# Scattering of Stable Heavy Hadrons

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# Stable Massive Particles

(Just about) every BSM scenario accommodates meta-stable massive objects (SMP).

Hierarchy problem alone suggests need to consider all conceivable signatures of new physics at TeV energies.

SMPs, Missing Et, jets, leptons important observables LHC searches.

Searches must be performed for different types of SMPs

Aim: Geant-based scattering models for colour neutral, triplet, octet exotic objects.

: Flexibility to allow conceivable experimental signatures.

| SMP | LSP | Scenario | Conditions |
|---|---|---|---|
| $\tilde{\tau}_1$ | $\tilde{\chi}_1^0$ | MSSM | $\tilde{\tau}_1$ mass (determined by $m^2_{\tilde{\tau}_{L,R}}$, $\mu$, $\tan\beta$, and $A_\tau$) close to $\tilde{\chi}_1^0$ mass. |
| | $\tilde{G}$ | GMSB | Large $N$, small $M$, and/or large $\tan\beta$. |
| | | $\tilde{g}$MSB | No detailed phenomenology studies, see [23]. |
| | | SUGRA | Supergravity with a gravitino LSP, see [24]. |
| | $\tilde{\tau}_1$ | MSSM | Small $m_{\tilde{\tau}_{L,R}}$ and/or large $\tan\beta$ and/or very large $A_\tau$. |
| | | AMSB | Small $m_0$, large $\tan\beta$. |
| | | $\tilde{g}$MSB | Generic in minimal models. |
| $\tilde{\ell}_{i1}$ | $\tilde{G}$ | GMSB | $\tilde{\tau}_1$ NLSP (see above). $\tilde{e}_1$ and $\tilde{\mu}_1$ co-NLSP and also SMP for small $\tan\beta$ and $\mu$. |
| | $\tilde{\tau}_1$ | $\tilde{g}$MSB | $\tilde{e}_1$ and $\tilde{\mu}_1$ co-LSP and also SMP when stau mixing small. |
| $\tilde{\chi}_1^+$ | $\tilde{\chi}_1^0$ | MSSM | $m_{\tilde{\chi}_1^+} - m_{\tilde{\chi}_1^0} \lesssim m_{\pi^+}$. Very large $M_{1,2} \gtrsim 2$ TeV $\gg \lvert\mu\rvert$ (Higgsino region) or non-universal gaugino masses $M_1 \gtrsim 4M_2$, with the latter condition relaxed to $M_1 \gtrsim M_2$ for $M_2 \ll \lvert\mu\rvert$. Natural in O-II models, where simultaneously also the $\tilde{g}$ can be long-lived near $\delta_{GS} = -3$. |
| | | AMSB | $M_1 > M_2$ natural. $m_0$ not too small. See MSSM above. |
| $\tilde{g}$ | $\tilde{\chi}_1^0$ | MSSM | Very large $m^2_{\tilde{q}} \gg M_3$, e.g. split SUSY. |
| | $\tilde{G}$ | GMSB | SUSY GUT extensions [25–27]. |
| | $\tilde{g}$ | MSSM | Very small $M_3 \ll M_{1,2}$, O-II models near $\delta_{GS} = -3$. |
| | | GMSB | SUSY GUT extensions [25–29]. |
| $\tilde{t}_1$ | $\tilde{\chi}_1^0$ | MSSM | Non-universal squark and gaugino masses. Small $m^2_{\tilde{q}}$ and $M_3$, small $\tan\beta$, large $A_t$. |
| $\tilde{b}_1$ | | | Small $m^2_{\tilde{q}}$ and $M_3$, large $\tan\beta$ and/or large $A_b \gg A_t$. |

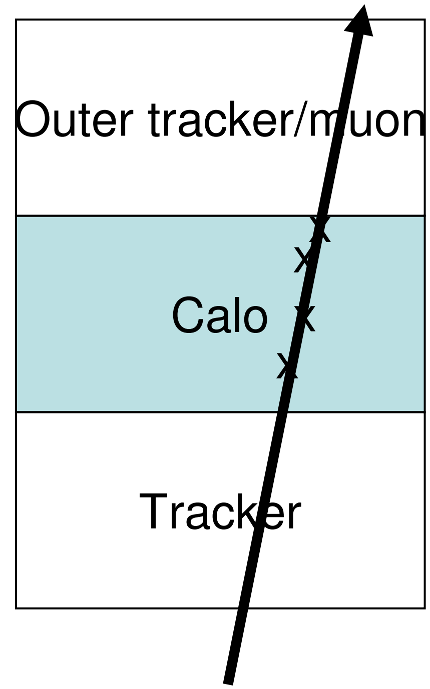
Table 1
Brief overview of possible SUSY SMP states considered in the literature. Classified by SMP, LSP, scenario, and typical conditions for this case to materialise in the given scenario. See text for details.

hep-ph/0611040

# SMPs and scattering

| SMP | charge | Scattering |
|---|---|---|
| lepton, free quark (fractional charge) | Electric | Ok |
| Colour triplet, octet (leading to H-hadron) | Colour | Hadronic scattering not well known |
| Dirac monopole, fractional magnetic charge | Magnetic | Ok |

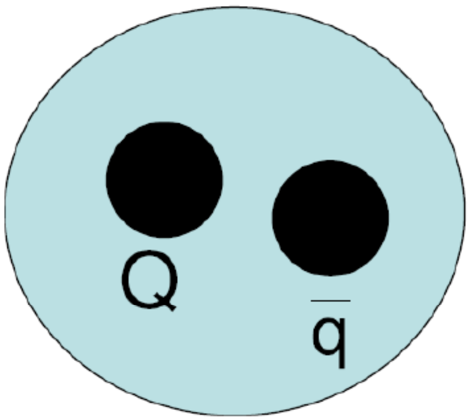
+ combinations of above.




