R-axion:
A New LHC physics signature involving muon pairs

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Arxiv:0810.5773
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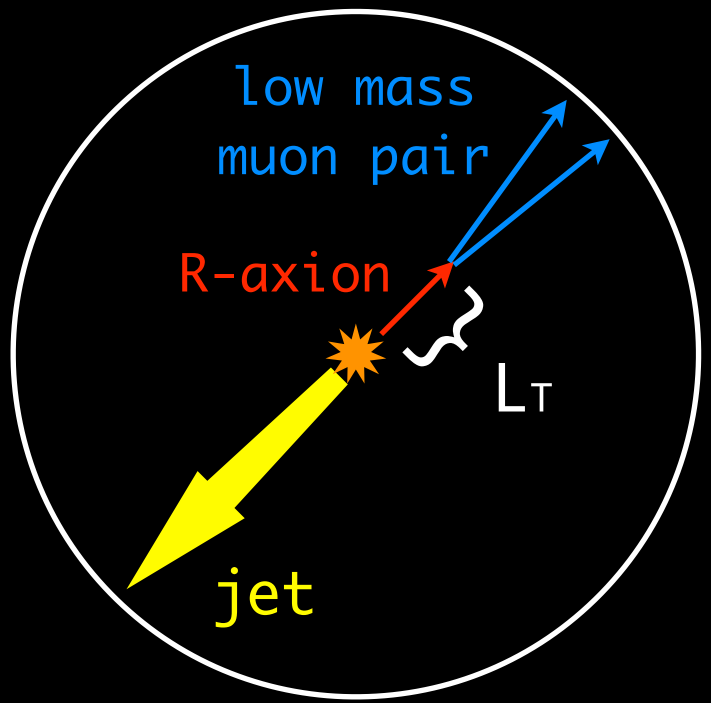
Introduction



R-axion: m_a=O(100)MeV

cτ=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
  - 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

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

$\tilde{q}$: Q_q, q: $Q_q - 1$, F_q: $Q_q - 2$

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

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

λ_α: 1, $F_{\mu\nu}$: 0, D: 0

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

↓

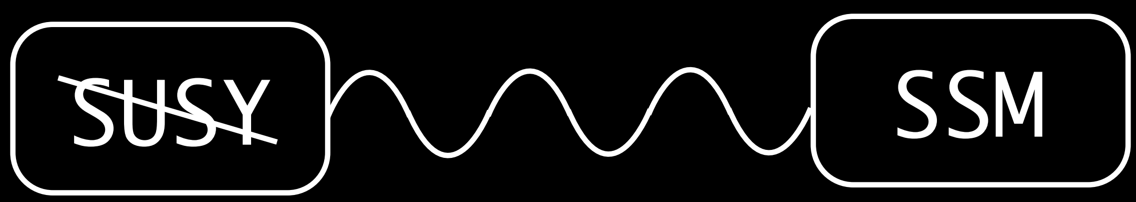
The model construction beyond the SSM often involves the R-symmetry!

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!



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
for the collider experiments...

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

↓

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?

In generic models with gauge mediation, R-breaking scale is bounded from below,

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

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

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

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

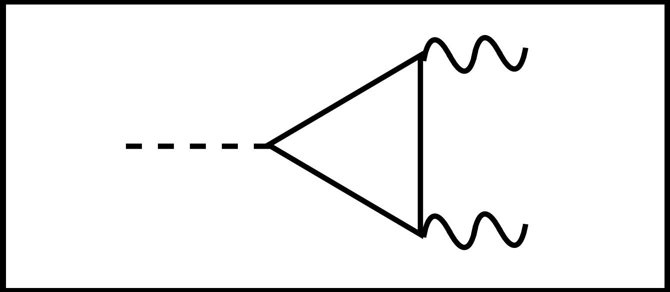
↓ R-axion is massive

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

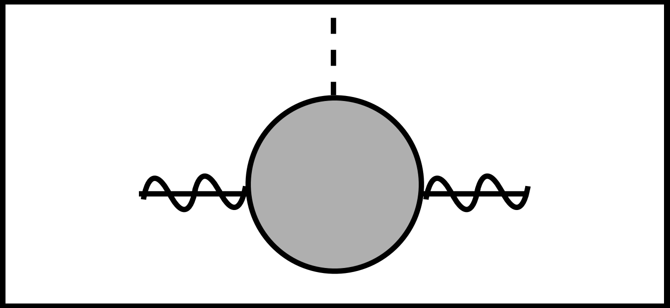
($m_{3/2}$ >O(1)eV in Gauge Mediation)

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)

