Hadronization Dependence in Antideuteron Production

Based on arXiv:1207.4560 [hep-ph], arXiv:1402.6259 [hep-ph]

Lars A. Dal

Department of Physics, University of Oslo

Antideuteron 2014
1st cosmic ray antideuteron workshop
Los Angeles, June 2014

Antideuteron Formation

- Formation of atomic nuclei not handled by Monte Carlos. Coalescence model currently state of the art in computing the antideuteron flux
  - Simple model: Nucleons with $\Delta p < p_0$ coalesce to form a nucleus
  - Ibarra, Wild: Additional condition: Close in position space – weakly decaying particles considered stable arXiv:1209.5539 [hep-ph]
  - p_0 calibrated against experimental data, large spread in best fit p_0-values

Calibration of p_0

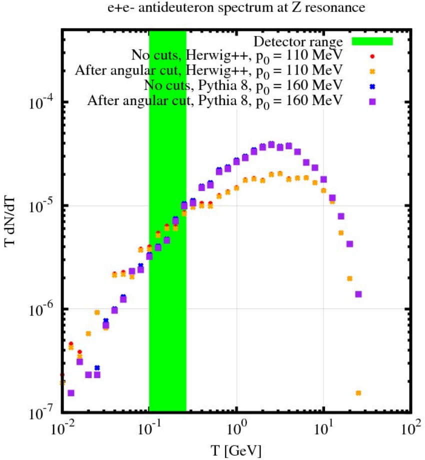
Best fit p_0-values [MeV] for various experiments

Experiment	Process	Pythia 6	Pythia 8	Herwig++
ALEPH	e^+e^-	–	192	159
CLEO	e^+e^-	–	133	145
ZEUS	ep	236	–	150
CERN ISR	pp	–	152	221
ALICE	pp	230	–	154

Table from arXiv:1402.6259 [hep-ph]. Pythia 6/8 values are from arXiv:1209.5539 [hep-ph].

- Why the difference between experiments, and why the difference between the Monte Carlos?

Calibration: A closer look

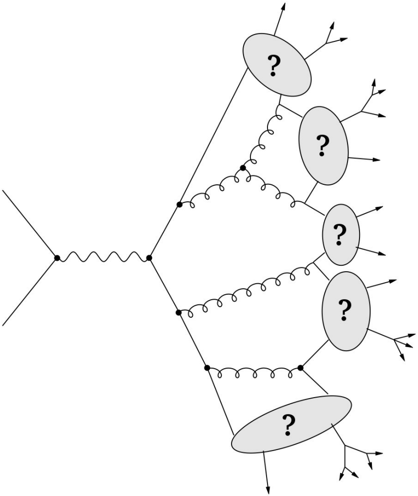


- Calibration: ALEPH ($e^+e^- \to Z$): Herwig++: $p_0 = 110$ MeV, Pythia: 160 MeV arXiv:1207.4560 [hep-ph] *
- Isotropic coalescence: $dN/dT \propto p_0^3$; p_0 only gives the normalization
- No calibration of p_0 can make the shapes of the spectra agree
- Problem: 2-particle correlations

* Note: Weak decays were included, thus the low numeric values of p_0

The issue of hadronization

- $p_0 \sim 100$ MeV$\lesssim \Lambda_{\mathrm{QCD}}$, sensitive to hadronization effects
- Perturbation theory for QCD breaks down at low energies, must resort to phenomenological models
- Monte Carlo: Several free parameters in these models tuned to fit experimental data
- Not specifically tuned to produce correct (anti)nucleon spectra



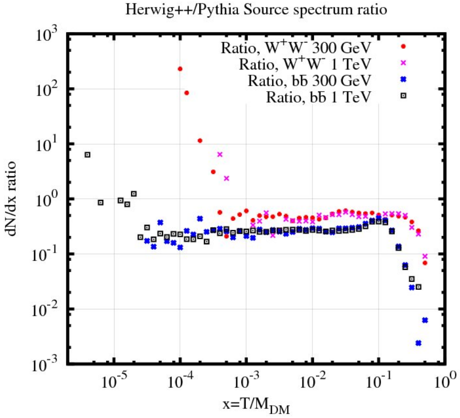
Uncertainty from Hadronization

UiO : Department of Physics
The Faculty of Mathematics and Natural Sciences

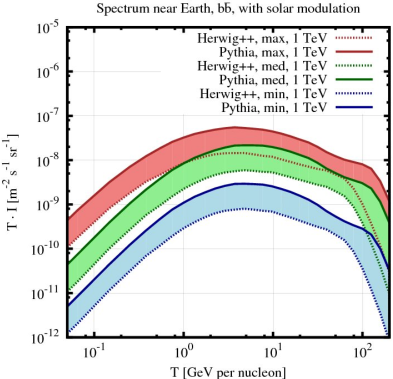
Uncertainty on spectrum due to hadronization?

