Photoproduction at COMPASS

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on behalf of the COMPASS collaboration

PHOTON-2017

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The COMPASS experiment

COMPASS (COmmon Muon Proton Apparatus for Structure and Spectroscopy)

is a fixed target experiment on a secondary beam of Super Proton Synchrotron at CERN

13 countries,
24 institutions,
~220 physicists

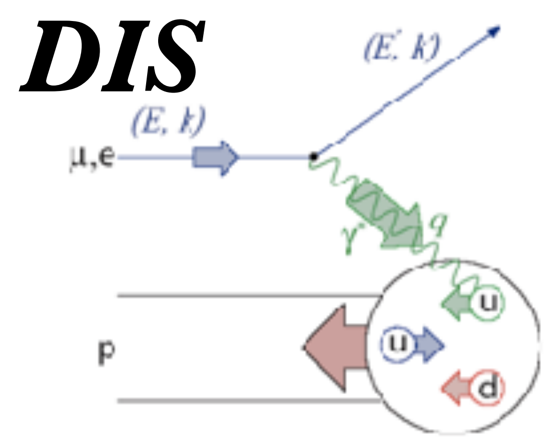
1996 - Proposal
2002-now - Physical data taking

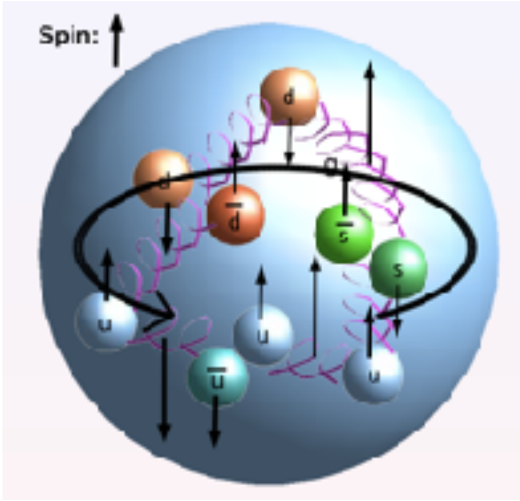
COMPASS: physics with muon and hadron beam

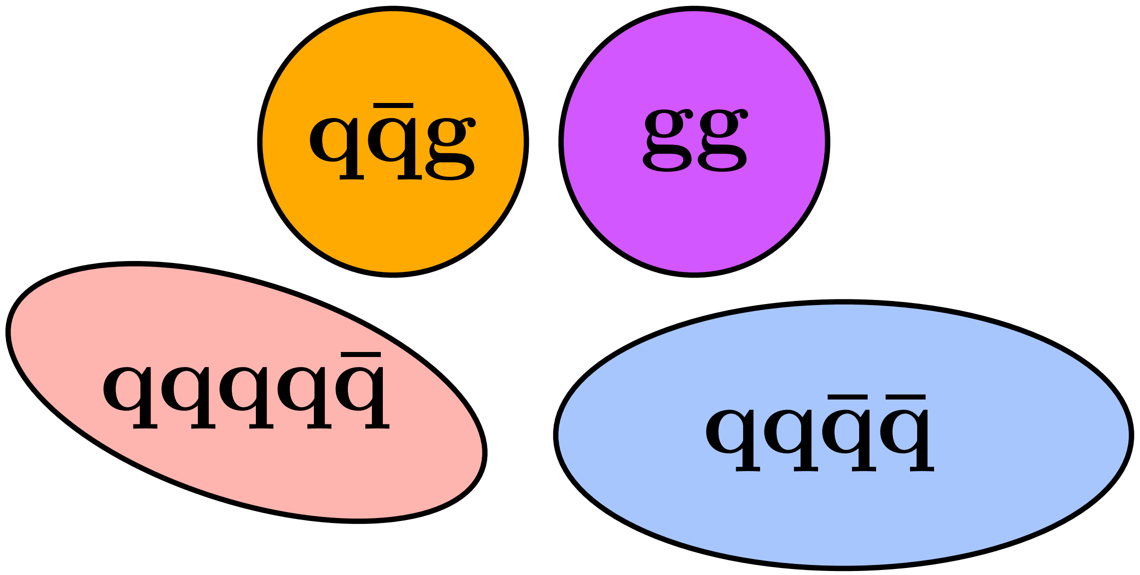
COMPASS ≈ SPIN PHYSICS + SPECTROSCOPY

Study of spin structure of nucleon with muon beam and polarized target:

- *(un)polarized and TMD PDFs and FFs*
- *Generalized PDFs*







Study of hadron structure and hadron spectroscopy with hadron beam:

- *Primakoff reactions*
- *diffractive and central production*
- *k_T-dependent PDFs via Drell-Yan process*

Spectroscopy with muon beam:

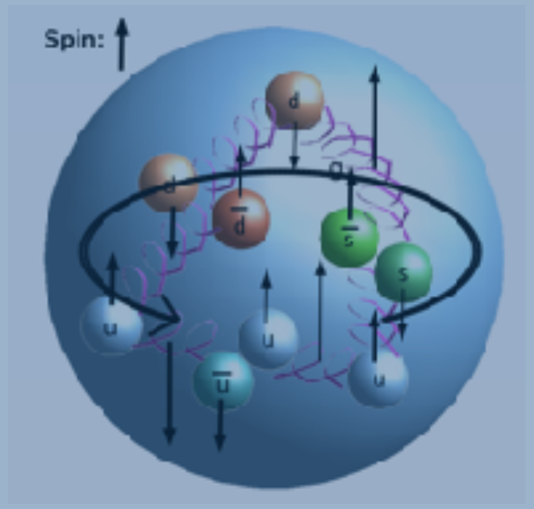
XYZ-states

Outline of this talk

COMPASS ≈ SPIN PHYSICS + SPECTROSCOPY

Study of spin structure of nucleon with muon beam and polarized target:

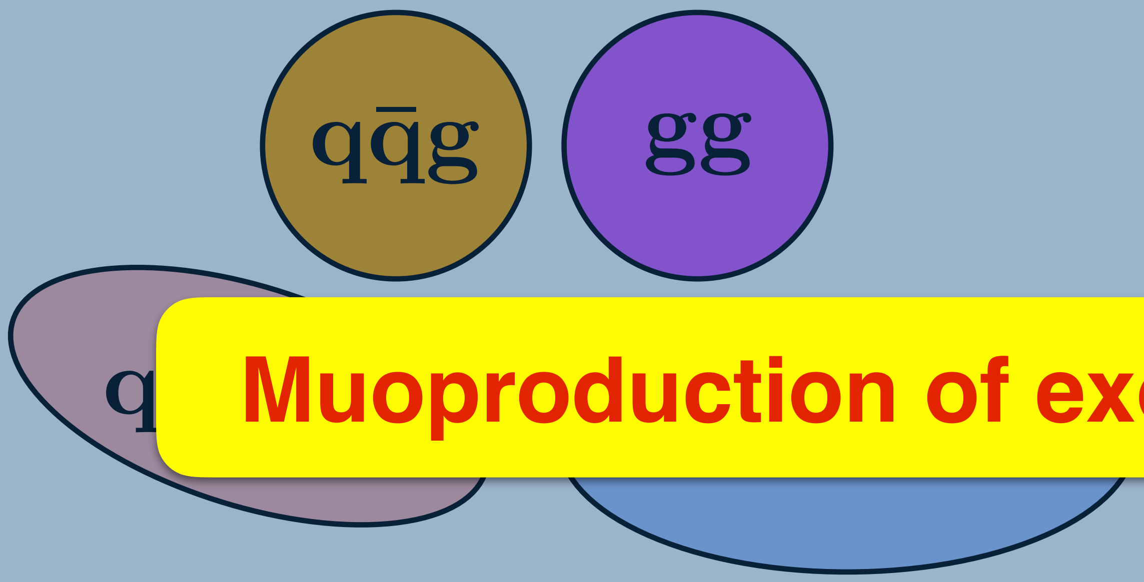
- *(ur*
-



Study of photon-meson scattering via low-t (Primakoff) reactions

...adron structure and hadron spectroscopy with hadron beam:

- *Primakoff reactions*
- *diffractive and central production*
- *...t PDFs via Drell-Yan process*

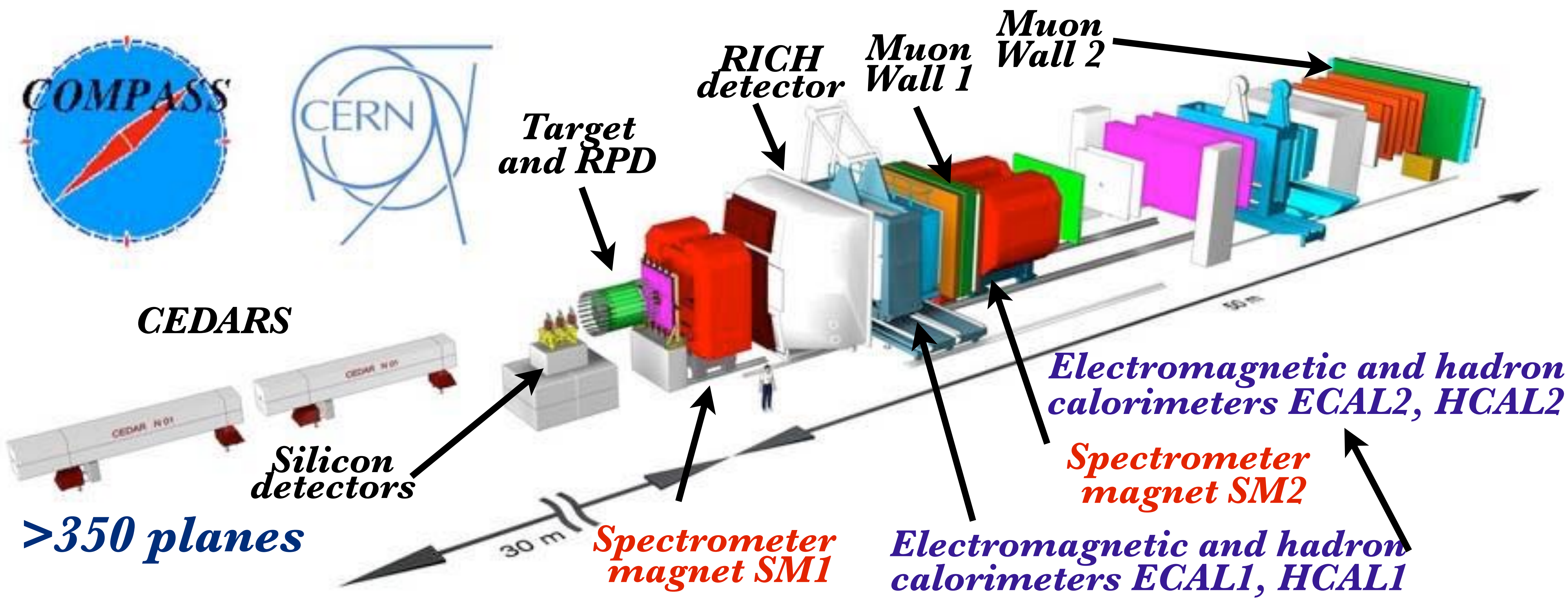


Muoproduction of exotic charmonia

Spectroscopy with muon beam: XYZ-states

The COMPASS setup

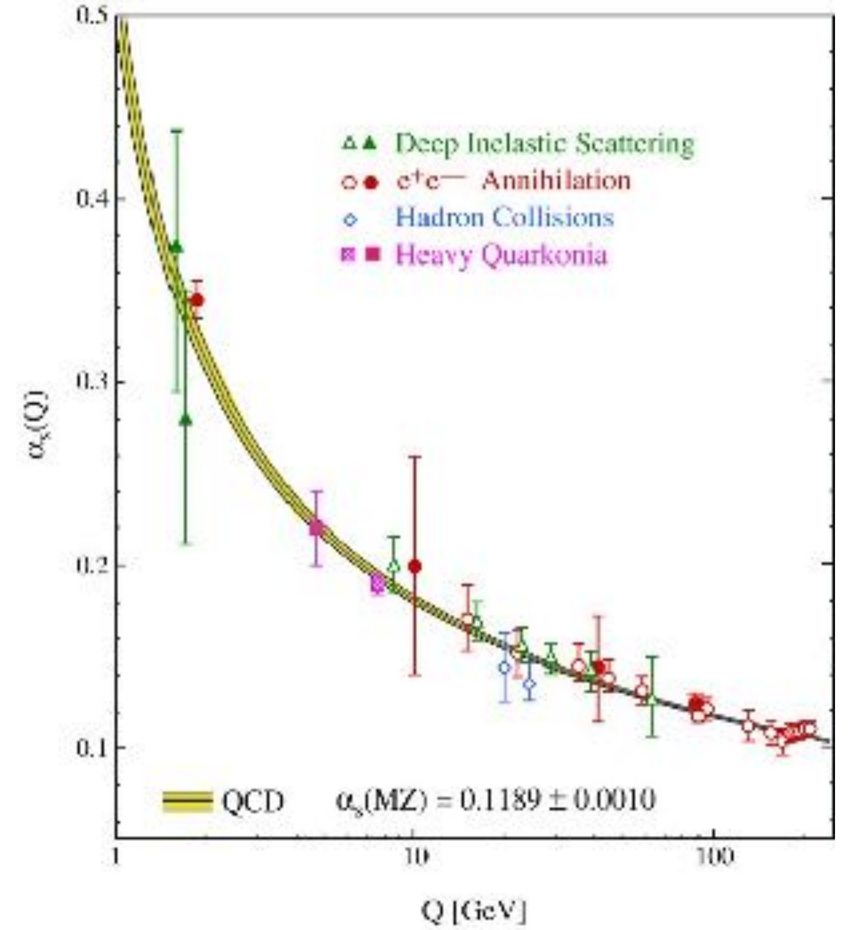
COMPASS layout for hadron program



- *Muon (160-200 GeV/c) and hadron (190 GeV/c) beams*
- *CEDAR detectors for beam particle identification (for hadron beam)*
- *Set of nuclear targets (from H to Pb), polarized ^{6}LiD and NH_3*

