Formation models for antideuterons from dark matter

Are Raklev

Based on Phys. Rev. D89 (2014) 103504 [arXiv:1402.6259] and Phys. Rev. D91 (2015) 123536 [arXiv:1504.07242] with **Lars A. Dal**.

Why search for antideuterons?

- Antideuterons ($\bar{\mathbf{d}}$) from dark matter annihilation/decay have extremely low standard astrophysics backgrounds at low energies. [Donato, Fornengo and Salati, Phys. Rev. D62 (2000) 043003]

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  - Standard model production from spallation (pH-collisions).

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- Are antideuterons any better than antiprotons? Depends…

  [Ibarra and Wild, JCAP 1302 (2013) 021]
  [see also Johannes Herms' talk today]

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  - $\overline{d}$ formation is nuclear physics.
  - Usually (simple) **coalescence models**

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    - $\bar{p}$ & $\bar{n}$ need to be produced at the same space-time location.

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  (As opposed to **statistical coalesence**.)

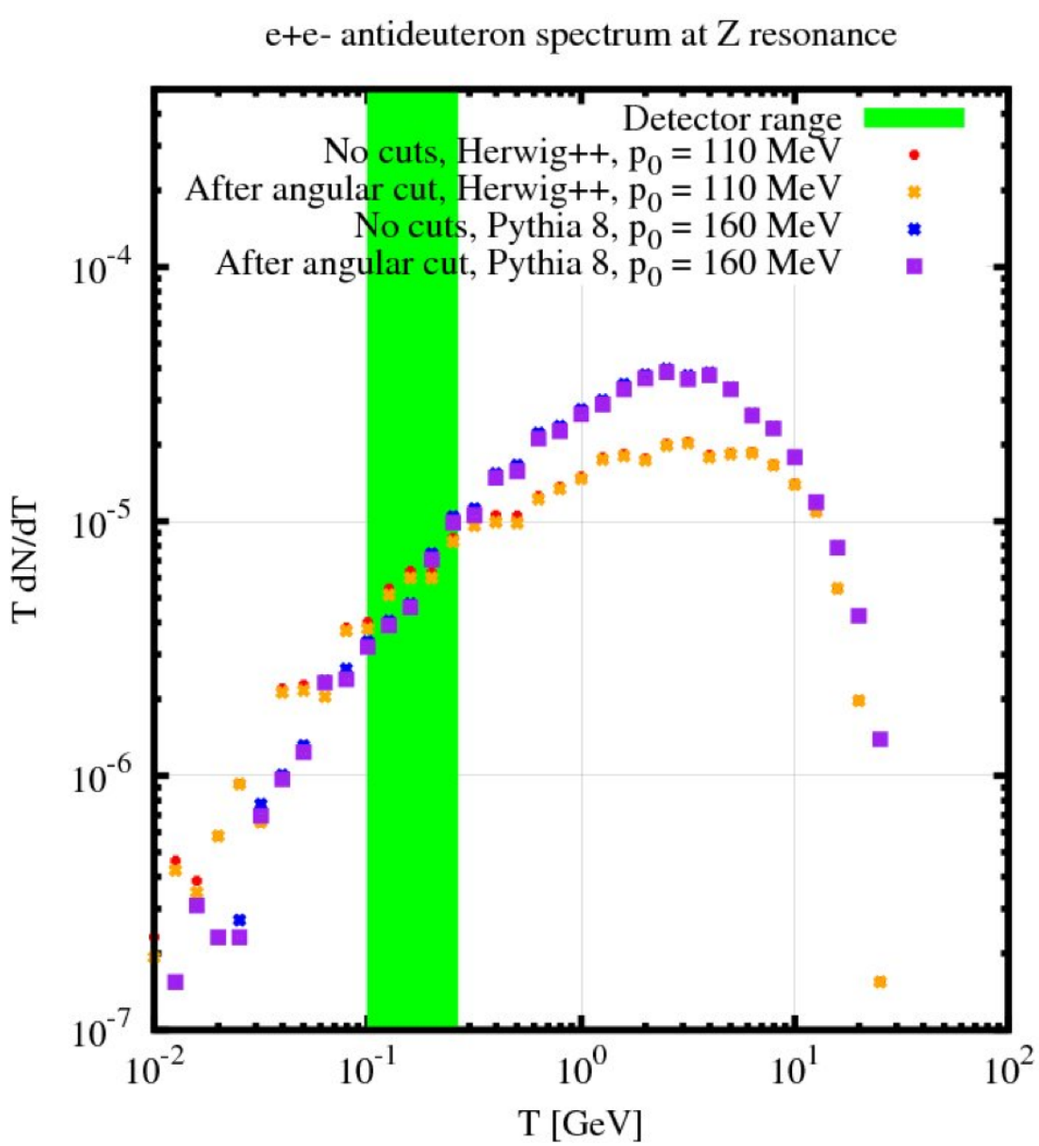
  - Very CPU expensive.

