# Diffractive mechanisms in $pp \longrightarrow pp\pi^0$ reaction at high energies

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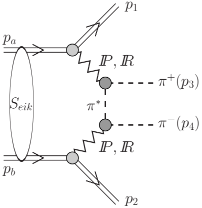
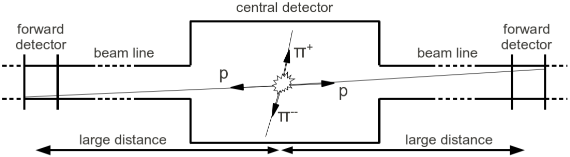
based on paper:

P. Lebiedowicz and A. Szczurek, *Exclusive $pp \to pp\pi^0$ reaction at high energies*, arXiv:1303.2882, in print in Phys. Rev. D

# Introduction

- $pp \to p\,\pi^+\pi^-\,p$ [a,b] and $pp \to p\,K^+K^-\,p$ [c] processes constitutes an irreducible background to $pp \to p\,M\,p$ processes, where *e.g.* $M = \sigma, f_0(980), f_2(1270), f_0(1500), f_2'(1525), \chi_{c0}$, glueball




[a] P. L. and A. Szczurek, Phys. Rev. D81 (2010) 036003
[b] R. Staszewski, P. L., M. Trzebiński, J. Chwastowski, A. Szczurek, Acta Phys. Pol. B42 (2011) 1861
[c] P. L. and A. Szczurek, Phys. Rev. D85 (2012) 014026

K. Goulianos, *New results on diffractive and exclusive production from CDF*, DIS2013

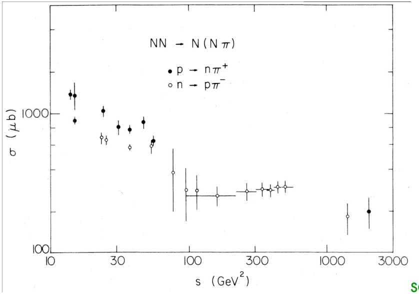
- $pp \to nn\,\pi^+\pi^+$

  P. L. and A. Szczurek, Phys. Rev. D83 (2011) 076002

# Introduction

$pp \to p(n\pi^+)$ and $pn \to p(p\pi^-)$ reactions was measured at CERN ISR and Fermilab

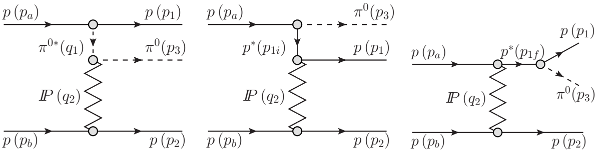
- slowly energy dependent total cross sections




see G. Alberi and G. Goggi, Phys. Rep. 74 (1981) 1

- invariant mass distributions peaked close to threshold
- sharp exponential peak in $d\sigma/dt$
- slope of differential cross section showing a strong dependence on the mass of the excited system
- nucleon resonance production

# $pp \to pp\pi^0$, diffractive bremsstrahlung mechanisms




$$
\begin{aligned}
\mathcal{M}^{(\pi-\text{exchange})}_{\lambda_a\lambda_b\to\lambda_1\lambda_2\pi^0} &= \bar{u}(p_1,\lambda_1)\, i\gamma_5 u(p_a,\lambda_a)\, S_\pi(t_1)\, g_{\pi NN}\, F_{\pi^* NN}(t_1) F_{I\!P\pi^*\pi}(t_1) \\
&\times \left(A^{\pi N}_{I\!P}(s_{23},t_2) + A^{\pi N}_{I\!R}(s_{23},t_2)\right)/(2s_{23}) \\
&\times (q_1+p_3)_\mu\, \bar{u}(p_2,\lambda_2)\gamma^\mu u(p_b,\lambda_b)
\end{aligned}
$$

$$
\begin{aligned}
\mathcal{M}^{(p-\text{exchange})}_{\lambda_a\lambda_b\to\lambda_1\lambda_2\pi^0} &= g_{\pi NN}\, \bar{u}(p_1,\lambda_1)\gamma^\mu S_N(p_{1i}^2) i\gamma_5 u(p_a,\lambda_a)\, F_{\pi NN^*}(p_{1i}^2)\, F_{I\!PN^*N}(p_{1i}^2)\, \mathcal{F}_{N^*}(s_{13},t_1) \\
&\times \left(A^{NN}_{I\!P}(s_{12},t_2) + A^{NN}_{I\!R}(s_{12},t_2)\right)/(2s_{12}) \\
&\times \bar{u}(p_2,\lambda_2)\gamma_\mu u(p_b,\lambda_b)
\end{aligned}
$$