QCD - true theory of strong interactions, but…

Since the constant of strong interactions $\alpha_S \sim 1$ at small energies, exact QCD formalism cannot make predictions with reasonable accuracy. Effective phenomenological models are needed



Chiral Perturbation Theory

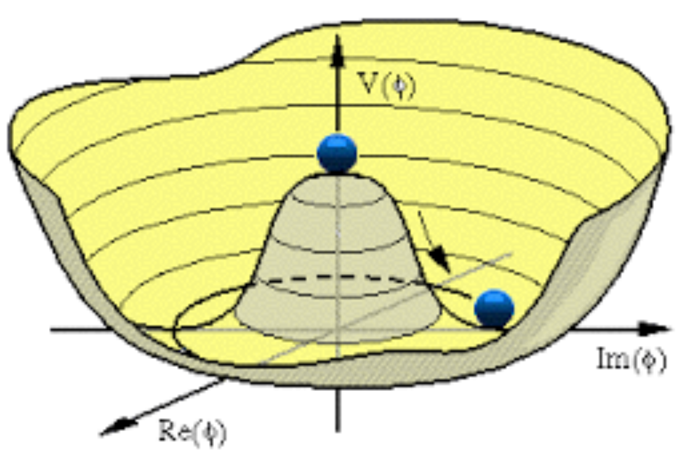
Mass of light quarks (u,d) is much smaller than the typical scale $M \approx 1$ GeV

$$\mathcal{L}_{QCD} = \mathcal{L}^0 + \mathcal{L}_m$$

mass term - a small perturbation

Chiral symmetric term

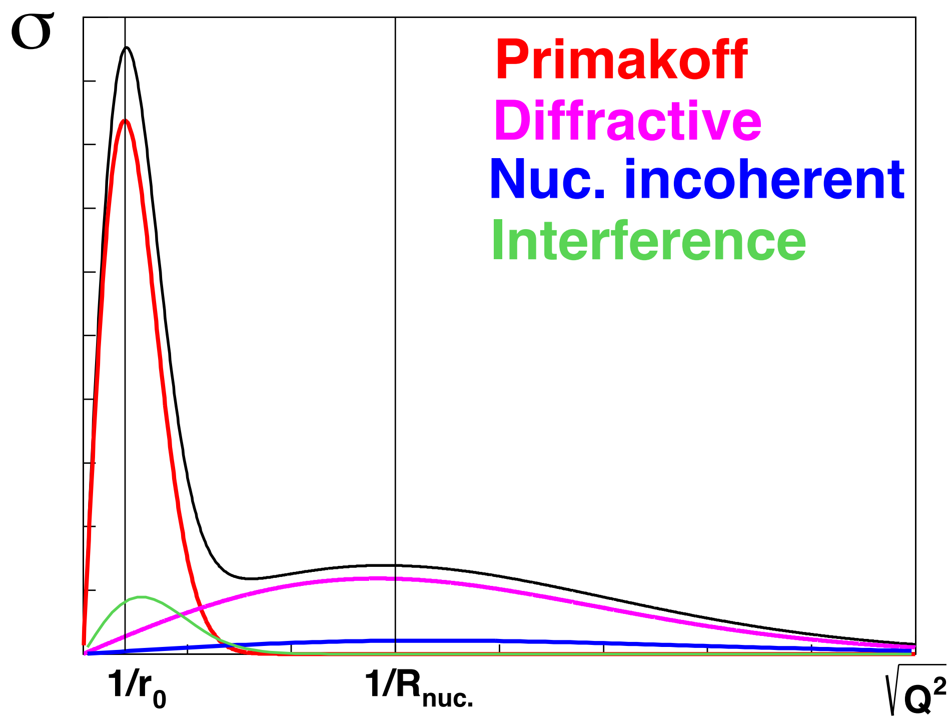
m_q/M , p/M - small parameters in expansion



Approximate chiral symmetry is in lagrangian but not in the mass spectrum of hadrons!

Pions are pseudo-Goldstone bosons in chiral theory.

Low-t reactions

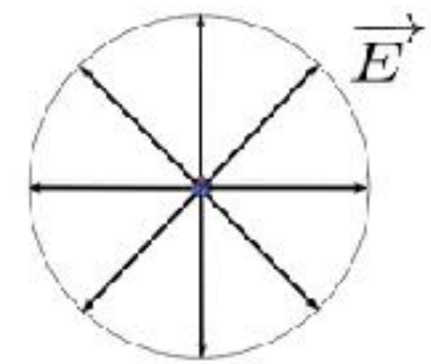


$\sigma = c_1(T_{Prim} + e^{i\varphi} T_{Diff})^2 + \sigma_{Inc}$

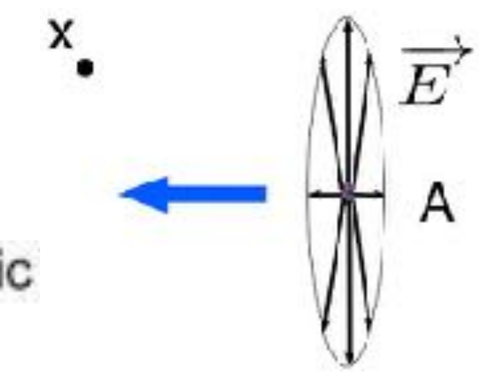
$= \sigma_{Prim} + \sigma_{Diff} + \sigma_{Int} + \sigma_{Inc}$

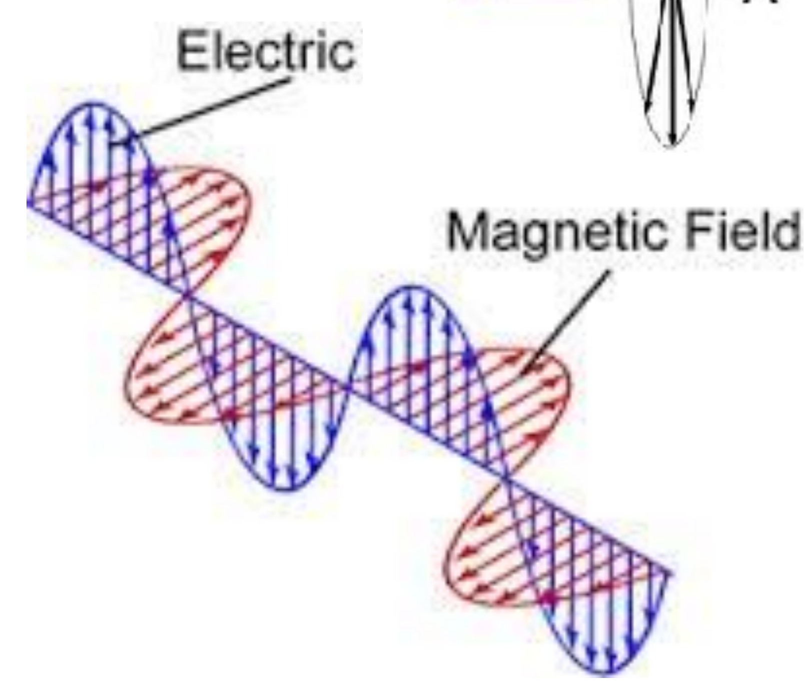
Electromagnetic field of fast charged particle is similar to a field of electromagnetic wave

$\sigma_{x\gamma}(\omega, Q^2) \rightarrow \sigma_{x\gamma}(\omega, 0)$



$$d\sigma_{xA} = \int n_\gamma(\omega) d\sigma_{x\gamma}(\omega) d\omega$$





density of equivalent photons:

$$n_\gamma(\omega) \sim \frac{Z^2\alpha}{\omega} ln \frac{E}{\omega}$$

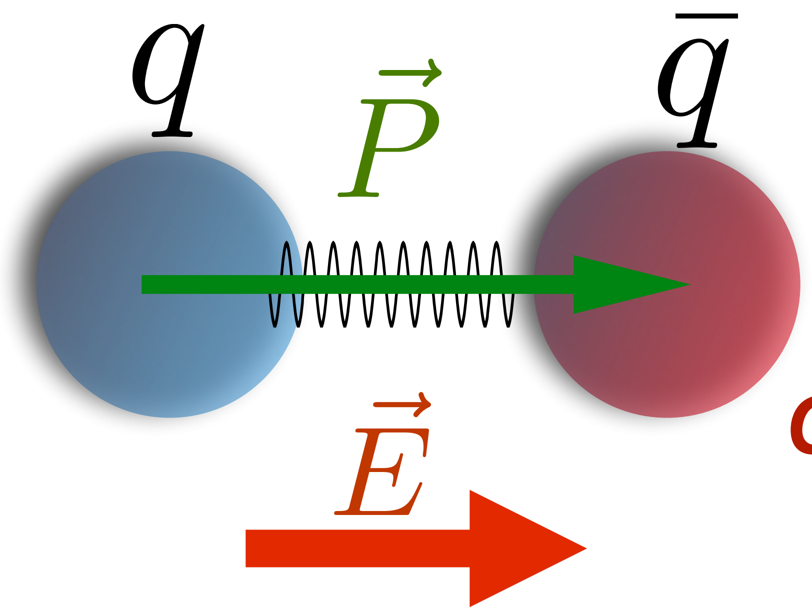
Polarizabilities of hadrons

Compton amplitude:

$$A(\gamma X \to \gamma X) =$$
$$(-\frac{\alpha}{m}\delta_{o\pm} + \alpha_X \omega_1 \omega_2)\hat{e}_1 \cdot \hat{e}_2 +$$
$$+\beta_X \omega_1 \omega_2 (\hat{e}_1 \times \hat{q}_1)(\hat{e}_2 \times \hat{q}_2) + \ldots$$

The electric and magnetic polarizabilities of a hadron are the quantities characterizing the rigidity of QCD system

$$H = \ldots -(\alpha_X E^2 + \beta_X H^2)/2$$



$$\vec{P} = \alpha_X \vec{E}$$
$$\vec{\mu} = \beta_X \vec{H}$$

PDG data:

	α_X, $10^{-4}\ fm^3$	β_X, $10^{-4}\ fm^3$
p	12.0±0.6	1.9∓0.6
n	12.5±1.7	2.7∓1.8

Chiral theory 2-loop approximation ($O(p^6)$) for π:

$$\alpha_\pi - \beta_\pi = (5.7 \pm 1.0) \times 10^{-4} fm^3$$
$$\alpha_\pi + \beta_\pi = (0.16 \pm 0.1) \times 10^{-4} fm^3$$

The most of other models: $8 \times 10^{-4} fm^3 \le \alpha_\pi - \beta_\pi \le 14 \times 10^{-4} fm^3$