Scattering of hadronic SMPs (H-hadrons,R-hadrons...) poorly understood but potentially significant effect.
Many/most searches rely on muon-like object.

Scattering can cause:
(1) energy loss
(2) disappearence of signal: $H^{+} + n \rightarrow H^{0} + p$
Generic/phase space model typically used: hep-ph/061216, hep-ph/0404001.
Complement with Triple-Regge implementation for systematic studies.

# Heavy hadron scattering




Heavy exotic meson from massive exotic colour triplet Q and SM quark $\overline{q}$.

$M_Q \approx M_H = 200$ GeV  $E = 1$ TeV

$\Rightarrow \gamma = E/M = 5$

$M_q \approx 0.2$ GeV $\Rightarrow KE_q = (\gamma - 1) M_q \approx$ GeV

Heavy quark doesn't interact

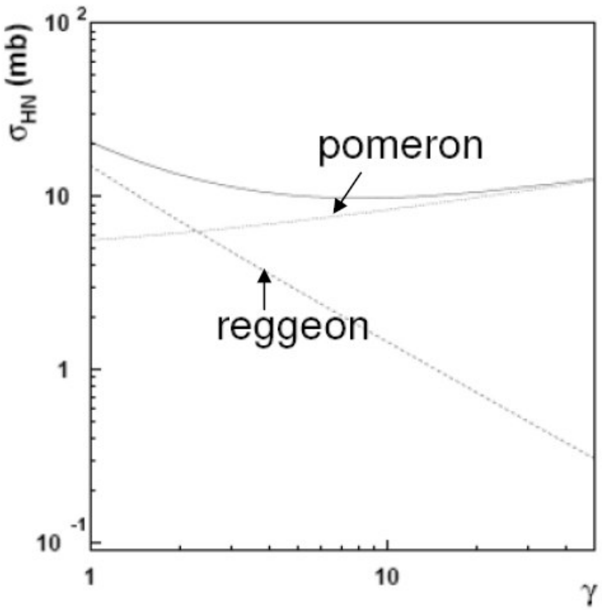
Low energy collision between SM quark in material.

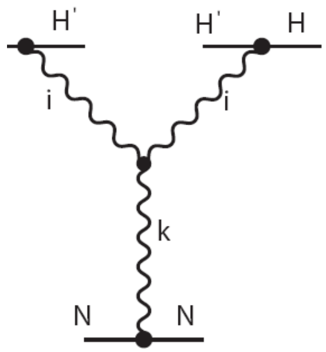
**Recent ref: hep-ex/0404001** (A.C. Kraan)

# Calculating energy loss

Interaction of heavy hadron: $H + N \rightarrow H' + X$

Triple Regge ansatz with parameters optimised from low energy scattering (arXiv:0710.3930, A. Kaidalov, D. Milstead et al.).




$$\frac{d^2\sigma_{RRR}}{dtdM_X^2}(\gamma, M_X^2) = \frac{1}{M_X^2}\sigma_R^2(\gamma)C_{RRR}\exp[(2B_{RH} + B_{RRR} + 2\alpha'_R\ln(\frac{2\gamma M_0^2}{M_X^2}))t]\left(\frac{M_0^2}{M_X^2}\right)^{\Delta_R} \quad (4)$$

$$\frac{d^2\sigma_{RRP}}{dtdM_X^2}(\gamma, M_X^2) = \frac{1}{M_X^2}\sigma_R^2(\gamma)C_{RRP}\exp[(2B_{RH} + B_{RRP} + 2\alpha'_P\ln(\frac{2\gamma M_0^2}{M_X^2}))t]\left(\frac{M_0^2}{M_X^2}\right)^{2\Delta_R-\Delta_P} \quad (5)$$

$$\frac{d^2\sigma_{PPR}}{dtdM_X^2}(\gamma, M_X^2) = \frac{11}{M_X^2}\sigma_P^2(\gamma)C_{PPR}\exp[(2B_{PH} + B_{PPR} + 2\alpha'_P\ln(\frac{2\gamma M_0^2}{M_X^2}))t]\left(\frac{M_0^2}{M_X^2}\right)^{2\Delta_P-\Delta_R} \quad (6)$$

$$\frac{d^2\sigma_{PPP}}{dtdM_X^2}(\gamma, M_X^2) = \frac{1}{M_X^2}\sigma_P^2(\gamma)C_{PPP}\exp[(2B_{PH} + B_{PPP} + 2\alpha'_P\ln(\frac{2\gamma M_0^2}{M_X^2}))t]\left(\frac{M_0^2}{M_X^2}\right)^{\Delta_P} \quad (7)$$

$$\Delta E = \frac{M_X^2 - m_N^2 + |t|}{2m_N} \qquad \langle E \rangle = \frac{\int_{m_N+m_\pi}^{M_{X\,max}} dM_X \int_{|t|_{min}}^{|t|_{max}} d|t| \Delta E \frac{d^2\sigma}{d|t|dM_X}}{\int_{m_N+m_\pi}^{M_{X\,max}} dM_X \int_{|t|_{min}}^{|t|_{max}} d|t| \frac{d^2\sigma}{d|t|dM_X}}$$

