The quasi-real electron method applied to backward meson production in hadron collisions

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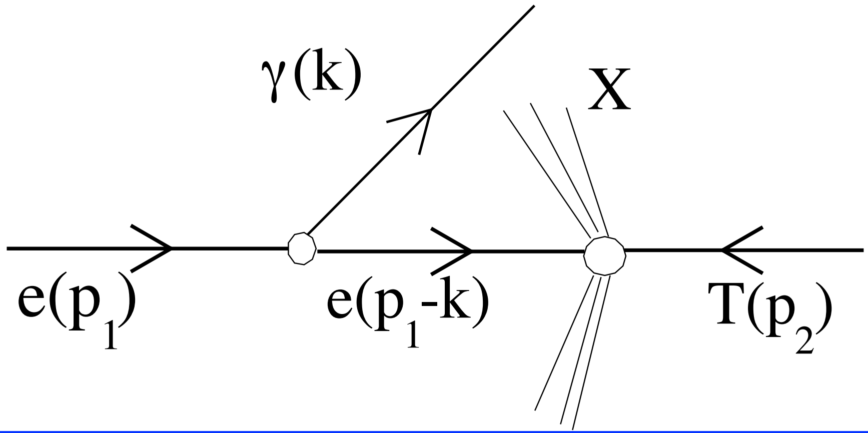
Seminar devoted to the memory of Professor Vladimir Nikolaevich Baier (27.09.1930 - 19.02.2010)

Novosibirsk, September 28-29, 2020

Plan

- Introduction: quasi real electron method
- ISR – FFs at BaBar, BES
- Backward meson production
- Application to NICA-SPD (PANDA …)
- Conclusions

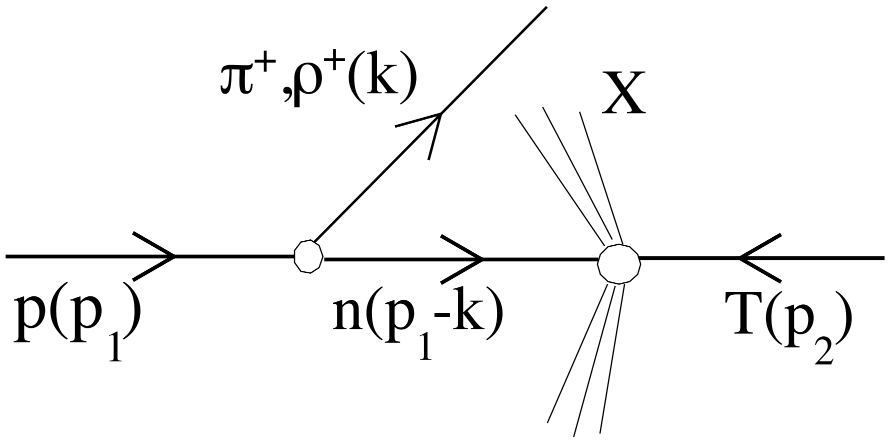
Backward light meson in pp or pA



‘Quasi real electron method’

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

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



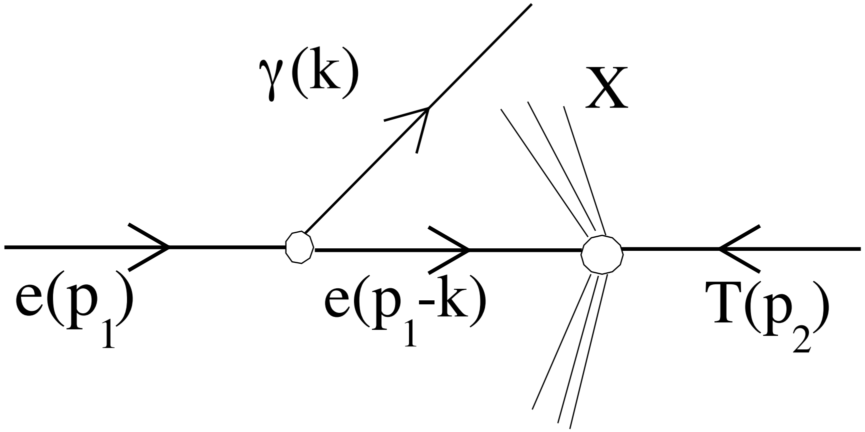
Application for SPD@NICA and PANDA@FAIR

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



- 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**

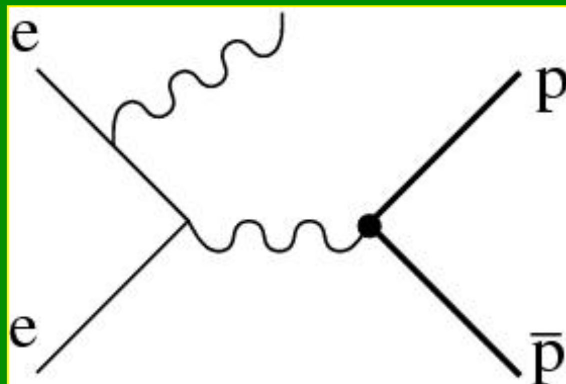
$$d\sigma_\gamma(s, x) = d\sigma(\bar{x}s)dW_\gamma(x), \quad \bar{x} = 1 - x,$$

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

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

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

Radiative return (ISR)



BABAR

$$e^+ + e^- \to p + \bar{p} + \gamma$$

$$\frac{d\sigma(e^+e^- \to p\bar{p}\gamma)}{dm\, d\cos\theta} = \frac{2m}{s} W(s,x,\theta)\, \sigma(e^+e^- \to p\bar{p})(m), \quad x = \frac{2E_\gamma}{\sqrt{s}} = 1 - \frac{m^2}{s},$$

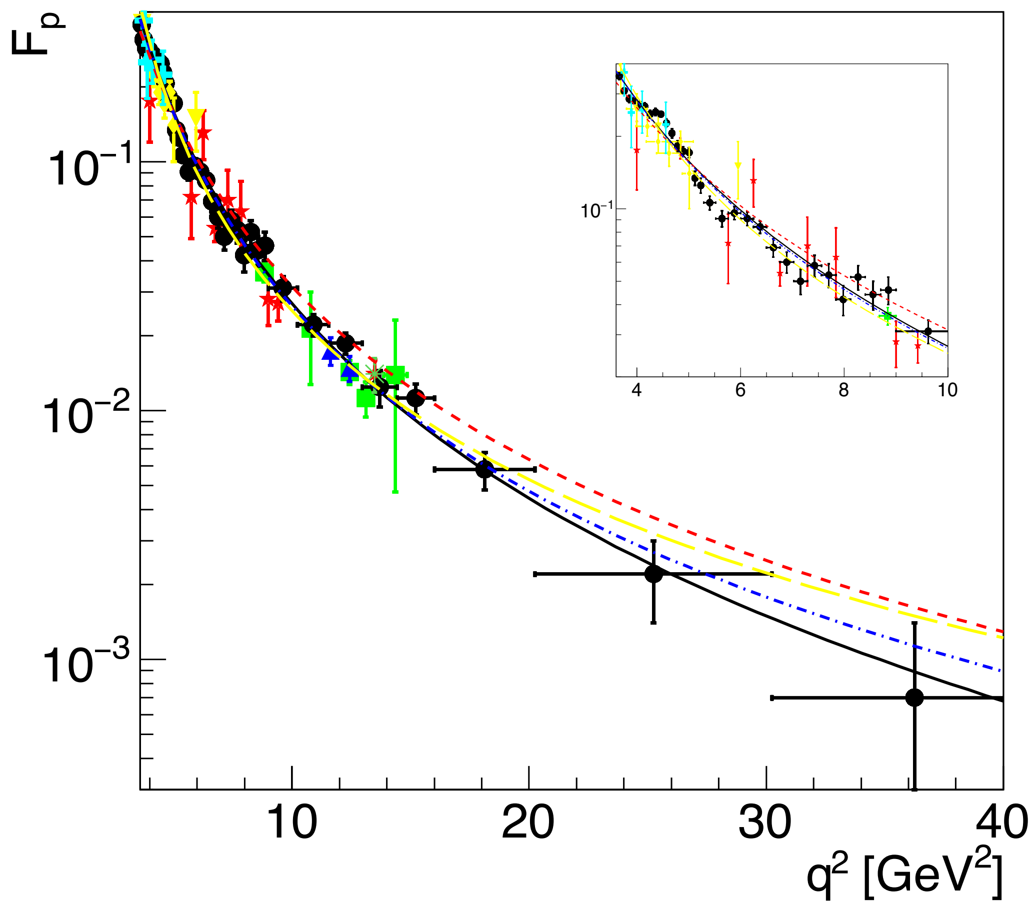
$$W(s,x,\theta) = \frac{\alpha}{\pi x}\left(\frac{2-2x+x^2}{\sin^2\theta} - \frac{x^2}{2}\right), \quad \theta >> \frac{m_e}{\sqrt{s}}.$$

