Some thoughts about the theory of meson production

M. Diehl

Deutsches Elektronen-Synchroton DESY

Workshop on Next-generation GPD studies with
exclusive meson production at EIC
Stony Brook, 5 June 2018

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Disclaimer

- this is not a regular talk (in particular, no new results)
- will present some thoughts about different theoretical issues
  - old and open problems
  - new developments in recent years
- my apologies if I have overlooked important references

Imaging partons in the nucleon or in nuclei

- basic idea: elastic scattering on quarks/gluons in target with a high-resolution probe (photon $\to$ meson transition)

  transverse momentum transfer to target
  $\underset{\text{FT}}{\to}$ transverse spatial distribution of partons

- two theoretical formalisms:
  - GPDs and hard-scattering factorisation
  - small-x factorisation (k_T fact., dipole picture, CGC)

  somewhat different physics emphasis, but both suitable for imaging
  at intermediate x both should be valid

Imaging partons in the nucleon or in nuclei

- for high-resolution images need either large Q^2 or small meson, or both
- conveniently seen in dipole formulation:
  typical dipole size r from wave fct overlap $\int dz\, \Psi_\gamma(Q,r,z)\, \Psi_M(r,z)$

$$\Psi_\gamma(Q,r,z) \sim K_{0,1}(\epsilon r)$$
$$\epsilon^2 = z(1-z)Q^2 + m_q^2$$

  $m_q =$ quark mass, $Q =$ photon virtuality, $z =$ mom. fraction of q in γ
  - Macdonald fcts $K_{0,1}(z) \sim e^{-z}$ for $z \gg 1$
  - for light quarks: small size of probe spoiled for z close to end-points
- quarkonium
  - J/Ψ: $m_c \sim 1.3\,\mathrm{GeV}$ large, but not very large
  - non-relativistic ansatz for meson wave function, more theory guidance than for light mesons, but not very precise
  - Υ: very high scales, lower rates
    different region of $x_V = (Q^2 + M_V^2)/(2pq)$

$\rightsquigarrow$ talk by S Joosten tomorrow

Imaging partons in the nucleon or in nuclei

- for high-resolution images need either large Q^2 or small meson, or both
- conveniently seen in dipole formulation:
  typical dipole size r from wave fct overlap $\int dz\, \Psi_\gamma(Q,r,z)\, \Psi_M(r,z)$

$$\Psi_\gamma(Q,r,z) \sim K_{0,1}(\epsilon r)$$
$$\epsilon^2 = z(1-z)Q^2 + m_q^2$$

  $m_q =$ quark mass, $Q =$ photon virtuality, $z =$ mom. fraction of q in γ
  - Macdonald fcts $K_{0,1}(z) \sim e^{-z}$ for $z \gg 1$
  - for light quarks: small size of probe spoiled for z close to end-points
- opportunity for EIC: J/Ψ production at large Q^2
  - efficiently decreases typical dipole size ($z \sim 1/2$)
    less sensitivity to meson wave fct, finer resolution
  - compared with $Q = 0$ have more observables (J/Ψ polarisation)
    $\rightsquigarrow$ validate theory description
  - missing: higher-order corrections in α_s
    in GPD framework: z dependence of J/Ψ wave fct

Imaging partons in the nucleon or in nuclei

from EIC White Paper:

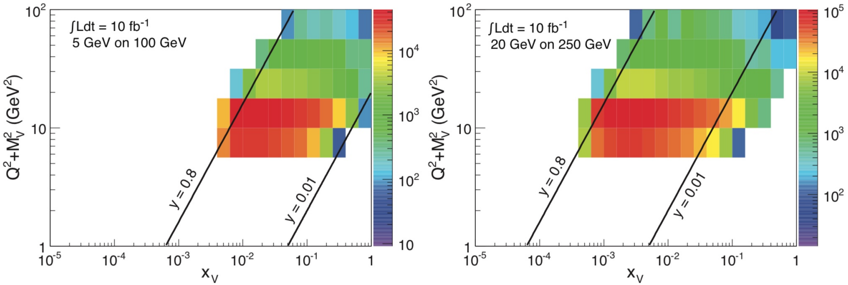
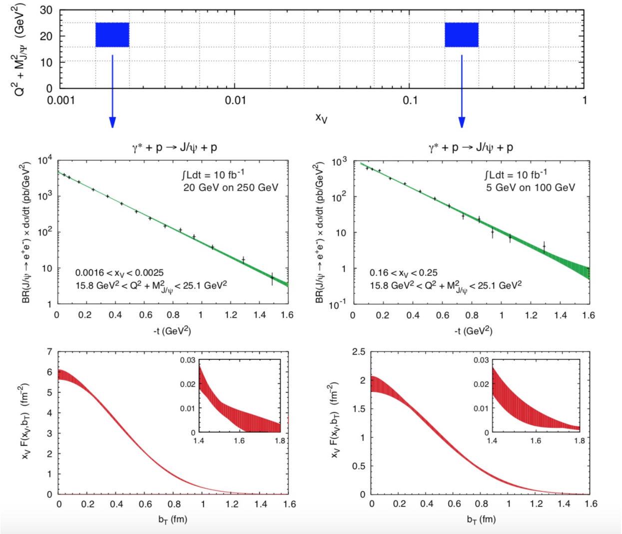