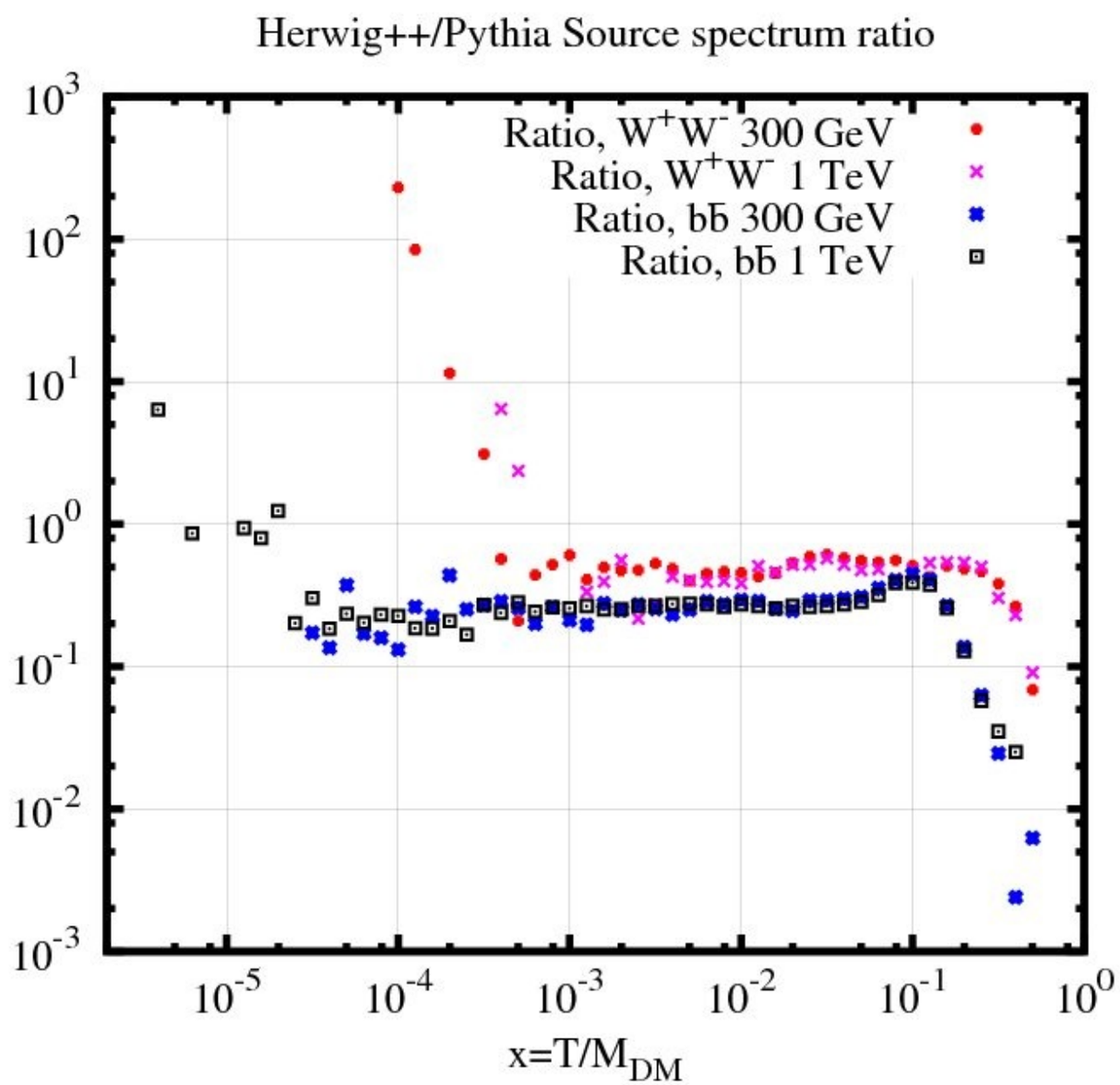
  - p_0 often tuned on **one** data point (ALEPH).

    $$\mathrm{BR}(Z \to \bar{d}X) = (5.9 \pm 1.8 \pm 0.5) \times 10^{-6}$$

Coalesence

[Dal and Kachelriess, Phys. Rev. D86 (2012) 103536]





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  - Step-function model too simple?
  - What about p_0-dependent (CoM energy) probability?
  - Why do pp experiments seem so different?

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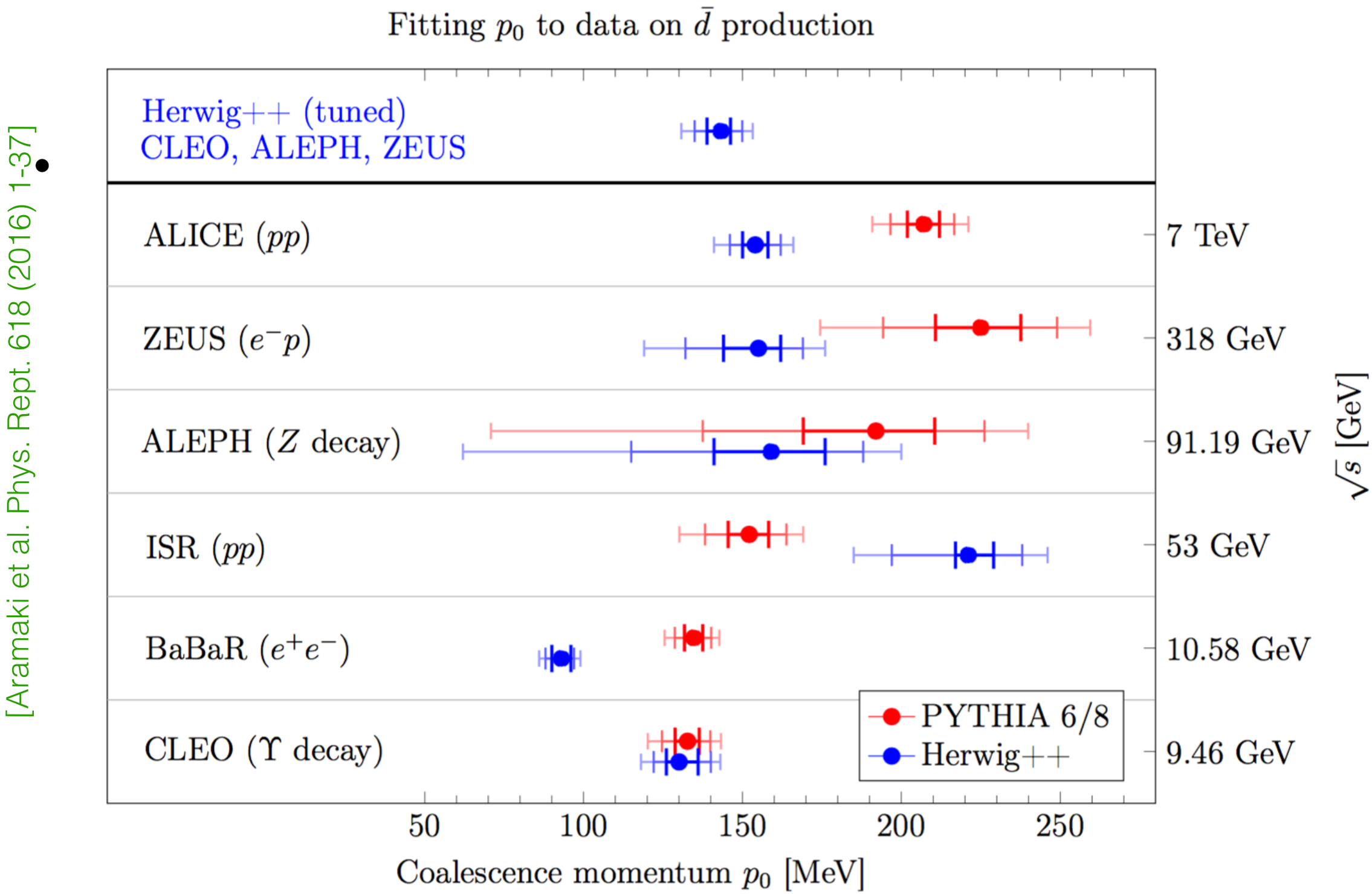

[Aramaki et al. Phys. Rept. 618 (2016) 1-37]

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Improving coalesence

- Fit of p_0 to a set of experiments (ALEPH, CLEO, ZEUS + LEP proton spectra) including HERWIG++ hadronization parameters

Parameter	Default value	Value at $\chi^2_{\min}$	Uncertainty[4]
p_0	–	143.2	$^{+6.2}_{-5.5}$
`ClMaxLight`	3.25	3.03	$^{+0.18}_{-0.15}$
`PSplitLight`	1.20	1.31	$^{+0.19}_{-0.32}$
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- Sounds simple, but 120 CPU hours per parameter point.