*B. Aubert (BABAR Collaboration) Phys Rev. **D73**, 012005 (2006)*

The Time-like Region

GE=GM 'effective FF'

- The Experimental Status
  - No determination of GE and GM
  - TL proton FFs twice larger than in SL at the same Q^2
  - Steep behaviour at threshold
  - Babar:Structures? Resonances?



S. Pacetti, R. Baldini-Ferroli, E.T-G , Physics Reports, 514 (2014) 1

Panda contribution: *M.P. Rekalo, E.T-G , DAPNIA-04-01, ArXiv:0810.4245.*

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  - TL proton FFs twice larger than in SL at the same Q^2
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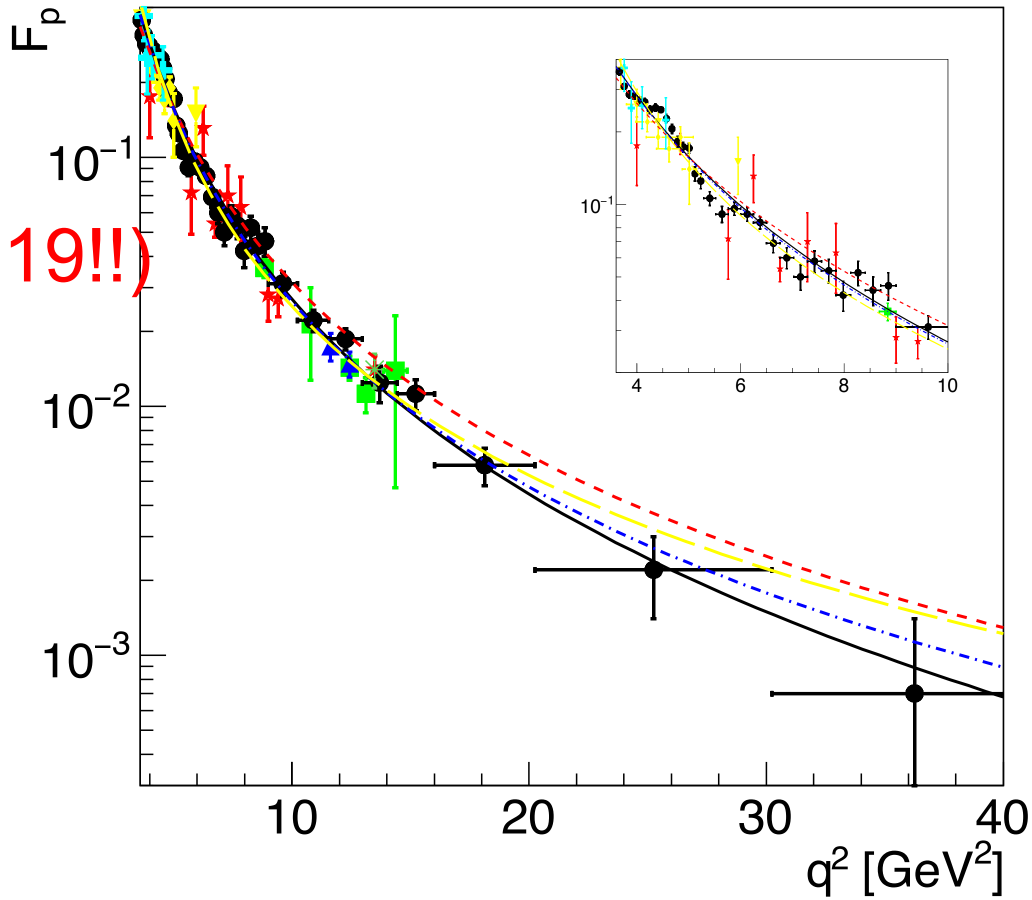

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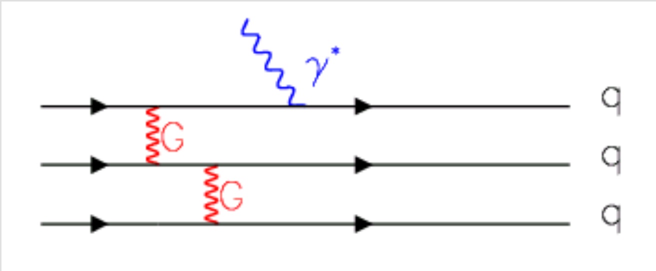


