Feasibility of measurements of $\bar{p}p \to \pi^0 J/\psi \to \pi^0 e^+ e^-$ to constrain pion-nucleon TDAs in $\bar{\text{P}}$ANDA

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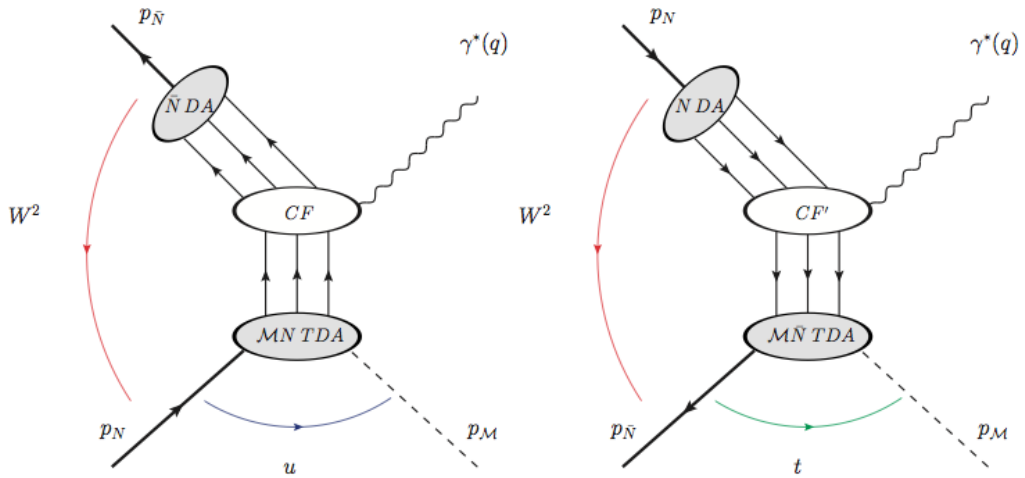
Outline

- Transition Distribution Amplitudes
- $\bar{\text{P}}$ANDA Experimental Setup
- Event Generation (Signal and Background)
- Efficiency and rejection estimation
- Effective signal to background

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

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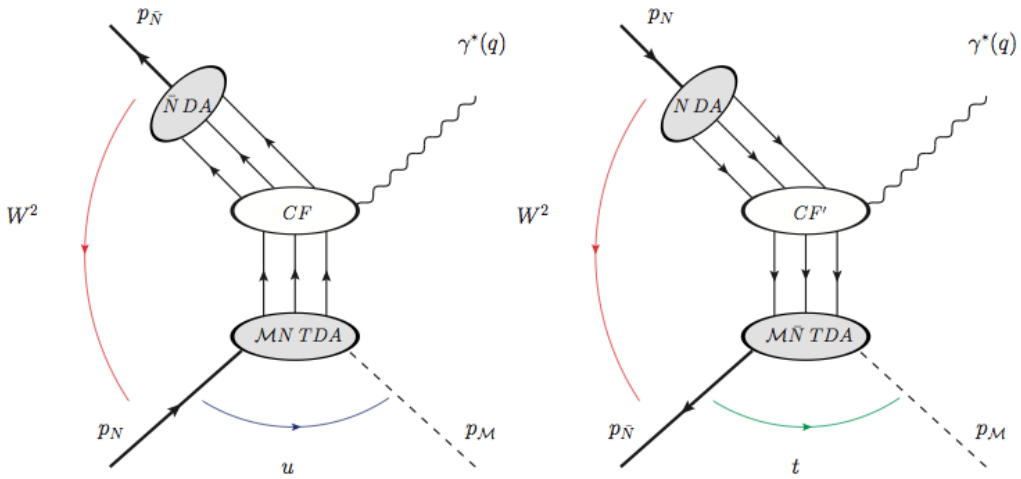

- π-N TDA : Fourier transform of non-diagonal (baryon-to-meson transition) matrix elements of non local three (anti-)quark operators on the light cone:

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

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

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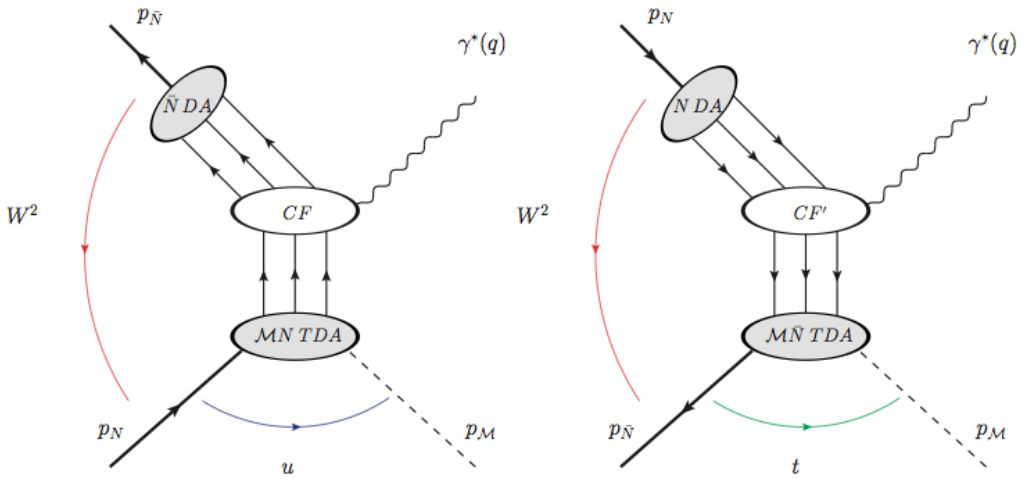

- DAs: Diagonal matrix elements of non local three (anti-)quark operators on the light cone