Figure 2.25: Expected number of events for exclusive J/Ψ production in bins of x_V and Q^2.

$$x_V = \frac{Q^2 + M_V^2}{W^2 + Q^2 + M_V^2}$$

Imaging partons in the nucleon or in nuclei

from EIC White Paper:



Higher order corrections: GPD factorisation

- long known: NLO for production of π (K), of ρ (ϕ, ω) and for $J/\Psi, \Upsilon$ photoproduction
  Belitsky, Müller 2001, Ivanov et al 2004
- detailed numerical studies Müller et al 2013
  at small x find size of corrections strongly dependent on GPDs
- vector meson results of Ivanov et al had mistake, now corrected
  tends to decrease size of corrections Jones et al 2015, Ivanov et al 2016
- calculation for η channel Duplančić et al 2016
- in general: NLO corrections can be large, both at low and high x
  also holds for e.m. pion form factor Melič et al 1999
- at small x: possibility to resum small-x logarithms
  Ivanov et al 2016

Higher order corrections

- at small x: possibility to resum small-x logarithms

  from Ivanov et al, arXiv:1601.07338

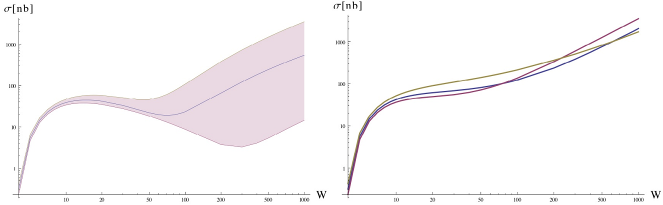
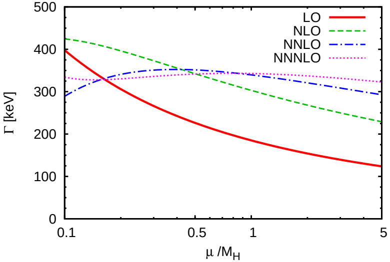


Figure 6. NLO(left panel) and resummed (right panel) photoproduction cross section (only gluonic GPDs included in both cases) as a function of $W = \sqrt{s_{\gamma p}}$ for $\mu_F^2 = M_{J/\psi}^2 \times \{0.5, 1, 2\}$ (pink, blue and yellow lines respectively)

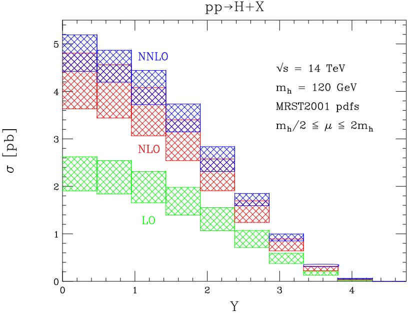
- in CGC formalism: NLO impact factors for $\gamma^* \to V$ Boussarie et al 2016

Higher order corrections

- more general perspective: NLO corrections are not always small
  situation in DIS or $e^+e^- \to$ hadrons is not typical



decay width for $H \to$ light hadrons
Baikov, Chetyrkin 2006



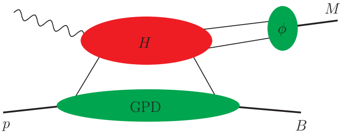
Higgs rapidity spectrum
Anastasiou et al 2005

- my take: use NLO results where available
  don't panic if 100% corrections between LO and NLO

Factorisation and end-point contributions: some reminders

Collinear factorisation theorem

Collins, Frankfurt, Strikman '96



- collinear subgraphs, in factorisation formula represented by GPD and by meson distribution amplitude (DA)
- hard subgraph, starting at order α_s
- at leading power only γ_L^* and M_L

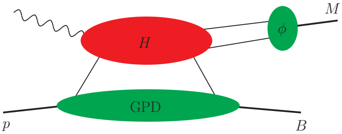
$$\mathcal{A}(\gamma_L^* p \to M_L B) \sim \frac{f_M}{Q} \qquad\qquad \frac{d\sigma_L}{dP_{M\perp}^2} \sim \frac{d\sigma}{dt} \sim \frac{f_M^2}{Q^6}$$