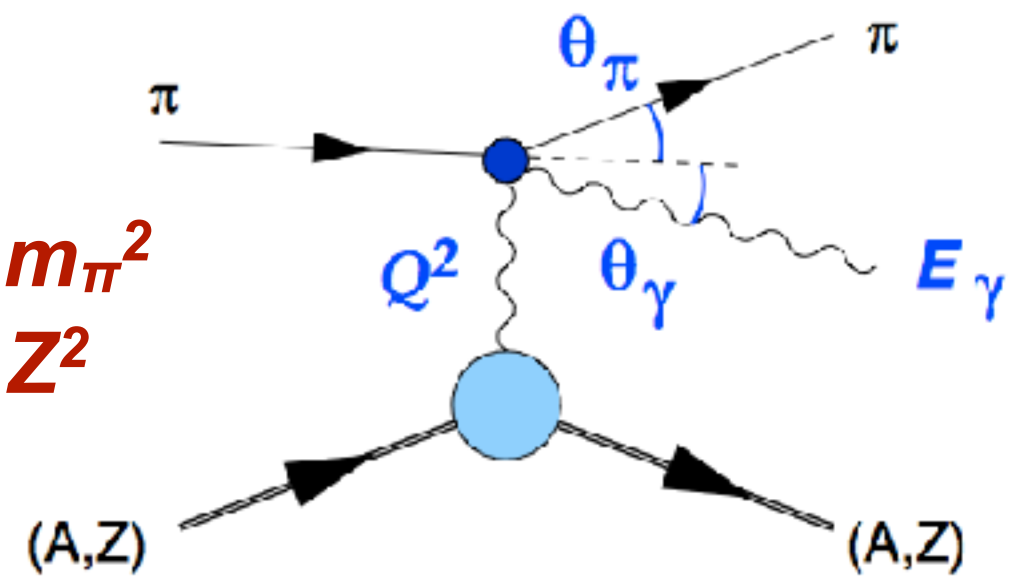
Polarizabilities and cross section

$$\frac{d\sigma}{ds\,dt\,dQ^2} = \frac{Z^2\alpha}{\pi(s-m_\pi^2)}\cdot F_{\text{eff}}^2(Q^2)\cdot\frac{Q^2-Q_{\text{min}}^2}{Q^4}\cdot\frac{d\sigma_{\pi\gamma}}{dt}$$

$$Q_{\text{min}} = (s-m_\pi^2)/2E_{\text{beam}}$$

$Q^2 \ll m_\pi^{\;2}$

$\sigma \sim Z^2$



Compton cross section:

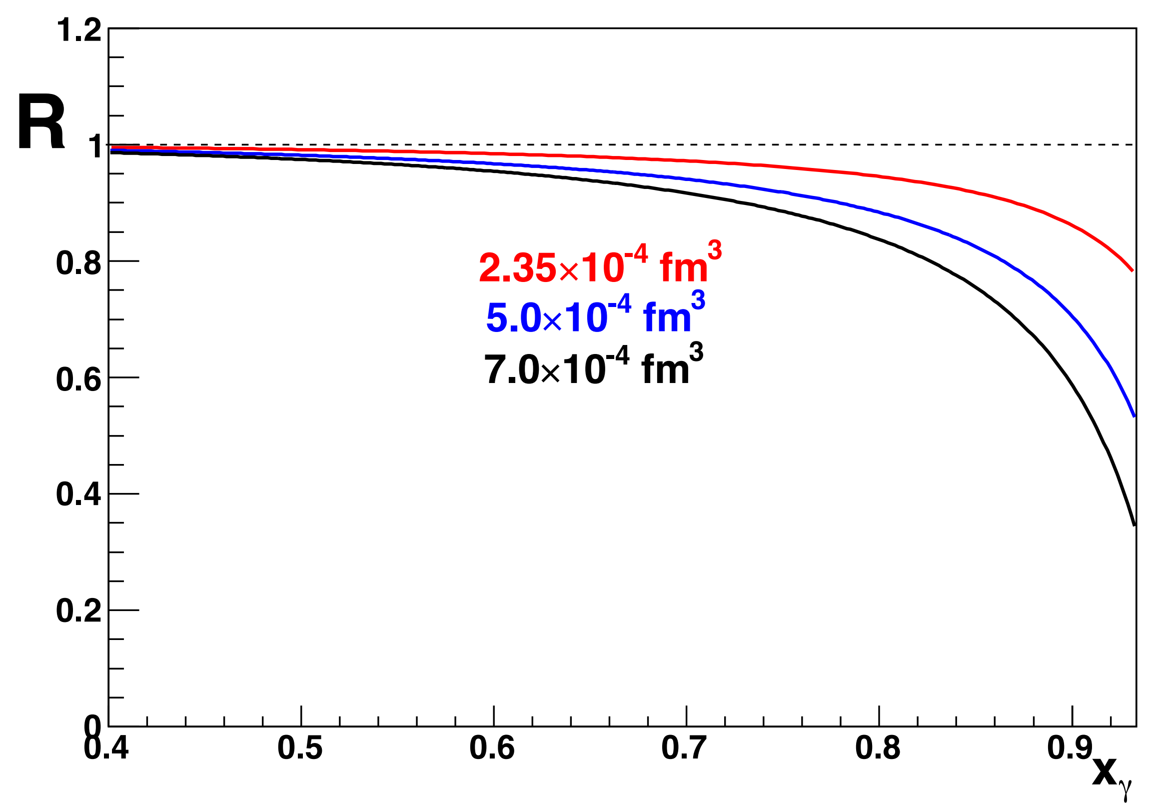
$$\frac{d\sigma_{\pi\gamma}}{d\Omega_{cm}} = \frac{\alpha^2(s^2z_+^2+m_\pi^4z_-^2)}{s(sz_++m_\pi^2z_-)^2} - \frac{\alpha\, m_\pi^3\,(s-m_\pi^2)^2}{4s^2(sz_++m_\pi^2z_-)}\cdot\mathcal{P}$$

$$z_\pm = 1\pm\cos\theta_{cm}$$

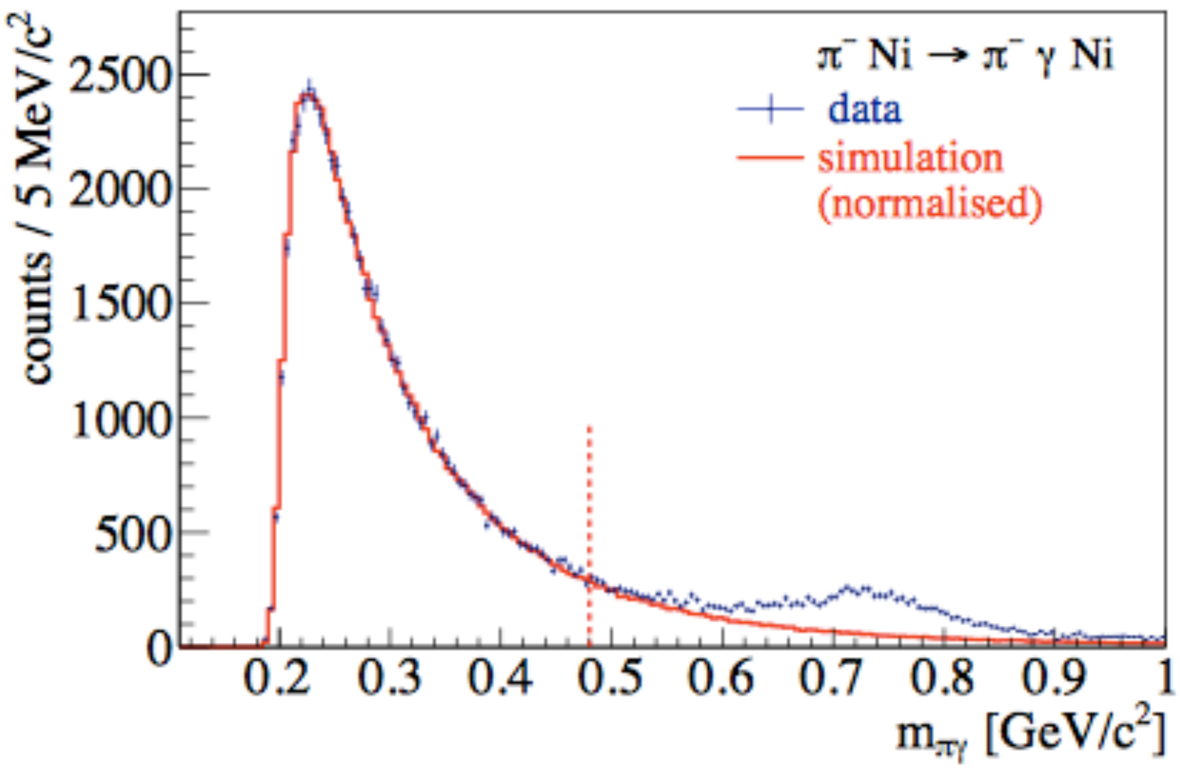
$$\mathcal{P} = z_-^2(\alpha_\pi-\beta_\pi)+\frac{s^2}{m_\pi^4}z_+^2(\alpha_\pi+\beta_\pi)$$

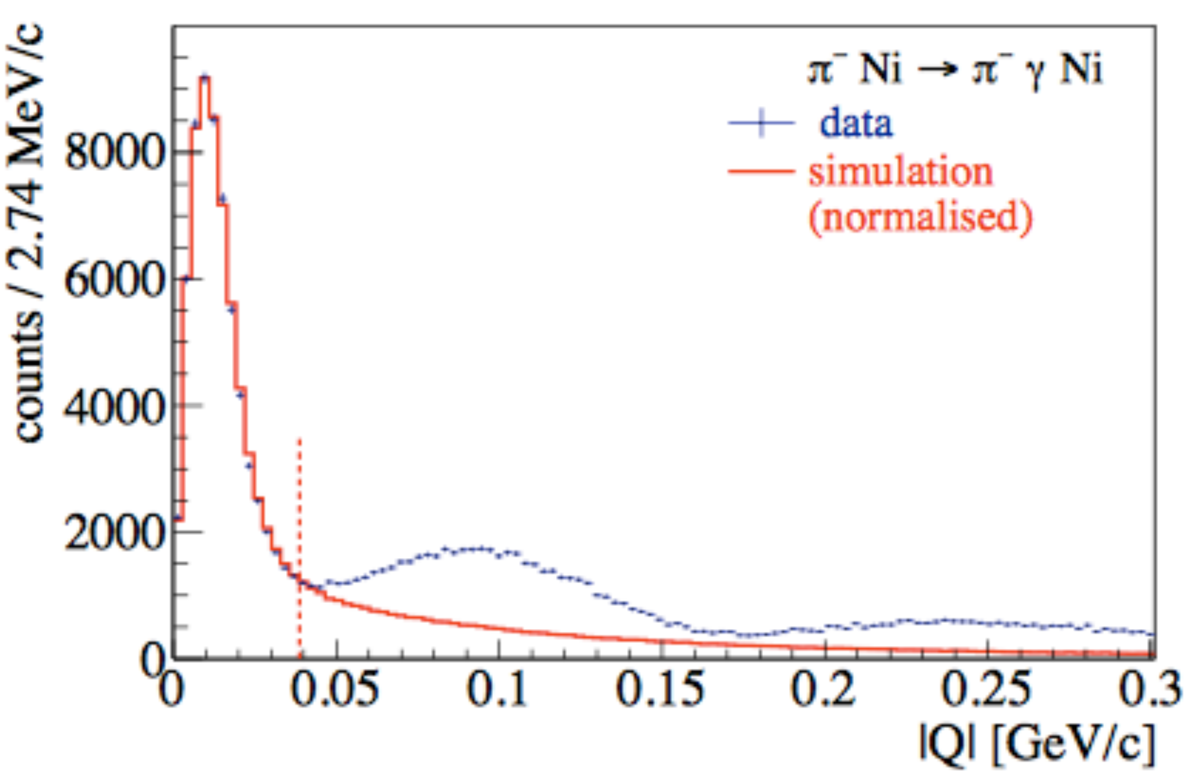
For the case $\alpha_\pi+\beta_\pi=0$:

