Single W Boson Photoproduction in p-p and p-A collisions

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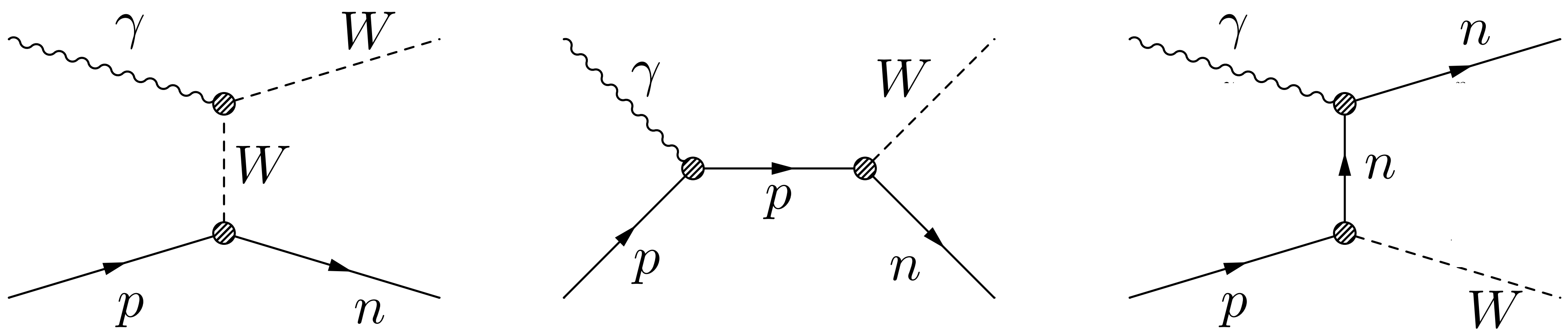
Motivation

- the couplings of gauge bosons among themselves belong to one of the least tested sectors of electroweak theory
- the photoproduction of single W bosons is a process well-suited to test the $WW\gamma$ coupling
- up to now very low rates for processes involving triple gauge boson coupling (HERA: 3 events for inclusive photoproduction [*Breitweg et al.,* Phys. Lett. B 471, 411 (2000)])
- Can these rates be improved in p-p and p-A collisions at LHC?
- exclusive photoproduction: neutron in forward direction
- in p-p collisions contributions from elastic and inelastic photon spectra

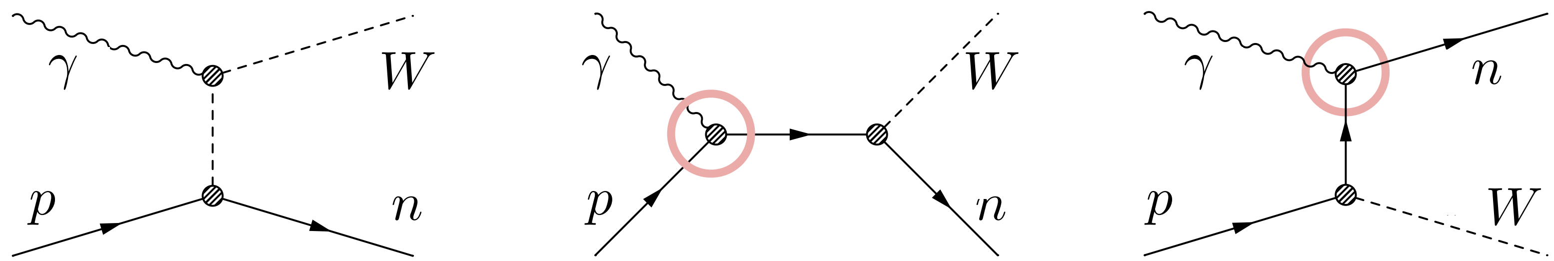
Exclusive Photoproduction of W

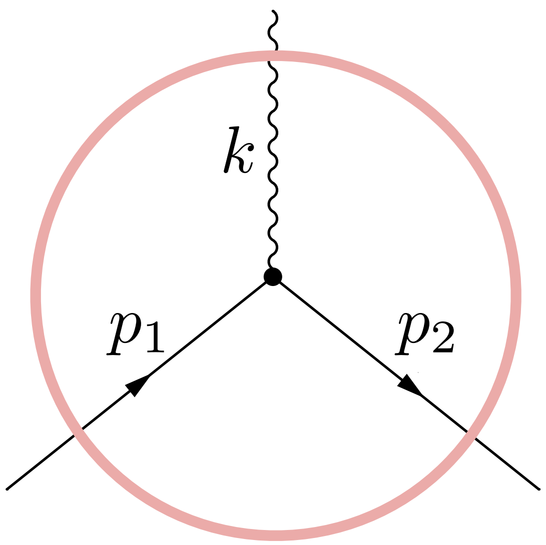
- we include three Feynman diagrams in our calculation



- appropriate electromagnetic and weak form factors have to be employed

Electromagnetic NN Vertex





$$\Gamma_{\mu}^{\gamma NN} = -ie\left[F_1^N(k^2)\gamma_\mu + i\frac{\kappa_N}{2M}F_2^N(k^2)\sigma_{\mu\nu}(p_2 - p_1)^\nu\right]$$

$$F_1^p(0) = F_2^p(0) = F_2^n(0) = 1$$

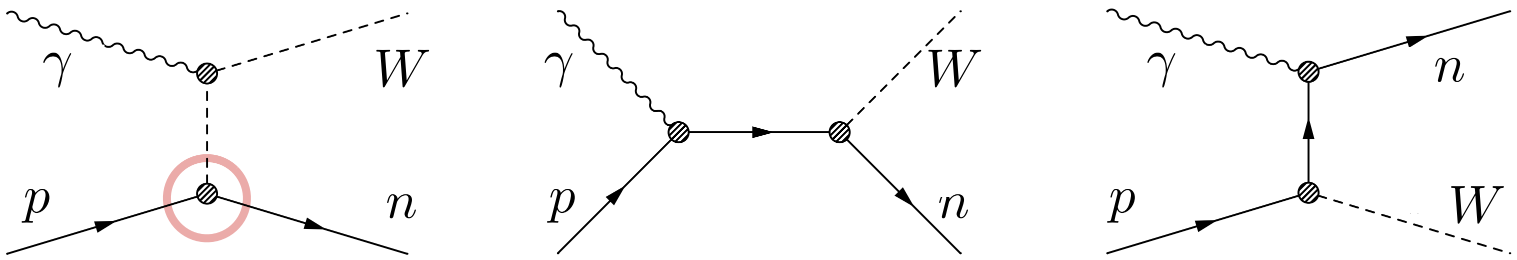
$$F_1^n(0) = 0$$

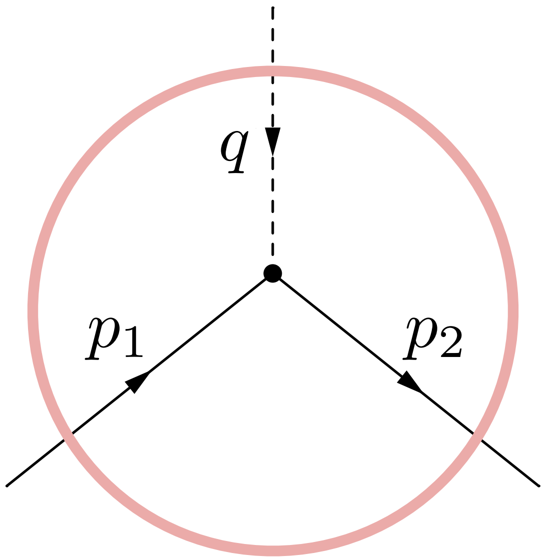
$$\kappa_p = 1.79 \qquad\qquad \kappa_n = -1.91$$

$$\sigma_{\mu\nu} = \frac{i}{2}\left[\gamma_\mu, \gamma_\nu\right]$$

Weak NN Vertex

(spacelike region)





$$
\begin{aligned}
\Gamma_\mu^{WNN} &= -ig\left[F_V(q^2)\gamma_\mu + iF_M(q^2)\sigma_{\mu\nu}q^\nu + F_S(q^2)q_\mu\right. \\
&+ F_A(q^2)\gamma_\mu\gamma_5 + iF_T(q^2)\sigma_{\mu\nu}q^\nu\gamma_5 \\
&+ \left. F_P(q^2)q_\mu\gamma_5\right]
\end{aligned}
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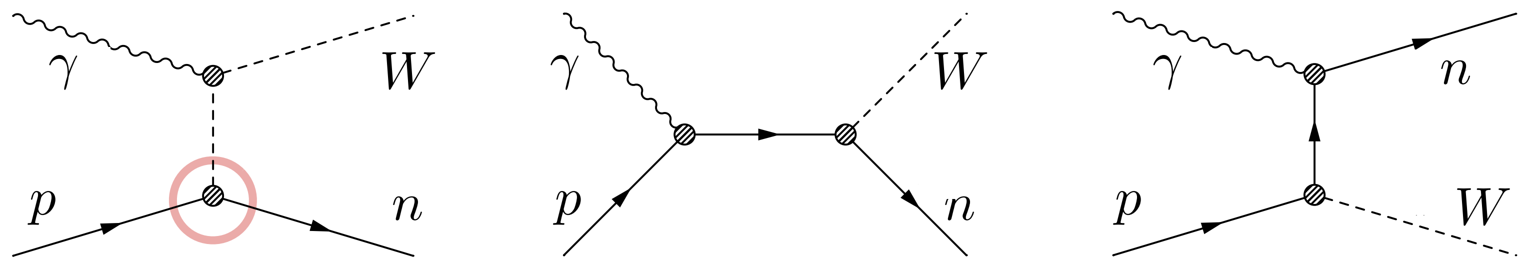

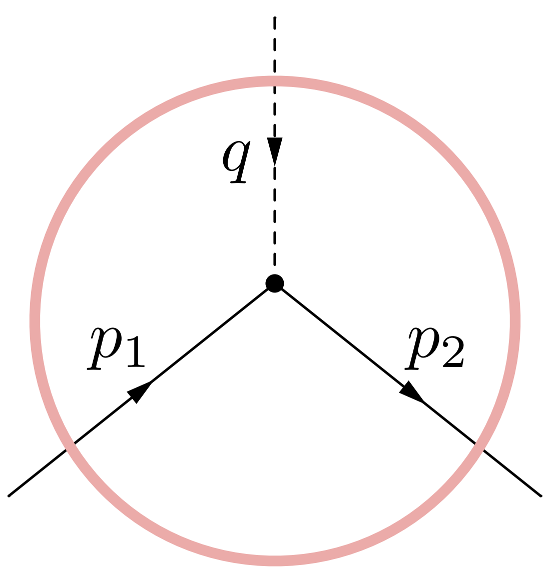

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\end{aligned}
$$

- conserved vector current hypothesis:

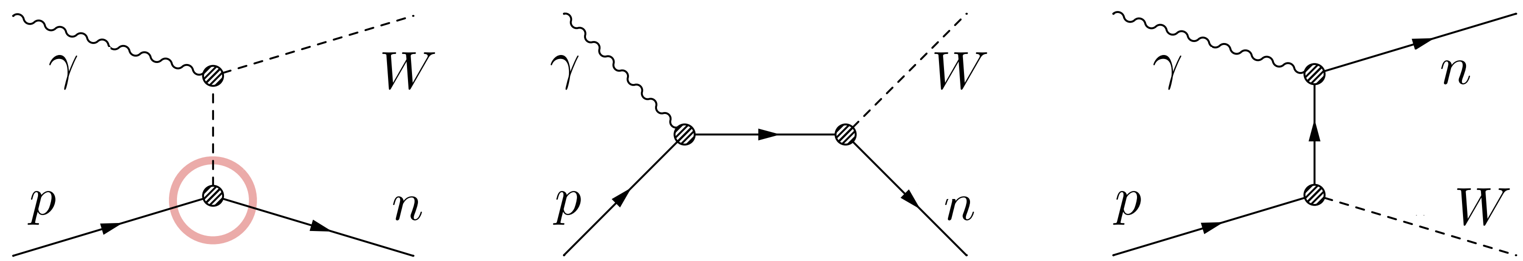
$$F_V(q^2) = F_1^p(q^2) - F_1^n(q^2) = \frac{1+\tau(1+(\kappa_p-\kappa_n))}{1+\tau}G_V(q^2) \qquad F_V(0)=1$$

