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Proton-proton to antinucleon cross sections for cosmic ray applications

QCD evolution workshop 2026
El Escorial

May 12th, 2026

Can our QCD-related expertise provide insights to other fields?

YES!

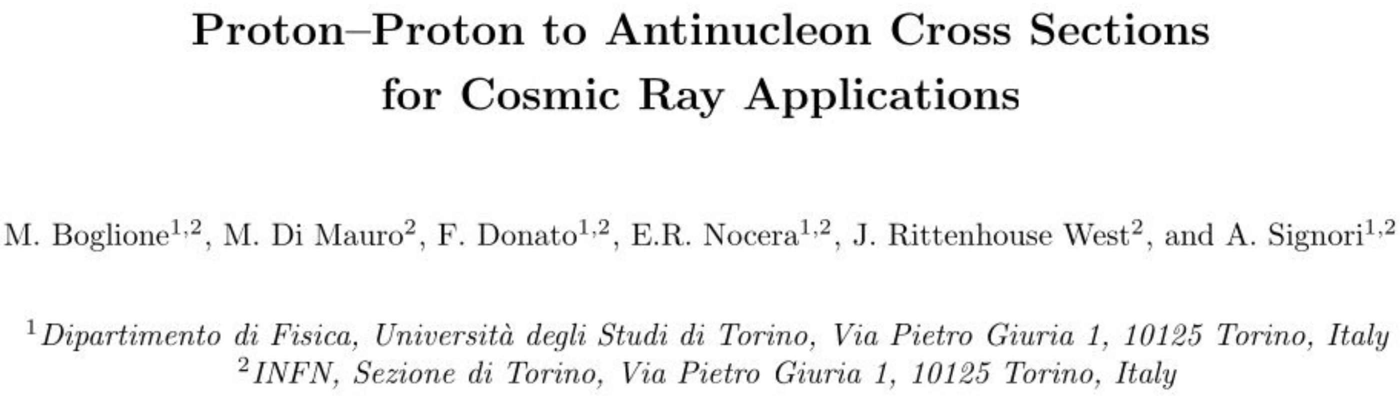
Which ones?

Astrophysics and dark matter searches

(for example)

Outline of the content

1. Dark matter: the case of antiprotons
2. nbar / pbar excess
3. QCD framework
4. The role of low pT



Proton–Proton to Antinucleon Cross Sections for Cosmic Ray Applications

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https://inspirehep.net/literature/3152378

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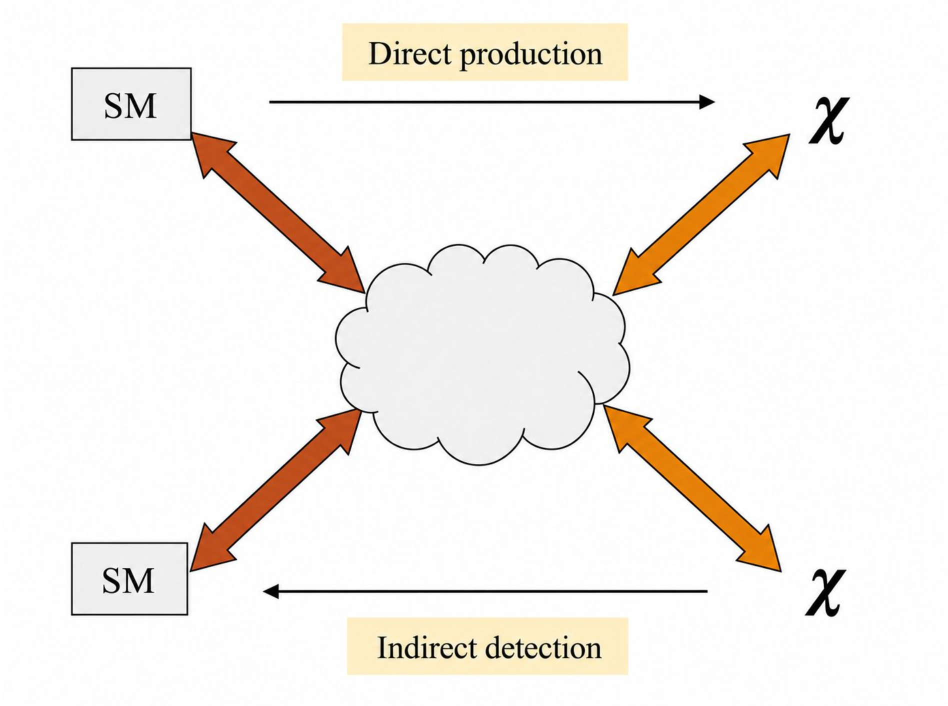
1. Dark matter: the case of antiprotons

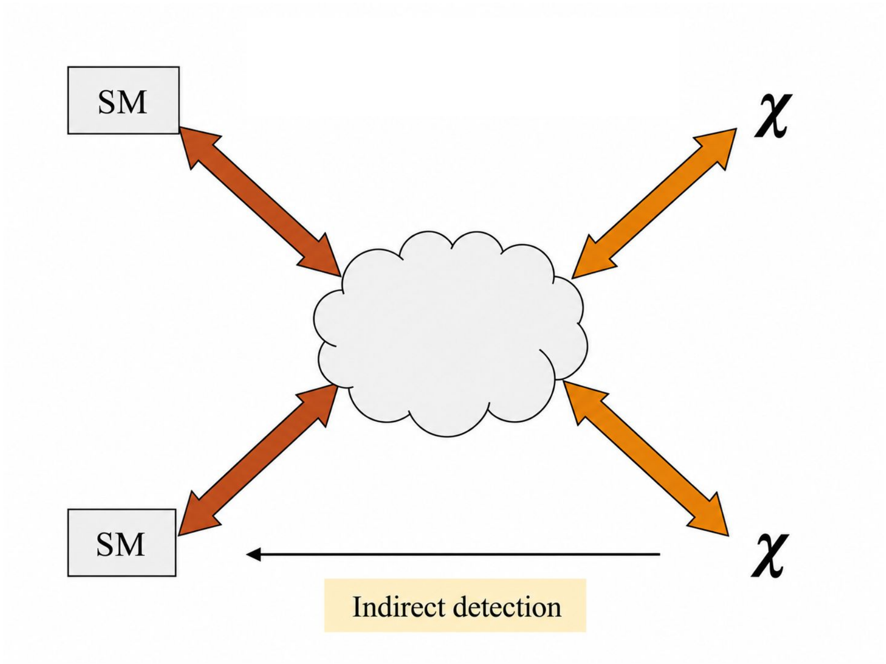
Dark matter investigations

See also D. Giordano's
(AMBER) slides



Indirect searches

See also D. Giordano's
(AMBER) slides



The **cosmic ray fluxes** measured by experiments are a powerful tool to **test dark matter scenarios** (indirect searches)

Golden channels:

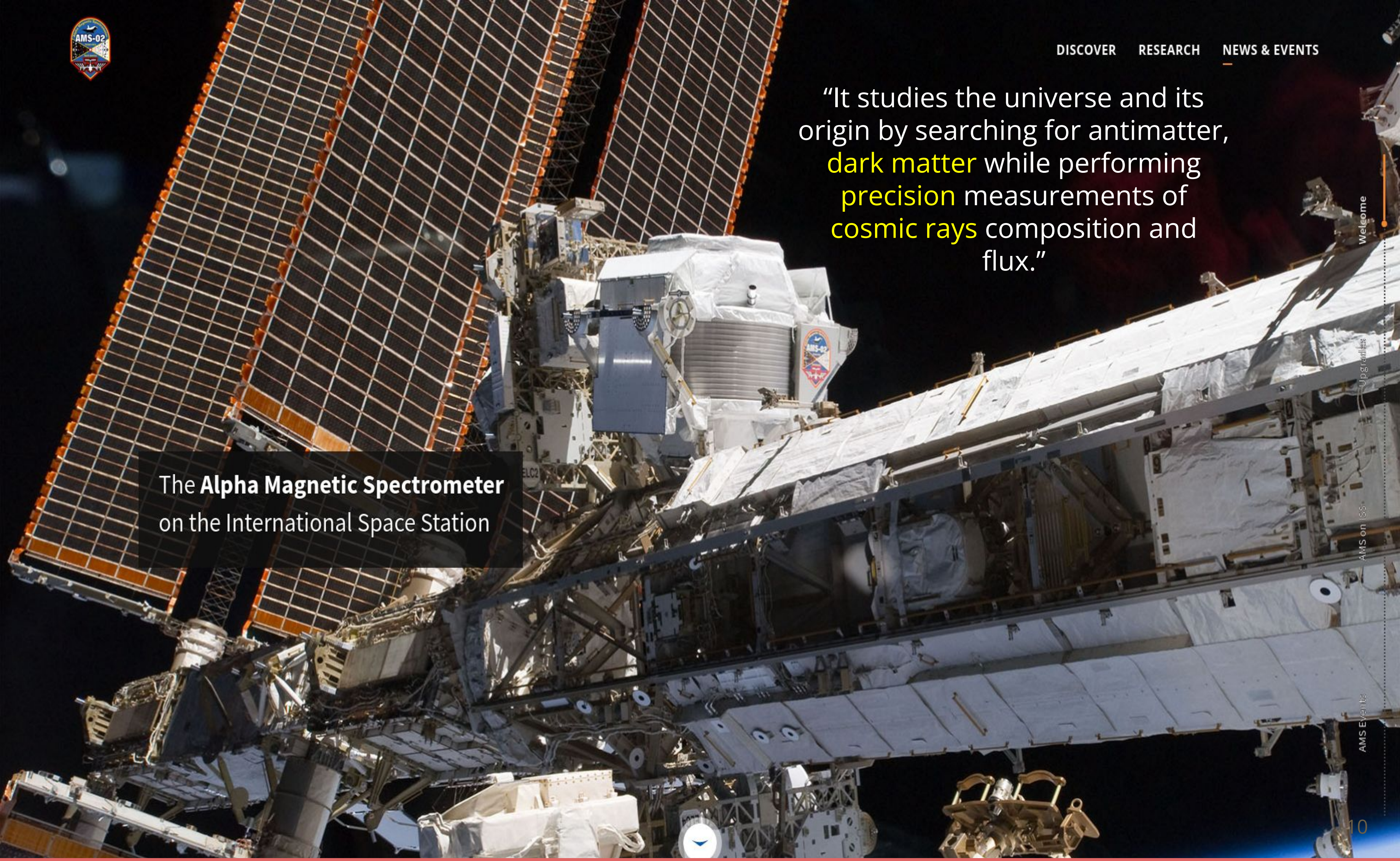
1. **Low energy (anti)-nuclei**
   (low statistics and low background)
2. **Positrons**
   (high statistics, high background)
3. **Antiprotons**
   (high statistics, high background)

How can we study the production and propagation of galactic cosmic rays?

“The Alpha Magnetic Spectrometer (AMS) is a particle physics detector designed to operate as an external module on the International Space Station. “

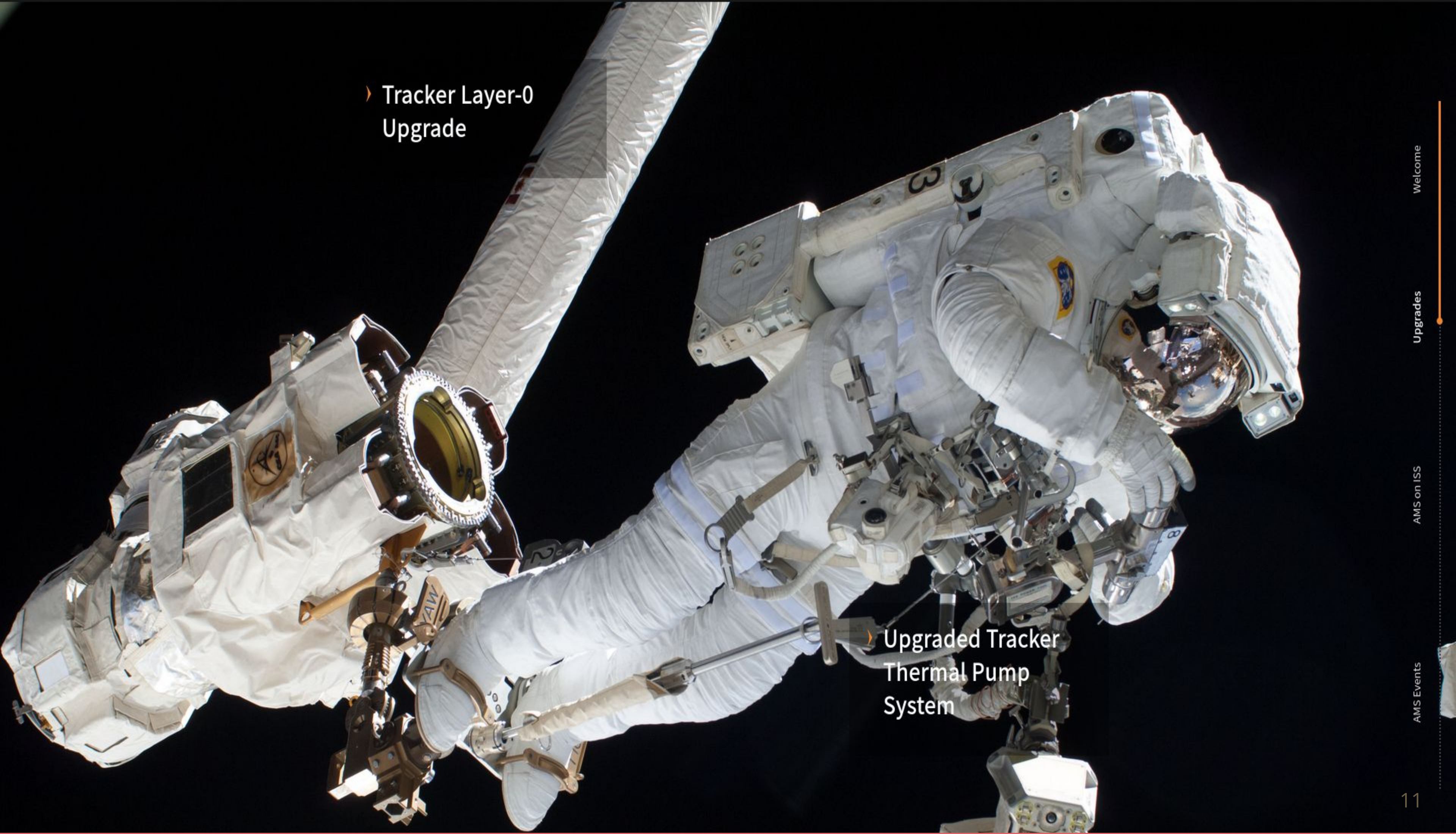
The **Alpha Magnetic Spectrometer** on the International Space Station

Welcome
Upgrades
AMS on ISS
AMS Events



"It studies the universe and its origin by searching for antimatter, dark matter while performing precision measurements of cosmic rays composition and flux."

