GPDs from charged current meson production in *ep* experiments

Marat Siddikov
In collaboration with Ivan Schmidt

UNIVERSIDAD TECNICA
FEDERICO SANTA MARIA

Based on:

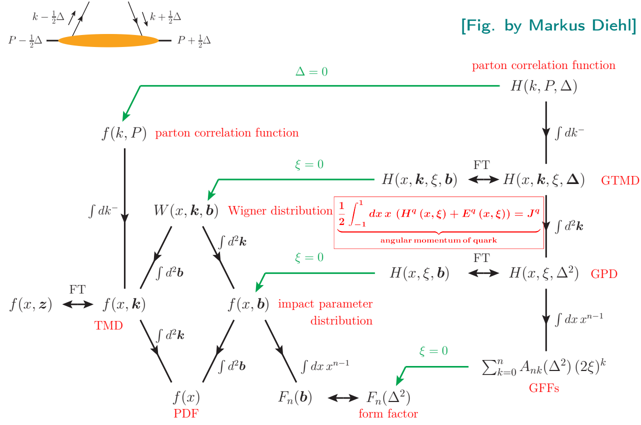
PRD 96 (2017), 096006, PRD 95 (2017), 013004, PRD 91 (2015) 073002, PRD 89 (2014) 053001

PRD 87 (2013) 033008, PRD 86 (2012) 113018

Nucleon (hadron) structure

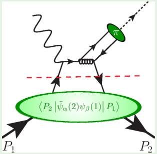
- Formidable theoretical problem (nonperturbative strongly interacting $\bar{q}qg$ ensemble)
- Parton distributions: concise descriptions of nonperturbative structure

Relations between parton distributions



- Helicity of partons/target might be flipped
- Each distribution depends on flavor

Factorization theorem



- Bjorken kinematics

$$Q^2 \to \infty, x_B = \text{const}$$

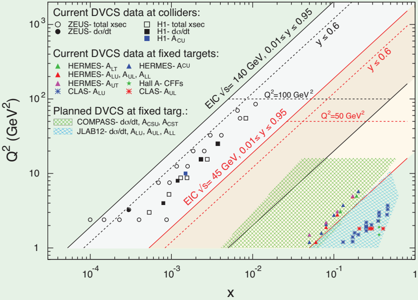
- $\mathcal{A} \sim \mathcal{C}_{\text{process}} \otimes H_{\text{target}}$
- Multiparton distributions are suppressed in this kinematics

Constraints

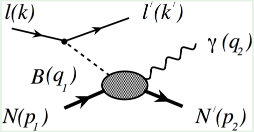
- Positivity
- Polynomiality

GPD extraction from DVCS

(EIC white paper, 1212.1701)



Kinematic coverage of DVCS experiments.

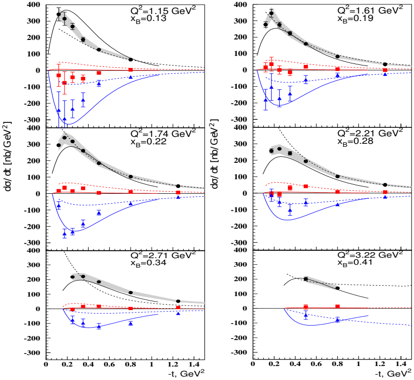


- Theoretically the cleanest, best understood is DVCS
- Interference with BH
  $\Rightarrow$ phase of the amplitude
- Polarization asymmetries
  $\Rightarrow$ separate $H, E, \tilde{H}, \tilde{E}$
- Sensitive only to

$$H_{DVCS} = \sum e_f^2 H^f + \mathcal{O}(\alpha_s) H^g$$

- DVMP may give access to GPD flavor structure, but theoretically is more complicated

Challenges in GPD extraction from pion production (CLAS)



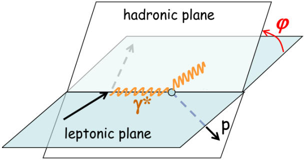
$$\frac{d^4\sigma}{dQ^2 dx_B dt d\phi_\pi} = \frac{\Gamma(Q^2, x_B, E)}{2\pi}(\sigma_T + \epsilon\sigma_L$$
$$+\epsilon \cos 2\phi_\pi \sigma_{TT}$$
$$+ \sqrt{2\epsilon(1+\epsilon)} \cos\phi_\pi \sigma_{LT})$$