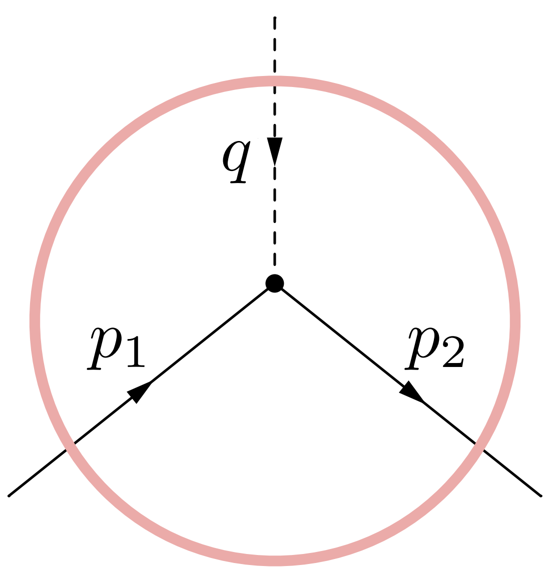
$$F_M(q^2) = \frac{1}{2M}(\kappa_p F_2^p(q^2) - \kappa_n F_2^n(q^2)) = \frac{1}{2M}\frac{\kappa_p-\kappa_n}{1+\tau}G_V(q^2)$$

$$G_V(q^2) = \left(1-\frac{q^2}{m_V^2}\right)^{-2} \qquad \tau = \frac{q^2}{4M^2} \qquad m_V^2 = 0.71\ GeV^2$$

Weak NN Vertex

(spacelike region)





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&+ \quad \left. F_P(q^2)q_\mu\gamma_5\right]
\end{aligned}
$$

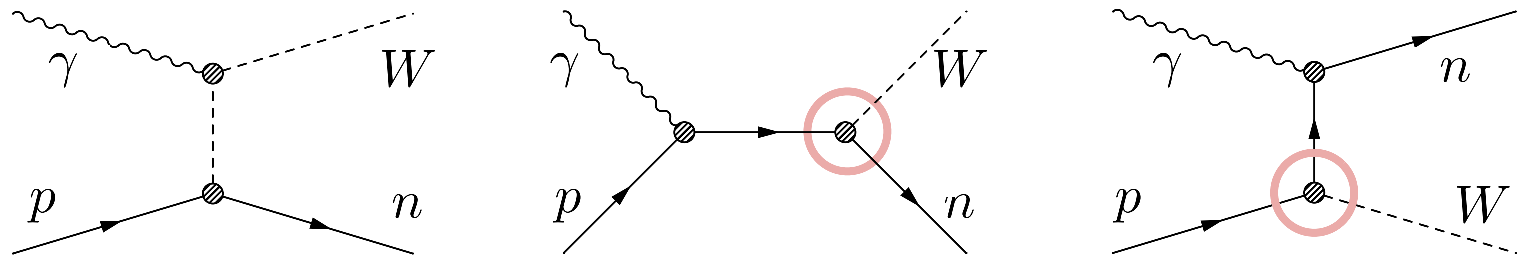
- by analogy with vector form factors , the axial vector form factor $F_A(q^2)$ is usually parameterized as a dipole form

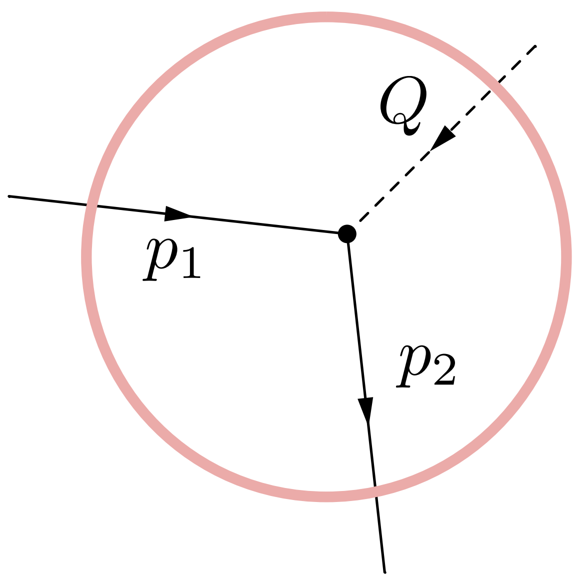
$$F_A(q^2) = F_A(0)\left(1 + \frac{q^2}{m_A^2}\right)^{-2}$$

with $F_A(0) = -1.26$ and $m_A = 0.95\ GeV$

Weak NN Vertex

(timelike region)



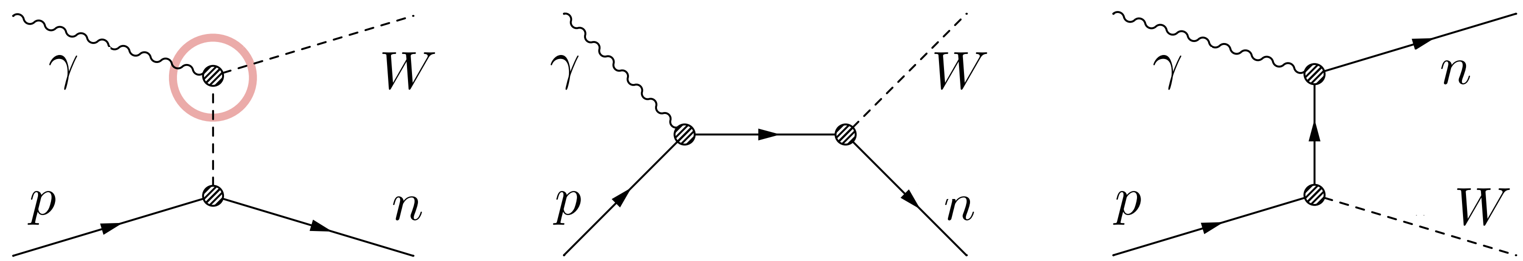


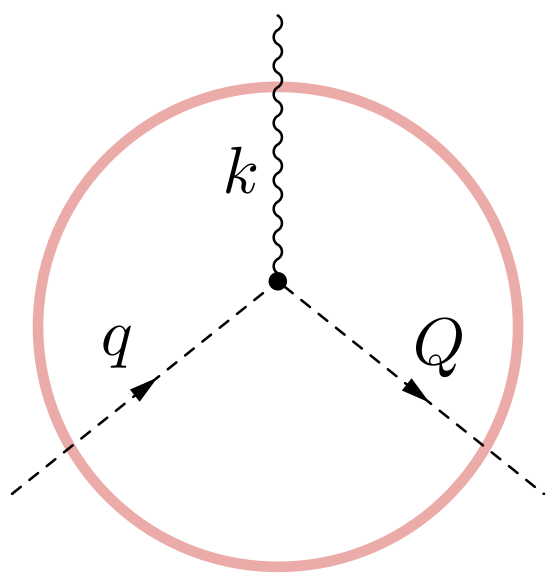
$$\Gamma_\mu^{WNN} = -ig\left[F_V(Q^2)\gamma_\mu + iF_M(Q^2)\sigma_{\mu\nu}Q^\nu + F_A(Q^2)\gamma_\mu\gamma_5\right]$$

here: $\qquad Q^2 = M_W^2$

- *Fearing et al.* [Phys. Rev. D5, 158 & 177 (1972)] and *Kallianpur* [Phys. Rev. D34, 3343 (1986)] use two different choices of timelike weak form factors:
  - constant timelike form factors
  - dipole timelike form factors

Triple Gauge Boson Coupling





$$\Gamma^{WW\gamma}_{\mu\alpha\beta} = ie \left\{ F_1^W(k^2) \left[(2Q-k)_\mu g_{\alpha\beta} - Q_\alpha g_{\mu\beta} - (Q-k)_\beta g_{\mu\alpha} \right] + \kappa_W F_2^W(k^2) \left[k_\beta g_{\mu\beta} - k_\alpha g_{\mu\beta} \right] \right\}$$

$$F_1^W(0) = F_2^W(0) = 1$$

- Standard Model Coupling recovered for $\kappa_W = 1$

Gauge Invariance

$$\mathcal{M}_{fi} = -ige\, \epsilon_\mu M^{\mu\beta} \epsilon_\beta^W$$

$$M^{\mu\beta} = M_1^{\mu\beta} + M_2^{\mu\beta} + M_3^{\mu\beta}$$

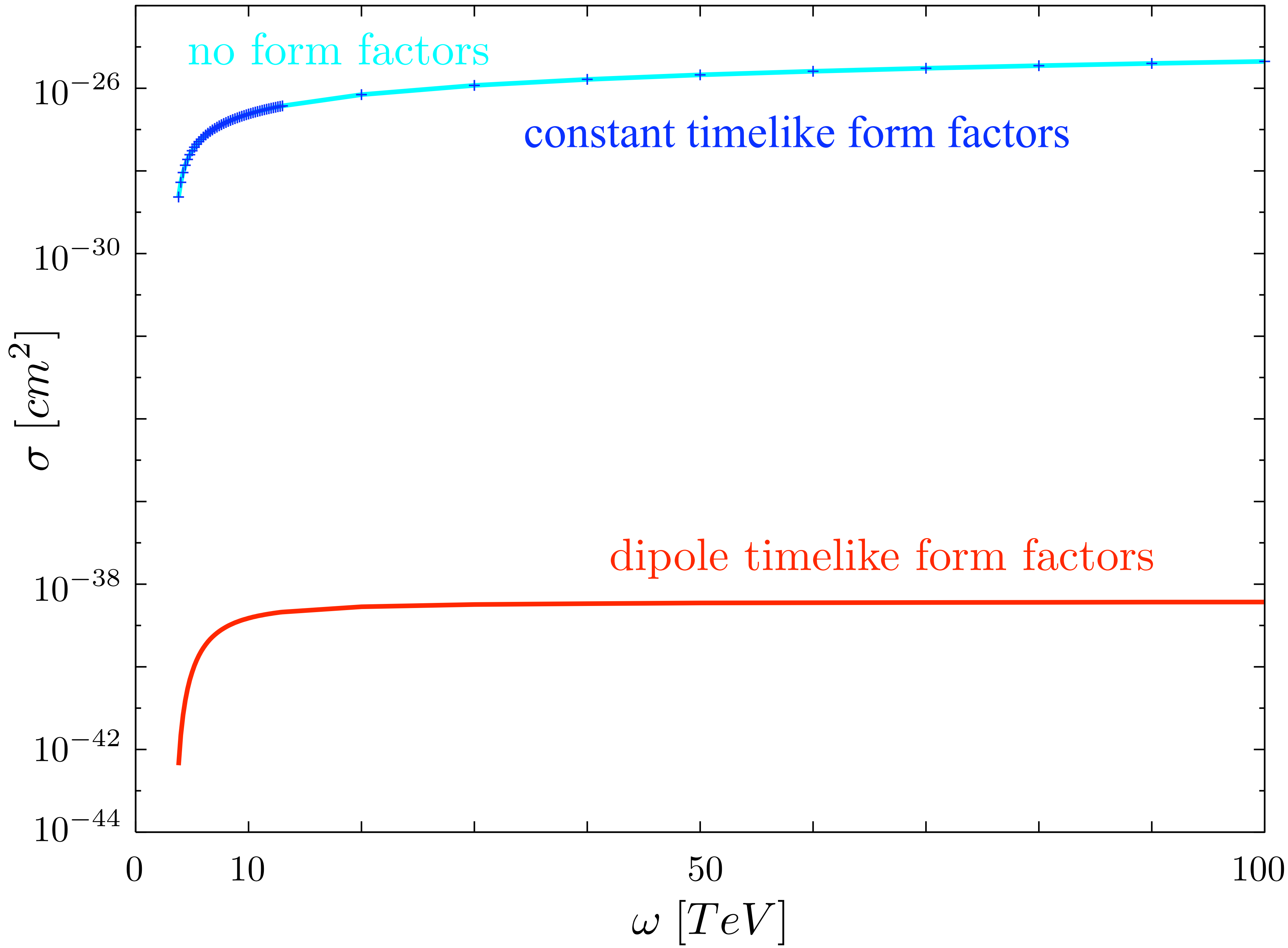
- employing weak vertices between offshell states results in loss of explicit gauge invariance

$$k_\mu M^{\mu\beta} \epsilon_\beta^W \neq 0$$

- *Fearing et al.* [Phys. Rev. D 5, 158 (1972)] introduce a technique how to maintain gauge invariance by adding a term $\Delta M^{\mu\beta}$
- $\Delta M^{\mu\beta}$ has to fulfill certain requirements:
  - it should cancel the extra terms arising
  - it should not contain new singularities in the physical region
  - it should satisfy $\Delta M \ll M$

$$M^{\mu\beta} \longrightarrow M^{\mu\beta} + \Delta M^{\mu\beta}$$

Results (Photoproduction)



- total photoproduction cross section as function of photon energy without form factors and with constant and dipole weak timelike form factors