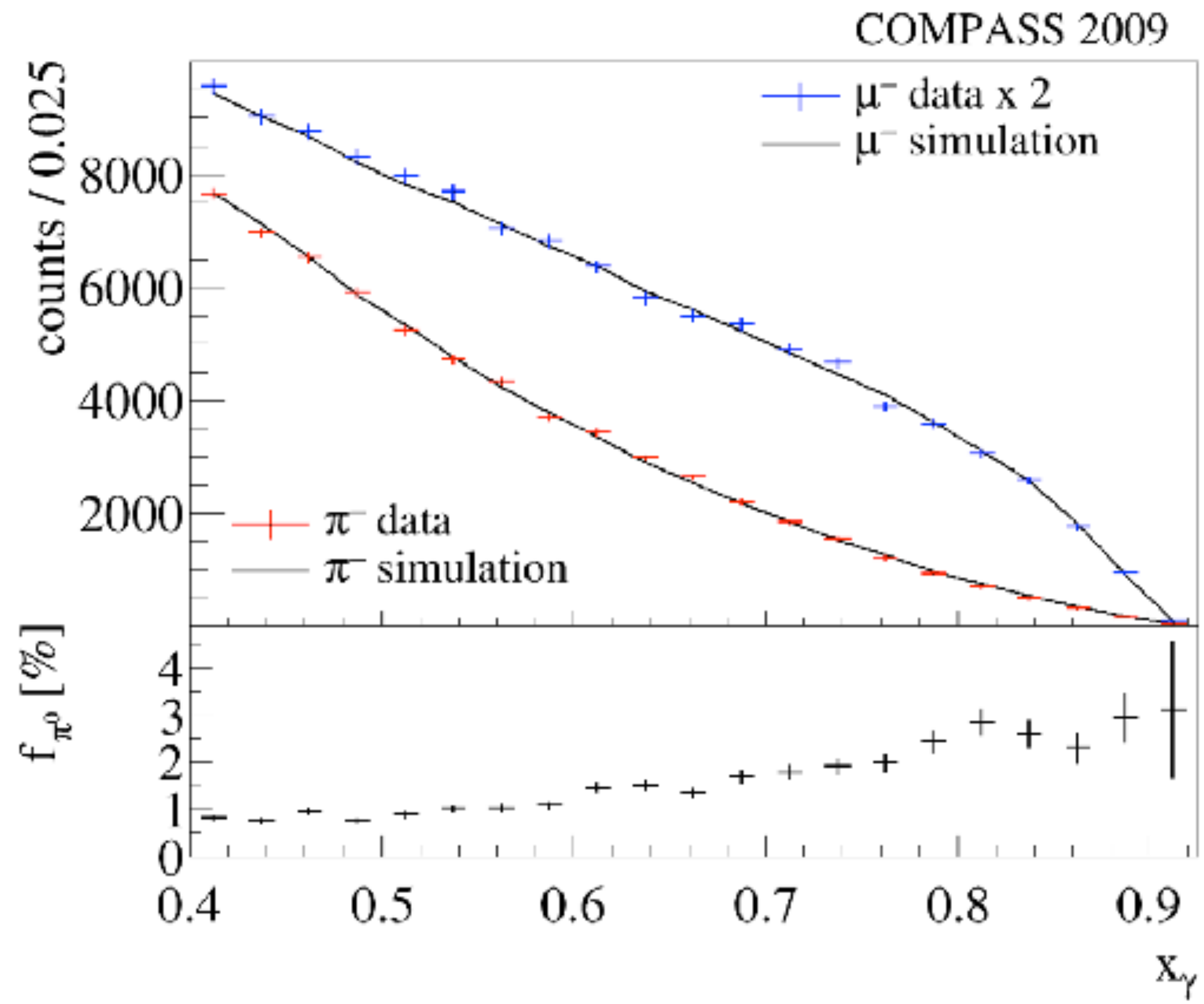
$$\mathbf{R} = \frac{\sigma}{\sigma_{\text{p.l.}}} \approx 1-\frac{3}{2}\cdot\frac{x_\gamma^2}{1-x_\gamma}\cdot\frac{m_\pi^3}{\alpha}\cdot\alpha_\pi$$



The measured kinematic distributions



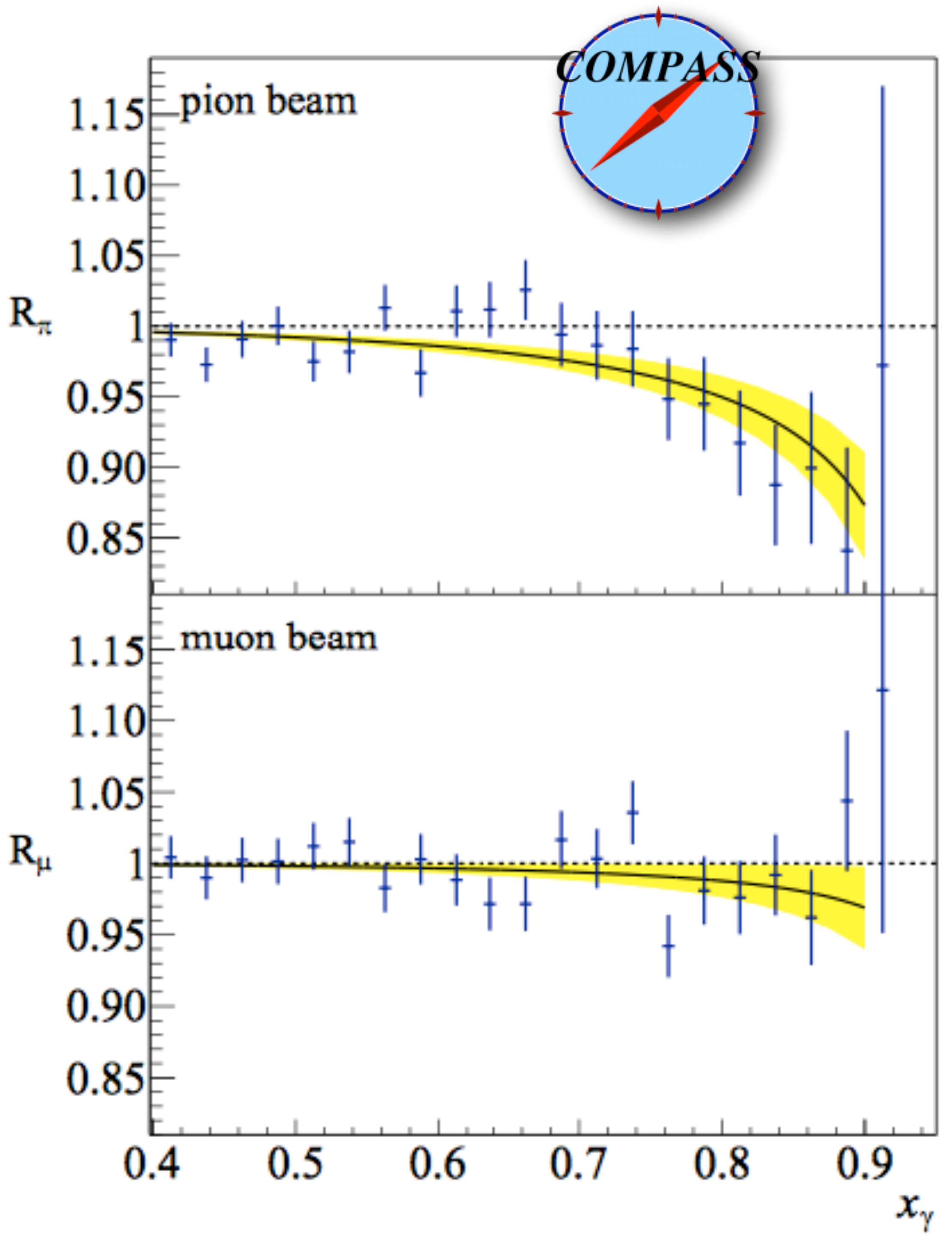




Background from the reaction $\pi^-Ni \rightarrow \pi^-Ni\ \pi^0$ is subtracted

The COMPASS result

Protvino: $\alpha_\pi = -\beta_\pi = (6.8 \pm 1.4_{stat} \pm 1.2_{syst}) \times 10^{-4}\ fm^3$, ***χPT:*** $\alpha_\pi \approx 2.8 \times 10^{-4}\ fm^3$



Under assumption $\alpha_\pi = -\beta_\pi$:

$\alpha_\pi = (2.0 \pm 0.6_{stat} \pm 0.7_{syst}) \times 10^{-4}\ fm^3$

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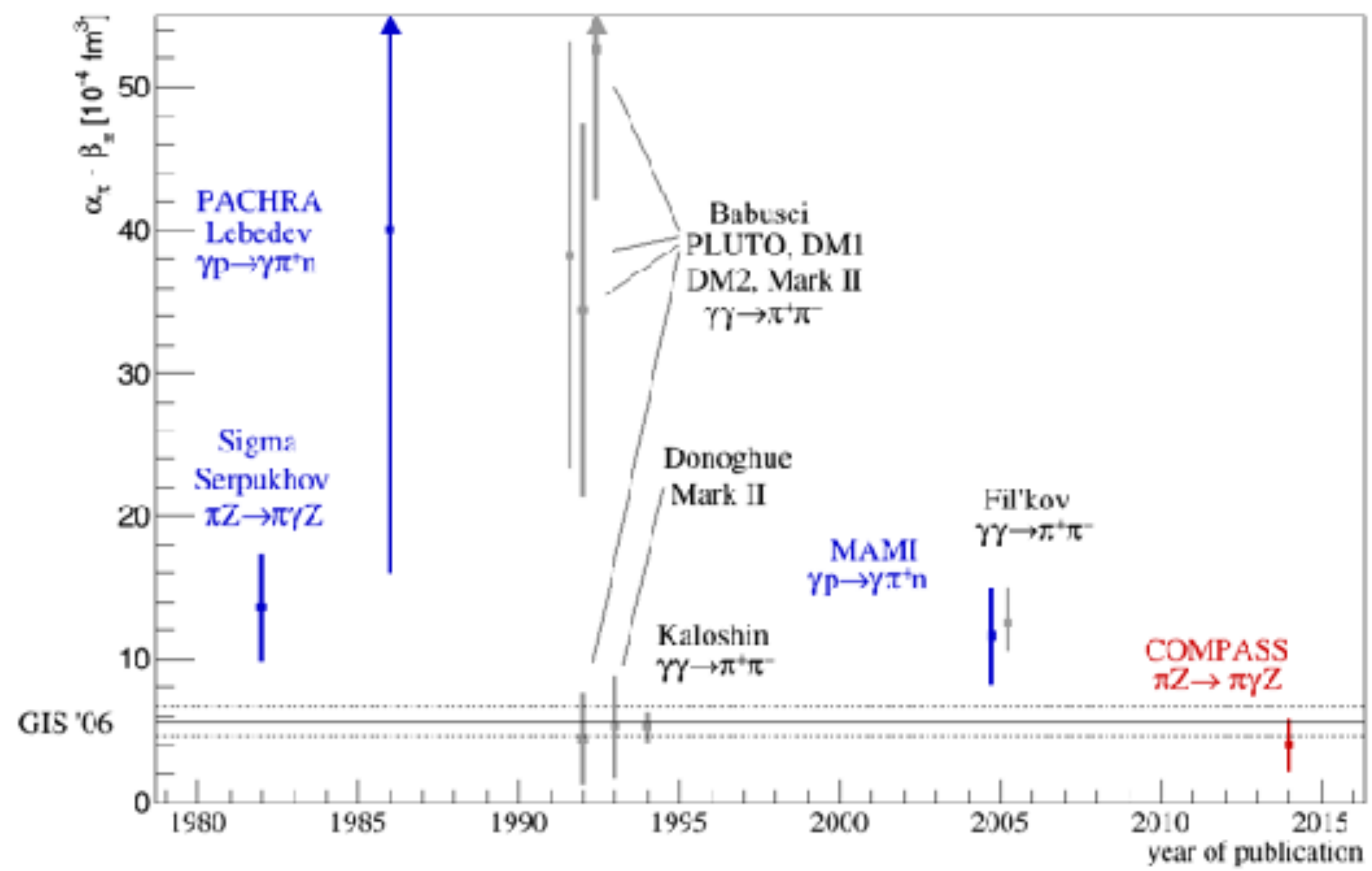
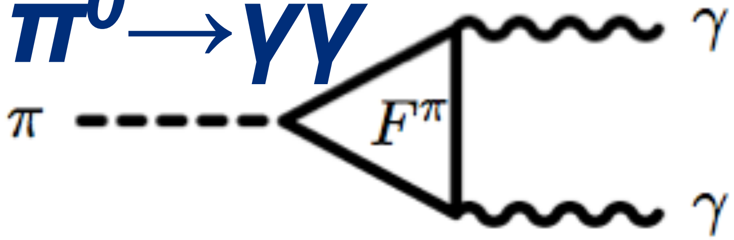


Larger statistics is under analysis.
Separate precision extraction of α_π ***and*** β_π ***is expected***

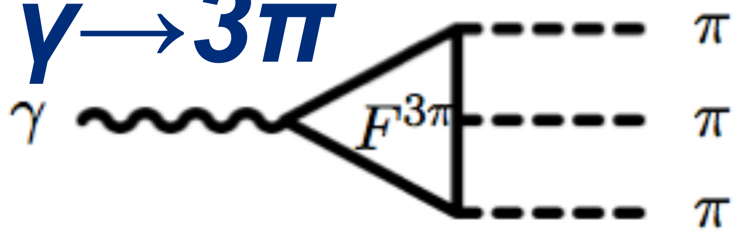
QCD chiral anomaly

Chiral anomaly: chiral symmetry on the level of the lagrangian but non conservation of chiral current

