Hadron Spectroscopy at COMPASS

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International Workshop XXXIX on Gross Properties of Nuclei and Nuclear Excitations

Hirschegg

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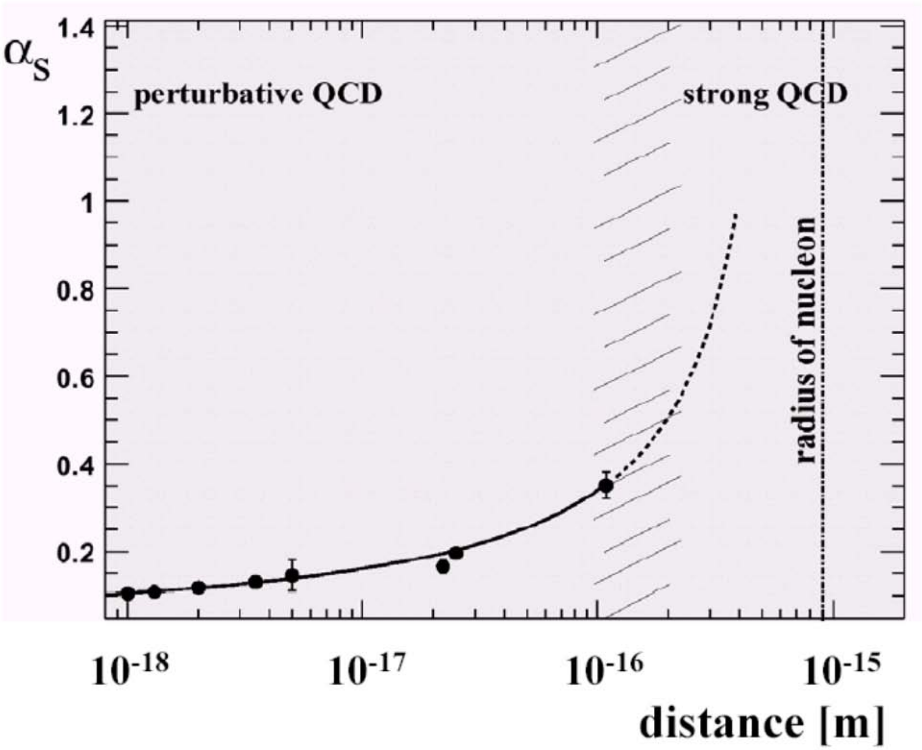
Thank you very much for the dinner

The Goal

Understand hadrons from the dynamics of quarks and gluons



⇨ **non-perturbative regime of QCD**

- Models: QM, bag, flux tube, ...
- Effective theories: χPT, ...
- Lattice-QCD

Experimental Tools

Deep Inelastic Lepton Scattering
and related hard e.m. processes

Nucleon Structure
- Helicity
- Transversity
- GPDs

Spectroscopy

QCD Bound States
- Mass spectrum
- Gluonic excitations
- Multi-quark systems

Processes at low Q^2

Hadron Structure at Low Energies
- Polarizabilities
- Chiral anomaly

$$\lambda = 1 / \sqrt{Q^2}$$

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QCD Bound States
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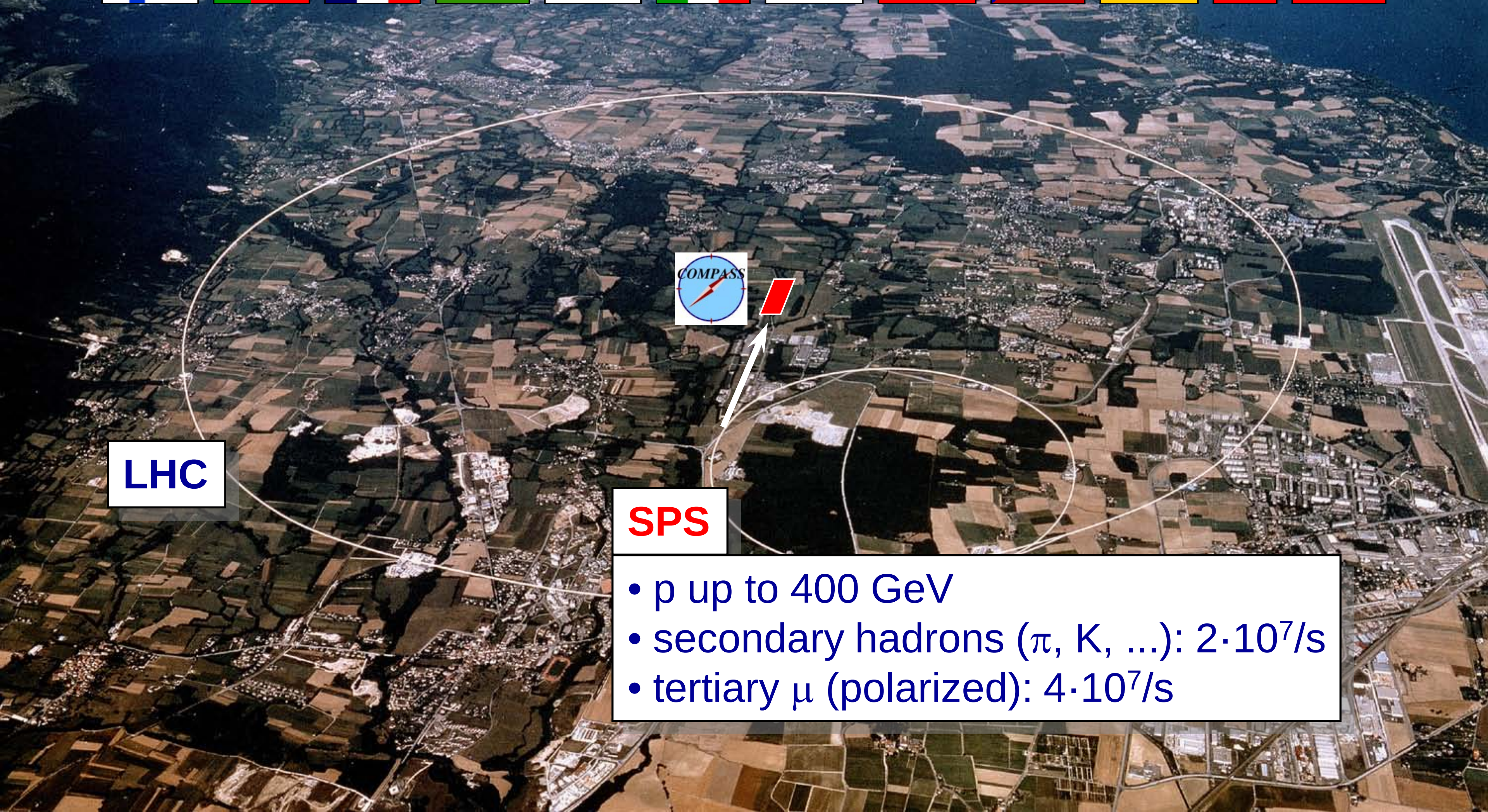
Processes at low Q^2

Hadron Structure at Low Energies
- Photoproduction
- Polarizabilities
- Chiral anomaly

$$\lambda = 1/\sqrt{Q^2}$$

COMPASS at CERN

COmmon **M**uon and **P**roton **A**pparatus for **S**tructure and **S**pectroscopy

