EXCLUSIVE LIMITS of DRELL YAN

Accessing GPDs and TDAs

B. Pire

CPhT, École Polytechnique, CNRS, PALAISEAU, France

Compass workshop

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based on works with

M. Diehl, E. Berger and L. Szymanowski, J.P. Lansberg

TWO EXCLUSIVE LIMITS

→ FORWARD region :

based on factorized description of forward DVCS

in terms of Generalized Parton Distributions (GPD)

→ BACKWARD region :

based on factorized description of backward DVCS

in terms of Transition Distribution Amplitudes (TDA)

(Fixed angle region : tiny cross sections)

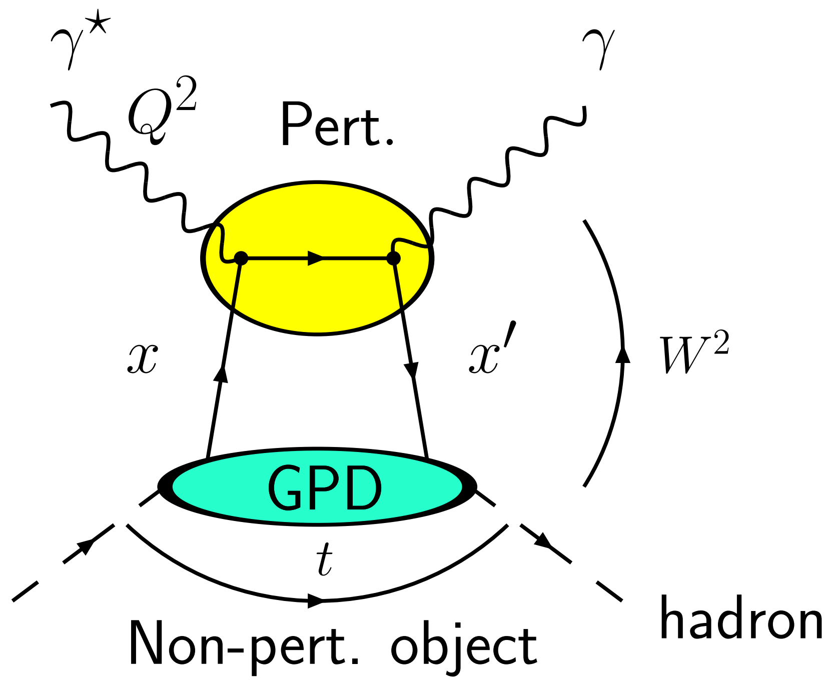
From spacelike DVCS to Timelike "TCS"

E.Berger, M. Diehl, BP : Eur.Phys.J.C23, 675(2002).

Success of factorized description of DVCS

$\gamma^* N \to \gamma N'$ **in terms of Generalized Parton Distributions**

$x \neq x'$



Initial Photon Beam allows to study crossed reaction

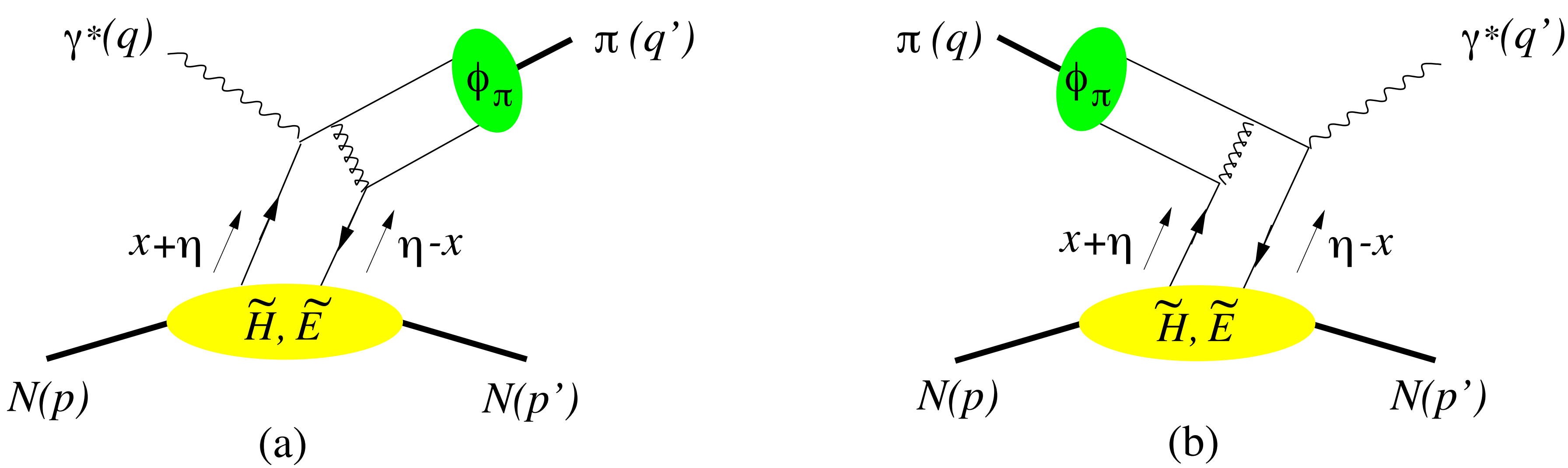
$\gamma N \to \gamma^* N'$ **in terms of the same GPDs**

at LHC : BP, L.Szymanowski, J.Wagner : Phys Rev. D79,014010(2009)

From $\gamma^* N \to \pi N'$ to $\pi N \to \gamma^* N'$

E.Berger,M.Diehl,BP,Phys Lett.B523

Pion beams reveal $\tilde{H}, \tilde{E}$ Generalized Parton distributions

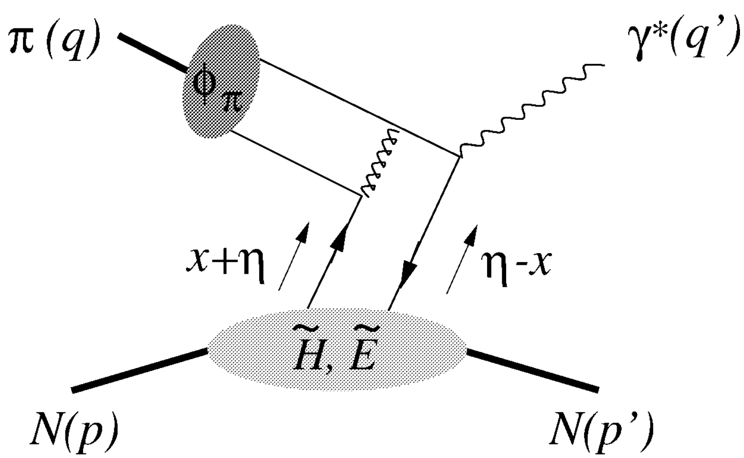


spacelike | **timelike** (= Exclusive Limit of Drell Yan process)

JLab or COMPASS physics $\Longleftrightarrow$ **COMPASS or JParc physics**

Exclusive lepton pair production in πN scattering

$$\pi N \to \gamma^* N'$$



(b)

