Pomeron Odderon interference in production of $\pi^+ - \pi^-$ pairs at LHC [Phys.Rev.D78:094009]

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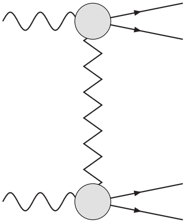
Motivation

- colorless gluonic exchange
  - $C = +1$: $\mathbb{P}$omeron, in pQCD described by BFKL equation
  - $C = -1$: $\mathbb{O}$dderon, in pQCD described by BJKP equation
- best but still weak evidence for $\mathbb{O}$: pp and $p\bar{p}$ data at ISR
- no evidence for perturbative $\mathbb{O}$
- $\mathbb{O}$ exchange much weaker than $\mathbb{P}$ $\Rightarrow$ two strategies in QCD
  - consider processes, where $\mathbb{P}$ vanishes due to C-parity conservation:
    exclusive $\eta, \eta_c, f_2, a_2, \ldots$ in ep; $\gamma\gamma \to \eta_c\eta_c \sim |\mathcal{M}_{\mathbb{O}}|^2$
    exclusive $J/\Psi, \Upsilon$ in pp ($\mathbb{P}\mathbb{O}$ fusion, not $\mathbb{P}\mathbb{P}$))
  - consider observables sensitive to the interference between $\mathbb{P}$ and $\mathbb{O}$ [first proposed by Brodsky, Rathsman, Merino 1999]
    $\sim \mathrm{Re}\, \mathcal{M}_{\mathbb{P}} \mathcal{M}_{\mathbb{O}}^*$
- $\mathbb{P}/\mathbb{O}$ coupling to proton not perturbatively calculable $\Rightarrow$ $\gamma^{(*)}\gamma^{(*)}$ collisions: hard process

The Process



- exclusive production of two $\pi^+\pi^-$ pairs $\longrightarrow$ colorless exchange between them
- C-parity of $\pi^+\pi^-$ pair not fixed

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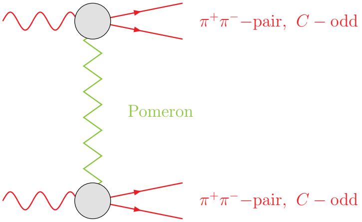

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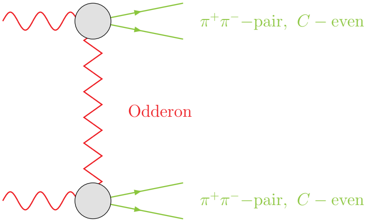

- exclusive production of two $\pi^+\pi^-$ pairs $\longrightarrow$ colorless exchange between them
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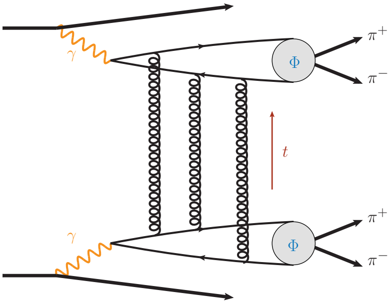
Kinematics, Framework



- Bremsstrahlung: photon virtuality $Q^2 \approx 0$, flux by Weizsäcker-Williams
- perturbative Regge limit: $s_{\gamma\gamma} \gg |t| \gg \Lambda^2_{\rm QCD}$
- photon Impact Factor known (in contrast to hadron IF)
- model $\mathbb{P}$ ($\mathbb{O}$) by 2 (3) gluons
- collinear approximation: $-t \gg m^2_{2\pi}$ $\rightarrow 2\pi$ GDA Φ: variables
  - quark momentum fraction z
  - polar angle θ in rest frame of 2π
  - invariant mass $m_{2\pi}$

Matrix Element

$\mathbb{P}$ exchange in $\gamma\gamma \to (\pi^+\pi^-)(\pi^+\pi^-)$:

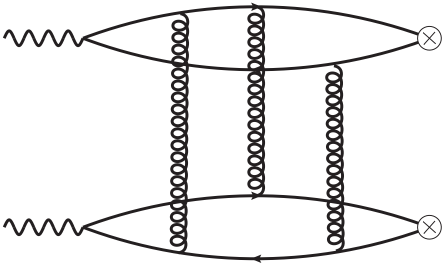
$$\mathcal{M}_{\mathbb{P}} \sim s \int \frac{d^2\vec{k}_1 \; d^2\vec{k}_2 \; \delta^{(2)}(\vec{k}_1 + \vec{k}_2 - \vec{p}_{2\pi})}{(2\pi)^2 \, \vec{k}_1^2 \, \vec{k}_2^2}$$

$$\times \left[\int_0^1 dz \, (z - \bar{z}) \, \vec{\varepsilon} \cdot \vec{Q}_{\mathbb{P}}(\vec{k}_1, \vec{k}_2) \; \Phi^{l=1}(z, \theta, m_{2\pi}^2) \right]$$

$$\times \left[\int_0^1 dz' \, (z' - \bar{z}') \, \vec{\varepsilon}' \cdot \vec{Q}'_{\mathbb{P}}(\vec{k}_1, \vec{k}_2) \; \Phi^{l=1}(z', \theta', m'^2_{2\pi}) \right]$$

Hard Matrix Element

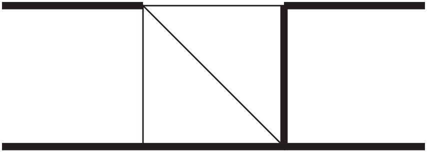
for Odderon: $2 \longrightarrow 2$ with four loops



in the high energy limit $(s_{\gamma\gamma} \gg |t|)$ ...

Hard Matrix Element

... most complicated diagram corresponds to



where all legs have different off-shellness + two parameter integrations: unknown analytically
(conformal tricks [Broadhurst 93', Pire, Szymanowski, S.W. 05', Pire, Segond, Szymanowski, S.W. 07'] usefull for $\mathbb{P}$ but not applicable for $\mathbb{O}$
$\Rightarrow$ use MC integration (CUBA-library [Hahn 2005] provides **Vegas**, Suave, Cuhre, Divonne)

Hard Matrix Element

typical integral for Odderon exchange:

$$\int_0^1 dz \int_0^1 du\, z(1-z)(1-2z)^2 u(1-u)(1-2u)^2$$

$$\times \int d^2 k_1 \int d^2 k_2 \, \frac{1}{\vec{k}_1^2 \vec{k}_2^2 \vec{k}_3^2} \frac{\left((\vec{k}_1 - z\vec{p}_{2\pi})\vec{\epsilon}_z\right)\left((\vec{k}_2 - u\vec{p}_{2\pi})\vec{\epsilon}_u\right)}{\left((\vec{k}_1 - z\vec{p}_{2\pi})^2 + \mu_1^2\right)\left((\vec{k}_2 - u\vec{p}_{2\pi})^2 + \mu_2^2\right)}$$

[z (u): longitudinal momentum fraction of quark of upper (lower) system, $k_{1,2,3}$: t-channel gluons, $\mu_1^2 = m_q^2 + z(1-z)Q^2$, $\vec{\epsilon}_{z,u}$: photon polarization vector]

Observables

θ dependence of 2π GDA:

- $\mathbb{P}$ exchange $\rightarrow$ C odd 2π system $\rightarrow$ $\Phi^{I=1} \sim \cos\theta + \ldots$
- $\mathbb{O}$ exchange $\rightarrow$ C even 2π system $\rightarrow$ $\Phi^{I=0} \sim c_0 + c_2 \cos(2\theta) + \ldots$

$$\int d\sigma(s, t, m_{2\pi}, m'_{2\pi}, \theta, \theta') \sim |\mathcal{M}_{\mathbb{P}}|^2 + |\mathcal{M}_{\mathbb{O}}|^2$$

Observables

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- $\mathbb{P}$ exchange $\longrightarrow$ C odd 2π system $\longrightarrow$ $\Phi^{I=1} \sim \cos\theta + \ldots$
- $\mathbb{O}$ exchange $\longrightarrow$ C even 2π system $\longrightarrow$ $\Phi^{I=0} \sim c_0 + c_2 \cos(2\theta) + \ldots$

$\Rightarrow$ consider double asymmetry:

$$\frac{\int \cos\theta \, \cos\theta' \, d\sigma(s,t,m_{2\pi},m'_{2\pi},\theta,\theta')}{\int d\sigma(s,t,m_{2\pi},m'_{2\pi},\theta,\theta')} \sim \frac{|\mathcal{M}_{\mathbb{O}} \, \mathcal{M}_{\mathbb{P}}|}{|\mathcal{M}_{\mathbb{P}}|^2 + |\mathcal{M}_{\mathbb{O}}|^2}$$

2π Distribution Amplitude

no experimental data on 2π GDA

starting point:

- expand GDA in Gegenbauer polynomials $C_n^{3/2}(2\,z-1)$ (diagonalize QCD ERBL evolution kernel)

  and Legendre polynomials $P_l(\beta\cos\theta)$, where $\beta = \sqrt{1-\frac{4m_\pi^2}{m_{2\pi}^2}}$

  $\zeta = \frac{1+\beta\cos\theta}{2}$=fraction of long. momenta $p_{2\pi}$ carried by π^+

- keep dominant contributions

2π Distribution Amplitude - isovector

Isovector case given by electromagnetic pion form factor

$$\Phi^{I=1}(z,\theta,m_{2\pi}) = 6z(1-z)\beta\cos\theta\, F_\pi(m_{2\pi}^2),$$

- modulus of F_π well measured in $e^+e^- \to \pi^+\pi^-$

2π Distribution Amplitude - isoscalar - ansatz I

For isoscalar case we use three ansätze - ansatz I:

- use phase shifts from elastic $\pi\pi$ scattering, moduli given by f_0 and f_2 resonance
  [Hägler, Pire, Szymanowski, Teryaev 2002]

$$\Phi^{I=0}(z,\theta,m_{2\pi}) = 5z(1-z)(2z-1)$$
$$\times\left(-\frac{3-\beta^2}{2}e^{i\delta_0(m_{2\pi})}\left|BW_{f_0}(m_{2\pi}^2)\right| + \beta^2 e^{i\delta_2(m_{2\pi})}\left|BW_{f_2}(m_{2\pi}^2)\right| P_2(\cos\theta)\right)$$

[BW: Breit-Wigner amplitude, P_2: Legendre polynomial, δ_l phase shifts from elastic $\pi\pi$ scattering (experiment)]

2π Distribution Amplitude - isoscalar - ansatz II

For isoscalar case we use three ansätze - ansatz II:

- use phase shifts from elastic $\pi\pi$ scattering, moduli given by Omnès function

$$\Phi^{I=0}(z,\theta,m_{2\pi}) = 5z(1-z)(2z-1)$$
$$\times\left(-\frac{3-\beta^2}{2}e^{i\delta_0(m_{2\pi})}f_0(m_{2\pi}^2)+\beta^2 e^{i\delta_2(m_{2\pi})}f_2(m_{2\pi}^2)P_2(\cos\theta)\right)$$

where

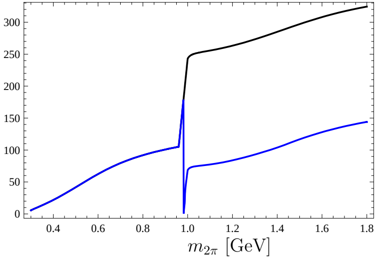
$$f_l(m_{2\pi}^2) = \exp\left(\pi I_l + \frac{m_{2\pi}^2}{\pi}\int_{4m_\pi^2}^{s_{\max}} ds\,\frac{\delta_l(s)}{s^2(s-m_{2\pi}^2-i\epsilon)}\right)$$
$$I_l = \frac{1}{\pi}\int_{4m_\pi^2}^{s_{\max}} ds\,\frac{\delta_l(s)}{s^2}$$

2π Distribution Amplitude - isoscalar - ansatz III

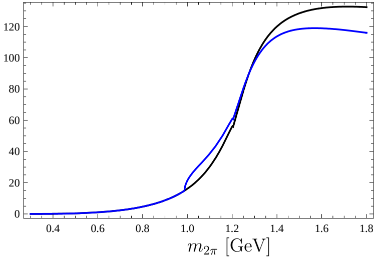
For isoscalar case we use three ansätze - ansatz III:

- like ansatz II but phase shift $\delta_{T,l}$ from $\mathcal{T}$-matrix $\frac{\eta_l e^{2i\delta_l}-1}{2i}$ [Warkentin, Diehl, Ivanov, Schäfer 2007]
- motivation: phase of form factor $\Gamma(s) = \langle\pi\pi|m_u\bar{u}u + m_d\bar{d}d|0\rangle$ follows above $K\bar{K}$ threshold rather $\delta_{T,l}$ than δ_l [Ananthanarayan et.al. 2004]