- Tw-2 contribution is small, probes

$$\sigma_L \sim \left| \{\tilde{H}, \tilde{E}\} \otimes \phi_{2;\pi} \right|^2$$

and underestimates significantly data

- Dependence on azimuthal angle ϕ_π between ee' and πp planes, should not exist in leading twist



- Signals that **tw-3 contributions are pronounced**

$$\sigma_{TT} \sim \left| \{H_T, E_T\} \otimes \phi_{3;\pi} \right|^2$$

$$\sigma_{LT} \sim \left| \{H_T, E_T\} \otimes \phi_{3;\pi} \right|^2$$

$\Rightarrow$This channel requires significantly larger Q^2 to access GPDs

GPDs from ρ_L-mesons

- Probe unpolarized GPDs $\{H,\ E\} \otimes \phi_{2;\pi}$, smaller twist-3 contributions

Challenge

- Vector meson wave function unknown
  - controlled by confinement (not SCSB), depends heavily on the model

Popular phenomenological parametrizations:

AdS/CFT wave function

$$\varphi_q^{(i)}(x,\mathbf{k}_\perp) = N_q^{(i)} \frac{4\pi}{\kappa} \sqrt{\frac{\log(1/x)}{1-x}} \sqrt{f_q^{(i)}(x)\bar{f}_q(x)} \times \exp\left[-\frac{\mathbf{k}_\perp^2}{2\kappa^2} \frac{\log(1/x)}{(1-x)^2} \bar{f}_q(x)\right].$$

- $f_q(x)$, $f_{\bar{q}}(x)$-unknown functions, can be fixed from (hypothetical) DIS on ρ-mesons

Boosted Gaussian WF

$$\varphi_q^{\rm BG}(x,\mathbf{k}_\perp) = \mathcal{N}_\lambda 2[x(1-x)]^{b_\lambda/2}\sqrt{2\pi R_\lambda^2}\exp\left(\frac{m_f^2 R_\lambda^2}{2}\right) \times \exp\left(-\frac{\boldsymbol{k}_\perp^2+m_f^2}{8[x(1-x)]^{b_\lambda}}R_\lambda^2\right)$$

everything except x and $\boldsymbol{k}_\perp$ are free parameters

Uncertainty in WF translates into significant uncertainty in extraction of GPDs from this channel

Our suggestion

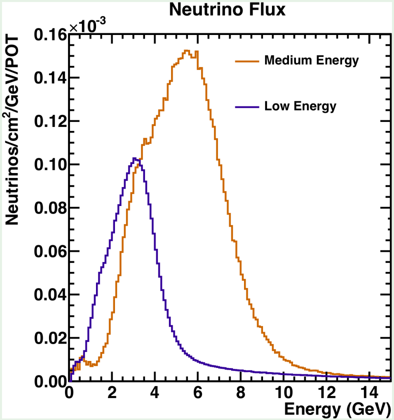
Charged current π/K-production can be used as a complementary source of information on GPDs

- $V - A$ structure of interaction $\Rightarrow$access to unpolarized GPDs H, E
  - Relative contribution of higher twist corrections smaller
- Good knowledge of pion and kaon WF, closeness of DAs due to $SU(3)_f \Rightarrow$can extract full flavor structure of GPD

Where such processes can be studied ?

MINERvA@Fermilab

- Extremely large luminosity
- Both ν_μ and $\bar{\nu}_\mu$ can be used

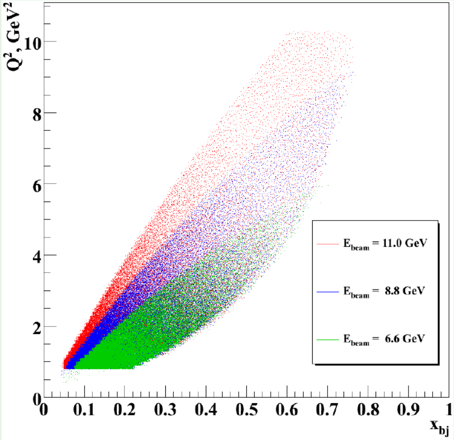


- Ongoing analysis of $\nu p \to \mu^- \pi^+ p$, $\bar{\nu} p \to \mu^+ \pi^- p$ in Bjorken kinematics