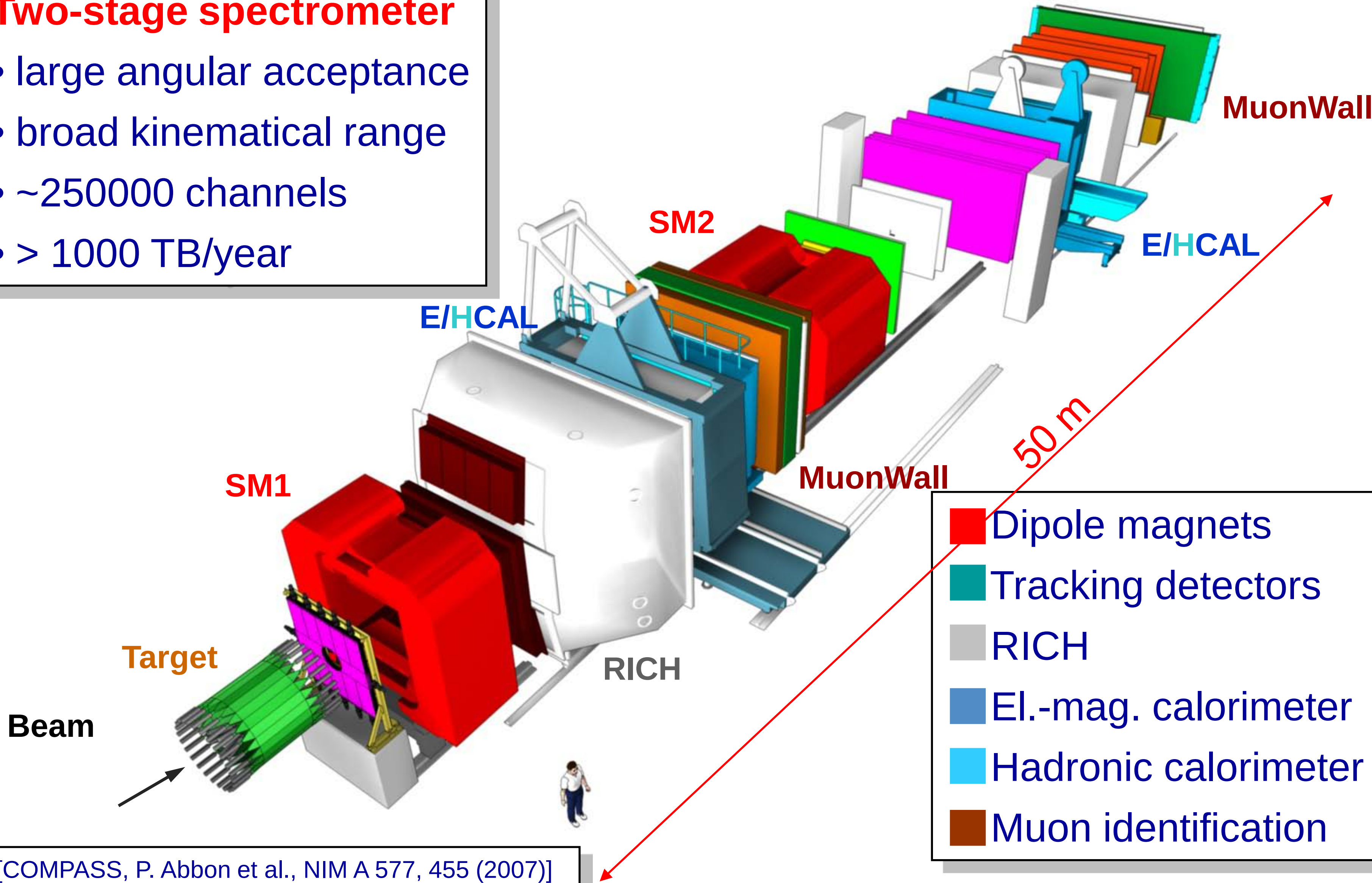


- p up to 400 GeV
- secondary hadrons (π, K, ...): $2\cdot10^7$/s
- tertiary μ (polarized): $4\cdot10^7$/s

The COMPASS Experiment

Two-stage spectrometer

- large angular acceptance
- broad kinematical range
- ~250000 channels
- > 1000 TB/year



- Dipole magnets
- Tracking detectors
- RICH
- El.-mag. calorimeter
- Hadronic calorimeter
- Muon identification

[COMPASS, P. Abbon et al., NIM A 577, 455 (2007)]

The COMPASS Experiment

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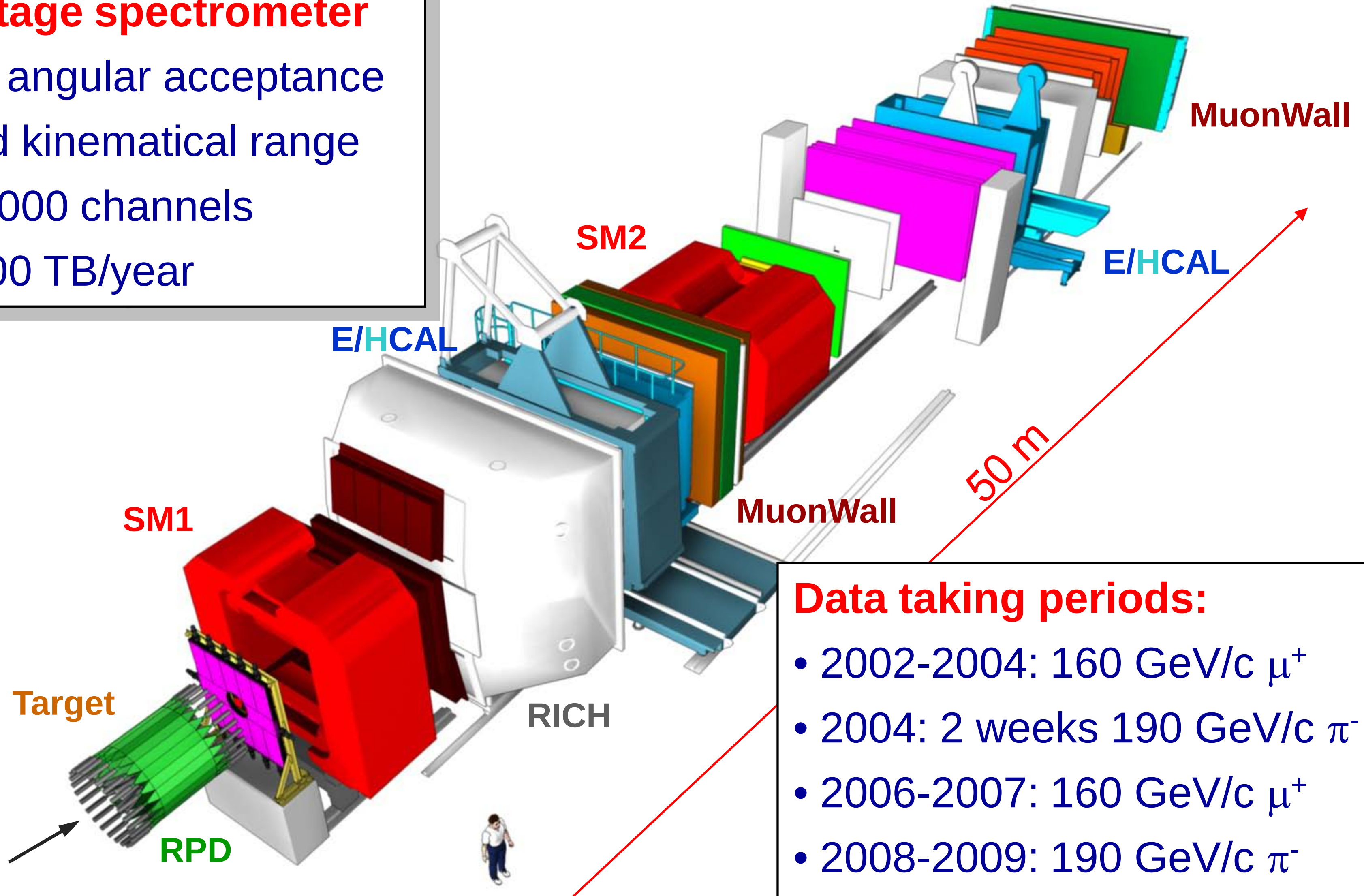
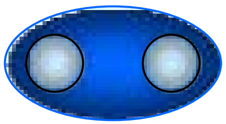


Data taking periods:

- 2002-2004: 160 GeV/c μ^+
- 2004: 2 weeks 190 GeV/c π^-
- 2006-2007: 160 GeV/c μ^+
- 2008-2009: 190 GeV/c π^-
- 2010: 160 GeV/c μ^+

[COMPASS, P. Abbon et al., NIM A 577, 455 (2007)]

QCD Bound States

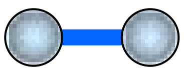


Quark model: bound state of $q\bar{q}$

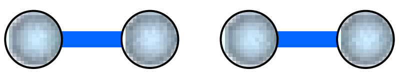
Quantum numbers: $I^G\,(J^{PC})$

$$P = (-1)^{L+1}\,,\; C = (-1)^{L+S}\,,\; G = (-1)^{I+L+S}$$

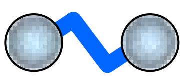
=

 $(q\bar{q})_0$

+

 $(q\bar{q})(q\bar{q})$

+

 $(q\bar{q})_8\,g$

+ Hybrids

 gg

Glueballs

+ ...