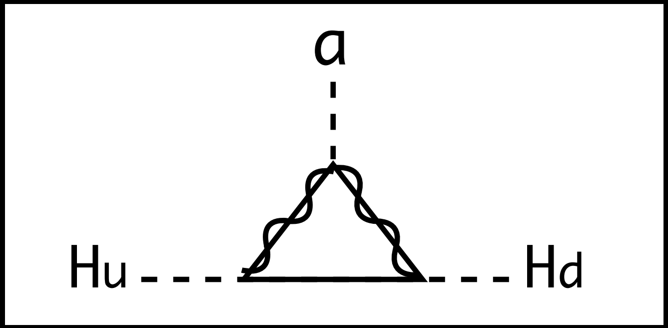
Yukawa coupling

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

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

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 μ =0)

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 $2m_\mu \lesssim m_a \lesssim 1\,\mathrm{GeV}$

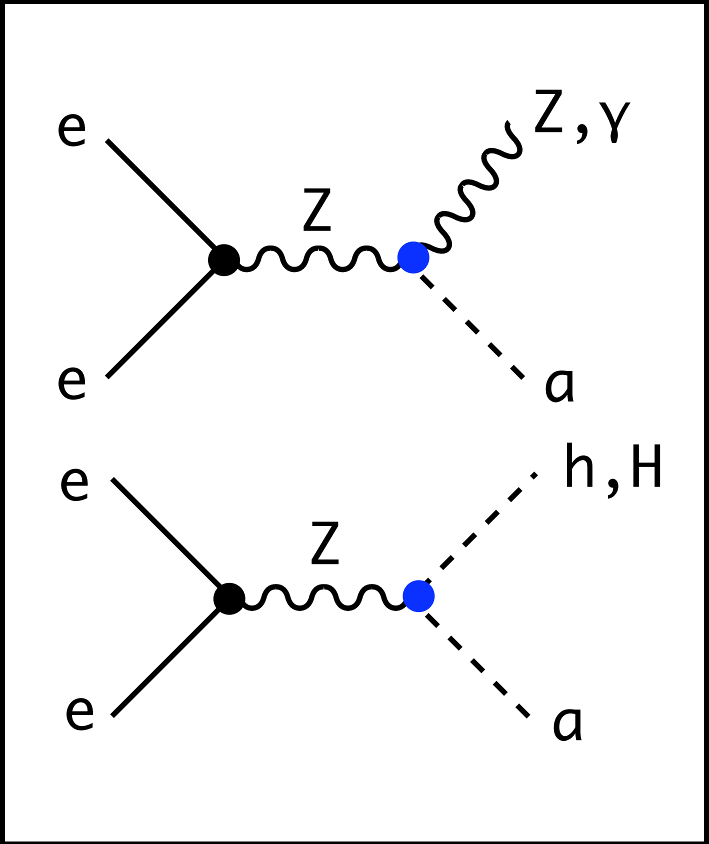
R-axion mainly decays into a muon pair via the Yukawa coupling

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

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

R-axion leaves a displaced vertex inside the collider!

R-axion at LEP



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

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

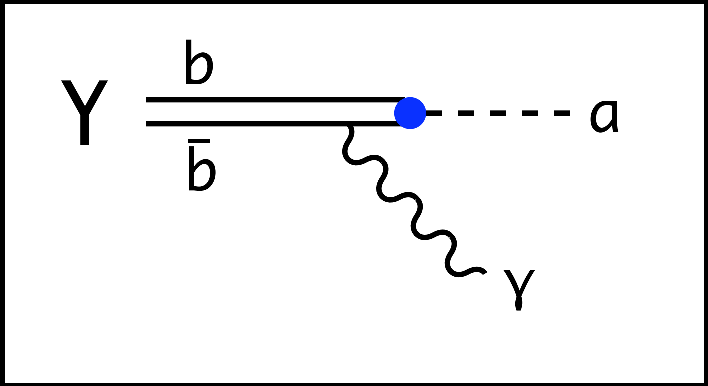
$$g_{\text{MSSM}}^{(A_0)} \times \frac{v}{f_R} \sin\beta \cos\beta$$

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

No R-axion at the LEP!

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 ⟶ $f_R > 10^3$ GeV

★ Astrophysical constraints

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

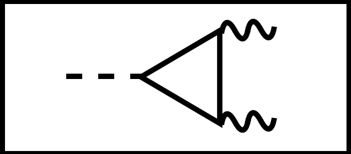
⟶ No constraints from astrophysics!