The **Alpha Magnetic Spectrometer** on the International Space Station



〉 Tracker Layer-0 Upgrade

〉 Upgraded Tracker Thermal Pump System

Welcome
Upgrades
AMS on ISS
AMS Events

The case of antiprotons

AMS
measures the
**total flux of
antiprotons**

$$\Phi^{\mathrm{t}}_{\bar{p}} = \Phi^{1}_{\bar{p}} + \Phi^{2}_{\bar{p}}$$

**“secondary”
antiprotons**:

ordinary (SM)
astrophysics

“primary” antiprotons:

- dark matter annihilation
- dark matter decay
- primordial black holes
- other exotic sources

This became a **major topic** because AMS measured the total flux with **unprecedented (percent level) precision**

The case of antiprotons

AMS measures the **total flux of antiprotons** →

$$\Phi^{\mathrm{t}}_{\bar{p}} \approx \Phi^{2}_{\bar{p}} \gg \Phi^{1}_{\bar{p}}$$

← "primary" antiprotons: **a faint signal**

↑ "secondary" antiprotons dominate (**large background**)

The question is:

do we understand the background with enough accuracy and precision?

Leading contributions to secondary antiprotons

direct

$$p\,p \rightarrow \bar{p}\,X$$

indirect

$$p\,p \rightarrow \bar{n}\,X \rightarrow \bar{p}\,X'$$

$$\bar{n} \rightarrow \bar{p}\,e^+\,\nu_e$$

What is the **relation** between the **direct** and **indirect** production of **antiprotons**?

$$\frac{\sigma(pp \rightarrow \bar{n}X)}{\sigma(pp \rightarrow \bar{p}X)} = ?$$

2. A nbar / pbar excess ?

Secondary antiprotons: nbar / pbar

$$\frac{\sigma(pp \to \bar{n}X)}{\sigma(pp \to \bar{p}X)}$$

$$\approx 1 \pm ?$$

Isospin (u, d)
symmetry

$$\lesssim 1.3 \pm ?$$

NA49
measurement

In the astrophysics literature two methodologies are typically employed :

1. **Models**
   (with **no knowledge** of **hadron structure** and/or **hadronization** via PDFs/FFs)

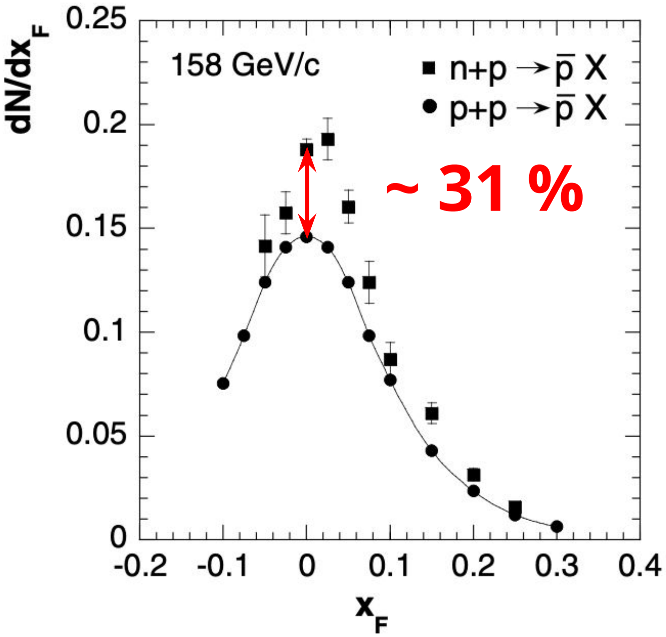
2. **Monte Carlo** event generators

Two major problems: lack of **predictive power** and estimation of **uncertainties**

The NA49 antineutron excess

NA49: a fixed-target experiment
at SPS, CERN

$$\sqrt{s} = 17.2\,\mathrm{GeV}$$



H.G. Fischer for the NA49 Collaboration
APH N.S., Heavy Ion Physics 17/2–4 (2003) 369

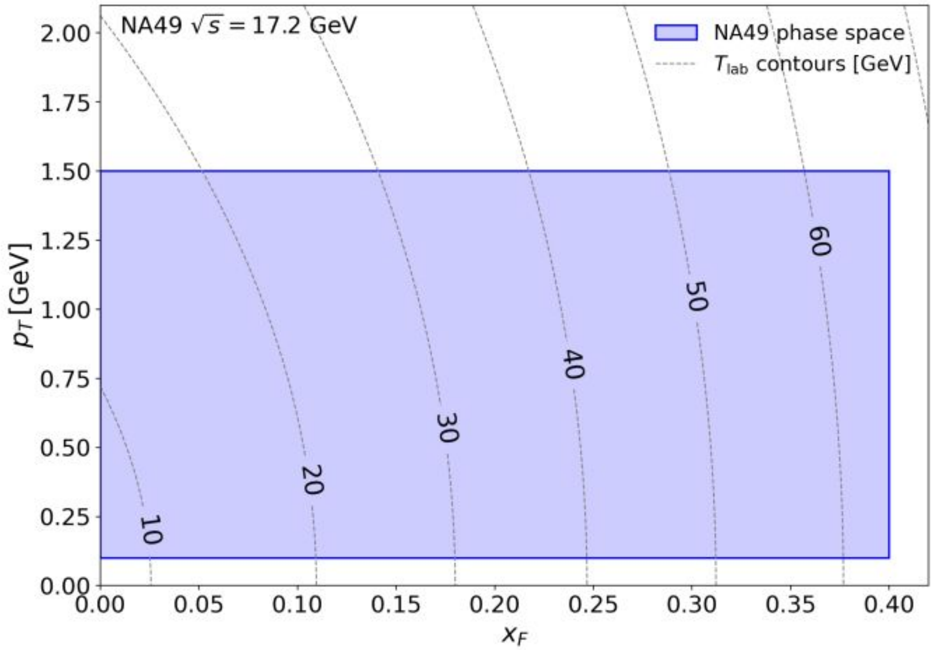
Measurements:

1. Lorentz invariant cross section for **pp to pbar X** in bins of xF and pT (and reconstruct xF distribution)
2. xF distribution (integrated over pT) for **pn to pbar X**

pn to pbar X as a proxy for **pp to nbar X**
(crossing symmetry - ?)

$$x_F = 2p_L/\sqrt{s} = x_2 - x_1$$

Kinematic coverage: NA49 and AMS



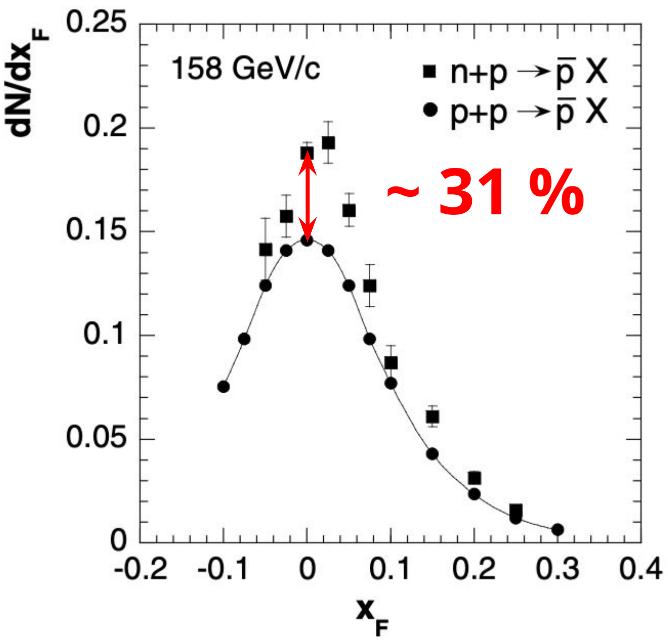
The xF and pT coverage of **NA49** partially **overlaps** with the region of interest for the **AMS** experiment

(ALICE: narrower coverage)

Is there **a more reliable way** to study this alleged excess and the associated **uncertainties**?