QCD: other color-neutral configurations with same quantum numbers ⇨ mixing

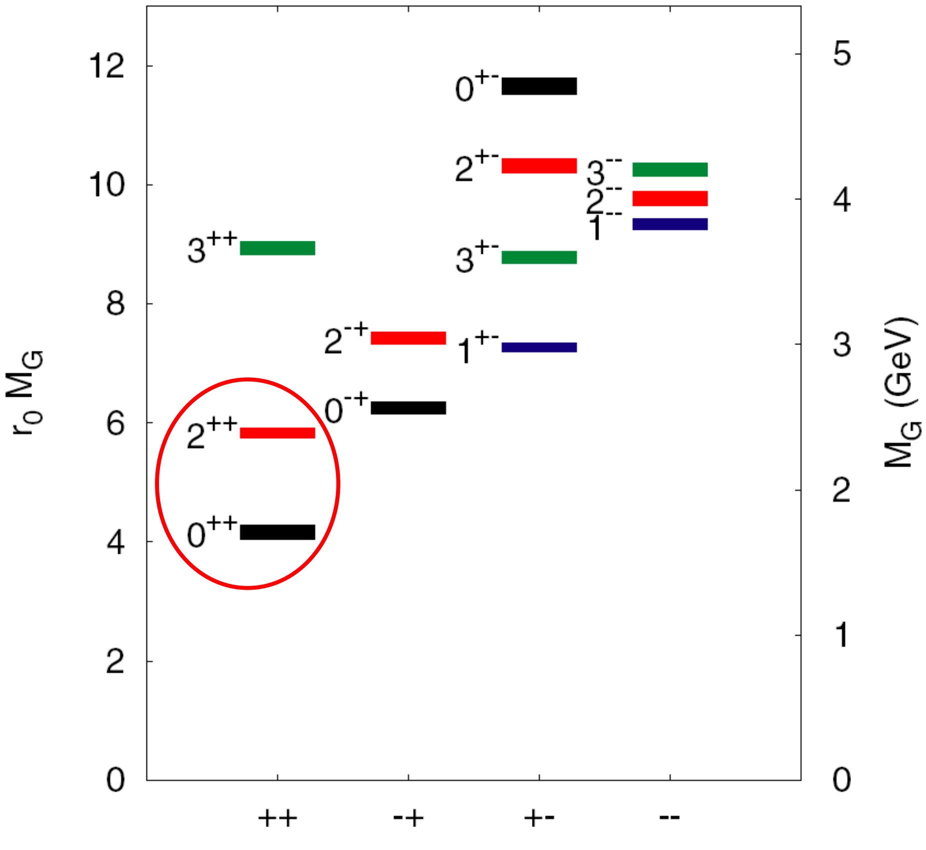
Decoupling only possible for

- narrow states
- vanishing leading $q\bar{q}$ term

⇨ exotic $J^{PC}: 0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, \ldots$

Glueballs

Quenched L-QCD prediction



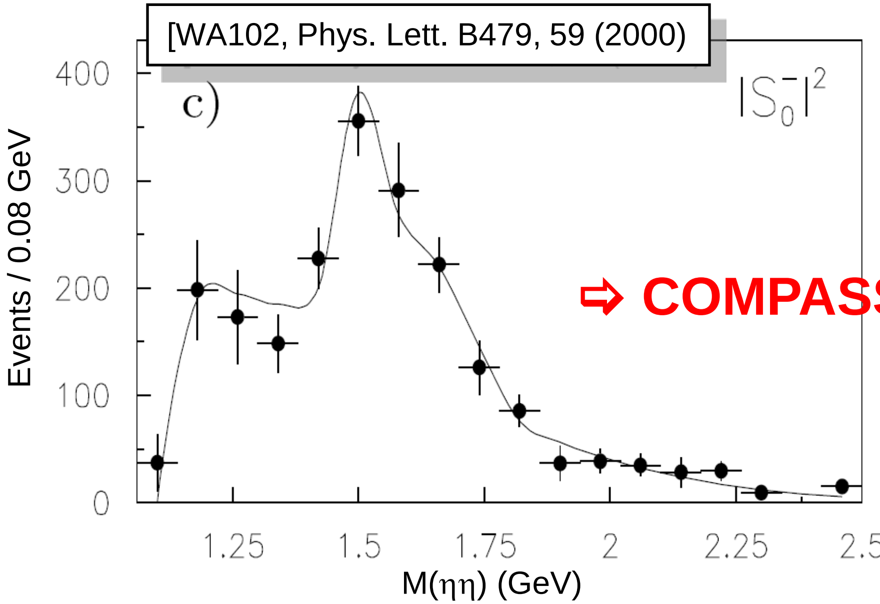
[Y. Chen et al., Phys. Rev. D 73, 014516 (2006)]

Lightest glueballs:

- $M \sim 1.7\,\mathrm{GeV}/c^2\ (J^{PC} = 0^{++})$
- $M \sim 2.4\,\mathrm{GeV}/c^2\ (J^{PC} = 2^{++})$

Experimental candidate:

- $f_0(1500)$ (Crystal Barrel, WA102)
  $J^{PC}=0^{++}$ ⇨ mixing with isoscalar mesons!



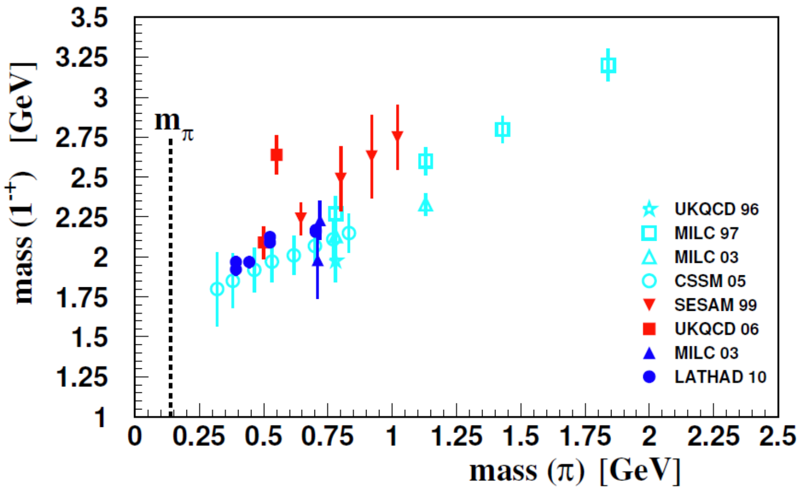
⇨ COMPASS

Hybrids with $J^{PC} = 1^{-+}$

Mass

Model	Mass (GeV/c²)	Reference
Bag Model	1.0 – 1.4	[Barnes and Close, Jaffe et al., Vainshtein et al]
QSSR	1.0 – 1.9	[Balitsky et al., Latorre et al., Narison et al.]
Flux Tube	1.8 – 2.0	[Isgur et al.]
Hamiltonian	2.1 – 2.3	[Cotanch et al.]

L-QCD predictions

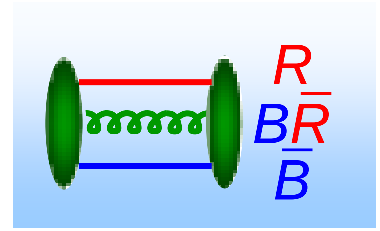


[C. Mayer, arXiv: 1004.5516v2]

Decay

Model	$b_1\pi$	$f_1\pi$	$\rho\pi$	ηp	$\eta' p$	$\eta(1295)p$	Reference
Flux Tube, $^3P_0$	170	60	5 - 20	0 - 10	0 – 10		[Isgur et al., Close et al.]
Flux Tube, IKP m=1.6 GeV/c²	24	5	9			2	[Isgur et al.]
Flux Tube, PSS m=1.6 GeV/c²	59	14	8			1	[Page et al.]
L-QCD	66	15					[McNeil and Michael]

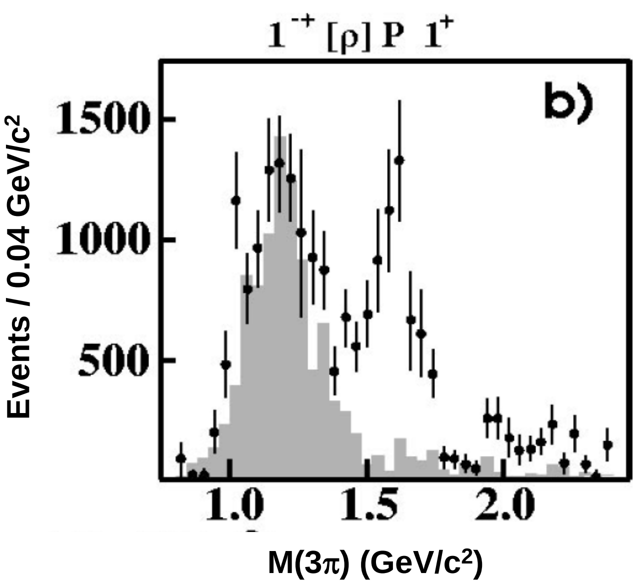
Hybrids



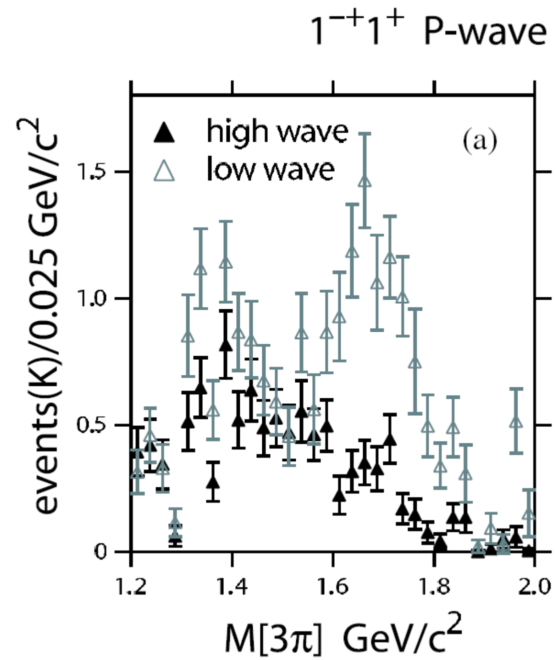
Light meson sector exotics $J^{PC}=1^{-+}$:

- π_1(1400) (E852, VES, Crystal Barrel)
- π_1(1600) (E852, VES, Crystal Barrel)
- π_1(2000) (E852)

resonant nature controversial...



