

Cosmic ray studies with the PAMELA space experiment



Roberta Sparvoli

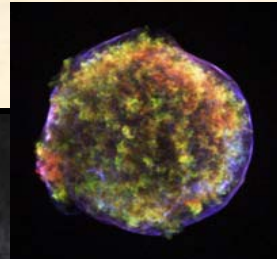
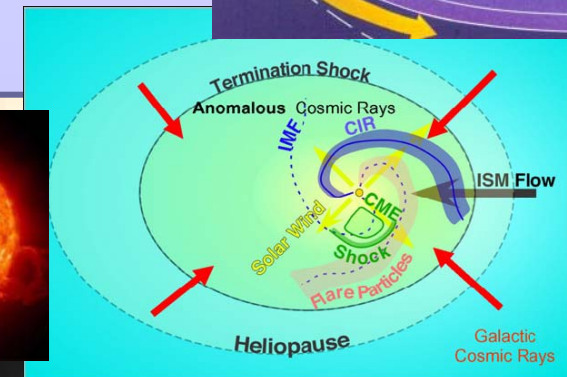
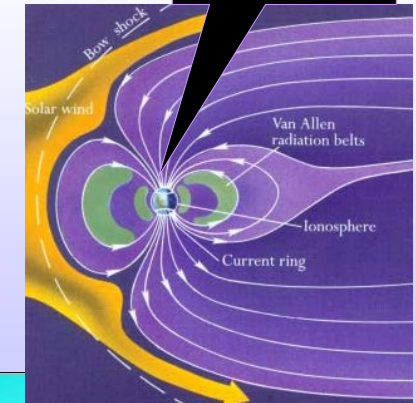
University of Rome "Tor Vergata" and INFN

PAMELA science

PAMELA is a Space Observatory @ 1AU

- Search for dark matter
- Search for primordial antimatter
- ... but also:
- Study of cosmic-ray origin and propagation
- Study of solar physics and solar modulation
- Study of terrestrial magnetosphere

PAMELA



Tha PAMELA collaboration

Italy



Bari



Florence



Frascati



Naples



Rome



Trieste



CNR, Florence



Russia



Moscow
St. Petersburg

Germany



Siegen

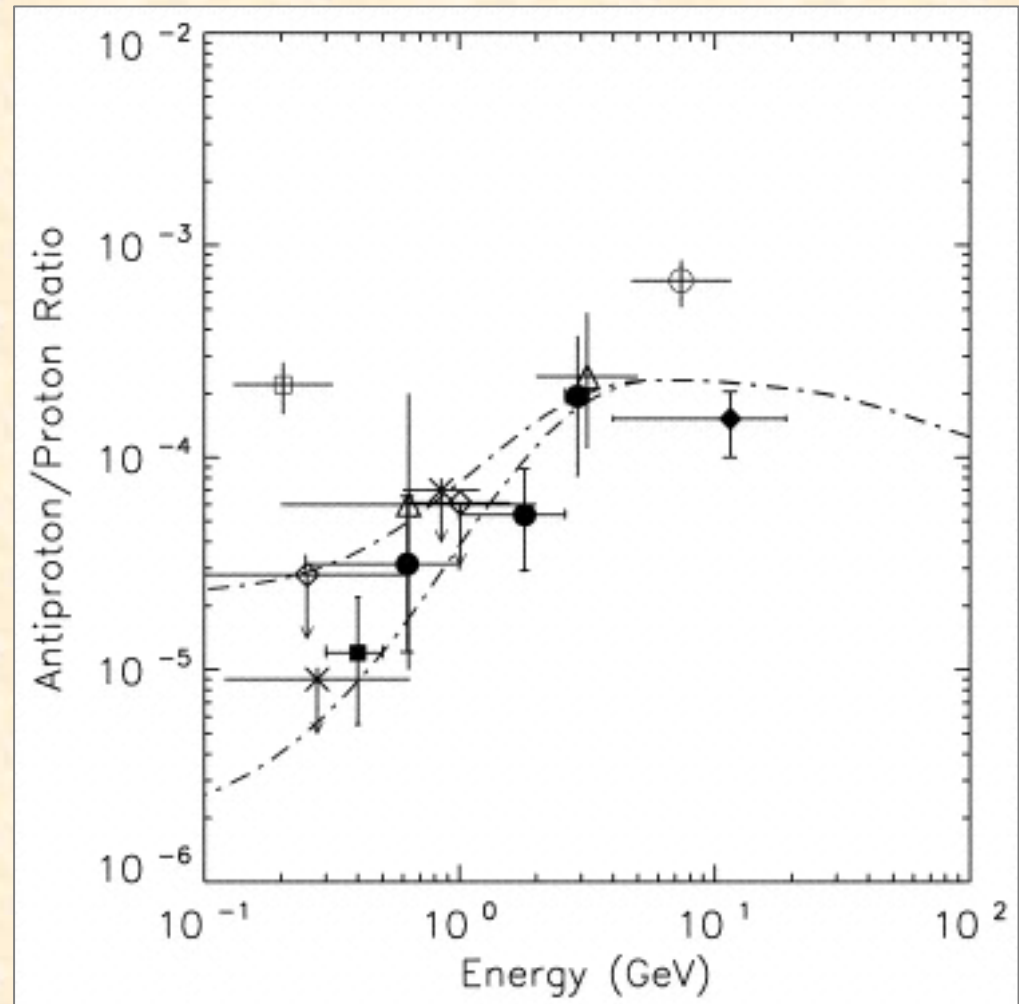
Sweden



KTH, Stockholm

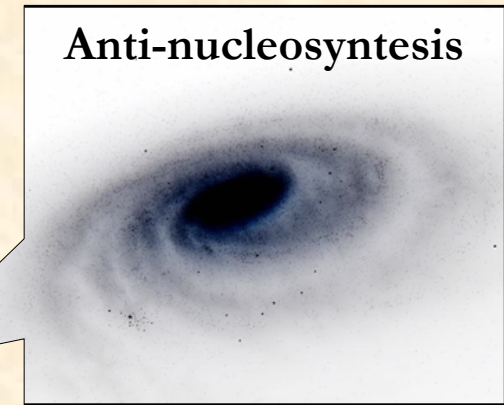
Everything starts with ...

- Antiprotons in the cosmic radiation are expected as "**secondary**" products of interactions of the primary cosmic radiation, principally protons, with the ambient interstellar medium (ISM).
- The first positive measurements [Golden 79, Bogomolov 90, Buffington 82] reported **higher** antiproton fluxes than predicted by contemporary models of cosmic ray transport.
- *Many different theories to justify these data were proposed at that time*

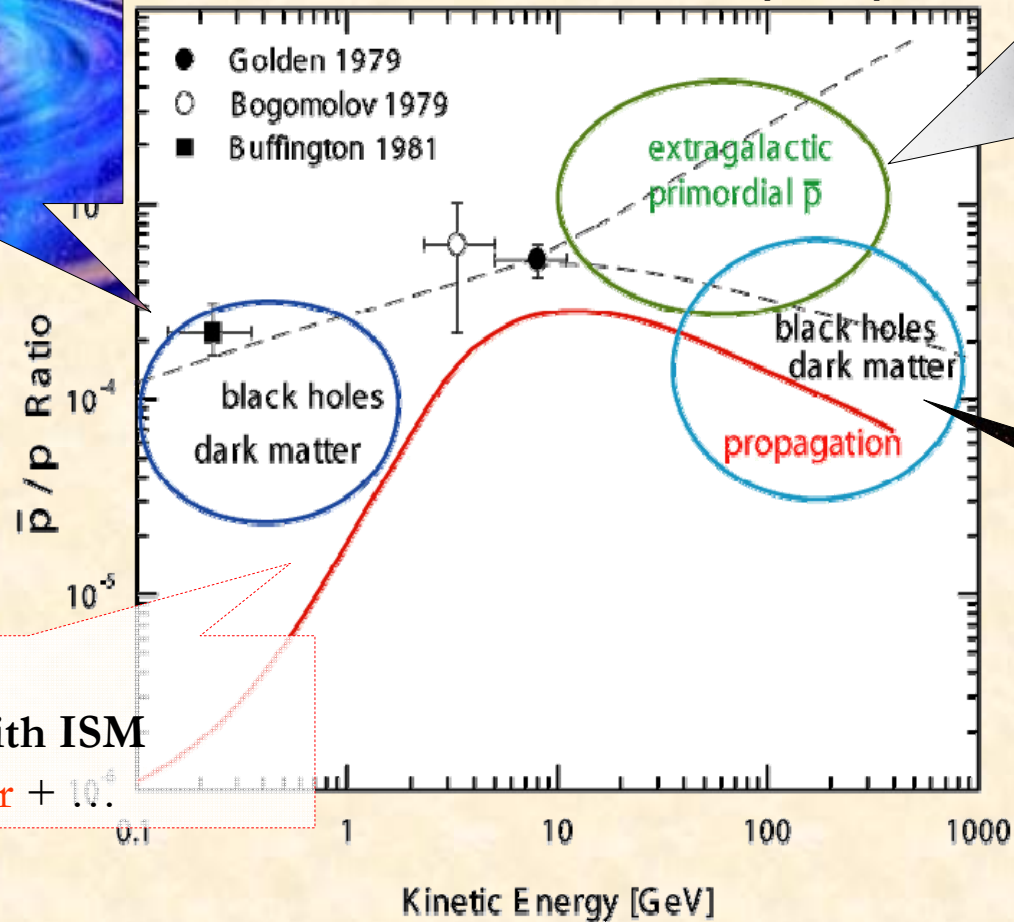


Golden et al. (1984; **open circle**), Bogomolov et al. (1987, 1990; **open triangle**), Buffington et al. (1981; **open square**)

Why CR antimatter?



First historical measurements of \bar{p}/p ratio



Background:

CR interaction with ISM

CR + ISM \rightarrow \bar{p} + γ



Cosmic-ray Antimatter from Dark Matter annihilation

Annihilation of relic Weakly Interacting Massive Particles (WIMPs) gravitationally confined in the galactic halo

→ Distortion of antiproton and positron spectra from purely secondary production

- A plausible dark matter candidate is neutralino (χ), the lightest SUSY Particle (LSP).

Most likely processes:

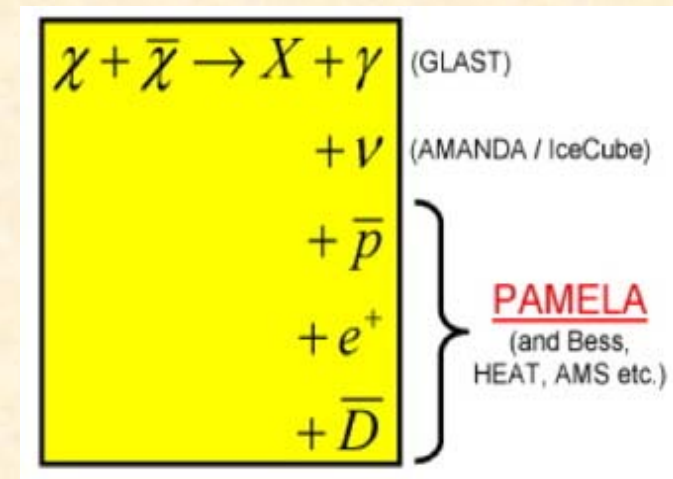
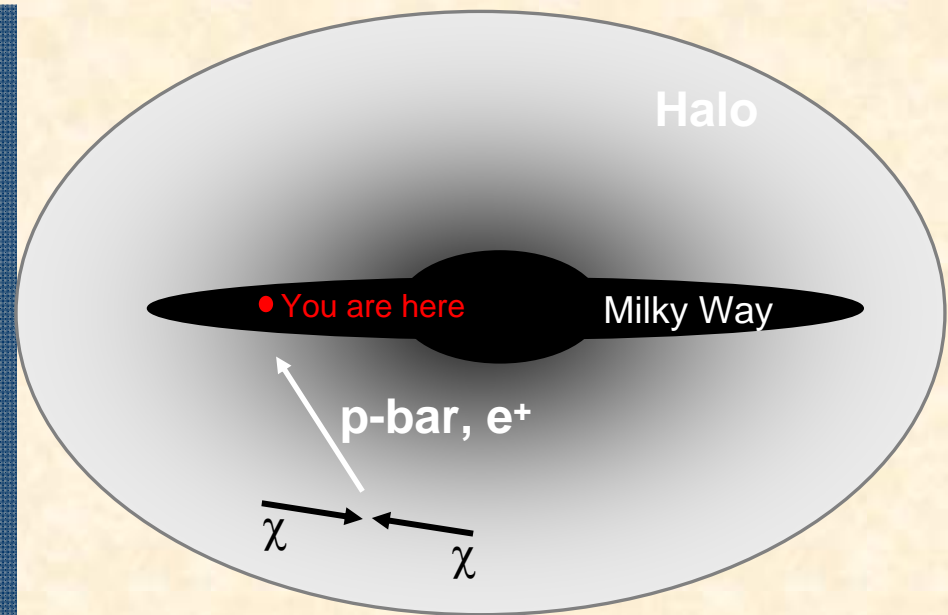
- $\chi\chi \rightarrow qq \rightarrow \text{hadrons} \rightarrow \text{anti-p}, e^+, \dots$
- $\chi\chi \rightarrow W^+W^-, Z^0Z^0, \dots \rightarrow e^+, \dots$
 \Rightarrow positron peak $E_{e^+} \sim M_\chi/2$
 \Rightarrow positron continuum $E_{e^+} \sim M_\chi/20$

- Another possible candidate is the lightest Kaluza-Klein Particle (LKP): $B^{(1)}$

Fermionic final states no longer suppressed:

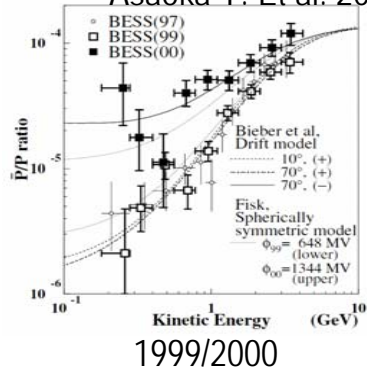
- $B^{(1)}B^{(1)} \rightarrow e^+e^-$

direct decay \Rightarrow positron peak $E_{e^+} \sim M_{B^{(1)}}$



Charge-dependent solar modulation

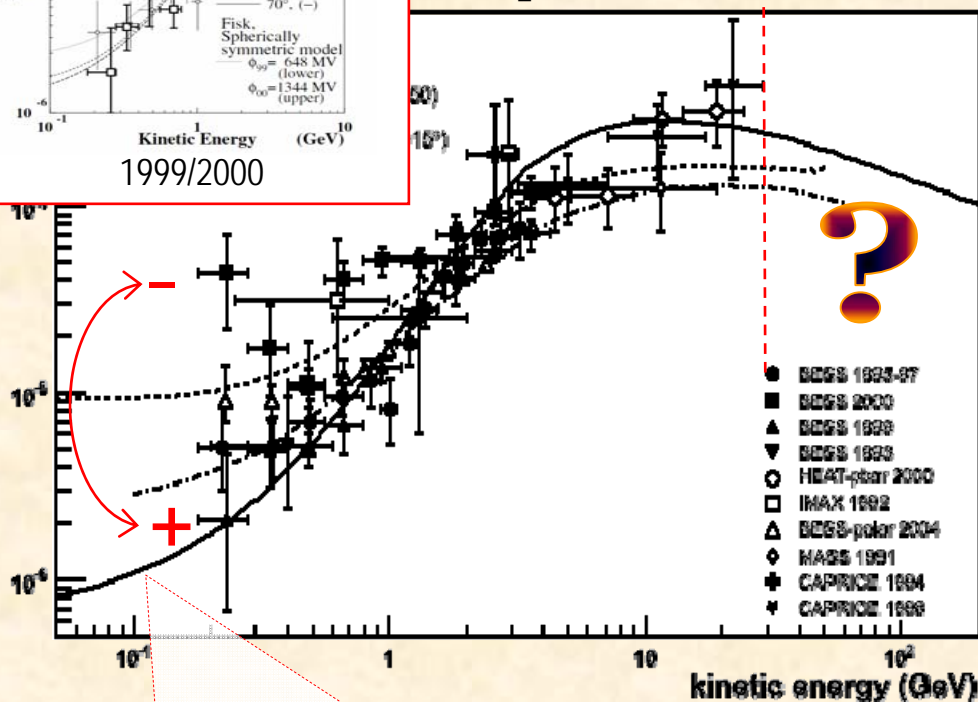
Asaoka Y. Et al. 2002



CR antimatter

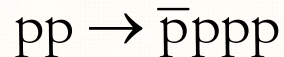
Experimental scenario before PAMELA

Antiprotons

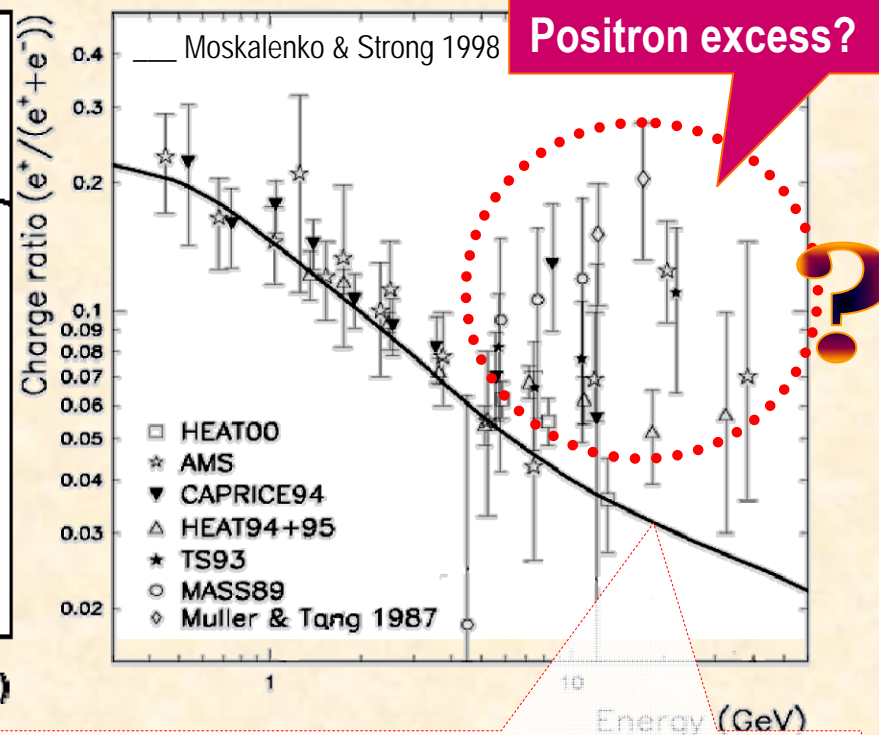


CR + ISM \rightarrow \bar{p} + ...

- Propagation dominated by nuclear interactions
- Kinematical threshold: $E_{th} \sim 5.6$ for the reaction



Positrons



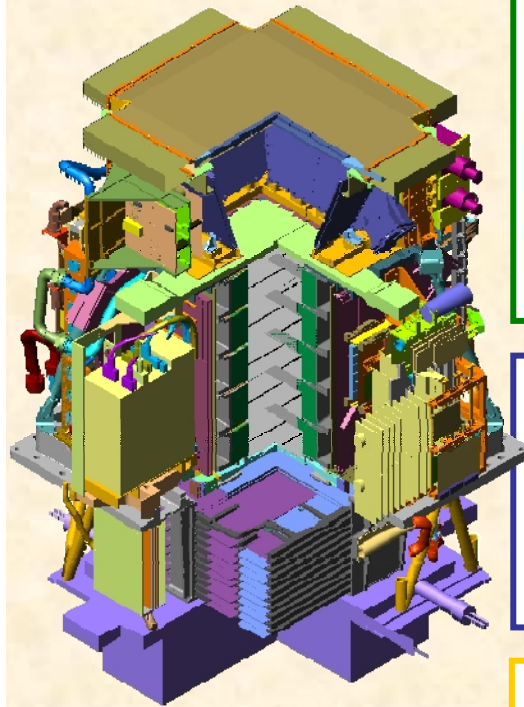
CR + ISM $\rightarrow \pi^\pm + x \rightarrow \mu^\pm + x \rightarrow e^\pm + x$

CR + ISM $\rightarrow \pi^0 + x \rightarrow \gamma\gamma \rightarrow e^\pm$

- Propagation dominated by energy losses (inverse Compton & synchrotron radiation)
- Local origin (@100GeV 90% from <2kpc)

PAMELA detectors

Main requirements → high-sensitivity antiparticle identification and precise momentum measure



GF: 21.5 cm² sr
Mass: 470 kg
Size: 130x70x70 cm³
Power Budget: 360W

Time-Of-Flight

plastic scintillators + PMT:

- Trigger
- Albedo rejection;
- Mass identification up to 1 GeV;
- Charge identification from dE/dX

Electromagnetic calorimeter

W/Si sampling (16.3 X0, 0.6 λ)

- Discrimination e⁺ / p, anti-p / e⁻ (shower topology)
- Direct E measurement for e⁻

Neutron detector

plastic scintillators + PMT:

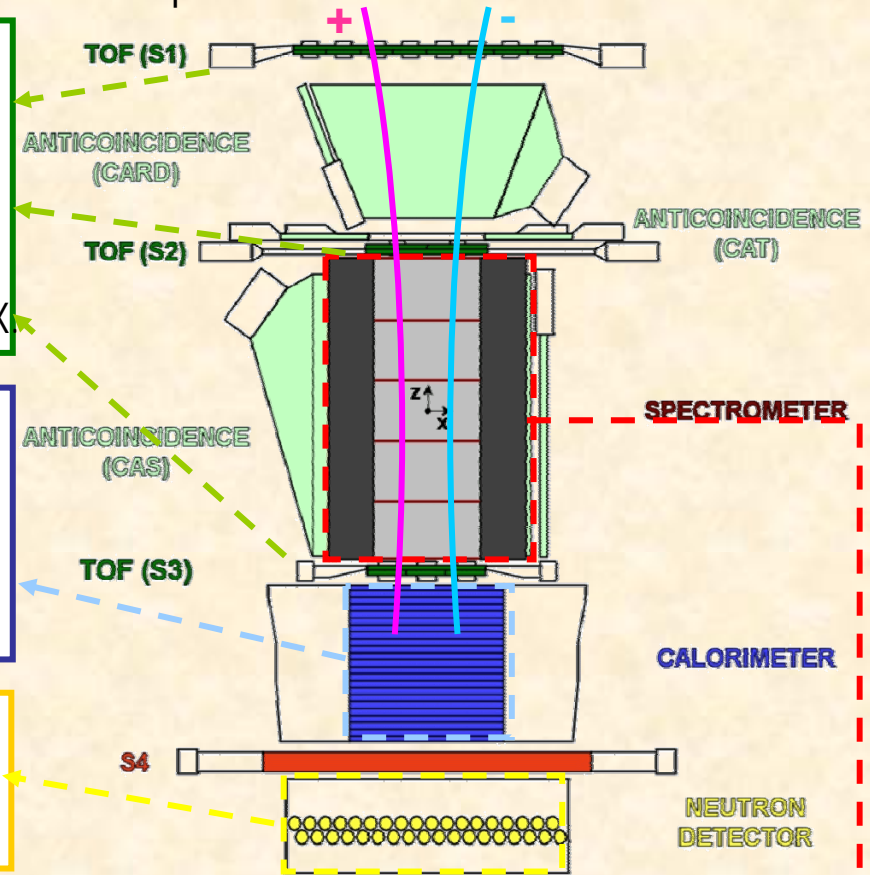
- High-energy e/h discrimination

Spectrometer

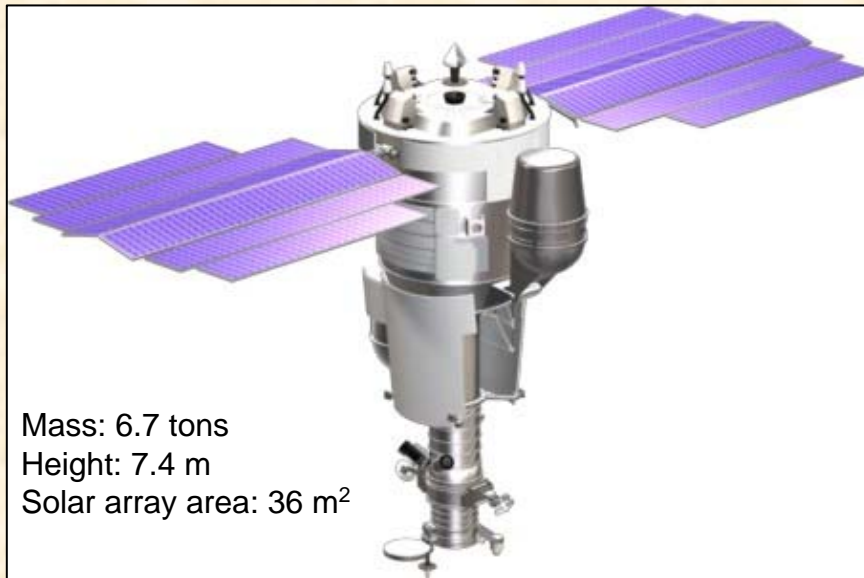
microstrip silicon tracking system + permanent magnet

It provides:

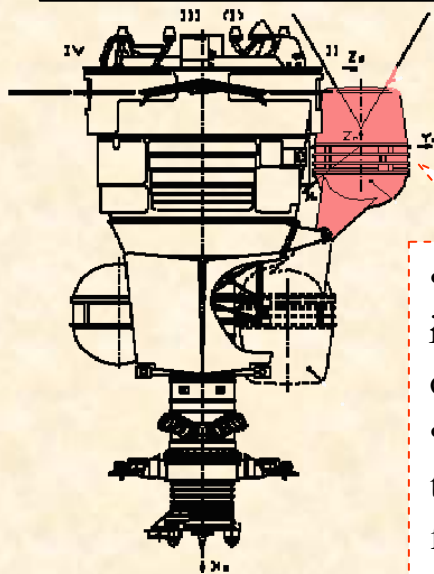
- **Magnetic rigidity** → $R = pc/Ze$
- **Charge sign**
- **Charge value from dE/dx**



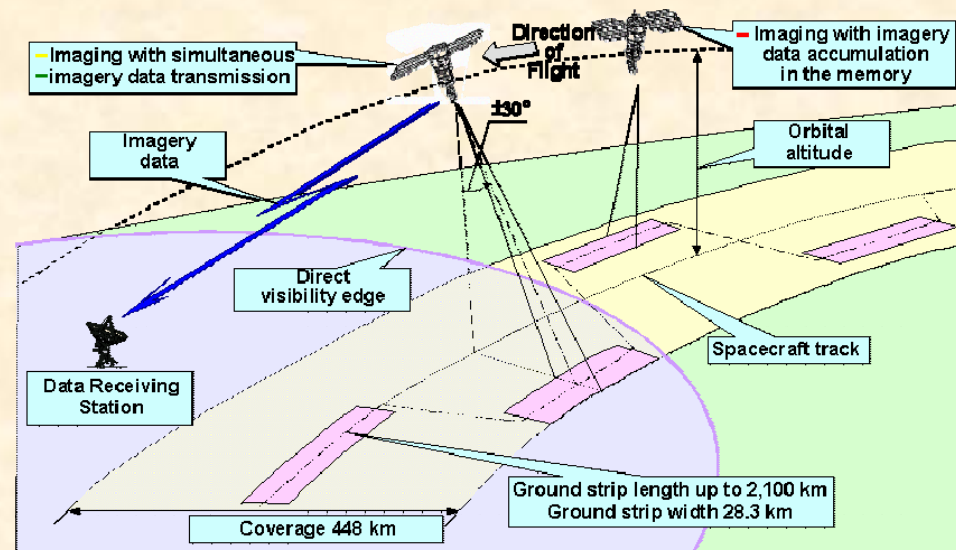
The Resurs DK-1 spacecraft



- Multi-spectral remote sensing of earth's surface
- *near-real-time high-quality images*
- Built by the Space factory TsSKB Progress in Samara (Russia)
- **Operational orbit parameters:**
 - **inclination $\sim 70^\circ$**
 - **altitude $\sim 360\text{-}600$ km (elliptical)**
- **Active life > 3 years**
- Data transmitted via Very high-speed Radio Link (VRL)



- PAMELA mounted inside a pressurized container
- moved from parking to data-taking position few times/year



PAMELA design performance

	<u>energy range</u>	<u>particles in 3 years</u>	Maximum detectable rigidity (MDR)
Antiprotons	80 MeV ÷ 190 GeV	O(10 ⁴)	
Positrons	50 MeV ÷ 270 GeV	O(10 ⁵)	
Electrons	up to 400 GeV	O(10 ⁶)	
Protons	up to 700 GeV	O(10 ⁸)	
Electrons+positrons	up to 2 TeV	(from calorimeter)	
Light Nuclei	up to 200 GeV/n	He/Be/C: O(10 ^{7/4/5})	
Anti-Nuclei search	sensitivity of 3x10 ⁻⁸ in	anti-He/He	

Magnetic curvature & trigger

spillover

shower
containment

Maximum detectable
rigidity (MDR)

- **Unprecedented statistics and new energy range for cosmic ray physics**
(e.g. contemporary antiproton and positron maximum energy ~ 40 GeV)
- **Simultaneous measurements of many species**

PAMELA milestones

Launch from Baikonur → June 15th 2006, 0800 UTC.

‘First light’ → June 21st 2006, 0300 UTC.

- Detectors operated as expected after launch
- Different trigger and hardware configurations evaluated

→ **PAMELA in continuous data-taking mode since commissioning phase ended on July 11th 2006**

Trigger rate* $\sim 25\text{Hz}$

Fraction of live time* $\sim 75\%$

Event size (compressed mode) $\sim 5\text{kB}$

$25\text{ Hz} \times 5\text{ kB/ev} \rightarrow \sim 10\text{ GB/day}$

(*outside radiation belts)

Till May 2008:

~ 500 days of data taking

~ 10 TByte of raw data downlinked

$\sim 12 \cdot 10^8$ triggers recorded and analysed

(Data from May till now under analysis)



Antiprotons

High-energy antiproton analysis

- Analyzed data July 2006 – February 2008 (~ 500 days)
- Collected triggers $\sim 10^8$
- Identified $\sim 10^{10}$ protons and $\sim 10^3$ antiprotons between 1.5 and 100 GeV (**100 p-bar above 20 GeV**)

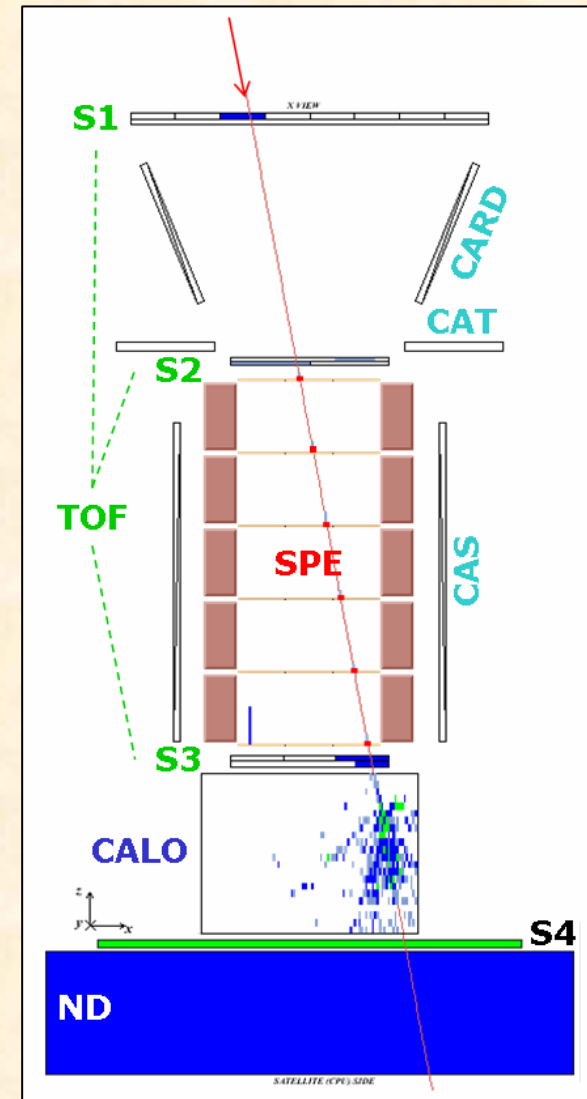
- Antiproton/proton identification:

- rigidity (R) \rightarrow SPE
- $|Z|=1$ (dE/dx vs R) \rightarrow SPE&ToF
- β vs R consistent with $M_p \rightarrow$ ToF
- p-bar/p separation (charge sign) \rightarrow SPE
- p-bar/ e^- (and p/ e^+) separation \rightarrow CALO

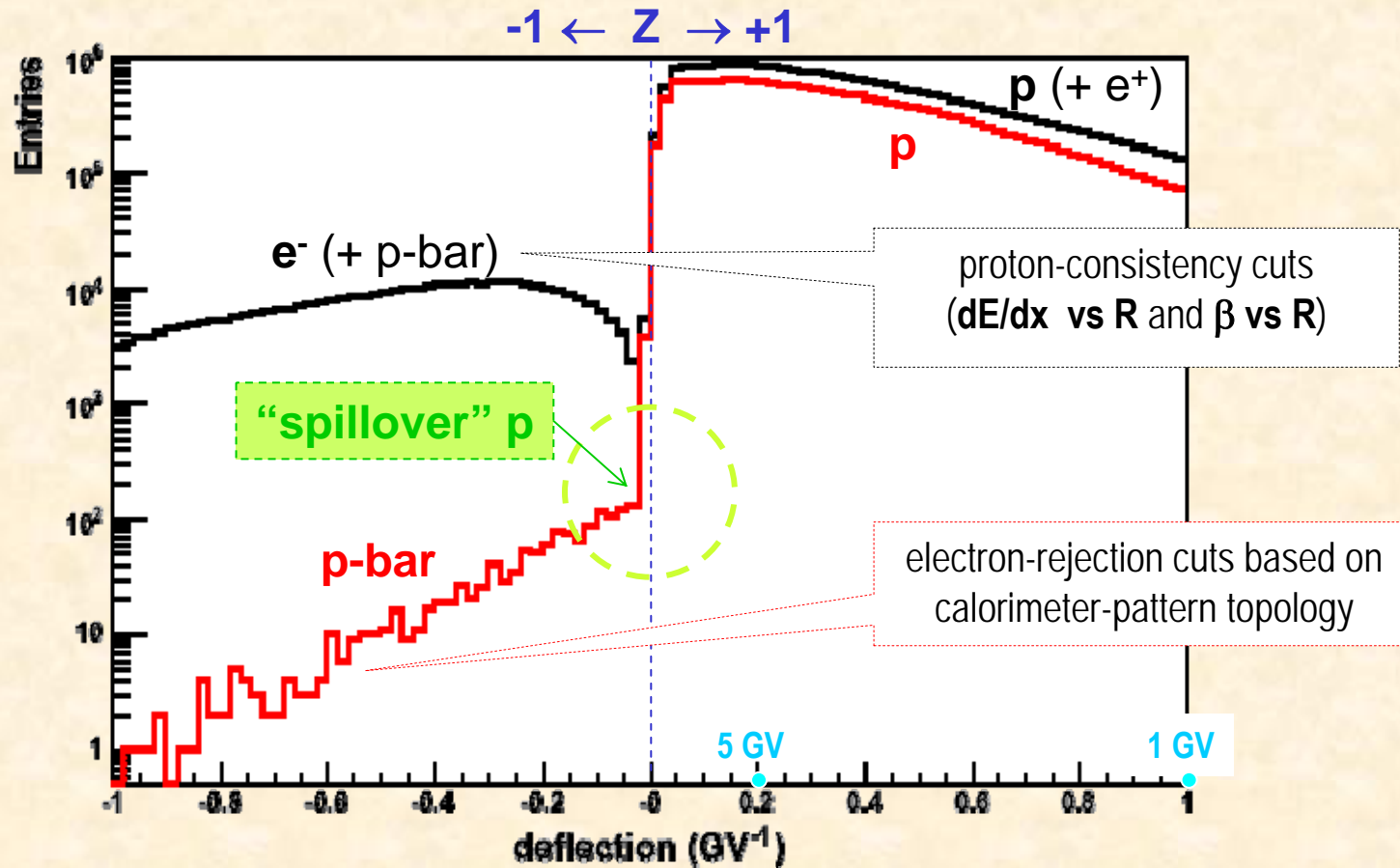
- Dominant background \rightarrow **spillover protons**:

- finite deflection resolution of the SPE \Rightarrow wrong assignment of charge-sign @ high energy
- proton spectrum harder than positron \Rightarrow p/p-bar increase for increasing energy (10^3 @1GV 10^4 @100GV)

\rightarrow Required strong SPE selection

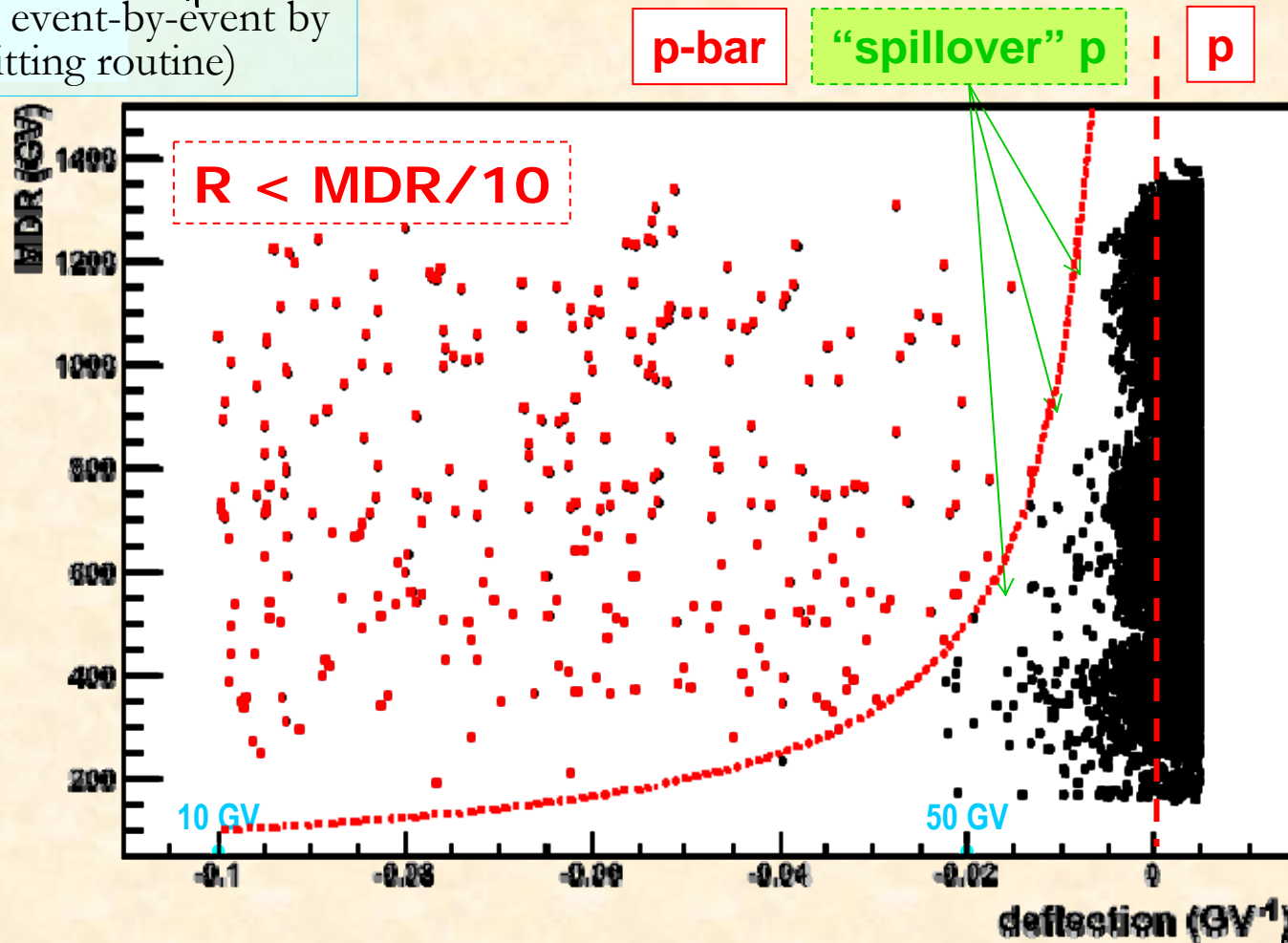


Antiproton identification



Proton-spillover background

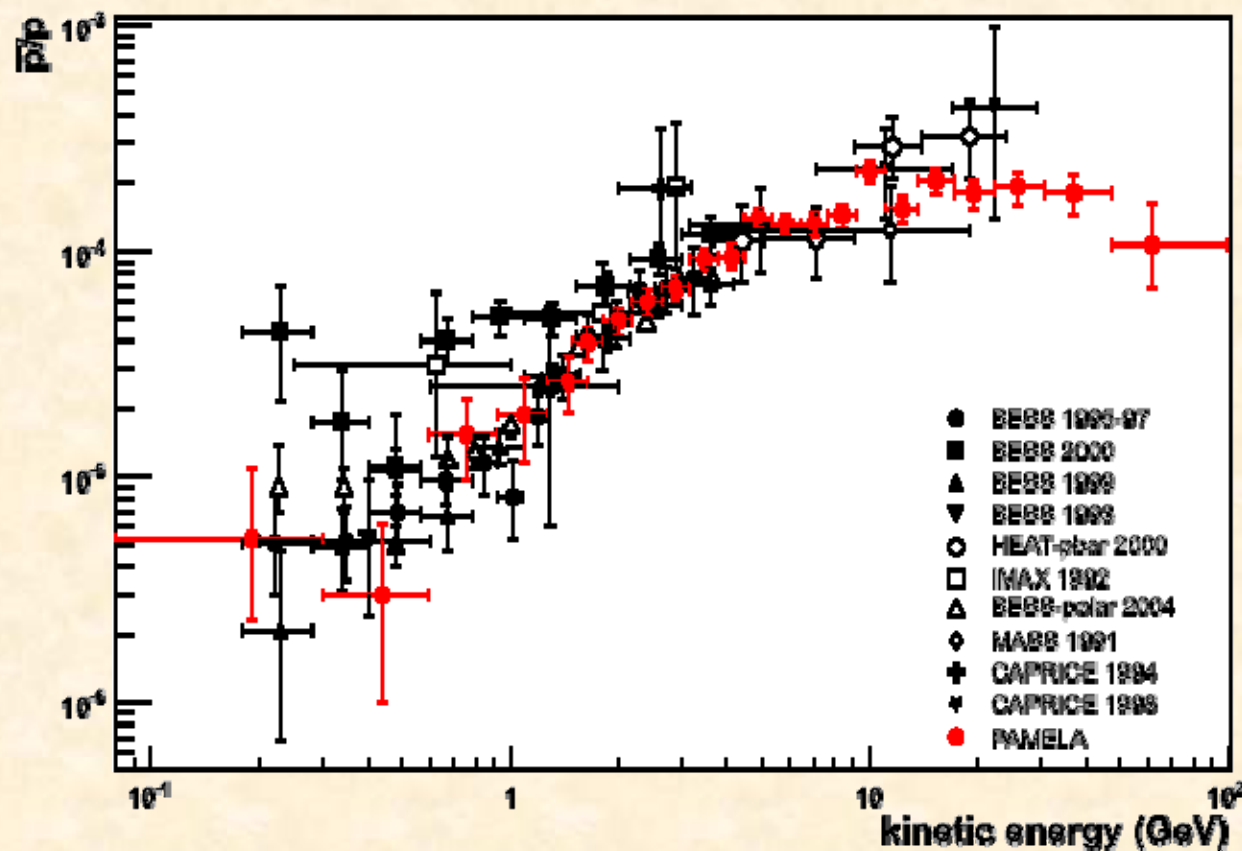
$\text{MDR} = 1/\sigma_\eta$
(evaluated event-by-event by
the fitting routine)



Electrons: efficiently removed by CALO

Pions (from interactions in dome) : about 3% in the pbar sample

PAMELA: Antiproton-to-proton ratio



← *preliminary* →
(Petter Hofverberg's PhD Thesis)

← PRL 102, 051101 (2009) →

Positrons

High-energy positron analysis

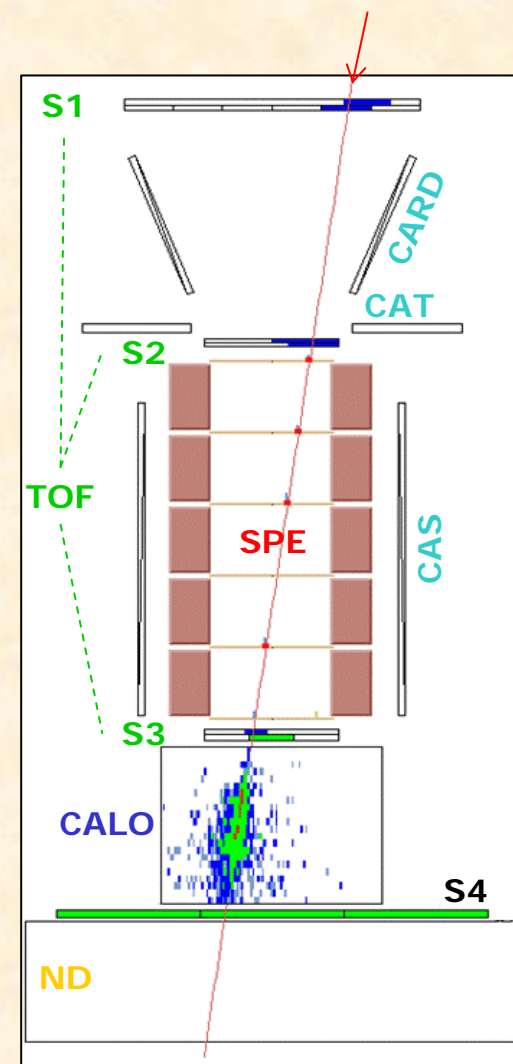
- Analyzed data July 2006 – February 2008 (~ 500 days)
- Collected triggers $\sim 10^8$
- Identified $\sim 150 \cdot 10^3$ electrons and $\sim 9 \cdot 10^3$ positrons between 1.5 and 100 GeV (**180 positrons above 20 GeV**)

