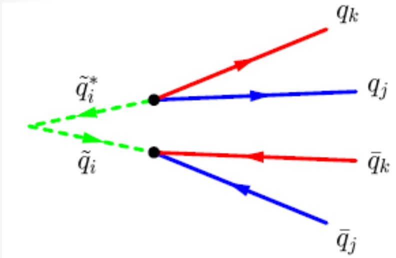
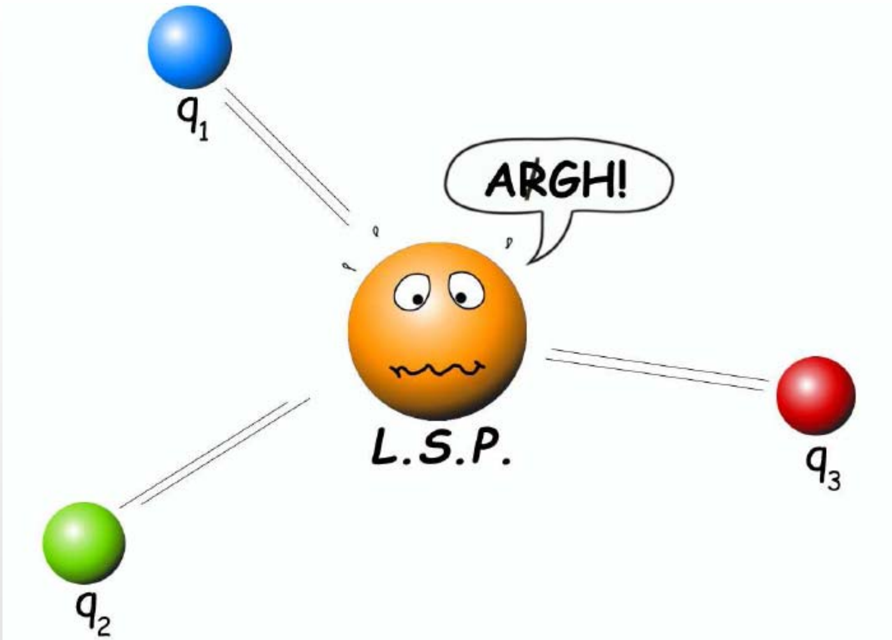
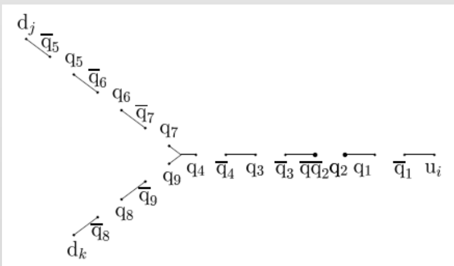
The Smoking Gun of Baryon Number Violation

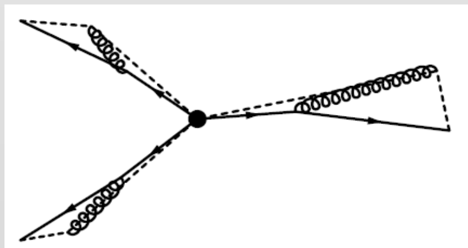


$$B_{i_1 i_2 i_3} = \epsilon^{\alpha_1 \alpha_2 \alpha_3} \prod_{n=1}^{3} P\left[e^{ig \int_{\mathcal{P}(x,x_n)} A_\mu \mathrm{d}x^\mu} q_{i_n}(x_n)\right]_{\alpha_n}$$





P. Skands
Fermilab



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- Baryon Number Violation (BNV) in SUSY
  - Implementation of 2- and 3-body decays in the PYTHIA generator
- BNV Colour Topologies
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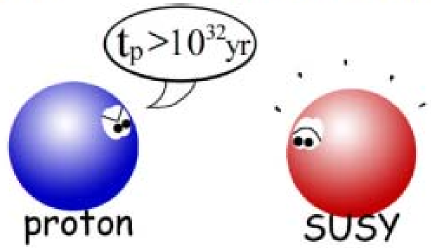
R, B, or L? (Fast-forward)

