Vector Meson Production in pp and pA collisions

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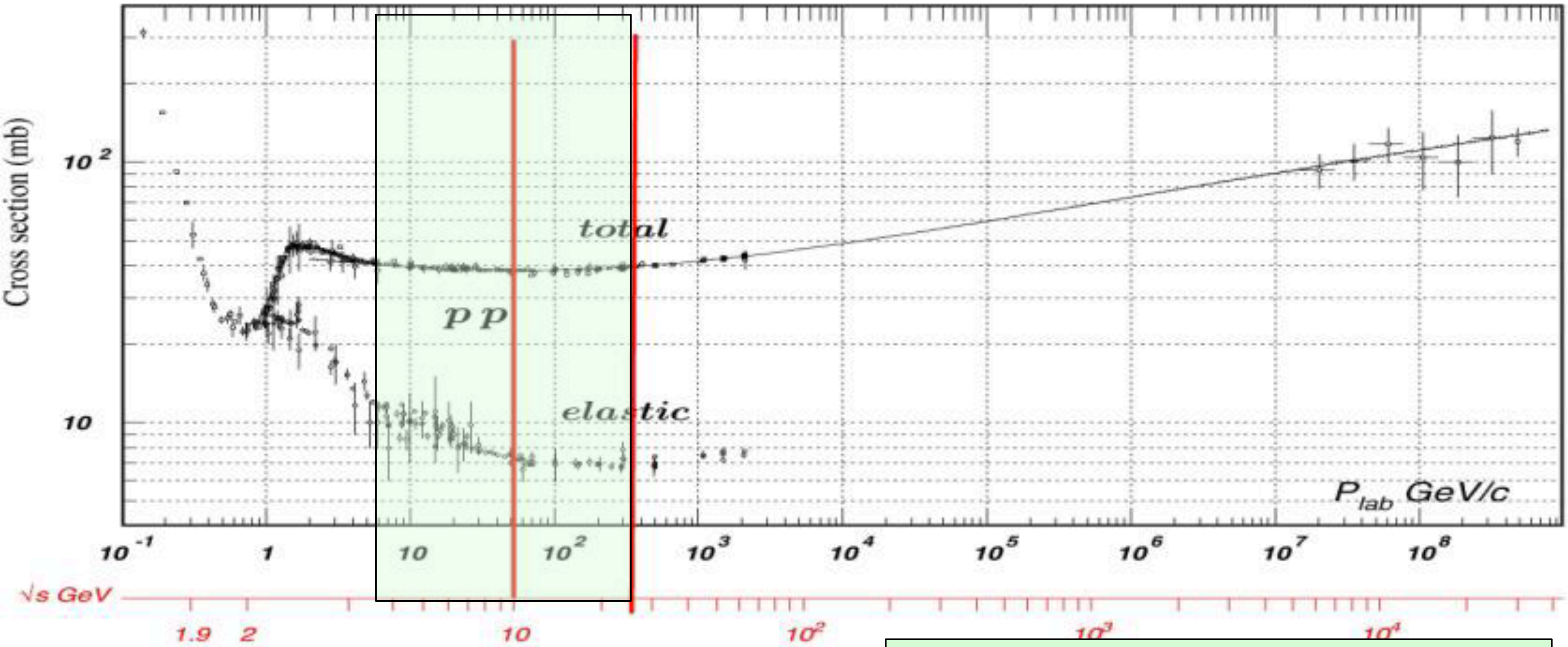
Cross sections for pp interaction



$\sigma_{tot}(pp) \approx 40$ mb

$\sigma_{el}(pp) \approx 7$ mb

NICA-SPD

- Polarized proton beams
- Sqrt(s) = 3.4-27 GeV
- $\mathcal{L}=(10^{29}-10^{32})\,cm^{-2}\,s^{-1}$

$N+N \to N+N+V,\ V=\rho,\omega,\phi,\ J/\Psi\ldots$

General Considerations for threshold production
(the threshold region may be quite wide : $q< m_c$)

$$S_i = 1,\ \ell_i = 1 \ \to\ j^P = 1^- \to S_f = 0,$$
$$\mathcal{M}(\mathrm{pp}) = 2 f_{10}[\tilde{\chi}_2 \sigma_y \vec{\sigma}\cdot(\vec{U}^* \times \hat{\vec{k}})\chi_1]\,(\chi_4^\dagger \sigma_y\, \tilde{\chi}_3^\dagger),$$

$$S_i = 1, \ell_i = 1 \to j^P = 1^- \to S_f = 0,$$
$$S_i = 0, \ell_i = 1 \to j^P = 1^- \to S_f = 1,$$

$$\mathcal{M}(\mathrm{np}) = f_{10}[\tilde{\chi}_2\sigma_y\vec{\sigma}\cdot(\vec{U}^* \times \hat{\vec{k}})\chi_1](\chi_4^\dagger\sigma_y\,\tilde{\chi}_3^\dagger) + f_{01}(\tilde{\chi}_2\,\sigma_y\chi_1)[\chi_4^\dagger\vec{\sigma}\cdot(\vec{U}^* \times \hat{\vec{k}})\sigma_y\tilde{\chi}_3^\dagger],$$

The dynamical information is contained in the amplitudes that are different for the different vector mesons

M.P. Rekalo, E.T.-G.. New J. Phys., 4,68(2002).

Isotopic effects

- *Large isotopic effects at threshold*

$$\frac{\sigma(np \to npJ/\psi)}{\sigma(pp \to ppJ/\psi)} = 5,$$

- Model independent prediction holding at threshold
- Not taken into account in most nuclear models and simulations

$N+N \rightarrow N+N+V$, $V=\rho,\omega,\phi$, J/Ψ…

Vector mesons are transversally polarized:

$\rho_{xx}=\rho_{yy}=1/2$; $\rho_{zz}=0$

For $V \rightarrow P+P$: $d\sigma \approx (\sin^2\theta)$ (P is a pseudoscalar meson)

For $V \rightarrow \mu^+ + \mu^-$: $d\sigma \approx (1+\cos^2\theta)$

Deviations indicate the presence of higher multipolarities

- All other spin one polarization observables vanish.
- Double spin polarizations depend on the ratio of amplitudes f_{01}/f_{10} . Explicit expressions are available.

M.P. Rekalo, E.T.-G.. New J. Phys. 4,68 (2002).

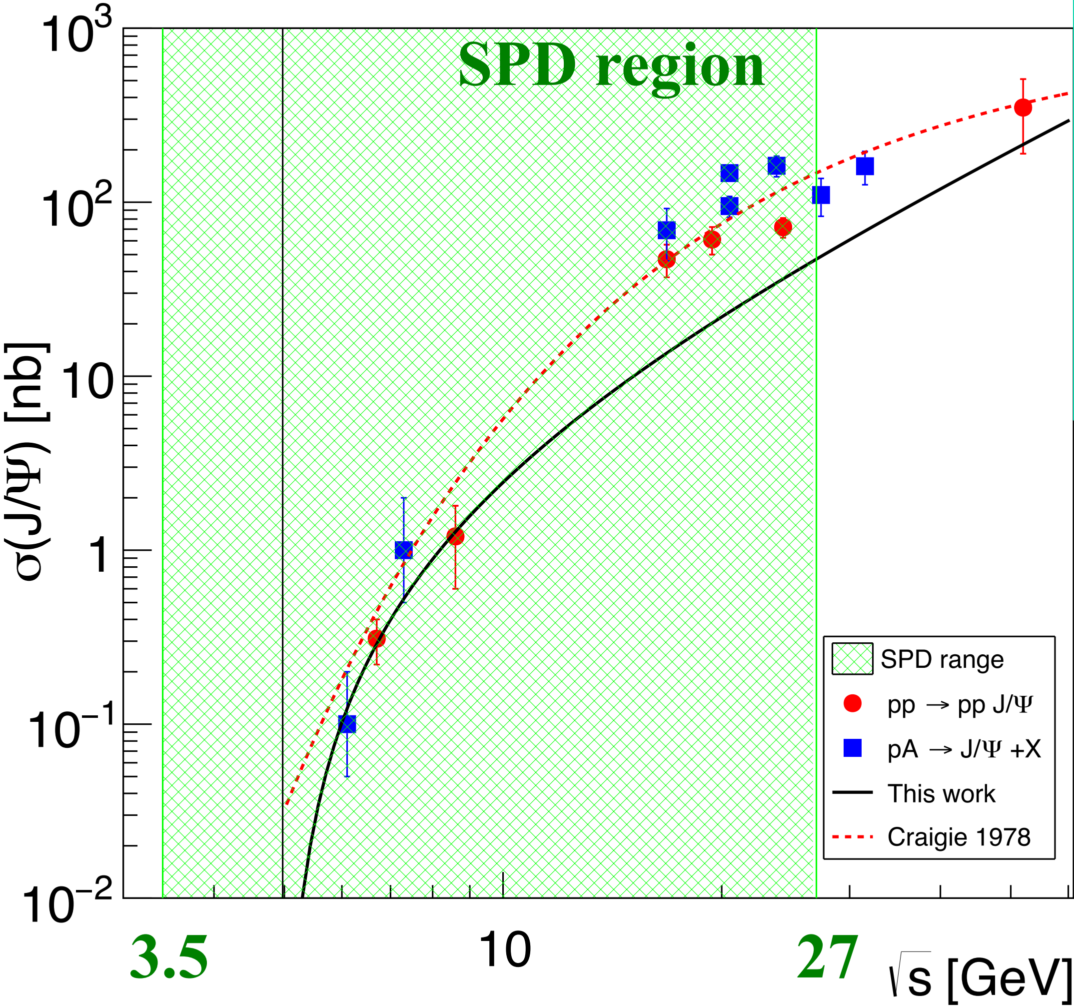
$N+N \to N+N+V$, $V=\rho,\omega,\phi$, $J/\Psi\ldots$

