Anti-deuteron production in WIMP annihilations

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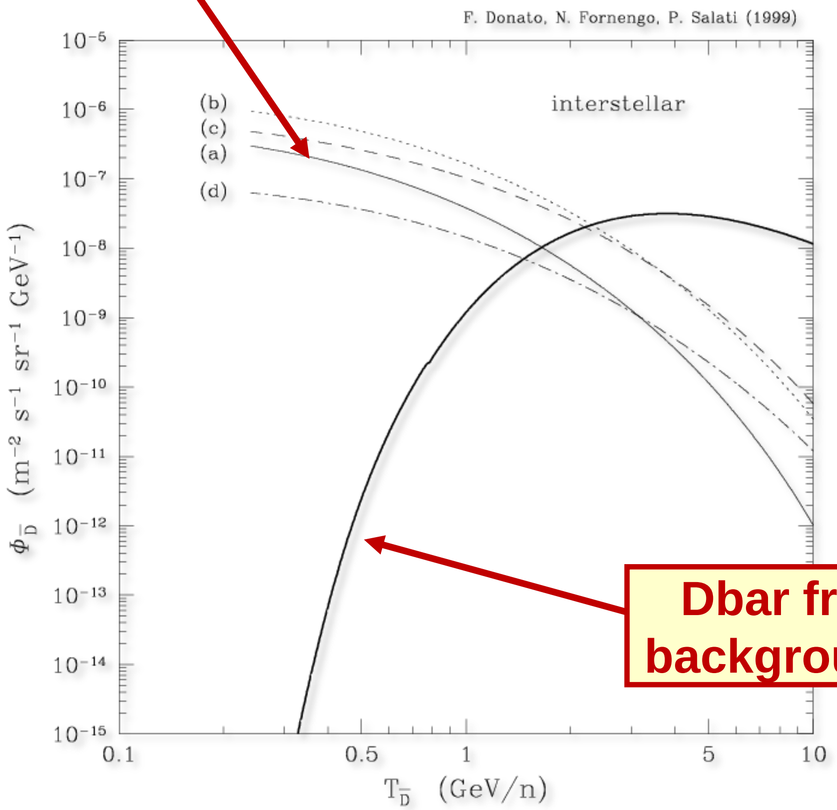
With J. Cornell, J. Edsjö, N. Karpenka, A. Putze, P. Scott

Overview

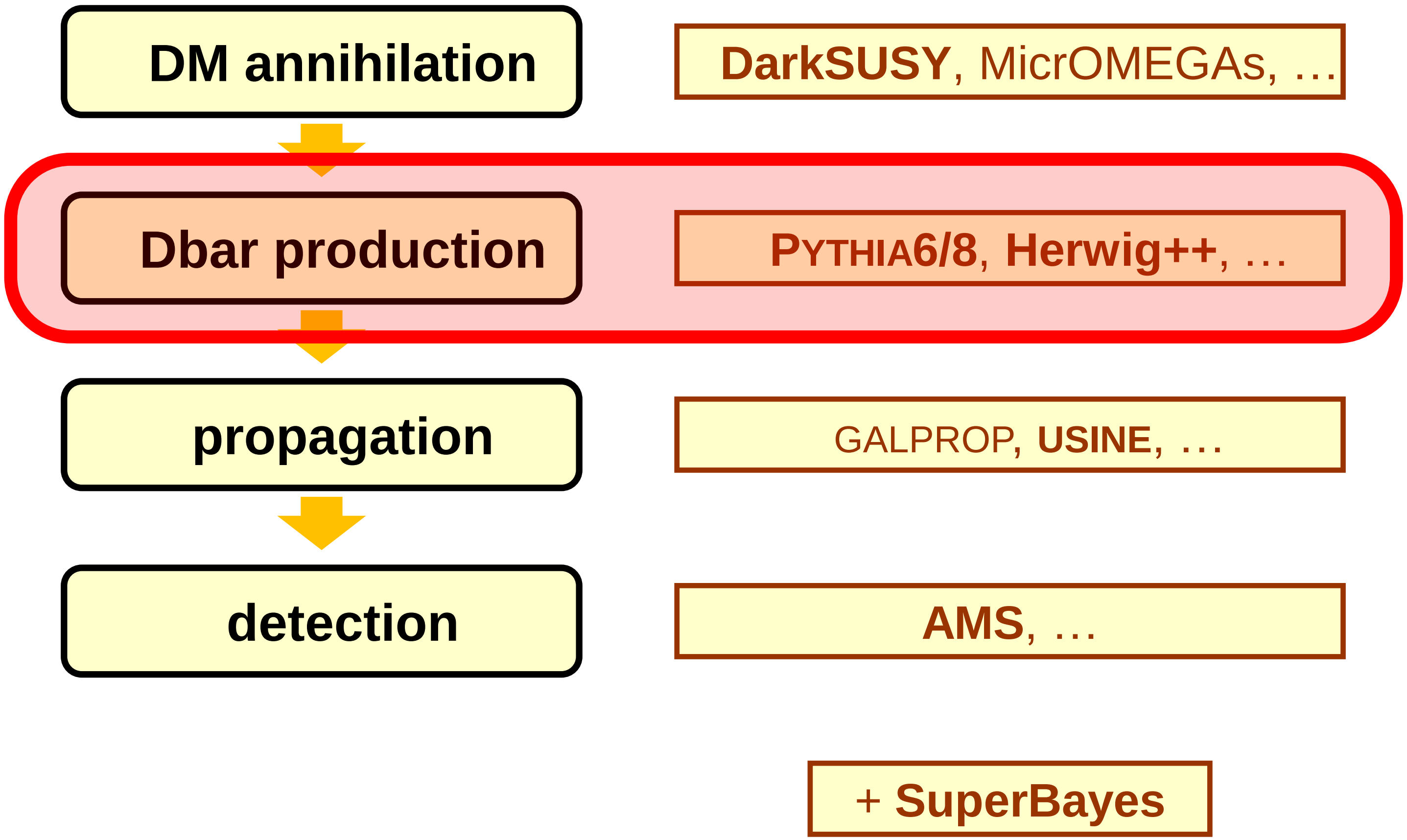
Donato, Fornengo & Salati,
Phys. Rev. **D62**, 043003 (2000)

Dbar from DM annihilations



Dbar from backgrounds

Overview



DM annihilation
DarkSUSY, MicrOMEGAs, …
Dbar production
PYTHIA6/8, Herwig++, …
propagation
GALPROP, USINE, …
detection
AMS, …
+ SuperBayes

Dbar production: MC generators

Talk by J. Cembranos

- **PYTHIA6:** Joakim Edsjö (nearly complete)
- **PYTHIA8:** CS (complete)
- **Herwig++**: Jonathan Cornell (in progress)
- **Herzog:** (Doug?)

Results:

- Mainly PYTHIA8
- Some very preliminary

Rest of analysis:
A. Putze (USINE)
P. Scott (SuperBayeS)
N. Karpenka

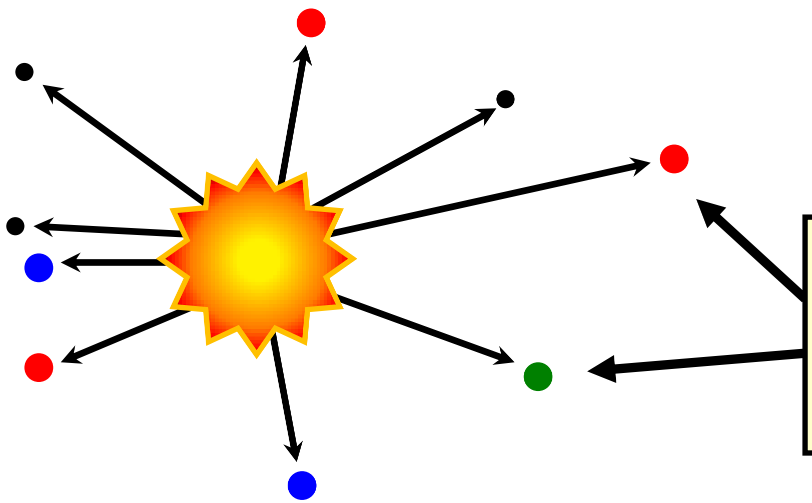
Outline

- Coalescence model
- Results
- Issues: vertex cut and relaxation
- MC generator comparison

Coalescence model

Coalescence model

J. Kapusta, Phys. Rev. **C21**, 1301 (1980)



If proton and neutron have momenta difference $\Delta p \leq p_0$, they coalesce into deuteron

