Polarization Observables in the Photoproduction of Two Pseudoscalar Mesons

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Outline

- Introduction and Motivation
- Formalism
- Parity Implications (and Other Relationships)
- Examples
- Conclusions

Premise:

Polarization measurements are essential for extracting amplitudes

Introduction and Motivation

Why do we need new observables?

Introduction and Motivation

Only alternative in treating a process like $\gamma N \to N\pi\pi$ is quasi-two-body (QTB) approach

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$$-P_\gamma\cos 2\Phi\left(\rho^1_{11}\sin^2\theta + \rho^1_{00}\cos^2\theta - \sqrt{2}\Re\rho^1_{1,0}\sin 2\theta\cos\phi - \rho^1_{1\,-1}\sin^2\theta\cos 2\phi\right)$$

$$\left.-P_\gamma\sin 2\Phi\left(\sqrt{2}\Im\rho^2_{10}\sin 2\theta\sin\phi + \Im\rho^2_{1\,-1}\sin^2\theta\sin 2\phi\right)\right]$$

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Similar expression needed for each QTB contribution:
c'est pas très efficace

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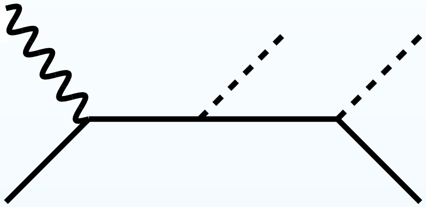

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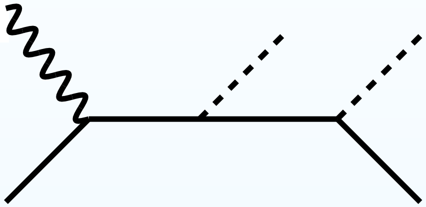

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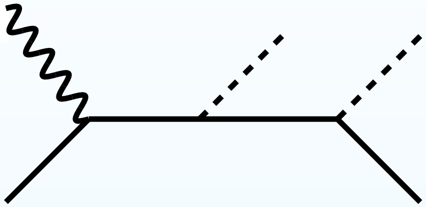

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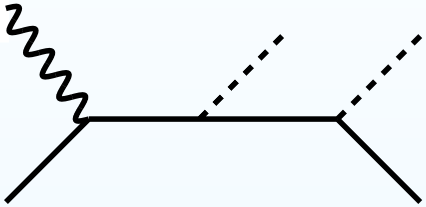

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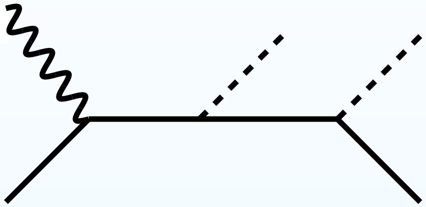

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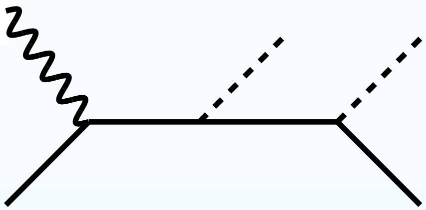

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Technique used to obtain new observables: direct calculation

Valid for $N\pi$, $N\pi\pi$ (and $N(n\pi)$ for that matter)

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For even numbers of pions, $\vec{A}$ is a vector, B_{ij} are components of a pseudotensor.

$$|\mathcal{M}|^2 = \varepsilon_i(\lambda_\gamma)\varepsilon_l(\lambda_\gamma)\chi^\dagger(\lambda_{N'})\left(A_i + \sigma_j B_{ij}\right)\phi(\lambda_N)\phi^\dagger(\lambda_N)\left(A_l^* + \sigma_k B_{lk}^*\right)\chi(\lambda_{N'})$$

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$$= \varepsilon_i\varepsilon_l^* \mathrm{Tr}\left[\frac{1}{2}\left(1 + \vec{\sigma}\cdot\vec{\Lambda}_f\right)\left(A_i + \sigma_j B_{ij}\right)\frac{1}{2}\left(1 + \vec{\sigma}\cdot\vec{\Lambda}_i\right)\left(A_l^* + \sigma_k B_{lk}^*\right)\right]$$

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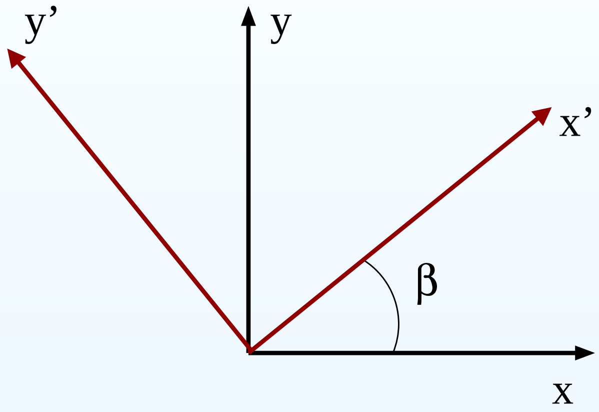
For a beam of N circularly polarized photons with momentum $\vec{k}$ along the z-axis, with $\frac{1+\delta_\odot}{2}$ photons polarized along the positive z axis, and $\frac{1-\delta_\odot}{2}$ photons polarized along the negative z axis (corresponding to degree of circular polarization $\delta_\odot$)

$$\frac{1}{N}\sum_{\text{photons}} \vec{\varepsilon}\cdot\vec{a}\vec{\varepsilon}^* \cdot \vec{b} = \vec{a}\cdot\vec{b} - \hat{k}\cdot\vec{a}\hat{k}\cdot\vec{b} - i\delta_\odot \hat{k}\cdot\vec{a}\times\vec{b}$$

For N linearly polarized photons, with $\frac{1+\delta_\ell}{2}$ polarized along the x' axis, and $\frac{1-\delta_\ell}{2}$ along the y' axis (δ_ℓ is the degree of linear polarization)



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$$+\delta_\ell\left[\cos 2\beta\,(a_x b_x - a_y b_y) + \sin 2\beta\,(a_x b_y + a_y b_x)\right]$$

After some manipulation, the cross section can be written

$$\begin{aligned}
\rho_f I \quad = \quad & I_0 \Big\{ \Big(1 + \vec{\Lambda}_i \cdot \vec{P} + \vec{\sigma} \cdot \vec{P}' + \Lambda_i^{\alpha} \sigma^{\beta'} \mathcal{O}_{\alpha\beta'} \Big) \\
& + \delta_{\odot} \Big(I^{\odot} + \vec{\Lambda}_i \cdot \vec{P}^{\odot} + \vec{\sigma} \cdot \vec{P}^{\odot\prime} + \Lambda_i^{\alpha} \sigma^{\beta'} \mathcal{O}^{\odot}_{\alpha\beta'} \Big) \\
& + \delta_{\ell} \Big[\sin 2\beta \Big(I^{s} + \vec{\Lambda}_i \cdot \vec{P}^{s} + \vec{\sigma} \cdot \vec{P}^{s\prime} + \Lambda_i^{\alpha} \sigma^{\beta'} \mathcal{O}^{s}_{\alpha\beta'} \Big) \\
& + \cos 2\beta \Big(I^{c} + \vec{\Lambda}_i \cdot \vec{P}^{c} + \vec{\sigma} \cdot \vec{P}^{c\prime} + \Lambda_i^{\alpha} \sigma^{\beta'} \mathcal{O}^{c}_{\alpha\beta'} \Big) \Big] \Big\} ,
\end{aligned}$$

Parity Implications (and Other Relationships)

In terms of helicity amplitudes,

$$\begin{aligned} I_0 = & \left|\mathcal{M}^{+}_{++}\right|^2 + \left|\mathcal{M}^{+}_{+-}\right|^2 + \left|\mathcal{M}^{+}_{-+}\right|^2 + \left|\mathcal{M}^{+}_{--}\right|^2 \\ & + \left|\mathcal{M}^{-}_{++}\right|^2 + \left|\mathcal{M}^{-}_{+-}\right|^2 + \left|\mathcal{M}^{-}_{-+}\right|^2 + \left|\mathcal{M}^{-}_{--}\right|^2 \end{aligned}$$

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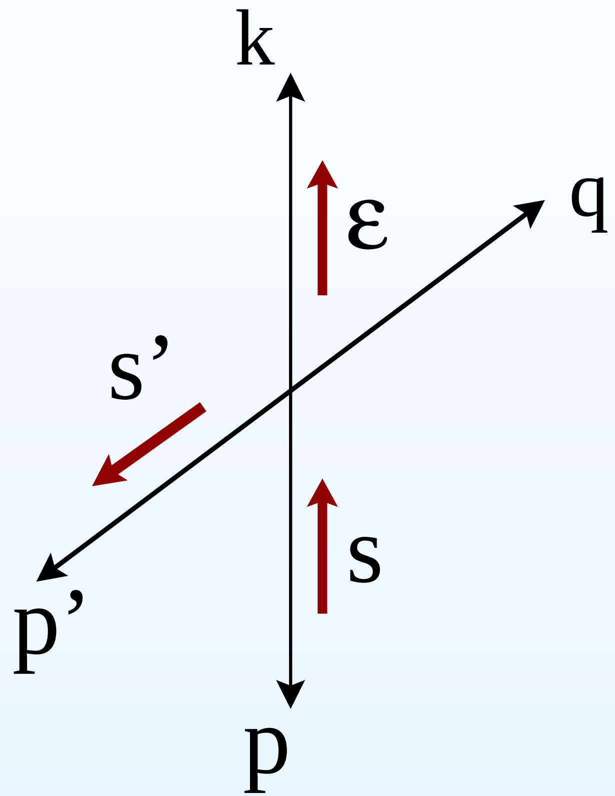
Similar questions arise for many observables


k
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q
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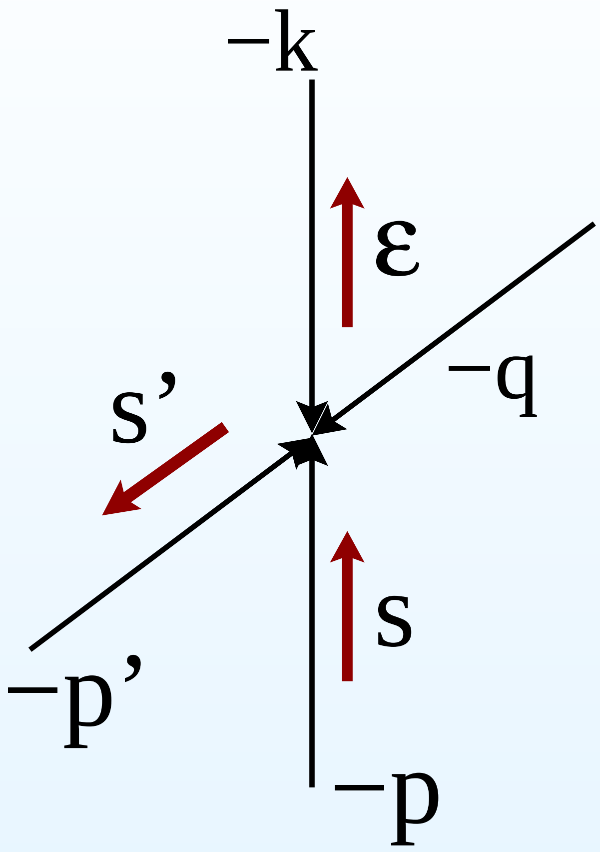
p


