Isolated meson electroproduction at high transverse momentum with 22 GeV electrons

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Based on old and new work with Andrei Afanasev and Christian Wahlquist

Topic: Semi-Exclusive Deep Inelastic Scattering

- $\boxed{e + p \rightarrow e + \text{meson} + X}$ with mesons at high $k_\perp$ and mostly pions.
- Especially: Isolated mesons (i.e., not part of a jet)
- Mostly: Calculated perturbatively.
- Why isolated pions/mesons?
  - May be dominant process at highest $k_\perp$.
  - Measure high-x quark distributions.
  - "Designer currents": pick flavor of meson to select flavor of quark.
  - Basic subprocess same as in Generalized Parton Distributions (GPD's)

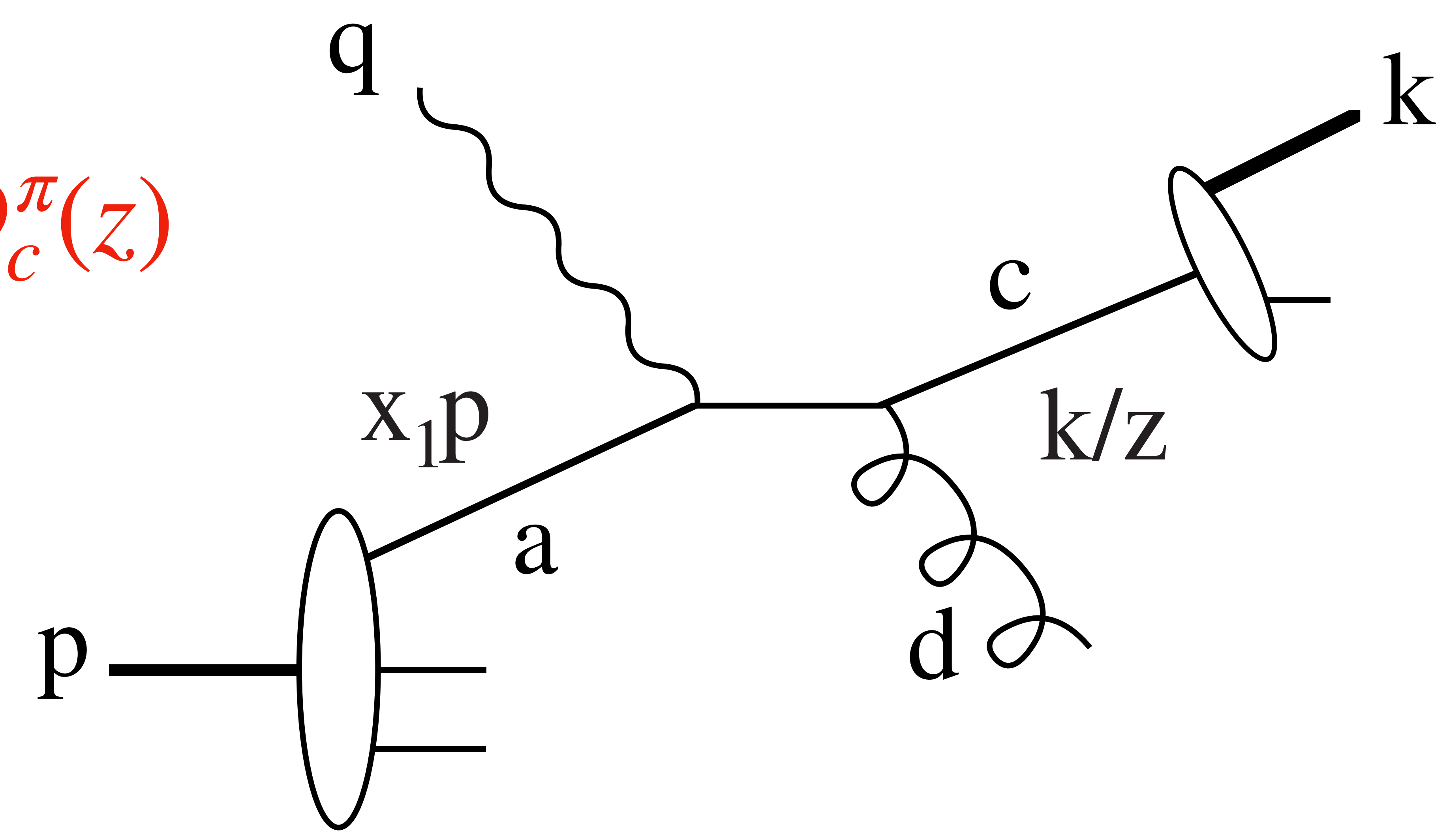
Outline

- Introduction
- Three processes (two for contrast plus one to focus on)
  - Fragmentation processes
  - Soft processes proceeding via Vector Meson Dominance (VMD)
  - Higher twist hard processes, yielding high $k_\perp$ isolated mesons.
- Some cross section plots
- Summary

Fragmentation

- Basic cross section calculation,

$$\sigma = \int dx_1 d\hat{t} dz \; G_{a/p}(x_1) \frac{d\hat{\sigma}}{d\hat{t}}(\gamma^* + a \to c + d) \, D_c^{\pi}(z)$$



- Where
  - $G_{a/p}$ = distribution function for a in p
  - $d\hat{\sigma}/d\hat{t}$ = subprocess cross section
  - $D_c^{\pi}(z)$ = fragmentation function

- Two generic subprocesses,
  - "QCD Compton," $\gamma^* + q \to q + g$
  - "Gluon fusion," $\gamma^* + g \to q + \bar{q}$

more fragmentation

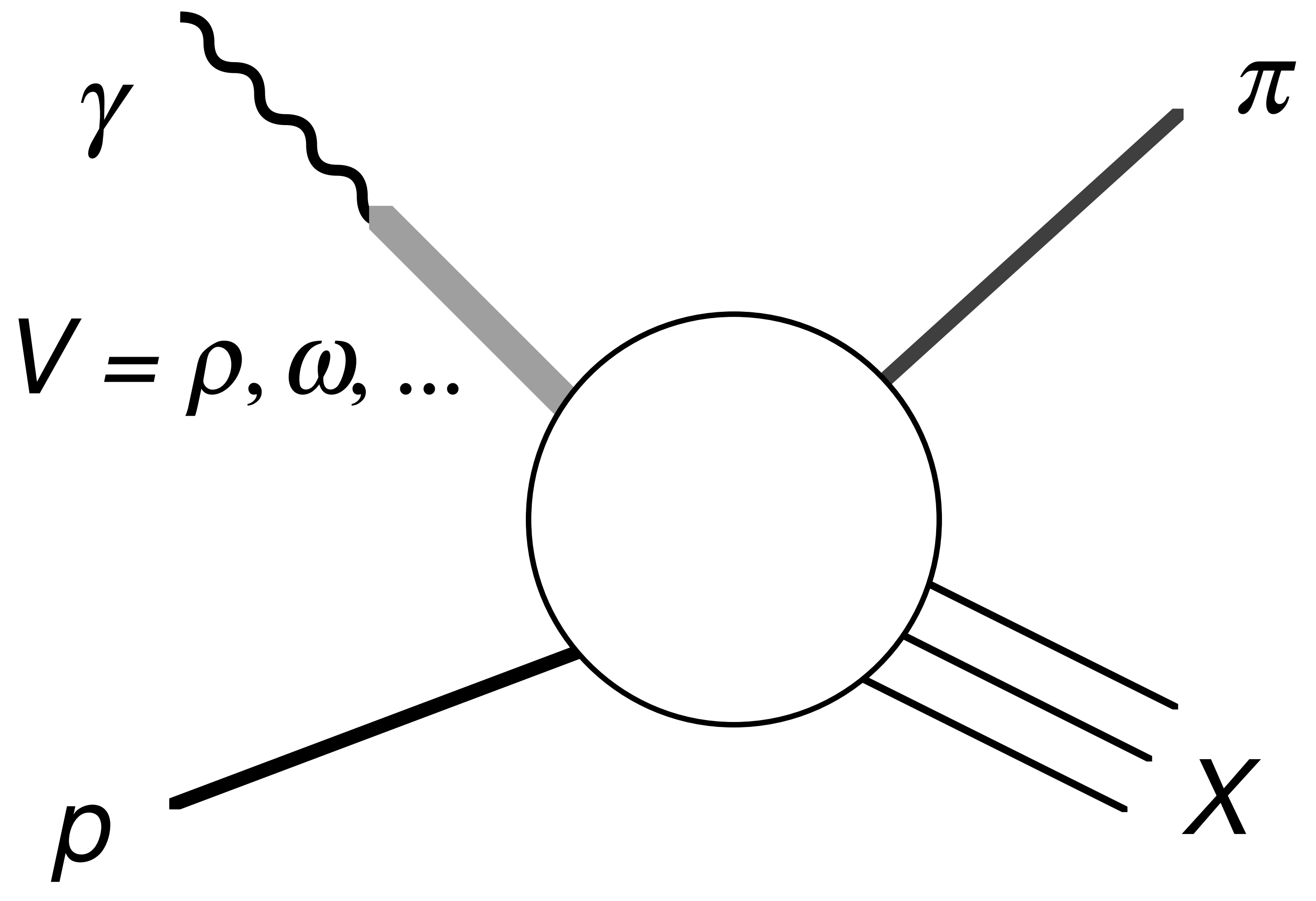
- Part is easily calculable perturbatively, e.g., for QCD Compton,

