R-axion:

A New LHC physics signature involving muon pairs

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Arxiv:0810.5773
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Introduction

One of the main goal of the upcoming experiments at the LHC is the discovery of SUSY particles.

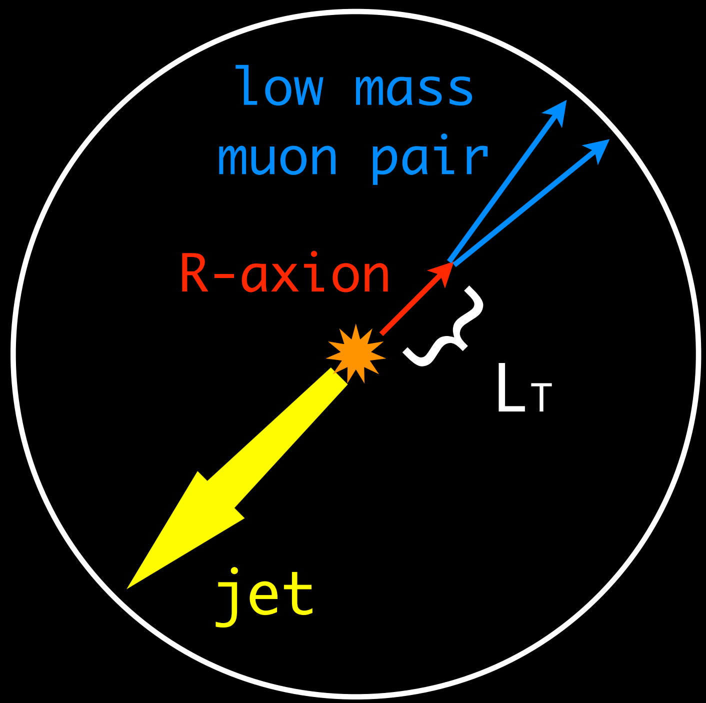
Once the SUSY is confirmed what's next?

The next question is how the SUSY is realized and how it's broken.

In most cases, it's difficult to see the structure of the SUSY breaking sector directly and we look for clues of the structure in the details of the mass spectrum of SUSY particles...

In a class of models which involves "R-axion", we can get a direct glimpse of the SUSY breaking sector!

Introduction



R-axion: m_a=O(100)MeV

$c\tau$=O(1)ps

Mainly decays into a muon pair

Production cross section:

σ=O(10)fb (pT>100GeV) at the LHC

Can we detect the R-axion by searching for a displaced vertex at the LHC?

Outline

- Theoretical Background
  - R-symmetry and R-axion
  - R-axion properties
  - Constraints
- R-axion at LHC
  - R-axion production at LHC
  - R-axion reconstruction
  - (Very Rough) Background Estimation

R-symmetry and R-axion

- What is R-symmetry?

The R-symmetry is a U(1) symmetry under which fields in the same supermultiplet rotate differently.

ex) If we assign R-charge Q_q to a quark squark multiplet

$$\Phi_q = (\tilde{q}, q, F_q)$$

$$\underset{Q_q}{\tilde{q}} \qquad \underset{Q_q - 1}{q} \qquad \underset{Q_q - 2}{F_q}$$

The R-charge of the gauginos is uniquely fixed to 1.

$$W_\alpha = (\lambda_\alpha, F_{\mu\nu}, D)$$

$$\underset{1}{\lambda_\alpha} \qquad \underset{0}{F_{\mu\nu}} \qquad \underset{0}{D}$$

R-symmetry and R-axion

- How is the R-symmetry important?

We need to break SUSY to realize the Standard Model

↓

SUSY breaking models require R-symmetry
(or non-generic superpotential) Nelson & Seiberg '93

↓

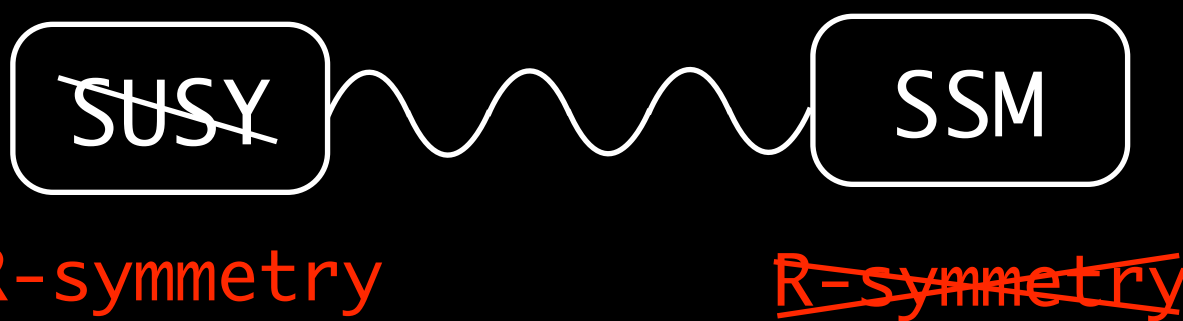
The model construction beyond the SSM often involves the R-symmetry!

R-symmetry and R-axion

- R-symmetry must be broken!

$$\mathcal{L} = \frac{1}{2} m_{1/2} \underbrace{\lambda\,\lambda}_{\text{R-charge:2}}$$

Gaugino mass terms require an R-symmetry breaking!



$\boxed{\text{R-symmetry is broken at some point}}$

R-symmetry and R-axion

- How do we break? (Model dependent)

★ Gravity Mediation → Explicit R-breaking

R-symmetry leaves little trace to the collider experiments...

★ Gauge Mediation → Explicit R-breaking / Spontaneous R-breaking

R-symmetric Messenger Sector!

The model predicts a light NG-boson: R-axion

Can we detect the R-axion at the LHC?

Properties of R-axion

- How low can we take the R-symmetry breaking scale?

★ Case I: Minimal Gauge Mediation

$$W = kS\psi\bar{\psi} \qquad \langle S \rangle = M + F\theta^2$$

coupling constant

Messengers: Charged Under the SM gauge group

R-charges: S(2), ψ(0), $\bar{\psi}$(0)

⟶ M is an order parameter of the R-symmetry.

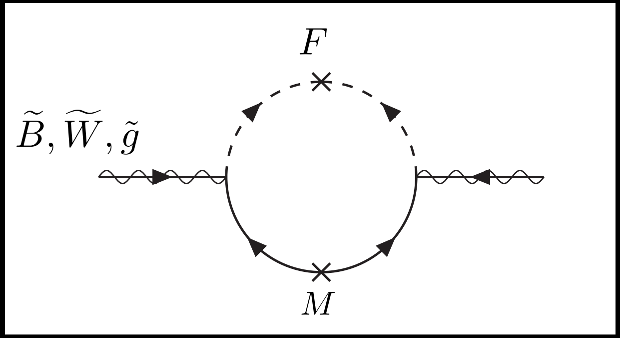
[Other possible U(1) choices have been broken by F.]

Properties of R-axion

- How low can we take the R-symmetry breaking scale?

★ Case I: Minimal Gauge Mediation

$$m_{\rm gaugino} \simeq \frac{\alpha}{4\pi}\frac{F}{M} < \frac{\alpha}{4\pi} kM$$



[Non-tachyonic Messengers: $F < kM^2$]

Properties of R-axion

- How low can we take the R-symmetry breaking scale?

★ Case II: Additional Messenger Model

Izawa, Nomura, Tobe & Yanagida '97

$$W = kS\psi\bar{\psi} + m\psi\bar{\psi}' + m\psi'\bar{\psi}$$

$$m_{\mathrm{gaugino}} \sim \frac{\alpha}{4\pi}\frac{kM}{m}\left|\frac{kF}{m^2}\right|^2\frac{kF}{m} < \frac{\alpha}{4\pi}kM$$

[Non-tachyonic Messengers: $kF/m^2 < 1$]

Properties of R-axion

- How low can we take the R-symmetry breaking scale?

