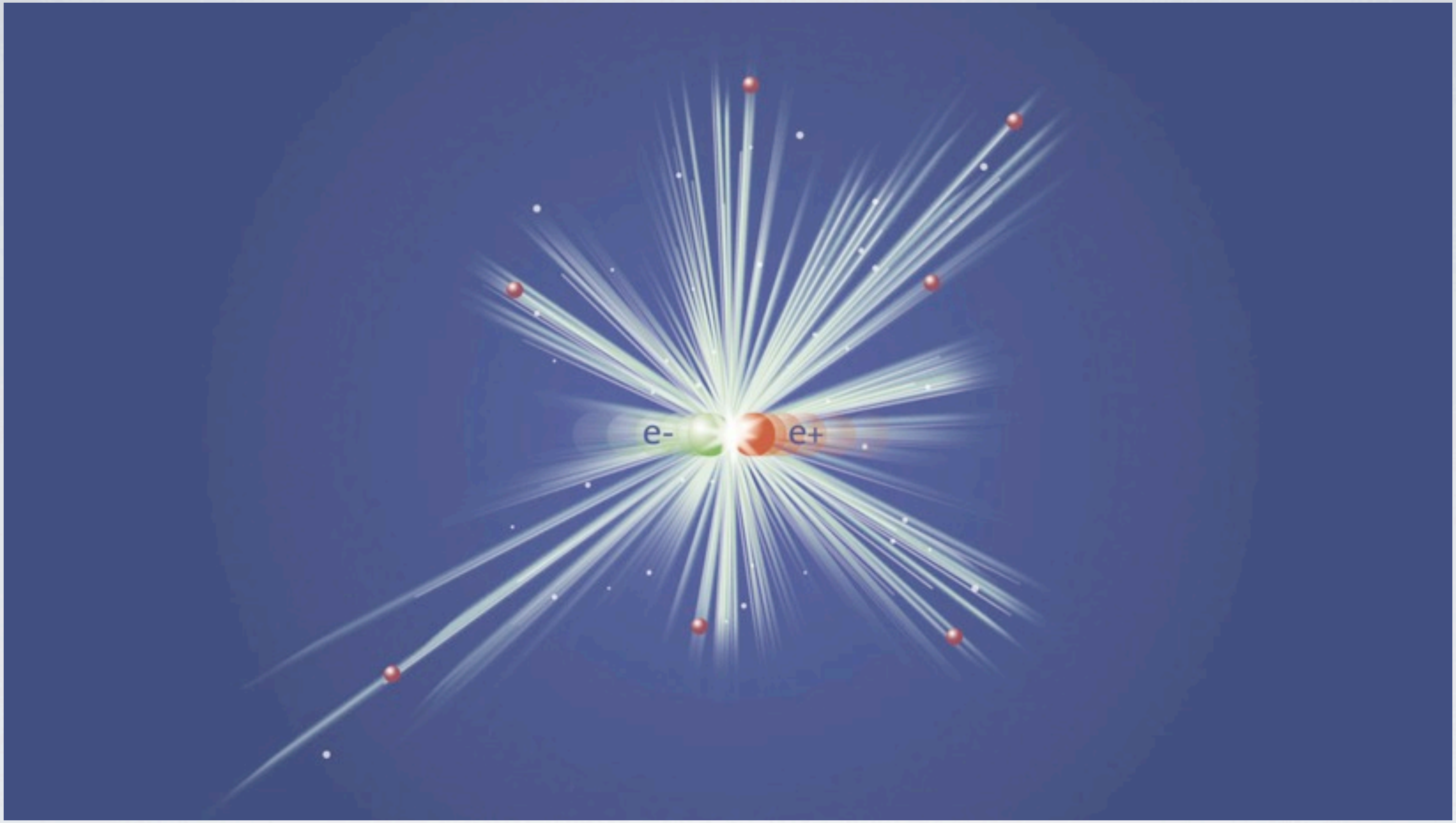

Measuring the Mass of a New Particles from LHC

2010 KIAS & SNU Winter School

Why physicists built the LHC?

They want to see ‘something’ through it.

They want to see ‘something’ through it.
Something more fundamental building blocks of matters around us.

As you know, from the lecture,
there are some problems with the Higgs mechanism.

To solve this problem, so called hierarchy problem, physicists made a new concept called "Supersymmetry"

Through the supersymmetry, simply, physicists tells us that there must be "supersymmetric partners" for each elementary particles.

So they suggested a new recipe to describe the universe.

Until then, this was the whole components of their recipe.

u	c	t	γ
d	s	b	g
ν_e	ν_μ	ν_τ	W
e	μ	τ	Z

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u	c	t	γ
d	s	b	g
ν_e	ν_μ	ν_τ	W
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And they changed it,

into this new recipe table with Higgs particle and supersymmetric partners so called "sparticles"

$\tilde{\gamma}$	$\tilde{t}$	$\tilde{c}$	$\tilde{u}$		u	c	t	γ
$\tilde{g}$	$\tilde{b}$	$\tilde{s}$	$\tilde{d}$		d	s	b	g
$\tilde{W}$	$\tilde{\nu_\tau}$	$\tilde{\nu_\mu}$	$\tilde{\nu_e}$		ν_e	ν_μ	ν_τ	W
$\tilde{Z}$	$\tilde{\tau}$	$\tilde{\mu}$	$\tilde{e}$	$\tilde{H}\|H$	e	μ	τ	Z

$$\tilde{h}^0, \tilde{h}^\pm, \tilde{A} \;\; | \;\; A, h^\pm, h^0$$

$$\tilde{\chi_1}, \tilde{\chi_2}, \tilde{\chi_3}, \tilde{\chi_4}$$

In TeV scale collider, particle physicists expect that they can see these superpartners.

So our problem is **to determine the masses** of some supersymmetric particles that created during the TeV scale collision of electron-positron or proton-proton in LHC.

Problem #1.

$$\tilde{q} \to q\chi_2 \to q(l^- \widetilde{l^+}) \to q(l^- l^+ \chi_1)$$

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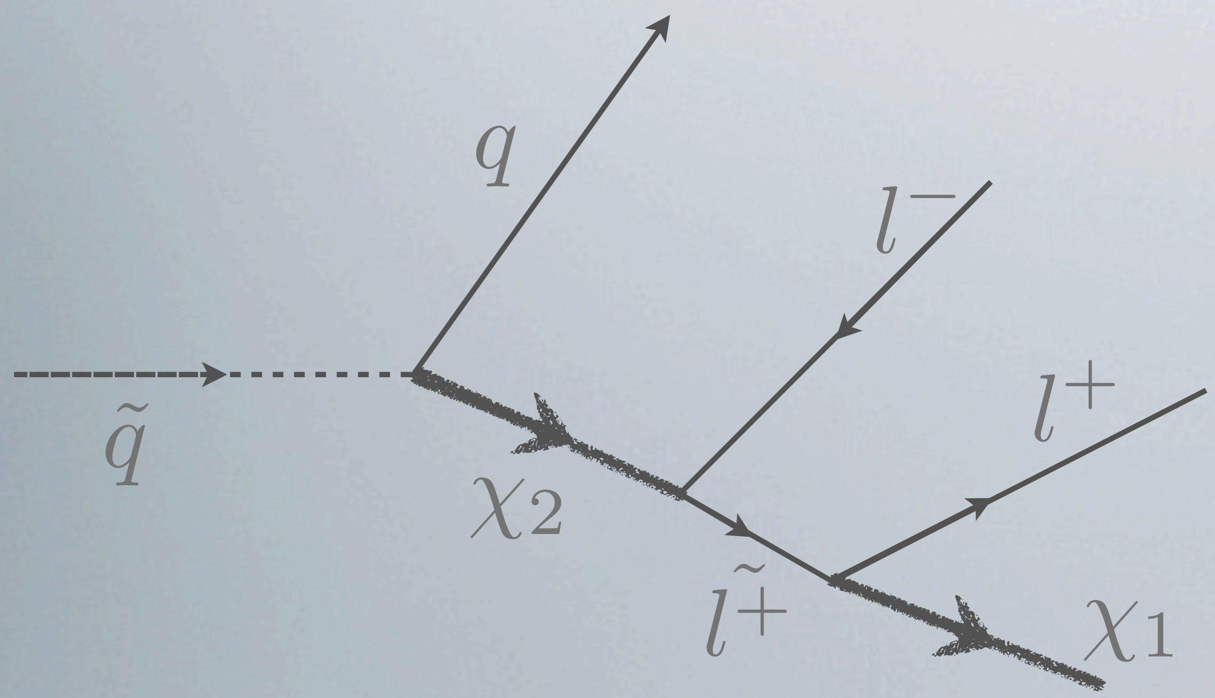

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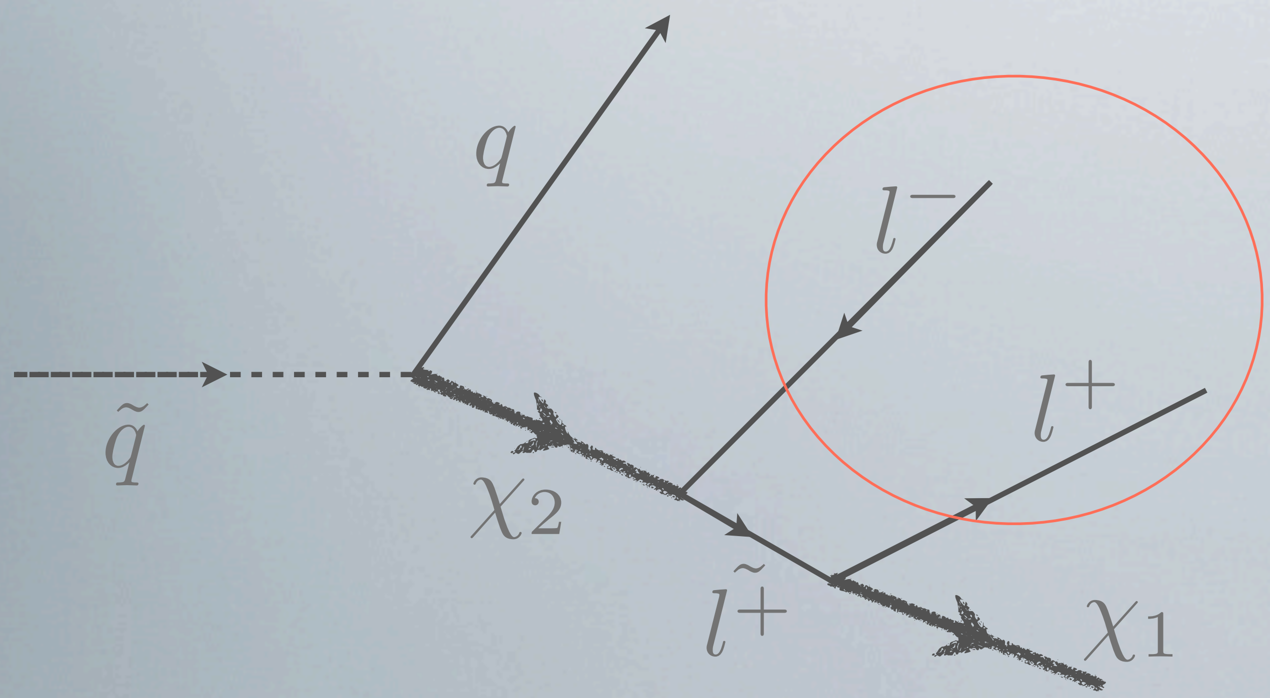

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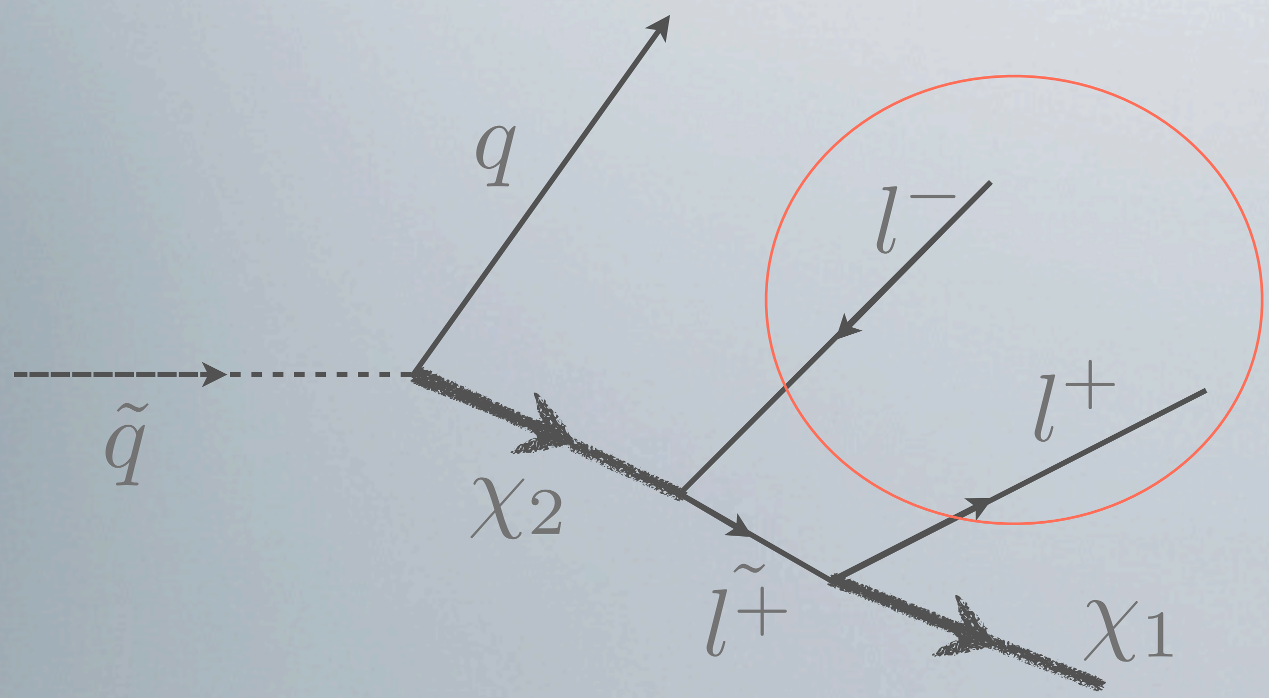

Define invariant mass distribution

$$m^2_{l^-l^+} \equiv (p_{l^-} + p_{l^+})^2$$
$$= 2E_{l^-}E_{l^+}(1 - \cos\theta_{l^+l^-})$$

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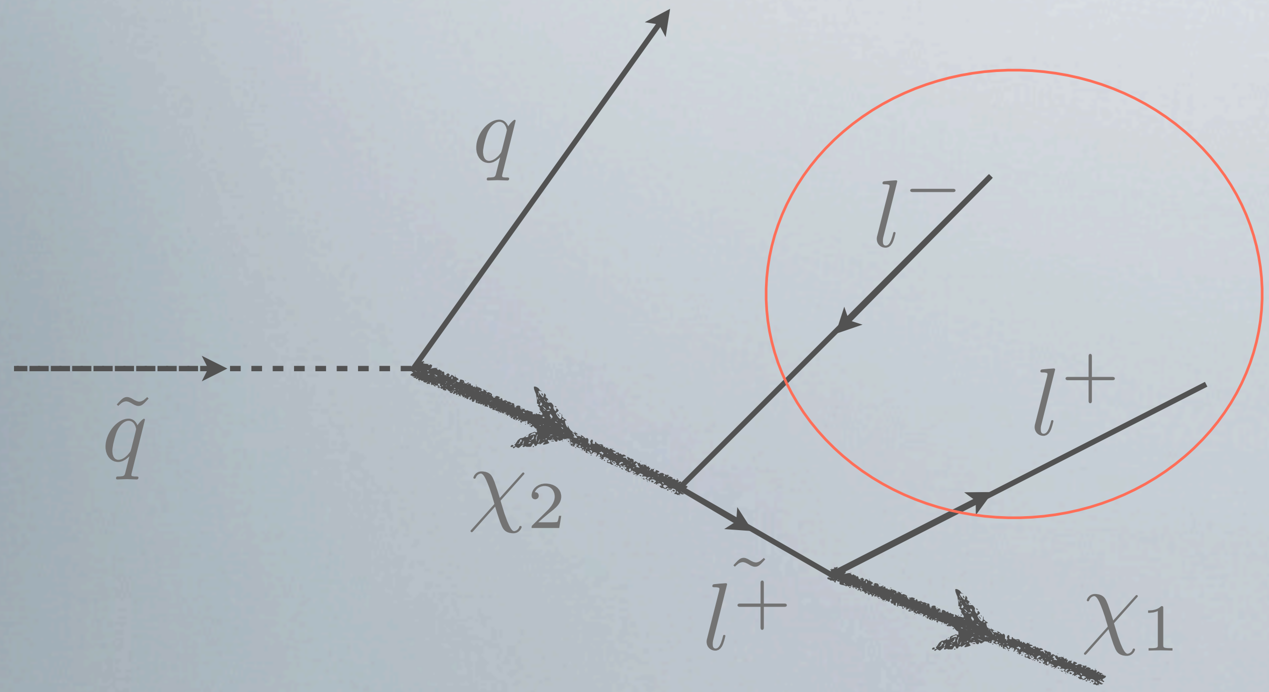

