The Production of Anti-Matter in our Galactic Backyard

J. Orloff (L.P.C. Clermont-Ferrand)

(w. P. Chardonnet & P. Salati, LAPP)

Phys. Lett. B409, 313

- Motivations
- $p + p \to \bar{p} + X$
- $p + p \to \bar{p} + \bar{n} + X$: factorisation
- $\bar{p} + \bar{n} \to \bar{D}$: coalescence
- Cosmic rays: p
- " : $\bar{p}$, $\bar{D}$, ${}^3\overline{He}$
- Conclusion

Motivations

- Measures ($\bar{p}$) & exp. bounds ($\bar{D}, \bar{He}, \ldots$) on antimatter cosmic fluxes improve constantly

- Convey precious signals of interesting physics like:
  - antimatter stars, clumps, galaxies...
  - primordial B-H
  - physics beyond S-M, e.g. SUSY D.M. (Donato)

- $\bar{p}$ flux is well known & understood; recent anal. at low p higher than expected.

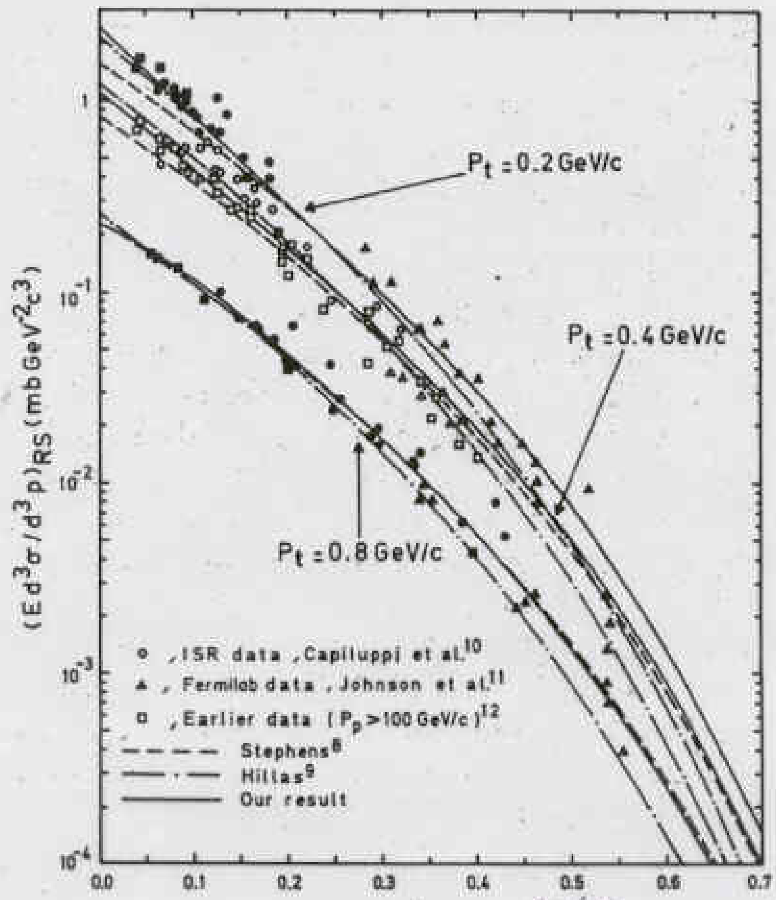
- $\bar{D}$, $\bar{He}$, ... can be produced by same process:

$$p\ (\text{primary C.R.}) + p\ (\text{interstellar H at rest})$$
$$\rightarrow \bar{D} + X$$

⇒ Need to estimate this "standard" background to more exotic signals.

$\bar{p}$ production in p-p collisions

Tan & Ng (PRD 26 (82) 1179) introduced a phenom. expr.:



$x_R = E/E_{max}$; $E_{max} = \dfrac{s + m_p - (3m_p)^2}{2\sqrt{s}}$

FIG. 1. The $\bar{p}$ invariant cross section at $\sqrt{s} \geq 10$ GeV. See Eq. (2) for our parametrized result.

$$E \frac{d^3\sigma}{dk^3} = f(x_R)\, e^{-A(x_R) p_t - B(x_R) p_t^2} \cdot F_{LE} \quad (mb/GeV^2)$$

- $f(x_R) = 3.34\, e^{-17.6 x_R}\, \Theta(0.5 - x_R) + 2.1 (1 - x_R)^{7.8}$
- $A(x_R) = 3.95\, e^{-2.76 x_R}$; $B(x_R) = 40.5\, e^{-3.91 x_R}\, x_R^{2.13}$
- $F_{LE} \sim 1 + O(10^{-3})$ except close to threshold

$\bar{p} + \bar{n}$ production: factorisation

• $1\bar{p}$: $dN_{\bar{p}} = F_{\bar{p}}(\sqrt{s}, k_{\bar{p}})\ d^3k_{\bar{p}}$ # $\bar{p}$ produced in a p·p coll.