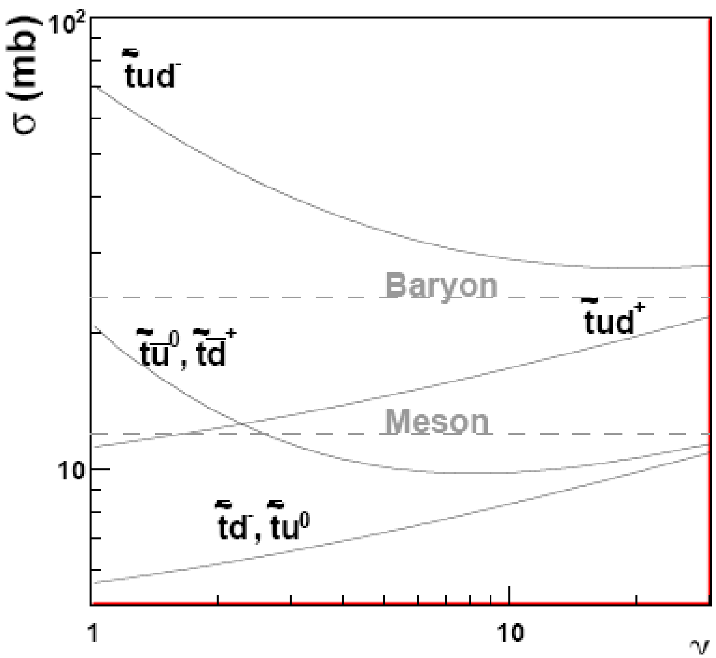
# Implementation in Geant-4

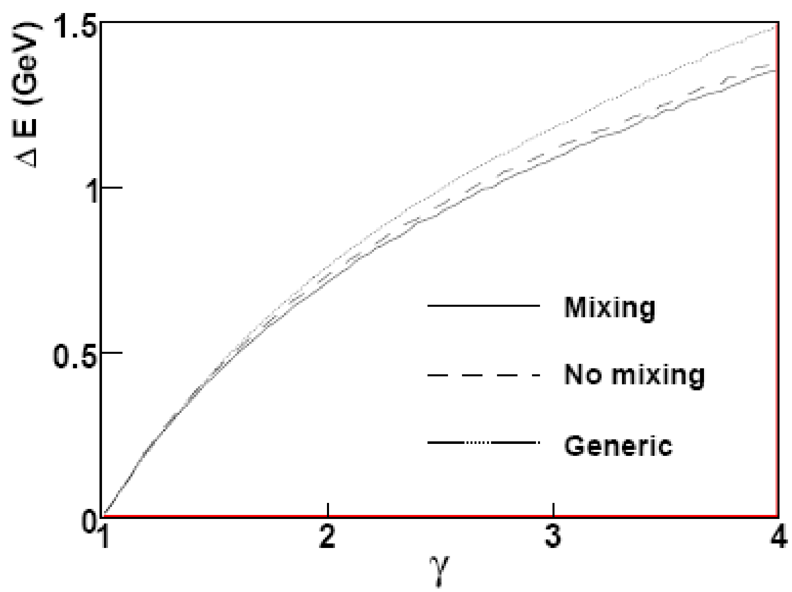
Build on framework of generic/phase space model:
hep-ph/061216, hep-ph/0404001.

Include: electromagnetic energy loss, multiple scattering
: nuclear effects: excitation, fragmentation, "black track particles"
: stopping

Include: possibility of minimal or maximal oscillation/mixing $H^0 \to \bar{H}^0$.

Exotic hadrons: stop,sbottom and gluino-based hadrons.

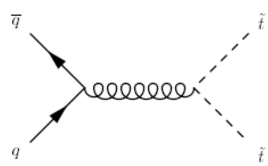


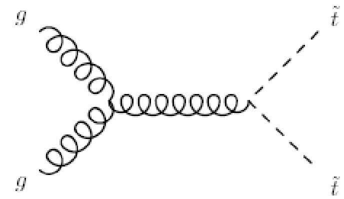



# Squark production at the LHC

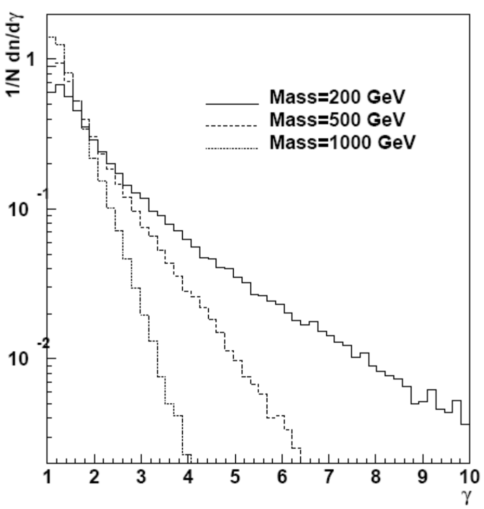
Direct pair-production of exotic quarks (squarks).

$$p + p \rightarrow \tilde{q} + \overline{\tilde{q}} + X.$$

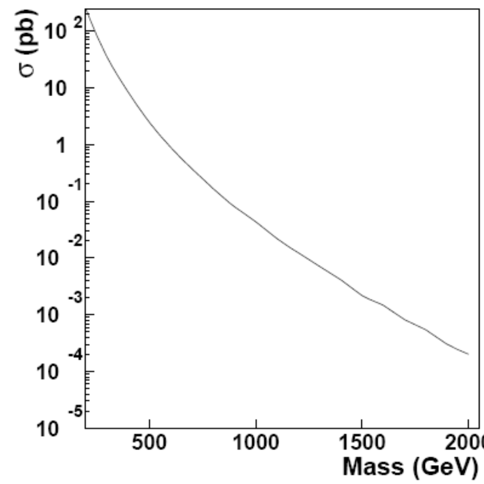



Pythia for kinematics and initial meson/baryon composition.




| $R$-hadron | Fraction (%) |
|---|---|
| $R^+_{\tilde{t}\bar{d}}$ | 39.6 |
| $R^0_{\tilde{t}\bar{u}}$ | 39.6 |
| $R^+_{\tilde{t}\bar{s}}$ | 11.8 |
| $R^{++}_{\tilde{t}}$ baryons | 0.8 |
| $R^+_{\tilde{t}}$ baryons | 6.7 |
| $R^0_{\tilde{t}}$ baryons | 1.5 |




Promising "first data" search. Current limits > 200 GeV.