$\pi^0 \rightarrow \gamma\gamma$



$\gamma \rightarrow 3\pi$



For $\pi^-\gamma \rightarrow \pi^- \pi^0$:

$$F_{3\pi}(0,0,0) = \frac{F_\pi(0,0,0)}{ef^2}$$

Low-energy theorem:

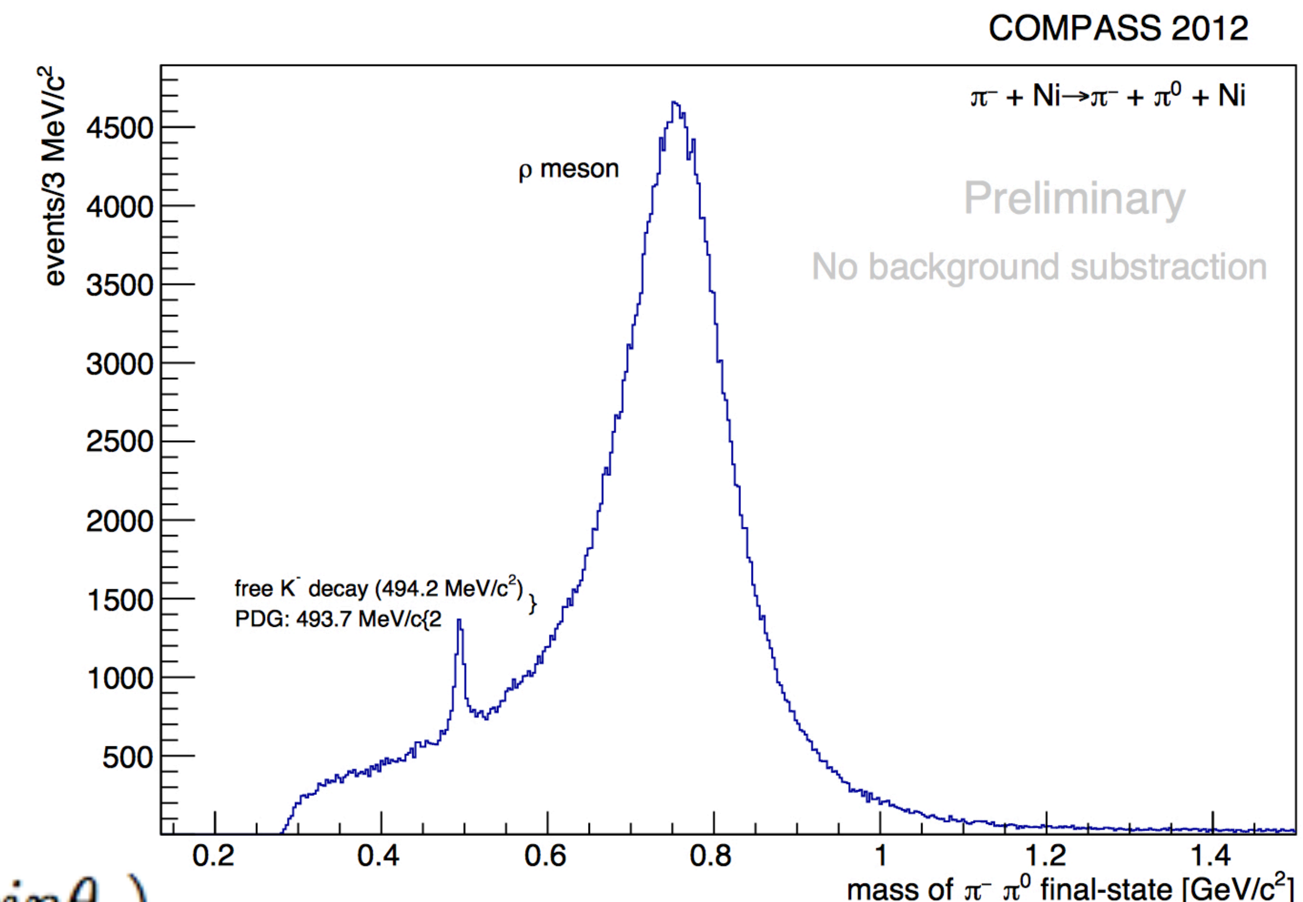
$$F_{3\pi} = \frac{eN_c}{12\pi^2 F_\pi^3} = (9.78 \pm 0.05)\,\mathrm{GeV}^{-3}$$

SIGMA (Protvino, 1987): 10.7±1.2 GeV^{-3}
π-e scattering (2005): 9.6±1.1 GeV^{-3}

For $\pi^-\gamma \rightarrow \pi^-\eta$:

$$F_{\eta\pi\pi\gamma}(0,0,0) = \frac{e}{4\pi^2 f_\pi^3}\left(\frac{f_\pi}{f_8}\frac{cos\theta_p}{\sqrt{3}} - \frac{f_\pi}{f_0}\sqrt{\frac{2}{3}}sin\theta_p\right)$$

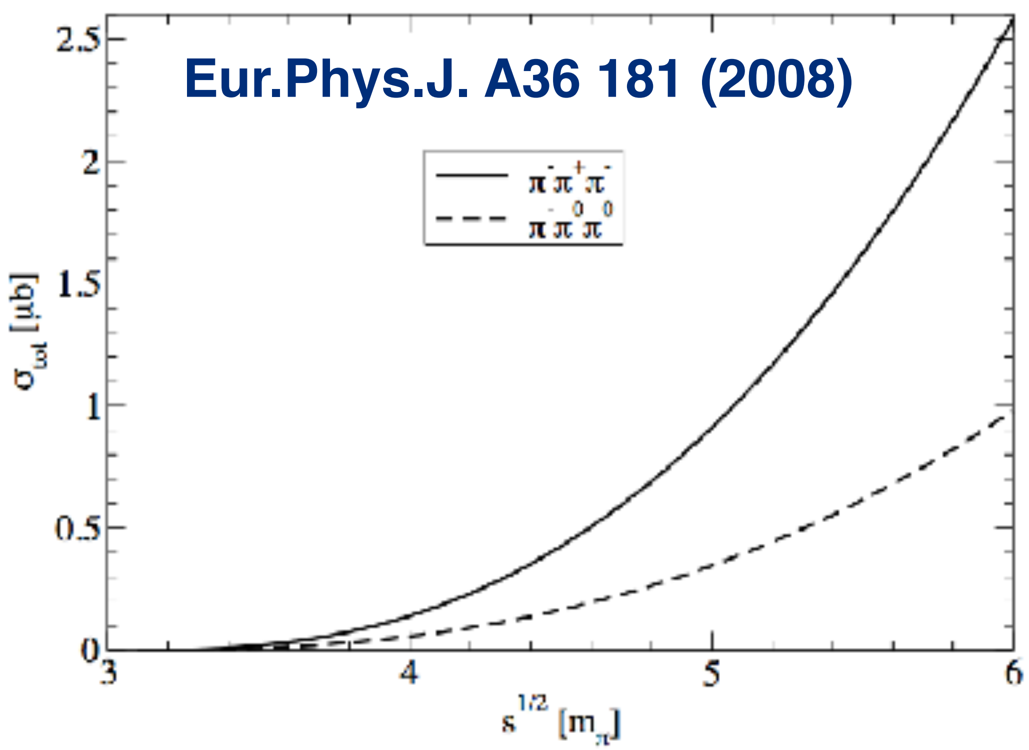
$$F_{\eta\pi\pi\gamma}(0,0,0) = 6.5 \pm 0.3\ \mathrm{GeV}^{-3}$$