[S.U. Chung et al., PRD 65, 072001 (2002)]



[A.R. Dzierba et al., PRD 73, 072001 (2006)]

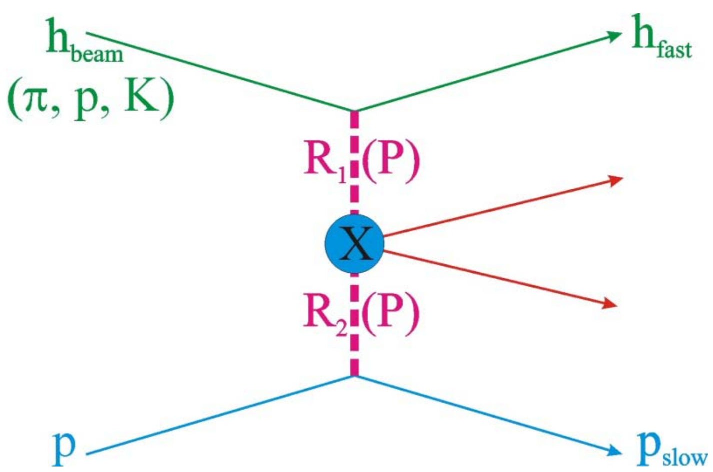
⇨ **COMPASS**

Hadron Reactions at COMPASS

Three production mechanisms

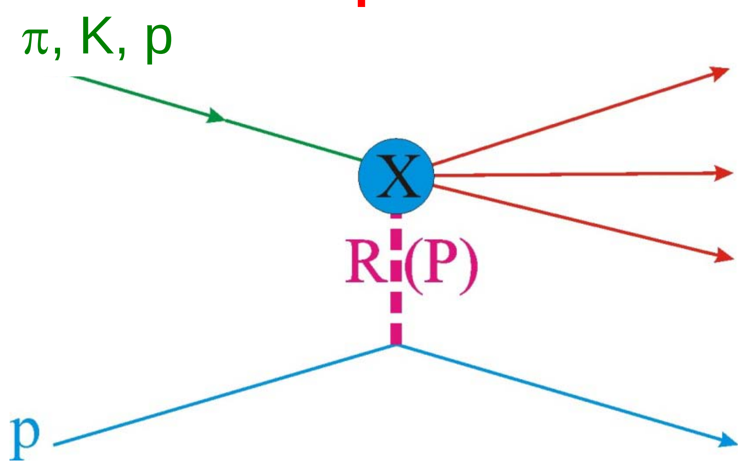
studied in parallel using **proton, pion** and **kaon** projectiles

Central production



- Double Reggeon exchange
- Rapidity gap between p_{slow}, h_{fast}, X
- Possible source of glueballs

Diffractive dissociation
Photoproduction

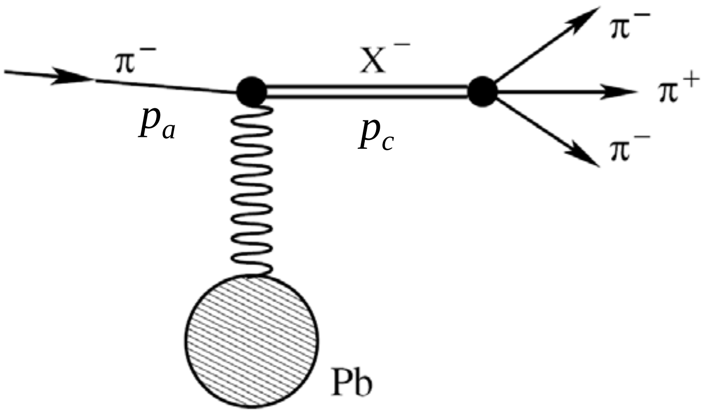


- Reggeon (Photon) exchange
- Forward kinematics
- Study of J^{PC}-exotic mesons

⇨ **Goal: 10× world statistics**

Diffractive Reactions at COMPASS

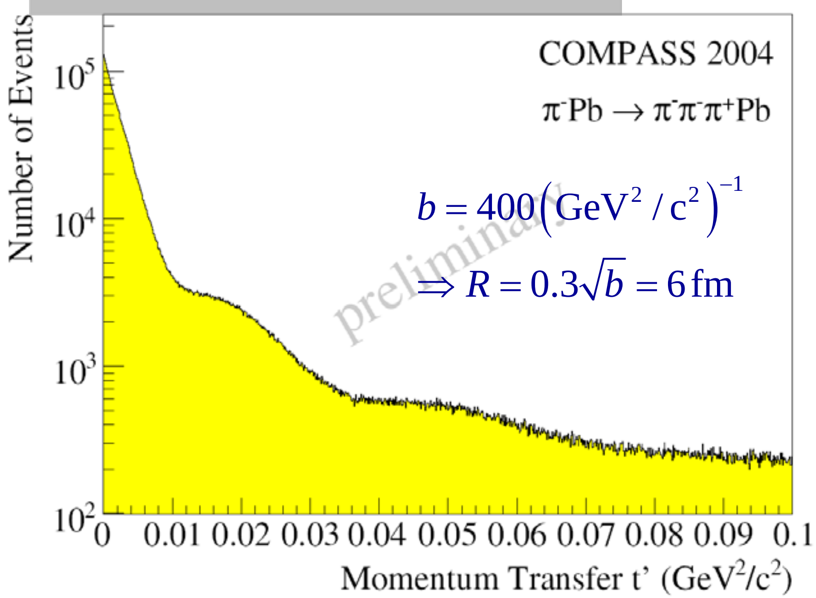
Example: $\pi^- + \text{Pb} \rightarrow \pi^-\pi^-\pi^+ + \text{Pb}$

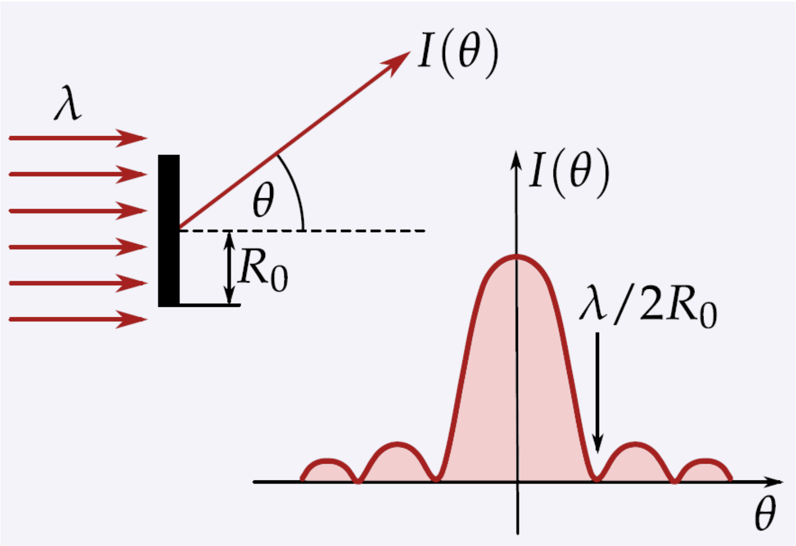


- 4π vertex in Pb target
- Exclusivity ⇨ target stays intact
- Momentum transfer

$$-t \equiv Q^2 = -(p_a - p_c)^2$$

Diffraction on Pb nuclei





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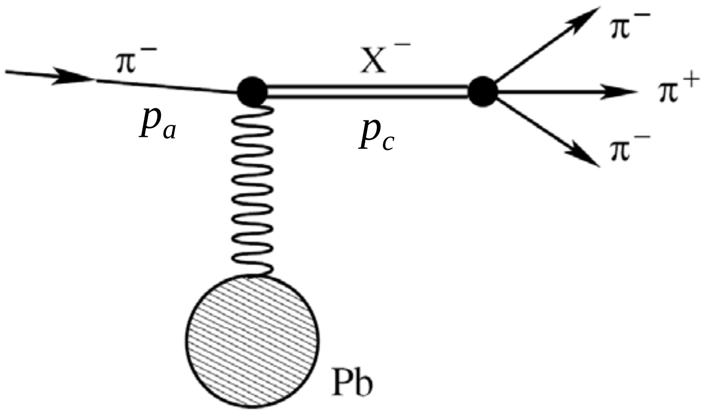

