# Exotic colored particles at the LHC

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General definition: any non standard model fields could be called exotic...

- New Physics typically predicts a set of exotic fields
- SUSY partners. Similar to SM particles but with different spins
- KK modes. Similar to SM particles but with different masses
- New Physics generally solve some theoretical problems
- The Signatures are well studied...
- "Standard Exotics"

# Exotic Exotics!

- Distinguished signatures at LHC
- Background free and/or strongly produced at LHC.
- Be prepared and do not miss them...
- Colored Particles—Large Production Rate

## Di-quark in 6 representation of SU(3). (with R. Mohapatra)

- SUSY $SU(2)_L \times SU(2)_R \times SU(4)_c$
- See-saw for neutrino masses
- neutron-anti-neutrino oscillation
- light $\Delta_{uu}$ with $M \sim TeV$
- large coupling to the third generation

# Like-sign Top pair Production

- QCD—pair production of top-anti-top.
- Single Production: $uu \rightarrow 6 \rightarrow tt \rightarrow bbW + W+ \rightarrow bbEE$
- Like-sign dilepton with two b jets
- Background—misidentifications.

# General Di-quark singature and b charge identification

- QCD background is large for two jets events.
- identify the di-quark form the third generation.
- Signature of light $\Delta_{dd}$ , $uu \rightarrow 6 \rightarrow bb$
- Signature of light $\Delta_{ud}$ , $ud \rightarrow 6 \rightarrow tb \rightarrow bbW+ \rightarrow bbE$
- Making use of the information from the third generation jets!

## Quasi-stable heavy colored particles (with P. Langacker and B. Nelson)

- Ordinary families 3 $\times(L_{-\frac{1}{2}}$ , $Q_{\frac{1}{6}}$ , $\overline{u}_{-\frac{2}{3}}$ , $\overline{d}_{\frac{1}{3}}$ , $e_1^+$ , $\overline{\nu}_0$ ) with $Q' = 1$
- Higgs doublets $h_{u\frac{1}{2}}$ , $h_{d-\frac{1}{2}}$ with $Q' = -2$
- Exotic quarks 2 $\times(D_{t-\frac{1}{3}}$ , $\overline{D}_{\frac{t1}{3}})$ with $Q' = -3$, transforming as (3,1) under $SU(3) \times SU(2)$
- Exotic leptons 2 $\times(L_{s-\frac{1}{2}}$ , $\overline{L}_{\frac{s1}{2}})$ with $Q' = -2$, transforming as (1,2) under $SU(3) \times SU(2)$
- SM singlets $S$ with $Q' = 4$ , $T$ with $Q' = 6$,

# Cosmological bound from BBN

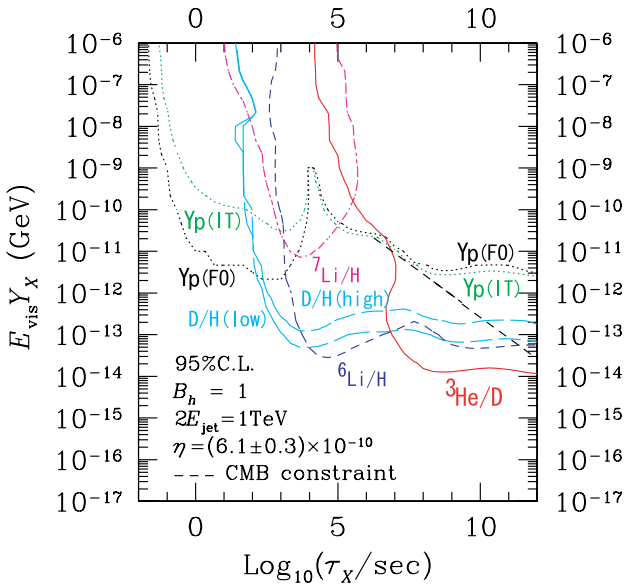
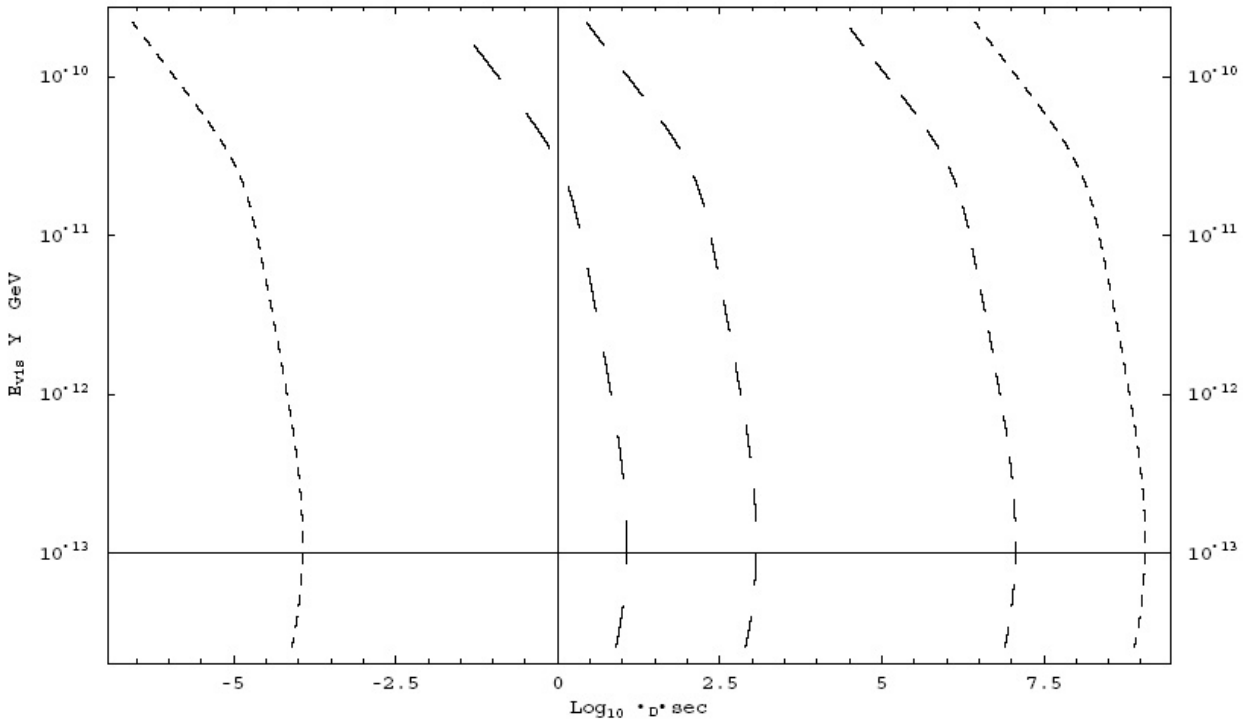