Bjorken variable $\tau = \frac{q'^2}{s-M^2}$

skewness $\eta = \frac{(p-p')^+}{(p+p')^+} = \frac{\tau}{2-\tau}$

At lowest order, spacelike (ξ) and timelike ($-\eta$) amplitudes are equal

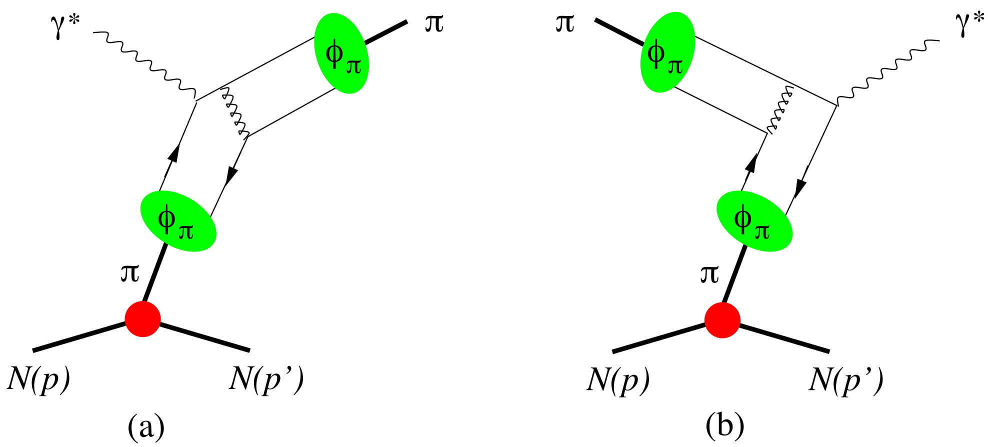
At higher orders, significant differences in the hard amplitude (recall K-factor in Drell-Yan vs DIS)

$\to$ critical check of the factorization procedure and of the universality of GPDs.

$\tilde{H}$ and $\tilde{E}$ GPDs

➩ $\tilde{H}(x, \xi = 0, t = 0) = \Delta q(x)$

➩ $\tilde{E}$ **unknown : Pion pole dominance often assumed**

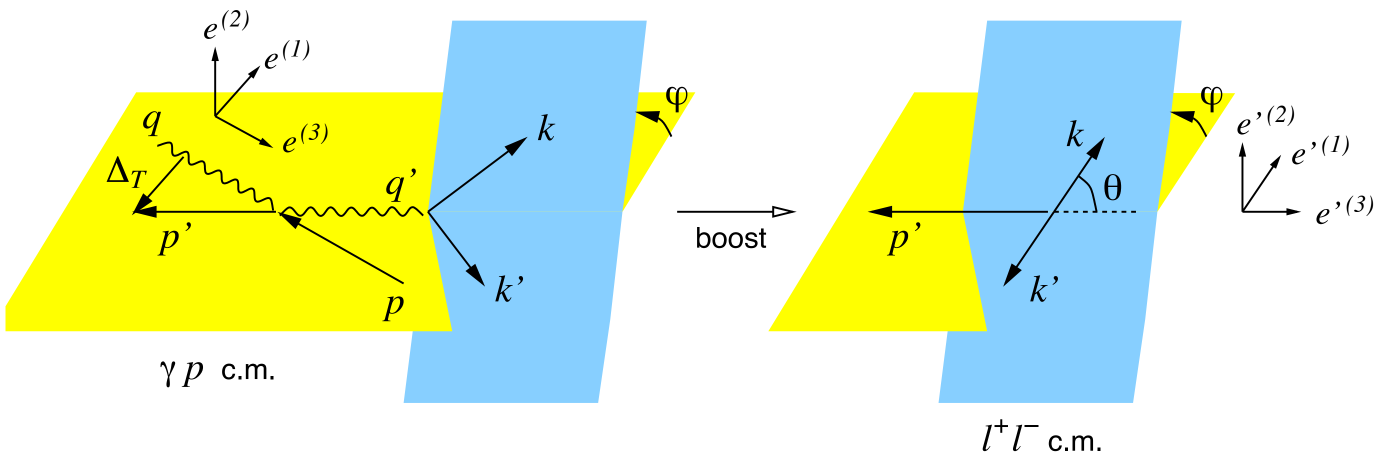


to be tested

➩ $t-$**dependence** $\rightarrow$ **proton femtophotography**

Lepton angular distribution

Dominant Amplitude : longitudinal γ^*



$$\frac{d\sigma}{dQ'^2\,dt\,d(\cos\theta)\,d\varphi} = \frac{\alpha_{\rm em}}{256\,\pi^3}\,\frac{\tau^2}{Q'^6}\sum_{\lambda',\lambda}|M^{0\lambda',\lambda}|^2\,\sin^2\theta$$

Crucial Test of the validity of the twist expansion

if σ_T not small, extract GPDs from σ_L only !

Cross sections

Amplitude $$M^{0\lambda',\lambda}(\pi^- p \to \gamma^* n) = -ie\,\frac{4\pi}{3}\,\frac{f_\pi}{Q'}$$
$$\times \quad \frac{1}{(p+p')^+}\,\bar{u}(p',\lambda')\left[\gamma^+\gamma_5\,\tilde{\mathcal{H}}^{du}(-\eta,\eta,t) + \gamma_5\frac{(p'-p)^+}{2M}\,\tilde{\mathcal{E}}^{du}(-\eta,\eta,t)\right]u(p,\lambda).$$

⇨ $$\frac{d\sigma(\pi^- p \to \mu^+\mu^- n)}{dQ'^2 dt} = \frac{4\pi\alpha_{em}^2}{27}\,\frac{\tau^2}{Q'^8}\,f_\pi^2$$

$$.\ [((1-\eta^2)|\tilde{\mathcal{H}}^{du}|^2 - 2\eta^2\mathcal{R}e\,(\,\tilde{\mathcal{H}}^{du*}\tilde{\mathcal{E}}^{du}\,)\ - \eta^2\frac{t}{4M^2}\,|\tilde{\mathcal{E}}^{du}|^2]$$

with $$\tilde{\mathcal{H}}^{du}(\xi,\eta,t) = \frac{8}{3}\,\alpha_S\int_{-1}^{1} dz\,\frac{\phi_\pi(z)}{1-z^2}$$
$$\times\int_{-1}^{1} dx\,\left[\frac{e_d}{\xi - x - i\epsilon} - \frac{e_u}{\xi + x - i\epsilon}\right]\left[\tilde{H}^d(x,\eta,t) - \tilde{H}^u(x,\eta,t)\right]$$

and similar eqn for $\tilde{\mathcal{E}}^{du}$.