- Most general MSSM Superpotential:

$$\begin{aligned} W &= \epsilon_{ab}\Big[(Y_E)_{ij}H_1^a L_i^b \bar{E}_j + (Y_D)_{ij}H_1^a Q_i^b \bar{D}_j + (Y_U)_{ij}H_2^b Q_i^a \bar{U}_j \\ &\quad + \frac{1}{2}\lambda_{ijk}L_i^a L_j^b E_k + \lambda'_{ijk}L_i^a Q_j^b D_k - \epsilon_i L_i^a H_2^b - \mu H_1^a H_2^b\Big] - \frac{1}{2}\lambda''_{ijk}U_i D_j D_k \end{aligned}$$

- But LNV+BNV makes bad cocktail!

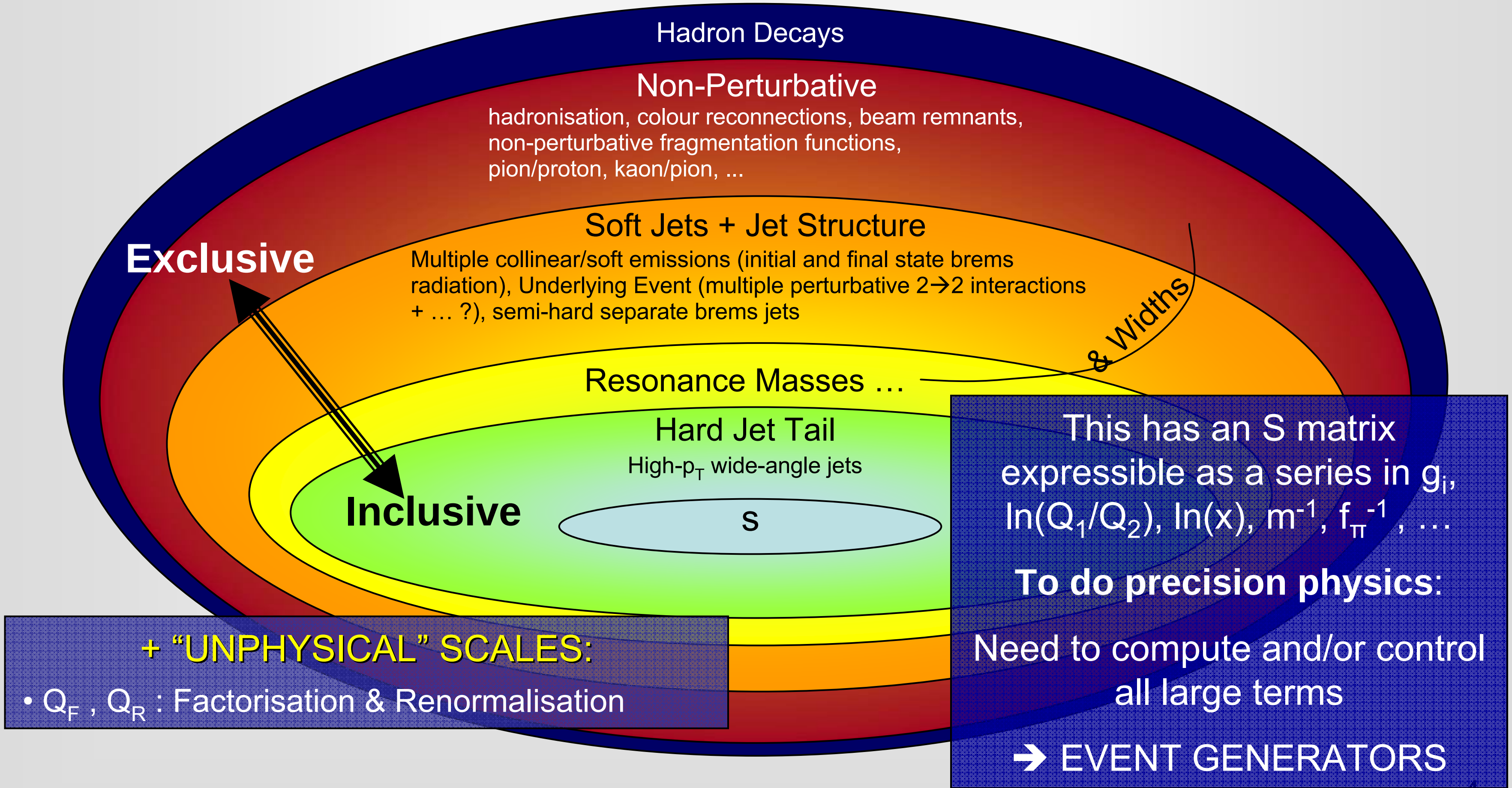


- To save proton, R, B, or L cons. imposed.
  - R → CDM candidate, but no deep motivation.
  - B and L more robust with higher dimension operators.

Decent physics case + interesting to explore phenomenology

Collider Phenomenology

- General problem: how to obtain fully exclusive descriptions of collider final states (in any physics model, SM or BSM)



Implementation of 2- and 3-body decays in PYTHIA

$$W_{\mathrm{BNV}} = \lambda''_{ijk}\epsilon_{abc}\bar{U}_{ia}\bar{D}_{jb}\bar{D}_{kc}$$

(abc = colour, ijk = generation)

- Couplings between chiral multiplets.
  - Sfermions: 2-body decays.
  - Gauginos/Higgsinos: 3-body decays (via sfermion resonances).
- $\epsilon_{abc} \to$ 'baryonic' colour flow.