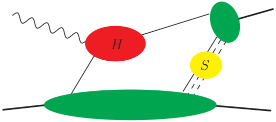
only two observables: σ_L and $A_{UT}^{\sin(\phi-\phi_S)}$

Factorisation and end-point contributions: some reminders

Collinear factorisation theorem

Collins, Frankfurt, Strikman '96





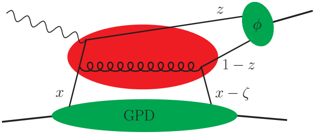
- collinear subgraphs, in factorisation formula represented by GPD and by meson distribution amplitude (DA)
- hard subgraph, starting at order α_s
- at leading power only γ_L^* and M_L

$$\mathcal{A}(\gamma_L^* p \to M_L B) \sim \frac{f_M}{Q} \qquad \frac{d\sigma_L}{dP_{M\perp}^2} \sim \frac{d\sigma}{dt} \sim \frac{f_M^2}{Q^6}$$

only two observables: σ_L and $A_{UT}^{\sin(\phi-\phi_S)}$

- soft exchanges between coll. subgraphs cancel in sum over graphs at leading-power accuracy

The problem of end-point contributions

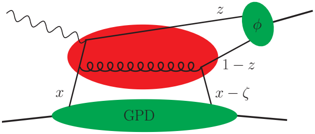


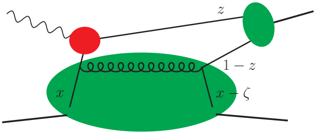
- in collinear approx. have denominators of gluon × quark propagators

$$\frac{1}{Q^2 \frac{\zeta-x}{\zeta}\,(1-z) - i\epsilon}\;\frac{1}{Q^2\,(1-z)}$$

- for γ_L^*: $(1-z)^2$ in denominator cancelled by $\phi(z) \propto z(1-z)$ and by factor $(1-z)$ from fermion trace

The problem of end-point contributions



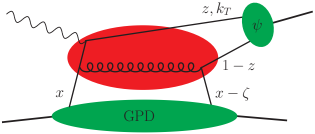


- in collinear approx. have denominators of gluon × quark propagators

$$\frac{1}{Q^2 \frac{\zeta - x}{\zeta}(1-z) - i\epsilon} \, \frac{1}{Q^2 (1-z)}$$

- for γ_L^*: $(1-z)^2$ in denominator cancelled by $\phi(z) \propto z(1-z)$ and by factor $(1-z)$ from fermion trace
- for γ_T^*: no $(1-z)$ from fermion trace
  - in collin. "factorisation formula" have $\int_0^1 dz/(1-z)$ divergence
  - endpoint region $z \approx 1$ not power suppressed compared with $z \sim \frac{1}{2}$

A phenomenological way out



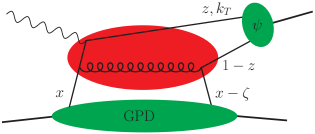
several papers for small x_B
Guichon, Guidal, Vanderhaeghen '99
Goloskokov, Kroll '05-now

- in hard scattering do not make collinear approx. but include k_T
  - on meson side replace $\phi(z) \to$ light-cone wave function $\psi(z, k_T^2)$
  - may or may not retain k_T on proton side
- propagators become finite for $z \to 1$:

$$\frac{1}{Q^2 \frac{\zeta - x}{\zeta} (1-z) + \vec{k}_T^2 - i\epsilon} \; \frac{1}{Q^2 (1-z) + \vec{k}_T^2}$$

  - makes calculation possible for γ_T^*
  - gives important corrections to leading-twist result for γ_L^* unless $Q^2 \sim$ tens of GeV^2

A phenomenological way out



several papers for small x_B
Guichon, Guidal, Vanderhaeghen '99
Goloskokov, Kroll '05-now

- propagators become finite for $z \to 1$:

$$\frac{1}{Q^2 \frac{\zeta - x}{\zeta} (1 - z) + \vec{k}_T^2 - i\epsilon} \; \frac{1}{Q^2 (1 - z) + \vec{k}_T^2}$$

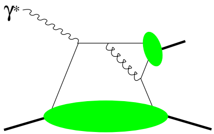
- not a systematic treatment of power-suppressed contributions
- contributions from $z \approx 1$ finite but not suppressed
  $\rightsquigarrow$ problem of further soft gluon exchanges remains
- but: quite successful phenomenology at small x_B and fixed-target energies

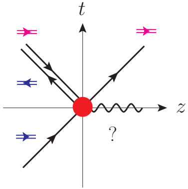
Another reminder: Helicity selection rules