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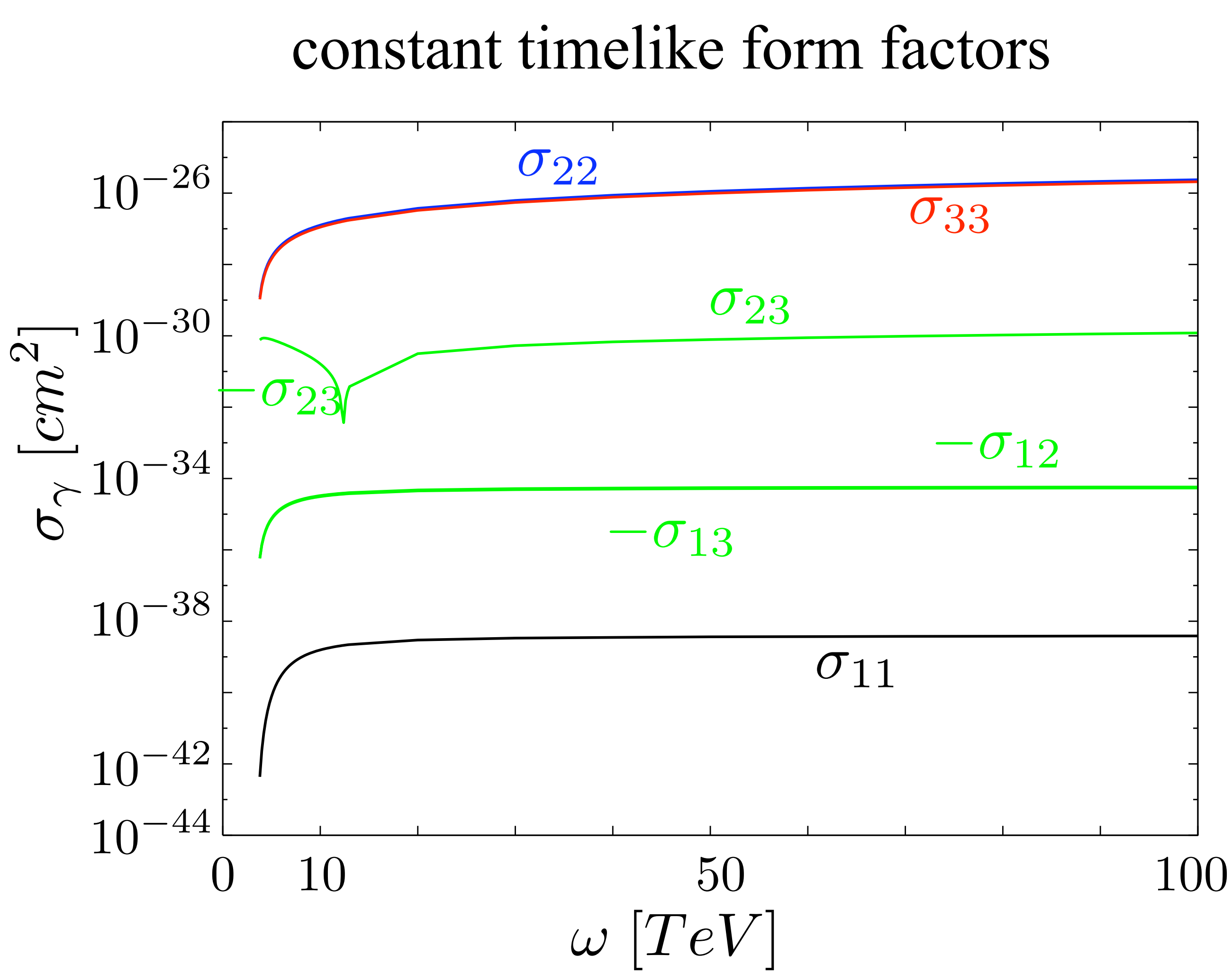

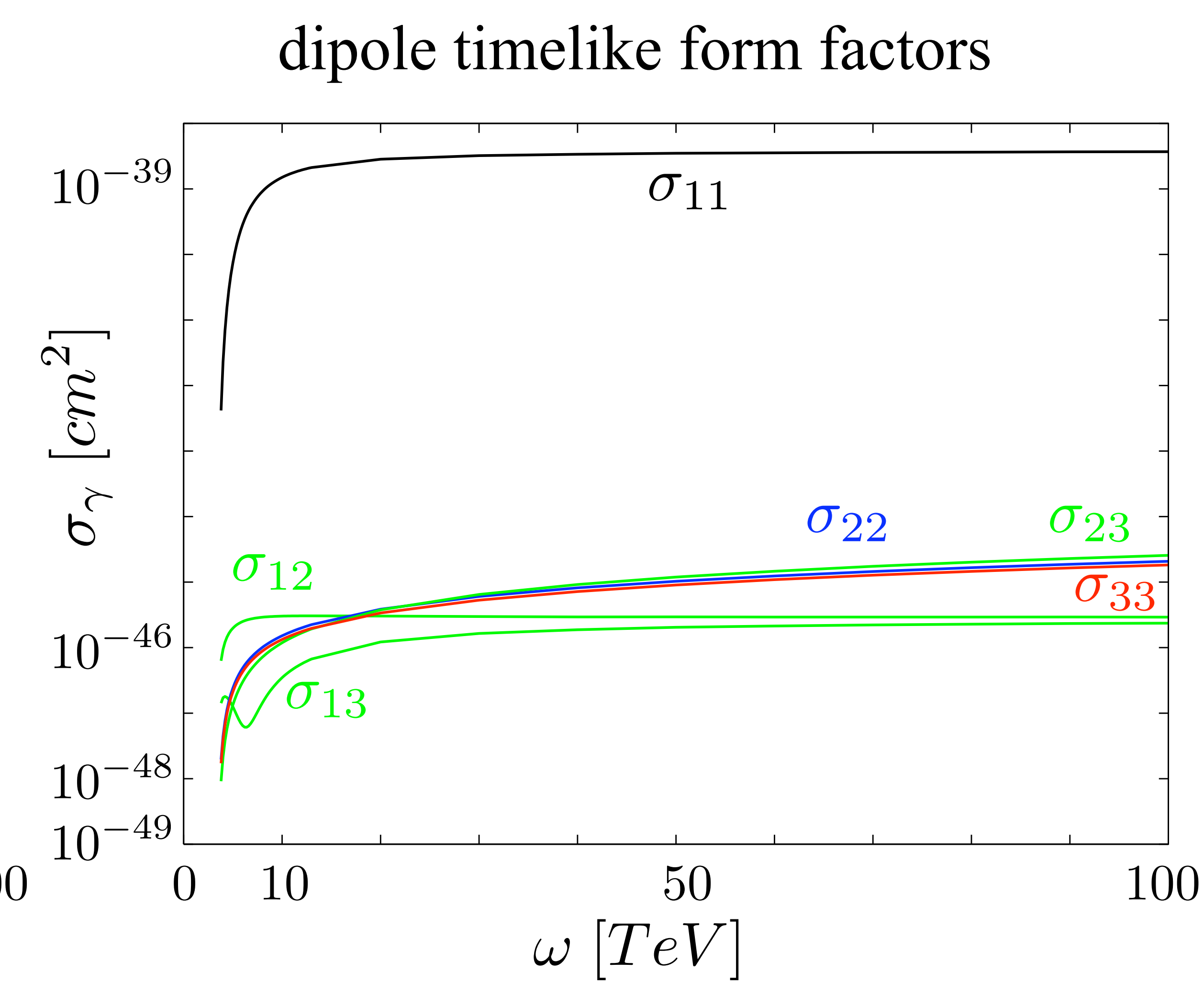

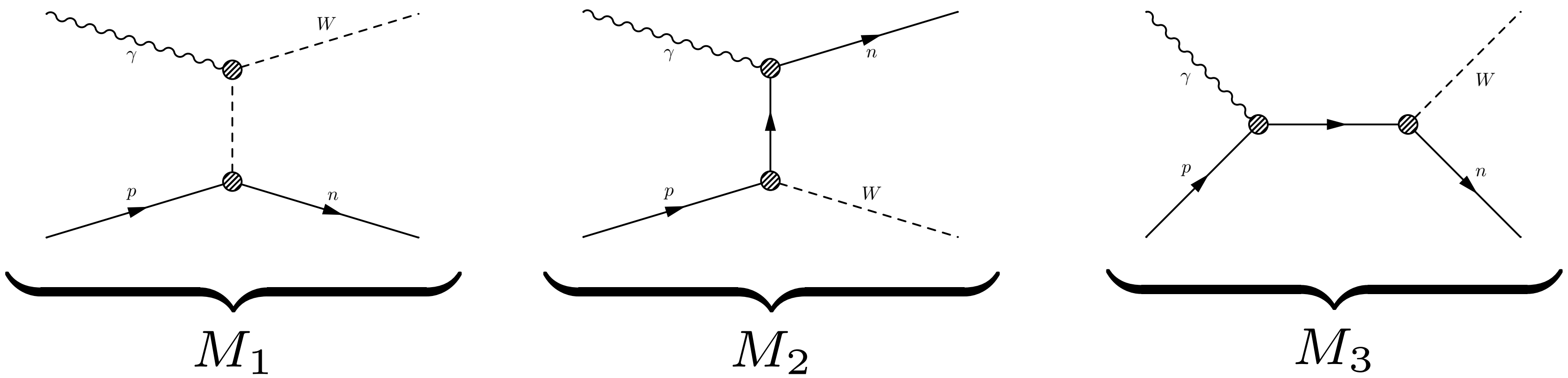

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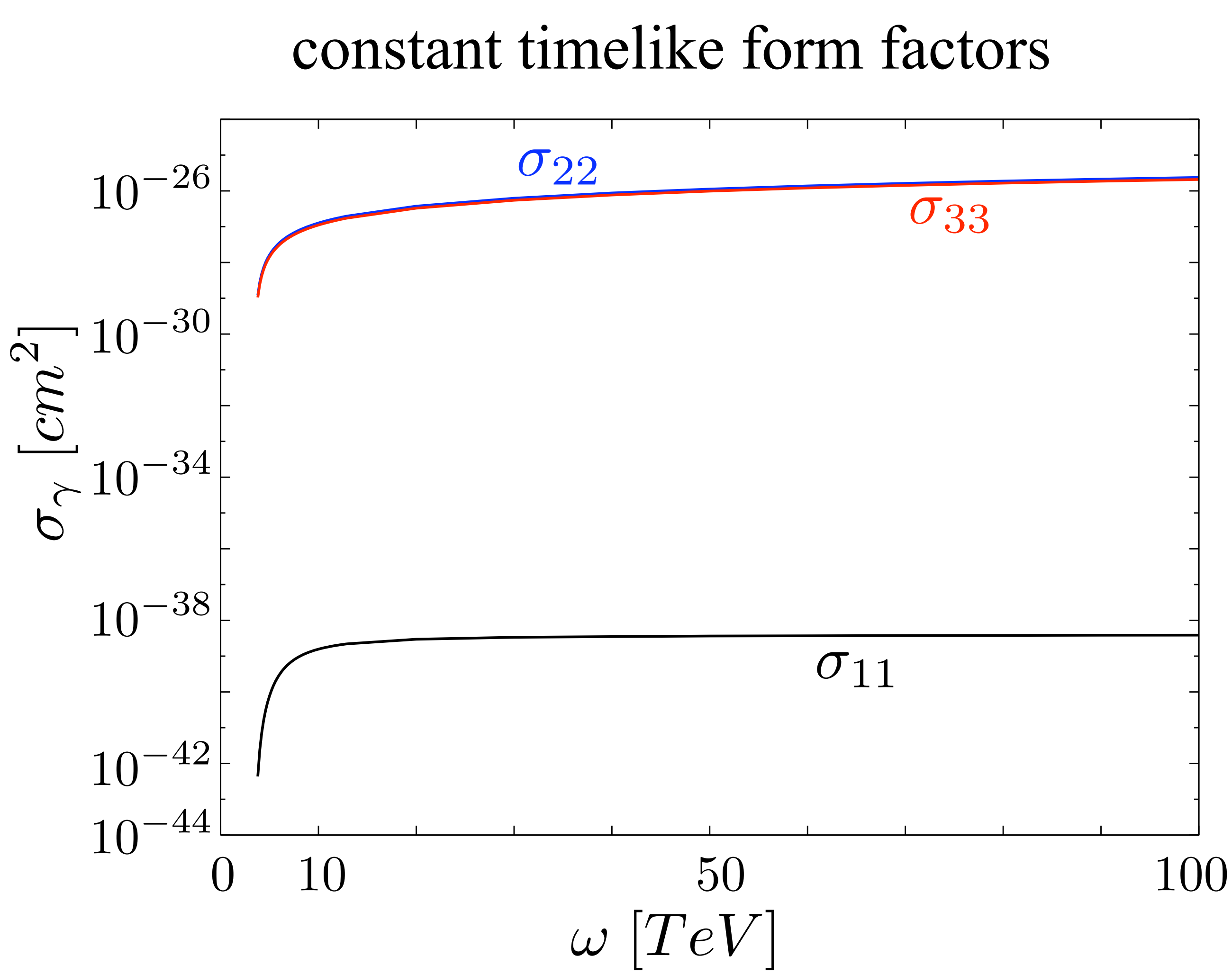