UTFSM MINERvA group: J. Miller *et al.*

Jefferson Laboratory

- Monochromatic beam, $E_e = 11$ GeV
- Luminosity $\mathcal{L} = 10^{36}\mathrm{cm}^{-2} s^{-1}$
- Beam/target can be polarized

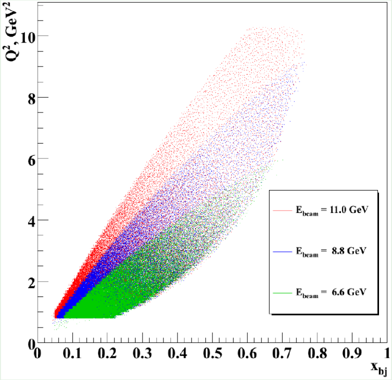


- Suggested process: $ep \to \nu_e \pi^- p$

Charged current studies in *ep* experiments

Kinematic coverage of JLAB

- Monochromatic beam, $E_e = 11$ GeV
- Luminosity $\mathcal{L} = 10^{36}\mathrm{cm}^{-2}s^{-1}$
- Beam/target can be polarized



Suggested process: $ep \to \nu_e \pi^- p$

- Neutrino ν_e momentum reconstructed via momentum conservation

$$p_\nu = p' + p_\pi - p - p_e$$

-final hadrons are charged, kinematics resolution should be good.

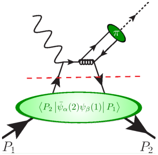
Variables x_B, t, Q^2 are functions of pion and proton energies E_π, E_p and angle $\theta_{\pi p}$ between π^- and p

$$t = 2\, m_p \left(m_p - E_p\right)$$

$$-Q^2 = 2m_p^2 + m_\pi^2 - 2m_p \left(E_\pi + E_p\right) +$$
$$+ 2E_\pi E_p - 2\sqrt{E_p^2 - m_p^2}\,\sqrt{E_\pi^2 - m_\pi^2}\cos\theta_{\pi p}$$

$$x_B = \frac{Q^2}{Q^2 + m_\pi^2 + 2E_\pi E_p - 2\sqrt{E_p^2 - m_p^2}\,\sqrt{E_\pi^2 - m_\pi^2}\cos\theta_{\pi p}}$$

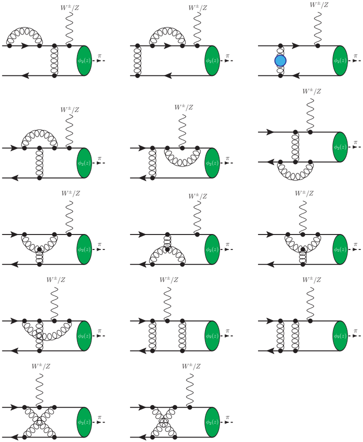
Cross-section in collinear factorization framework



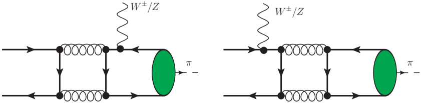
- Coef. functions known up to NLO (JETPL **80**, 226; EPJC **52**, 933)
- Weak dependence on factorization scale for $\mu_F \gtrsim 3$ GeV
- Scale choice: $\mu_R = \mu_F = Q$
- Estimates of NNLO corrections: $\mu_R = \mu_F \in (0.5, 2)Q$
- NLO corrections increase all the cross-sections $\gtrsim$50%

$\Rightarrow$NNLO corrections are needed !