- Electron/positron identification:

- rigidity (R) \rightarrow SPE
- $|Z|=1$ ($dE/dx=MIP$) \rightarrow SPE&ToF
- $\beta=1 \rightarrow$ ToF
- e^-/e^+ separation (charge sign) \rightarrow SPE
- e^+/p (and $e^-/p\text{-bar}$) separation \rightarrow CALO

- Dominant background \rightarrow **interacting protons**:

- fluctuations in hadronic shower development $\Rightarrow \pi_0 \rightarrow \gamma\gamma$ might mimic pure em showers
- proton spectrum harder than positron $\Rightarrow p/e^+$ increase for increasing energy (10^3 @1GV 10^4 @100GV)



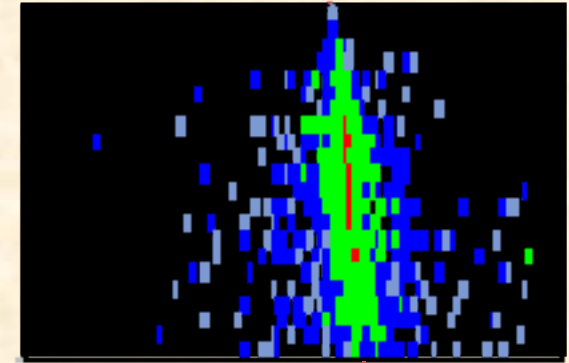
\rightarrow Required strong CALO selection

✦ **Roberta Sparvoli** ✦ March 2nd, 2009 ✦ La Thuile

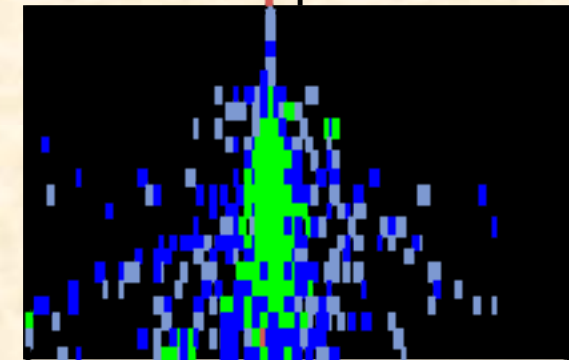
Positron identification with CALO

- Identification based on:
 - **Shower topology** (lateral and longitudinal profile, shower starting point)
 - **Total detected energy** (energy-rigidity match)
- Analysis key points:
 - **Tuning/check of selection criteria with:**
 - test-beam data
 - simulation
 - flight data → dE/dx from SPE & neutron yield from ND
 - **Selection of pure proton sample from flight data** (“pre-sampler” method):
 - *Background-suppression method*
 - *Background-estimation method*

51 GV positron



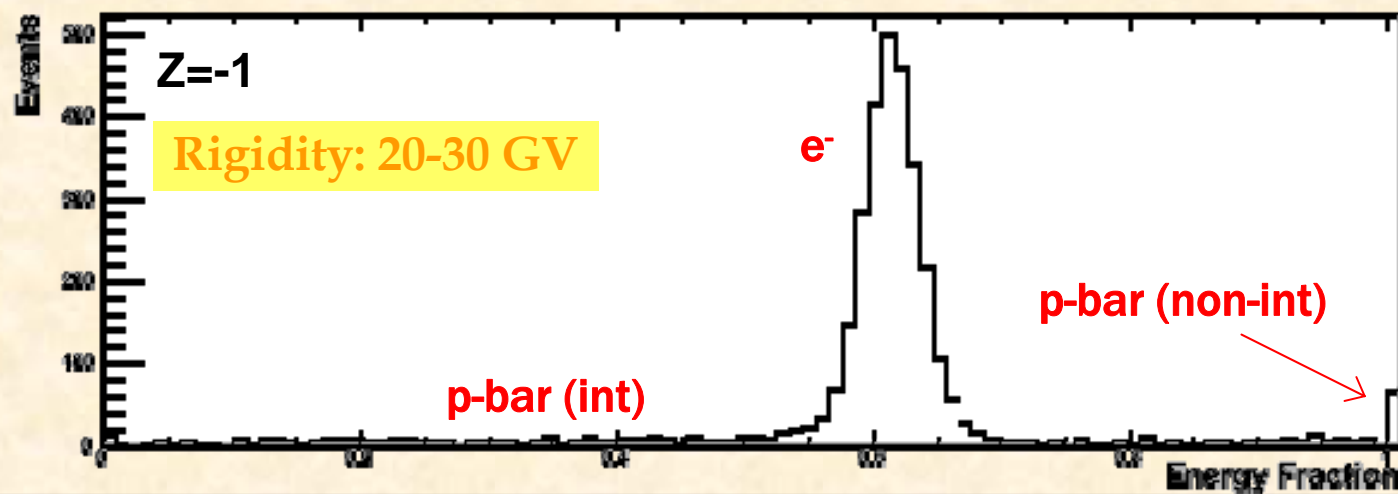
80 GV proton



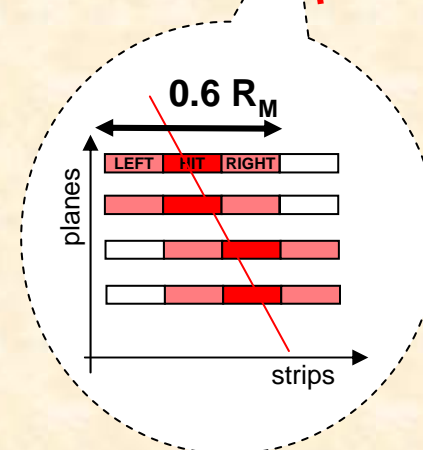
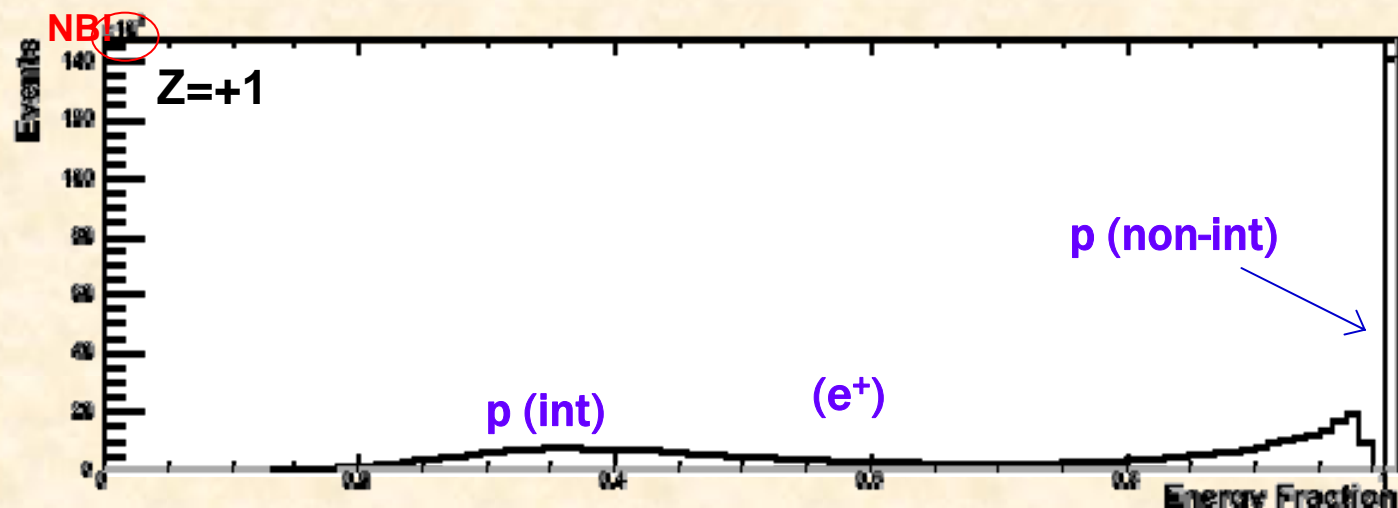
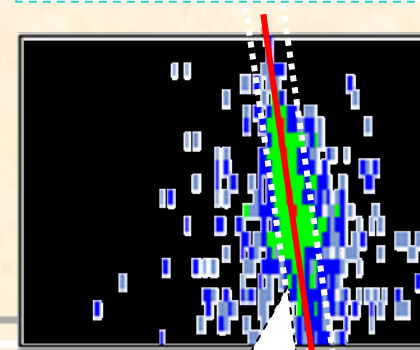
Final results make **NO USE** of test-beam and/or simulation calibrations.

The measurement is based only on flight data
with the **background-estimation** method

Positron identification

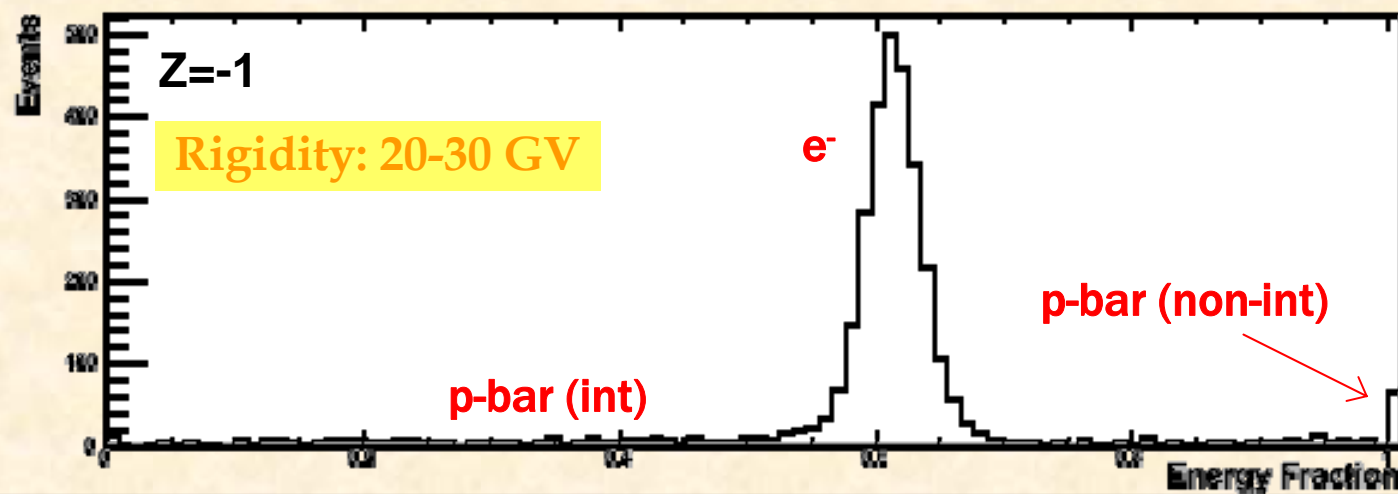


Fraction of charge released along the calorimeter track

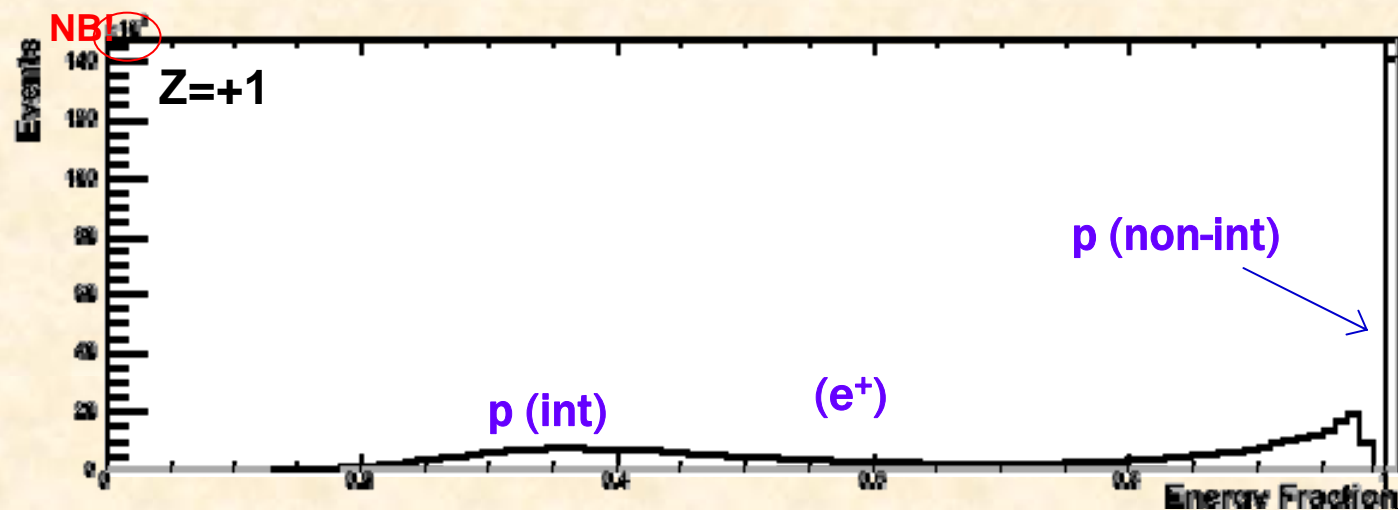


N.B: for em showers
90% of E contained
in 1 R_M !

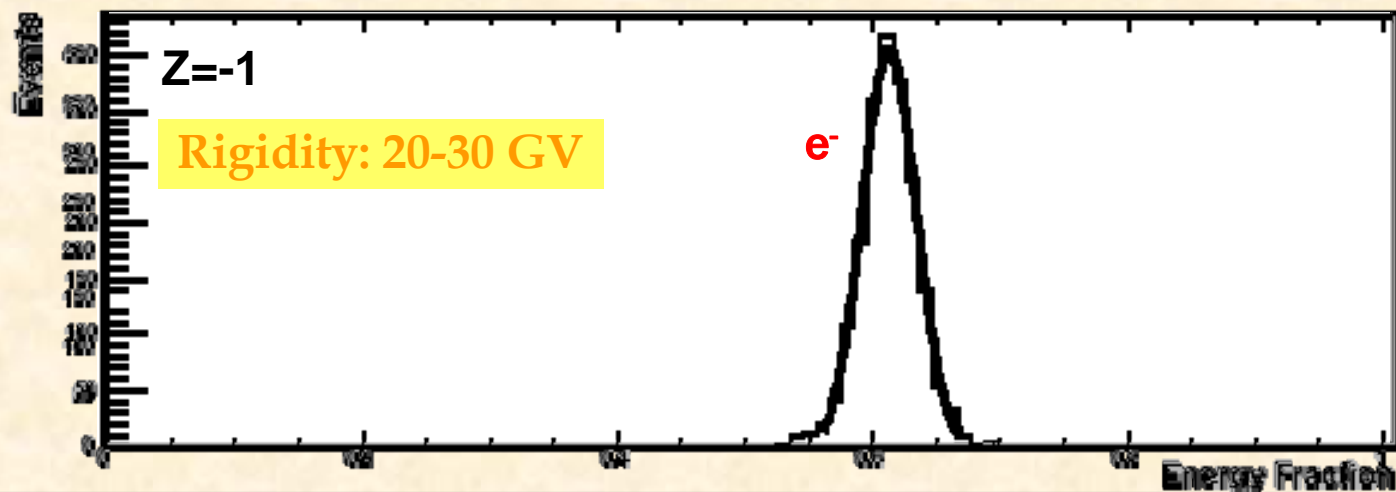
Positron identification



Fraction of charge released along the calorimeter track



Positron identification



Fraction of charge
released along the
calorimeter track

+

Constraints on:

Energy-momentum
match

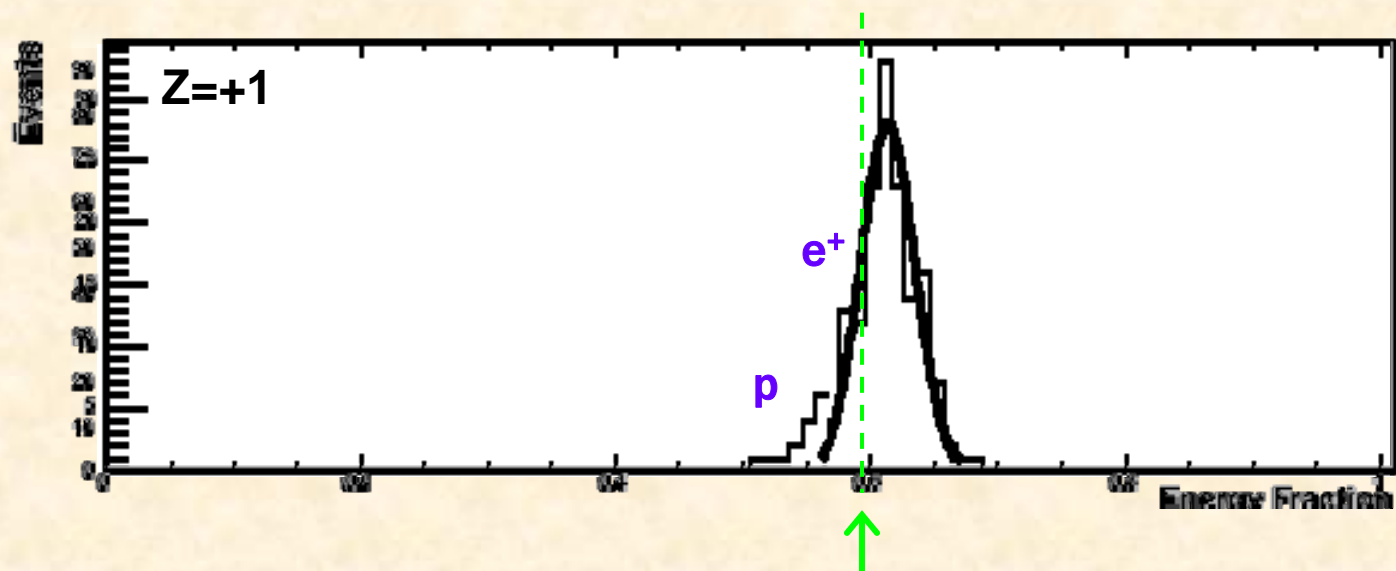
Shower starting-point

Longitudinal profile

Lateral profile

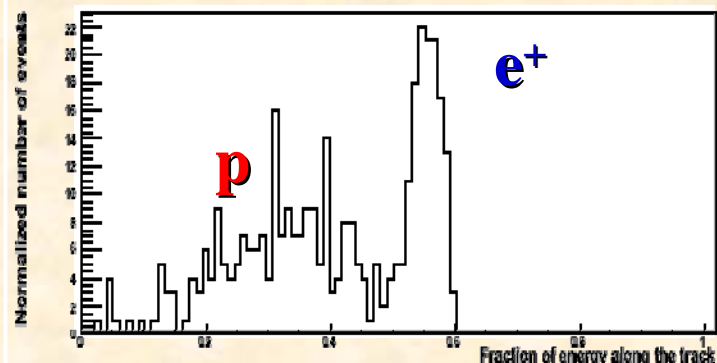
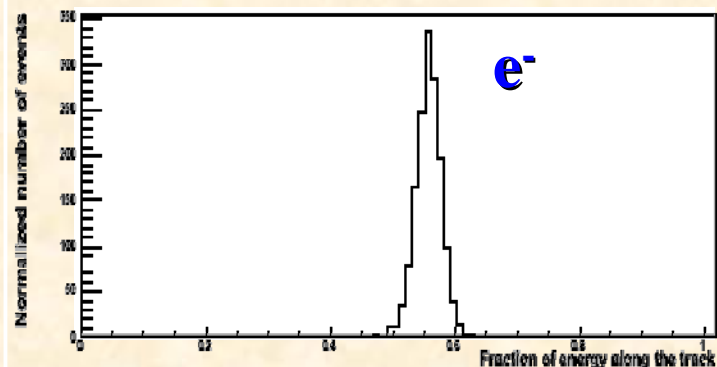


*BK-suppression
method*



Check of calorimeter selection

Flight data
Rigidity: 20-30 GV



Fraction of charge
released along the
calorimeter track

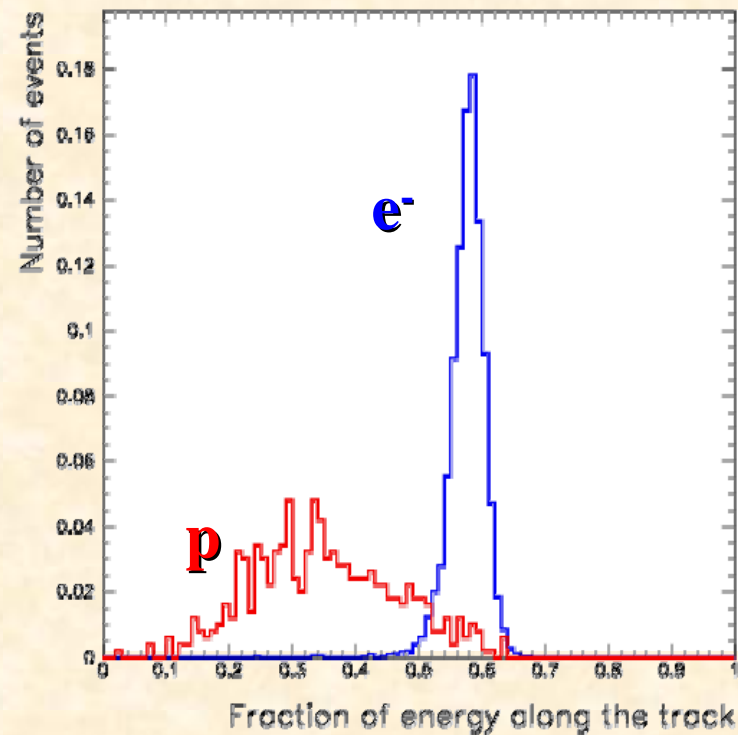
+

Constraints on:

Energy-momentum
match

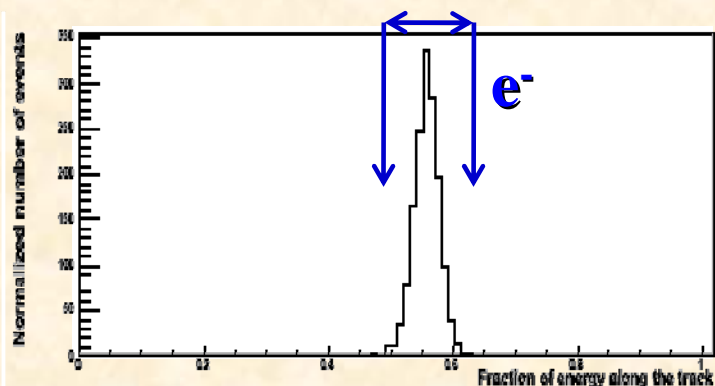
Shower starting-point

Test beam data
Momentum: 50 GeV/c



Check of calorimeter selection

Flight data
Rigidity: 20-30 GV



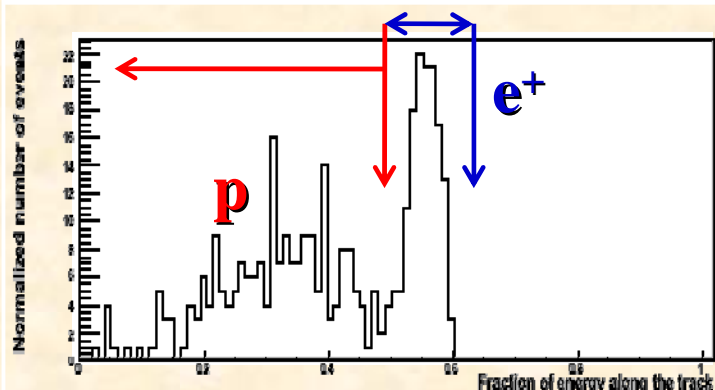
Fraction of charge
released along the
calorimeter track

+

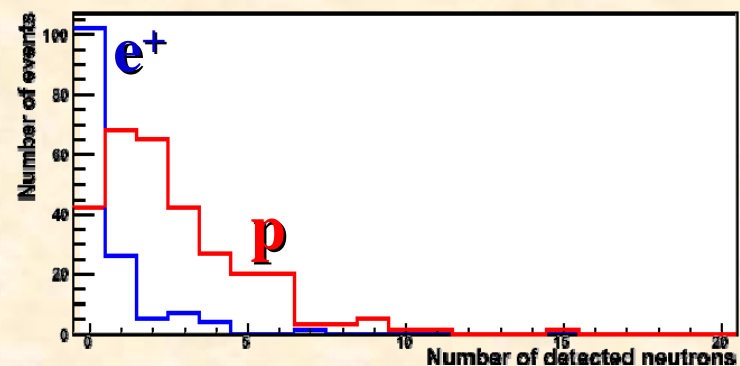
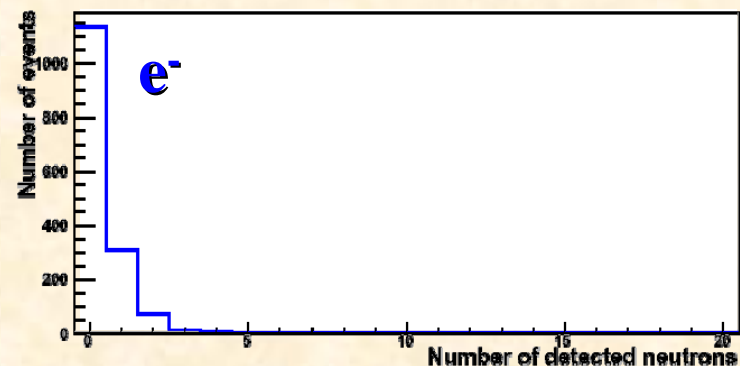
Constraints on:

Energy-momentum
match

Shower starting-point

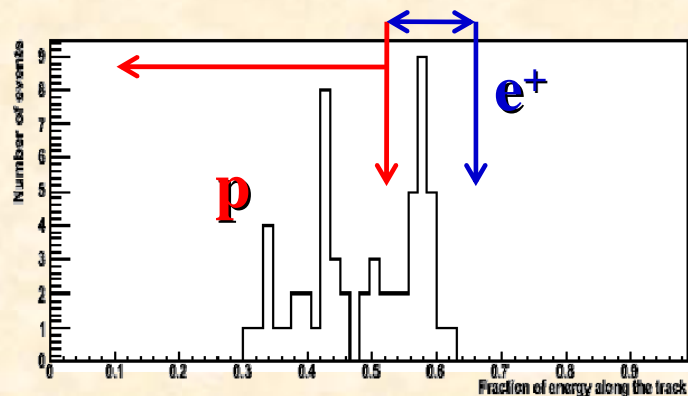
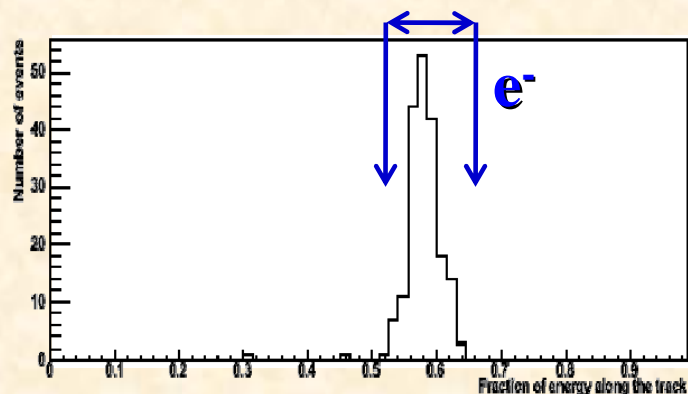


Flight data
Neutron yield in ND



Check of calorimeter selection

Flight data
Rigidity: 42-65 GV



Fraction of charge
released along the
calorimeter track

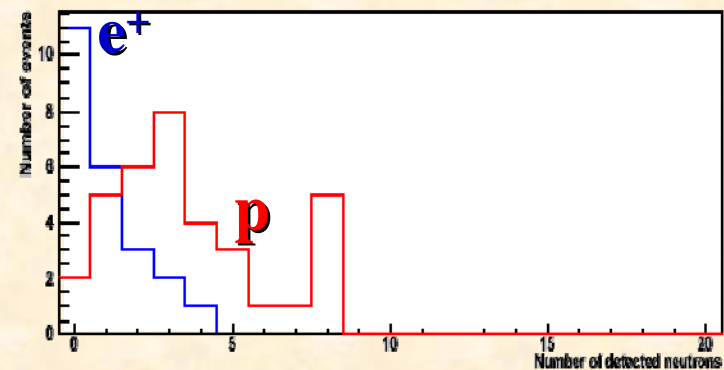
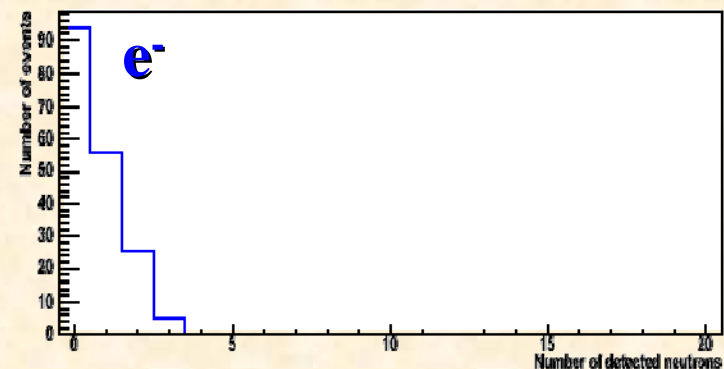
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Constraints on:

Energy-momentum
match

Shower starting-point

Flight data
Neutron yield in ND



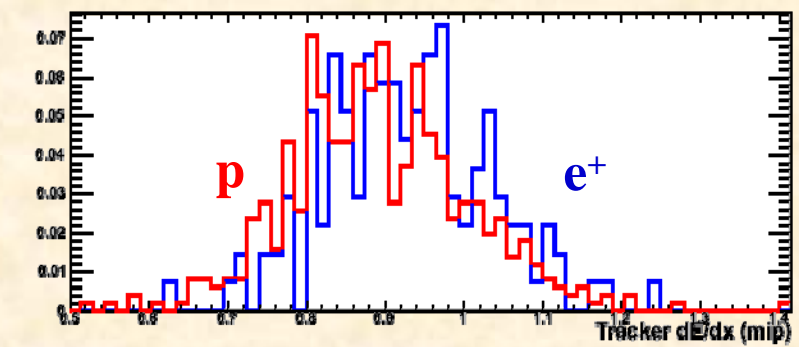
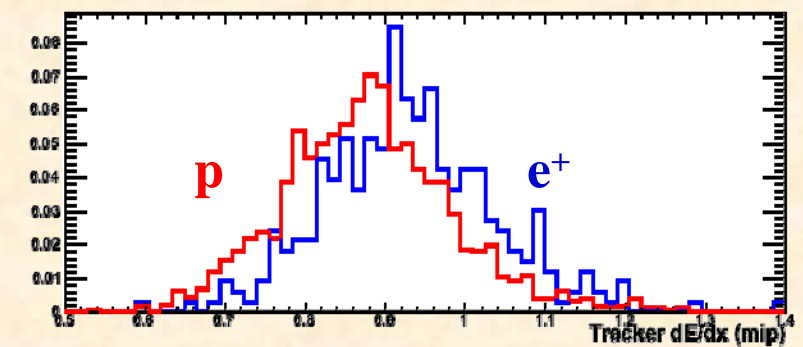
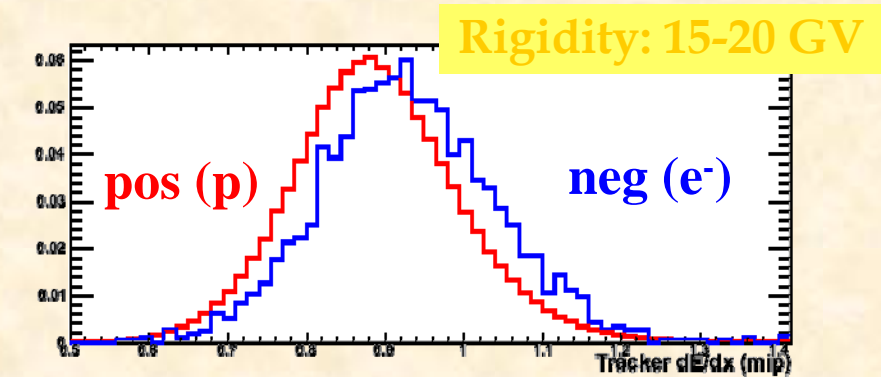
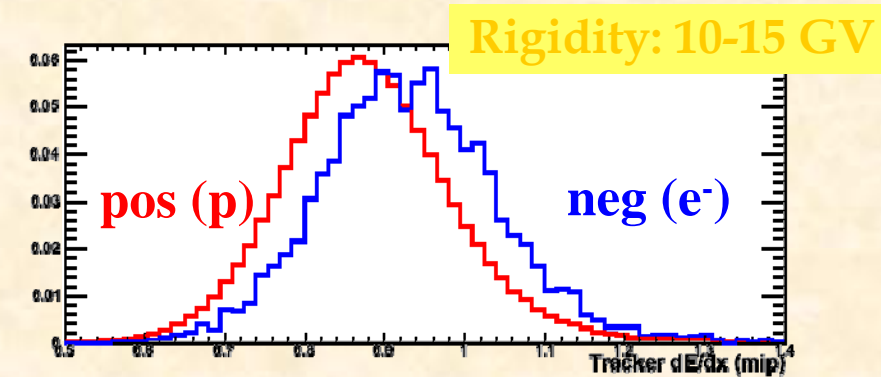
Check of calorimeter selection

Energy loss in silicon tracker detectors:

$$\longrightarrow -\frac{dE}{dx} = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 T_{\max}}{I^2} - \beta^2 \left(\frac{\delta(\beta\gamma)}{2} \right) \right]$$

Relativistic rise

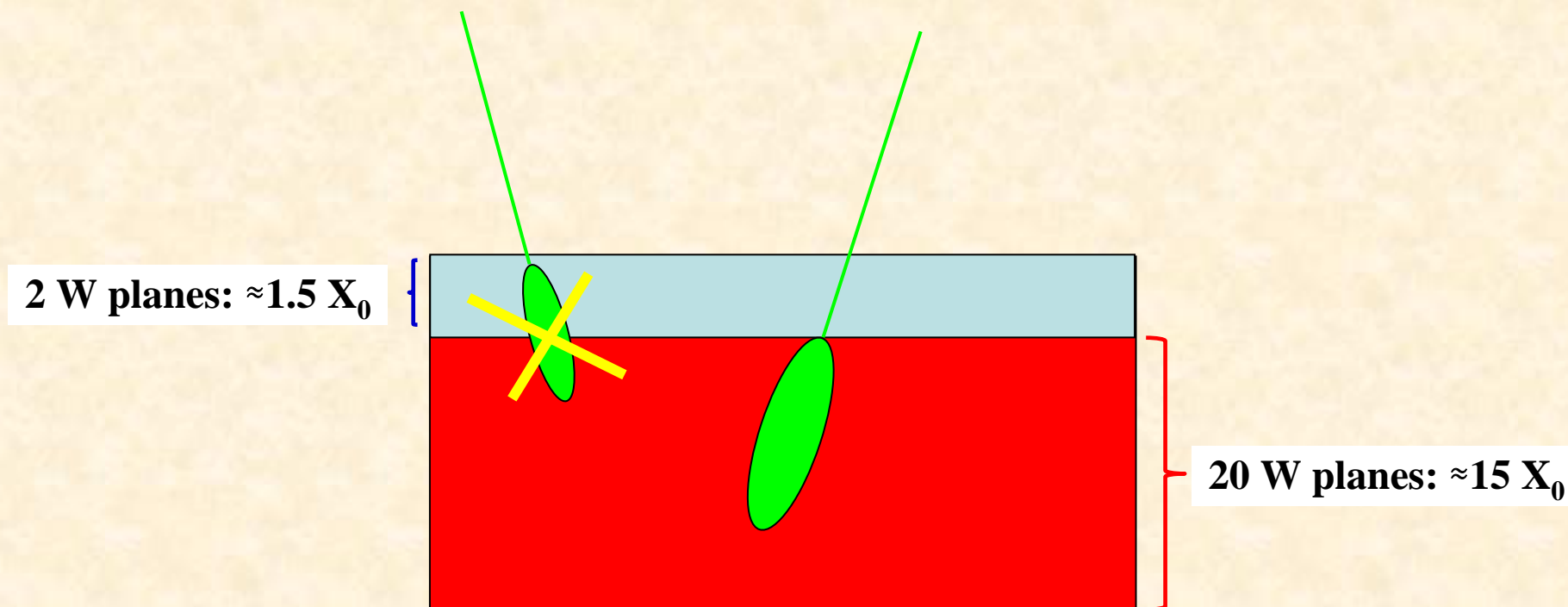
- Top: positive (mostly p) and negative events (mostly e^-)
- Bottom: positive events identified as p and e^+ by trasversal profile method



The “pre-sampler” method

Selection of a pure sample of protons from flight data

CALORIMETER: 22 W planes: $16.3 X_0$



Only 2% of electrons and positrons do not interact in the first 2 CALO planes

Proton background evaluation

Rigidity: 20-28 GV

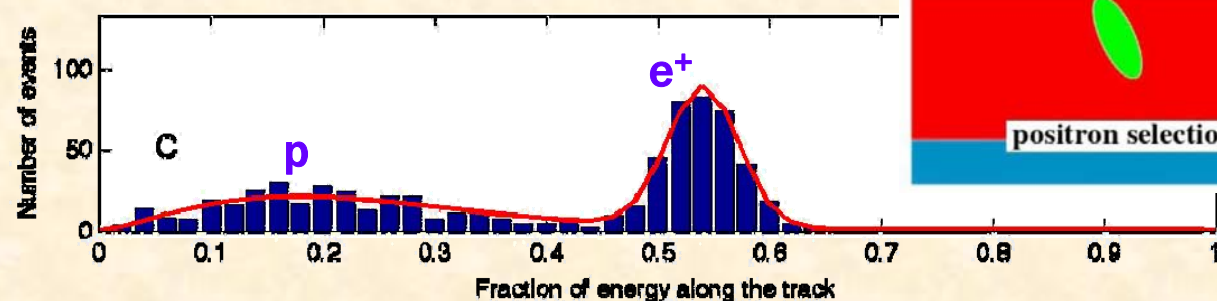
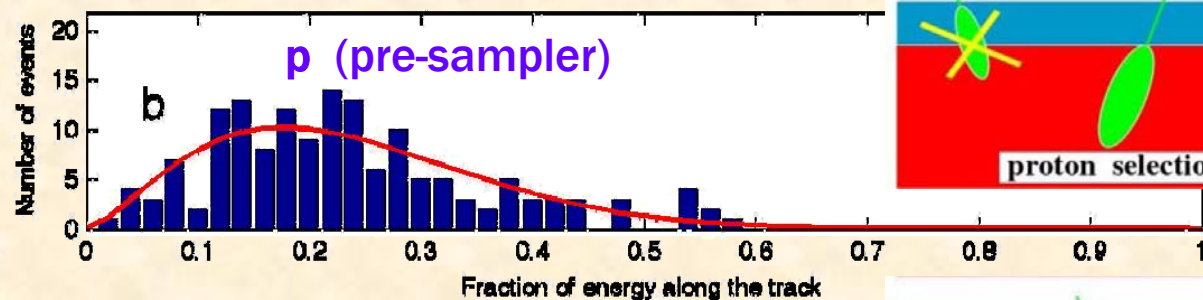
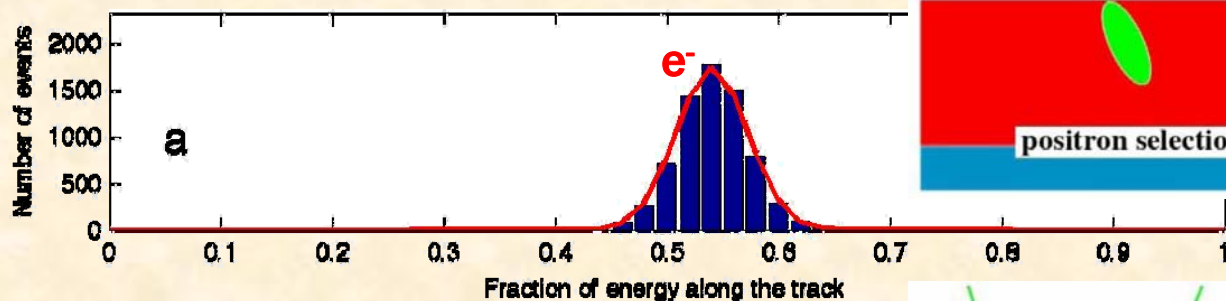
Fraction of charge released along the calorimeter track (left, hit, right)

+

Constraints on:

Energy-momentum match

Shower starting-point



Proton background evaluation

Rigidity: 28-42 GV

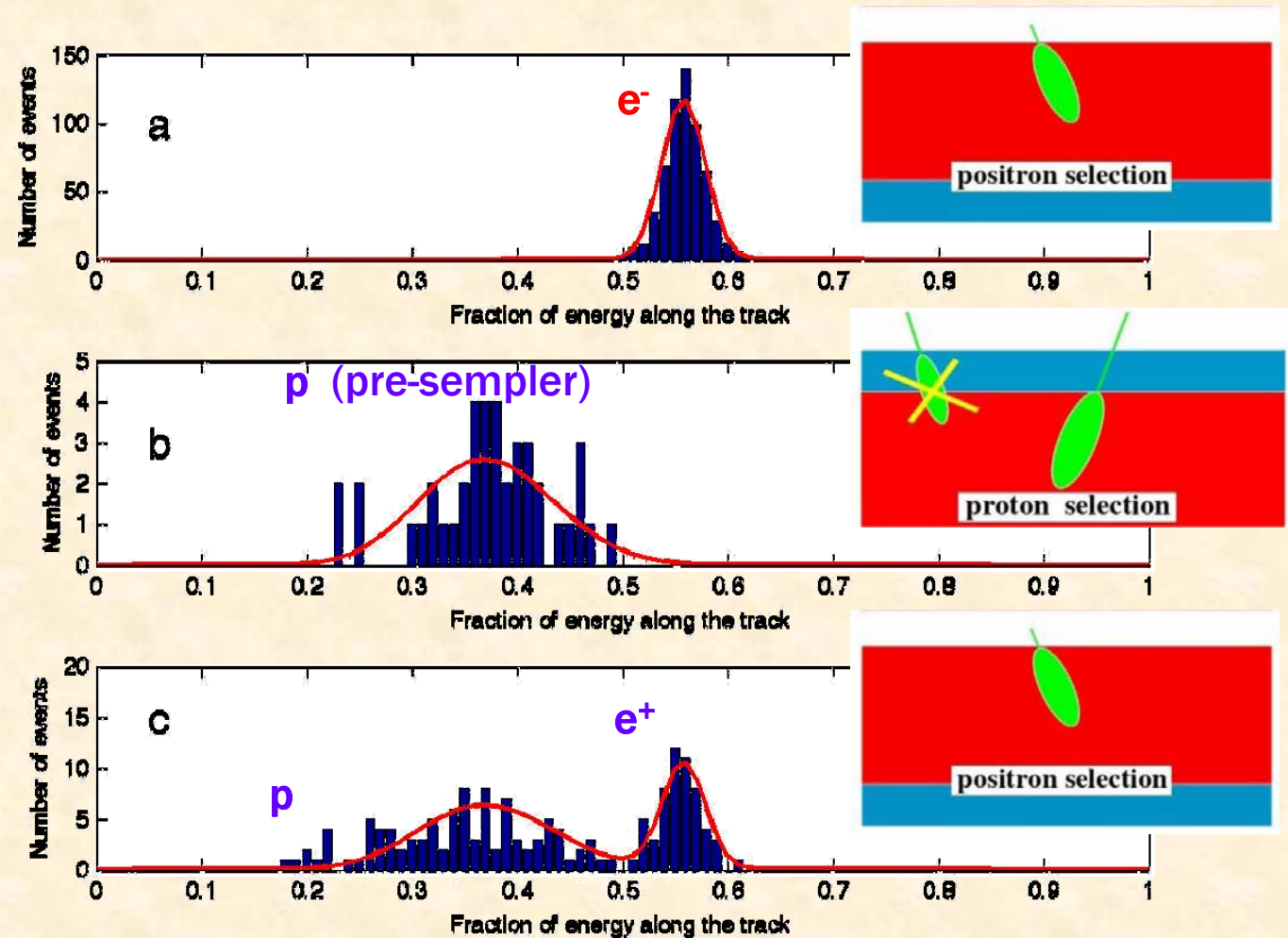
Fraction of charge
released along the
calorimeter track (left,
hit, right)

