Cascade $c\bar{c}$ and $b\bar{b}$ Production

H.D, T.Ruf

- Full simulation implementation strategy
- $c\bar{c}$
- $b\bar{b}$
- HNL acceptances
- Background
- What about J/ψ?
- Conclusions

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

SHiP
Search for Hidden Particles

SHiP-NOTE-2015-009
December 2015

Heavy Flavour Cascade Production in a Beam Dump

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CERN

Abstract

SHiP will use a 400 GeV/c proton beam impinging on a several interaction length long Molybdenum target. Heavy flavour hadrons produced in the dump can decay semi-leptonically, which can produce both the Heavy Neutral Leptons as signal, but also potential background from muons and neutrinos. The absolute rate of heavy flavour production is taken from measurements. Pythia is used to predict the phase space distribution of the charm and beauty hadrons which are produced both in the primary interaction of the 400 GeV/c proton and in interactions of the secondaries produced in the cascade. The full cascade production of both HNL and background is compared to that reported in the SHiP Technical Proposal, where only the primary pN interactions were taken into account.

Heavy Flavour production on Mo target

- $\chi_{c\bar{c}(b\bar{b})} = \frac{\sigma(\mathrm{pp}\to\mathrm{c\bar{c}(b\bar{b})X})}{\sigma_{\mathrm{Total}}\to\mathrm{Y}}$
- In TP used the following numbers:
  - pN(p): $\chi_{c\bar{c}}$=18 μb/40 mb = 0.45$\times 10^{-3}$
  - pN(p): $\chi_{b\bar{b}}$= 0.43$\times 10^{-7}$
  - pN(Mo):$\chi_{c\bar{c}}$=18 μb/10.7 mb = 1.7$\times 10^{-3}$
  - pN(Mo):$\chi_{b\bar{b}}$=1.6$\times 10^{-7}$
  - Used σ_{Total}: $\frac{\sigma_{\mathrm{elastic}}}{\sigma_{\mathrm{Total}}} = 0.17$, hence "very conservative"
- Cascade production:
  - A secondary particle will interact, and can produce another $c\bar{c}(b\bar{b})$-pair.
    Hence: need to get p,n,π,K+N$\to$ $c\bar{c}(b\bar{b})$ cross-sections as a function of "beam" momentum.
  - Note: πN: $\sigma_{Total} \approx$ 25 mb, 1.6$\times$ smaller than for pN interactions.
    Hence: need to get σ_{Total} also as function of "beam" momentum.

Implementation in Simulation

Used Pythia 6 as implemented in FairShip (need FORTRAN version, since Pythia 8 init takes to long, and we need an init for every secondary particle)

Following steps in FairShip/macro/makeCascade.py:

1 use Pythia to get the cross-sections vs momentum for p,n,π,K

2 calculate $\chi_{\rm norm}$ values for all "beams" and all momenta: $\chi_{\rm norm} = \frac{\chi}{\chi^{\rm max}_{\rm 400GeV}}$

3 Put 400 GeV proton on the "beam-stack".

4 While particles on "beam-stack":

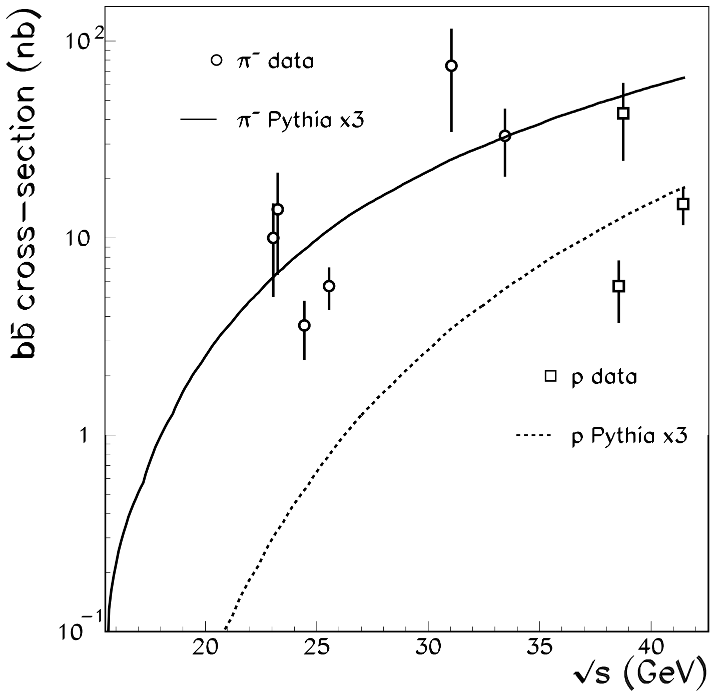
- if random(0-1)$< \chi_{\rm norm}$: produce a signal $c\bar{c}(b\bar{b})$ $\rightarrow$ntuple
- Produce total cross-section event, and add new stable particles with p$>$threshold on the "beam-stack"
- Remove used particle from "beam-stack"

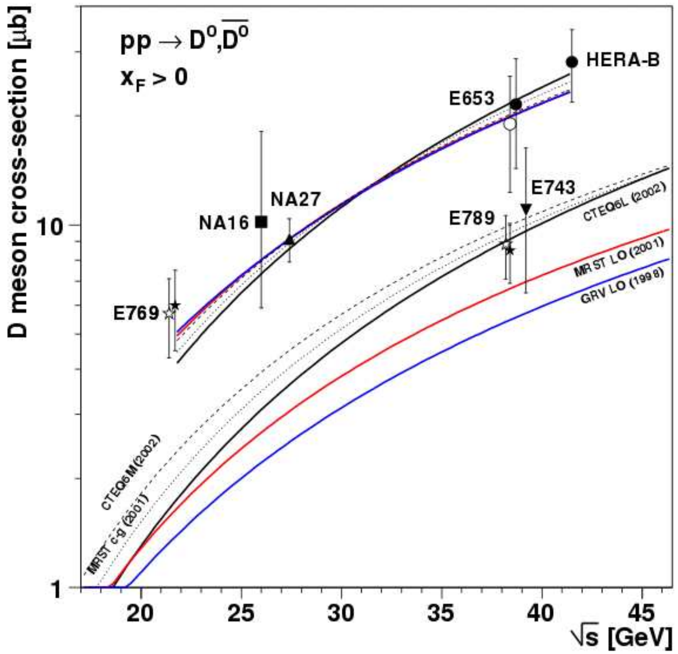
5 Goto 3

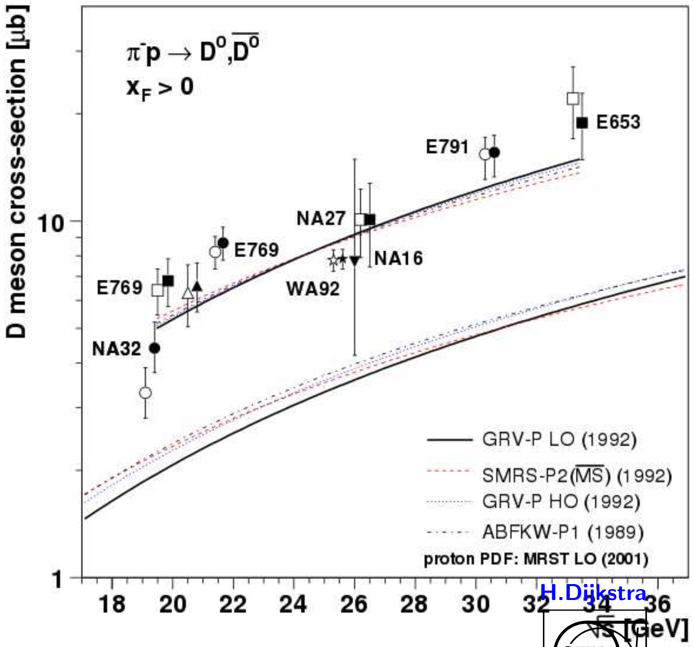
- Ntuple will contain correct mix of D(B)-mesons.
- Use Ntuple as input to generate semileptonic signal decays to f.i. HNL using Pythia.

Validate Pythia for $\chi_{\rm norm}$ Determination

- Reproduce from http://arxiv.org/pdf/hep-ph/0609101v1.pdf
- $c\bar{c}$ dominated by gg-fusion $\rightarrow \sigma(pp) \approx \sigma(\pi p)$
- $b\bar{b}$ dominated by $q\bar{q}$-annihilation $\rightarrow \sigma(pp) \ll \sigma(\pi p)$







- $b\bar{b}$ curves from makeCascade.py
- K-factors arbitrary, just the $\sqrt{s}$ dependence counts.

Pythia seems reasonable!