$$
\begin{aligned}
\mathcal{M}^{(\text{direct production})}_{\lambda_a\lambda_b\to\lambda_1\lambda_2\pi^0} &= g_{\pi NN}\, \bar{u}(p_1,\lambda_1) i\gamma_5 S_N(p_{1f}^2)\gamma^\mu u(p_a,\lambda_a)\, F_{\pi N^* N}(p_{1f}^2)\, F_{I\!PNN^*}(p_{1f}^2) \\
&\times \left(A^{NN}_{I\!P}(s,t_2) + A^{NN}_{I\!R}(s,t_2)\right)/(2s) \\
&\times \bar{u}(p_2,\lambda_2)\gamma_\mu u(p_b,\lambda_b)
\end{aligned}
$$

**Drell-Hiida-Deck model**

see $pp \to pp\omega$ [a] and $pp \to pp\gamma$ [b] processes

[a] A. Cisek, P. L., W. Schäfer and A. Szczurek, Phys. Rev. D83 (2011) 114004

[b] P. L. and A. Szczurek, arXiv:1302.4346, see Szczurek talk @ DIS2013

# $pp \to pp\pi^0$, diffractive bremsstrahlung mechanisms

- The energy dependence of the elastic scattering $A(s,t)$ was parametrized in the Regge-like form with pomeron ($i = \mathbb{P}$) and reggeon ($i = \mathbb{R}$ = $f_2, \rho, a_2, \omega$) exchanges

$$A_i^{el}(s,t) = \eta_i \, C_i \, s \left(\frac{s}{s_0}\right)^{\alpha_i(t)-1} \exp\left(\frac{B_i^{el} t}{2}\right)$$

  the effective slope of the elastic differential cross section $B(s) = B_i^{el} + 2\alpha_i' \ln(s/s_0)$
  where we use the scale parameter $s_0 = 1$ GeV$^2$
  $B_{\mathbb{P}}^{NN} = 9$ GeV$^{-2}$, $B_{\mathbb{P}}^{\pi N} = 5.5$ GeV$^{-2}$, $B_{\mathbb{R}}^{NN} = 6$ GeV$^{-2}$, $B_{\mathbb{R}}^{\pi N} = 4$ GeV$^{-2}$
  $C_i$, $\eta_i$ and $\alpha_i(t) = \alpha_i(0) + \alpha_i' \, t$ from Donnachie-Landshoff analysis of the total $NN$ and $\pi N$ cross sections and the optical theorem $\sigma^{tot}(s) \cong 1/s \, \mathrm{Im} A^{el}(s, t=0)$
  see P. L. and A. Szczurek, Phys. Rev. D81 (2010) 036003

- off-shell nucleon

$$F(p^2) = \frac{\Lambda_N^4}{(p^2 - m_p^2)^2 + \Lambda_N^4}$$

  off-shell pion

$$F(t) = \exp\left(\frac{t - m_\pi^2}{\Lambda_\pi^2}\right)$$

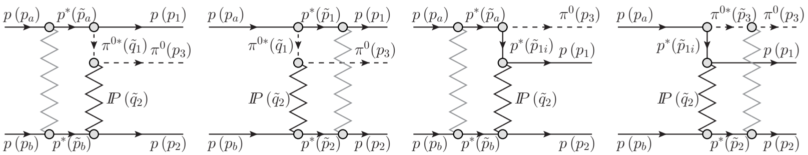
- We use a generalized pion propagator

$$S_\pi(t) \to \beta_M(s) S_\pi(t) + \beta_R(s) \mathcal{P}^\pi(t,s)$$

  where the pion Regge propagator gives a suppression for large values of $t$

$$\mathcal{P}^\pi(t,s) = \frac{\pi \alpha_\pi'}{2\Gamma(\alpha_\pi(t)+1)} \, \frac{1 + \exp(-i\pi\alpha_\pi(t))}{\sin(\pi\alpha_\pi(t))} \left(\frac{s}{s_0}\right)^{\alpha_\pi(t)}$$

- We improve the $\rho$-exchange amplitude to reproduce the high-energy Regge dependence: $\mathcal{F}_{N^*}(s_{13}, t_1)$




$$\mathcal{M}_{\rm abs}(-\boldsymbol{p}_{1\perp},-\boldsymbol{p}_{2\perp}) = \mathcal{M}(-\boldsymbol{p}_{1\perp},-\boldsymbol{p}_{2\perp}) - \delta\mathcal{M}(-\boldsymbol{p}_{1\perp},-\boldsymbol{p}_{2\perp})$$