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

Nucleon-to-meson TDAs

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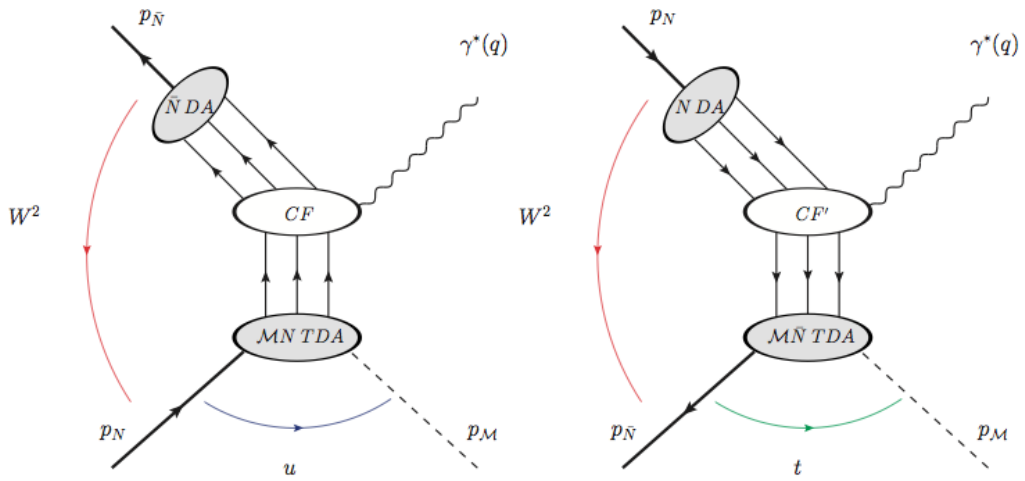
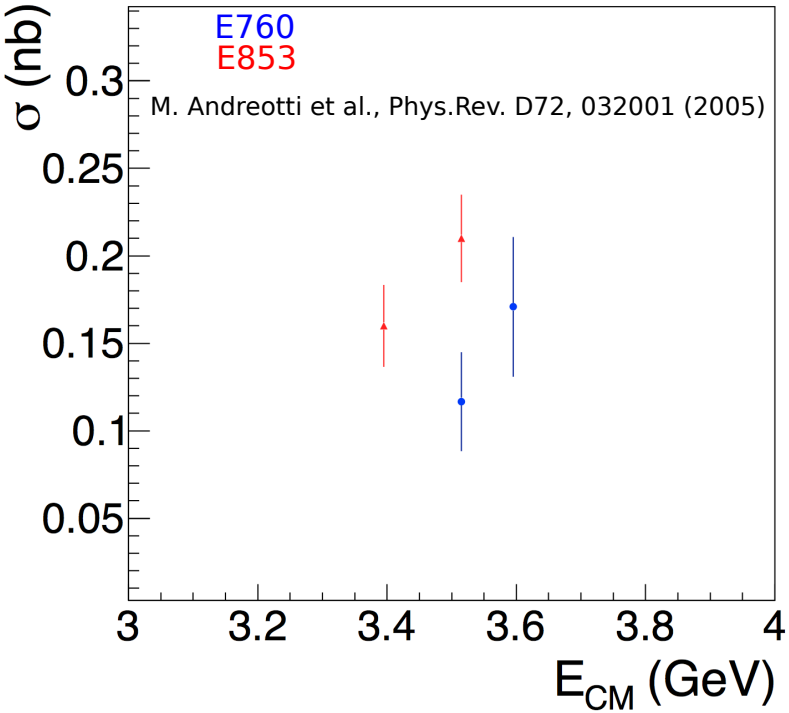
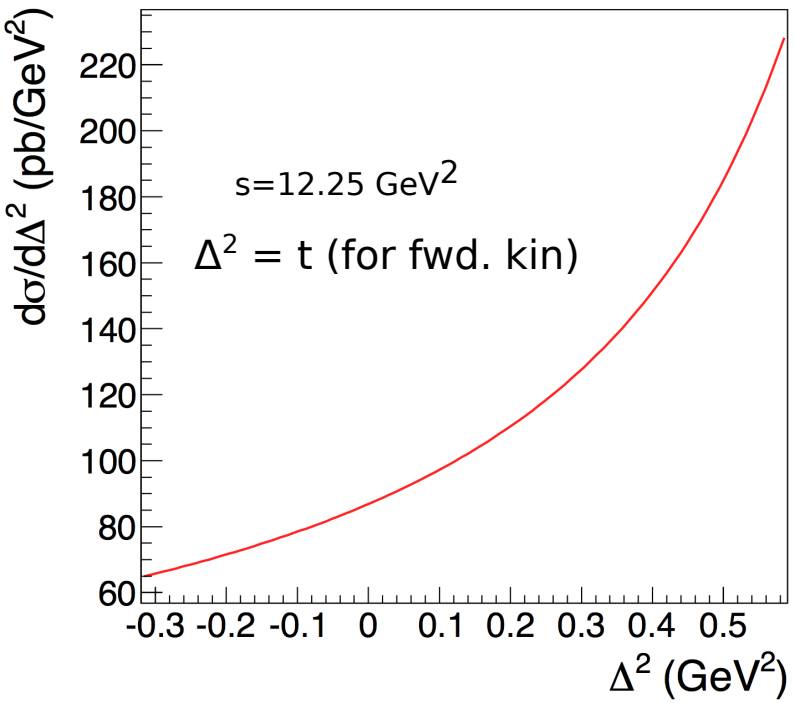


- Feasibility study completed by M. Carmen Mora Espí (submitted to EPJA)
- Forward and backward kinematic regions, at s=5 GeV^2 and s=10 GeV^2
- Expected signal event rate for 2 fb^{-1} is 3350 (@ s=5 GeV^2) and 465 (@ s=10 GeV^2)
- S/B is assumed $\sigma(\bar{p}p \to \pi^0\gamma^* \to \pi^0 e^+e^-)/\sigma(\bar{p}p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

π-N TDAs in $\bar{p}p \to \pi^0 J/\psi \to \pi^0 e^+ e^-$

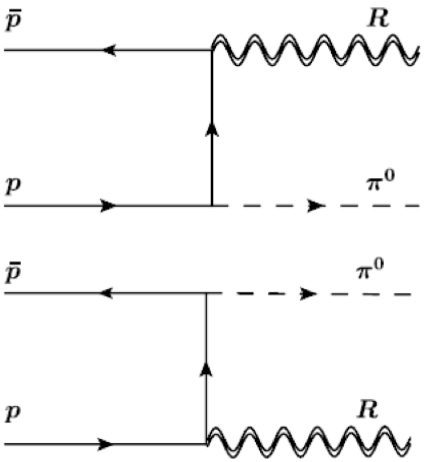
- Higher signal cross section and large q^2 $(= M^2_{J/\psi})$ -B. Pire et. al. Physics Letters B 724 (2013) 99107
- Reduces uncertainty on DAs by using $J/\psi \to p\bar{p}$ partial decay width data

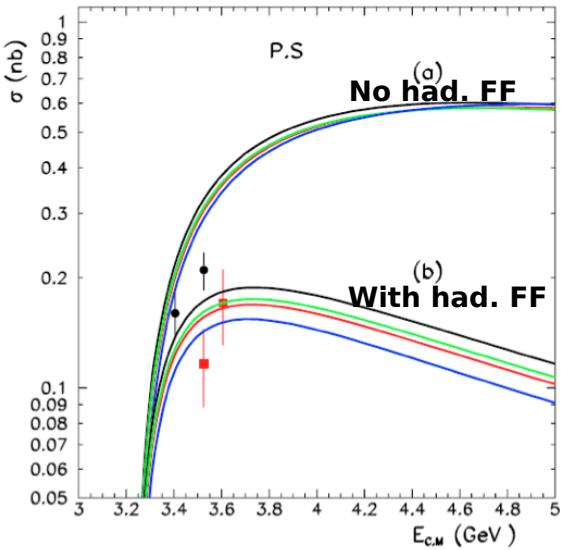


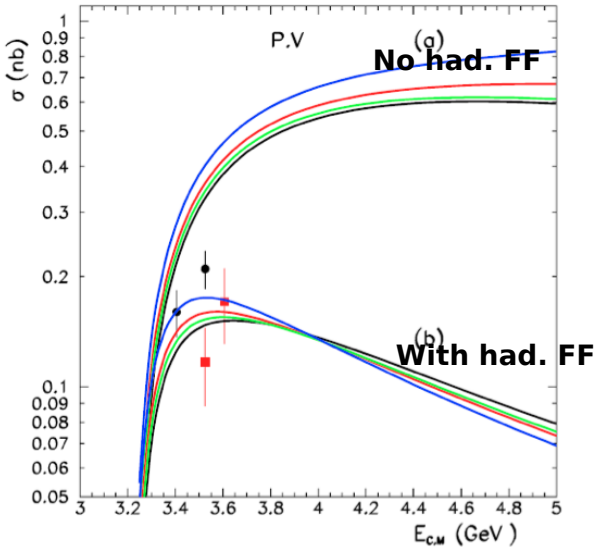


- X-sect. predictions reproduce existing data from Fermilab at $\sqrt{s} = 3.5$ GeV (M_{h_c})
- Test of universality of TDAs by comparing to $\bar{p}p \to \pi^0 \gamma^* \to \pi^0 e^+ e^-$ at different q^2