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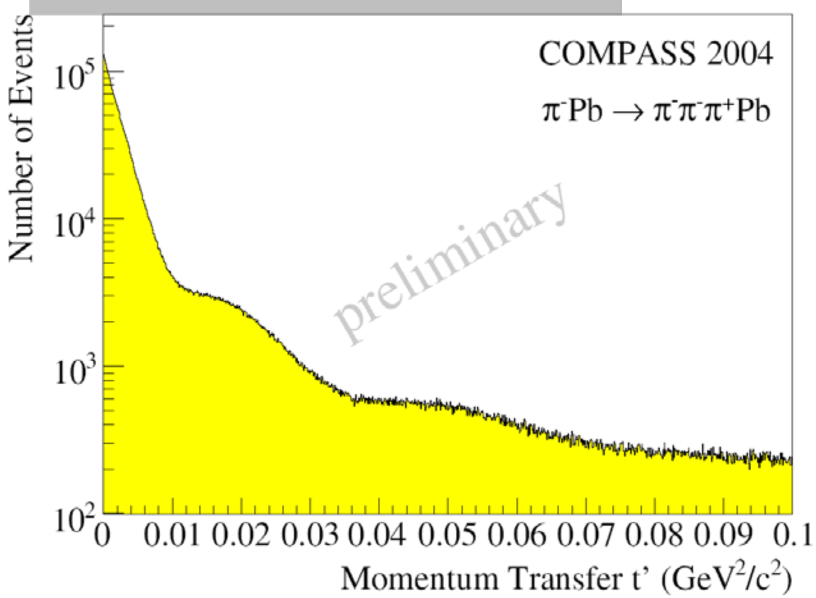
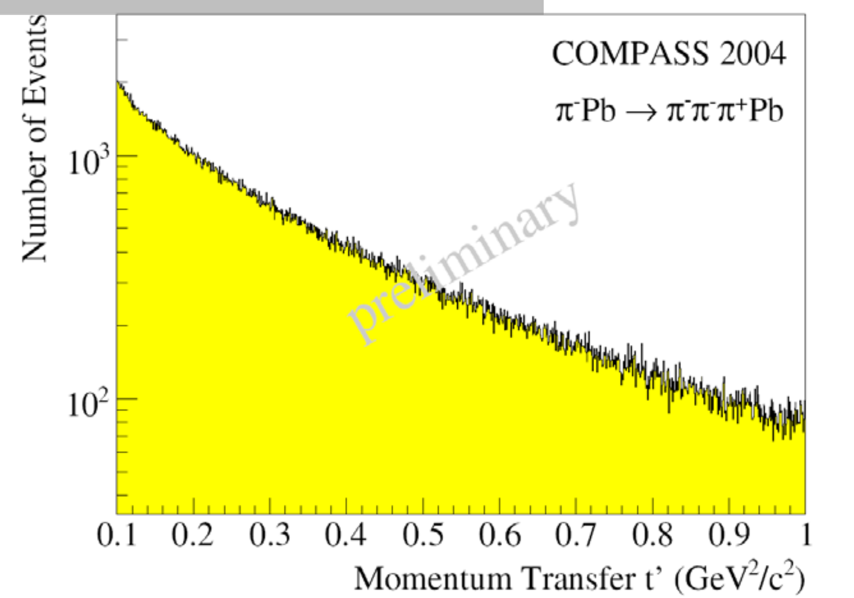


Diffraction on nucleons



Diffractive Reactions at COMPASS

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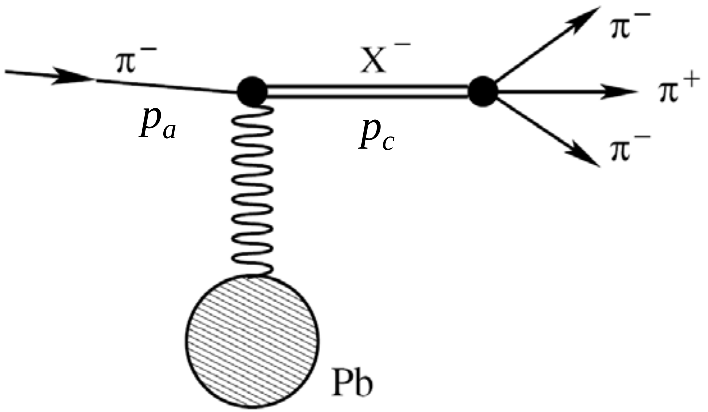
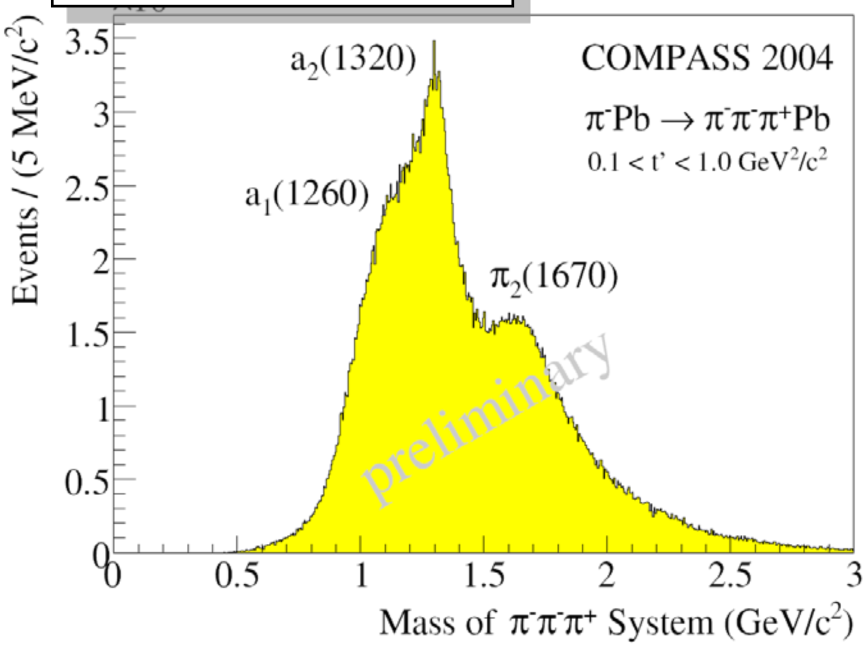
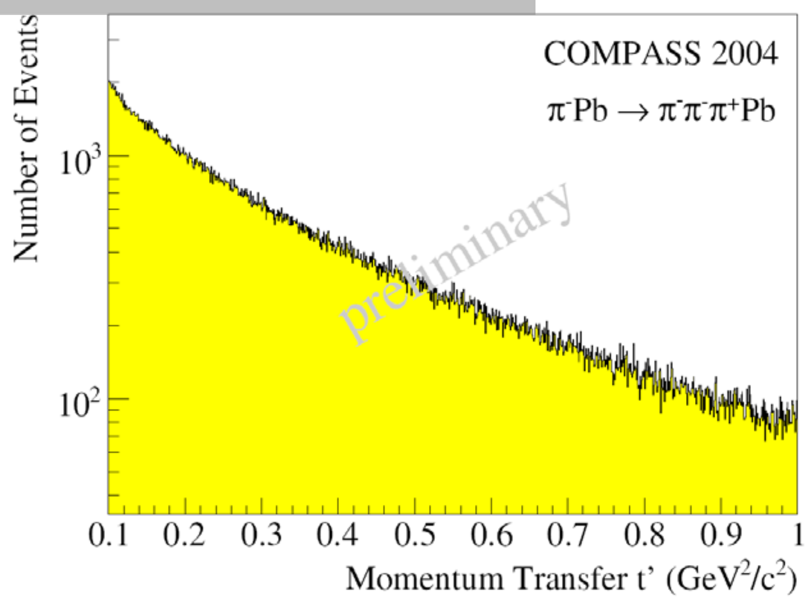


3π invariant mass



Diffraction on nucleons



Partial Wave Analysis

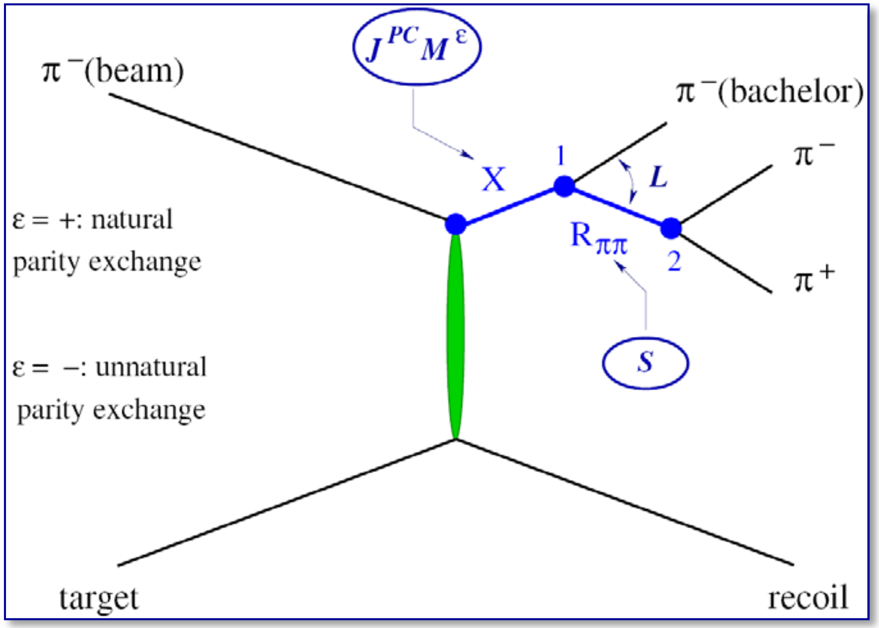
- Many different resonances are produced which decay into same final state
- Goal:
  - find and disentangle (all) contributing resonances
  - determine **mass, width** and **quantum numbers** J^P of resonances

