State Research Center
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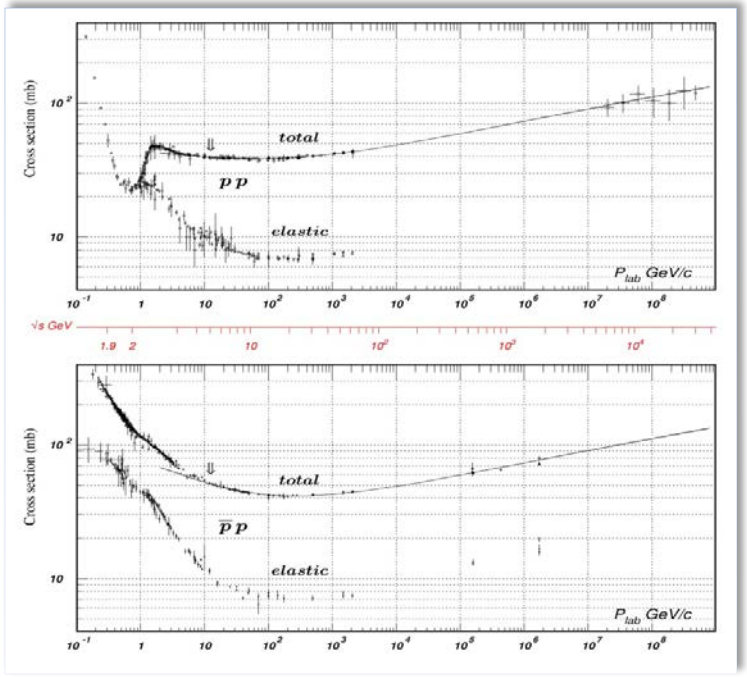
Pion-proton and pion-pion collisions: from GeV to TeV energy domains

Roman Ryutin

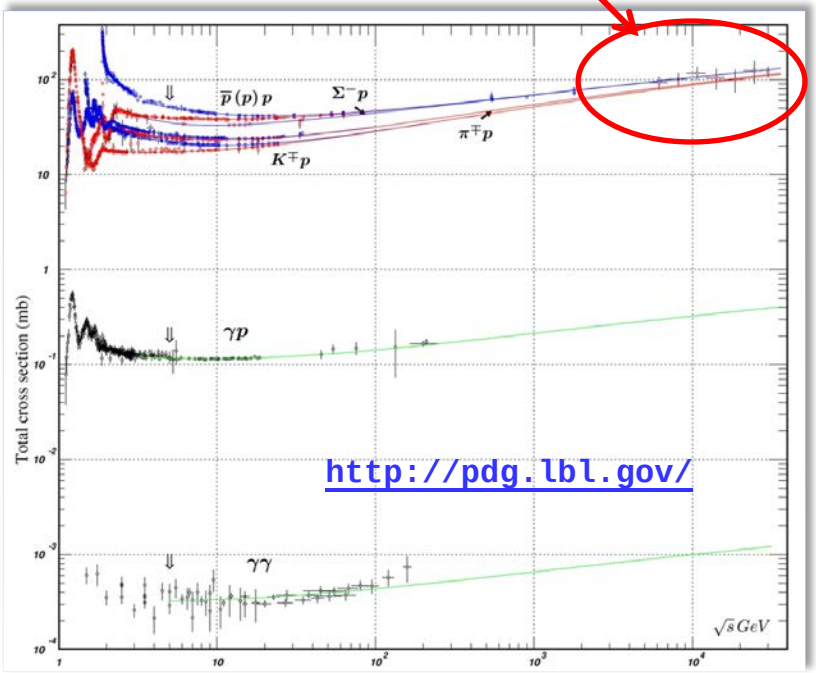
Workshop on QCD and Diffraction – Various Faces of QCD
(15-17 November 2018, Cracow)

Historical outlook and motivations

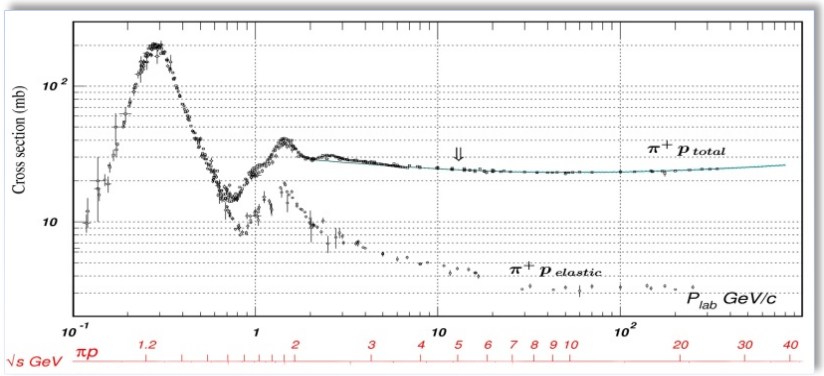
pp (pp): $\sqrt{s}_{max}$ ~10 TeV

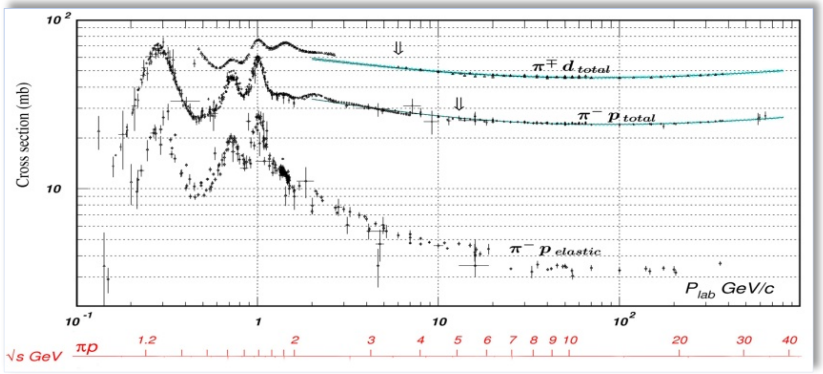


Universality of strong interactions



π p: $\sqrt{s}_{max}$ ~30-40 GeV!

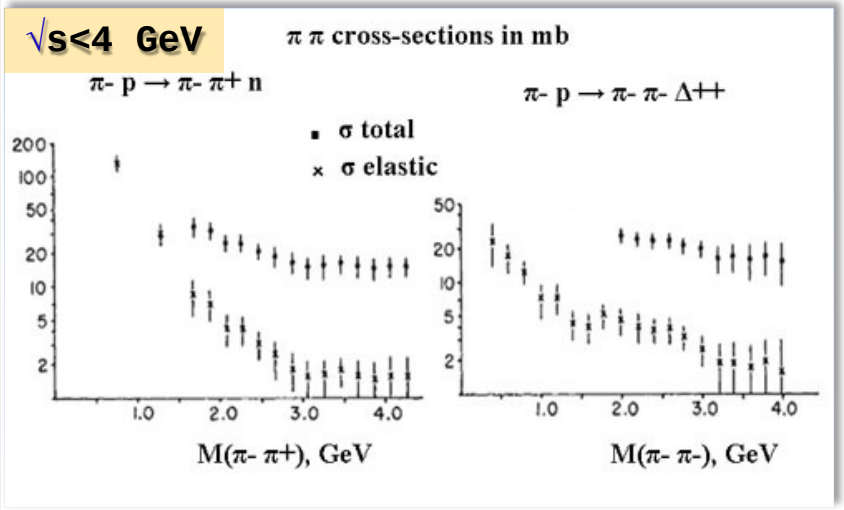




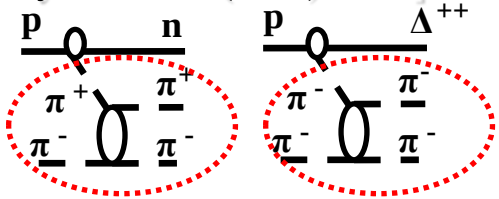
Historical outlook and motivations

First attempts to extract $\pi\pi$ cross-sections

$\sqrt{s}$<4 GeV



[W.J. Robertson, W.D. Walker, J.L. Davis, Phys. Rev. D7 (1973) 2554]



$$\frac{d\sigma_{\pi p}}{dt dM^2_{\pi\pi} dt_{\pi\pi}} \sim \frac{|t|}{(t-m_\pi^2)^2}\frac{d\sigma^{el}_{\pi\pi}}{dt_{\pi\pi}}$$

$$\frac{d\sigma^{el}_{\pi\pi}}{dt_{\pi\pi}} = e^{\beta t_{\pi\pi}} \frac{d\sigma^{el}_{\pi\pi}}{dt_{\pi\pi}}\Big|_{t_{\pi\pi}=0},$$