Alternative models $\bar{p}p \to \pi^0 J/\psi \to \pi^0 e^+ e^-$

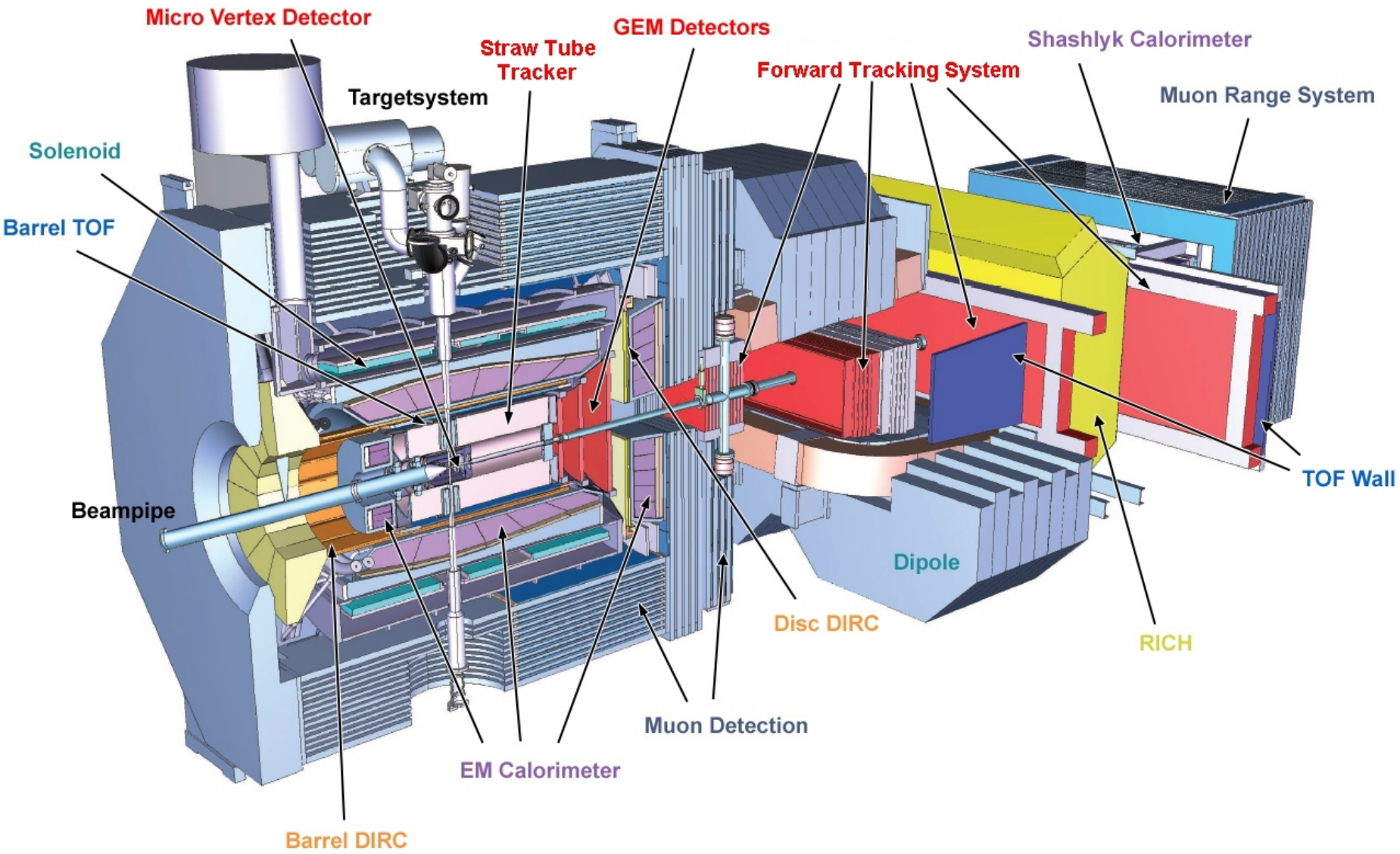




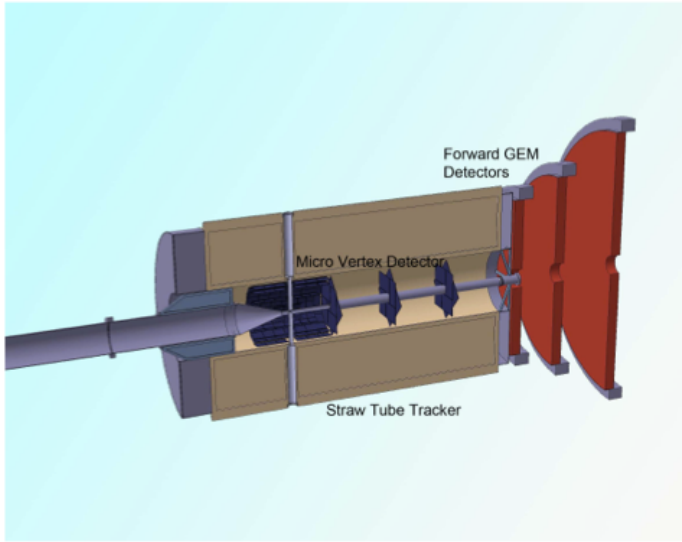


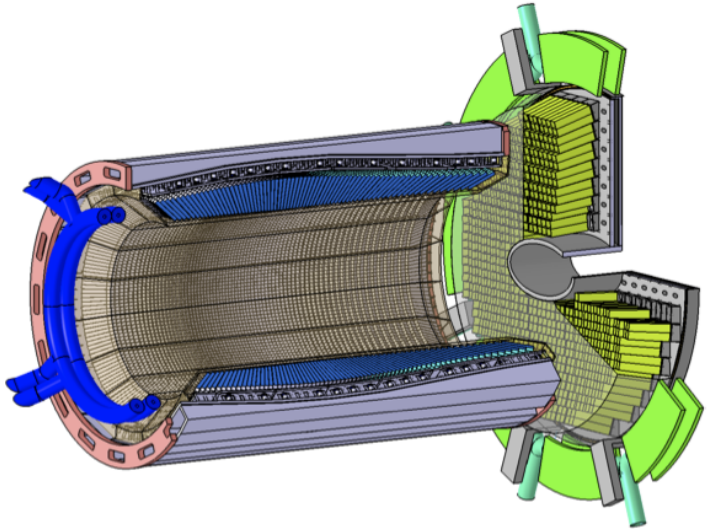
- Alternative calculation based on effective Lagrangian approach
  (J. Van de Wiele, S. Ong Eur.Phys.J. C73, 2640 (2013))
- Different colors $\Longrightarrow$ different parameters of $\bar{p}pJ/\psi$ Lagrangian
- Good description of Fermilab data with both PS and PV πNN coupling
- However a dipole hadronic form factor at the πNN vertex to take into account the offshell nature of the exchanged nucleon is required to reproduce the data

$\bar{\text{P}}$ANDA detector



Tracking and PID for Nucleon Structure Physics Program

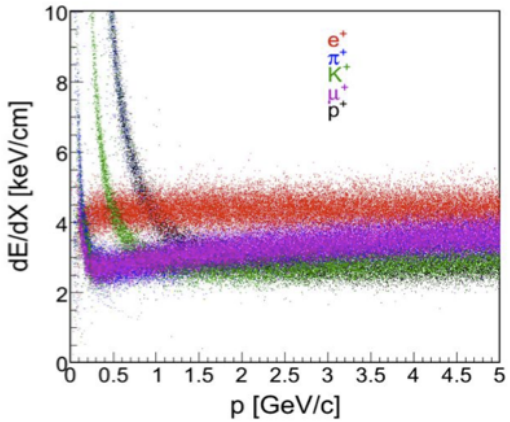




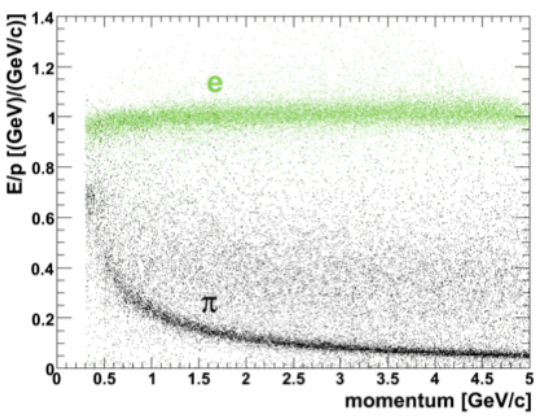
Large coverage (2π, $5^\circ < \theta < 145^\circ$)
Silicon MVD and Straw Tube and GEM tracker
dE/dx for PiD from STTs