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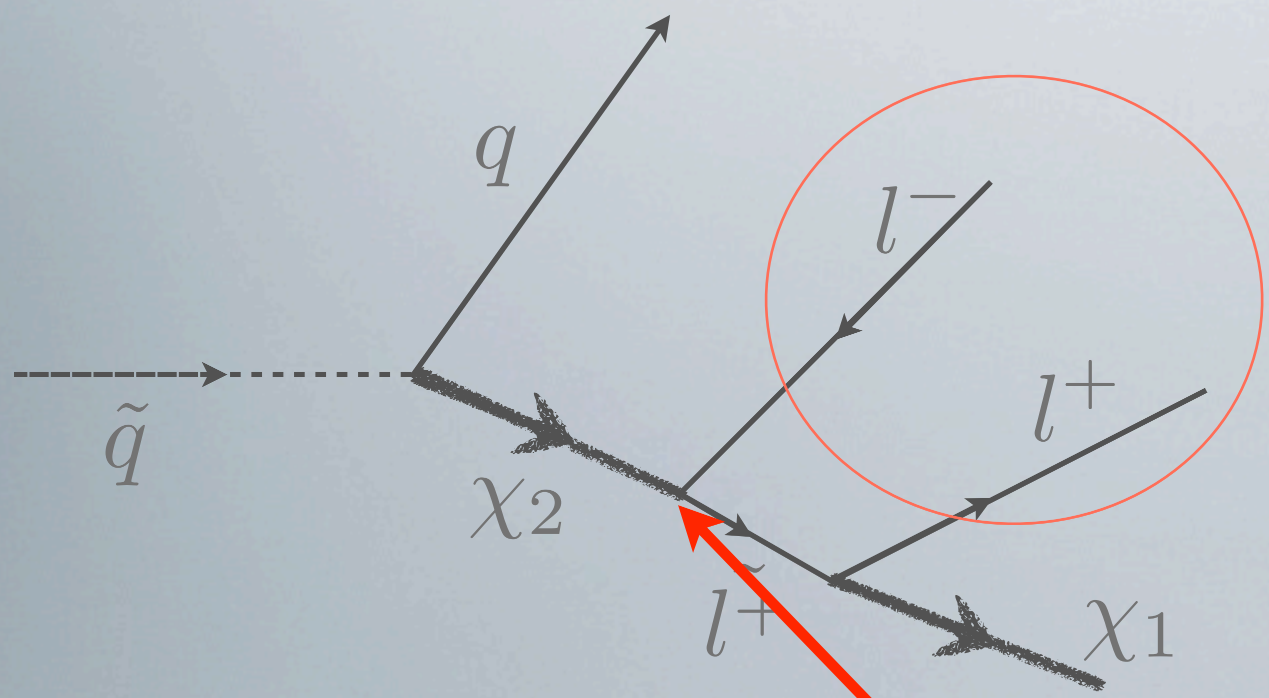

Define invariant mass distribution

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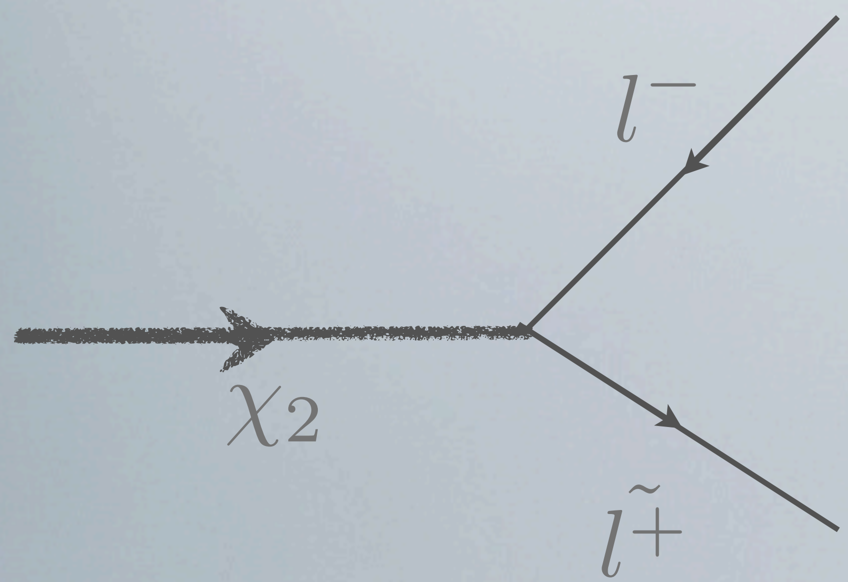
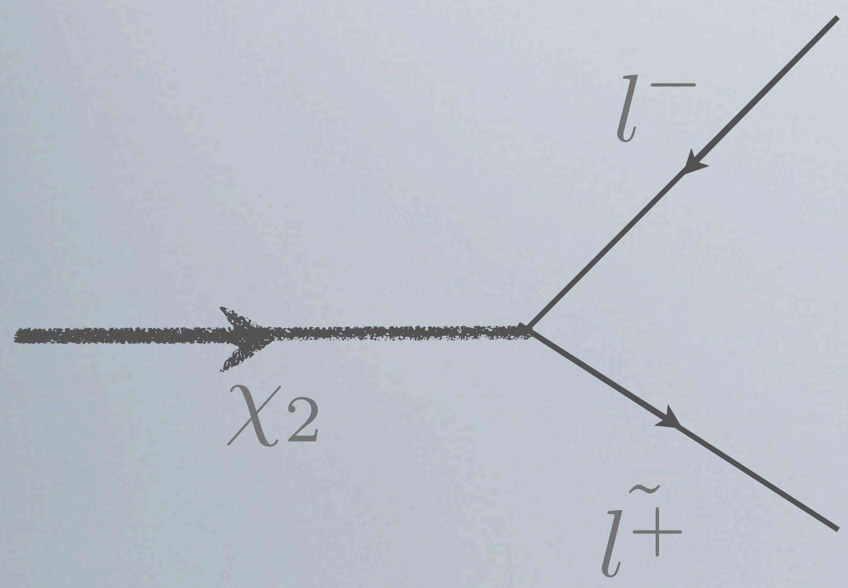
For convenience, we use the rest frame of slepton.

Let's do some calculation of the vertex that describing the decay of the first neutralino.


l^-
χ_2
$\tilde{l^+}$

The conserved quantities are,



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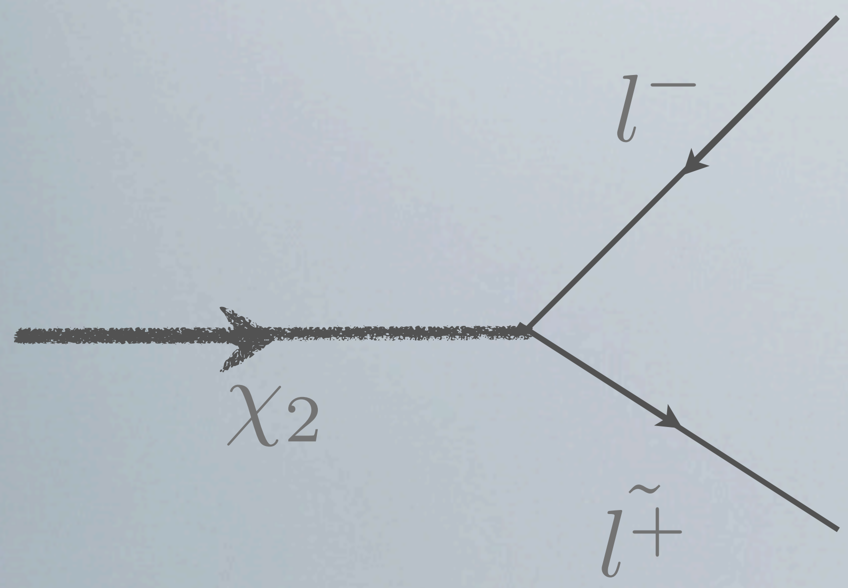

$$E_{\chi_2} = E_{l^-} + E_{\tilde{l^+}}$$

$$\vec{p_{\chi_2}} = \vec{p_{l^-}} + \vec{0}$$

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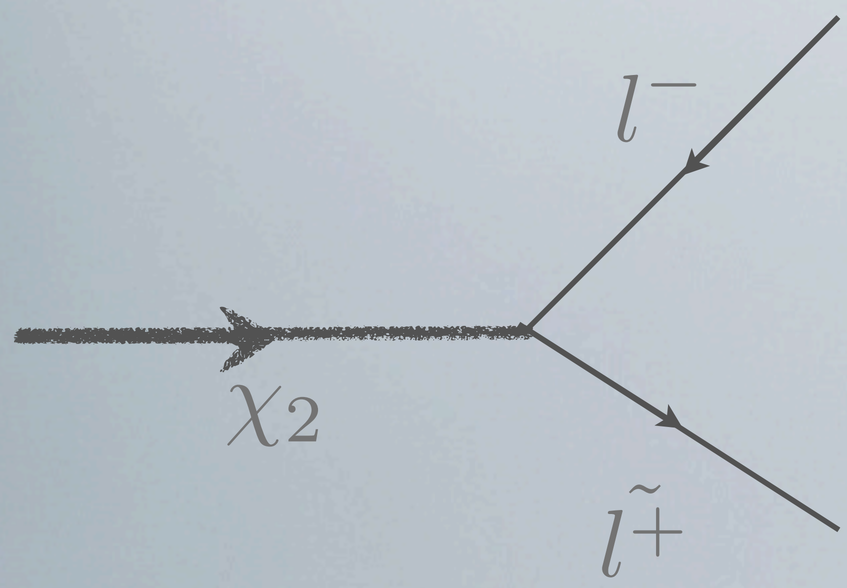

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and note the invariances.

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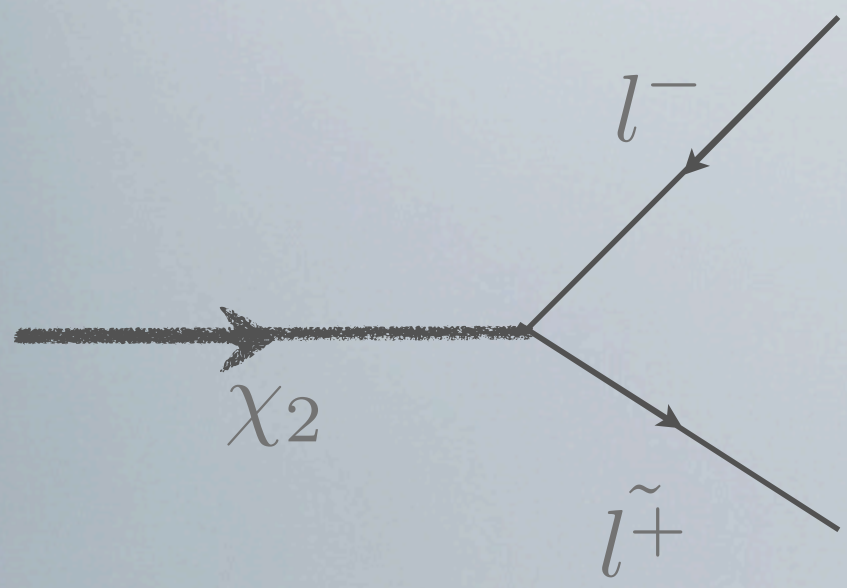

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$$E^2_{\tilde{l^+}} = p^2_{\tilde{l^+}} + m^2_{\tilde{l^+}} = m^2_{\tilde{l^+}}$$

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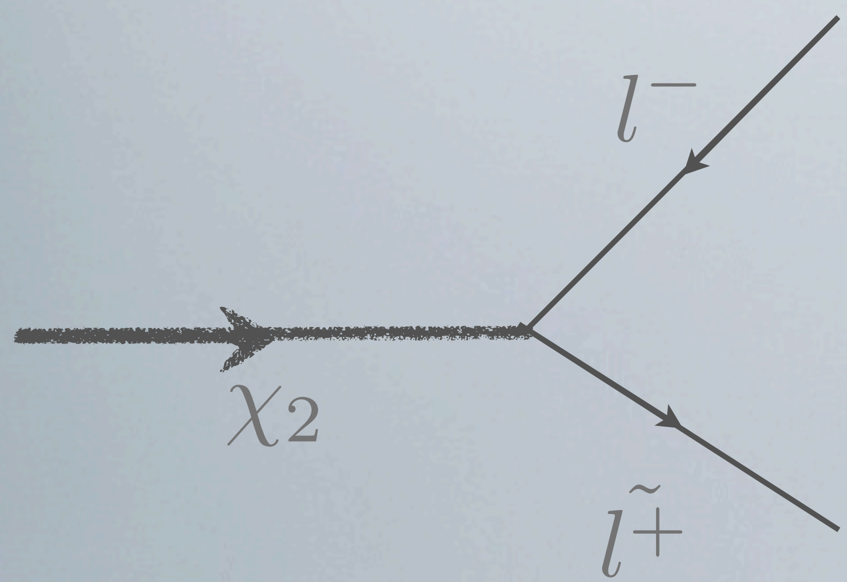

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Then we have next result.

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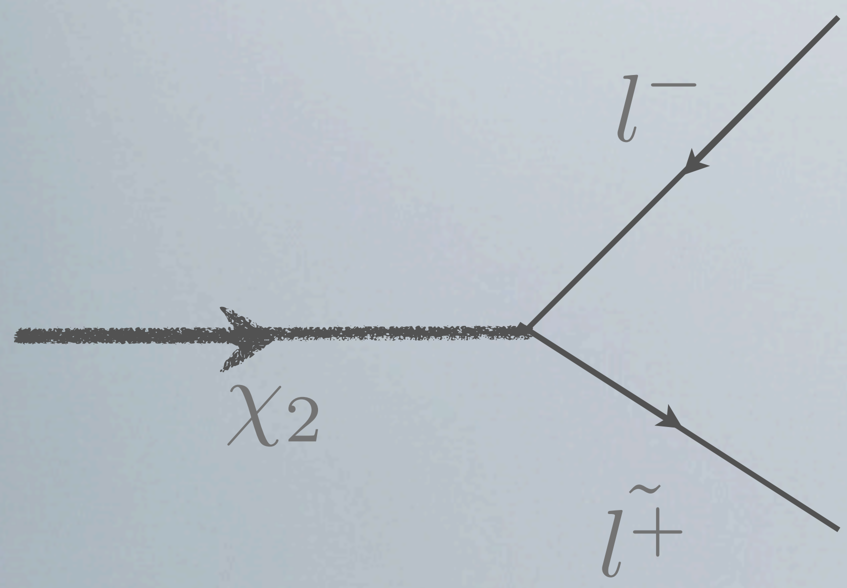

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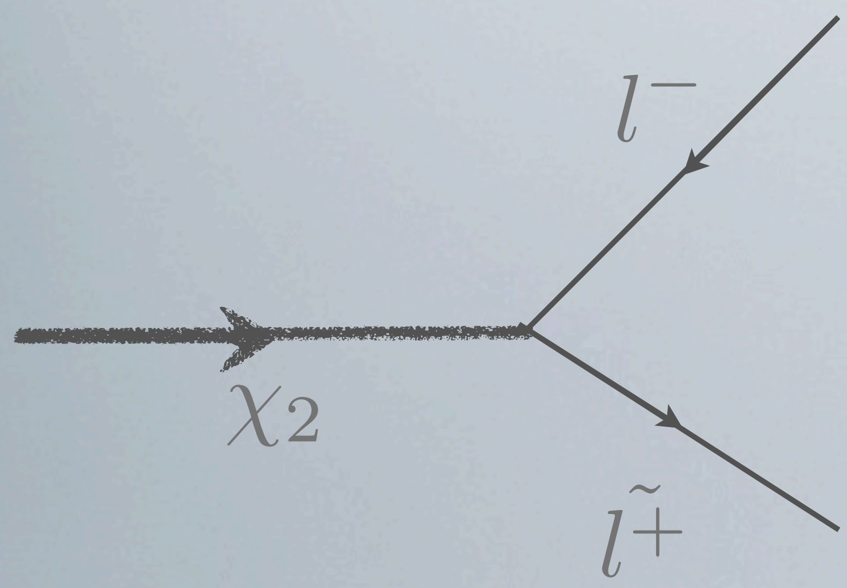

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Then we have next result.

$$E_{l^-} = \frac{m^2_{\chi_2} - m^2_{l^+}}{2m_{\tilde{l}^+}}$$

Let's check it in detail on the board.

$$E_{\chi_2}^2 = E_{l^-}^2 + E_{\tilde{l}^+}^2 + 2E_{l^-}E_{\tilde{l}^+}$$

- Energy conservation

$$= p_{l^-}^2 + m_{\tilde{l}^+}^2 + 2E_l E_{\tilde{l}^+}$$

- lepton is massless

$$= p_{\chi_2}^2 + m_{\chi_2}^2$$

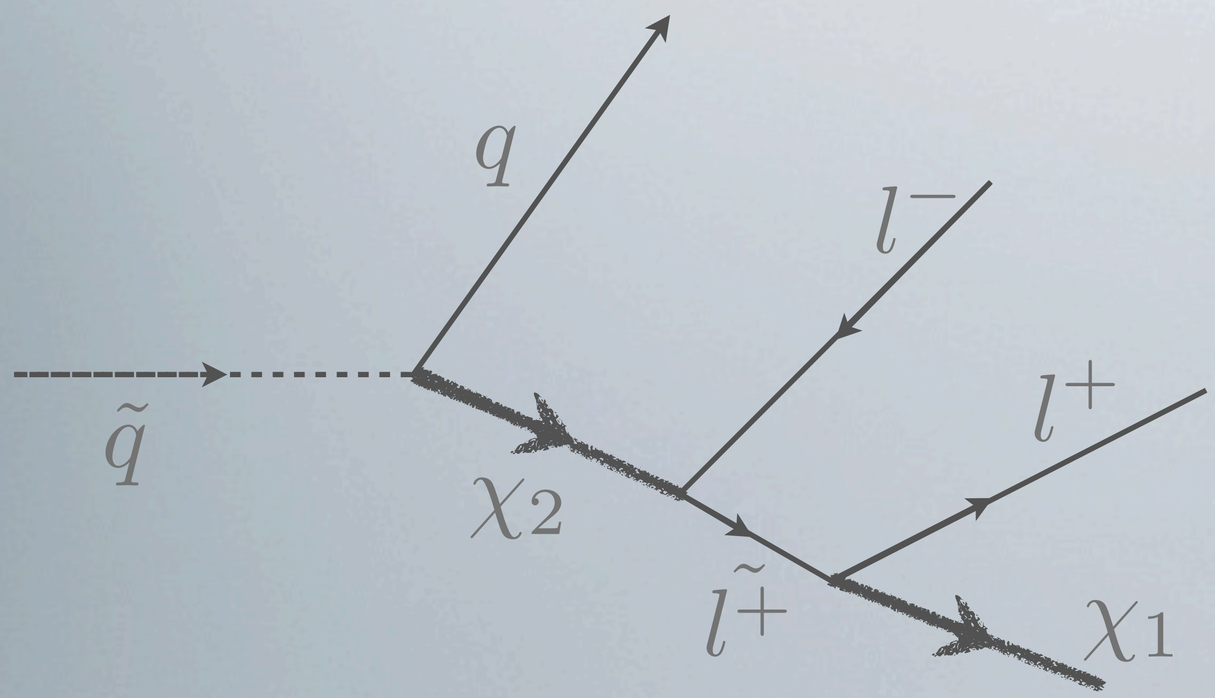
- invariance of neutralino

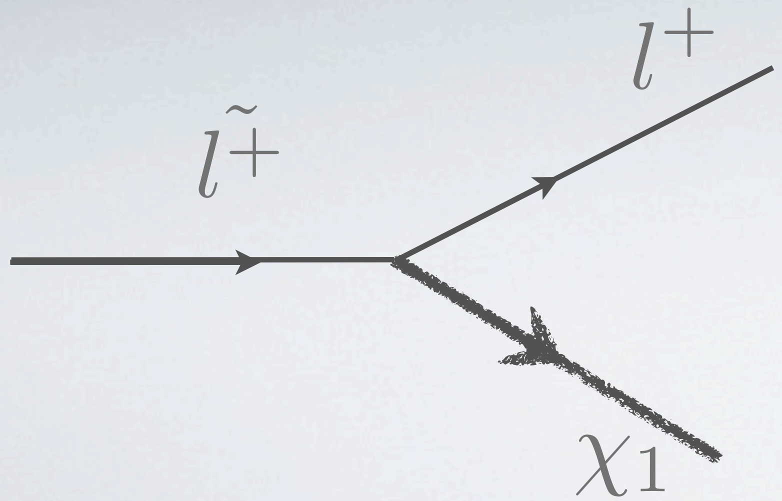
$$\Rightarrow m_{\chi_2}^2 - m_{\tilde{l}^+}^2 = 2E_{l^-}E_{\tilde{l}^+}$$

$$\Rightarrow E_{l^-} = \frac{m_{\chi_2}^2 = m_{\tilde{l}^+}^2}{2E_{\tilde{l}^+}}$$

- We find the answer.

