Update on feasibility study of pion-nucleon TDAs measurements through $\pi^0 J/\psi$ in P̄ANDA

P̄ANDA Collaboration Meeting

Ermias ATOMSSA

Institut de Physique Nucléaire d'Orsay

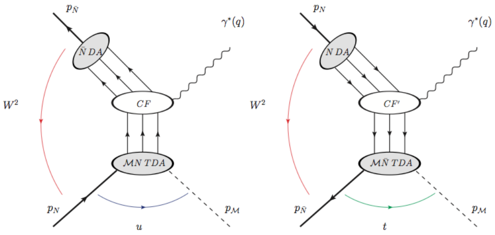
December 9, 2014

Outline

- Reminders
- Improvements
- New analysis procedure and some results
- Considerations on other background sources
- Outlook

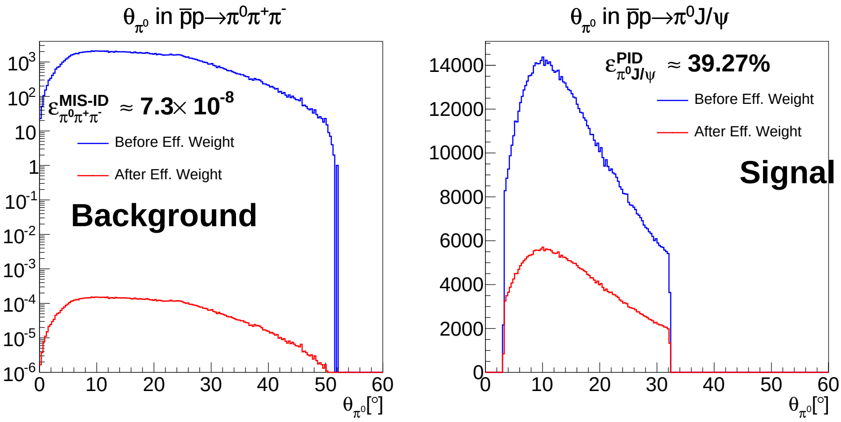
Nucleon-to-meson TDAs through $\bar{p}p \to \pi^0 J/\psi \to \pi^0 e^+ e^-$

J-P. Lansberg et. al. Phys. Rev. D 75 (2007) 074004



- Occur in collinear factorization of $\bar{p}p \to \pi^0\gamma^* \to \pi^0 e^+e^-$ and $\bar{p}p \to \pi^0 J/\psi \to \pi^0 e^+e^-$
- π-N TDAs : paramterizations of hadronic matrix elements as a function of momentum fractions (x_i), skewness (ξ) and momentum transfer squared ($\Delta^2 = \mathrm{t/u}$)
- Universality: non dependece on W^2 and q is one proposed signature of factorization
- Feasibility of measurements to constrain π-N TDAs through
  - Complimentary to already published work M. Carmen Mora Espí

Reminder from previous presentation

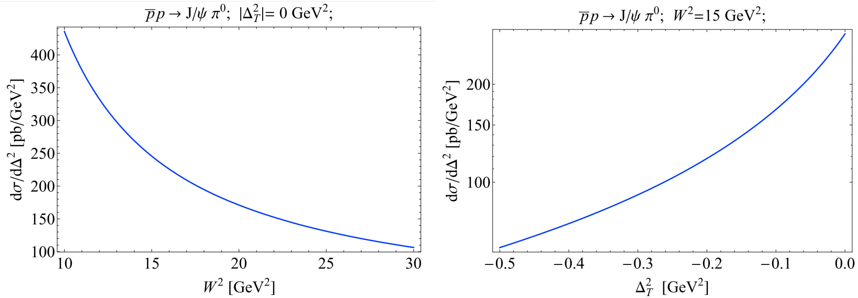


- Estimated counts rates based on parametrized efficiencies on generator output
  - $\mathcal{C}_{SIG} = \mathcal{R}^{tot}_{SIG} \cdot \varepsilon^{SIG}_{M} \cdot \varepsilon^{MIS-ID}_{\pi^0\pi^+\pi^-} \approx 1.3 \times 10^4 \times 0.64 \times 0.39 = 3.3 \times 10^3$
  - $\mathcal{C}_{BG} = \mathcal{R}^{tot}_{BG} \cdot \varepsilon_t \cdot \varepsilon^{SIG}_{M} \cdot \varepsilon^{PID}_{\pi^0 J/\psi} \approx 4.0 \times 10^{11} \times 0.05 \times 7.3 \times 10^{-8} = 1.5 \times 10^3$
  - S/B: about $\mathcal{C}_{SIG}/\mathcal{C}_{BG} \approx 2.3$

Improvements from last presentation

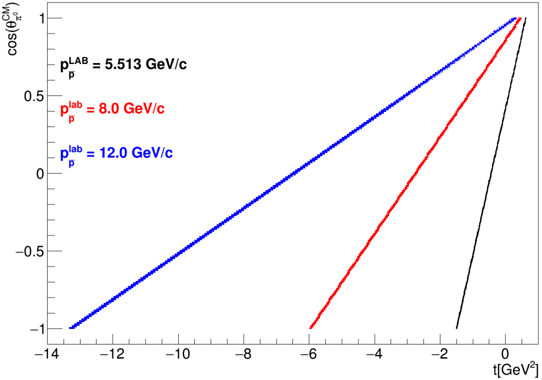
- Signal generation
  - Both small u and t approximations included
  - Three different energies ($p_{\bar{p}} = 5.513$, 8 and 12 GeV/c)
- Full MC (GEANT+PandaROOT reconstruction) used whenever possible
  - Every step except e^+e^- EID efficiency for $\bar{p}p \to \pi^0 J/\psi \to \pi^0 e^+ e^-$ analysis
  - Every step except $\pi^+\pi-$ mis-id rate for $\bar{p}p \to \pi^0\pi^+\pi^-$ analysis
- Full analysis chain
  - EID and exclusivity cuts
  - Handling $\gamma - \gamma$ combinatoric background
  - Background subtraction