- Problem: HEP event generators do not do nucleon coalescence/fusion (no deuterons)
- Must generate D/Dbar from nucleons ourselves

Analytic approximation

- Treat proton and neutron spectra as *independently* isotropic $\Rightarrow \quad N_D \propto \dfrac{1}{M_{DM}^2}$

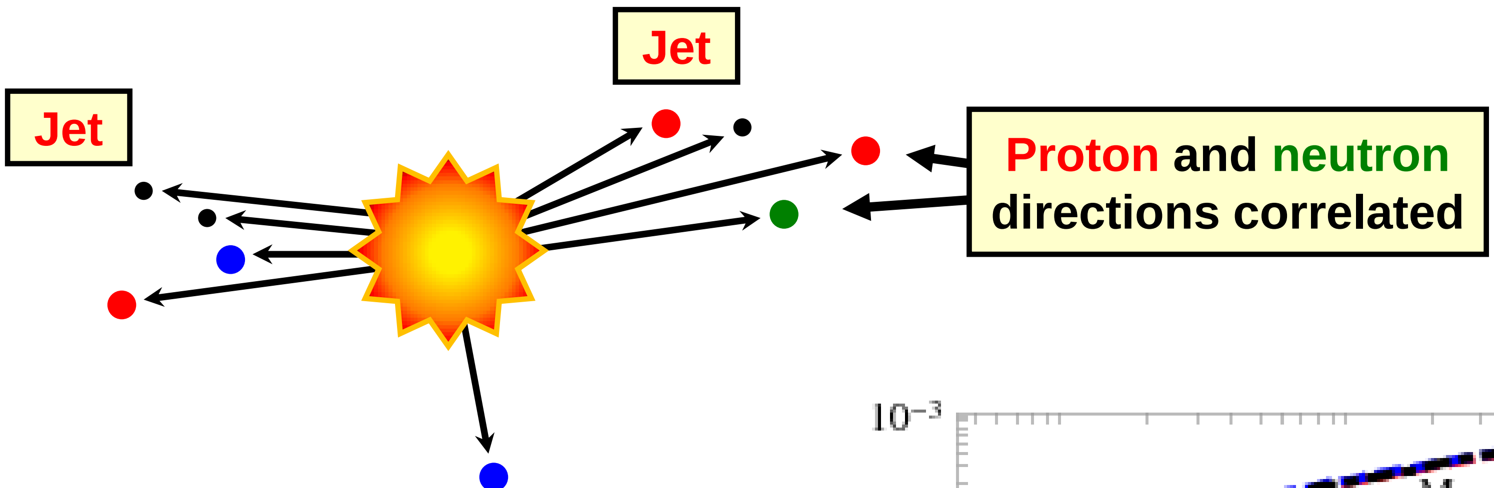
- **Advantage:** simple, easy to calculate
  - Simply tabulate $^{dN}/_{dp}$ for each nucleon [O(1) nucleon / annihilation]

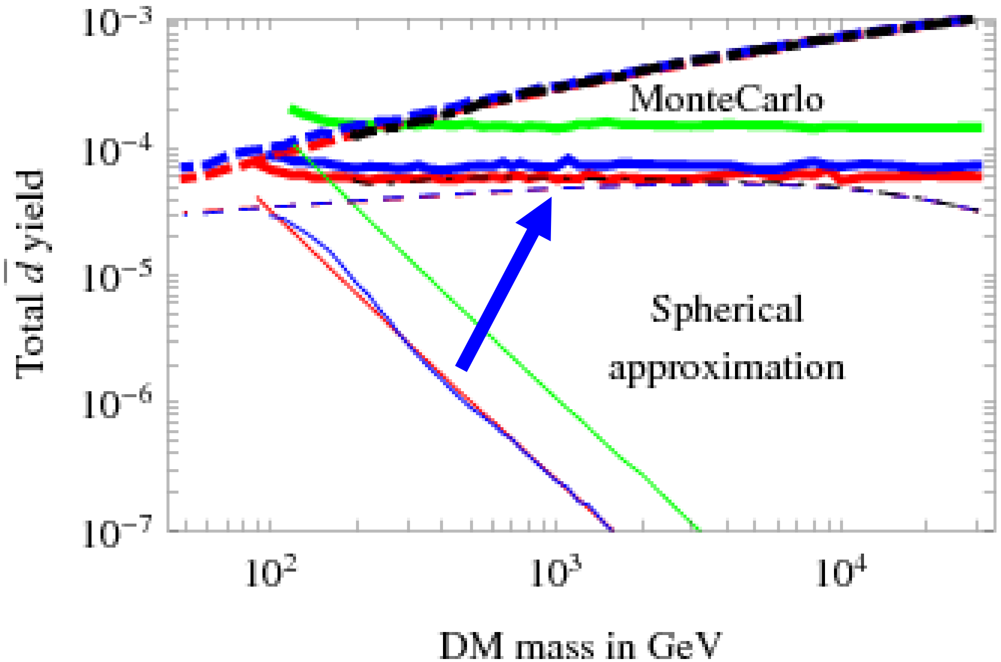
- **Disadvantage:** results are wrong

Jets: directions are correlated

Monte carlo (event-level) modeling

Kadastik, Raidal & Strumia, Phys.Lett. **B683**, 248 (2010)





- No $1/M^2$ factor
- Example: Z channel

  Changing M changes Z boost, but Z rest frame identical

Coalescence parameter p_0

ALEPH Collab., Phys. Rev. Lett. **639**, 192 (2006)

ALEPH:

Dbars produced per 10^6 Z hadronic resonance decays over $0.62 \leq p \leq 1.03$ GeV/c

5.9 ± 1.8 (stat) ± 0.5 (sys)

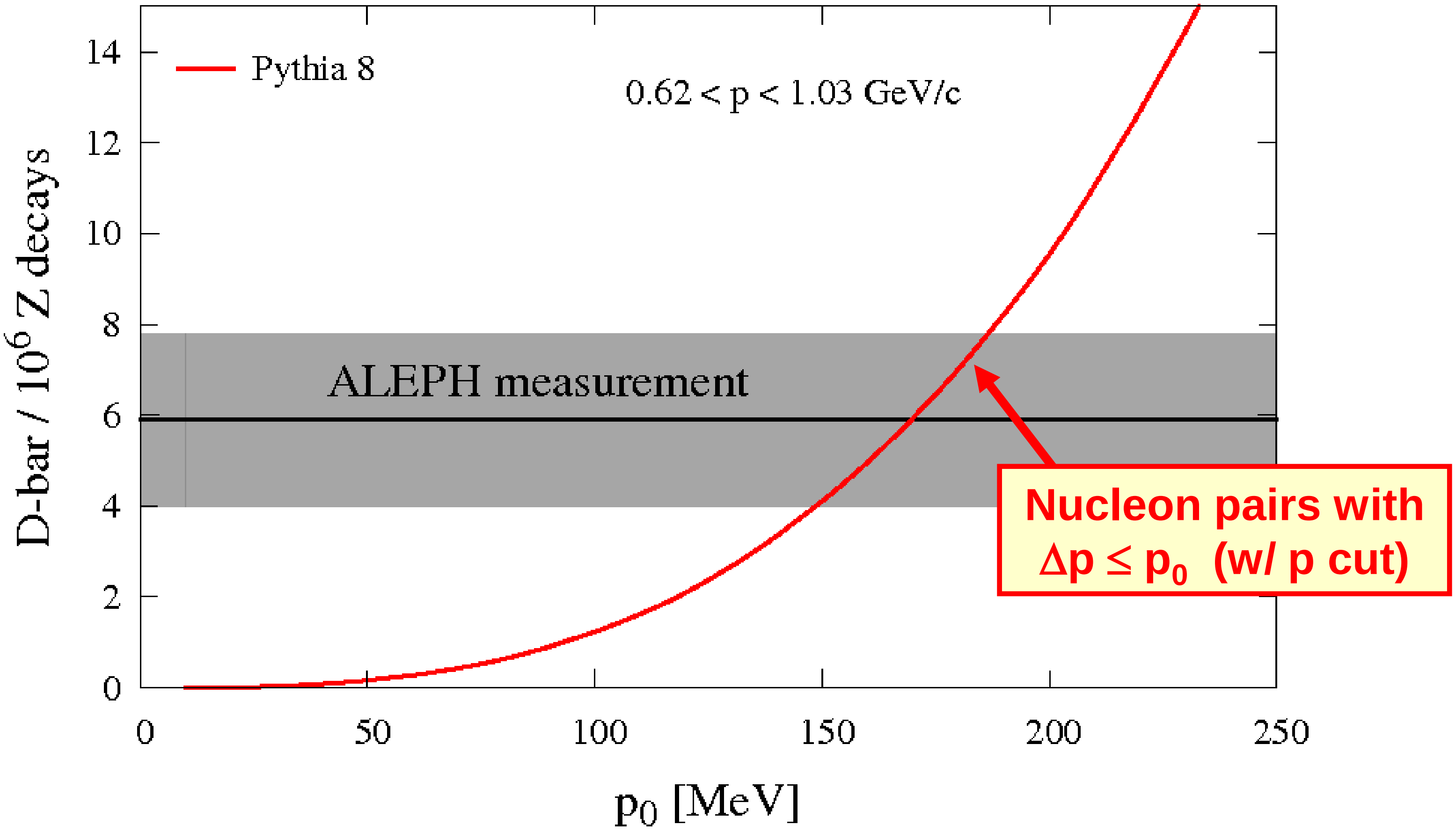
Determine p_0:

- Simulate Z resonance decays
- Bin by Δp of proton-neutron pairs
- Find p_0 such that pairs with $\Delta p \leq p_0$ represent above fraction

Different physics models/implementations

$\Rightarrow$ *MC generator specific p_0*

Coalescence parameter p_0



Coalescence parameter p_0

2×10^9 Z resonance decays (each)

	Herwig++	PYTHIA6	PYTHIA8	
no vertex cut	117.3	172.6	169.7	$\pm$ 0.3 MeV

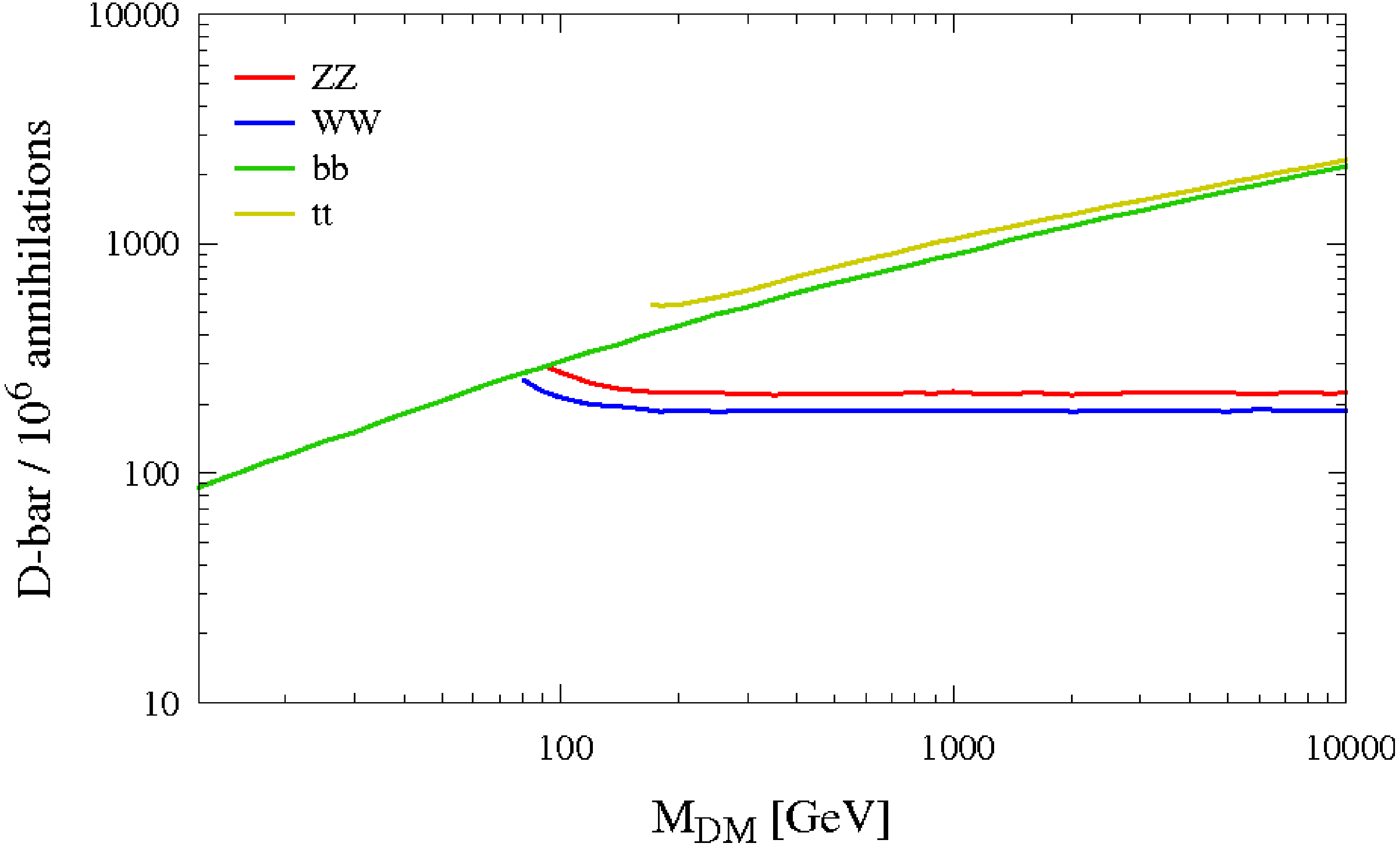
ALEPH measurement: $\pm$ 20 MeV

Hadronization

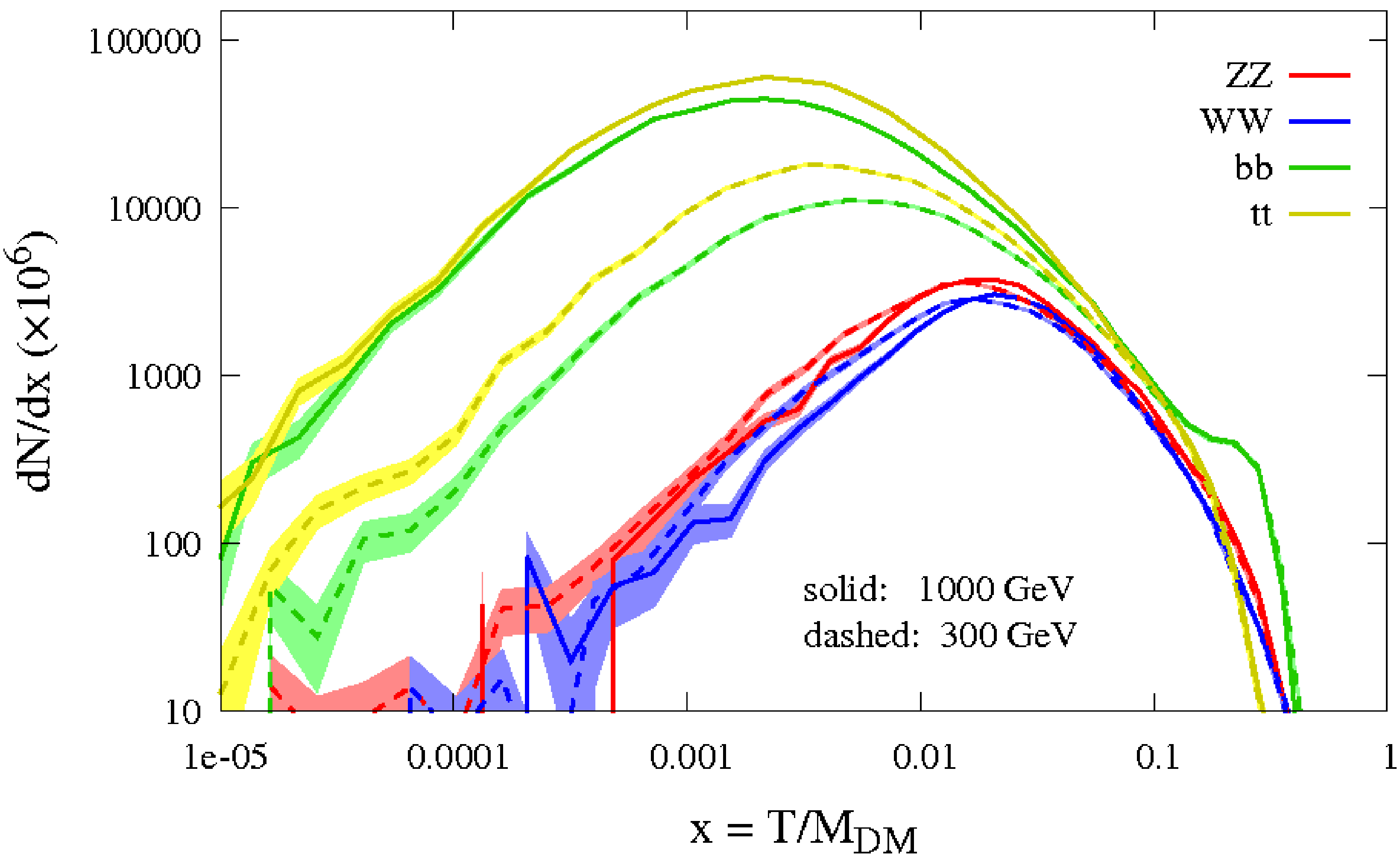
- PYTHIA: string fragmentation (Lund model)
- Herwig: cluster fragmentation

Results

Dbar production rates



Dbar spectrum



Vertex Cut

Where are the nucleons produced?