Let's check second vertex.





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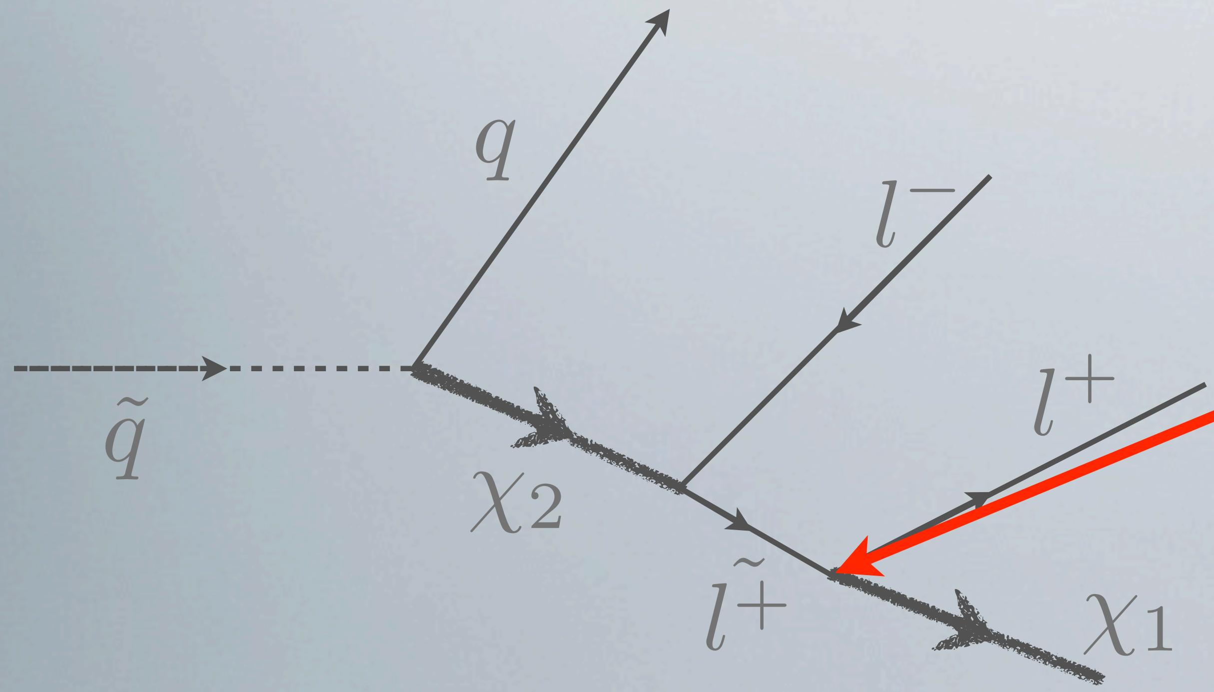

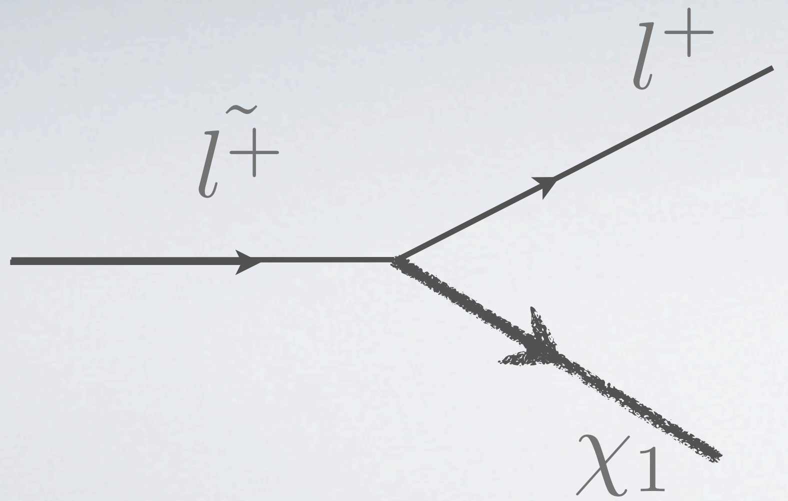

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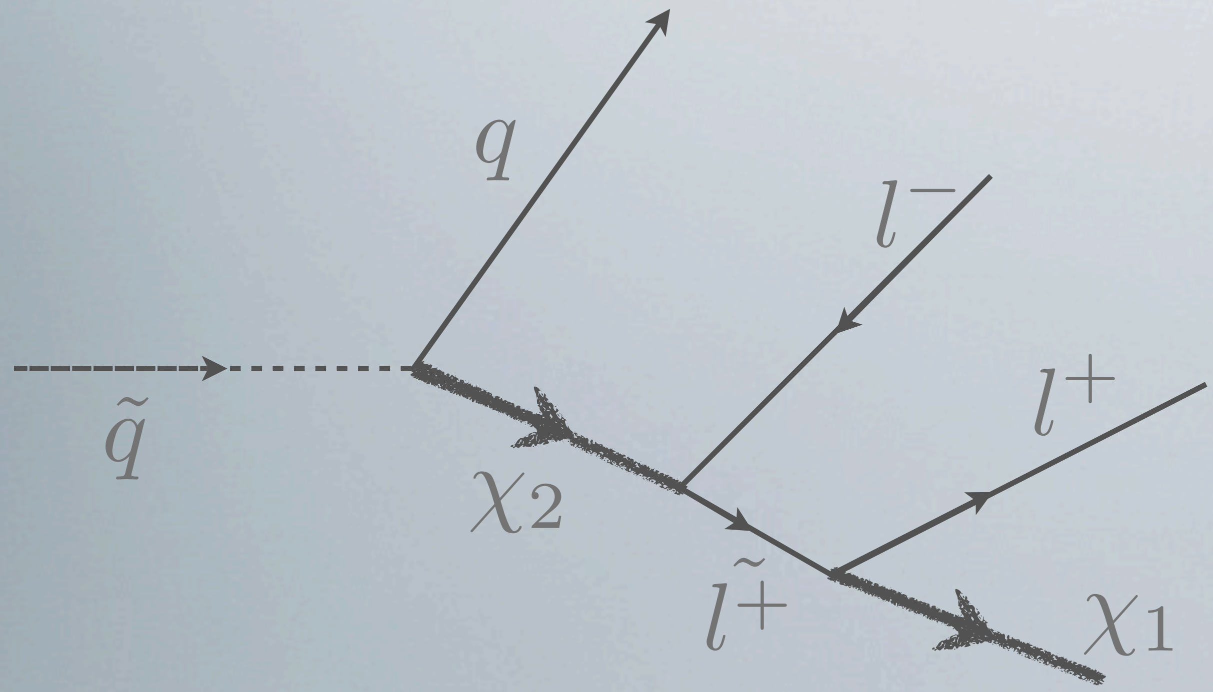
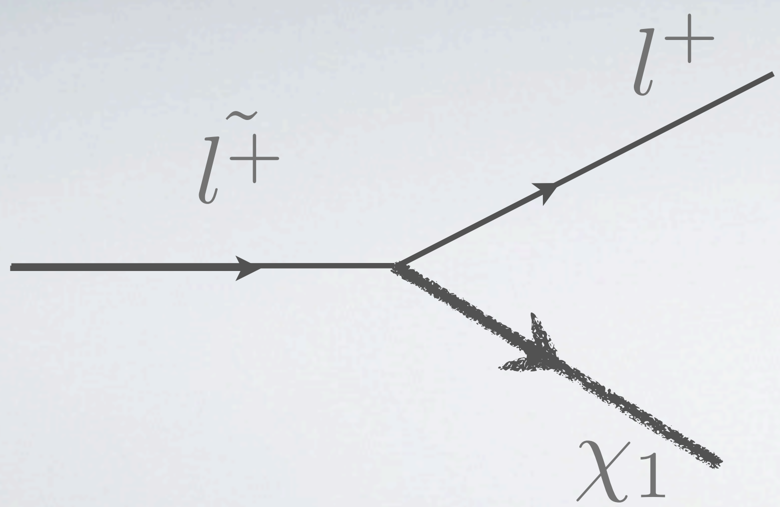
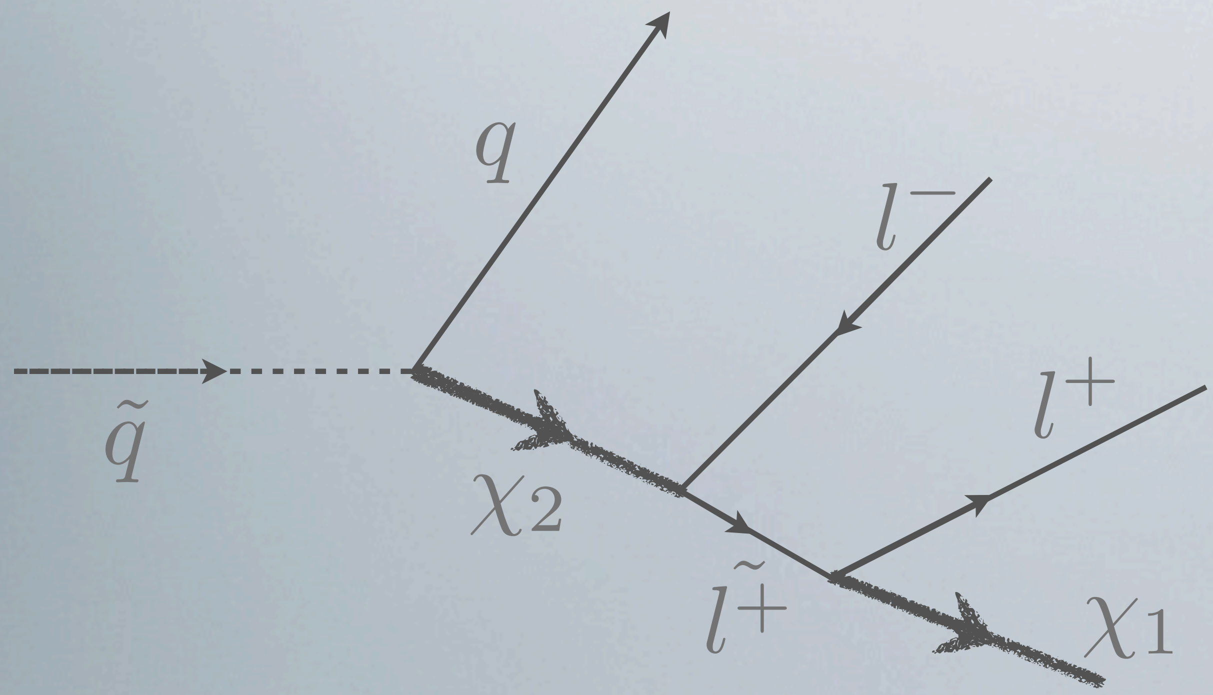
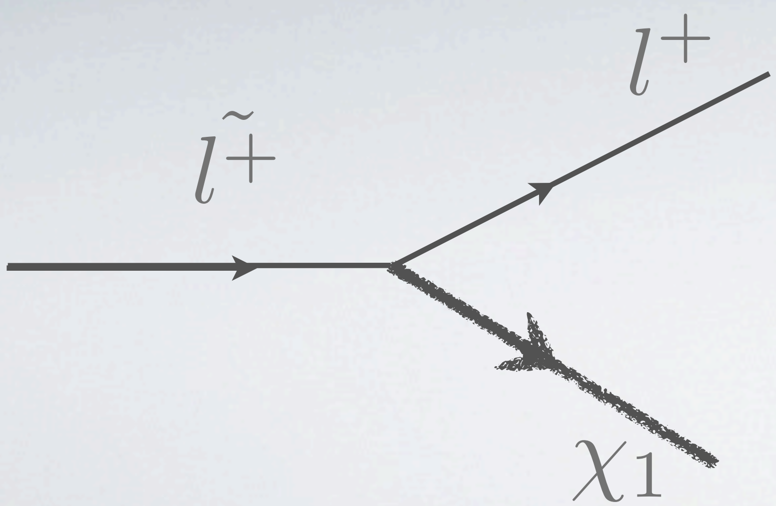




Let's check second vertex.

- <u>Conserved quantities</u>





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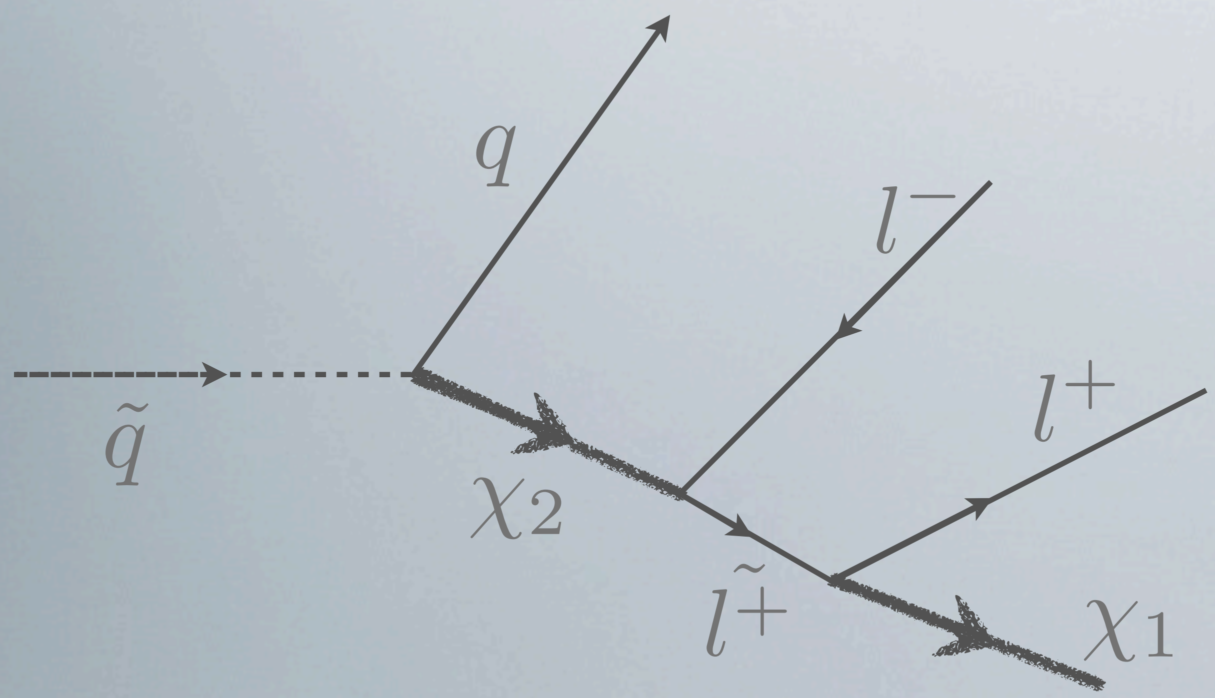

- <u>Conserved quantities</u>

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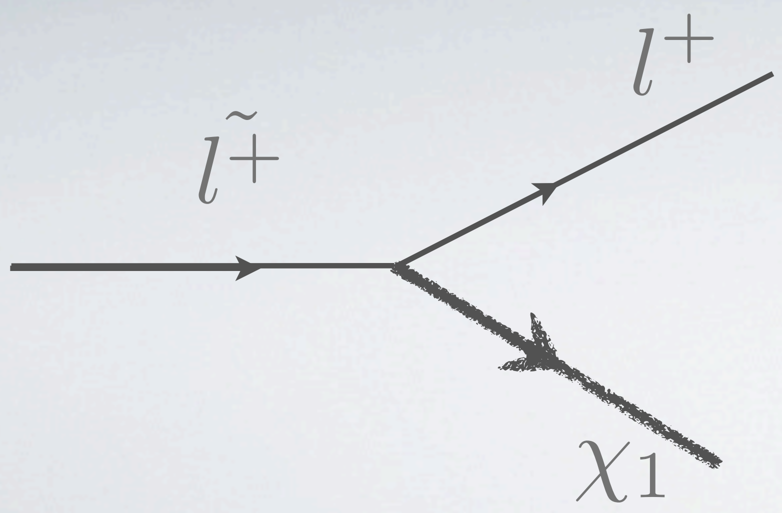