Remember $\xi = -\eta$

Target Transverse Spin asymmetry

At the twist 2 level : $$\frac{d^{\uparrow}\sigma - d^{\downarrow}\sigma}{d^{\uparrow}\sigma + d^{\downarrow}\sigma} = A_{\mathrm{UT}}^{\sin(\phi-\phi_S)} \sin(\phi - \phi_S) + \text{other harmonics}$$

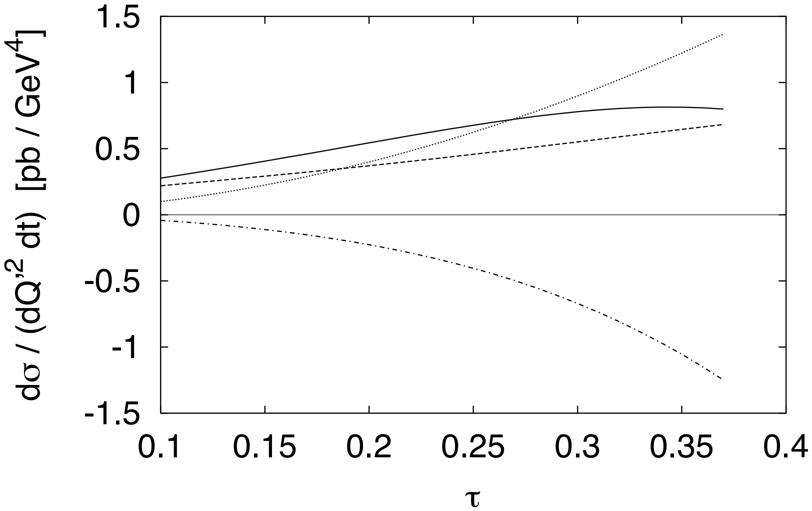
$$A_{UT} = \frac{-2\sqrt{\frac{t-t_{min}}{t_{min}}}\,\eta^2\,\mathcal{I}m\,(\,\tilde{\mathcal{H}}\,\tilde{\mathcal{E}}^*\,)}{(1-\eta^2)|\tilde{\mathcal{H}}|^2-\frac{t}{4M^2}|\eta\tilde{\mathcal{E}}|^2-2\eta^2\mathcal{R}e(\tilde{\mathcal{H}}\tilde{\mathcal{E}}^*)}$$

⇨ New information on GPDs.

e.g. if $\tilde{E}$ is well modelized by pion pole, $\tilde{\mathcal{E}}$ is real $\rightarrow A_{UT} \sim \tilde{H}(x, \xi = x, t)$

Cross section estimates

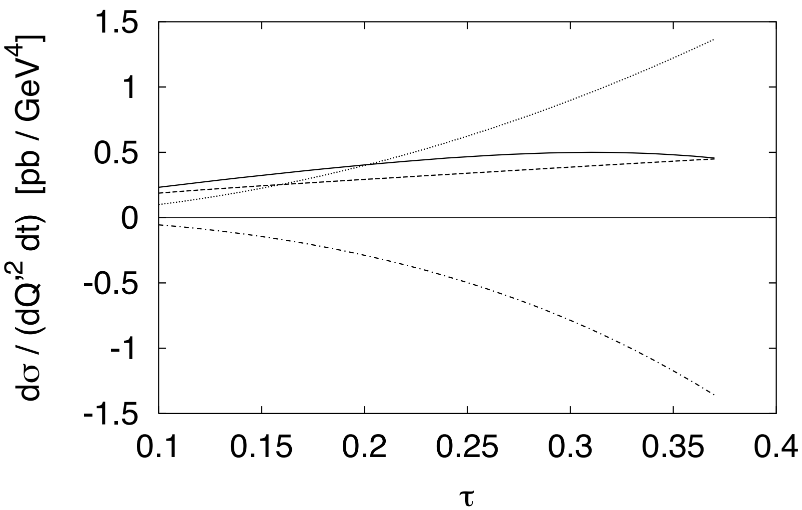
E.Berger,M.Diehl,BP,Phys Lett.B523



$\pi^- p \to \mu^+ \mu^- n$; $Q^2 = 5$; $t = -0.2$; $\tau = \frac{Q^2}{s - M^2}$

Solid = total ; dashed : $\tilde{H}^2$;