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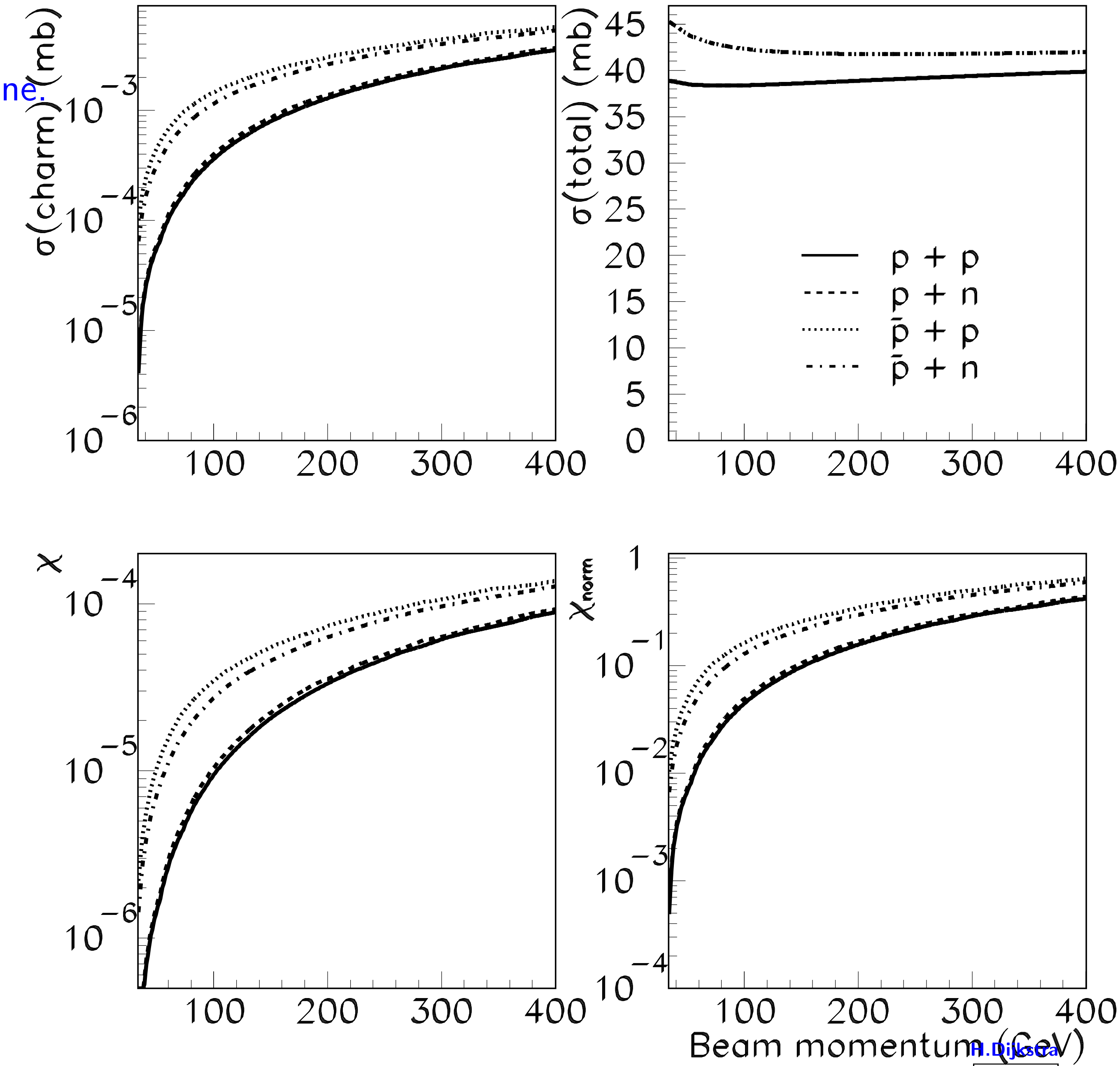
Steps 1&2) Get $\chi_{\rm norm}$

- Use Pythia to get σ at 20 points, interpolated with straight line.
- Target: mix p and n, hence get σ for both independently.



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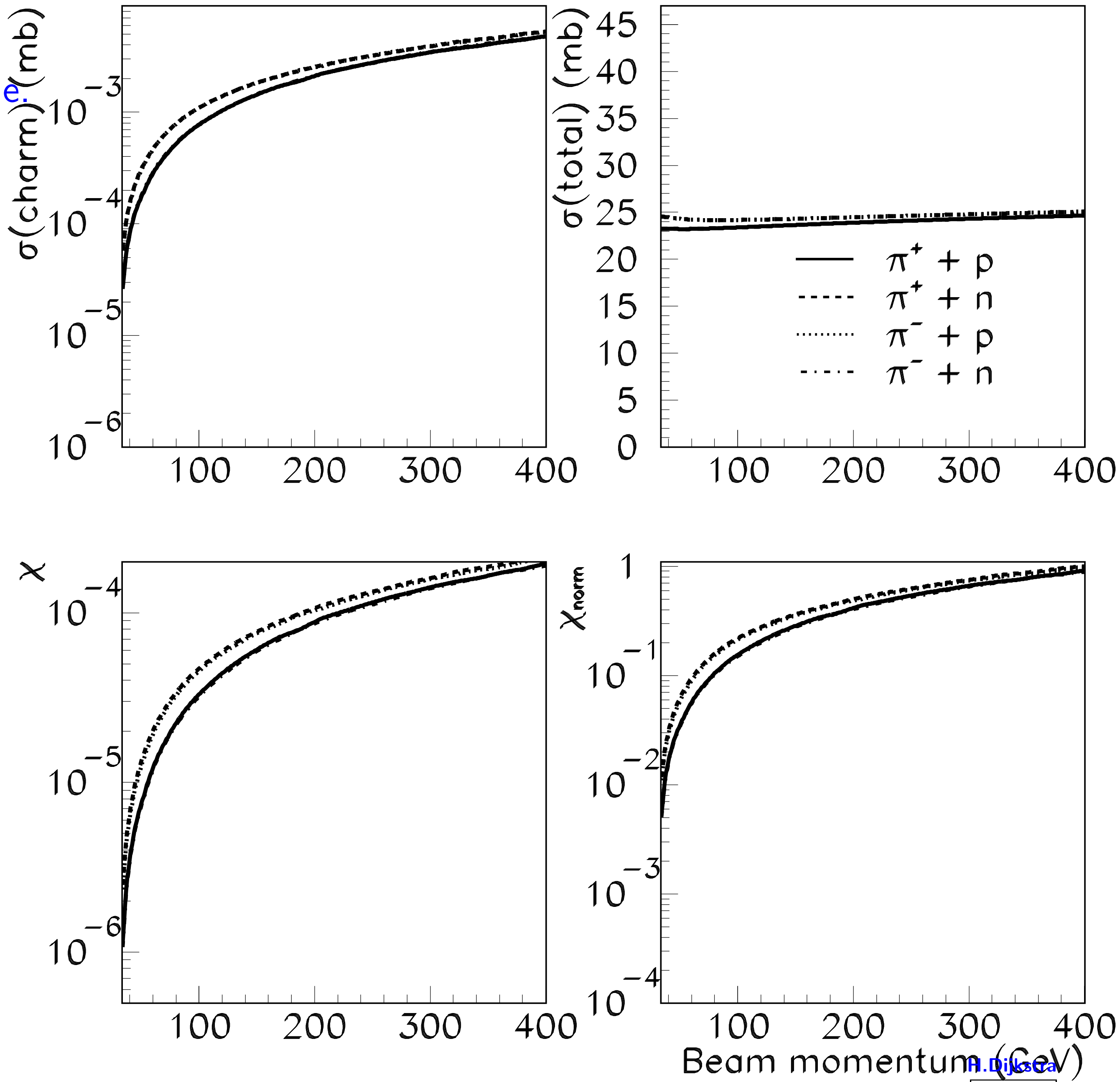
Steps 1&2) Get $\chi_{\rm norm}$

- Use Pythia to get σ at 20 points, interpolated with straight line.
- Target: mix p and n, hence get σ for both independently.
- $\chi^{\rm max}_{\rm 400GeV}$:
  $\pi^+(400{\rm GeV}) + {\rm n} \rightarrow {\rm c\bar{c}} + {\rm X}$



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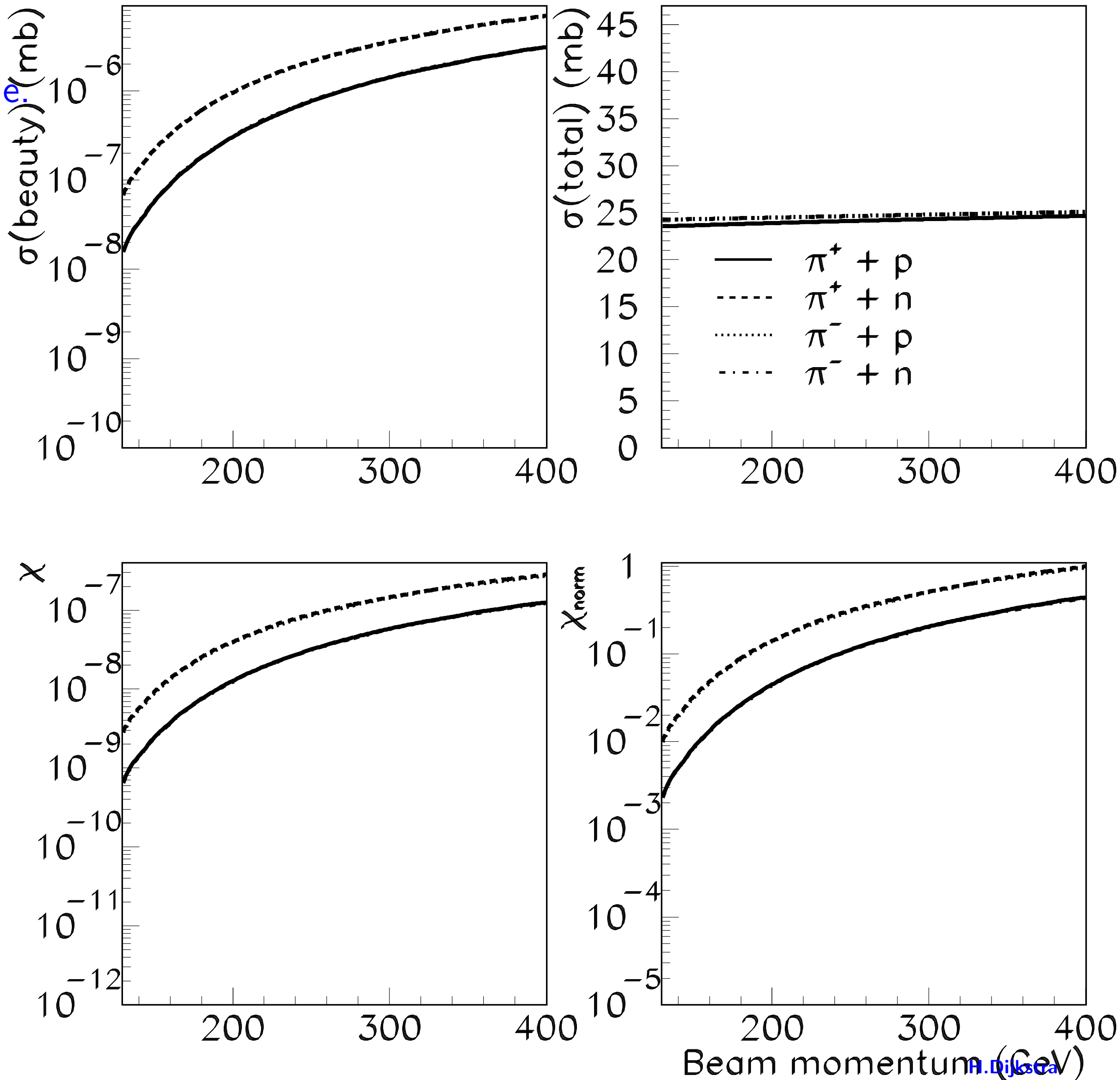