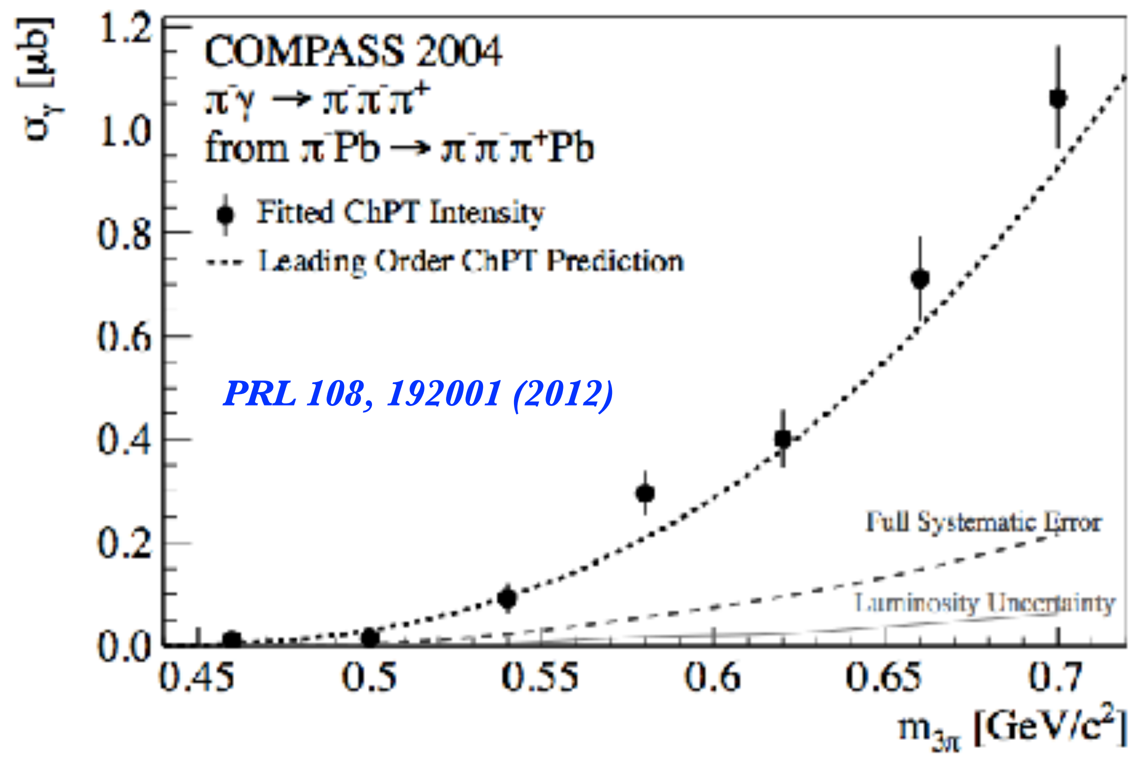


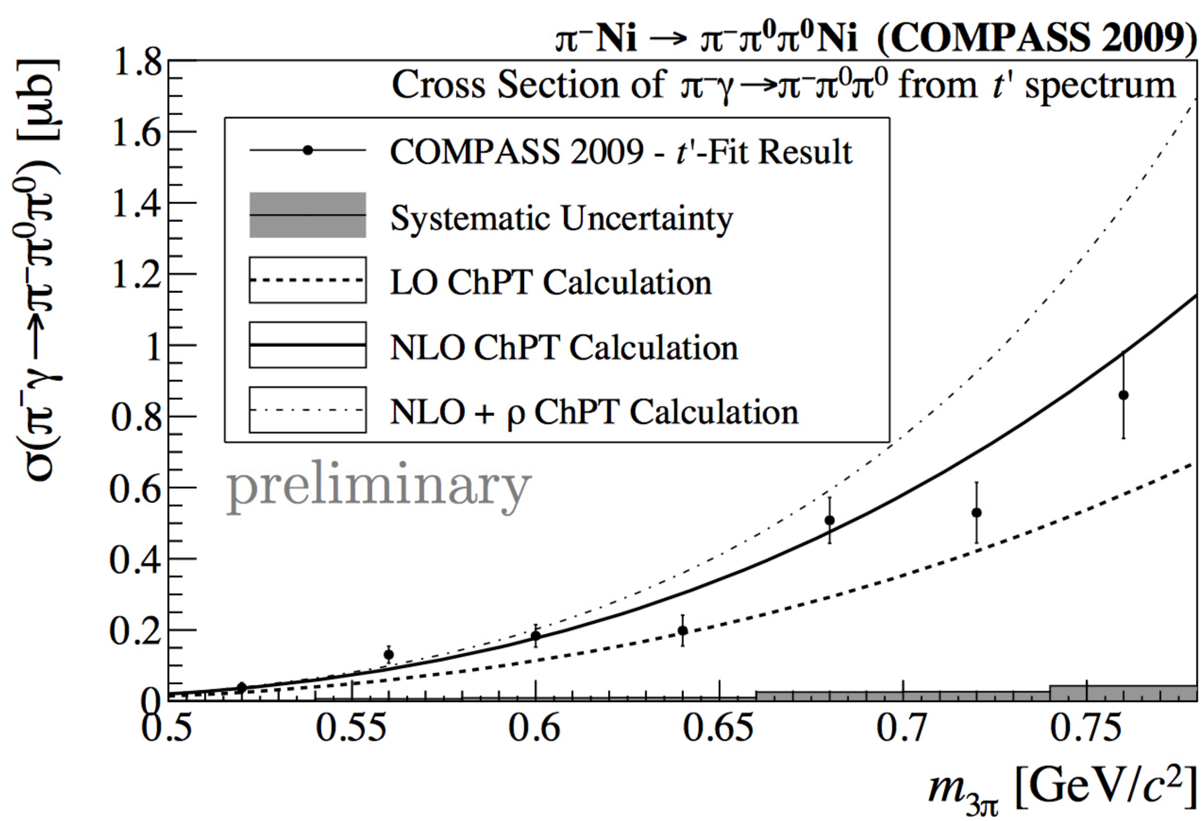
VES (Protvino, 1998): 6.9±0.7 GeV^{-3}

πγ cross sections near threshold: $\pi^- \rightarrow \pi^- \pi \pi$

χPT prediction for γπ→3π cross sections

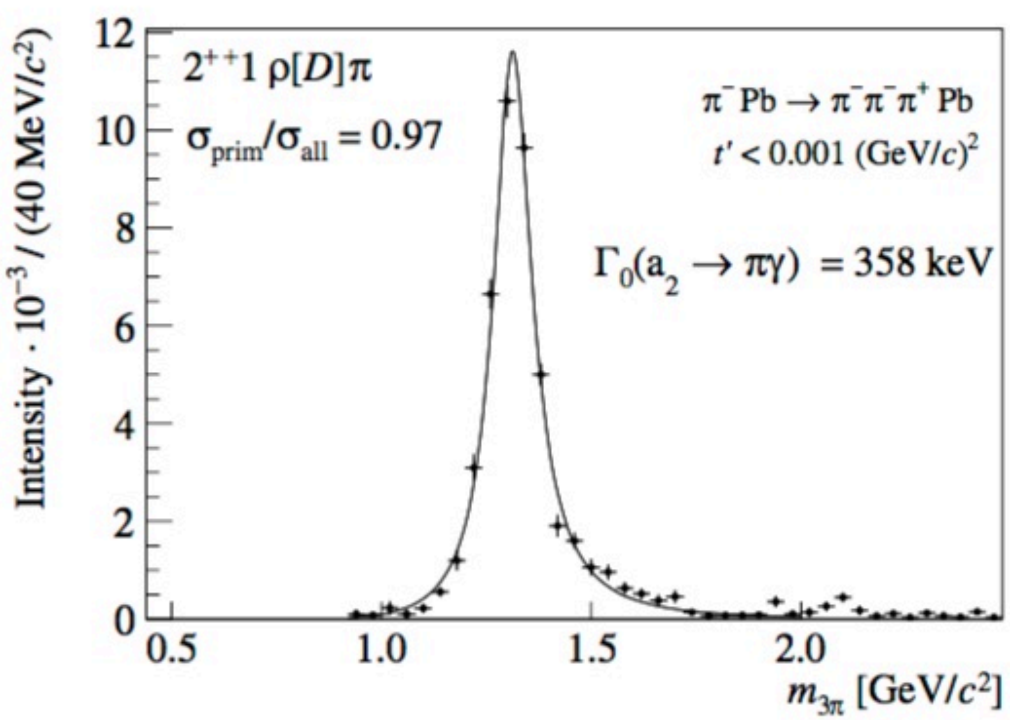


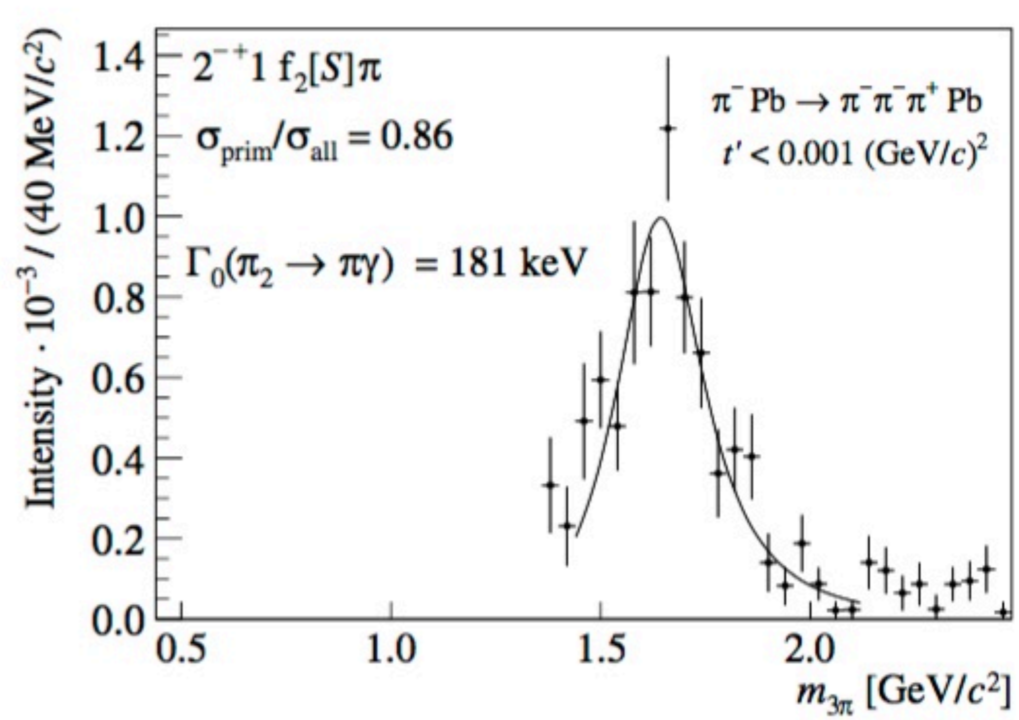




Radiative widths of mesons

$$\sigma_{\mathrm{Primakoff},X} = \int_{m_1}^{m_2} \int_0^{t'_{\max}} \frac{\mathrm{d}\sigma}{\mathrm{d}m\,\mathrm{d}t'}\,\mathrm{d}t'\,\mathrm{d}m = \Gamma_0(X \to \pi\gamma) C_X .$$





	$a_2(1320)$	$\pi_2(1670)$
This measurement	$(358 \pm 6 \pm 42)$ keV	$(181 \pm 11 \pm 27)$ keV $\cdot$ $(0.56/\mathrm{BR}_{f_2\pi})$
SELEX [21]	$(284 \pm 25 \pm 25)$ keV	*EPJA 50 (2014) 79*
S. Cihangir *et al.* [24]	(295 ± 60) keV	
E.N. May *et al.* [25]	(0.46 ± 0.11) MeV	
VMD model [1]	(375 ± 50) keV	
Relativ. Quark model [2]	324 keV	
Cov. Osc. Quark model [3]	235 keV	
Cov. Osc. Quark model [4]	237 keV	2 values: 335 keV and 521 keV

Kaon polarizabilities

Theoretical predictions:

$_\chi$PT prediction $O(p^4)$:

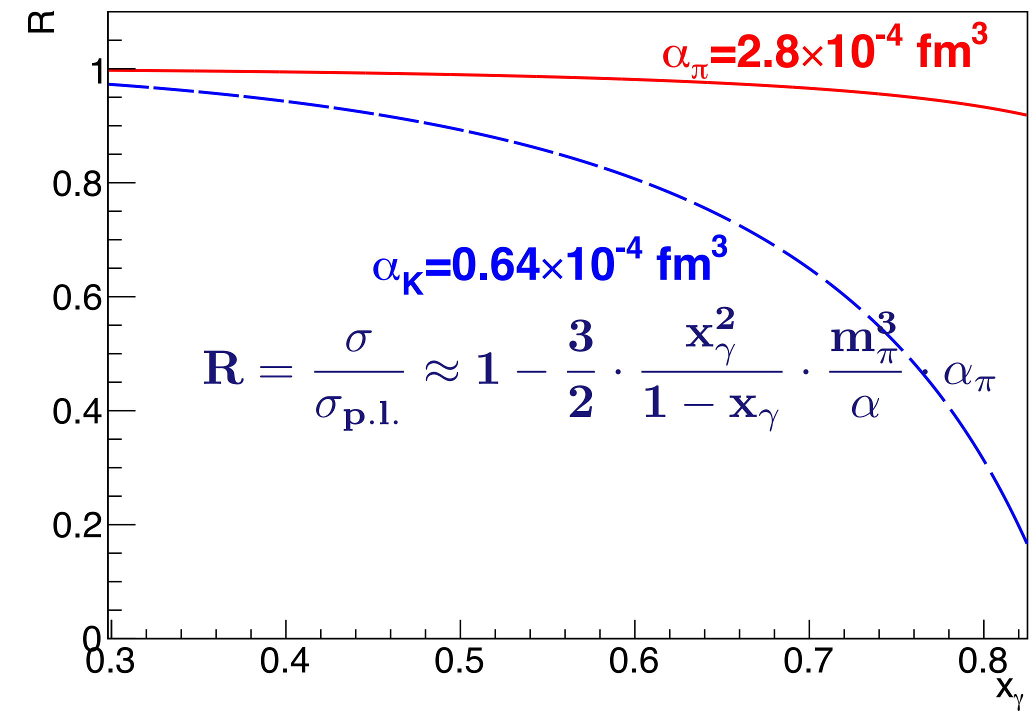
$$\alpha_K + \beta_K = 0$$

$$\alpha_K = \alpha_\pi \times \frac{m_\pi F_\pi^2}{m_K F_K^2} \approx \frac{\alpha_\pi}{5} \approx 0.6 \times 10^{-4} fm^3$$

Quark confinement model:

$$\alpha_K + \beta_K = 1.0 \times 10^{-4} fm^3$$

$$\alpha_K = 2.3 \times 10^{-4} fm^3$$



Polarization effect ~m^3

$$\sigma_{Prim} \sim \frac{1}{m^2}$$

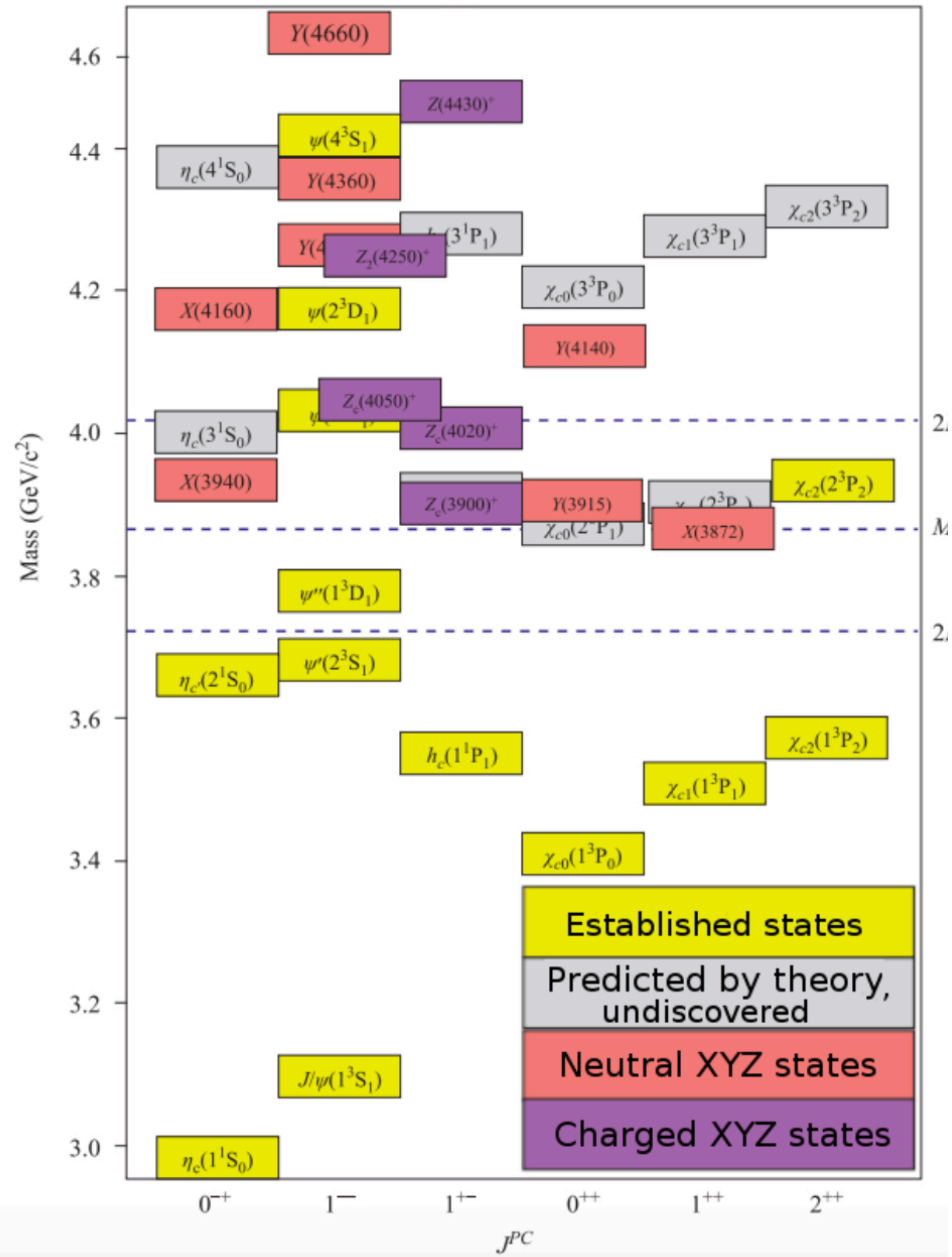
Exp. result: $\alpha_K < 200 \times 10^{-4}$ fm^3 (1973)