In a large class of the models with gauge mediation, R-breaking scale is bounded from below,

$$m_{\text{gaugino}} \lesssim \frac{\alpha}{4\pi} f_R \longleftarrow \text{R-breaking scale}$$

$$\Big\downarrow \quad m_{\text{gaugino}} > O(100)\,\text{GeV}$$

$$f_R \gtrsim 10^4\,\text{GeV}$$

Properties of R-axion

Mass of R-axion

R-symmetry is slightly broken by

- Anomaly to the SSM gauge symmetry
- In supergravity, the R-symmetry is broken by a constant in the superpotential which is necessary to set the cosmological constant to zero

[The Minimal R-breaking Scenario]

EX.)

supergravity

$$W = \Lambda_{\rm susy}^2 S + \underbrace{m_{3/2} M_P^2}_{\text{R-breaking}} \qquad \boxed{V = m_{3/2}\Lambda_{\rm susy}^2 S + c.c.}$$

R-axion: $S \to \frac{f_R}{\sqrt{2}} e^{ia/f_R}$

Properties of R-axion

- Mass of R-axion

R-symmetry is slightly broken by

- Anomaly to the SSM gauge symmetry
- In supergravity, the R-symmetry is broken by a constant in the superpotential which is necessary to set the cosmological constant to zero

EX.)

$$m_a^2 = \frac{2\sqrt{2}\, m_{3/2}\Lambda_{\rm susy}^2}{f_R} = \frac{2\sqrt{6}\, m_{3/2}^2 M_P}{f_R}$$

$$m_{3/2} = \frac{\Lambda_{\rm susy}^2}{\sqrt{3}\, M_P}$$

Properties of R-axion

- Mass of R-axion

R-symmetry is slightly broken by

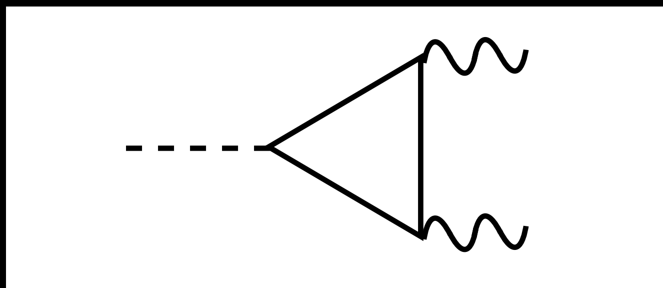
- ★ Anomaly to the SSM gauge symmetry
- ★ In supergravity, the R-symmetry is broken by a constant in the superpotential which is necessary to set the cosmological constant to zero

EX.)

$$m_a \simeq 300\,\mathrm{MeV} \times \left(\frac{m_{3/2}}{10\,\mathrm{eV}}\right)\left(\frac{f_R}{10^4\,\mathrm{GeV}}\right)^{-1/2}$$

Properties of R-axion

- R-axion interaction (at messenger scale)

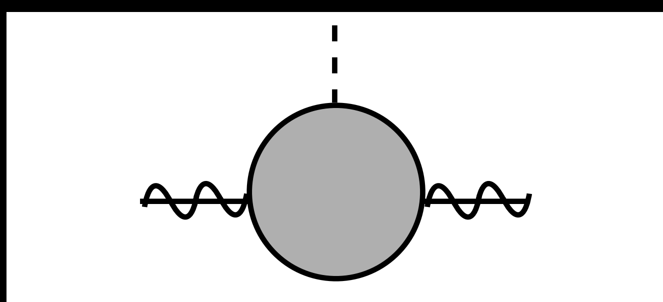


messenger loops

anomaly coupling

$$C_H \frac{g^2}{32\pi^2}\frac{a}{f_R}F\tilde{F}$$

(C_H=0,-1,...,-5)



Yukawa coupling

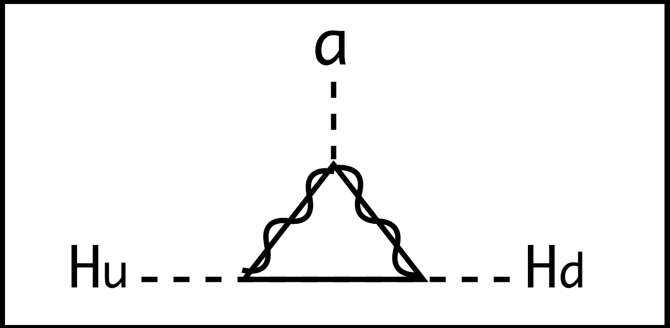
$$\frac{1}{2}m_{1/2}\,e^{-ia/f_R}\,\lambda\,\lambda$$

$$\longrightarrow \frac{1}{2}\frac{m_{1/2}}{f_R}\,a\,\lambda\,\lambda$$

These interactions are by-products of the Gauge Mediation!

Properties of R-axion

- R-axion interaction (at lower scale)



Higgsino-Gaugino loop

→

R-axion-Higgs coupling

$$B\mu\, e^{-ia/f_R}\, H_u H_d$$

(R-charge of HuHd =2)

R-axion mixes with CP-odd Higgs bosons!

$$H_u \sim \frac{v}{f_R}\cos^2\beta\,\sin\beta \times a, \quad H_d \sim \frac{v}{f_R}\sin^2\beta\,\cos\beta \times a, \quad (\tan\beta = v_u/v_d)$$

(v=246GeV)

Yukawa couplings to the SM fermions

$$\lambda_u = i\,m_u/f_R\,\cos^2\beta, \quad \lambda_{d,\ell} = i\,m_{d,\ell}/f_R\,\sin^2\beta$$

Properties of R-axion

Decay of R-axion

For $2m_\mu \lesssim m_a \lesssim 1\text{GeV}$

R-axion mainly decays into a muon pair via the Yukawa coupling
[$a \to 2\pi$ forbidden, $a \to 3\pi$ phase space suppression]

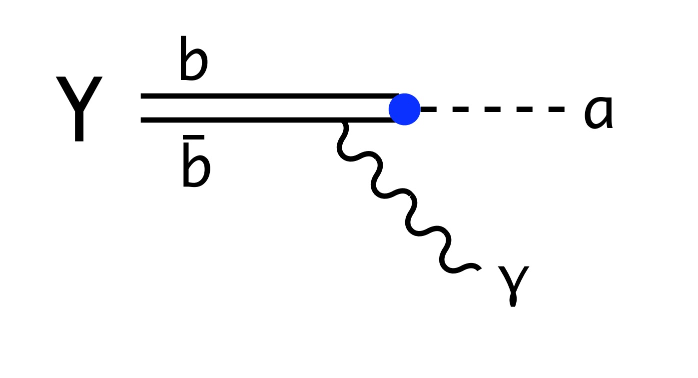
$$\Gamma_{\mu\mu} \simeq 1.3 \times 10^{-12}\,\text{GeV} \times \sin^4\beta \left(\frac{m_a}{300\,\text{MeV}}\right)\left(\frac{10^4\,\text{GeV}}{f_R}\right)^2 \left(1 - \frac{4m_\mu^2}{m_a^2}\right)^{1/2}$$

$$c\tau_{\mu\mu} \simeq \underline{150\,\mu\text{m}} \times \frac{1}{\sin^4\beta}\left(\frac{300\,\text{MeV}}{m_a}\right)\left(\frac{f_R}{10^4\,\text{GeV}}\right)^2 \left(1 - \frac{4m_\mu^2}{m_a^2}\right)^{-1/2}$$

R-axion leaves a displaced vertex inside the collider!

Constraints on fR

- Rare decay of Υ(1S) and J/ψ



$$\frac{Br(\Upsilon \to a+\gamma)}{Br(\Upsilon \to \mu^+\mu^-)} = \frac{\lambda_b^2}{2\pi\alpha}$$

$$\lambda_b = \frac{i m_b}{f_R} \sin^2\beta$$

Wilczek '77

$Br(\Upsilon \to a\gamma) < 10^{-(5-6)}$ CLEO '08 $\longrightarrow$ $f_R > 10^3$ GeV

- Astrophysical constraints

R-axion is heavier than the temperatures of most astrophysical events.

$\longrightarrow$ No constraints from astrophysics!

Constraints on fR

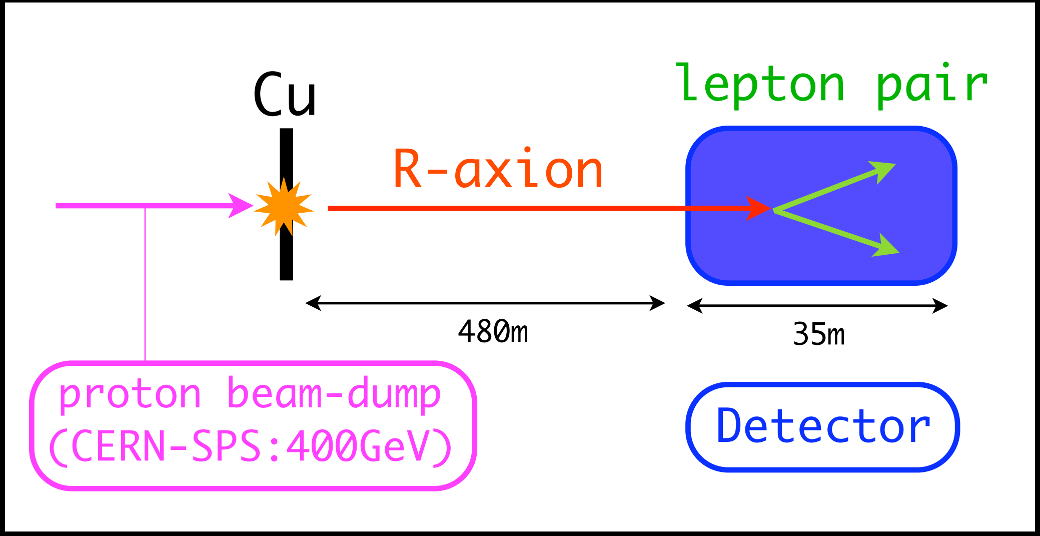
★ Beam-Dump experiments
[cτ >> O(1) m]