$$\tilde{\mathrm{d}}_j \to \bar{\mathrm{u}}_i\bar{\mathrm{d}}_k\ ,\quad \tilde{\chi}^0_n \to \mathrm{u}_i\mathrm{d}_j\mathrm{d}_k,\ + \mathrm{c.c.}\quad ,\ \tilde{g} \to \mathrm{u}_i\mathrm{d}_j\mathrm{d}_k,\ + \mathrm{c.c.}$$
$$\tilde{\mathrm{u}}_i \to \bar{\mathrm{d}}_j\bar{\mathrm{d}}_k\ ,\quad \tilde{\chi}^+_n \to \mathrm{u}_i\mathrm{u}_j\mathrm{d}_k,\ \bar{\mathrm{d}}_i\bar{\mathrm{d}}_j\bar{\mathrm{d}}_k$$

Partial widths: LO ME's, (only 3rd gen massive)

Dreiner, Richardson, Seymour: JHEP 04(2000)008

Kinematics: isotropic 3-body (good when intermediate states very off shell).

Final state parton multiplicity increased by subsequent showers

NB: only MSSM pair production included (no single sparticle production)

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Colour Topologies

Confinement potential: non-perturbative breakups → hadrons

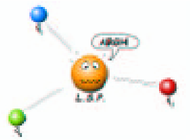
Not a priori calculable → QCD-inspired phenomenological models

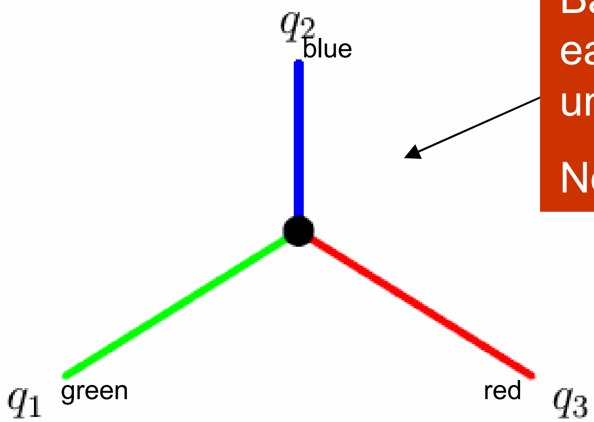
Semi-classical, based on colour dipoles: “Clusters” or “String pieces”

‘Ordinary’ colour topology

(e.g. $Z^0 \to q\bar{q}$):

‘Baryonic’ colour topology

(e.g. ):



Basic problem easy to understand:

No dipole!