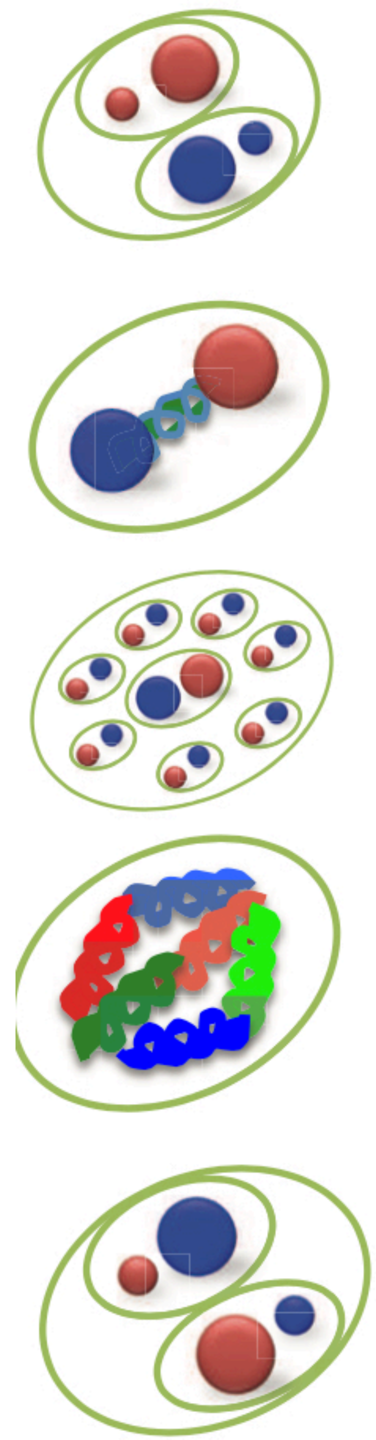
- from kaonic atoms spectra

Presently COMPASS has ~2.4% of kaons in hadron beam…

RF-separated hadron beam enriched by kaons is under discussion

Exotic charmonia





tetraquark

hybrid meson

hadro-quarkonium

glueball

molecule

...

XYZ production mechanisms

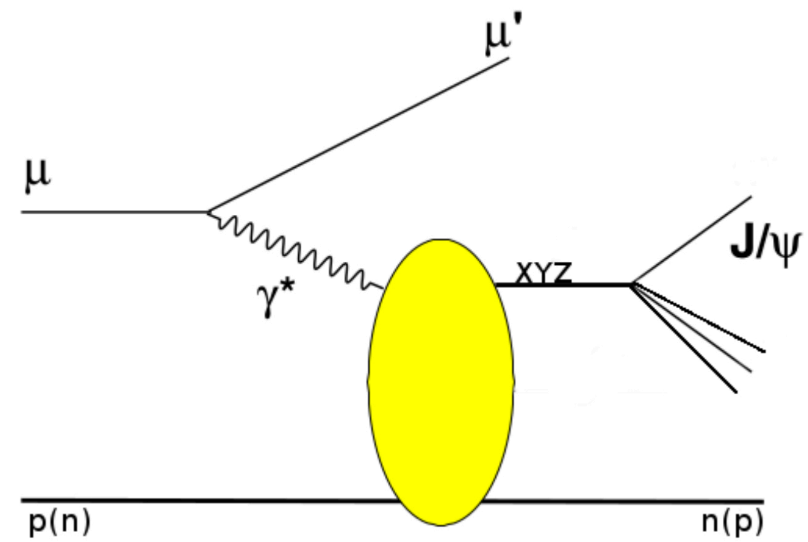
direct production in e^+e^- collisions;

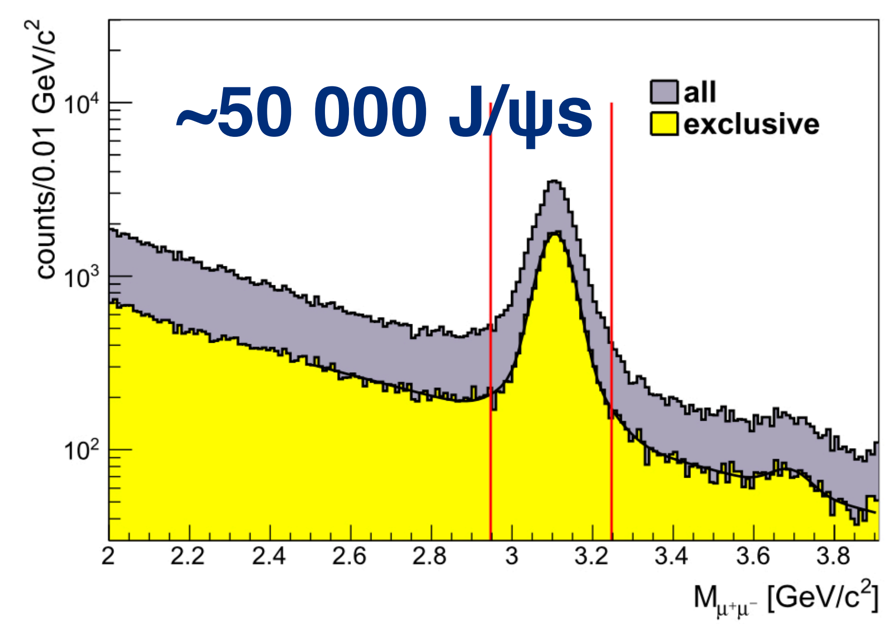
direct production in hadron collisions;

B decays;

γ*γ* collisions;

COMPASS: photo-(muo-)production off nucleon





We cover range of $\sqrt{s_{\gamma N}}$ from 6 to 19 GeV

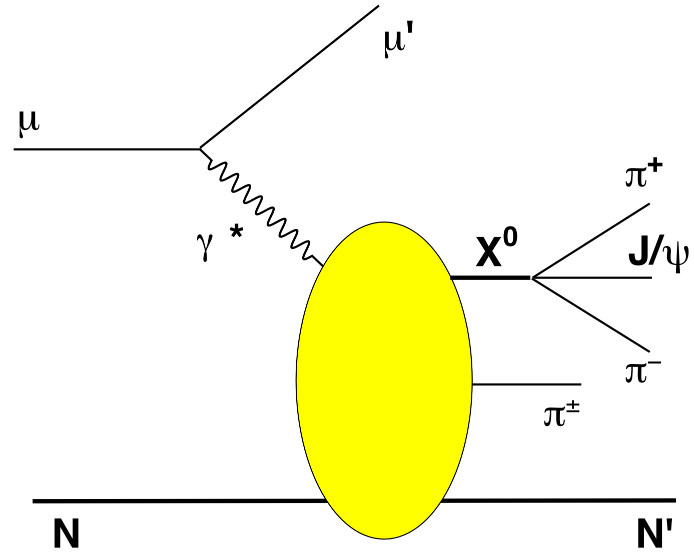
Muo(photo)production of exotic charmonia: X(3872)

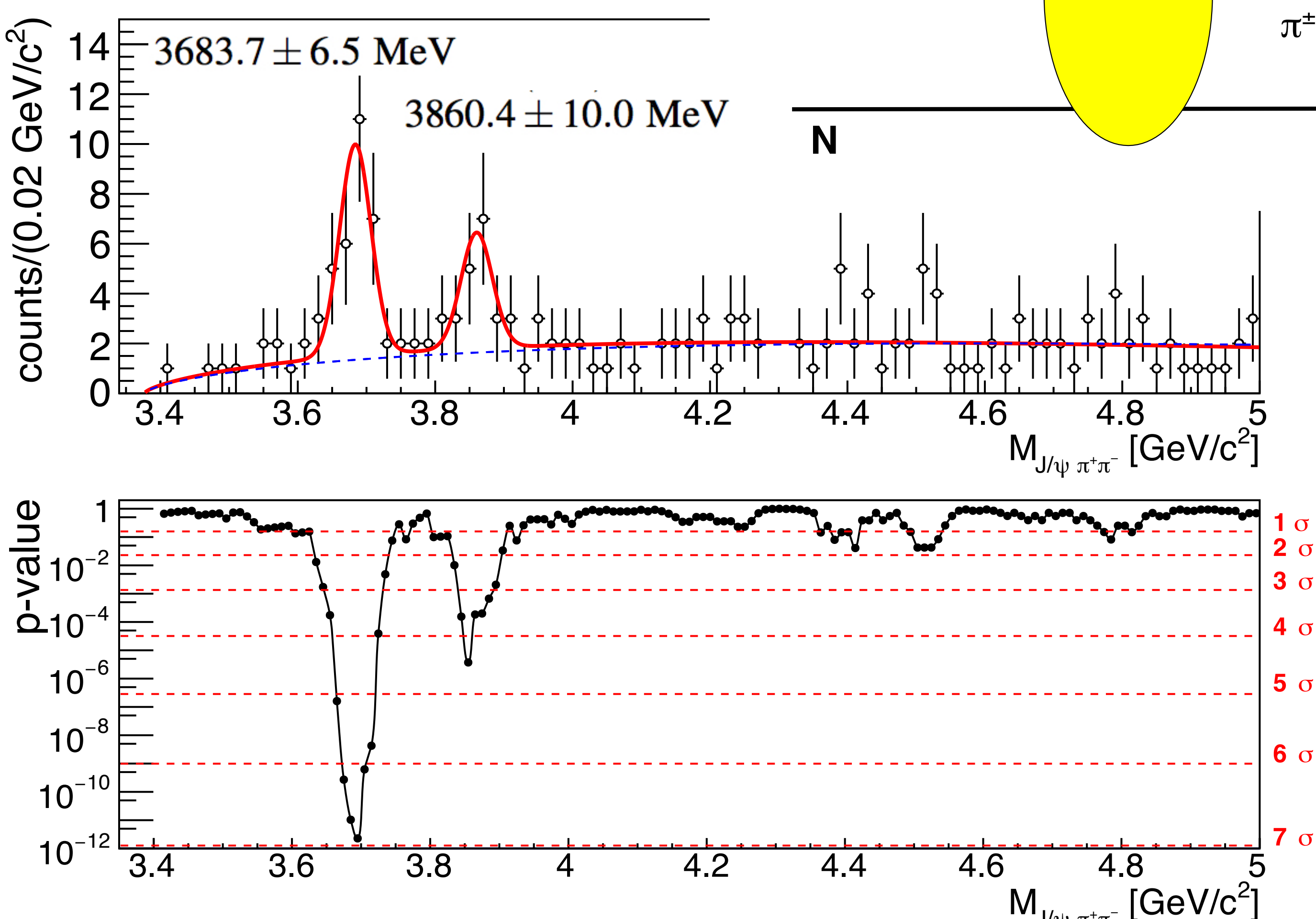
X(3872)

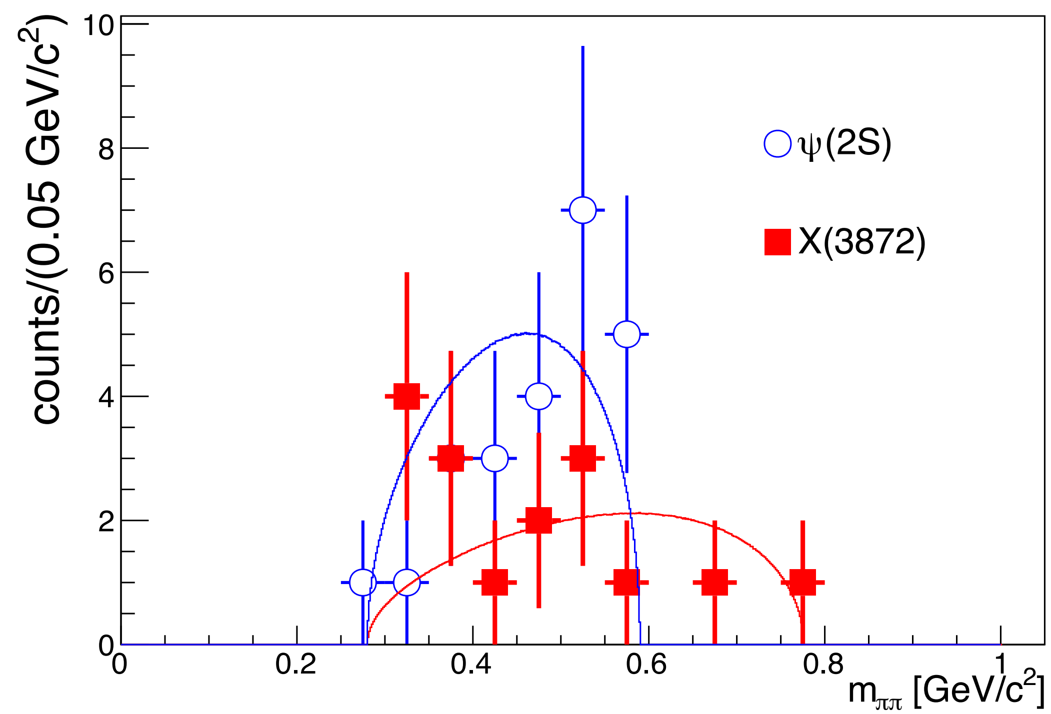
First observation of exotic charmonia in photoproduction!