Consider 300 GeV sample point.

# Exotic Quark-based Hadrons

From heavy SM quark spectra:

Degenerate mesons, lightest baryons: $\tilde{t}ud$, $\tilde{b}ud$

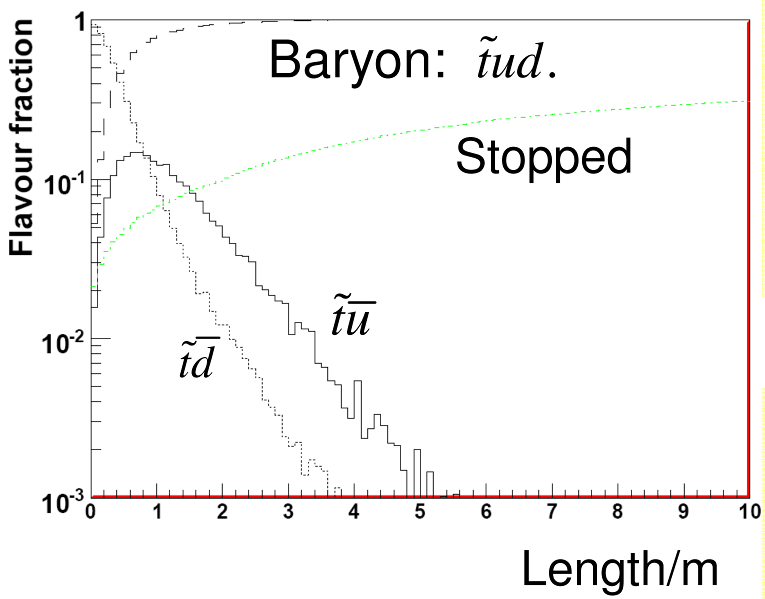
Annihilation of anti-baryons.

Consider $\tilde{t}$.

Mesons can convert to baryons eg: $\tilde{t}\bar{u} + p \rightarrow \tilde{t}ud + \pi^0$

Reverse reaction suppressed (hep-ph/0404001).

$\Rightarrow$ exotic hadrons start as mesons and end up as baryons.



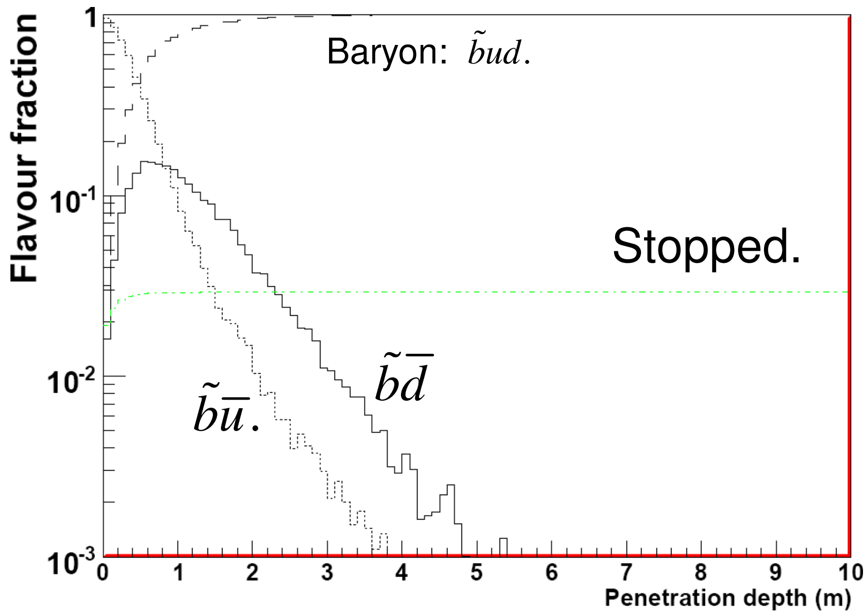

Propagation through iron with Geant-4 of hadron starting as $\tilde{t}\bar{d}$.

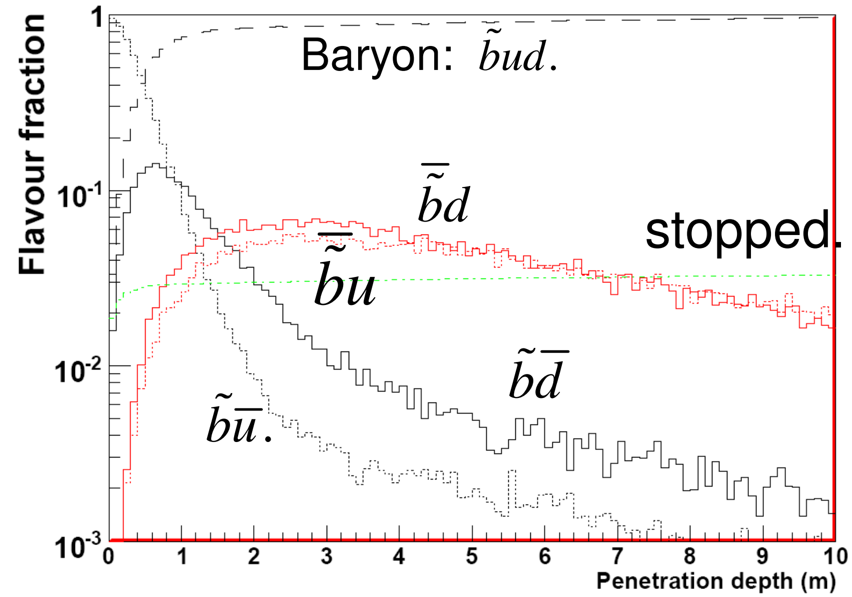
No mixing.

Typical calo: 1-2m of iron.