−k
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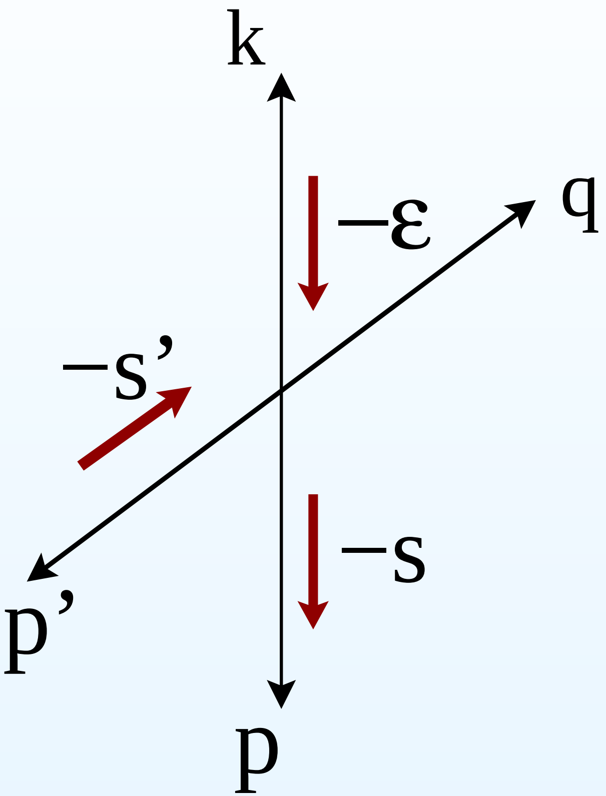
k
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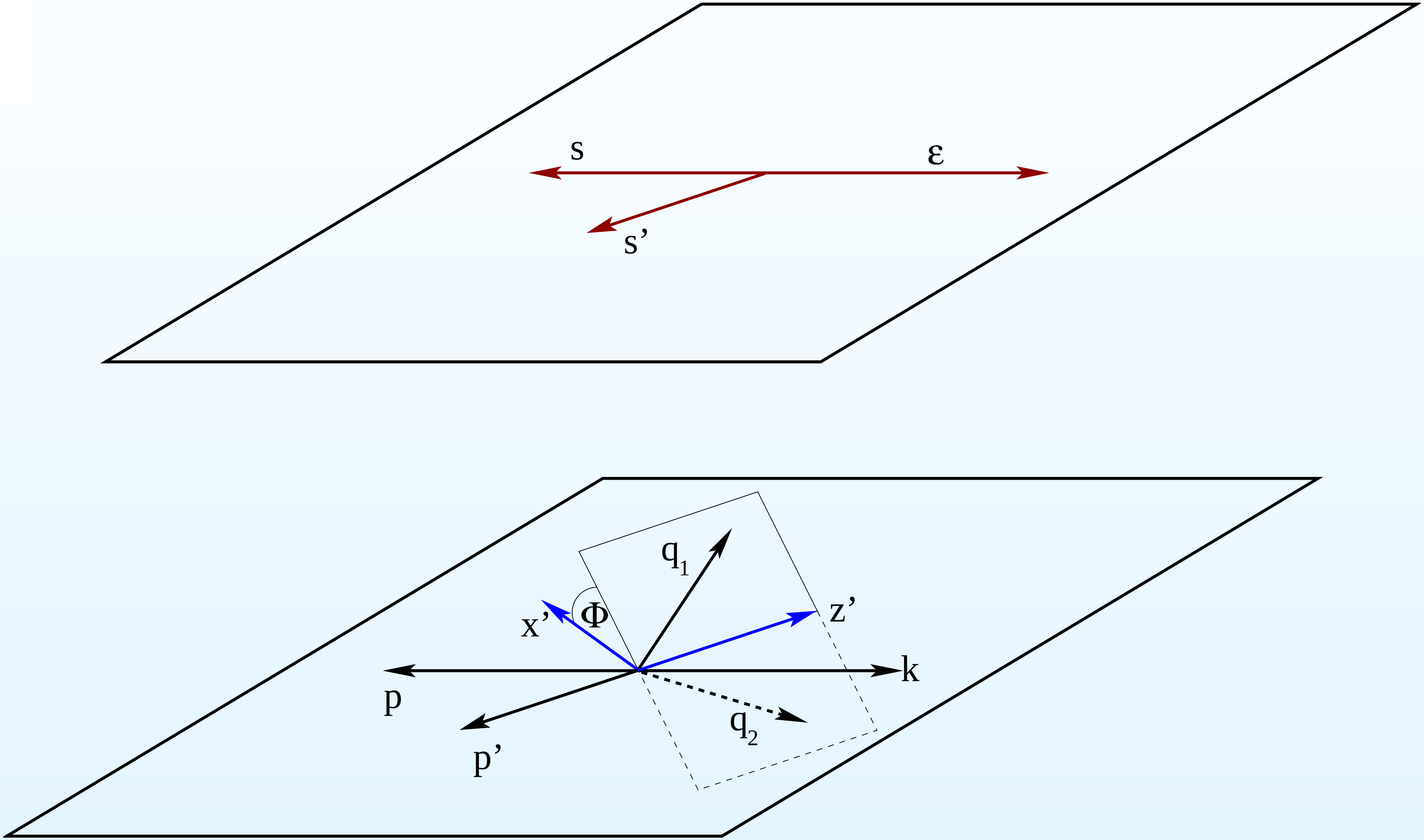
The upshot of this is that

$$\mathcal{M}^{\lambda_\gamma}_{\lambda_N,\lambda_{N'}}(\theta,\Theta) = \pm\mathcal{M}^{-\lambda_\gamma}_{-\lambda_N,-\lambda_{N'}}(\theta,\Theta),$$

and $I^{\odot}$ would indeed vanish for $\gamma N \to N\pi$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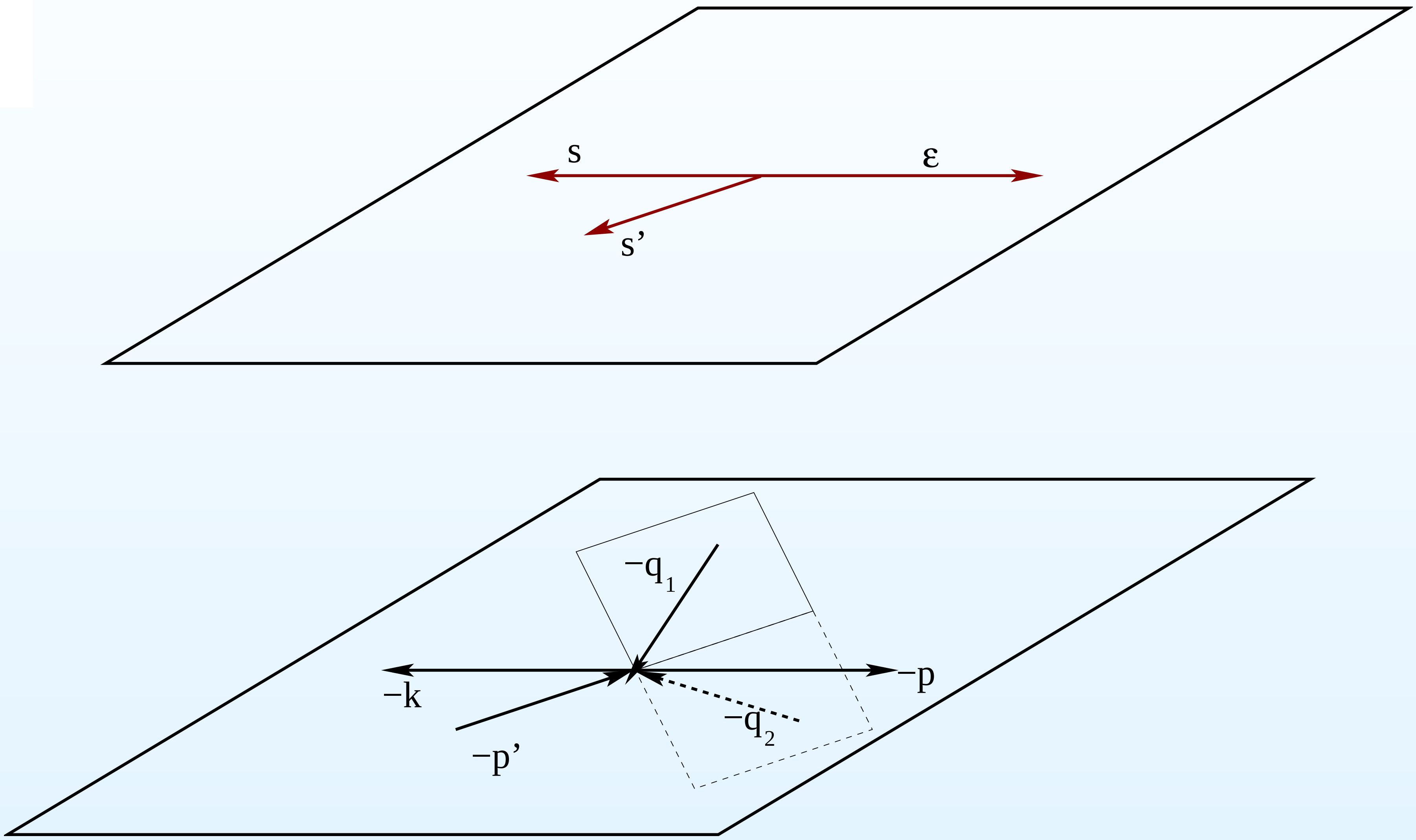
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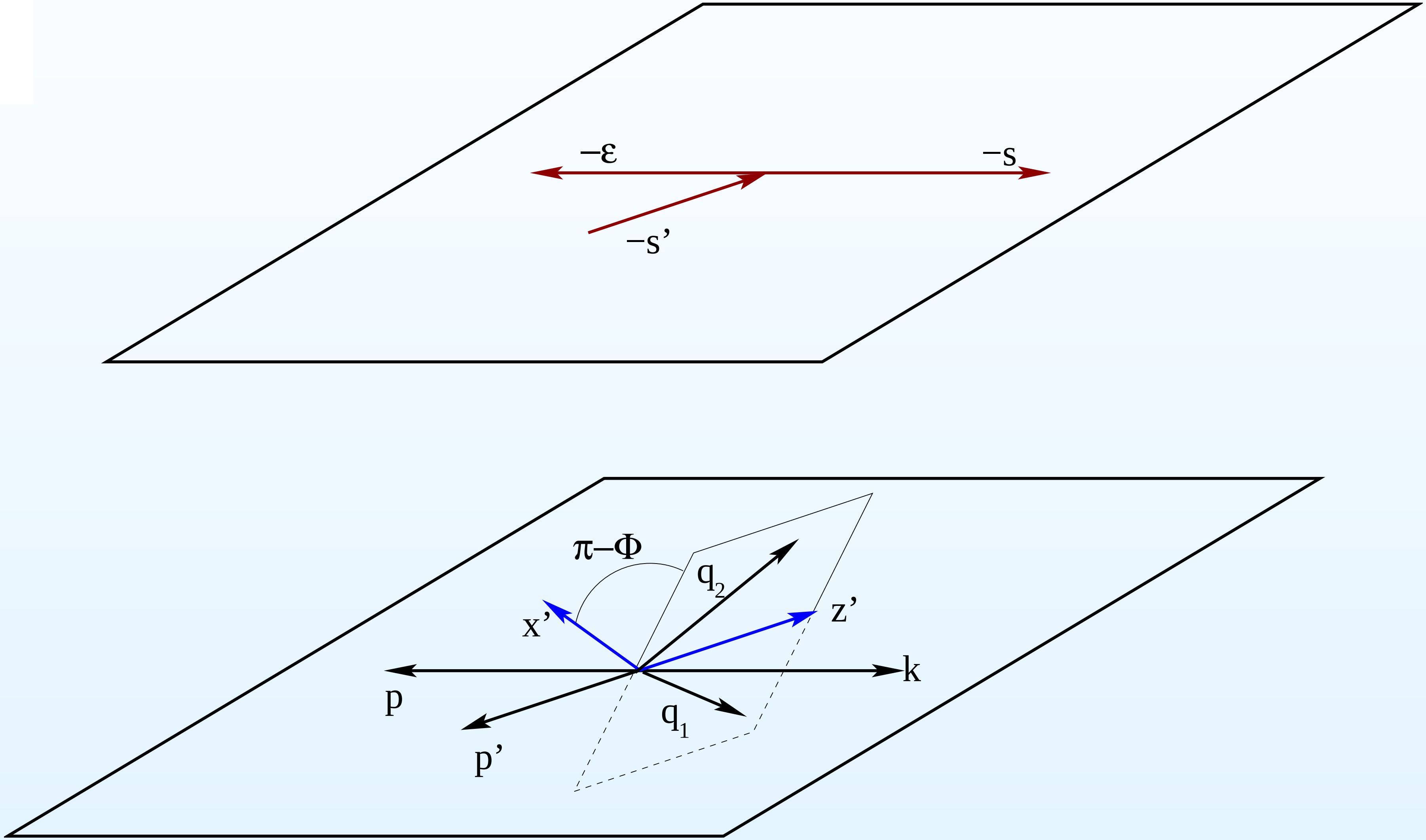
−ε
−s
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If we compare $N\pi$ and $N\pi\pi$ final states, $N\pi\pi$ observables that are odd have analogs that vanish in $N\pi$, while $N\pi\pi$ observables that are even are non-vanishing in $N\pi$.

