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...

LHC may give us a Surprise!

- New physics with Exotic Signatures
- Quantum Field Theory and self-consistent
- Distinguished signatures at LHC
- Background free and/or strongly produced at LHC.
- Be prepared and do not miss them...

Colored Particles—Large Production Rate

- 3 (Quasi-stable heavy colored particles) (with P. Langacker and B. Nelson)
- 3 (Di-quark and Lepto-quark) (with P. Langacker and B. Nelson)
- 8 (Dirac gluino)
- 6 (Neutron oscillation)
- Quirks and Strings (with M. Luty and S. Nasri)

Quasi-Stable Colored Particles

- Ordinary families $3 \times (L_{-\frac{1}{2}}\ , Q_{\frac{1}{6}}\ , \bar{u}_{-\frac{2}{3}}\ , \bar{d}_{\frac{1}{3}}\ , e^{+}_{1}\ , \bar{\nu}_{0}\ )$ with $Q' = 1$
- Higgs doublets $h_{u\frac{1}{2}}\ , h_{d_{-\frac{1}{2}}}$ with $Q' = -2$
- Exotic quarks $2 \times (D_{t_{-\frac{1}{3}}}\ , \bar{D}_{\frac{t1}{3}})$ with $Q' = -3$, transforming as (3,1) under $SU(3) \times SU(2)$
- Exotic leptons $2 \times (L_{s_{-\frac{1}{2}}}\ , \bar{L}_{\frac{s1}{2}})$ with $Q' = -2$, transforming as (1,2) under $SU(3) \times SU(2)$
- SM singlets S with $Q' = 4$, T with $Q' = 6$,

Allowed operators

- dimension 4 operators
  - SH_uH_d , $TD_t\bar{D}_t$, $SL_s\bar{L}_s$
  - $L_sQ\bar{d}$, $\bar{L}_sQ\bar{u}$, L_sLe^+ , $\bar{L}_sL\bar{\nu}$
  - SH_uL_s , $SH_d\bar{L}_s$, $H_uL_s\bar{\nu}$, $H_dL_se^+$
- dimension 5 operators
  - $\bar{D}_tQH_dS$, $\bar{D}_tQL_sS$, $\bar{D}_tQQ\bar{u}$, $D_t\bar{d}\bar{\nu}\bar{\nu}$, $D_t\bar{u}e^+\bar{\nu}$, $\bar{D}_tQL\bar{\nu}$ $[B_D = \frac{1}{3}]$
  - $\bar{D}_t\bar{u}\bar{u}e^+$, $D_tQQ\bar{\nu}$, $\bar{D}_t\bar{d}\bar{u}\bar{\nu}$ $[B_D = -\frac{2}{3}]$

life time as a function of mass scales

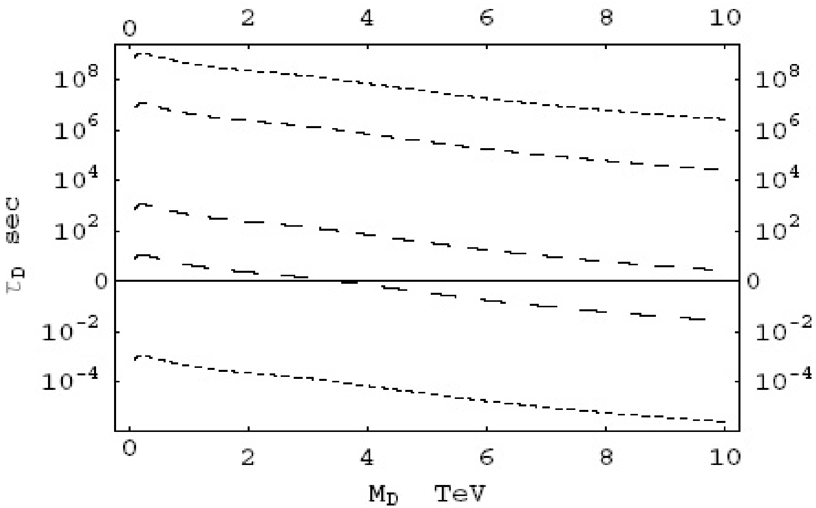


Figure 1: The lifetime of the quasi-stable exotic particle. The curves correspond to different mass suppression scales in the higher-dimensional operators. $M = 10^{13}, 10^{15}, 10^{16}, 10^{18}, 10^{19}$ GeV from below to above. The turns in the curves correspond to different decay channels dominating.