Stop hadrons are dominantly baryonic and charged $\tilde{t}ud$ : $Q = e$

# Propagation of sbottom-based hadrons



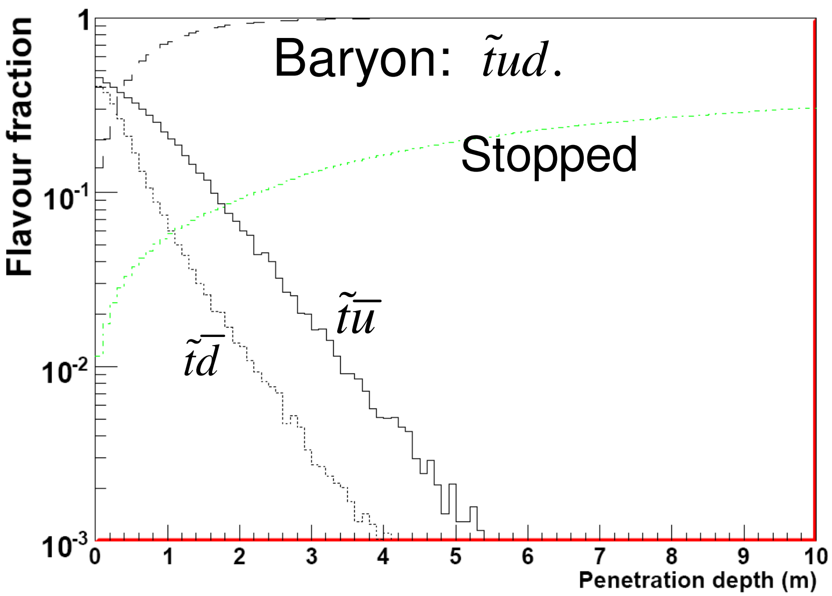




Propagation through iron with Geant-4 of hadron starting as $\tilde{b}\overline{u}$.
No mixing.

Propagation through iron with Geant-4 of hadron starting as $\tilde{b}\overline{u}$.
Mixing.

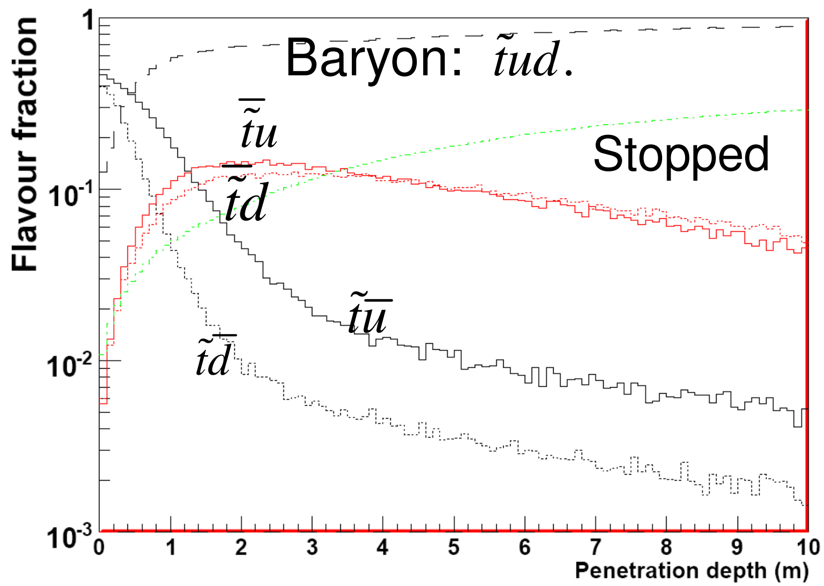
Hadrons are dominantly baryonic and uncharged $\tilde{b}ud$ : $Q = 0$.

# Particle composition with depth




Propagation through iron with Geant-4 of hadron starting with mixture of $\tilde{t}$-hadrons given by Pythia/Lund string.

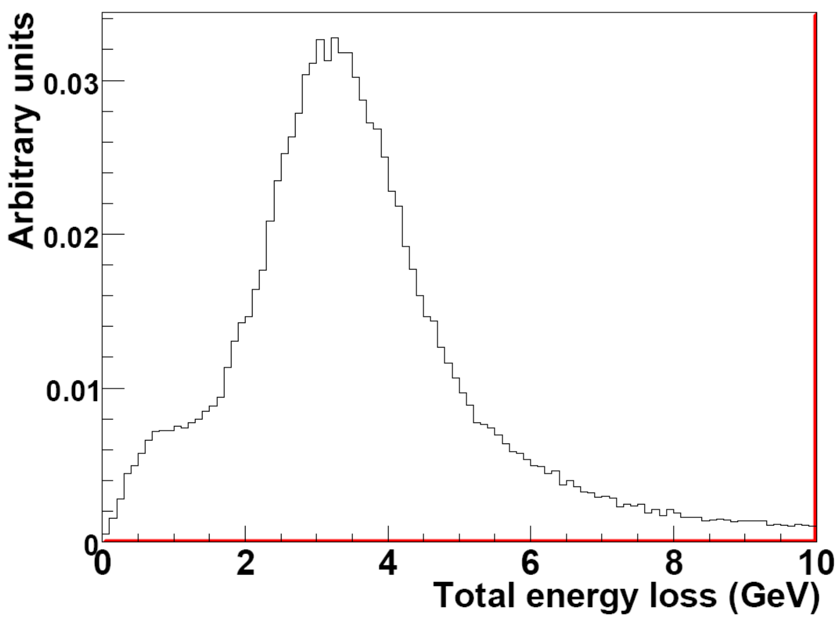
No mixing.