- How does such a system fragment?
- Could a Baryon excess be observed?

String Topologies

How does the system hadronize?

- Assume vacuum still acts as dual colour superconductor
→colour vortex lines ~ string picture still applicable

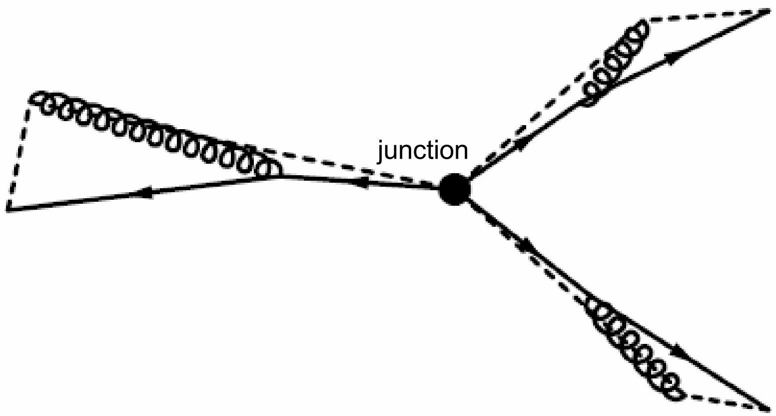
- Q then: **which** string topology? Y, Δ, V, … ?

$$B_{i_1 i_2 i_3} = \epsilon^{\alpha_1\alpha_2\alpha_3} \prod_{n=1}^{3} P\left[e^{ig\int_{\mathcal{P}(x,x_n)} A_\mu \mathrm{d}x^\mu} q_{i_n}(x_n)\right]_{\alpha_n}$$

Montanet, Rossi, Veneziano : Phys.Rep.63(1980)149

& Minimization of potential energy ~ string length (V(r) = κr)

➔ Picture of Y-shaped topology with 'string junction'



(Warning: This picture was drawn in a "pedagogical projection" where distances close to the center are greatly exaggerated!)

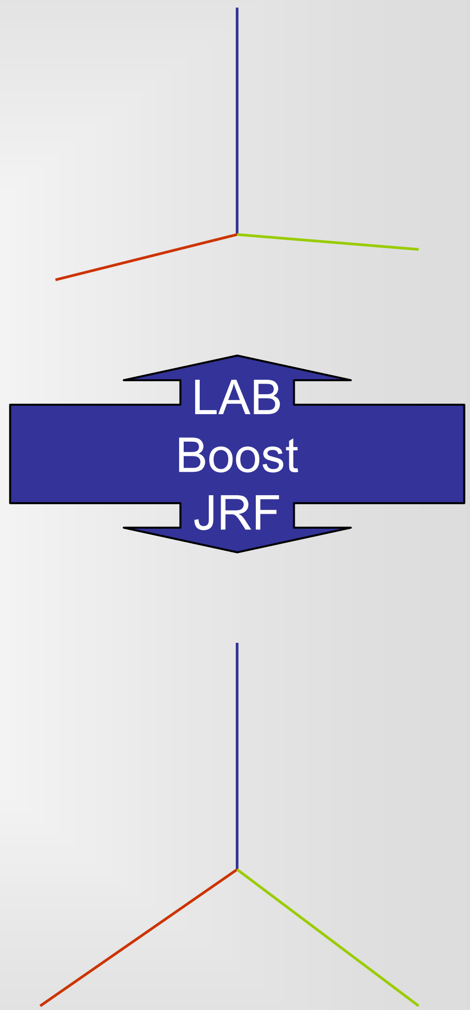
The Junction

How does the junction act / move?