Cosmological bound and Proton decay bound

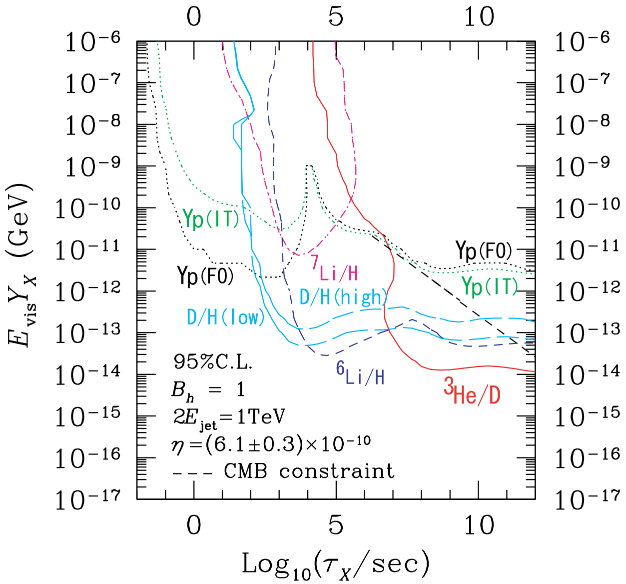
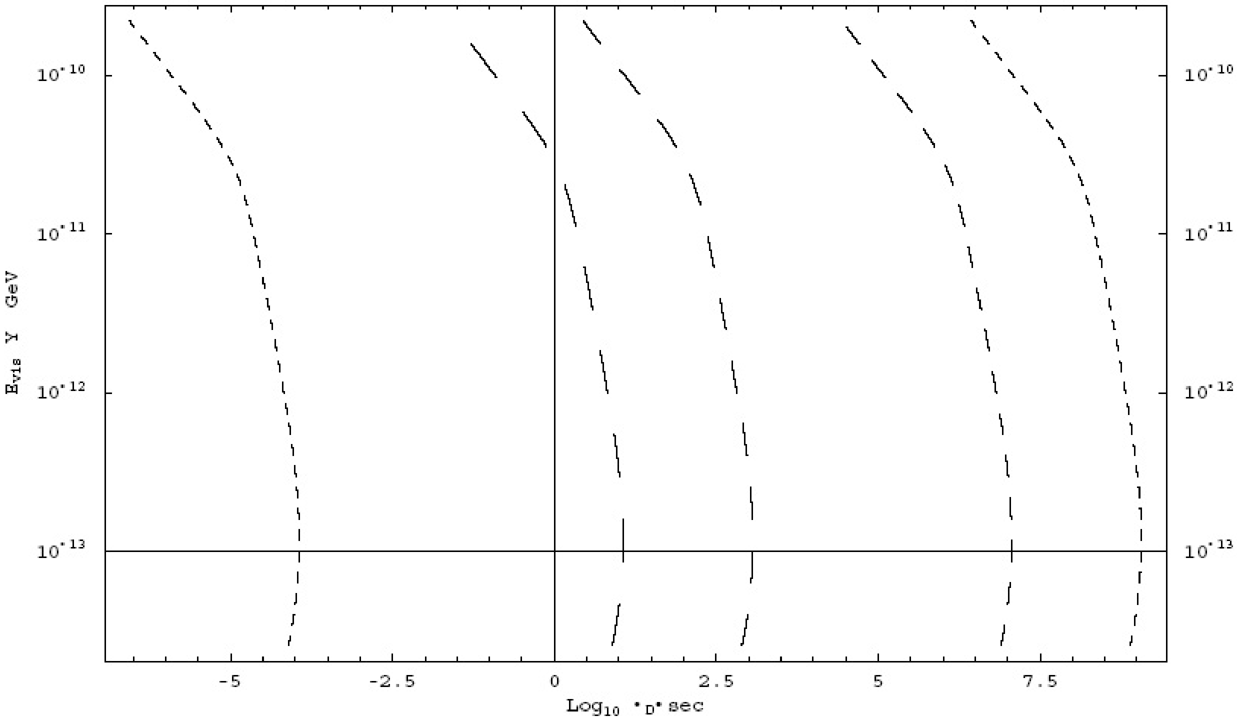


Figure 2: Astrophysical bound on the long lived particles (From M. Kawasaki, K. Kohri and T. Moroi, arXiv:astro-ph/0402490)

life time vs relic abundance



Collider Signature of quasi-stable colored particles

- Hardronization. Charged R-hardron vs neutral R-hardron.
- Hardron 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-hardron will leave a track

Di-quark and Lepto-quark

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
- study the production rate, decay rates,implementing PDF
- generate parton level events using Comphep.
- imbed them into PYTHIA

Di-quark and Simulation Software

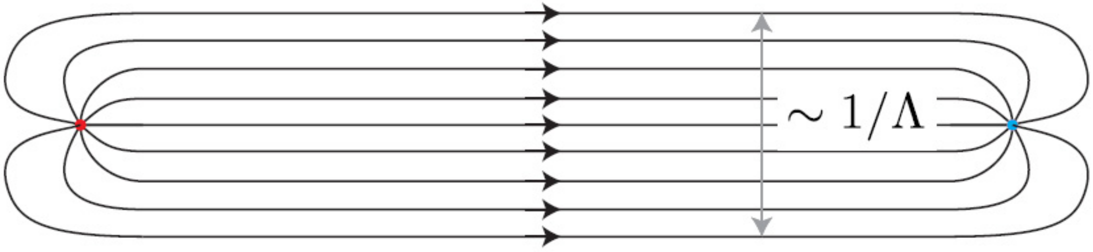
- add Lepto quark into Comphep—Follow the rules
- Lepto quark is already built in PYTHIA
- add Di-quark into Comphep?
- deal with special color structure in Comphep
- color flow in PYTHIA?
- it is interesting and important to make the simulation software easy extendable.