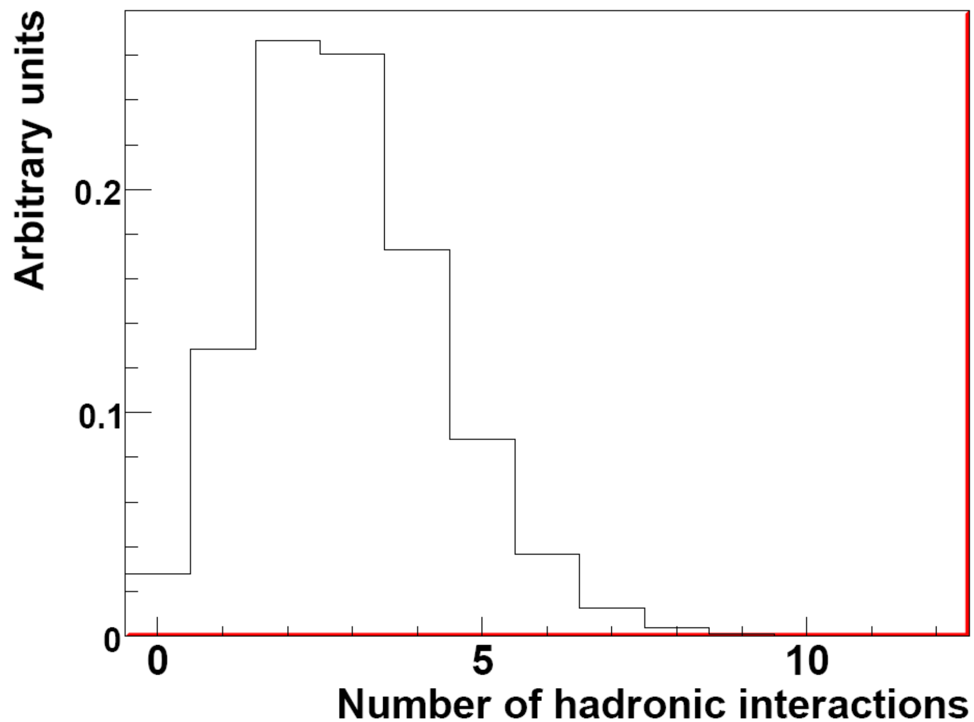



Propagation through iron with Geant-4 of hadron starting with mixture of $\tilde{t}$-hadrons given by Pythia/Lund string.

Mixing.

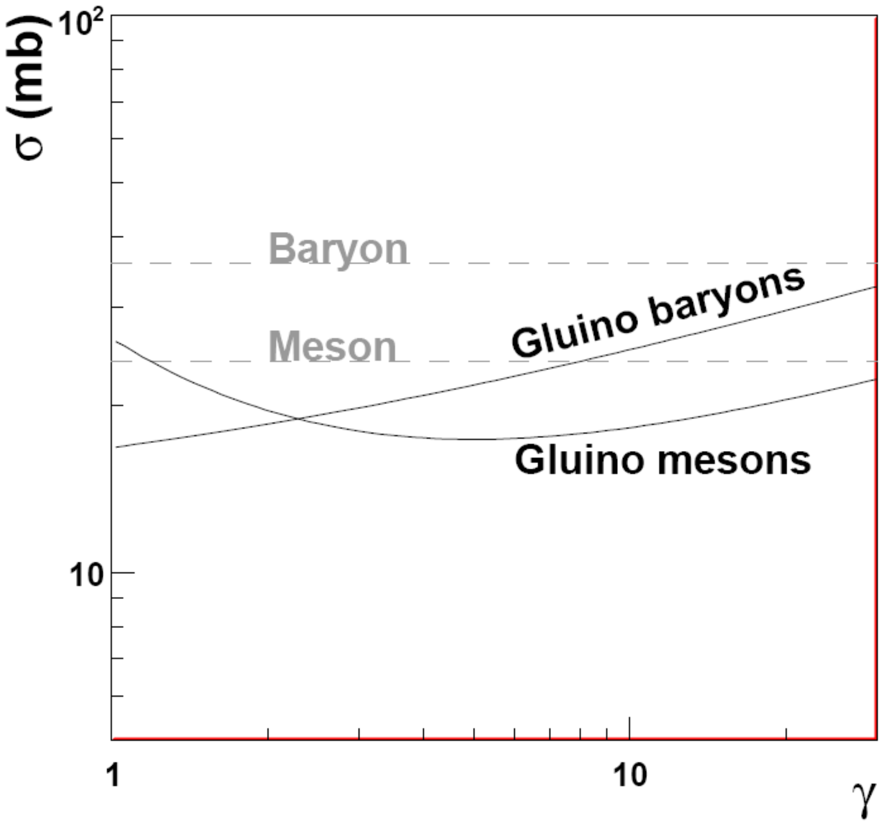
# Energy loss and number in hits




Propagation through 1m of iron with Geant-4 of hadron starting from $\tilde{t}\bar{d}$ . No mixing.