From parity,

$$
\begin{aligned}
I_0 &= -\mathcal{O}^c_{yy'} & P_y &= -P^c_{y'} \\
P_{y'} &= -P^c_y & \mathcal{O}_{xx'} &= -\mathcal{O}^c_{zz'} \\
\mathcal{O}_{xz'} &= \mathcal{O}^c_{zx'} & \mathcal{O}_{yy'} &= -I^c \\
\mathcal{O}_{zx'} &= \mathcal{O}^c_{xz'} & \mathcal{O}_{zz'} &= -\mathcal{O}^c_{xx'} \\
P^{\odot}_x &= \mathcal{O}^s_{zy'} & P^{\odot}_z &= -\mathcal{O}^s_{xy'} \\
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all at $\Phi = 0$, $\Phi = \pi$, $\Phi = 2\pi$.

Note that because $I_0 = -\mathcal{O}^c_{yy'}$, $\mathcal{O}^c_{yy'} = -1$ at $\Phi = 0$, $\Phi = \pi$, $\Phi = 2\pi$.

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$$P_{y'} = -P^c_y \qquad \mathcal{O}_{xx'} = -\mathcal{O}^c_{zz'}$$
$$\mathcal{O}_{xz'} = \mathcal{O}^c_{zx'} \qquad \mathcal{O}_{yy'} = -I^c$$
$$\mathcal{O}_{zx'} = \mathcal{O}^c_{xz'} \qquad \mathcal{O}_{zz'} = -\mathcal{O}^c_{xx'}$$
$$P^{\odot}_x = \mathcal{O}^s_{zy'} \qquad P^{\odot}_z = -\mathcal{O}^s_{xy'}$$
$$P^{\odot}_{x'} = -\mathcal{O}^s_{yz'} \qquad P^{\odot}_{z'} = \mathcal{O}^s_{yx'}$$
$$P^s_x = -\mathcal{O}^{\odot}_{zy'} \qquad P^s_z = \mathcal{O}^{\odot}_{xy'}$$
$$P^s_{x'} = \mathcal{O}^{\odot}_{yz'} \qquad P^s_{z'} = -\mathcal{O}^{\odot}_{yx'}$$

all at $\Phi = 0$, $\Phi = \pi$, $\Phi = 2\pi$.

Note that because $I_0 = -\mathcal{O}^c_{yy'}$, $\mathcal{O}^c_{yy'} = -1$ at $\Phi = 0$, $\Phi = \pi$, $\Phi = 2\pi$.

All other observables vanish at $\Phi = 0$, $\Phi = \pi$, $\Phi = 2\pi$.

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$$= \left[1 + \xi P_y + \zeta \left(I^{\odot} + \xi P^{\odot}_y\right)\right]^2 - \left[P_{y'} + \xi \mathcal{O}_{yy'} + \zeta \left(P^{\odot}_{y'} + \xi \mathcal{O}^{\odot}_{yy'}\right)\right]^2$$

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The analagous count for $N\pi$ gives 7 independent observables, 7 observables that must be measured for extraction of amplitudes (up to quadrant ambiguities in their phases)

Relationships can be manipulated to give two sets of inequalities

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$$1+P_y^2+\left(I^{\odot}\right)^2+\left(P_y^{\odot}\right)^2 \geq \left\{P_{y'}^2+\mathcal{O}_{yy'}^2+\left(P_{y'}^{\odot}\right)^2+\left(\mathcal{O}_{yy'}^{\odot}\right)^2,\right.$$

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Discussed in detail in W. Roberts and T. Oed, Phys. Rev. C 71, 055201 (2005)

What observables need to be measured?

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To obtain the amplitudes of the (transversity) amplitudes, we *MUST* measure differential cross section, along with P_y, $P_{y'}$, $\mathcal{O}_{yy'}$, $I^{\odot}$, $P_y^{\odot}$, $P_{y'}^{\odot}$ and $\mathcal{O}_{yy'}^{\odot}$, (angular distributions and mass distributions only probe $I_0 = \left|\mathcal{M}^+_{++}\right|^2 + \left|\mathcal{M}^+_{+-}\right|^2 + \left|\mathcal{M}^+_{-+}\right|^2 + \left|\mathcal{M}^+_{--}\right|^2 + \left|\mathcal{M}^-_{++}\right|^2 + \left|\mathcal{M}^-_{+-}\right|^2 + \left|\mathcal{M}^-_{-+}\right|^2 + \left|\mathcal{M}^-_{--}\right|^2$)

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For instance, four of these phase differences can be extracted by measuring any 4 of the 8 observables $P_{x'}$, $P_{z'}$, $\mathcal{O}_{yx'}$, $\mathcal{O}_{yz'}$, $P_{x'}^{\odot}$, $P_{z'}^{\odot}$, $\mathcal{O}_{yx'}^{\odot}$, and $\mathcal{O}_{yz'}^{\odot}$,

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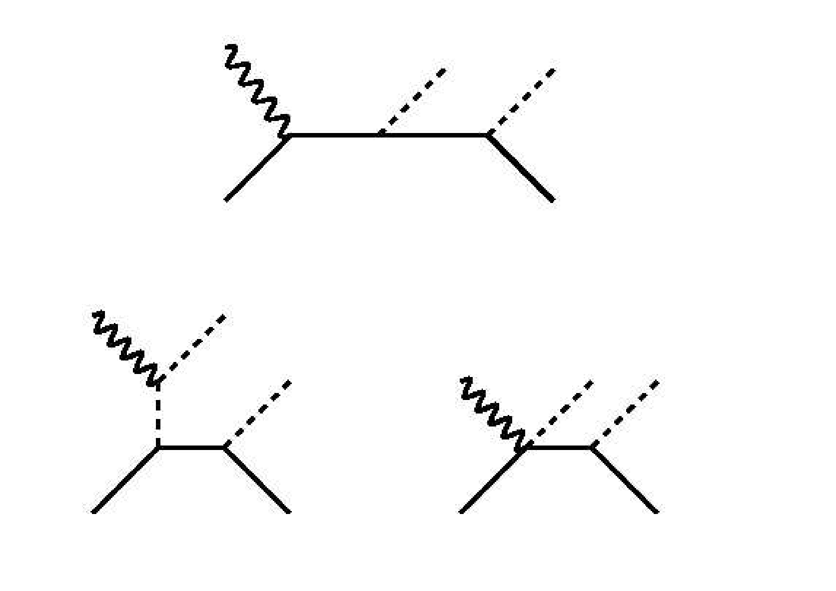
'Complete' set of experiments requires measurement of single, double and triple polarization observables (including observables with both linearly and circularly polarized photons), along with the differential cross section