A toy model / test case

- Unstable gravitino dark matter (R-parity violation)
  - Interesting as model because of UDD-operators in superpotential:

$$W \sim \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k$$

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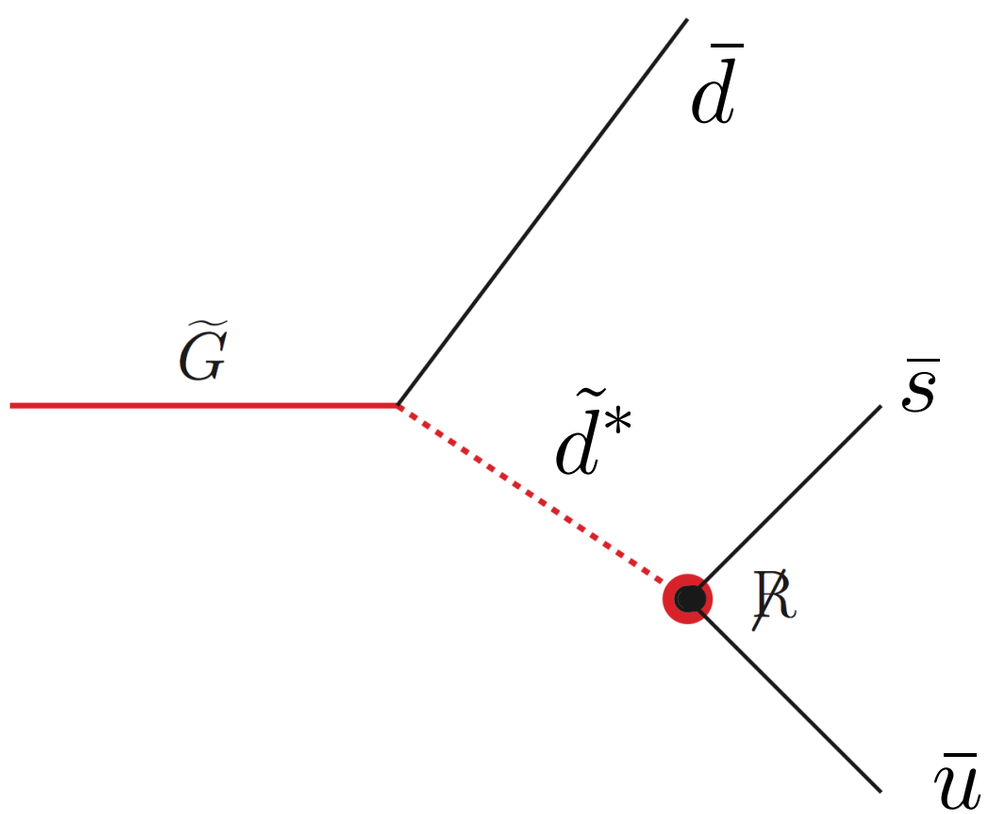
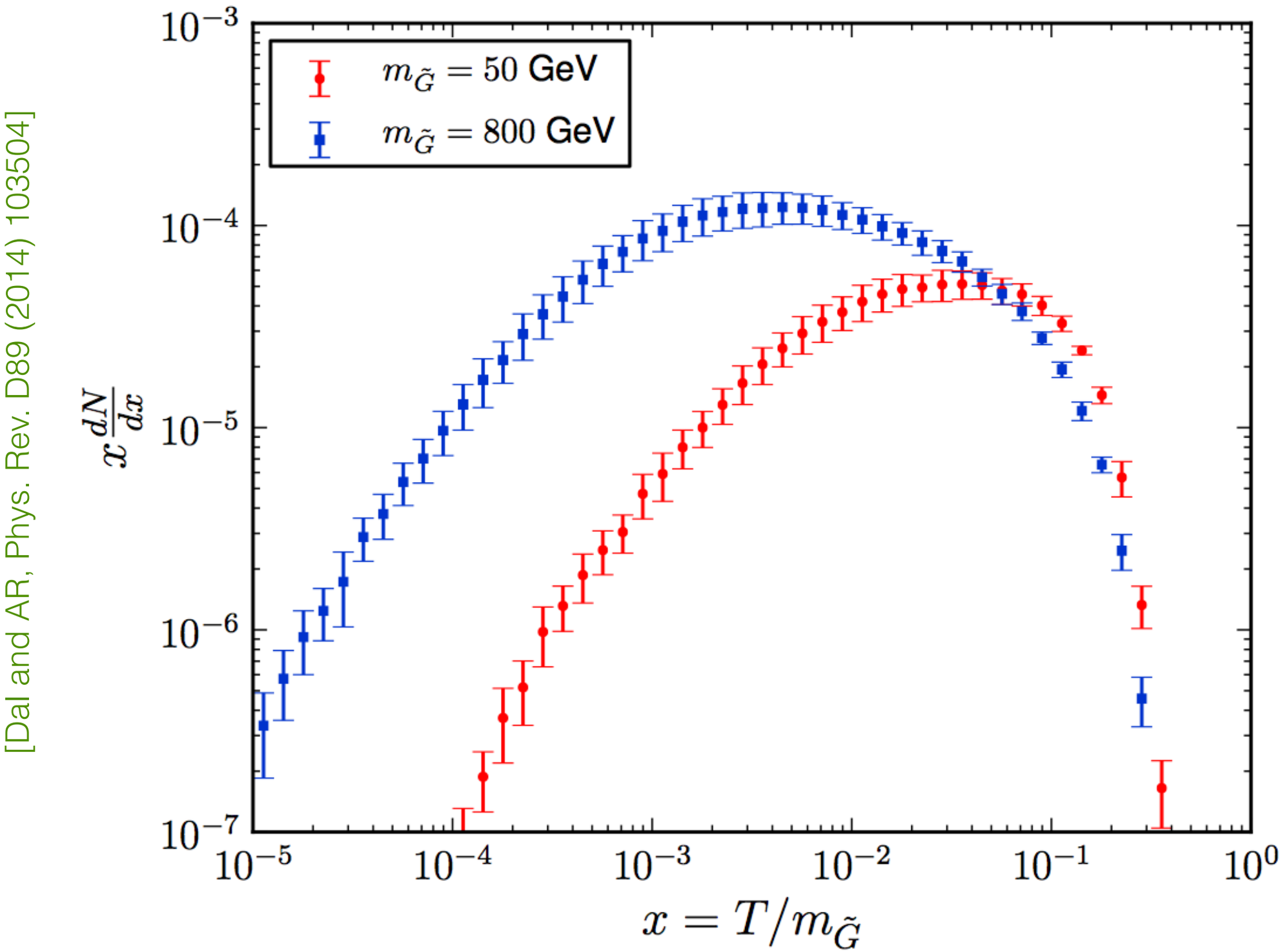