R-axion at LHC

R-axion production

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

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



gluino loops
top loops

$\longrightarrow$

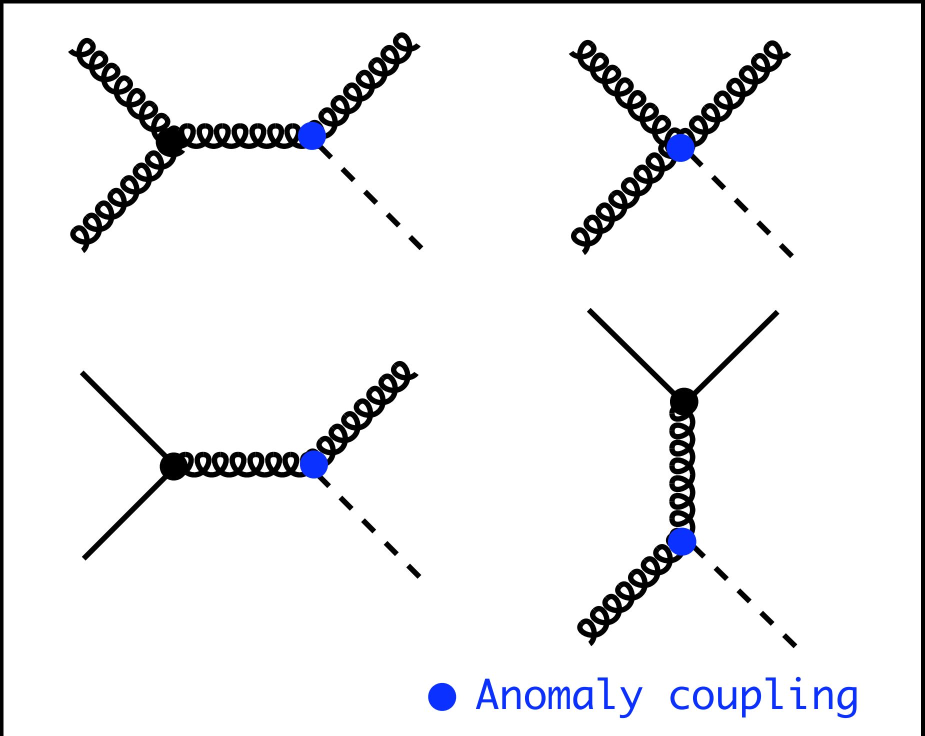
effective anomaly coupling

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

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

R-axion at LHC

- R-axion production



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

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

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

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

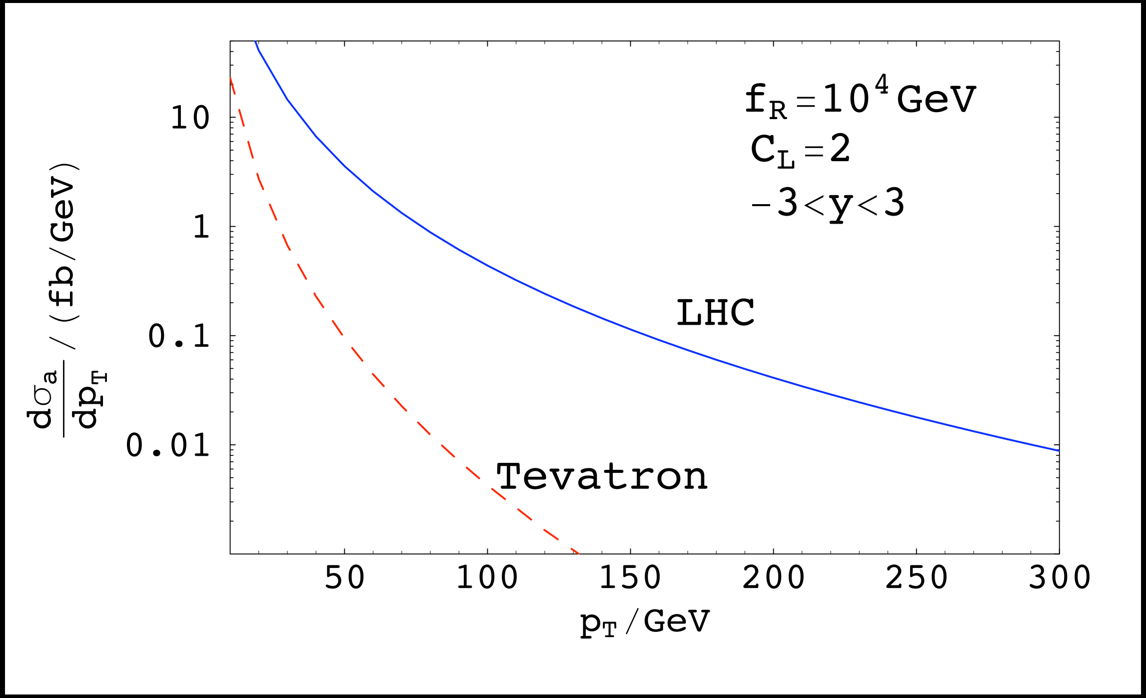
$C_L = (C_H + 3 - \cos^2\beta)$

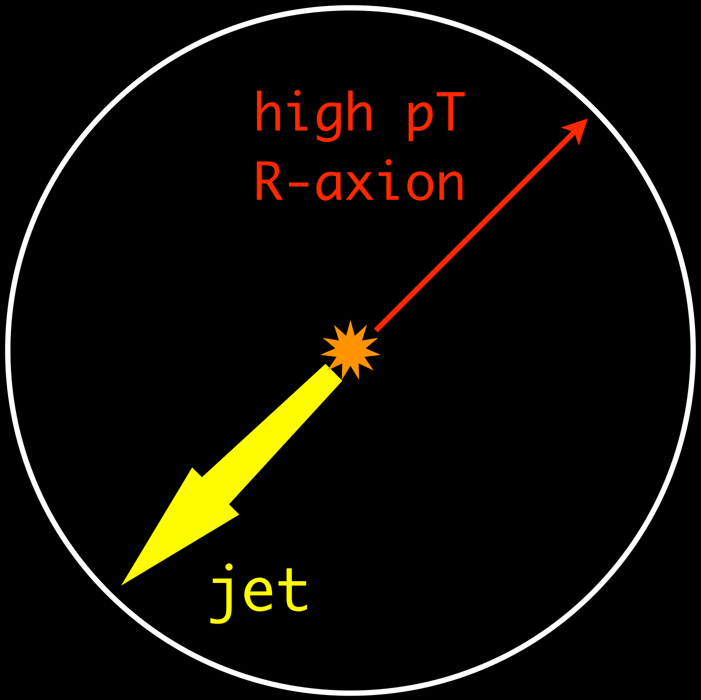
(cf. MSSM CP-odd: $f_R = v$, $C_L = 1$)