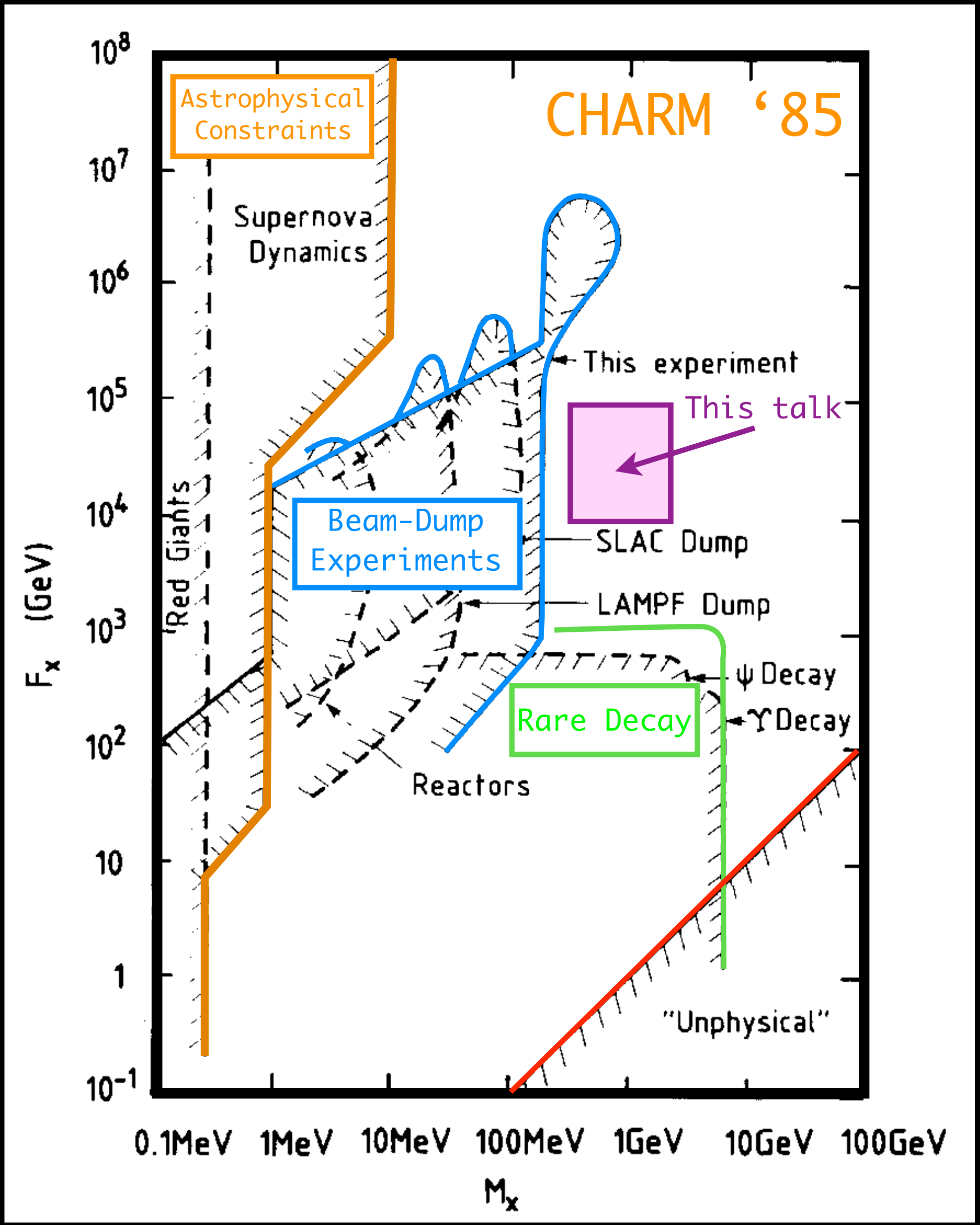
For ma > 2 mμ:

R-axion has a long lifetime for relatively large fR.

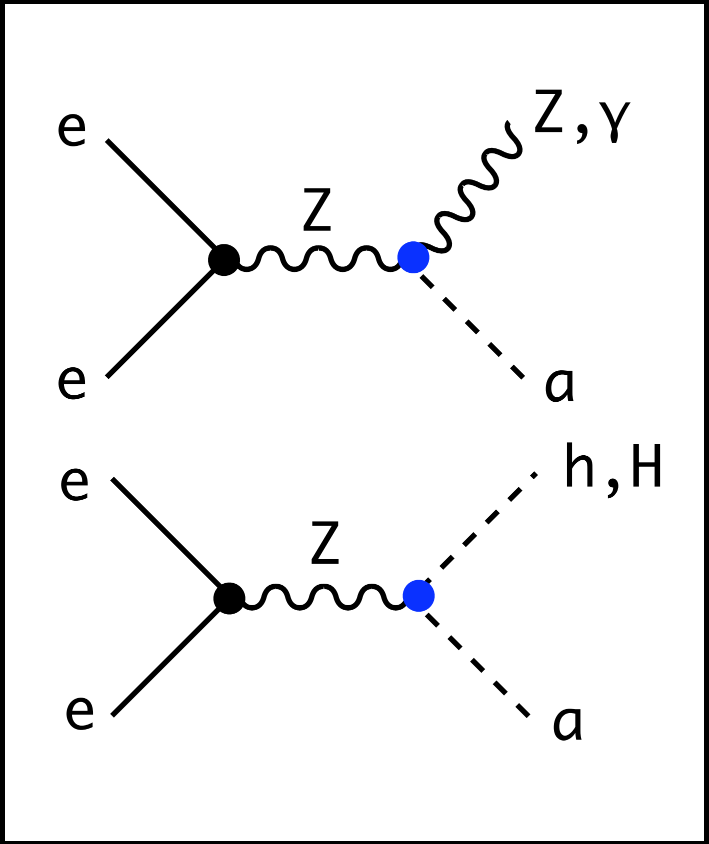
For ma < 2 mμ:

R-axion mainly decays into an electron pair.[cτ >> O(1)m]





R-axion at LEP



$$\frac{g_2^4 C_{L,2} + g_Y^4 C_{L,Y}}{g_2^2 + g_Y^2} \frac{a}{32\pi^2 f_R} F_Z \tilde{F_Z}$$

$$\frac{g_2^2 C_{L,2} + g_Y^2 C_{L,Y}}{g_2^2 + g_Y^2} \frac{\sin 2\theta_W \, a}{32\pi^2 f_R} F_Z \tilde{F_A}$$

$$g_{\mathrm{MSSM}}^{(A_0)} \times \frac{v}{f_R} \sin\beta \cos\beta$$

At LEP, for fR~10^4GeV:
Cross sections for those processes are well below 1fb

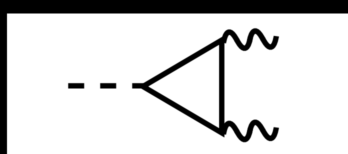
No R-axion at the LEP!

R-axion at LHC

R-axion production

The dominant processes with a large transverse momentum are: $gg \to ga$, $gq \to qa$, and $qq \to ga$.

Below gluino and top mass scale, those processes are well described by using effective anomaly coupling