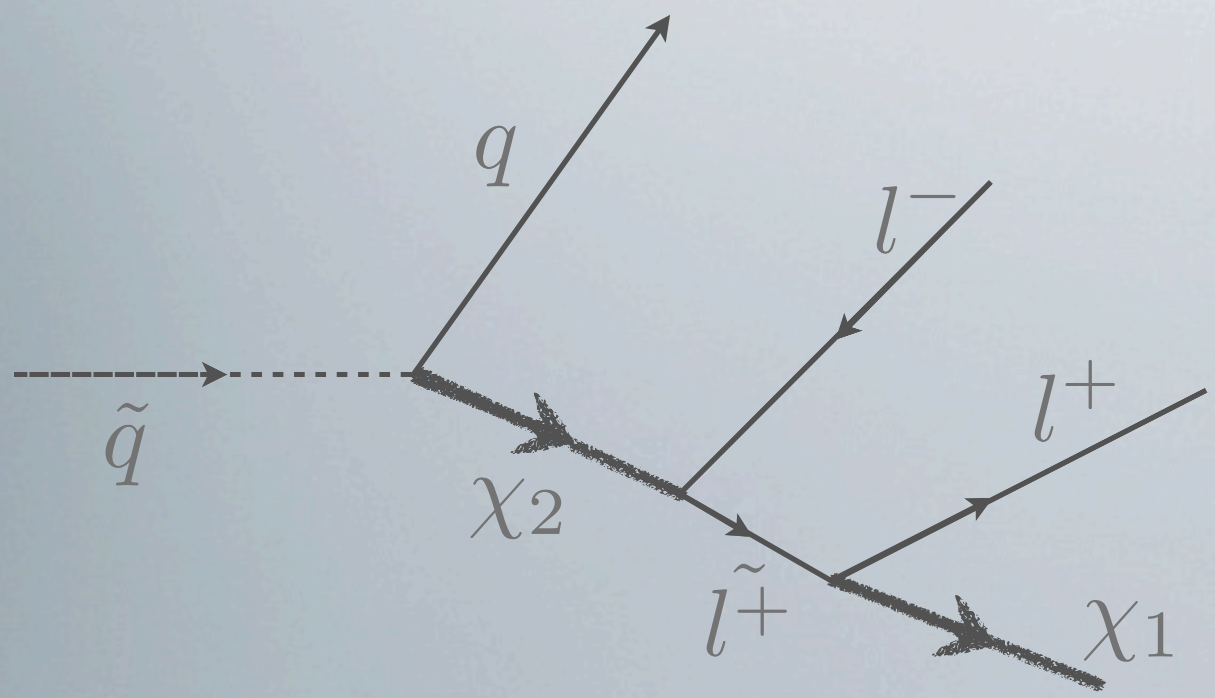

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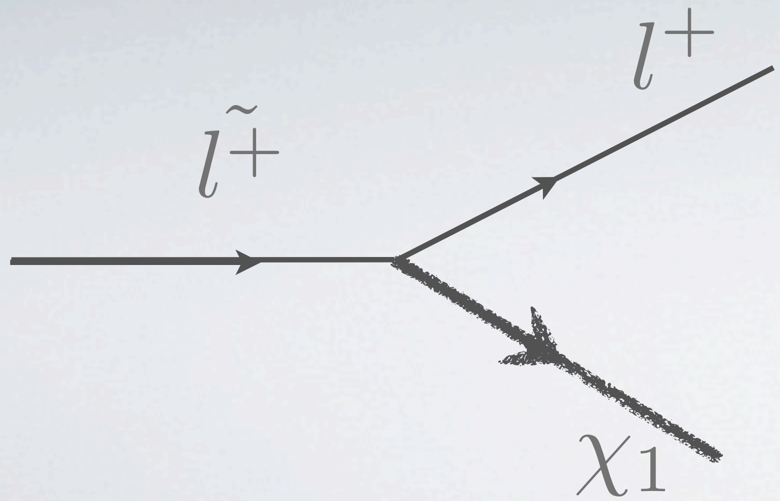

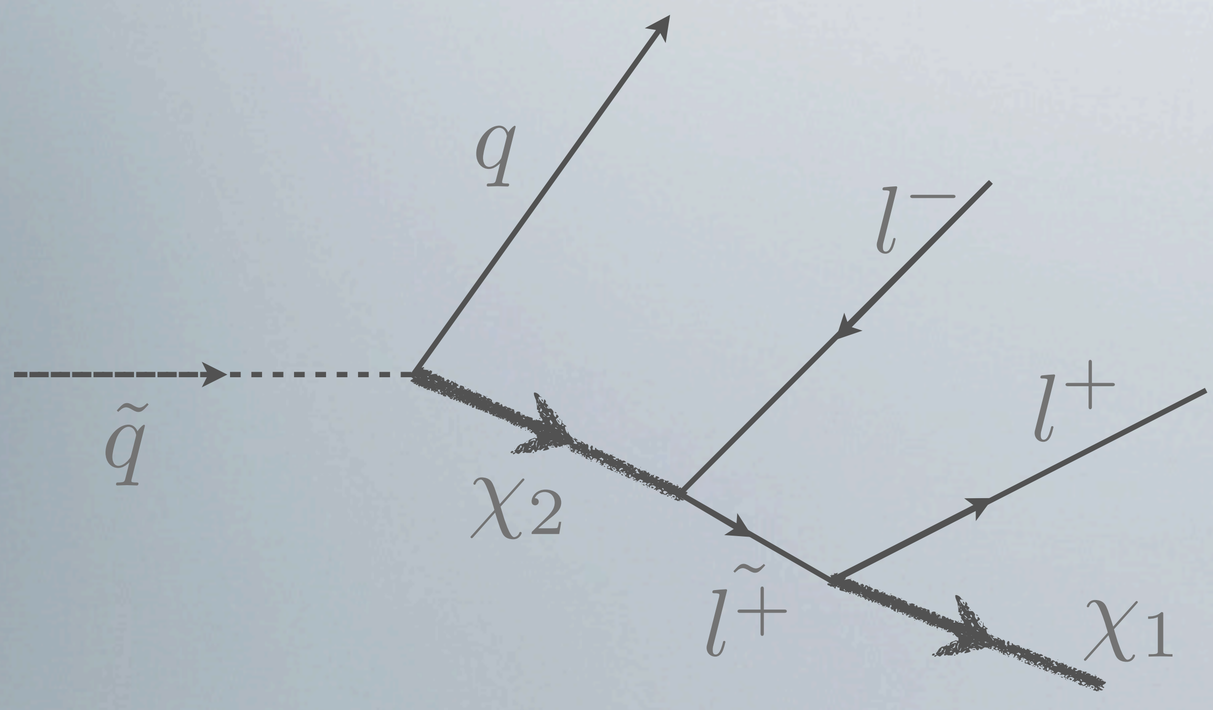

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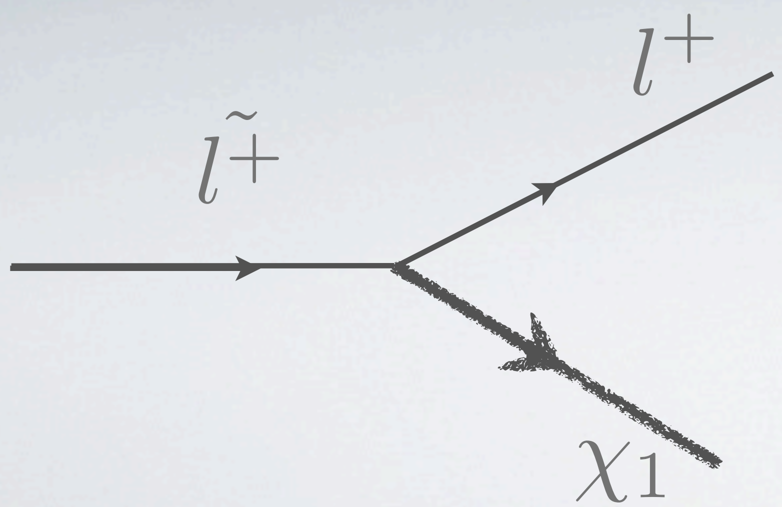

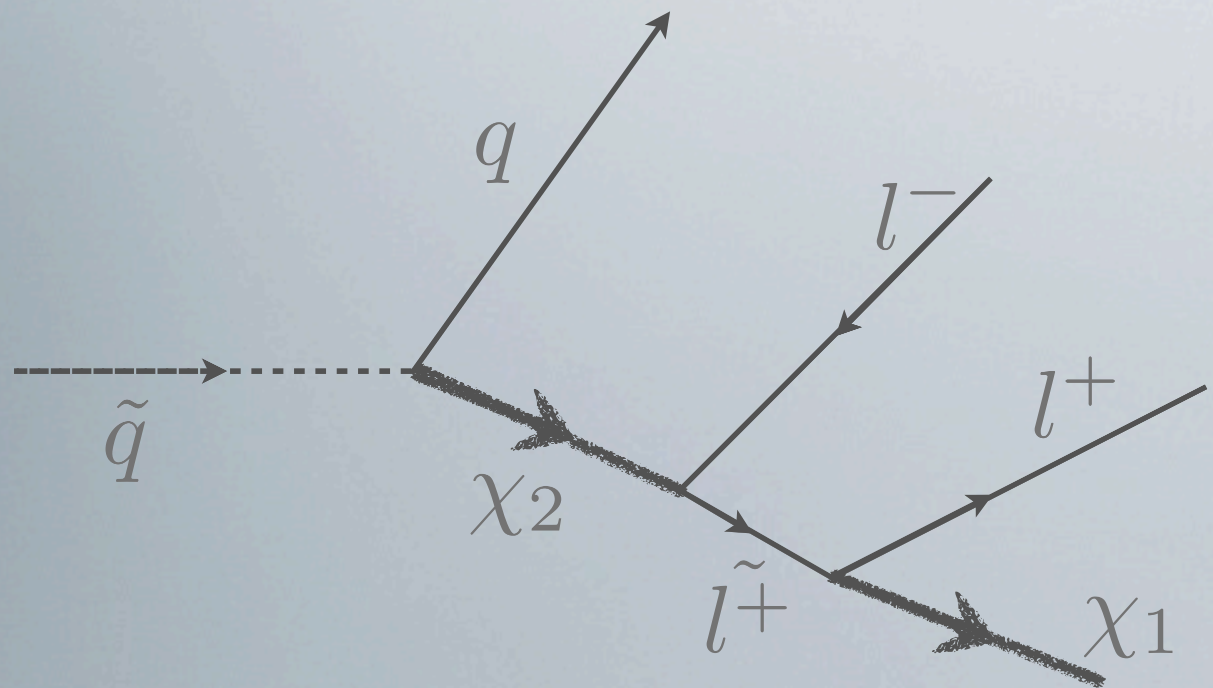

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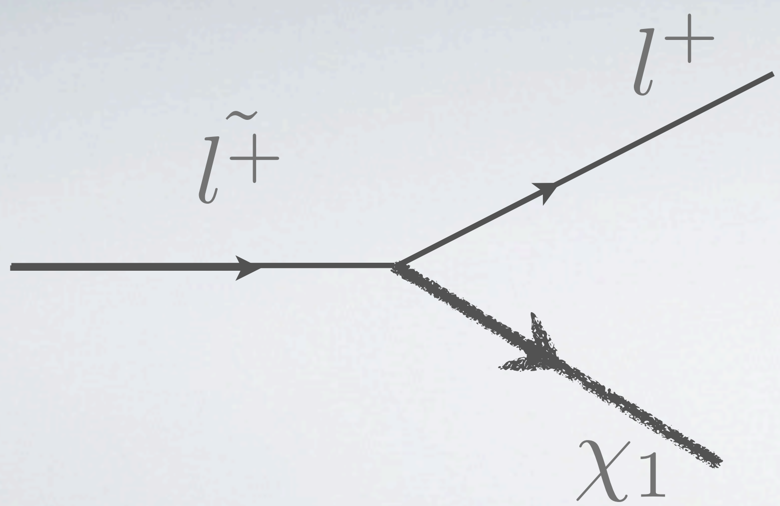
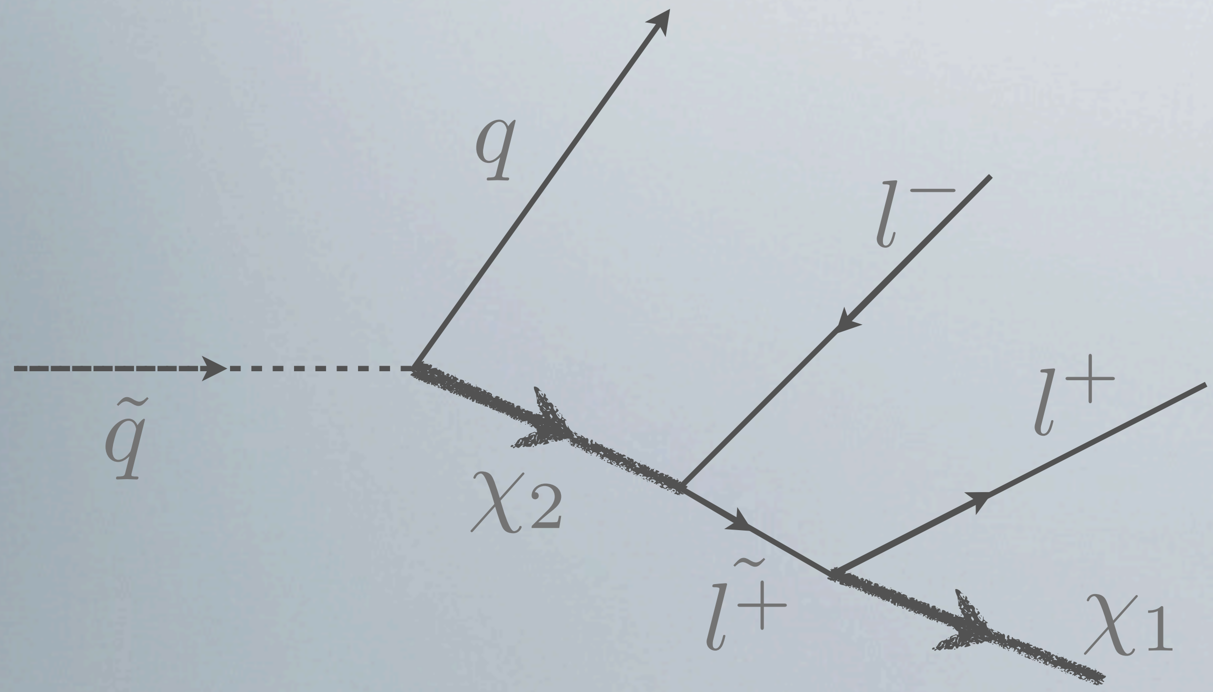
$$E_{\tilde{l}^+}^2 = p_{\tilde{l}^+}^2 + m_{\tilde{l}^+}^2 = m_{\tilde{l}^+}^2$$

$$E_{\chi_1}^2 = p_{\chi_1}^2 + m_{\chi_1}^2$$



By similar calculation, we have next relation



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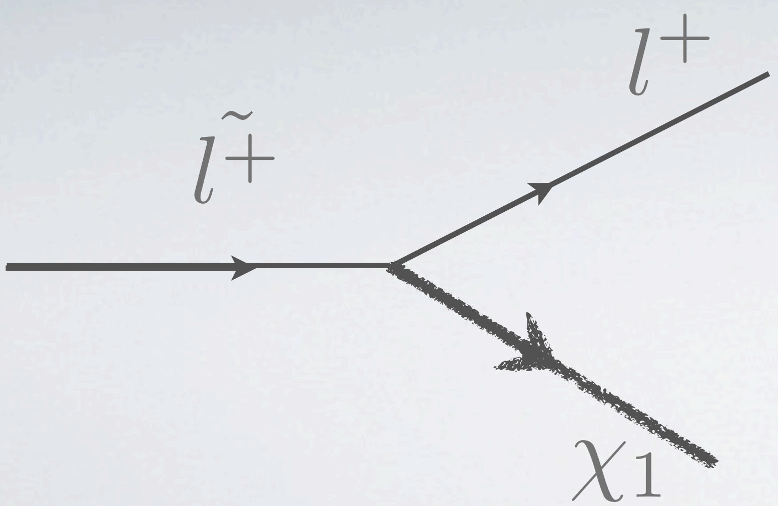

By similar calculation, we have next relation

$$E_{l^+} = \frac{m^2_{l^+} - m^2_{\chi_1}}{2m_{\tilde{l^+}}}$$

$$E_{\tilde{l}+}^2 = (E_{l+} + E_{\chi_1})^2$$ - Energy conservation

$$= E_{l+}^2 + E_{\chi_1}^2 + 2E_{l+}E_{\chi_1}$$

$$\Rightarrow m_{\tilde{l}+}^2 = E_{l+}^2 + \vec{p}_{\chi_1} \cdot \vec{p}_{\chi_1} + m_{\chi_1}^2 + 2E_{l+}E_{\chi_1}$$ - We are in rest frame of slepton.

$$\Rightarrow m_{\tilde{l}+}^2 - m_{\chi_1}^2 = p_{l+}^2 + p_{\chi_1}^2 + 2E_{l+}E_{\chi_1}$$ - lepton is massless

$$= (\vec{p}_{l+} + \vec{p}_{\chi_1})^2 + 2(E_{l+}E_{\chi_1} - p_{l+}p_{\chi_1}\cos\theta_{l_+\chi_1})$$

$$= 2(E_{l+}E_{\chi_1} + p_{l+}p_{\chi_1})$$ - back-to-back scattering

$$= 2E_{l+}(E_{\chi_1} + p_{\chi_1})$$ - lepton is massless

$$= 2E_{l+}(E_{\tilde{l}+} - E_{l+} + p_{\chi_1})$$ - Energy conservation and back-to-back

$$= 2E_{l+}E_{\tilde{l}+}$$

$$\therefore E_{l+} = \frac{m_{l+}^2 - m_{\chi_1}^2}{2m_{\tilde{l}+}}$$ - Consider the frame then we reach the answer.

$$E_{\tilde{l}+}^2 = (E_{l+} + E_{\chi_1})^2$$ - Energy conservation

$$= E_{l+}^2 + E_{\chi_1}^2 + 2E_{l+}E_{\chi_1}$$

$$\Rightarrow m_{\tilde{l}+}^2 = E_{l+}^2 + \vec{p}_{\chi_1} \cdot \vec{p}_{\chi_1} + m_{\chi_1}^2 + 2E_{l+}E_{\chi_1}$$ - We are in rest frame of slepton.