PbWO crystal EMCal, APDs (barrel) VPT (forward)
Operation at -25°C for optimal photon production
Wide dynamic range: $\gtrsim$ 3 MeV
Excellent resolution: $\sigma(E)/E \approx 1\% \oplus 2\%/\sqrt{E(GeV)}$

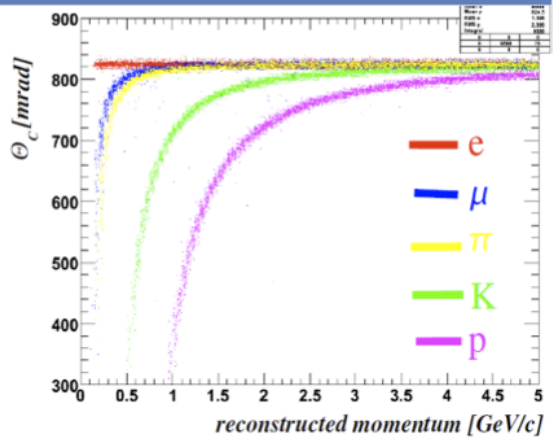
Straw Tube Tracker



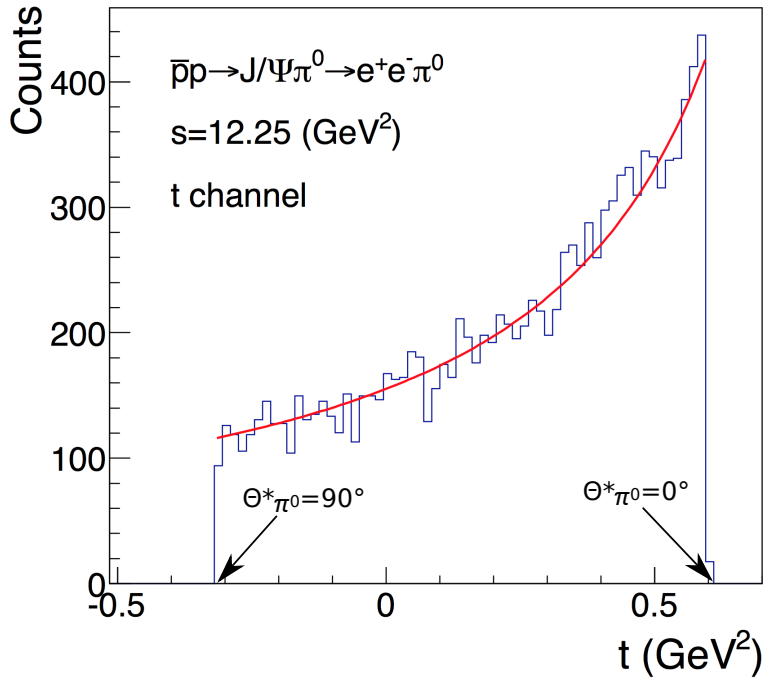
ElectroMagneticCalorimeter



DIRC(Cerenkov)



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



- New event generator based on TDA model for $\bar{p}p \to \pi^0 J/\psi \to \pi^0 e^+ e^-$ reaction (collaboration K. Semenov/B. Ma)
- $s = 12.25$ GeV^2 picked to correspond to Fermilab data points

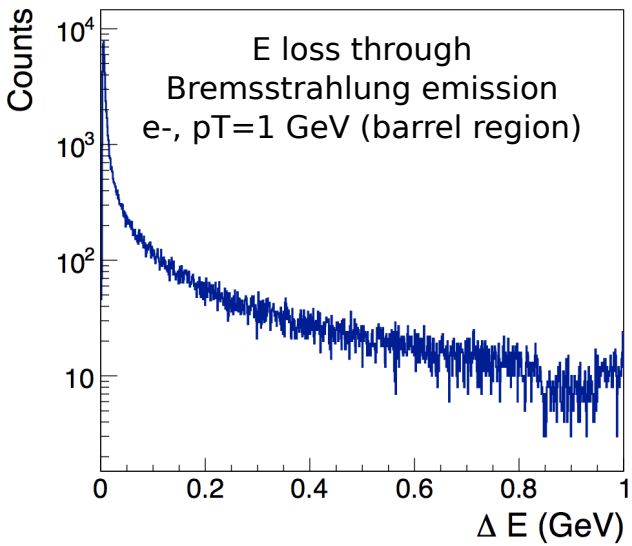
Expected signal rate in forward kinematics for s=12.25 GeV^2 for 2 fb^{-1} with 100% Acc·ε:

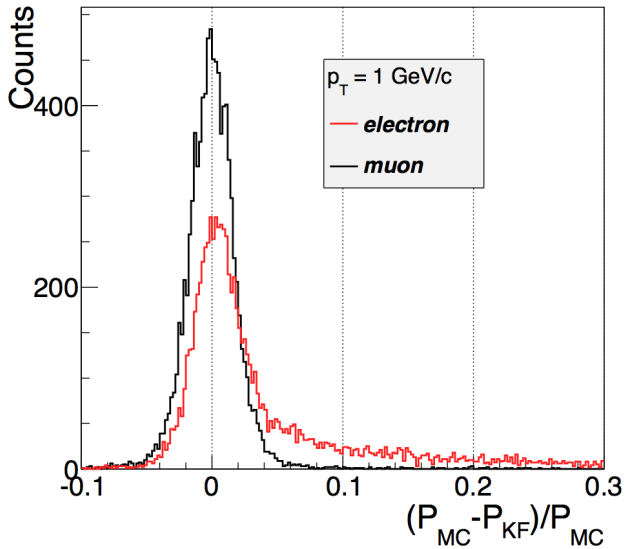
$$\mathcal{R}^{tot}_{SIG} = \mathcal{L}_{int}\sigma \mathrm{BR} = 2fb^{-1} \cdot 105\mathrm{pb} \cdot 5.94\% \approx 13\mathrm{k}$$

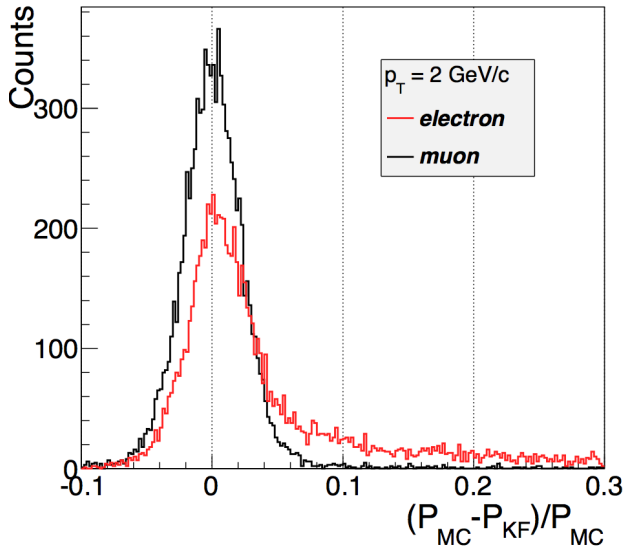
Electron momentum reconstruction in $\bar{P}$ANDA

Resolution loss due to Bremsstrahlung

- Significant radiation length in and before tracking detectors
- Higly non Gaussain energy loss by electrons due to Bremsstrahlung photon emission
- Kalman filter used for track reconstruction assumes Gaussian errors and thus can not handle Bremsstrahlung $\Longrightarrow$ resolution loss