Dash-dotted : Re$(\tilde{H}.\tilde{E})$; dotted : $\tilde{E}^2$

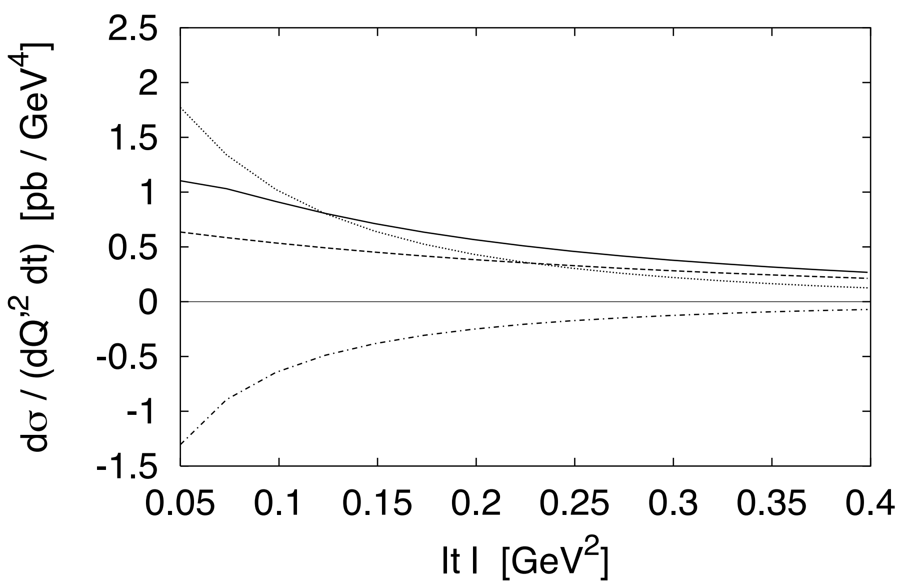


$\pi^+ n \to \mu^+ \mu^- p$; $Q^2 = 5$; $t = -0.2$

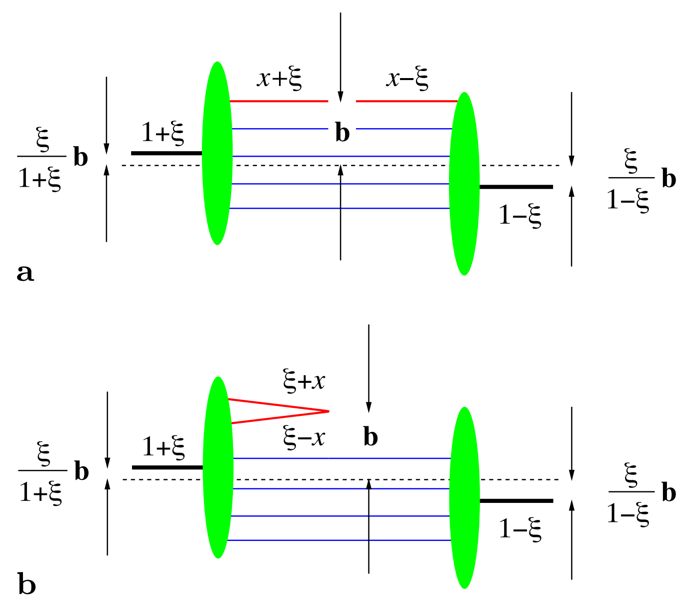
$t-$ dependence and femtophotography

E.Berger,M.Diehl,BP,Phys Lett.B523

M.Diehl,EPHJA,C25

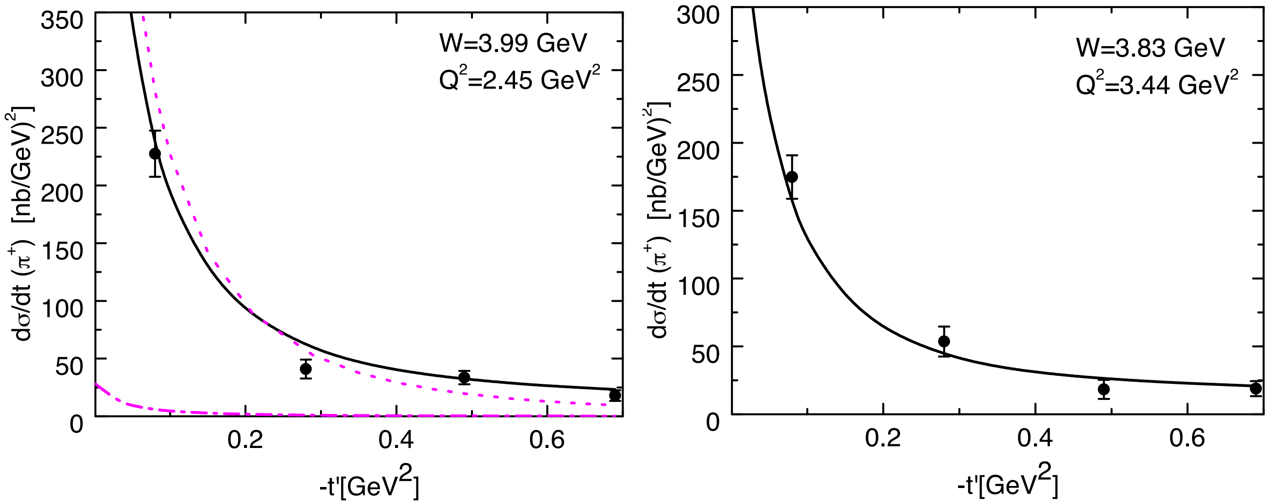


$$\vec{\Delta}_T \longrightarrow \vec{b}_T$$



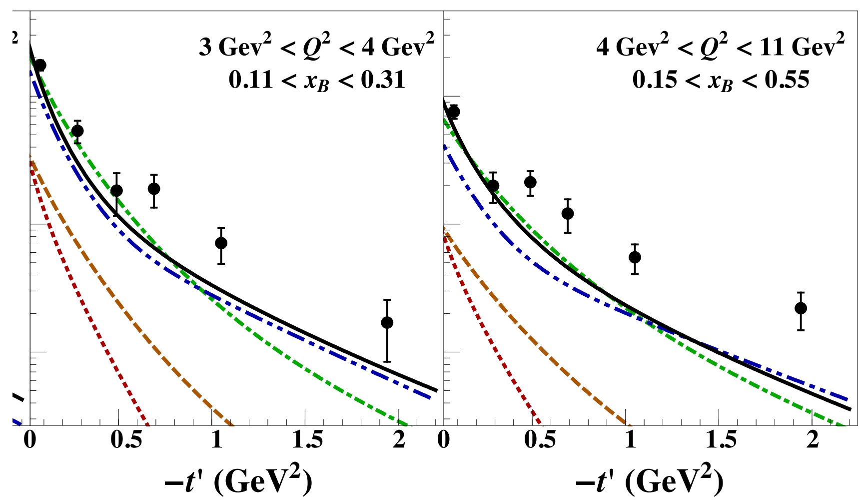
Status of spacelike $\gamma^*(Q)p \to \pi N$

Data from HERMES :



$\sigma_T + \epsilon\sigma_L$ σ_T **vs** σ_L **?**

(also data from JLab)



2 contradictory phenom. analysis

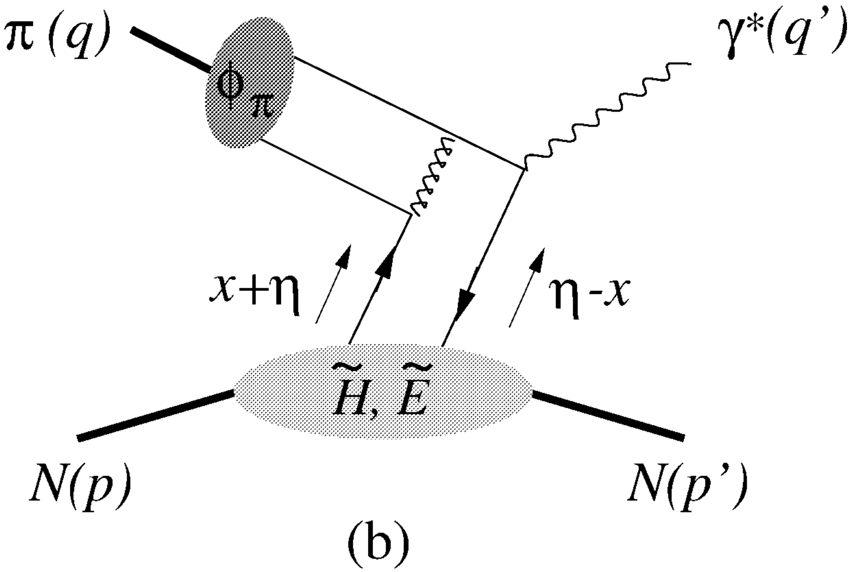
π-exchange with exp FF ;

S. Goloskokov and P.Kroll, EPJ, C65

QCD with $\alpha_S = .8$

C. Bechler, D. Muller, ArXiv 0906.2571

Compass Opportunity



Sufficient rates ($O(1-10/$hour)

Transverse spin asymmetry

$1 < q'^2 < 10\, GeV^2$, **small** $t = (q-q')^2$, **fixed** $\xi = \frac{p^+_N - p^+_{N'}}{p^+_{N'} + p^+_N}$