Signatures and Backgrounds

- isolate from the SUSY sample
- $\Delta = |m_{D_{1/2}} - m_{D_0}|$
- case 1: $\Delta < m_{LSP}$
  - Boson $\longrightarrow$ 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 $\longrightarrow$ 2 hard jets (or 1 jet + lepton)
  - if fermion is heavier. fermion $\longrightarrow$ 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

Quirks and Strings

Ordinary QCD when $r > 1/\Lambda$,color tub forms



- string will break
- exist light quarks
- QCD with only heavy quark?
- strong interactions $\longrightarrow$ string interactions
- "quark" $\longrightarrow$ "quirk"

"InfraColor"

Extend standard model gauge group:

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

Quirks at the LHC

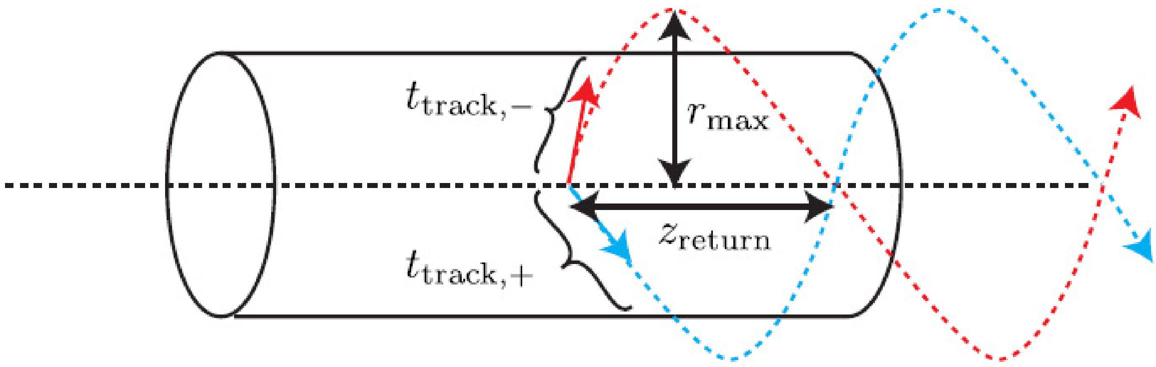


Figure 3: $\sigma \sim pb$ (strong production)

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

Cosmology Bound

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

quirks and strings at LHC

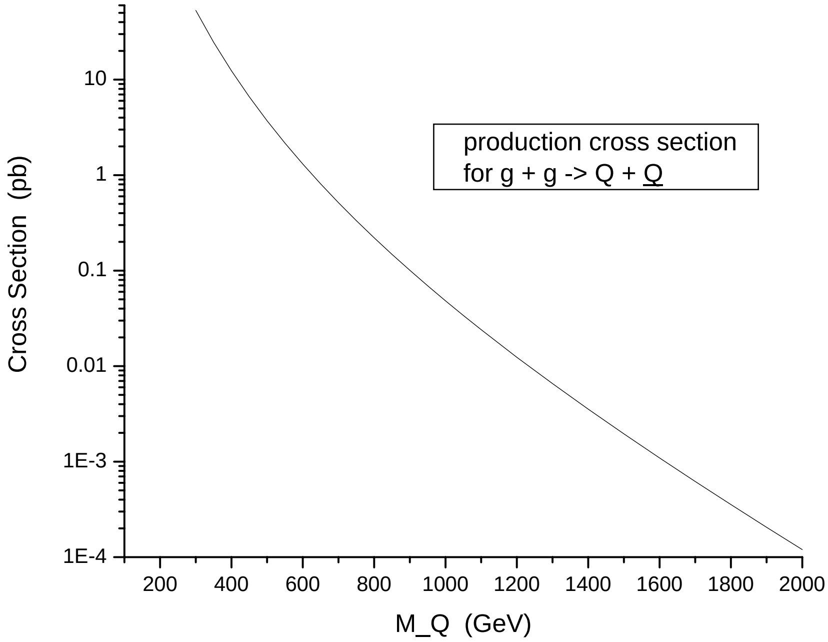
Quirk = heavy stable , strongly interacting , charged