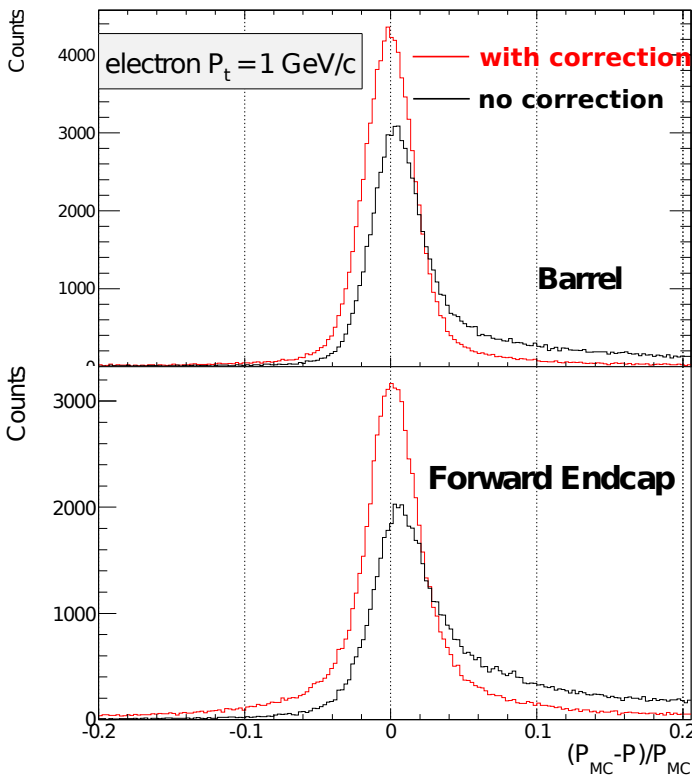


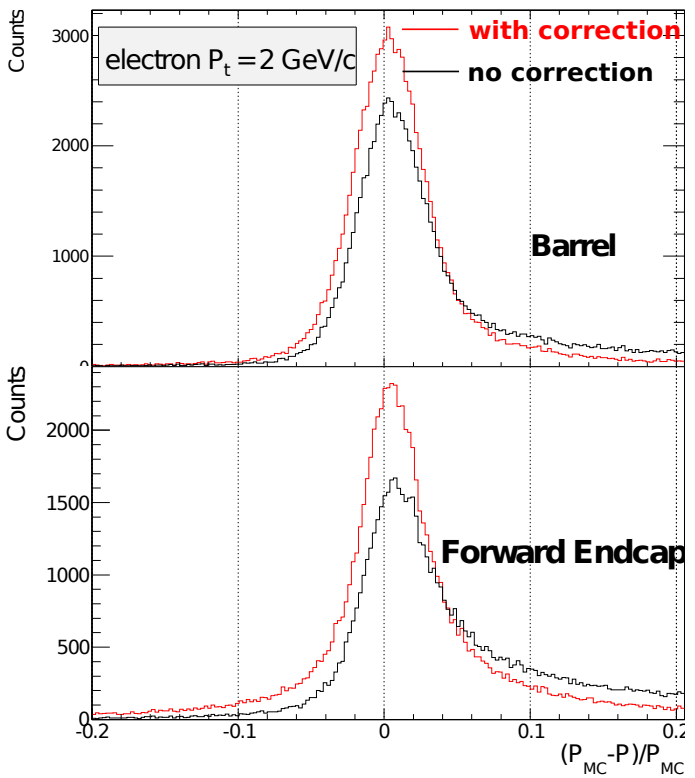




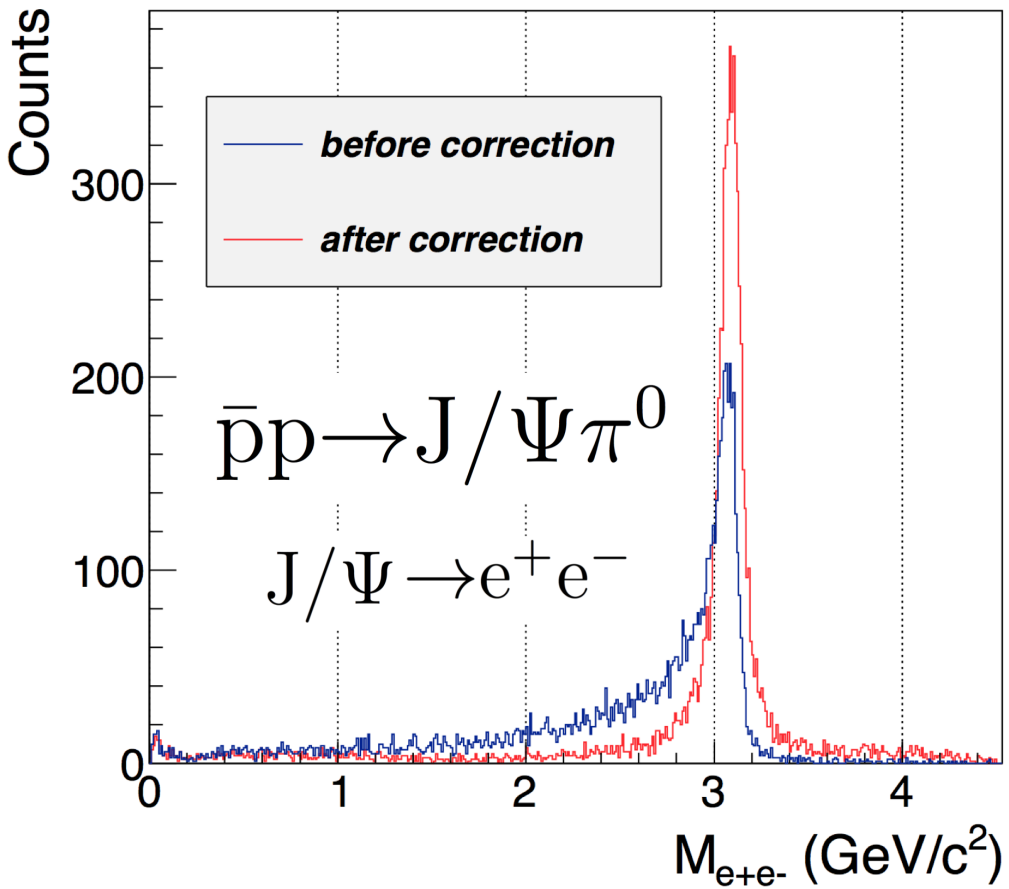
Event by event correction of Bremsstrahlung

- Thesis work by Binsong Ma (Defended on September 23 2014)
- Exploit spatial correlation between γ_{Brem} and e^+/e^- clusters
- Combined with low threshold EMCal, possible to
  - Find Bremsstrahlung photon candidates track by track
  - Correct each track's momentum by adding back total energy from all γ_{Brem}
- Approach works: clear improvement in electron momentum resolution





Improvement on J/ψ reconstruction

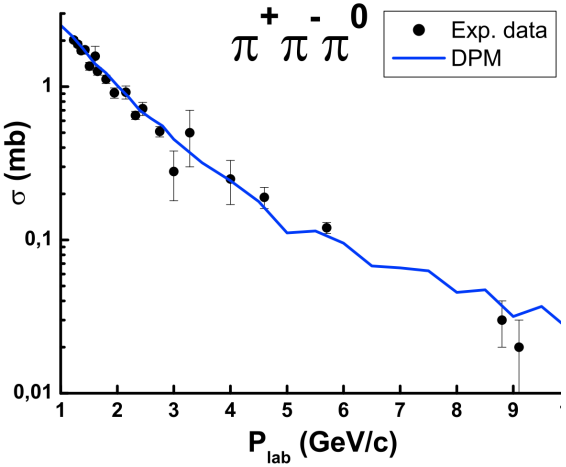


- Allows to improve mass cut efficiency on e^+e^- from J/ψ by 70%
- A mass cut of $2.96 < M_{inv} < 3.22$ has an efficiency of $\varepsilon_M^{SIG} = 64\%$ for signal events
  $\Longrightarrow \mathcal{R}_{SIG} \cdot \varepsilon_M^{SIG} = 8.3$k events