$\Leftrightarrow \sigma_{\bar{p}} \doteq E_{\bar{p}} \dfrac{d^3\sigma_{\bar{p}}}{dk^3_{\bar{p}}} = E_{\bar{p}}\ F_{\bar{p}}(\sqrt{s}, k_{\bar{p}}) \cdot \sigma_{p\cdot p}$ $\sigma_{pp} \sim 44$ mb

• $2\bar{p}$ or $\bar{p}+\bar{n}$: naïve factorization: (each pair produced independently.)

$$F_{\bar{p},\bar{n}}(k_{\bar{p}}, k_{\bar{n}}) = F_{\bar{p}}(k_{\bar{p}}) \cdot F_{\bar{n}}(k_{\bar{n}}) . R$$

R = 1 if no correlations, but violates threshold
→ take instead:

$$F_{\bar{p},\bar{n}}(\sqrt{s}, k_{\bar{p}}, k_{\bar{n}}) = \frac{1}{2}\ \underbrace{F_{\bar{p}}(\sqrt{s}, k_{\bar{p}})}_{\text{produced first}} \cdot F_{\bar{n}}(\underbrace{\sqrt{s} - 2E_{\bar{p}}}_{\text{remaining en.}}, k_{\bar{n}}) + (\bar{n} \leftrightarrow \bar{p})$$

Rem:

- relativistic covariant: $\times\, E_{\bar{p}}\, E_{\bar{n}}$ on both members.
- $F_{\bar{p}} = F_{\bar{n}}$
- using both forms of factorisation Ansätze
  → idea of threshold corrections.

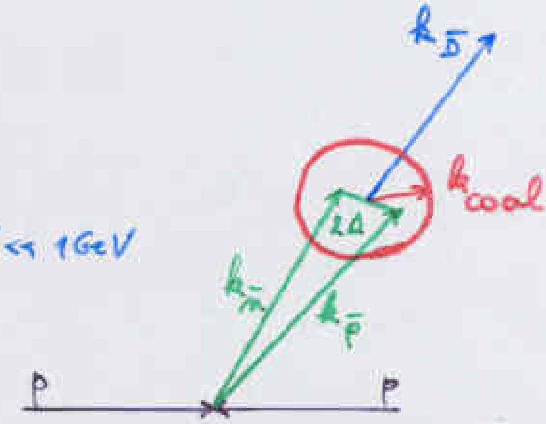
$\bar{p} + \bar{n} \to \bar{D}$: Coalescence.

Indep. of production, assume a coalescence probability:

$$F_{\bar{D}}(\sqrt{s}, k_{\bar{D}}) = \int d^3k_{\bar{n}}\, d^3k_{\bar{p}}\, C(k_{\bar{D}}; k_{\bar{n}}, k_{\bar{p}})\, F_{\bar{p},\bar{n}}(\sqrt{s}, k_{\bar{p}}, k_{\bar{n}})$$

with

$$C = \delta^3(k_{\bar{n}} + k_{\bar{p}} - k_{\bar{D}}) \cdot g\left(\frac{k_{\bar{p}} - k_{\bar{n}}}{2}\right)$$