- heavy muon
- monojet + heavy muon
- decay of quirk in flight or stopped

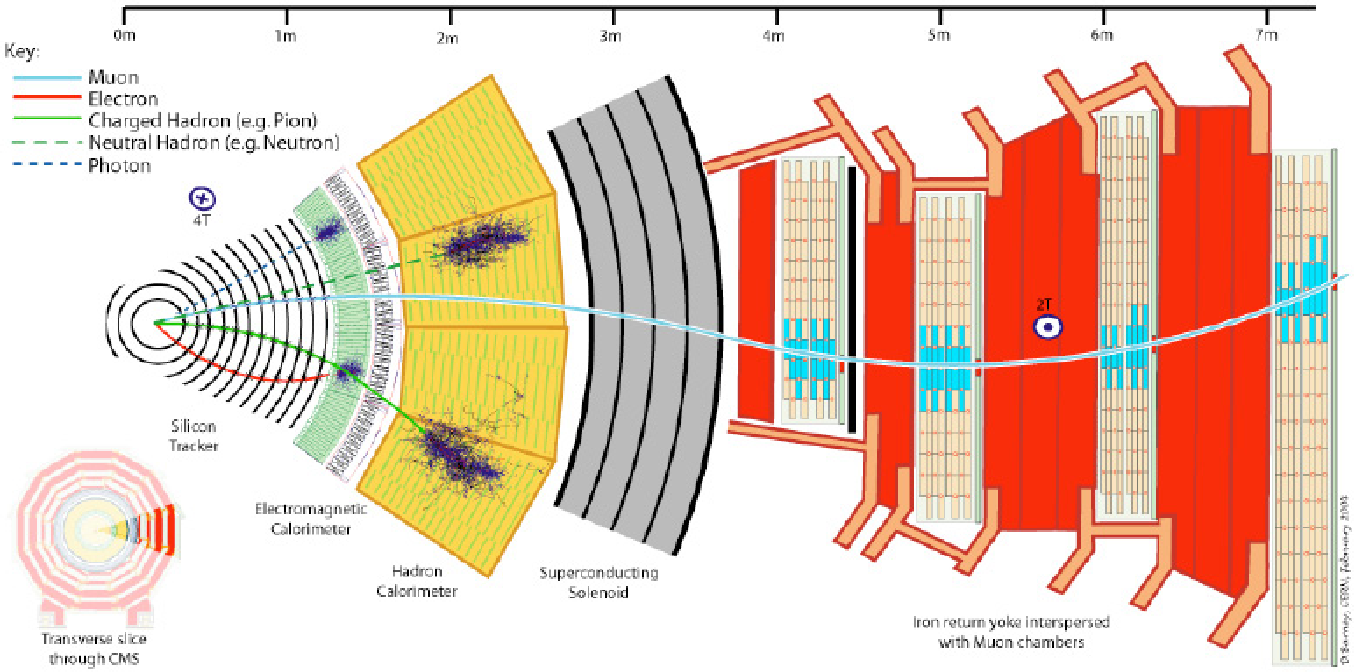
the effects of strings

- curvatures in ϕ = constant plane