Event generation for $\bar{p}p \to \pi^0 J/\psi \to \pi^0 e^+ e^-$



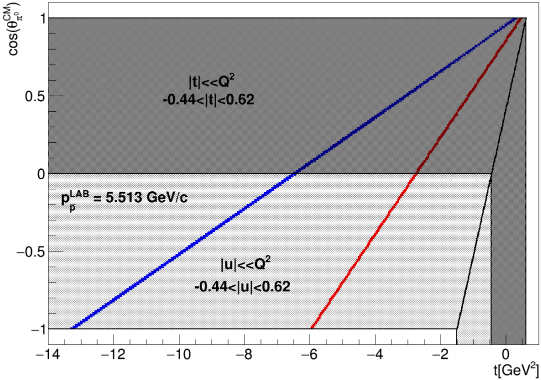
- Based on TDA formalism prediction in B. Pire et. al. Phys. Lett. B 724 (2013) 99197
  - Reproduces existing data from Fermi Lab at =5.513 GeV/c
- Two validity ranges
  - Small $|t| << Q^2$, forward going π^0 (wrt. $\bar{p}$), $\Delta^2 = t$
  - Small $|u| << Q^2$, backward going π^0 (wrt. $\bar{p}$), $\Delta^2 = u$
- Highly peaked at forward and backward angles

Validity domain at different energies



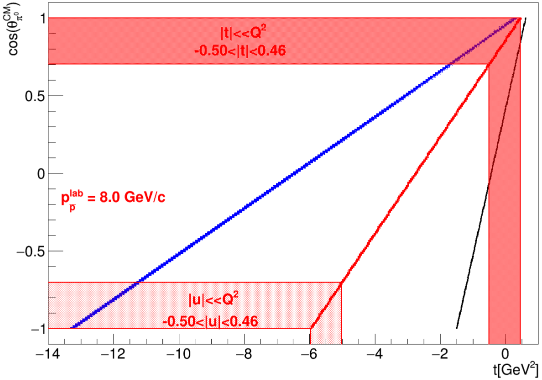
- Phase space coverage strongly dependent on energy
- Low beam energies (eg. $p^{lab}_{\bar{p}} = 5.513$ GeV/c): all available phase space is within validity range (Small $|t|$ for $0 < \cos\theta^{CM}_{\pi^0} < 1$, small $|u|$ for $-1 < \cos\theta^{CM}_{\pi^0} < 0$)
- Higher beam energies: decay products too forward/backward $\Longrightarrow$ poor efficiency
- Number of events simulated normalized to integrated cross section over validity range

Validity domain at different energies



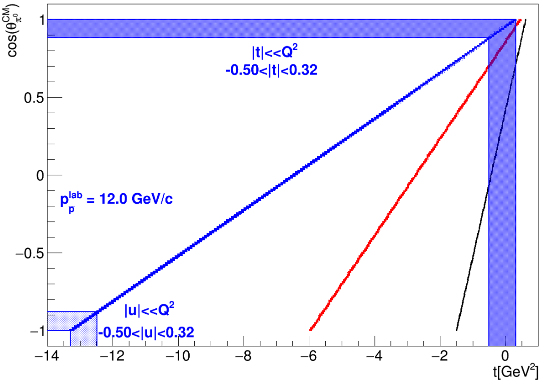
- Phase space coverage strongly dependent on energy
- Low beam energies (eg. $p_{\bar{p}}^{lab} = 5.513$ GeV/c): all available phase space is within validity range (Small $|t|$ for $0 < \cos\theta_{\pi^0}^{CM} < 1$, small $|u|$ for $-1 < \cos\theta_{\pi^0}^{CM} < 0$)
- Higher beam energies: decay products too forward/backward $\Longrightarrow$ poor efficiency
- Number of events simulated normalized to integrated cross section over validity range

Validity domain at different energies



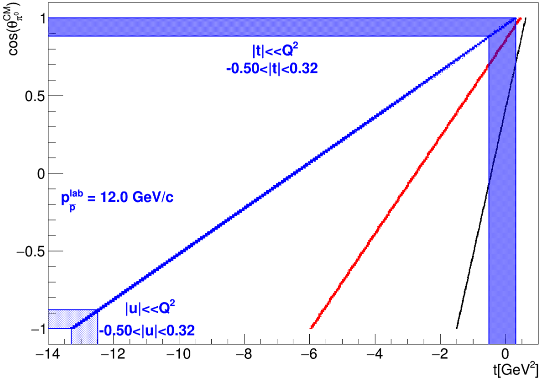
- Phase space coverage strongly dependent on energy
- Low beam energies (eg. $p_{\bar{p}}^{lab} = 5.513$ GeV/c): all available phase space is within validity range (Small $|t|$ for $0 < \cos\theta_{\pi^0}^{CM} < 1$, small $|u|$ for $-1 < \cos\theta_{\pi^0}^{CM} < 0$)
- Higher beam energies: decay products too forward/backward $\Longrightarrow$ poor efficiency
- Number of events simulated normalized to integrated cross section over validity range