Since g has small support, assume:

$$g(\Delta) = \begin{cases} 1 & \Delta < k_{coal} \sim 60\,\mathrm{MeV} \ll 1\,\mathrm{GeV} \\ 0 & \Delta > k_{coal} \end{cases}$$

$$\to F_{\bar{D}}(\sqrt{s}, k_{\bar{D}}) \simeq \frac{4\pi}{3} k_{coal}^3 \cdot F_{\bar{p},\bar{n}}\left(\sqrt{s}, \frac{k_{\bar{D}}}{2}, \frac{k_{\bar{D}}}{2}\right)$$

$$\simeq \quad '' \quad \cdot F_{\bar{p}}\left(\sqrt{s}, \frac{k_{\bar{D}}}{2}\right) F_{\bar{n}}\left(\sqrt{s}, \frac{k_{\bar{D}}}{2}\right)$$

$$F_{\bar{T}}(\sqrt{s}, k_{\bar{T}}) \simeq \left(\frac{4\pi}{3} k_{coal}^3\right)^3 \cdot F_{\bar{p}}\left(\sqrt{s}, \frac{k_{\bar{T}}}{3}\right) F_{\bar{n}}\left(\sqrt{s}, \frac{k_{\bar{T}}}{3}\right)^2$$

$\vdots$

Rem: • If not in $\bar{D}$ rest frame, use rel. inv.

$$B_{\bar{D}} \doteq \frac{m_{\bar{D}}}{m_{\bar{p}} m_{\bar{n}}} \cdot \frac{4\pi}{3} k_{coal}^3 \sim 1.7\ 10^{-3}\,\mathrm{GeV}^{-2}$$

- A single parameter k_{coal} or $B_{\bar{D}}$ describes coal. and correl.
- $\to$ $B_{\bar{D}}$ is smaller than B_D (larger correl..)
- Does it work? $\bar{D}$ ~ ok ; $\bar{T}$: no data...

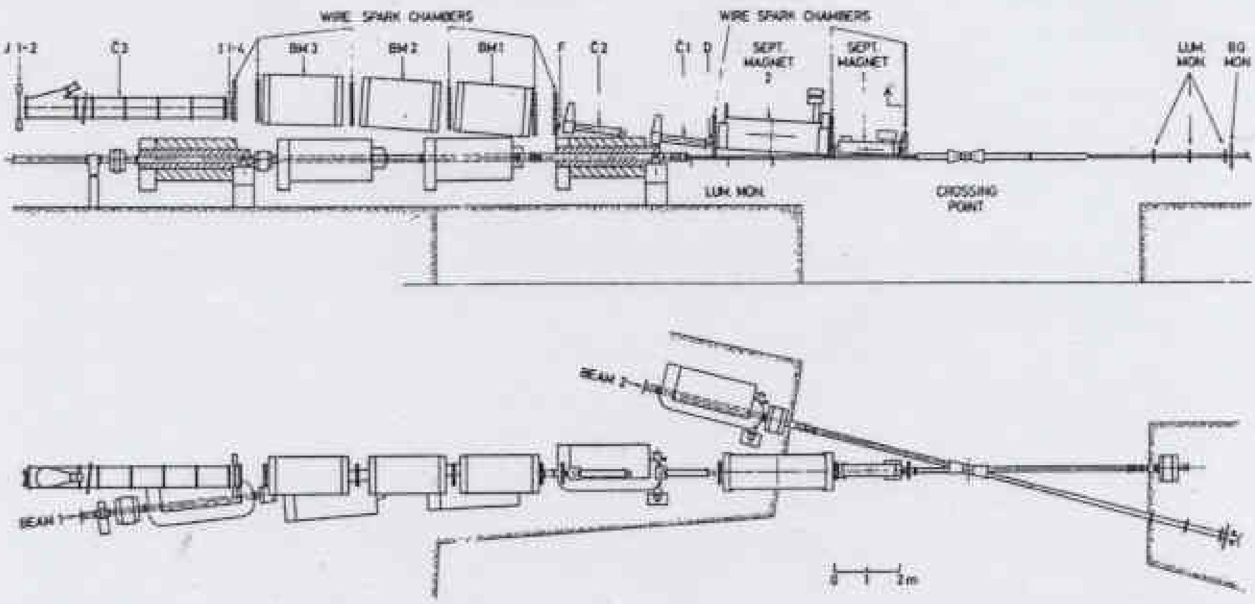


Fig. 1. Side and top views of the small angle spectrometer (SAS), located above the ISR beam 1. BM 1,2,3 are bending magnets, LUM MON is a set of counters for measuring the ISR luminosity. BG MON is a set of counters used to distinguish beam/beam from beam/gas events (see text).