$$\frac{d\hat{\sigma}}{d\hat{t}} = \frac{8\pi\alpha\alpha_s}{3(\hat{s}+Q^2)^2}\left\{-\frac{\hat{u}}{\hat{s}} - \frac{\hat{s}}{\hat{u}} + 2\frac{Q^2}{\hat{s}\hat{u}}(\hat{t} - \hat{k}_\perp^2)\right\}$$

- Then: Get $G(x)$ from analyses of DIS,
  Get Get $D(z)$ from analyses of $e^+e^- \to$ hadrons

- Show results after discussion of soft processes.

soft processes, a.k.a. VDM



- Approximate soft processes by vector meson dominance: Photon enters but fluctuates to a rho or omega or phi or excitations thereof.

- Interacts as hadron. Not calculable ab initio. Amplitude obtained using various relations.

- E.g.,

$$f(\gamma p \to \pi^+ X)\Big|_{\rho\mathrm{MD}} = \frac{e}{f_\rho} f(\rho^0 p \to \pi^+ X), \qquad \text{(for } q^2 = 0\text{)}$$

and rho decay constant f_ρ got from $\Gamma(\rho \to e^+ e^-)$.

Parameterization of hadronic process.

- Still more stuff:

  - Don't have ρ^0 beams. Use π^+ or π^- data instead, for example $\pi^+ \ldots \to \pi^0 \ldots$

  - Bosetti et al. (e.g.) have semi-exclusive π in, π out data at many angles but limited energy range.

  - Lots of data on $pp \to \pi X$ at $90°$ CM.

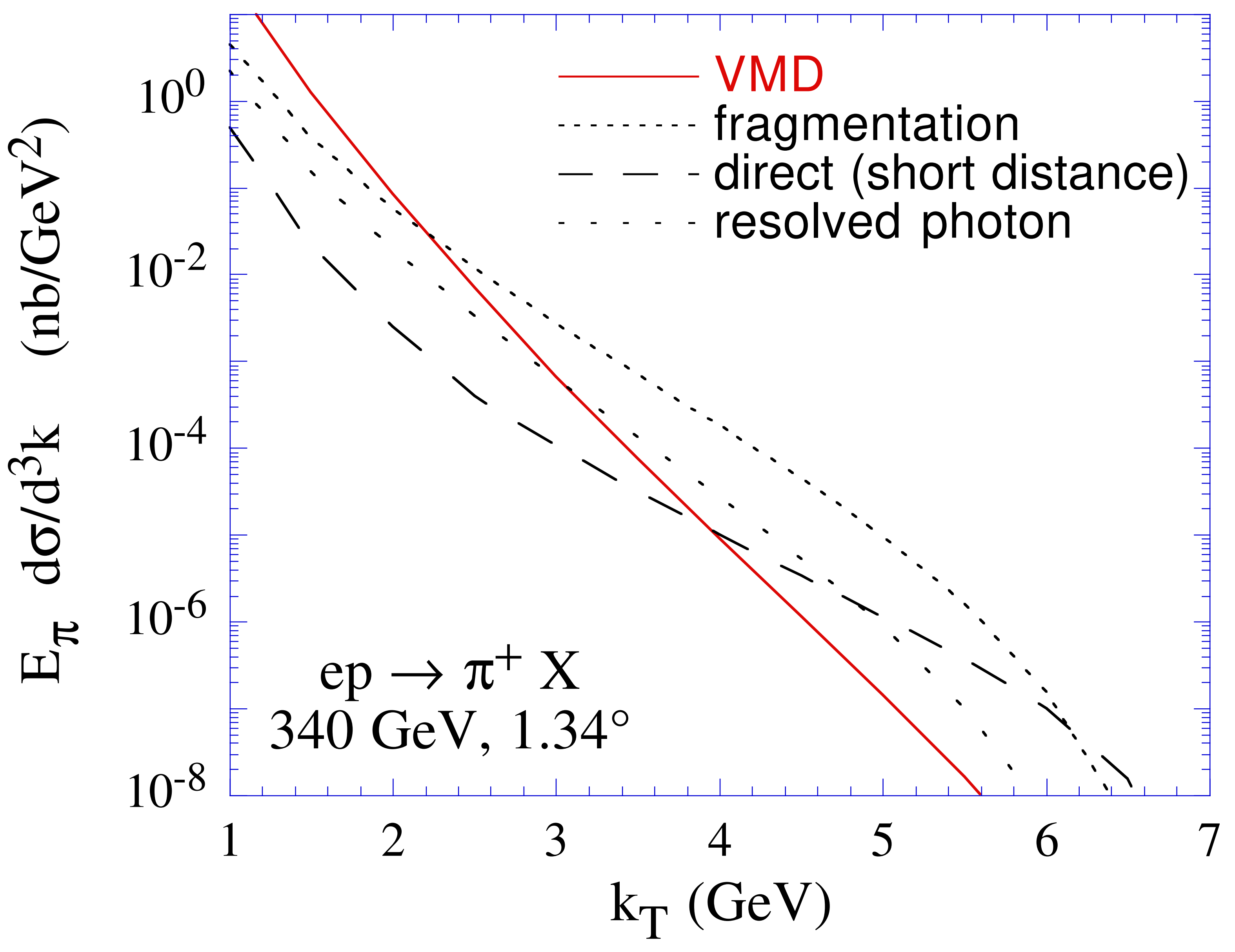
    Where data overlap, pion σ about 2/3 proton σ

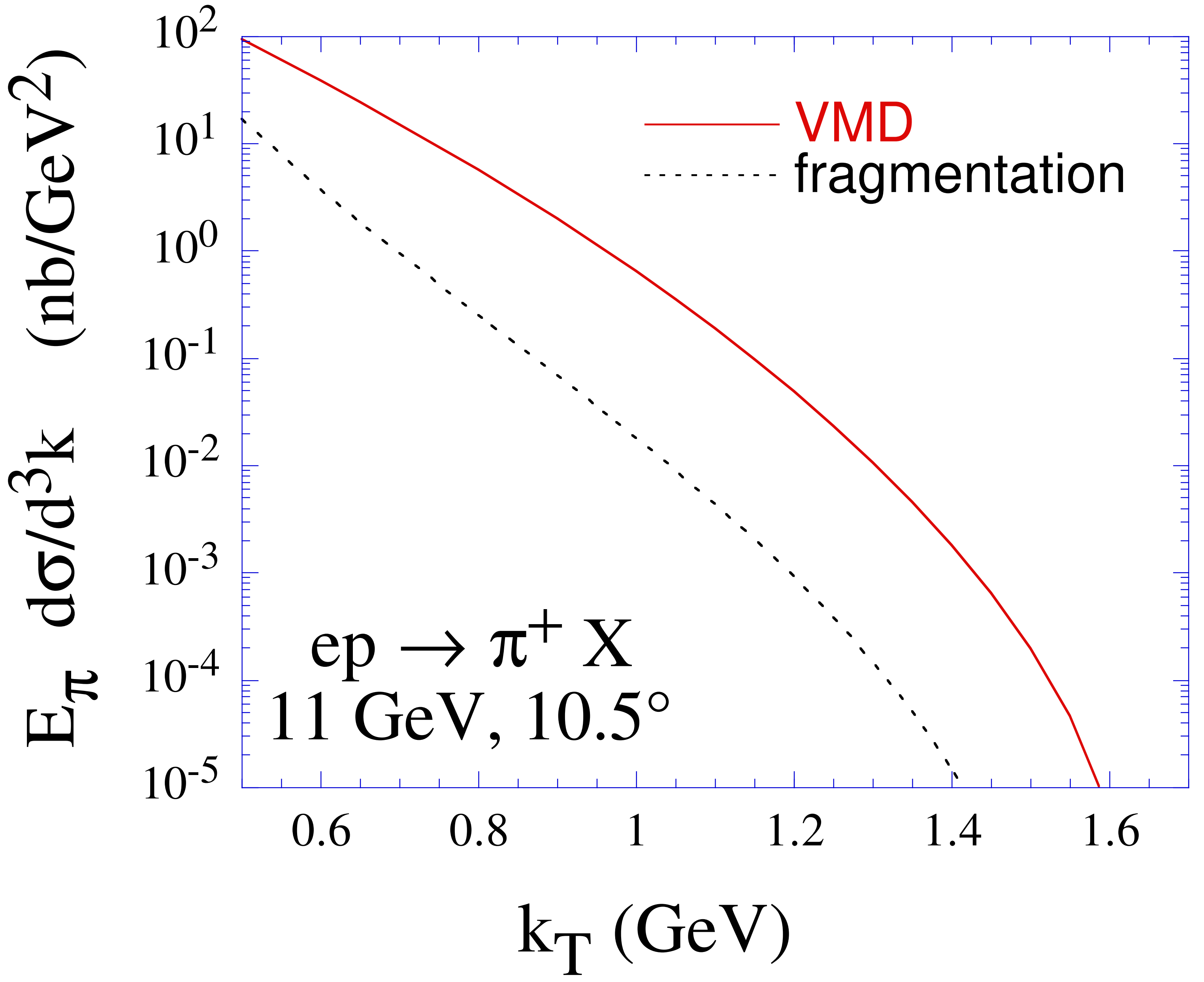
  - So get angular distribution from pion data, and energy dependence of pp data. Also estimate contributions from other VM (ϕ, ω, excitations).