+

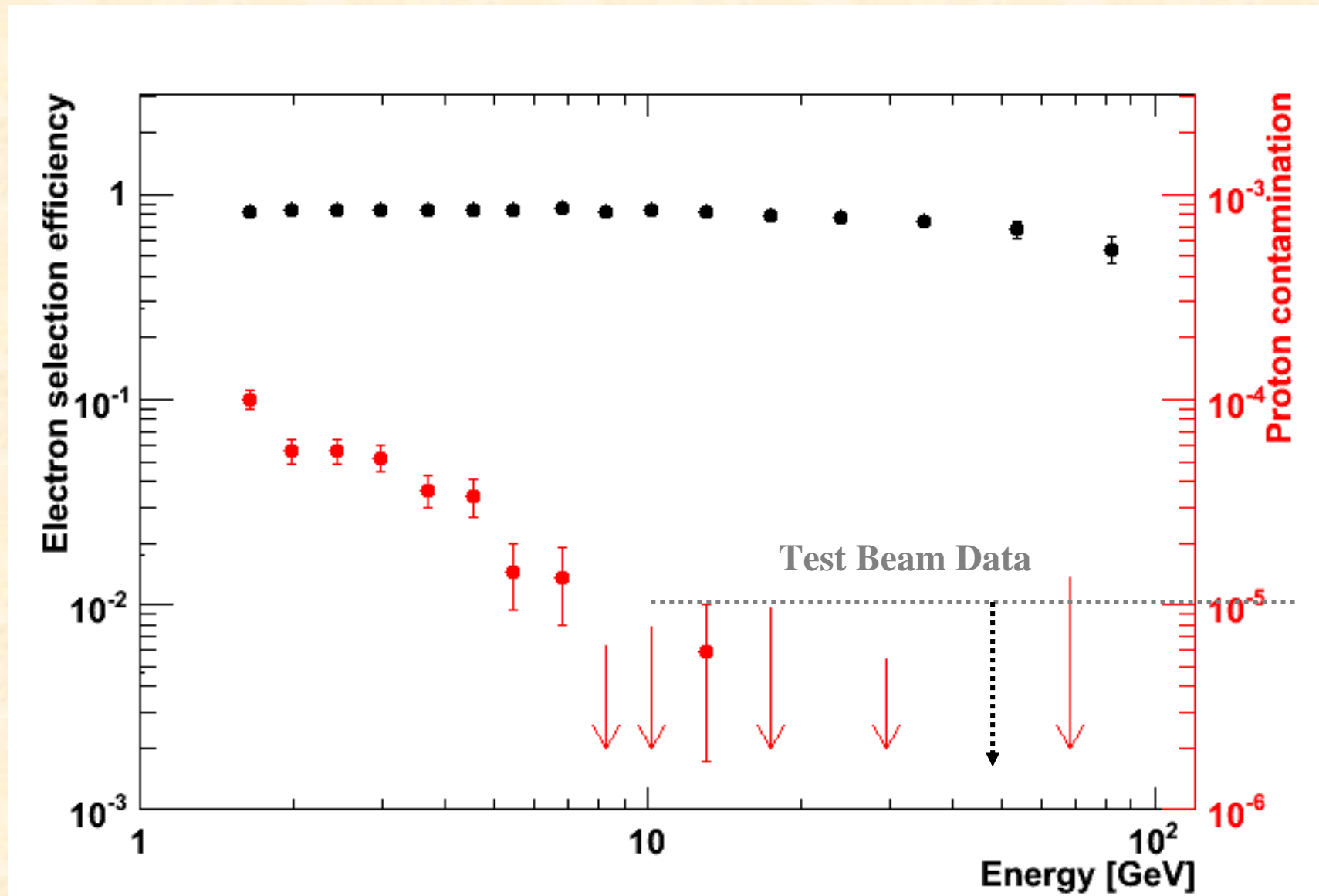
Constraints on:

Energy-momentum
match

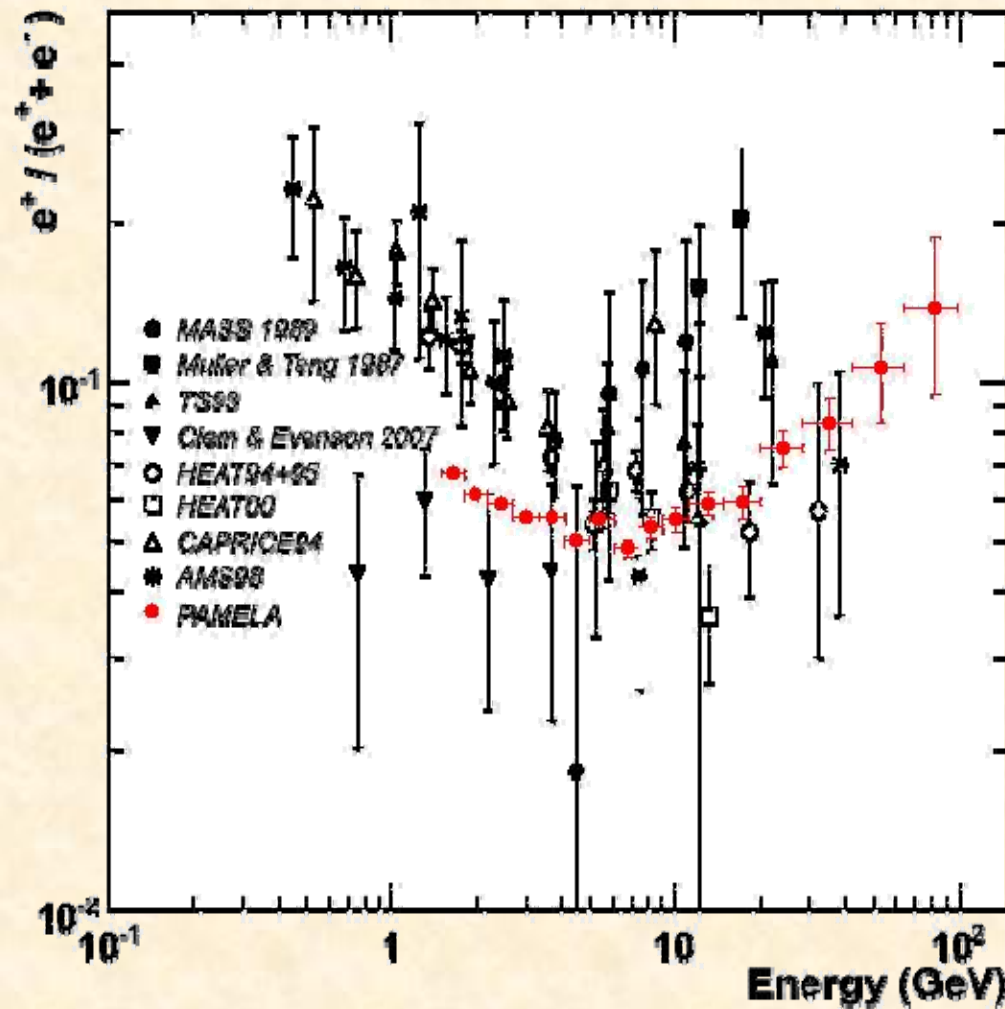
Shower starting-point



Positron selection with calorimeter

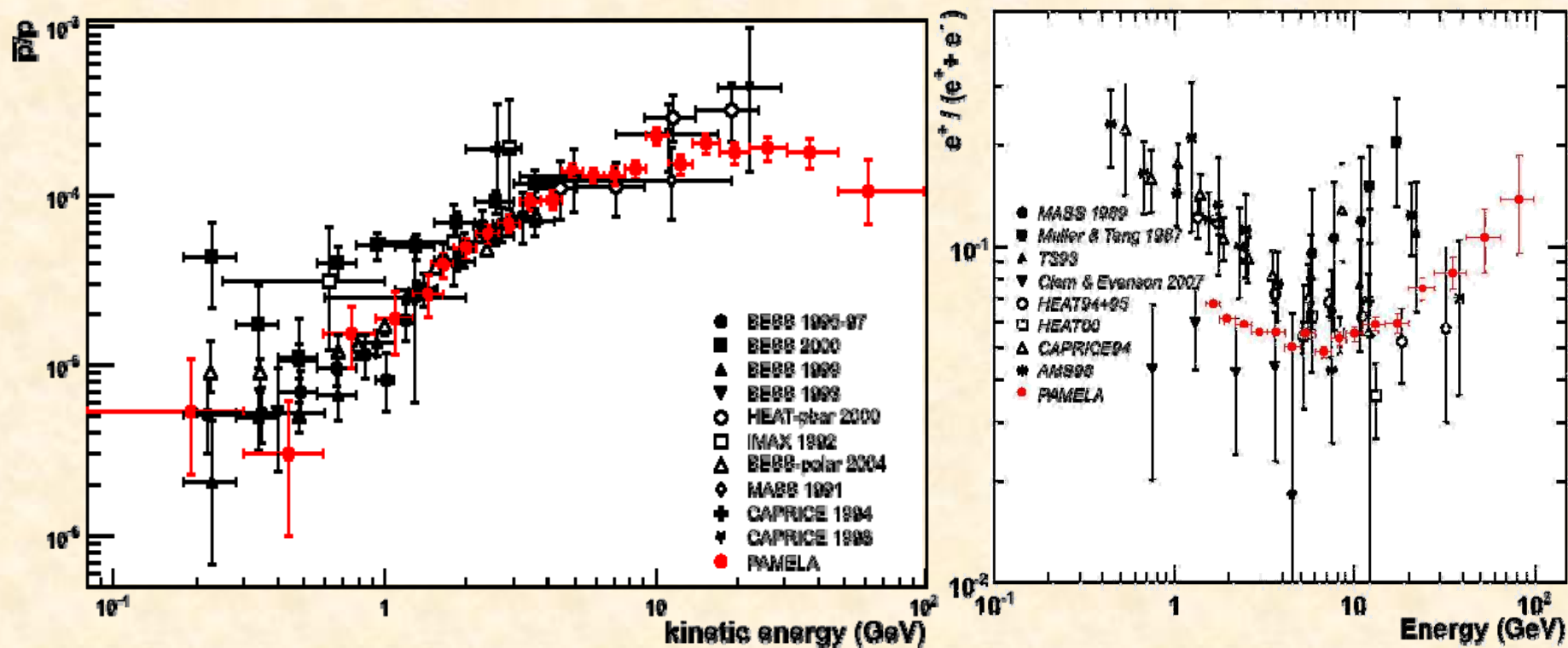


PAMELA: Positron fraction



astro-ph 0810.4995
Accepted by NATURE

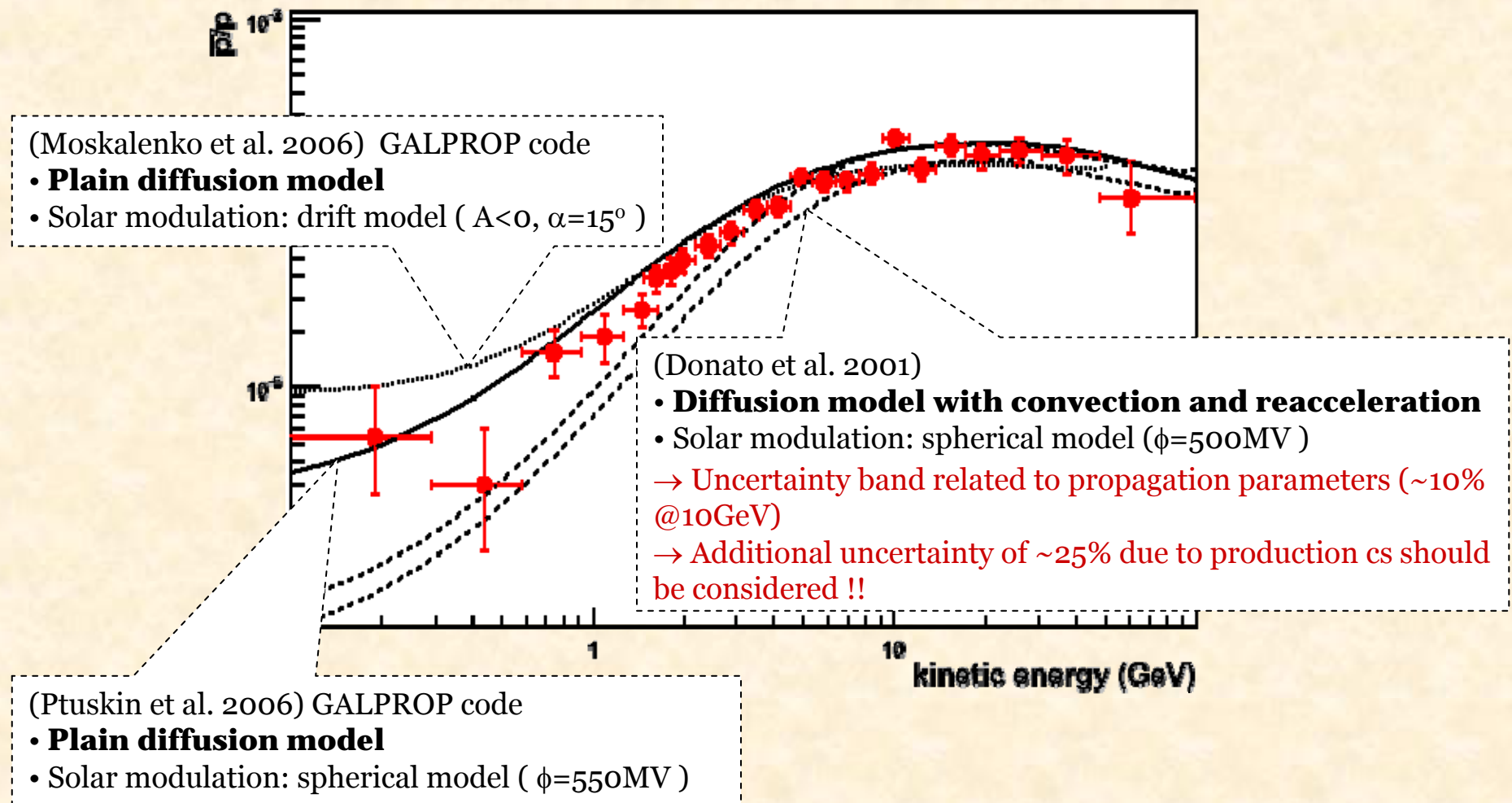
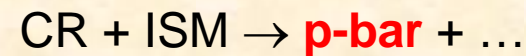
PAMELA antimatter data:



Do we have any antimatter excess in CRs?

Antiproton-to-proton ratio

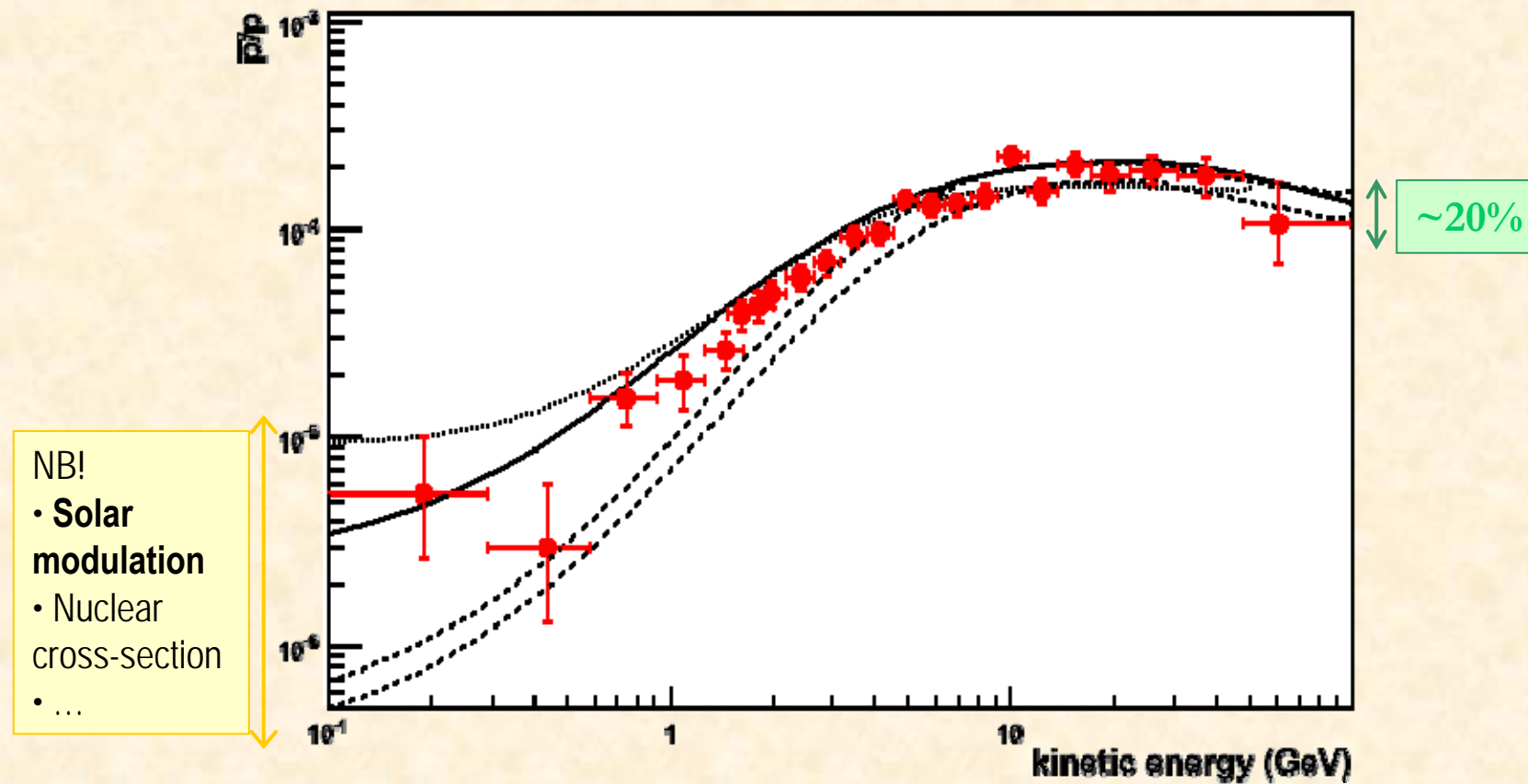
Secondary Production Models



Antiproton-to-proton ratio

Secondary Production Models

CR + ISM \rightarrow **p-bar** + ...



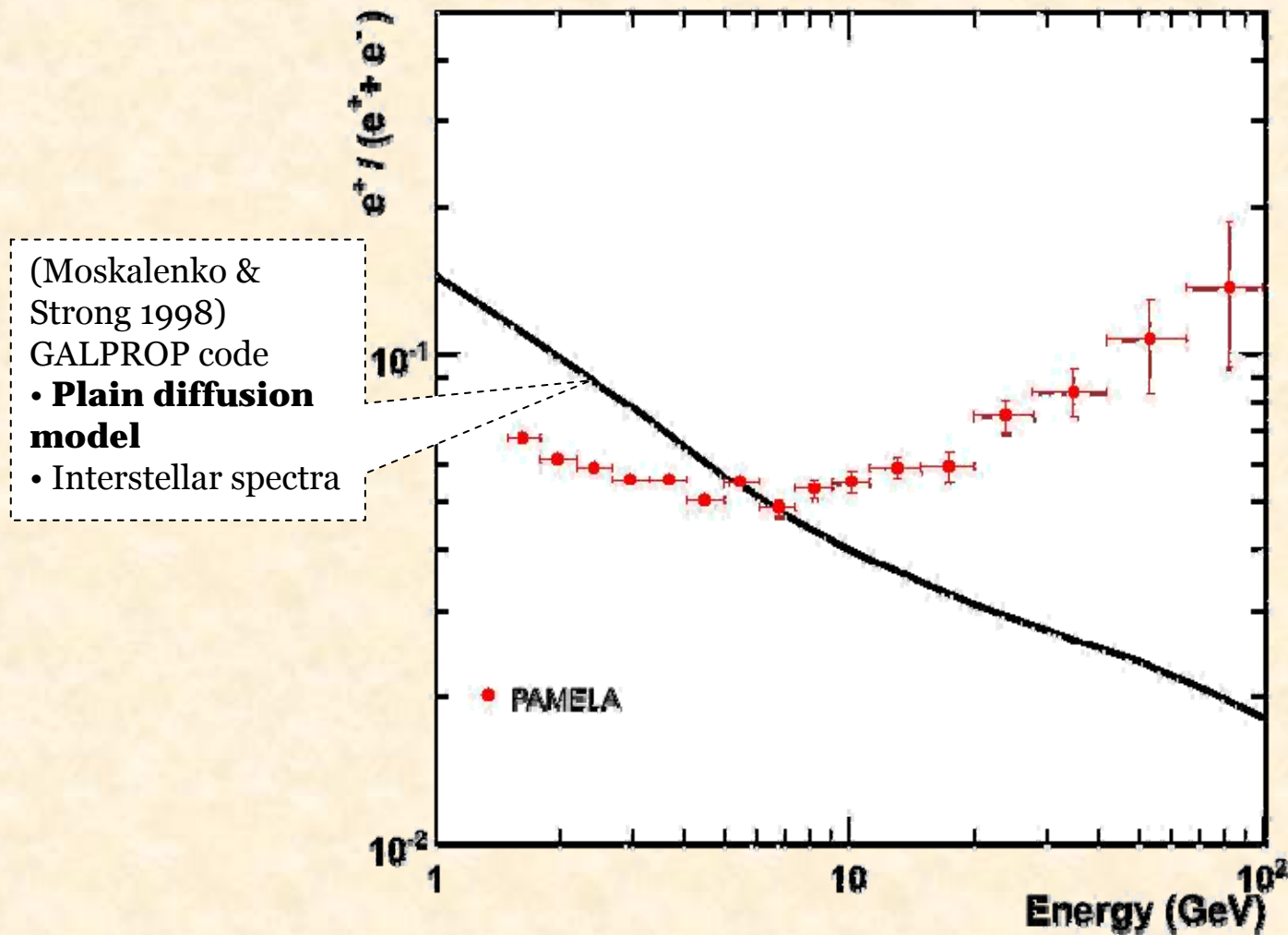
No evidence for any antiproton excess

Positron fraction

Secondary Production Models

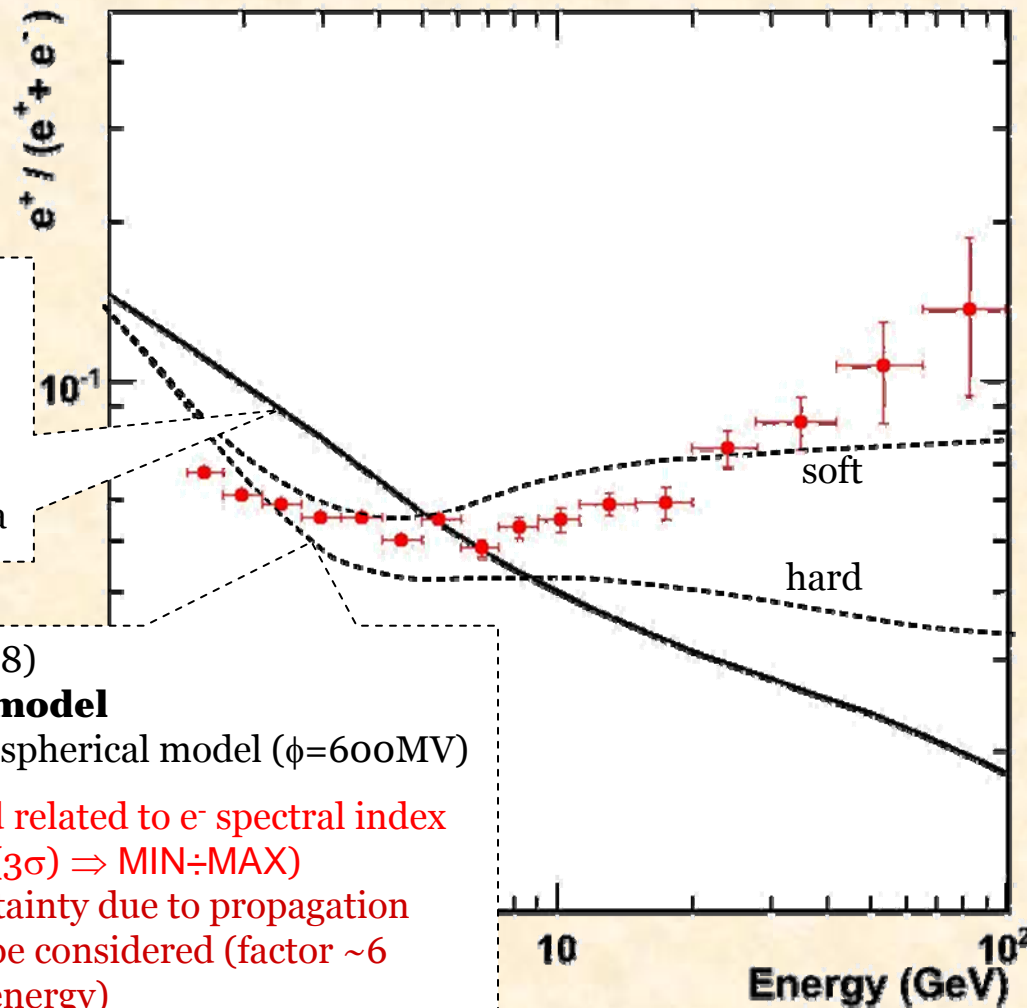
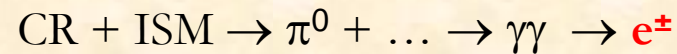
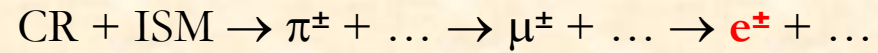
CR + ISM $\rightarrow \pi^\pm + \dots \rightarrow \mu^\pm + \dots \rightarrow e^\pm + \dots$