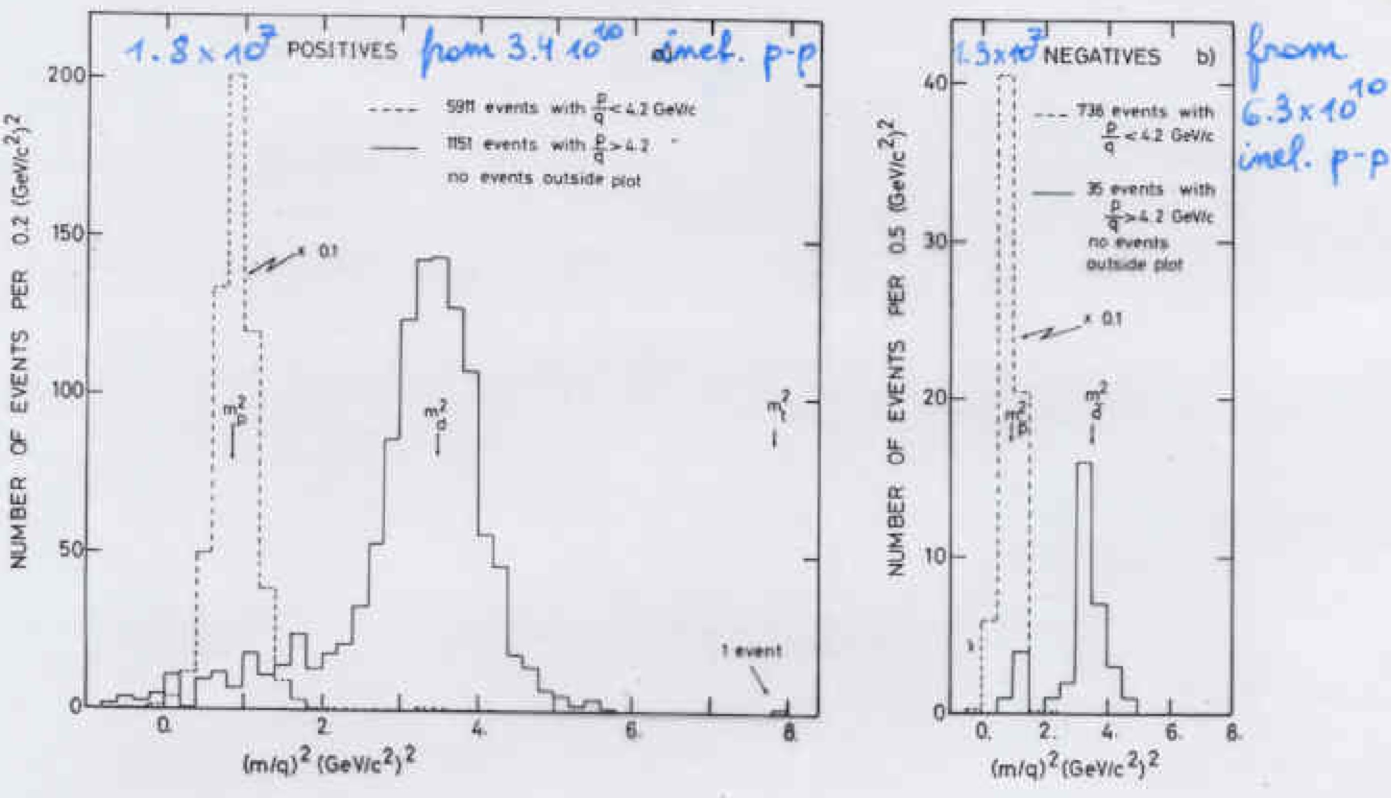