gluino loops

top loops

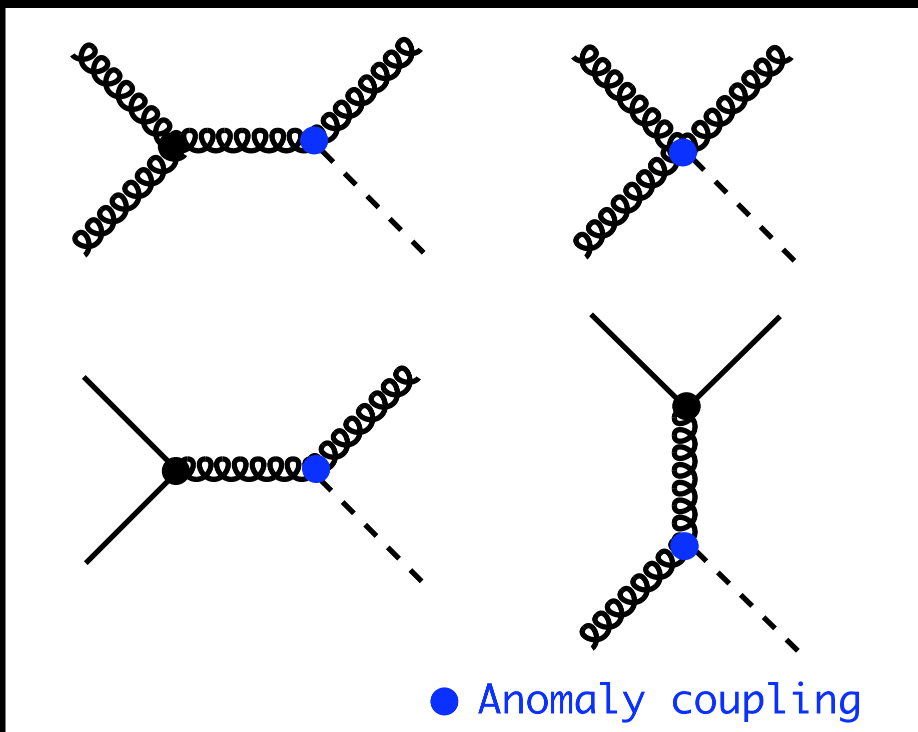
effective anomaly coupling

$$(C_H + 3 - \cos^2\beta)\,\frac{g^2}{32\pi^2}\frac{a}{f_R}F\tilde{F}$$

$(C_H = 0, -1, \ldots, -5)$

R-axion at LHC

R-axion production



$$|\mathcal{M}(gg \to ga)|^2 = \frac{3k}{32}\left(\frac{s^4+t^4+u^4}{s\,t\,u}\right)$$

$$|\mathcal{M}(q\bar{q} \to ga)|^2 = \frac{k}{9}\left(\frac{t^2+u^2}{s}\right)$$

$$|\mathcal{M}(gq \to qa)|^2 = -\frac{k}{24}\left(\frac{s^2+u^2}{t}\right)$$

$$k = \frac{C_L^2\, g_s^6}{64\pi^4\, f_R^2}$$

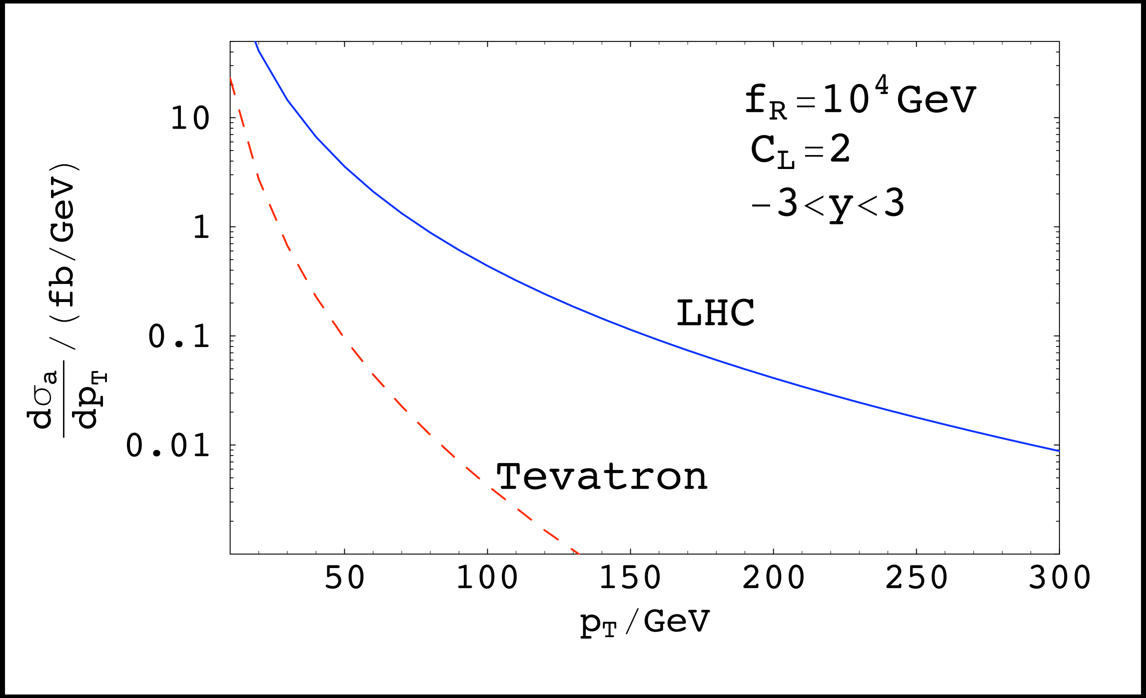
$C_L=(C_H+3-\cos^2\beta)$

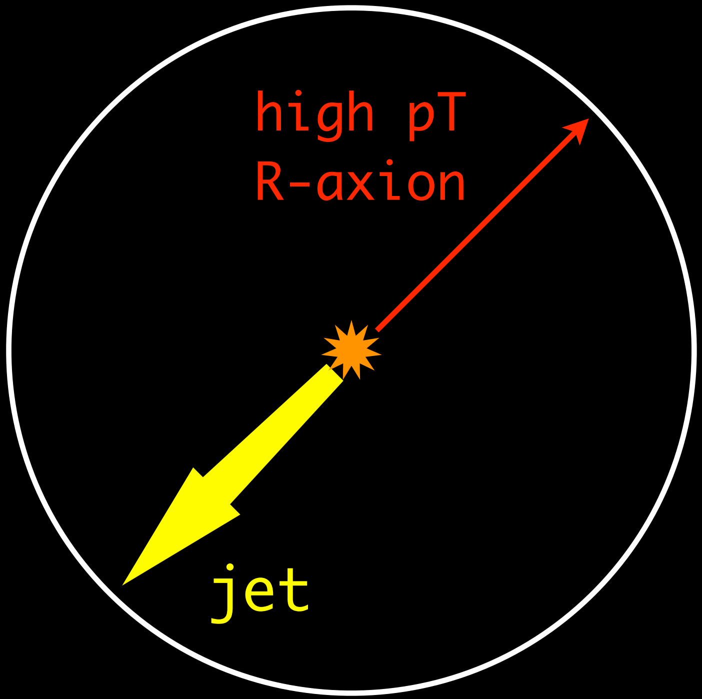
(cf. MSSM CP-odd: $f_R=v$, $C_L=1$)