- returning quirks

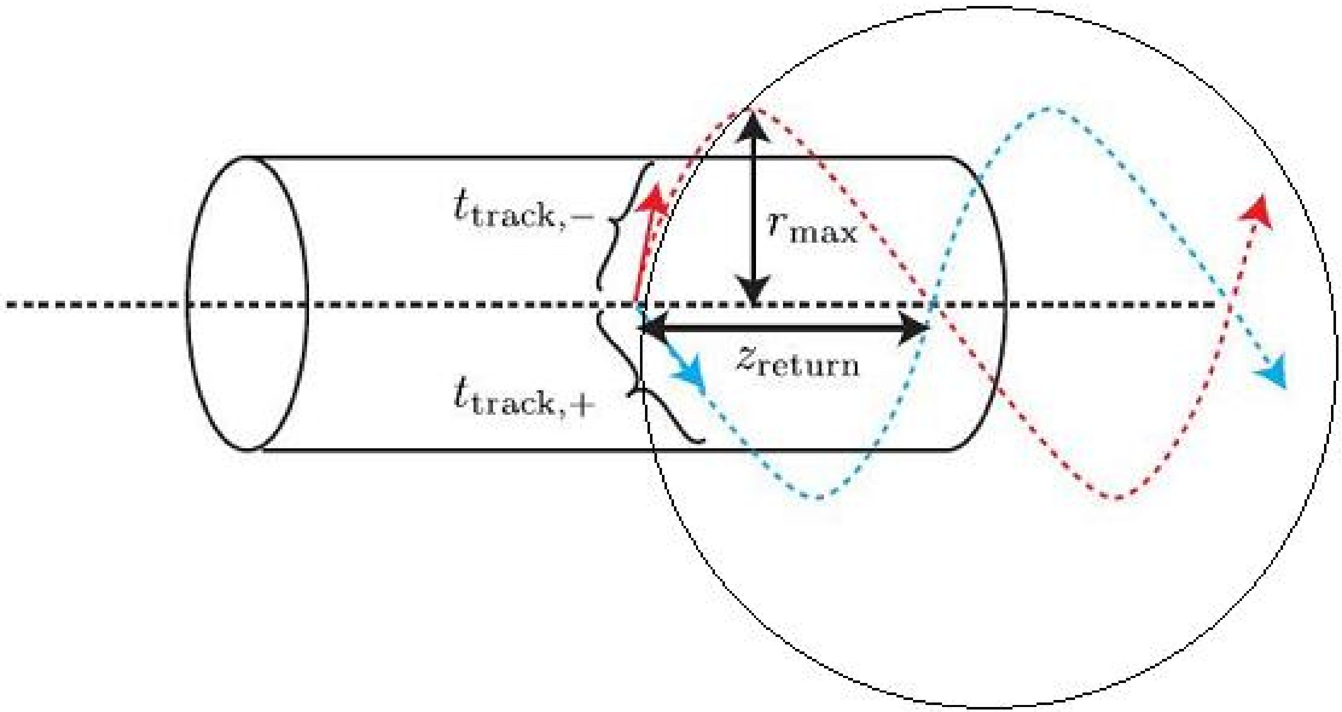
Production Cross Section



CMS geometry

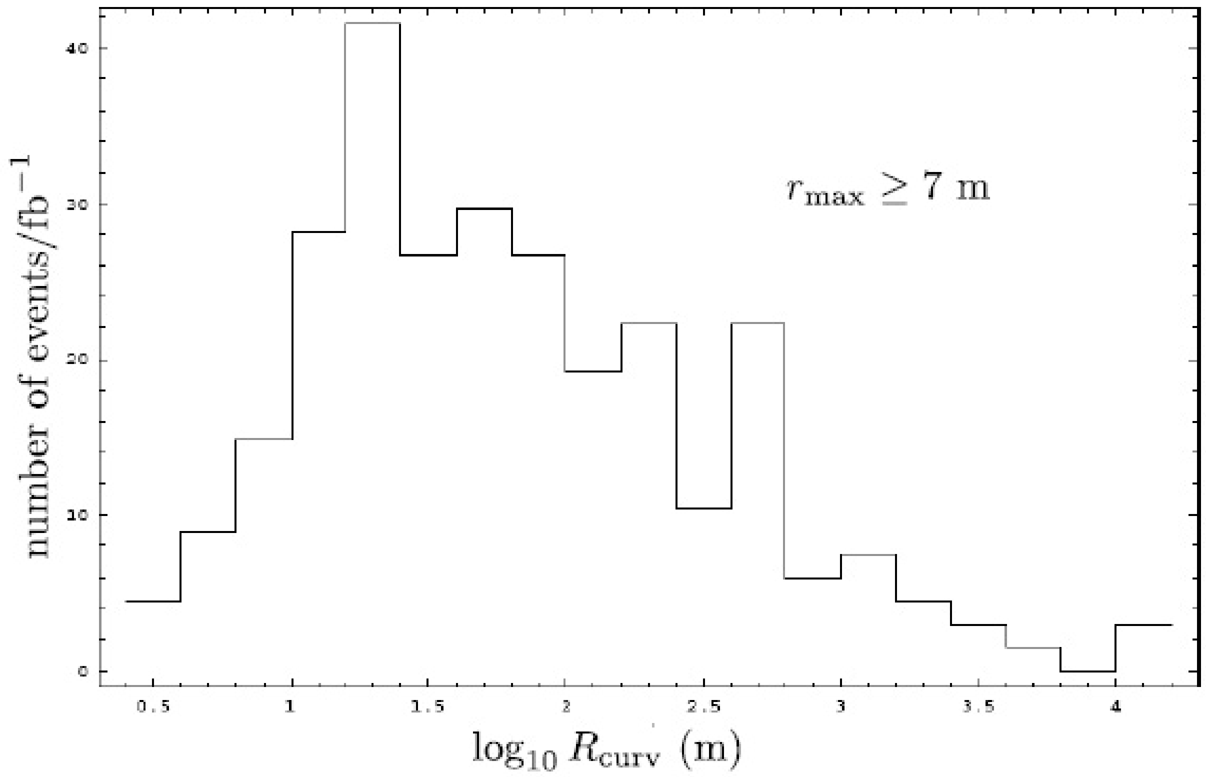


Definition of curvatures