Figure 1: Astrophysical bound on the long lived particles (From M. Kawasaki, K. Kohri and T. Moroi, arXiv:astro-ph/0402490)

# life time vs relic abundance



# Collider Signature of quasi-stable colored particles

- Hadronization. Charged R-hadron vs neutral R-hadron.
- Hadron calorimeter. Small amount of energy deposited here.
- O(1)GeV/collision and O(10) collisions
- Pass level one calorimeter trigger?
- Muon chamber. Only charged R-hadron will leave a track

# SUSY Di-quark and Lepto-quark (with P. Langacker and B. Nelson)

Table 1: Decomposition of the $E_6$ fundamental representation **27** under $SO(10)$ and $SU(5)$, and their $U(1)_\chi$, $U(1)_\psi$, $U(1)_\eta$ , secluded sector $U(1)'_s$, and neutral-N model $U(1)_N$ charges.

| $SO(10)$ | $SU(5)$ | $2\sqrt{10}Q_\chi$ | $2\sqrt{6}Q_\psi$ | $2\sqrt{15}Q_\eta$ | $2\sqrt{15}Q_s$ | $2\sqrt{10}Q_N$ |
|---|---|---|---|---|---|---|
| 16 | 10 $(u, d, \overline{u}, \overline{e})$ | $-1$ | 1 | $-2$ | $-1/2$ | 1 |
| | $\overline{5}$ $(\overline{d}, \nu, e)$ | 3 | 1 | 1 | 4 | 2 |
| | $1\overline{N}$ | $-5$ | 1 | $-5$ | $-5$ | 0 |
| 10 | 5 $(D, H'_u)$ | 2 | $-2$ | 4 | 1 | $-2$ |
| | $\overline{5}$ $(\overline{D}, H'_d)$ | $-2$ | $-2$ | 1 | $-7/2$ | $-3$ |
| 1 | 1 $S_L$ | 0 | 4 | $-5$ | 5/2 | 5 |

# SUSY model with Di-quarks and Lepto-quarks

- $W_{L_Q} \sim \lambda_6 D u^c e^c + \lambda_7 DQL + \lambda_8 D d^c \nu^c$
- $W_{D_Q} \sim \lambda_9 DQQ + \lambda_{10} D u^c d^c$
- R-parity still conserved.
- D and Higgs have similar R-parity assignments.
- if only one set of superpotential, B and L conserved

# Exotics and Simulation Software

- add Di-quark into Comphep?
- deal with special color structure in Comphep
- color flow in PYTHIA?
- it is interesting and important to make the simulation software easy extendable.

## Signatures and Backgrounds

- isolate from the SUSY sample
- $\Delta = |m_{D_{1/2}} - m_{D_0}|$
- case 1: $\Delta < m_{LSP}$
  - Boson $\rightarrow$ 2 hard jets or 1 jet + lepton
  - fermions hard to isolate from SUSY sample
- case 2: $\Delta > m_{LSP}$ but smaller than other super-partners
  - Boson $\rightarrow$ 2 hard jets (or 1 jet + lepton)
  - if fermion is heavier. fermion $\rightarrow$ 2 hard jets (or 1 jet + lepton) + missing ET
- case 3: $\Delta > min(m_{\tilde{g}}, m_{\tilde{f}})$. Similar to MSSM. Hard to isolate from SUSY sample