Kao '93

R-axion at LHC

- Transverse momentum distribution

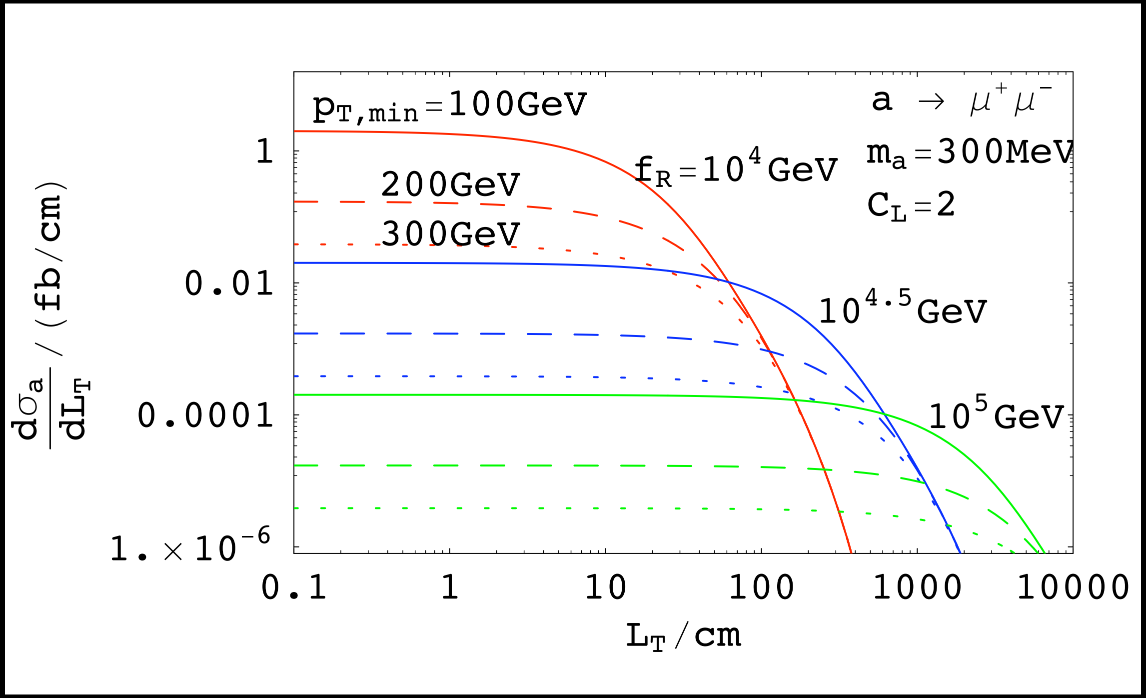


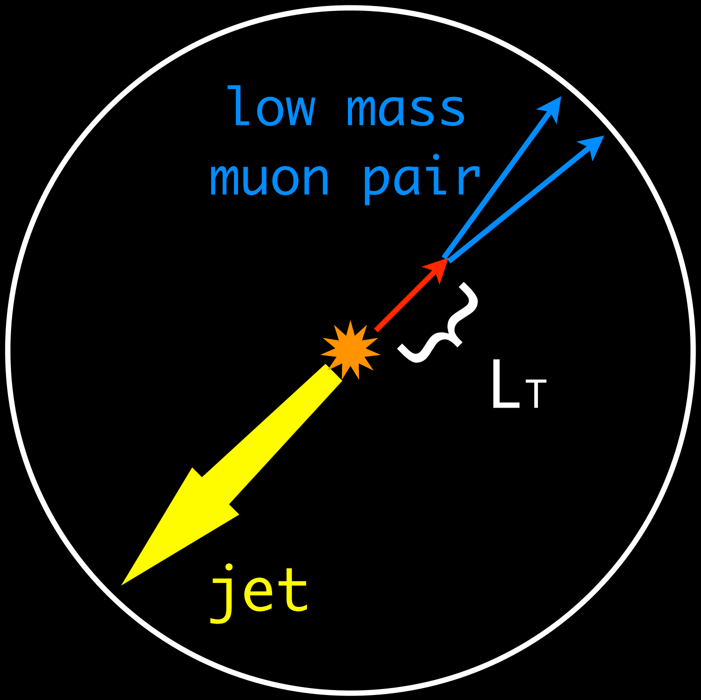


The R-axion production: σ = 10-100 fb for pT>100GeV

R-axion at LHC

- Transverse decay length distribution



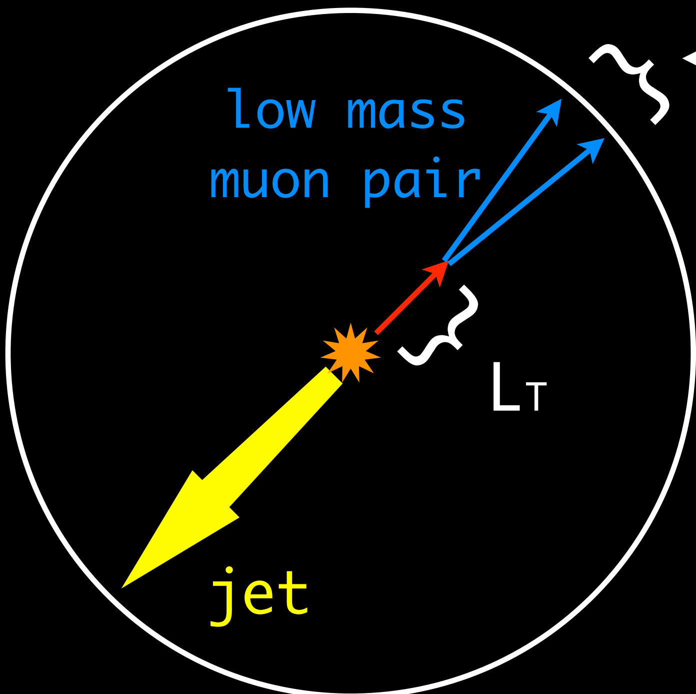


The R-axion leaves a displaced vertex from which a low mass muon pair is produced!

R-axion at LHC

R-axion Reconstruction

Typical open angle between two muons are very small:



$\varphi_{\mu\mu} \sim 2m_a/p_T \sim$ 1-10 mrad.
(at the inner detector)

We need to measure the transverse impact parameters of the two muons!

↓

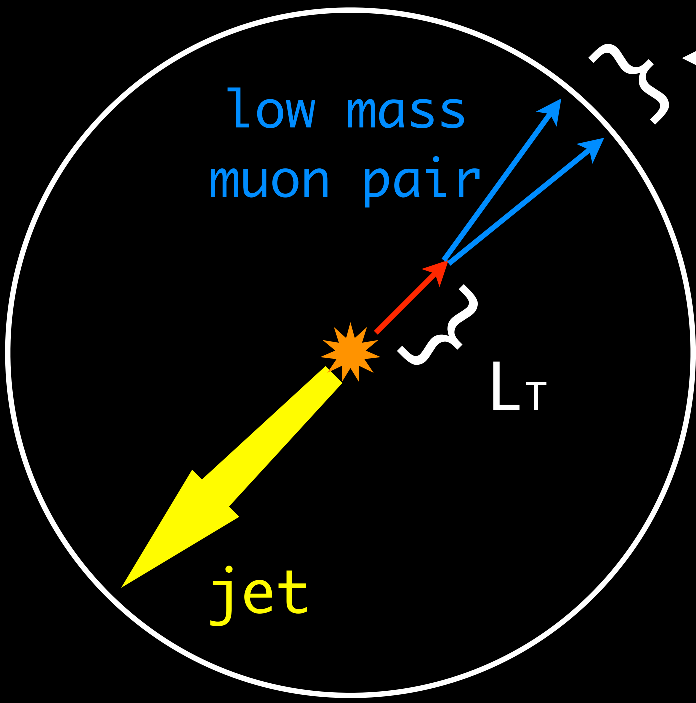
The challenge is to separate the two muon tracks by inner detectors!

$d_0 \sim c\tau = O(100)\mu m$

R-axion at LHC

R-axion Reconstruction

Typical open angle between two muons are very small:



$\leftarrow$ $\varphi_{\mu\mu} \sim 2m_a/pT \sim 1\text{-}10$ mrad.

For L_T>beam-pipe:

- ★ Muons do not hit the first few layers of the pixel detector

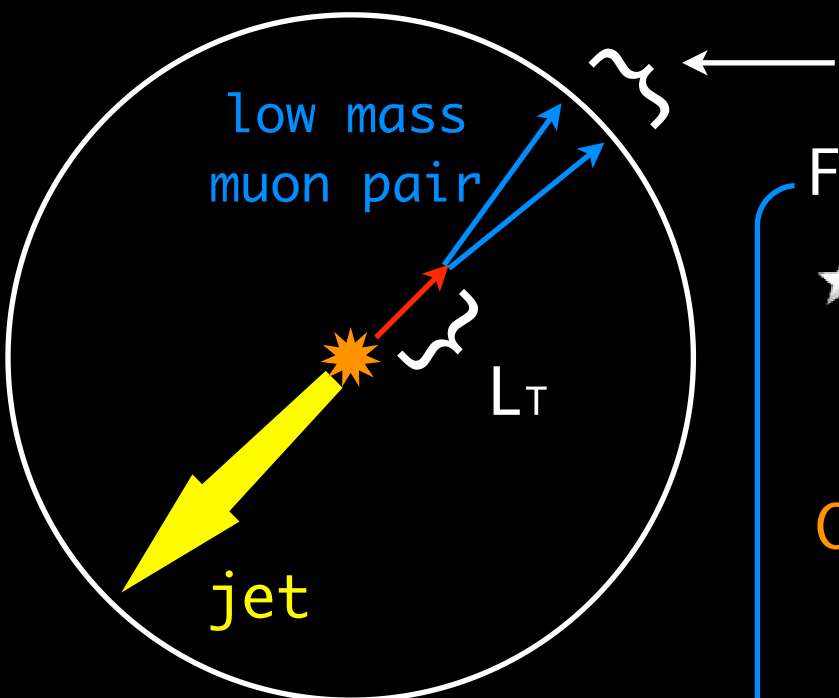
  → Track-resolutions get worse

- ★ Background from the muon pair photo-production requires careful study

R-axion at LHC

R-axion Reconstruction

Typical open angle between two muons are very small:



$\varphi_{\mu\mu} \sim 2m_a/p_T \sim$ 1-10 mrad.

For L_T<beam-pipe:

- ★ Distance between two muon tracks at pixel detectors (r=4,10,13cm) ~O(100)μm.

Can we separate them? with pixels;

Atlas: 50x400μm^2

CMS: 100x100μm^2

Does the muon trigger work for “isolated muon pairs”?

R-axion at LHC

- R-axion Reconstruction

If the trigger and tracking system work for a muon pair in the same way for an isolated muon;

$$\sigma_\phi \simeq 0.075 \oplus \frac{1.8}{p_T/\mathrm{GeV}\sqrt{\sin\theta}} \quad (\mathrm{mrad})$$

$$\sigma_{\cot\theta} \simeq 0.70 \times 10^{-3} \oplus \frac{2.0 \times 10^{-3}}{p_T/\mathrm{GeV}\sqrt{\sin\theta}}$$

$$\sigma_{d_0} \simeq 11 \oplus \frac{73}{p_T/\mathrm{GeV}\sqrt{\sin\theta}} \quad (\mu\mathrm{m})$$

Atlas TDR

The displaced vertex search will be successful!