(Formulas in ACW 2000. See also parameterization by Szczurek, Uleshchenko, and Speth.)

A plot of things so far

- Some plots with final electron not observed (i.e., photons generally very close to on-shell).





(Ignore long dash and dotted curves for now)

- Soft (i.e., VMD) pretty big for almost real photons.

Direct process

- Notes: For $\gamma^* p \to \pi X$ directly,

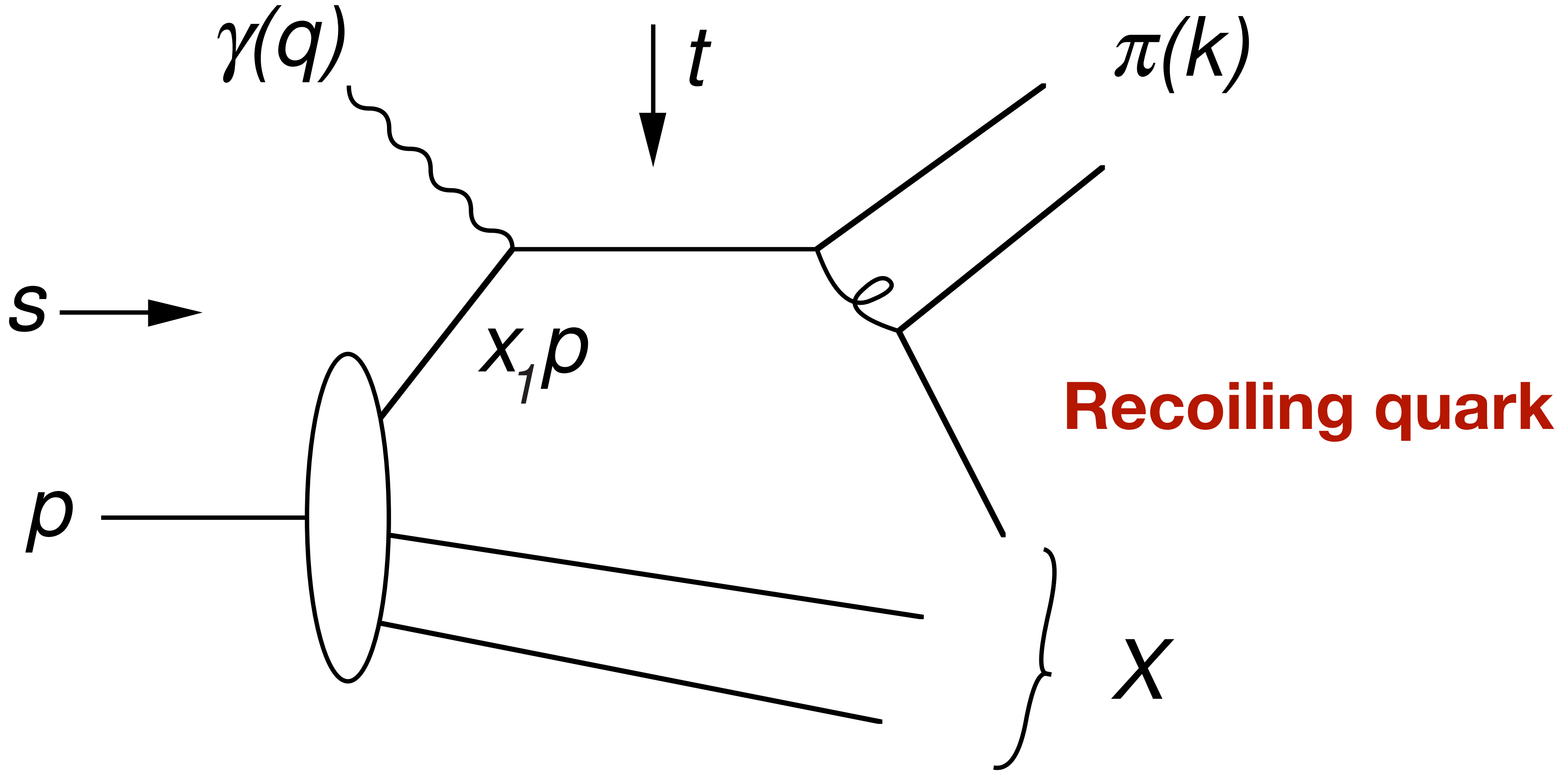
$$\frac{d\sigma}{dx_1 dt} = \sum_a G_{a/p}(x_1) \frac{d\hat{\sigma}}{dt}$$

- Special note: x_1 is fixed by observable quantities

- Subprocess Mandelstam variables
  $\hat{s} = (p_1 + q)^2, \quad \hat{t} = t = (q - k)^2, \quad \hat{u} = (p_1 - k)^2$

- Overall and observable Mandelstam variables
  $s = (p + q)^2, \qquad t = (q - k)^2, \qquad u = (p - k)^2$

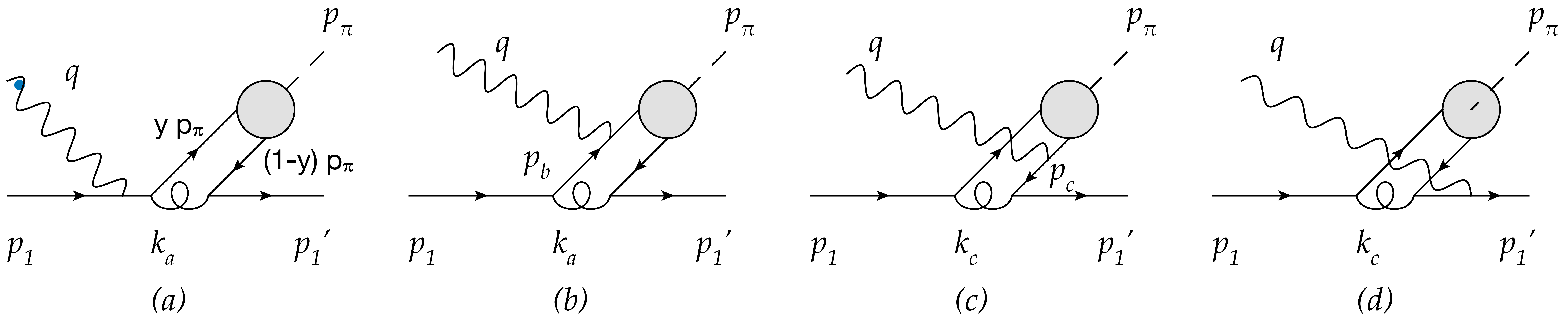
  - with $p_1 = x_1 p$, find $\boxed{x_1 = -t \,/\, (s + u + Q^2)}$



- Some references: Berger, Brodsky; Baier, Grozins; Brandenberg, Khoze, Müller; Hyer; Milana, Wakely, Wahlquist, Afanasev, me