Validity domain at different energies



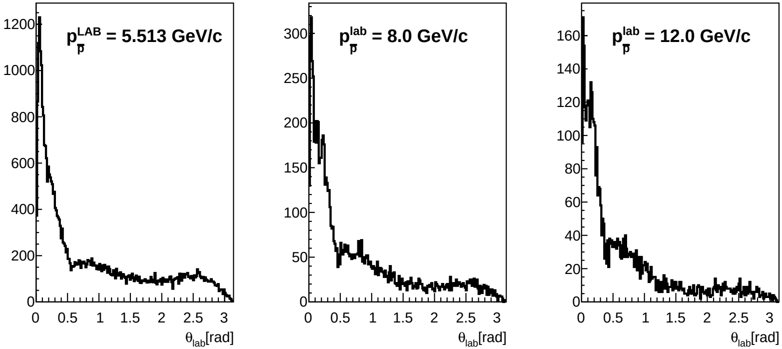
- Phase space coverage strongly dependent on energy
- Low beam energies (eg. $p^{lab}_{\bar{p}} = 5.513$ GeV/c): all available phase space is within validity range (Small $|t|$ for $0 < \cos\theta^{CM}_{\pi^0} < 1$, small $|u|$ for $-1 < \cos\theta^{CM}_{\pi^0} < 0$)
- Higher beam energies: decay products too forward/backward $\Longrightarrow$ poor efficiency
- Number of events simulated normalized to integrated cross section over validity range

Event rates for $\bar{p}p \to \pi^0 J/\psi \to \pi^0 e^+ e^-$



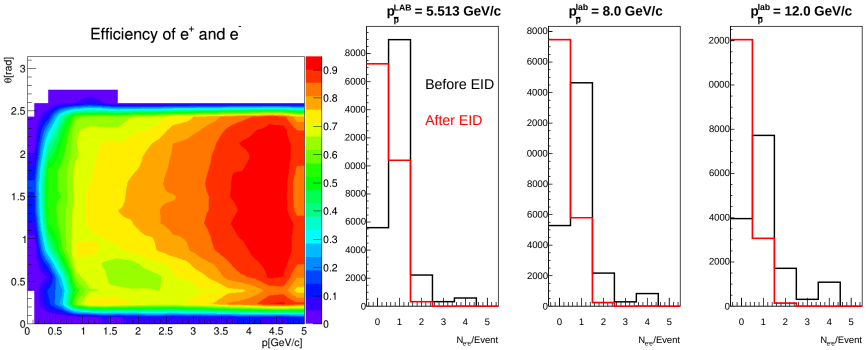
- Number of simulated events (assuming 2 fb^{-1})
  - From integrated rates within the validity range
  - 28k at $p_{\bar{p}}$=5.513 GeV/c, 24k at $p_{\bar{p}}$=8 GeV/c, and 15k at $p_{\bar{p}}$=12 GeV/c
  - Very slow decay as a function of $p_{\bar{p}}$

$\bar{p}p \to \pi^0\pi^+\pi^-$ event generation



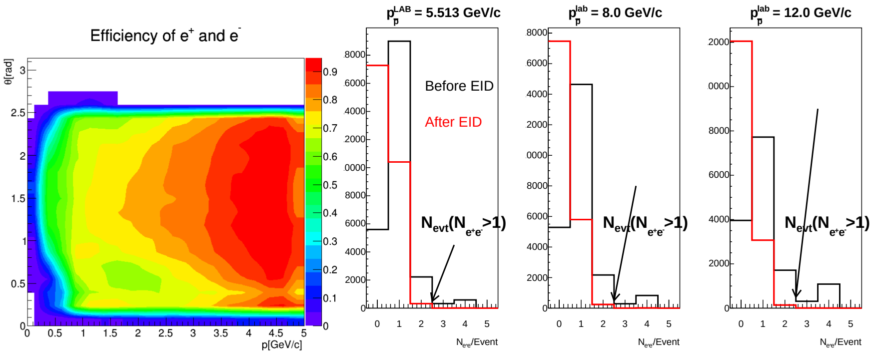
- DPM used as event generator for spectra
- Cross sections were set to intra(extra)polation of closest available data points
  - 0.2 mb ($p_{\bar{p}}$=5.513 GeV/c), 0.05 mb ($p_{\bar{p}}$=8 GeV/c) and 0.001 mb (=12 GeV/c)
  - Decay rate much faster than $\bar{p}p \to \pi^0 J/\psi \to \pi^0 e^+ e^-$ (comes at a cost of signal efficiency)
- Number of events estimated to survive EID cuts on charged pion were passed to full GEANT simulation (π^0 's are analyzed in the full GEANT MC)

Electron Identification

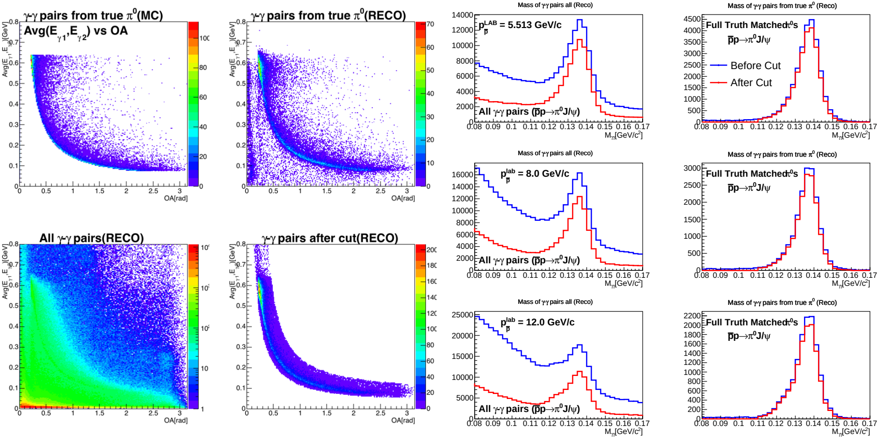


- Signal: Accept electrons with a probability set to the efficiency parametrized as a function of **true** p and θ
- Background: Number of events already takes into account EID: accept all tracks
- EID efficiency drops significantly at higher energies
- After EID, require only one candidate e^+e^- in event
  - For $\bar{p}p \to \pi^0\pi^+\pi^-$ this condition is not applied to avoid double counting
  - Instead, best MC truth matching pair is accepted as the only pair in the event