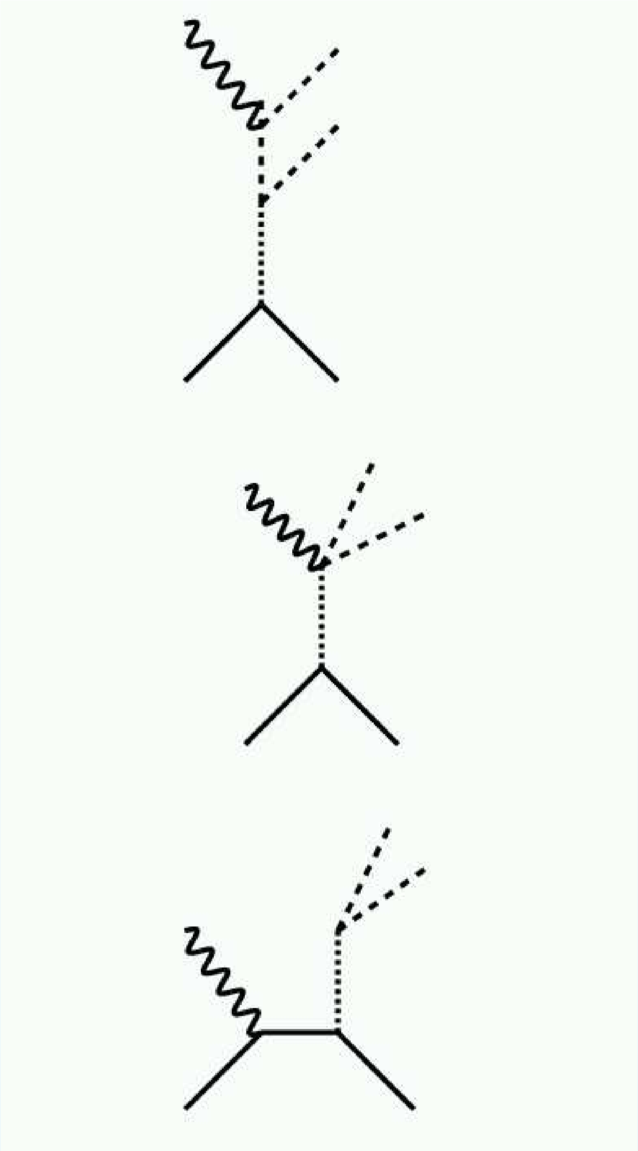
Examples

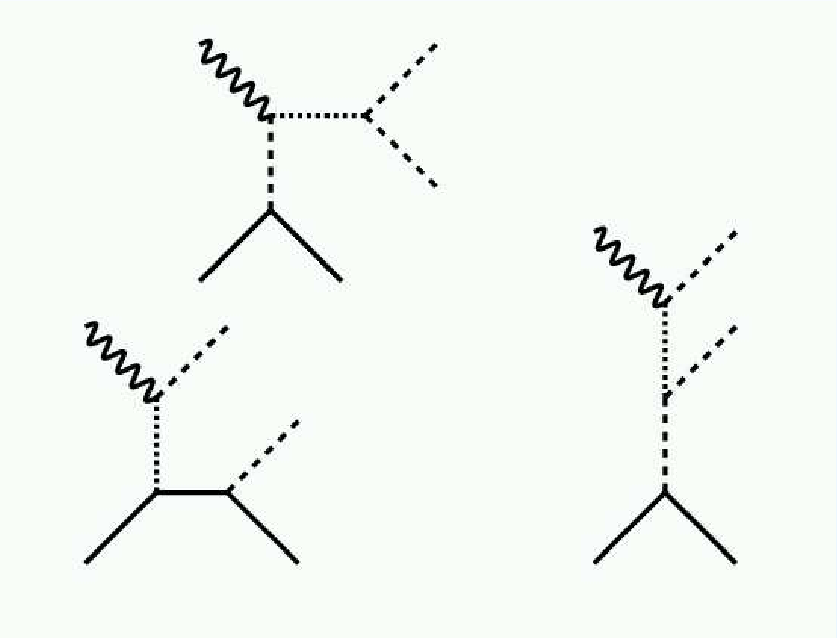
In $\gamma N \to N\pi\pi$ (or $\gamma N \to NK\overline{K}$), observables are 5-fold differential, and so can be shown in a variety of ways (even Dalitz plots, for observables that are even under $\Phi \leftrightarrow 2\pi - \Phi$).

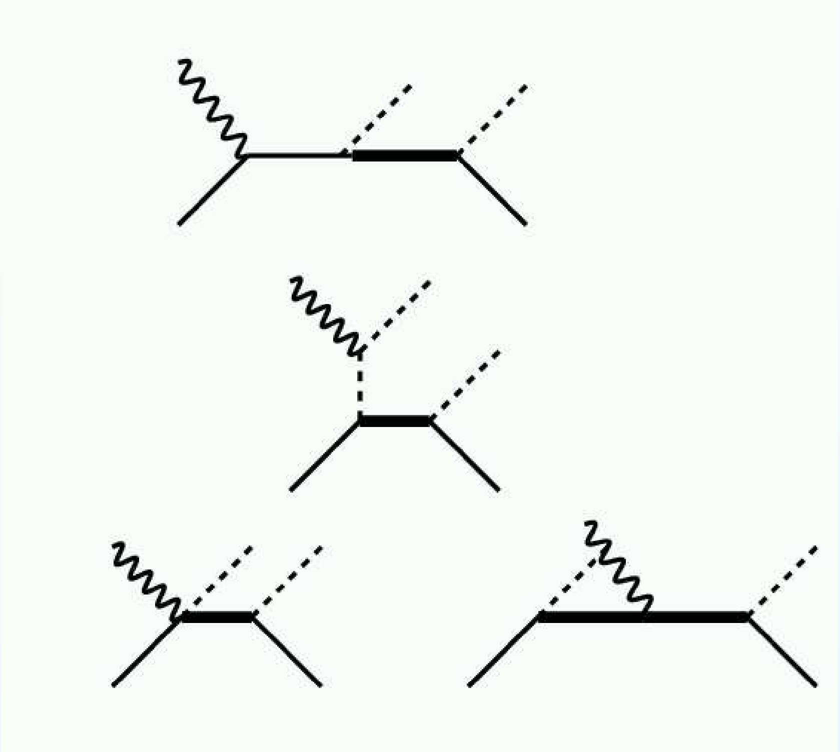
To illustrate these observables, I use a ‘simple’ model

Examples









Model includes $s-$ (and $u-$) channel hyperons: $\Lambda(1405)$, $\Lambda(1520)$, $\Lambda(1600)$, $\Lambda(1670)$, $\Lambda(1690)$, $\Lambda(1800)$, $\Lambda(1810)$, $\Lambda(1890)$, $\Sigma(1385)$, $\Sigma(1580)$, $\Sigma(1620)$, $\Sigma(1660)$, $\Sigma(1670)$, $\Sigma(1750)$, $\Sigma(1880)$, $\Sigma(1940)$;