$I^G(J^{PC}) = 0^+(1^{++})$

Mass $m = 3871.69 \pm 0.17$ MeV
$m_{X(3872)} - m_{J/\psi} = 775 \pm 4$ MeV
$m_{X(3872)} - m_{\psi(2S)}$
Full width $\Gamma < 1.2$ MeV, CL = 90%



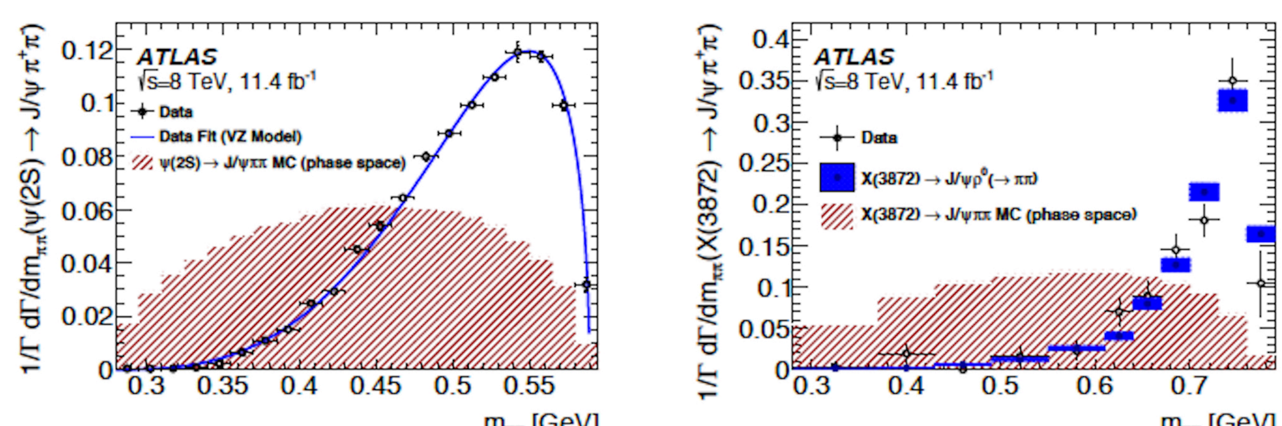




13.2±5.2 X(3872) events

$$\sigma_{\gamma N \to X(3872)\pi N'} \times \mathcal{B}_{X(3872)\to J/\psi\pi\pi} = 71 \pm 28(\text{stat}) \pm 39(\text{syst})\ \text{pb}$$

COMPASS result for dipion mass spectrum is in tension with previous observations:



ATLAS: ψ(2S) and X(3872)

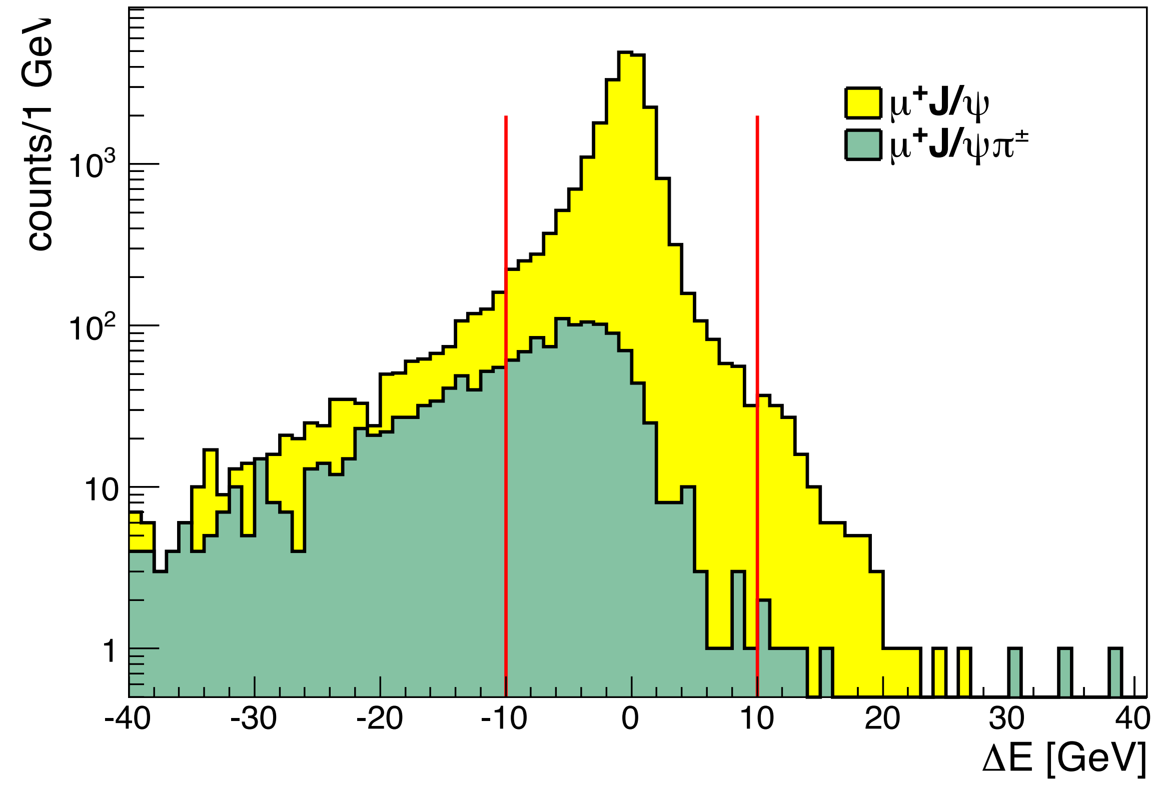
Muo(photo)production of exotic charmonia: $Z_c(3900)$

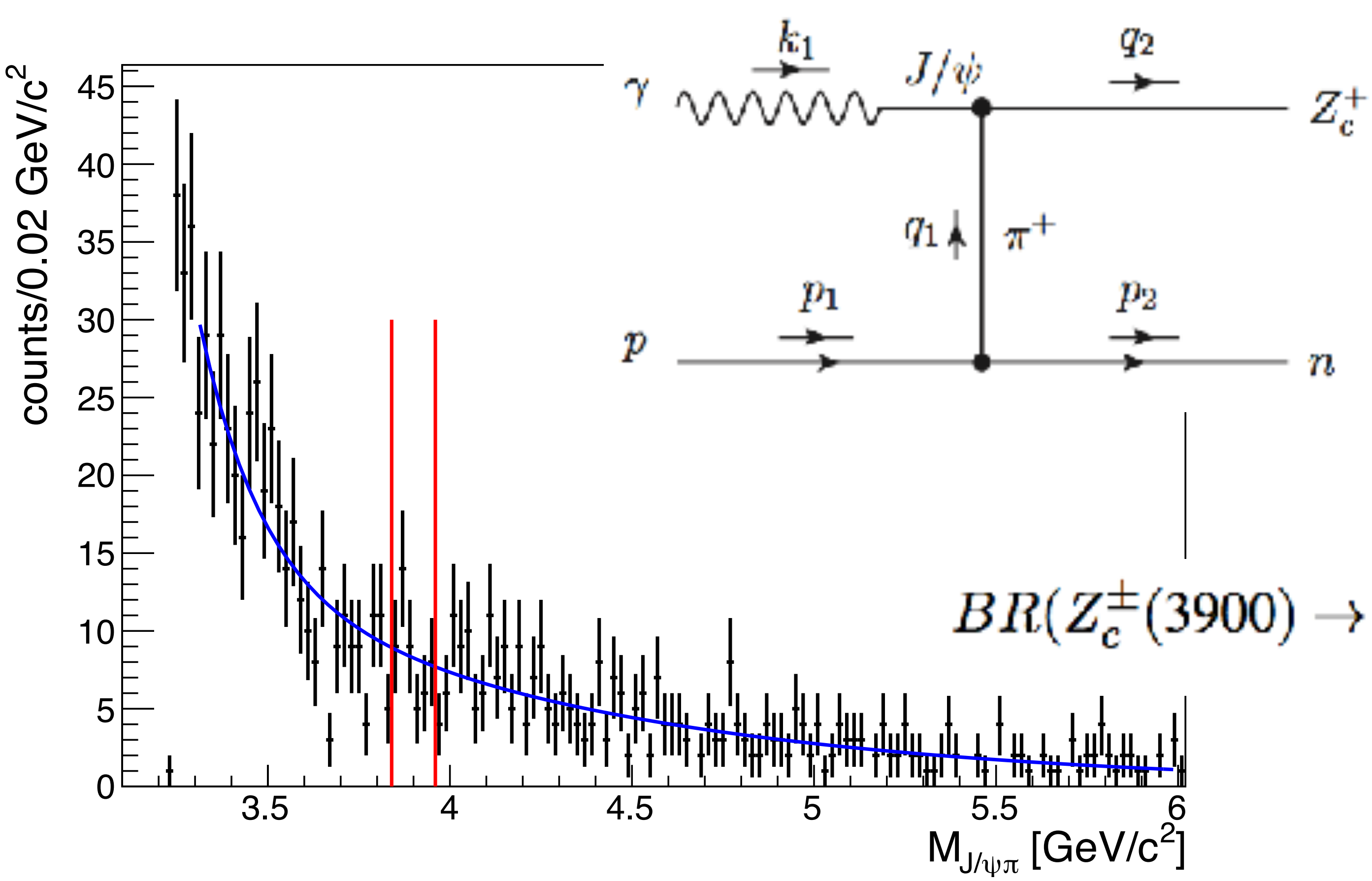
$X(3900)$

$$I^G(J^{PC}) = 1^+(1^{+-})$$

Mass $m = 3886.6 \pm 2.4$ MeV (S = 1.6)
Full width $\Gamma = 28.1 \pm 2.6$ MeV

7 years (2002-2011) of data taking with muon beam and nuclear target (^{6}LiD and NH_3)





$$BR(Z_c^{\pm}(3900) \to J/\psi\pi^{\pm}) \times \sigma_{\gamma\ N \to Z_c^{\pm}(3900)\ N}\Big|_{\langle\sqrt{s_{\gamma N}}\rangle = 13.8\ \text{GeV}} < 52\ \text{pb}.$$

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SUMMARY

- ***Low-t reactions provide unique possibility to study processes induced by photons. Study of such reactions is one of the main goals of the COMPASS experiment. Main directions of low-t studies at COMPASS are:***
    - *pion and kaon polarizabilities;*
    - *chiral anomaly study;*
    - *meson radiative width;*
    - *$\sigma_{\pi\gamma}$ dynamics for ChPT tests.*

- ***Exclusive photoproduction of exotic charmonia off a nuclear target is a new opportunity to clarify nature of the XYZ states. COMPASS performed:***
    - *first search for exclusive photoproduction of the $Z_c(3900)$;*
    - *first observation of photoproduction of the X(3872)*
    - *more results are expected*