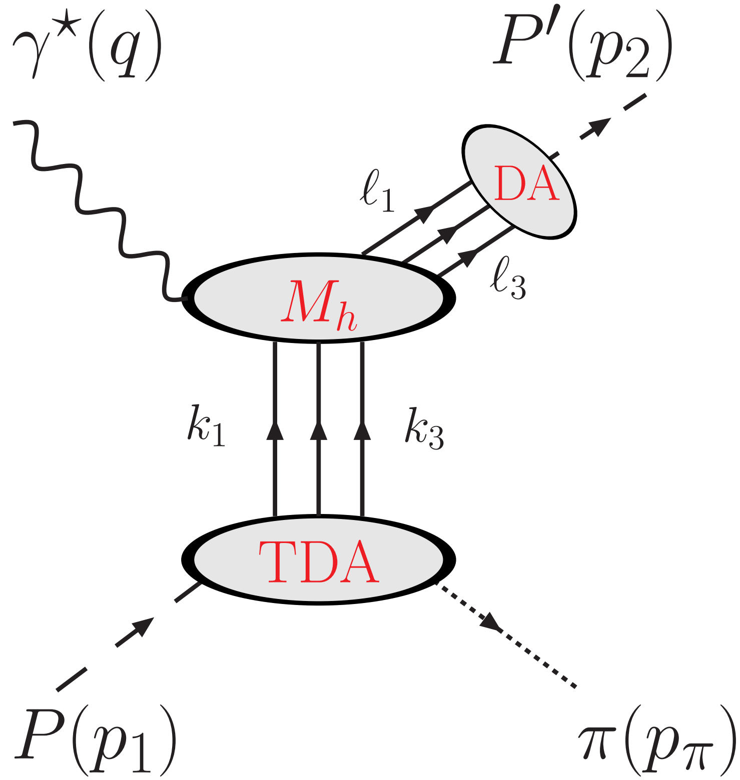
Measure lepton pair momentum ; deduce missing mass$^2 = \bar{M}^2$.

Select small $\bar{M}^2 \approx M_p^2$. (*(or detect final proton with recoil detector ?)*

Small ξ : lepton pair forward.

How to factorize backward electroproduction $\gamma^* N \to N'\pi$

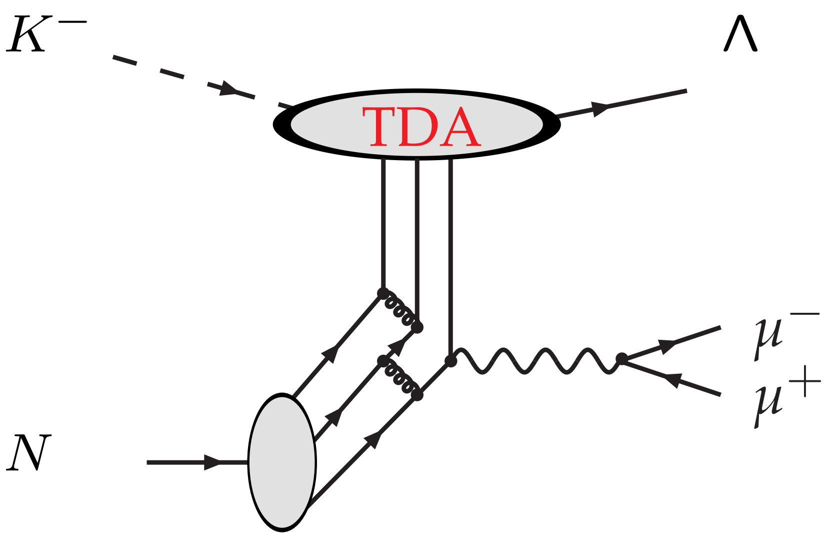
BP, L Szymanowski, PRD71 and PLB622

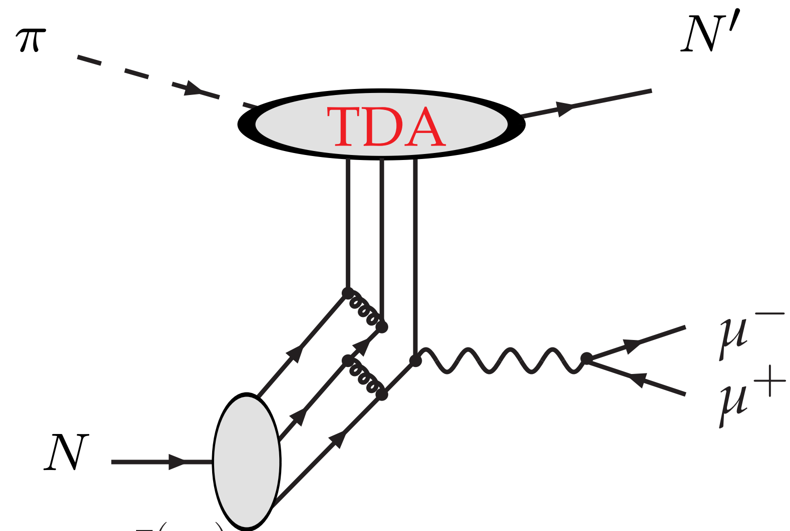


at large q^2, *small* $t = (p_{N'} - p_\pi)^2$, *fixed* $\xi = \frac{p^+_{N'} - p^+_\pi}{p^+_{N'} + p^+_\pi}$

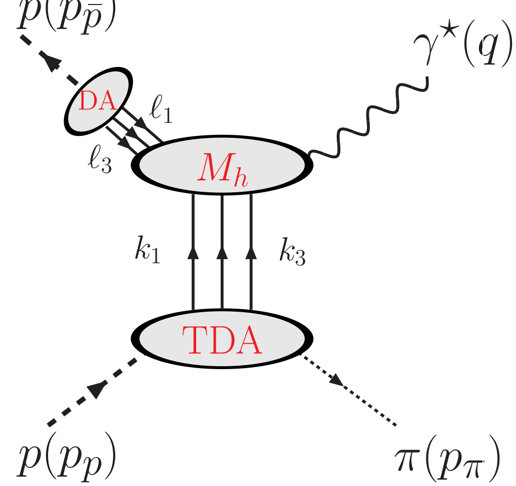
$\rightarrow$ factorize timelike versions of backward $\gamma^* N \rightarrow N'\pi$

$K^- N \rightarrow \Lambda\gamma^*$ $\qquad$ $\pi N \rightarrow N'\gamma^*$





at large q^2, small t, fixed ξ



$\bar{N} N \rightarrow \pi\gamma^*$

Interpretation of the $N \to \pi$ TDAs

Develop proton wave function as (schematically) $|qqq> + \ \ |qqq\pi> + ...$

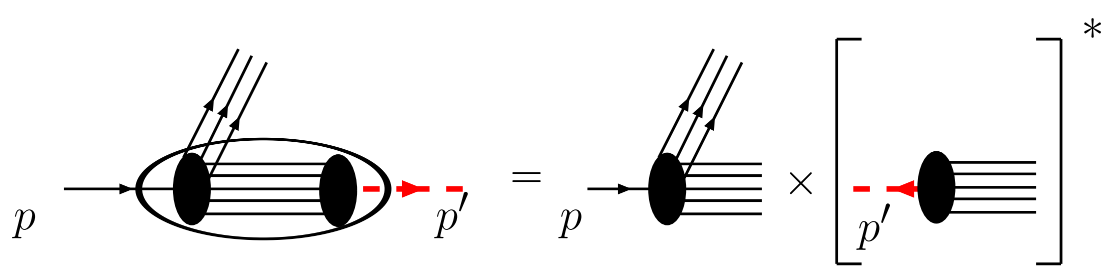
$|qqq>$ **is described by proton DA :** $\langle 0|\, \epsilon^{ijk} u^i_\alpha(z_1\, n) u^j_\beta(z_2\, n) d^k_\gamma(z_3\, n)\, |p(p,s)\rangle \Big|_{z^+=0,\, z_T=0}$