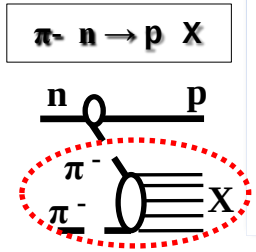
$$\frac{d\sigma^{el}_{\pi\pi}}{dt_{\pi\pi}}\Big|_{t_{\pi\pi}=0} = \frac{1}{16\pi}(\sigma^{tot}_{\pi\pi})^2,$$

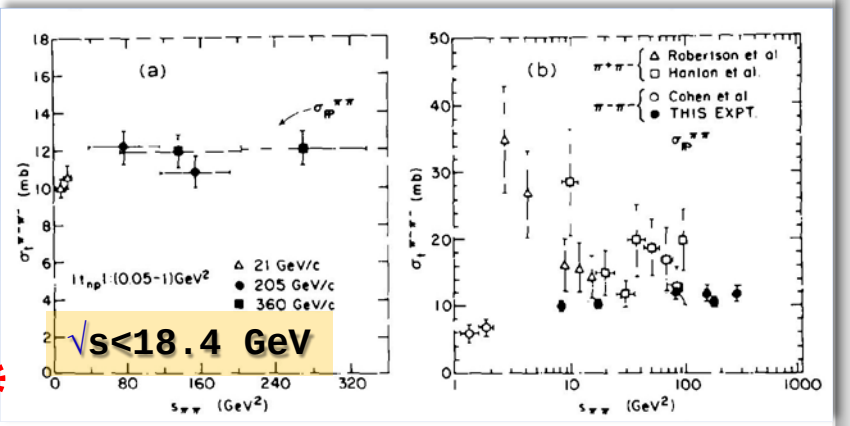
$$\sigma^{tot}_{\pi\pi} = \sqrt{16\pi\,\beta\,\sigma^{el}_{\pi\pi}}$$

Basic idea is to extrapolate charge exchange cross-sections to the resonance region $t \to m_\pi^2$:

[G.F. Chew, F.E. Low, Phys. Rev. 113 (1959) 1640]
[C. Goebel, Phys. Rev. Lett. 1 (1958) 337]

[H. Abramowicz et al., Nucl. Phys. B166 (1980) 62]



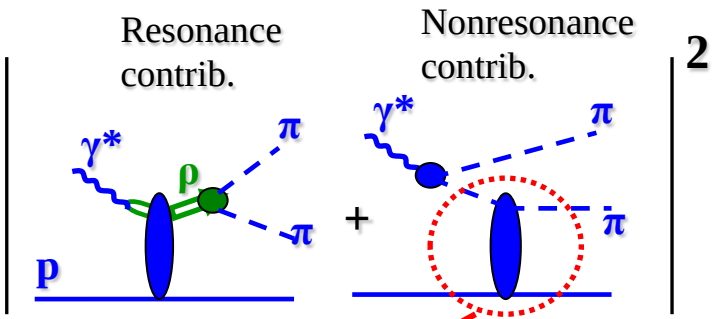


Historical outlook and motivations

Model dependent extraction of the π p cross-section

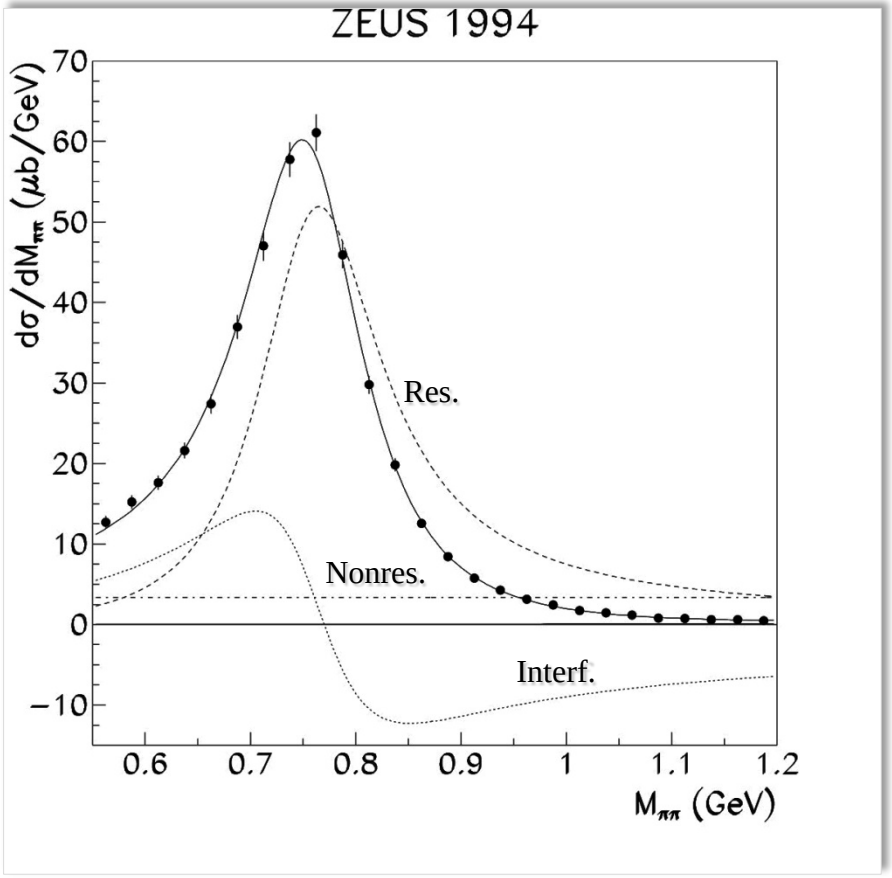
$$\gamma^* p \rightarrow \pi^+ \pi^- p$$

[M.G. Ryskin, Y.M. Shabelski, Yad. Fiz. 61(1998) 89]
[J.Breitweg (ZEUS Collab.), Eur. Phys. J. C2 (1998) 247]