$\delta\mathcal{M}$ for the diagrams with "initial-state" absorption is the sum of convolution integral

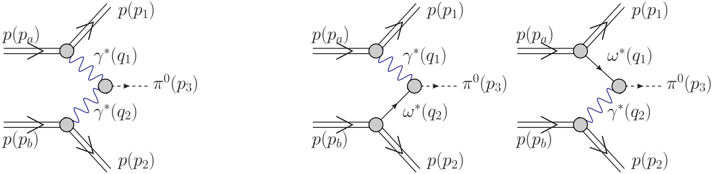
$$\delta\mathcal{M}^{\rm initial\,state\,abs}_{\lambda_a\lambda_b\to\lambda_1\lambda_2\pi^0}(-\boldsymbol{p}_{1\perp},-\boldsymbol{p}_{2\perp}) = \frac{i}{8\pi^2 s}\int d^2k_\perp\, A^{NN}_{\lambda_a\lambda_b\to\lambda'_a\lambda'_b}(s,\boldsymbol{k}_\perp)\left[\mathcal{M}^{(\pi-{\rm exchange})}_{\lambda'_a\lambda'_b\to\lambda_1\lambda_2\pi^0}(-\tilde{\boldsymbol{p}}_{1\perp},-\tilde{\boldsymbol{p}}_{2\perp}) + \mathcal{M}^{(p-{\rm exchange})}_{\lambda'_a\lambda'_b\to\lambda_1\lambda_2\pi^0}(-\tilde{\boldsymbol{p}}_{1\perp},-\tilde{\boldsymbol{p}}_{2\perp})\right]$$

and in the case of diagrams with "final-state" absorption we have

$$\begin{aligned}\delta\mathcal{M}^{\rm final\,state\,abs}_{\lambda_a\lambda_b\to\lambda_1\lambda_2\pi^0}(-\boldsymbol{p}_{1\perp},-\boldsymbol{p}_{2\perp}) \quad = \quad & \frac{i}{8\pi^2}\int d^2k_\perp \frac{1}{s_{12}}\mathcal{M}^{(\pi-{\rm exchange})}_{\lambda_a\lambda_b\to\lambda'_1\lambda'_2\pi^0}(-\tilde{\boldsymbol{p}}_{1\perp},-\tilde{\boldsymbol{p}}_{2\perp})\, A^{NN}_{\lambda'_1\lambda'_2\to\lambda_1\lambda_2}(s_{12},\boldsymbol{k}_\perp)\\ & + \frac{i}{8\pi^2}\int d^2k_\perp \frac{1}{s_{23}}\mathcal{M}^{(p-{\rm exchange})}_{\lambda_a\lambda_b\to\lambda_1\lambda'_2\pi^0}(-\tilde{\boldsymbol{p}}_{1\perp},-\tilde{\boldsymbol{p}}_{2\perp})\, A^{\pi N}_{\lambda'_2\to\lambda_2}(s_{23},\boldsymbol{k}_\perp)\end{aligned}$$

where $-\tilde{\boldsymbol{p}}_{1\perp} = -\boldsymbol{p}_{1\perp} + \boldsymbol{k}_\perp$, $-\tilde{\boldsymbol{p}}_{2\perp} = -\boldsymbol{p}_{2\perp} - \boldsymbol{k}_\perp$ and $\boldsymbol{k}_\perp$ is the momentum transfer

# $pp \to pp\pi^0$, new mechanisms




$$
\begin{aligned}
\mathcal{M}^{\gamma\gamma-\text{exchange}}_{\lambda_a\lambda_b\to\lambda_1\lambda_2\pi^0} &= e\,\bar{u}(p_1,\lambda_1)\gamma^{\mu}u(p_a,\lambda_a)\,F_1(t_1) \\
&\times \frac{g_{\mu\mu'}}{t_1}\,(-i)\,e^2\,\epsilon^{\mu'\nu'\rho\sigma}\,q_{1,\rho}q_{2,\sigma}\,F_{\gamma^*\gamma^*\to\pi^0}(t_1,t_2)\,\frac{g_{\nu\nu'}}{t_2} \\
&\times e\,\bar{u}(p_2,\lambda_2)\gamma^{\nu}u(p_b,\lambda_b)\,F_1(t_2) \\
\mathcal{M}^{\gamma\omega-\text{exchange}}_{\lambda_a\lambda_b\to\lambda_1\lambda_2\pi^0} &= e\,\bar{u}(p_1,\lambda_1)\gamma^{\mu}u(p_a,\lambda_a)\,F_1(t_1) \\
&\times \frac{g_{\mu\mu'}}{t_1}\,(-i)\,g_{\gamma\omega\pi^0}\,\epsilon^{\mu'\nu'\rho\sigma}\,q_{1,\rho}q_{2,\sigma}\,F_{\gamma^*\omega^*\to\pi^0}(t_1,t_2)\,\frac{-g_{\nu\nu'}+q_{\nu}q_{\nu'}/m_{\omega}^2}{t_2-m_{\omega}^2} \\
&\times g_{\omega NN}\,\bar{u}(p_2,\lambda_2)\gamma^{\nu}u(p_b,\lambda_b)\,F_{\omega NN}(t_2)\,\mathcal{F}_{\omega}(s_{23},t_2)
\end{aligned}
$$