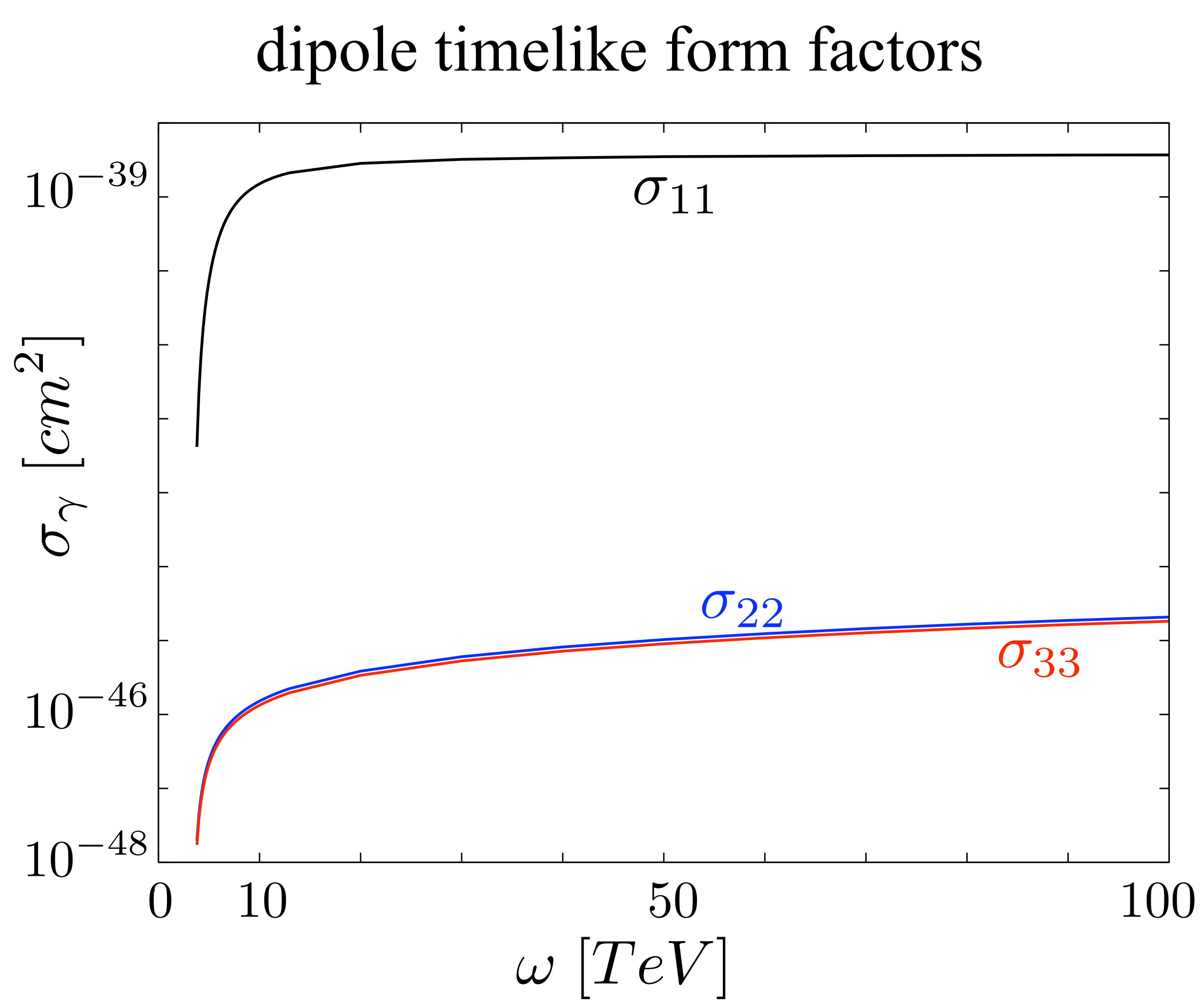

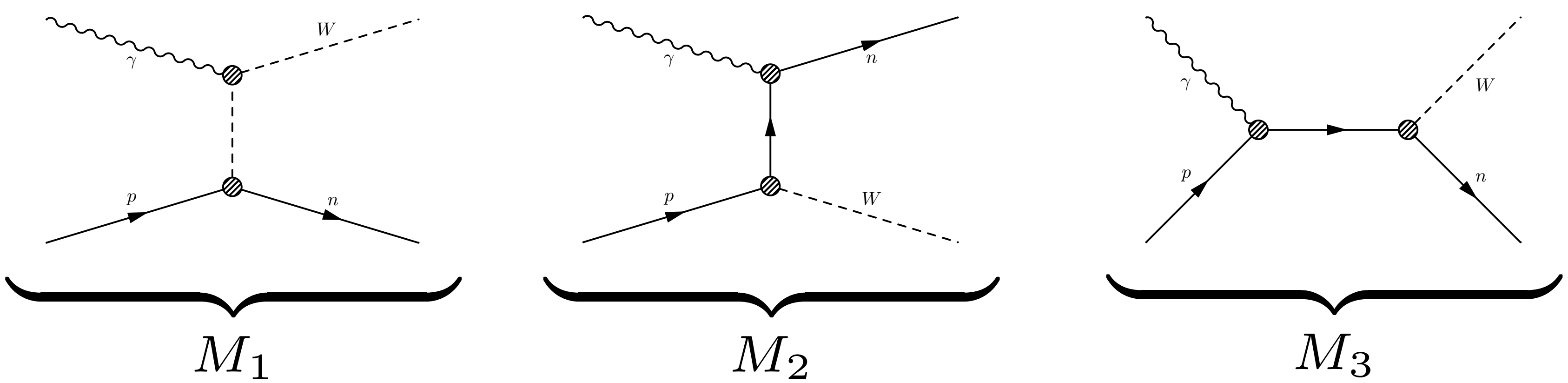

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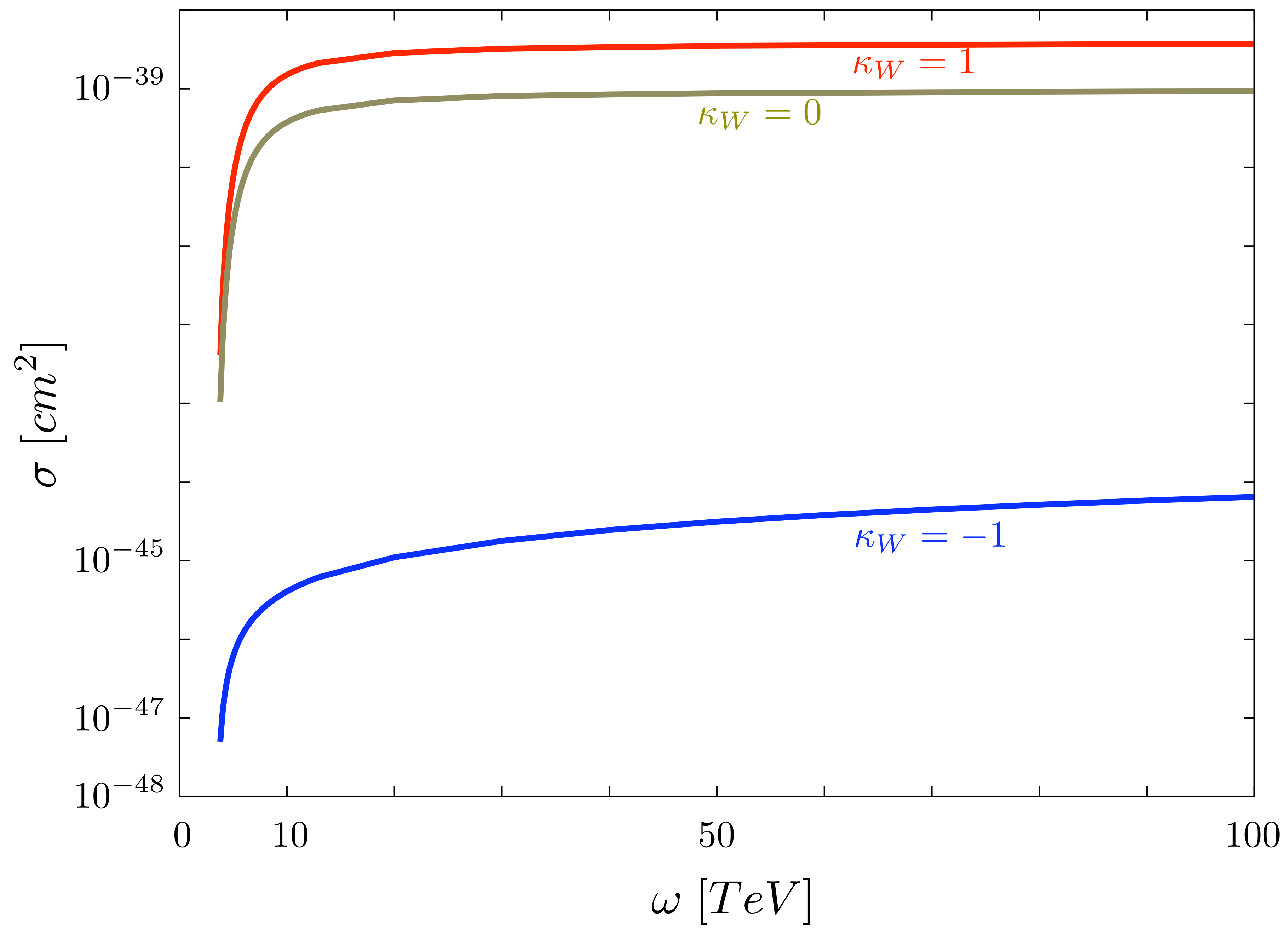

- total photoproduction cross section as function of photon energy for different values of κ_W

Equivalent Photon Approximation

- impact parameter larger than the extension of the nucleus/proton
- approximated equivalent photon spectrum for ion of radius R and mass M_A

$$f_{\gamma|A}(u) \approx \frac{2Z^2\alpha}{\pi} \ln\left(\frac{1}{uRM_A}\right) \qquad \omega = u \cdot E_A$$

- approximate proton spectrum can be derived in the same way as ion spectrum, with R being the charge radius of the proton

$$f_{\gamma|p}(u) \approx \frac{\alpha}{\pi} \ln\left(\frac{0.71\ GeV^2}{u^2 M_p^2}\right) \qquad \omega = u \cdot E_p$$

$$\sigma = \int \frac{du}{u}\, f_{\gamma|p/A}(u)\ \sigma_\gamma$$

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(proton, elastic)

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- parametrization from *Kniehl* [Phys. Lett. B 254, 267 (1991)]

$$f_{\gamma|p}(u) = \frac{\alpha}{2\pi} u \left[c_1 y \ln\left(1 + \frac{c_2}{z}\right) - (y + c_3) \ln\left(1 - \frac{1}{z}\right) + \frac{c_4}{z-1} + \frac{c_5 y + c_6}{z} + \frac{c_7 y + c_8}{z^2} + \frac{c_9 y + c_{10}}{z^3} \right]$$

$$y = \frac{1}{2} - \frac{2}{u} + \frac{2}{u^2} \qquad z = 1 + \frac{M_p^2}{0.71\ GeV^2} \frac{u^2}{1-u}$$

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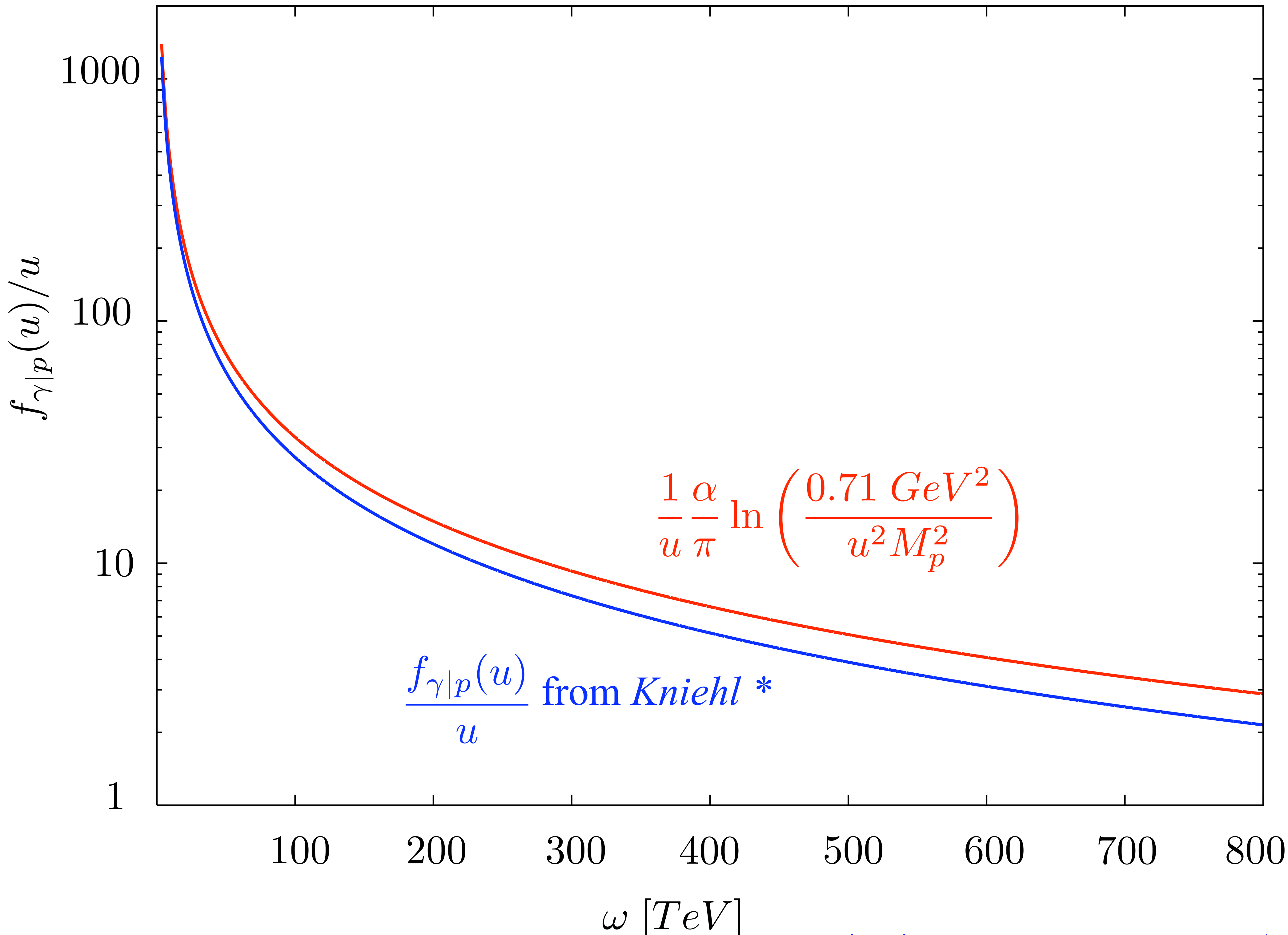