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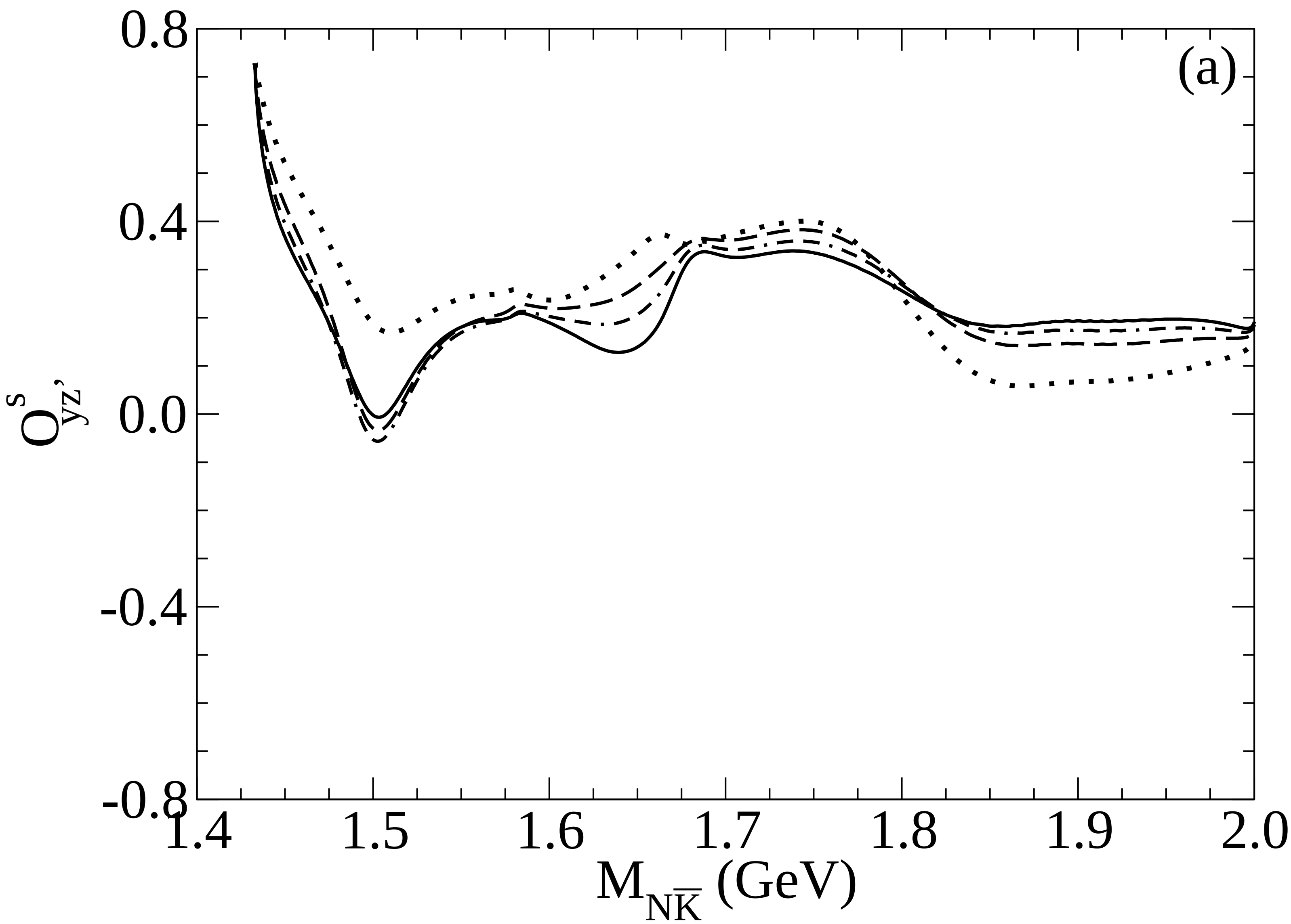
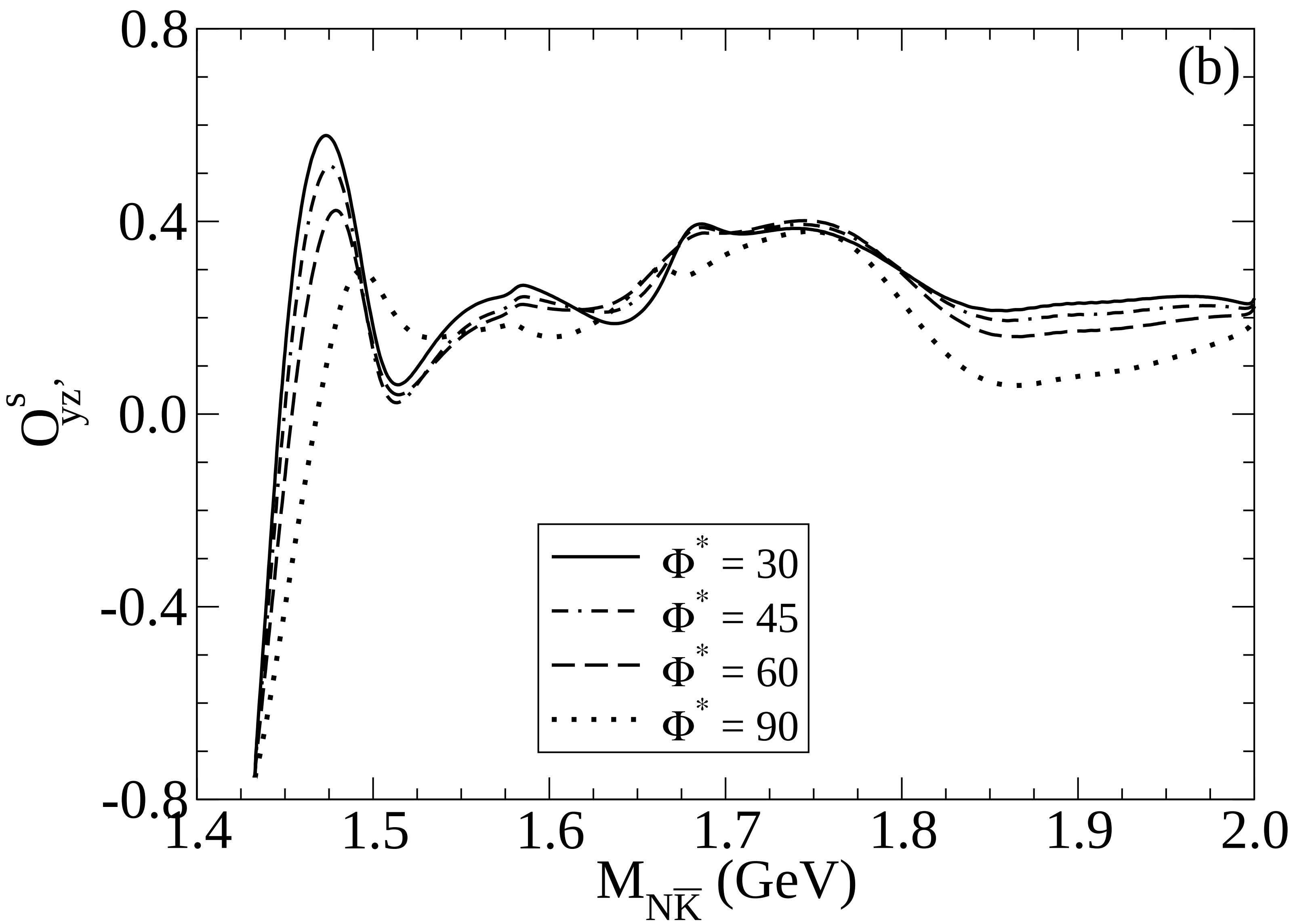
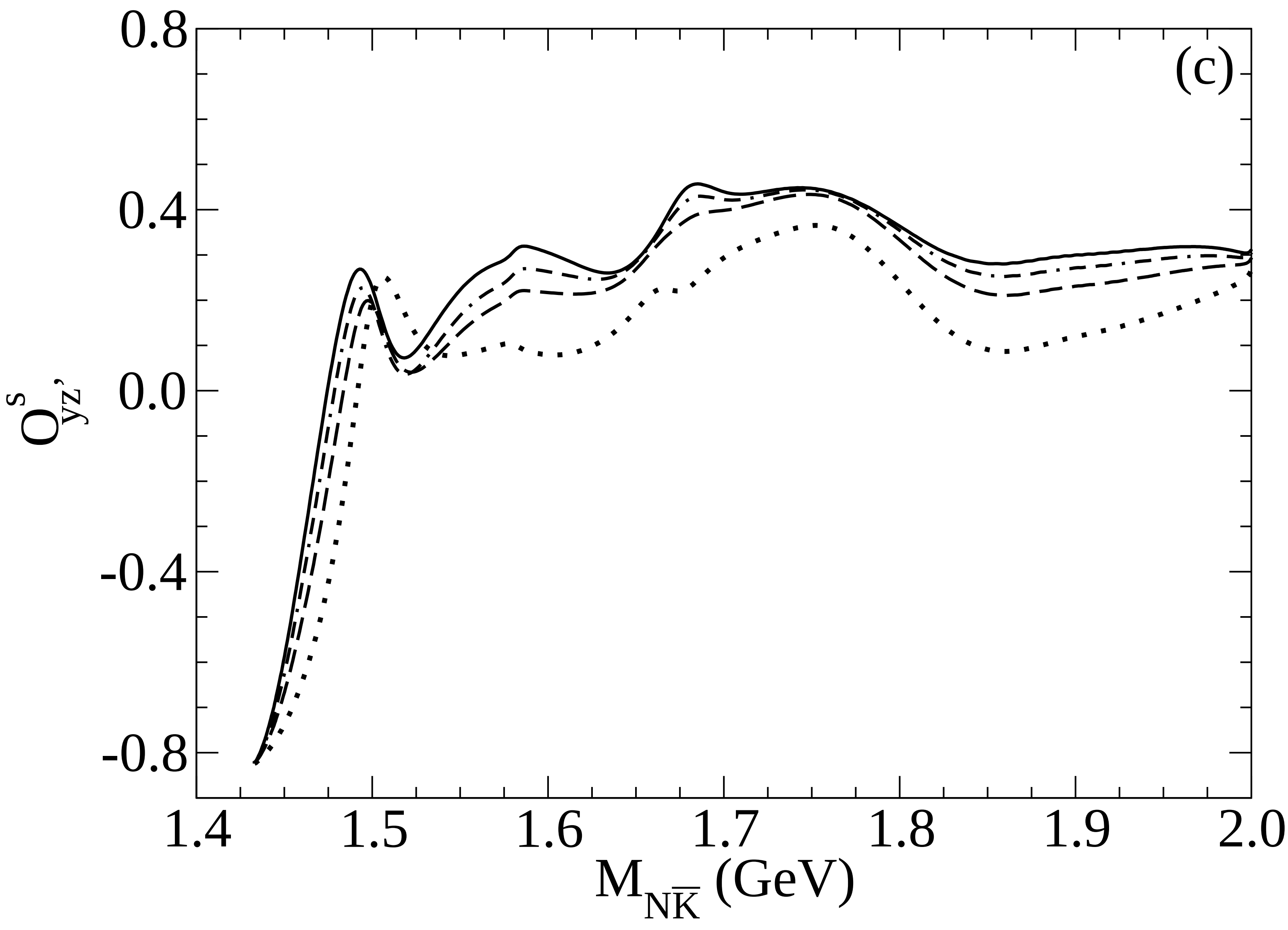
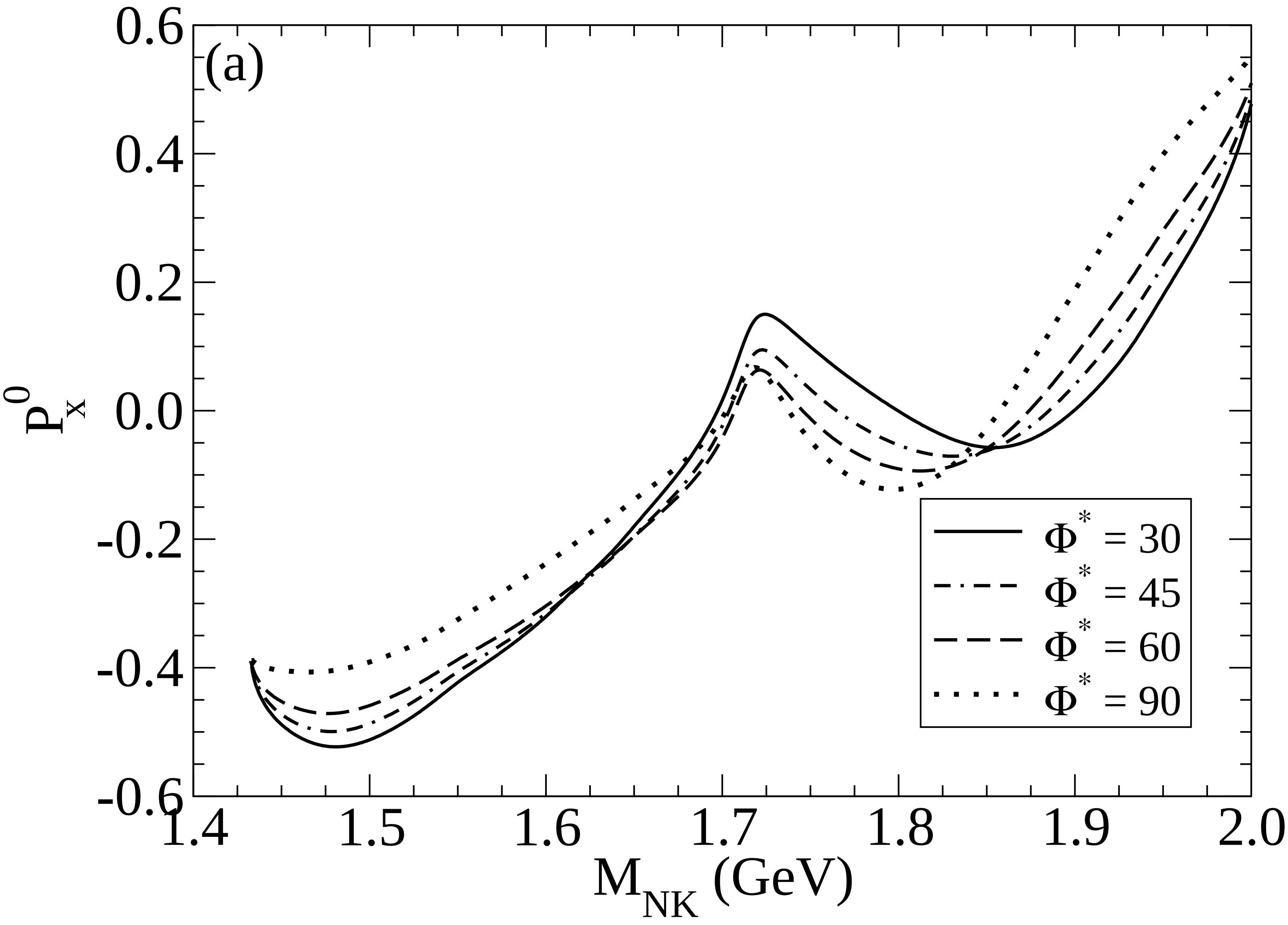
Nevertheless, should be sufficient to illustrate the salient points (W. Roberts, Phys. Rev. C 70, 065201 (2004) for more details.)