Measuring polarization effects would pinpoint the threshold region and constrain strongly the amplitudes in this region.

M.P. Rekalo, E.T.-G.. New J. Phys. 4,68 (2002).

J/Ψ production

M.P. Rekalo, E.T.-G.. New J. Phys., 4,68(2002).

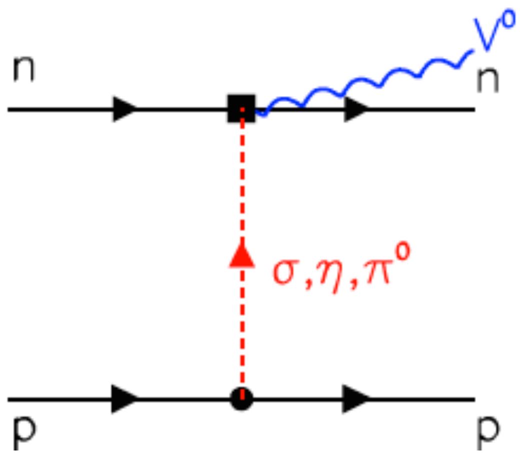


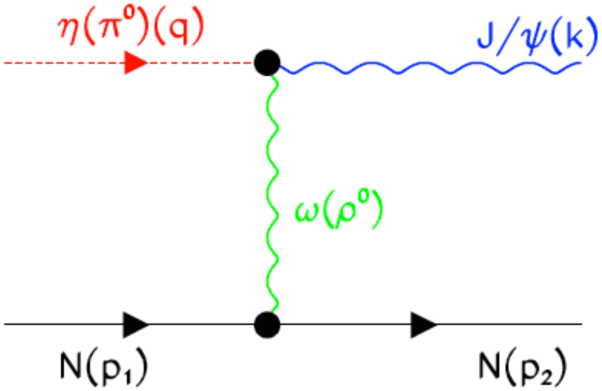
R. Vogt. Phys. Rept., 310, 197 (1999).

1) Hard process at parton level
2) Formation of $c\bar{c}$ pairs
   (not pre-existing in the proton)
3) Hadronization of cc pairs into J/Ψ
4) FSI

1) Effective proton size: $r_c \approx 1/m_c$
2) Large isotopic effects :
   $\sigma_{np} >> \sigma_{pp}$
3) Polarization phenomena

$N+N\to N+N+V,\ V=\rho,\omega,\phi,\ J/\Psi\ldots$





$$Q=\sqrt{s}-2m-m_V$$

$$R(J/\psi,\phi)=\frac{\sigma(\mathrm{pp}\to\mathrm{pp}J/\psi)}{\sigma(\mathrm{pp}\to\mathrm{pp}\phi)}\simeq\frac{g^2(J/\psi\to\pi\rho)}{g^2(\phi\to\pi\rho)}\left(\frac{t_\phi-m_\pi^2}{t_{J/\psi}-m_\pi^2}\right)^2\left[\frac{F(t_{J/\psi})}{F(t_\phi)}\right]^2,$$

$g(\mathrm{V}\to\pi\rho)$: coupling constant for the decay $\mathrm{V}\to\pi\rho$,

$t_V=-mm_V$: 4-momentum transfer at threshold

$F(t)$: form factor for the vertex $\pi^*\rho^*\mathrm{V}^0$, $F_V(t)=\frac{1}{1-\frac{t}{\Lambda_V^2}}$, $\Lambda_V\simeq m_V$

≈ 10: takes into account the size of $c\bar{c}$ compared to $s\bar{s}$

$N+N \to N + N + J/\Psi$

Expected counting rate:

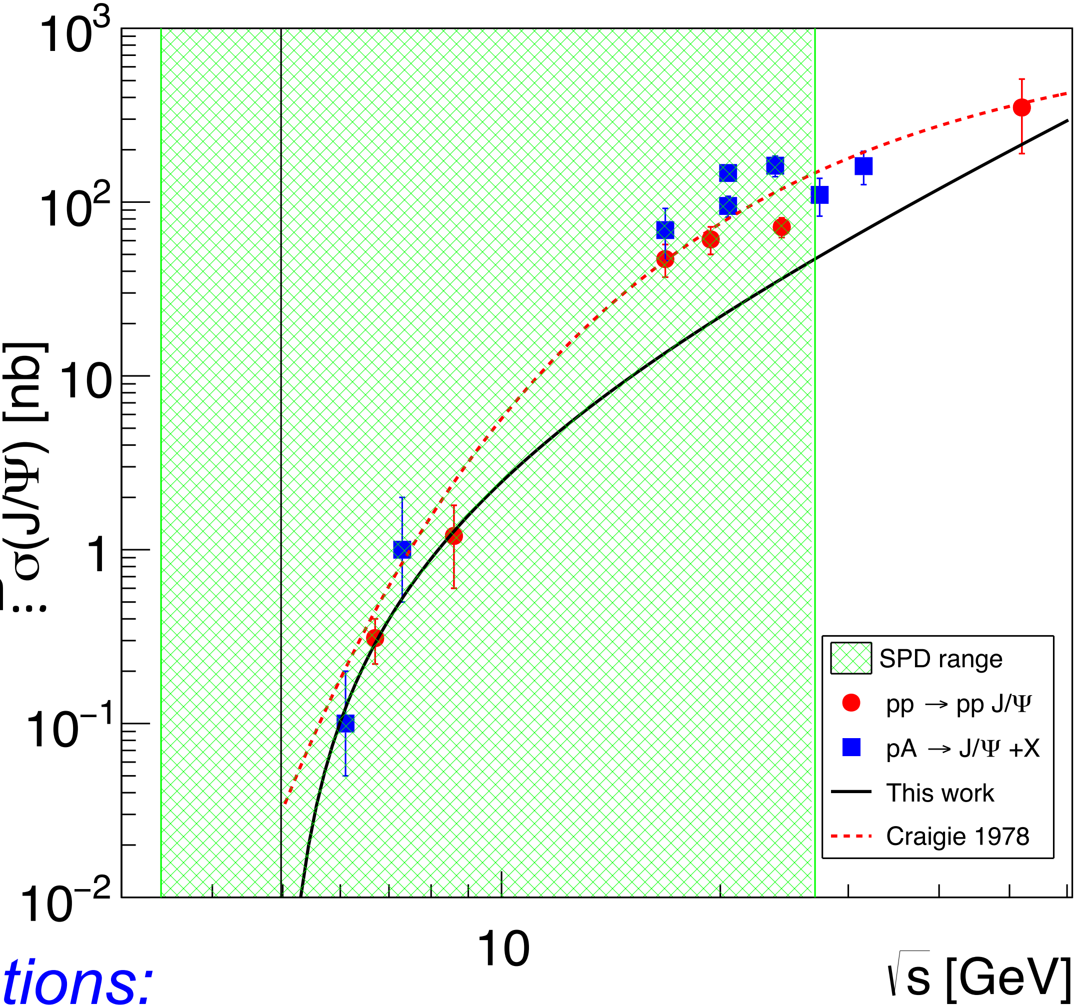
For : $\mathcal{L}=10^{30}$ cm^{-2} s^{-1}
$\sigma < 100$ nb
one expects :
< 300 counts/h

Not corrected for efficiency, acceptance, reconstruction…

upper limit!