CR + ISM $\rightarrow \pi^0 + \dots \rightarrow \gamma\gamma \rightarrow e^\pm$



Positron fraction

Secondary Production Models

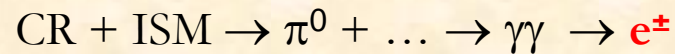
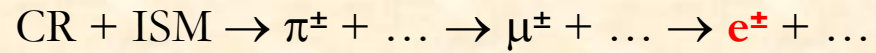


(Moskalenko & Strong 1998)
GALPROP code
• **Plain diffusion model**
• Interstellar spectra

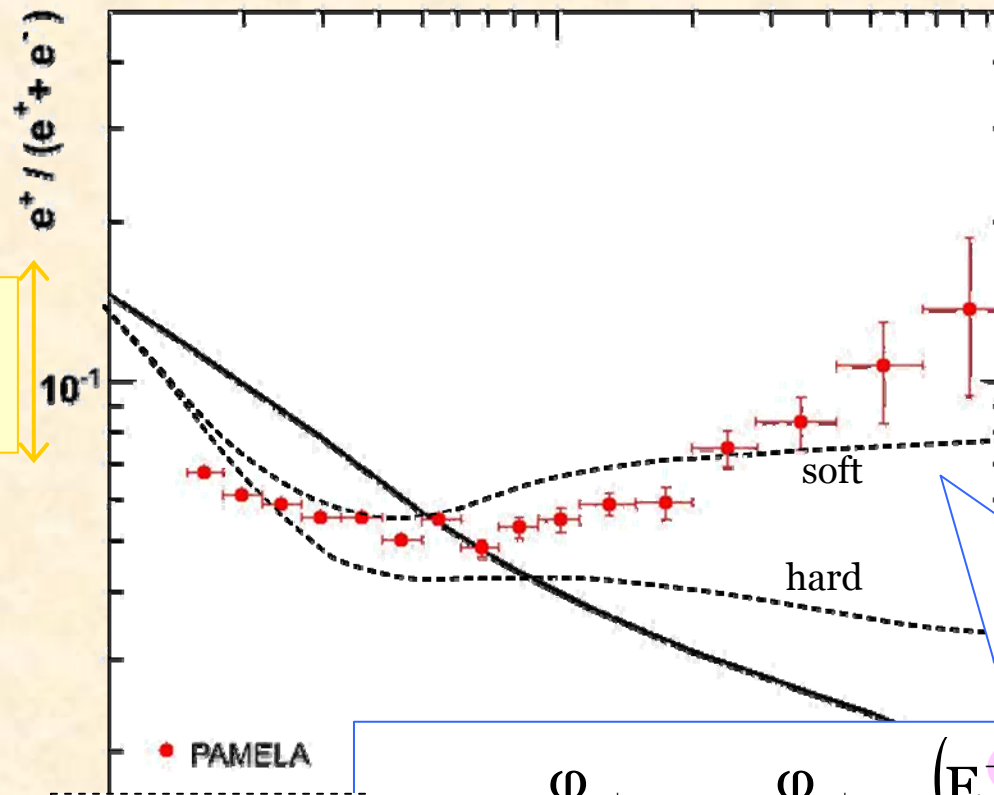
(Delahaye et al. 2008)
• **Plain diffusion model**
• Solar modulation: spherical model ($\phi=600\text{MV}$)
→ Uncertainty band related to e^- spectral index ($\gamma_e = 3.44 \pm 0.1$ (3σ) \Rightarrow MIN÷MAX)
→ Additional uncertainty due to propagation parameters should be considered (factor ~ 6 @1GeV ~ 4 @high-energy)

Positron fraction

Secondary Production Models



NB!
• Solar modulation



Increasing
positron fraction
only if
 $\lambda_e - \lambda_p > 0.6$
→ **unlikely**
(Serpico 2008)

$$N_P \propto Q_P \lambda_{\text{esc}}^1$$

$$\frac{N_S}{N_P} \propto \lambda_{\text{esc}}^1 \cdot \sigma_{P \rightarrow S}$$

$$F = \frac{\varphi_{e^+}}{\varphi_{e^+} + \varphi_{e^-}} \sim \frac{\varphi_{e^+}}{\varphi_{e^-}} \sim \frac{(E^{-\lambda_p - \delta}) \cdot E^{-1}}{E^{-\lambda_e - 1}} \sim E^{\lambda_e - \lambda_p - \delta}$$

p spectral index @source

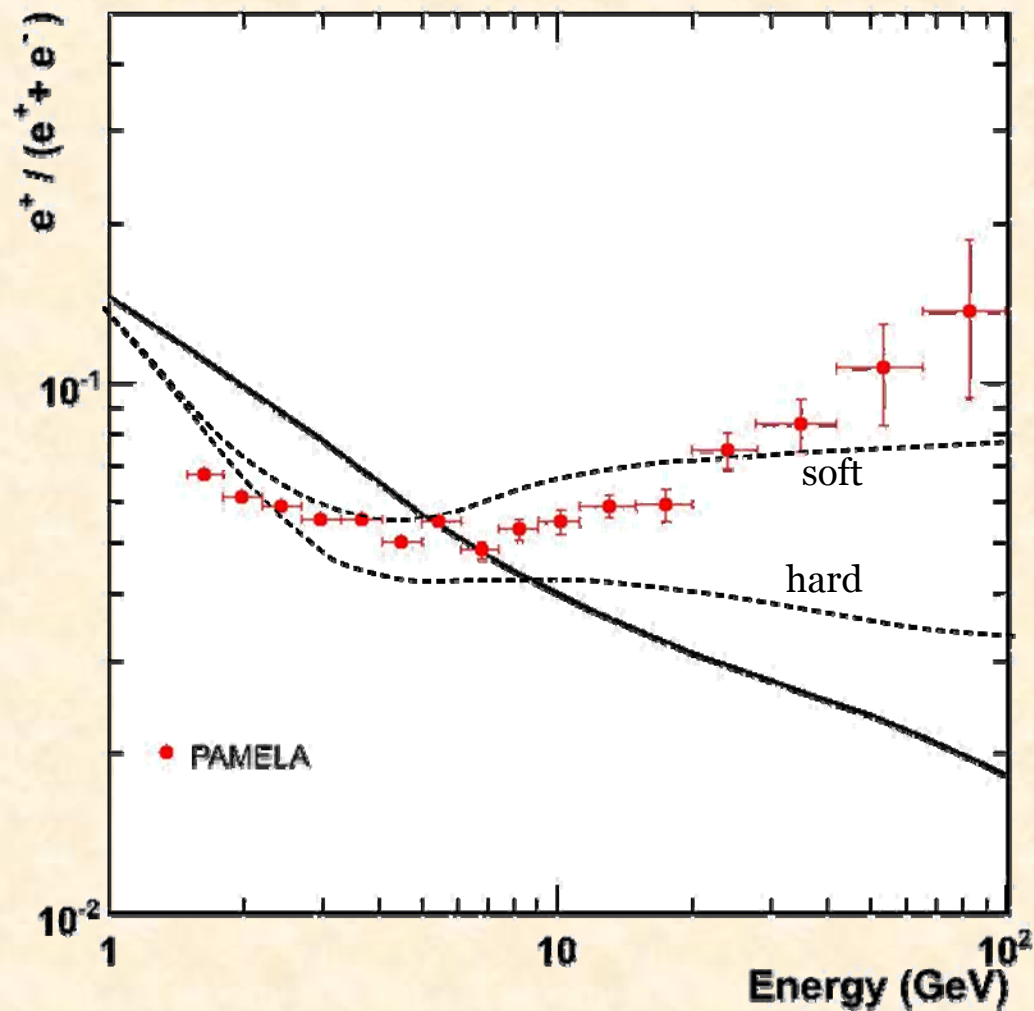
e⁻ spectral index @source

nuclear diffusion ($\delta \sim 0.6$ from B/C)

lepton diffusion & en.loss (l=1 if en.loss dominate)

Positron fraction

Secondary Production Models

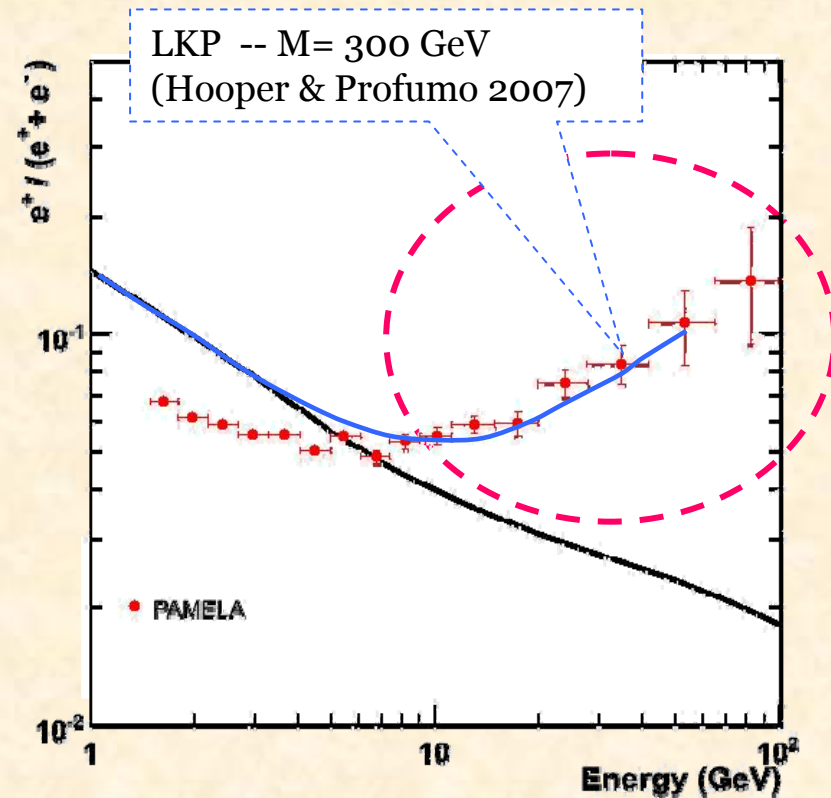


Quite robust evidence for a positron excess

Primary positron sources

Dark Matter

- e^+ yield depend on the dominant decay channel
 - **LSPs (SUSY)** seem disfavored due to suppression of e^+e^- final states
 - low yield (relative to $p\text{-bar}$)
 - soft spectrum from cascade decays
 - **LKPs** seem favored because can annihilate directly in e^+e^-
 - high yield (relative to $p\text{-bar}$)
 - hard spectrum with pronounced cutoff @ $M_{\text{LKP}} (>300 \text{ GeV})$
- Boost factor required to have a sizable e^+ signal
 - NB: constraints from $p\text{-bar}$ data!!
- Other hypothesis possible and under study (i.e. Minimal DM Model, ...)



Results

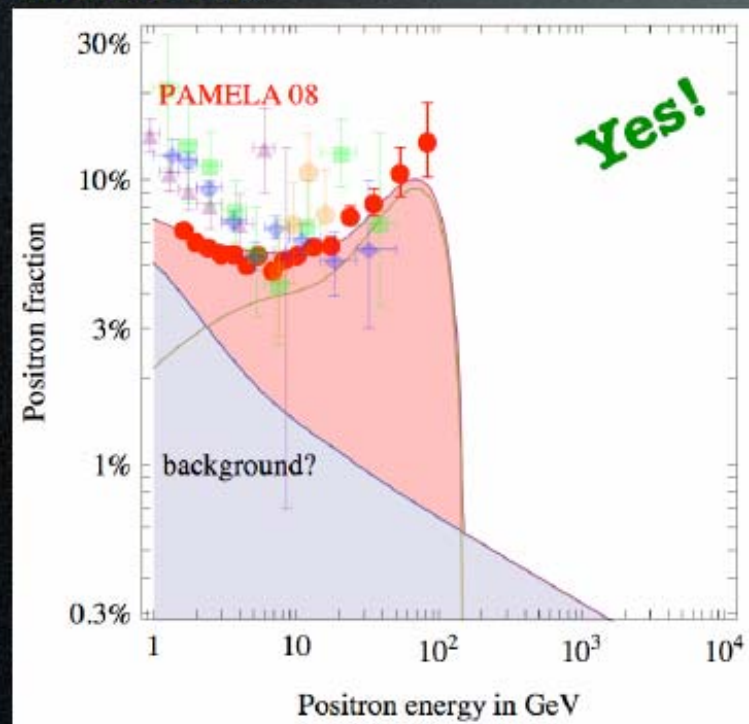
Which DM spectra can fit the data?

E.g. a DM with: -mass $M_{\text{DM}} = 150 \text{ GeV}$

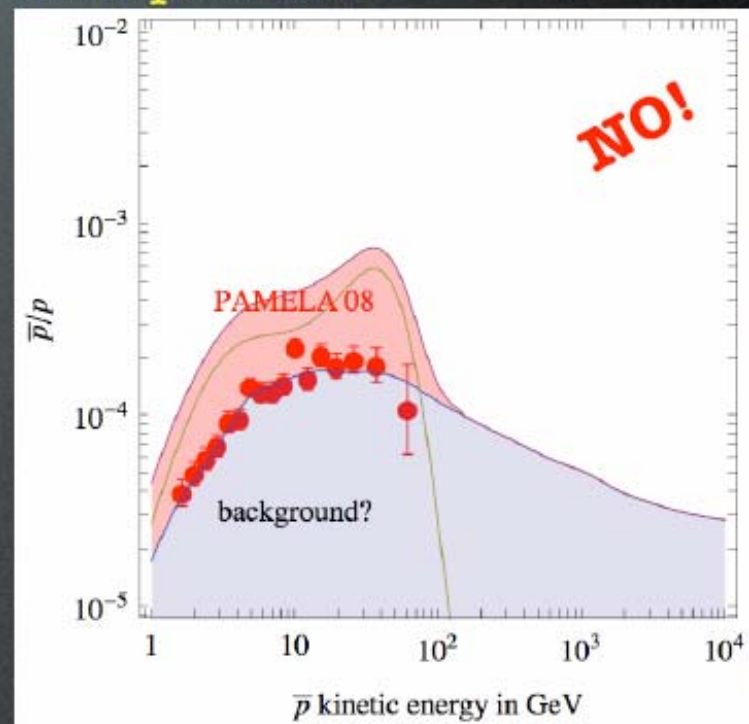
-annihilation $\text{DM DM} \rightarrow W^+ W^-$

(a possible SuperSymmetric candidate: wino)

Positrons:



Anti-protons:



[insisting on Winos]

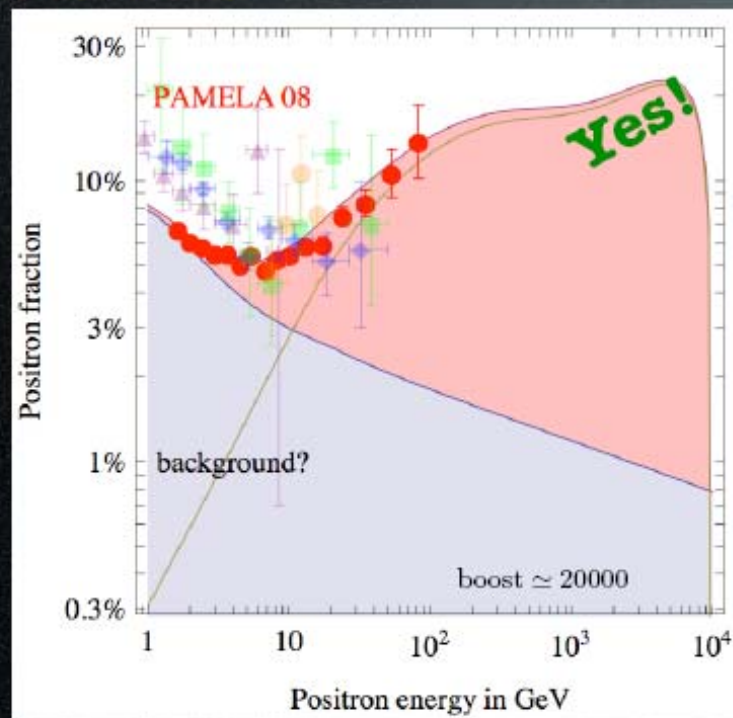
Courtesy of M. Cirelli

Results

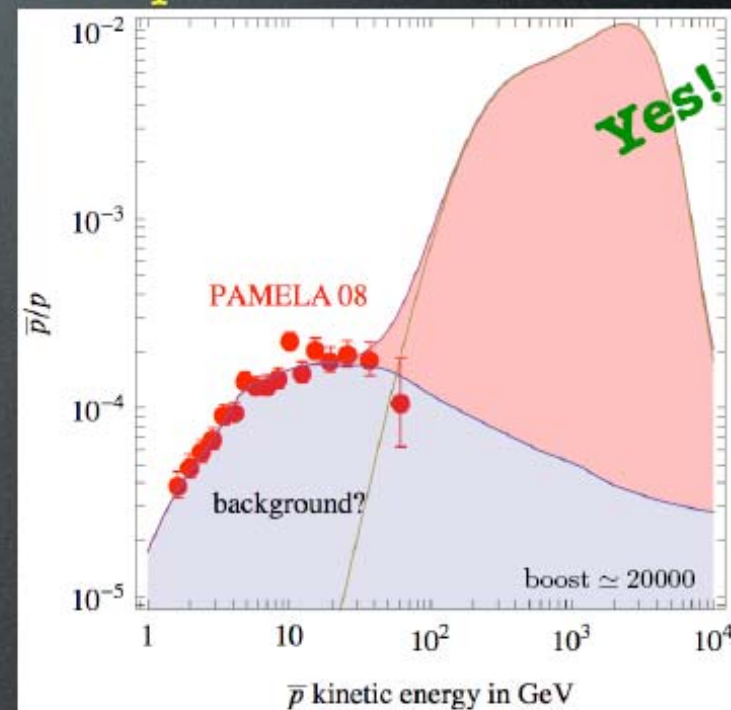
Which DM spectra can fit the data?

E.g. a DM with: -mass $M_{\text{DM}} = 10 \text{ TeV}$
-annihilation $\text{DM DM} \rightarrow W^+ W^-$
but...: -boost $B = 2 \cdot 10^4$ **No...**

Positrons:



Anti-protons:



Courtesy of M. Cirelli

Results

Which DM spectra can fit the data?