Gravitino $\bar{\mathbf{d}}$ spectrum



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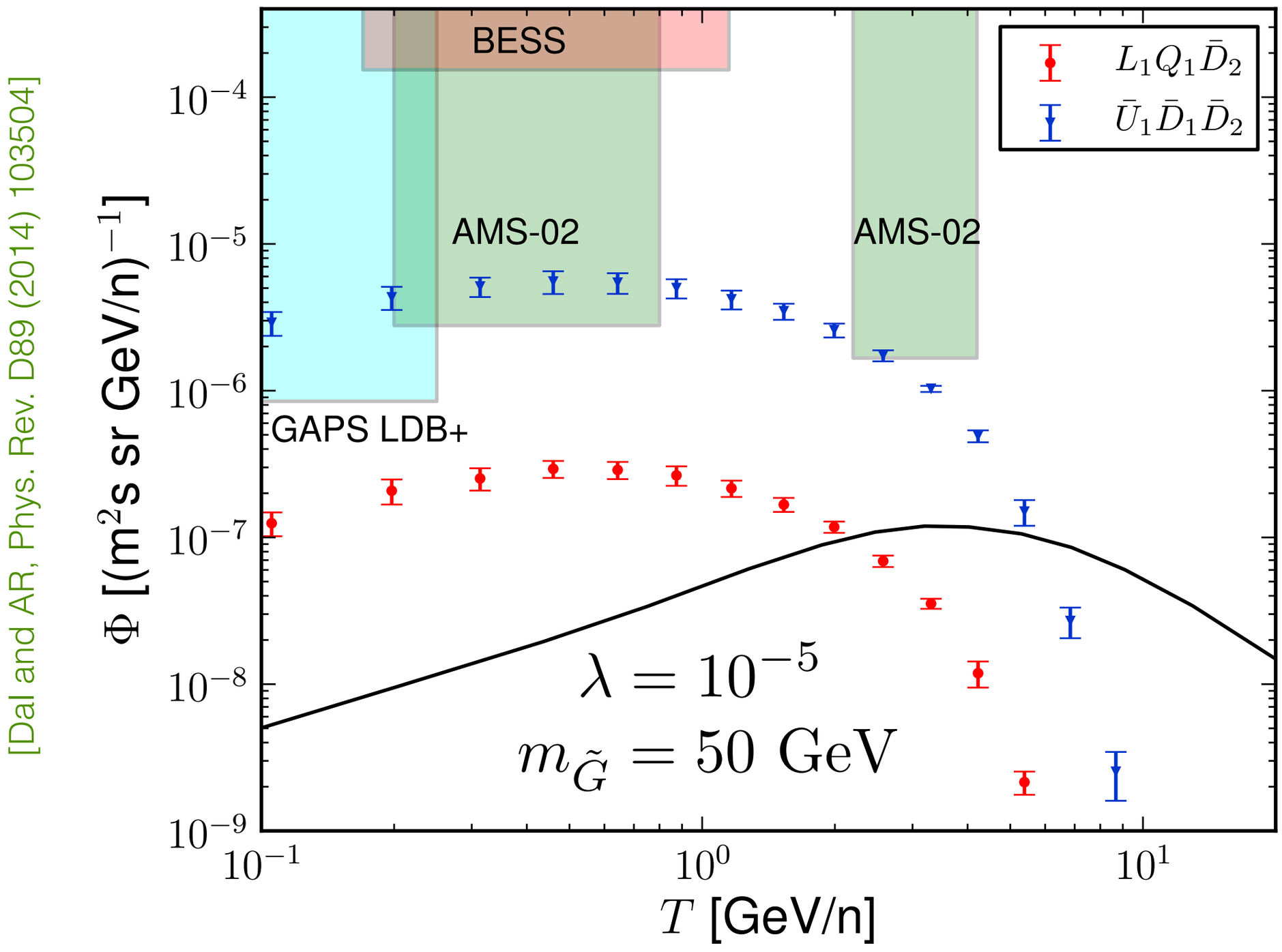
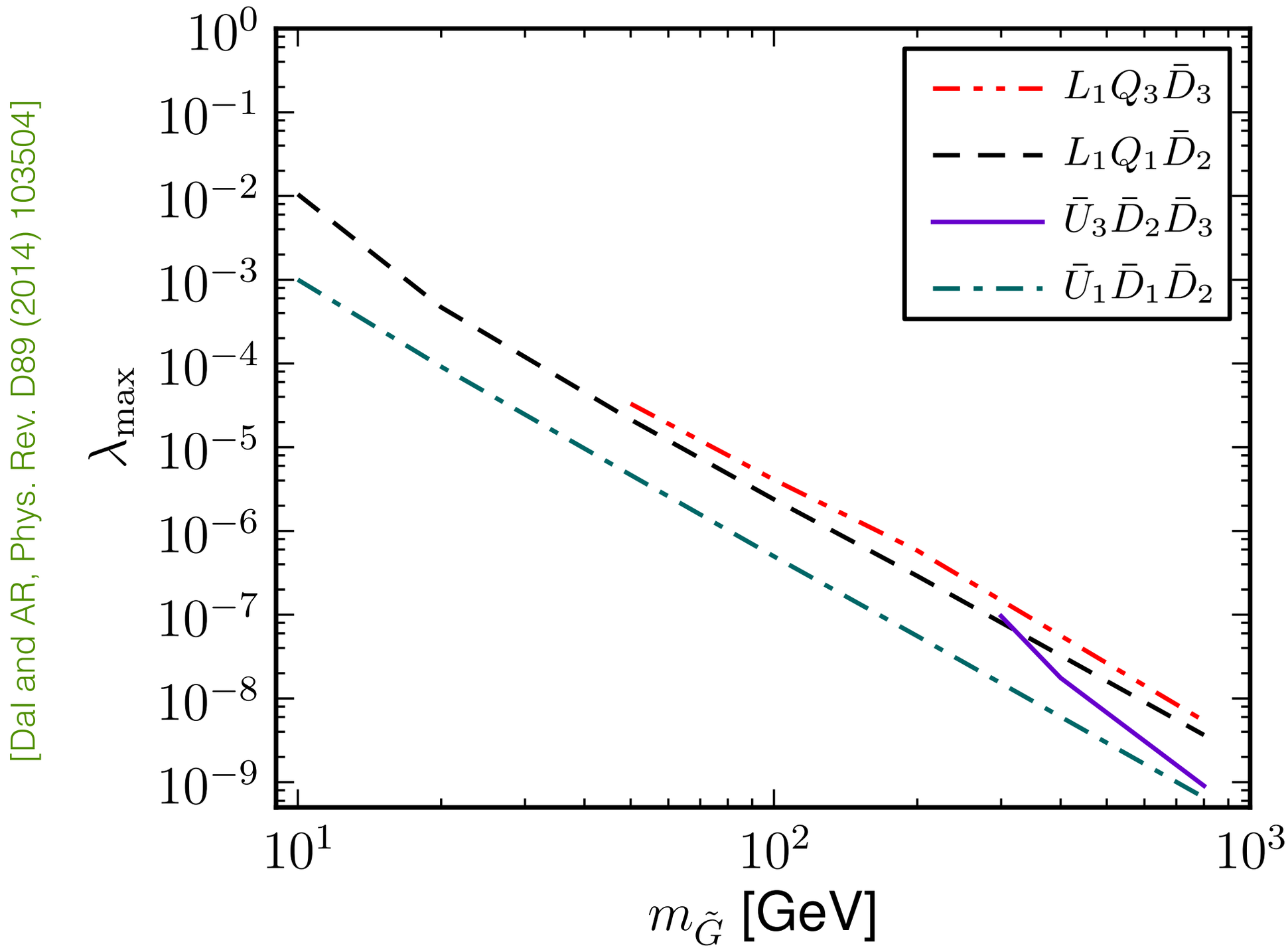
$\bar{d}$ flux at Earth