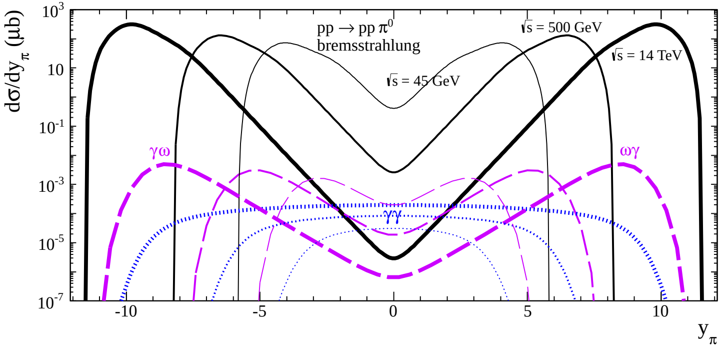
$\gamma^*\gamma^*\pi^0$ anomalous coupling, the strenght fixed from $\pi^0 \to \gamma\gamma$,
on-shell normalization $F_{\gamma^*\gamma^*\to\pi^0}(t_1,t_2) = \frac{N_c}{12\pi^2 f_\pi}(1-t_1/m_\rho^2)(1-t_2/m_\rho^2)$

strong coupling of omega to nucleon, $g^2_{\omega NN}/4\pi = 10$

$F_{\omega NN}(t) = \exp\left(\frac{t-m_\omega^2}{\Lambda^2_{\omega NN}}\right)$, $\Lambda_{\omega NN} = 1$ GeV and $g_{\omega\pi^0\gamma} \simeq 0.7\ \text{GeV}^{-1}$ obtained from the $\omega$ partial decay width

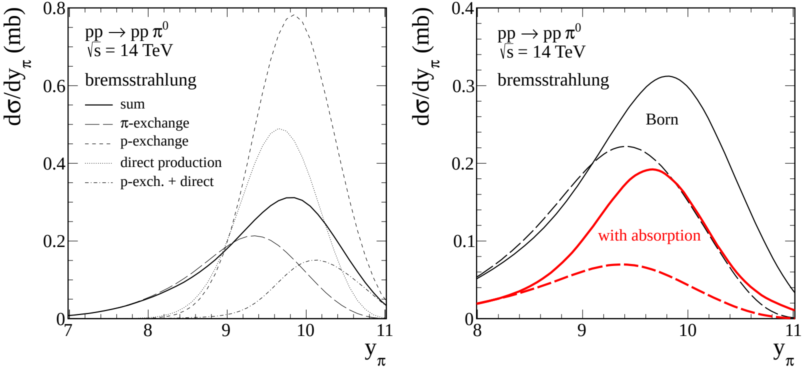
$F_{\gamma^*\omega^*\to\pi^0}(t_1,t_2) = \frac{m_\rho^2}{m_\rho^2-t_1}\exp\left(\frac{t_2-m_\omega^2}{\Lambda^2_{\omega\pi\gamma}}\right)$, $\Lambda_{\omega\pi\gamma} = 0.8$ GeV as found from the fit to the $\gamma p \to \omega p$ exp. data