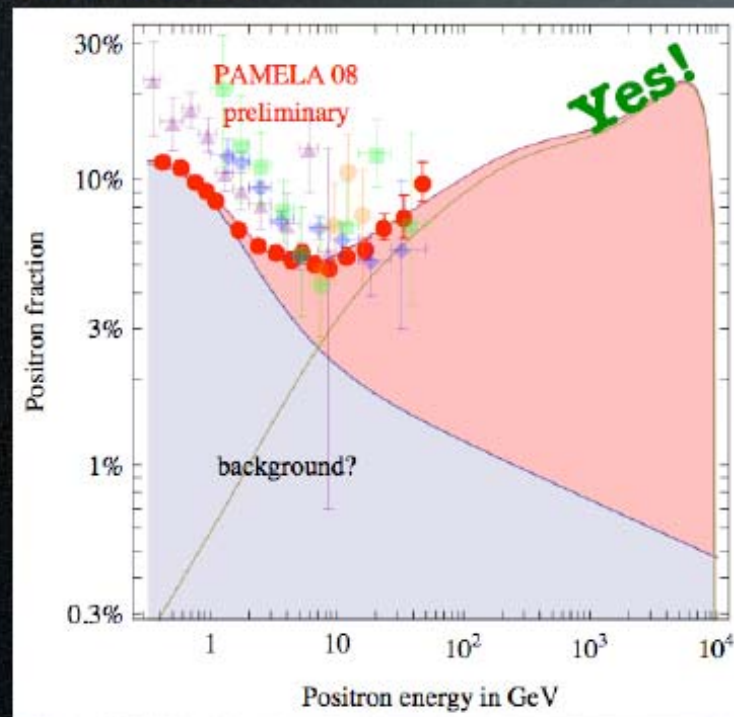
E.g. **Minimal DM**: -mass $M_{\text{DM}} = 9.7 \text{ TeV}$

[Cirelli, Strumia
et al. 2006]

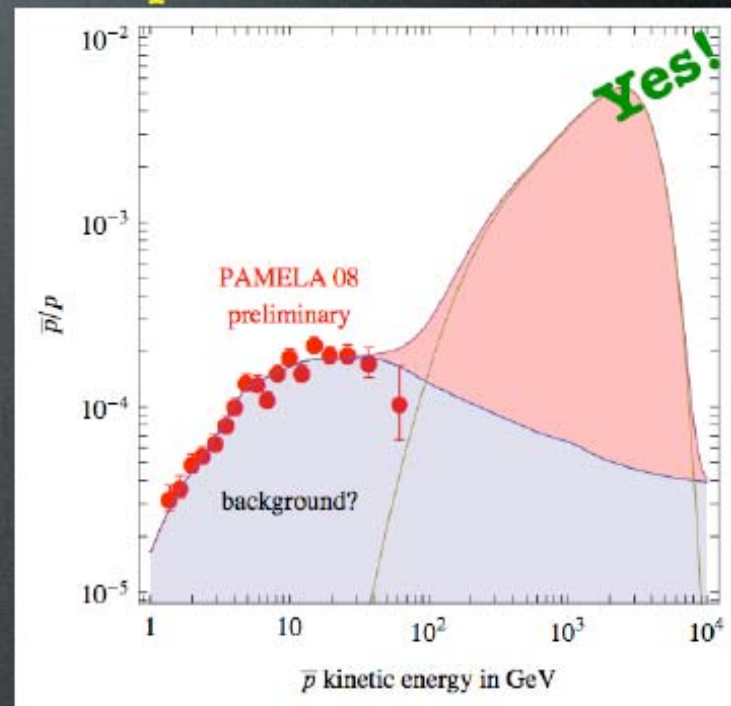
-annihilation $\text{DM DM} \rightarrow W^+ W^-$

-boost $B \simeq 30$ **yes!**

Positrons:



Anti-protons:



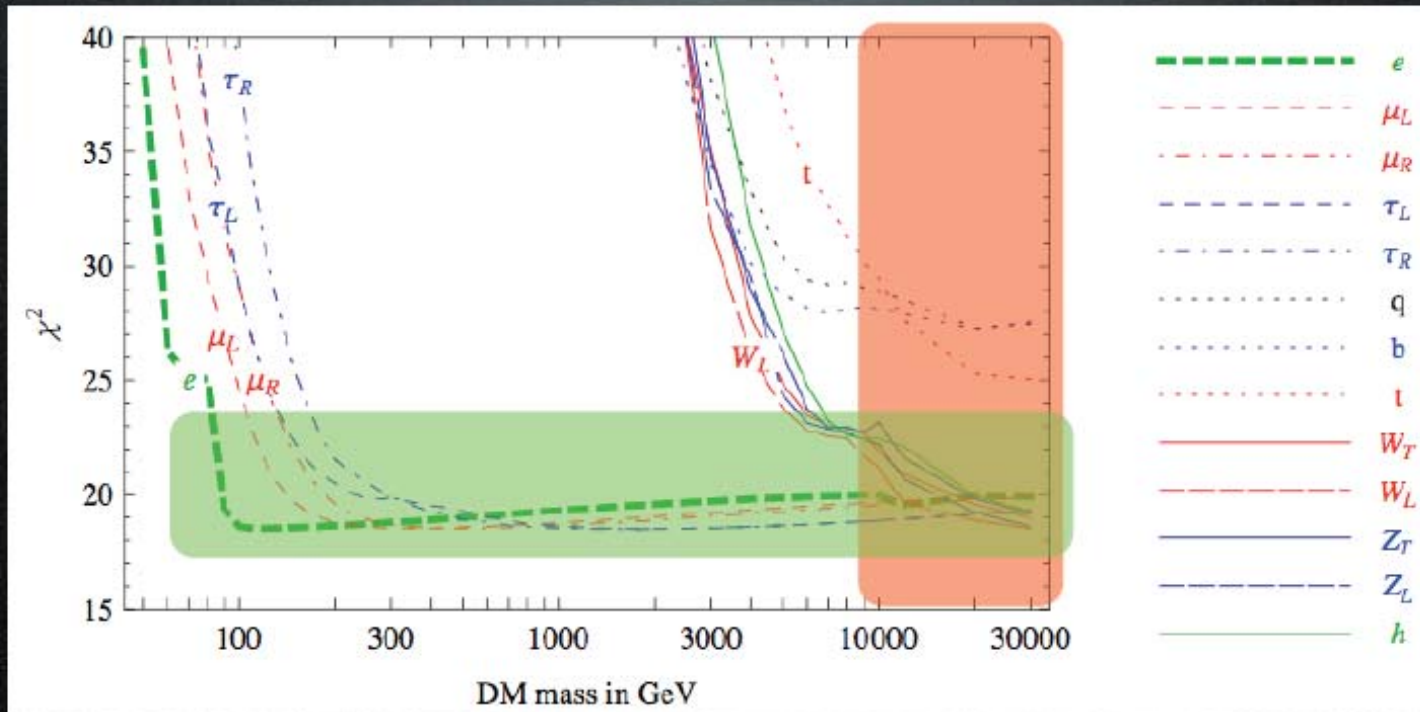
Courtesy of M. Cirelli

Results

Which DM spectra can fit the data?

Model-independent results:

fit to PAMELA positrons + anti-protons



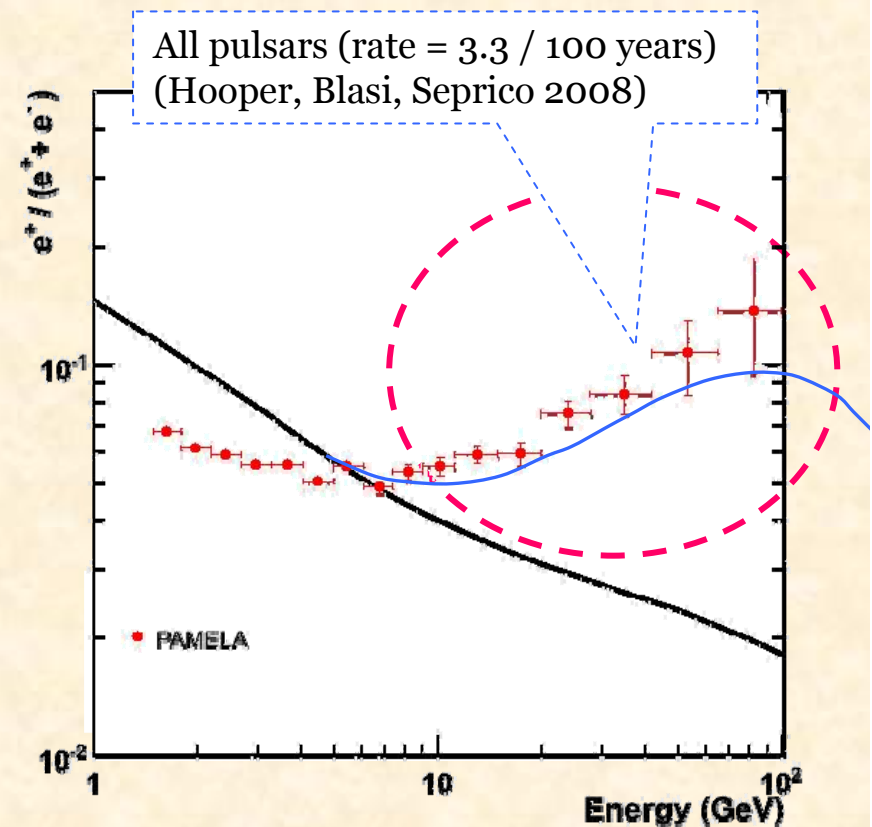
- (1) annihilate into leptons (e.g. $\mu^+\mu^-$) or
- (2) annihilate into W^+W^- with mass $\gtrsim 10$ TeV

Courtesy of M. Cirelli

Primary positron sources

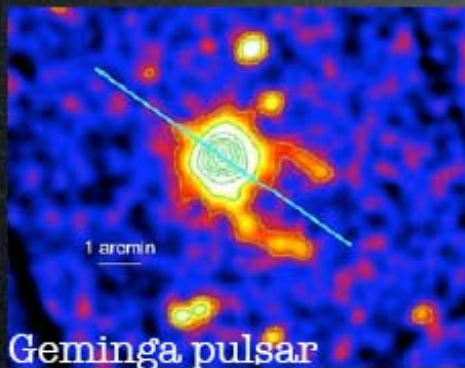
Astrophysical processes

- Local **pulsars** are well-known sites of e^+e^- pair production (the spinning B of the pulsars strips e^- that emit gammas then converting to pairs trapped in the cloud, accelerated and then escaping at the Poles) :
 - they can individually and/or coherently contribute to the e^+e^- galactic flux and explain the PAMELA e^+ excess (both spectral feature and intensity)
 - No fine tuning required
 - if one or few nearby pulsars dominate, anisotropy could be detected in the angular distribution
 - possibility to discriminate between pulsar and DM origin of e^+ excess



Astrophysical explanation?

Or perhaps it's just a **young, nearby** pulsar...

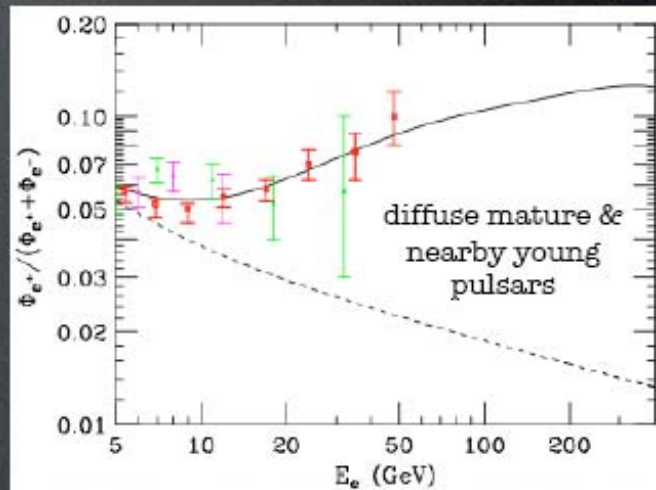
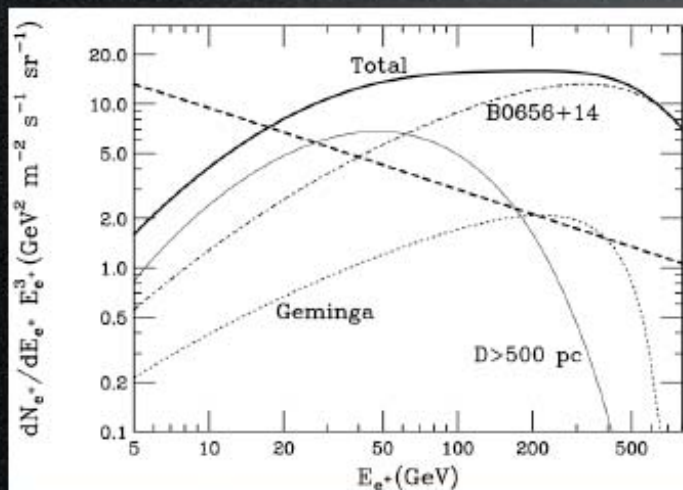


'Mechanism': the spinning \vec{B} of the pulsar strips e^- that emit γ that make production of e^\pm pairs that are trapped in the cloud, further accelerated and later released at $\tau \sim 0 \rightarrow 10^5$ yr.

Must be young ($T < 10^5$ yr) and nearby (< 1 kpc);
if not: too much diffusion, low energy, too low flux.

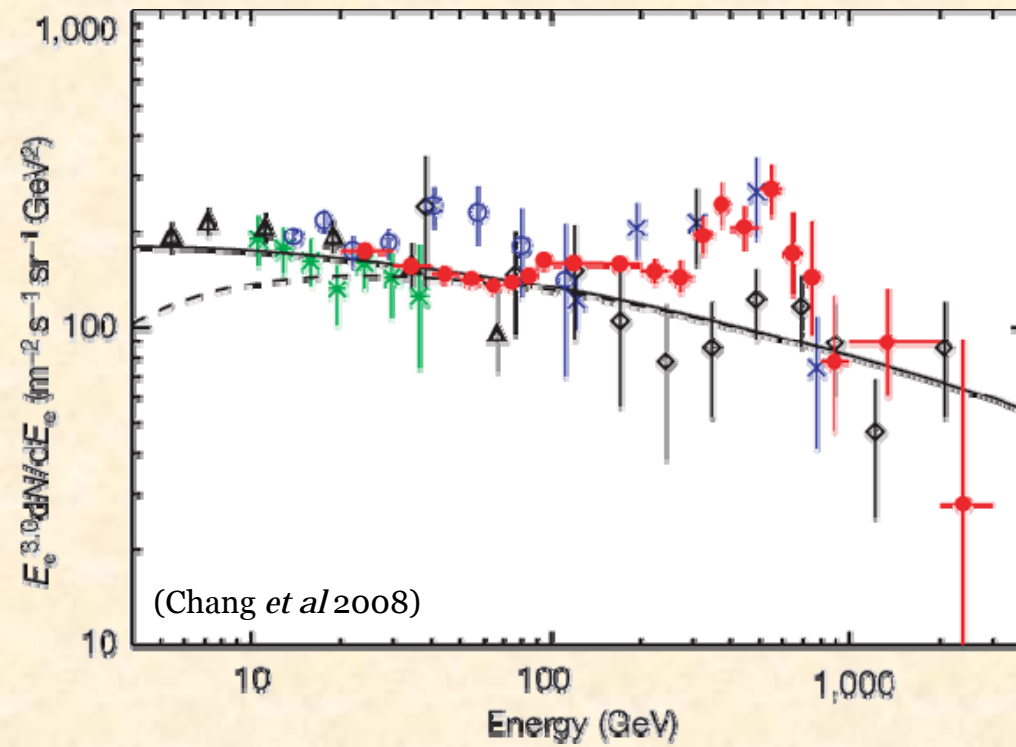
Predicted flux: $\Phi_{e^\pm} \approx E^{-p} \exp(E/E_c)$ with $p \approx 2$ and $E_c \sim \text{many TeV}$

Try the fit with known nearby pulsars and **diffuse mature pulsars**:



Hooper, Blasi, Serpico 2008

Courtesy of M. Cirelli



PAMELA positron excess might be connected with ATIC
electron+positron structures

PAMELA is also studying ...

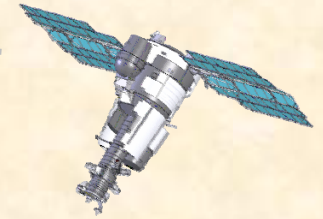
**Galactic cosmic-ray origin &
propagation**

Solar physics

Magnetospheric physics

Work in progress !! No time to talk about it ..

Conclusions (I)



- PAMELA is the first space experiment which is measuring the antiproton and positron cosmic-ray components to the high energies ($>100\text{GeV}$) with an unprecedented statistical precision
 - search for evidence of DM candidates
 - “direct” measurement of particle acceleration in astrophysical sources (pulsars?)
- Furthermore:
 - PAMELA is providing measurements on low-mass elemental (and isotopical) spectra with an unprecedented statistical precision
 - study of particle origin and propagation in the interstellar medium
 - PAMELA is able to measure the high energy tail of solar particles.
 - PAMELA is measuring composition and spectra of trapped and re-entrant albedo particles in the Earth magnetosphere

**Very interesting results on the positron side:
Evidence of new physics ?**

Conclusions (II)

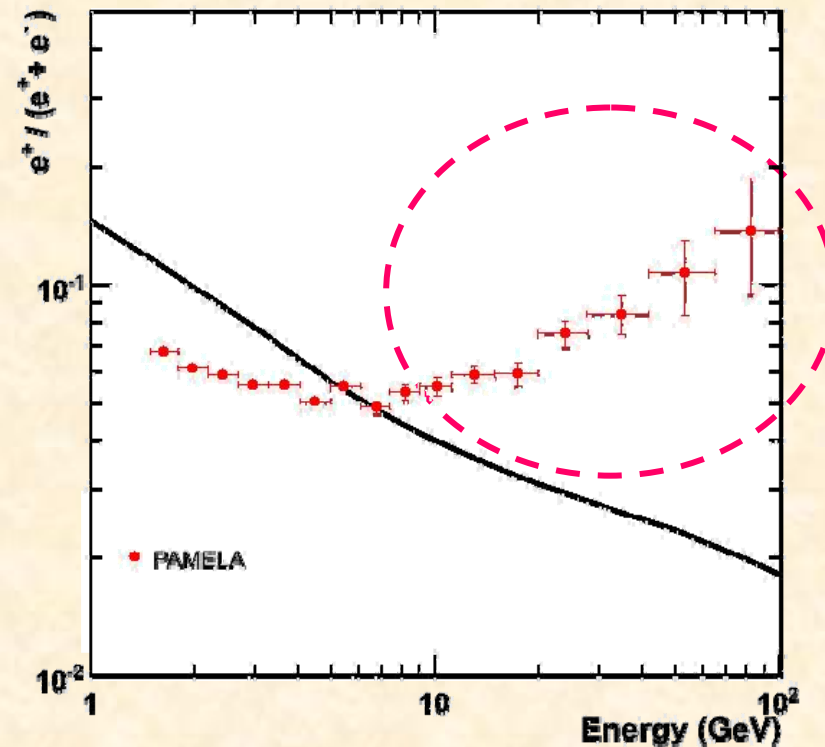
PAMELA positron fraction alone insufficient to understand the origin of positron excess

Additional experimental data will be provided
by PAMELA:

- e^+ fraction @ higher energy (up to 300 GeV)
- individual e^- and e^+ spectra
- anisotropy (...maybe)
- high energy $e^+ + e^-$ spectrum (up to 2 TV)

Complementary information from:

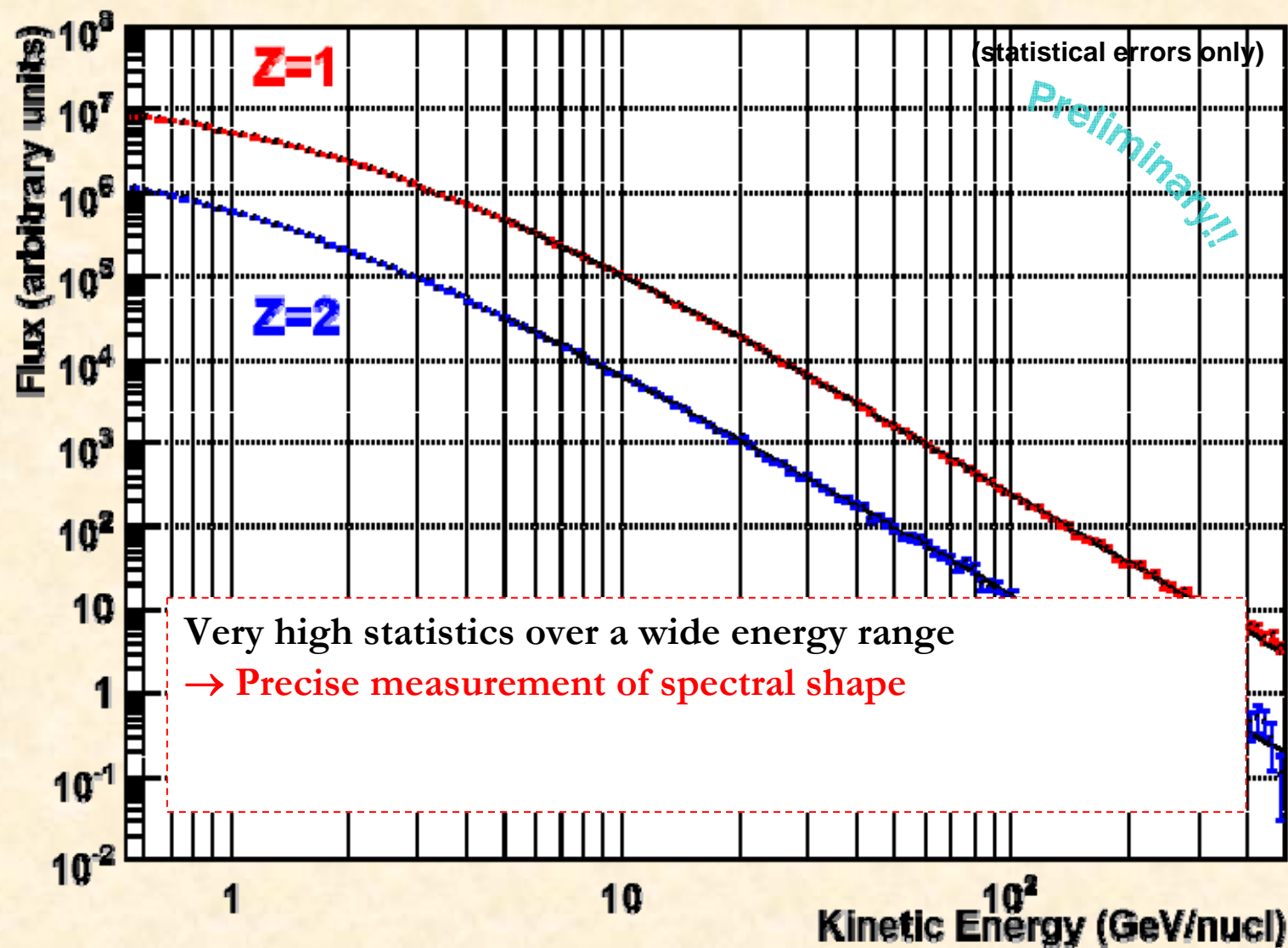
- gamma rays
- neutrinos



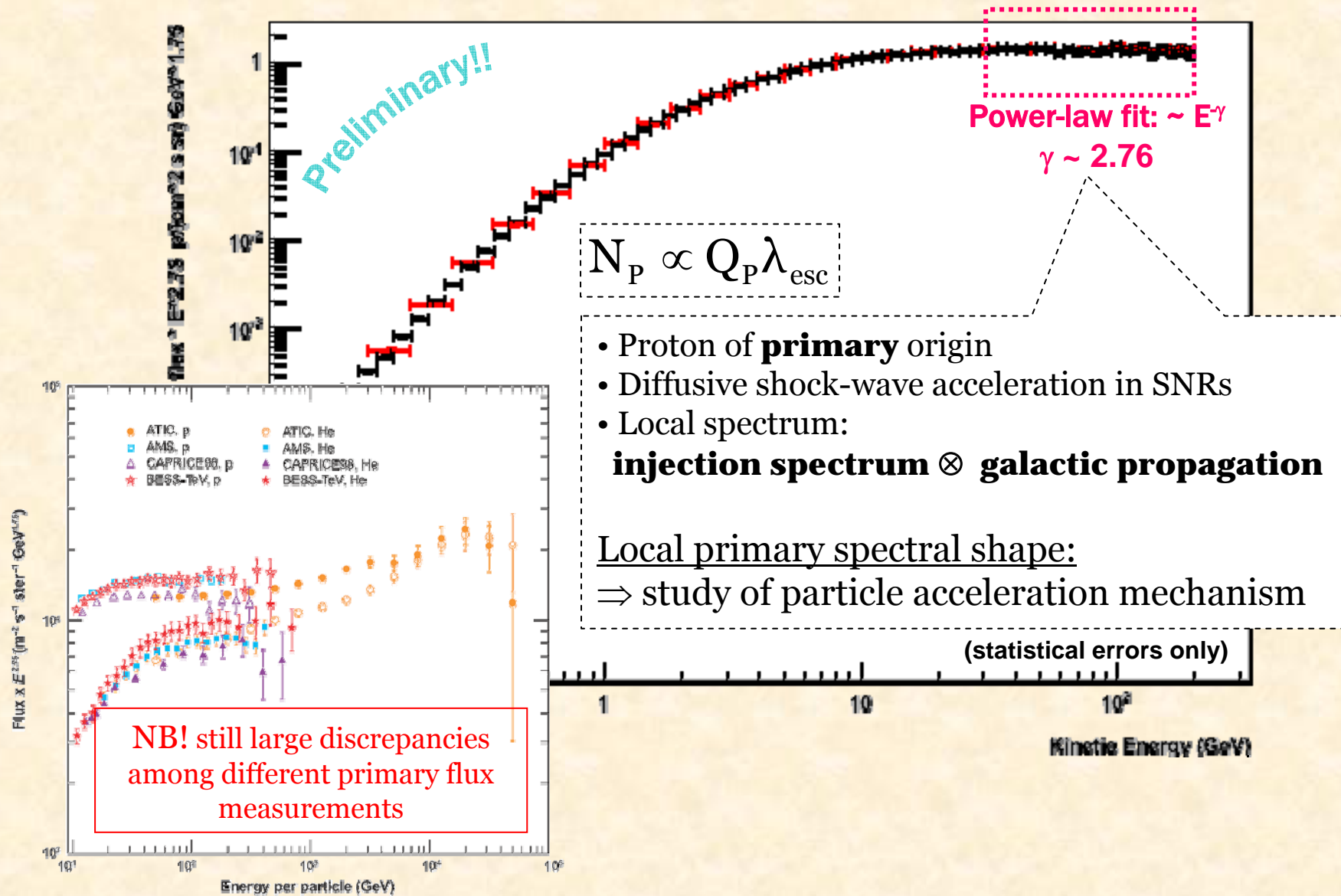
Very exciting time when LHC starts to work !