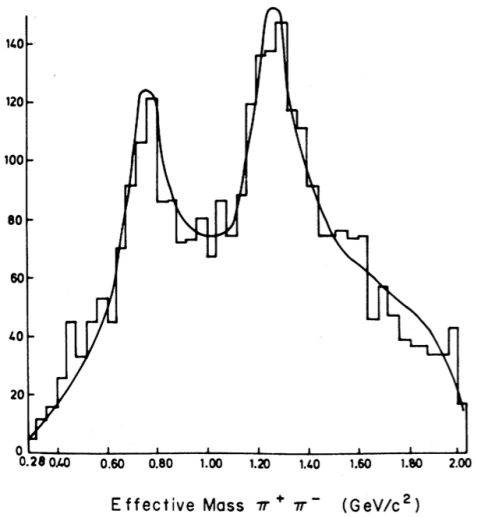
$\pi^0\pi^+\pi^-$ background

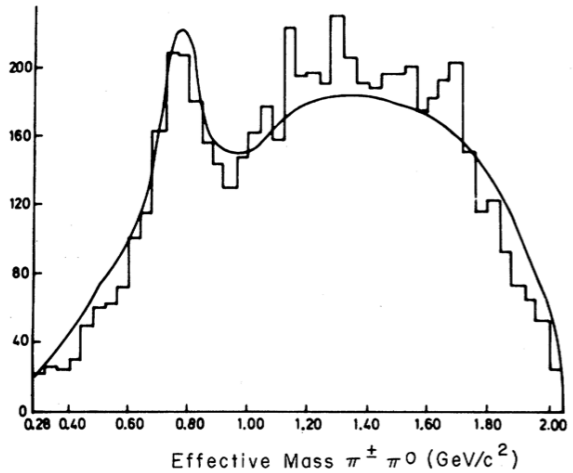
- Main background $\pi^0\pi^+\pi^-$ similar event topology and kinematically very close to signal
- Cross section relatively well known

A. Galoyan, AIP Conf.Proc.796:79-82,2005



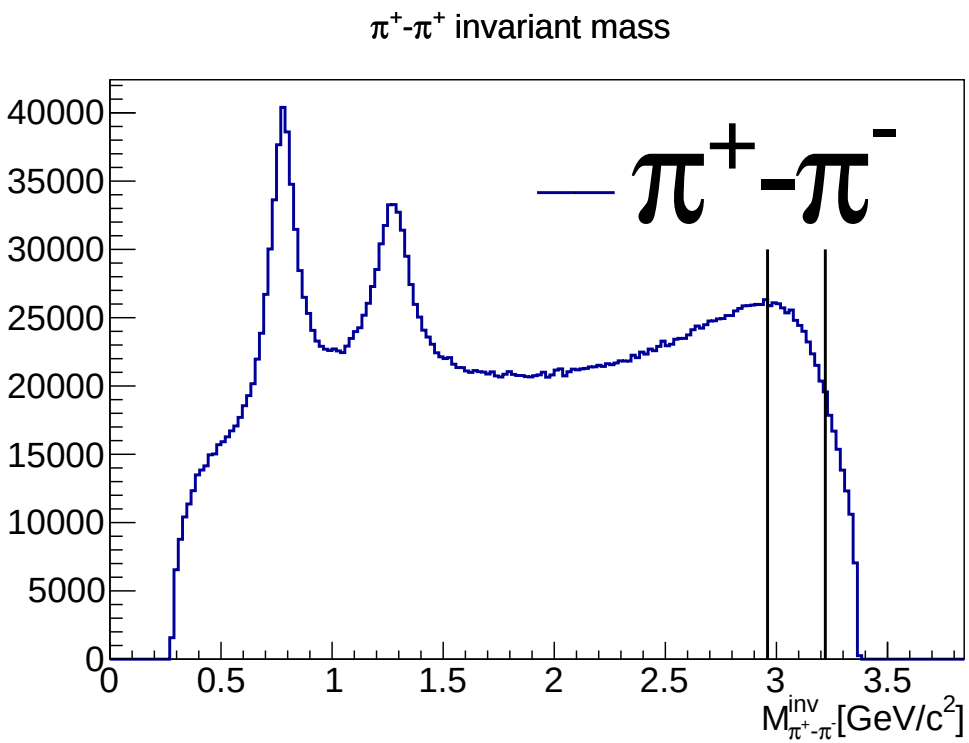
Phys. Rev. D 7, 577 (1974)





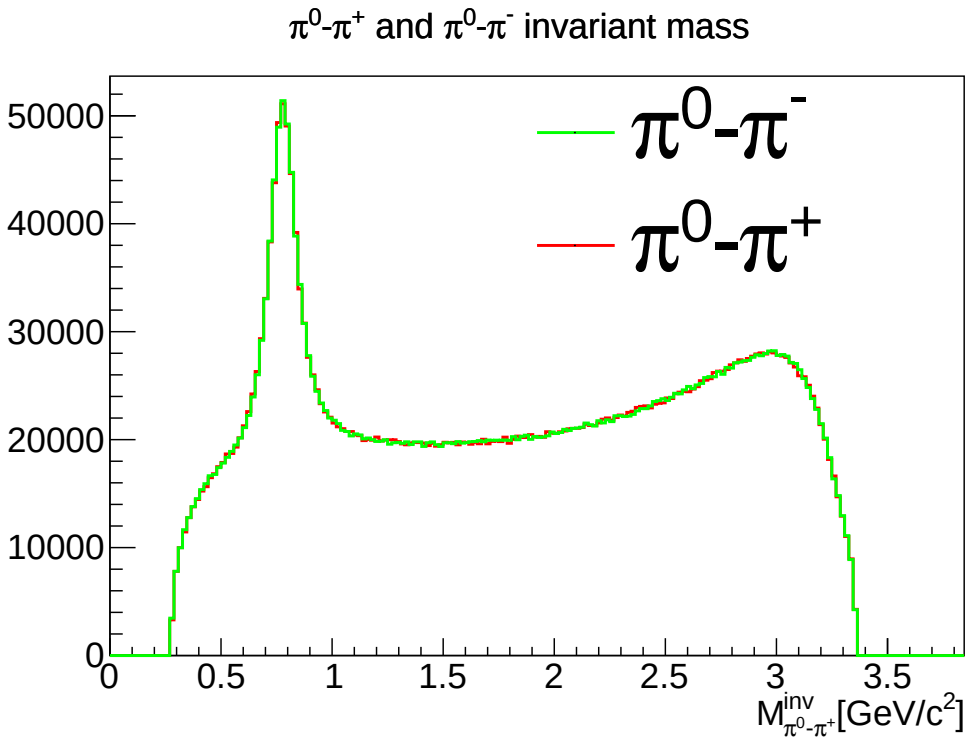
- Data from CERN-HERA 84-01, 1984 and references therein
- Interpolated x-sect at $p_{\bar{p}} = 5.51$ GeV/c of σ =0.2±0.05 mb used for BG rate estimations
- DPM reproduces both cross-sections and invariant mass distributions of data

$\pi^0\ \pi^+\pi^-$ Background distributions from DPM



- Rate estimation restricted to $-0.5 < t[\mathrm{GeV}^2] < 0.6$, $2.96 < M_{inv}[\mathrm{GeV/c}^2] < 3.22$
- Rejection from J/ψ mass cut is ≈90%
- ρ and f_0 resonances peaks in $\pi^+\pi^-$
- Contribute outside the J/ψ mass selection window $2.96 < M_{inv} < 3.22$

$\pi^0\ \pi^+\pi^-$ Background distributions from DPM



- Rate estimation restricted to $-0.5 < t[\mathrm{GeV}^2] < 0.6$, $2.96 < M_{inv}[\mathrm{GeV/c}^2] < 3.22$
- Rejection from J/ψ mass cut is ≈90%
- $\rho^+ and \rho^-$ resonance peaks in $\pi^0\pi^+$ and $\pi^0\pi^-$ respectively
- Provide a means to empirically control background contamination

Background rate estimates

- Total rate of $\bar{p}p \rightarrow \pi^0\pi^+\pi^-$ for 2 fb^{-1} integrated luminosity