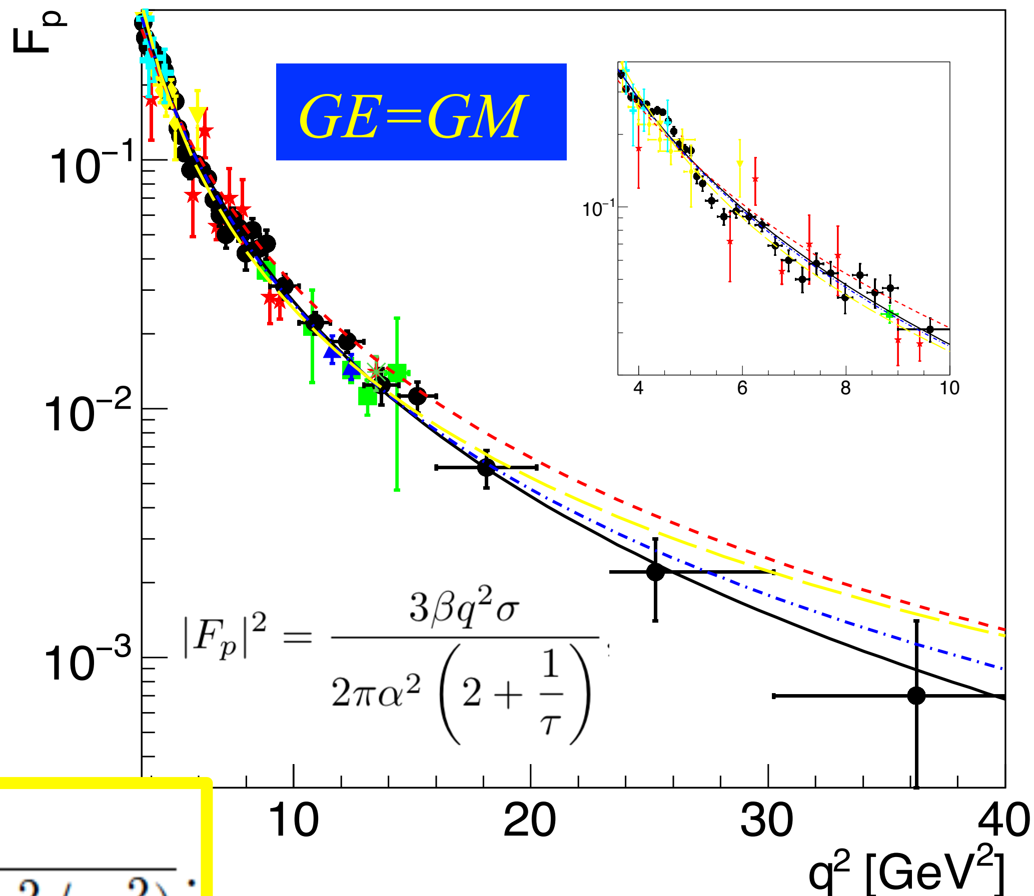
Expected QCD scaling $(q^2)^2$

$$|F_{scaling}(q^2)| = \frac{\mathcal{A}}{(q^2)^2 \log^2(q^2/\Lambda^2)}$$

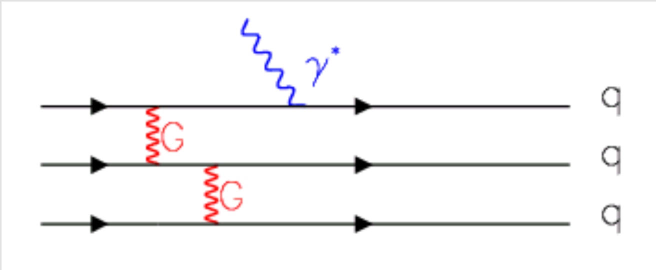
$$\frac{\mathcal{A}}{(1+q^2/m_a^2)\left[1-q^2/0.71\right]^2},$$

$$|F_{T3}(q^2)| = \frac{\mathcal{A}}{(1-q^2/m_1^2)(2-q^2/m_2^2)}.$$

$$e^+ + e^- \to \bar{p} + p\,,$$
$$\bar{p} + p \to e^+ + e^-$$



The Time-like Region

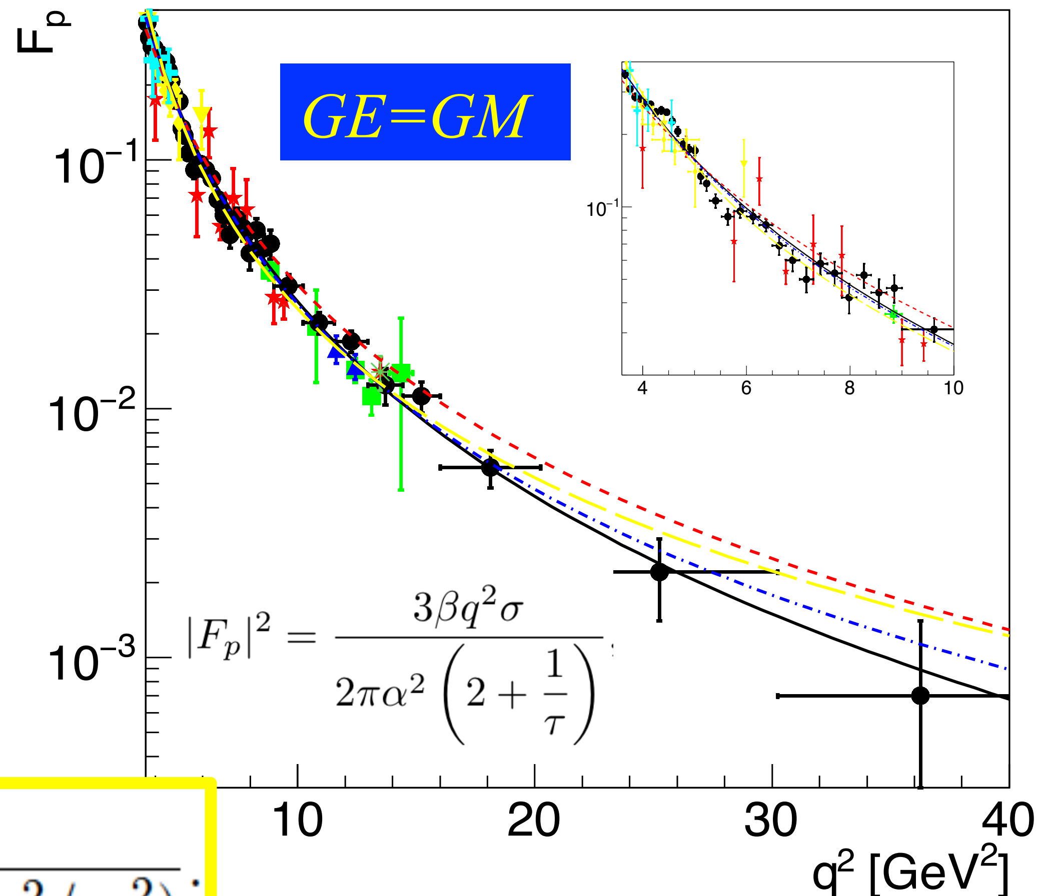


Expected QCD scaling $(q^2)^2$

$$e^+ + e^- \to \bar{p} + p\,,$$
$$\bar{p} + p \to e^+ + e^-$$

$$\frac{\mathcal{A}}{(q^2)^2\left[\log^2(q^2/\Lambda^2)+\pi^2\right]}.$$

$$\frac{\mathcal{A}}{(1+q^2/m_a^2)\left[1-q^2/0.71\right]^2},$$

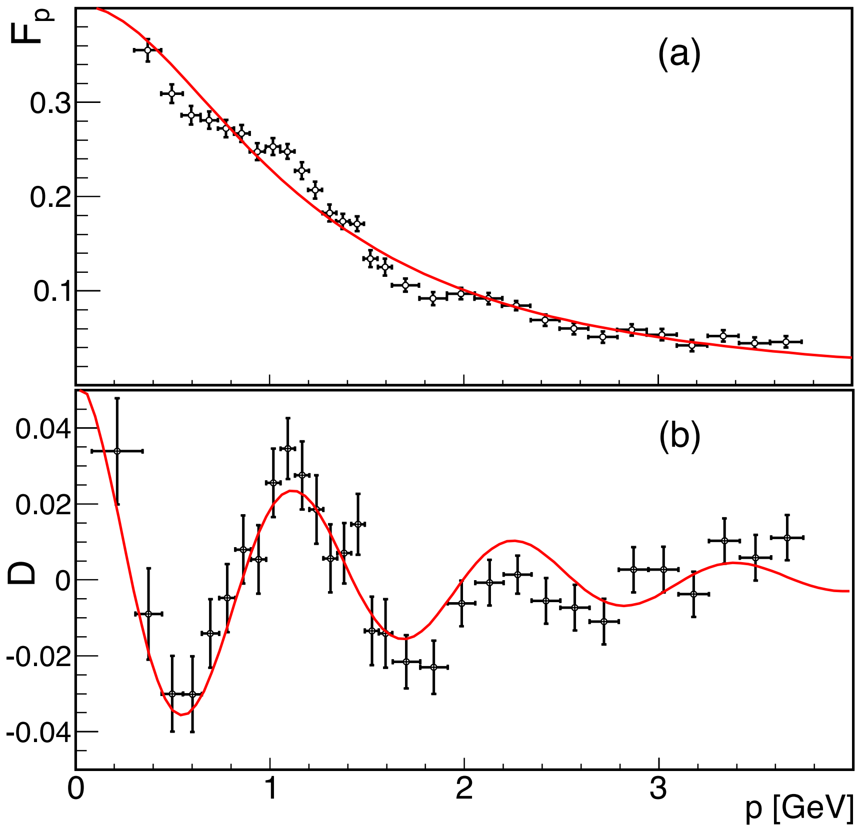


$$|F_p|^2 = \frac{3\beta q^2\sigma}{2\pi\alpha^2\left(2+\frac{1}{\tau}\right)}$$

$$|F_{T3}(q^2)| = \frac{\mathcal{A}}{(1-q^2/m_1^2)(2-q^2/m_2^2)}.$$

Oscillations : regular pattern in P_{Lab}

The relevant variable is p_{Lab} associated to the relative motion of the final hadrons.