- The movement of the string junction is crucial,
  it is the smoke of the BNV gun!
- A junction is a topological feature of the string confinement field: $V(r) = \kappa r$. Each string piece acts on the other two with a constant force, $\kappa \vec{e}_r$.
- $\Longrightarrow$ in junction rest frame (JRF) the angle is 120° between the string pieces.
- Or better, 'pull vectors' lie at 120°:

$$p^{\mu}_{\text{pull}} = \sum_{i=1,N} p^{\mu}_i e^{-\sum_{j=1}^{i-1} \frac{E_j}{\kappa}}$$

(since soft gluons 'eaten' by string)

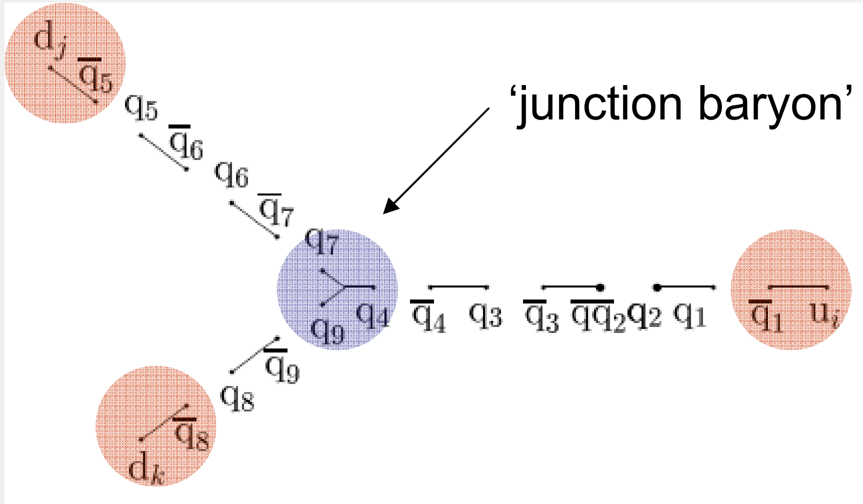


Inverse boost ➔ handle on motion of the baryon number, *<u>through</u>* <u>fragmentation</u>

T. Sjostrand, PS Nucl.Phys.B659(2003)243

Hadronisation

'Ordinary strings' → same fragmentation functions, u:d:s, etc



Technically: 2 least energetic strings fragmented outwards-in

When little energy left, remains collapsed into diquark

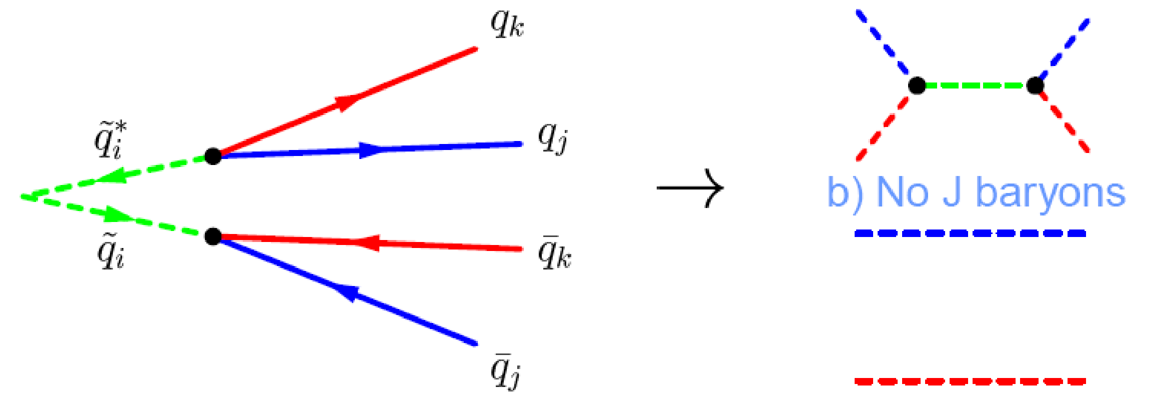
→remaining qq – q string piece fragmented as usual

Note: **baryon number** can be entirely separated from **leading flavours**

T. Sjostrand, PS Nucl.Phys.B659(2003)243

(More Complicated Topologies)