Kao '93

R-axion at LHC

- Transverse momentum distribution

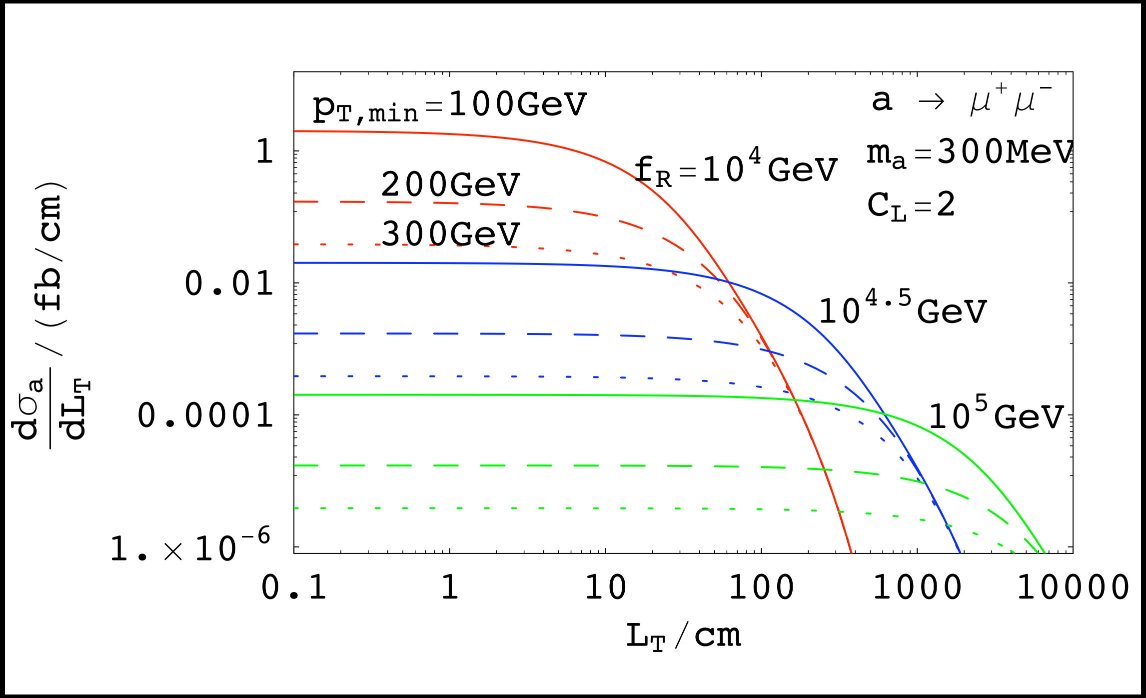


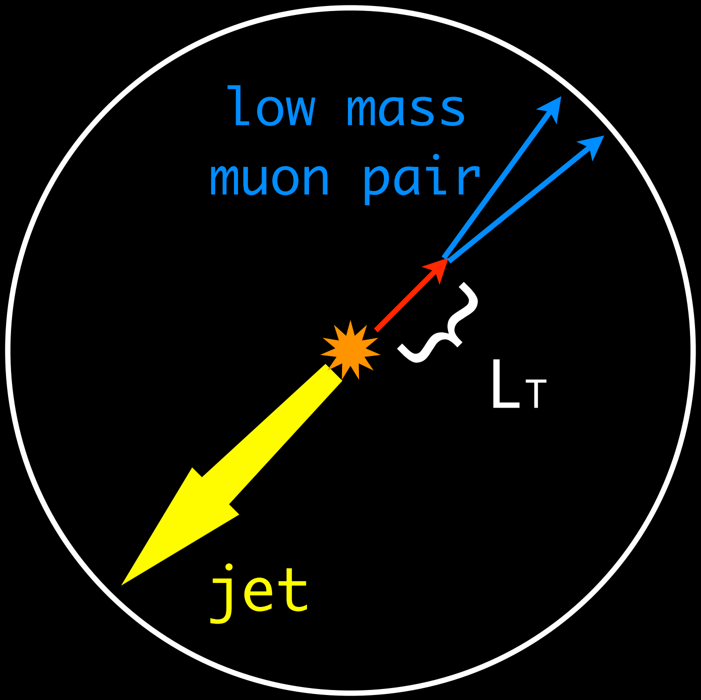


The R-axion production: σ = 10-100 fb for pT>100GeV

R-axion at LHC

- Transverse decay length distribution



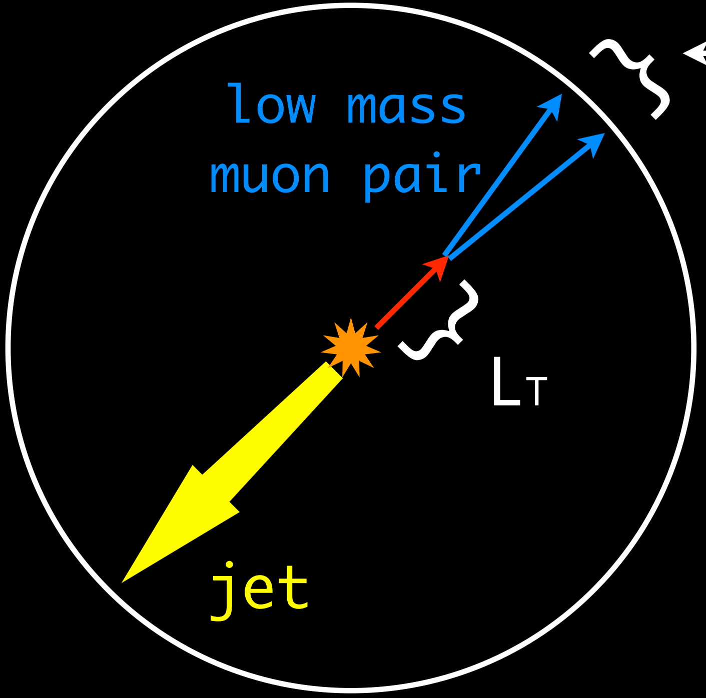