3. QCD framework

xF distribution



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Lorentz-invariant cross section:
function of **pT** and xF (or y)

$$\left.\frac{d\sigma}{dx_F}\right|_{x_F=0} = \pi\sqrt{s}\int_0^\infty dp_T\,\frac{p_T}{m_T}\left(E\frac{d^3\sigma}{dp^3}\right)\Bigg|_{x_F=0}$$

Integration over the **full pT range**

Lorentz-invariant cross section: pT dependence

$$\left(E\frac{d^3\sigma}{dp^3}\right)$$

Large pT:
pQCD, collinear factorization

Small pT:
resummation and non-perturbative effects (?)

Need unified treatment

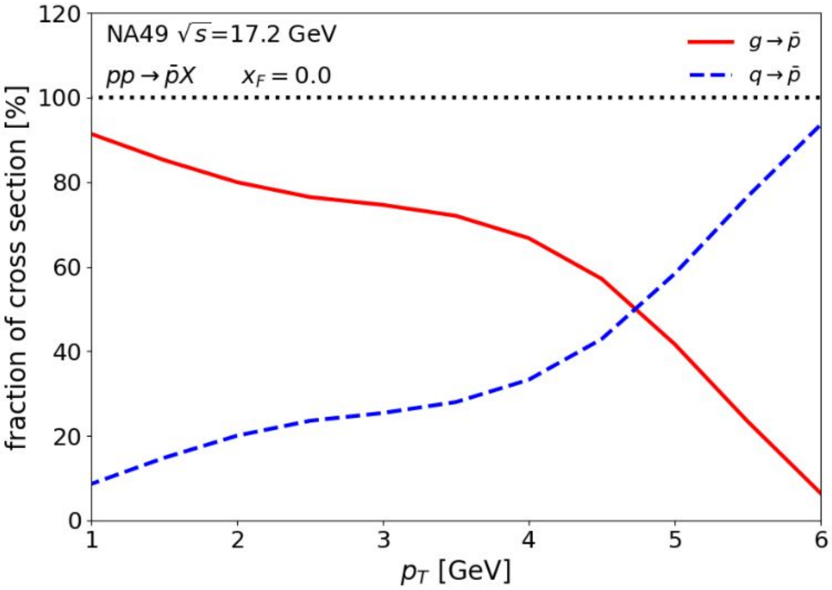
$$E\frac{d^3\sigma}{dp^3} = \sum_{a,b,c} \hat{\sigma}^c_{ab}(\mu_R^2, \mu_F^2, \mu_f^2) \otimes f_a(x_1, \mu_F^2) \otimes f_b(x_2, \mu_F^2) \otimes D_c^h(z, \mu_f^2) \quad + \mathcal{O}(M/p_T)$$

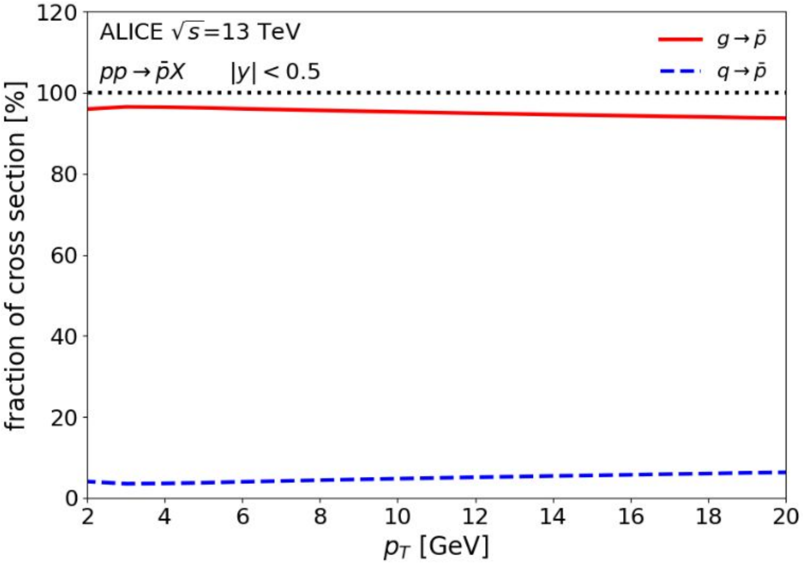
Hard interactions

collinear PDFs

collinear FFs

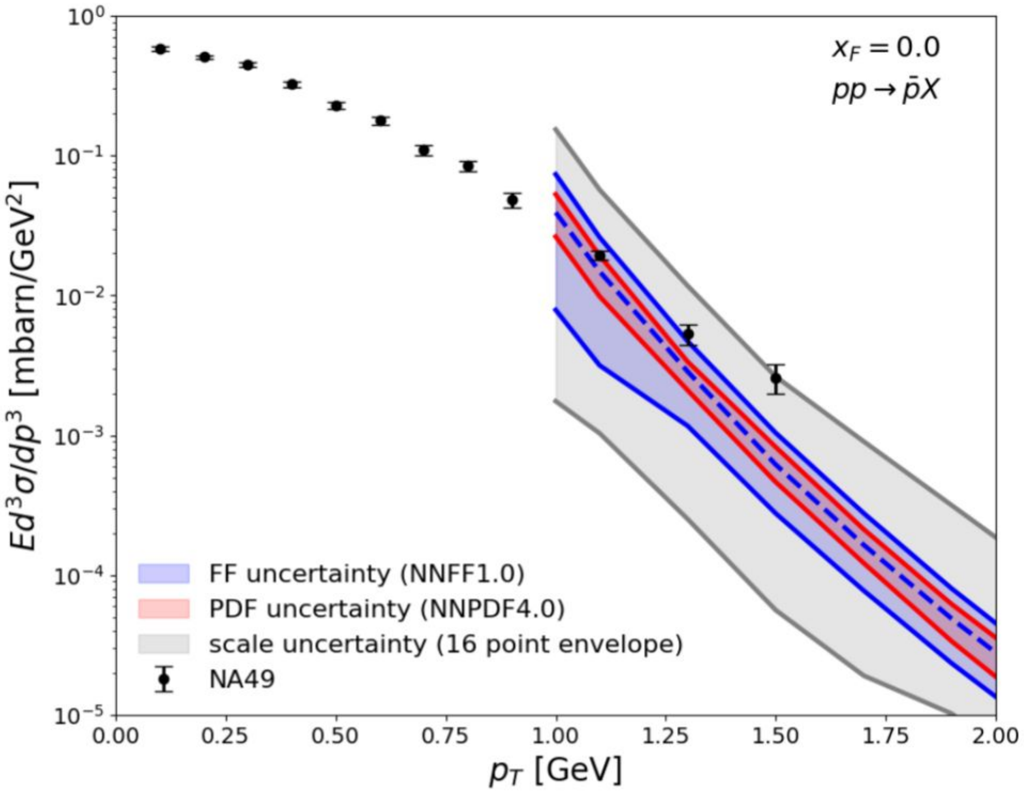
What do we expect?