# Gluino scattering



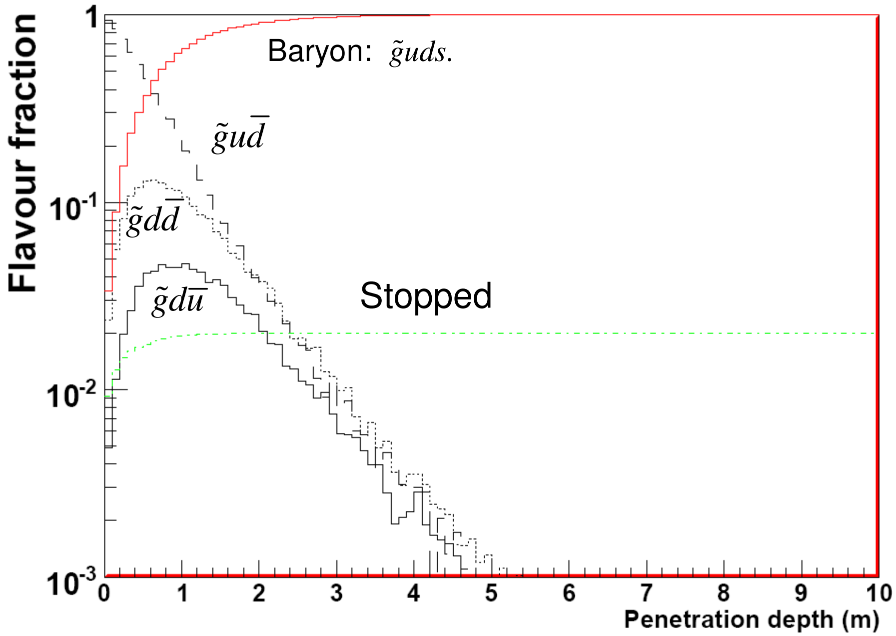

| $R$-hadron | PYTHIA Fraction (%) | HERWIG Fraction (%) |
|---|---|---|
| $R^{+}_{\tilde{g}u\bar{d}}$, $R^{-}_{\tilde{g}d\bar{u}}$ | 34.2 | 28.2 |
| $R^{0}_{\tilde{g}u\bar{u}}$, $R^{0}_{\tilde{g}d\bar{d}}$ | 34.2 | 28.2 |
| $R^{+}_{\tilde{g}u\bar{s}}$, $R^{-}_{\tilde{g}s\bar{u}}$ | 9.7 | 17.5 |
| $R^{0}_{\tilde{g}d\bar{s}}$, $R^{0}_{\tilde{g}s\bar{d}}$, $R^{0}_{\tilde{g}s\bar{s}}$ | 10.4 | 26.1 |
| $R^{0}_{\tilde{g}g}$ | 9.9 | — |
| $R^{++}_{\tilde{g}}$, $R^{--}_{\tilde{g}}$ (anti)baryons | 0.1 | — |
| $R^{+}_{\tilde{g}}$, $R^{-}_{\tilde{g}}$ (anti)baryons | 0.8 | — |
| $R^{0}_{\tilde{g}}$ (anti)baryons | 0.7 | — |

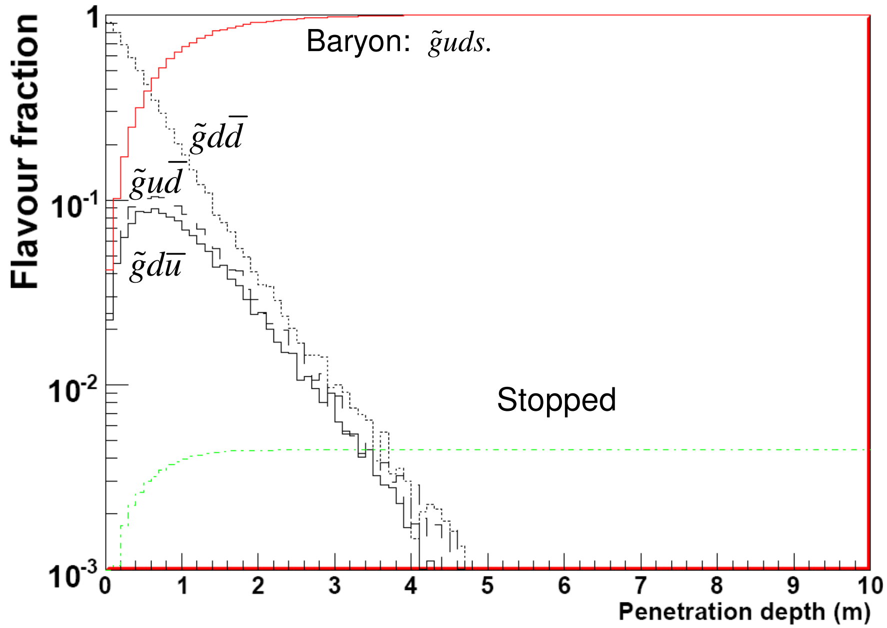
Mass hierarchy for gluino-based hadrons more uncertain.

Take degenerate mesons $(\tilde{g}u\bar{u})$, gluino-balls $\tilde{g}g$.

Lightest stable baryon $\tilde{g}uds$ (neutral): PLB153:311,1985 (Farrar et al.).