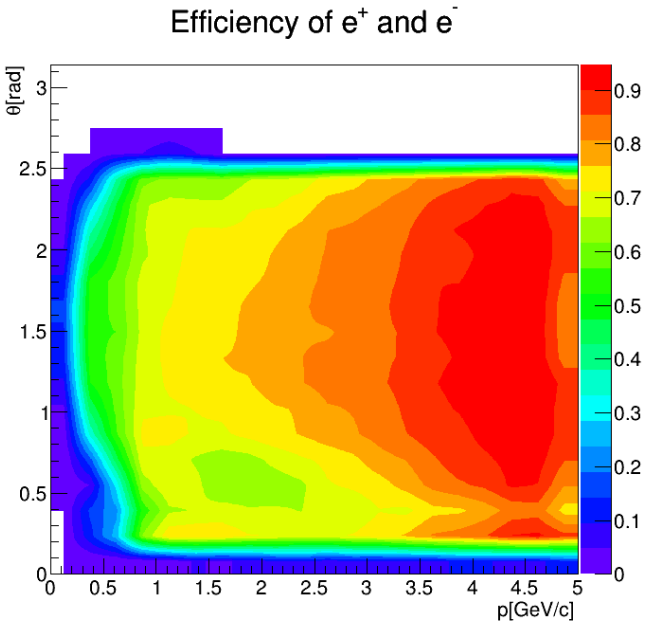
$$\mathcal{R}^{BG}_{tot} = \mathcal{L}_{int}\sigma = 2fb^{-1} \cdot \ 0.2 \pm 0.05mb \ \approx \ (4 \pm 0.1) \times 10^{11}$$

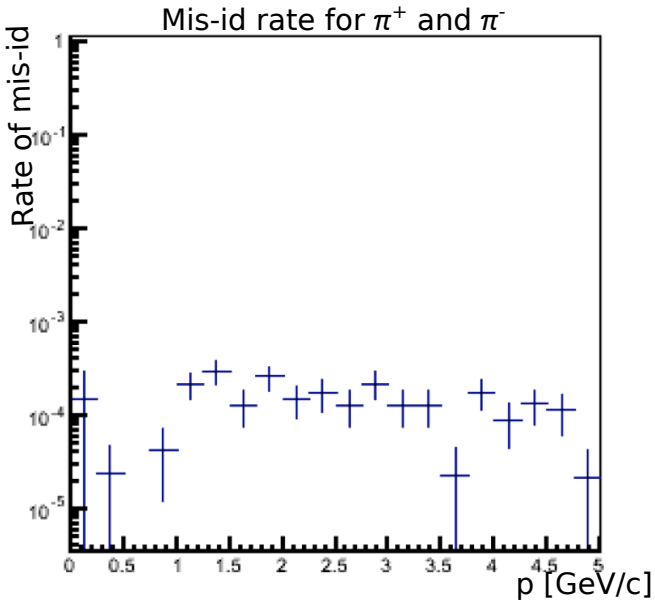
- Reduction by 95% for forward π^0 emission after J/ψ mass cut ($\varepsilon_t \cdot \varepsilon^{BG}_M \approx$5%)
- Expected background rate that has to be dealt with PID and kinematic fits:

$$\mathcal{R} = \mathcal{R}^{BG}_{tot} \cdot \varepsilon_t \cdot \varepsilon^{BG}_M = (4 \pm 0.1 \times 10^{11}) \cdot 5\% \ \approx \ (2 \pm 0.05) \times 10^{10}$$

  which gives S/B ratio before PID of $\approx 8.2\times10^3/2\times10^{10} \approx 4.1\times10^{-7}$
- PID will therefore be critical for this measurement

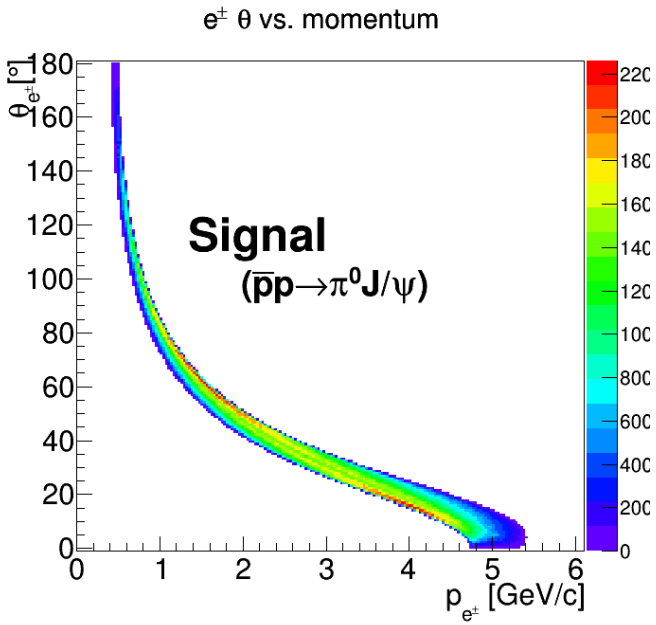
PID efficiency for electrons and charged pions

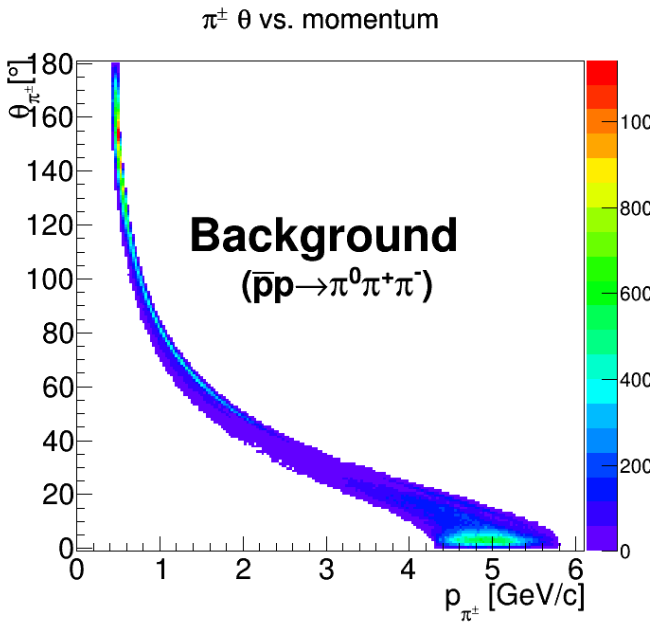




- Effect of PID cuts studied using parametrized efficiency and rejection
- The parametrization was based on a Bayesian classifier developped by R. Kunne using response to electrons and pions in a full MC (using EMC, STT, DIRC and DISC)
- Efficiency of $e^{\pm}$ and mis-id rate of $\pi^{\pm}$ were calculated as a function of (θ,p) and p respectively by requiring a combined probability of 99.9% of being an electron
- For each track from the simulation, a weight proportional to the corresponding efficiency was applied