*[Phys. Lett. B 254, 267 (1991)]

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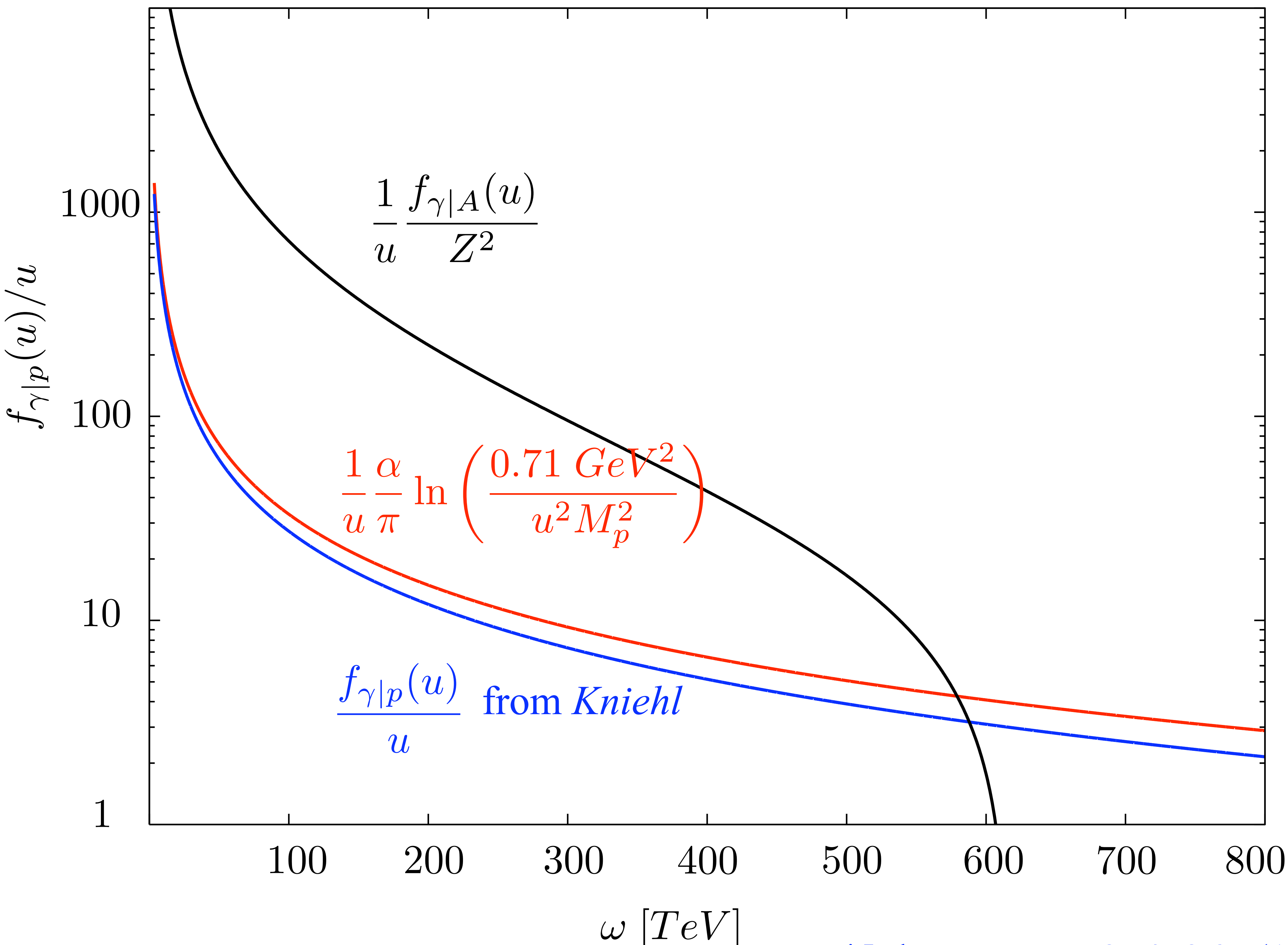
(elastic)



*[Phys. Lett. B 254, 267 (1991)]

Results (p-p and p-A collisions)

- total cross sections:
  - p-p collisions: $\sim 5 \cdot 10^{-40}\ cm^2$
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- luminosities:
  - p-p collisions: $L_{pp} \approx 10^{29} \ldots 10^{34}\ cm^{-2}s^{-1}$
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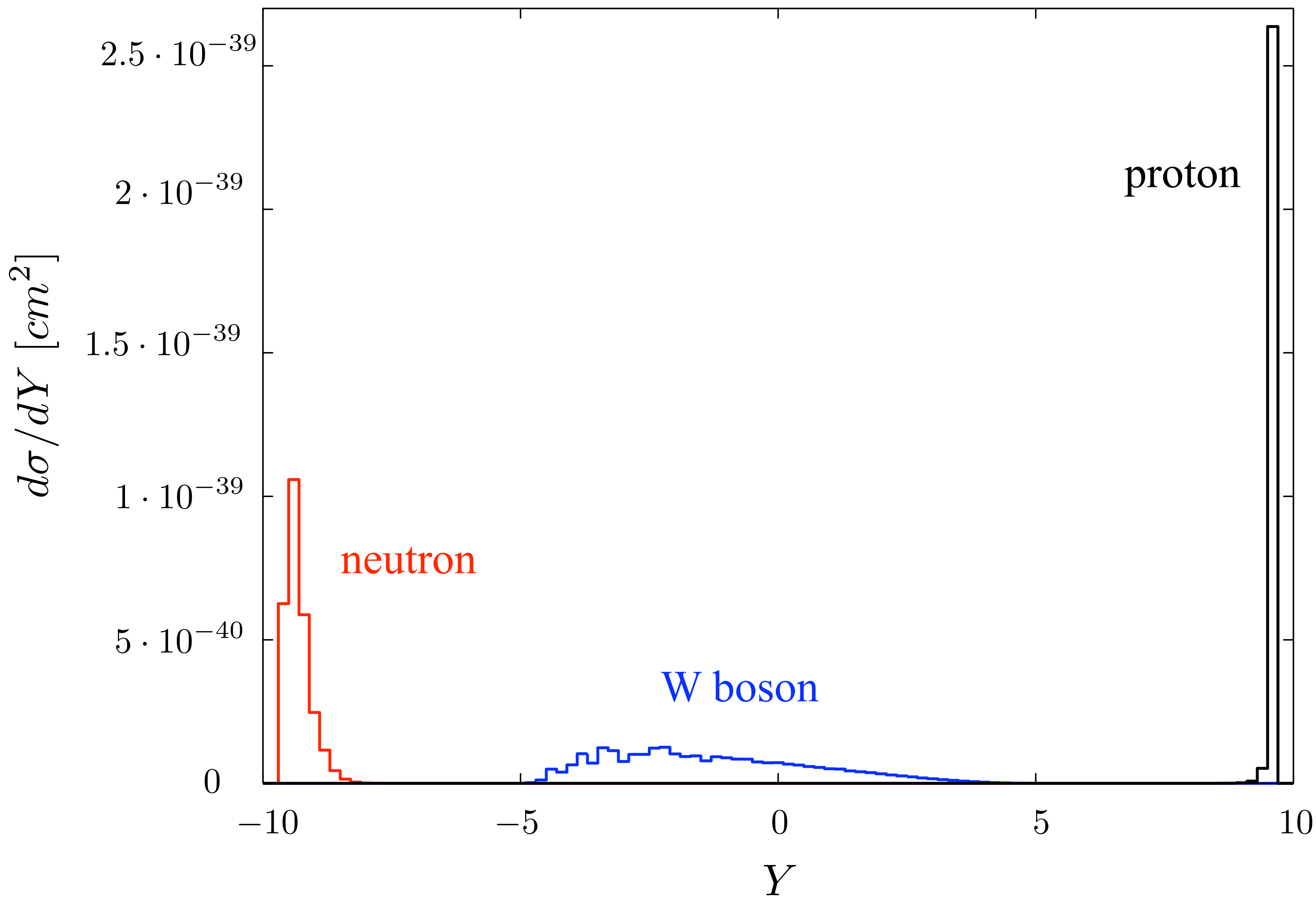
→ $5 \cdot 10^{-4} \ldots 50 \text{ events}/10^7 s$ p-p collisions

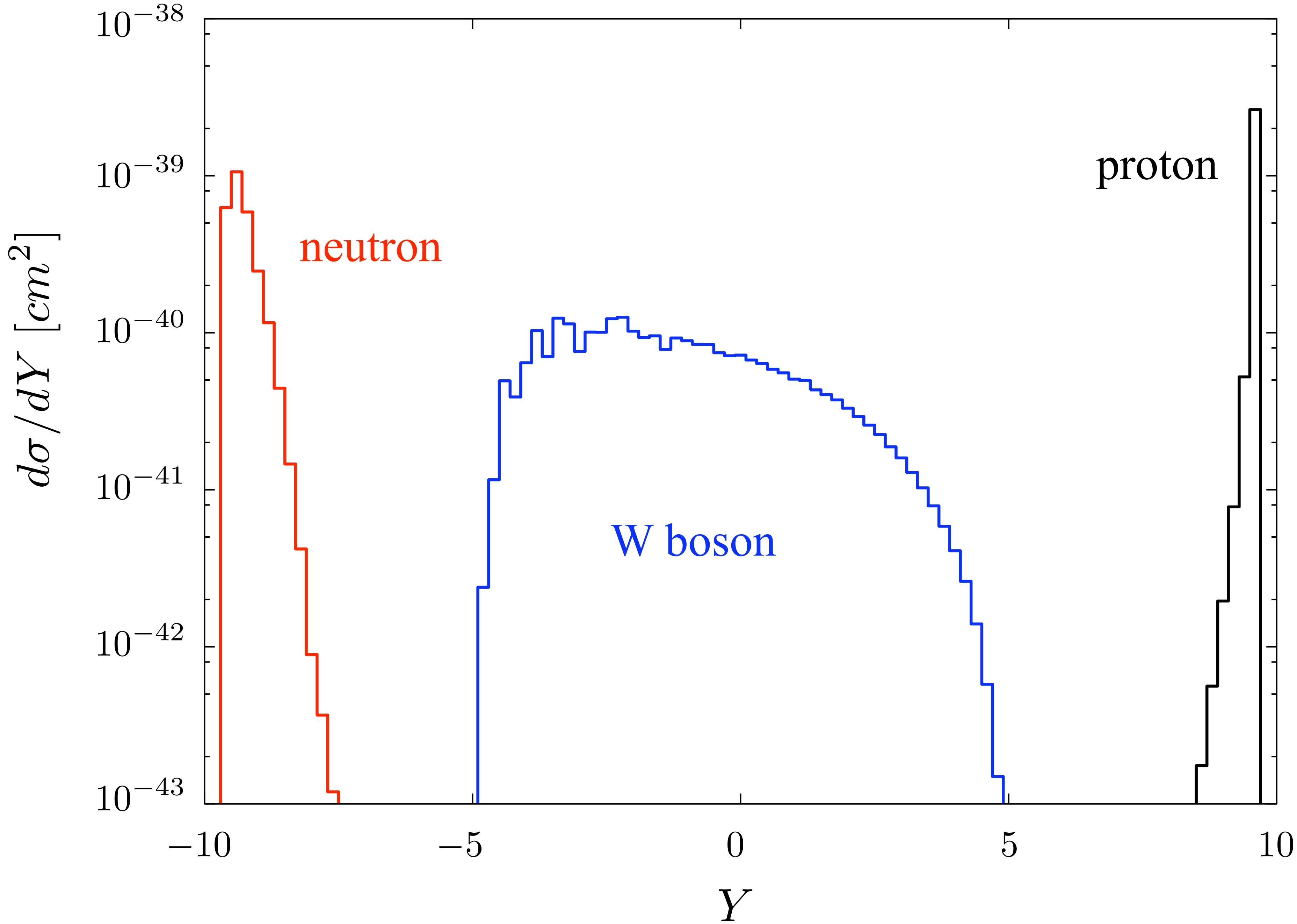
$\text{at least } 0.1 \text{ events}/10^6 s$ Pb-p collisions