Direct process, page 2

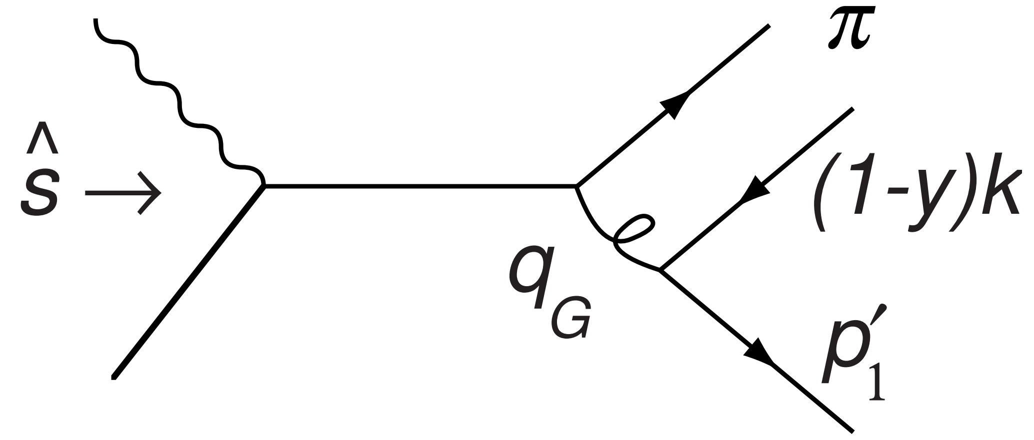
- Subprocess calculable using pQCD and (arguably) known pion $q\bar{q}$ Fock component wave function. Given by "distribution amplitude" $\phi_\pi(y)$.



For $Q^2 = 0$, need $I_\pi = \int_0^1 dy \, \frac{\phi_\pi(y)}{y}$; For $Q^2 \neq 0$, need $I'_\pi = \int_0^1 dy \, \frac{\phi_\pi(y)}{y - (1-y)Q^2/t}$

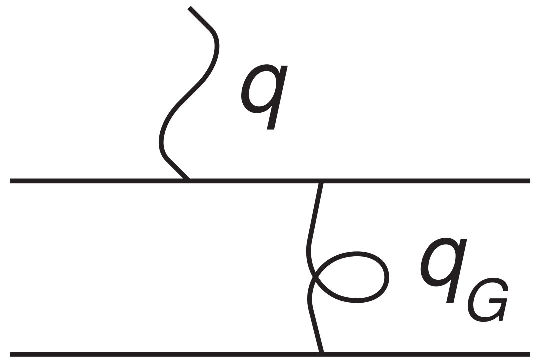
- For π^+ (e.g.), initial up quark dominates, so $\sum_{\text{quarks}}$ needs only one term.

Direct process, side remarks

- 

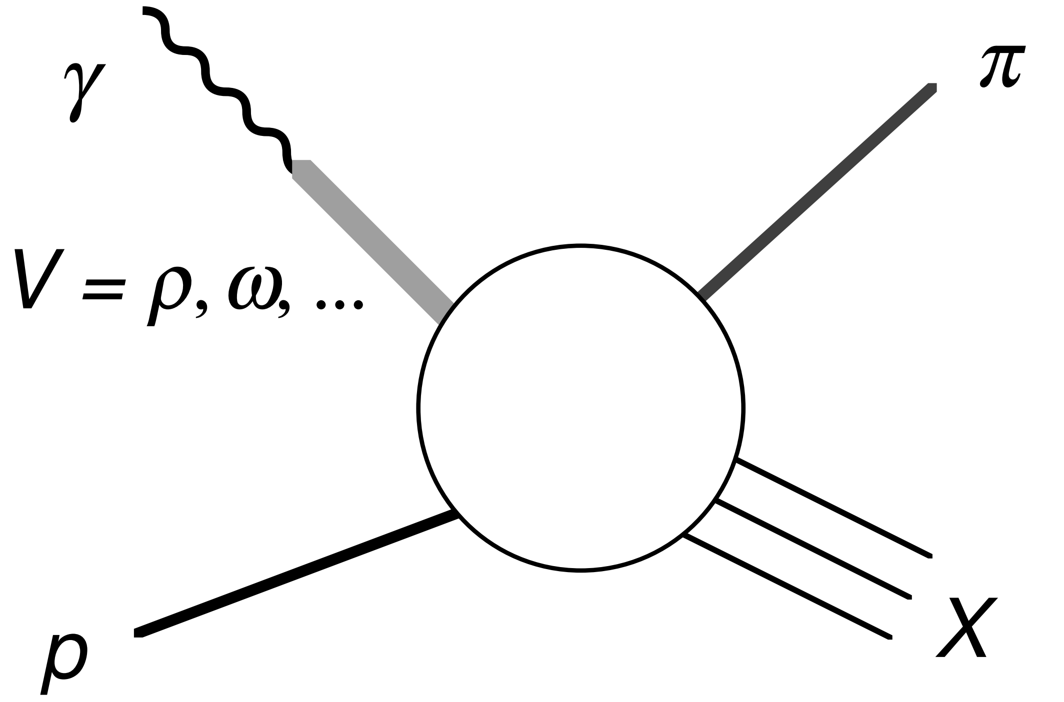
$q_G^2 = (1-y)\hat{s} = x_1(1-y)s \approx \frac{1}{6}s \approx 8\,\text{GeV}^2$ (for 22 GeV JLab)

Pion form factor uses same distribution amplitude and same I_π integral, and

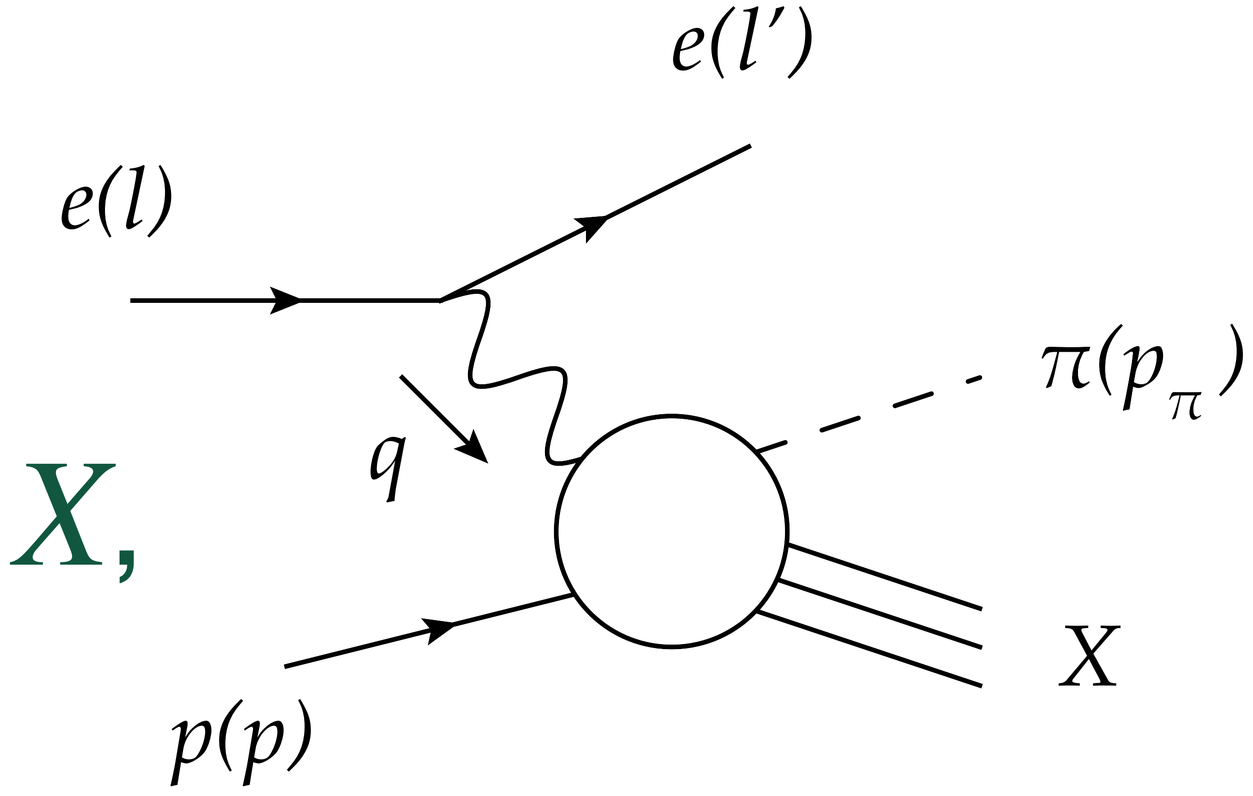


$q_G^2 \approx \frac{1}{9}q^2, \;\Rightarrow$ JLab SEDIS as good as pion FF at $Q^2 = 72$ GeV^2

- For VMD at $Q^2 \neq 0$, propagator suppresses ρMD contributions by $(m_\rho^2/(m_\rho^2+Q^2))^2 < 1/7$ for $Q^2 \approx 1$ GeV^2.