# Rapidity distribution of $\pi^0$



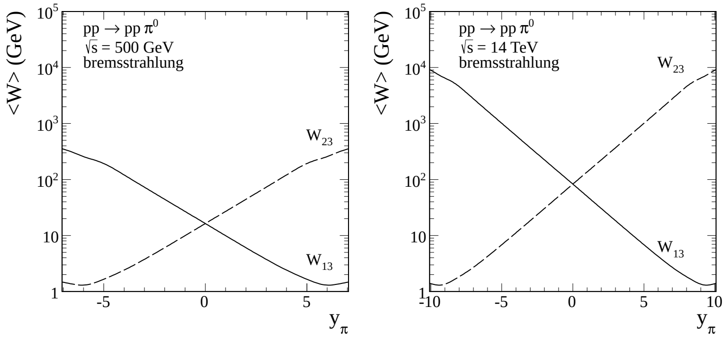

- $\pi^0$-**bremsstrahlung** contribution and $\omega\gamma$ $(\gamma\omega)$ exchanges peaks at forward (backward) region of rapidity, respectively
- $\gamma\gamma$ fusion contributes at midrapidity
- neutral pions could be measured by ZDC detector at $|\eta_{\pi^0}| > 8 - 9$
- $\omega\gamma$ $(\gamma\omega)$ exchanges are small at $y \sim 0$ due to $\omega$ reggezation
- we have used $\Lambda_N = \Lambda_\pi = 1$ GeV

# Rapidity distribution of $\pi^0$




- individual $\pi^0$-bremsstrahlung contributions to the Born cross section – large cancellation between initial ($p$-exchange) and final state radiation (direct production)
- absorption effects included
- uncertainties of form factors: solid lines ($\Lambda_N = \Lambda_\pi = 1$ GeV), dashed lines ($\Lambda_N = 0.6$ GeV and $\Lambda_\pi = 1$ GeV)

# $\langle W_{ij} \rangle \ (y_{\pi^0})$ distribution

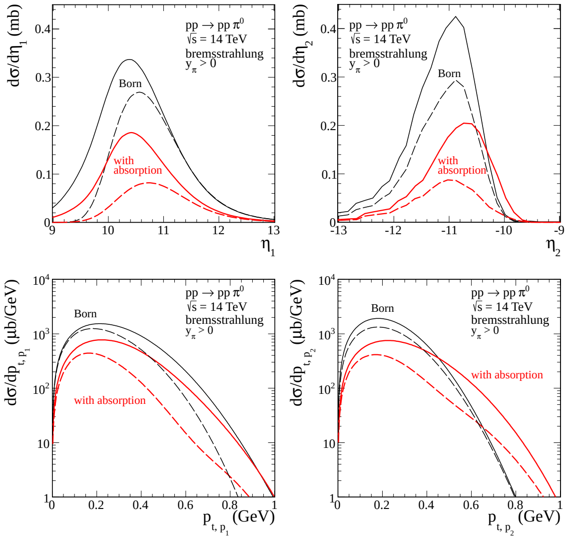



- diffractive excitation of nucleon resonances

  – when the energy in $\pi N$ subsystem $W_{ij} \in \mathrm{R}$ (the nucleon resonance domain)
- only some nucleon resonances can be excited diffractively

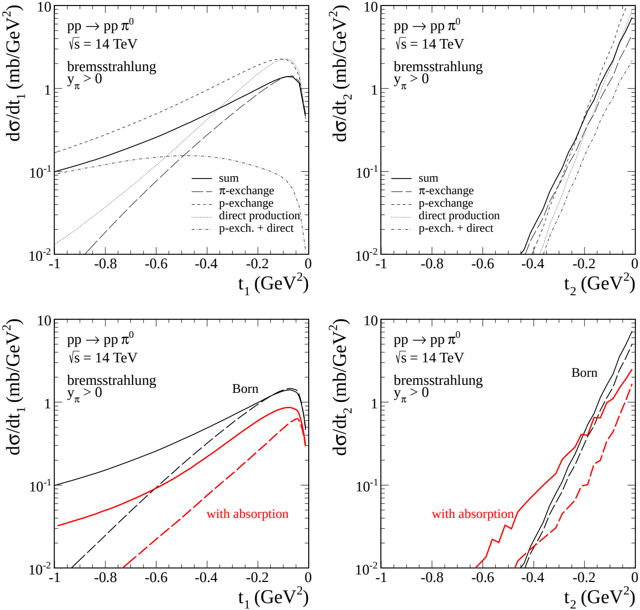
  see L. Jenkovszky, O. Kuprash, R. Orava and A. Salii, arXiv:1211.5841
- one way to introduce resonances in DHD model is to include them as intermediate states in the direct production