- WIMP annihilation hadronization process: many nucleons produced at initial vertex

- …but heavier baryons & mesons also produced. Later decays produced nucleons away from initial vertex

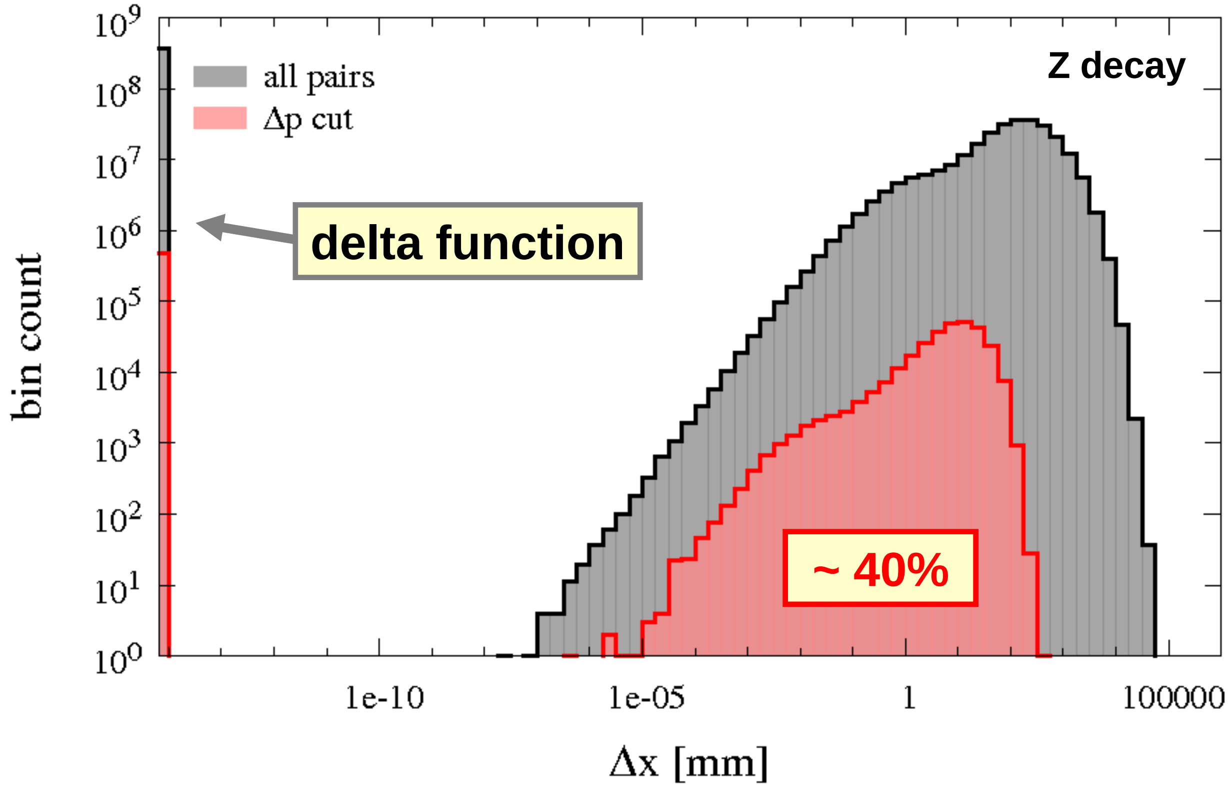
- Can nucleons produced at different locations have similar momentum (i.e. small Δp)?
  - Δx usually (always?) neglected
  - Jet structure?