Electron Identification

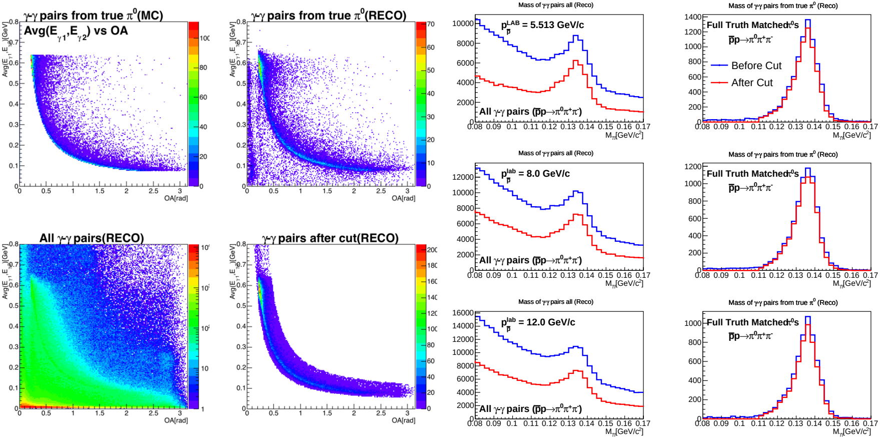


- Signal: Accept electrons with a probability set to the efficiency parametrized as a function of **true** p and θ
- Background: Number of events already takes into account EID: accept all tracks
- EID efficiency drops significantly at higher energies
- After EID, require only one candidate e^+e^- in event
  - For $\bar{p}p \to \pi^0\pi^+\pi^-$ this condition is not applied to avoid double counting
  - Instead, best MC truth matching pair is accepted as the only pair in the event



- Significant combinatoric background from neutral candidates
- Distinct signal opening angle - energy correlation from combinatoric background
- Sufficient to reduce background with minimal cost on true π^0 's
- In addition a mass cut of $0.1 < M_{\gamma-\gamma} < 0.165$ is applied before subsequent steps

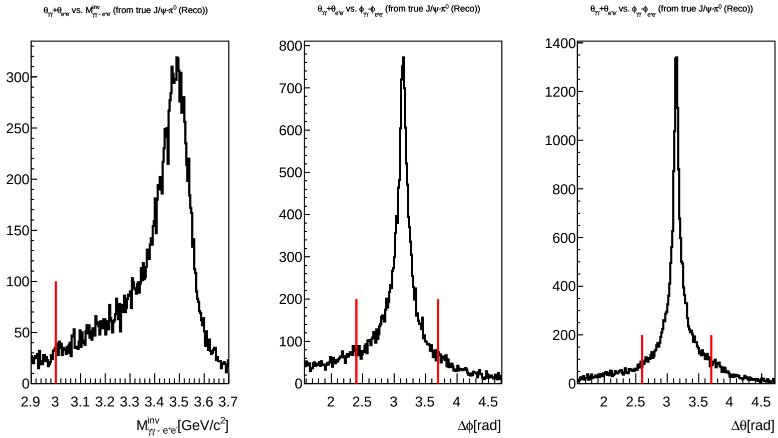
π^0 selection



- Significant combinatoric background from neutral candidates
- Distinct signal opening angle - energy correlation from combinatoric background
- Sufficient to reduce background with minimal cost on true π^0 's
- In addition a mass cut of $0.1 < M_{\gamma-\gamma} < 0.165$ is applied before subsequent steps

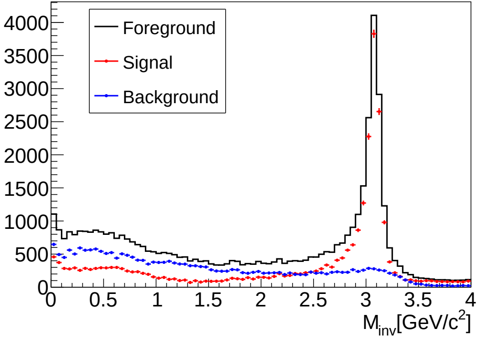
Exclusivity and kinematic cuts

- At this point, there is one e^+e^- pair and any number of $\gamma\gamma$ pairs in event
- The most back to back $\gamma\gamma$ pair is picked
- Potentially an additional cut on $\Delta\phi$ and $\Delta\theta$ could be applied, but is not useful against $\bar{p}p \to \pi^0\pi^+\pi^-$ (not applied here)



Summary of analysis Steps

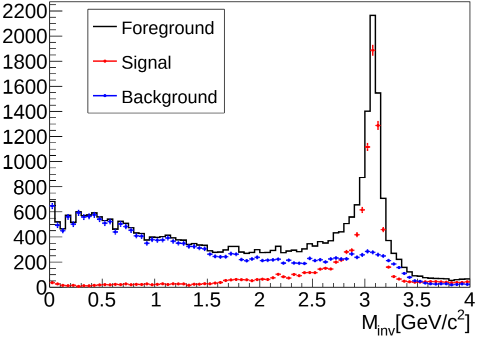
- All charged tracks
- Require EID (Only signal)
- Require $N_{e+e-} = 1$
  (Truth match for BG)
- Require $N_{\pi^0} > 0$
- Pick most BtoB γ