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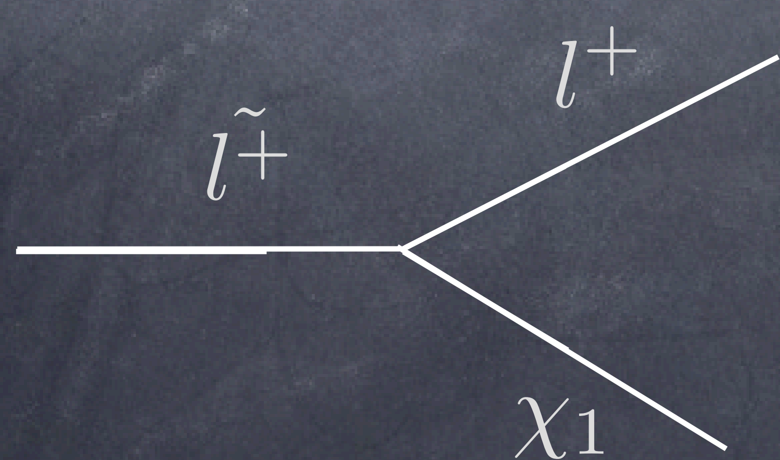

So our conclusion is,

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$$m_{l^+l^-}^2 = 2\left(\frac{m_{\tilde{l}^+}^2 - m_{\chi_1}^2}{2m_{\tilde{l}^+}}\right)\left(\frac{m_{\chi_2}^2 - m_{\tilde{l}^+}^2}{2m_{\tilde{l}^+}}\right)(1 - \cos\theta_{l^+l^-})$$

So our conclusion is,

$$m^2_{l^+l^-} = 2\left(\frac{m^2_{\tilde{l}^+} - m^2_{\chi_1}}{2m_{\tilde{l}^+}}\right)\left(\frac{m^2_{\chi_2} - m^2_{\tilde{l}^+}}{2m_{\tilde{l}^+}}\right)(1 - \cos\theta_{l^+l^-})$$

$$0 < m_{l^+l^-} < m^{\max}_{l^+l^-}$$

So our conclusion is,

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$$0 < m_{l^+l^-} < m_{l^+l^-}^{\max}$$

$$m_{l^+l^-}^{\max} = \sqrt{\frac{(m_{\tilde{l}^+}^2 - m_{\chi_1}^2)(m_{\chi_2}^2 - m_{\tilde{l}^+}^2)}{m_{\tilde{l}^+}^2}}$$

So our conclusion is,

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$$m_{l^+l^-}^{\max} = \sqrt{\frac{(m_{\tilde{l}^+}^2 - m_{\chi_1}^2)(m_{\chi_2}^2 - m_{\tilde{l}^+}^2)}{m_{\tilde{l}^+}^2}}$$

Also, problem #2 can be solved by similar method. If you choose your coordinate as a rest frame of neutralino, it is much easier to calculate.

Problem #3.

$$e^+e^- \to (\tilde{\mu}^-\tilde{\mu}^+) \to (\mu^-\chi_1)(\mu^+\chi_1)$$

$$e^+e^- \to (\tilde{\mu}^-\tilde{\mu}^+) \to (\mu^-\chi_1)(\mu^+\chi_1)$$

$$e^+e^- \to (\tilde{\mu}^-\tilde{\mu}^+) \to (\mu^-\chi_1)(\mu^+\chi_1)$$

We want to decide the mass of smuon and neutralino.

$$e^+e^- \to (\tilde{\mu}^- \tilde{\mu}^+) \to (\mu^- \chi_1)(\mu^+ \chi_1)$$

In this case of e+e- collision, we perfectly know the total energy of the system.

$$e^+e^- \to (\tilde{\mu}^-\tilde{\mu}^+) \to (\mu^-\chi_1)(\mu^+\chi_1)$$

Assume that we have an electron-positron colliding system of known center of momentum energy.

$$e^+e^- \rightarrow (\tilde{\mu}^- \tilde{\mu}^+) \rightarrow (\mu^- \chi_1)(\mu^+ \chi_1)$$

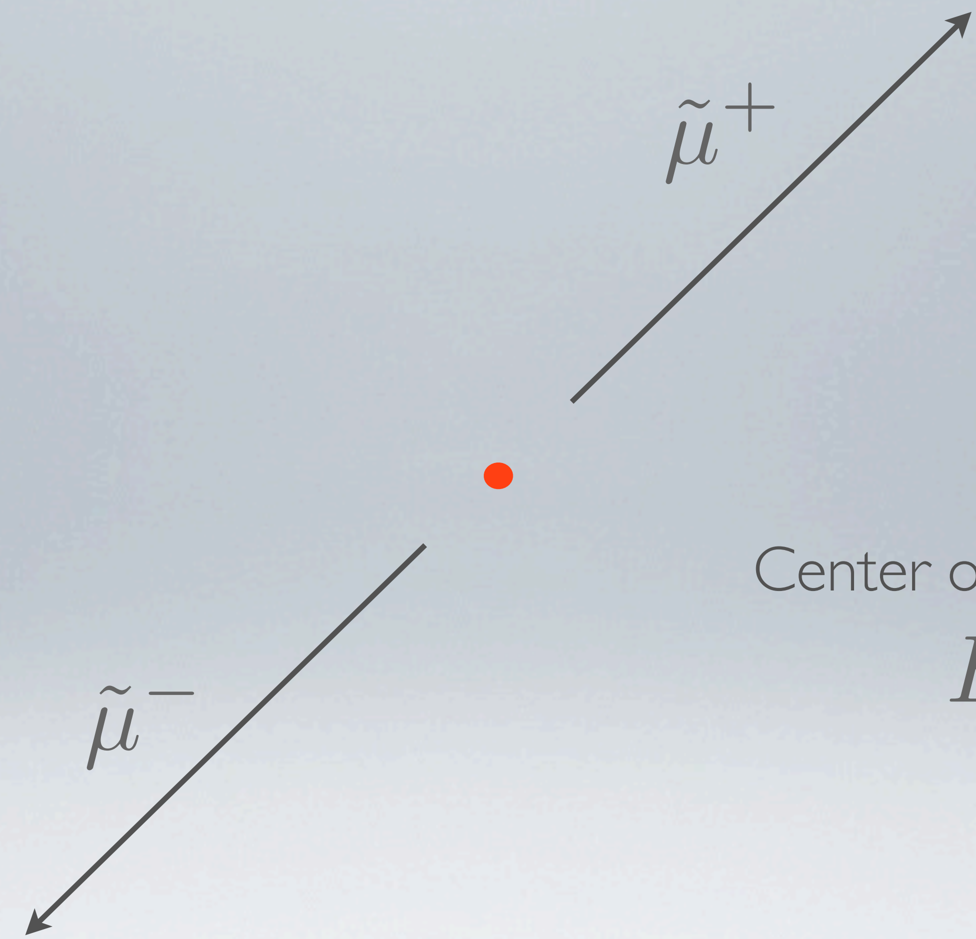
Assume that we have an electron-positron colliding system of known center of momentum energy.

$$e^+e^- \rightarrow (\tilde{\mu}^-\tilde{\mu}^+) \rightarrow (\mu^-\chi_1)(\mu^+\chi_1)$$

Assume that we have an electron-positron colliding system of known center of momentum energy.

Physicists expect that
they create a pair of supersymmetric partner of muon,
the anti-muon pair.

$$e^+e^- \to (\tilde{\mu}^-\tilde{\mu}^+) \to (\mu^-\chi_1)(\mu^+\chi_1)$$

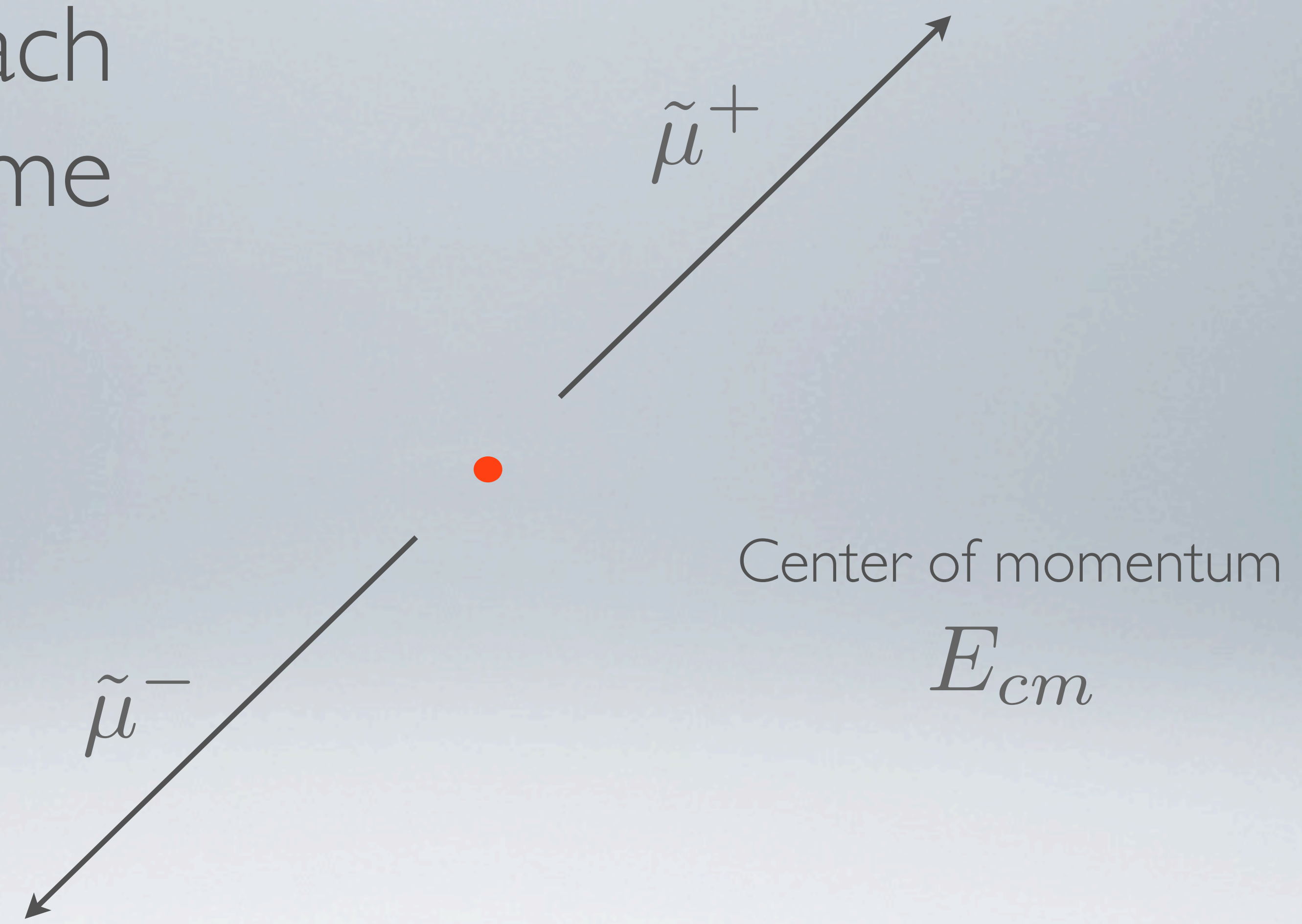


Center of momentum

E_{cm}

$$e^+e^- \to (\tilde{\mu}^-\tilde{\mu}^+) \to (\mu^-\chi_1)(\mu^+\chi_1)$$

In this point, each smuons get same energy.



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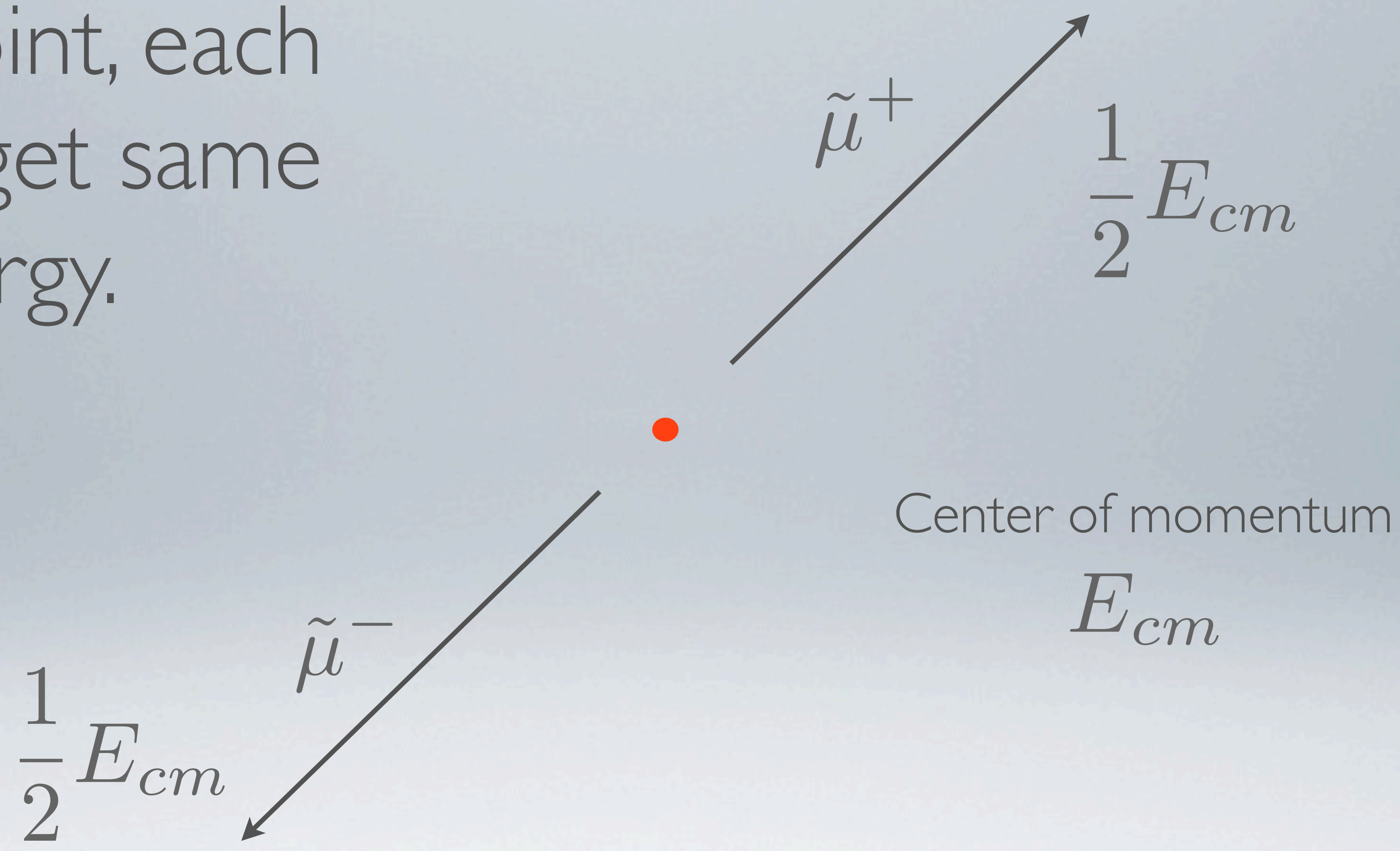

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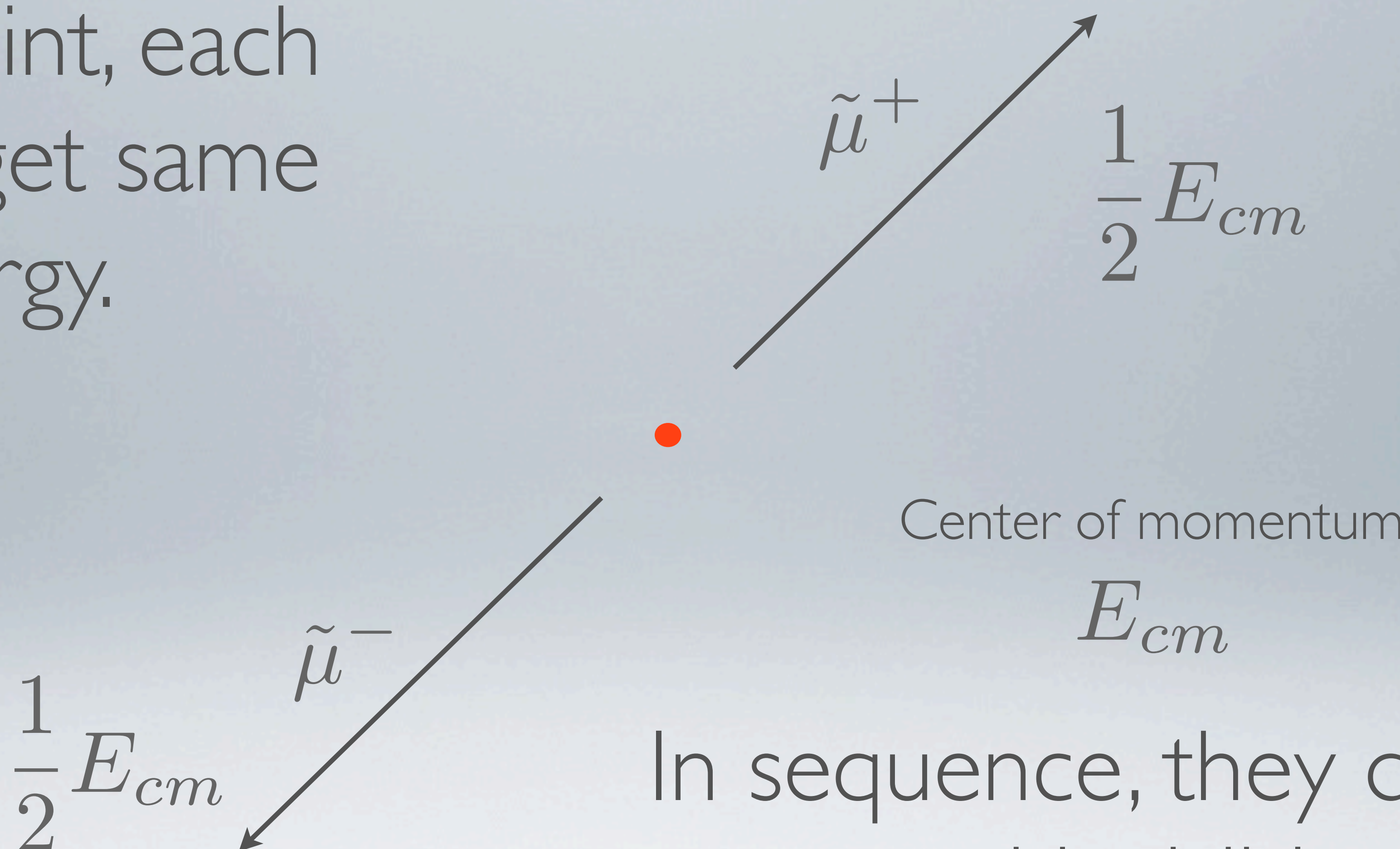