# Exotic hadrons with gluinos



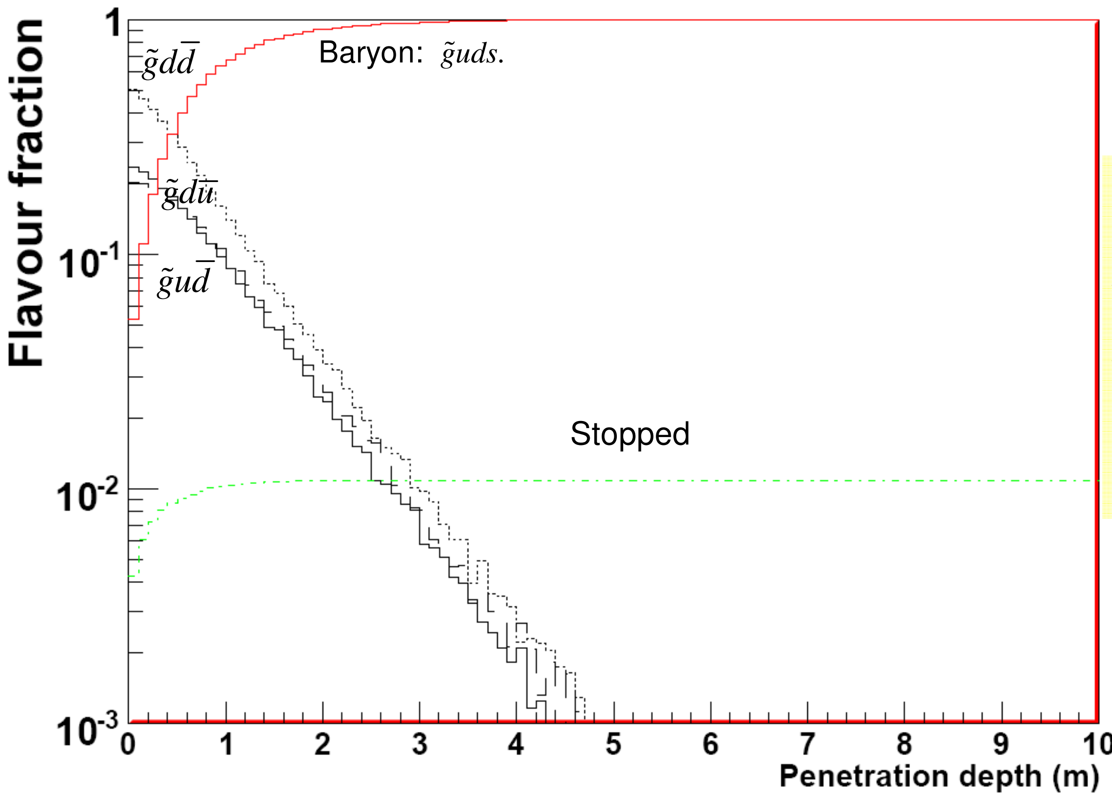




Propagation through iron with Geant-4 of hadron starting as $\tilde{g}u\bar{d}$.

Propagation through iron with Geant-4 of hadron starting as $\tilde{g}\bar{d}d$.

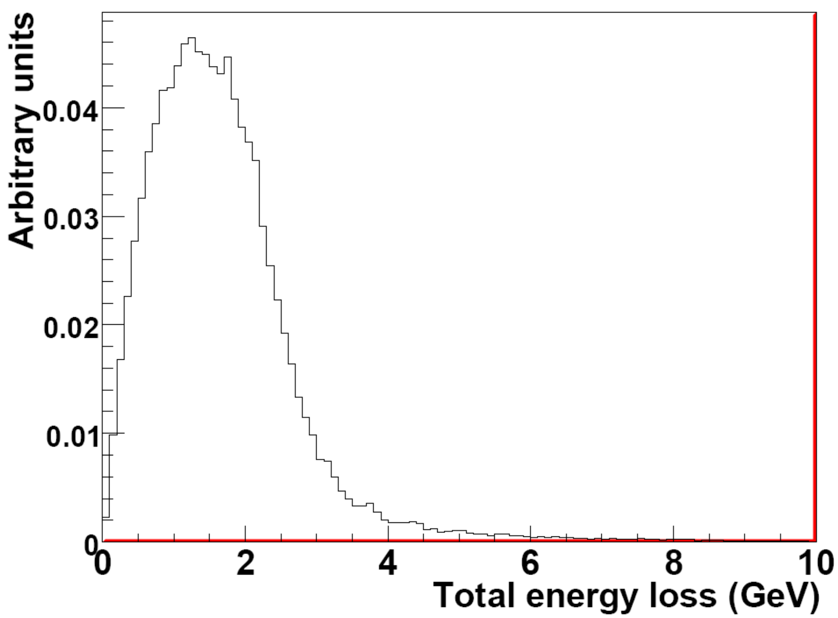
Hadrons are dominantly baryonic and neutral $\tilde{g}uds:\ Q=0$.

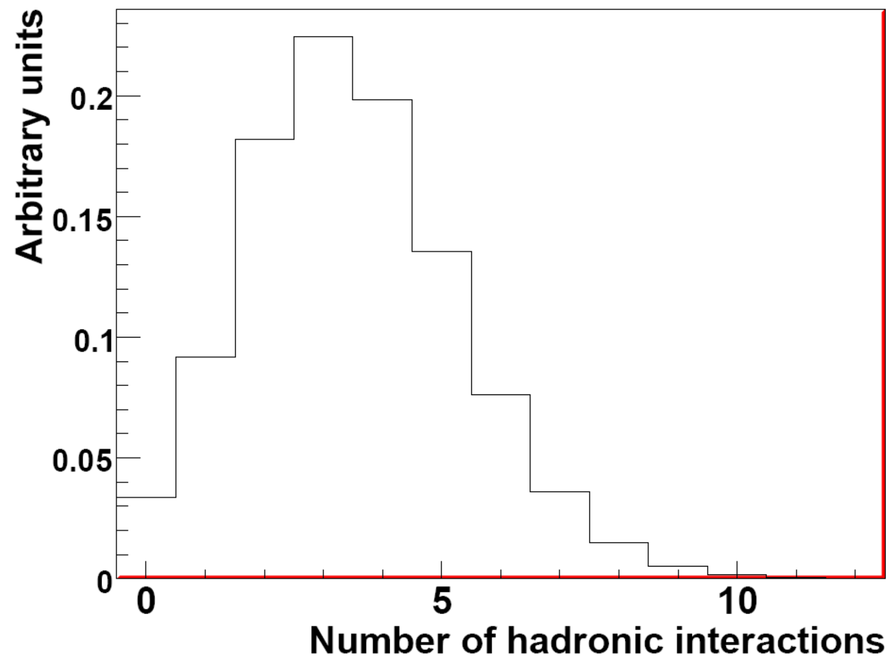
# Particle composition with depth




Propagation through iron with Geant-4 of hadron starting with mixture of $\tilde{g}$-hadrons given by Pythia/Lund string.

# Energy loss and number in hits




Propagation through 1m of iron with Geant-4 of hadron starting from $\tilde{g}u\bar{d}$ .

# Summary

- Stable massive particles are an important observable for new physics
- Hadronic scattering of SMPs poorly understood
  - Hadronic scattering can impede or enhance searches
- New model in Geant-4 for use in searches at LHC, Tevatron, cosmic ray showers