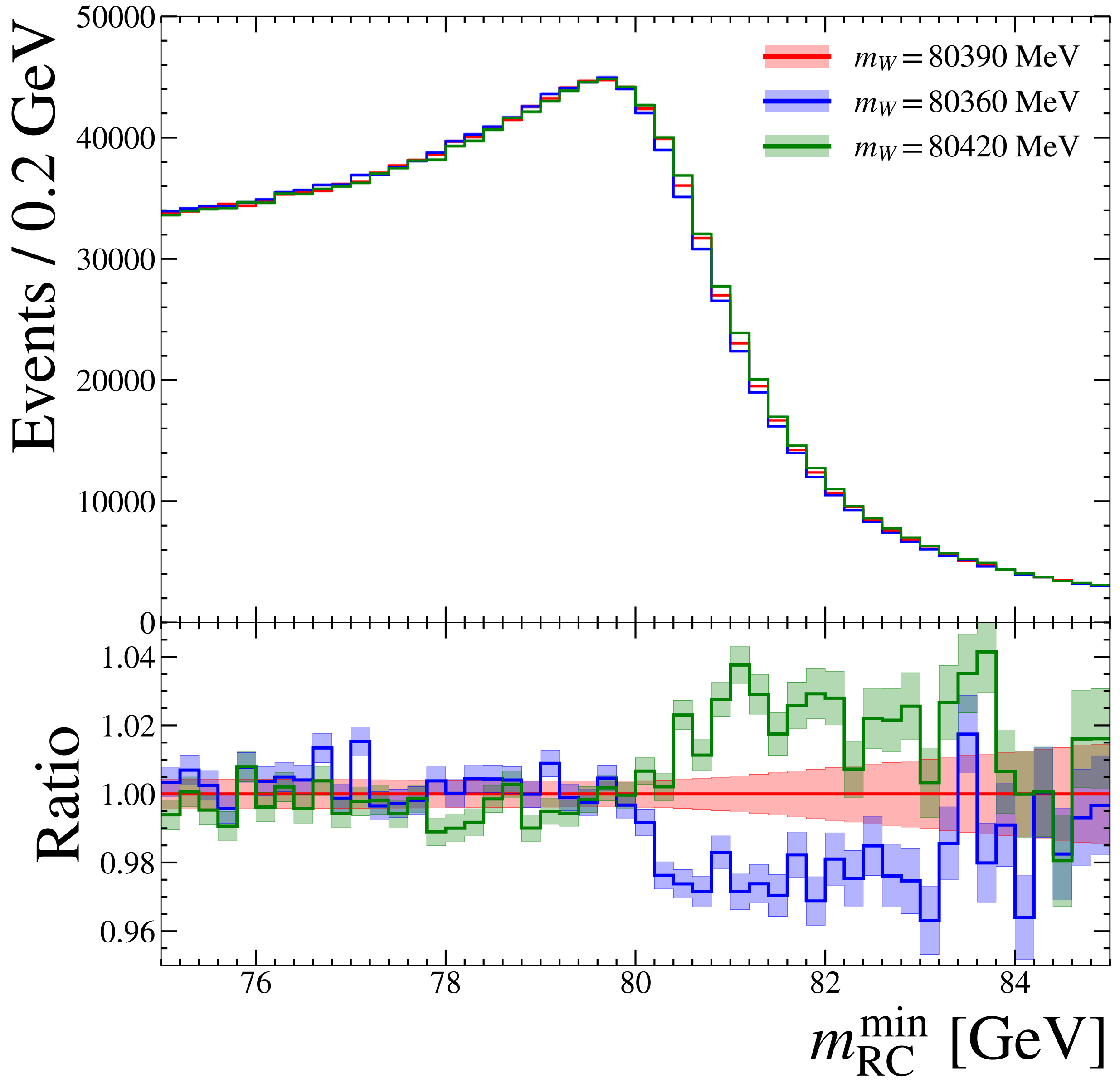


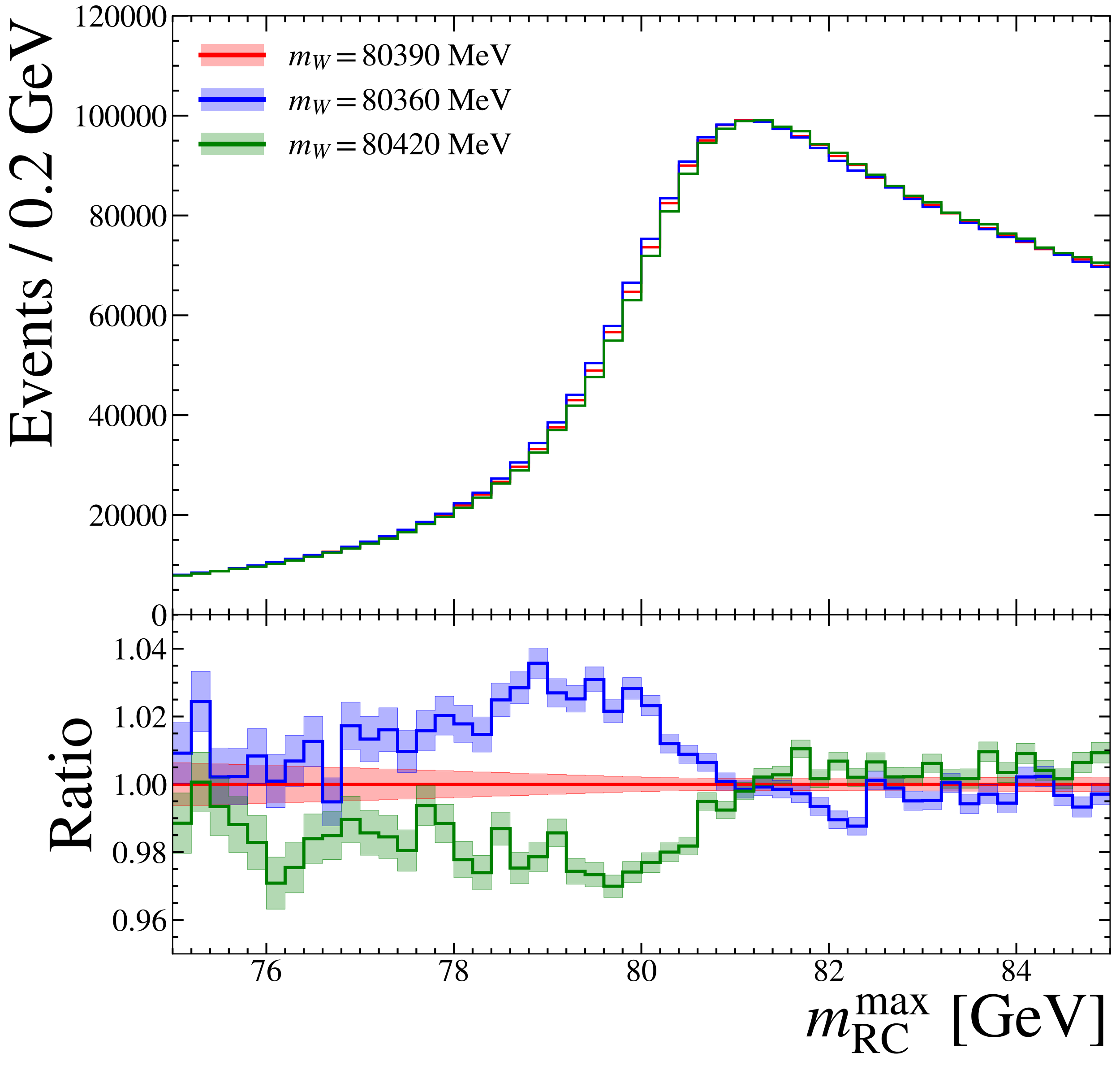


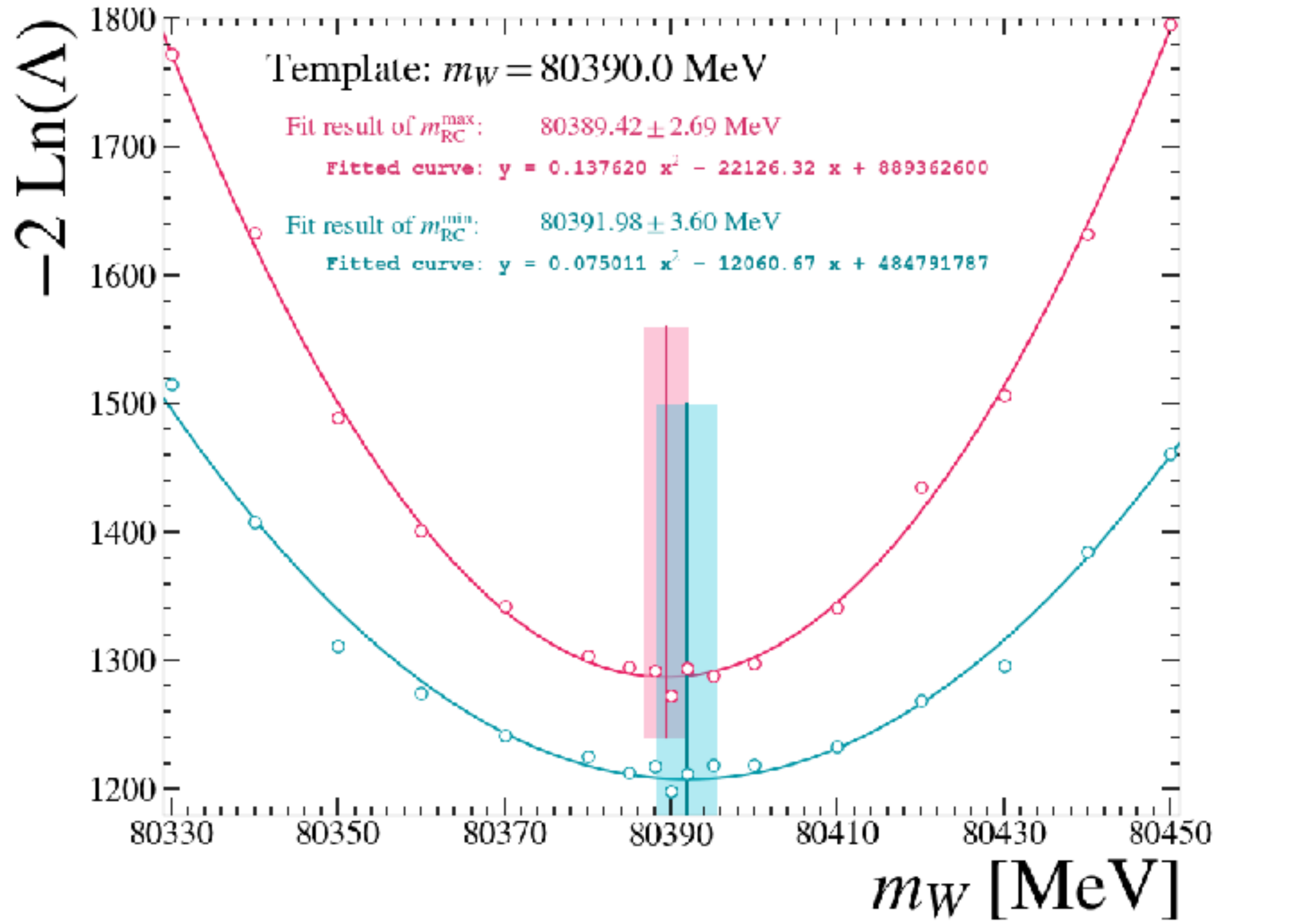
Application in Precision measurement

Measuring the W boson mass in full-leptonic decay channel

- $e^+e^- \to WW \to \ell\ell'\nu\nu$.
- The backgrounds are much more cleaner.
- The distributions of $m_{\mathrm{RC}}^{\mathrm{min}}$ and $m_{\mathrm{RC}}^{\mathrm{max}}$ are sensitive to m_W.







- Template-fit to MC data.
- The uncertainty is about 3 MeV at CEPC. The precision is at same order of semi-leptonic decayed channel ($\ell\nu qq'$), please see CEPC CDR.
- The uncertainty may be affect by the beam energy uncertainty.

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Aug-14, 2023

In collaboration with Jin–Min Yang, Yang Zhang & Rui Zhu.

Based on arXiv: 2211.01832