# $\eta_p$ and $p_{\perp,p}$ distributions for $y_{\pi^0} > 0$ at $\sqrt{s} = 14$ TeV

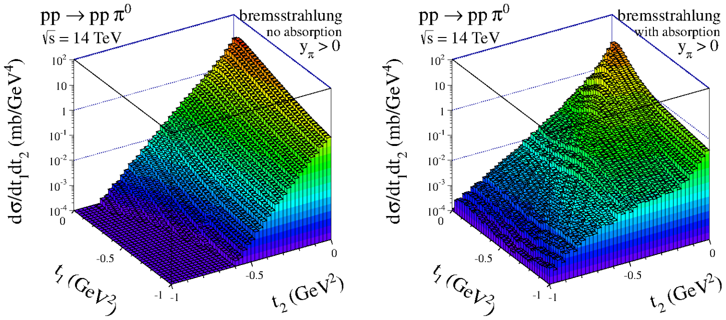



- protons could be measured by ALFA (ATLAS) or TOTEM (CMS) detectors
- absorption causes a transverse momentum dependent damping of the cross section at small $p_{\perp,p}$ and an enhancement at large $p_{\perp,p}$

# $t$ distribution for $y_{\pi^0} > 0$ at $\sqrt{s} = 14$ TeV

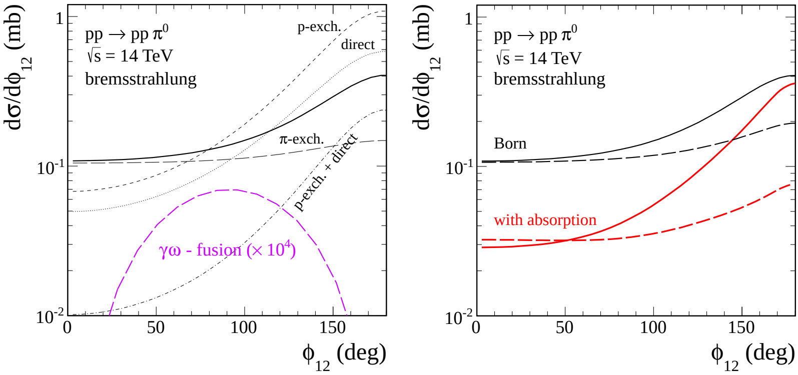


# $(t_1, t_2)$ distribution for $y_{\pi^0} > 0$ at $\sqrt{s} = 14$ TeV



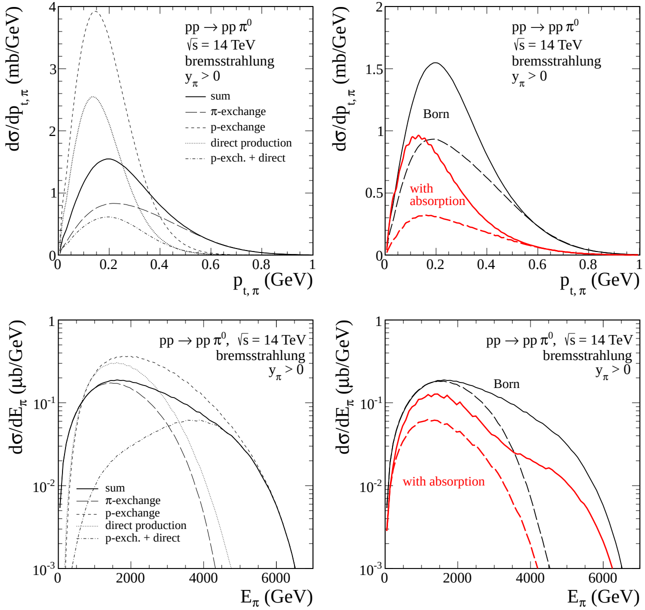

- distributions in $t_1$ or $t_2$ are different because we have limited to the case of $y_{\pi^0} > 0$

# Distribution in azimuthal angle between outgoing protons for $y_{\pi^0} > 0$ at $\sqrt{s} = 14$ TeV

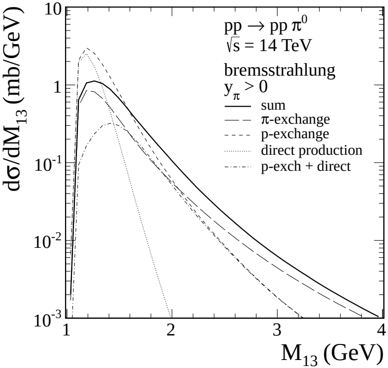


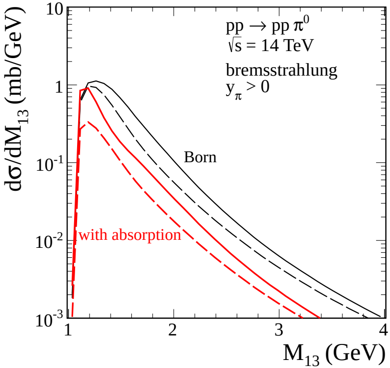

- $\pi^0$-bremsstrahlung contribution is peaked at back-to-back configuration ($\phi_{12} = \pi$)
- convenient way to fix relative contribution of different diagrams