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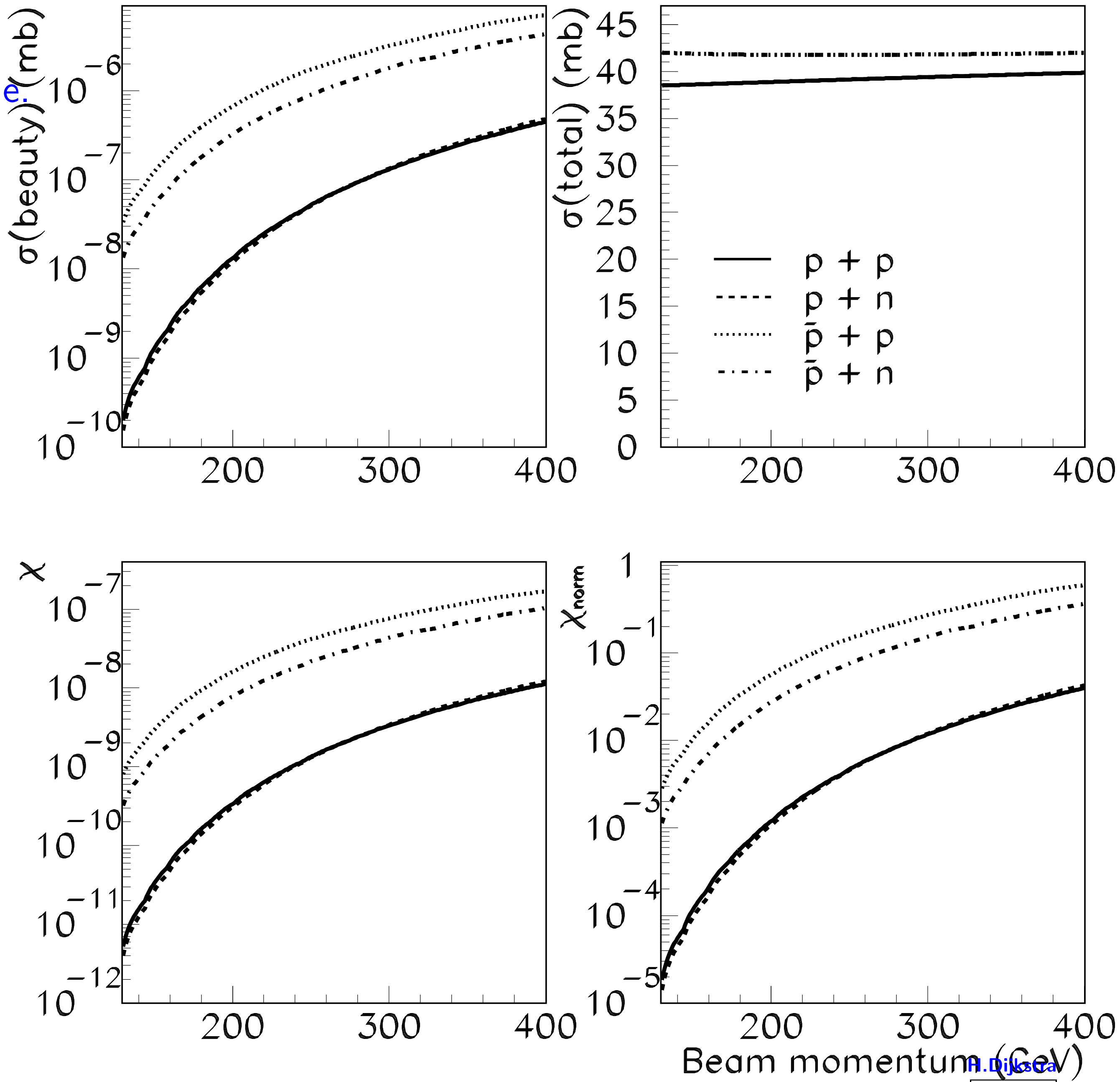
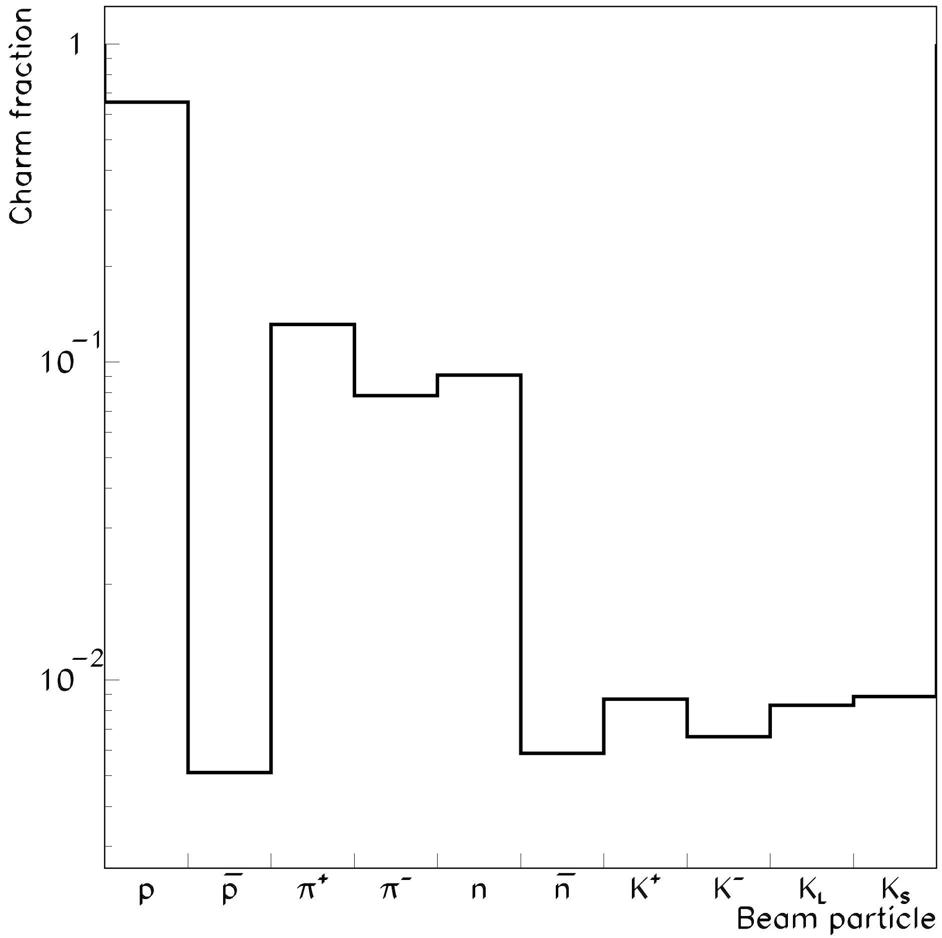
Steps 1&2) Get $\chi_{\rm norm}$

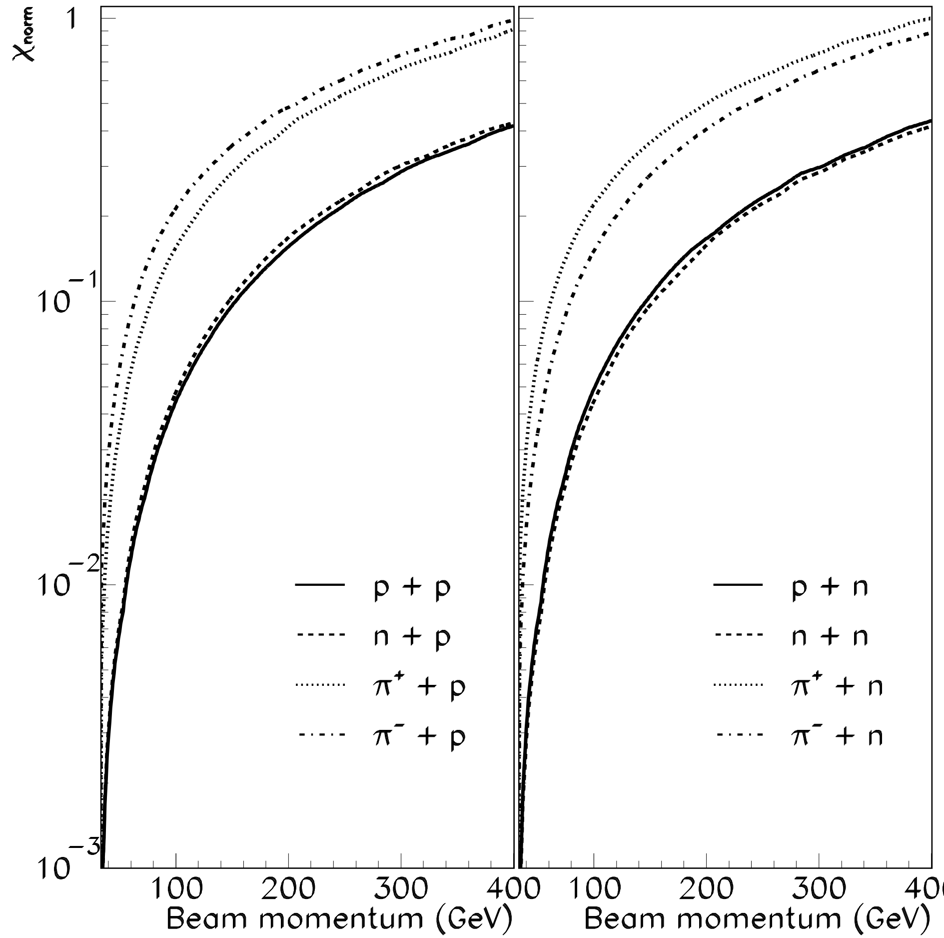
- Use Pythia to get σ at 20 points, interpolated with straight line.
- Target: mix p and n, hence get σ for both independently.
- $\chi^{\rm max}_{\rm 400GeV}$: $\pi^+(400{\rm GeV}) + {\rm n} \rightarrow {\rm b\bar{b}} + {\rm X}$
- Hence: $\chi_{\rm norm}$: ${\rm p}(400{\rm GeV}) + {\rm p} \rightarrow {\rm b\bar{b}} + {\rm X} = 0.04$



Step 4) Produce $c\bar{c}$

- p+$\pi^{\pm}$+n=65+21+9=95 % main contributors to signal production.
- Molybdenum: 43% of nucleons is proton, generate with correct mix.