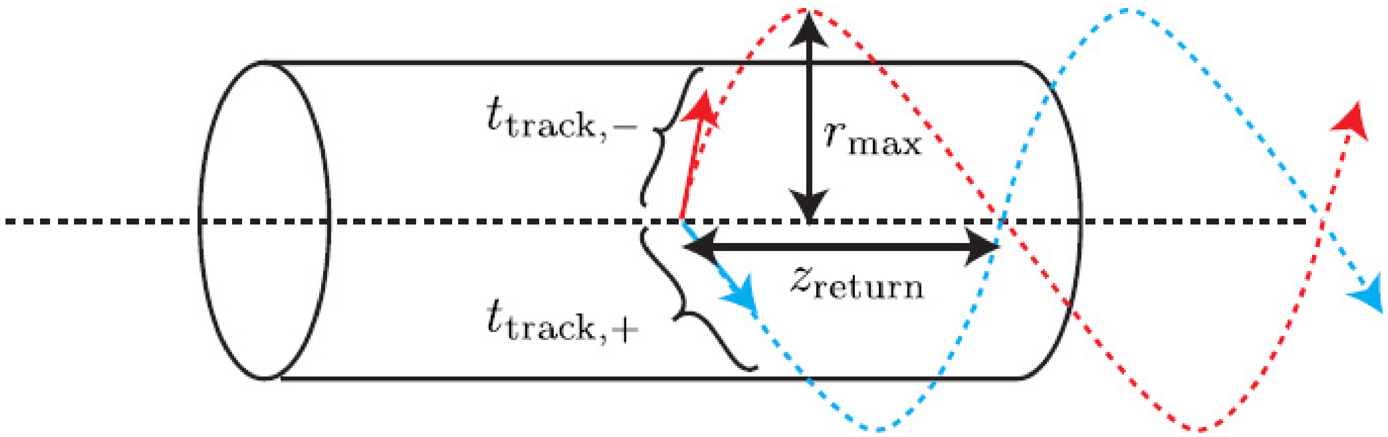


Curvature in muon chamber

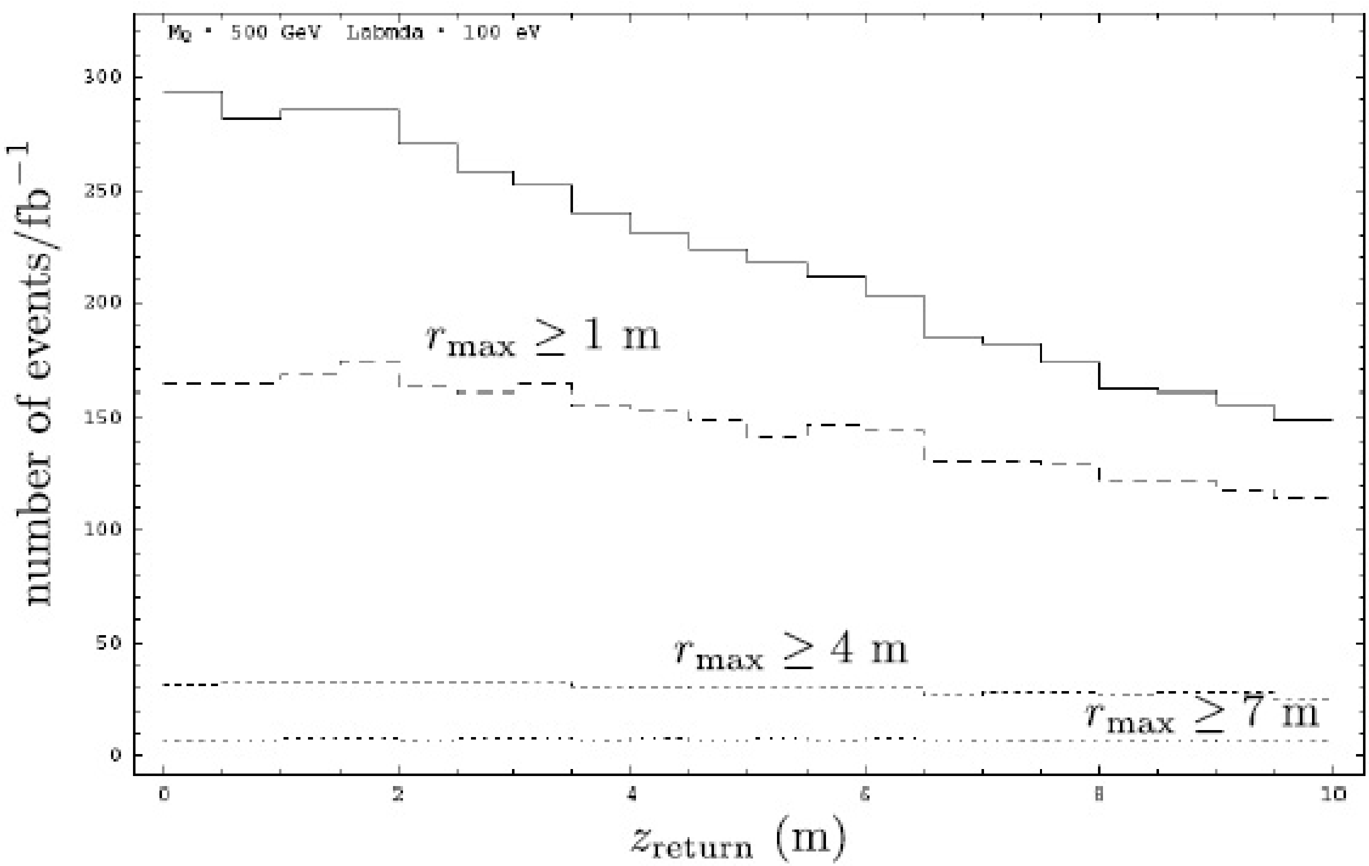
$$m_Q = 500 \text{ GeV}, \Lambda = 100 \text{ eV}$$