BR($J/\Psi \to l^+l^-$)

$$(\simeq 5.9 \pm 0.5)10^{-2}.$$

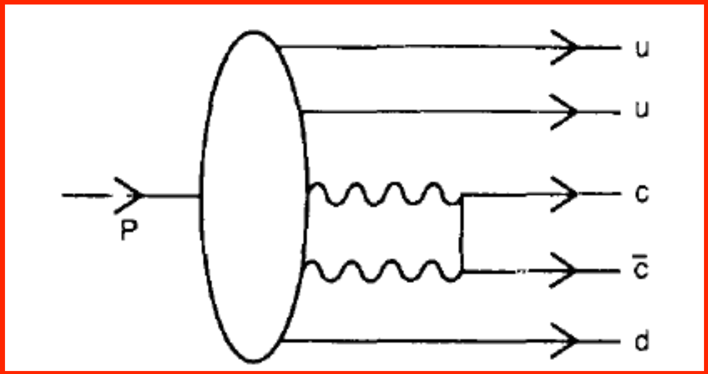


Useful parametrizations:

$$\sigma[nb] = ae^{-bM_{J/\Psi}/\sqrt{(s)}};$$

$$\sigma[nb] = 0.097(Q[\mathrm{GeV}])^2.$$

Open Charm: $N+N \to N+\overline{D}+\Lambda_c\,(\Sigma_c)$

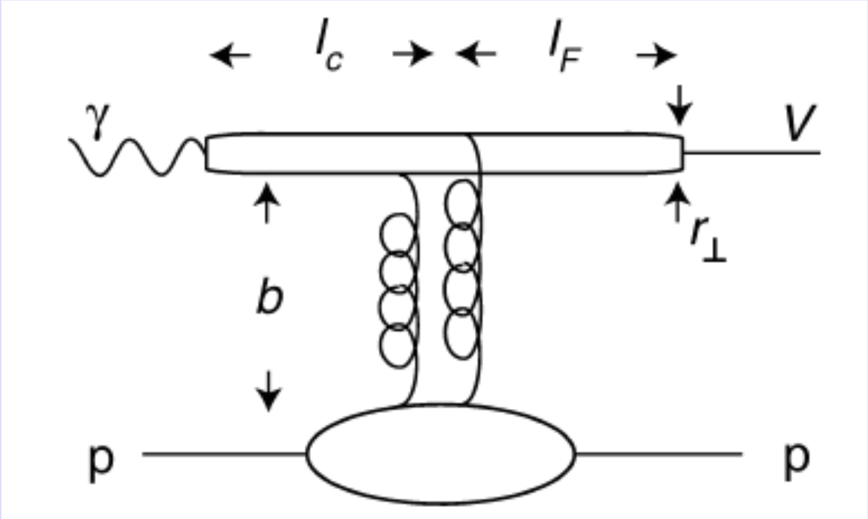


Intrinsic charm:
proton Fock state

- All partons must transfer their energy to to charm quarks within $t \approx 1/m_c$
- In case of deuteron: all 6 quarks must be involved (at threshold)

hidden color part of the D wave function

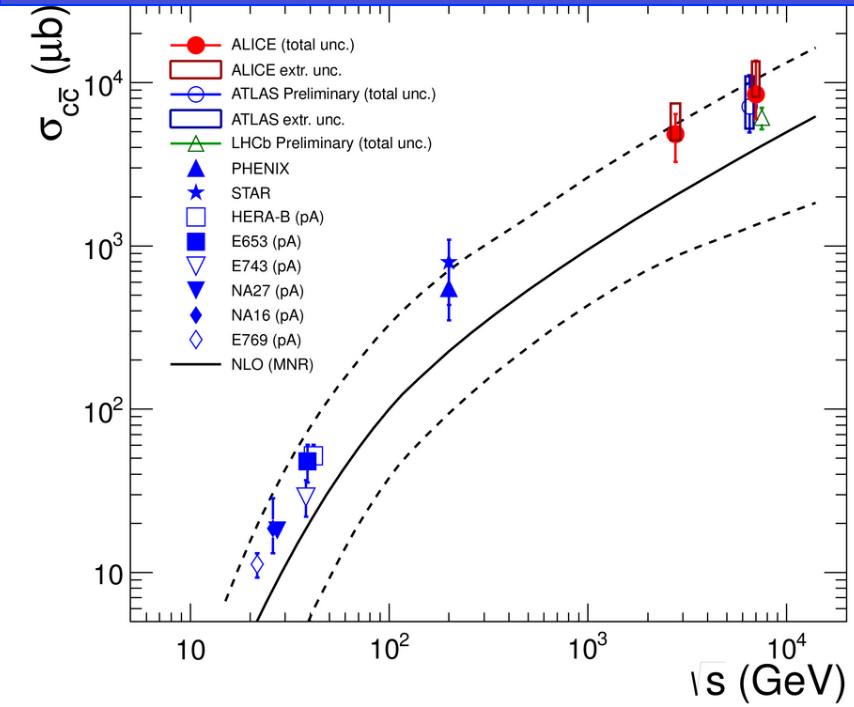
V. Matveev, P. Sorba Lett. Nuovo Cimento, 20 (1977) 435

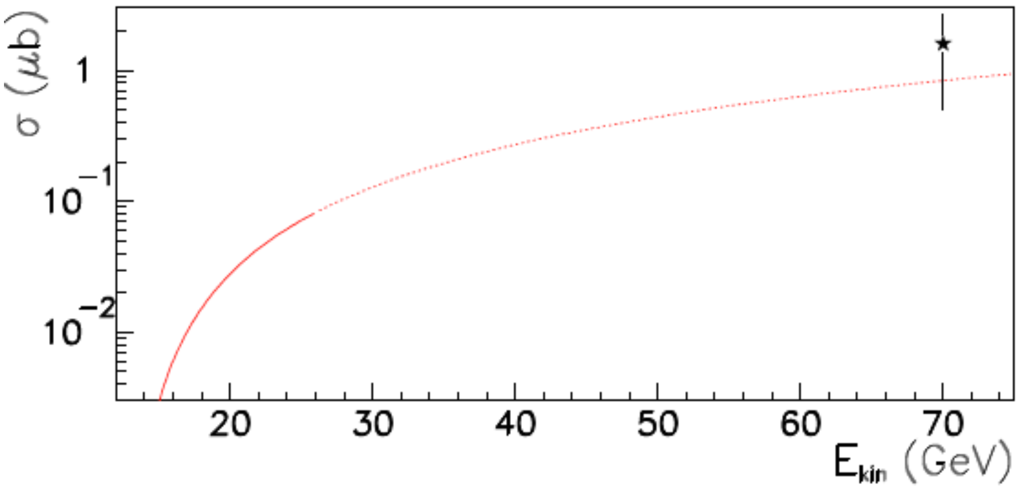


- Characteristic scales
  - Transverse size
    $r_T \approx 1/m_c \approx 0.13$ fm
- Small impact parameter

S.J. Brosky et al., Phys., lett. B498,23(2001)