Gluon fragmentation dominates: even with large isospin (u,d) breaking effects, one should expect the Lorentz-invariant cross section for **pbar** and **nbar** to be **(very) similar**

Lorentz-invariant cross section: data vs theory



Large pT: NLO calculation
(De Florian https://inspirehep.net/literature/601000)

NNLO recently available:
https://inspirehep.net/literature/2900464

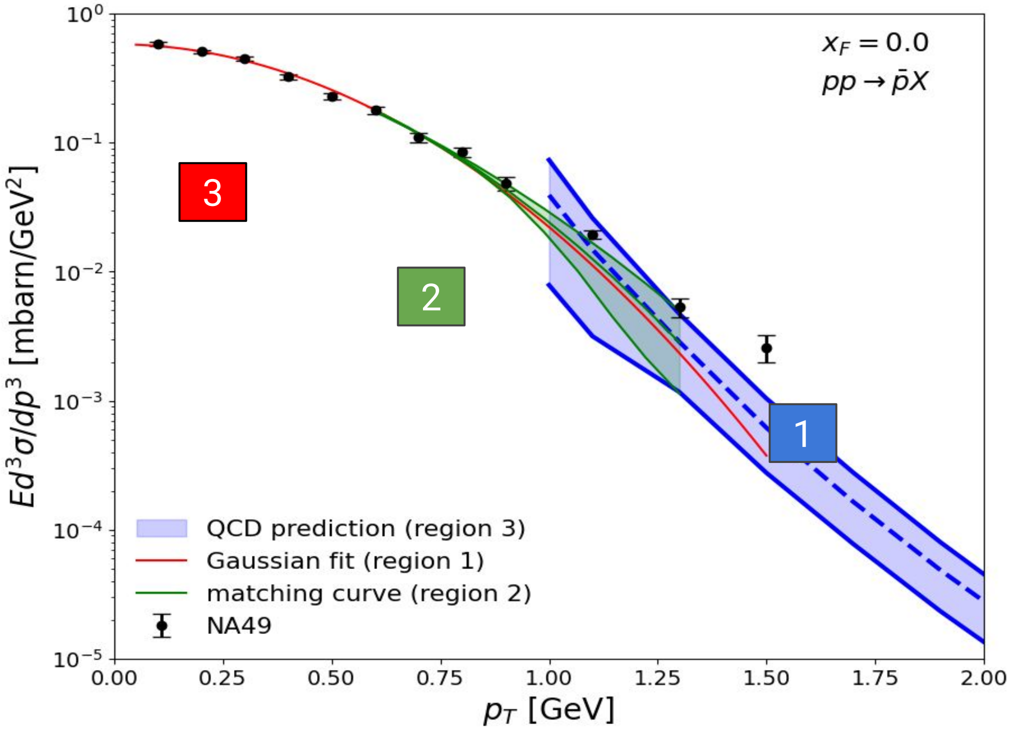
pT > 1 GeV

FFs: NNFF1.0
Other potential choices: KKP, AKK, HKNS, DSS, NPC23

PDFs: NNPDF4.0

Hierarchy of uncertainties:
Scales > FFs > PDFs

Connecting small and large pT

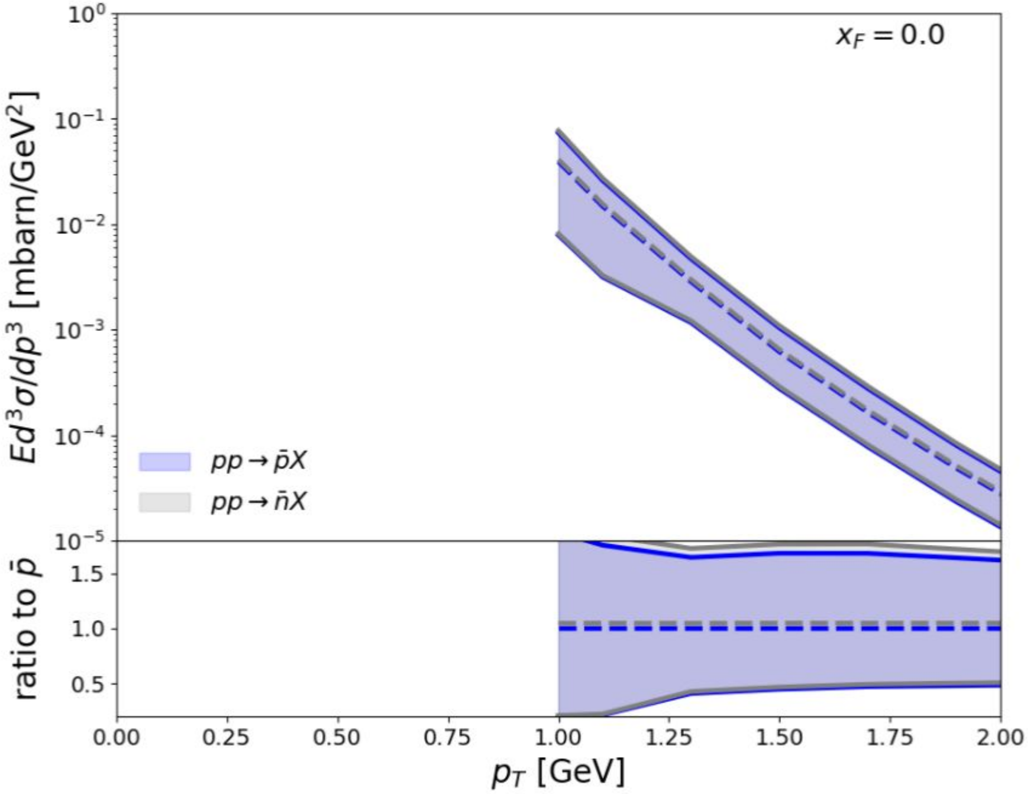


1. Large pT: pQCD prediction at NLO
2. smooth matching curve
3. data-driven Gaussian parametrization at low pT based on NA49 data (**no physics**)