δ_0 and $\delta_{T,0}$



δ_2 and $\delta_{T,2}$



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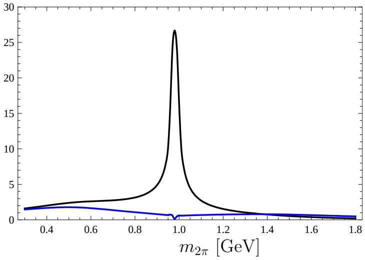
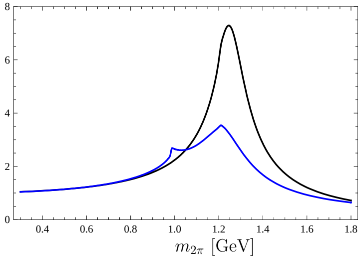
$|f_0|$ from δ_0 and $\delta_{T,0}$



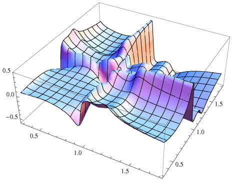
$|f_2|$ from δ_2 and $\delta_{T,2}$



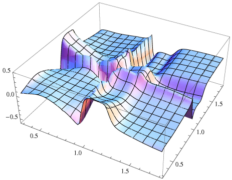
Double Differential

at given t asymmetry depends on $m_{2\pi}$ of both 2π systems

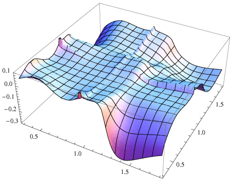
ansatz I



ansatz II



ansatz III



double differential cross section hard to measure . . .

Definition Single Differential

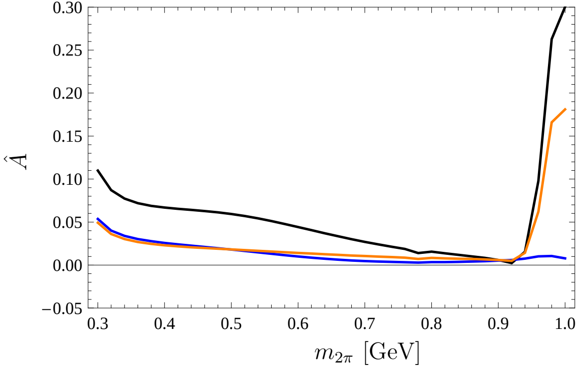
…integrate asymmetry for one $\pi^+\pi^-$ pair

$$\hat{A}(m_{2\pi}, t) \equiv \frac{\int_{m^2_{\min}}^{m^2_{\max}} d\,m'^2_{2\pi} \int d\cos\theta \, d\cos\theta' \; |\mathcal{M}|^2 \cos\theta \; \cos\theta'}{\int_{m^2_{\min}}^{m^2_{\max}} d\,m'^2_{2\pi} \int d\cos\theta \, d\cos\theta' \; |\mathcal{M}|^2}$$

Single Differential at $t = -1\mathrm{GeV}^2$

To get single differential observable: integrate asymmetry for one $\pi^+\pi^-$ pair from .3 GeV to m_ρ=776 MeV

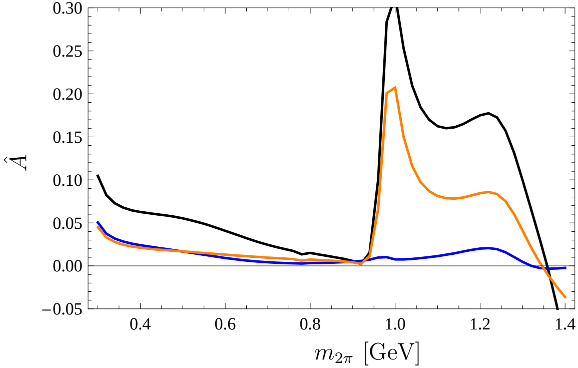
ansatz I, ansatz II, ansatz III



Single Differential at $t = -2\mathrm{GeV}^2$

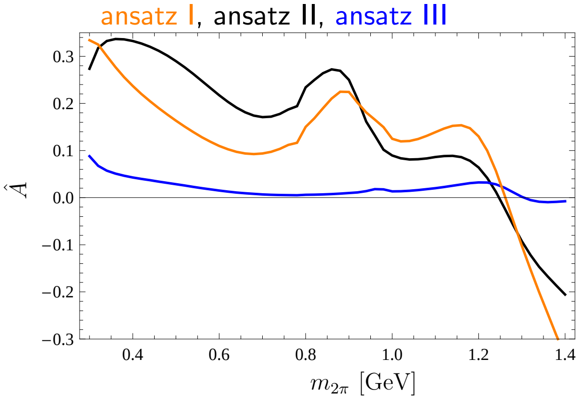
Integrate asymmetry for one $\pi^+\pi^-$ pair from .3 GeV to m_ρ=776 MeV