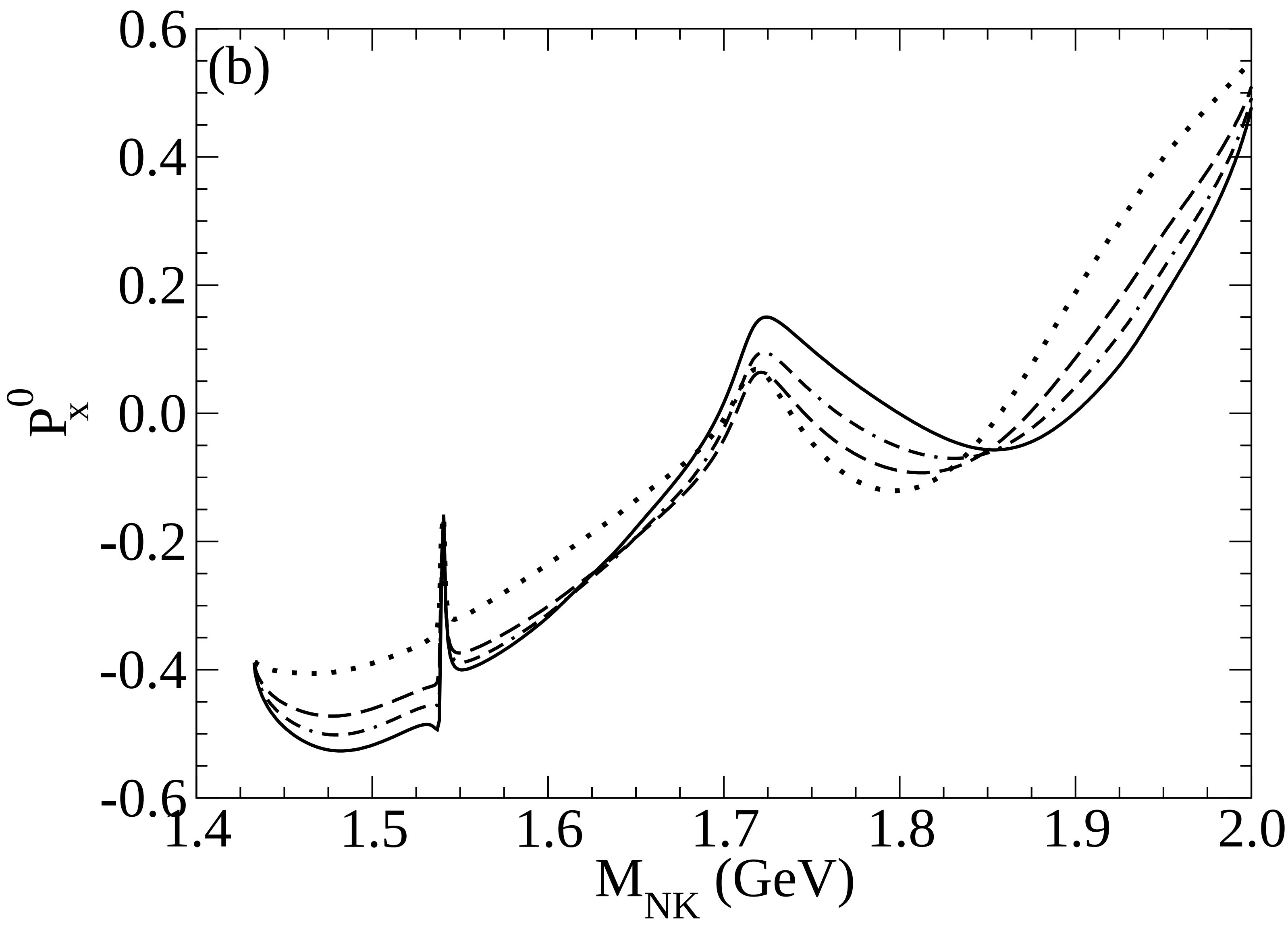


0.8
0.4
0.0
-0.4
-0.8
1.4
1.5
1.6
1.7
1.8
1.9
2.0
(a)
$O^{s}_{yz'}$
$M_{N\bar{K}}$ (GeV)

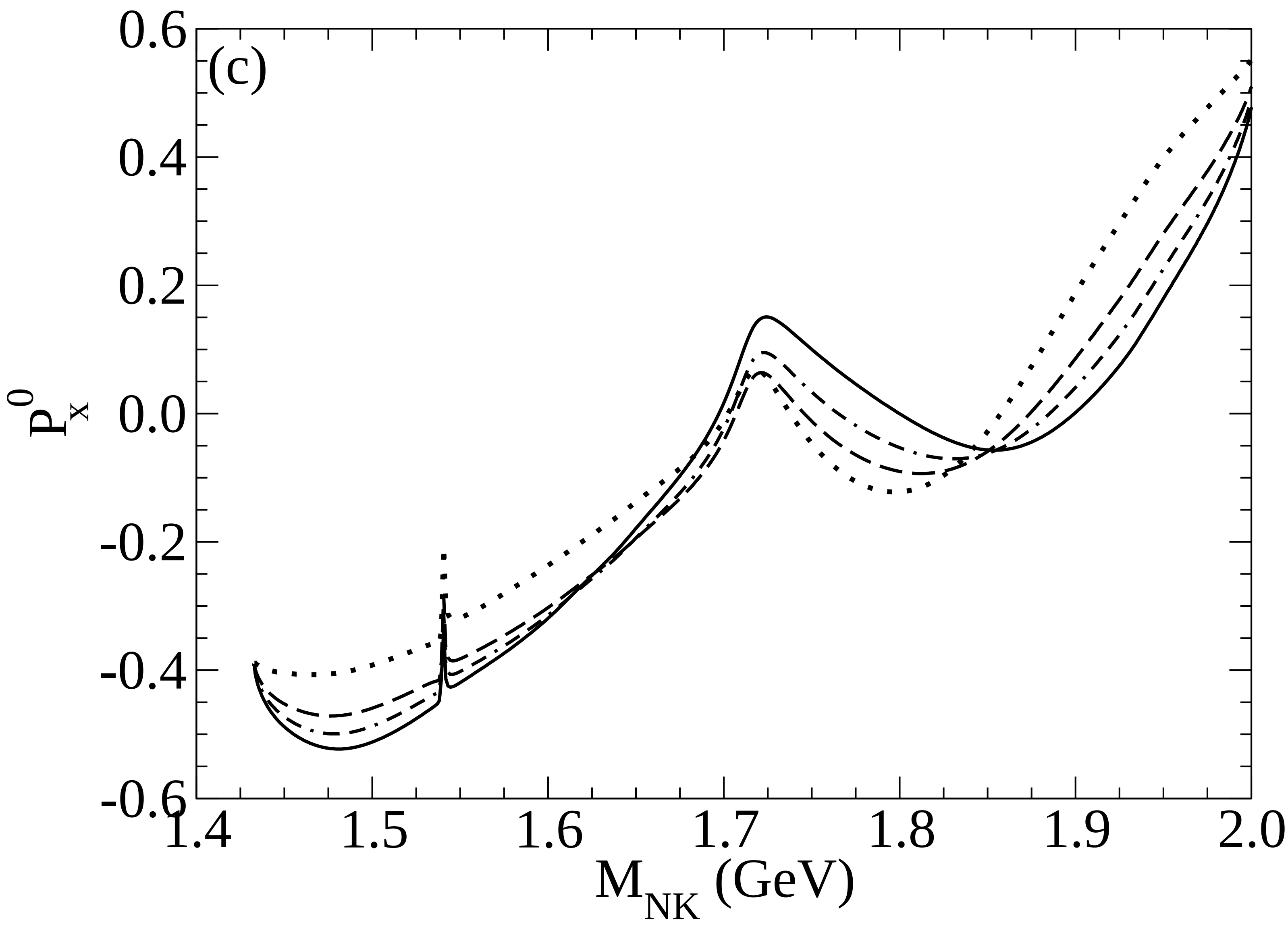

0.8
0.4
0.0
-0.4
-0.8
(b)
$O^{s}_{yz'}$
$\Phi^* = 30$
$\Phi^* = 45$
$\Phi^* = 60$
$\Phi^* = 90$
1.4
1.5
1.6
1.7
1.8
1.9
2.0
$M_{N\bar{K}}$ (GeV)

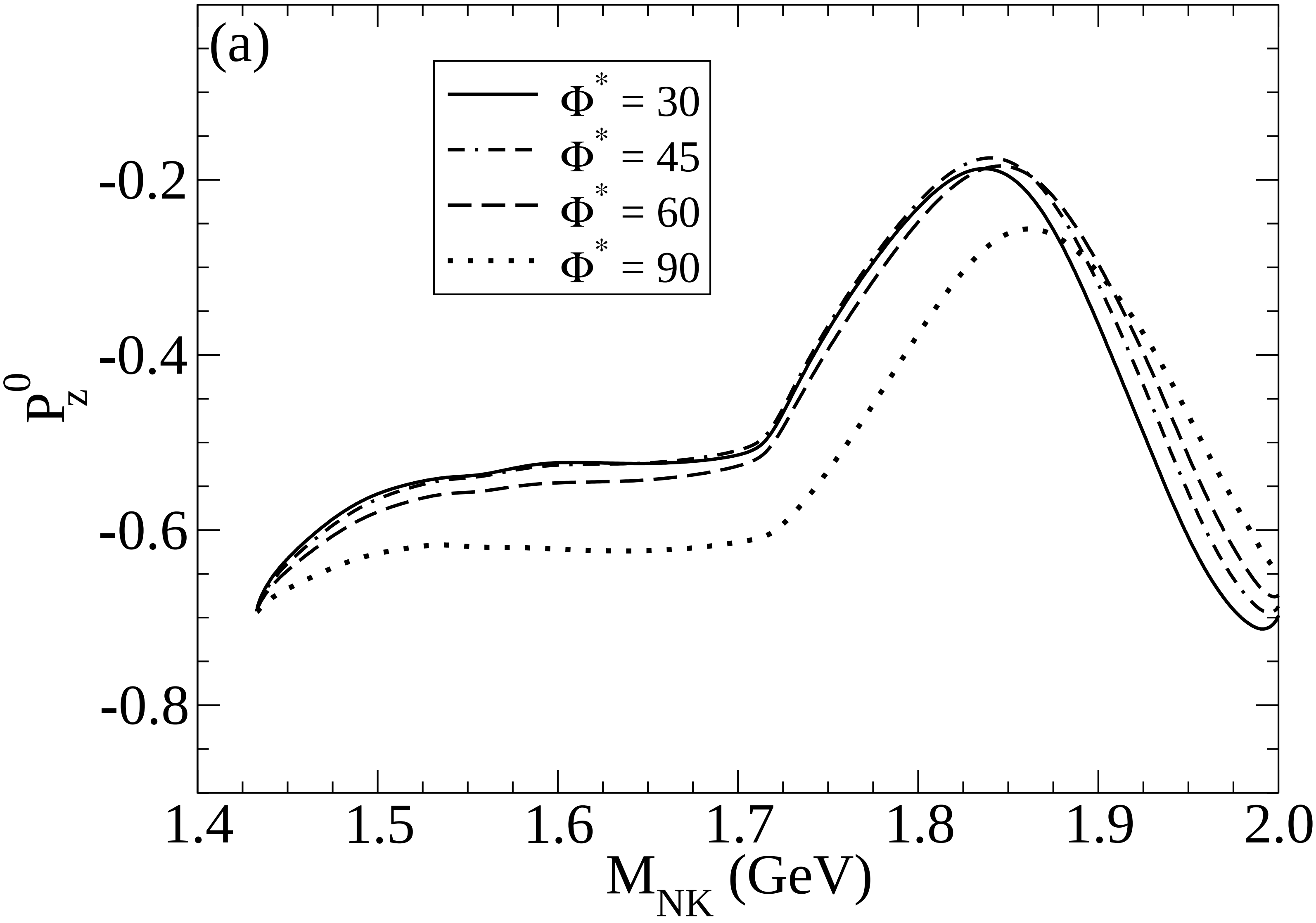

(c)
0.8
0.4
0.0
-0.4
-0.8
$O^s_{yz'}$
1.4
1.5
1.6
1.7
1.8
1.9
2.0
$M_{N\bar{K}}$ (GeV)