Results (p-p collision)



- differential cross section as function of rapidity in p-p collision

Results (p-p collision)



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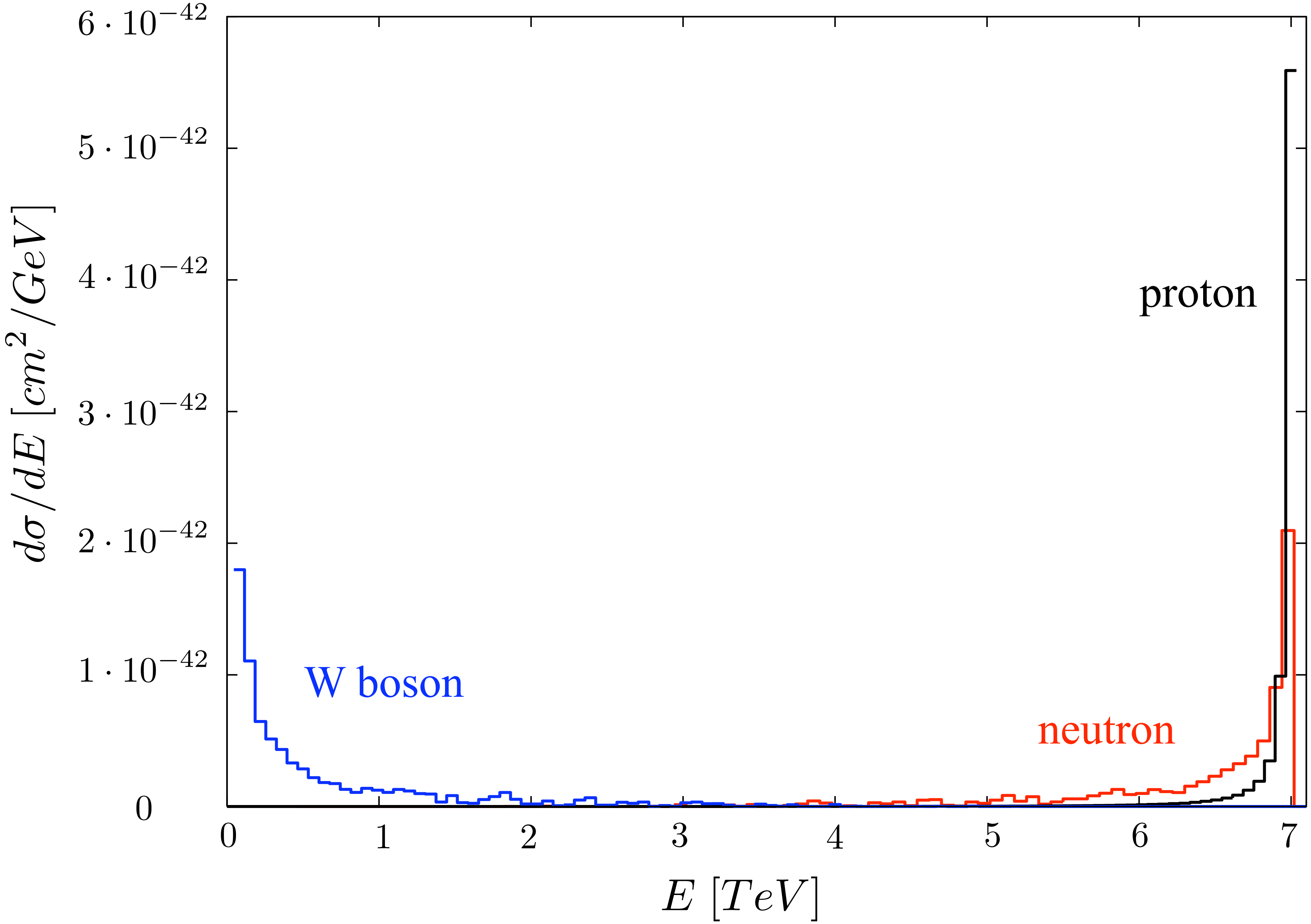
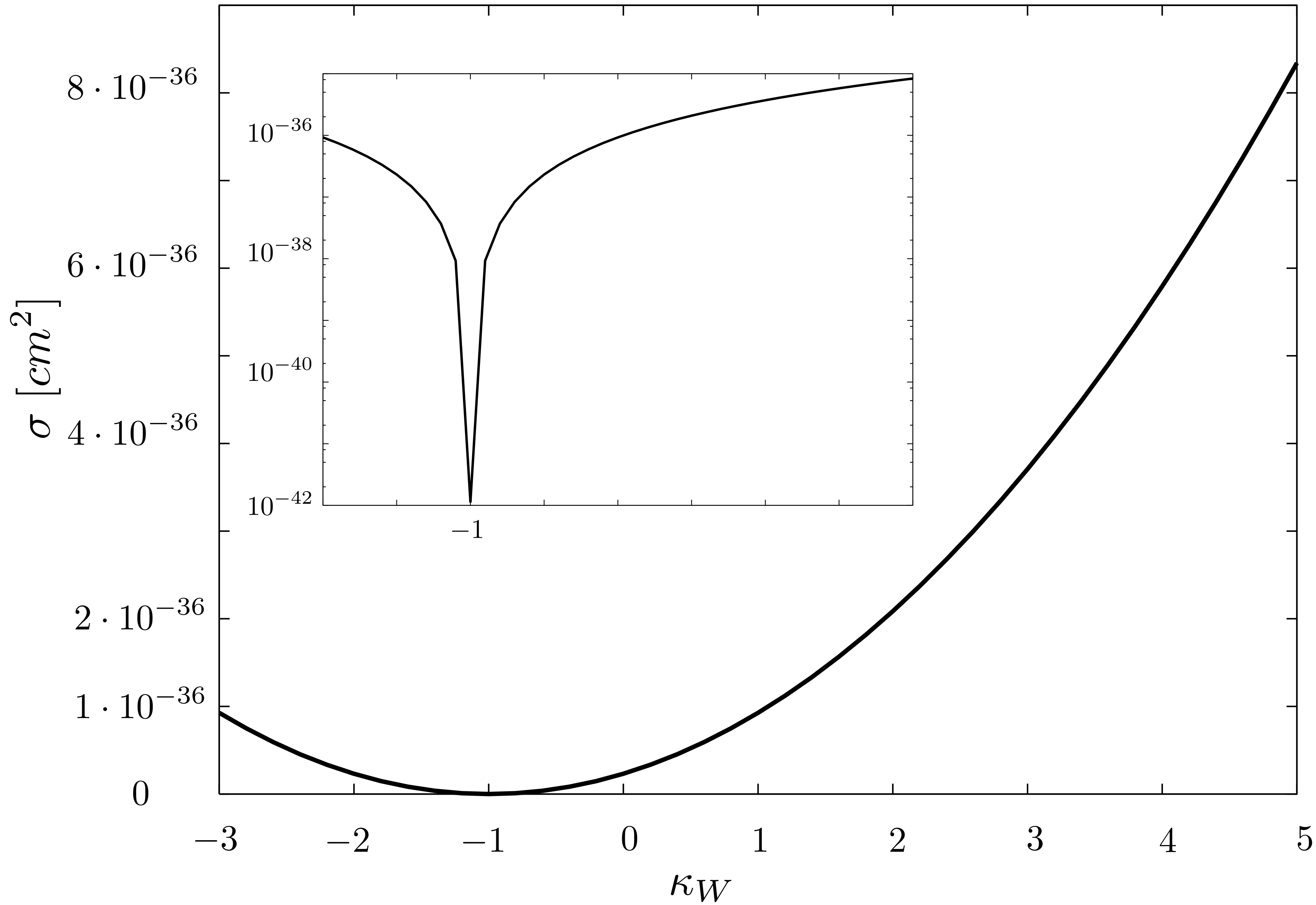


- differential cross section as function of energies in p-p collision, incident particles at 7 TeV

Results (p-A collision)



- total cross section as function of κ_W in Pb-p collision

Equivalent Photon Approximation
(proton, inelastic)

- for large momentum transfers Q^2 of the photon, the proton should be regarded as a collection of partons, which radiate as pointlike particles
- for simplicity, we neglect the dependence of the parton distribution functions on Q^2

$$\sigma = \int dx \int du \sum_{q_i} e_i^2 f_{q_i|p}(x, Q_{av}^2) f_{\gamma|q_i}(u) \sigma_\gamma$$

$$f_{\gamma|q} = \frac{\alpha}{2\pi} \frac{1 + (1-u)^2}{u} \ln\left(\frac{Q_{max}^2}{Q_{min}^2}\right) \qquad \omega = x \cdot u \cdot E_p$$

$$Q_{min}^2 = 1\ GeV^2 \qquad Q_{max}^2 = M_W^2$$

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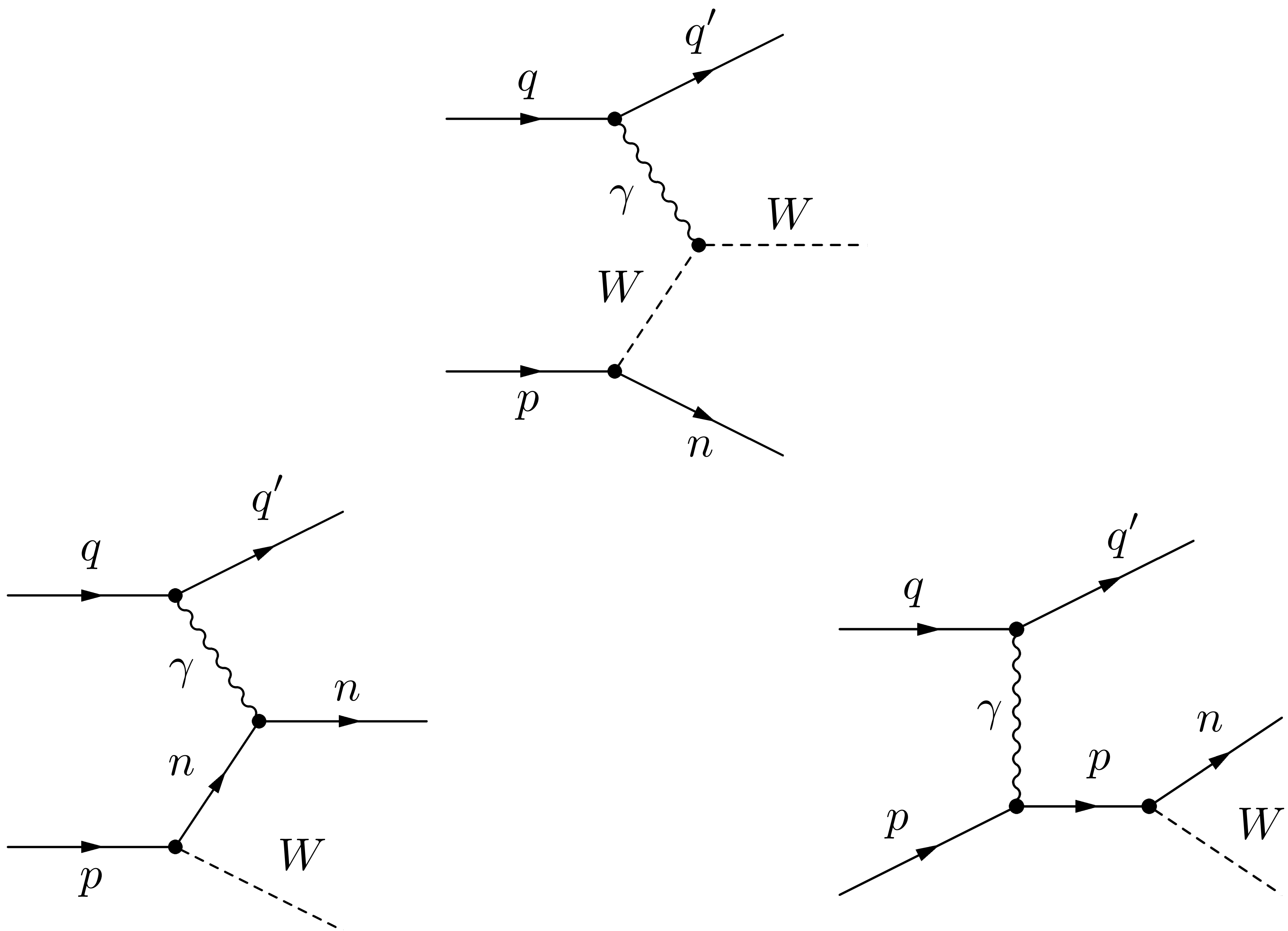