# $p_{\perp,\pi^0}$ and $E_{\pi^0}$ distributions for $y_{\pi^0} > 0$ at $\sqrt{s} = 14$ TeV



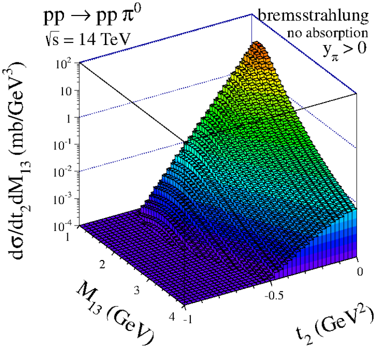
# Distribution in proton-pion invariant mass $M_{13}$ for $y_{\pi^0} > 0$ at $\sqrt{s} = 14$ TeV

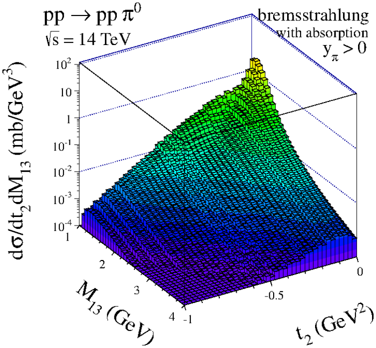



- The diffractive non-resonant background contributes at small $\pi^0 p$ invariant mass and could be therefore misinterpreted as the Roper resonance $N^*(1440)$
- $\pi^0$-bremsstrahlung gives a sizable contribution to the low mass ($M_X > m_p + m_{\pi^0}$) single diffractive cross section

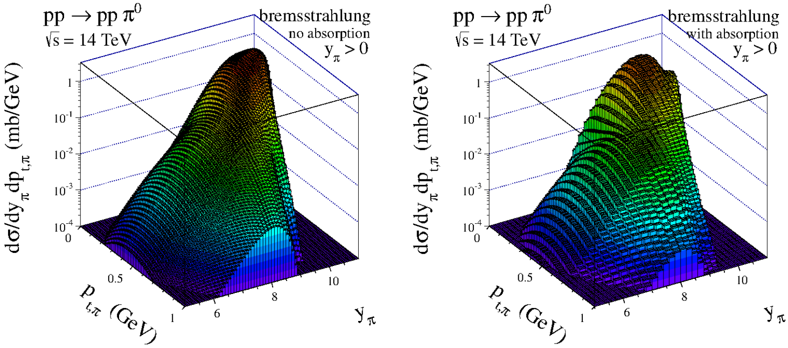
# Distribution in $(t_2, M_{13})$ for $y_{\pi^0} > 0$ at $\sqrt{s} = 14$ TeV



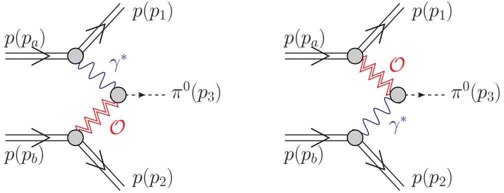

- strong dependence of slope in $t$ on the mass of the supplementary excited $p\pi^0$ system – similar effect was observed at ISR energies
- large contribution comes from the $\pi$-exchange component while the baryon exchange terms are suppressed due to amplitude cancellations
- absorptive effects could be partially responsible for the irregular structure in space $(t_2, M_{13})$ at small $|t_2|$ and $M_{13} \sim 1.3$ GeV

# Distribution in $(y_{\pi^0}, p_{\perp,\pi^0})$ for $y_{\pi^0} > 0$ at $\sqrt{s} = 14$ TeV




- sizable correlations is partially due to interference of different components (amplitudes)