The R-axion leaves a displaced vertex from which a low mass muon pair is produced!

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.

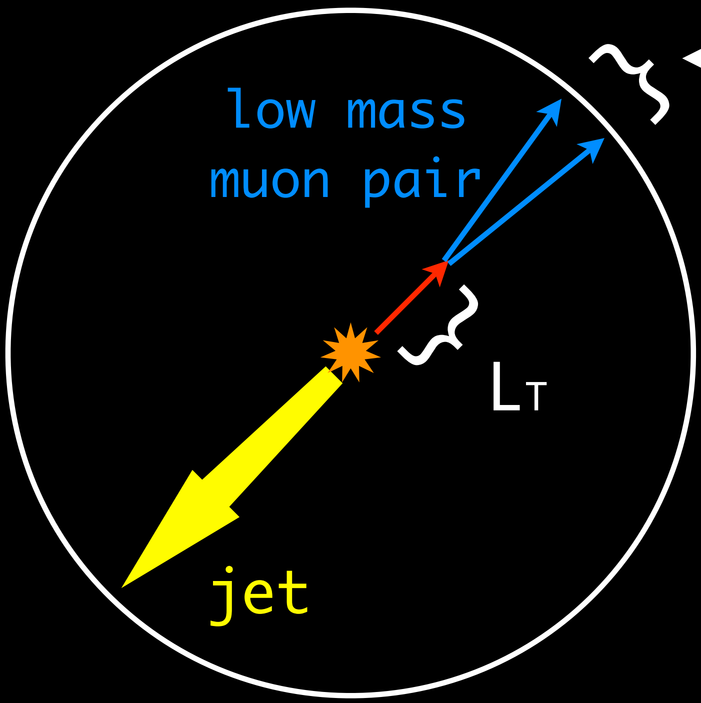
The challenge is to separate the two muon tracks!
We also need to measure the transverse impact parameters of the two muons!