Define matrix elements sensitive to $|qqq\ \pi>$ **part : the TDAs**

$$\langle \pi(p')|\, \epsilon^{ijk} u^i_\alpha(z_1\, n) u^j_\beta(z_2\, n) d^k_\gamma(z_3\, n)\, |p(p,s)\rangle \Big|_{z^+=0,\, z_T=0}$$

light cone matrix elements of operators obeying usual RG evolution equations

➩ The $\pi \to N$ TDAs provides information on the next to minimal Fock state in the baryon



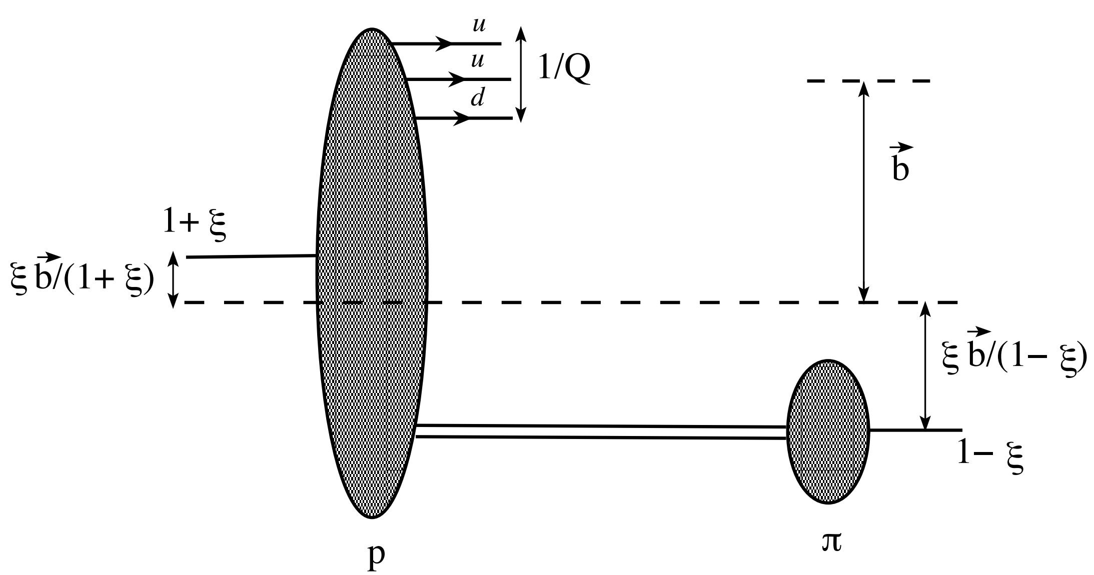
$Proton = |u\ d\ d\ \pi^+>$ with small transverse separation for the quark triplet

Impact parameter interpretation

- As for GPDs Fourier transform $\Delta_T \to b_T$

$$F(x_i, \xi, t = \Delta^2) \to \tilde{F}(x_i, \xi, b_T)$$

$\longrightarrow$ Transverse picture of pion cloud in the proton



if factorization works

Define Transition Distribution Amplitudes

- **Dirac decomposition at leading twist :**

$$4\langle\pi^0(p')|\,\epsilon^{ijk}u^i_\alpha(z_1)u^j_\beta(z_2)d^k_\gamma(z_3)\,|p(p,s)\rangle\Big|_{z^+=0,\,z_T=0} =$$

$$\frac{-f_N}{2f_\pi}\Big[V_1^0(\hat{P}C)_{\alpha\beta}(B)_\gamma + A_1^0(\hat{P}\gamma^5C)_{\alpha\beta}(\gamma^5B)_\gamma - 3T_1^0(P^\nu i\sigma_{\mu\nu}C)_{\alpha\beta}(\gamma^\mu B)_\gamma] +$$
$$V_2^0(\hat{P}C)_{\alpha\beta}(\hat{\Delta}_TB)_\gamma + A_2^0(\hat{P}\gamma^5C)_{\alpha\beta}(\hat{\Delta}_T\gamma^5B)_\gamma + T_2^0(\Delta_T^\mu P^\nu\sigma_{\mu\nu}C)_{\alpha\beta}(B)_\gamma$$
$$+T_3^0(P^\nu\sigma_{\mu\nu}C)_{\alpha\beta}(\sigma^{\mu\rho}\Delta_T^\rho B)_\gamma + \frac{T_4^0}{M}(\Delta_T^\mu P^\nu\sigma_{\mu\nu}C)_{\alpha\beta}(\hat{\Delta}_TB)_\gamma$$

$B =$ **nucleon spinor** $V_i(z_i), A_i(z_i), T_i(z_i)$ **are the TDAs**

V_1 **and** T_1 **dominant . If isospin = 1/2,** $T_1 = f(V_1)$

- **Fourier transform each TDA, → momentum fractions representation**

$$F(z_i) = \int_{-1+\xi}^{1+\xi} d^3x\delta(\sum x_i - 2\xi)e^{-iPn\Sigma x_i z_i}\,F(x_1,x_2,x_3,\xi,t,Q^2)$$

$$F = V_i, A_i, T_i$$

➫ **Write the Amplitude** ($\pi N(p_2) \to N'(p_1)\mu^+\mu^-$)

$$\mathcal{M}^{\lambda}_{s_1 s_2} = -i\frac{(4\pi\alpha_s)^2\sqrt{4\pi\alpha_{em}}f_N^2}{54 f_\pi Q^4}\Bigg[\underbrace{\bar{u}(p_2,s_2)\not{\varepsilon}(\lambda)\gamma^5 u(p_1,s_1)}_{\mathcal{S}^{\lambda}_{s_1 s_2}}\underbrace{\int_{-1+\xi}^{1+\xi} d^3x \int_0^1 d^3y\left(2\sum_{\alpha=1}^{7}T_\alpha + \sum_{\alpha=8}^{14}T_\alpha\right)}_{I}$$

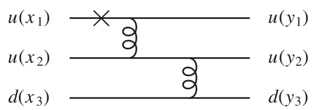
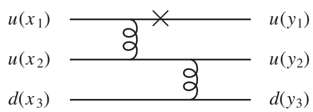
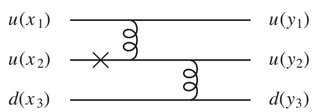
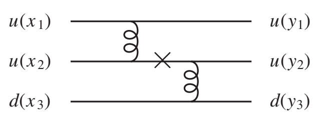
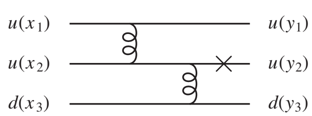
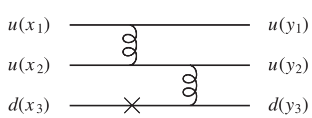
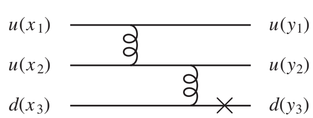
$$-\underbrace{\varepsilon(\lambda)_\mu \Delta_{T,\nu}\bar{u}(p_2,s_2)(\sigma^{\mu\nu}+g^{\mu\nu})\gamma^5 u(p_1,s_1)}_{\mathcal{S}'^{\lambda}_{s_1 s_2}}\underbrace{\int_{-1+\xi}^{1+\xi} d^3x \int_0^1 d^3y\left(2\sum_{\alpha=1}^{7}T'_\alpha + \sum_{\alpha=8}^{14}T'_\alpha\right)}_{I'}\Bigg],$$