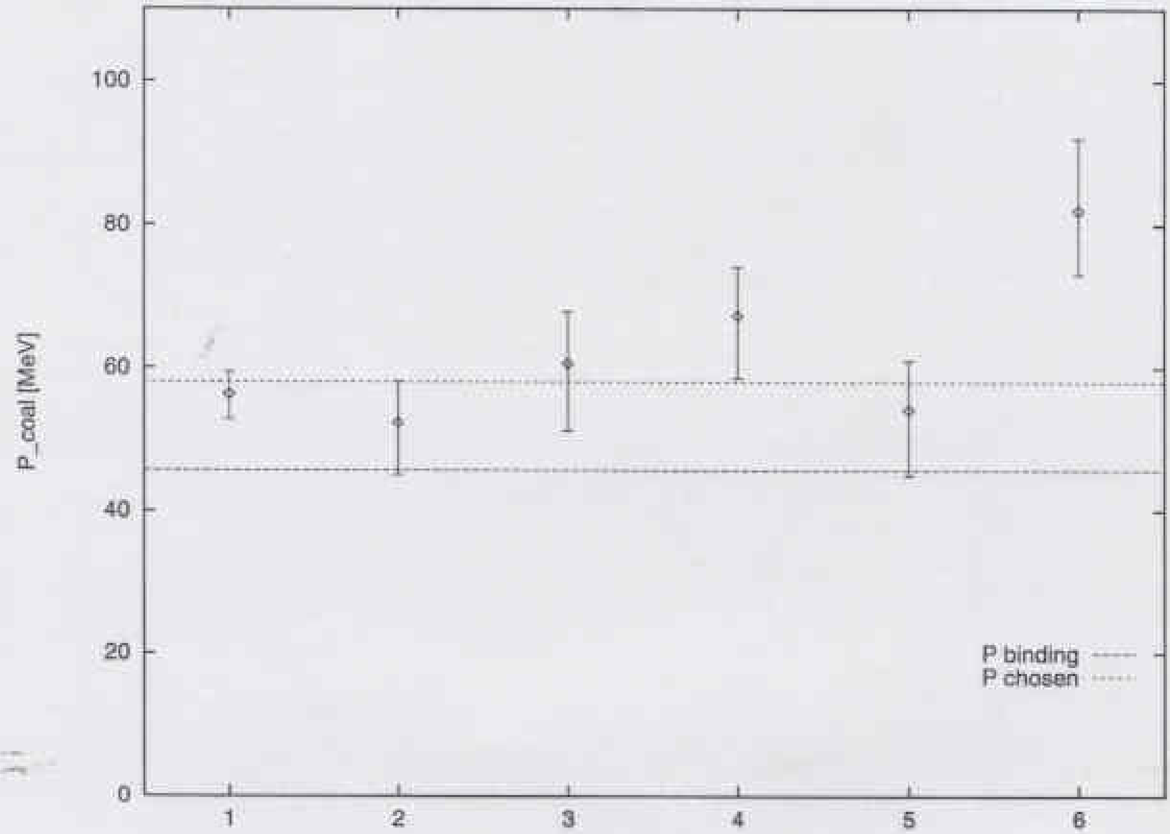