- Properly normalized signal and background rates for $p_{\bar{p}}$=5.513 GeV/c at 2 fb^{-1}
- Kinematic region: $0.44 < |t| < 0.63$ or $0.44 < |u| < 0.63$ in both signal and background

Summary of analysis Steps

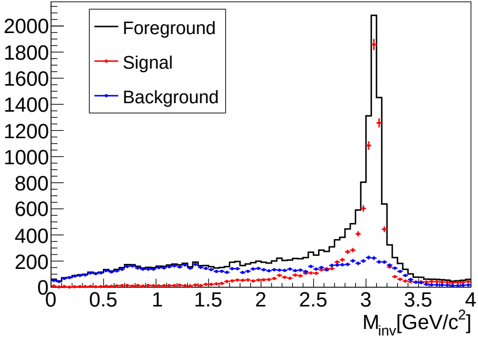
- All charged tracks
- Require EID (Only signal)
- Require $N_{e+e-} = 1$ (Truth match for BG)
- Require $N_{\pi^0} > 0$
- Pick most BtoB γ



- Properly normalized signal and background rates for $p_{\bar{p}}$=5.513 GeV/c at 2 fb^{-1}
- Kinematic region: $0.44 < |t| < 0.63$ or $0.44 < |u| < 0.63$ in both signal and background

Summary of analysis Steps

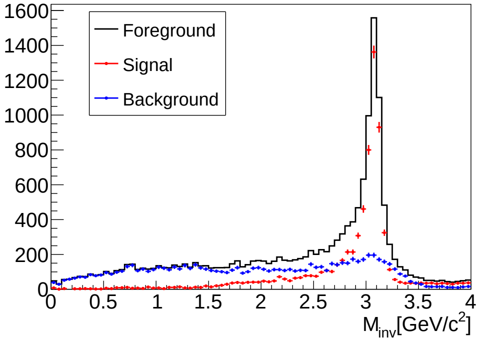
- All charged tracks
- Require EID (Only signal)
- Require $N_{e+e-} = 1$ (Truth match for BG)
- Require $N_{\pi^0} > 0$
- Pick most BtoB γ



- Properly normalized signal and background rates for $p_{\bar{p}}$=5.513 GeV/c at 2 fb^{-1}
- Kinematic region: $0.44 < |t| < 0.63$ or $0.44 < |u| < 0.63$ in both signal and background

Summary of analysis Steps

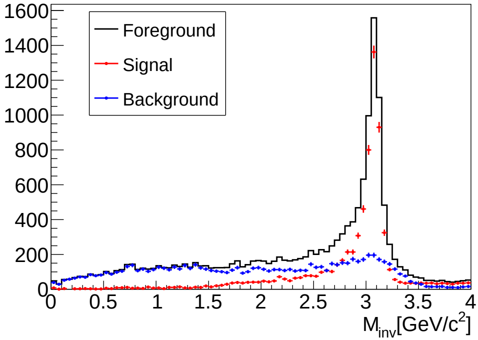
- All charged tracks
- Require EID (Only signal)
- Require $N_{e+e-} = 1$ (Truth match for BG)
- Require $N_{\pi^0} > 0$
- Pick most BtoB γ



- Properly normalized signal and background rates for $p_{\bar{p}}$=5.513 GeV/c at 2 fb^{-1}
- Kinematic region: $0.44 < |t| < 0.63$ or $0.44 < |u| < 0.63$ in both signal and background

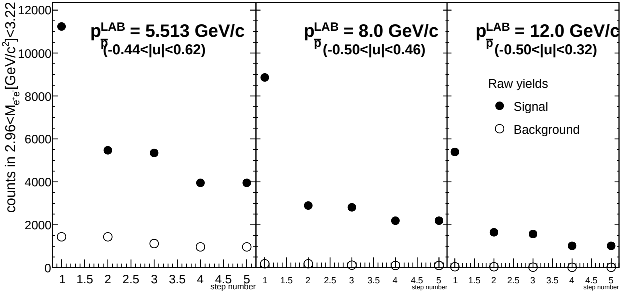
Summary of analysis Steps

- All charged tracks
- Require EID (Only signal)
- Require $N_{e+e-} = 1$
  (Truth match for BG)
- Require $N_{\pi^0} > 0$
- Pick most BtoB γ



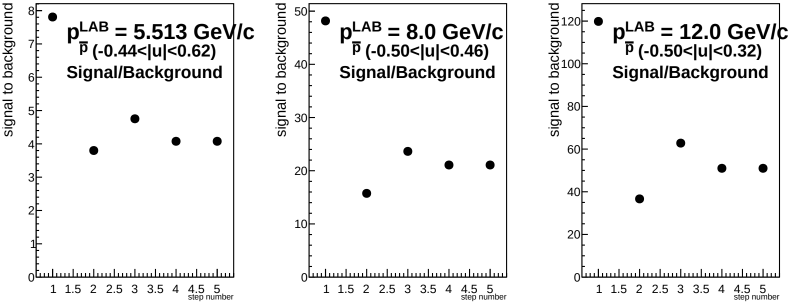
- Properly normalized signal and background rates for $p_{\bar{p}}$=5.513 GeV/c at 2 fb^{-1}
- Kinematic region: $0.44 < |t| < 0.63$ or $0.44 < |u| < 0.63$ in both signal and background