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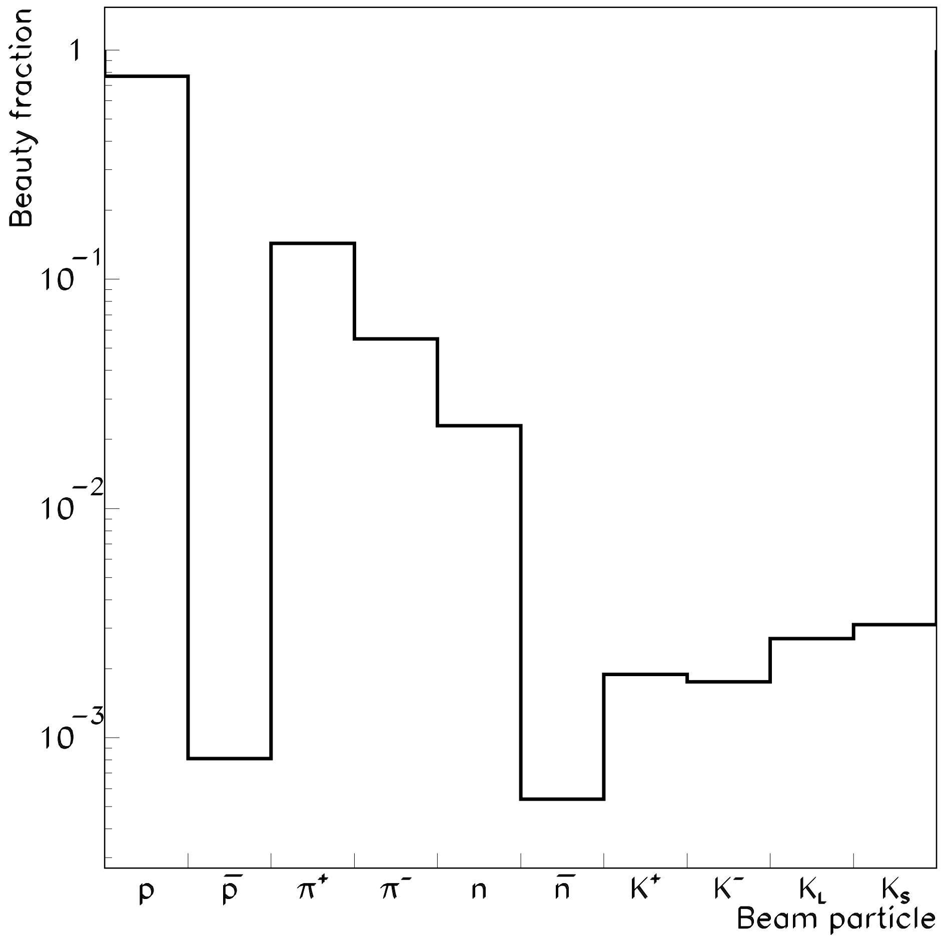
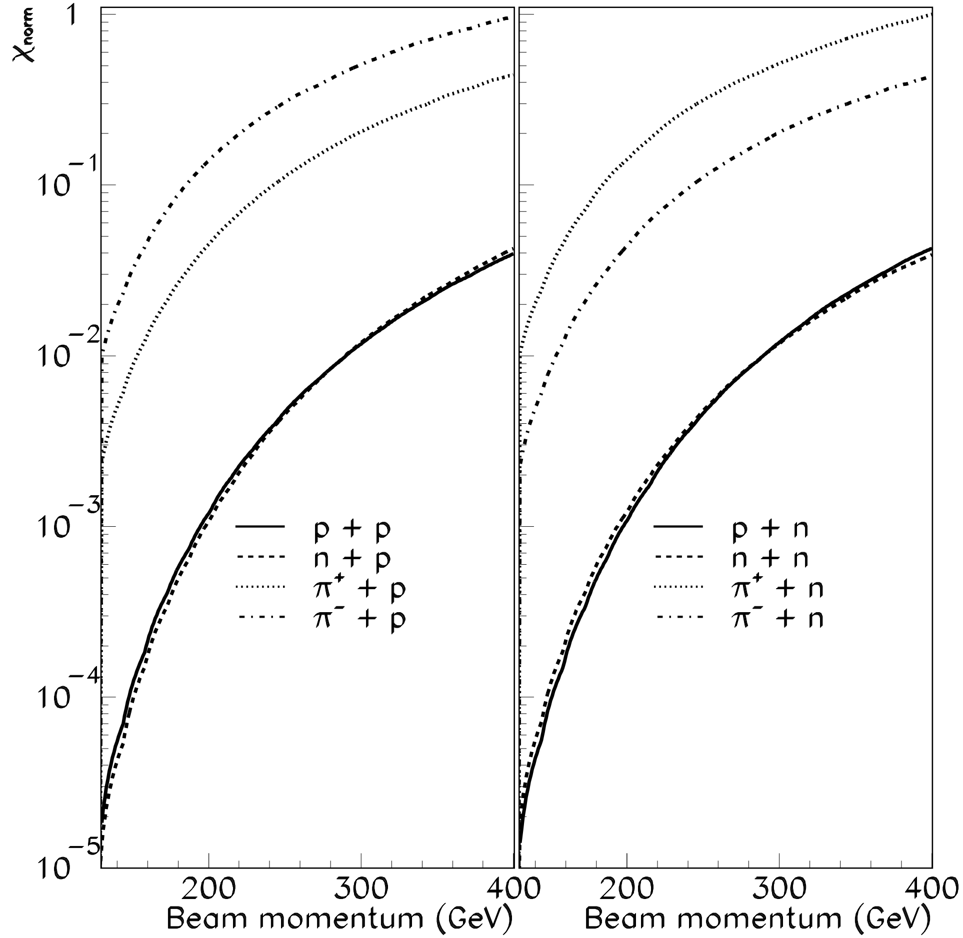
Step 4) Produce $b\bar{b}$

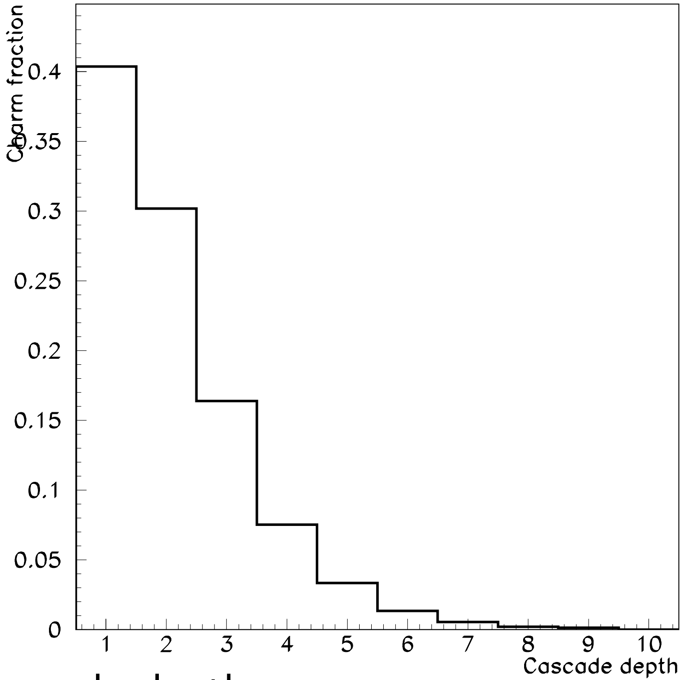
- p+$\pi^{\pm}$+n=77+20+2=99% main contributors to signal production.
- Molybdenum: 43% of nucleons is proton, generate with correct mix.





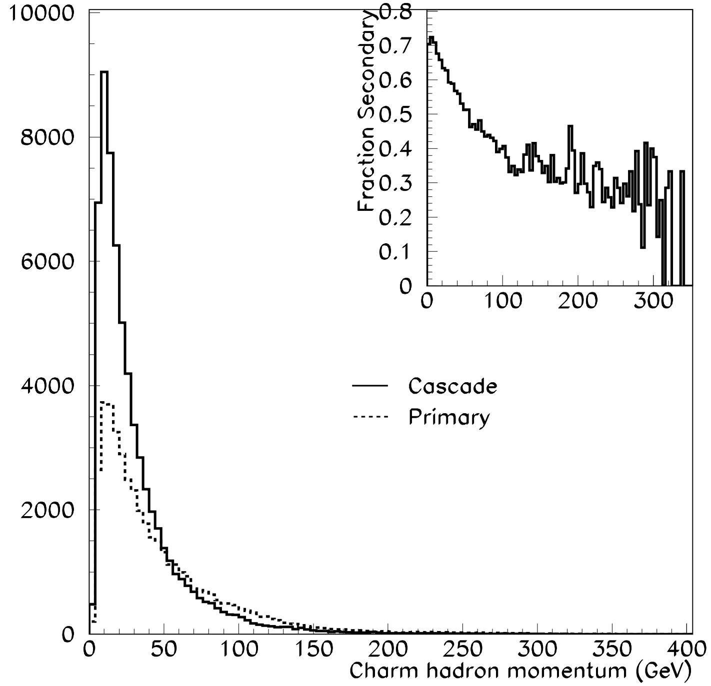
Steps 4) Charm plots

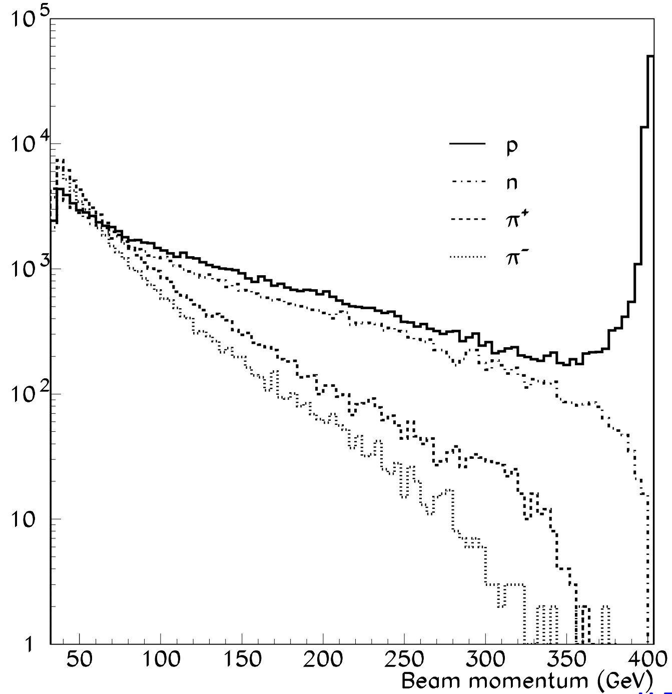
- TP addendum: only first cascade $\frac{\text{Total}}{\text{Primary}} = 1.61$
- Now: all cascade till kinematic limit.
- Full cascade $\frac{\text{Total}}{\text{Primary}} = 2.31$



Cascade depth:

1. 400 GeV pN
2. Products of 1
3. Products of 2 etc..