Open Charm: $N+N \to N+\overline{D}+\Lambda_c\,(\Sigma_c)$

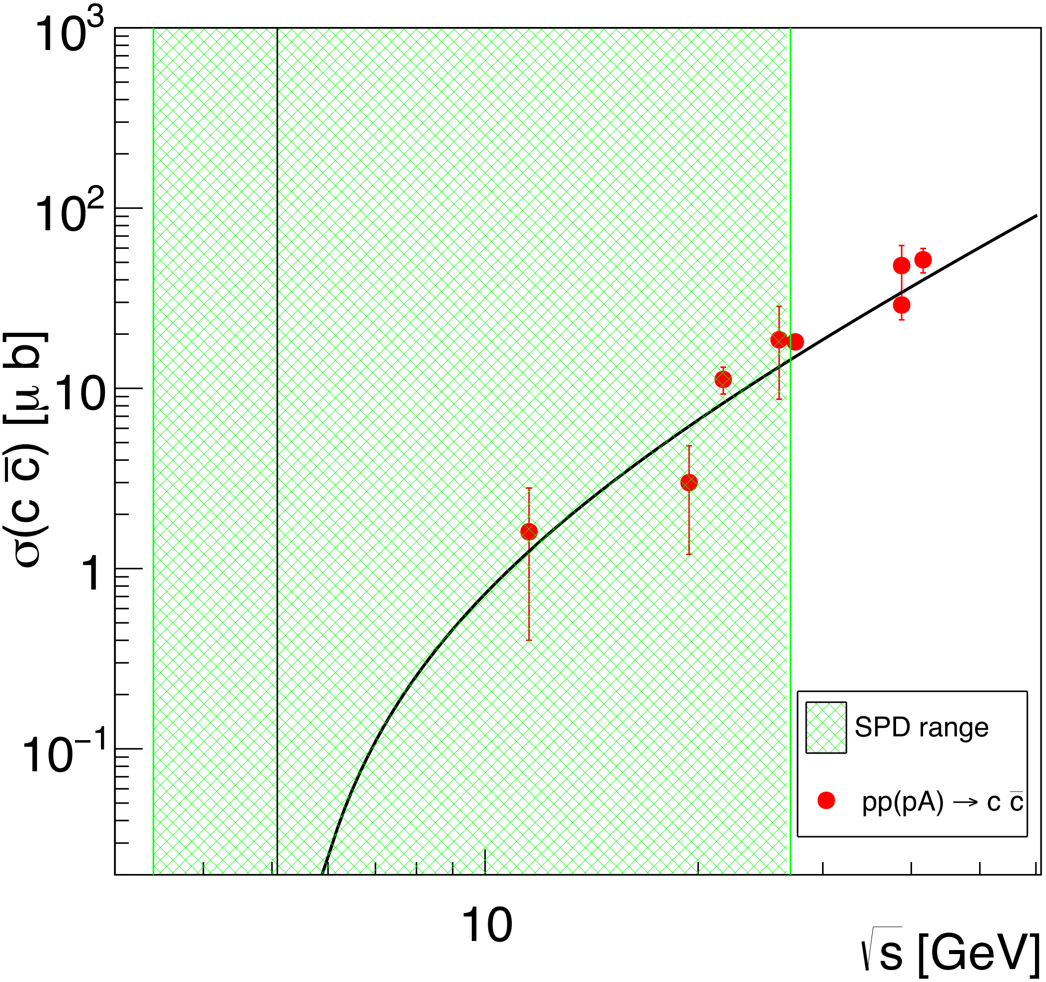




- Cross sections ≈ μb
- Dynamics of charm creation in NN, NA, and AA-collisions
- Spin and isospin effects
- Analogy with strangeness production: interaction
  $N\Lambda_s$ $N\Lambda_c$
- Information on
  -scattering length,
  -effective radius,
  -hadronic form factors …

M.P. Rekalo, E.T.-G.. Eur. Phys. J. A16, 575 (2003).

Inclusive Charm production



Expected counting rate:

For : $\mathcal{L}=10^{30}$ cm^{-2} s^{-1}

$\sigma \sim 10\ \mu b$

one expects :

3×10^4 counts/h

Not corrected for efficiency, Acceptance, reconstruction...

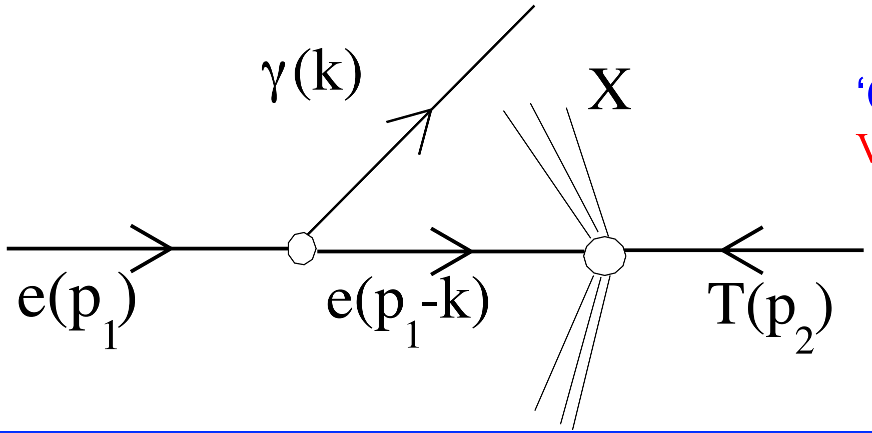
upper limit

at the highest energy

Useful parametrization:

$$\sigma[\mu b] = 0.03(Q[\mathrm{GeV}])^2$$

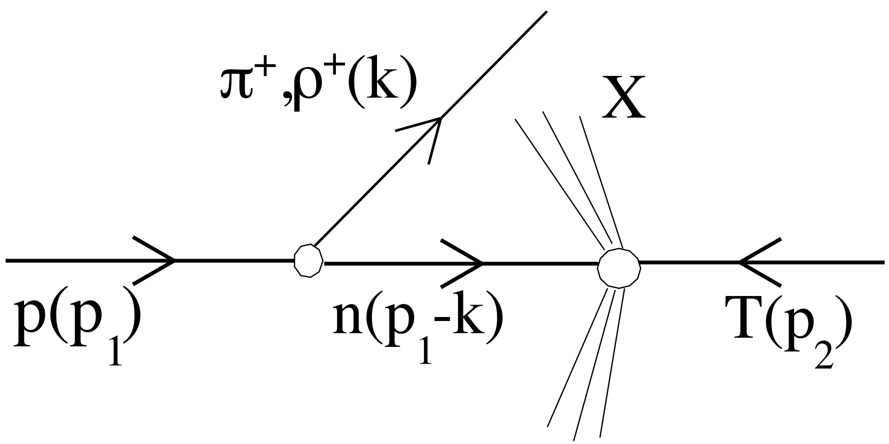
Backward light meson in pp or pA



'Quasi real electron method'

V.N. Baier, V. S. Fadin, V.M. Katkov (1973)

Extension of the *QED quasi real electron method* mechanism to light meson emission in pp or pA collisions



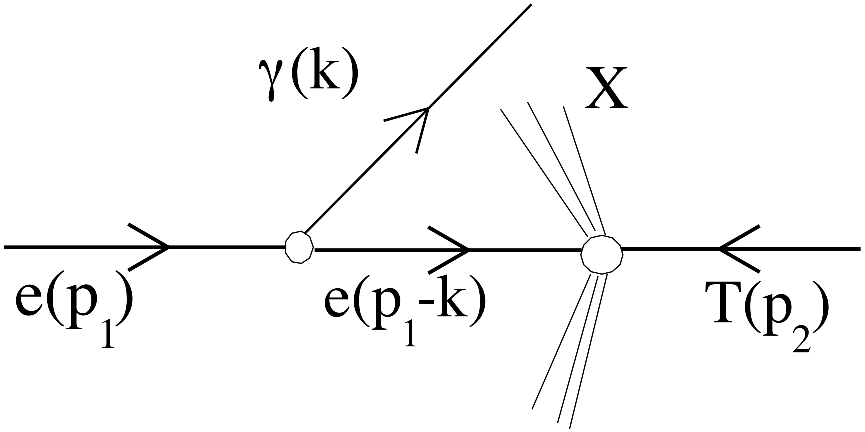
- Collinear emission probability has logarithmic enhancement
- Factorization of the cross section

Production of neutron beams?

E.A. Kuraev et al., Phys. Elem. Part and At. Nuclei 12 (2015) 1

Quasi Real Electron Method

V.N. Baier, V. S. Fadin, V.A. Khoze, Nucl. Phys. B65 (1973) 381



- Hard photon: the virtual electron after the hard collinear photon emission **is almost on mass shell**

$$\mathcal{M}_\gamma(p_1,p_2) = e\overline{\mathcal{T}}(p_2)\frac{\hat{p}_1-\hat{k}+m}{-2p_1k}\hat{\varepsilon}(k)u(p_1).$$