# Two different type exotic particles: Example I—Triquark

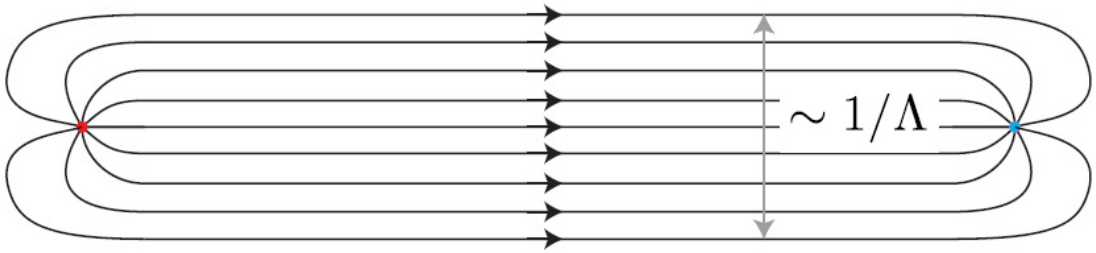
- scaler 6 and fermion $\overline{10}$ of SU(3)
- Y1 $6uu$ and Y2 $6u\overline{10}$
- $m_6$ and $m_{10}$
- decay production of $\overline{10}$, 3 jets final states
- $33 \rightarrow 6 \rightarrow 3 + \overline{10} \rightarrow 4\ jets$
- Three-jet invariant mass peak.

# Two different type exotic particles: Example II—leptodiquark

- scaler $6_1 s$ and fermion $\overline{6}_{2f}$ of SU(3)
- Y1 $6_{1s} uu$ and Y2 $6_{1s} \overline{6}_{2f} e$
- $m_{6s}$ and $m_{6f}$
- decay production of $\overline{6}_{2f}$, 2 jets + lepton final states
- $33 \rightarrow 6_{1s} \rightarrow 3 + \overline{6}_{2f} \rightarrow 3\ jets + lepton$

## Quirks and Strings (with M. Luty and S. Nasri)

- N flavor of exotic colored particle $D_i$ with mass $m_D \sim TeV$
- Global flavor SU(N) symmetry between the exotic particles
- Promote to local SU(N) symmetry
- Become strongly coupled at IR.
- $\Lambda \sim 100eV$




- like QCD with only heavy quark and no light quark
- Pair produced and attached by a long string that never break!
- The string could extend as long as 10 meters.
- strong interactions $\longrightarrow$ string interactions
- "quark" $\longrightarrow$ "quirk"

## "InfraColor"

Extend standard model gauge group:

- $SU(N_c)_{IC} \times SU(3)_C \times SU(2)_W \times U(1)_Y$
- $Q \sim (N, 3, 1)_{-1/3}$
- $\overline{Q} \sim (\overline{N}, \overline{3}, 1)_{1/3}$
- $L \sim (N, 1, 2)_{1/2}$
- $\overline{L} \sim (\overline{N}, 1, 2)_{-1/2}$
- $5 + \overline{5}$ of SU(5)
- $\Lambda_{IC} \ll \Lambda_{QCD}$