$$F_{osc}(p) \equiv A \exp(-Bp) \cos(Cp + D).$$

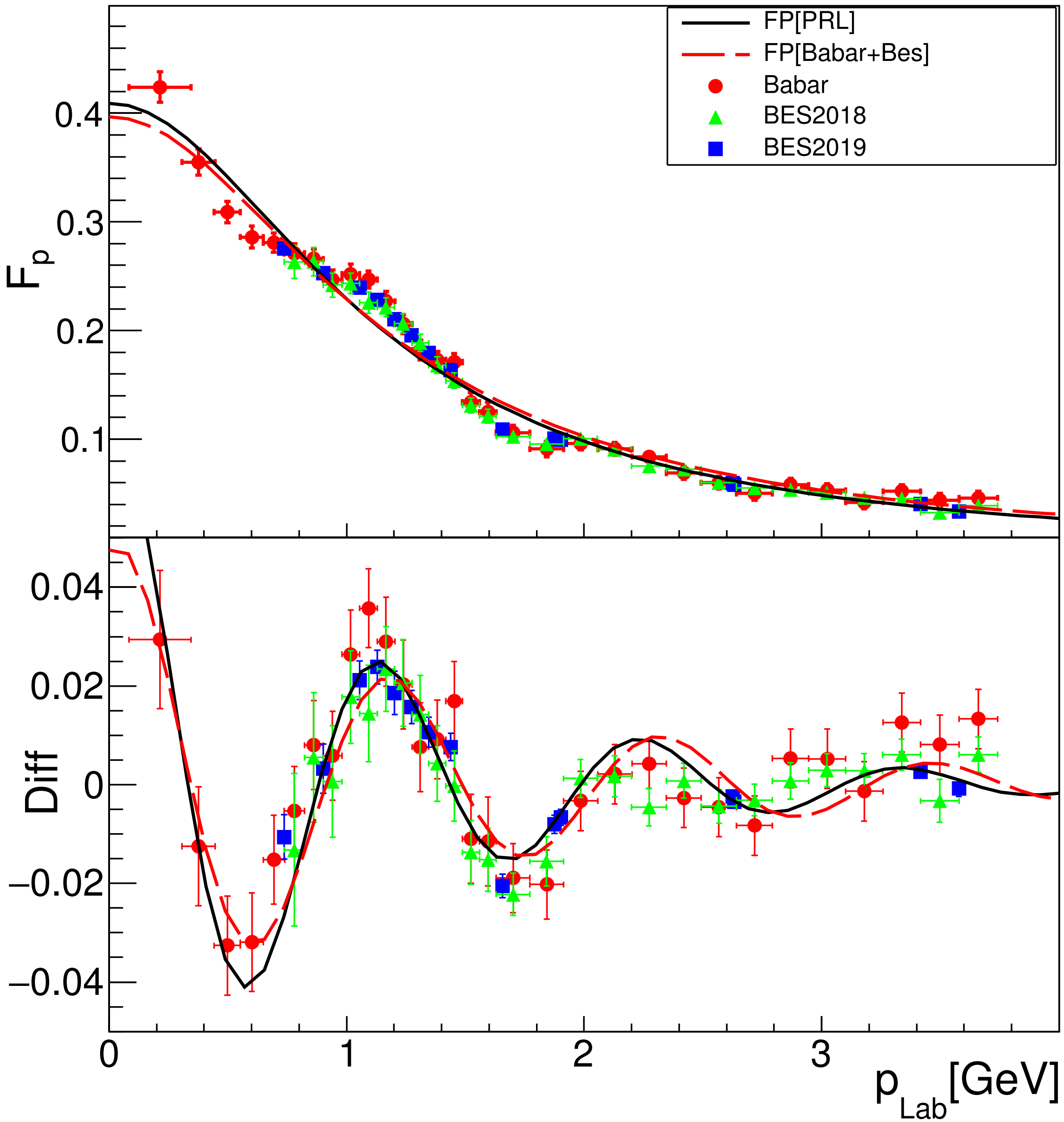
$A \pm \Delta A$	$B \pm \Delta B$ $[GeV]^{-1}$	$C \pm \Delta C$ $[GeV]^{-1}$	$D \pm \Delta D$	$\chi^2/n.d.f$
0.05 ± 0.01	0.7 ± 0.2	5.5 ± 0.2	0.03 ± 0.3	1.2

A: Small perturbation B: damping
C: r < 1fm D=0: maximum at p=0

Simple oscillatory behaviour
Small number of coherent sources

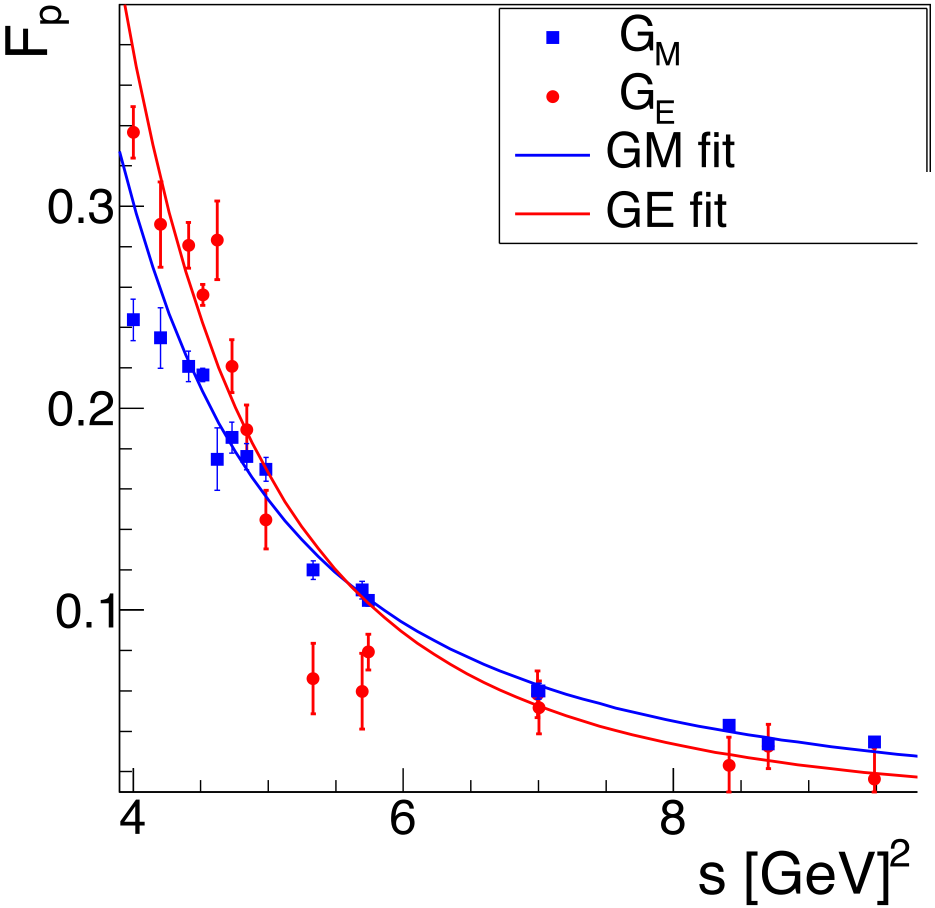
A. Bianconi, E. T-G. Phys. Rev. Lett. 114,232301 (2015)