Background Estimation

- Prompt muon pairs: light meson decay, Drell-Yan process

  $\longrightarrow$ Suppressed by the impact parameter measurement.

- Muon pairs in heavy meson (B,D) decays

  $\longrightarrow$ They are not suppressed by the impact parameter measurement. We need careful study.

- Fake muon pairs ($\pi \to \mu$) in K meson decay

  $\longrightarrow$ Fake rate is small enough.

- Muon photo-production at detector material

  $\longrightarrow$ We are safe as long as the R-axion decays inside the beam pipe.

Background Estimation

★ Muon pairs in heavy meson (B,D) decays

(B,D) meson: $c\tau = O(100)\mu m$ ~ R-axion

Signal: σ~10fb (pT>100GeV)

Background: $\sigma_{B,D}$~10nb (pT>100GeV)

We need a suppression factor better than 10^{-6}.

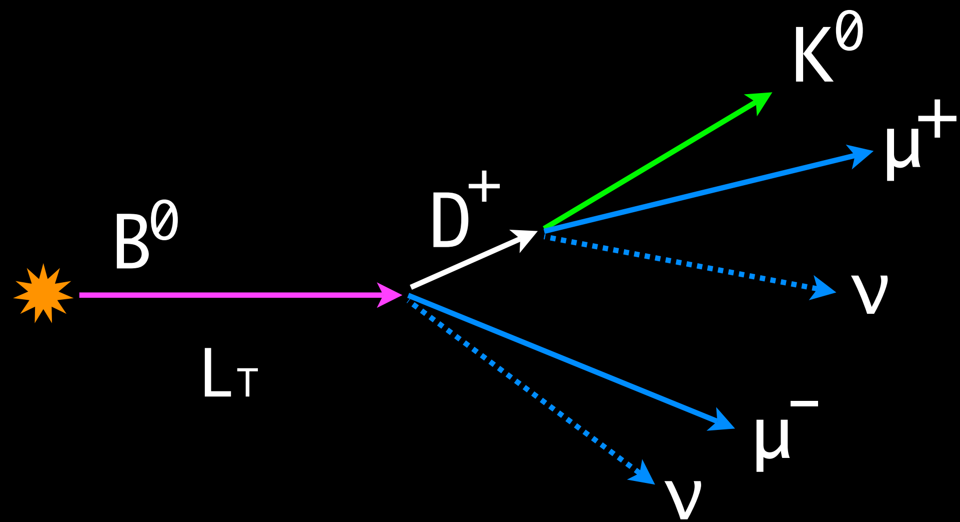
Fortunately, branching ratios of most decay modes involving muon pairs are small.

By combining with muon pair isolation cut, invariant mass cut, most of them are not serious.

Background Estimation

- Background from a cascade B decay ($Br \sim 10^{-2}$):

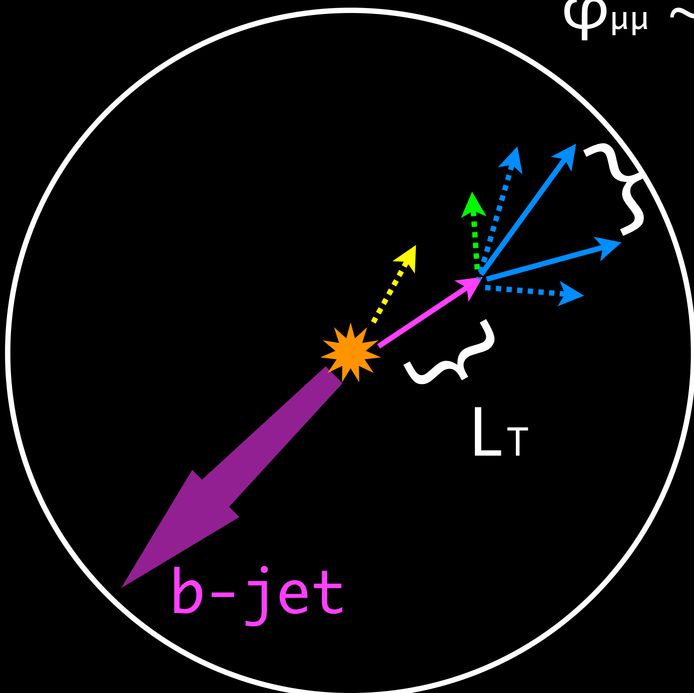
$$B^0 \longrightarrow D^{\pm}+\mu^{\mp}+\nu \longrightarrow K^0+\mu^+\mu^-+\nu\nu$$



Although the D meson decay leaves a displaced vertex, the D meson vertex and the muon track is to close to be distinguished!

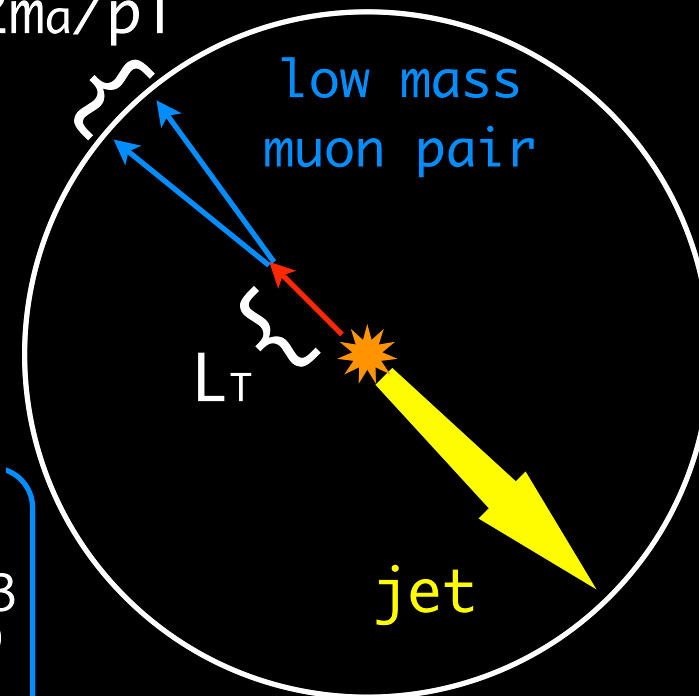
Background Estimation

Background



$\varphi^{B}_{\mu\mu} \sim 2m_B/p_T \longleftrightarrow \varphi^{a}_{\mu\mu} \sim 2m_a/p_T$

Signal



impact parameter

$d_0 \sim L_T \varphi_{\mu\mu}$

$\downarrow$

Event Shape Difference Suppression

$$\sim (\varphi^{B}_{\mu\mu}/\varphi^{a}_{\mu\mu})^3 \sim (m_a/m_B)^3$$

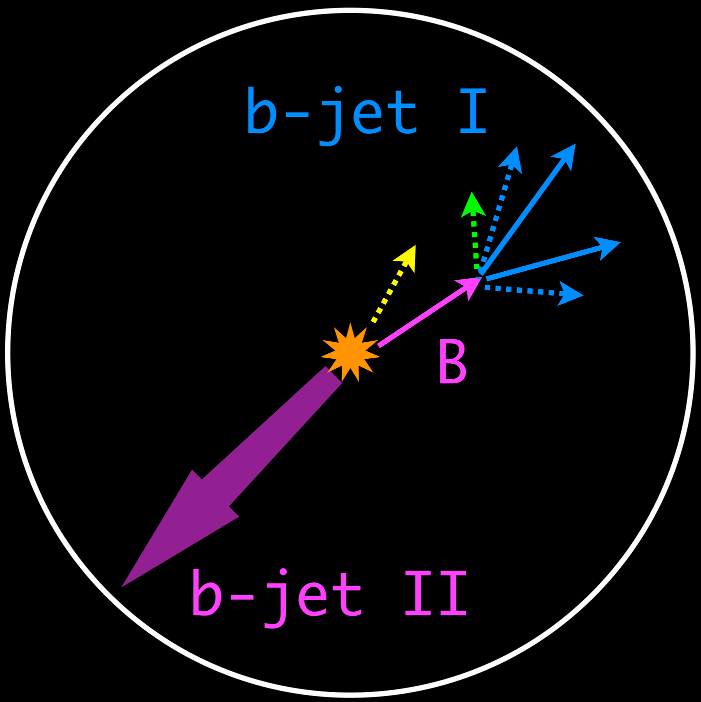
$$\sim 10^{-(2-3)}$$

b-jet veto ~ 0.1

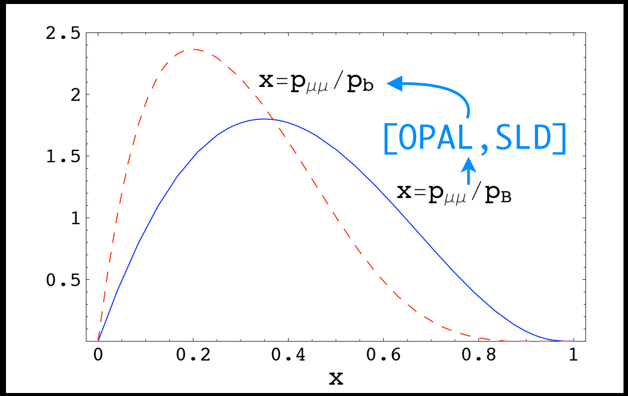
Ill balanced pT $\longleftrightarrow$ well balanced pT