Laying on some formulas



- Write full cross section as flux factor time cross section for virtual photon semi-inclusive scattering, $\gamma^* + p \to \pi + X$,

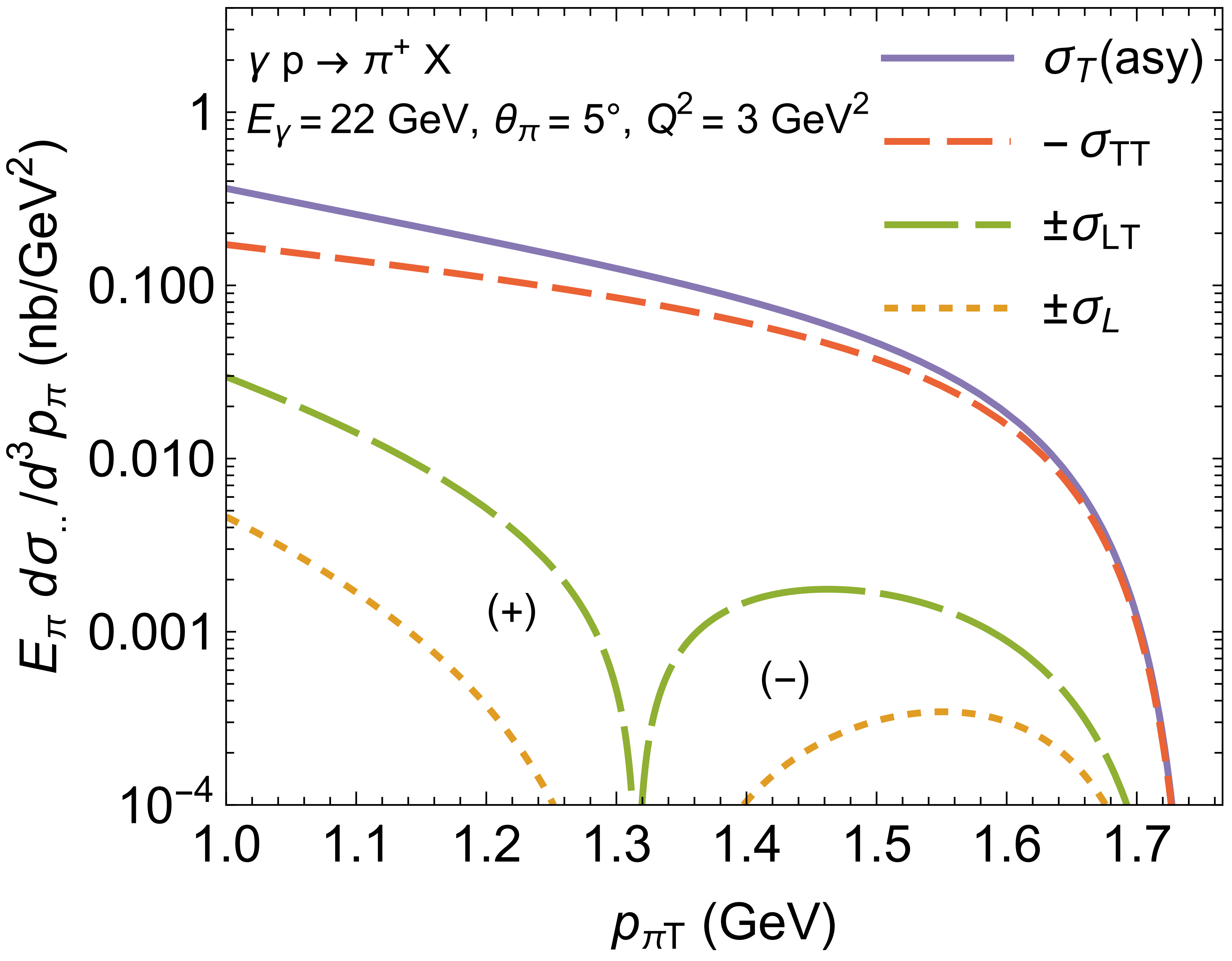
$$E'\omega_\pi \frac{d^6\sigma}{d^3l' d^3p_\pi} = \frac{\alpha}{2\pi^2} \frac{|\vec{q}\,|}{EQ^2} \frac{1}{1-\epsilon}$$

$$\times\, \omega_\pi \frac{d}{d^3p_\pi} \left\{ \sigma_T + \epsilon\sigma_L + \epsilon \cos(2\phi_h)\sigma_{TT} + \sqrt{2\epsilon(1+\epsilon)} \cos\phi_h\, \sigma_{LT} - (2\lambda_e)\sqrt{2\epsilon(1-\epsilon)} \sin\phi_h\, \sigma'_{LT} \right\}$$

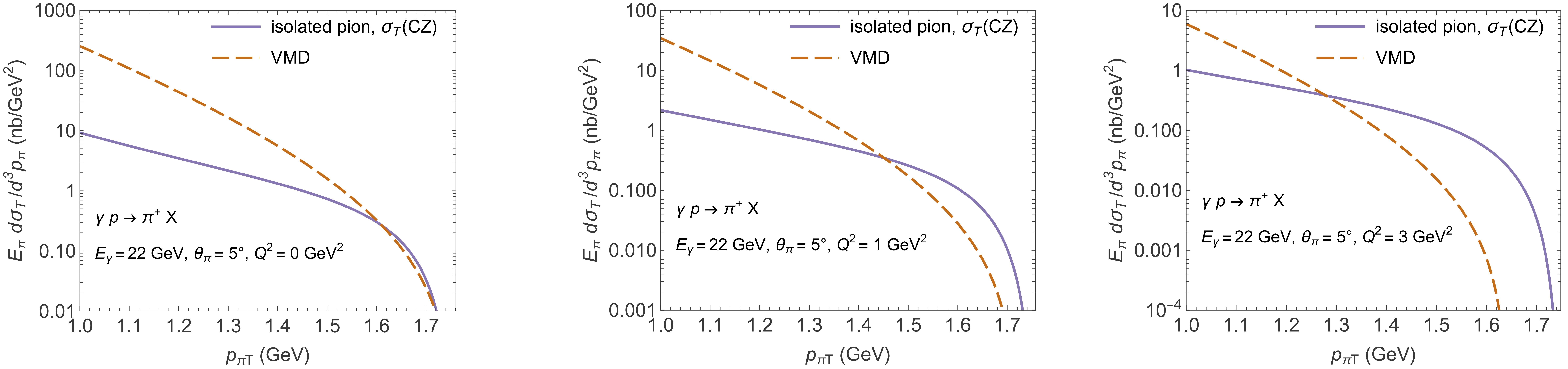
- where ϵ is the usual

$$\epsilon = \left(1 + 2\tau(1+\tau)\tan^2(\theta_e/2)\right)^{-1} \quad \text{with} \quad \tau = \nu^2/Q^2$$