# Quirks at the LHC

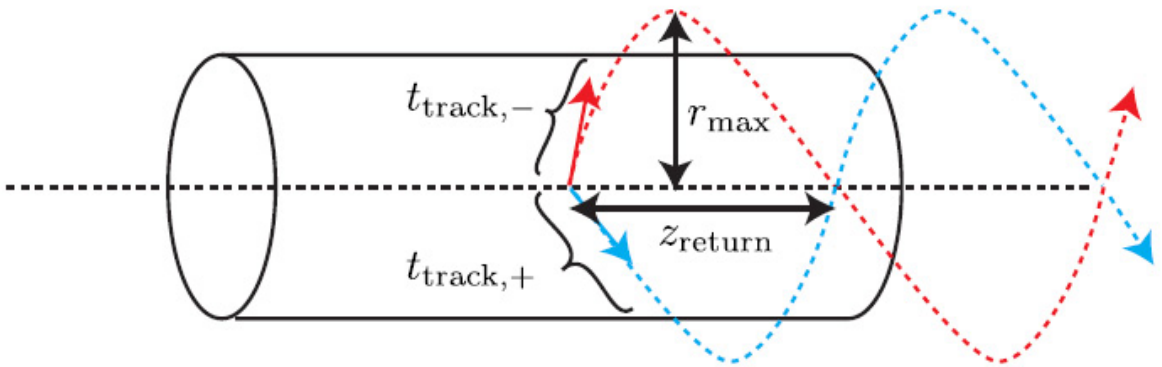


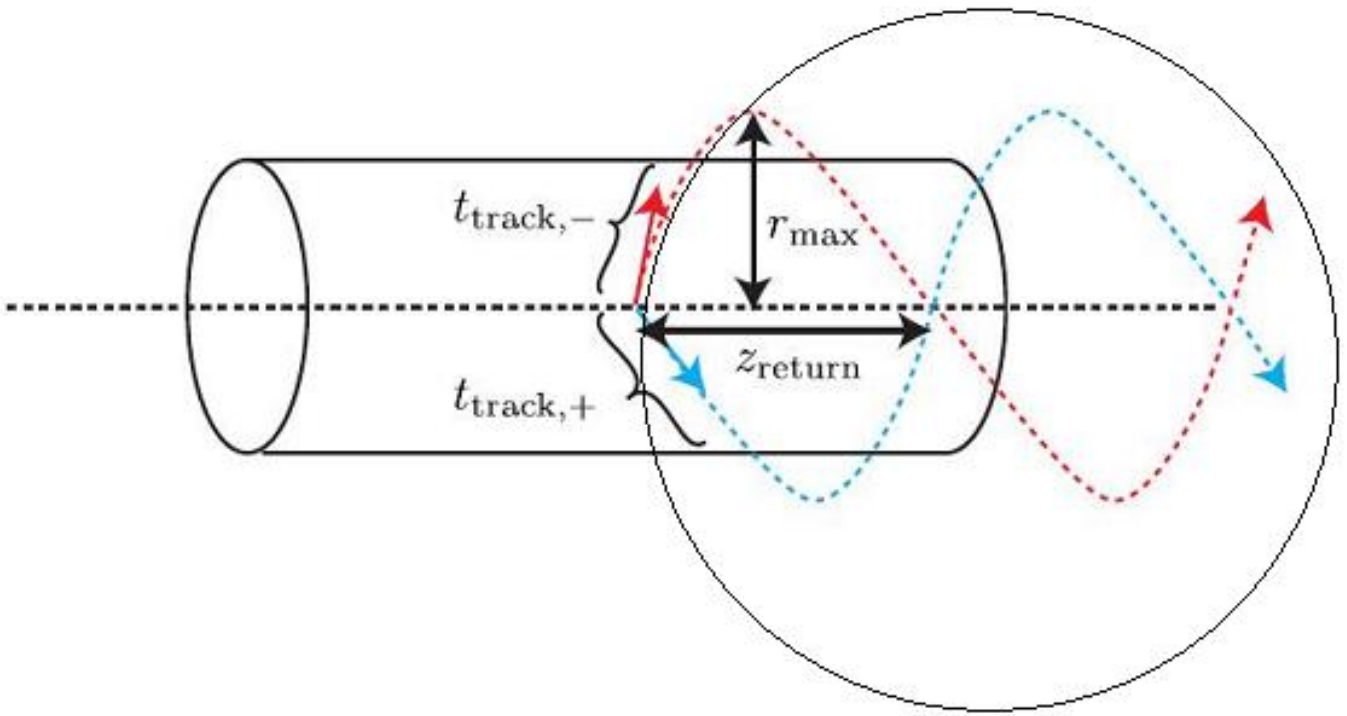

Figure 2: $\sigma \sim pb$ (strong production)

- $r_{max} \sim \frac{m_Q}{\Lambda_{IC}^2} \sim 10m(\frac{m_Q}{TeV})(\frac{\Lambda_{IC}}{100eV})^2$
- re-annihilation?