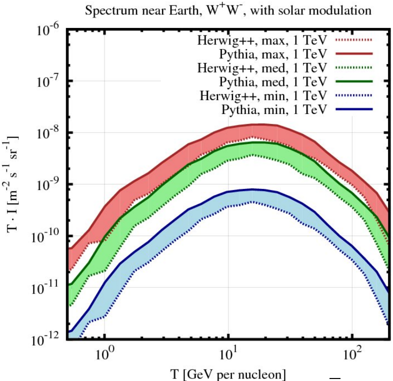
Dal, Kachelrieß arXiv:1207.4560 [hep-ph]

- ALEPH calibration: Herwig++: $p_0 = 110$ MeV, Pythia 8: $p_0 = 160$ MeV
- Comparison of antideuteron spectra generated with Herwig++ and Pythia
- Large discrepancies, especially at high and low energies



Uncertainty in the final flux





- Uncertainty comparable to that from propagation for $b\bar{b}$ at high energies
- Uncertainty induced by the discrepancy seen at low $x = T/M_{\mathrm{DM}}$ expected to appear in the W^+W^- channel for higher DM masses

Tuning of Hadronization Models

- The idea: Tune hadronization parameters specifically to reproduce antideuteron spectrum
- Uncertainties in the parameters allow us to find corresponding uncertainty on antideuteron flux
- What if we break processes that we don't tune against?
- Tuning Herwig++: Dal, Raklev arXiv:1402.6259 [hep-ph]
  - Re-tune most important Herwig++ hadronization parameters together with p_0
  - Tune against antideuteron spectra from ALEPH ($e^+e^- \to Z$), ZEUS (ep) and CLEO (Υ (1S) decay)
  - Also tune against (anti)proton spectra from ALEPH and OPAL for consistency
  - 4-dimensional parameter space, each parameter point costs ~ 120 CPU core hours

Best Fit Parameters

Some 40000 CPU core hours later...

Parameter	Default value	Best fit value	Uncertainty $(1\sigma)^*$
p_0 [MeV]	–	143.2	$^{+6.2}_{-5.5}$
`ClMaxLight`	3.25	3.03	$^{+0.18}_{-0.15}$
`PSplitLight`	1.20	1.31	$^{+0.19}_{-0.32}$
`PwtDIquark`	0.49	0.48	$^{+0.15}_{-0.04}$

Best fit $\chi^2/\mathrm{d.o.f} = 10.6/14.2$

- Highly correlated parameters, challenging to locate best fit point
- Default parameters are reasonably close to best fit point

* Non-parabolic uncertainty calculated using the `MINOS` algorithm in `Minuit`

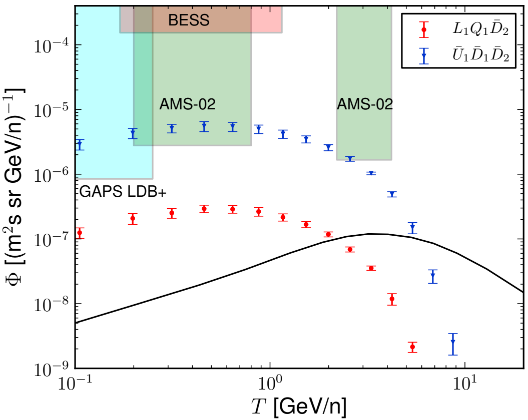
Application: Gravitino Dark Matter

- Gravitino: Supersymmetric partner of the graviton
- R-parity violation: Gravitino unstable but long lived, good DM candidate
- RPV operators of interest: $\lambda'_{ijk} L_i Q_j \bar{D}_k$, $\lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k$
- $\Phi_{\bar{d}} \propto \Gamma \propto \lambda^2$; fluxes can easily be re-scaled to any value of λ
- Goal: Set limits on trilinear RPV couplings λ and Gravitino masses $m_{\tilde{G}}$

UiO : Department of Physics
The Faculty of Mathematics and Natural Sciences

Antideuteron Spectrum Near Earth

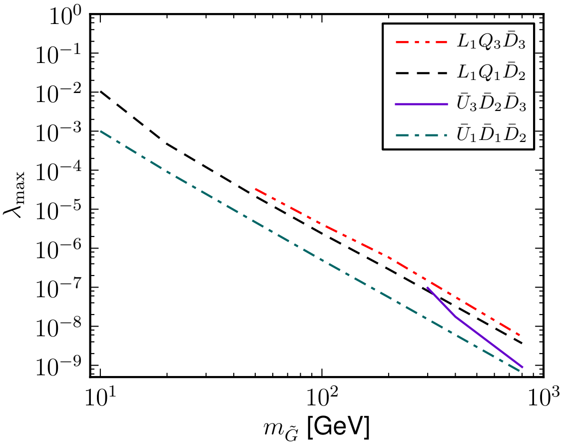
- Propagation: NFW DM density profile, 'med' set of diffusion parameters



- $m_{\tilde{G}} = 50$ GeV, $\lambda = 10^{-5}$
- Flux increases with increasing mass and RPV coupling
- Can set limits on mass and RPV coupling from experiments