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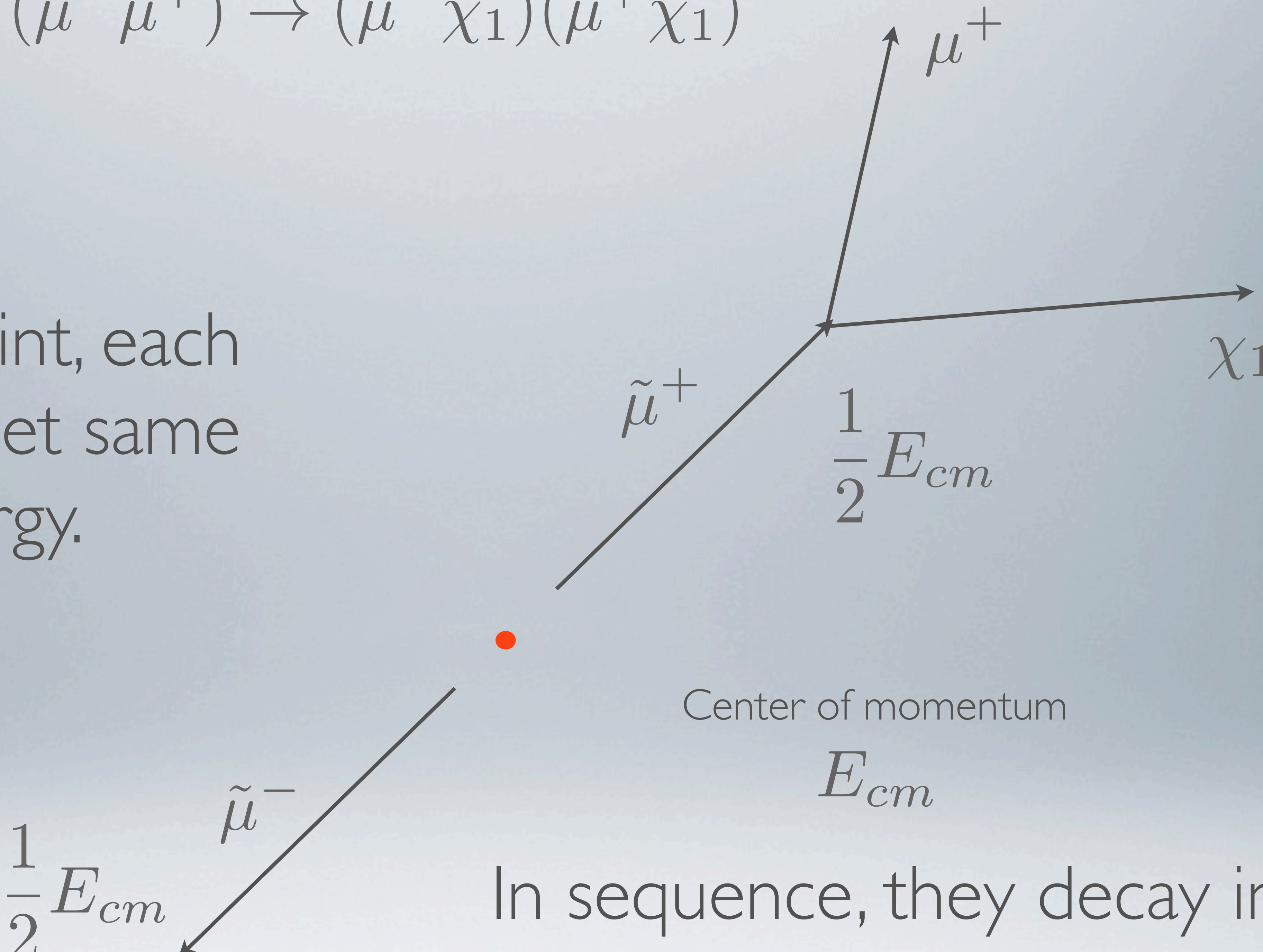

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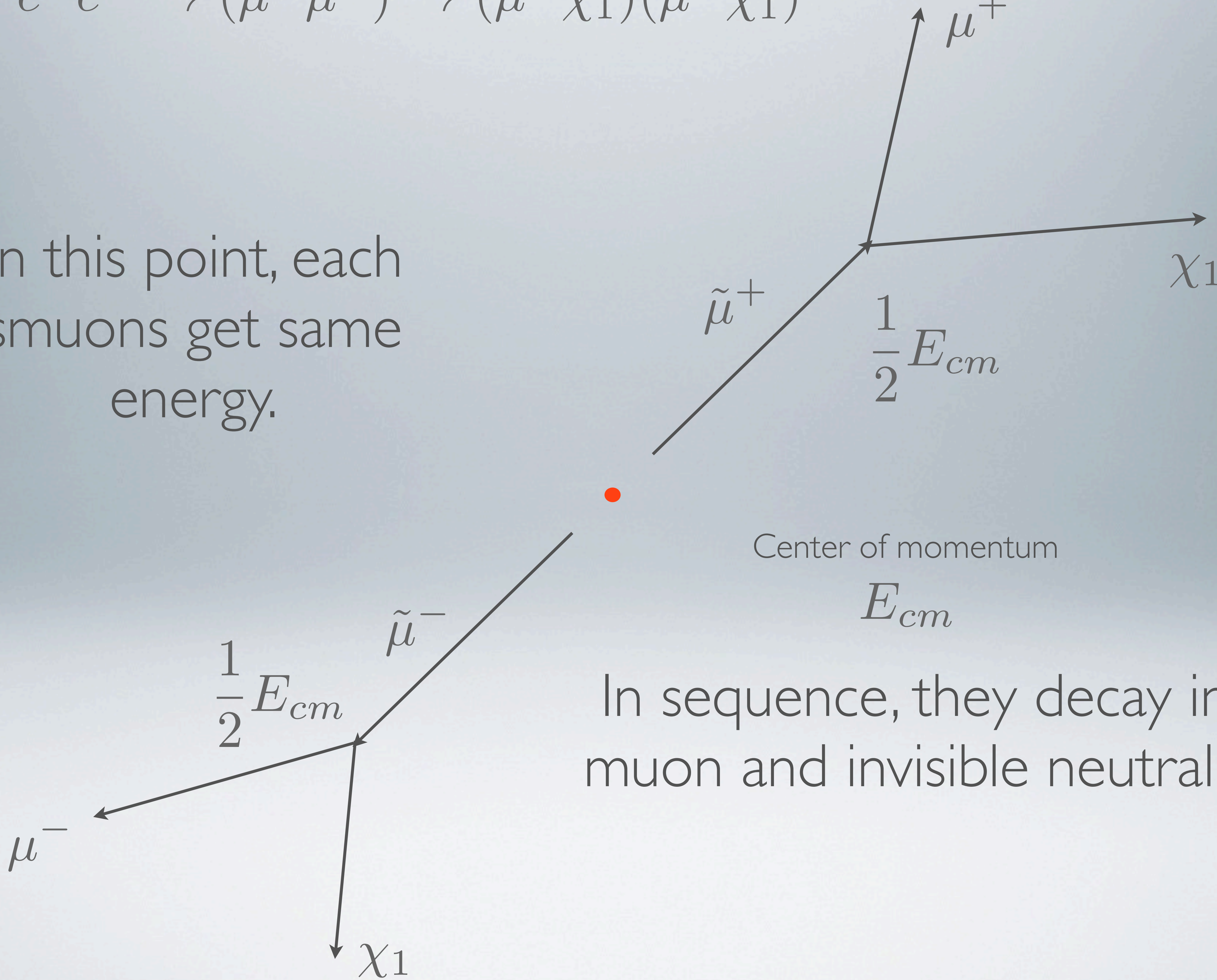

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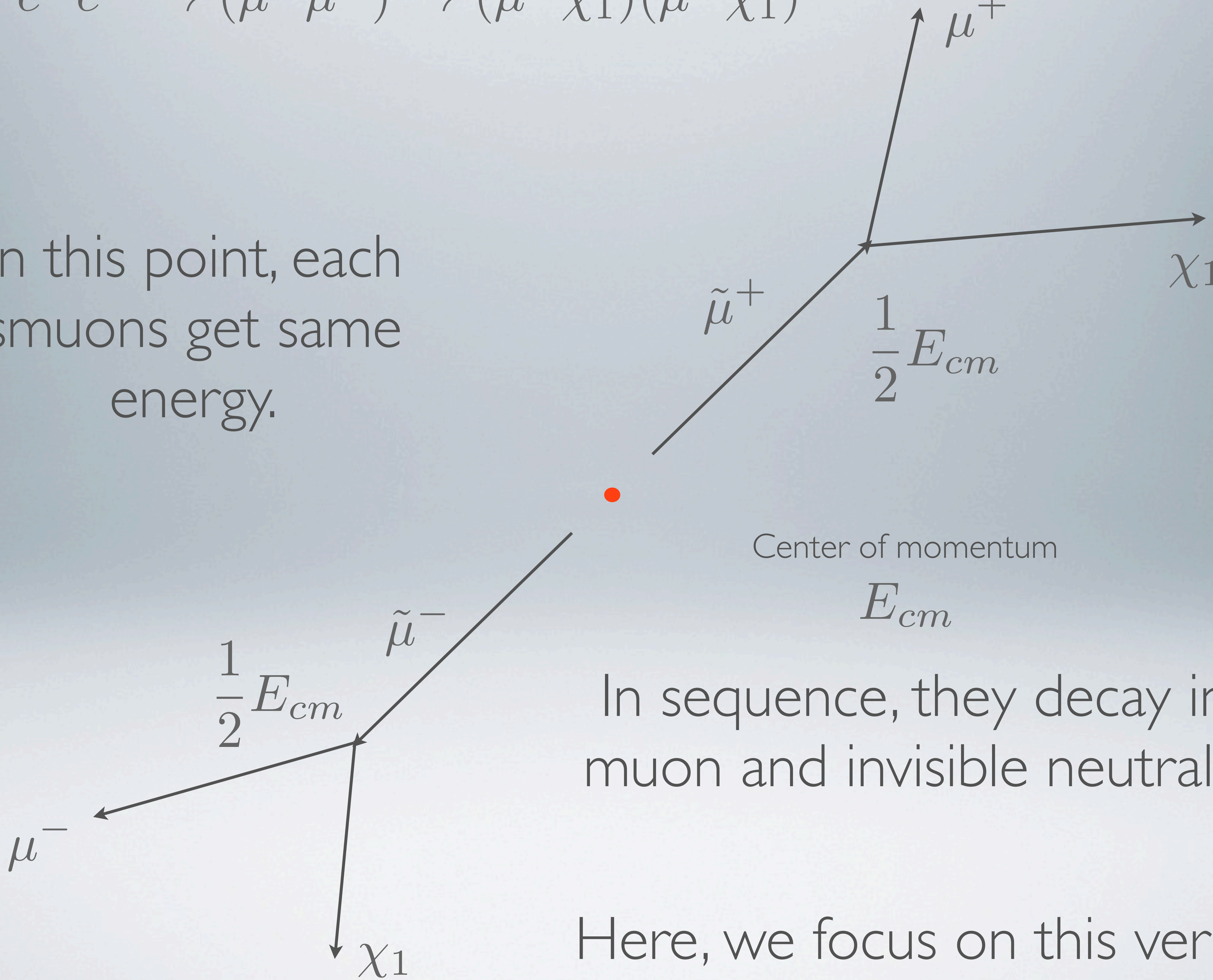

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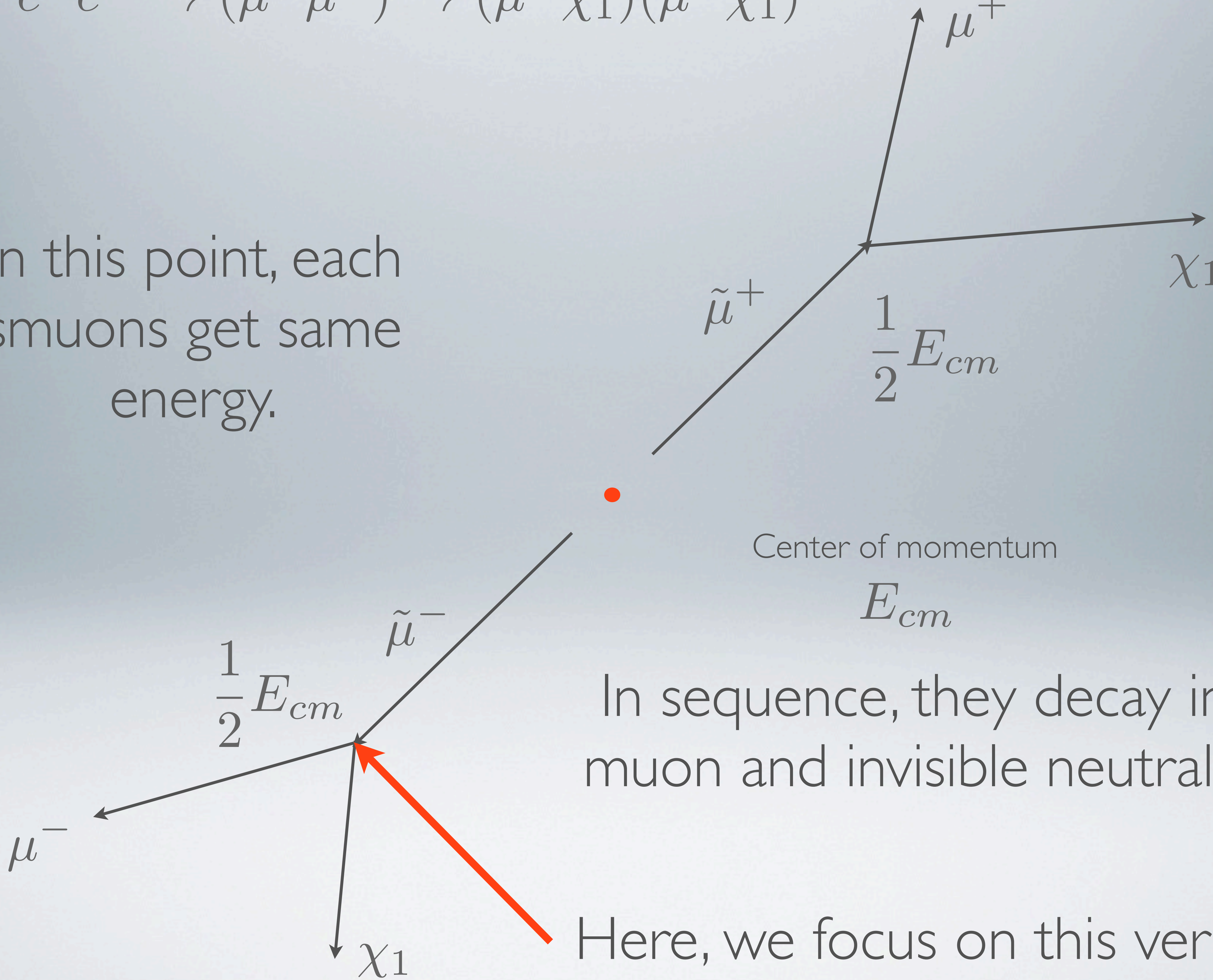

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Center of momentum

E_{cm}

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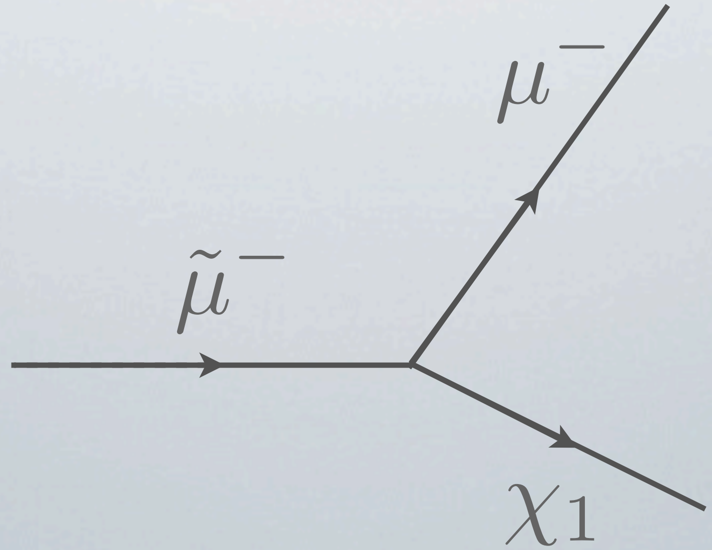


$$\tilde{\mu}^- \to \mu^- \chi_1$$

Conserved quantities (in the *rest frame of smuon*)

$$E_{\tilde{\mu}^-} = E_{\chi_1} + E_{\mu^-}$$

$$0 = \vec{p}_{\mu^-} + \vec{p}_{\chi_1}$$

Invariant forms

$$E^2_{\tilde{\mu}^-} = p^2_{\tilde{\mu}^-} + m^2_{\tilde{\mu}^-} = m^2_{\tilde{\mu}^-}$$

Let's solve it on the board.