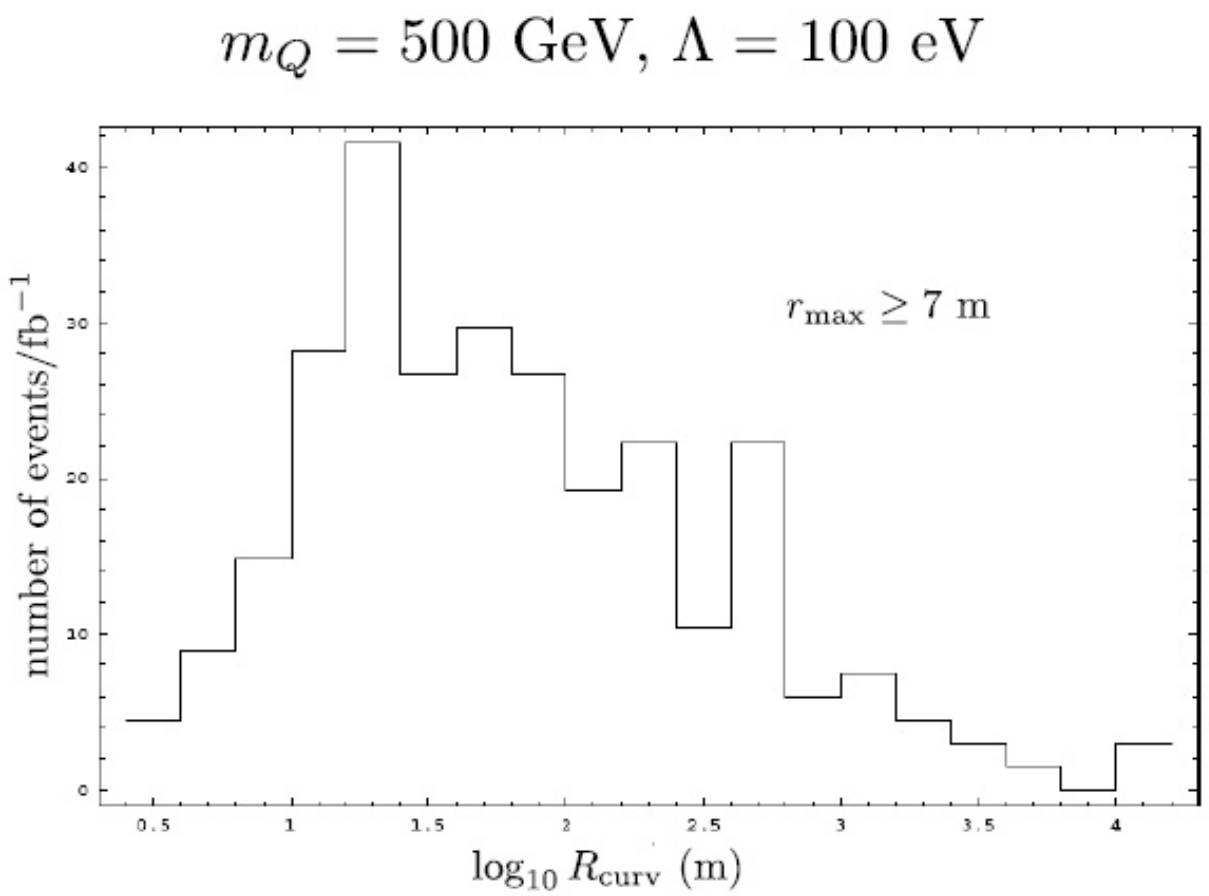
## Cosmology Bound

- BBN $\rightarrow \Lambda_{IC} < 100eV$ or $\Lambda_{IC} > 10MeV$
- quirk life time $< \mu s$
- or low reheating temperature