- Stop pair production at an LC:



2 possibilities:

- a) 2 junction baryons
- b) junction-junction annihilation

Select between a/b based on which topology has smallest 'string length'
→ non-trivial kinematical dependence

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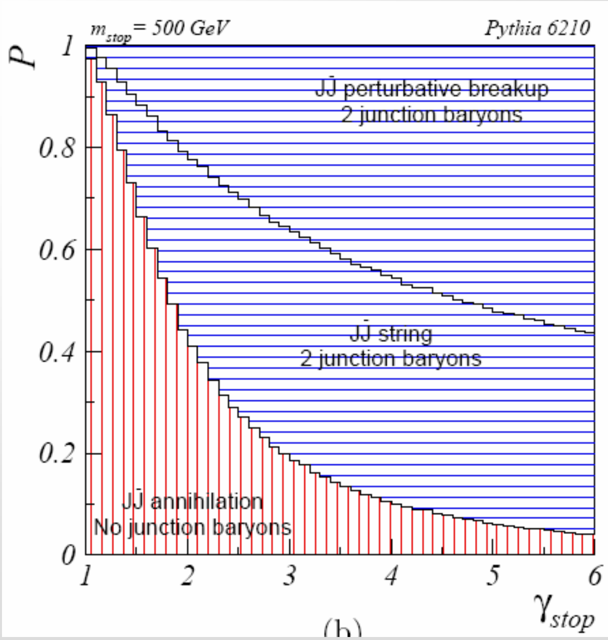
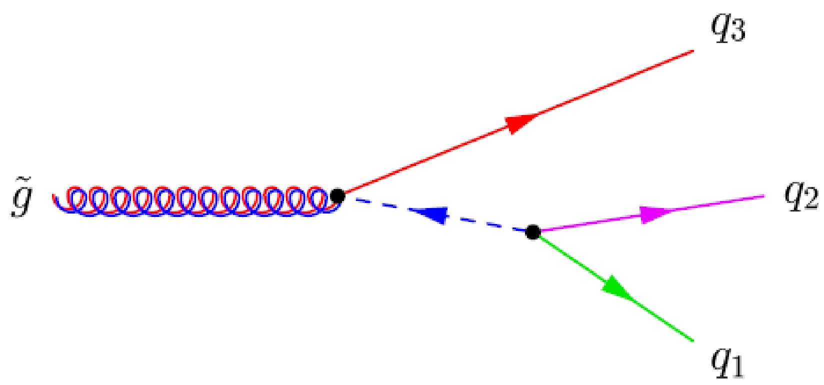


(More Complicated Topologies)

- Colour flow in gluino decays:



- Selected according to (off–shell) resonance propagators.