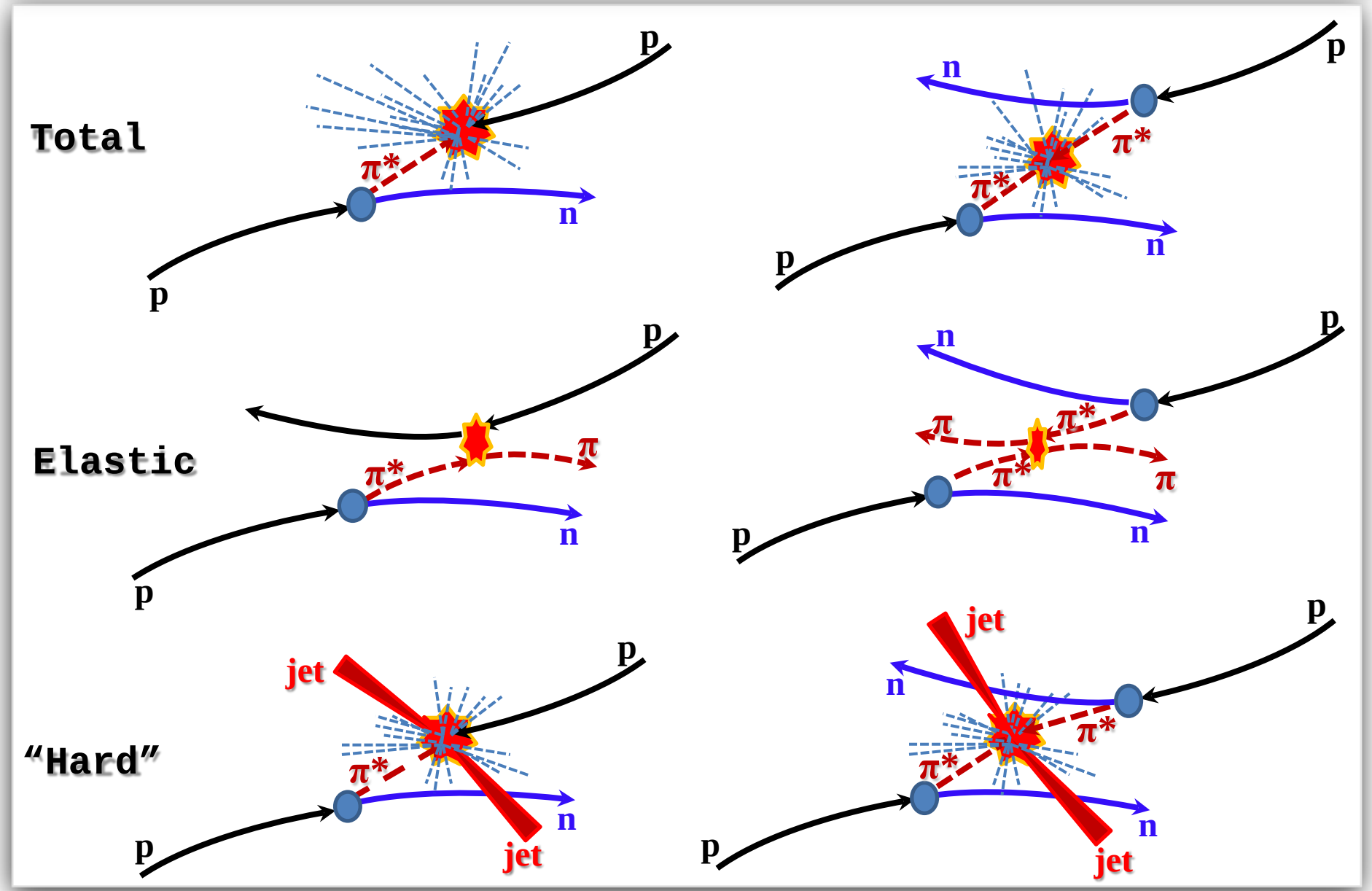


$\sigma_{el}(\pi p)$

$\sigma_{tot}(\pi p) = 31 \pm 3.6$ mb at $\sqrt{s} = 50$ GeV

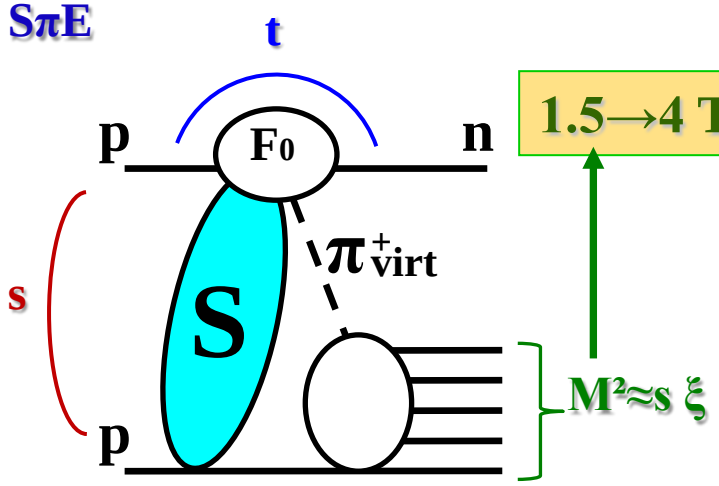


Charge exchange processes (single and double pion exchanges)



Pion exchange processes (pion cross-sections)

SπE



1.5→4 TeV, √s=7 TeV

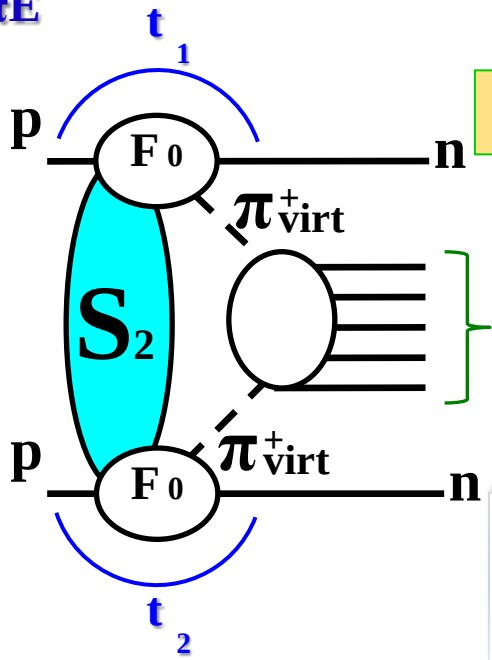
$$F_0(\xi,t)=\frac{G^2_{\pi^+pn}}{16\pi^2}\frac{-t}{(t-m_\pi^2)^2}e^{2bt}\xi^{1-2\alpha_\pi(t)}$$

$$-t\simeq\frac{\vec{q}^{\,2}+m_p^2\xi^2}{1-\xi},\quad G^2_{\pi^+pn}/(8\pi)=13.75$$

$$\alpha_\pi(t)\simeq 0.9(t-m_\pi^2),\quad b\sim 0.3\ \mathrm{GeV}^{-2}$$

$$\frac{d\sigma_{S\pi E}}{dt\,d\xi}=F_0(\xi,t)S(s/s_0,\xi,t)\sigma_{\pi^+p}(s\,\xi)$$

DπE



0.35→2.8 TeV, √s=7 TeV

$$\frac{d\sigma_{D\pi E}}{dt_1dt_2d\xi_1d\xi_2}=F_0(\xi_1,t_1)F_0(\xi_2,t_2)S_2(s/s_0,\xi_{1,2},t_{1,2})\sigma_{\pi^+\pi^+}(s\,\xi_1\xi_2)$$

Assumption:

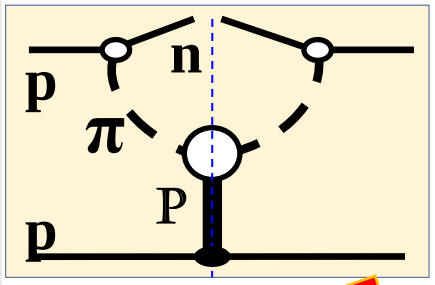
$$\sigma_{\pi^+_{virt}p}(s;\{m_p^2,t\})\simeq\sigma_{\pi^+p}(s;\{m_p^2,m_\pi^2\}),$$

$$\sigma_{\pi^+_{virt}\pi^+_{virt}}(s;\{t_1,t_2\})|\simeq\sigma_{\pi^+\pi^+}(s;\{m_\pi^2,m_\pi^2\})$$

Basic contribution
|t|<0.3 GeV²
virtual → real pion

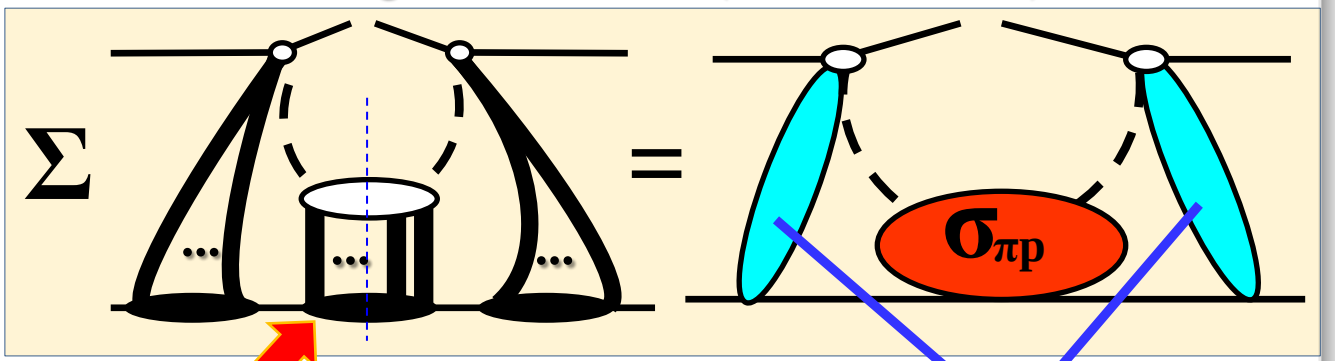
Pion exchange processes (unitarity)

SπE Born term

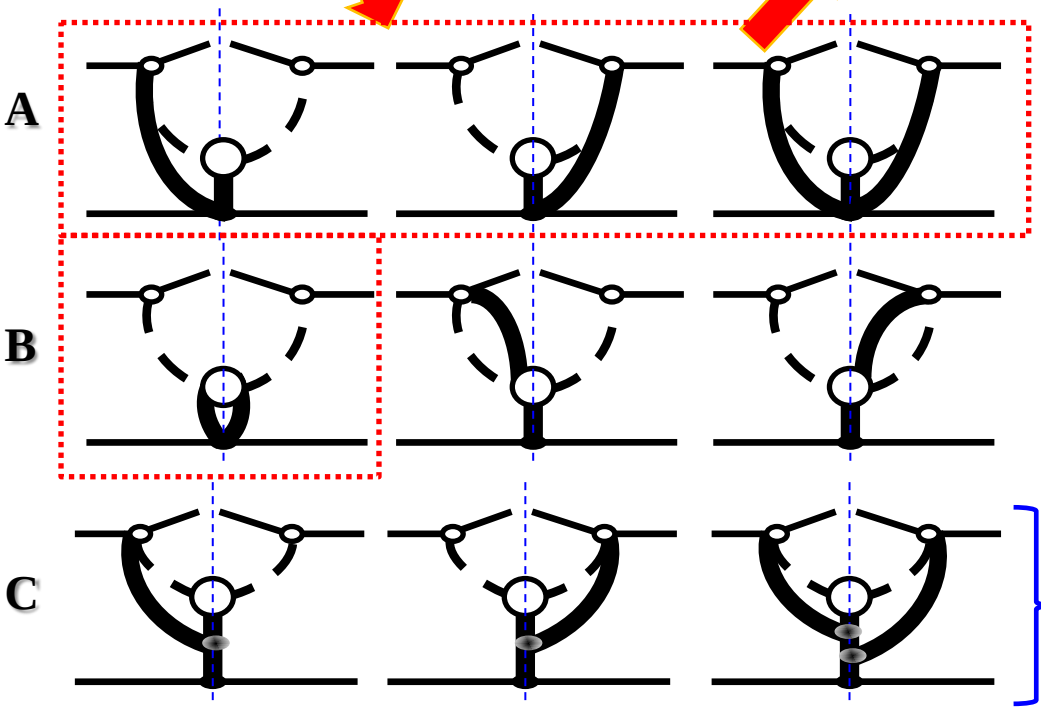


Absorbtion

Leading contributions (eikonalization)