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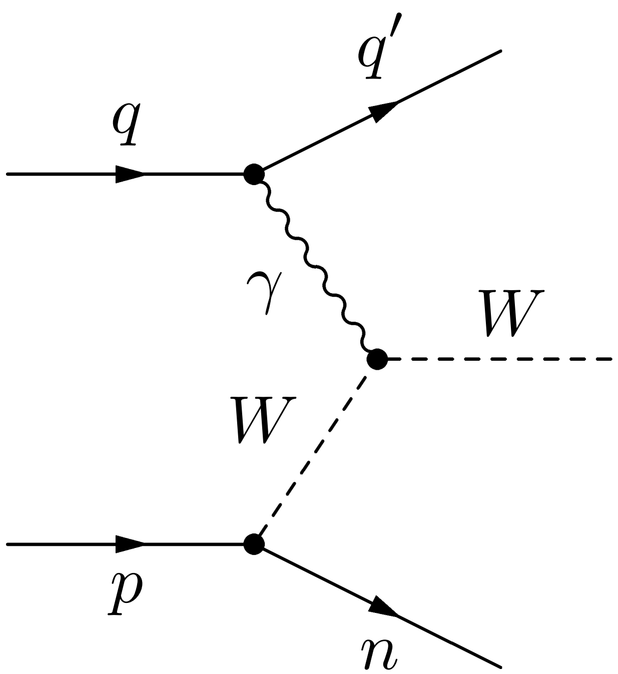

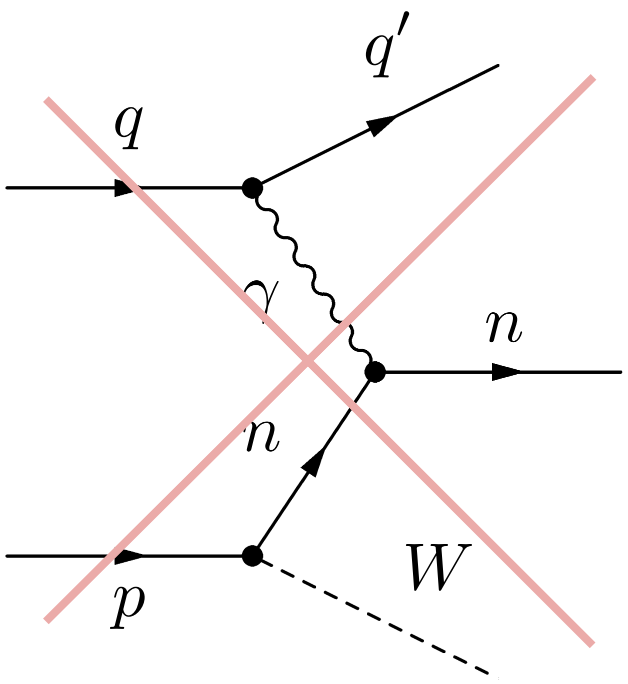

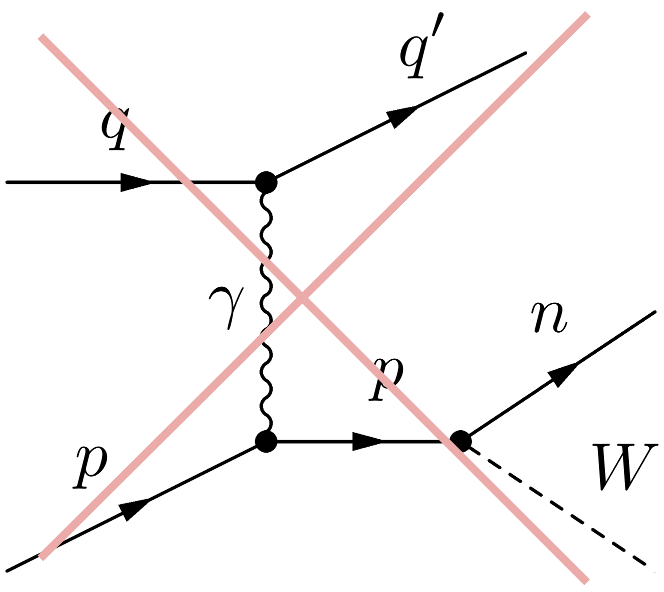

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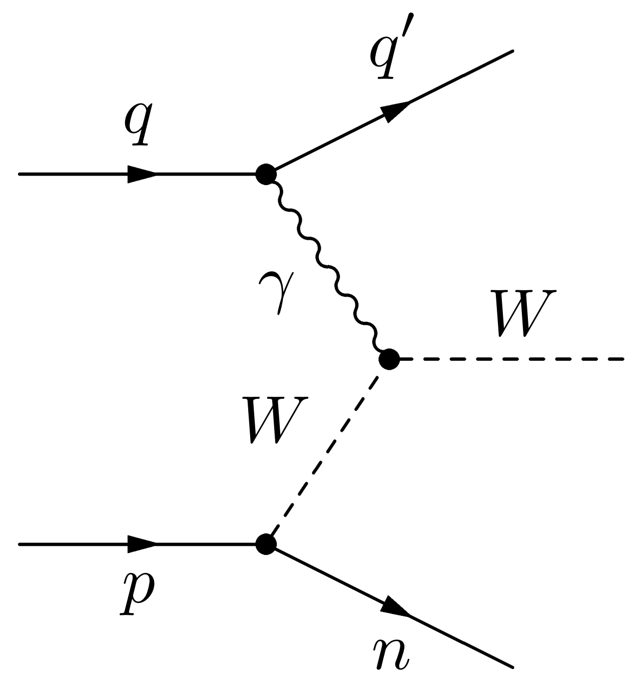

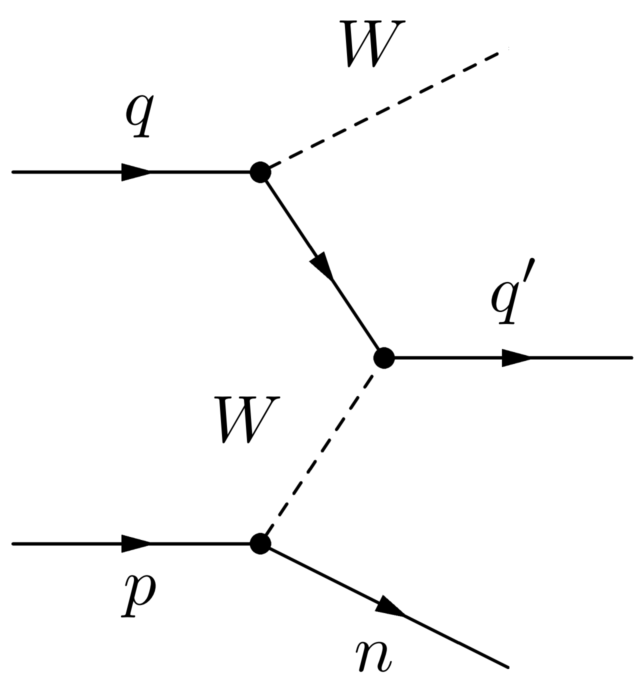

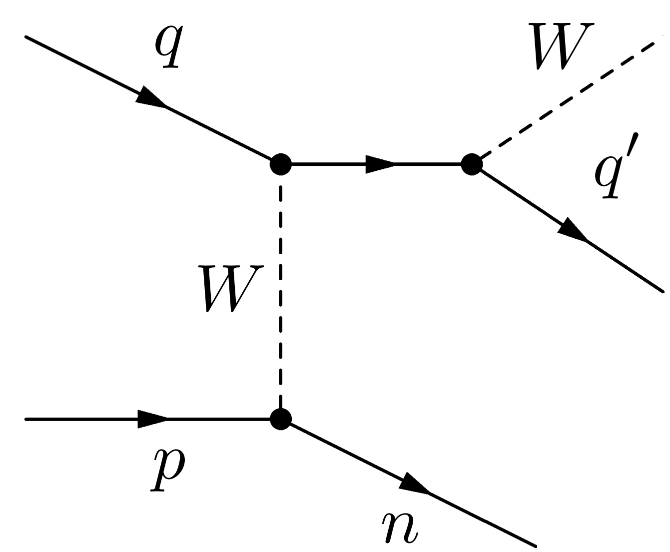

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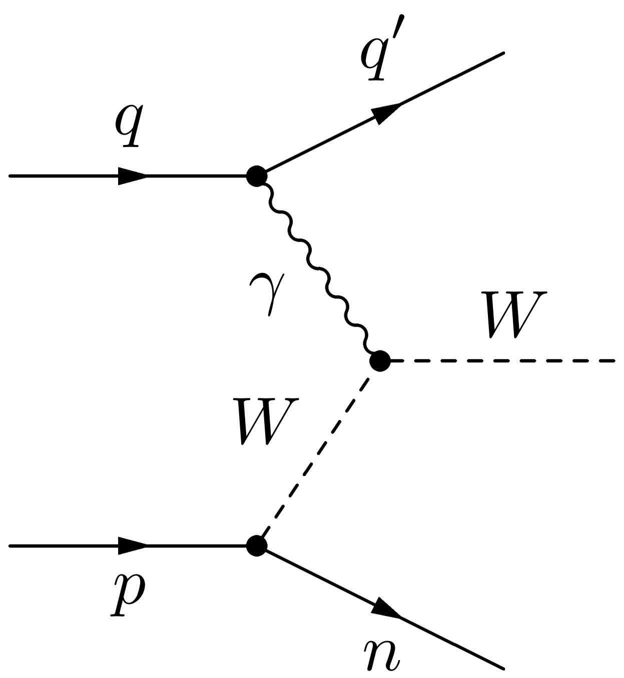
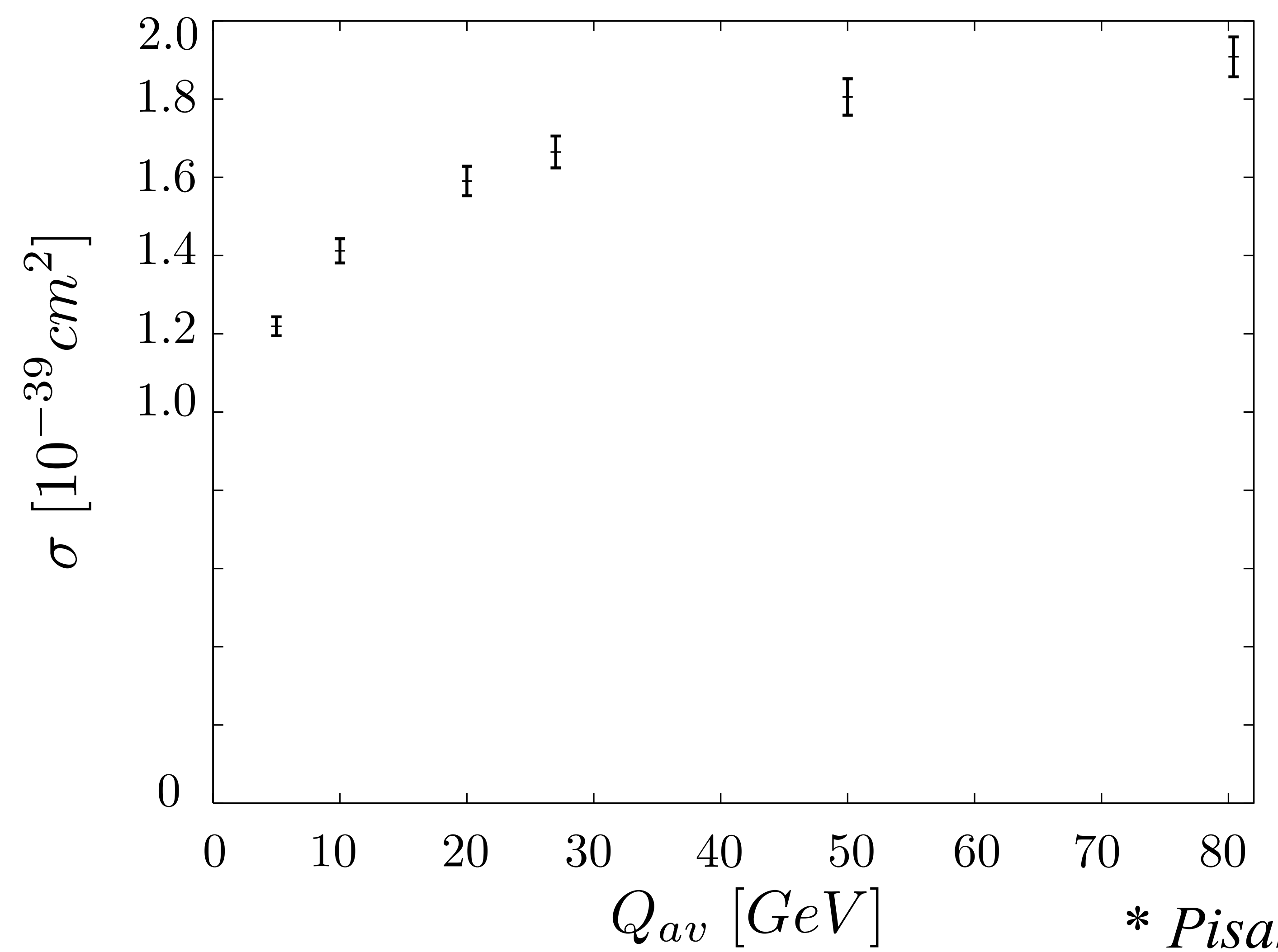