Fornengo, Maccione & Vittino, arxiv:1306.4171

Nucleon pair separation Δx

Distance between pair of nucleons

After $\Delta p \leq p_0$ cut

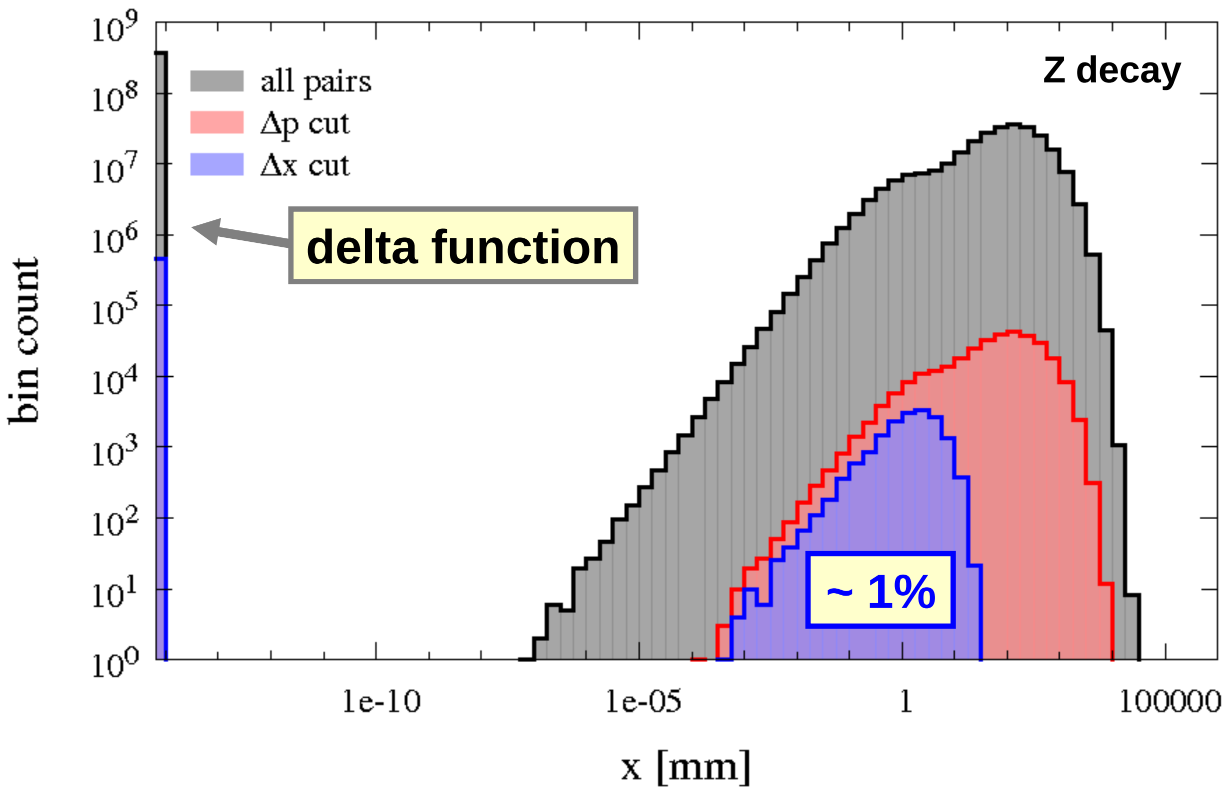


Nucleon pairing distance

Distance from annihilation vertex to nucleon pairing

After $\Delta p \leq p_0$ cut

After $\Delta x \leq 1$ fm cut

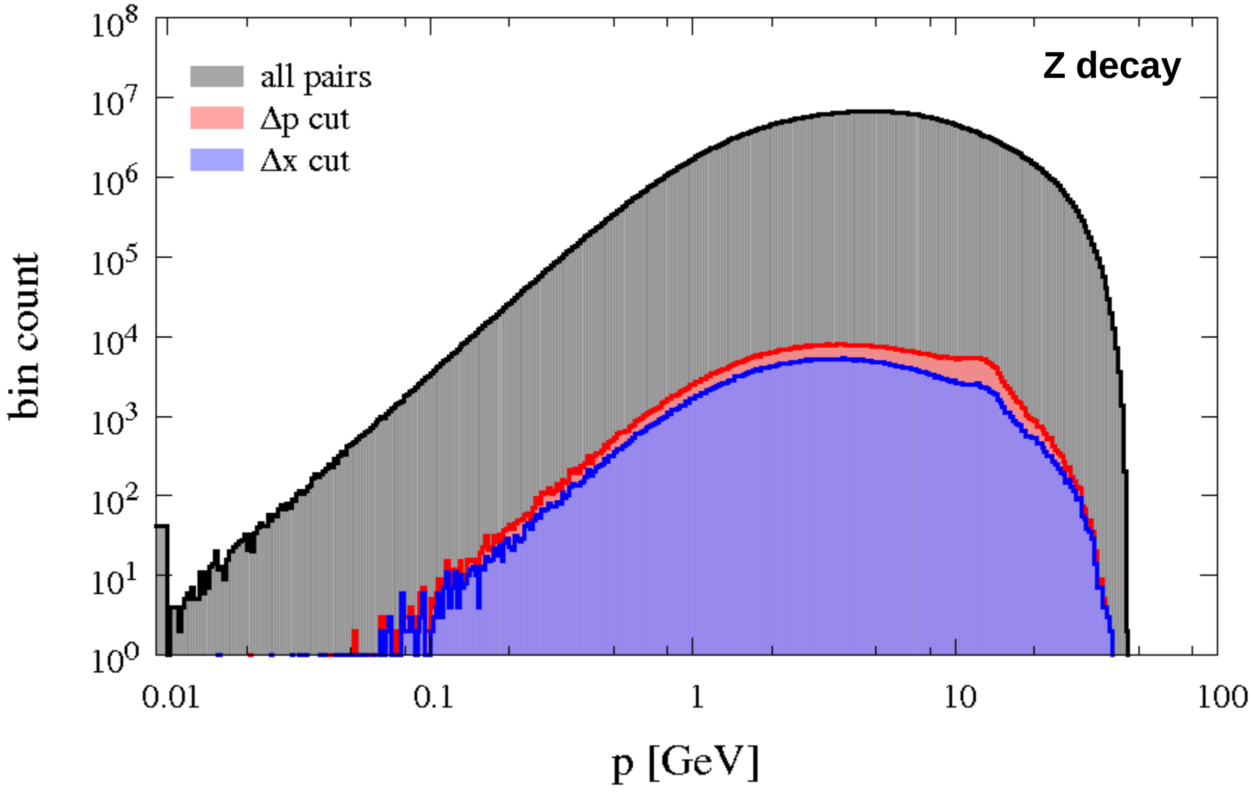


Momentum distribution

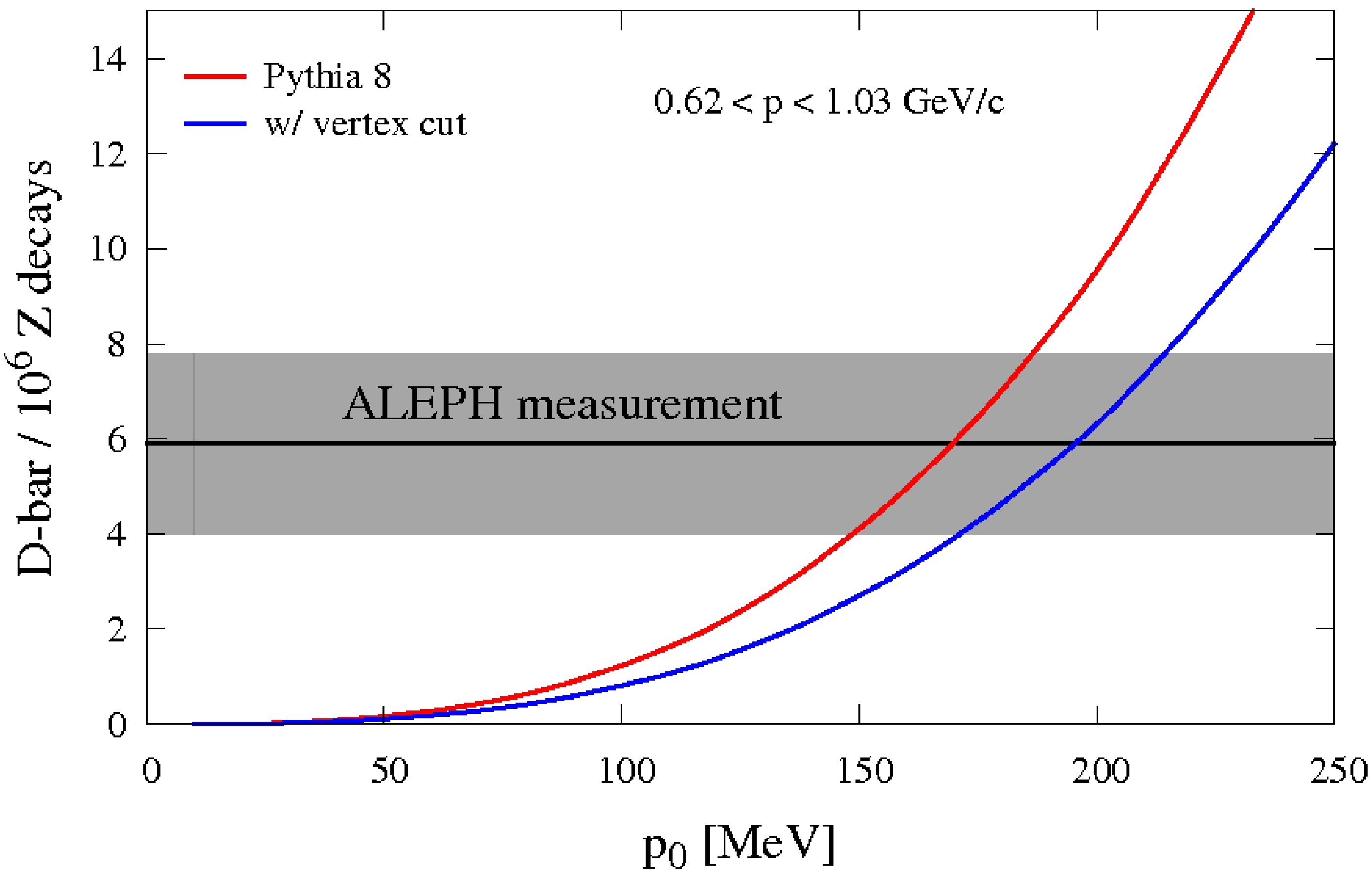
Nucleon pair net momentum