    ⇨ angular distributions of decay products
- Interference effects ⇨ small resonances may be enhanced
- Take into account experimental acceptance

Partial Wave Analysis

Isobar model:

- X decays via sequence of 2-body decays
- Intermediate resonances: isobars
- Partial wave: χ = ***J^PC^M^ε^[isobar R]L***
- Decay amplitudes $A_\chi(m,\tau)$ calculable
  - 3 variables for each 2-body vertex $m_{\text{mother}}, (\theta,\varphi)$ in mother r.f.
  - 3π decay: $m, \{\theta_{\text{GJ}}, \phi_{\text{GJ}}, m_R, \theta_{\text{H}}, \phi_{\text{H}}\} \equiv \tau$
  - contain angular distributions and isobar parameterizations



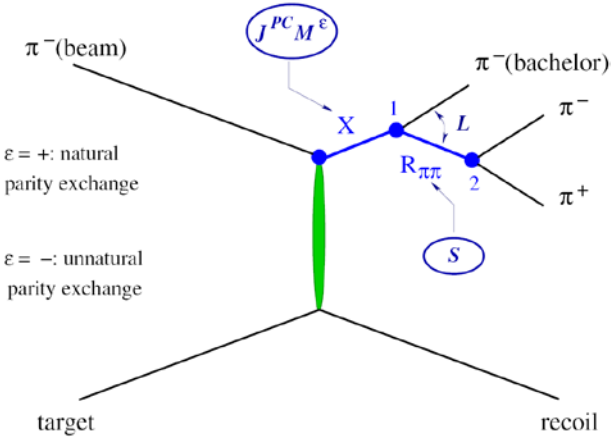
Reflectivity basis: linear combinations

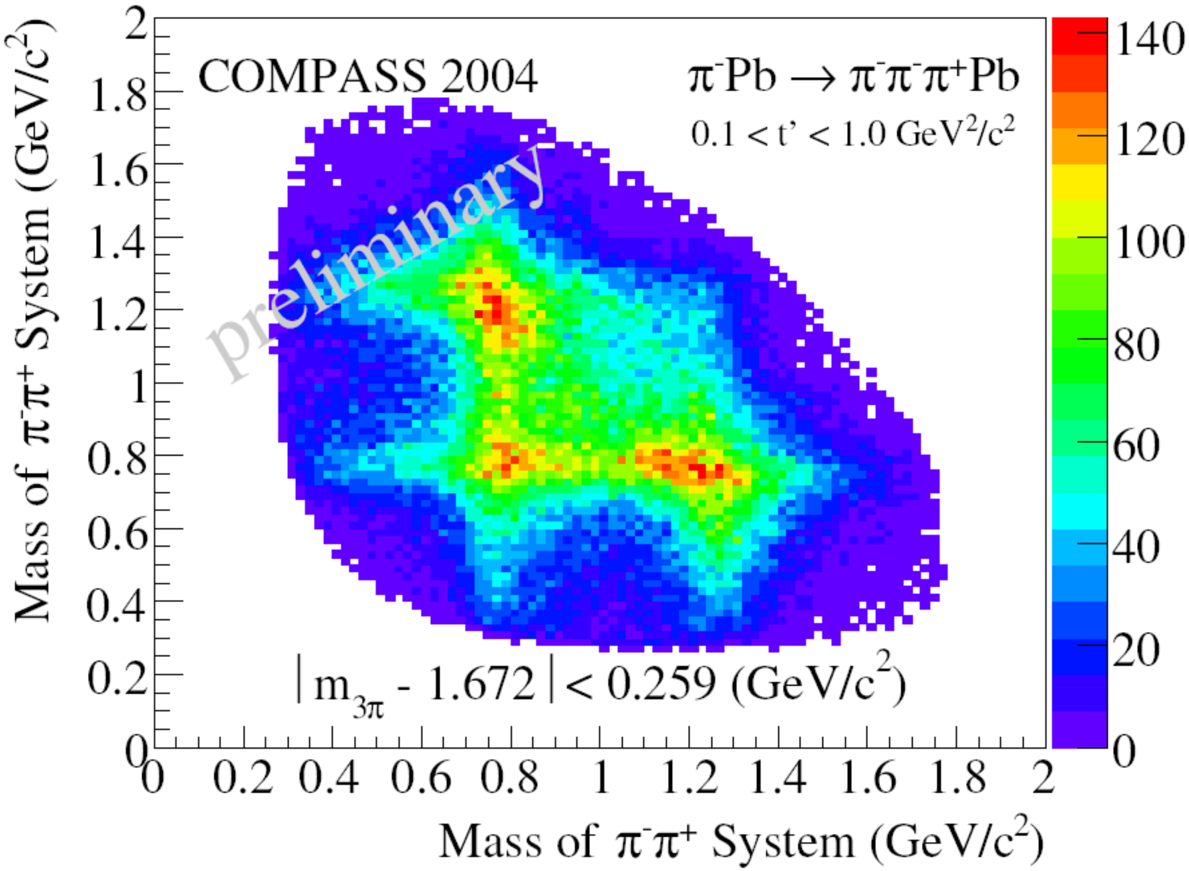
$$|\boldsymbol{p}\,\varepsilon\,j\,m\rangle = \theta(m)\Big[\,|\boldsymbol{p}\,j\,m\rangle - \varepsilon P(-1)^{j-m}\,|\boldsymbol{p}\,j\,{-m}\rangle\Big]$$

$$\theta(m) = \begin{cases} 1/\sqrt{2} & , \quad m > 0 \\ 1/2 & , \quad m = 0 \\ 0 & , \quad m < 0 \end{cases}$$

Real Life…

Example: $\pi_2(1670) \rightarrow f_2(1270)\,\pi$, $f_2(1270) \rightarrow \pi\,\pi$





PWA Technique

Illinois / Protvino / Munich Program – BNL / Munich Program

1. **PWA** of angular distributions in 40 MeV **mass bins**

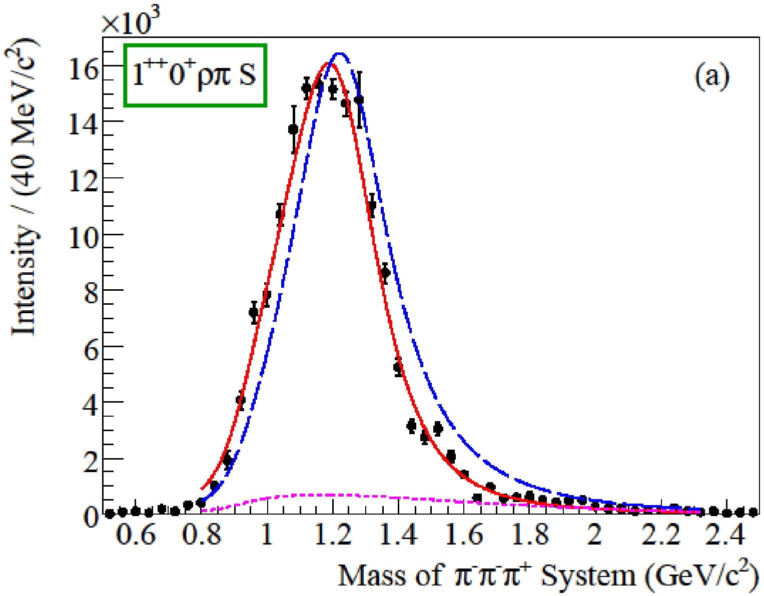
$$I_{\text{indep}}(\tau,m)=\sum_{\varepsilon=\pm1}\sum_{r=1}^{N_r}\left|\sum_i T_{ir}^{\varepsilon}A_i^{\varepsilon}(\tau,m)\right|^2$$