Fig. 3. (a) Distribution of $(m/q)^2$ for positive particles with $(p/q) < 4.2$ GeV/c (dashed lines) and $(p/q) >$ GeV/c (full lines). m is the particle mass and q its charge per electron charge. (b) Same as (a) for negative particles.

Coalescence momentum for various data



	p_l (GeV)	p_t (GeV)	$\sqrt{s}$ (GeV)	$E_{\bar{D}} \frac{d^3\sigma_{\bar{D}}}{dk^3}$ (mb/GeV^2)
1	1.44	1.14	11.5	$9.1 \pm 1.6 \times 10^{-8}$
2	1.09	1.5	11.5	$2.2 \pm 0.8 \times 10^{-8}$
3	4.8	0.16	53	$6.8 \pm 2.7 \times 10^{-5}$
4	5.6	0.21	53	$5.6 \pm 1.9 \times 10^{-5}$
5	6.6	0.3	53	$1.4 \pm 0.6 \times 10^{-5}$
6	0	$0.2 \rightarrow 0.7$	53	$1.18 \pm 0.4 \times 10^{-3} \times e^{-(2.6 \pm 0.5) p_t}$

1,2: Abramov et al., Sov. J. Nucl. Phys 45(1987)845

2,3,4: Albrow et al. Nucl. Phys. B97 (1975)189

6: Gibson et al., Lett. Nuovo Cim. 21 (1978) 189

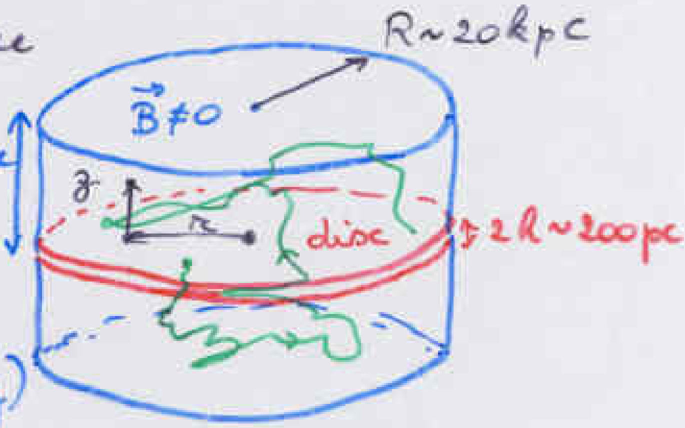
Cosmic ray production & propagation: p

- Stars → gas in I.S. medium (C, N, O; p..), accelerated by SN-shocks → primary C.R.
- Collisions in disc ($\sim 1\,H/cm^3$) → secondaries (Li, Be, B; $\bar{p}$, ...); spend only $\sim$ 3 Myears in disk.

  BUT $\dfrac{{}^{10}Be\,(2.3My)}{{}^{9}Be}$ ⇒ must stay $\sim$ 30 My in galaxy

⇒ • ∃ larger confining zone where stellar wind → random $\vec{B}$

(Berezinsky; Webber, Lee, Gupta)



$$K = 6.10^{23}\,m^2 s^{-1} \left(1 + \frac{\mathcal{R}}{3\,GeV}\right)^{0.6}$$

(diffusion coeff; $\mathcal{R}$ = rigidity)

$$\frac{\partial n_p}{\partial t} = 0 = K(E_p)\,\Delta\, n_p(E_p) - \underbrace{2h\,\delta(z)\,\Gamma_p\, n_p}_{\text{absorption}} + 2h\,\delta(z)\,Q_p(E_p, r)$$

$$\Gamma_p = \sigma_{pp} \cdot v_p \cdot \overbrace{n_H}^{\sim 1\,cm^{-3}}$$

In flat box ($L \ll R$) limit:

$$n_p(E_p, r, z{=}0) \simeq \underbrace{\frac{h}{K(E_p)/L + h\Gamma_p} \cdot Q_p^{\circ}(E_p)}_{\sim\, \mathcal{R}_p^{-2.7}/\sqrt{1+(1.5\,GV/\mathcal{R}_p)^2}\ \text{(observed)}} \overbrace{\left(\frac{r}{R}\right)^{0.6} e^{-3r/R}}^{Q_p(E_p,\, r) = \text{source}}$$

Rem: - the factorisation $(E_p) \times (r)$ remains without approx.

- energy dependance from both source Q_p° and diffusion K
- $h\Gamma_p$ negligible for p, but source for $\bar{p}$, $\bar{D}$, ...

Cosmic ray production & propagation: χ $(= \bar{p}, \bar{D}, {}^3\overline{He})$

$$K \, \Delta n_\chi - 2h\,\delta(z)\,\Gamma_\chi n_\chi + 2h\,\delta(z)\,Q_\chi(E_\chi, r) = 0$$

Same stationary diffusion, new source Q_χ:

$$Q_\chi(E_\chi, r) = \phi_p(E_\chi, r)\, h\, n_H\, \sigma_{pp} \cdot N_\chi^{eff}(E_\chi)$$

with

$$N_\chi^{eff}(E_\chi) = \int_{E_{min}}^{\infty} dE_p \, \frac{\phi_p(E_p, r)}{\phi_p(E_\chi, r)} \cdot \int d^3k_\chi \, F_\chi\left(\sqrt{m_p E_p}, k_\chi\right) \delta\left(E_\chi - \text{mass shell}\right)$$