After $\Delta p \leq p_0$ cut

After $\Delta x \leq 1$ fm cut



Coalescence parameter p_0



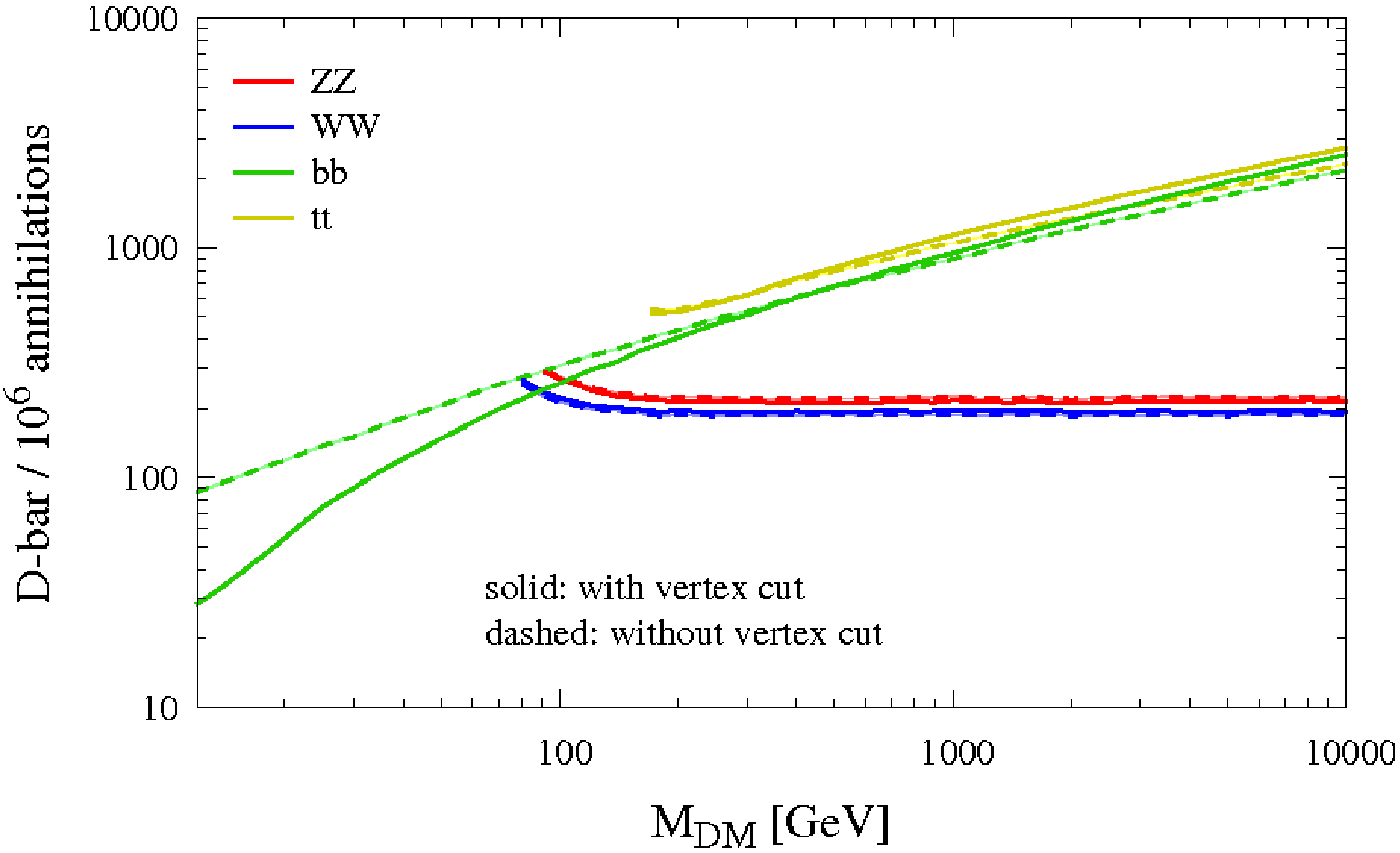
Coalescence parameter p_0

	Herwig++	PYTHIA6	PYTHIA8	
no vertex cut	117.3	172.6	169.7 $\pm$ 0.3	MeV
vertex cut	160.0	201.5	195.6 $\pm$ 0.4	

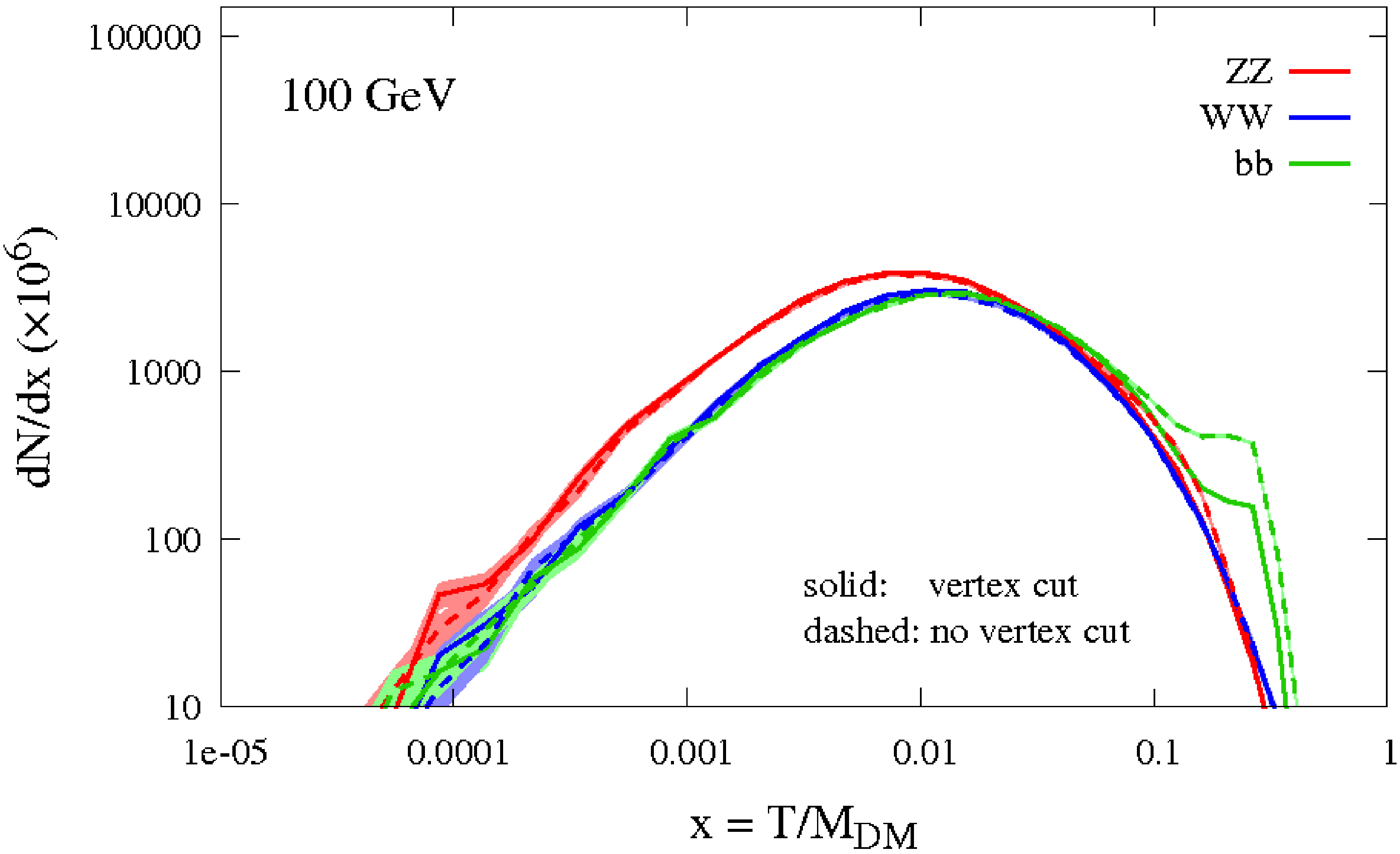
O(50%) increase in pairs passing $\Delta p \leq p_0$,
but O(20-40%) fail to pass Δx cut:
***partial* cancelation**

Results (with vertex cut)