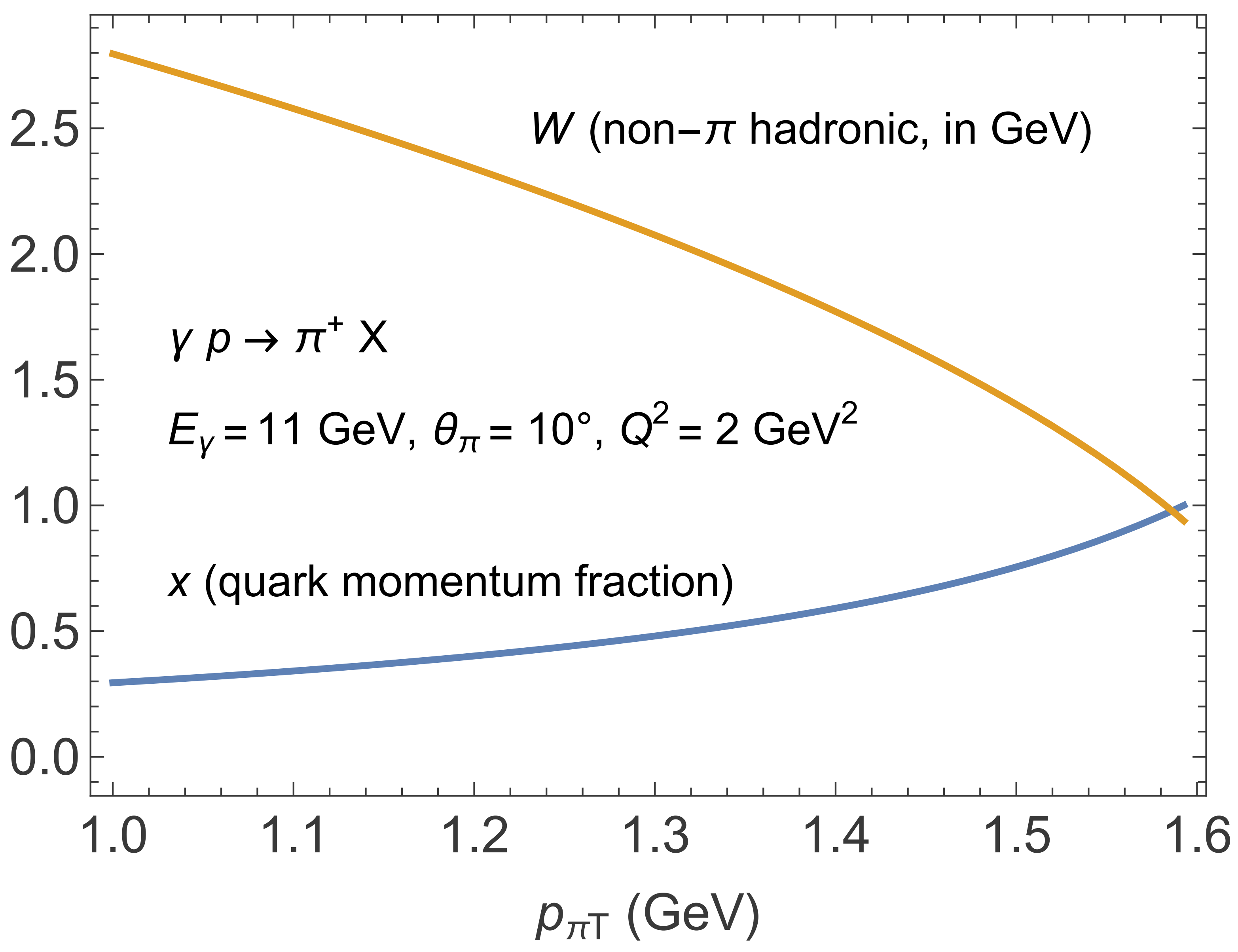
Plot of “sub-cross sections”