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

R-axion at LHC

R-axion Reconstruction

Typical open angle between two muons are very small:



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

For L_T>beam-pipe:

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

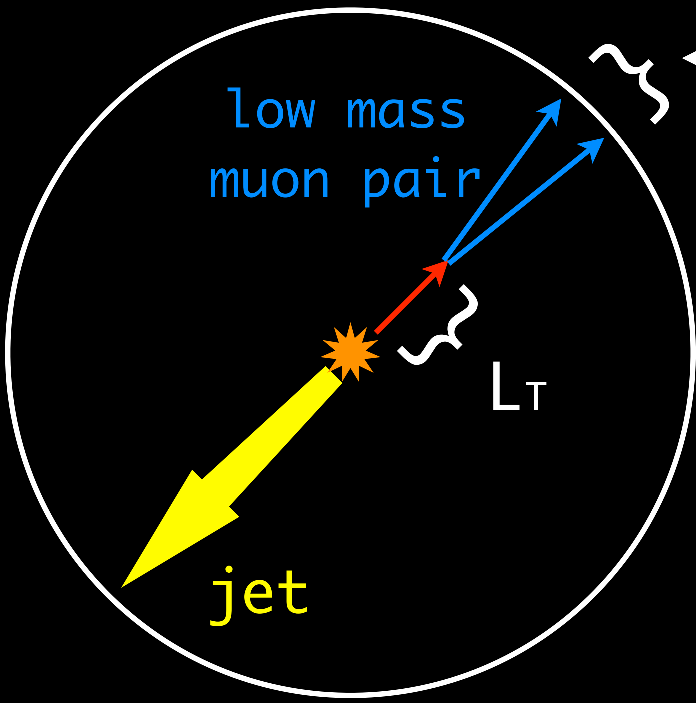
  → Track-resolutions get worse

- 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: $50\times400\mu m^2$

CMS: $100\times100\mu m^2$

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

  ⟶ Suppressed by the impact parameter measurement.

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

  ⟶ They are not suppressed by the impact parameter measurement. We need careful study.

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

  ⟶ Fake rate is small enough.

- ★ Muon photo-production at detector material

  ⟶ 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: $\sigma \sim 10fb$ ($p_T > 100GeV$)

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

↓

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

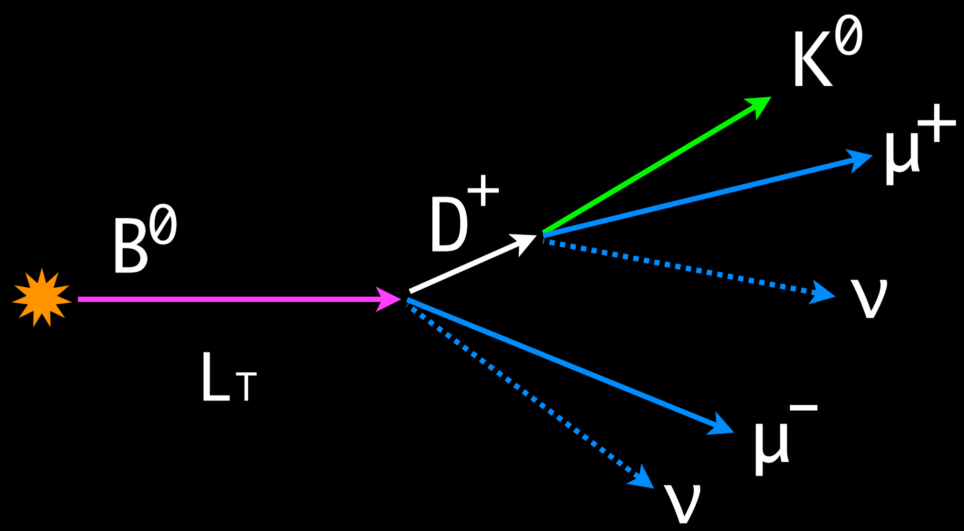
Fortunately, branching ratios of most decay modes involving muon pairs are small.

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

Background Estimation

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

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

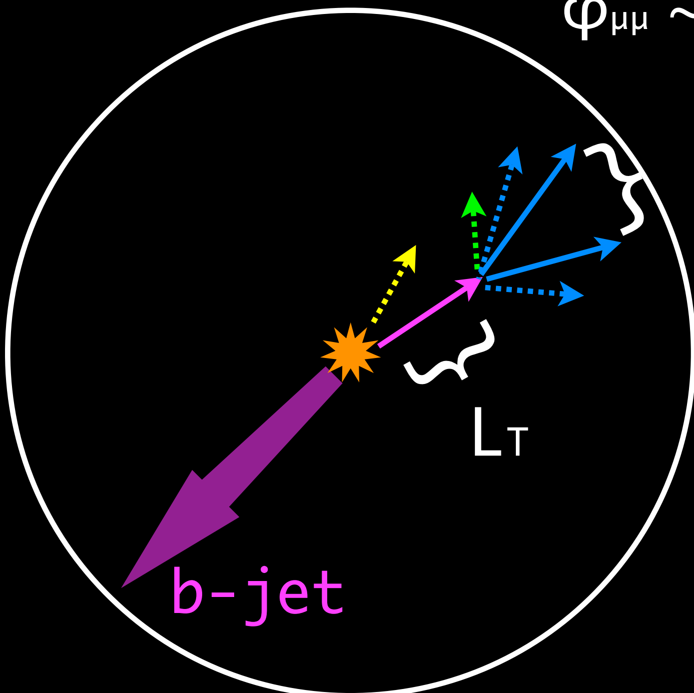


Although the D meson decay leaves a displaced vertex, the D meson vertex and the muon track is to close to be distinguished!