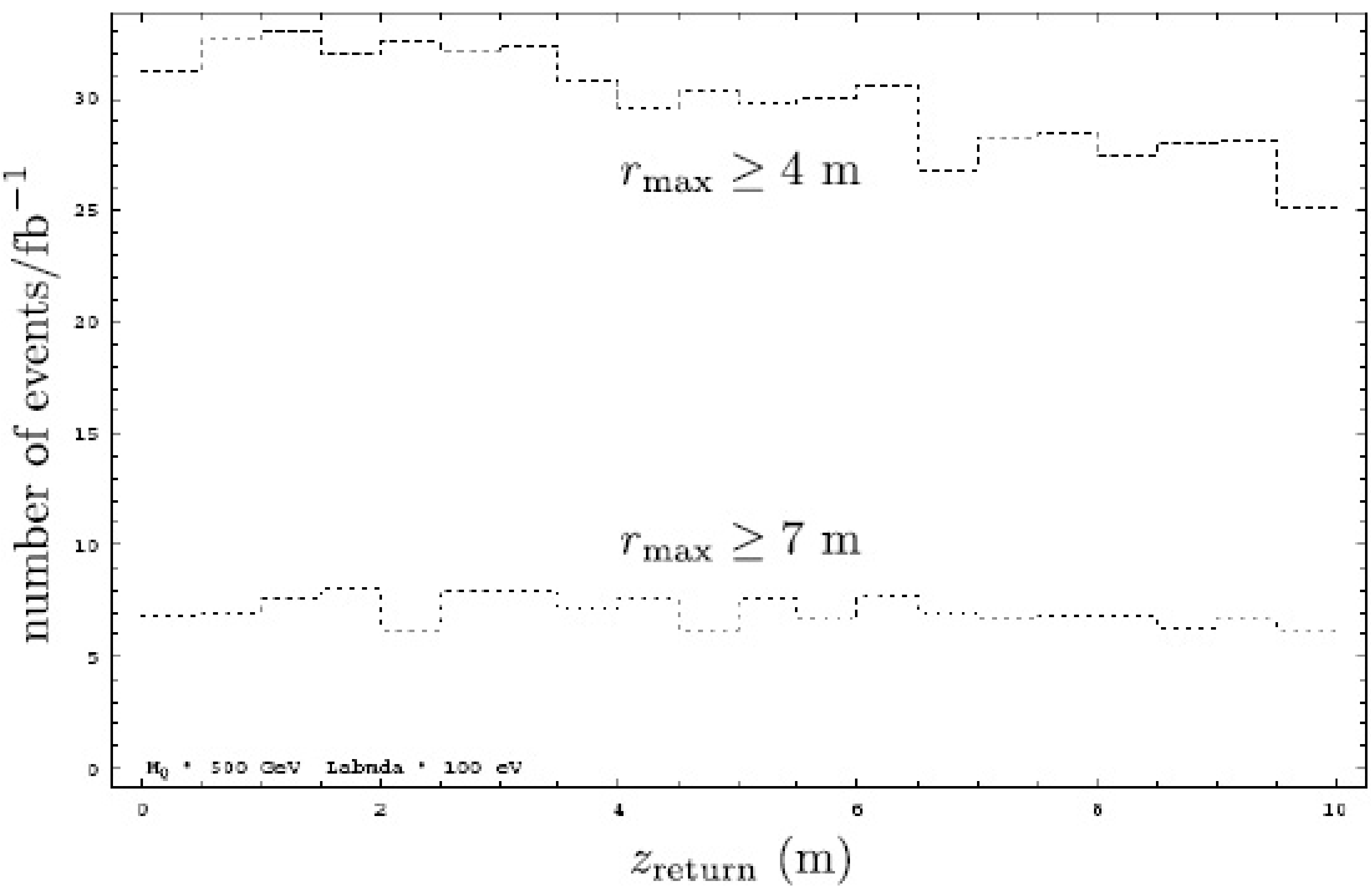
Definition of kinetic variables



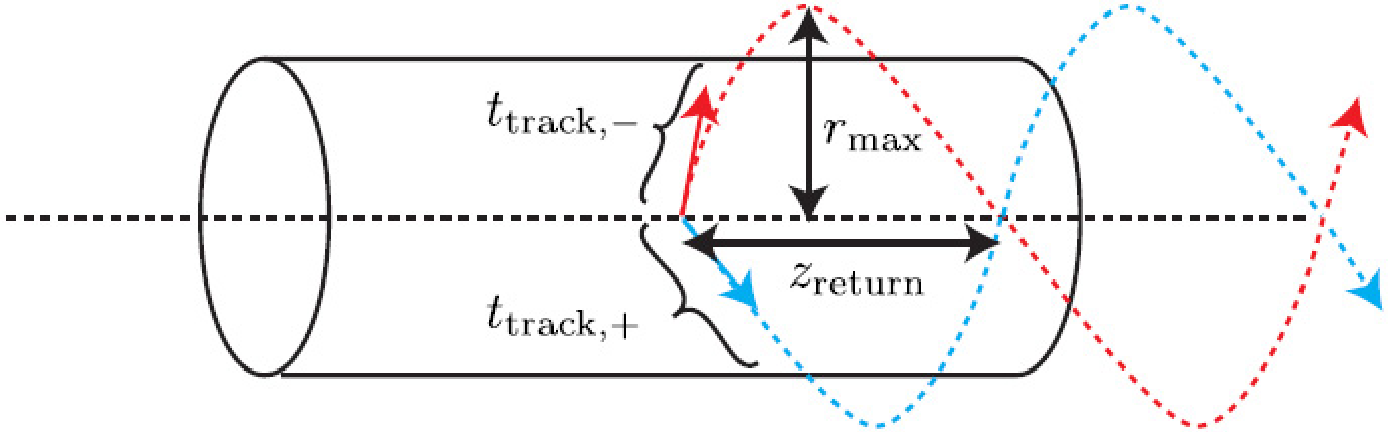
$m_Q = 500$ GeV, $\Lambda = 100$ eV



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

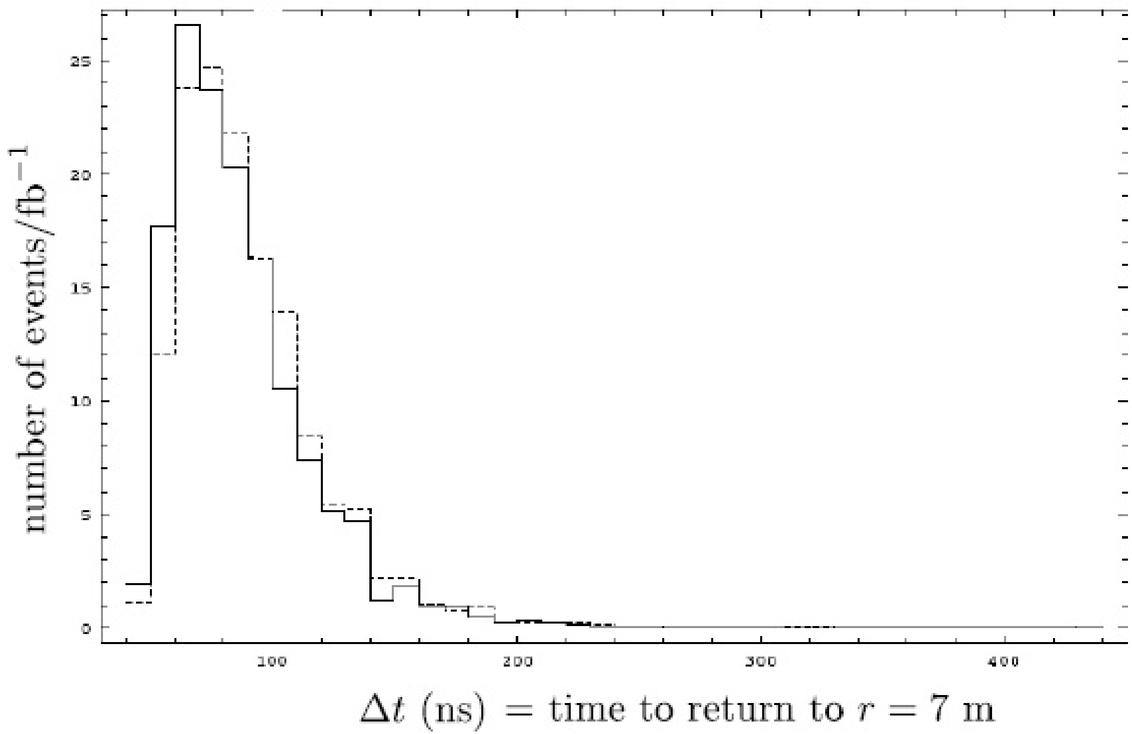


Definition of kinetic variables

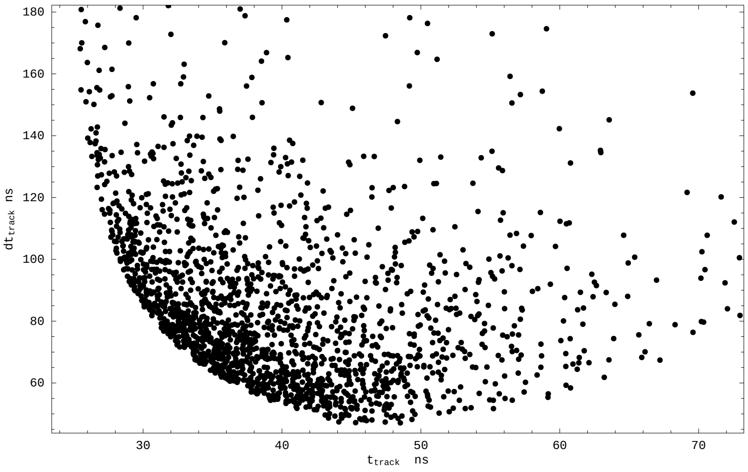


Returned Quirk hit muon chamber