$$|(p_1 - k)^2 \; m^2| \ll 2p_1p_2$$

$$\hat{p}_1-\hat{k}+m = \sum_s u_s(p_1-k)\bar{u}^s(p_1-k)$$

- **Factorization of the cross section**

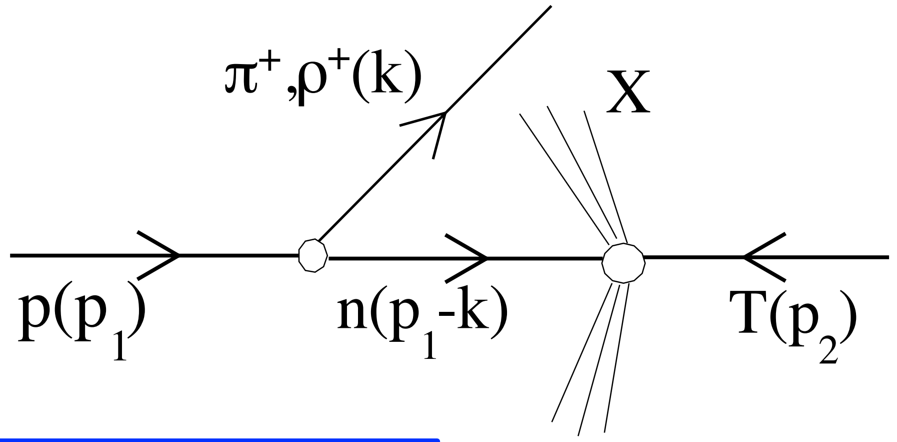
$$d\sigma_\gamma(s,x) = d\sigma(\bar{x}s)dW_\gamma(x), \quad \bar{x} = 1-x,$$

$$dW_\gamma(x) = \frac{\alpha}{\pi}\frac{dx}{x}\left[\left(1-x+\frac{1}{2}x^2\right)\ln\frac{E^2\theta_0^2}{m_e^2}-(1-x)\right],$$

$$x = \frac{\omega}{E}, \quad \theta<\theta_0\ll 1, \quad \frac{E\theta_0}{m_e}\gg 1,$$

Collinear emission probability has logarithmic enhancement (small mass of the intermediate electron)
QRE method

$p+T \rightarrow n+T+h^+$



The matrix element:

$$\mathcal{M}^{pT}_{h_+}(p_1,p_2)) = \mathcal{M}_{nT}(p_1-k,p_2)\mathcal{T}^{pn}_{h_+}(p_1,p_1-k),$$

The matrix element for the subprocess :

$$\mathcal{T}^{pn}_{\pi}(p_1,p_1-k) = \frac{g}{m_h^2-2p_1k}\bar{u}_n(p_1-k)\gamma_5 u_p(p_1),$$

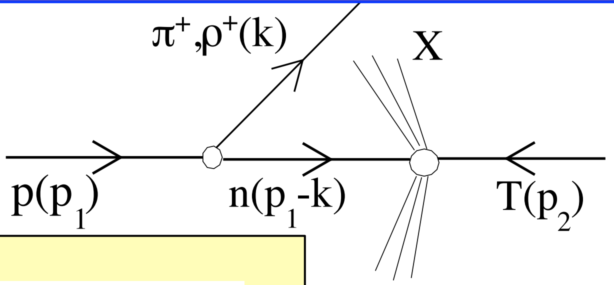
$p \rightarrow n+\pi$

$$\mathcal{T}^{pn}_{\rho}(p_1,p_1-k) = \frac{g}{m_h^2-2p_1k}\bar{u}_n(p_1-k)\hat{\epsilon}u_p(p_1),$$

$p \rightarrow n+\rho$

$p+T \to n+T+h^+$

The cross section for ρ emission:



$$d\sigma^{pT\to h_+X}(s,x) = \sigma^{nT\to X}(\bar{x}s)\,dW_{h_+}(x)$$

$$\frac{dW_{\rho^i}(x)}{dx} = \frac{g^2}{4\pi^2}\frac{1}{x}\sqrt{1-\frac{m_\rho^2}{x^2E^2}}\left[\left(1-x+\frac{1}{2}x^2\right)L-(1-x)\right],$$

$$1 > x = \frac{E_\rho}{E} > \frac{m_\rho}{E},\quad L = \ln\left(1+\frac{E^2\theta_0^2}{M^2}\right), \qquad (9)$$

g ≈ 6 Strong coupling (for ρ and π emission)
θ_0: (small) meson emission angle

V.N. Baier, V.S. Fadin, V.A. Khoze, Nucl Phys. B. 65 (1973) 381

p+T→ n+T+ π

The cross section for π emission :

$$d\sigma^{pT\to h_0X}(s,x) = \sigma^{pT\to X}(\bar{x}s)\,dW_{h_0}(x)$$

$$\sum |\mathcal{M}_{pn}(p_1,p_1-k)|^2 = \frac{g^2}{[m_\pi^2-2(p_1k)]^2}Tr(\hat{p}_1-\hat{k}+M)\gamma_5(\hat{p}_1+M)\gamma_5$$

$$= \frac{4(p_1k)g^2}{[m_\pi^2-2(p_1k)]^2} \quad (p_1k)=E\omega(1-bc), 1-b^2\approx\frac{m_\pi^2}{\omega^2}+\frac{M^2}{E^2}$$

Angular integration :

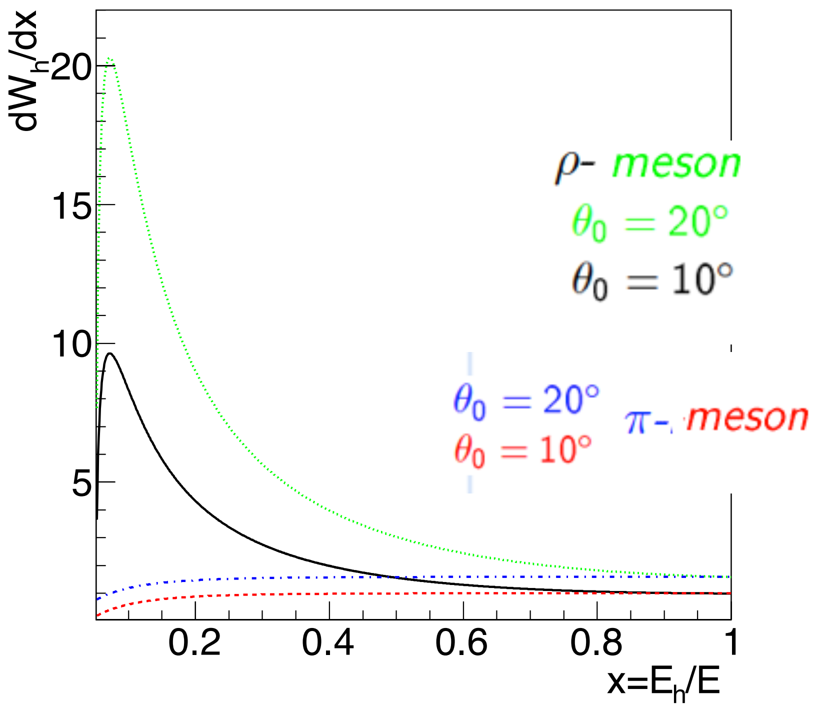
$$1-(\theta_0^2/2)<c<1,\ c=\cos(\vec{k},\vec{p}_1)$$

$$\frac{dW_\pi^i(x)}{dx} = \frac{g^2}{8\pi^2}\sqrt{1-\frac{m_\pi^2}{x^2E^2}}\left[L+\ln\frac{1}{d(x)}+\frac{m_\pi^2}{xd(x)M^2}\right],$$

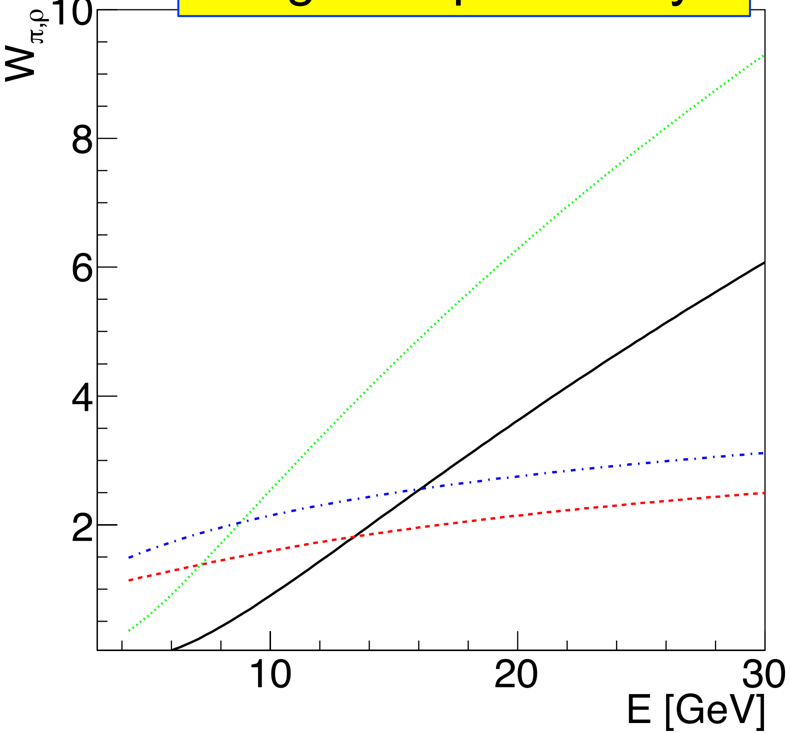
$$x = \frac{E_\pi}{E}>\frac{m_\pi}{E},\quad d(x)=1+\frac{m_\pi^2\bar{x}}{M^2x^2},\quad \bar{x}=1-x,$$