Prospective limits from GAPS



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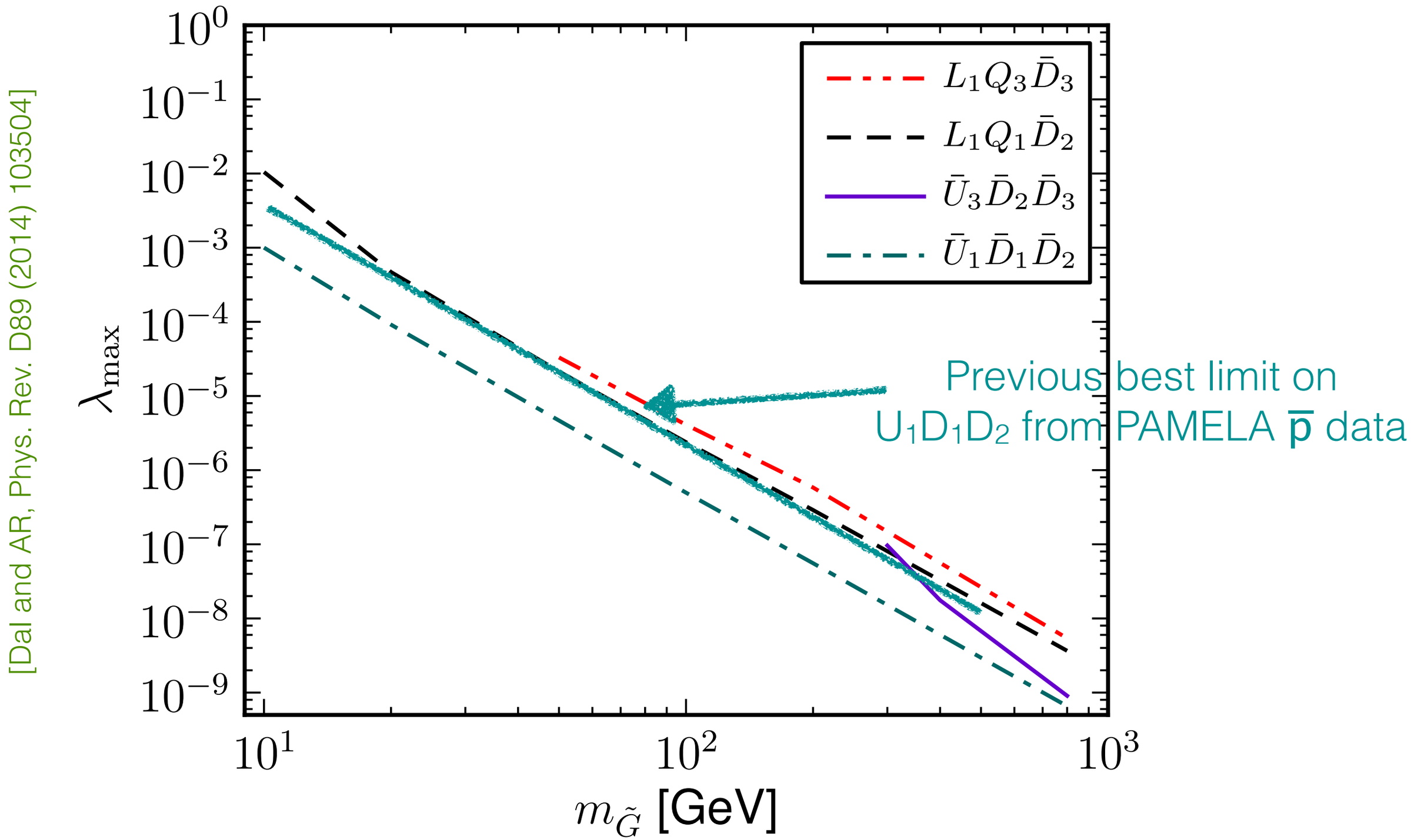
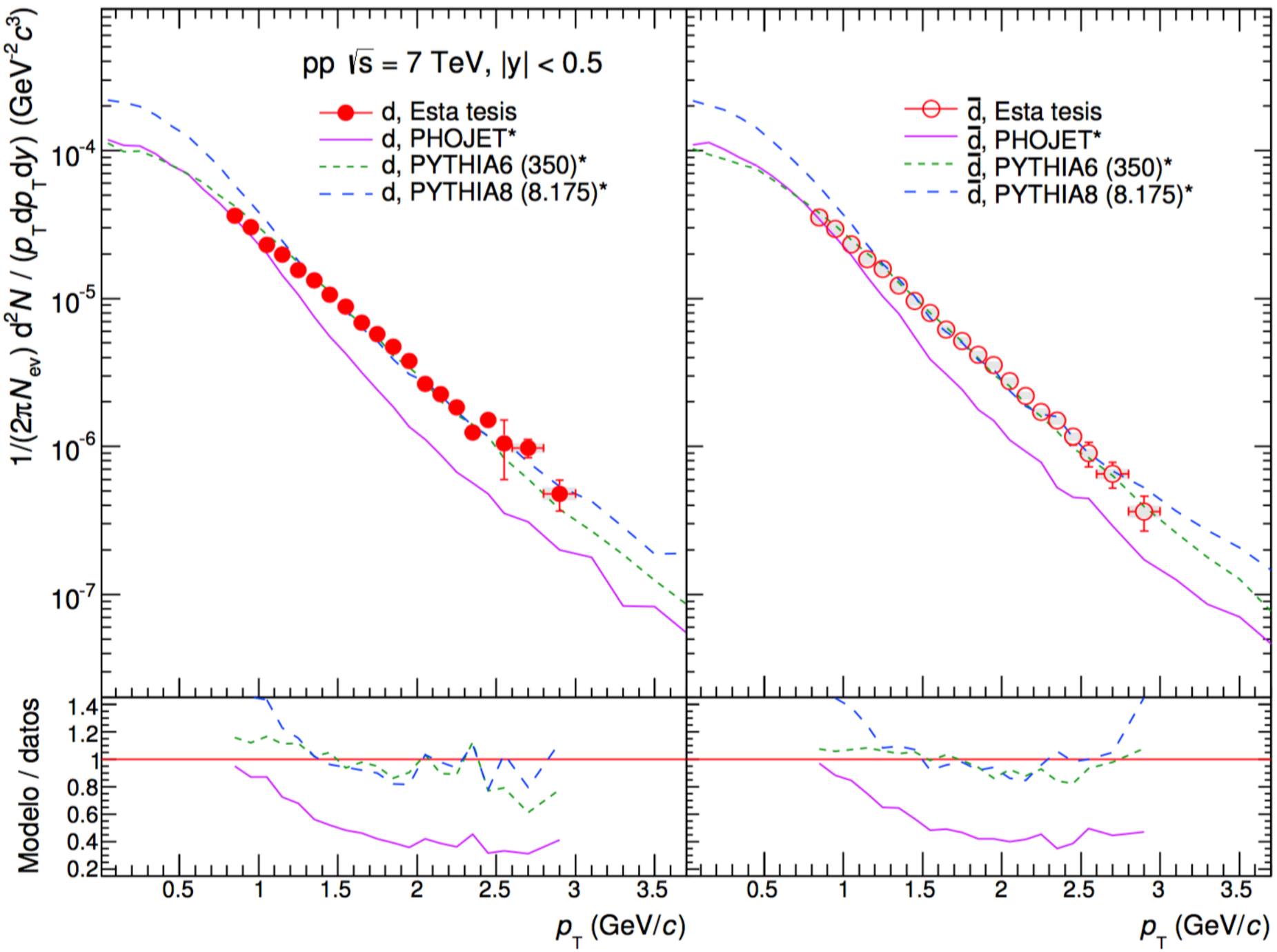