Background Estimation

Background | Signal

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



impact parameter

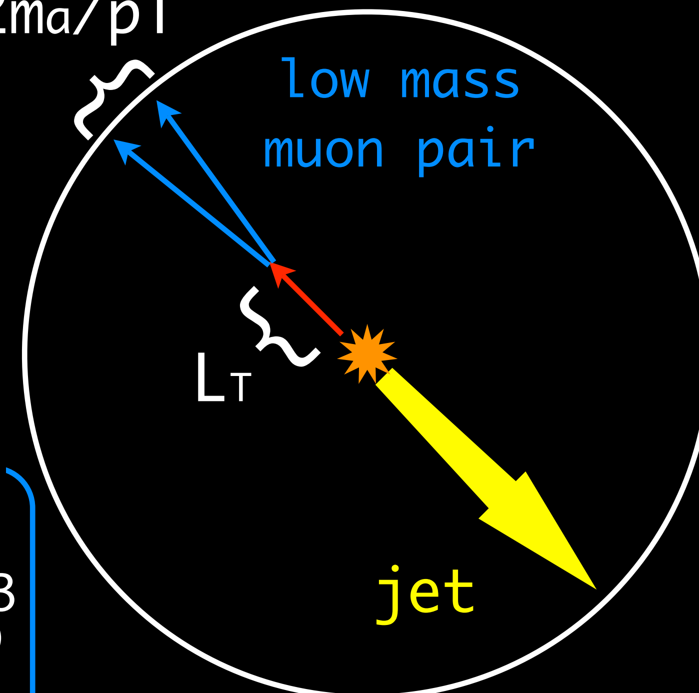
$d_0 \sim L_T \varphi_{\mu\mu}$

↓

Event Shape Difference Suppression

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

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

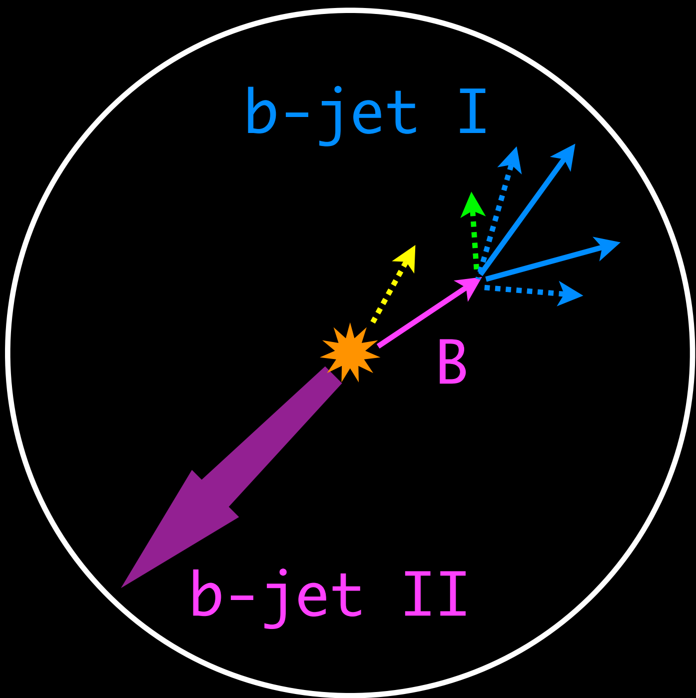


b-jet veto ~ 0.1

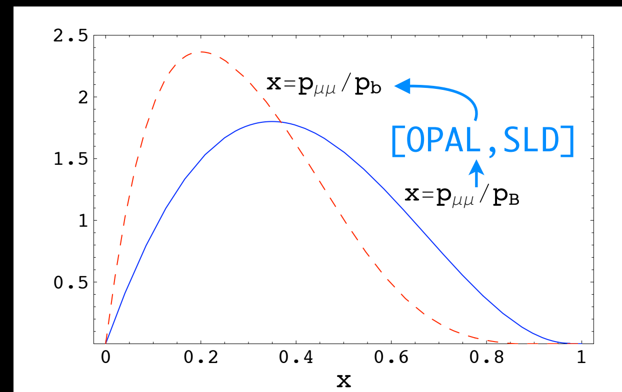
Ill balanced pT ⟷ well balanced pT

Background Estimation

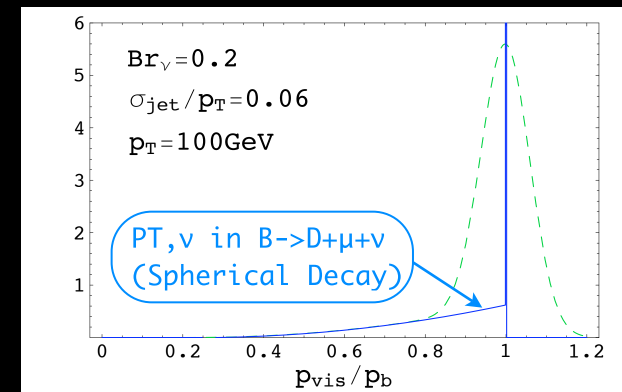
★ Missing pT veto



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

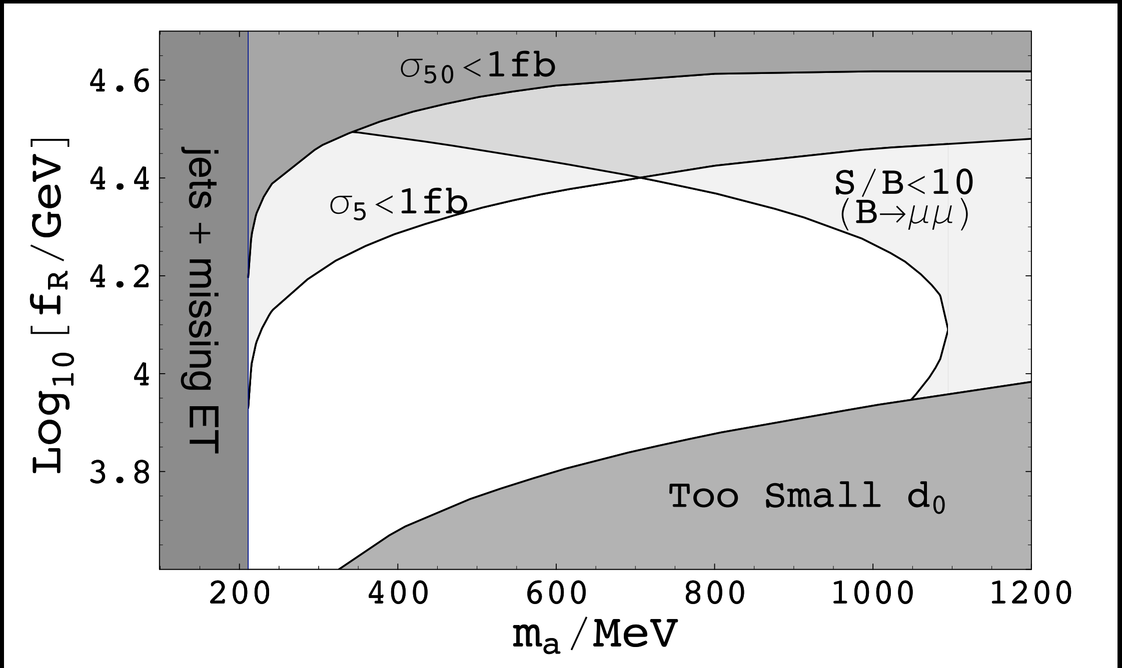
$$\sim 10^{-2} \times 10^{-(2-3)} \times 10^{-1} \times 10^{-2} \sim 10^{-(7-8)}$$

- Br (10^{-2})
- Event Shape Difference ($10^{-(2-3)}$)