Oscillations : confirmed by BESIII

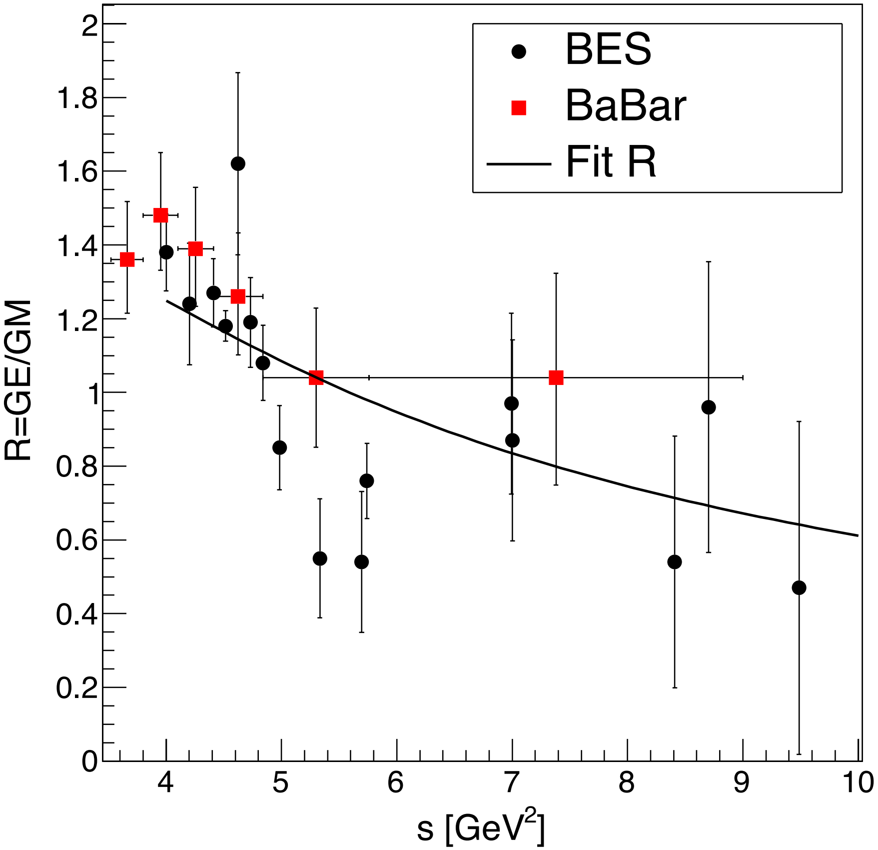


- *ISR BaBar*
- *ISR BESIII*
- *Beam scan*

G_E & G_M

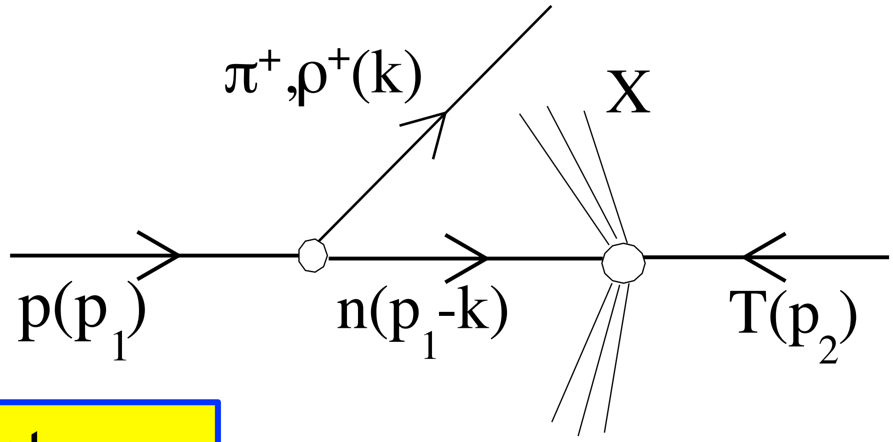


Ratio R



First individual FF determination in TL region !

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



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 :

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

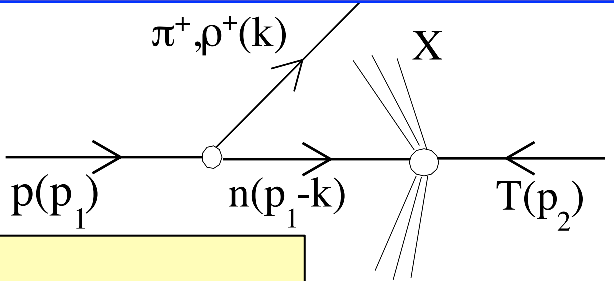
$p \to n+\pi$

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

$p \to n+\rho$

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

The cross section for ρ emission:



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

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

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

$g \approx 6$ 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

$p+T \to n+T+\pi$

The cross section for π emission :

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

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

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

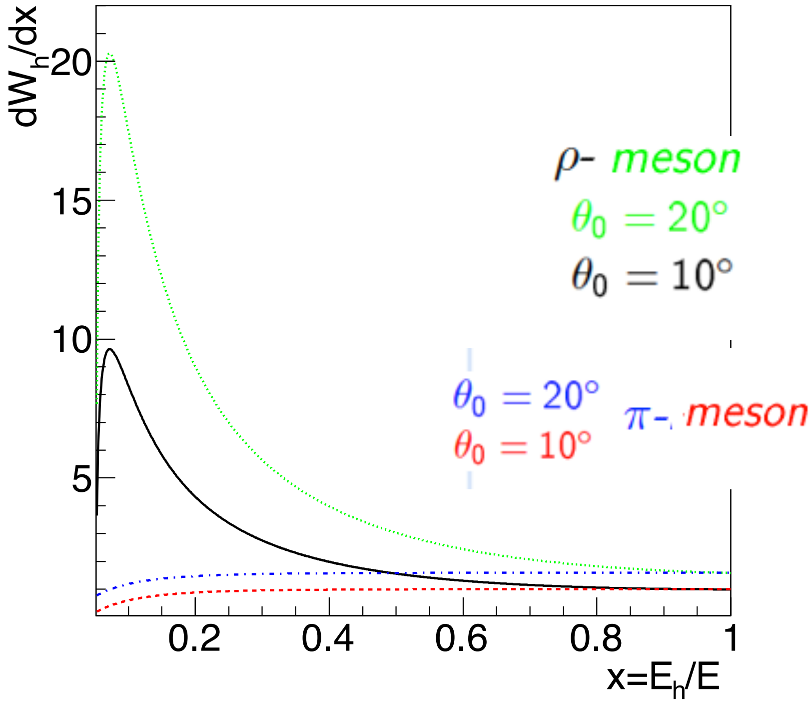
Angular integration : $1-(\theta_0^2/2) < c < 1,\ c=\cos(\vec{k},\vec{p}_1)$

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

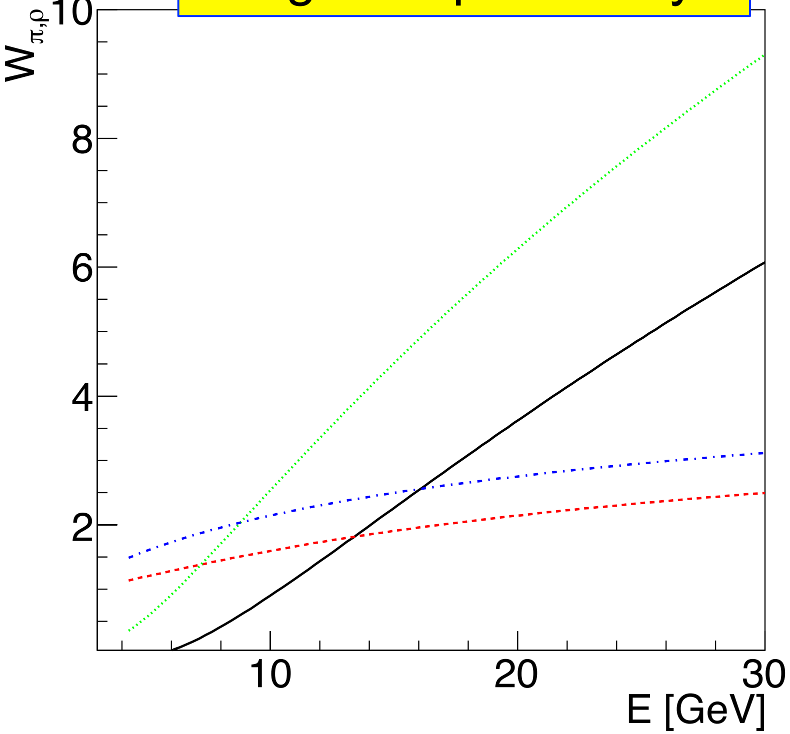
$$x = \frac{E_\pi}{E} > \frac{m_\pi}{E},\ d(x)=1+\frac{m_\pi^2\bar{x}}{M^2x^2},\quad \bar{x}=1-x,$$