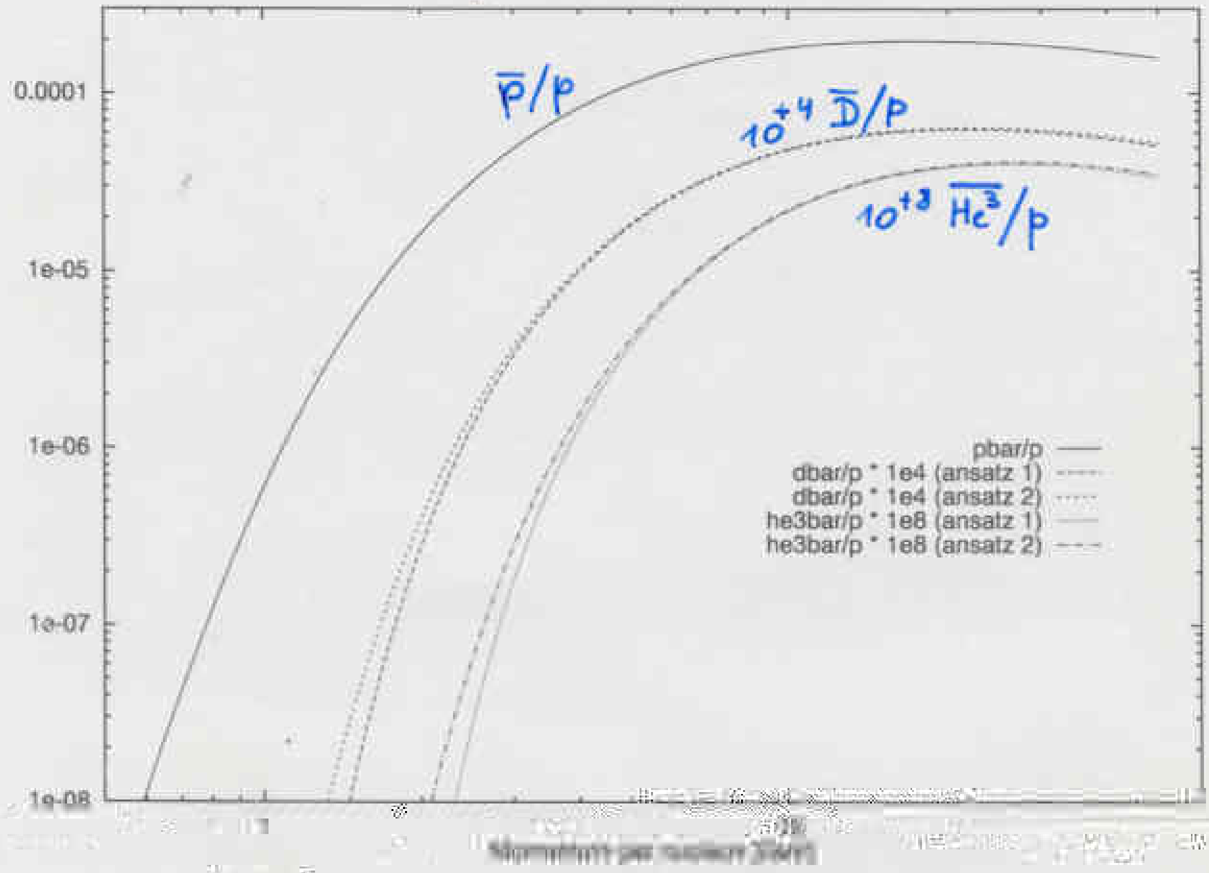
= eff. # χ produced at E_χ, given $\phi_p(E_p)$