ALICE means trouble for coalesence



[Serradilla, CERN-THESIS-2013-322]

A new formation model

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- Taking a step away from the step function, a probabilistic coalesence:

$$P(\bar{p}\bar{n} \to \bar{d}X|k) = \frac{\sigma_{\bar{p}\bar{n}\to\bar{d}X}(k)}{\sigma_0}$$

[Dal and AR, Phys. Rev. D91 (2015) 123536]

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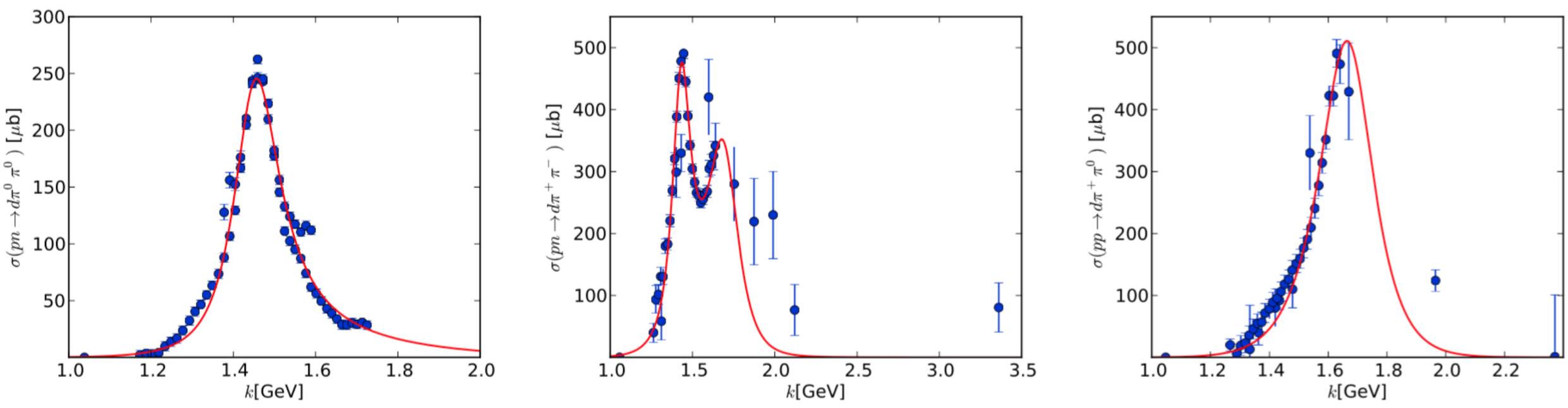
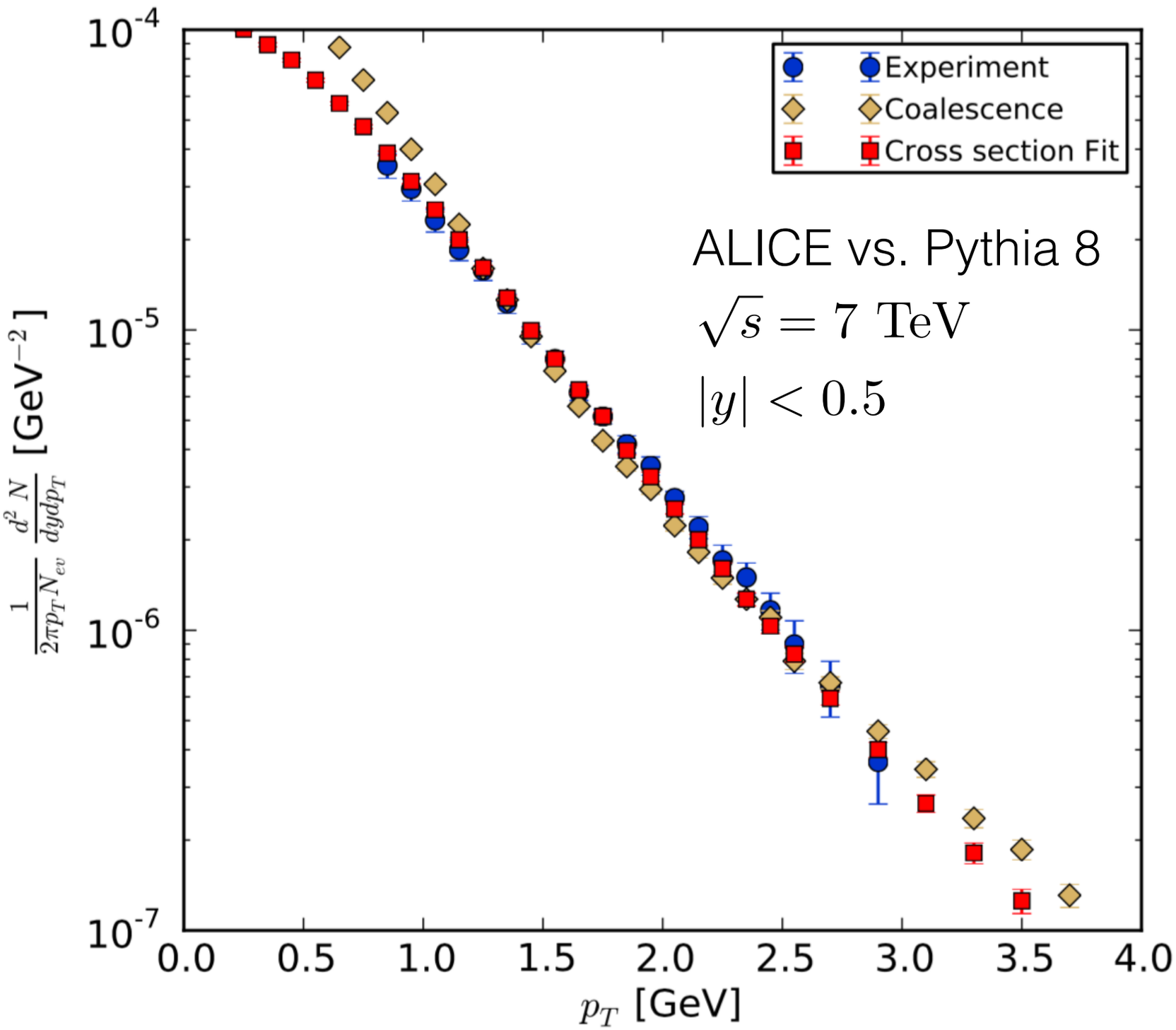
- Based on cross section data. One free parameter σ_0.