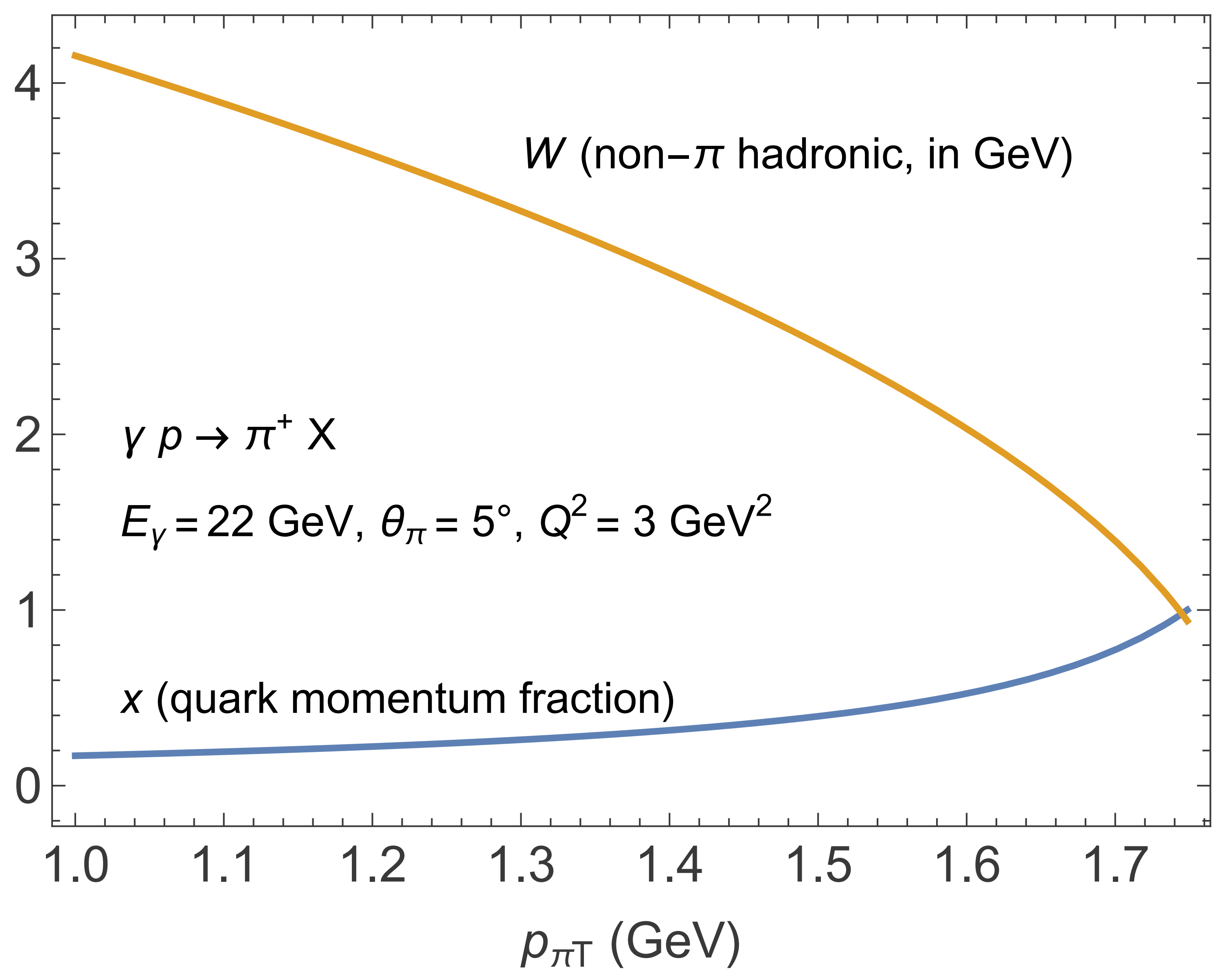
- 

Comparison plots, at several Q^2



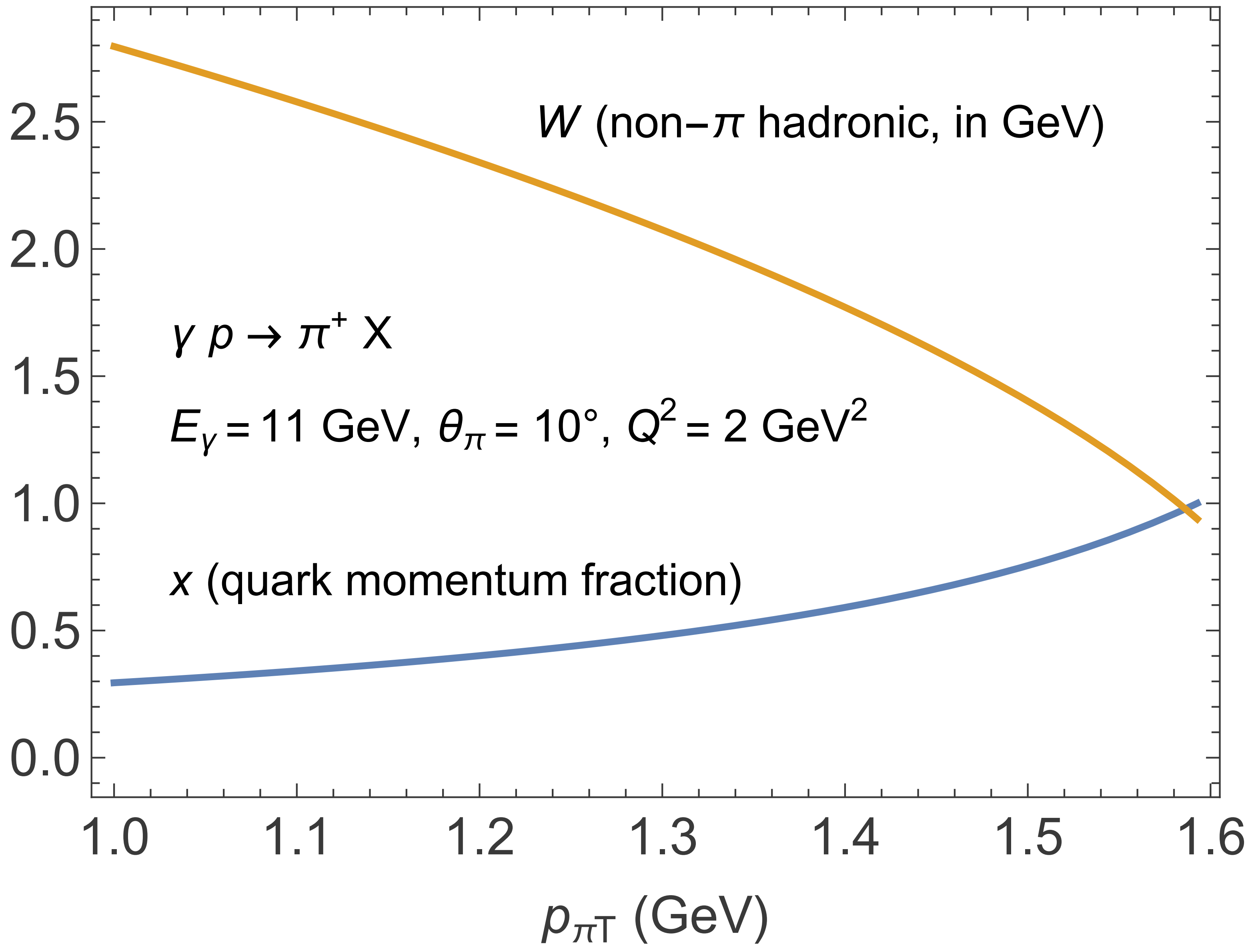
Recoiling mass and x plots

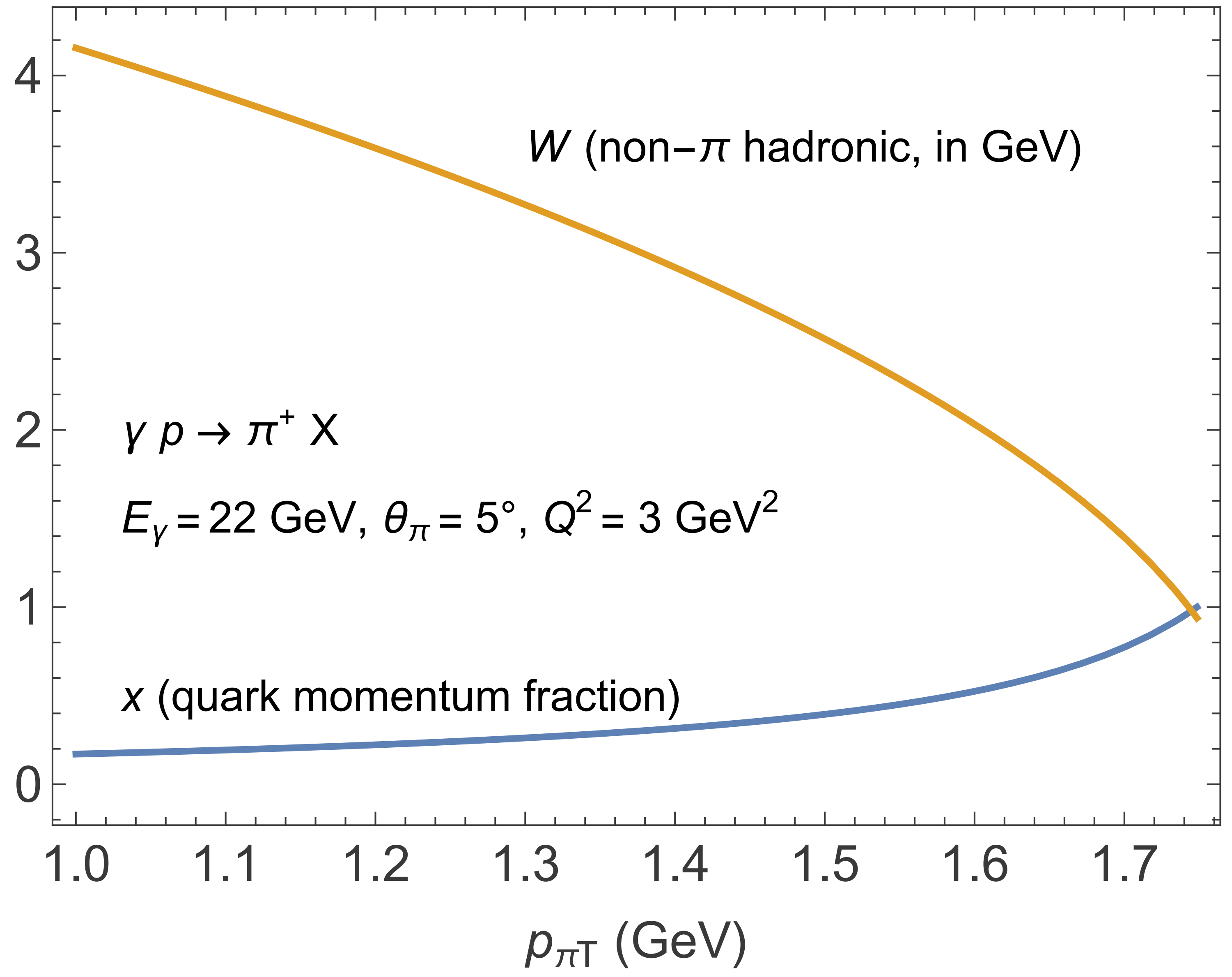




- Plots show recoiling (not the isolated pion) hadronic mass, and also x.
- For 22 GeV, significant window where we are out of the resonance region.

Recoiling mass and x plots





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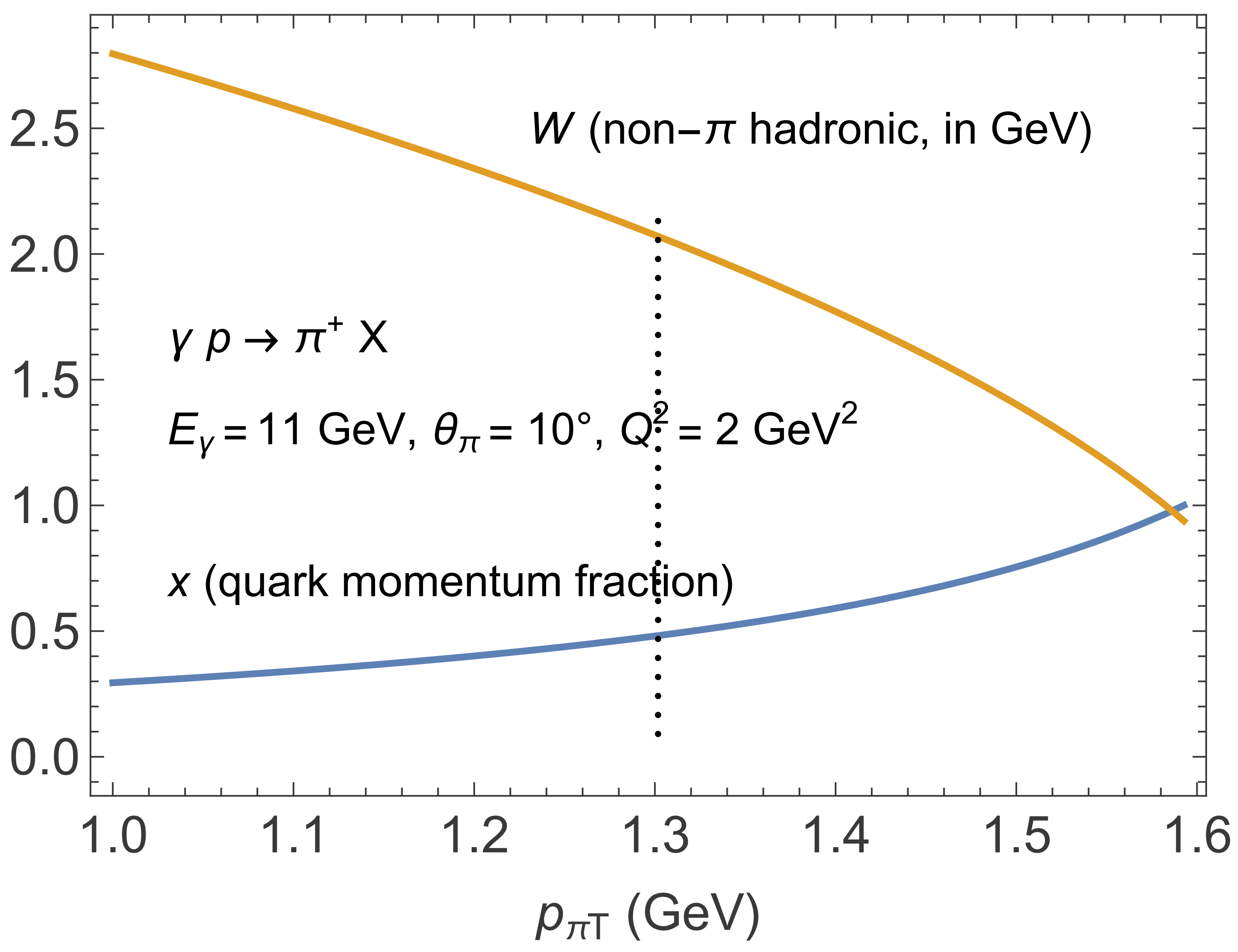