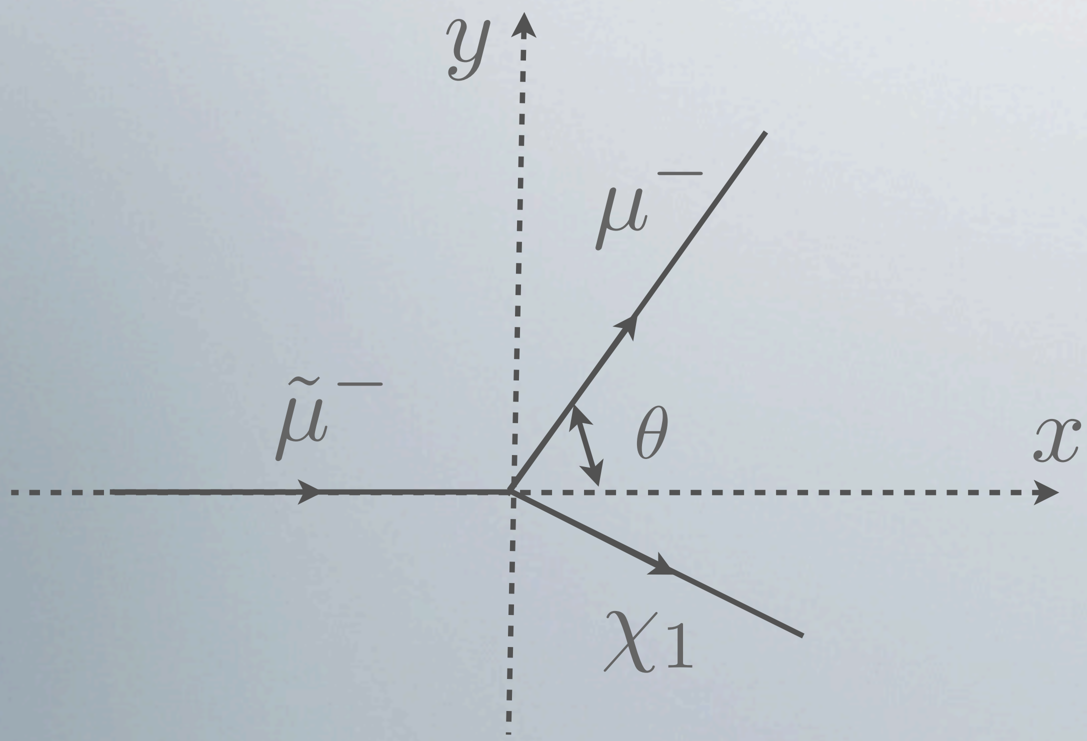
$$p_\mu = p_{\chi_1} = \sqrt{E_{\chi_1}^2 - m_{\chi_1}^2}$$ - Invariance

$$= \sqrt{E_{\chi_1}^2 + E_{\mu^-}^2 - 2E_{\tilde{\mu}^-}E_{\mu^-} - m_{\chi_1}^2}$$ - Energy conservation

$$E_\mu^2 = E_{\chi_1}^2 + E_{\mu^-}^2 - 2E_{\tilde{\mu}^-}E_{\mu^-} - m_{\chi_1}^2$$ - Let muon is massless

$$E_{\mu^-} = p_{\mu^-} = \frac{1}{2E_{\tilde{\mu}}}(E_{\tilde{\mu}}^2 - m_{\chi_1}^2)$$

So, after we get the momentum of muon
in rest smuon frame, we have to boost back it
to our original center of momentum coordinate system
of electron-positron.



Operate <u>inverse</u>
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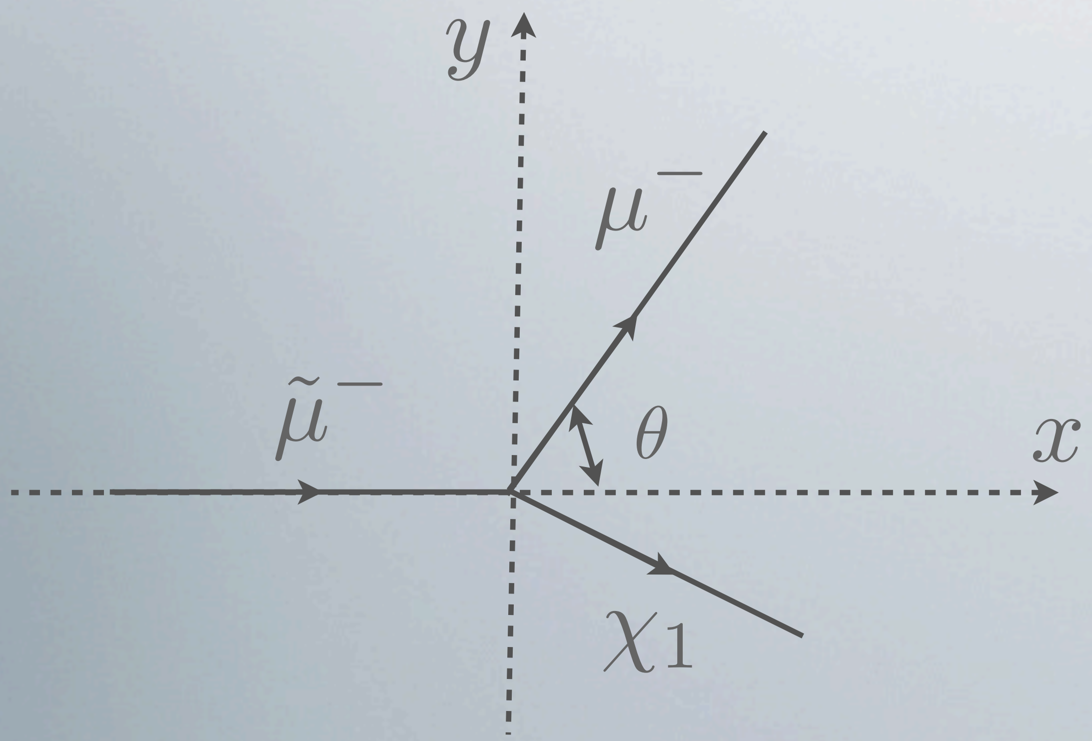

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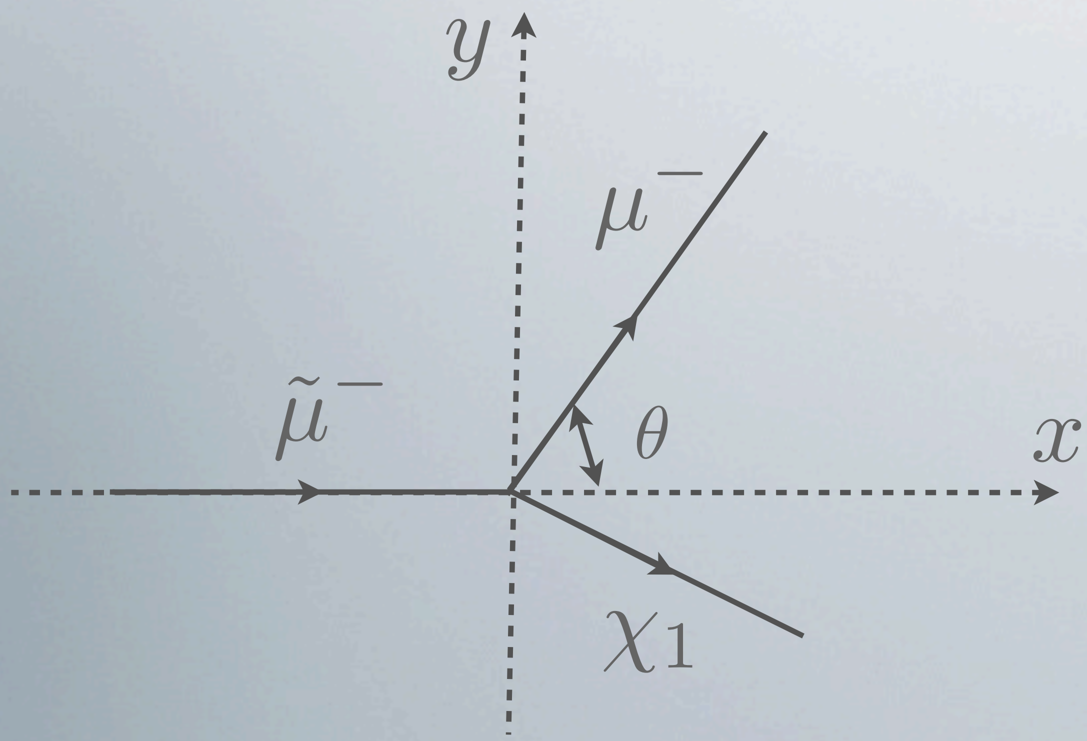
$$\begin{pmatrix} p_0 \\ p_x \\ p_y \\ p_z \end{pmatrix} = \begin{pmatrix} \gamma & \beta\gamma & 0 & 0 \\ \beta\gamma & \gamma & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} p'_0 \\ p'_x \\ p'_y \\ p'_z \end{pmatrix}_{\tilde{\mu}}$$



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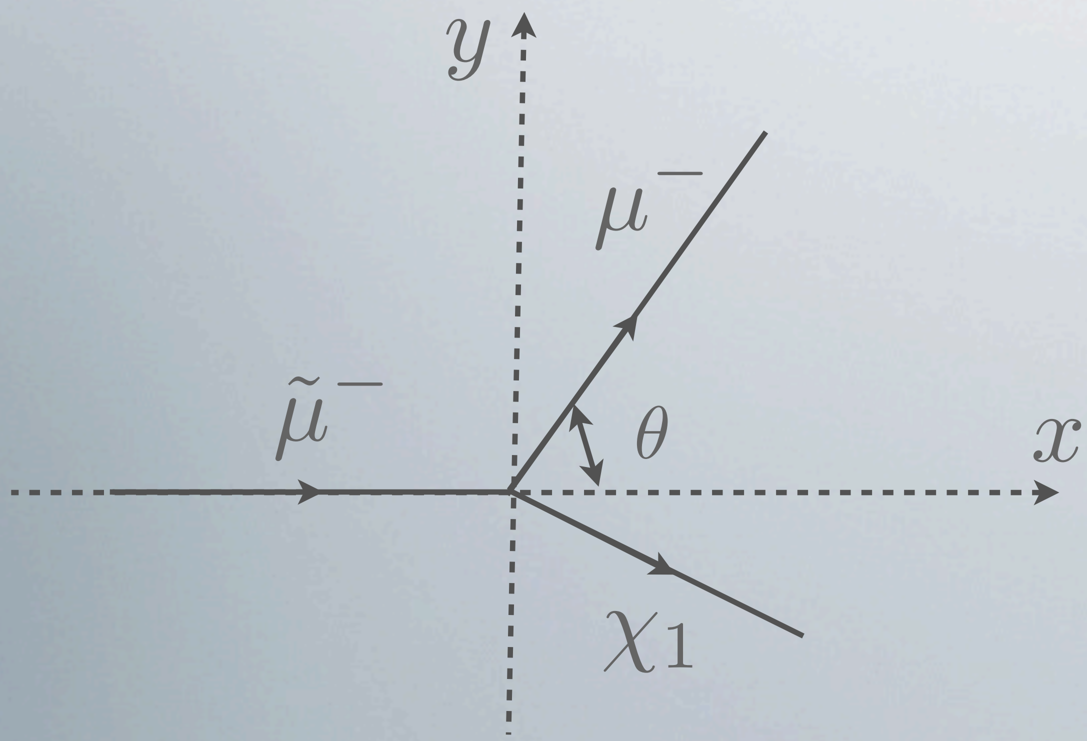

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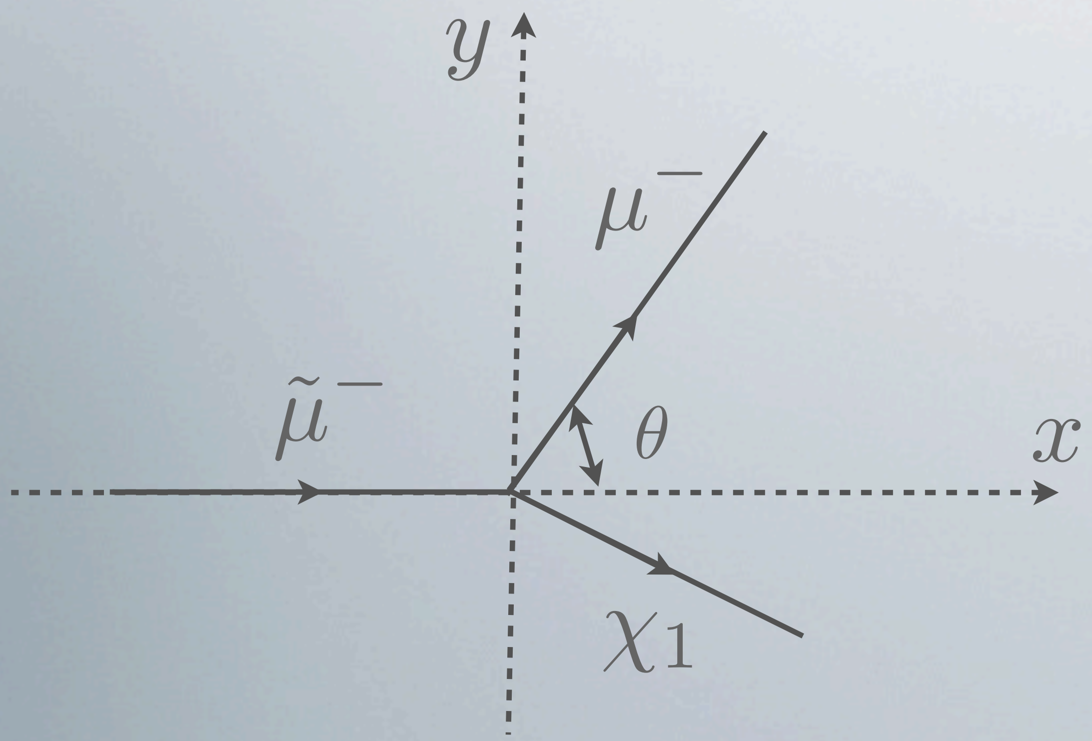

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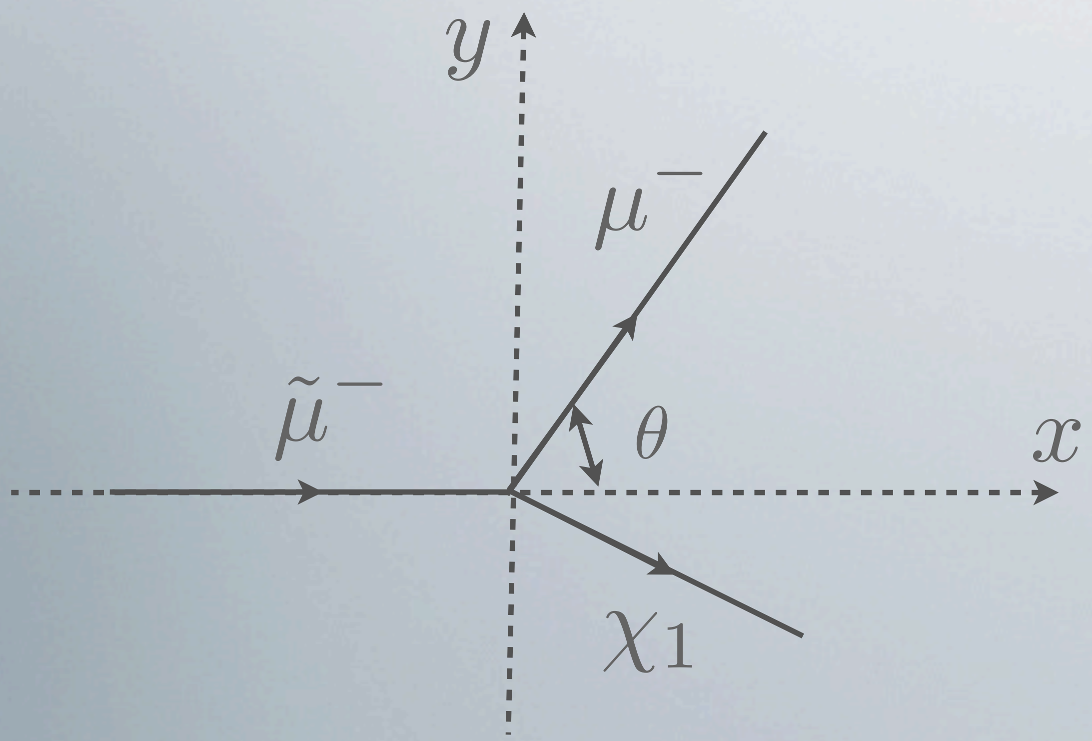

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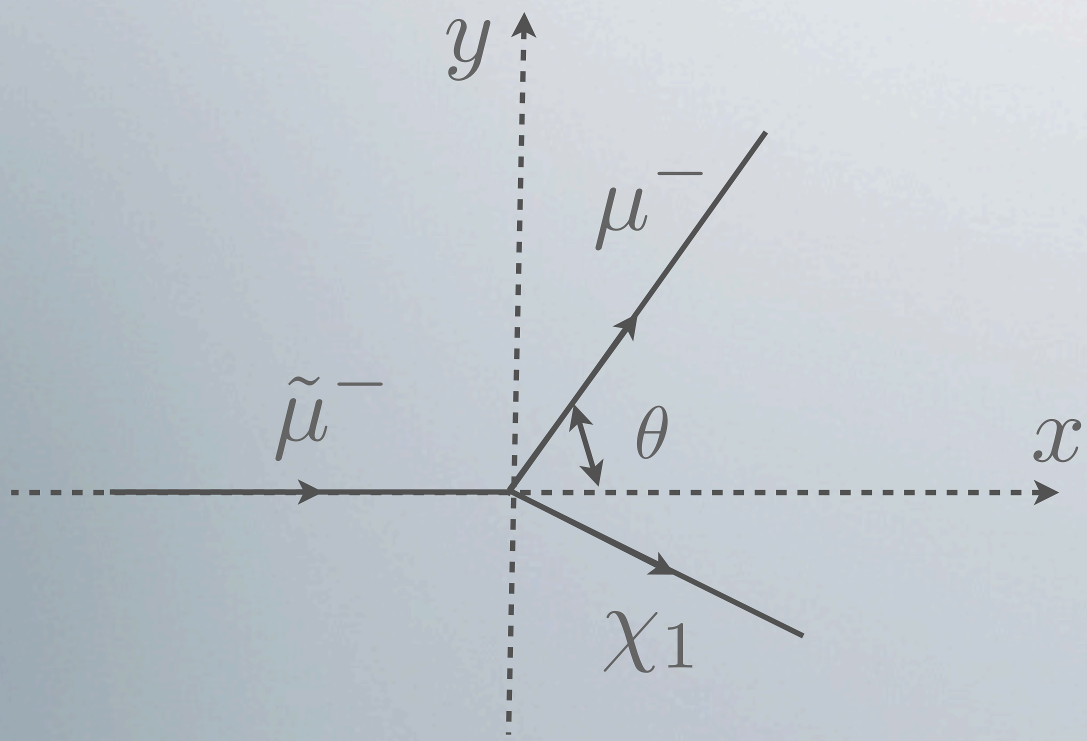

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Known quantities

Can be measured by exp.