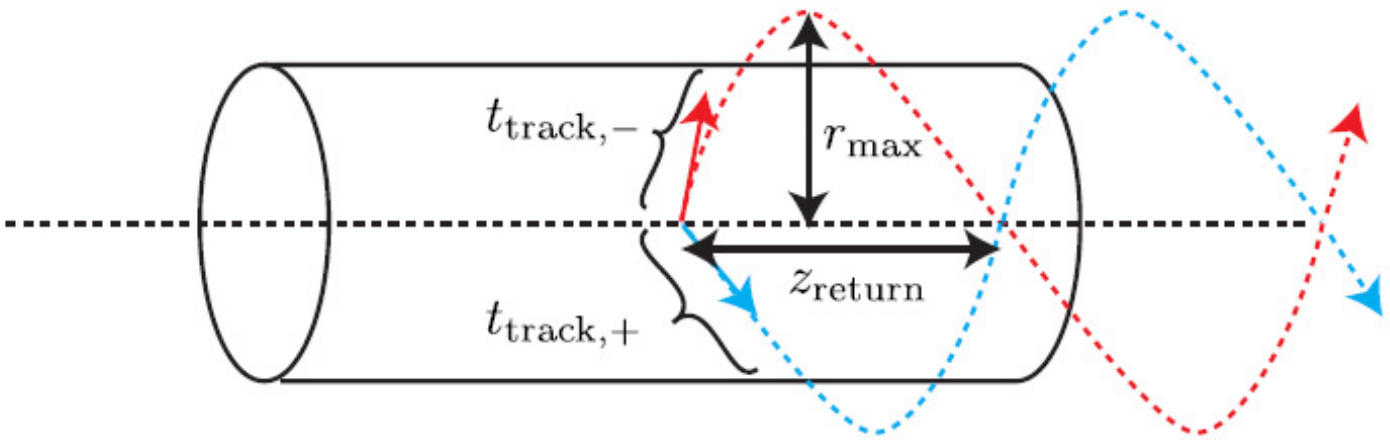
# Definition of curvatures



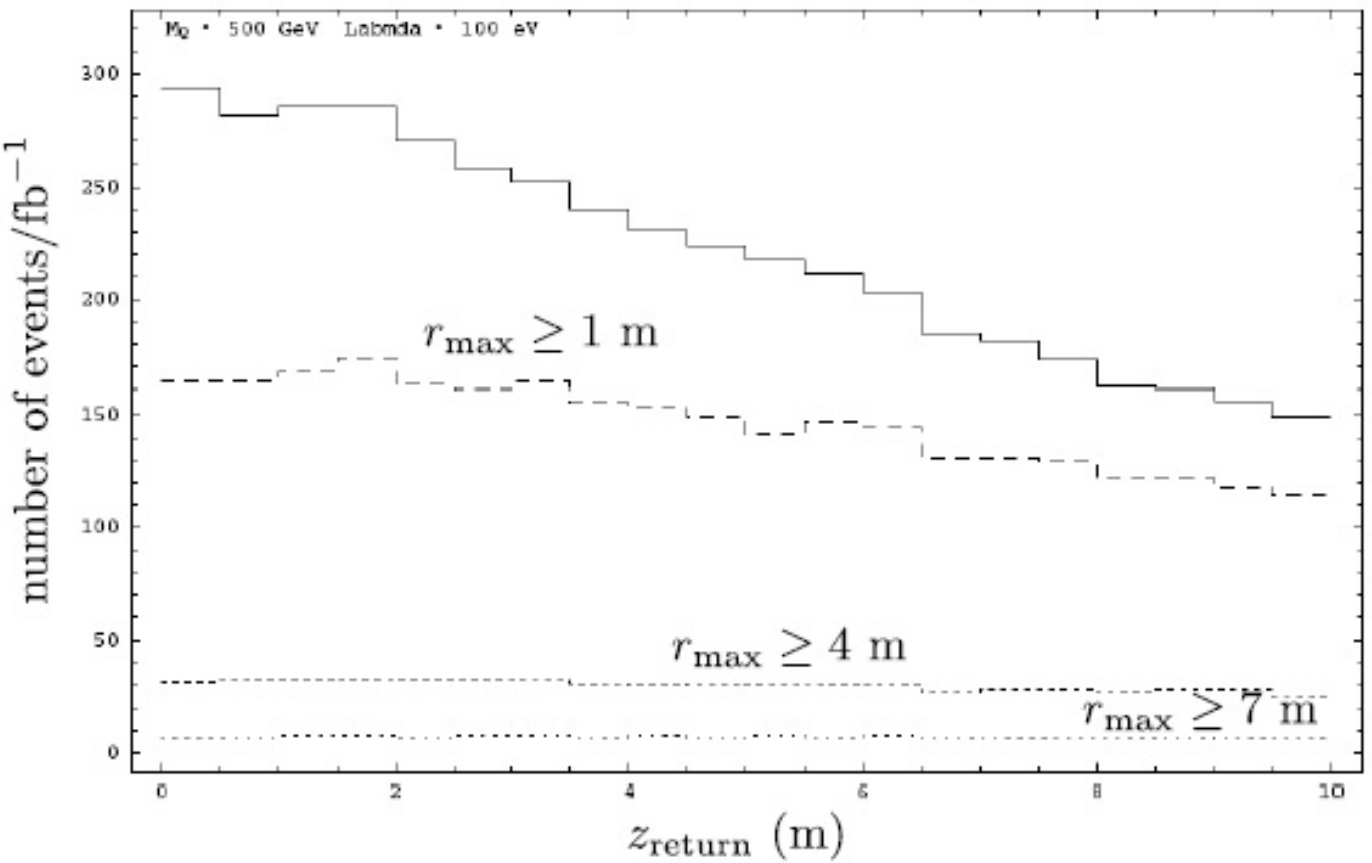
## Curvature in muon chamber



# Definition of kinetic variables



$m_Q = 500$ GeV, $\Lambda = 100$ eV



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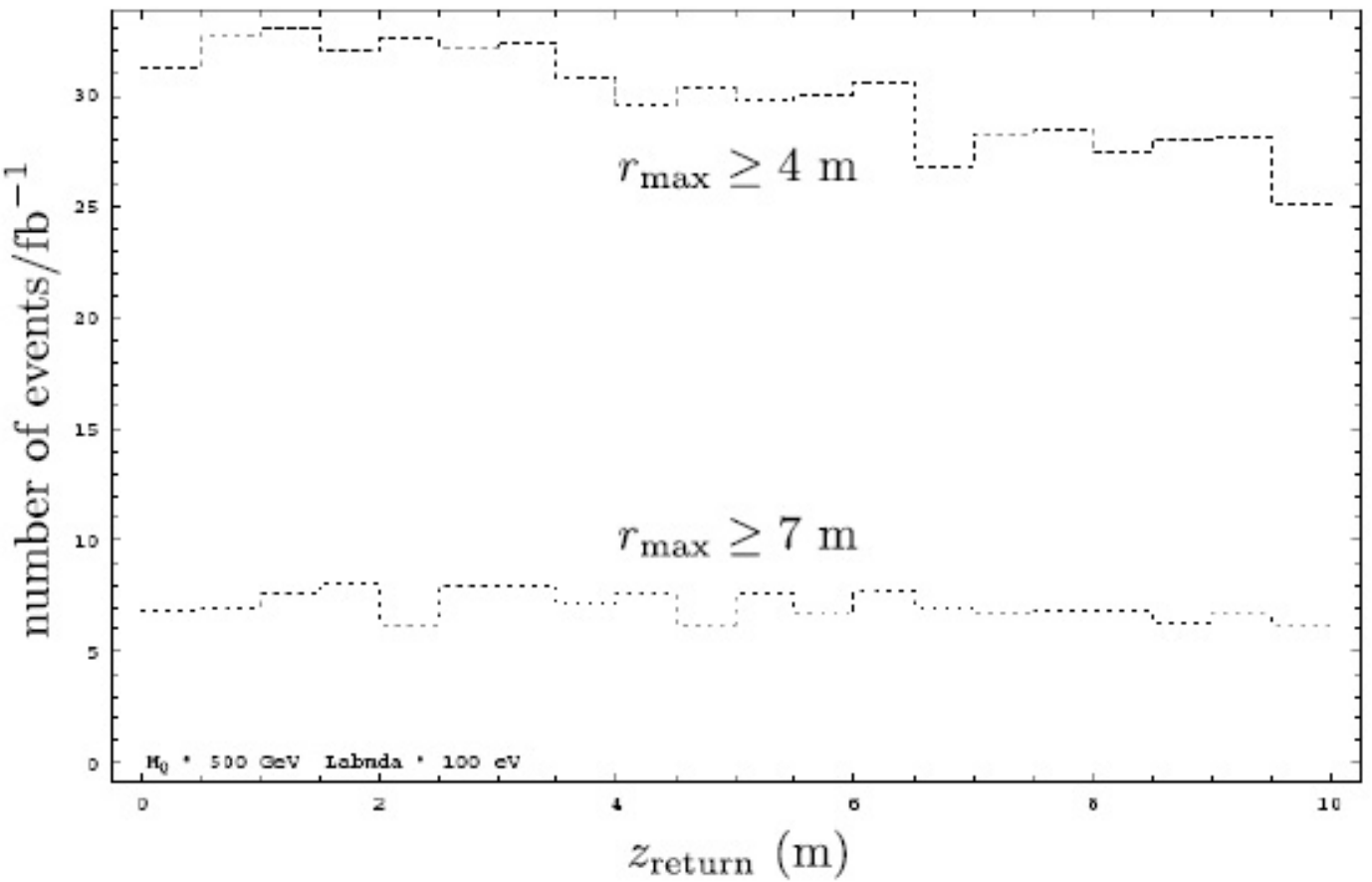