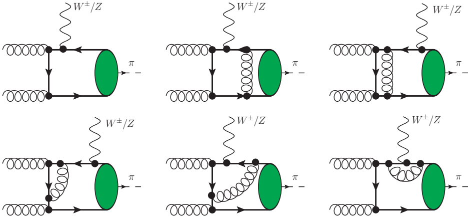
- NLO coefficient functions



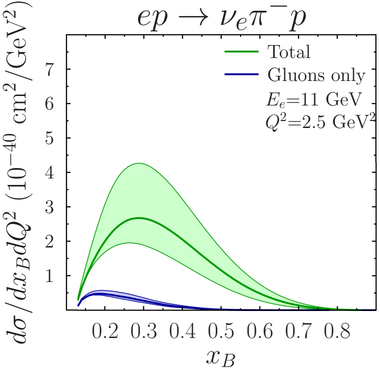
- Sea quarks contribution

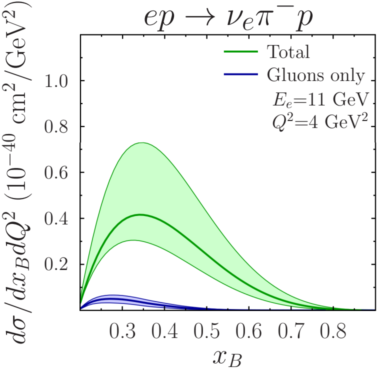


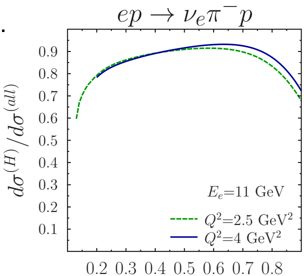
- Gluons contribution (LO+NLO)



Results for the $e \to \nu_e M$ (NLO in α_s)

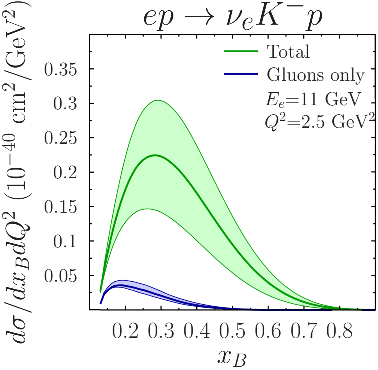


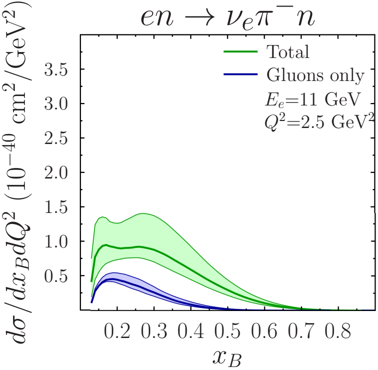


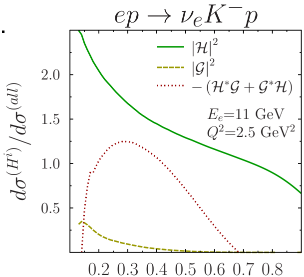


- Estimates were done with Kroll-Goloskokov parametrization
- <u>**Mostly sensitive to GPD H_u, H_d**</u> ($\gtrsim$ 80% of result).
- Gluons give minor contribution and slightly *decrease* the cross-section (interference term $q - g$ is negative)

Results for the $e \to \nu_e M$ (NLO in α_s)







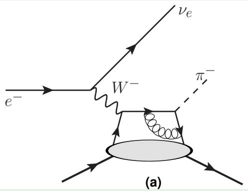
- For K-mesons, suppression by an order of magnitude (Cabibbo forbidden), smaller statistics
  - Sizeable <u>*negative*</u> contribution from interference $\mathcal{H}^*\mathcal{G} + \mathcal{G}^*\mathcal{H}$
- For neutrons the cross-section is of the same order ($\sim$ 40% less than in $ep \to \nu_e \pi^- p$), but kinematics reconstruction might be more difficult

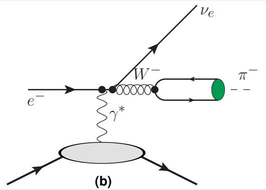
Contaminations by twist-3 & Bethe-Heitler mechanisms

Twist-3 contributions

- Quark spin flip $\Rightarrow$ probe transversity GPDs $\{H_T,\, E_T,\, \tilde{H}_T,\, \tilde{E}_T\} \otimes \phi_{3;\pi}$

Bethe-Heitler mechanism (diagram (b))

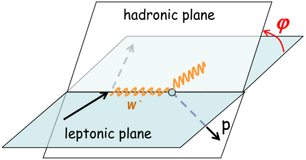




- formally is suppressed by α_{em}
- kinematically is enhanced by $Q^2/\left(t \cdot \alpha_s^2(Q^2)\right) \gg 1$ in Bjorken kinematics

- Both mechanisms generate azimuthal asymmetry

$$\frac{d^4\sigma^{(tot)}}{dt\, dQ^2 d\ln\nu\, d\varphi} = \frac{1}{2\pi}\frac{d^3\sigma^{(DVMP)}}{dt\, dQ^2 d\ln\nu} \times \left[1 + \sum_n \left(c_n \cos n\varphi + s_n \sin n\varphi\right)\right]$$