Integrate over pT to obtain the xF distribution at xF=0

Repeat for nbar production

Lorentz-invariant cross section: nbar production



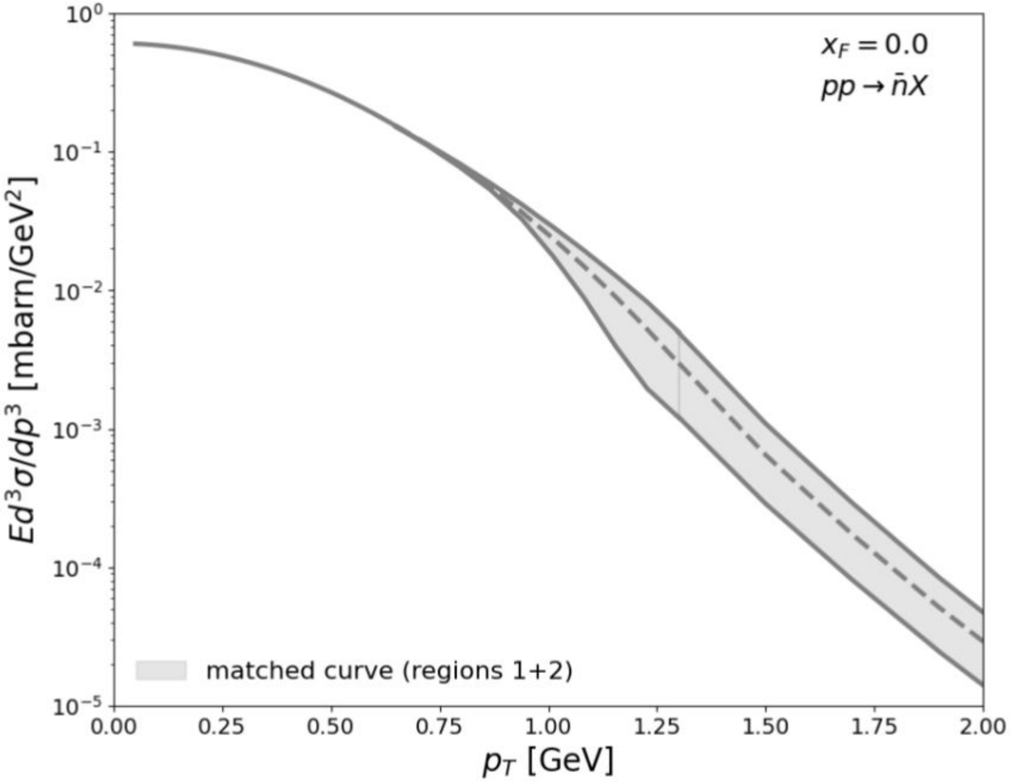
No data exists
(NA49 measured pn to pbar X)

Implement **isospin symmetry** to obtain the **nbar FFs** from the pbar FFs (u to pbar = d to nbar)

Collinear factorization
for pT > 1 GeV

Only FFs uncertainty are displayed since scales and PDFs are the same

Connecting small and large pT



- Large pT: pQCD prediction at NLO based on **isospin symmetry**
- **Borrow the low pT model** from the pbar case, with a 3% shift (justified from the large pT region)

Integrate over pT to obtain the xF distribution at xF=0

Do we see an excess of nbar vs pbar?

Integrated cross sections at x_F = 0

$$(d\sigma/dx_F)_{pp\to\bar{p}X} \qquad 0.462^{+1.199}_{-0.331}\ \mu\text{barn}$$

$$(d\sigma/dx_F)_{pp\to\bar{n}X} \qquad 0.486^{+1.256}_{-0.431}\ \mu\text{barn}$$

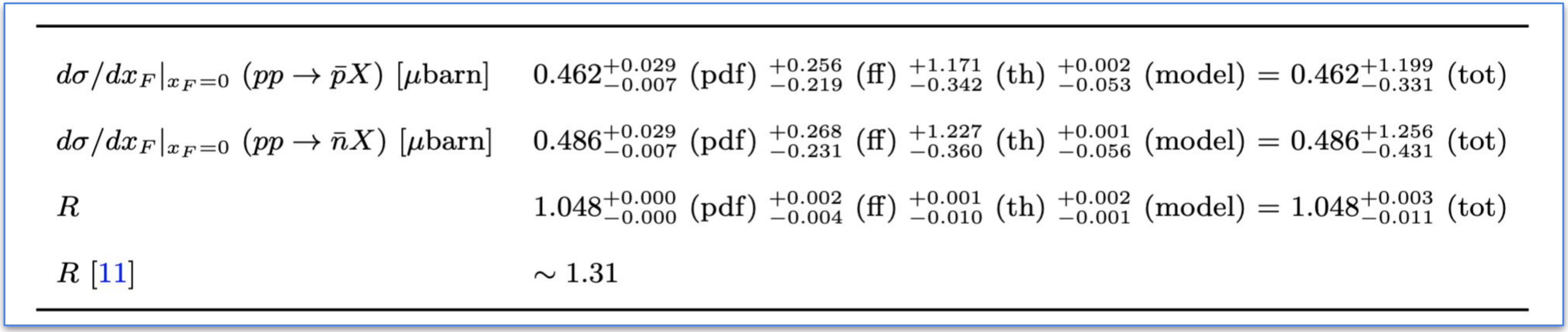
$$R = (d\sigma/dx_F|_{\bar{n}})/(d\sigma/dx_F|_{\bar{p}})\Big|_{x_F=0}$$

$$R_{QCD} = 1.048^{+0.003}_{-0.011}$$

$$R_{NA49} \sim 1.31$$

Approximately **4-5% excess**
at NA49 energy
assuming isospin symmetry and
modeling the low pT part

Uncertainty budget

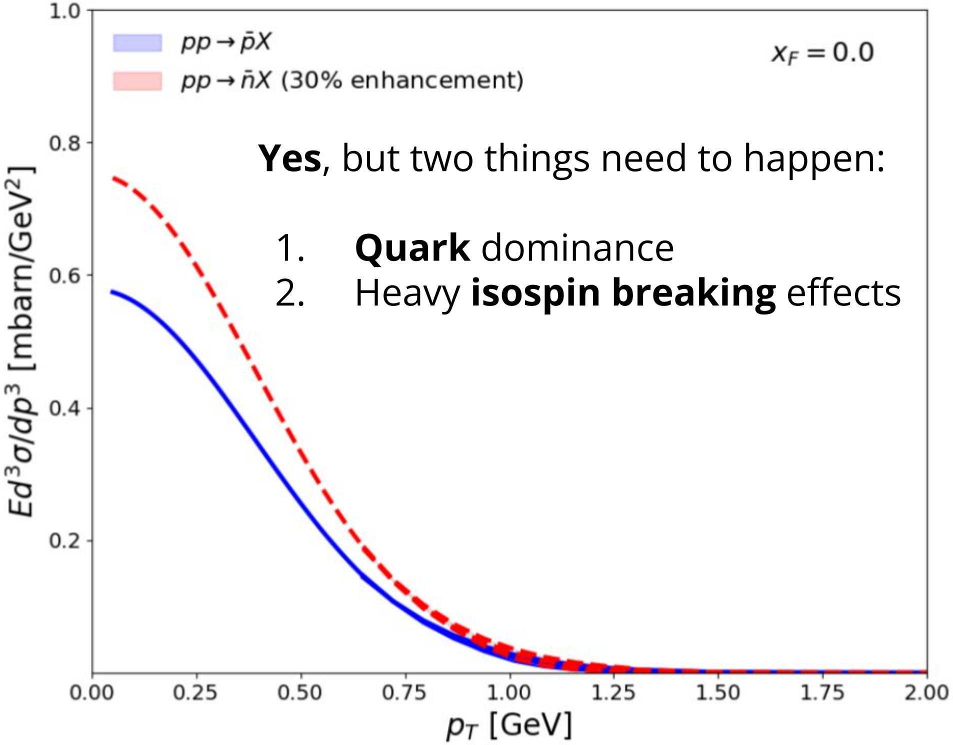


$d\sigma/dx_F\|_{x_F=0}\ (pp \to \bar{p}X)\ [\mu\text{barn}]$	$0.462^{+0.029}_{-0.007}\ (\text{pdf})\ ^{+0.256}_{-0.219}\ (\text{ff})\ ^{+1.171}_{-0.342}\ (\text{th})\ ^{+0.002}_{-0.053}\ (\text{model}) = 0.462^{+1.199}_{-0.331}\ (\text{tot})$
$d\sigma/dx_F\|_{x_F=0}\ (pp \to \bar{n}X)\ [\mu\text{barn}]$	$0.486^{+0.029}_{-0.007}\ (\text{pdf})\ ^{+0.268}_{-0.231}\ (\text{ff})\ ^{+1.227}_{-0.360}\ (\text{th})\ ^{+0.001}_{-0.056}\ (\text{model}) = 0.486^{+1.256}_{-0.431}\ (\text{tot})$
R	$1.048^{+0.000}_{-0.000}\ (\text{pdf})\ ^{+0.002}_{-0.004}\ (\text{ff})\ ^{+0.001}_{-0.010}\ (\text{th})\ ^{+0.002}_{-0.001}\ (\text{model}) = 1.048^{+0.003}_{-0.011}\ (\text{tot})$
R [11]	~ 1.31

1. Correlations in the ratio are fully taken into account
2. **Theory uncertainties** dominate the cross sections and the ratio
3. Then FFs uncertainties play a dominant role
4. PDFs uncertainties and model equally subdominant
5. **Uncertainties** are finally **well defined**, but **central value of R** strongly depends on **the low pT region**

4. The role of low pT

Is it possible to recover a 30% excess?