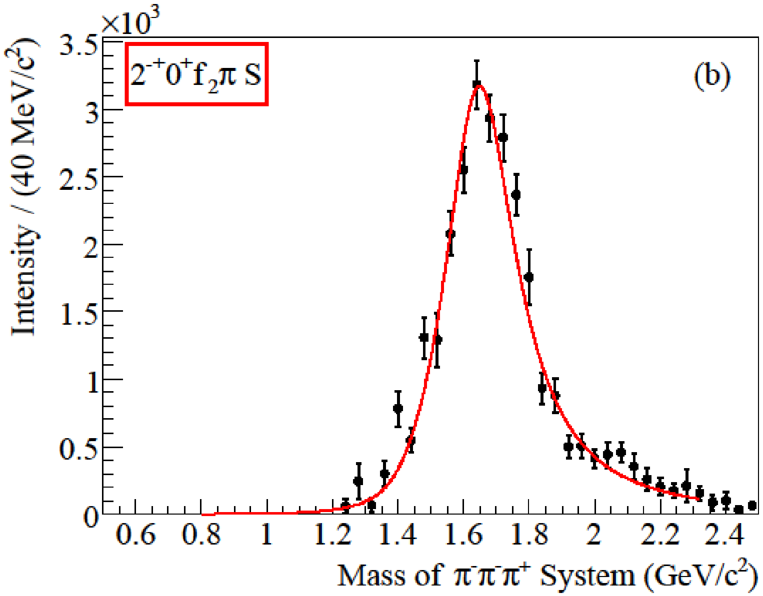
- Production amplitudes T_{ir}^{ε} ⇨ extended maximum likelihood fit
- Decay amplitudes $A_i^{\varepsilon}(\tau,m)$ (Zemach tensors, D functions)
- 41 partial waves $i=J^{PC}M^{\varepsilon}[...]L$

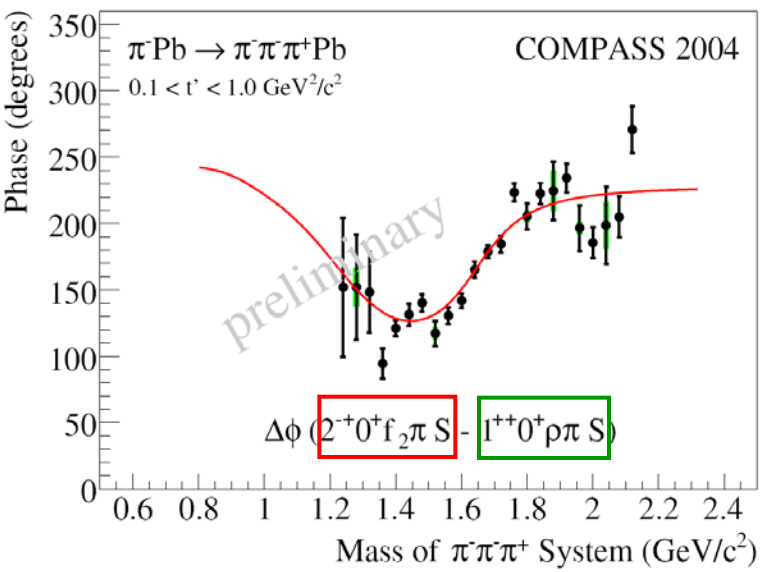
  $[...] = (\pi\pi)_S, \rho(770), f_0(980), f_2(1270), \rho_3(1690)$
- Background wave added incoherently
- No assumption on resonant behavior is made at this point!

2. **Mass-dependent χ^2 fit** to results of step 1
   - 6 waves
   - Parameterized by Breit-Wigner
   - Coherent background for some waves

$a_1(1260)$ and $\pi_2(1670)$ – $\pi^-\pi^-\pi^+$







- BW for $a_1(1260)$ + bgr

$$M = \left(1255 \pm 6\,^{+7}_{-17}\right)\ \mathrm{MeV}/c^2$$

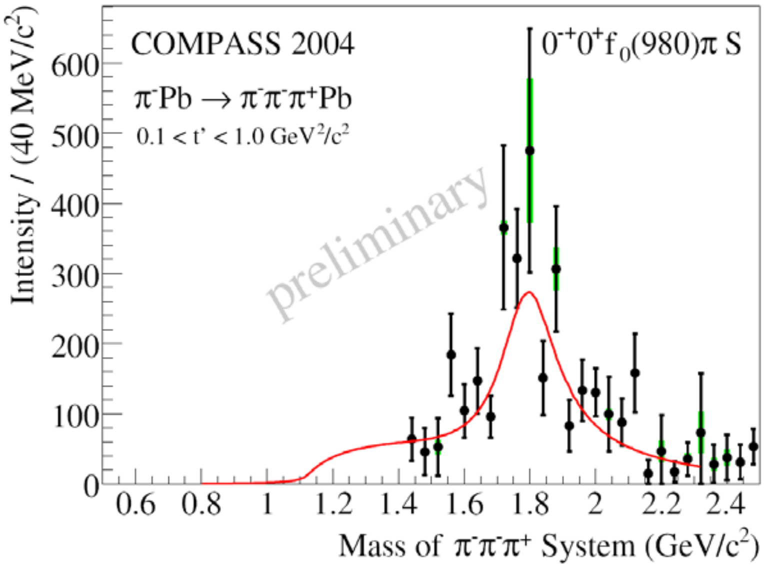
$$\Gamma = \left(367 \pm 9\,^{+28}_{-25}\right)\ \mathrm{MeV}/c^2$$