dW_h/dx

« Not normalized » probability



Integrated probability



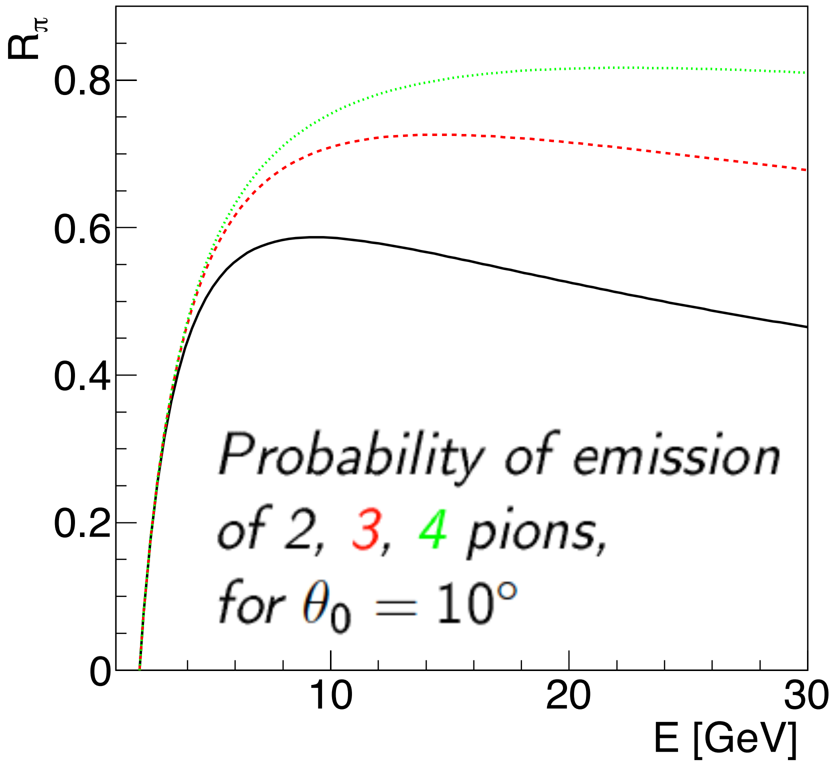
- W_i (integrated) may exceed unity, violating unitarity
- Correct by virtual emission of « soft » emission and absorption of off-mass shell mesons
- Poisson formula : $W_n = (a^n/n!)e^{-a}$

Renormalization factor

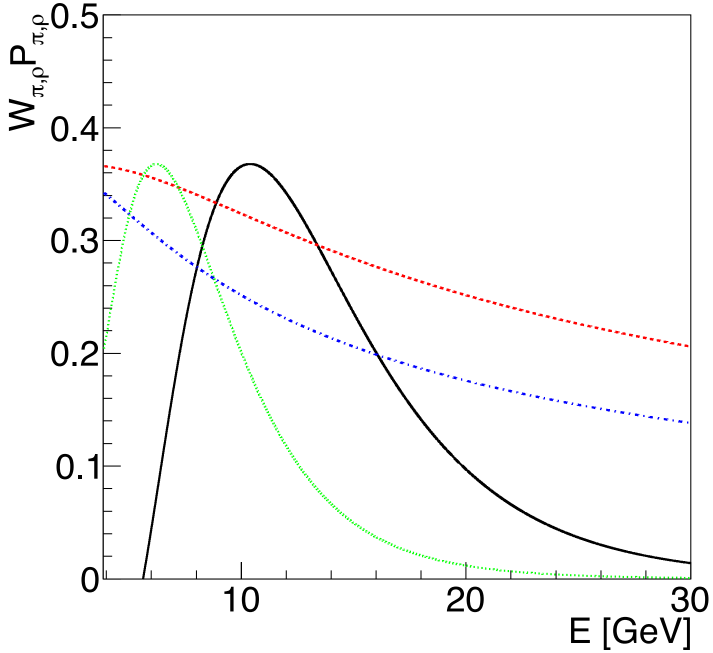
$$\sigma(s) \to \sigma(s) \times \mathcal{R}_\pi, \ \mathcal{R}_\pi = P_\pi \sum_{k=0}^{k=n} \frac{W_\pi^k}{k!}.$$