Yield and S/B ratio vs. beam energy



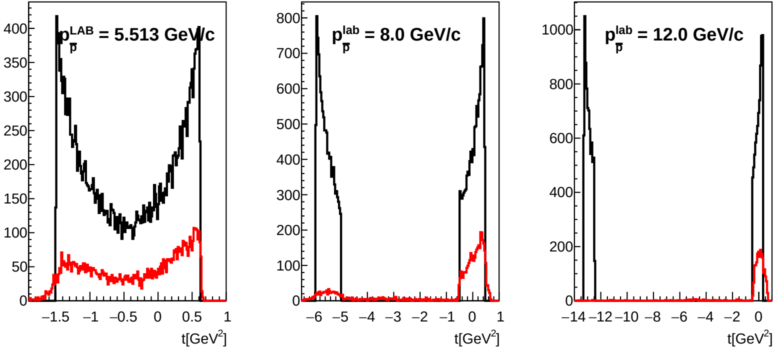
- Yield counts in $2.96 < M_{e^+e^-}[GeV/c^2] < 3.22$
- Background cross sections already highly suppressed wrt. to signal at higher beam energies
- Most severe efficiency loss comes from EID step
- Step after $N_{\pi^0} > 0$ most comparable to previous analysis, with some differences
  - Reconstruction efficiency was not taken into account previous analysis
  - Efficiency for π^0 lower than the parametrization previously used (based on single π^0 simulation) maybe due to high neutral candidate rate

Yield and S/B ratio vs. beam energy



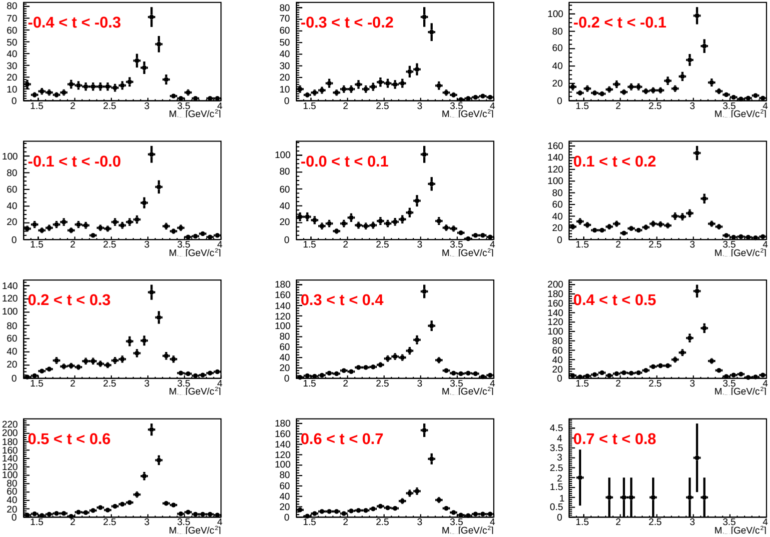
- Yield counts in $2.96 < M_{e^+e^-}[GeV/c^2] < 3.22$
- Background cross sections already highly suppressed wrt. to signal at higher beam energies
- Most severe efficiency loss comes from EID step
- Step after $N_{\pi^0} > 0$ most comparable to previous analysis, with some differences
  - Reconstruction efficiency was not taken into account previous analysis
  - Efficiency for π^0 lower than the parametrization previously used (based on single π^0 simulation) maybe due to high neutral candidate rate

t dependence of efficiency

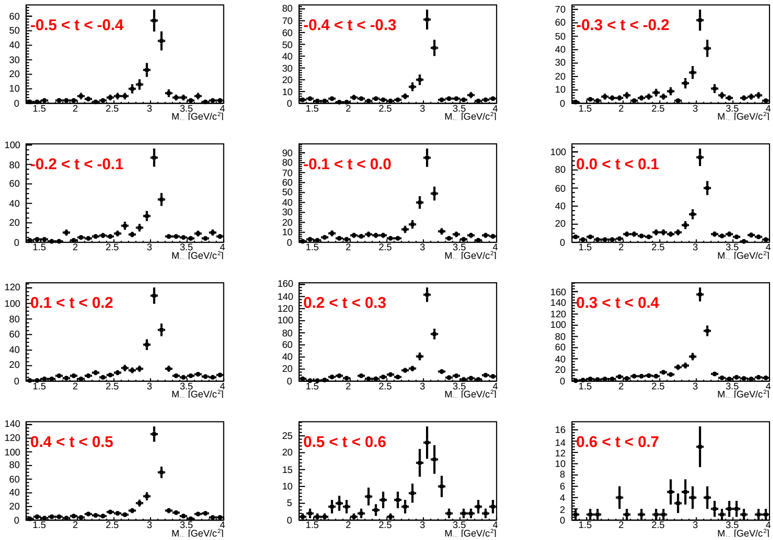


- Reasonable efficiency at lowest beam energy
- Very small to no efficiency for the small $|u|$ validity range at higher beam energies
- NB: cutoffs in t distribution are **NOT** an experimental limitation, but rather imposed by the validity range of the TDA formalism used for event generation