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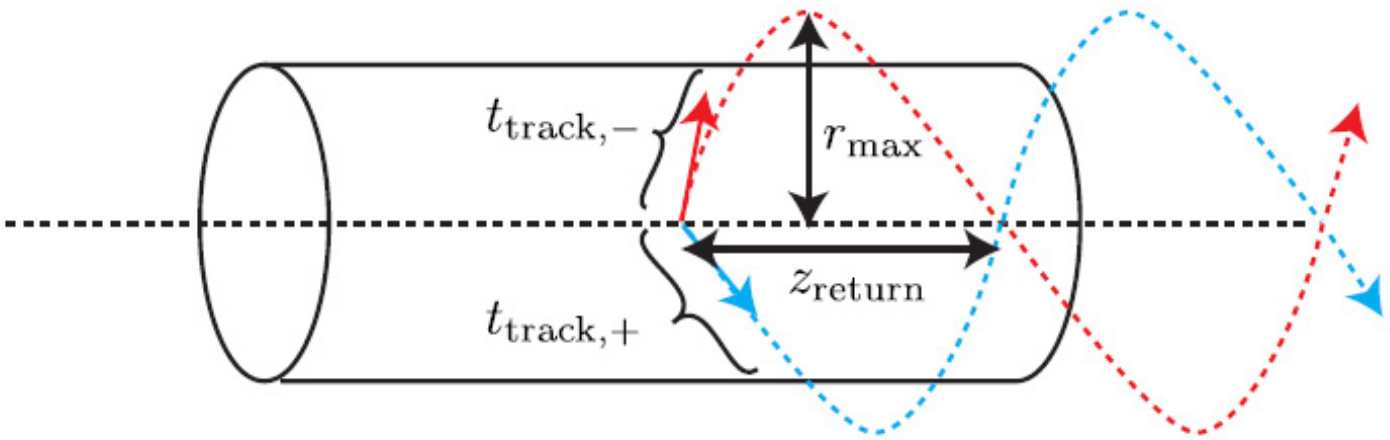
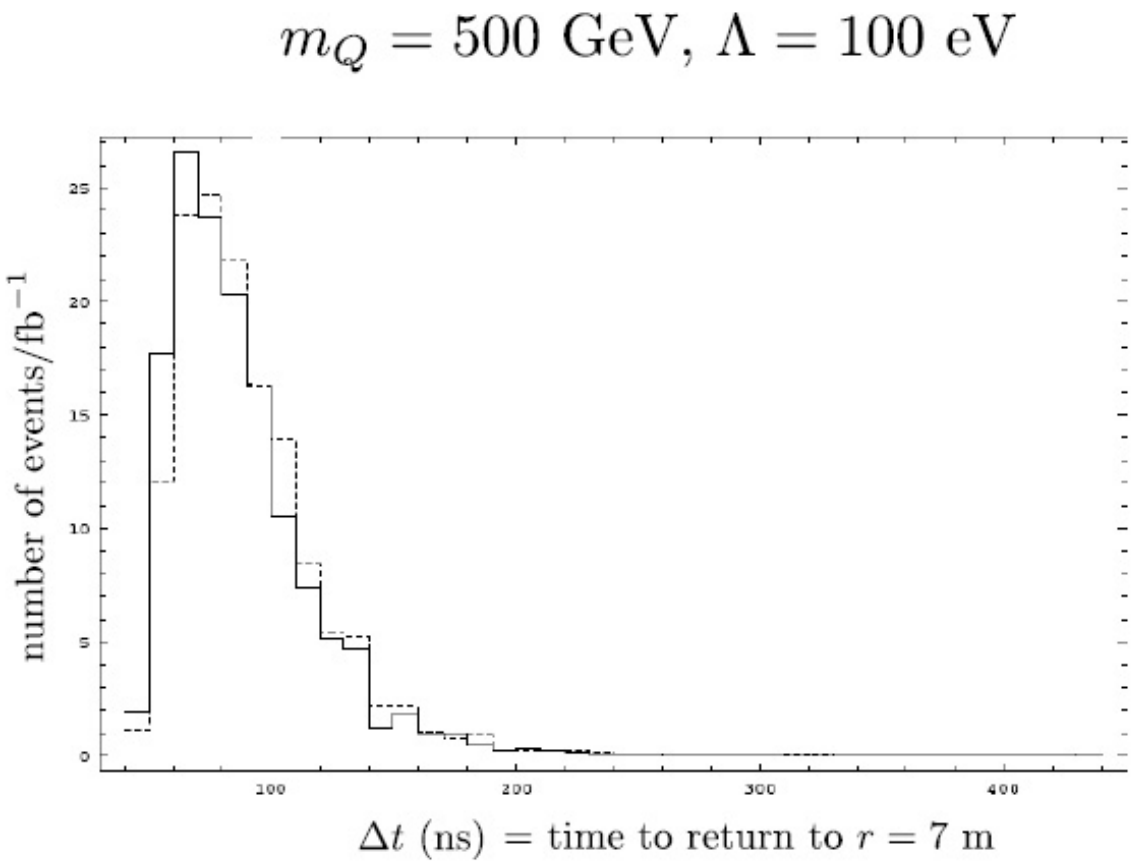
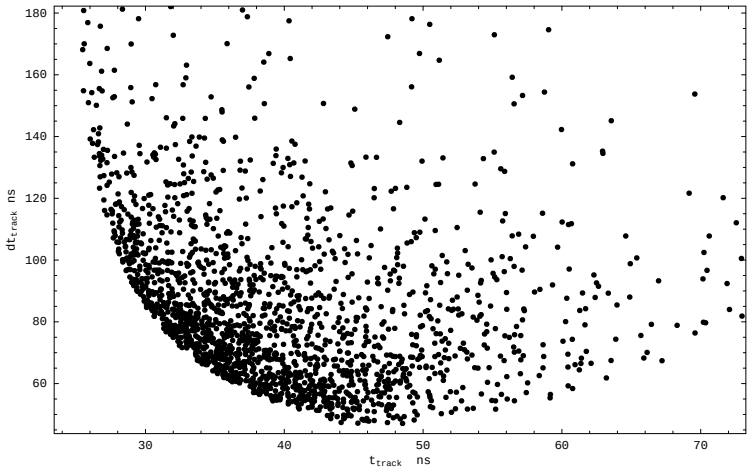