Yes, but two things need to happen:

1. **Quark** dominance
2. Heavy **isospin breaking** effects

We need a way to predict the low **pT spectrum** in a **reliable** way (as for the large pT region), but:

- **No TMD factorization** (pT is the only scale)
- **No collinear twist 3 factorization** (same reason)
- Insights from small-x physics?
- Other ideas?

Conclusions and outlook

We used pQCD to compute cross sections for astrophysical purposes:

- We constructed matched cross sections combining:
  - NLO pQCD at high p_T and data-driven modeling at low p_T
  - **Reliable estimate of theoretical uncertainties**

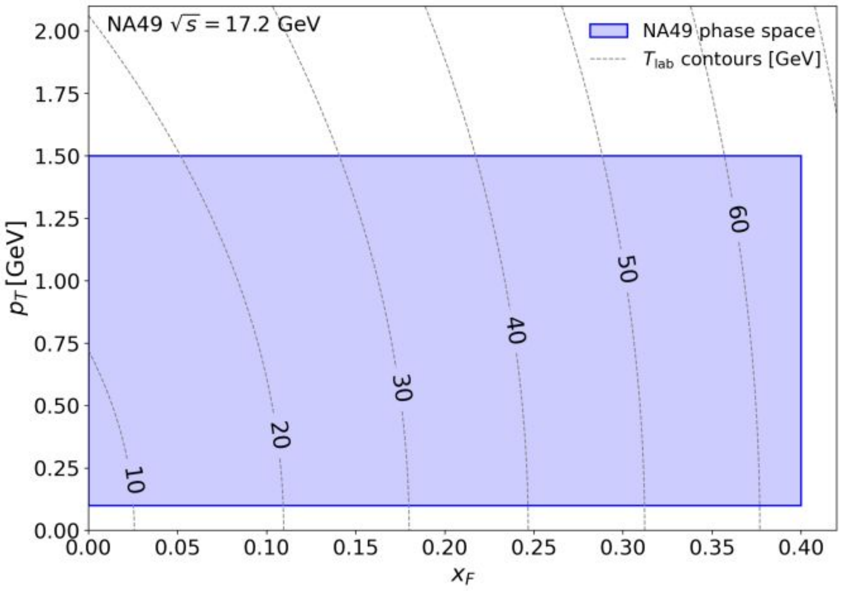
- p_T- integrated results yield:
  - Nbar / pbar ~ 4-5% excess at NA49 energies
  - **no evidence** for a large ~ 30% antineutron excess

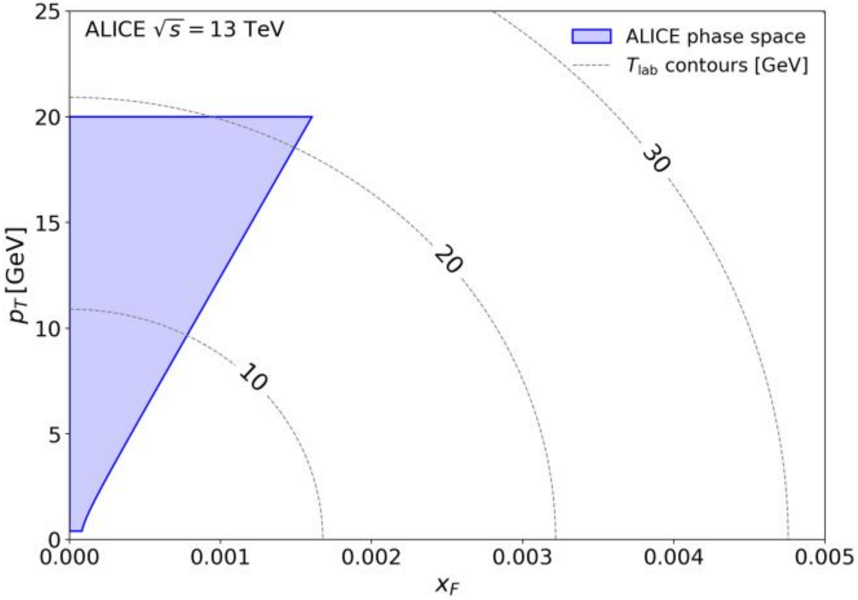
- The **low pT region** plays a significant role, but we don’t have theoretical control on that

- The **AMBER experiment** will provide tests on antiproton production cross sections
  - Dedicated measurements with beam energies 80, 160, 250 GeV
  - Improved precision on isospin effects (10% projected)