Differential mass plots at $p_{\bar{p}}$= 5.513 GeV/c

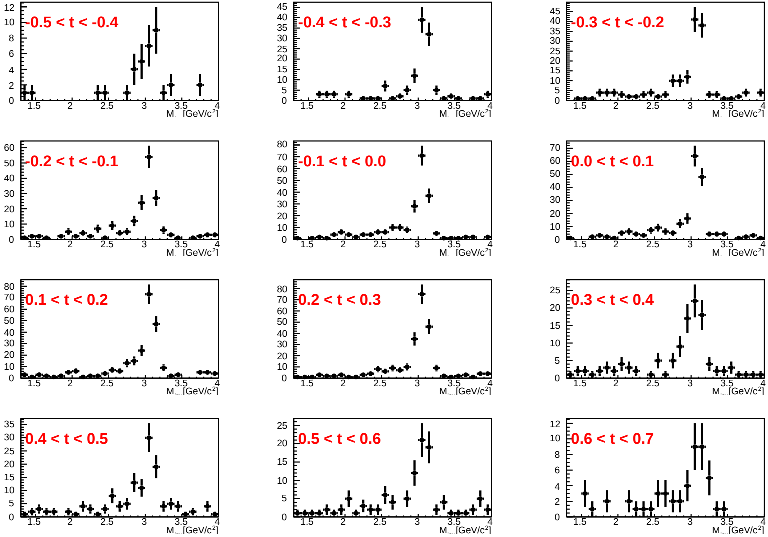


- Non negligible background that can be subtracted



- Background is less of an issue at higher beam energies

Differential mass plots at $p_{\bar{p}} = 12.0$ GeV/c



- Background is less of an issue at higher beam energies

Other sources of background

- J/ψ decay to $\pi^+\pi^-$
  - Very low BR (1.5×10^{-4}), in addition to suppression by EID
  - Not really a background if it could be reconstructed
- Multi pion events
  - Low probability of being reconstructed as $\pi^+\pi^-\ \pi^0$
  - Can further be suppressed by missing mass cut
- $\bar{p}p \to \pi^0\gamma^* \to \pi^0 e^+ e^-$
  - Can not be reduced with PID or kinematic cuts
  - x-section under the J/ψ mass peak (2σ) $\approx$0.048 pb^{-1}
  - Rate $\approx<$1% of signal

Summary and outlook

- Various improvements to π-N TDA feasibility study through $\bar{p}p \to \pi^0 J/\psi \to \pi^0 e^+ e^-$
  - Full MC used as much as possible,
  - Beam energy dependence explored
  - Both forward and backward validity regions
  - Full analysis chain
- Study of π-N TDA in $\bar{p}p \to \pi^0 J/\psi \to \pi^0 e^+ e^-$ feasible at all beam energies considered
  - S/B ≈4 at 5.513 GeV/c^2, ≈20 at 8 GeV/c^2 and ≈50 at 12 GeV/c^2,
- Some items still on the to do list
  - Treatment of EID in $\bar{p}p \to \pi^0 J/\psi \to \pi^0 e^+ e^-$ with full MC
  - Better parametrization of $\pi^+\pi^-$ efficiency
  - More quantitative look into other background sources
  - Proper signal counting, and efficiency correction
  - Exploring kinematic fit for additional rejection
- Stay tuned

Summary and outlook

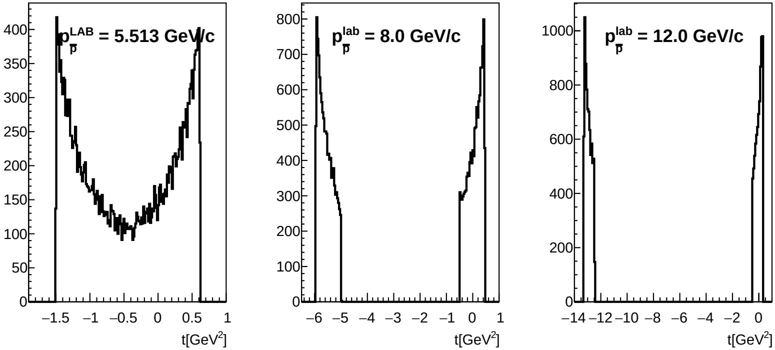
- Various improvements to π-N TDA feasibility study through $\bar{p}p \to \pi^0 J/\psi \to \pi^0 e^+ e^-$
  - Full MC used as much as possible,
  - Beam energy dependence explored
  - Both forward and backward validity regions
  - Full analysis chain
- Study of π-N TDA in $\bar{p}p \to \pi^0 J/\psi \to \pi^0 e^+ e^-$ feasible at all beam energies considered
  - S/B $\approx$4 at 5.513 GeV/c^2, $\approx$20 at 8 GeV/c^2 and $\approx$50 at 12 GeV/c^2,
- Some items still on the to do list
  - Treatment of EID in $\bar{p}p \to \pi^0 J/\psi \to \pi^0 e^+ e^-$ with full MC
  - Better parametrization of $\pi^+\pi^-$ efficiency
  - More quantitative look into other background sources
  - Proper signal counting, and efficiency correction
  - Exploring kinematic fit for additional rejection
- Stay tuned

Summary and outlook

- Various improvements to π-N TDA feasibility study through $\bar{p}p \to \pi^0 J/\psi \to \pi^0 e^+ e^-$
  - Full MC used as much as possible,
  - Beam energy dependence explored
  - Both forward and backward validity regions
  - Full analysis chain
- Study of π-N TDA in $\bar{p}p \to \pi^0 J/\psi \to \pi^0 e^+ e^-$ feasible at all beam energies considered
  - S/B $\approx$4 at 5.513 GeV/c^2, $\approx$20 at 8 GeV/c^2 and $\approx$50 at 12 GeV/c^2,
- Some items still on the to do list
  - Treatment of EID in $\bar{p}p \to \pi^0 J/\psi \to \pi^0 e^+ e^-$ with full MC
  - Better parametrization of $\pi^+\pi^-$ efficiency
  - More quantitative look into other background sources
  - Proper signal counting, and efficiency correction
  - Exploring kinematic fit for additional rejection
- Stay tuned