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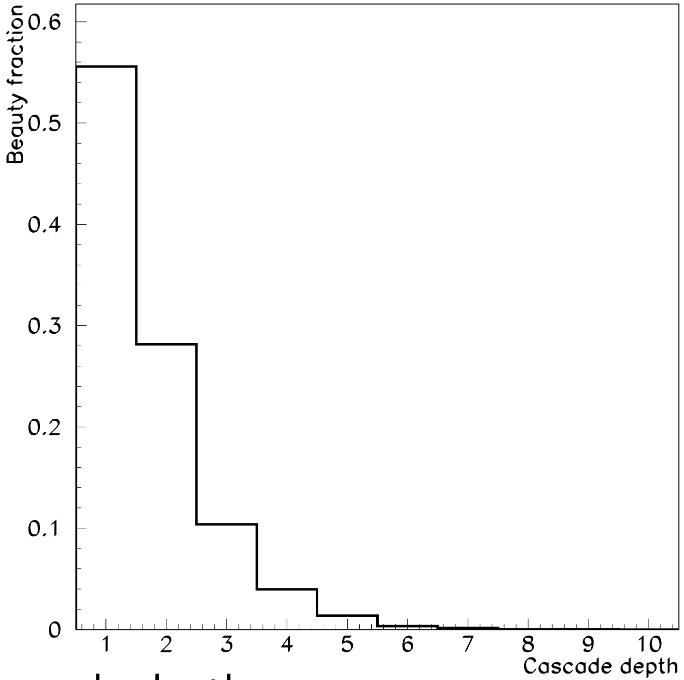
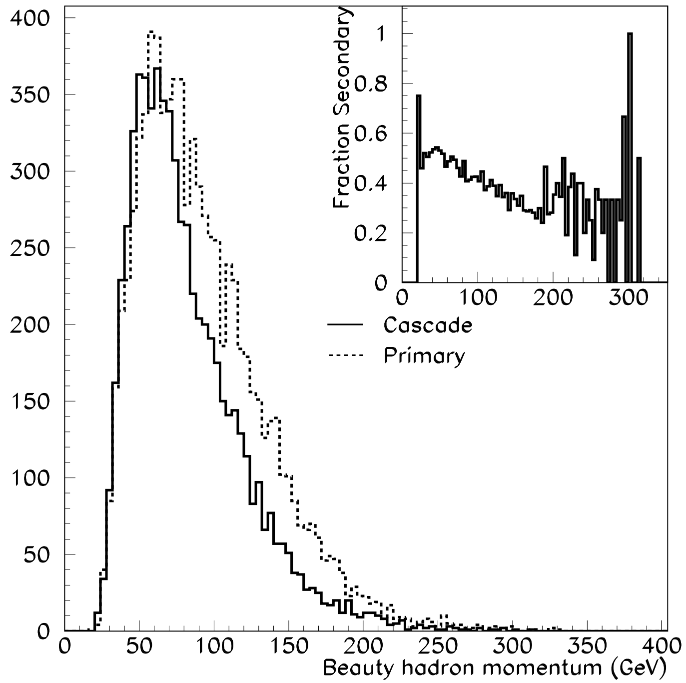
Steps 4) Beauty plots

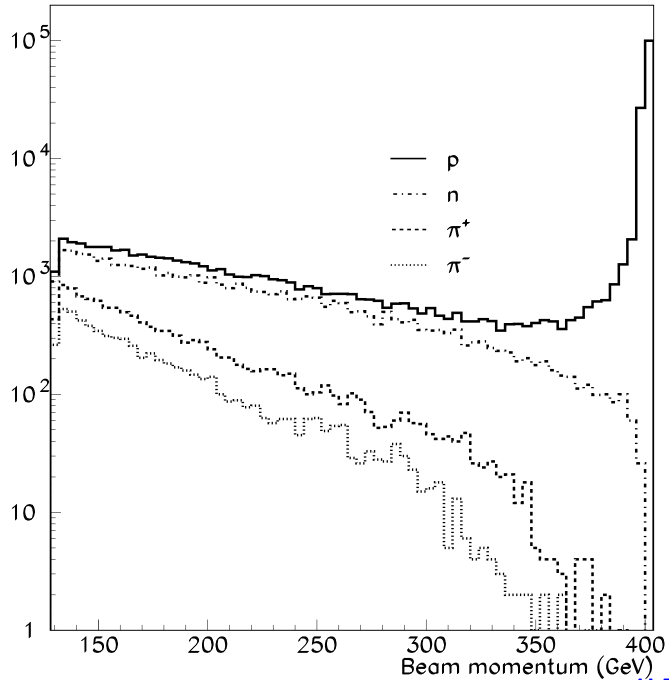
- TP addendum: only first cascade $\frac{\text{Total}}{\text{Primary}} = 1.54$
- Now: all cascade till kinematic limit.
- Full cascade $\frac{\text{Total}}{\text{Primary}} = 1.74$



Cascade depth:

1. 400 GeV pN
2. Products of 1
3. Products of 2 etc..





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Cascade and HNL Acceptance

Or: what is the correct Pythia tune?

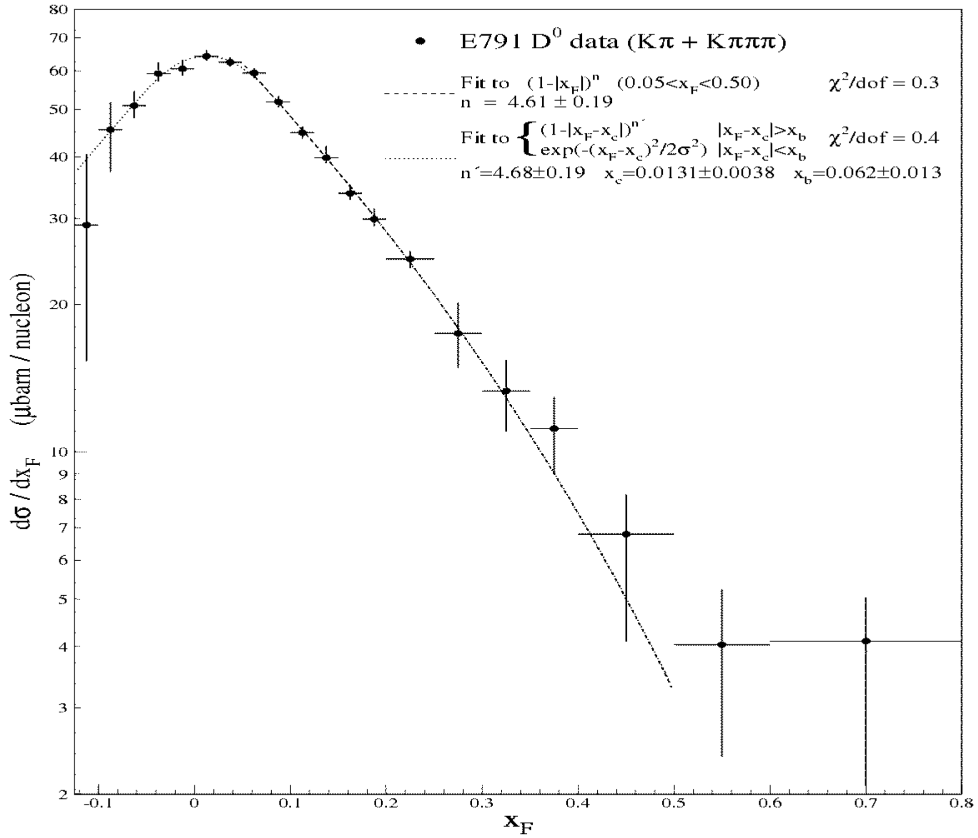
Chronology of Cascade sim:

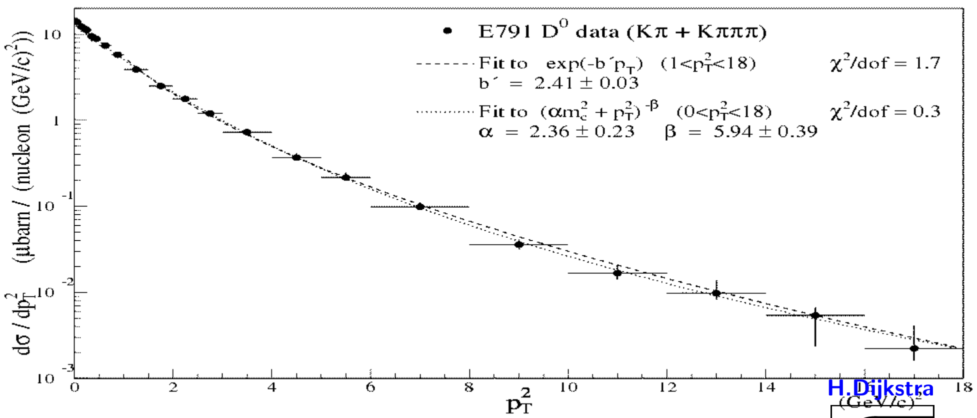
- First written in FORTRAN, and used default Pythia 6.205 (cernlib linux version). This produced $< p_T^{D^0} >= 0.84$ GeV
- Charm in the TP was produced with Pythia 8.1, This produced $< p_T^{D^0} >= 1.29$ GeV
- The FORTRAN Pythia in FairShip has version 6.4. This produced $< p_T^{D^0} >= 1.21$ GeV

Resulted in a very different (larger) HNL acceptance from Pythia 6.205 charm, and completely confused us.