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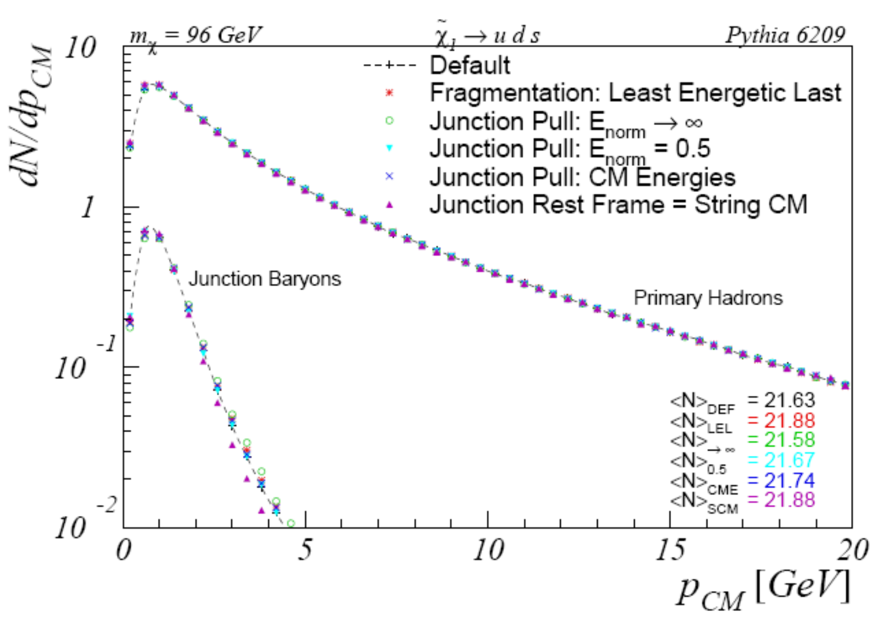
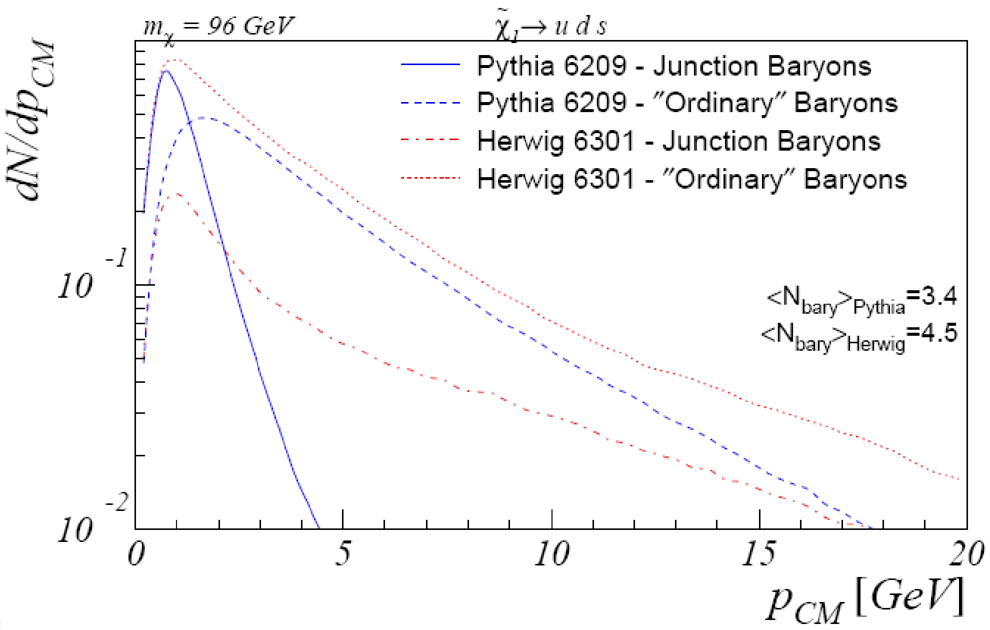
Variation of Fragmentation Assumptions





PYTHIA model: essentially stable

(provided junction Y topology 'agreed' upon)

PYTHIA vs HERWIG: it matters whether B flow modeled or not

(HERWIG impl. focussed on perturbative part)

Central Point ➔ Junction baryons are soft, in CM of decay

Slow Baryons @ LHC – How tough to do?

For the present study: (simplistic!)

"Detector" covers $|\eta| < 5$ with granularity $\Delta\eta \times \Delta\phi = 0.1$