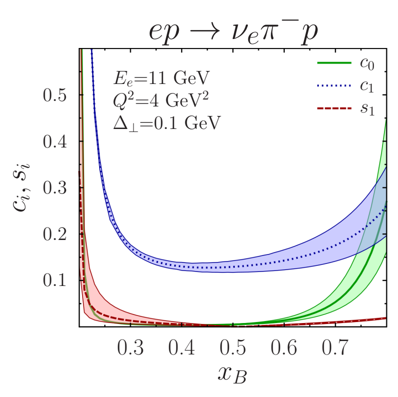
- Use harmonics c_n, s_n to quantize the effects of twist-3 and BH corrections

Contaminations by twist-3 & Bethe-Heitler mechanisms

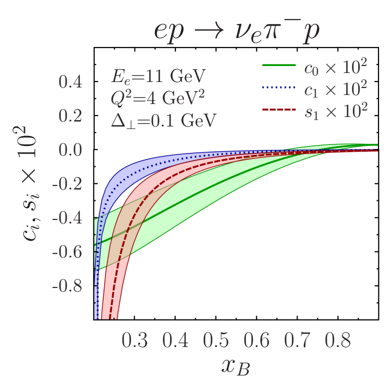
- Generate azimuthal asymmetry, quantify effect in terms of angular harmonics

$$\frac{d^4\sigma^{(tot)}}{dt\, dQ^2 d\ln\nu\, d\phi} = \frac{1}{2\pi}\frac{d^3\sigma^{(DVMP)}}{dt\, dQ^2 d\ln\nu} \times \left[1 + \sum_n \left(c_n \cos n\phi + s_n \sin n\phi\right)\right]$$

Twist-3 effects



Bethe-Heitler mechanism



- In both cases the angular harmonics are small

How do such events look like in lab frame?

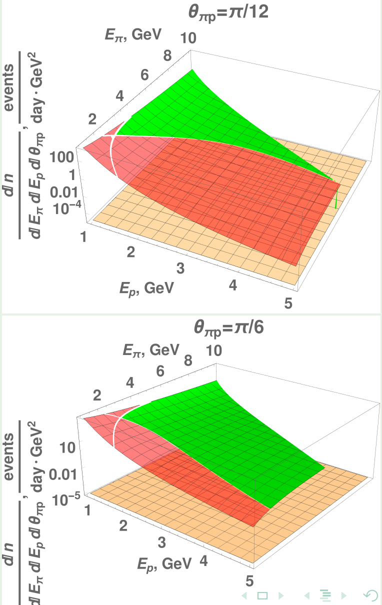
Kinematic reconstruction

- Need only energies E_π, E_p and angle $\theta_{\pi p}$

$$t = 2\,m_p\,(m_p - E_p)$$
$$-Q^2 = 2m_p^2 + m_\pi^2 - 2m_p\,(E_\pi + E_p) +$$
$$+\,2E_\pi E_p - 2\,|\vec{p}_\pi|\,|\vec{p}_p|\cos\theta_{\pi p}$$

$$x_B = \frac{Q^2}{Q^2 + m_\pi^2 + 2E_\pi E_p - 2\,|\vec{p}_p|\;|\vec{p}_\pi|\cos\theta_{\pi p}}$$
$$|\vec{p}_i| = \sqrt{E_i^2 - m_i^2}$$

- Luminosity $\mathcal{L} = 10^{35}\mathrm{cm}^{-2}s^{-1} \Rightarrow\sim 6\,\pi^-/\mathrm{day}$ in Bjorken kinematics (green region)
- Angles of interest: $(0.3 \lesssim \theta_{\pi p} \lesssim 0.8)\,\mathrm{rad}$
-smaller angles lead to small $W_{\pi p} \lesssim 2$ GeV (resonance region)
-larger angles lead to small $Q^2 \lesssim 2.5$ GeV