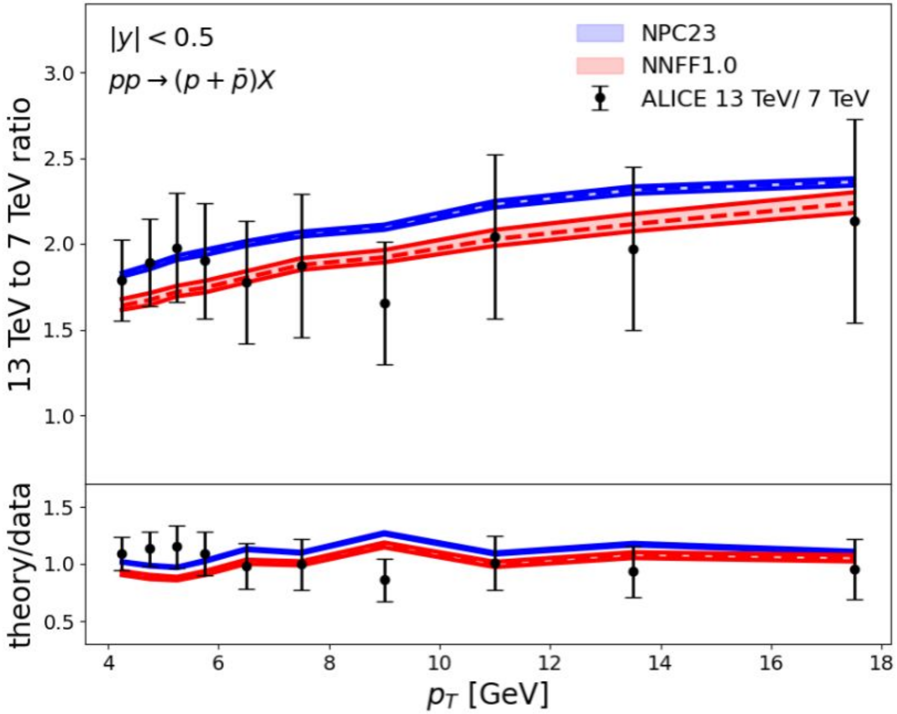
Backup

Kinematic coverage

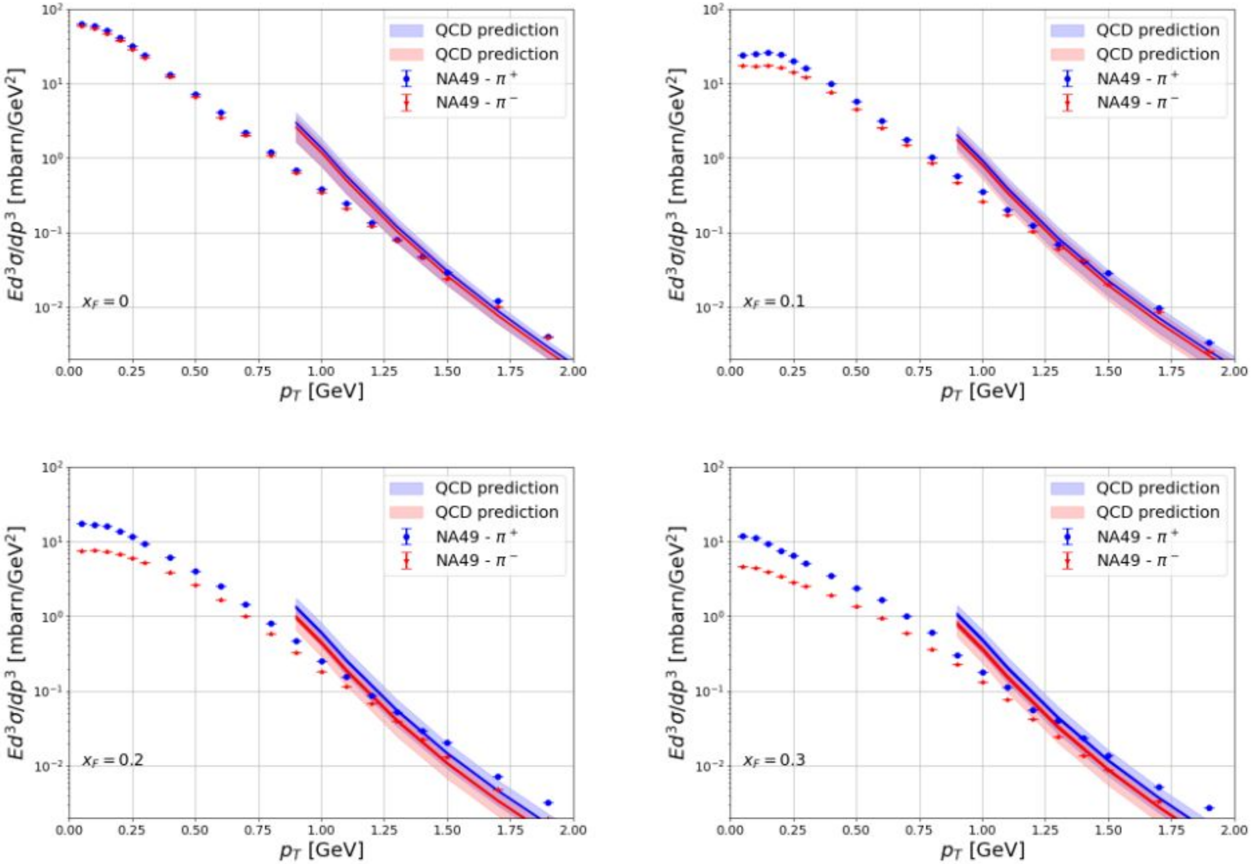




Validation against ALICE data

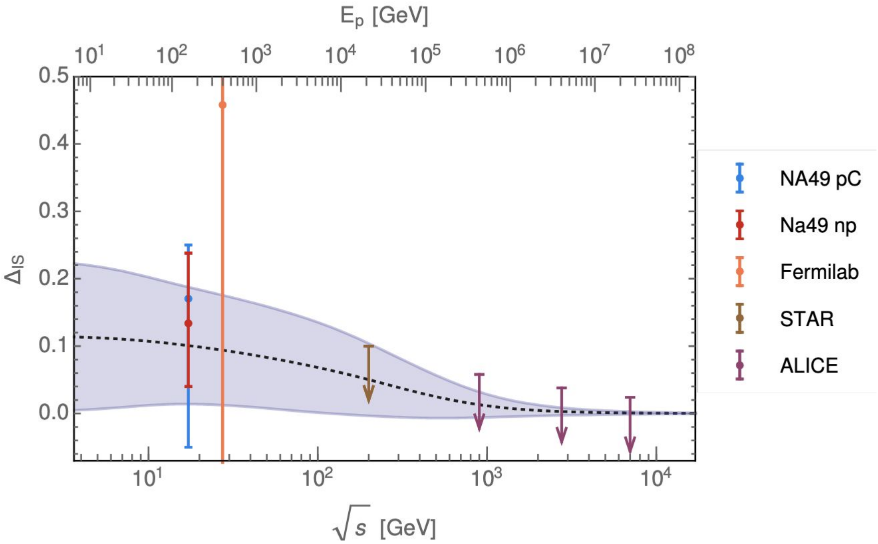


Charged pion production at NA49



Current data on isospin breaking

- Available data on the $\bar{n}/\bar{p}$ asymmetries from ALICE, STAR, Fermilab and NA49
- Most of them at large energies



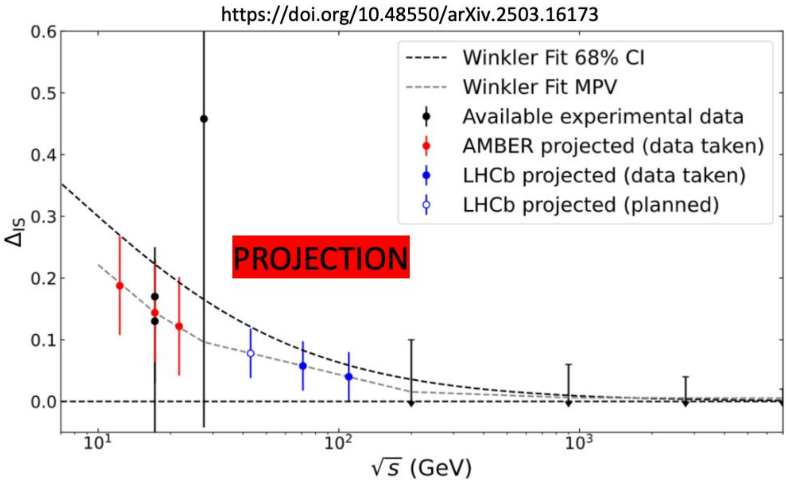
M.W. Winkler, J. Cosmol. Astropart. Phys. 02 (2017) 048

Isospin symmetry breaking

$$\Delta_{IS} = \frac{f^0_{\bar{n}}}{f^0_{\bar{p}}} - 1$$

The AMBER experiment

- 2023: AMBER collects data on p + He collisions at centre of mass energies from 10 to 21 GeV
- 2024: AMBER extends to p + H and p + D collisions to indirectly measure antiproton production asymmetry in p + n collisions



D. Maurin et al., arXiv:2503.16173v2 [astro-ph.HE]

Isospin symmetry breaking

$$\Delta_{IS} = \frac{f^0_{\bar{n}}}{f^0_{\bar{p}}} - 1$$