PID efficiency for electrons and charged pions





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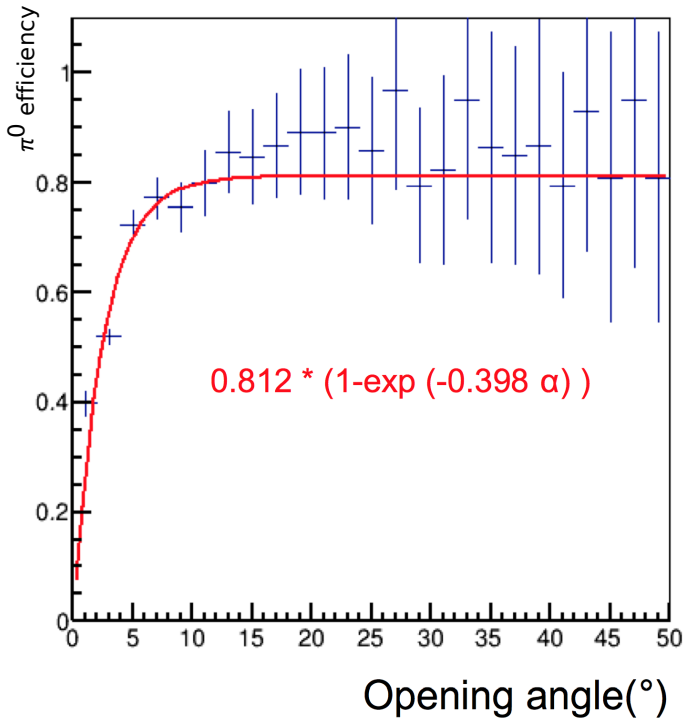
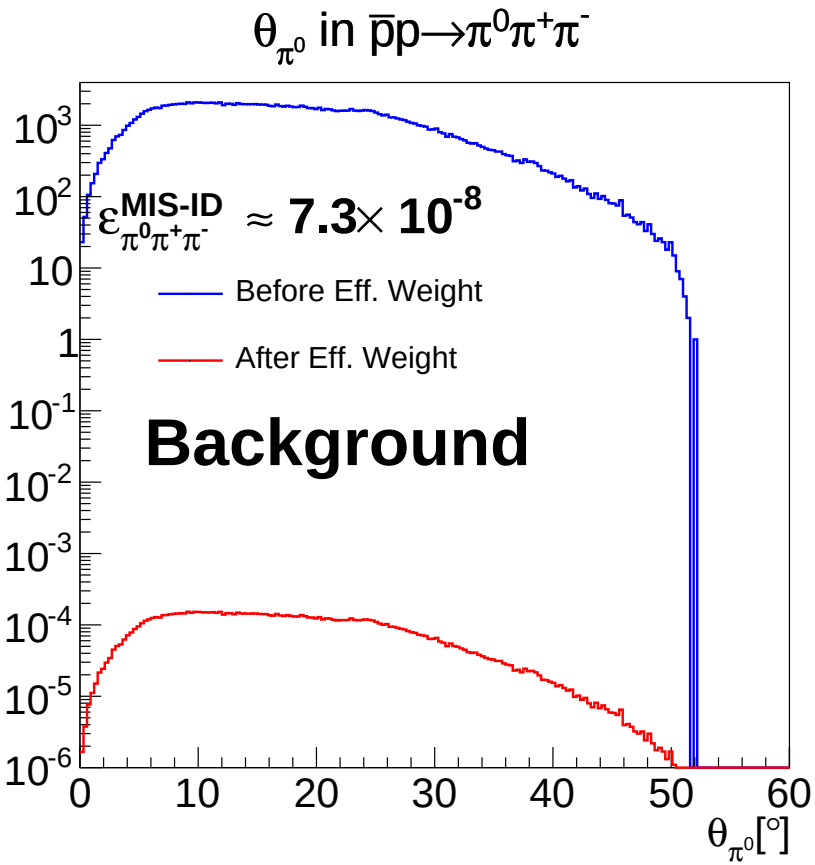
- For each track from the simulation, a weight proportional to the corresponding efficiency was applied
- Low efficiency for $e^{\pm}$ below $\approx$0.5 GeV doesn't affect efficiency for signal

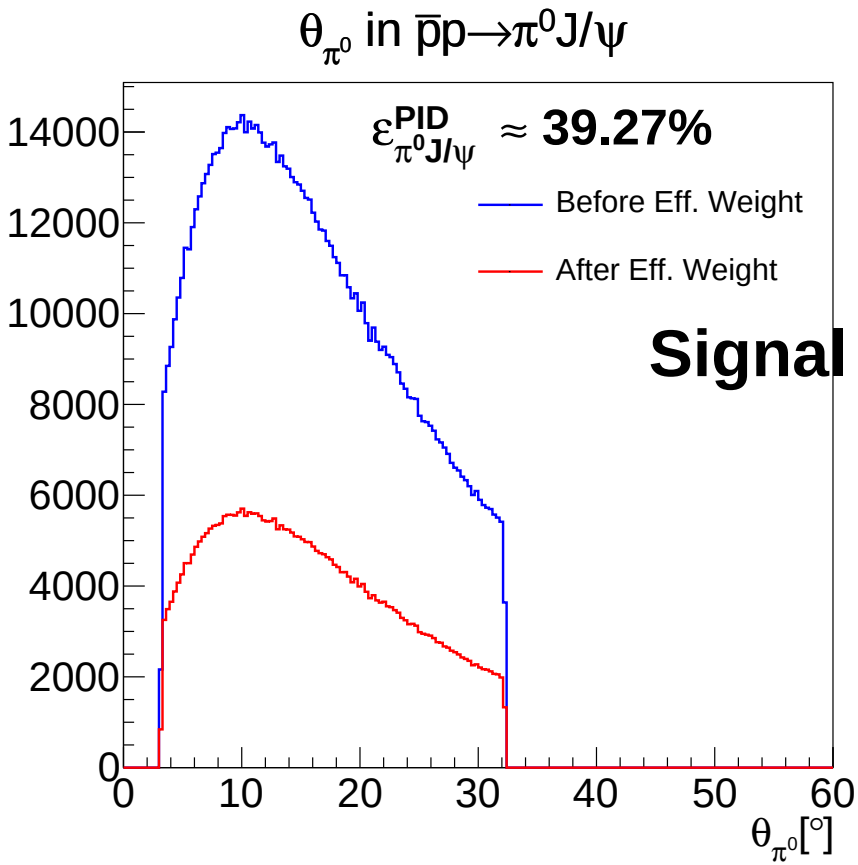
PID Efficiency for π^0



- Most of the efficiency variation ultimately comes from opening angle
- Minimum opening angle of $\approx 12^\circ$ ensures most of the signal lies in the plateau region of the efficiency (not affected by drop of efficiency at low opening angles)

Efficiency estimate of $\bar{p}p \rightarrow \pi^0 J/\psi \rightarrow \pi^0 e^+ e^-$ and $\bar{p}p \rightarrow \pi^0 \pi^+ \pi^-$





Effective Signal/Background

- Estimated S/B counts ratio based on ingredients presented above
  - Signal counts ($\mathcal{C}_{SIG}$)

$$\mathcal{C}_{SIG} = \mathcal{R}^{tot}_{SIG} \cdot \varepsilon^{SIG}_{M} \cdot \varepsilon^{MIS-ID}_{\pi^0\pi^+\pi^-} \approx 1.3 \times 10^4 \times 0.64 \times 0.39 = 3.3 \times 10^3$$

  - Background counts ($\mathcal{C}_{BG}$):

$$\mathcal{C}_{BG} = \mathcal{R}^{tot}_{BG} \cdot \varepsilon_t \cdot \varepsilon^{SIG}_{M} \cdot \varepsilon^{PID}_{\pi^0 J/\psi} \approx 4.0 \times 10^{11} \times 0.05 \times 7.3 \times 10^{-8} = 1.5 \times 10^3$$

- S/B will therefore come out to about $\mathcal{C}_{SIG}/\mathcal{C}_{BG} \approx 2.3$
- Further improvement should be possible with kinematic fits
- Background rejection at the percent level probably out of reach

  $\Longrightarrow$ precise measurement and subtraction of $\pi^0\pi^+\pi^-$ background needed.

Summary

- TDAs are universal non perturbative hadronic matrix elements that appear in factorized calculations of amplitudes that carry information about the structure of hadrons through correlations between constituents
- In $\bar{P}$ANDA , TDAs can be accessed through $\bar{p}p \to \pi^0\gamma^* \to \pi^0 e^+e^-$ or $\bar{p}p \to \pi^0 J/\psi \to \pi^0 e^+e^-$ (the later of which is more favorable due to higher S/B under the J/ψ peak)
- Good significance requires high performance PID, in particular $\pi^{\pm}$ rejection will be critical
- Rough estimation for forward kinematics based on parameterized efficiencies and rejections
  - S/B ratio of 2.3 before kinematic fit
  - Total count of events will be about 3.3k for 2 fb^{-1}
  - Needs some refinement, but orders of magnitude are realistic
- Background rejection at the percent level probably out of reach, but easy enough to subtract residual background