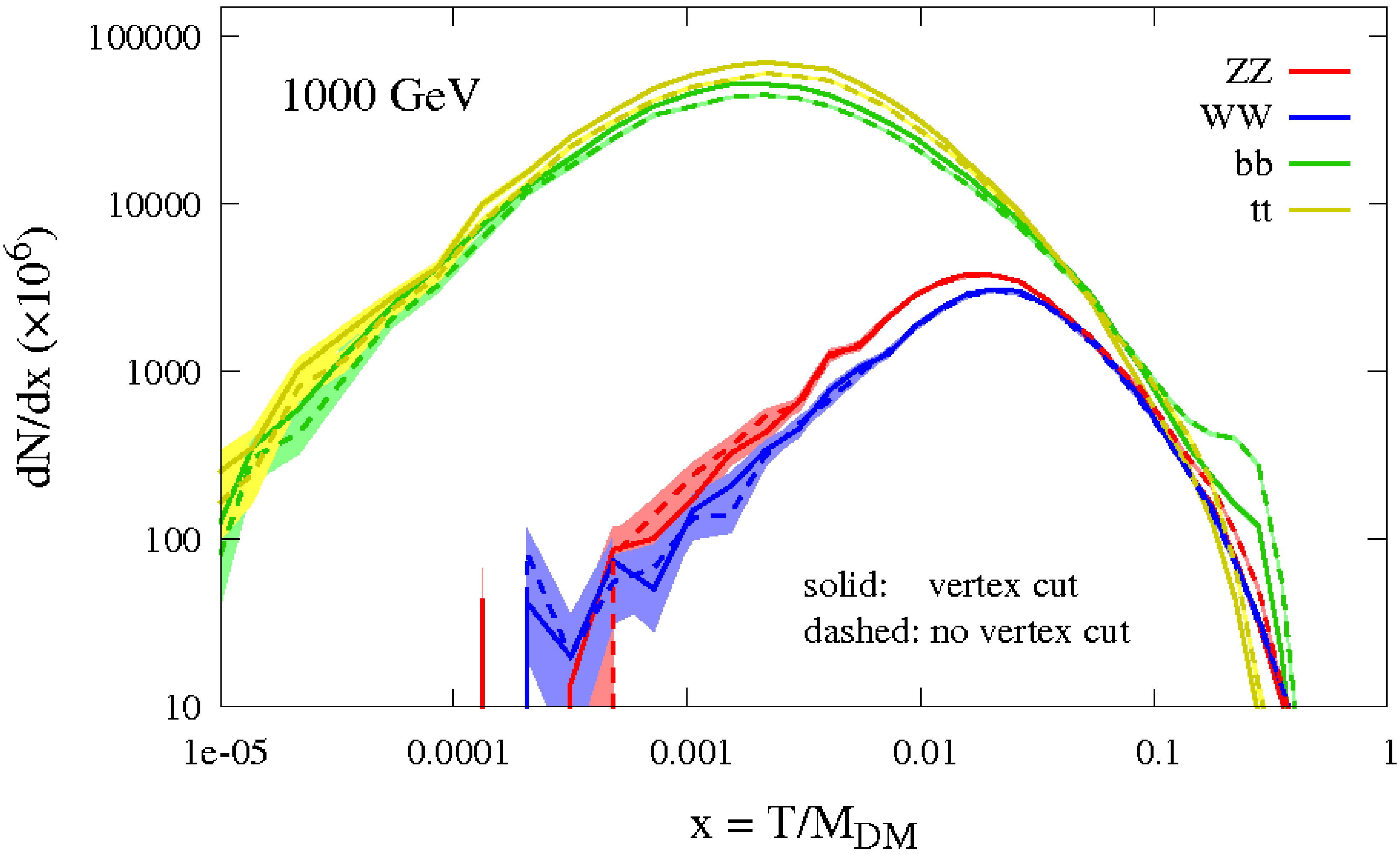
Dbar production rates



Dbar spectrum



Dbar spectrum



Relaxation

What happens to Δp?

- Nucleon pairs have excess energy due to $\Delta p \sim O(100\ \text{MeV})$. Also: binding energy (~2 MeV).

- Coalescence model: where does it go?

> Energy-momentum conservation during coalescence is not considered to be a problem because the deuteron is so weakly bound. After all, in the initial state of the heavy ion collision the nucleons are off their mass shell by ~8 MeV, there may be multiple two or three body collisions in the intermediate state as well as virtual pions to boost a final state deuteron on to its mass shell.

J. Kapusta, Phys. Rev. **C21**, 1301 (1980)

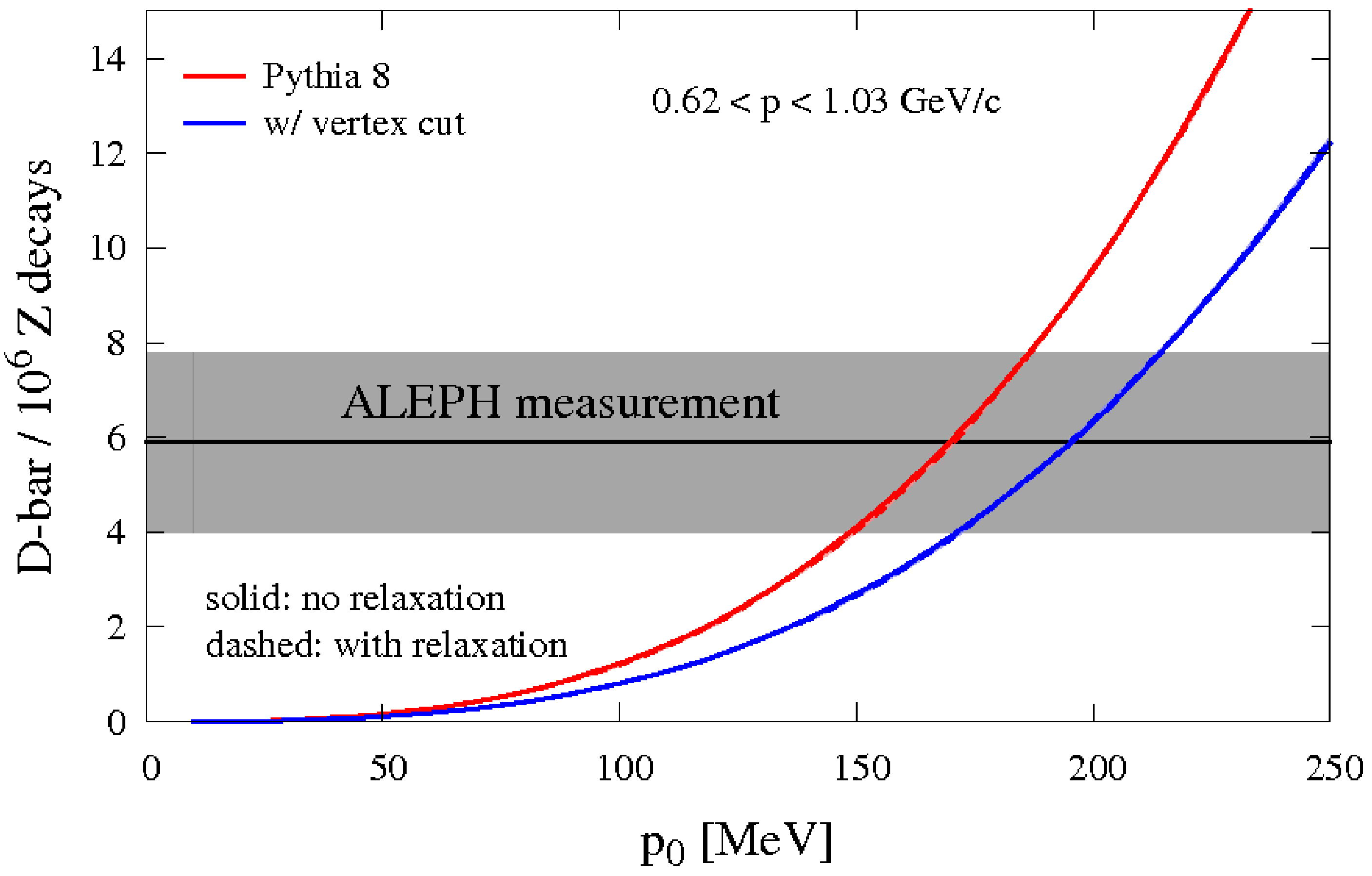
What happens to Δp?

- Pseudo-deuteron relaxation:
  emit one or more photons

- Reduction in nucleon pair effective mass
  $\Rightarrow$ reduced net momentum

- Momentum kick from particle emission
  - Worst case: single photon ("one kick")
  - Best case: multiple, isotropic emission ("iso-kick")

Coalescence parameter p_0



Coalescence parameter p_0

	Herwig++	PYTHIA6	PYTHIA8	
no vertex cut	117.3	172.6	169.7 ± 0.3	MeV
vertex cut	160.0	201.5	195.6 ± 0.4	
no vertex, iso-kick	117.2	172.1	170.6 ± 0.4	
vertex, iso-kick	156.6	201.0	195.2 ± 0.5	
no vertex, single kick	117.2	172.1		
vertex, single-kick	156.6	201.0		

ALEPH measurement: ± 20 MeV

Relaxation

- Δp ~ 200 MeV vs. M_D = 1876 MeV.
  Why does relaxation have negligible effect?