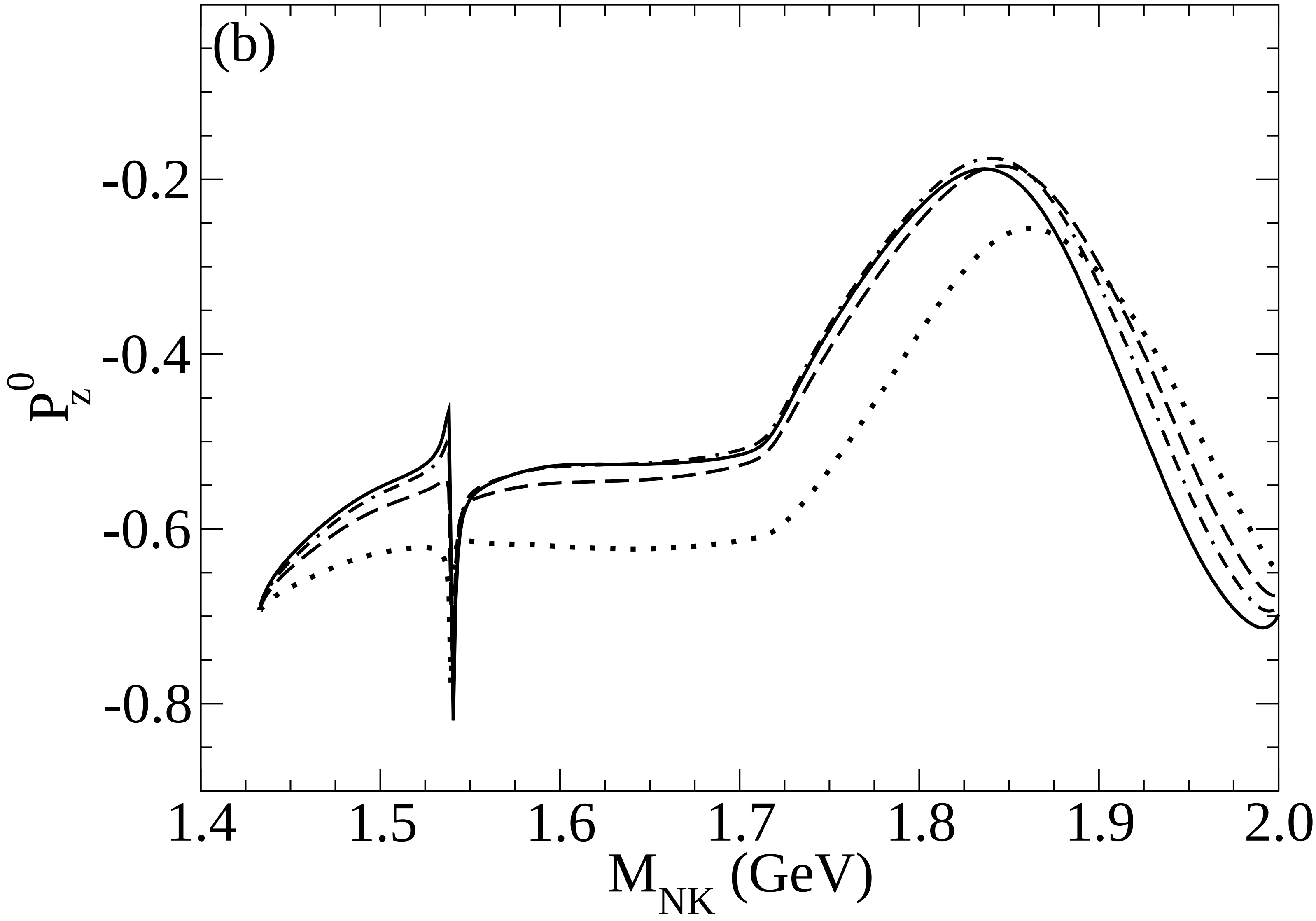

(a)
P_x^0
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
1.4
1.5
1.6
1.7
1.8
1.9
2.0
M_{NK} (GeV)
$\Phi^* = 30$
$\Phi^* = 45$
$\Phi^* = 60$
$\Phi^* = 90$



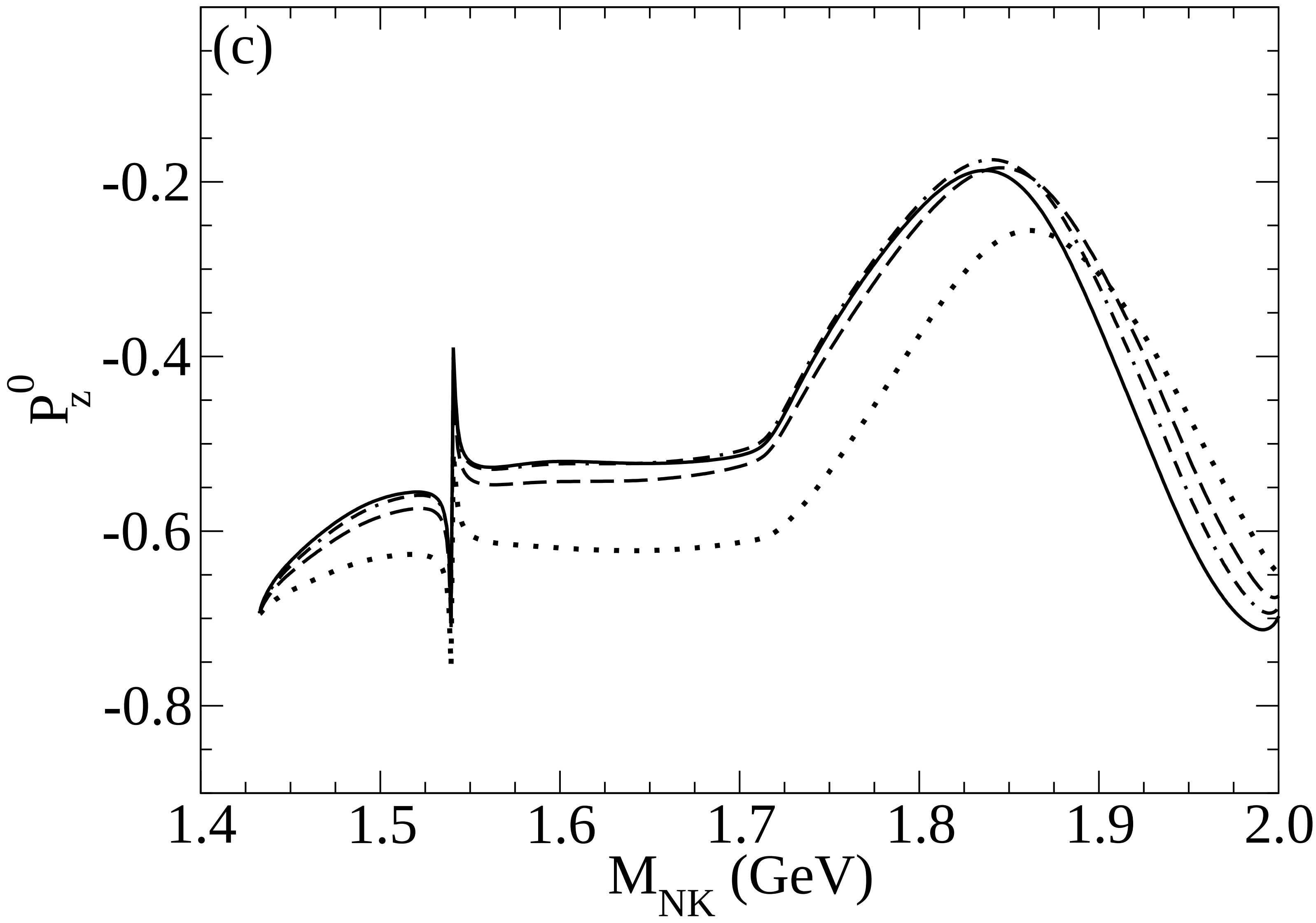
(b)
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
P_x^0
1.4
1.5
1.6
1.7
1.8
1.9
2.0
M_{NK} (GeV)

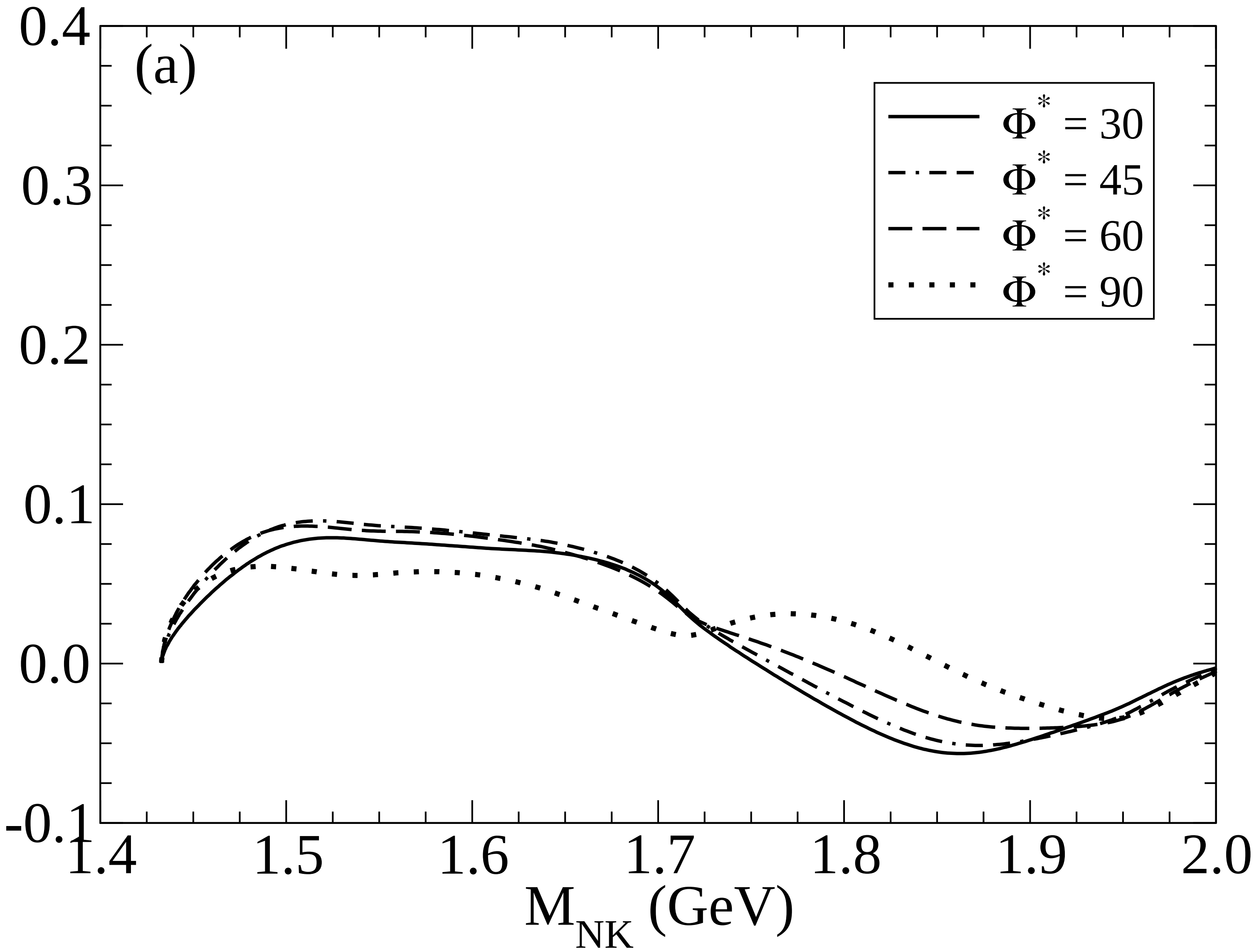

(c)
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
P_x^0
1.4
1.5
1.6
1.7
1.8
1.9
2.0
M_{NK} (GeV)