# $\gamma\mathcal{O}$ and $\mathcal{O}\gamma$ exchanges




Equivalent Photon Approximation

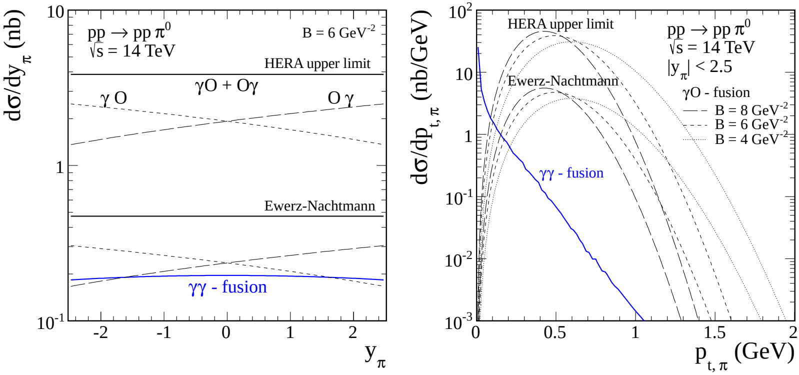
$$\frac{d\sigma}{dy\,dp_\perp^2} = z_1 f(z_1)\frac{d\sigma_{\gamma p\to\pi^0 p}}{dt_2}(s_{23}, t_2 \approx -p_\perp^2) + z_2 f(z_2)\frac{d\sigma_{\gamma p\to\pi^0 p}}{dt_1}(s_{13}, t_1 \approx -p_\perp^2)$$

$f(z)$ is an elastic photon flux in the proton, $z_{1/2} = \frac{m_\perp}{\sqrt{s}}\exp(\pm y)$, $m_\perp = \sqrt{m_\pi^2 + p_\perp^2}$

$$\frac{d\sigma_{\gamma p\to\pi^0 p}}{dt} = B^2(-t)\exp(Bt)\,\sigma_{\gamma p\to\pi^0 p}$$

- $d\sigma_{\gamma p\to\pi^0 p}/dt$ vanishes at $t = 0$ which is due to helicity flip in the $\gamma \to \pi^0$ transition
- The slope parameter can be expected to be typically as for other soft processes
- At LHC and at $y = 0$ typical energies in the $\gamma p$ subsystems are similar as at HERA

# Pion rapidity and $p_{\perp,\pi^0}$ distributions at $\sqrt{s} = 14$ TeV




- We show predictions for two different estimates of the $\gamma p \to \pi^0 p$ cross section (energy independent): $\sigma^{HERA\ upper\ limit}_{\gamma p \to \pi^0 p} = 49$ nb [a] and $\sigma^{Ewerz-Nachtmann}_{\gamma p \to \pi^0 p} = 6$ nb [b]

  [a] H1 Collaboration (C. Adloff *et al.*), Phys. Lett. B544 (2002) 35

  [b] A. Donnachie, H.G. Dosch and O. Nachtmann, Eur. Phys. J C45 (2006) 771, C. Ewerz and O. Nachtmann, Eur. Phys. J. C49 (2007) 685

- One can expect potential deviation from $\gamma\gamma$ contribution at $p_{\perp,\pi^0} \sim 0.5$ GeV as signal of odderon exchange

# Conclusions

- Large cross sections of the order of mb are predicted for the $pp \to pp\pi^0$ reaction

| Model (for $y_{\pi^0} > 0$) | $\sqrt{s} = 45$ GeV | $\sqrt{s} = 500$ GeV | $\sqrt{s} = 14$ TeV |
|---|---|---|---|
| No absorption | $103 - 146\ \mu b$ | $177 - 251\ \mu b$ | $402 - 575\ \mu b$ |
| Absorption in initial state | $46 - 76\ \mu b$ | $62 - 125\ \mu b$ | $94 - 357\ \mu b$ |
| Absorption in final state | $60 - 91\ \mu b$ | $84 - 139\ \mu b$ | $128 - 290\ \mu b$ |

lower limit ($\Lambda_N = 0.6$ GeV, $\Lambda_\pi = 1$ GeV) – upper limit ($\Lambda_N = \Lambda_\pi = 1$ GeV)

– absorptive effects lower the cross section by a factor 2 to 3

- Large contribution to single diffraction cross section

$$\sigma_{SD}^{DHD} = 3\ \sigma_{pp \to pp\pi^0}^{DHD}$$

- Monte Carlo generators do not include it
- Diffractive excitation of single resonances

$$\sigma_{pp \to pp\pi^0}^{N^*} = \sigma_{SD}^{N^*} \times BR(N^* \to N\pi) \times \frac{1}{3} \qquad \text{where } BR(N^* \to N\pi) \approx 65\%$$

- Contribution to large rapidity production (cosmic ray interactions)

  – very energetic photons ($\sim 0.5 - 2$ TeV)

- Searches for odderon exchange

  $\sigma_{pp \to pp\pi^0} < 20$ nb (at $\sqrt{s} = 14$ TeV and $|y_{\pi^0}| < 2.5$)