ansatz I, ansatz II, ansatz III



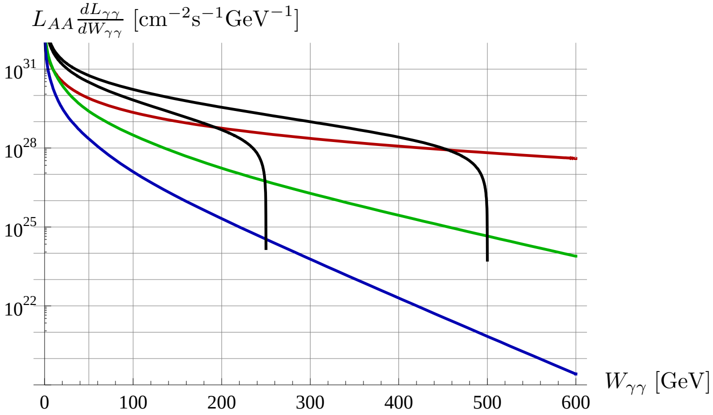
Single Differential at $t = -2\text{GeV}^2$

Integrate asymmetry for one $\pi^+\pi^-$ pair from m_{f_0} to $m_{\max}$=1400 MeV



Effective Luminosities

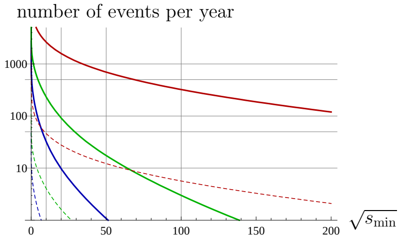
ee at ILC, pp at LHC, ArAR at LHC, PbPb at LHC



Rates at LHC

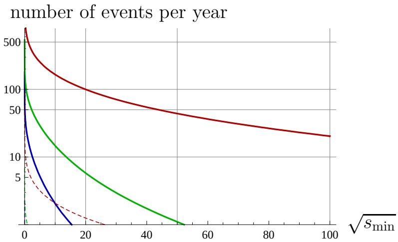
Rates at LHC per year: PbPb (1 month), ArAr (1 month), pp (6 months) after $\int_{s_{\min}} ds_{\gamma\gamma} \int^{t_{\min}} dt$

$t = -1$ GeV



dotted: just Odderon exchange

$t = -2$ GeV

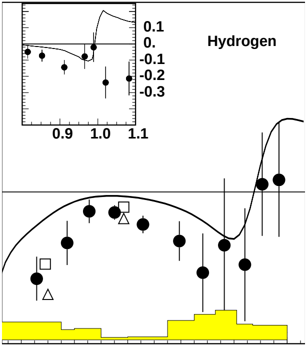


Summary and Outlook

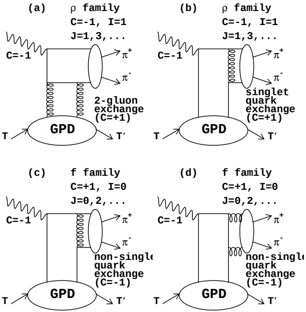
- asymmetry in $\gamma\gamma \to \pi^+\pi^-\pi^+\pi^-$: a promising candidate to find perturbative Odderon in ultraperipheral events
- only soft input: need for 2π-GDA from experiment
  very recent results from CLAS @ JLab: $f_0(980)$ seen $\Rightarrow$ scenarii I or II favored, and thus high asymetry expected
- background: $\mathbb{P} - \gamma$ and $\mathbb{P} - \mathbb{P}$ peripheral events
  - selection easier in heavy ion mode (detection of neutrons produced by giant dipole resonance), but low cross-section
  - Coulomb pole at $t = 0$ for $\gamma - \gamma$ mode $\to$ cut in p_t of $\pi^+\pi^-$ pairs to separate peripheral and ultraperipheral events (but smearing due to beam size +initial running condition: see Piotrzkowski)
- might be very hard to do at LHC:
  - pile-up in the high luminosity mode
  - tagging on $\pi^\pm$ of low $p_t \sim 1 - 2GeV$ very difficult
- life easier at ILC!

f_0

asymmetry in $\pi^+\pi^-$ production in *ep* scattering [HERMES 2004]



- big: calculation without f_0 [Lehmann-Dronke et.al. 2000,2001]
- inset: calculation with f_0 [Hägler et.al. 2002]