= baryon helicity conserving + baryon helicity violating amplitudes

➫ The Hard Amplitude is calculated from 21 Feynman diagrams

Interference of $\mathcal{S}$ and $\mathcal{S}'$ → Transverse spin asymmetry

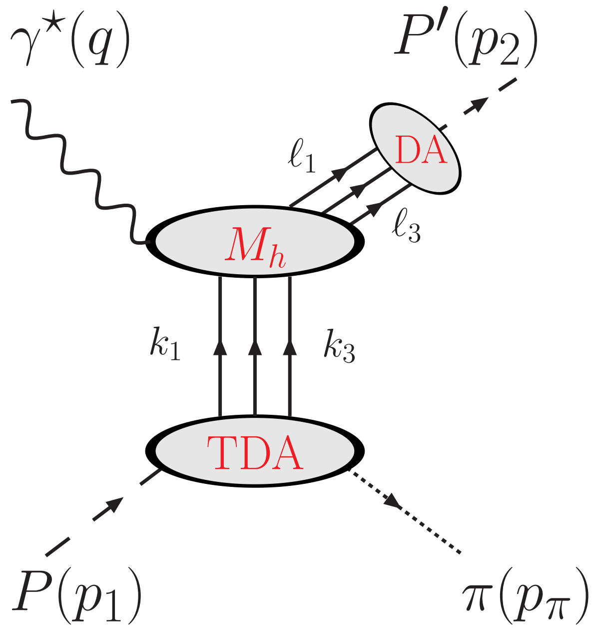
Hard amplitude

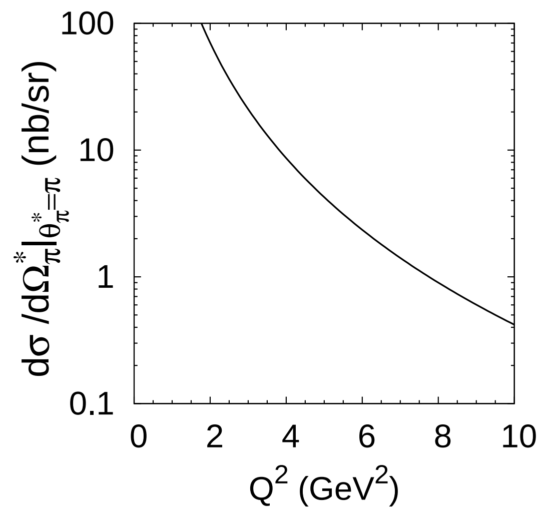
α		T_α	T'_α
1		$\frac{-Q_u(2\xi)^2[(V_1^{p\pi^0}-A_1^{p\pi^0})(V^p-A^p)+4T_1^{p\pi^0}T^p+2\frac{\Delta_T^2}{M^2}T_4^{p\pi^0}T^p]}{(2\xi-x_1-i\epsilon)^2(x_3-i\epsilon)(1-y_1)^2y_3}$	$\frac{-Q_u(2\xi)^2[(V_2^{p\pi^0}-A_2^{p\pi^0})(V^p-A^p)+2(T_2^{p\pi^0}+T_3^{p\pi^0})T^p]}{(2\xi-x_1-i\epsilon)^2(x_3-i\epsilon)(1-y_1)^2y_3}$
2		0	0
3		$\frac{Q_u(2\xi)^2[4T_1^{p\pi^0}T^p+2\frac{\Delta_T^2}{M^2}T_4^{p\pi^0}T^p]}{(x_1-i\epsilon)(2\xi-x_2-i\epsilon)(x_3-i\epsilon)y_1(1-y_1)y_3}$	$\frac{Q_u(2\xi)^2[2(T_2^{p\pi^0}+T_3^{p\pi^0})T^p]}{(x_1-i\epsilon)(2\xi-x_2-i\epsilon)(x_3-i\epsilon)y_1(1-y_1)y_3}$
4		$\frac{-Q_u(2\xi)^2[(V_1^{p\pi^0}-A_1^{p\pi^0})(V^p-A^p)]}{(x_1-i\epsilon)(2\xi-x_3-i\epsilon)(x_3-i\epsilon)y_1(1-y_1)y_3}$	$\frac{-Q_u(2\xi)^2[(V_2^{p\pi^0}-A_2^{p\pi^0})(V^p-A^p)]}{(x_1-i\epsilon)(2\xi-x_3-i\epsilon)(x_3-i\epsilon)y_1(1-y_1)y_3}$
5		$\frac{Q_u(2\xi)^2[(V_1^{p\pi^0}+A_1^{p\pi^0})(V^p+A^p)]}{(x_1-i\epsilon)(2\xi-x_3-i\epsilon)(x_3-i\epsilon)y_1(1-y_2)y_3}$	$\frac{Q_u(2\xi)^2[(V_2^{p\pi^0}+A_2^{p\pi^0})(V^p+A^p)]}{(x_1-i\epsilon)(2\xi-x_3-i\epsilon)(x_3-i\epsilon)y_1(1-y_2)y_3}$
6		0	0
7		$\frac{-Q_d(2\xi)^2[2(V_1^{p\pi^0}V^p+A_1^{p\pi^0}A^p)]}{(x_1-i\epsilon)(2\xi-x_3-i\epsilon)^2y_1(1-y_3)^2}$	$\frac{-Q_d(2\xi)^2[2(V_2^{p\pi^0}V^p+A_2^{p\pi^0}A^p)]}{(x_1-i\epsilon)(2\xi-x_3-i\epsilon)^2y_1(1-y_3)^2}$

T_i **and** T'_i **real for** $x_1, x_2, x_3 > 0$

Backward electroproduction

JP Lansberg, BP, L Szymanowski, PRD75



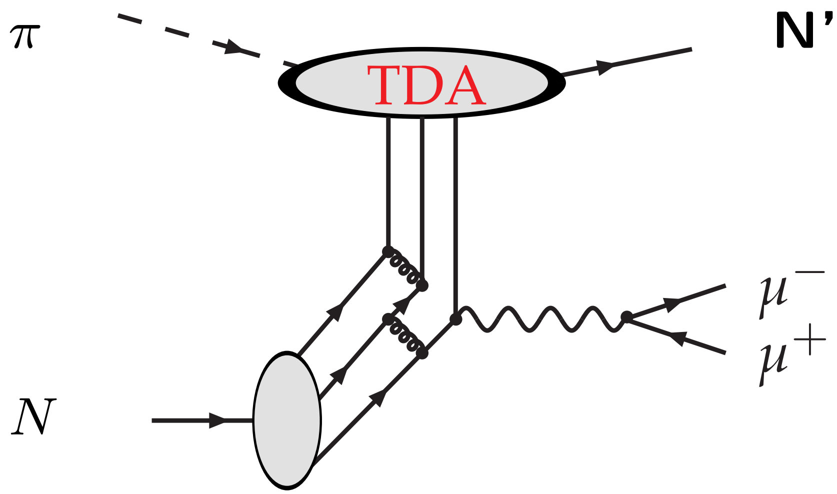


at JLab

Data are being analyzed with outgoing π^0, π^+ and ω ...