Results (p-p collisions)

- total cross sections:
  - p-p collisions, elastic: $\sim 5 \cdot 10^{-40}\ cm^2$
  - p-p collisions, inelastic: $\sim 1.7 \cdot 10^{-39}\ cm^2$

$$Q_{av}^{2\,*} = \frac{Q^2_{max} - Q^2_{min}}{\log Q^2_{max} - \log Q^2_{min}}$$

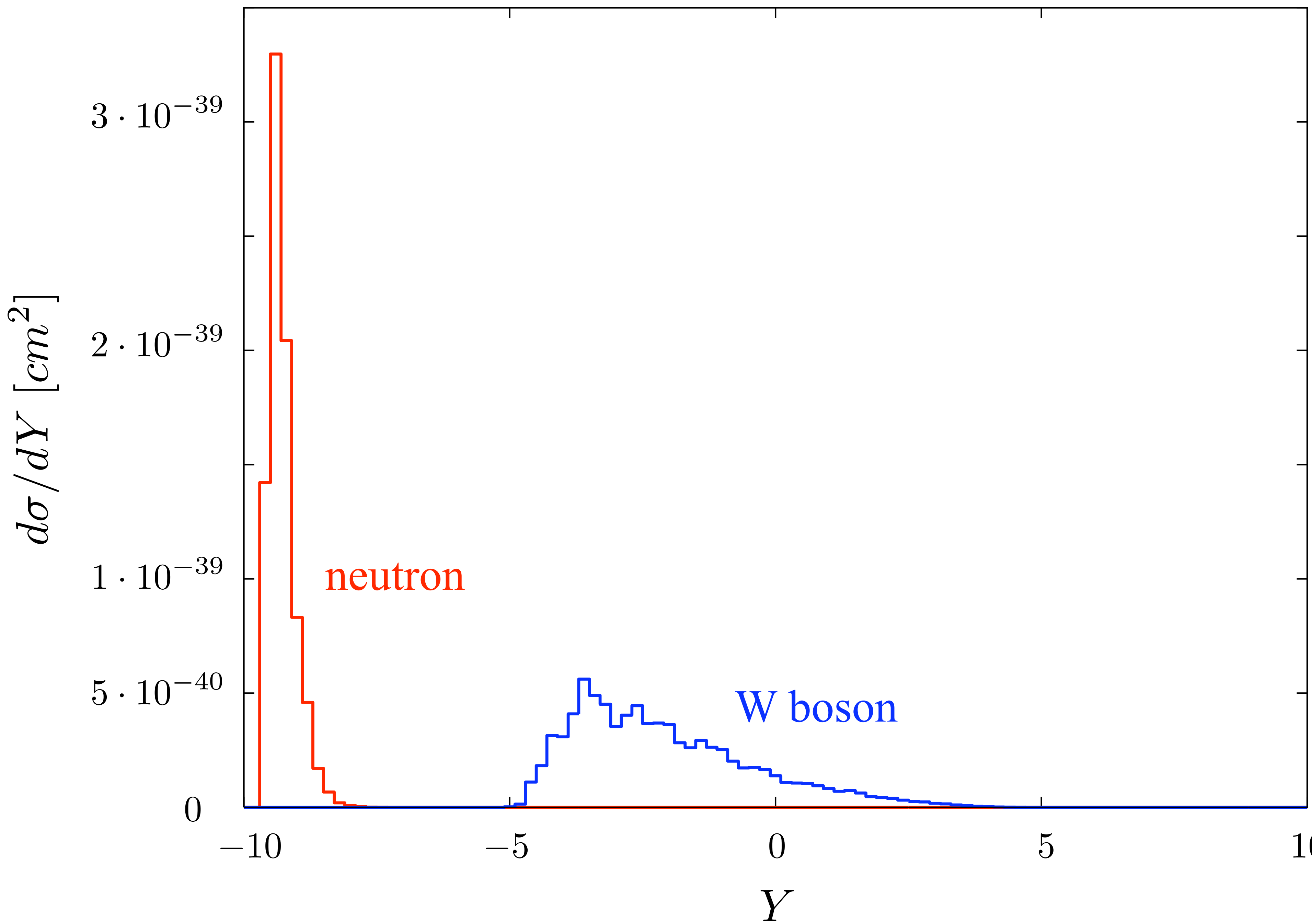


$$(1.2 \ldots 1.9) \cdot 10^{-39}\ cm^2$$

$$1\ GeV \leq Q_{av} \leq M_W$$

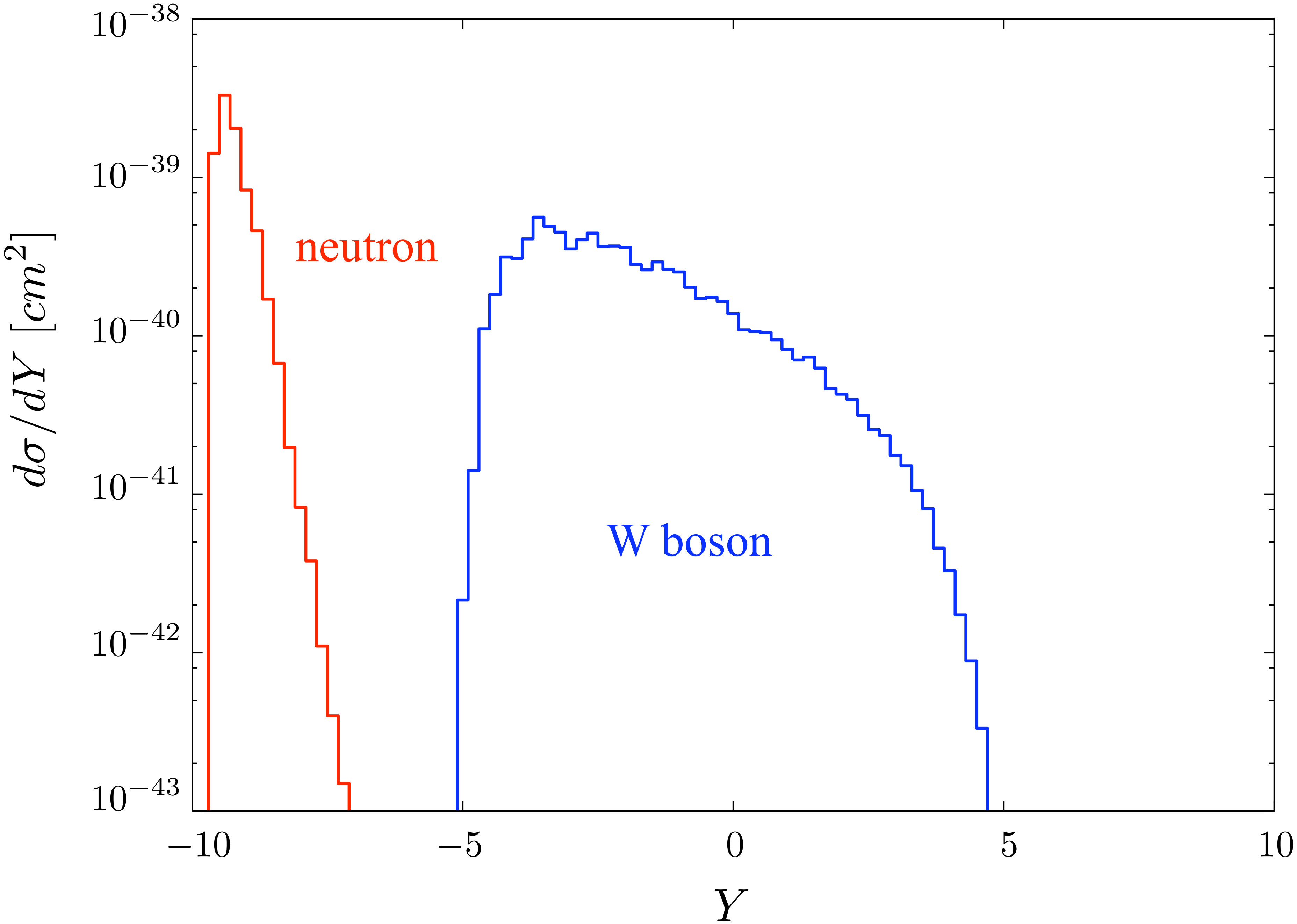
* *Pisano* [Eur. Phys. J. C 38, 79 (2004)]

Results (p-p collisions)



- differential cross section as function of rapidity in p-p collision (inelastic EPA)

Results (p-p collisions)



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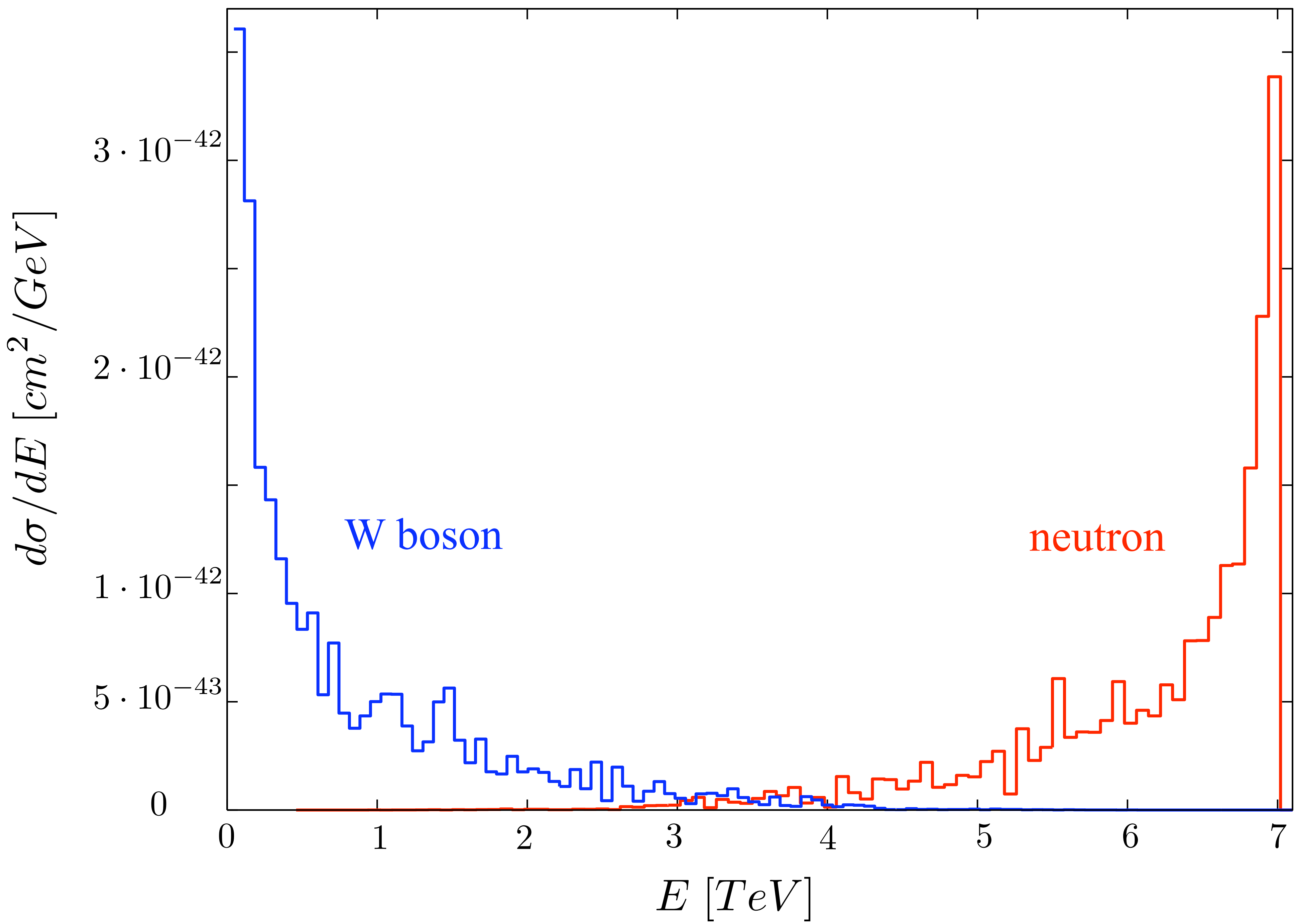

- differential cross section as function of energies in p-p collision, incident particles at 7 TeV

Conclusion

- we give an estimate of the total cross section for exclusive single W boson production in p-p and p-Pb collisions
- in p-p collisions two possibilities: elastic and inelastic EPA
- for elastic EPA & for timelike form factors which fall off:
  - total cross section is sensitive to the anomalous magnetic moment of the W boson
  - differential and total cross sections do not depend on the choice of the form factors in the timelike region

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Open Questions

- feasibility of measuring this process
- Is it possible to distinguish single W boson production from other processes?
- inelastic EPA: two further diagrams exist, their contribution needs to be checked