## Returned Quirk hit muon chamber

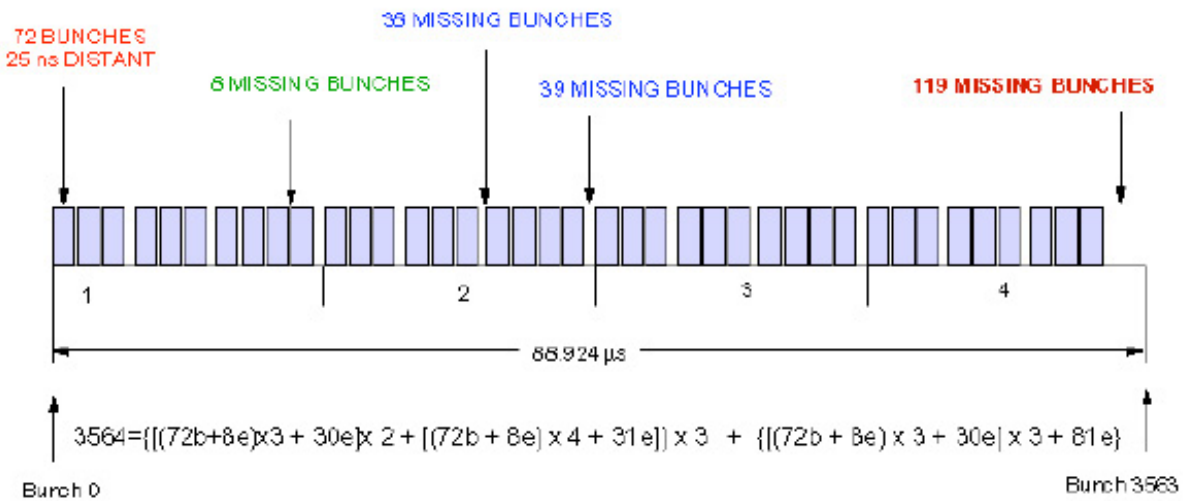


# Time delay between the two hits on muon chamber



# Timing is Everything...

## LHC bunch structure




Timing gaps $\sim \mu s$

# Conclusion

- Like-sign top production form Diquark 6 decay.
- Quasi-stable Colored Particles at LHC
- SUSY version of Di-quark and Lepto-quark
- signature of Tri-quark and Lepto-diqiark.
- Quirks and Strings