Which Pythia tuning is correct? Literature:

- E791: 90 k $D^0 + \bar{D}^0$ in 500 GeV $\pi^- + C$.
- http://arxiv.org/pdf/hep-ex/9906034.pdf
- Published nice differential p_T^2, X_F distributions.
- $< p_T^{D^0} >$=1.0 GeV





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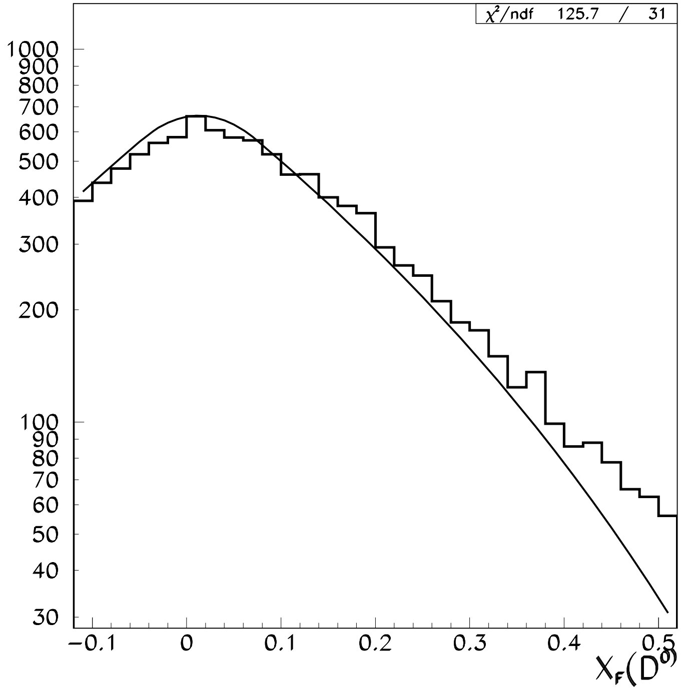
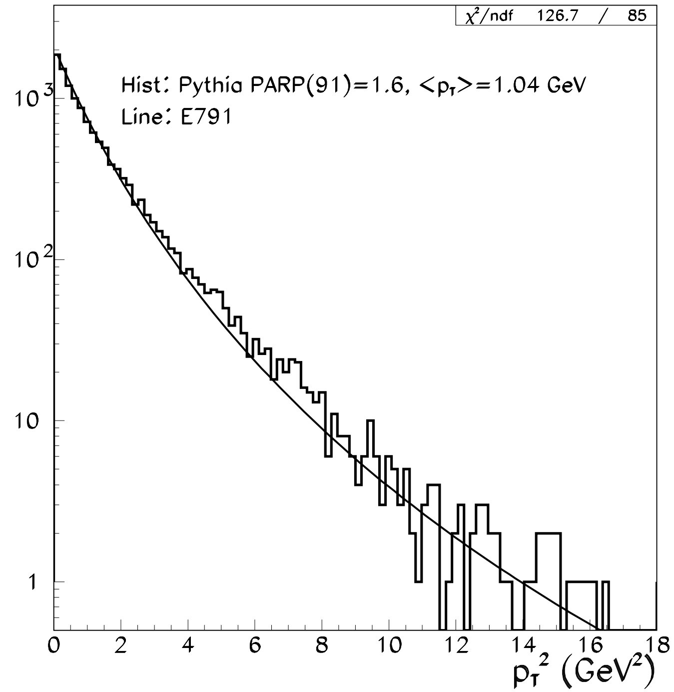
First Pythia Tune Attempt

- Pythia 6: PARP(91) varies p_T.
- PARP(91)=1.6: p_T is OK, but $\mathrm{X_F}$ is too large.
- Feeling for HNL acceptance systematic:
  - Pythia: generate D^0 with 500 GeV π^-+p
  - E791: generate D^0 according to p_T^2, $\mathrm{X_F}$ distributions.
  - Then for both: $D^0 \rightarrow \mathrm{HNL(1\ GeV)} + \mathrm{X}$, $\mathrm{HNL} \rightarrow \mu\pi$
  - SHiP-HNL acceptance: E791/Pythia=78 %.
- Hence: this Pythia tune is too optimistic?





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Anyway: use this Pythia tune to get a feeling:
(Mario Campanelli offered to investigate better tune)

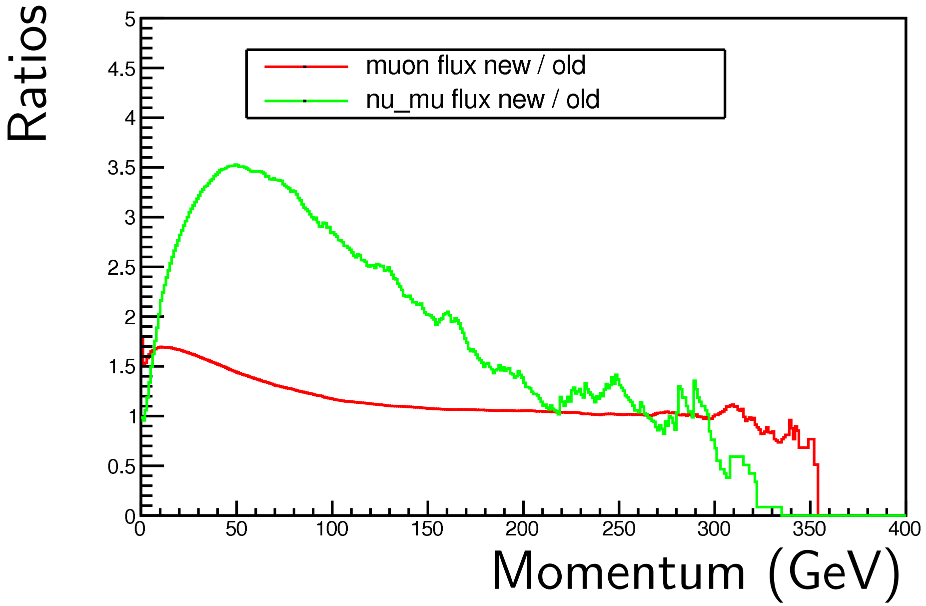
- 1 GeV HNL from charm:
  - Acceptance $\frac{\mathrm{Pythia6(primary)}}{\mathrm{Pythia8(primary)}} = 1.4$
  - Acceptance $\frac{\mathrm{Pythia6(all)}}{\mathrm{Pythia8(primary)}} = 2.6$
- 1(3) GeV HNL from beauty:
  - Acceptance $\frac{\mathrm{Pythia6(primary)}}{\mathrm{Pythia8(primary)}} = 1.07(1.03)$
  - Acceptance $\frac{\mathrm{Pythia6(all)}}{\mathrm{Pythia8(primary)}} = 1.7(1.9)$

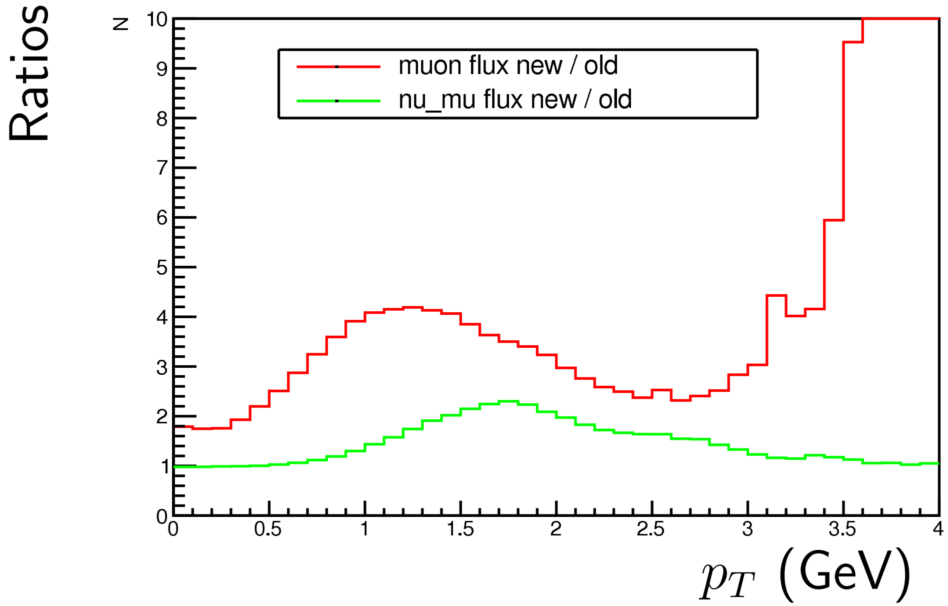
$\mu,\ \nu$ Backgrounds

What about background?

- TP: pN(Mo):$\chi_{c\bar{c}}$=18 μb/10.7 mb $= 1.7\times10^{-3}$
- But Pythia (pp, some version): $\chi_{c\bar{c}} = 8.9 \times 10^{-5}$
- Hence: Pythia gives a factor 19 smaller χ, in addition we now add Cascade charm.