Operator Definition of GDA

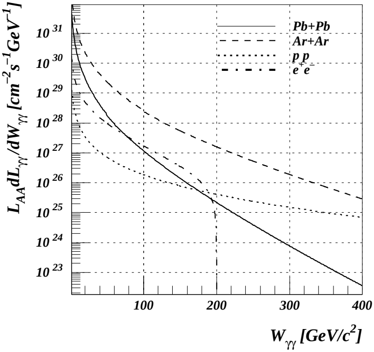
$$\Phi(z, \zeta, m_{2\pi}^2) = \int \frac{d\lambda}{2\pi} e^{-iz\lambda(q'n)} \langle \pi^+(k)\pi^-(k')|\bar{q}(\lambda n)\not{n} q(0)|0\rangle$$

with $2\zeta - 1 = \beta \cos\theta$, n: lightlike auxiliary vector, $q' = k + k'$

effective photon flux in the literature

Most recent report on UPC: K. Hencken *et al.*, Phys. Rept. **458** (2008) 1: pp with $L = 10^7\,\mathrm{mb}^{-1}\mathrm{s}^{-1}$ and $\sqrt{s} = 14000\,\mathrm{GeV}$

Hencken et.al.



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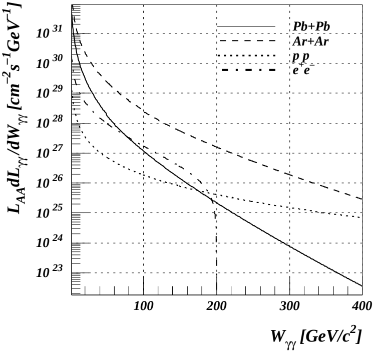
Baur et.al.



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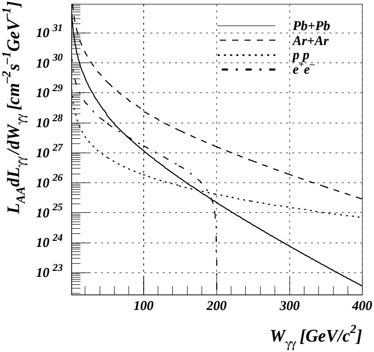
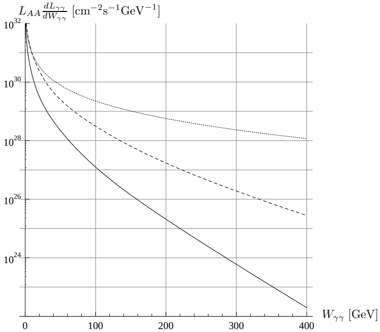
Baur et.al.

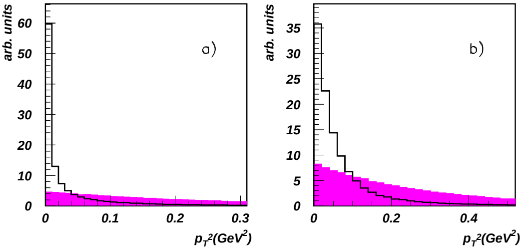


with design Lumi for all



Tagging the two photon production

[Piotrzkowski: Phys. Rev. D (2001) 63, 071502]



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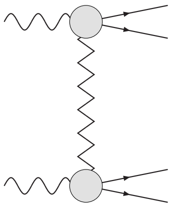

- exclusive production of two $\pi^+\pi^-$ pairs $\rightarrow$ colorless exchange between them
- C-parity of $\pi^+\pi^-$ pair not fixed
  - $\pi^+\pi^-$ pair C odd $\Rightarrow$ $\mathbb{P}$omeron
  - $\pi^+\pi^-$ pair C even $\Rightarrow$ $\mathbb{O}$dderon
- 2π GDA depends on polar angle θ in rest frame of 2π

$$\frac{\int \cos\theta_1 \ \cos\theta_2 \, d\sigma(s,t,m_{2\pi,1},m_{2\pi,1},\theta_1,\theta_2)}{\int d\sigma(s,t,m_{2\pi,1},m_{2\pi,1},\theta_1,\theta_2)} \sim \frac{|\mathcal{M}_{\mathbb{O}}\mathcal{M}_{\mathbb{P}}|}{|\mathcal{M}_{\mathbb{P}}|^2+|\mathcal{M}_{\mathbb{O}}|^2}$$

Single Differential at $t = -2\text{GeV}^2$

Integrate asymmetry for one $\pi^+\pi^-$ pair from .3GeV to m_ρ=776MeV

ansatz I, ansatz II, ansatz III for isoscalar GDA