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

Takes into account virtual corrections



« Normalized » probability

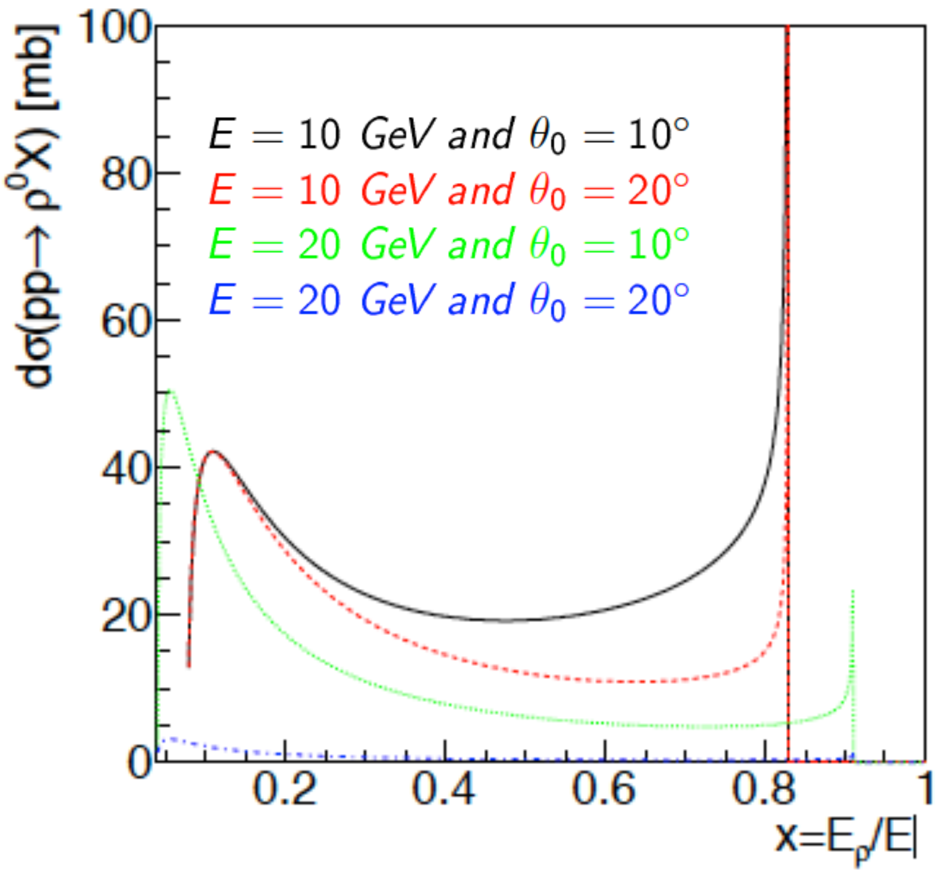


Two pion production from $pp \to \rho^0 X$

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

- 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 $\rho \to \pi^+\pi^-$

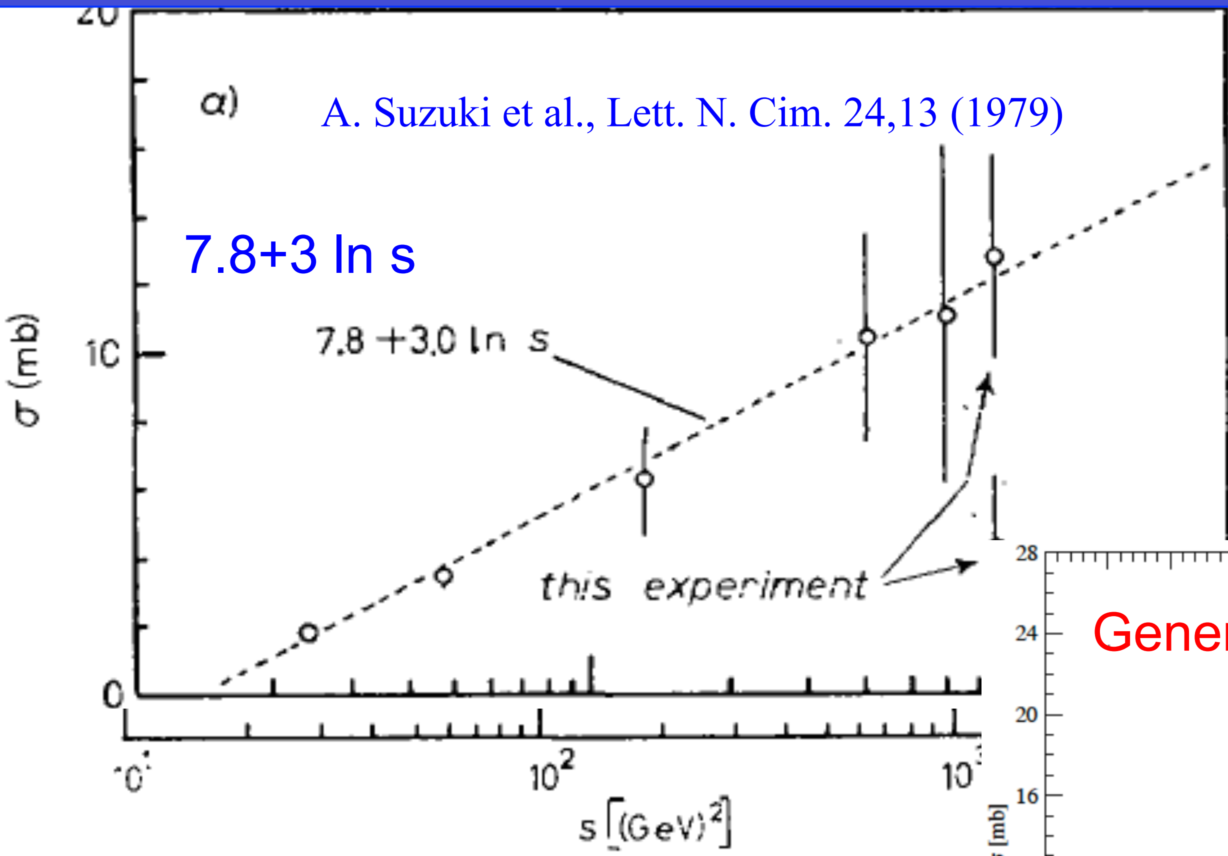
$$d\sigma(p,\bar{p})^{p\bar{p}\to\pi\rho X} = dW^0_\rho(x_\rho)\,dW^0_\pi(x_\pi)$$
$$\times\,[d\sigma(p-p_\rho,\bar{p}-p_\pi)^{p\bar{p}\to X}$$
$$+\,d\sigma(p-p_\pi,\bar{p}-p_\rho)^{p\bar{p}\to X}]\,P_\pi P_\rho,$$