- b-jet veto (10^{-1})
- $\not{E}_T$ veto (10^{-2})

⟶ 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

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	$Br_{\mu\mu}^{(X)}$	$P_{\rm geo}$	$\sigma_{X\to\mu\mu}$(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.

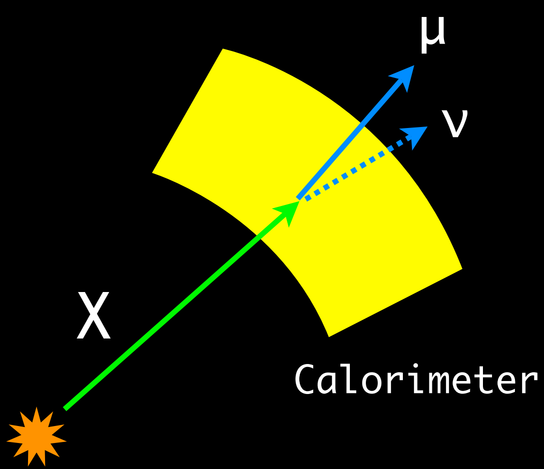
Background Estimation

- Fake muon probability (X=π,K)

$$P_{\mu/X} = P_{\text{mis-id}} \times Br_{X\to\mu+\nu} \times \int_0^{r_{\text{out}}} dL_T \frac{1}{c\tau_X}\frac{m_X}{p_{T,X}} \exp\left[-\frac{m_X}{p_{T,X}}\frac{L_T}{c\tau_X}\right] \times n_X(L_T)$$

In flight decay rate at LT

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)]

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

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.