Regge-eikonal models



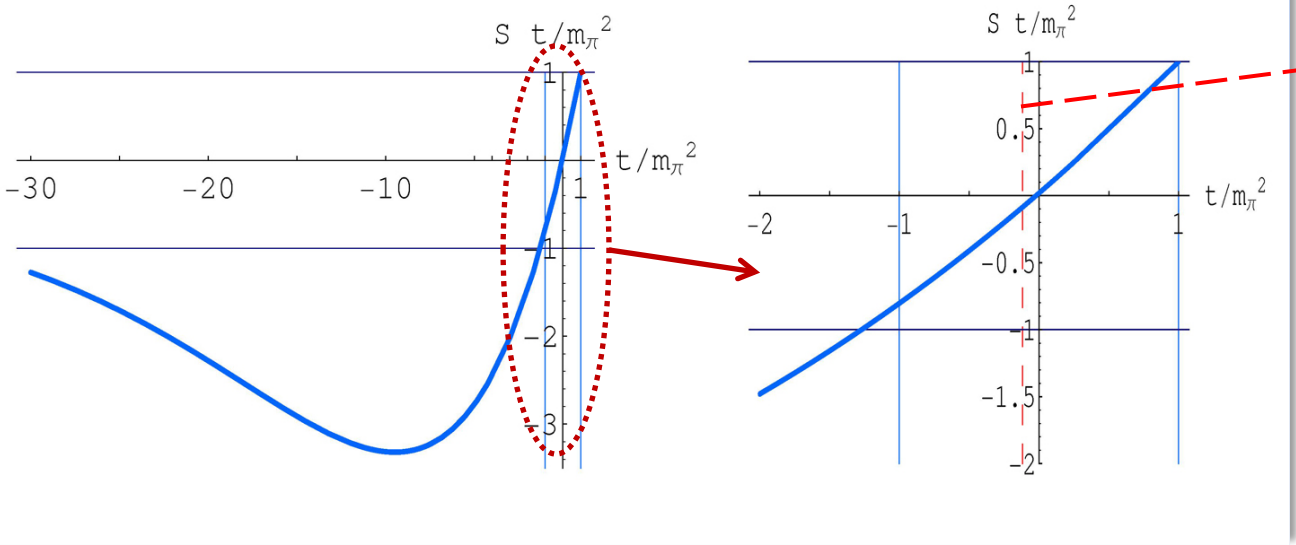
Possibility to interpret like πp scattering

"enhanced" diagrams with 3IP-vertexes

[A.B. Kaidalov, V.A. Khoze, A.D. Martin and M.G. Ryskin, Eur. Phys. J. C47 (2006) 385]

Pion exchange processes (extrapolation)

Функция $S*t/m_\pi^2$ для $\xi=0.05$



The boundary of phys.reg.:

$$t_0 = -\frac{m_p^2 \xi^2}{1-\xi}$$

Exact ("model independent") extrapolation procedure

$$\sigma_{\pi p}(s\,\xi;\{m_p^2,m_\pi^2\}) = \lim_{t\to m_\pi^2} \sigma_{\pi_{virt}p}(s\,\xi;;\{m_p^2,t\}) \frac{S\,(s/s_0,\xi,t)\,t}{m_\pi^2} =$$

$$= \lim_{t\to m_\pi^2} E(\xi,t) \frac{d\sigma_{\mathrm{S\pi E}}}{dt\;d\xi},$$

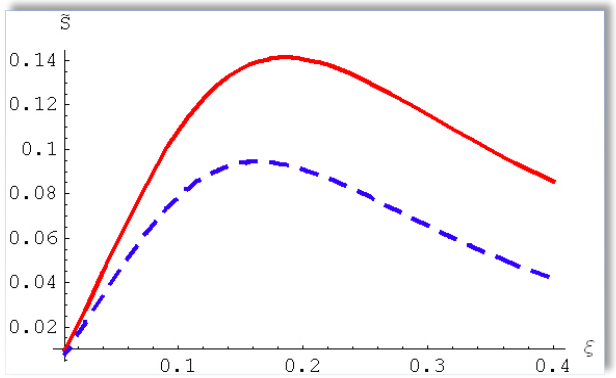
$$\sigma_{\pi\pi}(s\;\xi_1\xi_2;\{m_\pi^2\},m_\pi^2\}) = \lim_{t_{1,2}\to m_\pi^2} \sigma_{\pi_{virt}\pi_{virt}}(s\;\xi_1\xi_2;\{t_1,t_2\}) \frac{S_2\,(s/s_0,\xi_{1,2},t_{1,2})\,t_1 t_2}{m_\pi^4} =$$

$$= \lim_{t_{1,2}\to m_\pi^2} E(\xi_1,t_1)E(\xi_2,t_2) \frac{d\sigma_{\mathrm{D\pi E}}}{dt_1 dt_2 d\xi_1 d\xi_2}.$$

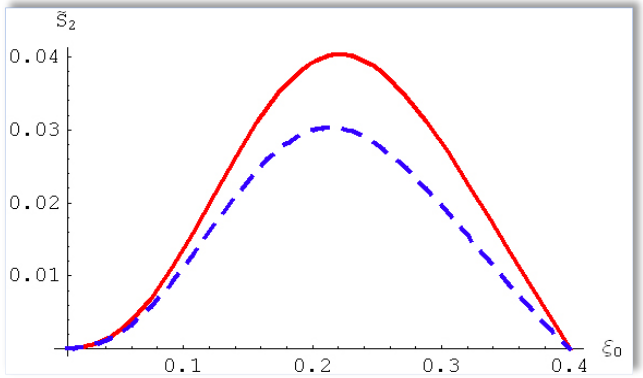
$$E(\xi,t) = -\frac{(t-m_\pi^2)^2}{m_\pi^2} \frac{16\pi^2}{G_{\pi^+pn}^2 e^{2bt} \xi^{1-2\alpha_\pi(t)}}$$

Pion exchange processes (integral extraction procedure)

(depends on the model for absorbtion, but can be normalized to pp cross-sections!)
With recent LHC measurements (TOTEM, …) theoretical error can be reduced to 1-3%.



$\sqrt{s}$=0.9 TeV
$\sqrt{s}$=7 TeV



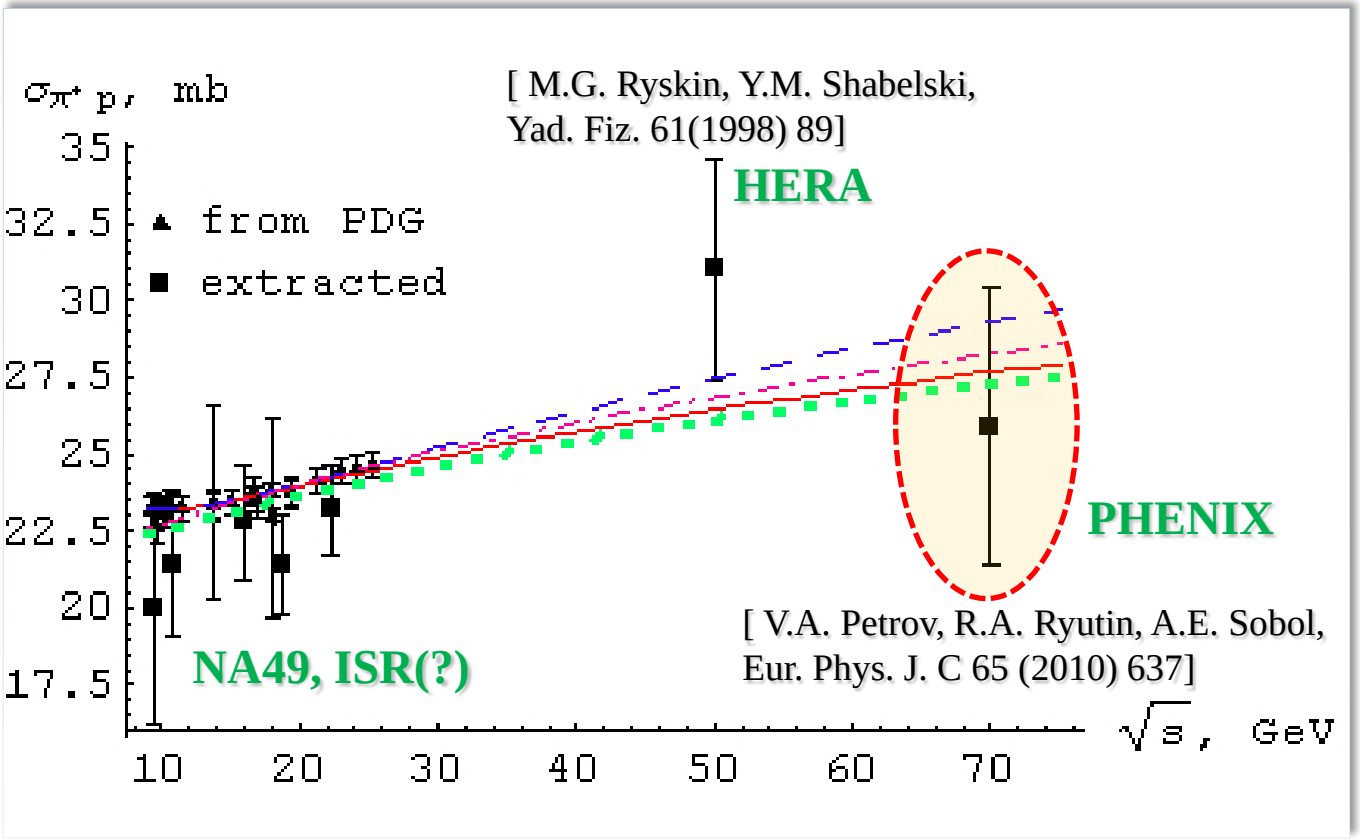
$$\tilde{S}(\xi) = \int_{t_{min}}^{t_{max}} dt\; S(s/s_0, \xi, t) F_0(\xi, t)$$