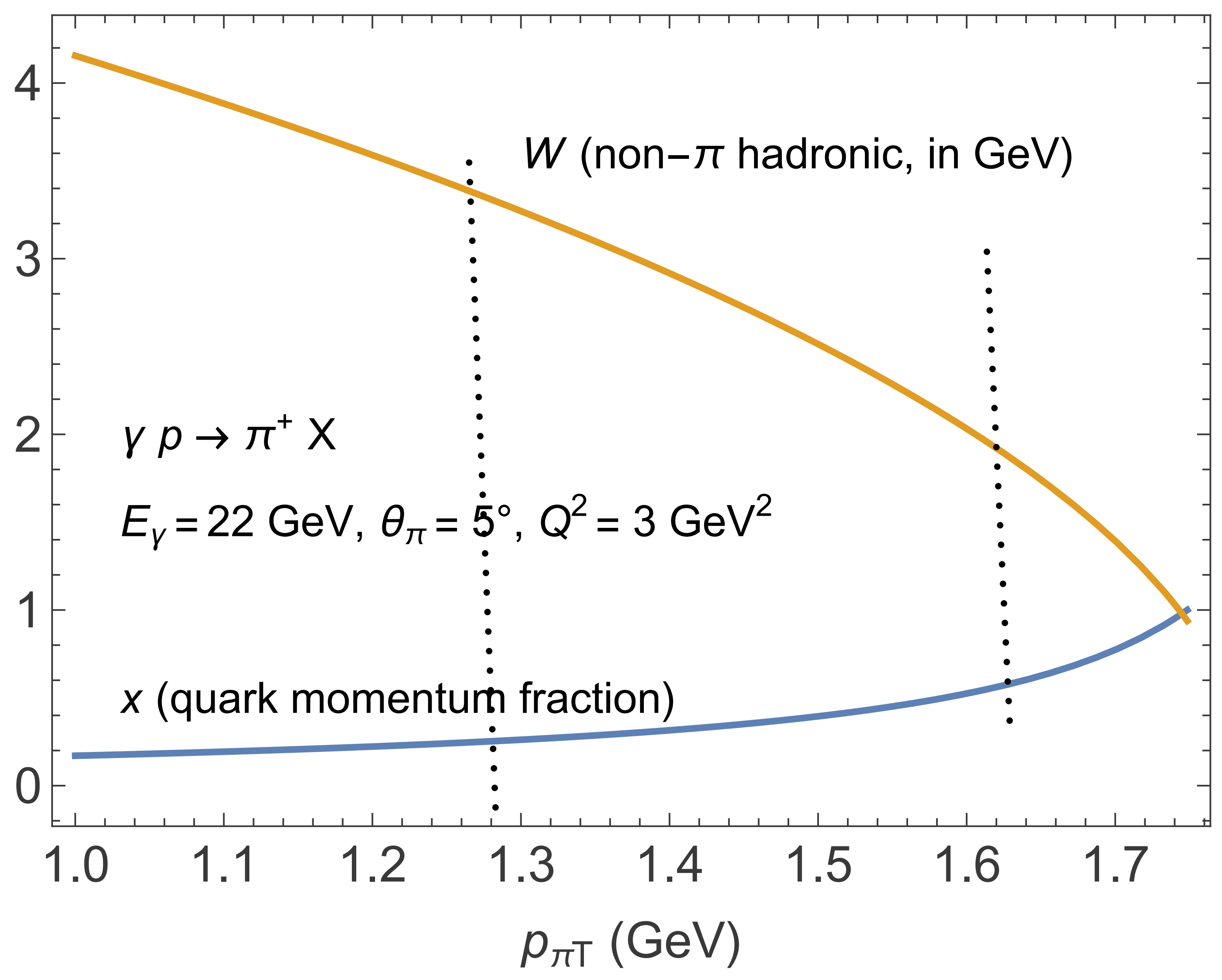

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Final remarks

- It appears that direct pion production, a hard higher twist process, can be seen above the soft "background" at high transverse momentum at JLab energies.
- Could be used to learn high-*x* form of quark pdfs, with ability to select flavor of quark by choosing flavor of pion. May also learn the (1/momentum fraction) moment of pion distribution amplitude, I_π
- Higher order processes could affect high $p_{\pi\perp}$ production, for example radiative corrections or initial transverse momentum effects upon rapidly falling cross section. See comments by J. Qiu.
- Side note: The basic subprocess for direct meson production is the same as for quasi-elastic production of mesons, in the region where that production can be described by generalized parton distributions.

The end

Past the end

Alternative cross section formula

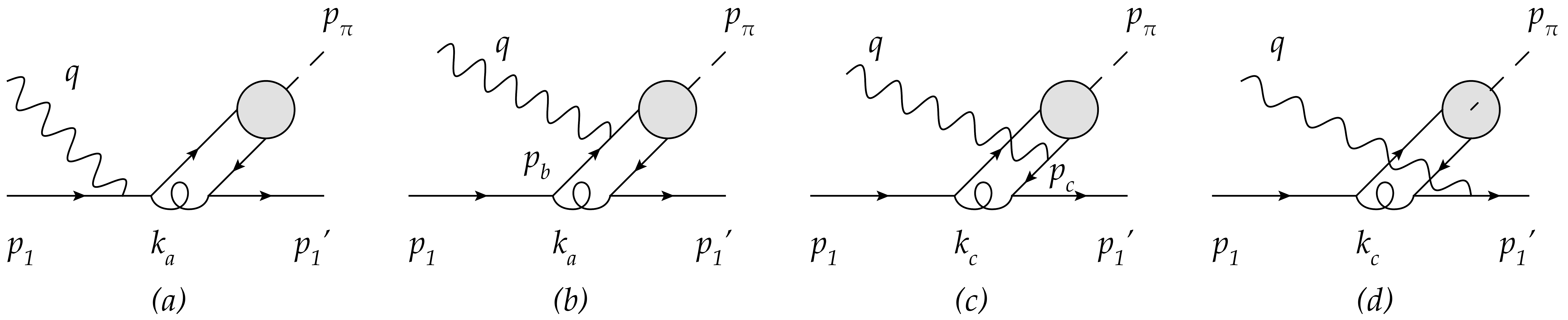
- For $e + p \to e + \pi + X$, without target polarization, in terms of structure functions,

$$\frac{d^6\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dp_{\pi\perp}^2} = \frac{\alpha^2}{2x_B Q^2(1-x_B)} \frac{y}{1-\epsilon}\left(1+\frac{m_p}{\nu}\right)$$

$$\times \left\{ F_{UU,T} + \epsilon F_{UU,L} + \epsilon \cos(2\phi_h) F_{UU}^{\cos 2\phi_h} + \sqrt{2\epsilon(1+\epsilon)}\cos\phi_h\, F_{UU}^{\cos\phi_h} - h\sqrt{2\epsilon(1-\epsilon)}\sin\phi_h\, F_{LU}^{\sin\phi_h} \right\}$$

- (θ = electron scattering angle in lab, ν = electron energy loss in lab, ϕ = azimuthal angle of pion-photon plane relative to electron scattering plane. Other new notation is exercise for viewer or reader.)

Subprocess cross sections



$$\frac{d\hat{\sigma}}{dt} = \frac{128}{27}\pi^2\alpha\alpha^2 I_\pi^2 \left(\frac{e_1}{\hat{s}} + \frac{e_2}{\hat{u}}\right)^2 \frac{\hat{s}^2 + \hat{u}^2}{\hat{s}^2(-t)}$$