Comparison to ALICE data



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Conclusions

- Searches for antideuterons can be a useful way to constrain (or discover!) certain models for dark matter.
- There are significant uncertainties in antideuteron formation models which we have quantified.
- We have introduced a new cross section based model as an alternative to the standard per event coalesence.
  - Code to evaluate coalesence probability available on arXiv as ancillary material.

Bonus material

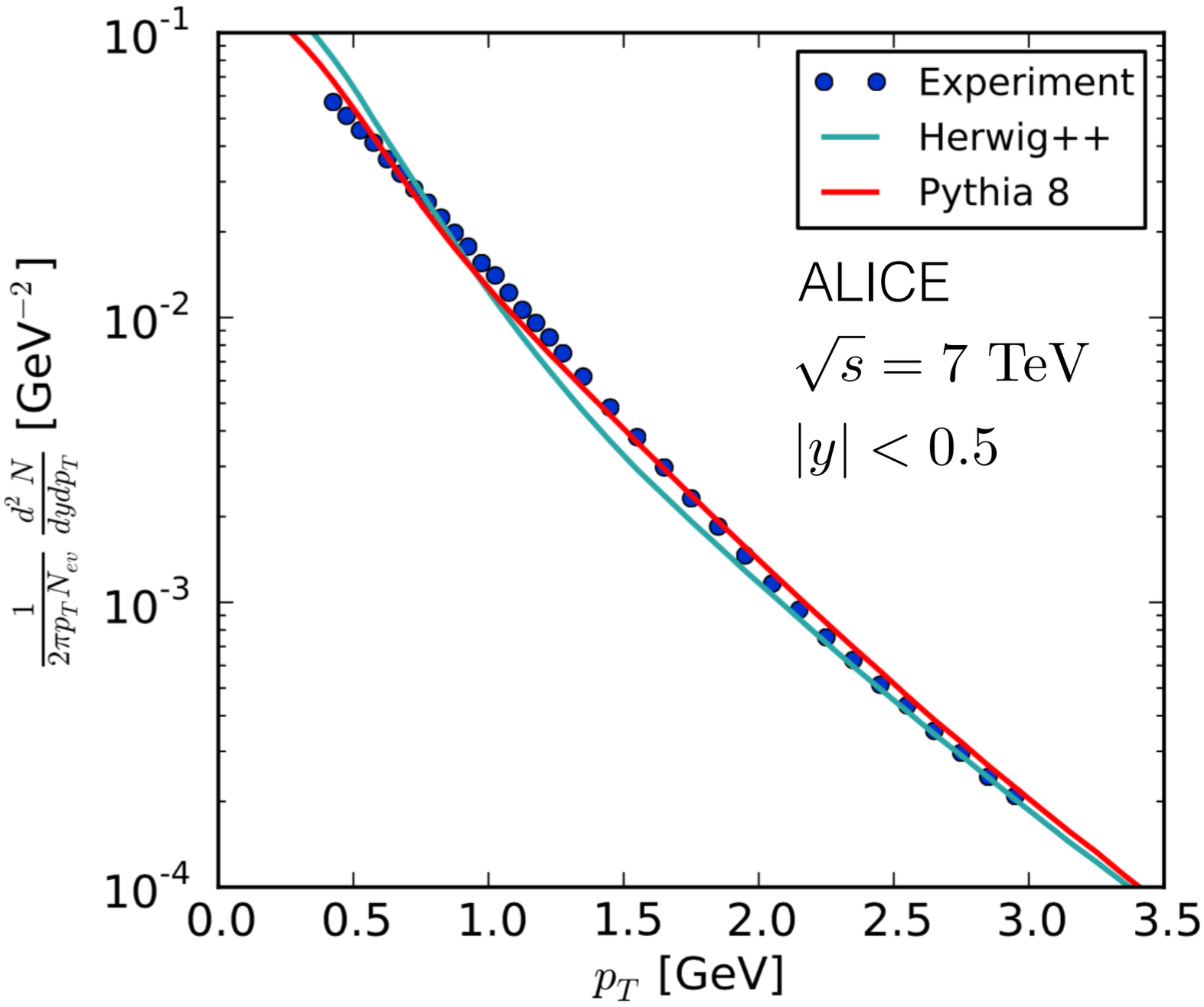
Antideuteron data fit to new coalesence model