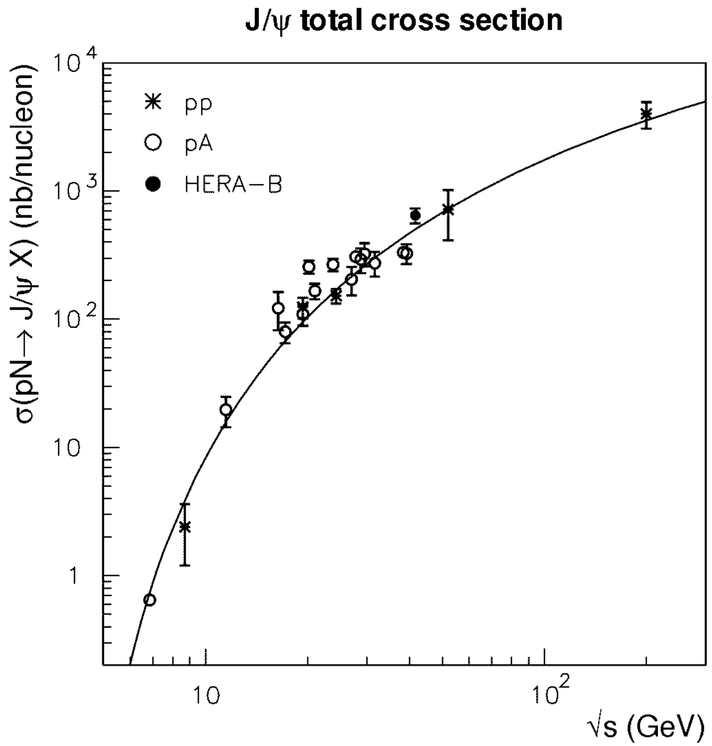
Removed $\nu,\ \mu$ from charm-decay from original files, and added in the new $\nu,\ \mu$ from charm with the appropriate weight.





J/ψ production: Pythia vs data.

- J/ψ rate produced by Pythia-8 is much larger than what is known experimentally.
- For a 400 GeV/c p $\sigma(pMo \to J/\psi X) \approx 180$ nb/nucleon, assuming $\sigma \propto A^{0.96}$.
- $\chi(J/\psi) \approx 1.7 \times 10^{-5}$. Pythia 8 produces $\chi(J/\psi) = 4.2 \pm 0.1 \times 10^{-5}$, hence more than twice what is expected from prompt J/ψ production.



HERA-B Collaboration: arxiv.org/pdf/hep-ex/0512029.pdf

This is even larger than what we expect taking the cascade production into account, albeit with a harder spectrum. Hence, it is proposed to not correct this rate with a separate production as used for charm and beauty.

- Hence, we have more than enough muons from J/ψ-decay in the sample.
- But do they have the correct spectrum???

Summary

Produced charm(beauty) hadrons with full cascade:

- Charm: full cascade $\frac{\text{Total}}{\text{Primary}} = 2.31$
- Beauty: full cascade $\frac{\text{Total}}{\text{Primary}} = 1.74$
- Health Warning: we should first get a reliable Pythia tune, before we conclude on the signal gain the cascade gives us!

Backgrounds:

$\mu \sim 50\%$ more rate, but very p_T dependent!

ν Up to 3.5$\times$ more rate at low momenta!

- A lot more plots+how to use new background:

  indico.cern.ch/event/460718/contribution/5/attachments/1186183/1721655/NuMuProdFlowUpdateII.pdf

BACKUP

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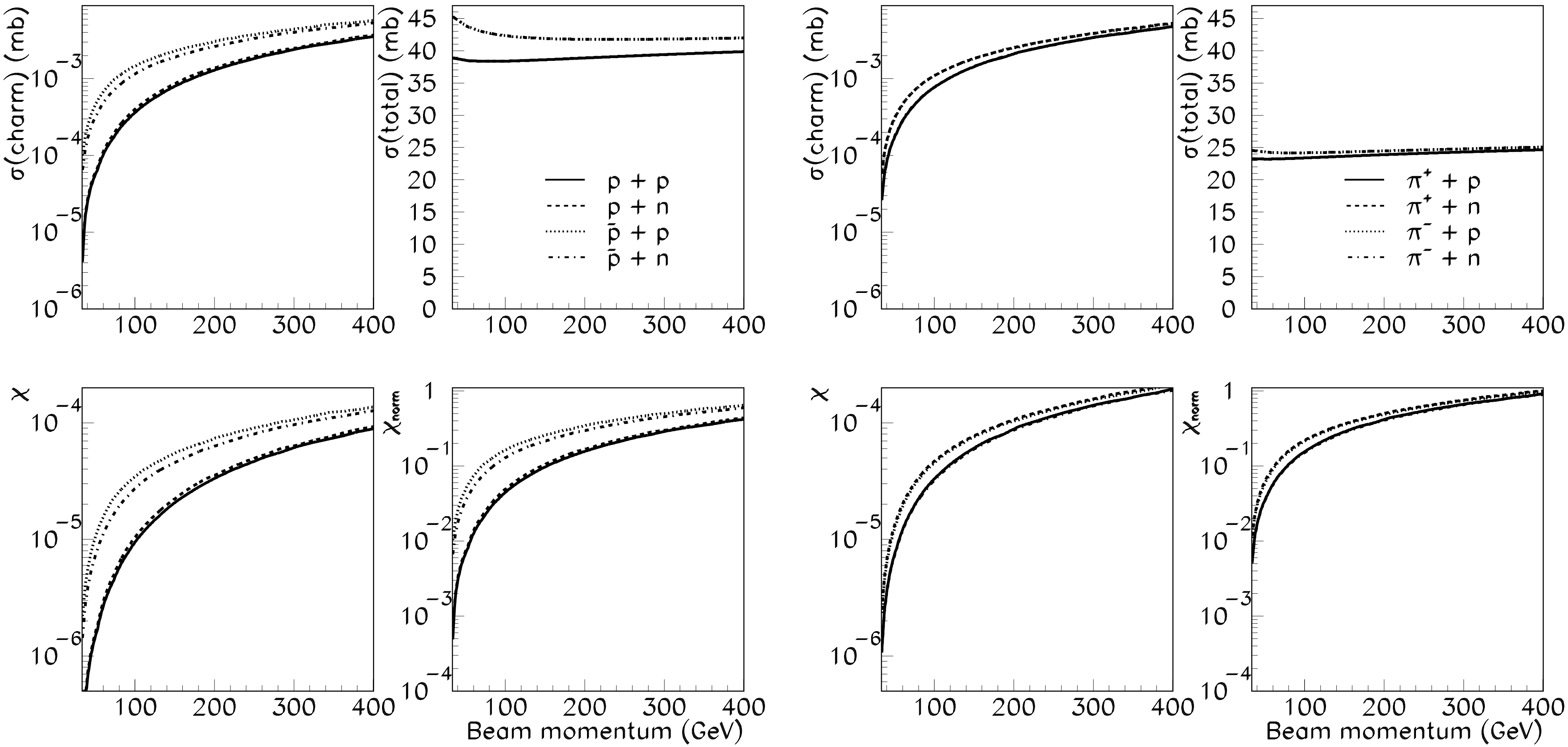
Steps 1&2) Get χ_{norm}



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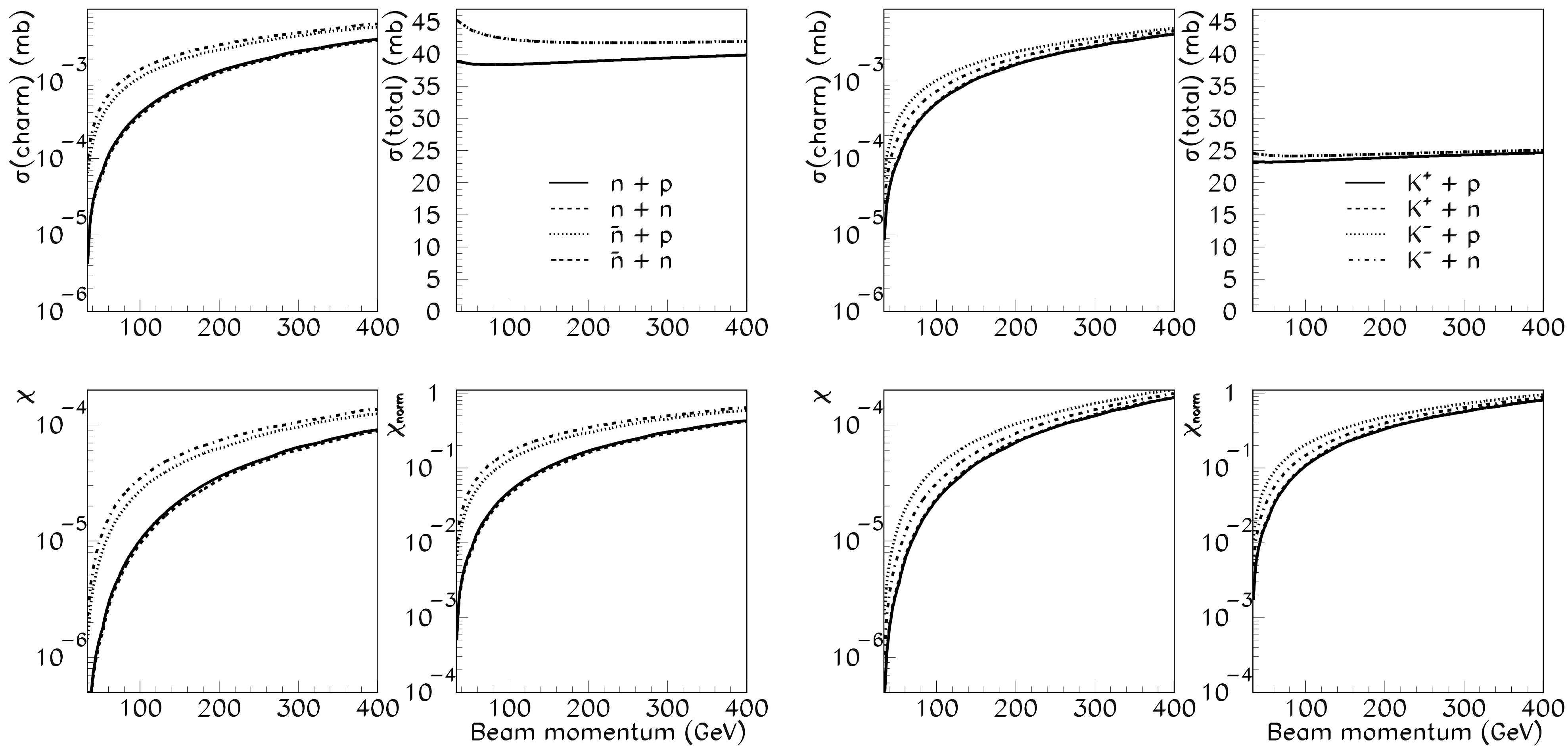