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

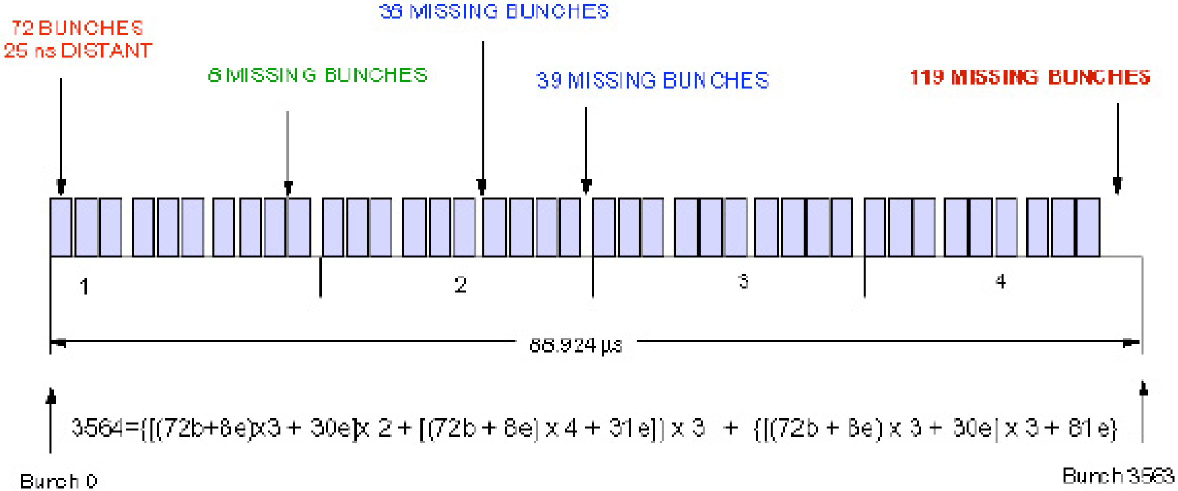


Time delay between the two hits on muon chamber



Timing is Everything...

LHC bunch structure



Timing gaps $\sim \mu s$

Conclusion

- Three types of exotic colored particles at LHC
- Quasi-stable Colored Particles
- Di-quark and Lepto-quark
- Quirk and String