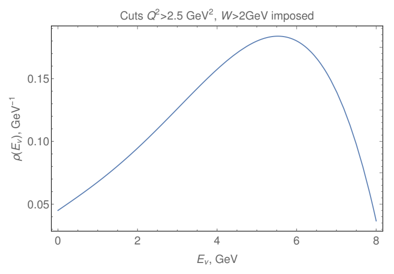


Cuts to eliminate backgrounds

Pion misidentification as electron

Elastic scattering $e^- p \to e^- p$

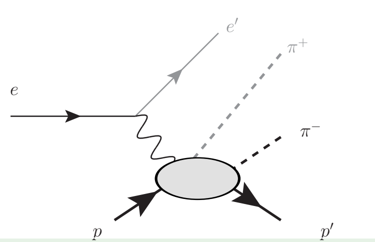
- Neutrino energy E_ν distribution after Bjorken regime cuts in $e^- p \to \nu_e \pi^- p$



- For elastic scattering "E_ν" $\equiv 0$

$\Rightarrow$Additional cut $E_\nu > 1$ GeV allows to get rid of elastic background

Multihadron photoproduction $e^- p \to X\pi^- p$



- Missing ("neutrino") momentum squared:

$$p_\nu^2 = \left(\sum_{i=\mathrm{undetected}} p_i\right)^2 \geq \left(\sum_{i=\mathrm{undetected}} m_i\right)^2$$

In case of true CCDVMP

$$p_\nu^2 = m_N^2 - Q^2 + 2E_e\left(E_p + E_\pi - m_N\right) - 2\sqrt{E_e^2 - m_e^2}\left(p_{p,z} + p_{\pi,z}\right) \equiv m_\nu^2 \lesssim (\ldots \mathrm{eV})^2$$

$\Rightarrow$Cut $p_\nu^2 < m_\pi^2$ to eliminate this background

Extension to ρ_l^- CC-production

DAs of π^- vs. ρ_L^-

Leading twist: Quark structure differs from pion only by γ_5:

$$\phi_{2;\pi}(u) \sim \int dz\, e^{i(2u-1)z} \langle 0 \,|\bar{\psi}(0)\gamma_+\gamma_5\psi(z)|\, \pi\rangle$$

$$\phi^{(L)}_{2;\rho}(u) \sim \int dz\, e^{i(2u-1)z} \langle 0 \,|\bar{\psi}(0)\gamma_+\psi(z)|\, \rho_L\rangle$$

$e \to e\, M$ case

γ_5 $\Rightarrow$sensitivity to different GPD sets,

ρ_L : (H, E) $\quad \langle p'|\bar{\psi}(0)\gamma_+\psi(z)|p\rangle$

π : $\left(\tilde{H}, \tilde{E}\right)$ $\quad \langle p'|\bar{\psi}(0)\gamma_+\gamma_5\psi(z)|p\rangle$

$e \to \nu_e\, M$ case

- sensitivity to exactly the same GPDs:

$$\gamma_5\gamma_\mu\,(1-\gamma_5) = \gamma_\mu\,(1-\gamma_5)$$

Charged current, asymptotic DA

- For $\phi_{2;\pi}(u) = \phi^{(L)}_{2;\rho}(u) = 6u(1-u)$ in the leading twist

$$\mathcal{A}^{(tw-2,asy)}_{e\to\nu_e\rho_L^-} = \mathcal{A}^{(tw-2,asy)}_{e\to\nu_e\pi^-}$$

Charged Current, realistic DA

In the leading twist meson DA enters as a multiplicative factor

$$\phi^{-1}_{2;M} = \int du\, \frac{\phi_{2;M}(u)}{u}$$

$$\Rightarrow \frac{d\sigma^{(tw-2)}_{e\to\nu_e\rho_L^-}}{d\sigma^{(tw-2)}_{e\to\nu_e\pi^-}} = \left(\frac{\phi^{-1}_{2;\rho_L}}{\phi^{-1}_{2;\pi}}\right)^2 = \text{const}$$

-any $(x_B,\, Q^2,\, t)$-dependence of this ratio$\Rightarrow$twist-three effects

Summary

- Charged current Deeply Virtual Pion Production can be used as an additional source of information on proton structure (its GPDs)
  - Can be studied at νp and ep experiments thanks to large luminosity of modern experiments.
  - Cross-section dominated by unpolarized GPDs H, E ; expect smaller contamination by higher twist and Bethe-Heitler corrections.
  - Need to impose cuts in (missing) neutrino energy $E_\nu \gtrsim 1\,\mathrm{GeV}$ and (missing) invariant mass ($m_\nu^2 \lesssim m_\pi^2$) to suppress backgrounds

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THANK YOU FOR YOUR ATTENTION!