Background Estimation

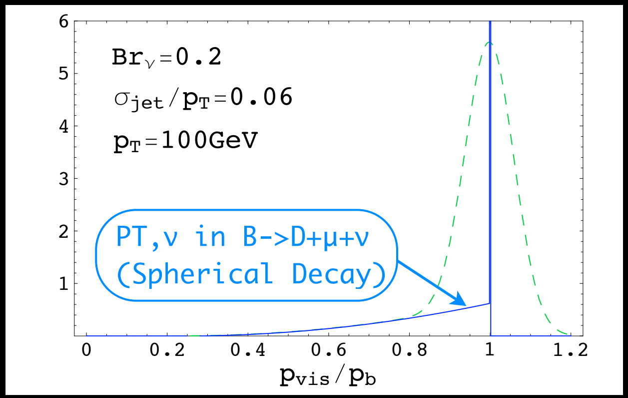
★ Missing pT veto



b-jet I



b-jet II



★ A Muon pair isn't likely to carry more than 80% of b-jet I.

★ Most pT of b-jet II is visible.

Missing pT veto results in a suppression ~ 10^{-2}

($\not{p}_T < 0.2 p_T$)

Background Estimation

★ Background from a cascade B decay (Br~10^{-2}):

$$B^0 \longrightarrow D^{\pm} + \mu^{\mp} + \nu \longrightarrow K^0 + \mu^+ \mu^- + \nu\nu$$

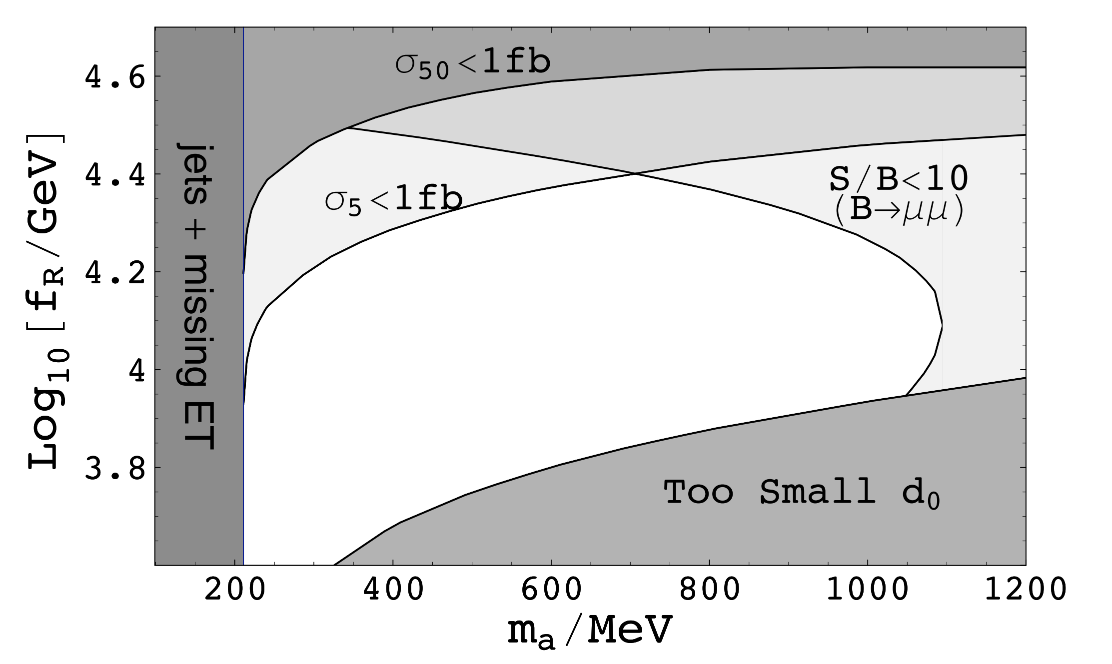
Resultant suppression factor

$$\sim \underbrace{10^{-2}}_{\text{Br}} \times \underbrace{10^{-(2-3)}}_{\text{Event Shape Difference}} \times \underbrace{10^{-1}}_{\text{b-jet veto}} \times \underbrace{10^{-2}}_{\not{E}_T \text{ veto}} \sim 10^{-(7-8)}$$

$\longrightarrow$ Background cross section is below 1 fb

Parameter Analysis

[σ_5 (L_T<5cm) σ_{50} (L_T<50cm)]



(Efficiency of R-axion detection:100%)

- R-axion Cross Section: independent of m_a
- Decay length gets shorter for the heavy m_a, larger f_R

Background from the cascade decay gets severer for the heavy m_a.

R-axion search at the LHC is possible for m_a=200-1000 MeV and f_R=10^4 GeV!

Summary

- R-axion: interrelated with the nature of SUSY breaking sector, messenger sector, Higgs sector

- R-axion can be very light with the mass in 100MeV range.

- R-axion produces the striking signature: displaced vertex from which a muon pair is produced.

  Challenges are:
  - Is the trigger system OK?
  - Can we separate two muon tracks?

- Background from heavy mesons can be suppressed

Summary

Future works:

- Can we detect R-axion with lighter or heavier mass?
  - lighter mass: looks like missing ET
  - heavier mass: leaves no displaced vertex
- R-axion production associated with heavy quarks or SUSY particle production.
  - Associated production with a fermion pair is suppressed due to the pseudo scalar nature of the R-axion.

Backup

Properties of R-axion

- R-charge assignment of the SSM fields

	SU(2)	$\mathrm{U}(1)_{\mathrm{Y}}$	$\mathrm{U}(1)_{\mathrm{R}}$
H_u	$\mathbf{2}$	$1/2$	X_u
H_d	$\mathbf{2}$	$-1/2$	X_d
Q_L	$\mathbf{2}$	$1/6$	X_Q
$\bar{U}_R$	$\mathbf{1}$	$-2/3$	$X_{\bar{U}}$
$\bar{D}_R$	$\mathbf{1}$	$1/3$	$X_{\bar{D}}$
λ	-	-	1

μ-term: $X_u + X_{\bar{D}} = 2$

Yukawa: $X_d + X_Q + X_{\bar{U}} = 2$

Yukawa: $X_d + X_Q + X_{\bar{D}} = 2$

Properties of R-axion

- R-charge assignment of the SSM fields

$$V = (|\mu|^2 + m_{H_u}^2)|H_u|^2 + (|\mu|^2 + m_{H_d}^2)|H_d|^2$$
$$-(e^{ia/f_R}\,B\mu\,H_u^0 H_d^0 + c.c.) + \frac{1}{8}(|H_u^0|^2 - |H_d^0|^2)^2$$

(neglect m_a)

$$H_u^0 = \frac{1}{\sqrt{2}}(v_u + \rho_u)e^{i\xi_u/v_u}, \quad H_d^0 = \frac{1}{\sqrt{2}}(v_d + \rho_d)e^{i\xi_d/v_d}$$

$$v^2 \equiv v_u^2 + v_d^2 = 4m_Z^2/(g^2 + {g'}^2) \simeq (246\,\mathrm{GeV})^2 \qquad \tan\beta \equiv v_u/v_d$$

$$\begin{aligned} |\mu|^2 + m_{H_u}^2 &= B\mu\cot\beta + (m_Z^2/2)\cos 2\beta, \\ |\mu|^2 + m_{H_d}^2 &= B\mu\tan\beta - (m_Z^2/2)\cos 2\beta, \end{aligned}$$

Properties of R-axion

- R-charge assignment of the SSM fields

$$V_{\rm mix} = \frac{1}{2}\mathbf{x}^t \mathcal{M}^2 \mathbf{x}, \quad \mathbf{x} = \begin{pmatrix} \xi_u \\ \xi_d \\ \tilde{a} \end{pmatrix}$$

$$\mathcal{M}^2 = B\mu \begin{pmatrix} \cot\beta & 1 & -r\cos\beta \\ 1 & \tan\beta & -r\sin\beta \\ -r\cos\beta & -r\sin\beta & r^2\cos\beta\sin\beta \end{pmatrix} \qquad r = v/f_R$$