$$\tilde{S}_2(\xi_0) = \int_{t_{min}}^{t_{max}} dt_1 dt_2 \int_{-y_0}^{y_0} dy\; S_2(s/s_0, \{\xi_0 e^{\pm y}\}, \{t_i\}) F_0(\xi_0 e^{y}, t_1) F_0(\xi_0 e^{-y}, t_2)$$

$$\sigma_{\pi^+ p}(M^2_{\pi p}) = \frac{\frac{d\sigma_{S\pi E}}{d\xi}}{\tilde{S}(s,\xi)}, \quad \xi \simeq \frac{M^2_{\pi p}}{s}$$

$$\sigma_{\pi^+\pi^+}(M^2_{\pi\pi}) = \frac{\frac{d\sigma_{D\pi E}}{d\xi_0}}{\tilde{S}_2(s,\xi_0)}, \quad \xi_0 = \frac{M_{\pi\pi}}{\sqrt{s}}, \; y_0 = \ln\frac{\xi_{\max}\sqrt{s}}{M_{\pi\pi}}$$

Extracted pion proton cross-sections at low energies



COMPETE

[B. Nicolescu et al. (COMPETE Coll.),
ArXiv: hep-ph/0110170]

DL

[A. Donnachie, P.V. Lanshoff,
Phys. Lett. B296 (1992) 227]

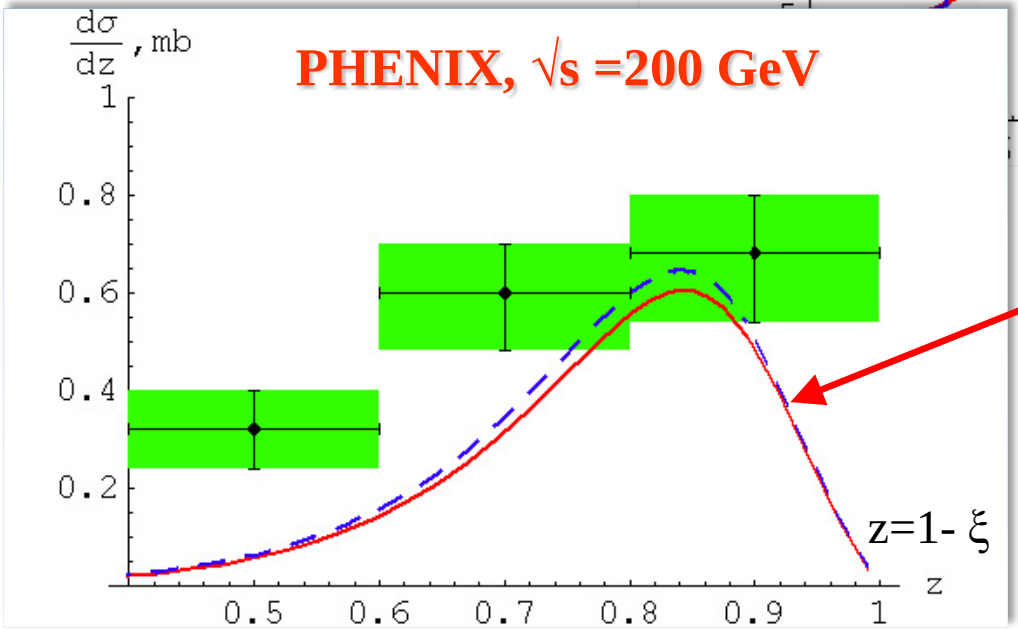
GP

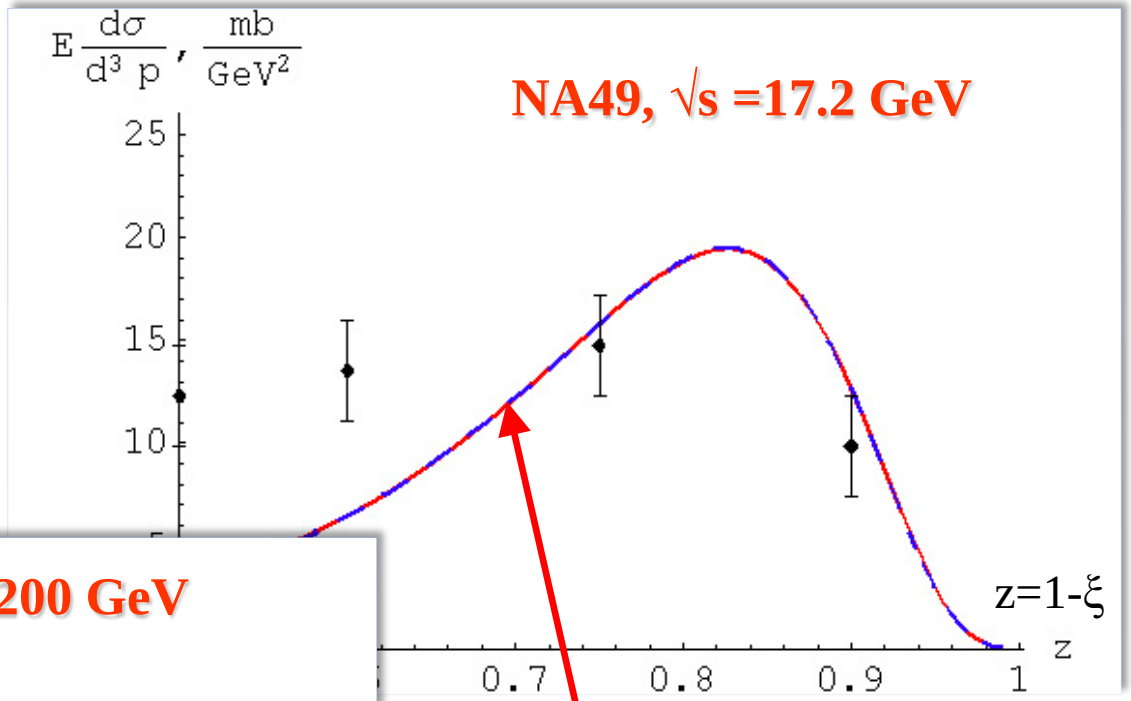
[A.A. Godizov, V.A. Petrov,
JHEP 0707 (2007) 083]

BSW

[C. Bourrely, J. Soffer, T. T. Wu,
Eur. Phys. J. C28(2003)97]

Experimental data at low energies





Theor.