- selection of helcities in hard-scattering part
- ingredients: conservation of angular mom. and of chirality
  - scattering collinear → ang. mom. J^z = sum of helicities
  - chirality conserved by quark-gluon and quark-photon coupling

chirality	$+1$	-1
q helicity	$+1/2$	$-1/2$
$\bar{q}$ helicity	$-1/2$	$+1/2$

light meson production (not J/Ψ or Υ)





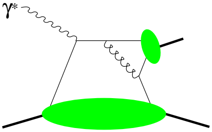
(analogous argument for graphs with gluon GPD)

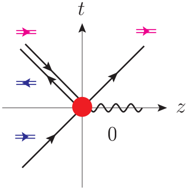
Another reminder: Helicity selection rules

- selection of helcities in hard-scattering part
- ingredients: conservation of angular mom. and of chirality
  - scattering collinear → ang. mom. J^z = sum of helicities
  - chirality conserved by quark-gluon and quark-photon coupling

chirality	$+1$	-1
q helicity	$+1/2$	$-1/2$
$\bar{q}$ helicity	$-1/2$	$+1/2$

light meson production (not J/Ψ or Υ)





(analogous argument for graphs with gluon GPD)

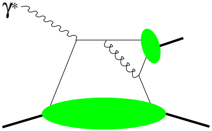
- dominant transition: $\mathcal{A}(\gamma^*_L \to \text{meson}_L) \sim 1/Q$

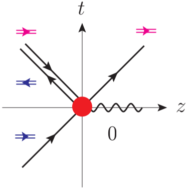
Another reminder: Helicity selection rules

- selection of helcities in hard-scattering part
- ingredients: conservation of angular mom. and of chirality
  - scattering collinear → ang. mom. J^z = sum of helicities
  - chirality conserved by quark-gluon and quark-photon coupling

chirality	$+1$	-1
q helicity	$+1/2$	$-1/2$
$\bar{q}$ helicity	$-1/2$	$+1/2$

light meson production (not J/Ψ or Υ)





(analogous argument for graphs with gluon GPD)

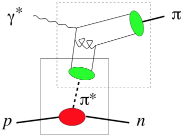
- $\mathcal{A}(\gamma_L^* \to V_T)$ not possible at leading power

MD, Gousset, Pire 1998; Colins, MD 1999

Transverse photons

- $\mathcal{A}(\gamma_T^* \to V_T) \sim 1/Q^2$, but sizeable at $Q^2 \sim$ few GeV^2 (ρ and ϕ data)
  can describe phenomenologically by keeping k_T finite in hard scattering
- $\mathcal{A}(\gamma_T^* \to \text{meson}_L) \sim 1/Q^2$
  several studies using chiral-odd twist-three meson wave function (π or ρ)
  $\rightsquigarrow$ access to chiral-odd GPDs
  Ahmad, Liuti, Goldstein 2009-15; Goloskokov, Kroll 2010-11
  but: sensitive to endpoints $z \sim 0$ or 1, divergent in collinear factorisation
- note: no endpoint problem in high-energy factorisation
  obtain finite impact factors for $\gamma_T^* \to \rho_{T,L}$
  Anikin et al 2010-11; Boussarie et al 2016

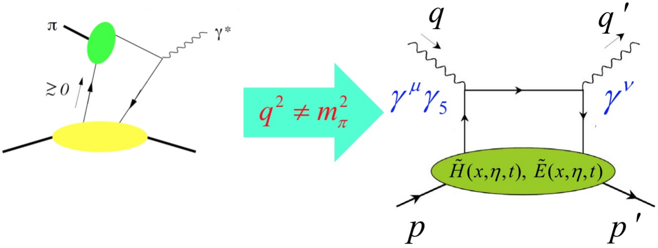
End-point contributions in π production



- end-point contribution in pion form factor long known closely related with pion electroproduction
- model end-point contribution using light-cone sum rules

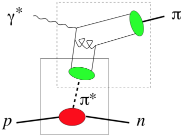
  Braun, Khodjamirian, Maul 1999
- analogous work in progress for $\pi p \to \gamma^* n$, planned for $\gamma^* p \to \pi n$

  K Tanaka, talk at POETIC 8, Regensburg, March 2018



distinct from nonfactorisable π exchange contribution (with $\tilde{E}$)

End-point contributions in π production



- end-point contribution in pion form factor long known closely related with pion electroproduction
- model end-point contribution using light-cone sum rules

  Braun, Khodjamirian, Maul 1999

- analogous work in progress for $\pi p \to \gamma^* n$, planned for $\gamma^* p \to \pi n$

  K Tanaka, talk at POETIC 8, Regensburg, March 2018