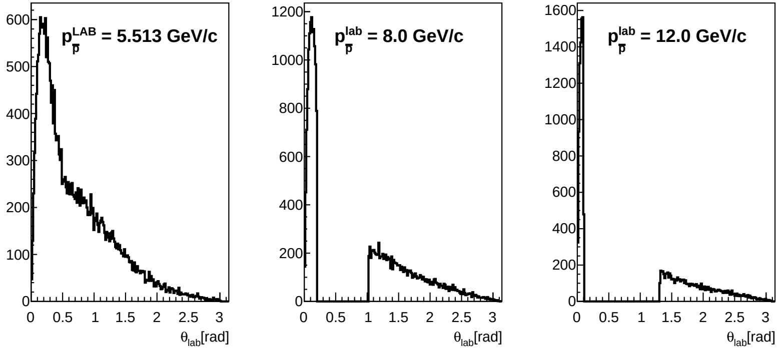
Backup

Generated distributions for signal simulation



- Highly peaked at forward and backward angles
- Integrated rates with assumed luminosity of 2 fb^{-1}
  - 28k at $p_{\bar{p}}$=5.513 GeV/c, 24k at $p_{\bar{p}}$=8 GeV/c, and 15k at $p_{\bar{p}}$=12 GeV/c
  - Very slow decay as a function of $p_{\bar{p}}$

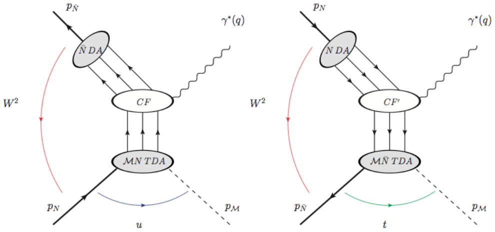
Generated distributions for signal simulation



- Highly peaked at forward and backward angles
- Integrated rates with assumed luminosity of 2 fb^{-1}
  - 28k at $p_{\bar{p}}$=5.513 GeV/c, 24k at $p_{\bar{p}}$=8 GeV/c, and 15k at $p_{\bar{p}}$=12 GeV/c
  - Very slow decay as a function of $p_{\bar{p}}$

Nucleon-to-meson TDAs

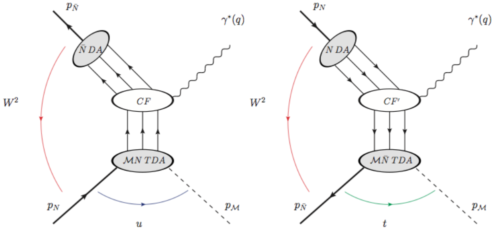
J-P. Lansberg et. al. Phys. Rev. D 75 (2007) 074004



- Occur in collinear factorization of $\bar{p}p \to \pi^0\gamma^* \to \pi^0 e^+e^-$ and $\bar{p}p \to \pi^0 J/\psi \to \pi^0 e^+e^-$
- Valid only for large values of $s = (p_N + p_{\bar{N}})^2 = W^2$
  - Backward kinematics (small $|u|$), π^0 in direction of nucleon (probes π-N TDAs)
  - Forward kinematics (small $|t|$), π^0 in direction of anti-nucleon (probes π-$\bar{N}$ TDAs)
- CF: Hard sub-process amplitude

Nucleon-to-meson TDAs

J-P. Lansberg et. al. Phys. Rev. D 75 (2007) 074004



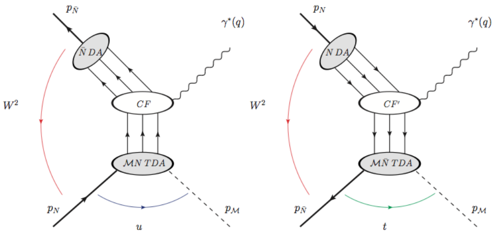
- π-N TDA : Fourier transform of non-diagonal (baryon-to-meson transition) matrix elements of non local three (anti-)quark operators on the light cone:

$$< \pi^0(p_\pi)|\varepsilon_{c_1c_2c_3}u_\rho^{c_1}(\lambda_1 n)u_\tau^{c_2}(\lambda_2 n)u_\xi^{c_3}(\lambda_3 n)|N^p(p_N,S_N) >$$

parameterized as a function of momentum fractions (x_i), skewness (ξ) and momentum transfer squared (Δ^2 = t/u in fwd/bwd kinematics resp.) independent of W^2 and q

Nucleon-to-meson TDAs

J-P. Lansberg et. al. Phys. Rev. D 75 (2007) 074004

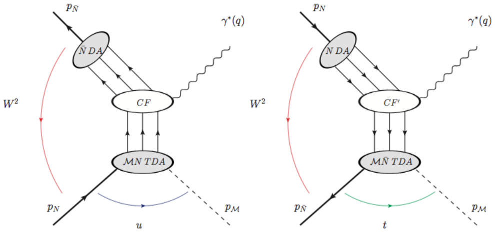


- DAs: Diagonal matrix elements of non local three (anti-)quark operators on the light cone

$$< 0|\varepsilon_{c_1 c_2 c_3} u_\rho^{c_1}(\lambda_1 n) u_\tau^{c_2}(\lambda_2 n) u_\xi^{c_3}(\lambda_3 n)|N^p(p_N, S_N) >$$

Nucleon-to-meson TDAs

J-P. Lansberg et. al. Phys. Rev. D 75 (2007) 074004



- Feasibility study completed by M. Carmen Mora Espí (submitted to EPJA)
- Forward and backward kinematic regions, at s=5 GeV^2 and s=10 GeV^2
- Expected signal event rate for 2 fb^{-1} is 3350 (@ s=5 GeV^2) and 465 (@ s=10 GeV^2)
- S/B is assumed $\sigma(\bar{p}p \to \pi^0\gamma^* \to \pi^0 e^+e^-)/\sigma(\bar{p}p \to \pi^0\pi^+\pi^-) \approx 10^{-6}$
- Cross-section measurements are readily feasible under this assumption