- Final Problem -

In $p\bar{p}$ collision,

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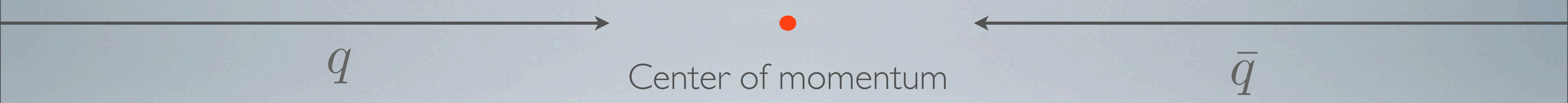

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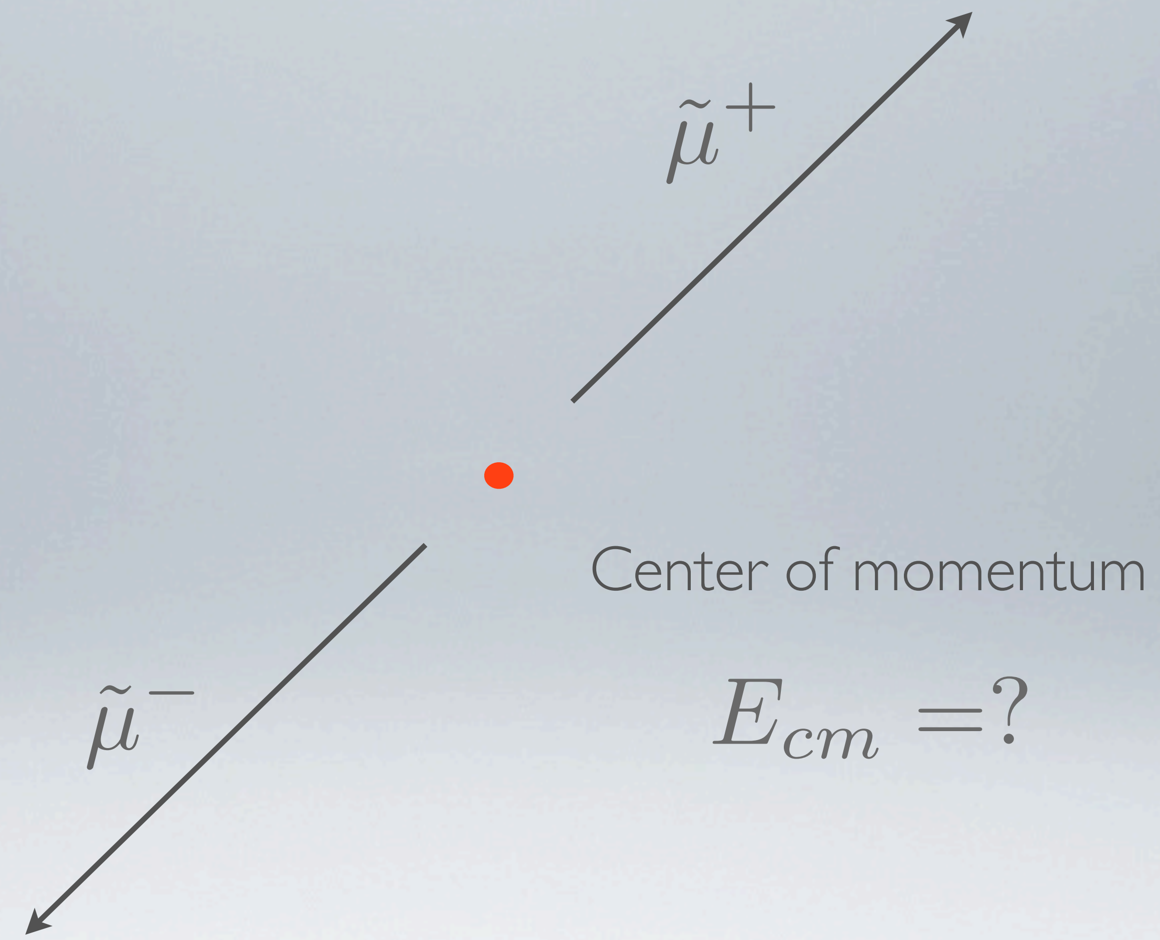
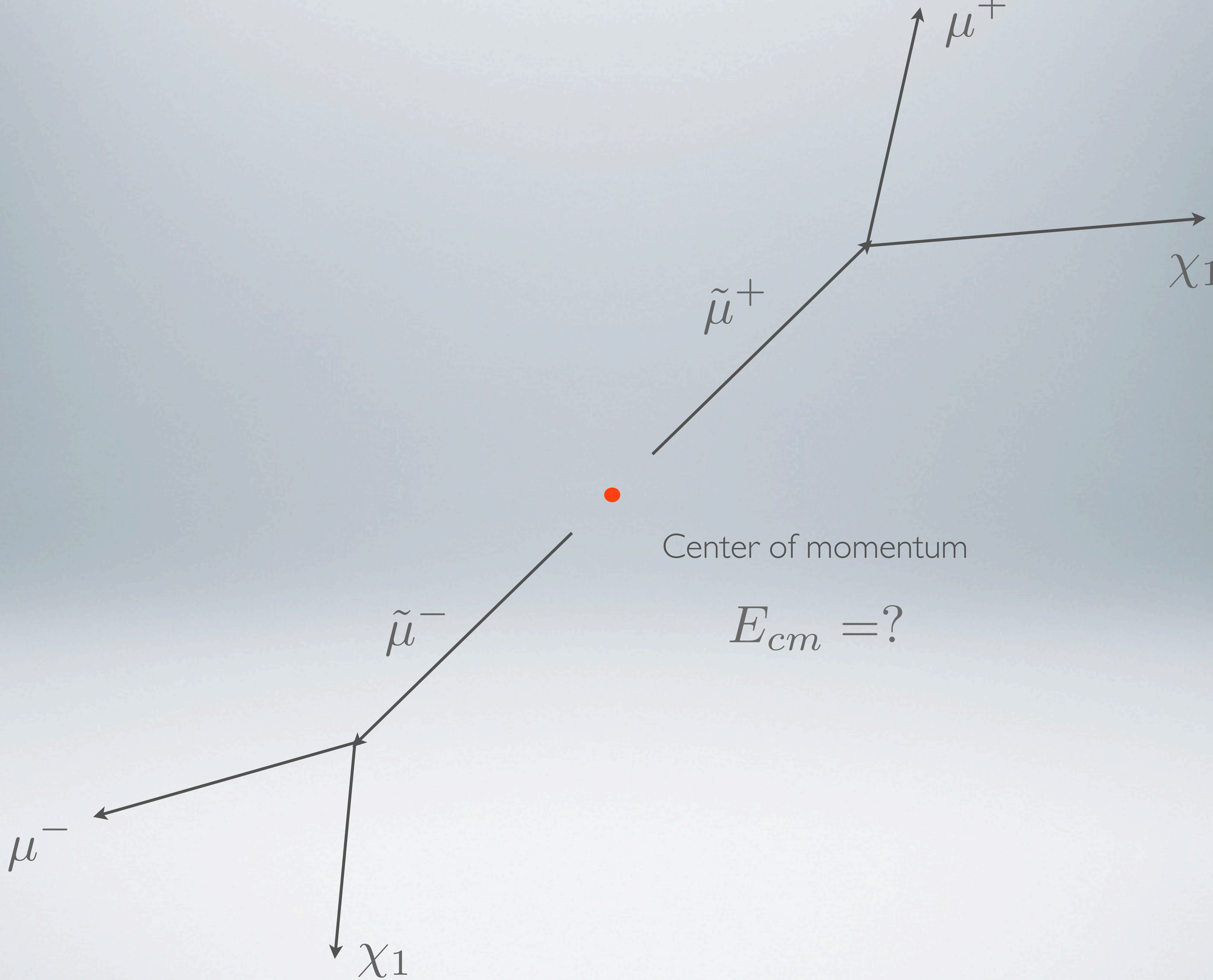
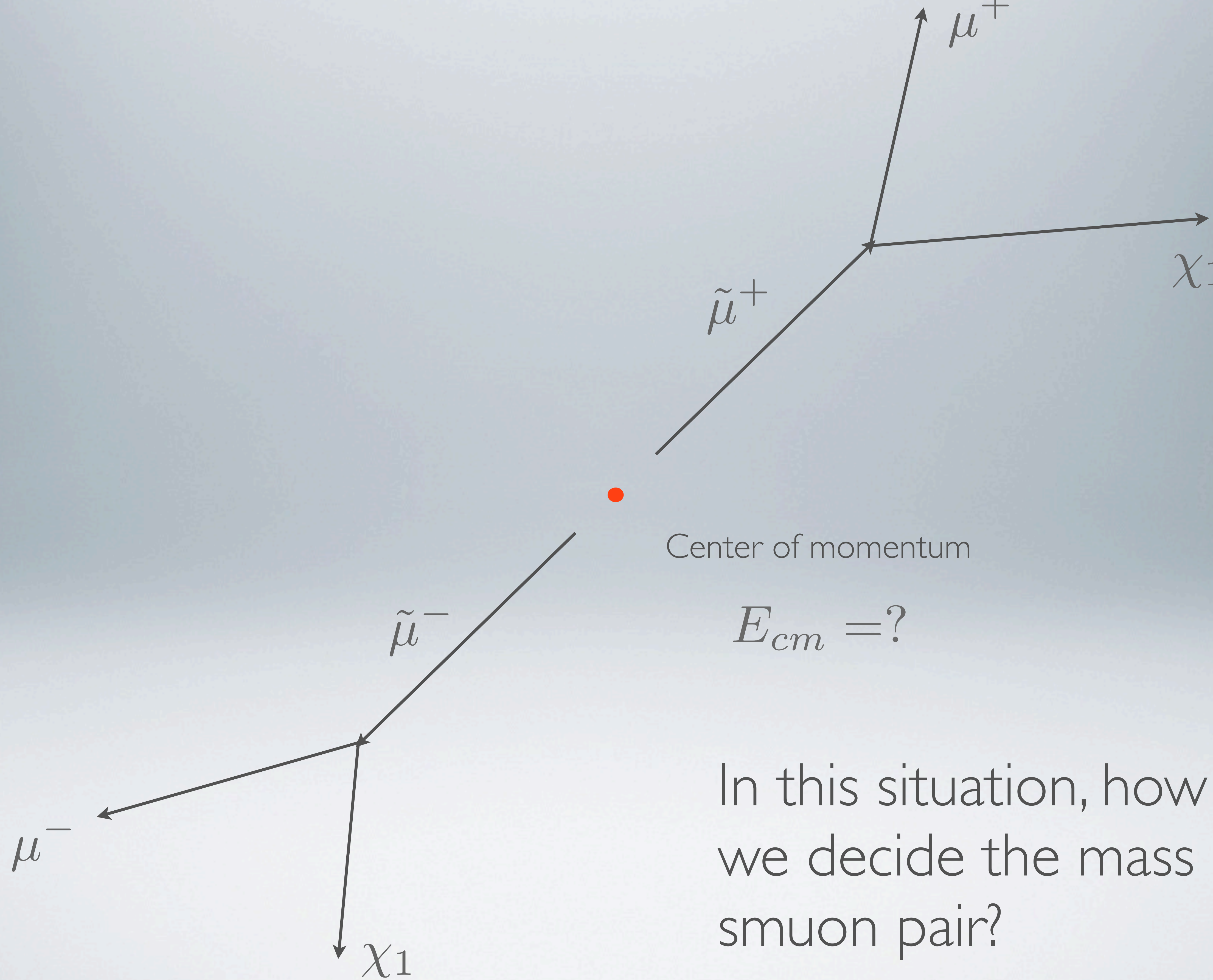



μ^+
χ_1
$\tilde{\mu}^+$
Center of momentum
$E_{cm} =?$
$\tilde{\mu}^-$
μ^-
χ_1



In this situation, how can we decide the mass of smuon pair?

So, refresh our brain now.

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Here, B $(= E_{\chi_1})$ is missing information.(^^)

We suggest a statistical method.
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Remember that, superpartners were introduced because of anomalies of Higgs mechanism.

If SUSY is right, because SUSY introduced for the settlement of Higgs mechanism problem in SM, every statistical behaviors or effects of sparticles must explain well the exp. results.

So, to make the problem easier, assume that
there are only three kinds of particles or sparticles (A,B,X)
in collision.

i.e. suppose another decays or productions are
can be measured
or
can be calculated.

$$E_{cm} = \left[\sum E_{\mu^\pm} + \sum E_{\chi_1} \right] + E_{all}$$

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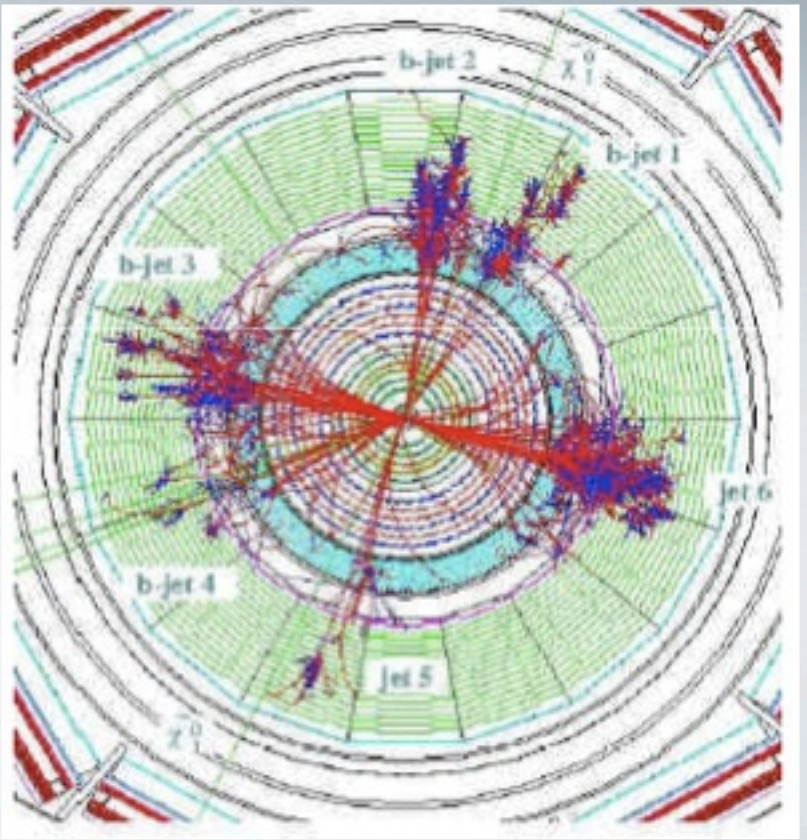

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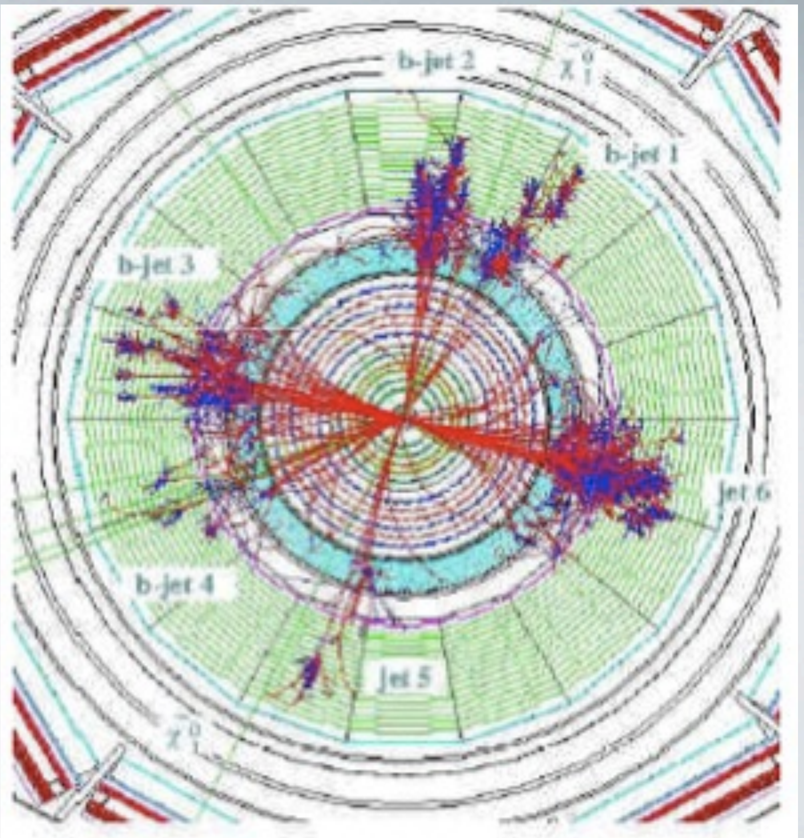
$$E_{\mu^-} + < E_{\chi_1} > \approx E_{\tilde{\mu}^-}$$



Thank you for your attention!!