Monte Carlo	Experiments	Data points	Best fit p_0 [MeV]	$\chi^2_{p_0}$	Best fit $1/\sigma_0$ [barn^{-1}]	$\chi^2_{\sigma_0}$
Herwig++	ALICE ($\bar{d}$), ISR	38	187	646	3.50	196
	BABAR, CLEO, LEP	16	96	73.6	0.68	29.2
	All experiments	54	123	2859	1.43	2146
Pythia 8	ALICE ($\bar{d}$), ISR	38	193	255	2.63	58.2
	BABAR, CLEO, LEP	16	140	30.5	1.18	16.7
	All experiments	54	174	888	2.13	510

Dof 37 for ALICE & ISR, 15 for BABAR, CLEO & LEP

Why you should be carefull with Pythia & Herwig

[Dal and AR, Phys. Rev. D91 (2015) 123536]



Statistical coalesence

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- Models traditionally used **statistical coalescence**

$$\frac{dN_{\bar{d}}}{dT_{\bar{d}}} = \frac{p_0^3}{6} \frac{m_{\bar{d}}}{m_{\bar{n}} m_{\bar{p}}} \frac{1}{\sqrt{T_{\bar{d}}^2 + 2m_{\bar{d}} T_{\bar{d}}}} \frac{dN_{\bar{n}}}{dT_{\bar{n}}} \frac{dN_{\bar{p}}}{dT_{\bar{p}}}$$

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- Shown to be bad.

[Kadastik, Raidal and Strumia, Phys. Lett. B683 (2010) 248–254]
[Dal and Kachelriess, Phys. Rev. D86 (2012) 103536]

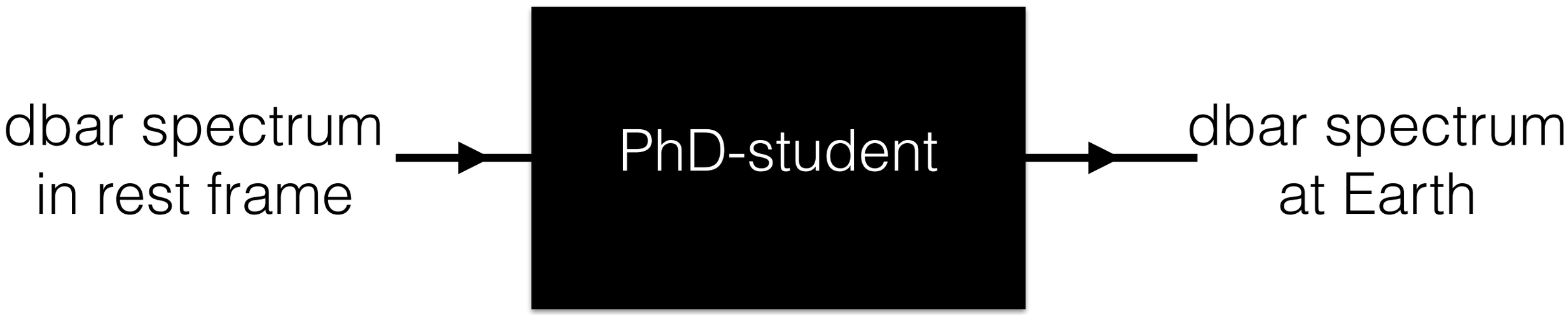
Improving coalesence

- Individual and common fits of HERWIG++ to a set of antideuteron measurements

Experiment	χ^2, best fit p_0	χ^2, $p_0 = 152$ MeV	N_{bins}
ALEPH	0.0	0.2	1
CLEO	7.6	10.5	5
ZEUS	3.7	3.8	3
CERN ISR	5.0	33.2	4+4
ALICE	5.1	5.5	9

[Dal and ARR, Phys. Rev. D89 (2014) 103504]

Propagation



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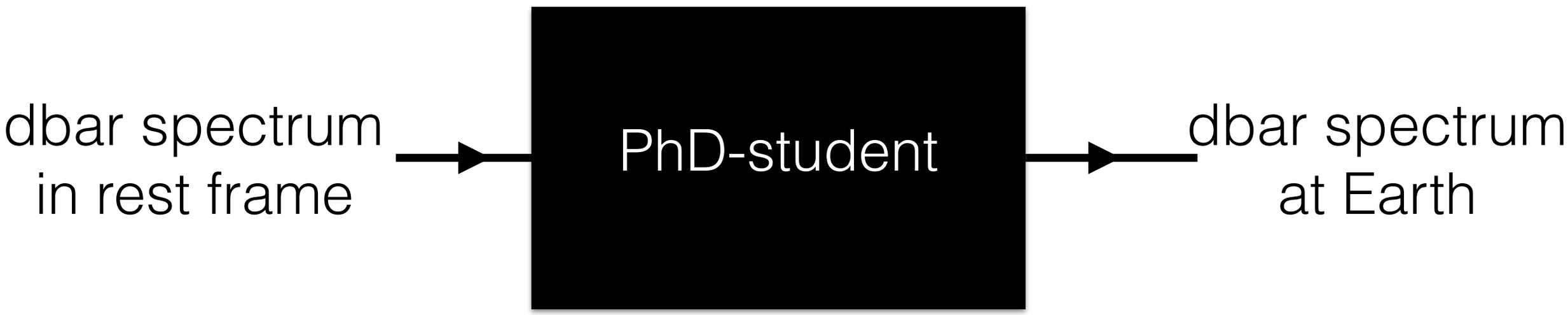

$$-D(T)\nabla^2 f + \frac{\partial}{\partial z}(\mathrm{sign}(z) f V_c) = Q - 2h\delta(z)\Gamma_{\mathrm{ann}}(T) f$$

Model	L in kpc	δ	D_0 in $\mathrm{kpc}^2\,\mathrm{Myr}^{-1}$	V_c in $\mathrm{km\,s}^{-1}$
max	15	0.46	0.0765	5
med	4	0.7	0.0112	12
min	1	0.85	0.0016	13.5

The standard plot

[Donato, Fornengo and Salati, Phys. Rev. D62 (2000) 043003]