Limits on RPV couplings

Prospective upper limits from GAPS



- 95% CL exclusion limits assuming 0 observed events
- Factor $2-4$ Stronger than existing limits on RPV couplings from PAMELA $\bar{p}$ data

Summary

- Antideuteron spectrum is highly sensitive to hadronization model
- Difference of factor ~ 3 in antideuteron spectrum between Herwig++ and Pythia at most energies, rapidly increasing towards high/low energies
- Tuning necessary for giving a consistent description
- Uncertainty from tuned parameters of factor < 2 after re-tuning
- Antideuterons can be used to set stronger limits on RPV couplings, in particluar for $\bar{U}\bar{D}\bar{D}$-operators

Backup Slides

Tuned Hadronization Parameters

Tuned Herwig++ hadronization parameters:

- `ClMaxLight`: Involved in specifying mass threshold for fission of clusters of light quarks
- `PSplitLight`: Controls mass distribution of clusters (of light quarks) produced in cluster fission
- `PwtDIquark`: Controls the probability of creating a diquark pair during cluster decay

Experiments: Number of bins

Experiment	N_{bins}
ALEPH	1
CLEO	5
ZEUS	3
CERN ISR	4+4
ALICE	9
ALEPH, $p/\bar{p}$	26

χ^2 from ALEPH proton data weighted down by factor 1/25 to keep it from dominating the parameter determination

Gravitino Dark Matter

- Thermal production of Gravitinos during reheating can give the right relic density

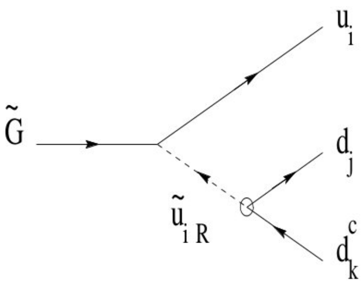
$$\Omega_{\tilde{G}} h^2 \simeq 0.21 \left(\frac{T_R}{10^{10}\ \text{GeV}} \right) \left(\frac{100\ \text{GeV}}{m_{\tilde{G}}} \right) \left(\frac{m_{\tilde{g}}(\mu)}{1\ \text{TeV}} \right)^2$$

Bolz, Brandenburg, Buchmuller; arXiv:hep-ph/0012052

- The reheating temperature T_R is weakly constrained, thus so is $m_{\tilde{G}}$

Gravitino RPV decays

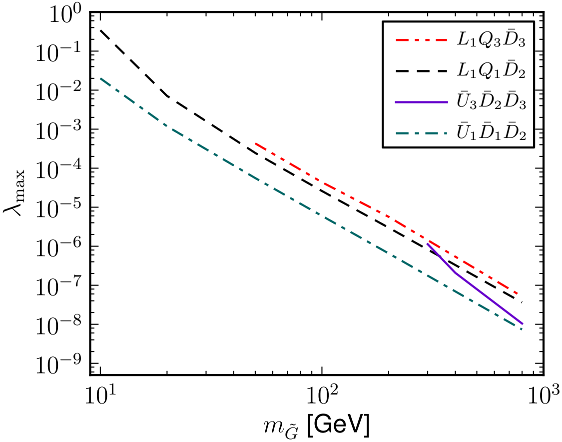
Tree-level Feynman diagrams for decays through $\bar{U}_i\bar{D}_j\bar{D}_k$-operators



Circle indicates RPV coupling

Coupling limits: BESS

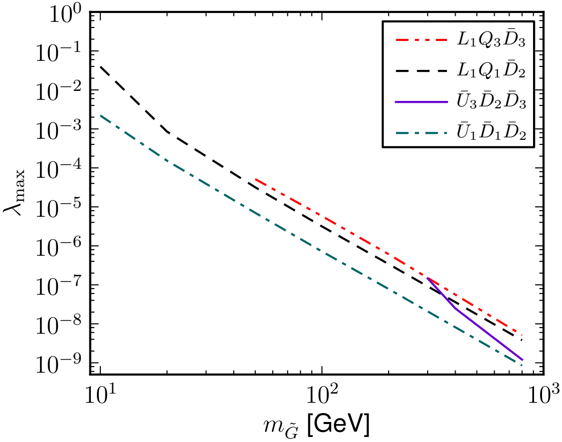
Current upper limits from GAPS



- 95% CL exclusion limits assuming 0 observed events
- Somewhat weaker than existing limits on RPV couplings from PAMELA $\bar{p}$ data

Coupling limits: AMS-02

Prospective upper limits from AMS-02



- 95% CL exclusion limits assuming 0 TOF events and 1 RICH event
- $\lesssim 1$ expected background event in the RICH detector
- $L_iQ_j\bar{D}_k$: Slightly weaker than $\bar{p}$ limits at low energies, roughly equal above a few hundred GeV
- $\bar{U}_i\bar{D}_j\bar{D}_k$: Factor ~ 1.5 Stronger than $\bar{p}$ limits