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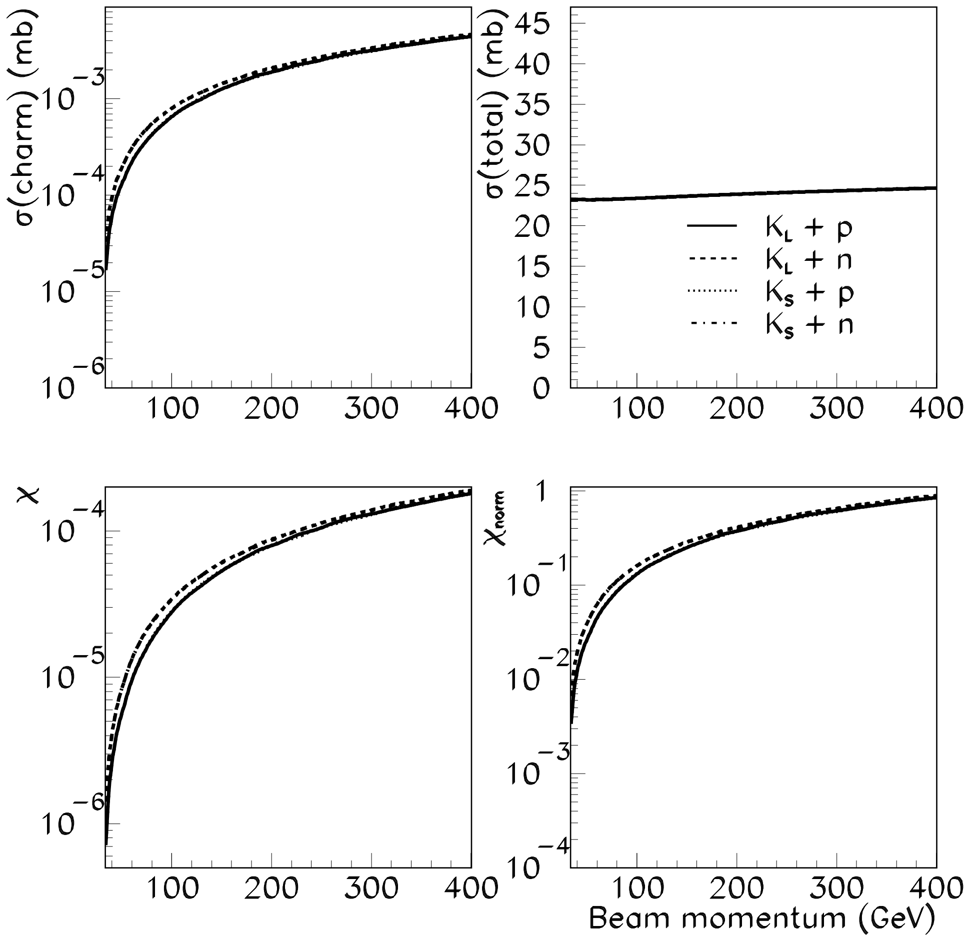

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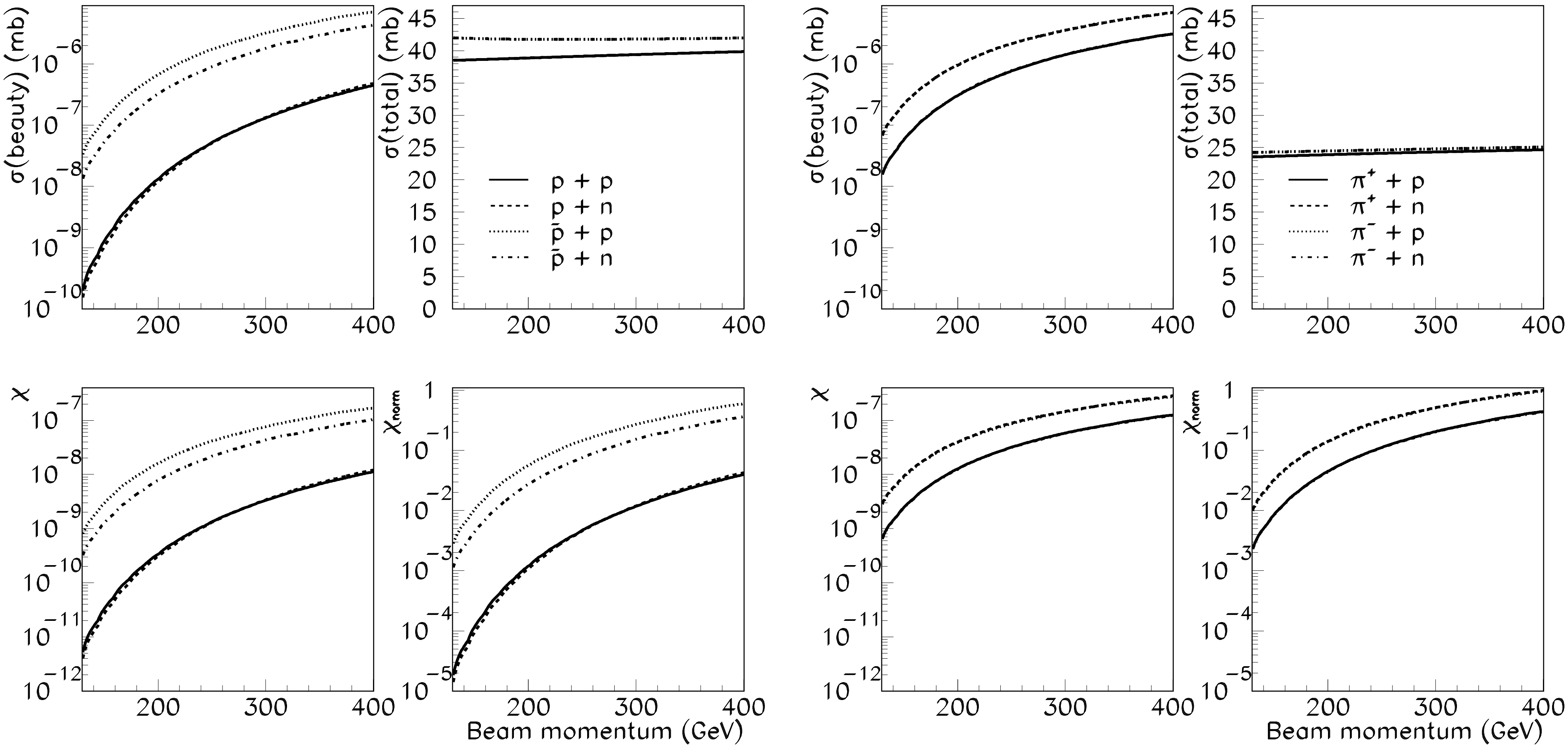

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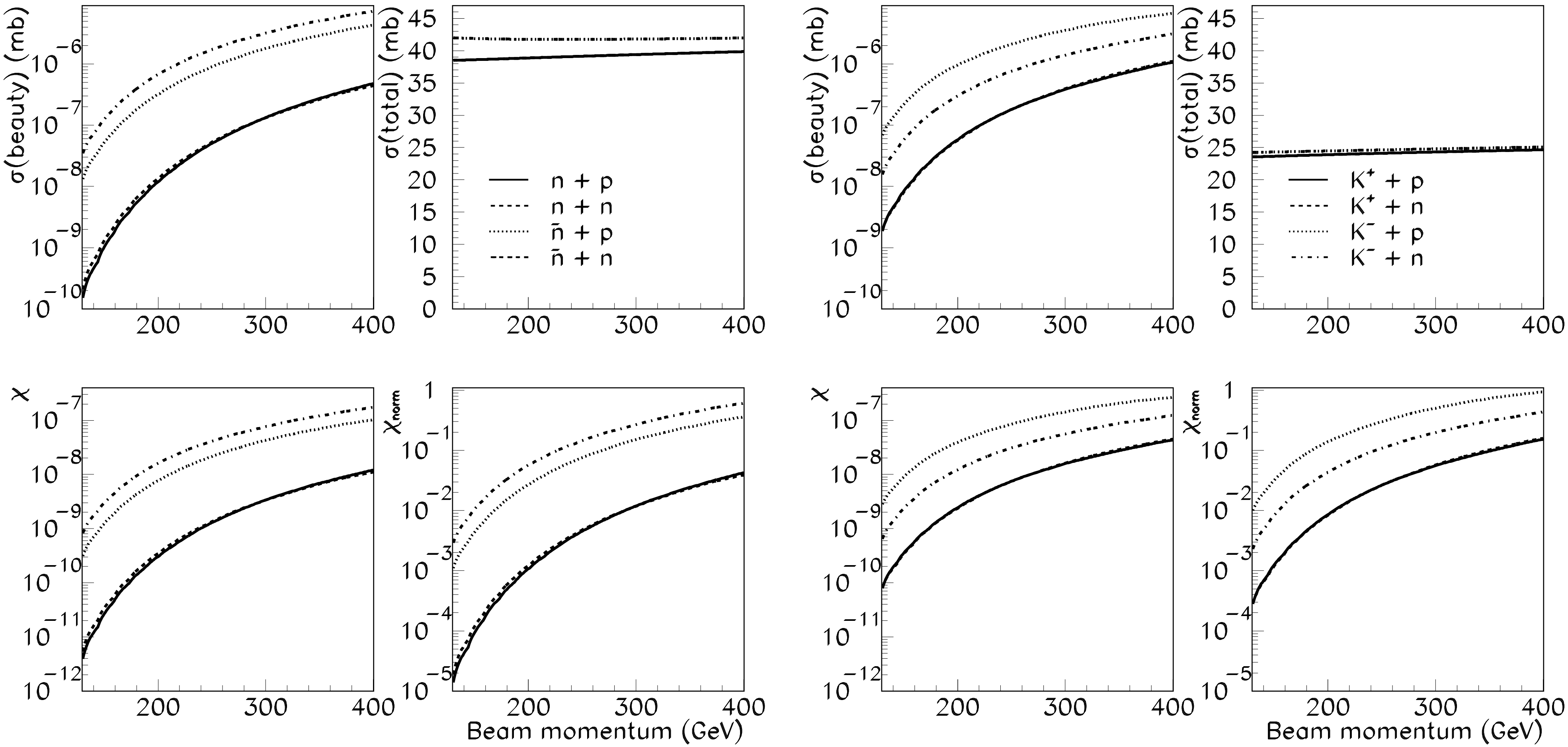

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