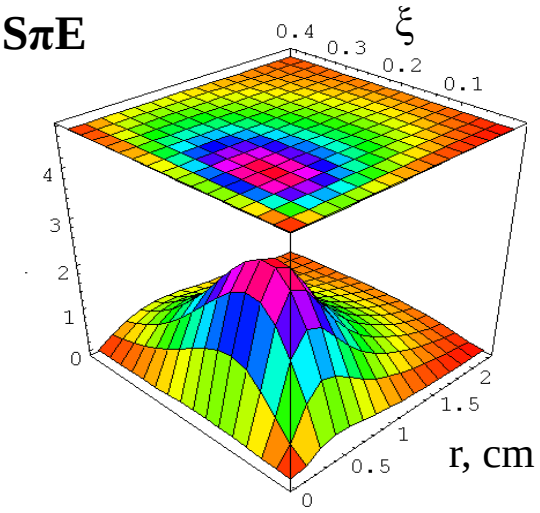
COMPETE

DL

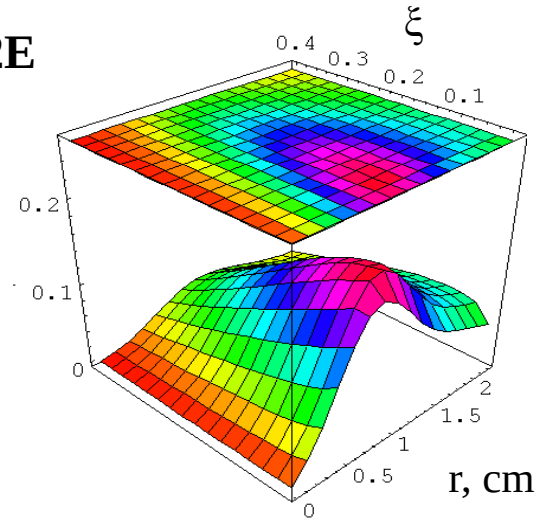
ρ and a2 contributions to Single Charge Exchange at 7 TeV

$d\sigma/dr d\xi$ **(mb/cm)**

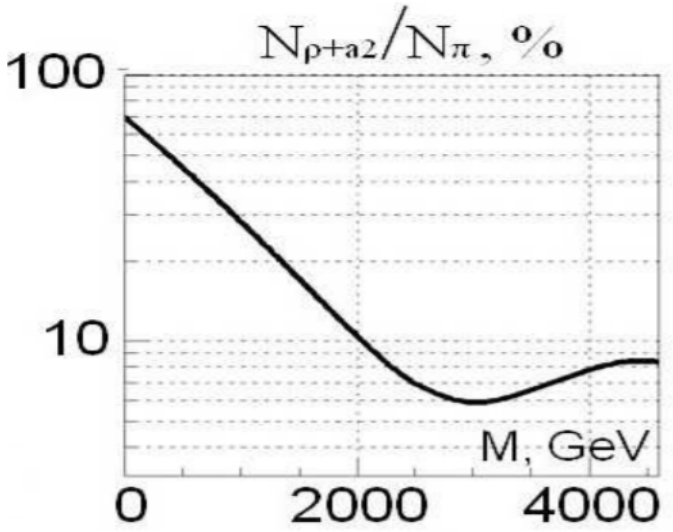
SπE



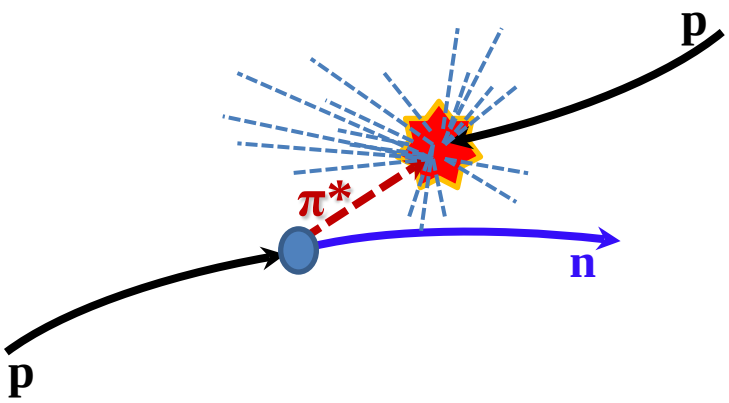
SρE+Sa2E

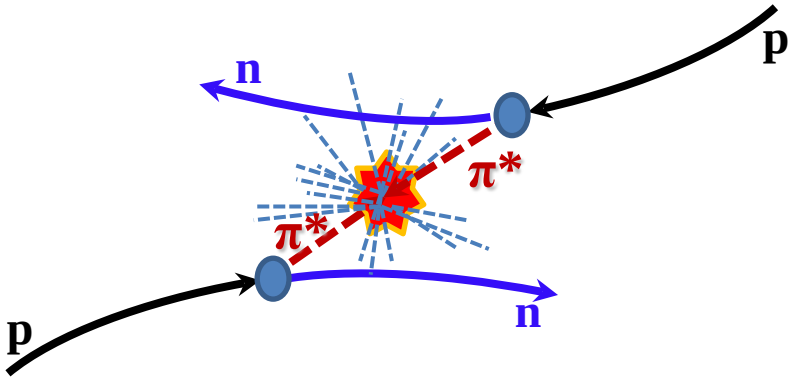


r = transverse distance from the ZDC geom. center



Results of simulations for inclusive SCE and DCE at 7 TeV





Signal and background
for inclusive SCE and DCE

SCE

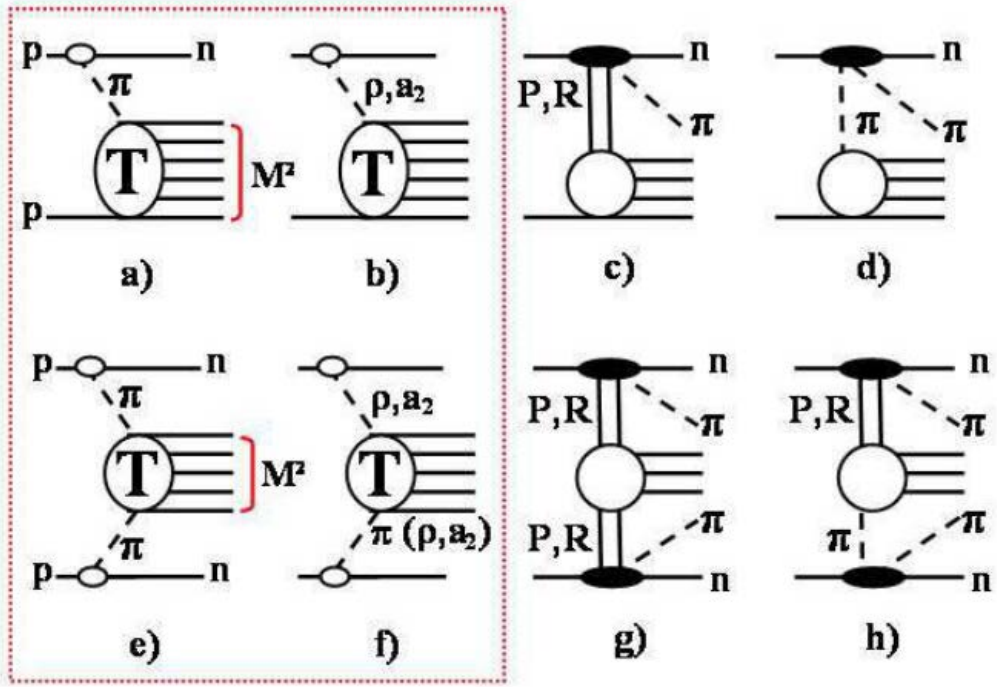
S/B ~ 10/6 without t cuts, only signal at ZDC and CMS detectors