dW_h/dx

« Not normalized » probability



Integrated probability



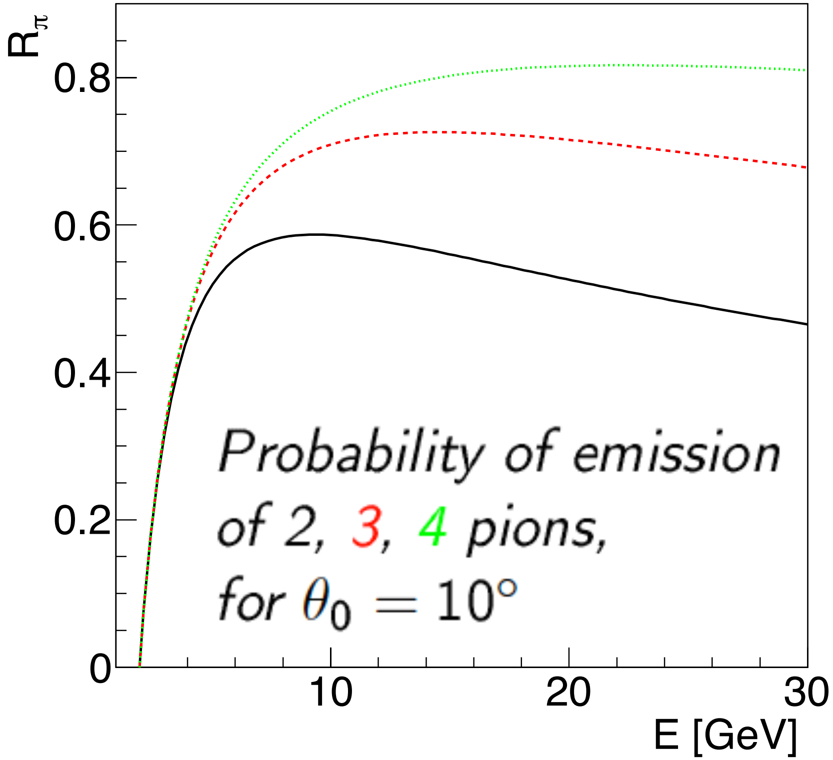
- W_i (integrated) may exceed unity, violating unitarity
- Correct by virtual emission of « soft » emission and absorption of off-mass shell mesons
- Poisson formula : $W_n = (a^n/n!)e^{-a}$

Renormalization factor

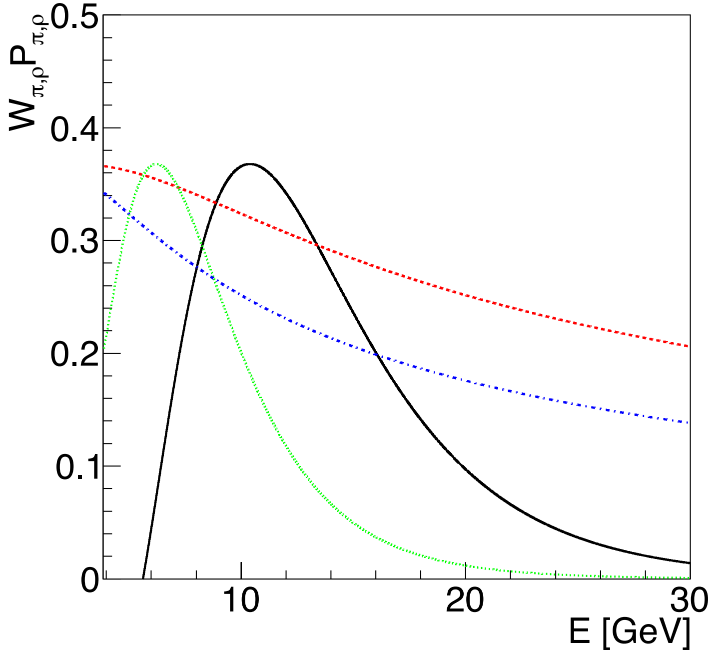
$$\sigma(s) \to \sigma(s) \times \mathcal{R}_\pi, \ \mathcal{R}_\pi = P_\pi \sum_{k=0}^{k=n} \frac{W_\pi^k}{k!}.$$

$$P_\pi = e^{-W_\pi}$$

Takes into account virtual corrections



« Normalized » probability



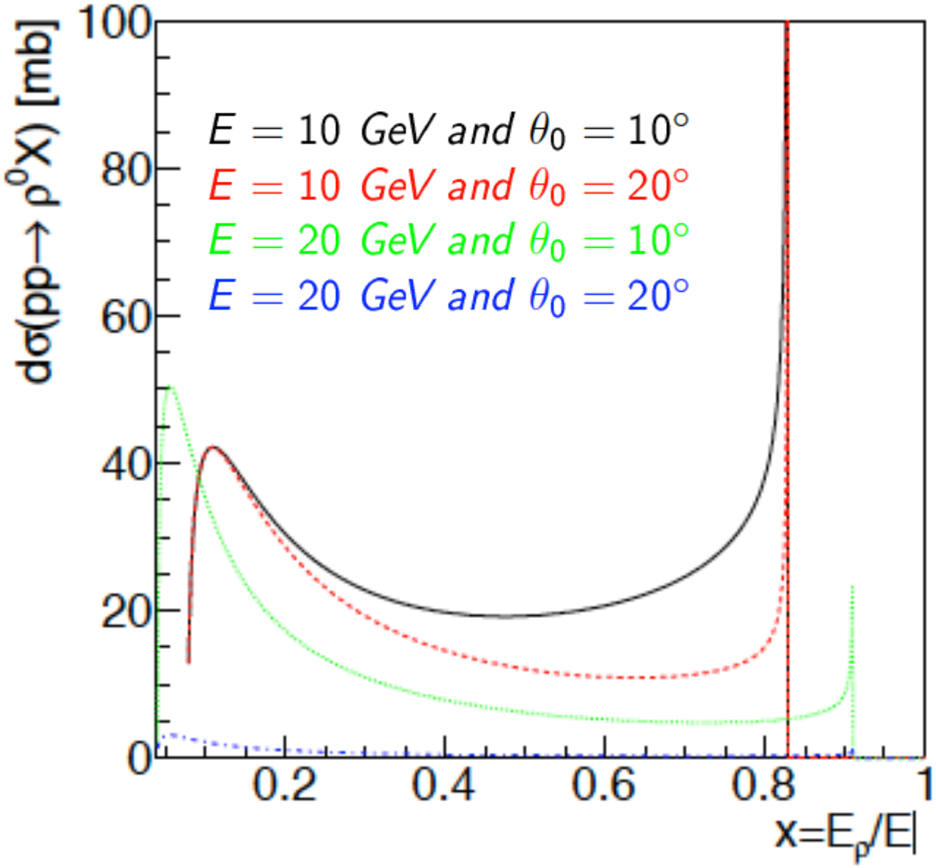
Two pion production from $pp \to \rho^0 X$

$$d\sigma^{p\bar{p}\to\rho^0 X} = 2\frac{dW_\rho(x)}{dx}\sigma^{p\bar{p}\to\rho^0 X}(\bar{x}s)\times P_\rho,$$

- Factor of 2: emission possible from each beam

- Characteristic peak at the end of the spectrum: **threshold effect**

in QED: $e^+e^- \to \mu^+\mu^-\gamma$
it corresponds to the creation of a muon pair:
$x_{max} = 1-4M^2_\mu / (4s)$