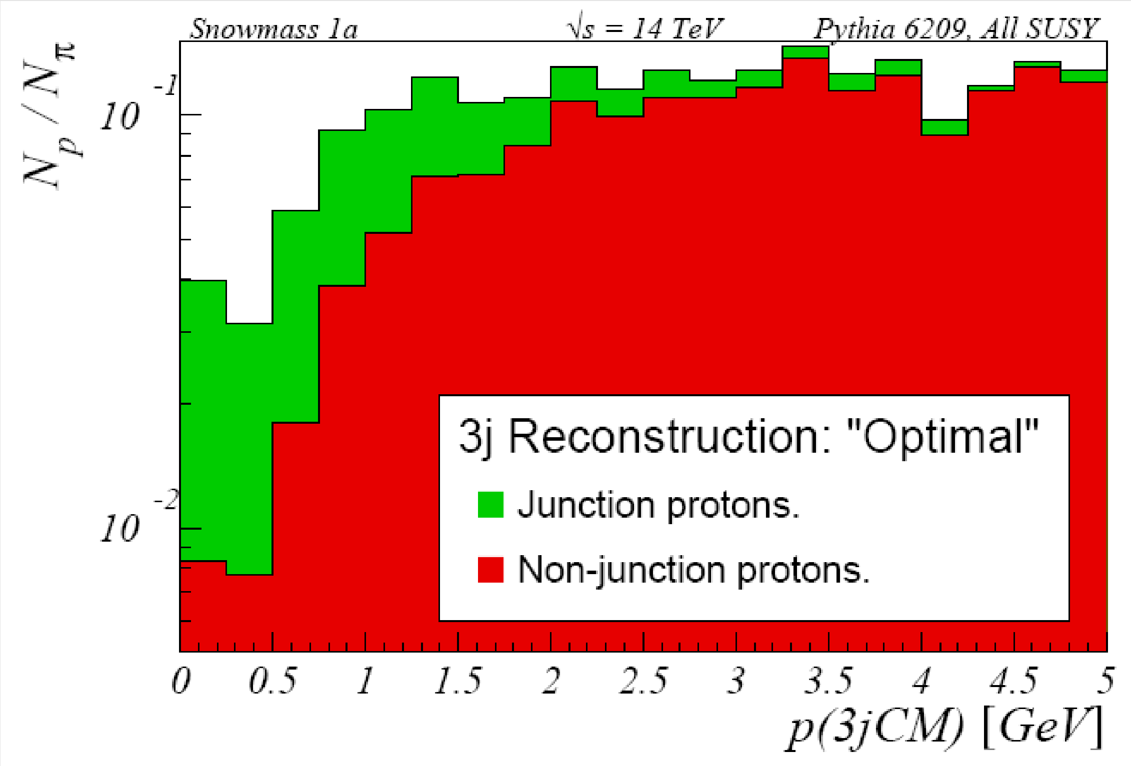
For $|\eta| < 2$, all charged hadrons with $p_\perp > 1$ GeV are reconstructed (100% eff, no mis-ID).

For $|\eta| < 5$, hard jets are reconstructed using cone algorithm.

We look for cascade-produced (boosted) $\tilde{\chi}_1^0$'s which decay via BNV: (Assume $m_{\tilde{\chi}_1^0} = 96$ GeV known)

8 reconstructed jets.
Candidate $\tilde{\chi}_1^0$: systems of 3 jets with combined $p_\perp > 200$ GeV.
The 3 jets occupy a small detector region, $R_{jj}^{max} < 0.8$.
The 3 jets reconstruct to $m_{\tilde{\chi}_1^0} \pm 10$ GeV.
Candidate junction proton: within $\Delta R_{p3j} = 0.5$ of the 3-jet system momentum direction.

Slow Baryons @ LHC – How tough to do?



Not trivial. But with high cross sections (low masses) may be feasible. Would be **smoking gun of Baryon Number Violation.**

ILC highly interesting as well. Model applicable to any collider type.

Summary and Outlook

- RPV-SUSY → interesting phenomenology
- Esp. BNV has antisymmetric colour structure in interaction term which does not appear in SM (neglecting sphalerons …)
- Detailed model focussing on NP aspects (flow of baryon number) shows new aspects:

Smoking gun of BNV = excess of soft baryons (in CM of decay)

- Available in the PYTHIA generator (see e,g, PYTHIA 6.4 manual, published last week: JHEP05(2006)026, 582pp)
- Not trivial to 'catch the baryon' at LHC. Would need detailed study.
- Possibilities at ILC also remain to be explored
- Though we only applied it to BNV-SUSY, the fragmentation principles are universal, and could easily be used for other BNV physics (so far, we e.g. recycled it for proton remnant fragmentation in min-bias)