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

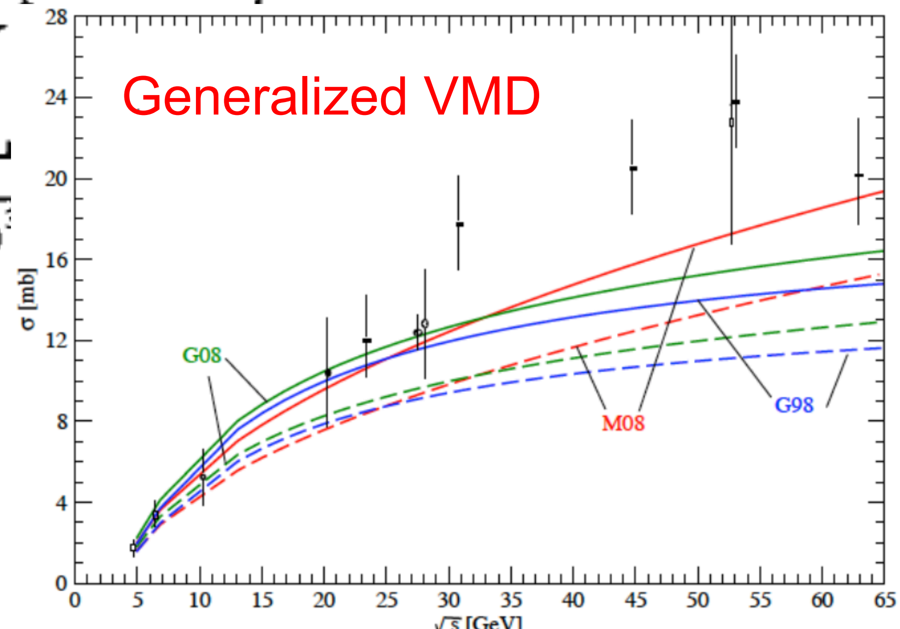
Empirical parametrization

A. Suzuki et al., Lett. N. Cim. 24,13 (1979)

7.8+3 ln s



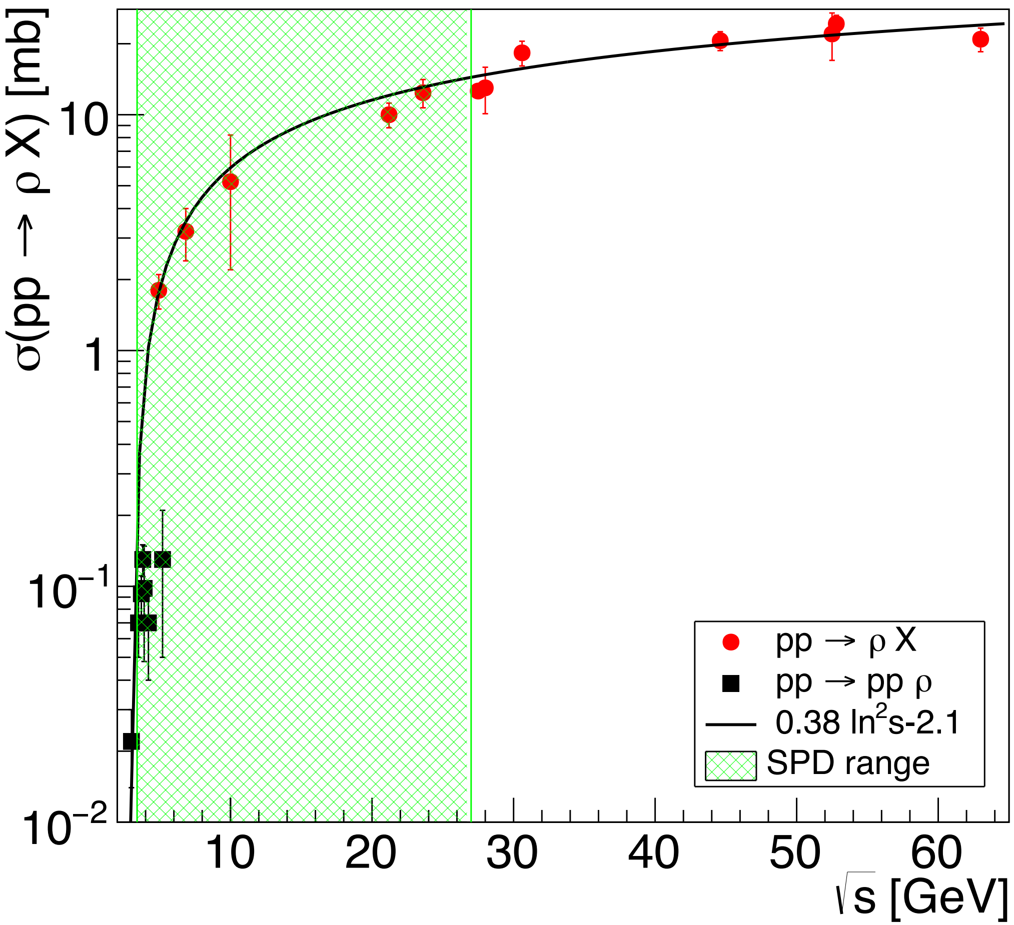
Generalized VMD



A.I. Machiavariani arXiv:1712.06395hep-ph

Experiments from the 1970's, mainly at CERN

Experiments for NICA-SPD



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

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

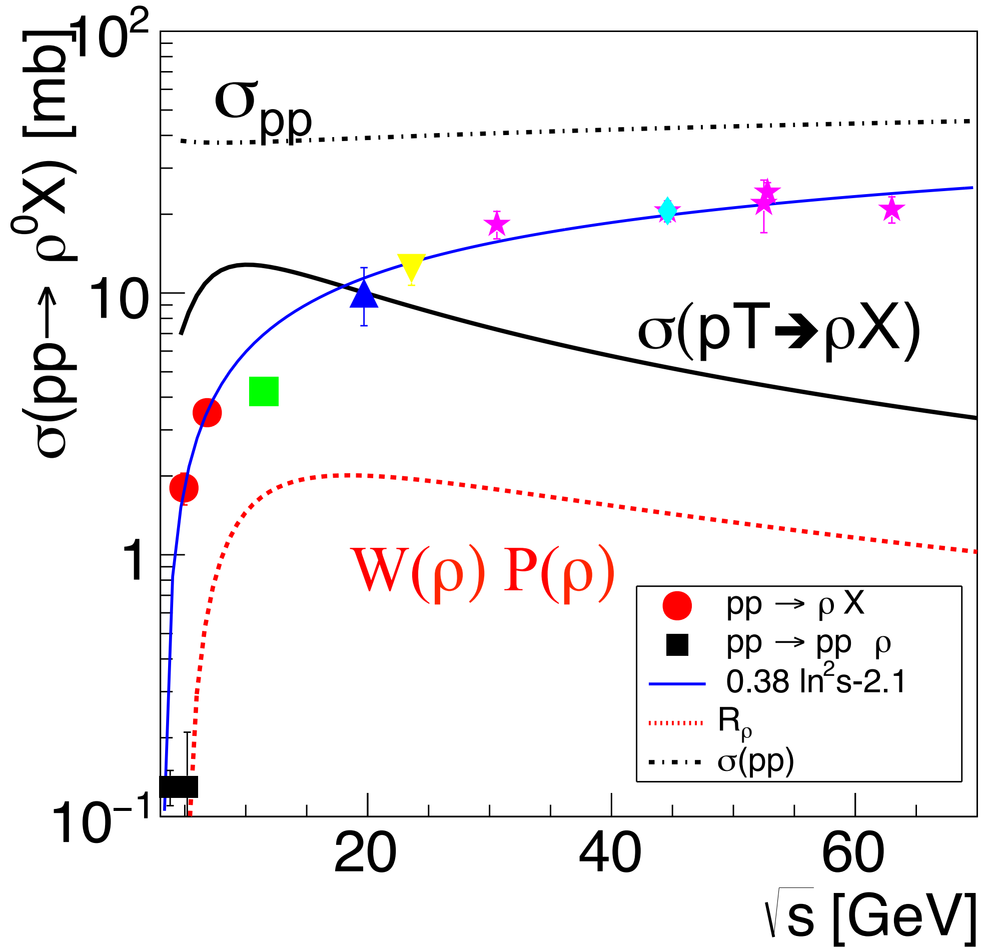
- Polarized proton beams
- Sqrt(s) = 3.4-27 GeV
- $\mathcal{L}=(10^{29}-10^{32})\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$

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

$\sigma=1$ mb

one expects 3000 counts/h

Model predictions



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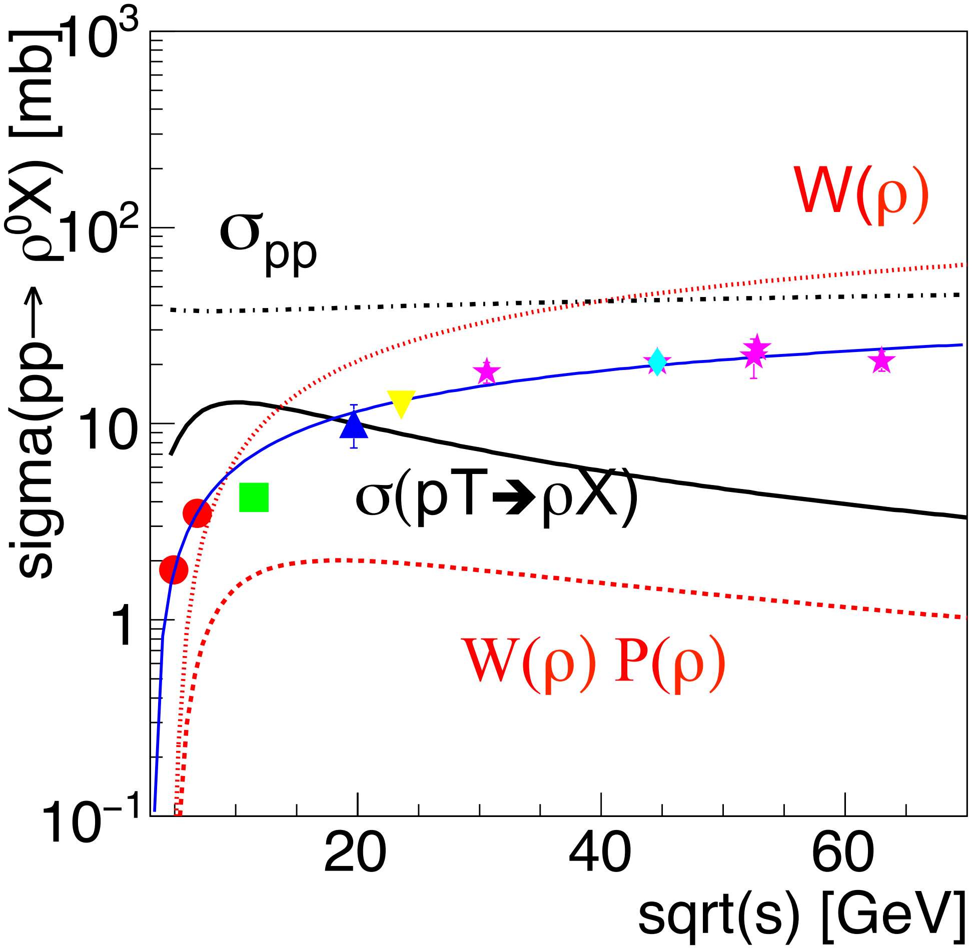
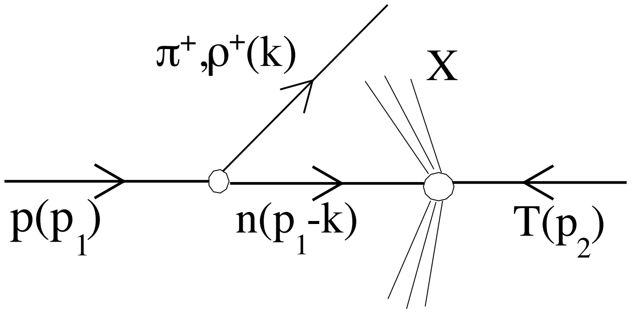
Producing a neutron beam?





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

- The quasi real electron method knows several recent applications

ISR method: allows a continuous beam energy change in fixed energy rings

- Application to hadron physics: backward meson production
  - PANDA: antiproton beams
  - NICA-SPD: proton and polarization
  - Neutron beams?

Thank you for attention

Спасибо за внимание