E.A. Kuraev et al., Phys. Elem. Part. and At. Nuclei 12 (2015) 1

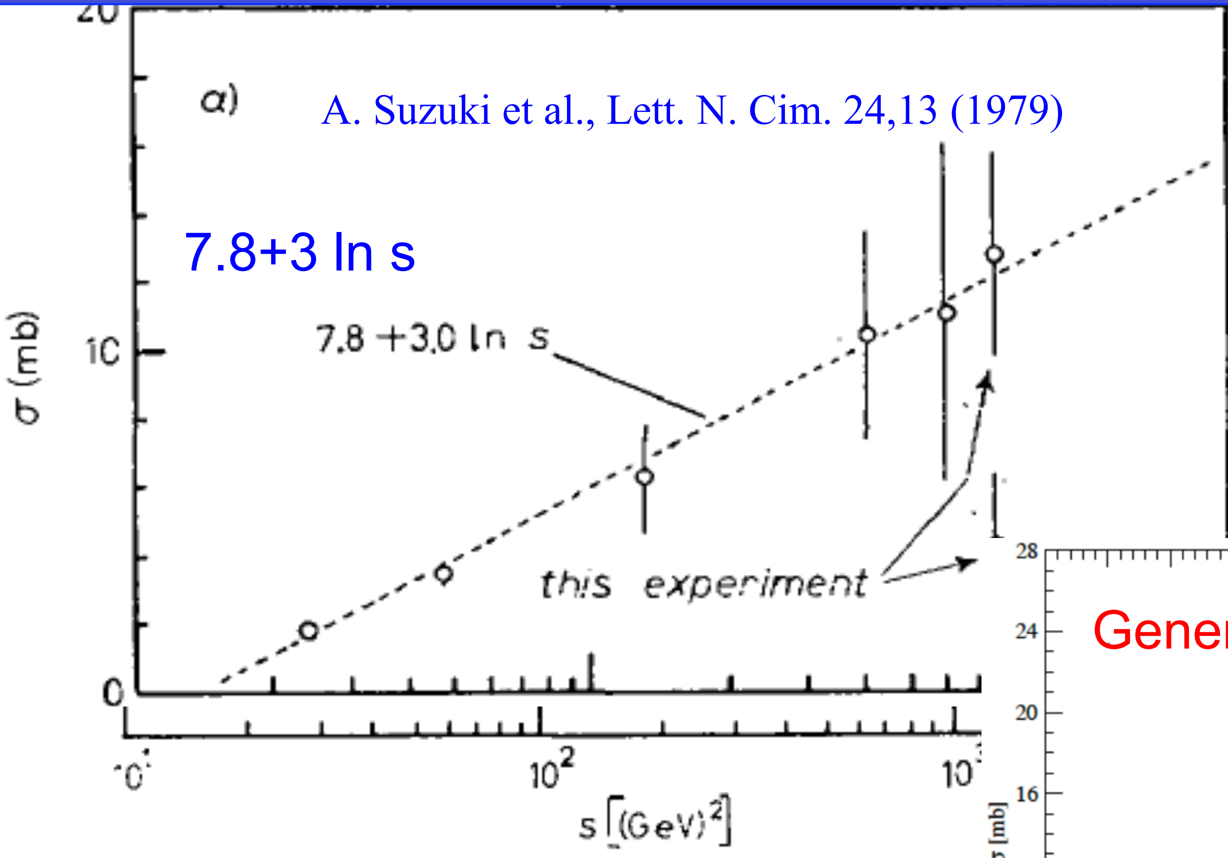
Three pion production

Assuming that the process occurs through:

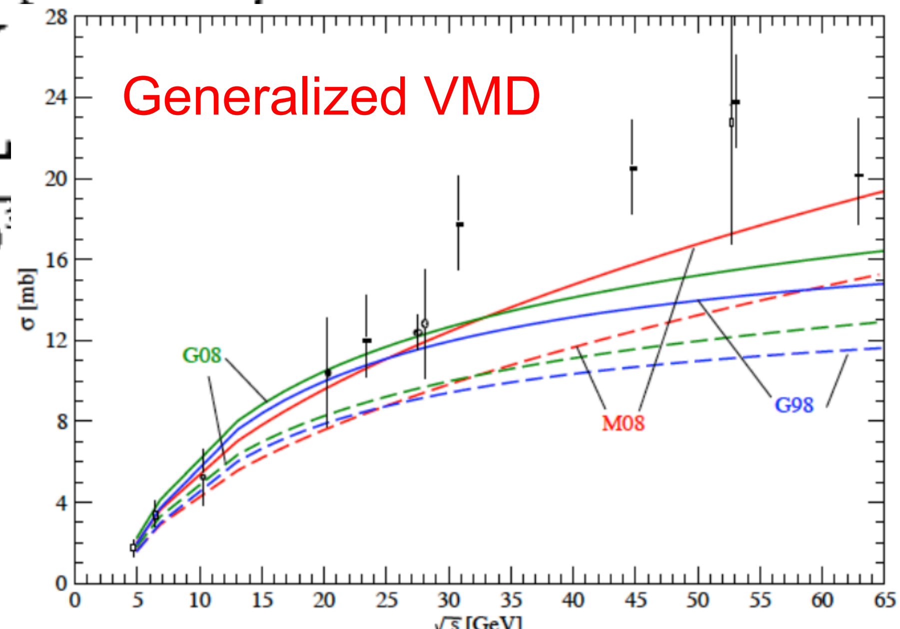
1. ρ-meson initial state emission
2. Subsequent decay $\rho \to \pi^+ \pi^-$

$$d\sigma(p,\bar{p})^{p\bar{p}\to\pi\rho X} = dW_\rho^0(x_\rho)\,dW_\pi^0(x_\pi)$$
$$\times\,[d\sigma(p-p_\rho,\bar{p}-p_\pi)^{p\bar{p}\to X}$$
$$+\,d\sigma(p-p_\pi,\bar{p}-p_\rho)^{p\bar{p}\to X}]P_\pi P_\rho,$$

Experimental status for $pp \to \rho^0 X$



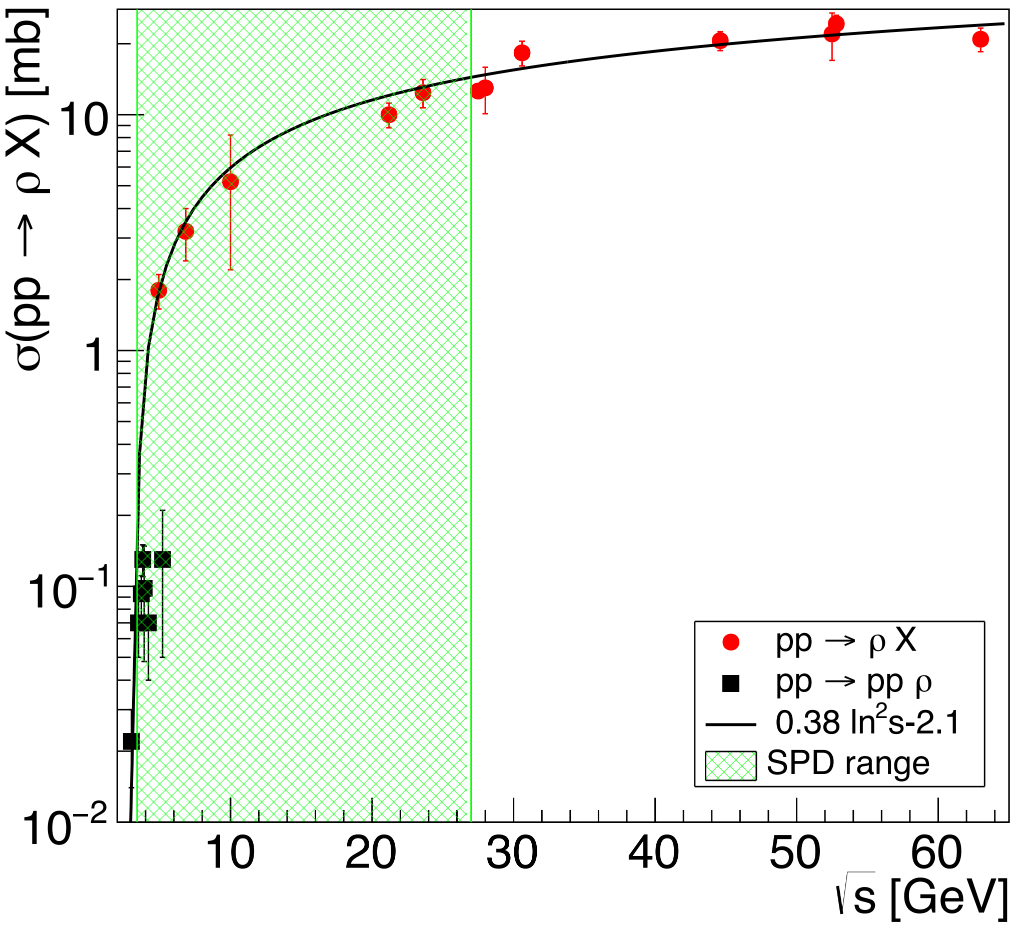
Empirical parametrization



A.I. Machiavariani arXiv:1712.06395hep-ph

Experiments from the 1970's, mainly at CERN

Experiments for NICA-SPD



- Polarized proton beams
- Sqrt(s) = 3.4-27 GeV
- $\mathcal{L}=(10^{29}-10^{32})\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$