- Fractional excess energy:

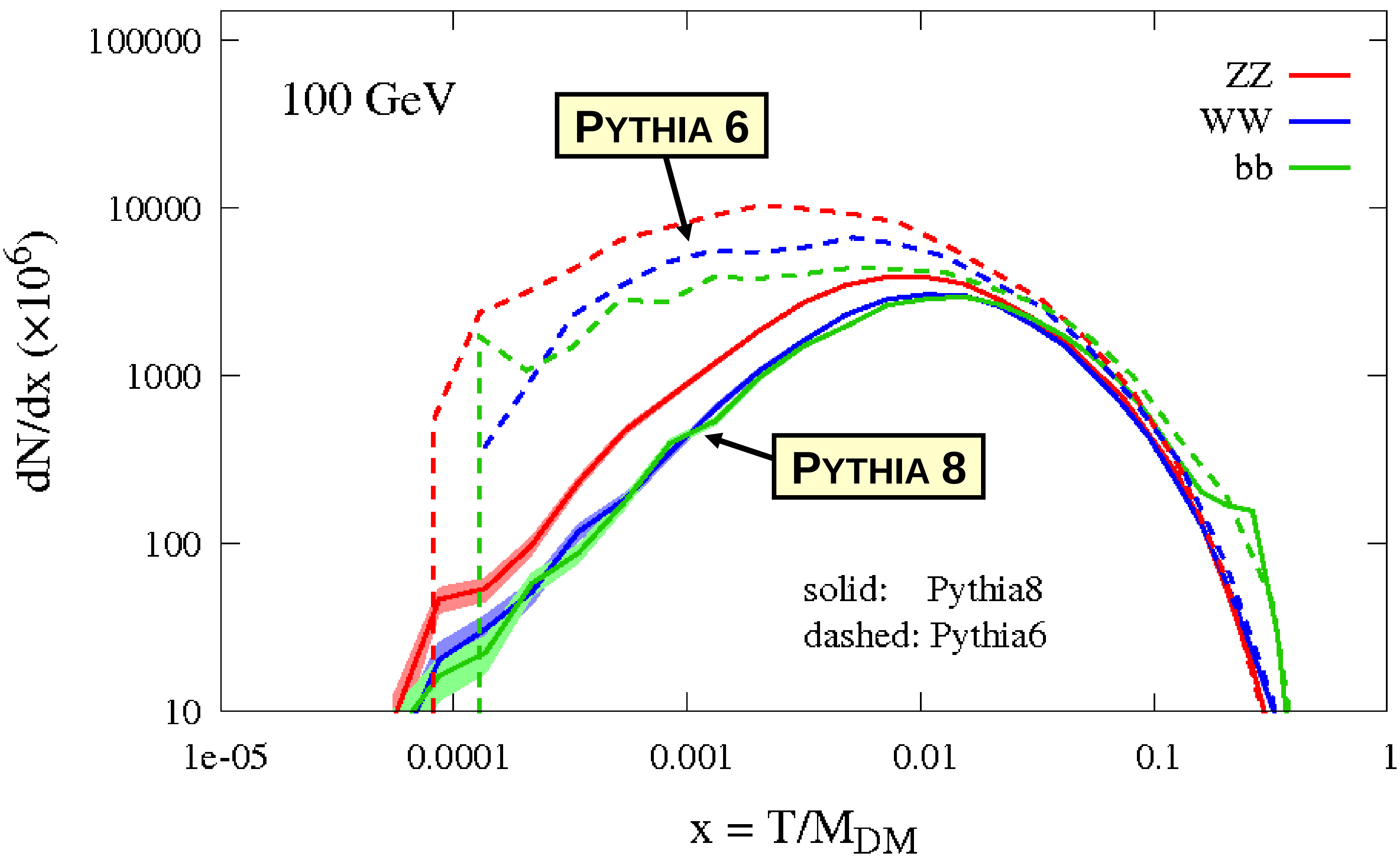
$$\frac{\Delta E}{M_D} \approx \frac{1}{2}\left(\frac{\Delta p}{M_D}\right)^2 \quad \leq 1\%$$

$\Rightarrow$ **Relaxation can be neglected.**

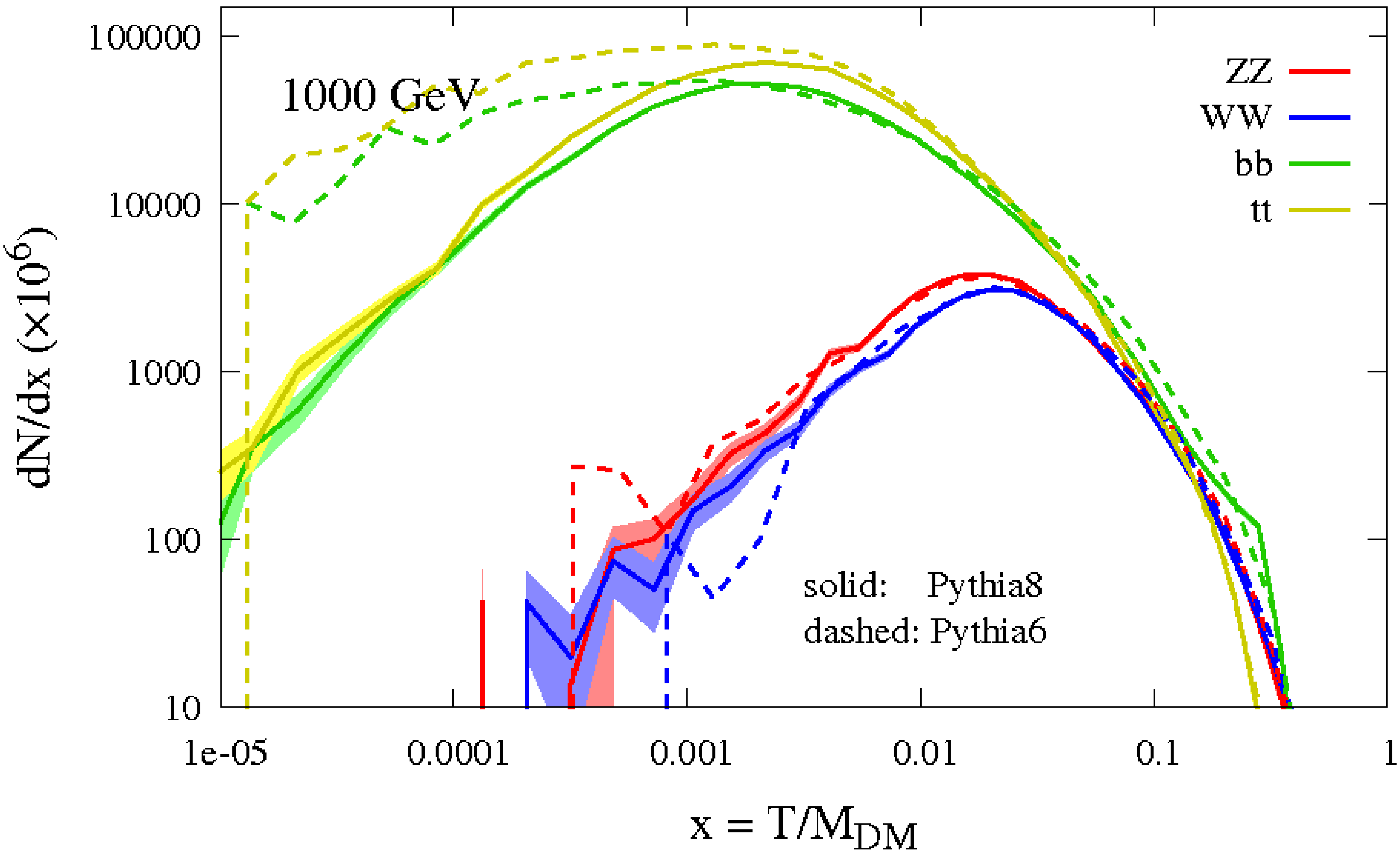
(technicalities rolled into p_0 determination)

MC Generator Comparison

Dbar spectrum



Dbar spectrum



MC generator comparison

- **PYTHIA6** **nearly complete** vs. **PYTHIA8** **complete**
  - Similar p_0 (w/ and w/o vertex cut)
  - Similar spectra for KE > 1 GeV
  - Spectra differ substantially for KE < 1 GeV (ROI)
    (*Reason unknown*)

- **Herwig++** **In progress**
  - Substantially smaller p_0
  - Preliminary indications: somewhat different vertex distribution

See also e.g.:
Cirelli et al., JCAP **1103**, 051 (2011)
Dal & Kachelriess, Phys.Rev. **D86**, 103536 (2012)

Summary and Remarks

- Dbar production issues
  - Per event angular correlations (important)
  - Vertex cut (somewhat important)
  - Relaxation (not important)

- MC generators
  - Potentially significant differences even with same underlying physics models (PYTHIA6 vs. PYTHIA8)
  - *Analysis incomplete: more investigation to come*

- Future
  - Dbar results into DarkSUSY public release?
  - Full Dbar analysis: astrophysics, propagation, etc.
    [Karpenka, Putze, Scott]