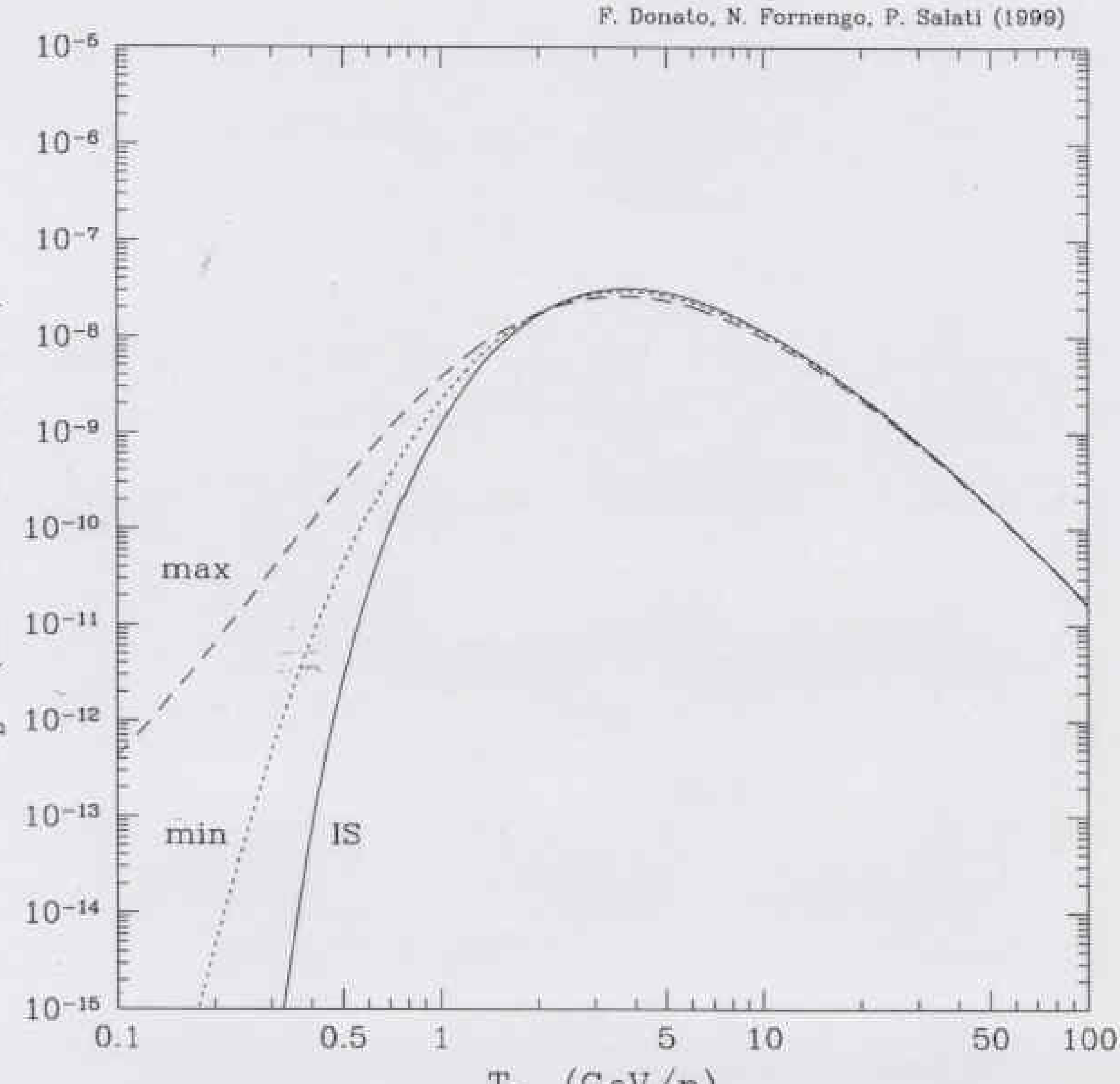
$$\rightarrow \phi_\chi(E_\chi, r) \underset{\substack{L \ll R \\ \Gamma_\chi < K/L}}{\simeq} \left[v_\chi \cdot \frac{L}{K(E_\chi)} \cdot n_H\, h\, \sigma_{pp} \cdot N^{eff}(E_\chi)\right] \phi_p(E_\chi, r)$$

- $\bar{p}$: $F_{\bar{p}}$ known
- $\bar{D}$: $F_{\bar{D}}$: only little exp. data → assume fact. & coal.
- ${}^3\overline{He}$: through $\bar{T} \rightarrow {}^3\overline{He}$ (no electrostatic repulsion)
  we tried same k_{coal} as for $\bar{D}$: probably too low...

$\bar{N}/p$ flux ratio ($\bar{N}$ from p-p collisions)

(= background for AMS anti-star discov.)





F. Donato, N. Fornengo, P. Salati (1999)
$\Phi_{\bar{D}}^{sec}$ ($m^{-2}\,s^{-1}\,sr^{-1}\,GeV^{-1}$)
$T_{\bar{D}}$ (GeV/n)
max
min
IS

Conclusion :

- AMS will most probably see "conventional" cosmic $\bar{D}$'s

  (we took a "lowest" value of k_{coal})

- Going further will require reliable estimate of this conventional flux, better than the $2 \to 4$ present factor.

  → more data ? (e.g. LEP1 → ~10→100 $\bar{D}$'s in raw data ("wrong $\frac{dE}{dx}$ protons"))

  → better understanding of $k_{coal}(\bar{D}) \neq k_{coal}(D)$

  → would help using ^4He data → $^4\overline{He}$ (no data)

- Notice : the $(10^{-4}/\text{nucleon})$ rule of thumb only valid for fixed k_{coal};

  if $k_{coal}(^4\overline{He}) = 20\, k_{coal}(\bar{D})$

  $\rightarrow \frac{^4\overline{He}}{\bar{D}} \sim 1$