For : $\mathcal{L}=10^{30}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$

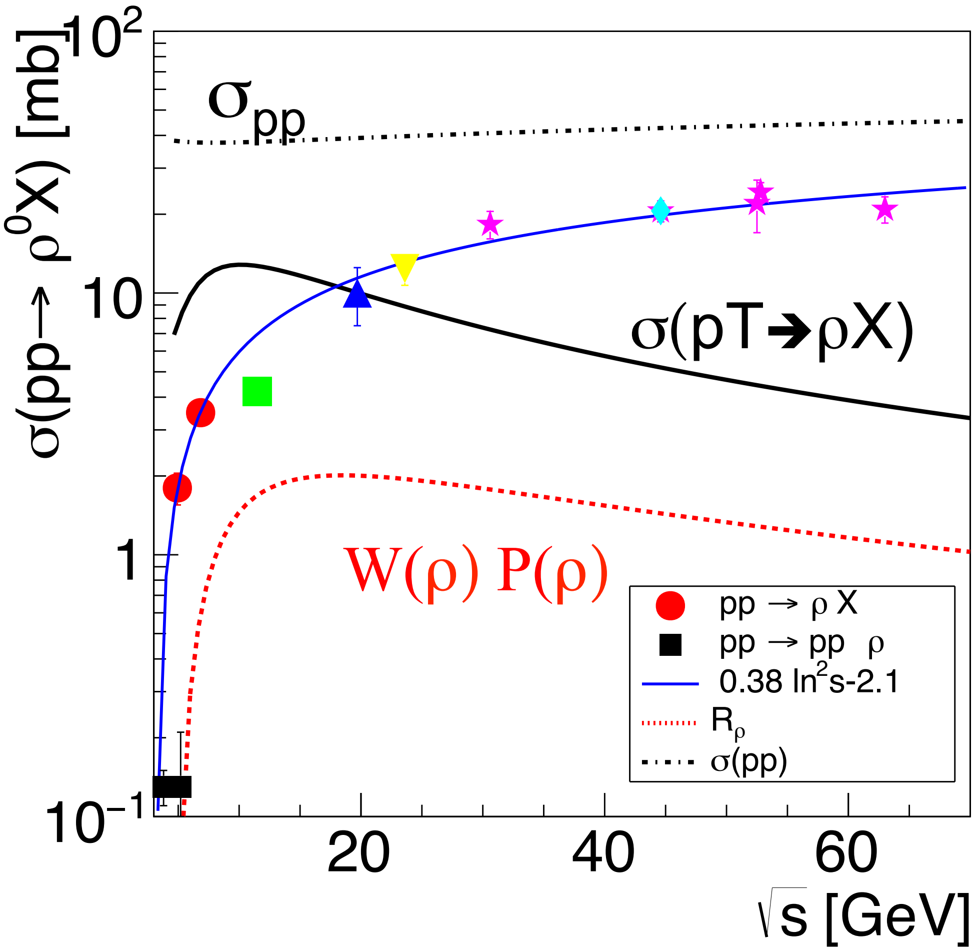
$\sigma=1$ mb

one expects 3000 counts/h

$\sigma(s)= 0.38 \log^2(s^2) -2.1$

M.G. Albrow et al., Nuclear Physics B155 (1979) 39-51

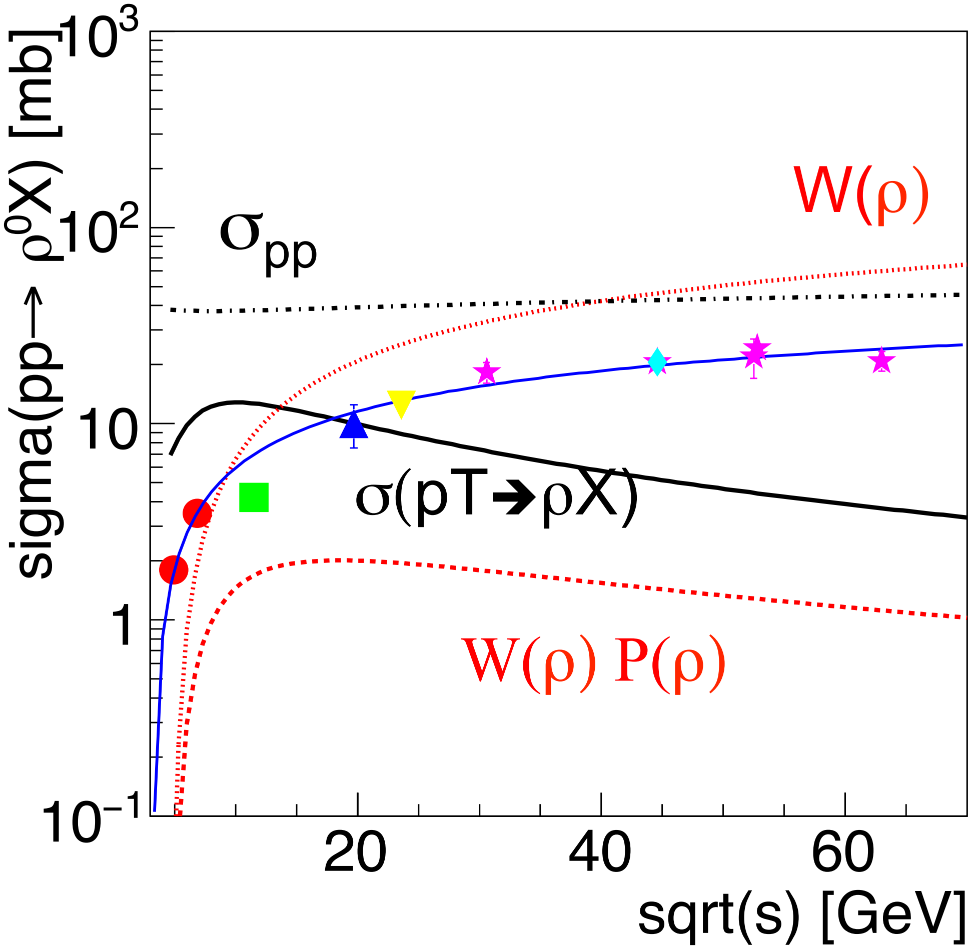
Model predictions

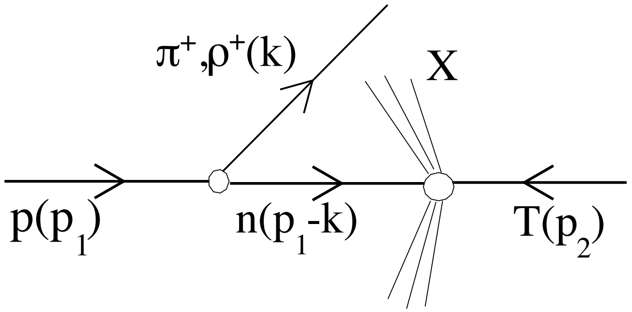


$\sigma(s) = 0.38 \log^2(s^2) - 2.1$

M.G. Albrow et al., Nuclear Physics B155 (1979)
39-51

Producing a neutron beam?





From the factorization hypothesis

$$\sigma^{nT\to X}(\bar{x}s) = \frac{d\sigma^{pT\to h^+X}/dx}{dW_+(x)/dx}$$

$\sigma(s) = 0.38 \log^2(s^2) - 2.1$

M.G. Albrow et al., Nuclear Physics B155 (1979) 39-51

Conclusions

- NICA-SPD can do a systematic study of meson production in pp and pA collisions, *charmed and light mesons in a large energy region above threshold.*

- To understand
  - the mechanism of charm production in nucleon and nuclei
  - the properties of mesons (*mass, width*) in nuclear matter

- Backward meson production (background free)
  - NICA-SPD: colliding beams and polarization
  - Neutron beams?

Thank you for attention

Спасибо за внимание