(a)
Φ* = 30
Φ* = 45
Φ* = 60
Φ* = 90
-0.2
-0.4
-0.6
-0.8
P_z^0
1.4
1.5
1.6
1.7
1.8
1.9
2.0
M_{NK} (GeV)

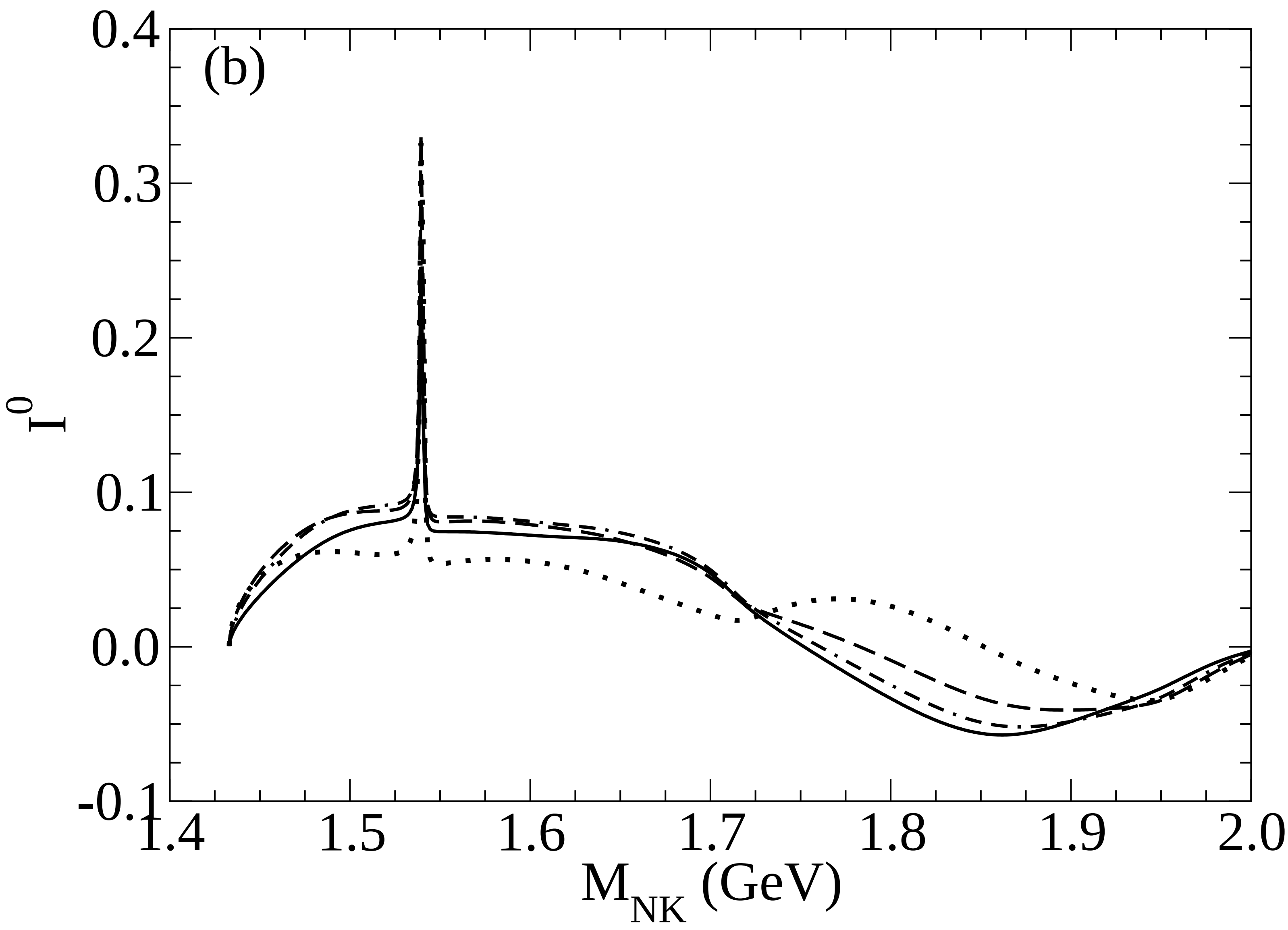


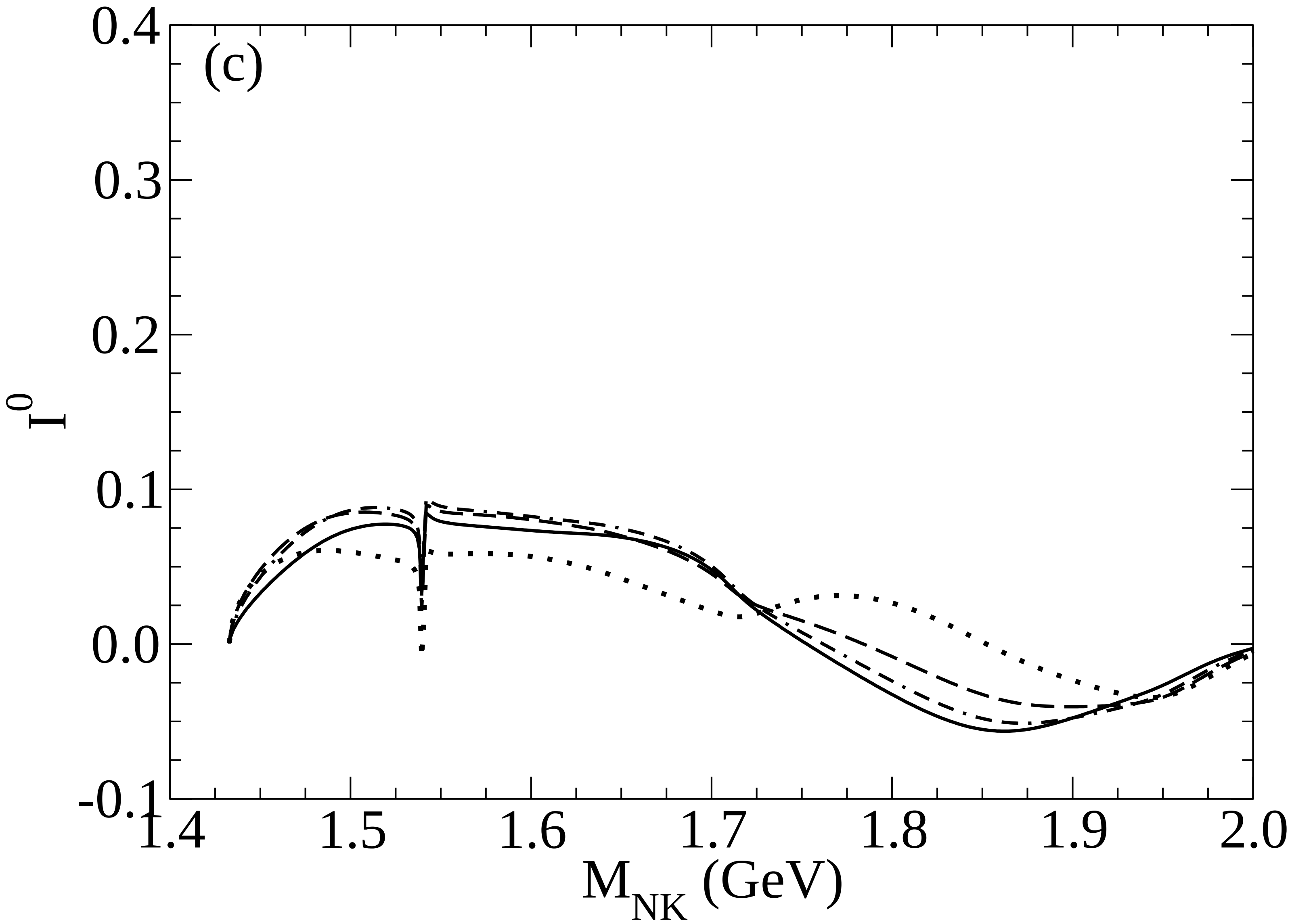
(b)
-0.2
-0.4
-0.6
-0.8
P_z^0
1.4
1.5
1.6
1.7
1.8
1.9
2.0
M_{NK} (GeV)


(c)
-0.2
-0.4
-0.6
-0.8
P_z^0
1.4
1.5
1.6
1.7
1.8
1.9
2.0
M_{NK} (GeV)



(a)
$\Phi^* = 30$
$\Phi^* = 45$
$\Phi^* = 60$
$\Phi^* = 90$
I^0
0.4
0.3
0.2
0.1
0.0
-0.1
1.4
1.5
1.6
1.7
1.8
1.9
2.0
M_{NK} (GeV)


(b)
0.4
0.3
0.2
0.1
0.0
-0.1
I0
1.4
1.5
1.6
1.7
1.8
1.9
2.0
MNK (GeV)


(c)
0.4
0.3
0.2
0.1
0.0
-0.1
I^0
1.4
1.5
1.6
1.7
1.8
1.9
2.0
M_{NK} (GeV)

Conclusions

Polarization observables are essential for extracting amplitudes of processes like $\gamma N \to N\pi$ and $\gamma N \to N\pi\pi$.

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- Polarization observables are essential for extracting amplitudes of processes like $\gamma N \to N\pi$ and $\gamma N \to N\pi\pi$.
- Such observables are very sensitive to underlying dynamics.
- Single, double and triple polarization measurements, along with the measurements using both circularly and linearly polarized photons, are needed to 'unambiguously' extract amplitudes
- Facilities are poised to make a number of measurements that will challenge (existing and future) models of such processes.