More to come with JLab@12 GeV

Compass Opportunity



also with ANTIPROTON beam

$(\pi \leftrightarrow \bar{N}')$

$1 < Q^2 < 10 GeV^2$, **small** $t = (p_\pi - p_{N'})^2$, **fixed** $\xi = \frac{p_\pi^+ - p_{N'}^+}{p_{N'}^+ + p_\pi^+}$

Measure lepton pair momentum ; deduce missing mass^2 = $\bar{M}^2$.

Select small $\bar{M}^2 \approx M_p^2$. **(antiproton case** $\approx M_\pi^2$**)**

Small $t = (p_{target} - q)^2$ **: lepton pair almost at rest in lab frame**

Transverse Target spin asymmetry

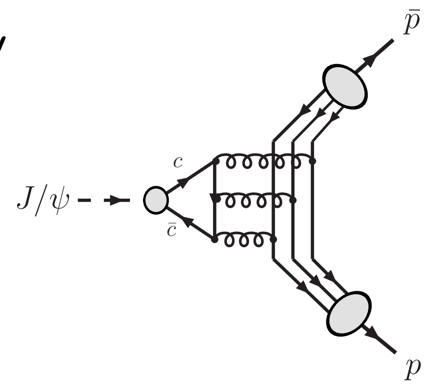
Recall $\mathcal{M} = \mathcal{S} T_i + \mathcal{S}' T'_i$; $\mathcal{S} (\mathcal{S}')$ is Nucleon helicity conserving (violating)

- Comes from Interference of $\mathcal{S}$ and $\mathcal{S}$'
- Leading twist (i.e. not $1/Q^2$) in eN and $\bar{N} N$ reactions
- zero in πN reaction
- Proportionnal to $\mathcal{I}$m $(T_i T_j'^*)$
  - absent in a hadronic (nucleon exchange) description
  - i.e. specific to a partonic (TDA) description

$\rightarrow$ transversally polarized Λ in $KN \rightarrow \Lambda\, \mu^+ \mu^-$

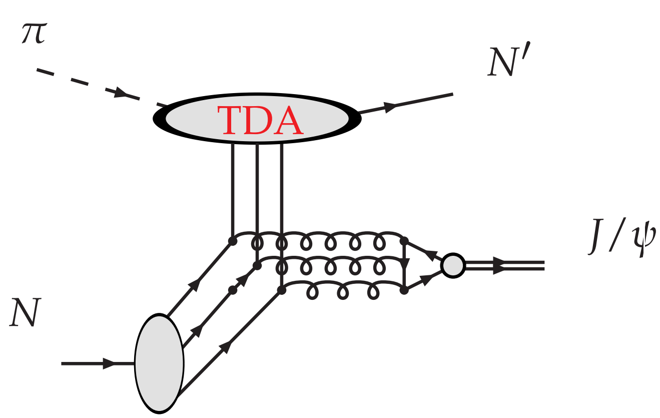
Extending Drell Yan to charmonium case : $\pi N \to N'\psi$

➯ Recall $\psi \to \bar{p}p$ decay



the amplitude of which is described with the help of proton (and $\bar{p}$) DAs

➯ Replace antiproton DA by $\pi \to N$ TDA $\quad \xi \approx \frac{M_\psi^2}{2 s_{\pi N}}$



ψ is isoscalar $\to$ Isospin $\frac{1}{2}$ part of $\pi \to N$ TDA selected by hard amplitude

Tests of the applicability of the TDA framework

The process amplitude Factorizes at large enough Q^2 :

$$\mathcal{M}(Q^2,\xi,t) = \int dxdy\phi(y_i)T_H(x_i,y_i,Q^2)F(x_i,\xi,t)$$

You know that you reach the right domain if you check :

- scaling law for the amplitude : $\mathcal{M}(Q^2,\xi) \sim \frac{\alpha_s(Q^2)^2}{Q^4}$, (up to log corrections)

- Dominance of transversely polarized virtual photon $\sigma_T >> \sigma_L$

➾ crucial test : Universality of TDAs $\rightarrow$ this description applies as well to spacelike and timelike reactions

$\rightarrow$ Backward DEMP $\gamma^* P \rightarrow P'\pi$ and Backward $\pi N \rightarrow N'\gamma^*$

Data exist (JLab) for Q^2 up to a few GeV^2 $\longrightarrow$ More to come !

Conclusions

➯ Exclusive limit of Drell Yan reactions with π (and $\bar{p}$) beams will yield crucial information on GPDs and TDAs !

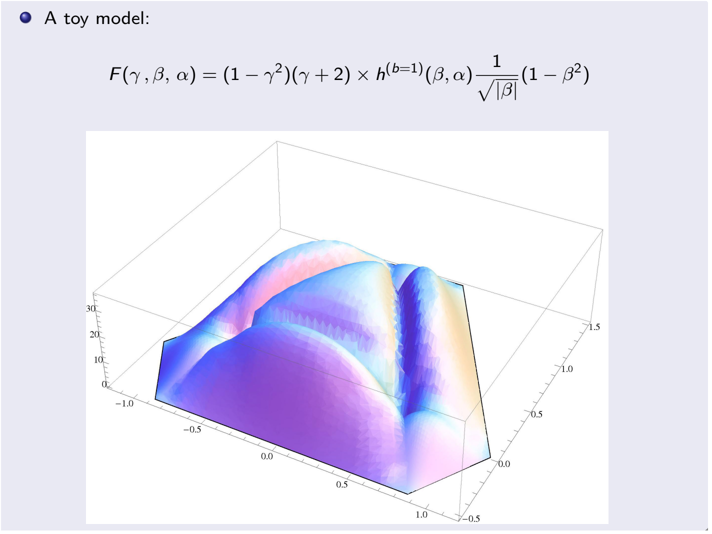
GPD and TDA physics explore confinement dynamics in hadrons

➯ More theoretical work still needed

- Improve the understanding of the Pert. part

  in particular wrt Timelike vs Spacelike scales

- More non pert. studies of GPDs and TDAs



➯ Experimental breakthrough expected from COMPASS (and JParc) :

- first measurements of $\tilde{H}(x,\xi,t)$, $\tilde{E}(x,\xi,t)$ at small ξ
- first measurements of TDA in a timelike regime

ready for simulation with Compass acceptance !