S/B ~ 100/8 for $|t|<0.2$ GeV^2

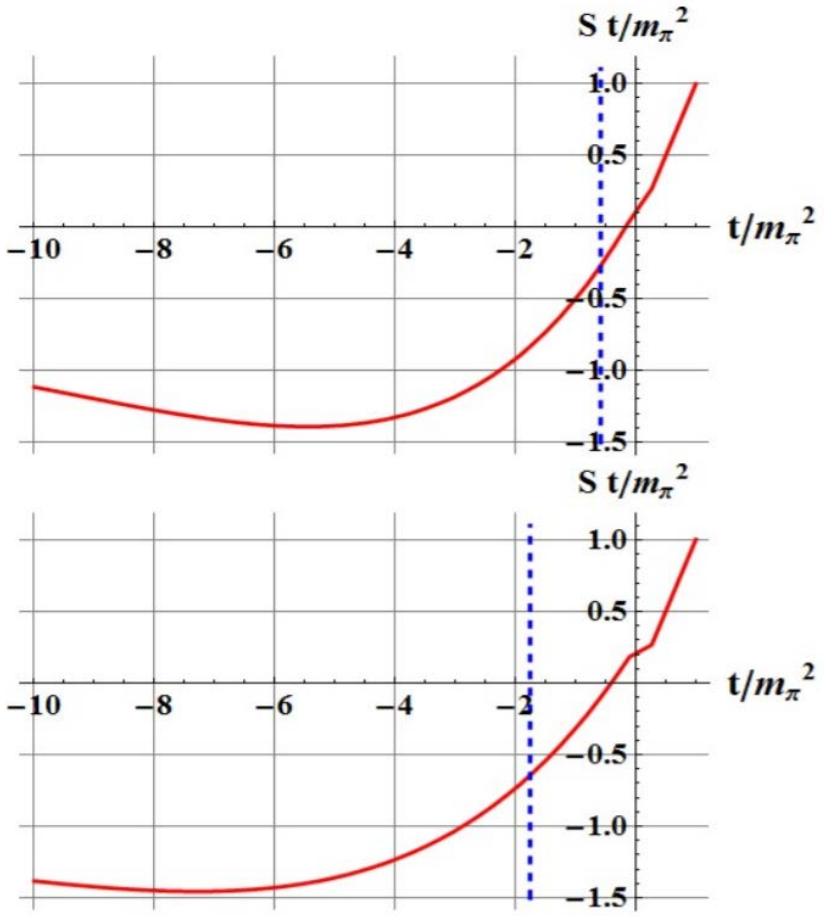
DCE

S/B ~ 10/7 without t cuts, only signal at ZDC and CMS detectors

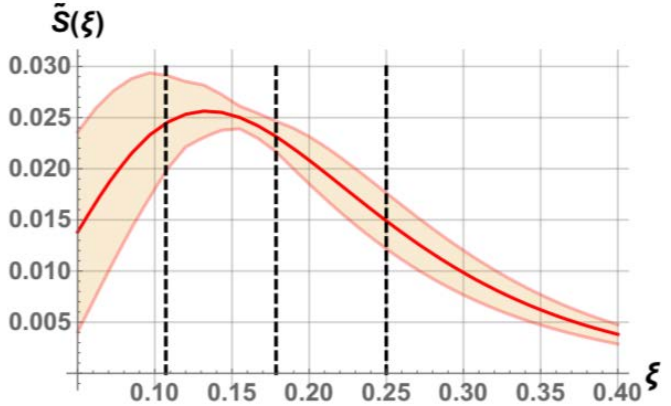
S/B ~ 100/7 for $|t|<0.3$ GeV^2



Extrapolation functions at 7 TeV (for SπE)



Function $S(\xi, t)$ t/m_π^2 versus t/m_π^2 at fixed $\xi = 0.107$ (upper figure) and $\xi = 0.179$ (lower figure). The boundary of the physical region $t_0 = -m_p^2\xi^2/(1-\xi)$ is represented by vertical dashed line.



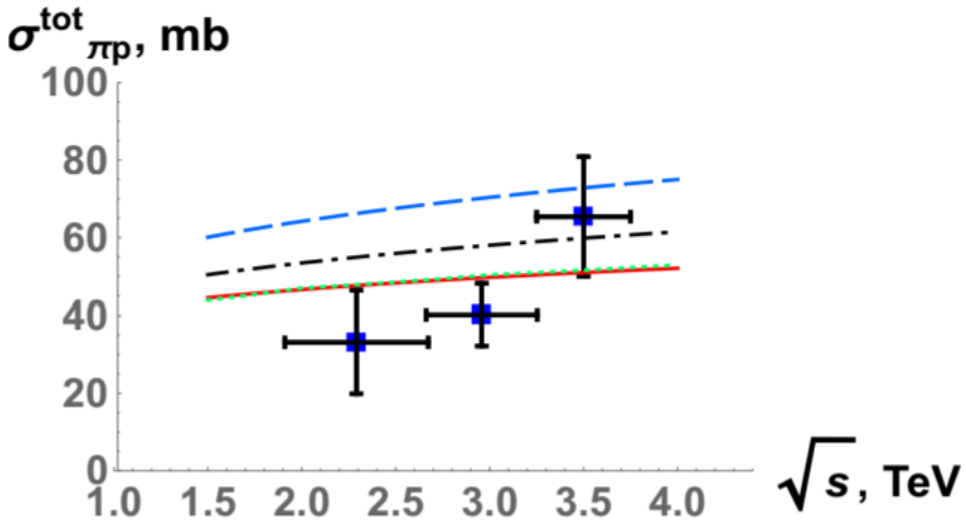
Rescattering corrections multiplied by formfactors for $\sqrt{s} = 7$ TeV ($\tilde{S}(s,\ \xi)$) integrated in the whole t regions of the LHCf data [19]: $\eta > 10.76$. Dashed vertical lines mark $\xi = 0.107, 0.179, 0.25$, which are used to extract $\sigma_{\pi p}$ cross-sections.

Pion-proton cross-sections from the LHCf data at 7 TeV

[LHCf Collab., O. Adriani et al., Phys. Lett. B 750 (2015) 360]

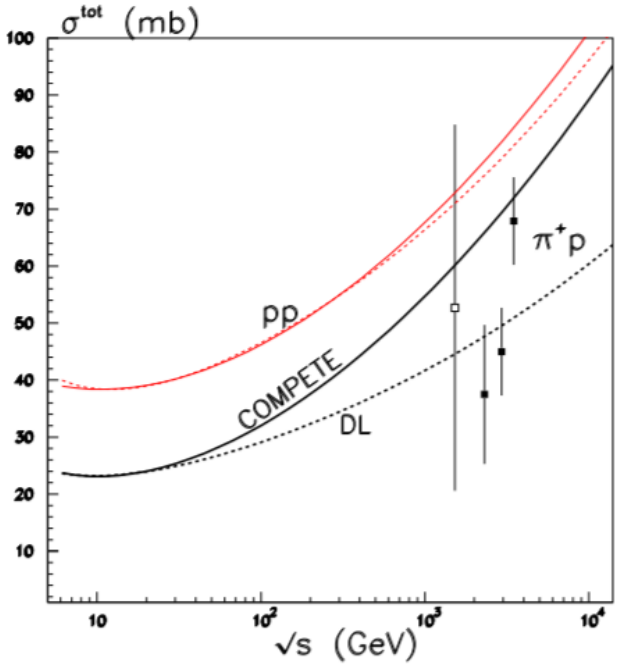
[R.A. Ryutin, Eur. Phys. J. C 77 (2017) 114]

$\sqrt{s}$, TeV	$\sqrt{\lvert t\rvert}/m_\pi$	q_0, GeV	$\sigma^{tot}_{\pi p}$, mb
2.291 ± 0.382	0.91 ± 0.29	0.132	33.15 ± 13.1
2.958 ± 0.296	1.41 ± 0.166	0.12	40.22 ± 7.76
3.5 ± 0.25	1.99 ± 0.11	0.112	65.43 ± 15.15



[V.A. Khoze, A.D. Martin and M.G. Ryskin, Phys. Rev. D 96 (2017) 034018]

$\sigma_{\rm tot}(\pi p)$	$\sqrt{s_{\pi p}}$ (TeV)
52.7 ± 32.1	1.52
$\mathbf{37.5 \pm 12.2}$	**2.31**
$\mathbf{45.0 \pm 7.7}$	**2.94**
$\mathbf{67.9 \pm 7.7}$	**3.48**

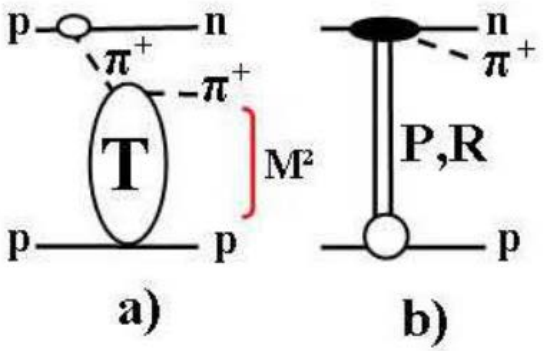


Results of simulations for exclusive SCE and DCE at 7 TeV

Signal and background for exclusive SCE and DCE.
Extraction of elastic pion proton and pion pion cross-sections.