↓ Mass Eigensystem

$$\begin{pmatrix} G_0 \\ A_0 \\ a \end{pmatrix} = \begin{pmatrix} \sin\beta & -\cos\beta & 0 \\ \kappa\cos\beta & \kappa\sin\beta & -\kappa r\sin\beta\cos\beta \\ \kappa r\cos^2\beta\sin\beta & \kappa r\sin^2\beta\cos\beta & \kappa \end{pmatrix} \begin{pmatrix} \xi_u \\ \xi_d \\ \tilde{a} \end{pmatrix}$$

$$\kappa = (1 + r^2\sin^2 2\beta)^{-1/2}$$

$$(m_{G_0}^2, m_{A_0}^2, m_a^2) = \left(0, \frac{2B\mu}{\kappa^2\sin 2\beta}, 0\right)$$

Properties of R-axion

- R-charge assignment of the SSM fields
  - Mixing and Yukawa Couplings

$$\xi_u \sim \kappa r \cos^2\beta \sin\beta \times a, \quad \xi_d \sim \kappa r \sin^2\beta \cos\beta \times a.$$

$$\lambda_u = i y_u/\sqrt{2}\, r \cos^2\beta \sin\beta = i m_u/f_R \cos^2\beta,$$

$$\lambda_d = i y_d/\sqrt{2}\, r \sin^2\beta \cos\beta = i m_d/f_R \sin^2\beta,$$

  - R-charge of Higgs bosons

$$R(G_0)=0 \longrightarrow X_u \sin^2\beta - X_d \cos^2\beta = 0$$

$$\longrightarrow \boxed{X_u = 2\cos^2\beta \quad X_d = 2\sin^2\beta}$$

Background Estimation

- Background from prompt muon pairs
  - Muon pairs from light meson decay

    $\sigma\sim 1\mu b$ ($p_T>100$GeV) $Br=10^{-(4-5)}$
  - Muon pairs from Drell-Yan

    $\sigma\sim 10pb$ ($p_T>100$GeV)

We need a suppression factor better than 10^{-5}.

Mis-measurement probability of the impact parameter

$$P_{d_0} \simeq \mathrm{Erfc}\left(\frac{d_0}{\sqrt{2}\sigma_{d_0}}\right)^2$$

For $d_0>45\mu m$, $P_{d_0} \ll 10^{-5}$

Background Estimation

- Background from (B,D) meson decays

process	$Br^{(X)}_{\mu\mu}$	$P_{\rm geo}$	$\sigma_{X\to\mu\mu}(\rm fb)$
$B^0 \to K^{*0}\mu^+\mu^-$	1.3×10^{-6}	$(m_a/m_B)^3$	10^{-4}
$B^0 \to J/\psi + X \to \mu^+\mu^- + X$	$\simeq 5.9\times10^{-5}$	$\lesssim 10^{-6}$	10^{-5}
$B^0 \to D^0 + X \to D^0 + \mu^+\mu^-$	$< 10^{-8}$	(m_a/m_B)	10^{-4}
$B^0 \to D^\pm + \mu^\mp + \nu \to \mu^+\mu^- + X$	10^{-2}	$(m_a/m_B)^3$	1
$B^0 \to \pi^-\mu^+\nu$	3×10^{-8}	$(m_a/m_B)^3$	10^{-5}
$D^0 \to \rho^0 + \mu^+\mu^-$	1.5×10^{-7}	$(m_a/m_D)^3$	10^{-3}
$D^0 \to \omega + K_S^0 \to \mu\mu + K_S^0$	10^{-6}	(m_a/m_D)	1
$D^0 \to \rho^0 + \pi^0 \to \mu\mu + \pi^0$	10^{-7}	(m_a/m_D)	10^{-1}
$D^0 \to K^\pm + \mu^\mp + \nu$	10^{-5}	$(m_a/m_D)^3$	10^{-1}
$D^0 \to \pi^\pm + \mu^\mp + \nu$	6×10^{-7}	$(m_a/m_D)^3$	10^{-2}

Fake Muon rate

$P_{\mu/K}<10^{-4}$

$P_{\mu/\pi}<10^{-4}$

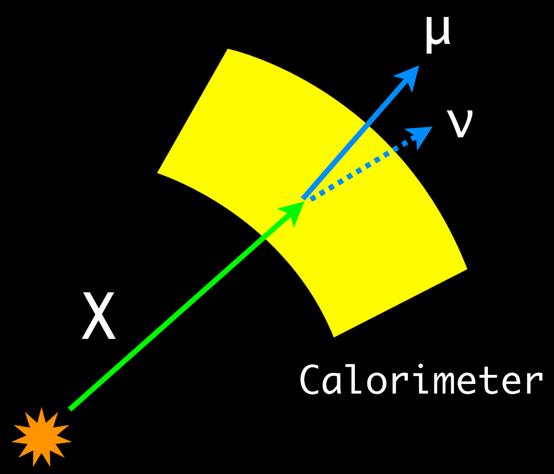
The branching ratios of the modes involving muon pairs are small.

By combining a suppression factors from differences of the event shape, missing pT veto etc, background cross section is well below 1fb.

Background Estimation

★ Fake muon probability (X=π,K)

$$P_{\mu/X} = P_{\text{mis-id}} \times Br_{X\to\mu+\nu} \times \int_0^{r_{\text{out}}} dL_T \underbrace{\frac{1}{c\tau_X}\frac{m_X}{p_{T,X}} \exp\left[-\frac{m_X}{p_{T,X}}\frac{L_T}{c\tau_X}\right]}_{\text{In flight decay rate at LT}} \times \underbrace{n_X(L_T)}_{\text{Punch through rate up to LT}}$$



$$n_X(L_T) \simeq 1 - \theta(L_T - r_{\text{in}}) \int_{r_{\text{in}}}^{L_T} dx \frac{11}{\Delta r_{\text{calo}}} \exp\left[-11\frac{(x - r_{\text{in}})}{\Delta r_{\text{calo}}}\right]$$

(rin=2m, rout=4m, Δrcalo = rout-rin)

Pmis-ID = 50% (π), Pmis-ID = 10% (K) AtlasTDR

Resultant Fake Rates

$P_{\mu/\pi} < 10^{-4}$ $P_{\mu/K} < 10^{-4}$

Background Estimation

- Background from K meson decays

Effective Branching ratios (pT>100GeV)

$$Br^{(\mathrm{eff})}(K_L^0 \to \mu(\pi) + \mu + \nu) = \left(\frac{m_K}{p_{T,K}} \frac{r_{\mathrm{pipe}}}{c\tau_{K_L}}\right) \times P_{\mu/\pi} \times Br(K_L^0 \to \pi + \mu + \nu) \simeq 10^{-9},$$

$$Br^{(\mathrm{eff})}(K_S^0 \to \mu(\pi) + \mu + \nu) = \left(\frac{m_K}{p_{T,K}} \frac{r_{\mathrm{pipe}}}{c\tau_{K_S}}\right) \times P_{\mu/\pi} \times Br(K_S^0 \to \pi + \mu + \nu) \simeq 10^{-9},$$

$$Br^{(\mathrm{eff})}(K_S^0 \to \mu(\pi) + \mu(\pi)) = \left(\frac{m_K}{p_{T,K}} \frac{r_{\mathrm{pipe}}}{c\tau_{K_S}}\right) \times P_{\mu/\pi}^2 \times Br(K_S^0 \to \pi + \pi) \simeq 3 \times 10^{-10},$$

$c\tau K_L$=15.3m, $c\tau K_S$=2.68cm

$Br(K_L \to \pi\mu\nu)$=27%, $Br(K_S \to \pi\mu\nu)=5\times10^{-4}$, $Br(K_S \to \pi\pi)$=68%

Background is highly suppressed!

Background Estimation

- Muon pair from photo-production at material

Background cross section

$\sigma_{\gamma\to\mu\mu} = P_{\gamma\to\mu\mu} \times \sigma_\gamma$ [$\sigma_\gamma \sim$ 1nb (pT>100GeV)]

$P_{\gamma\to\mu\mu} \sim \underline{10^{-30}\text{cm} \times (Z/4)^2} \times n \times \Delta L$

Small momentum transfer
Tsai '74

	Z	A	ρ (g·cm^{-3})	n (10^{22}cm^{-3})	$P_{\gamma\to\mu\mu}$
Be	4	9	1.85	12.3	4×10^{-8}
C	6	12	1.9-2.3	9.5-11	7×10^{-8}
Si	14	28	2.33	4.98	2×10^{-7}

[1mm thick material]

Background is small for the R-axion decaying inside of the beam-pipe.
Careful study is required for the R-axion decaying outside of the beam-pipe.

Background Estimation

- Muon pair from photo-production at material

Background cross section

$$\sigma_{\gamma\to\mu\mu} = P_{\gamma\to\mu\mu} \times \sigma_\gamma \qquad [\sigma_\gamma \sim 1\text{nb } (pT>100\text{GeV})]$$

$$P_{\gamma\to\mu\mu} \sim \underline{10^{-30}\text{cm} \times (Z/4)^2} \times n \times \Delta L$$