Back up slides

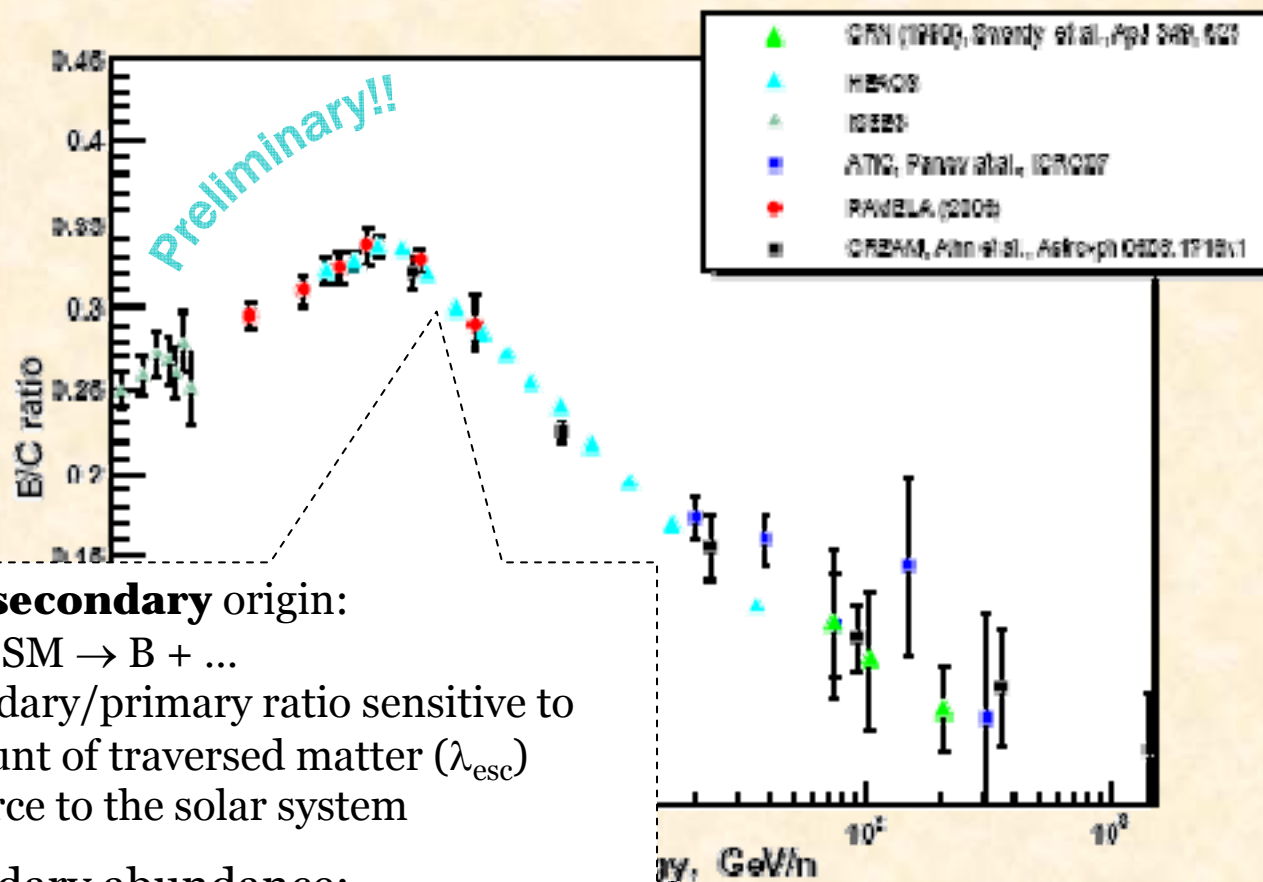
H and He spectra



Proton flux



Secondary nuclei



- B nuclei of **secondary** origin:
CNO + ISM \rightarrow B + ...
- Local secondary/primary ratio sensitive to average amount of traversed matter (λ_{esc}) from the source to the solar system

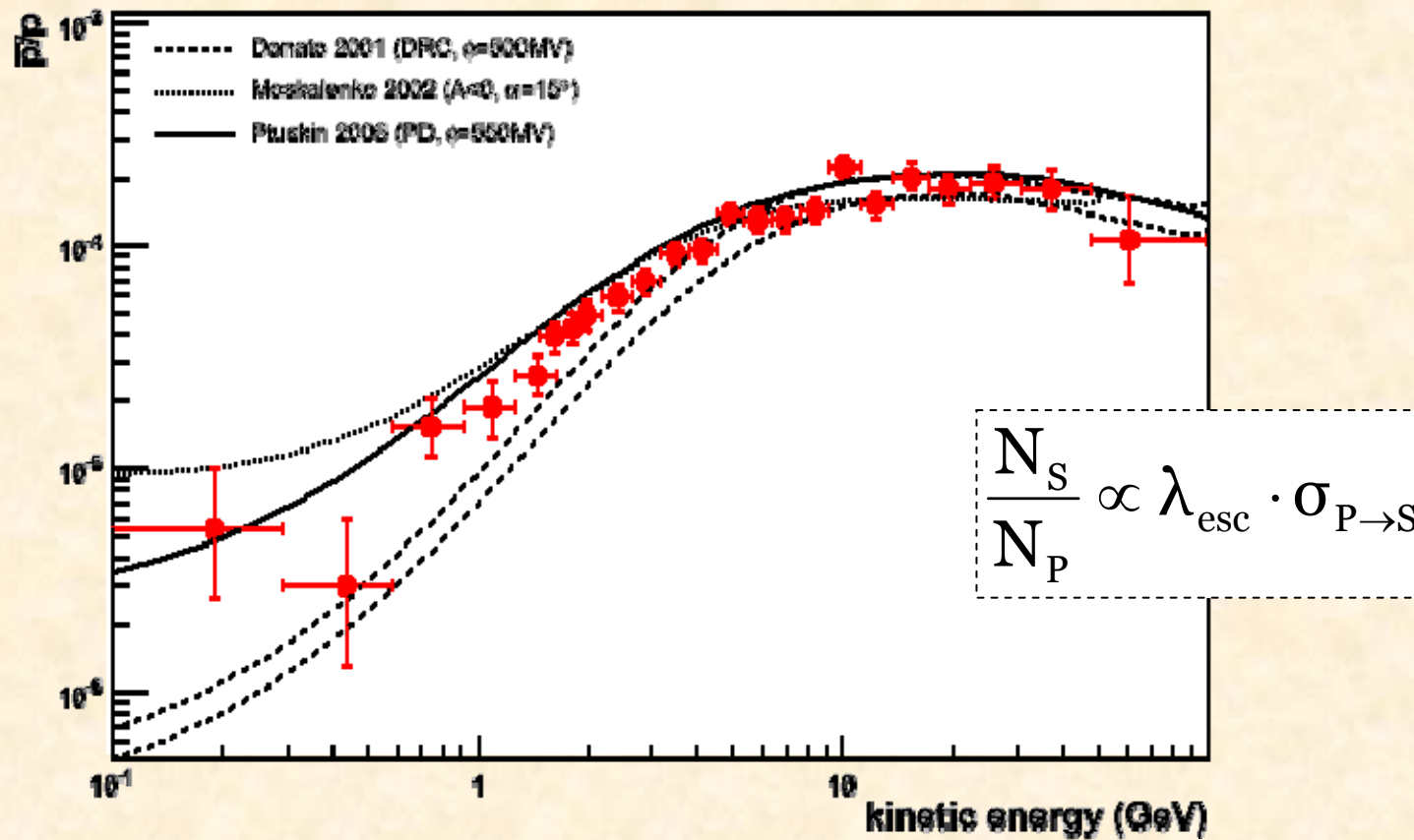
Local secondary abundance:

\Rightarrow study of galactic CR propagation

(B/C used for tuning of propagation models)

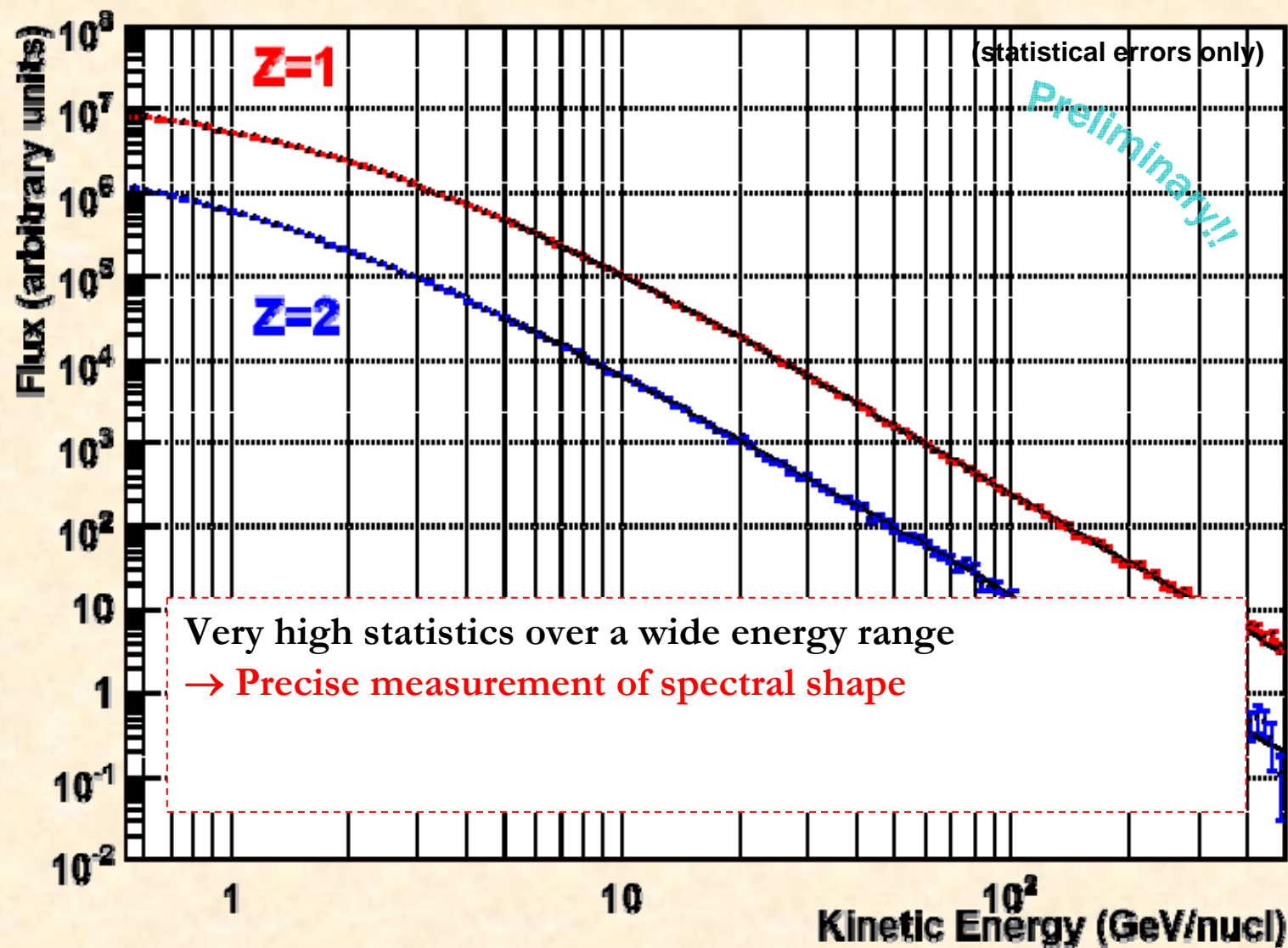
$$\frac{N_S}{N_P} \propto \lambda_{\text{esc}} \cdot \sigma_{P \rightarrow S}$$

Antiprotons

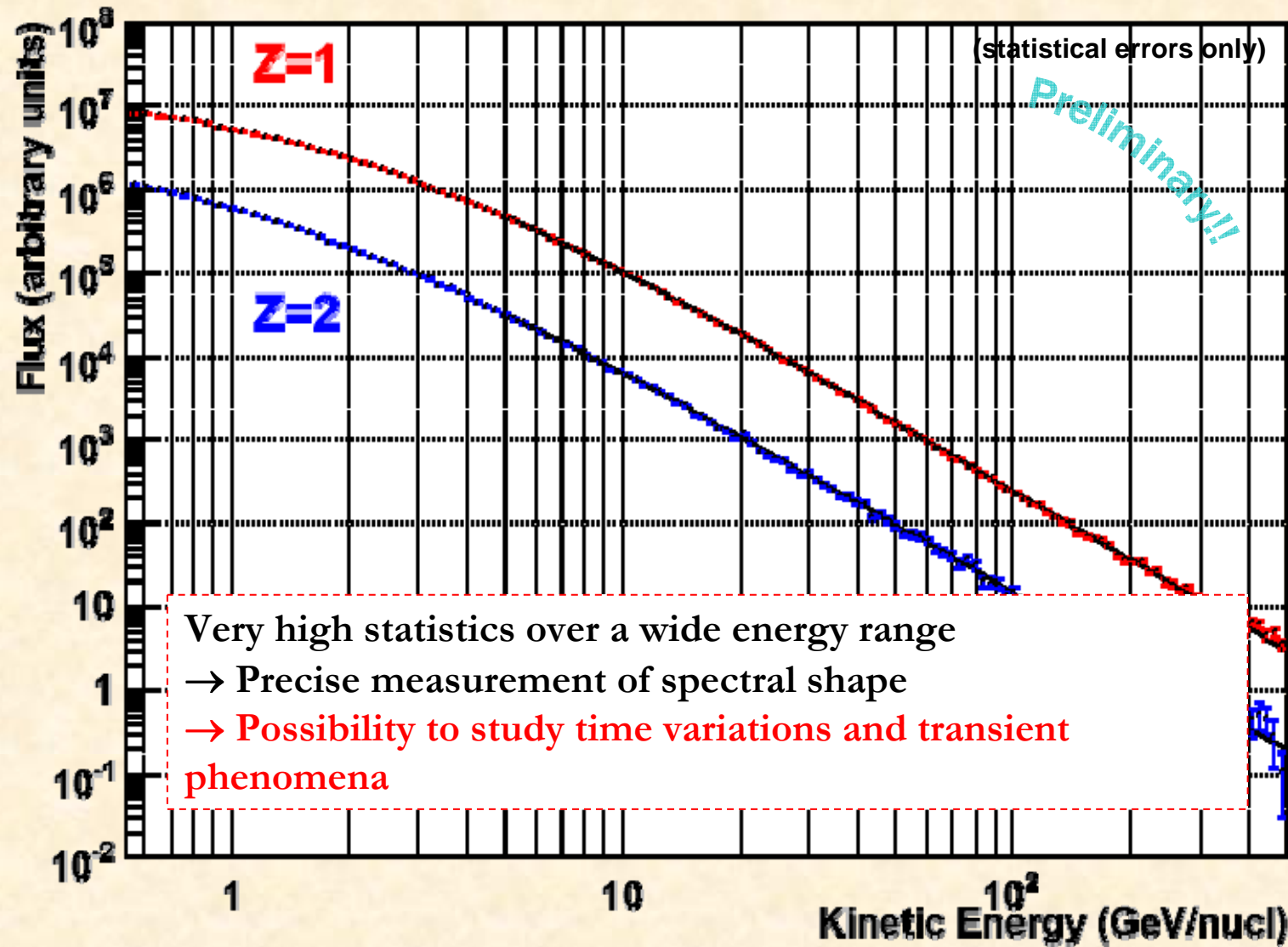


Antiprotons results can be used to constraint propagation models

H and He spectra

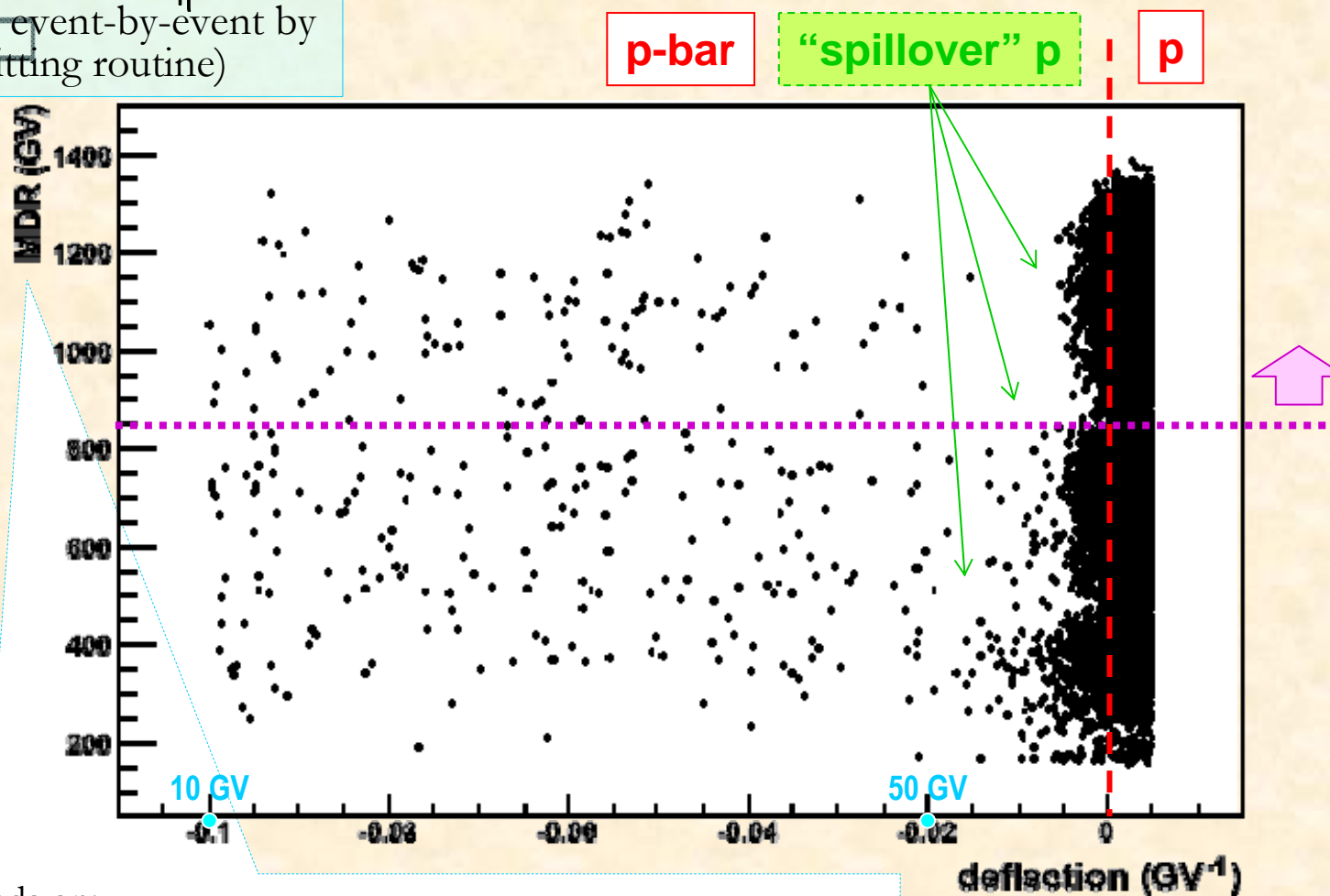


H and He spectra



Proton-spillover background

$\text{MDR} = 1/\sigma_\eta$
(evaluated event-by-event by
the fitting routine)



MDR depends on:

- number and distribution of fitted points along the trajectory
- spatial resolution of the single position measurements
- magnetic field intensity along the trajectory

Proton-spillover background

Minimal track requirements

Strong track requirements:

- strict constraints on χ^2 (~75% efficiency)
- rejected tracks with **low-resolution** clusters along the trajectory
 - faulty strips (high noise)
 - δ -rays (high signal and multiplicity)