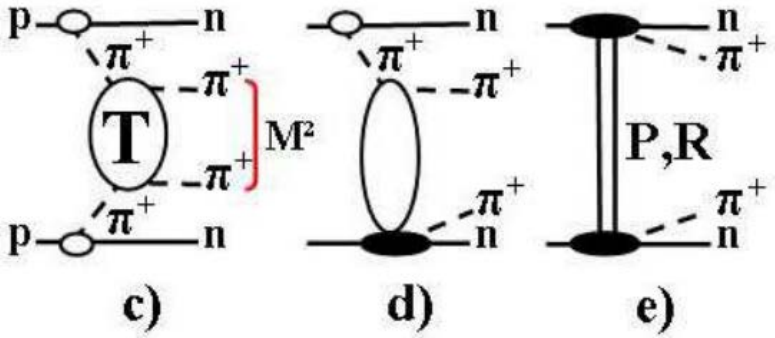
SCE

S/B ~ 1 without t cuts, only
signal at ZDC and CMS detectors
S/B ~ 1.7 for $|t|<0.2$ GeV² and
S/B ~ 5 if we use FSC

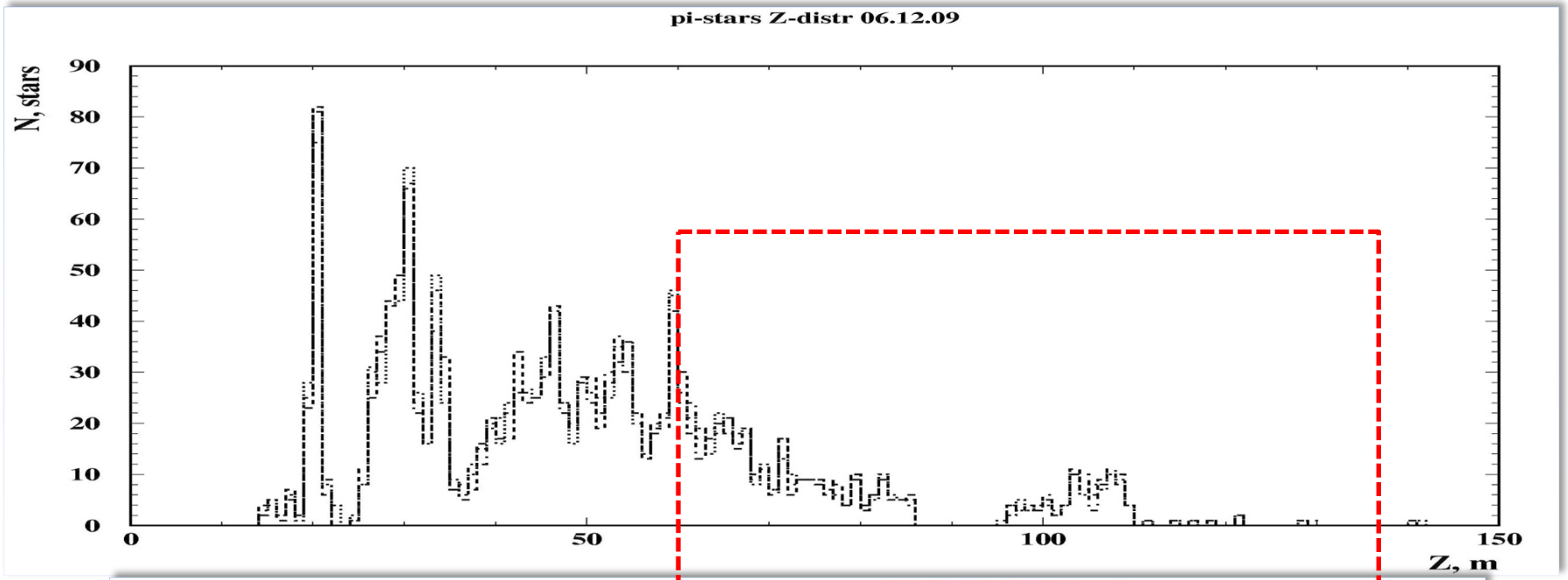


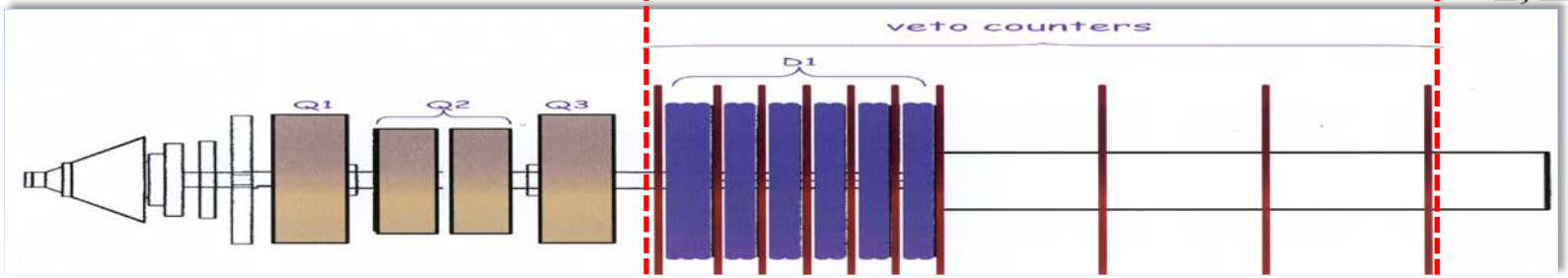
DCE

S/B ~ 1 without t cuts, only
signal at ZDC and CMS detectors
S/B ~ 2 for $|t|<0.25$ GeV² and
S/B ~ 7 if we use FSC



Results of simulations for exclusive SCE and DCE at 7 TeV





[M. Albrow et al., JINST 4, (2009) P10001]

Forward Shower Counters (FSC): 8<η<11

Results of simulations for “hard” SCE and DCE at 7 TeV

Signal and background for “hard” SCE and DCE.
Extraction of di-jet pion proton and pion pion cross-sections.

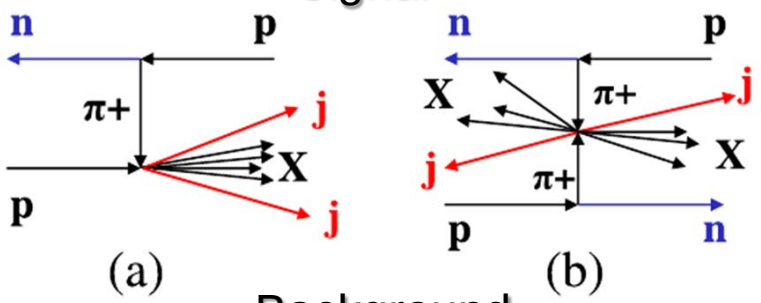
Before selections:

$$\sigma_{\mathrm{D}\pi\mathrm{E}} : \sigma_{\mathrm{S}\pi\mathrm{E}} : \sigma_{\mathrm{TOTAL}} = 1 : 7.6 : 530.$$

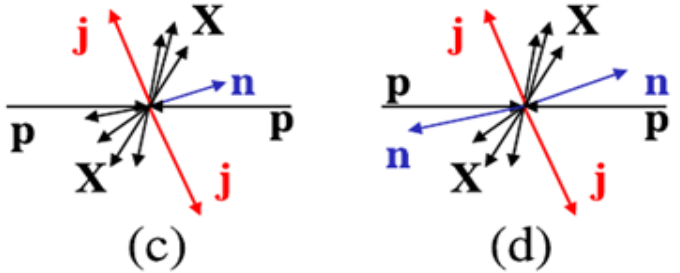
SCE
S/B ~ 0.22 without t cuts, only
signal at ZDC and CMS detectors
S/B ~ 1/0.065 (2% of events, σ ~ 2 nb)
selection $6990 < \sum(\mathrm{E}_{\mathrm{jets}} + \mathrm{E}_{\mathrm{neutrons}}) < 7010$ GeV

DCE
S/B ~ 0.76 without t cuts, only
signal at ZDC and CMS detectors
B ~ 0 (9% of events, σ ~ 50 pb)
selection $6990 < \sum(\mathrm{E}_{\mathrm{jets}} + \mathrm{E}_{\mathrm{neutrons}}) < 7010$ GeV

Signal



Background



Summary

• **CE (pp→nX) and DCE (pp→nXn) processes measured at LHC could provide us with unique information on π+p and π+π+ cross sections at very high c.m. energy (up to several TeV):** total, elastic, inclusive jet cross-sections, … => universal behaviour, value of absorbtion, diffractive patterns, parton distributions in a pion, …

• Cross-sections for CE & DCE processes are estimated to be 1.5 mb & 0.2 mb at ~10 TeV (very large number of events, even with low efficiency of registration)
• Model for charge exchange processes (with π, ρ and a2 reggeons) in the range $0<qt<0.5$ GeV, $0.0001<\xi<0.4$, $0.9\ \text{TeV}<\sqrt{s}<14\ \text{TeV}$ was developed and applied to MC (generator MonChER2.0)

• **Model-independent extraction of π+ p and π+ π+ cross-sections is possible for LHC if we can measure t-distributions**. It is not possible for the present design of ZDC. At this moment only model-dependent extraction is possible with uncertainties in absorbtion (can be normalized to pp, at present we have 1-3% model error, since we have the data from TOTEM)

• Backgrounds: SD,DD,CD,MB are suppressed at $|t|<0.25\ \text{GeV}^2$ (S/B~10). But even for the whole ZDC acceptance we can reach also S/B~10 with efficiency 1-3% for SπE and 5-10% for DπE without t-cuts, using the information from CMS detectors. Reggeon backgrounds can reach 8% at 7 TeV for CE and 43% for DCE. Pile-up is supposed to be low at first runs.
• **Total π p cross-sections were extracted from the real low energy data and LHCf data at 7 TeV.**
• For elastic cross-sections and t-measurements we need modifications of detectors (FSC, ZDC)
• Inclusive dijet π p and π π cross-sections (pion PDFs) could be extracted from the data with specific cuts.

The end

THANK YOU!