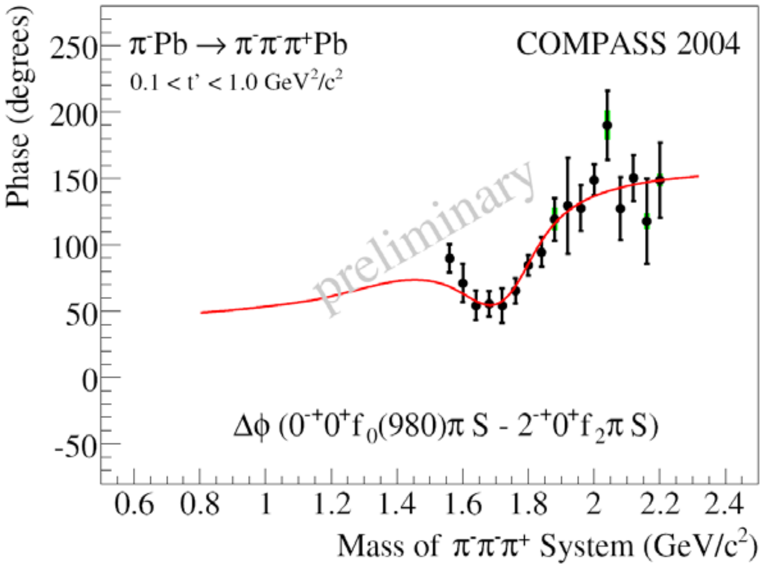
- BW for $\pi_2(1670)$

$$M = \left(1658 \pm 3\,^{+24}_{-8}\right)\ \mathrm{MeV}/c^2$$

$$\Gamma = \left(271 \pm 9\,^{+22}_{-24}\right)\ \mathrm{MeV}/c^2$$

$\pi(1800) - \pi^-\pi^-\pi^+$



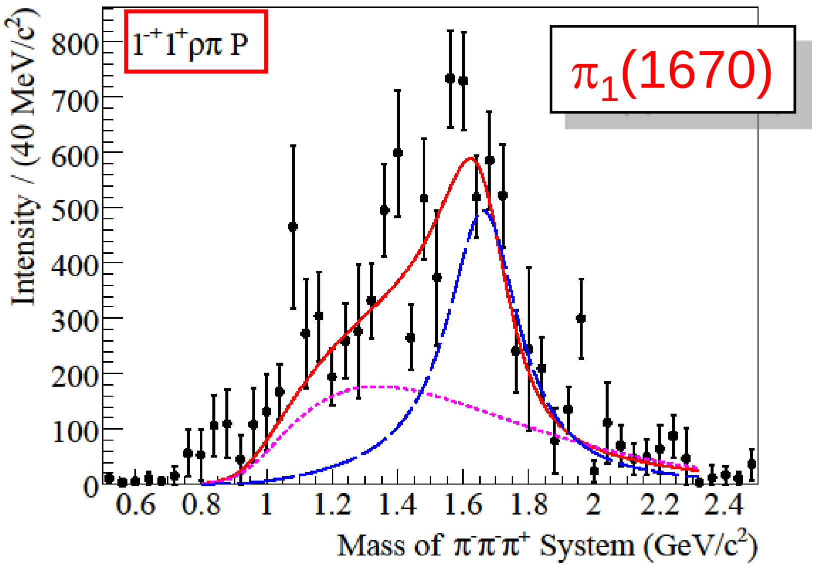


- Constant width BW for $\pi(1800)$ and low-mass background
- BW parameters

$$M = \left(1785 \pm 9\,^{+12}_{-6}\right)\,\mathrm{MeV}/c^2$$

$$\Gamma = \left(208 \pm 22\,^{+21}_{-37}\right)\,\mathrm{MeV}/c^2$$

$J^{PC}=1^{-+}$ Exotic Wave – $\pi^-\pi^-\pi^+$



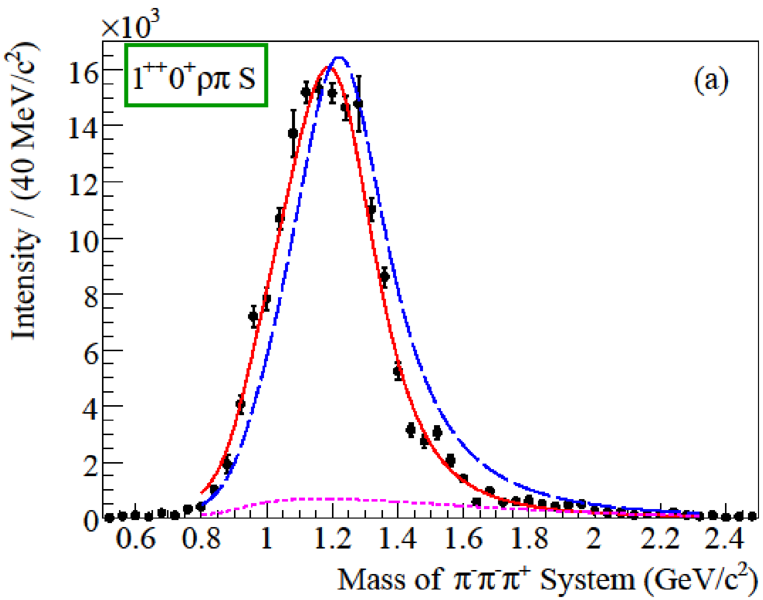
- BW parameters for $\pi_1(1600)$

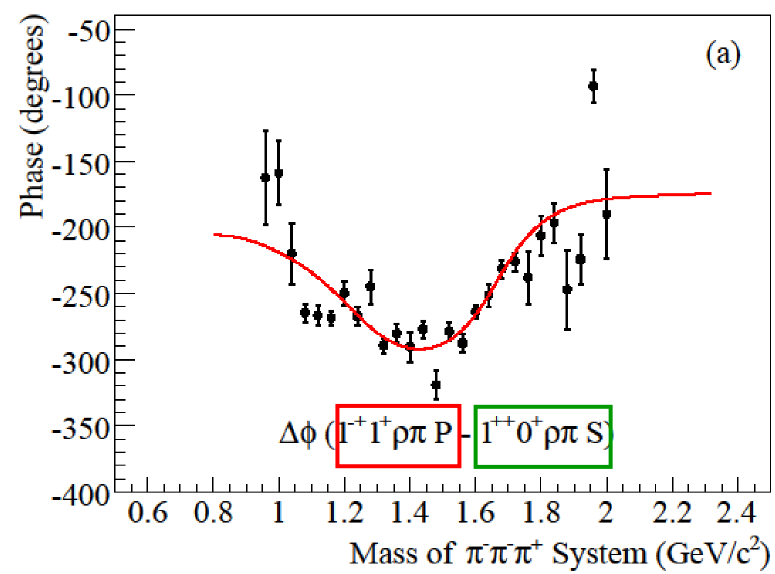
$$M = \left(1660 \pm 10\,^{+0}_{-64}\right)\,\mathrm{MeV}/c^2$$

$$\Gamma = \left(269 \pm 21\,^{+42}_{-64}\right)\,\mathrm{MeV}/c^2$$

- Leakage negligible: <5%

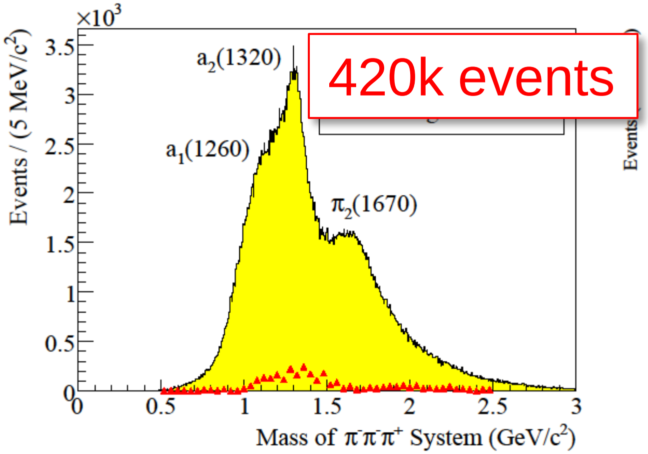
[Alekseev et al., Phys. Rev. Lett. 104, 241803 (2010)]



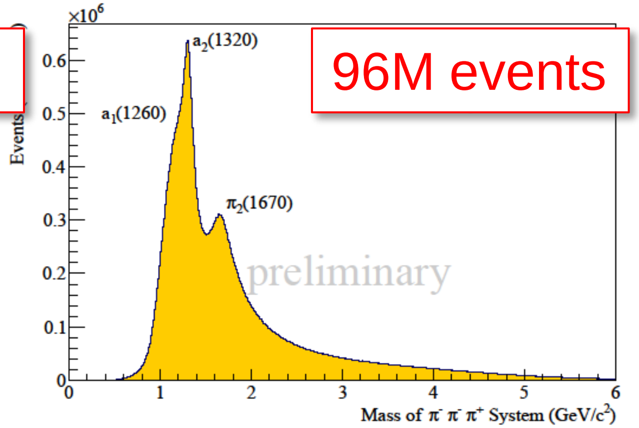


Diffractive Dissociation – 3π

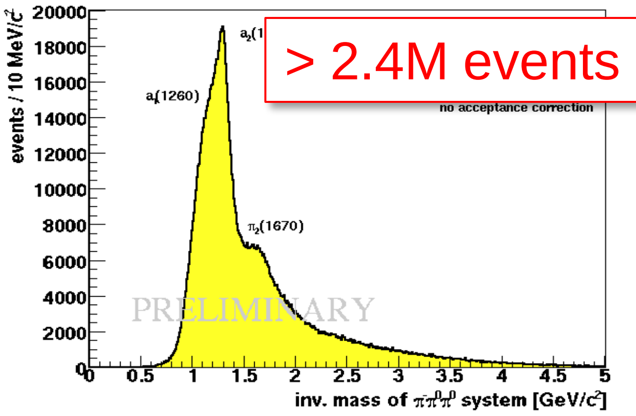
$\pi^- \mathrm{Pb} \rightarrow \pi^-\pi^-\pi^+ \mathrm{Pb}$



$\pi^- \mathrm{p} \rightarrow \pi^-\pi^-\pi^+ \mathrm{p}$



$\pi^- \mathrm{p} \rightarrow \pi^-\pi^0\pi^0 \mathrm{p}$



- Target: (2+1) cm Pb
- Trigger: Multiplicity
- No RPD

- Target: 40 cm lH2
- Trigger: Recoil proton
- RPD

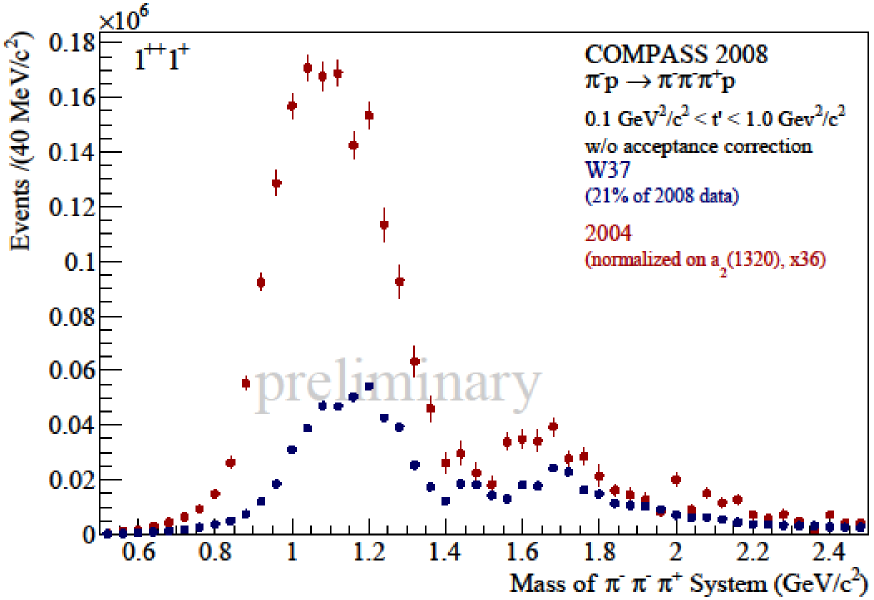
Adobe Acrobat Document

- Cross-check:
  - tracking vs
  - ECAL
- Isospin symmetry:
  - I=1 vs I=0 isobars
  - fulfilled

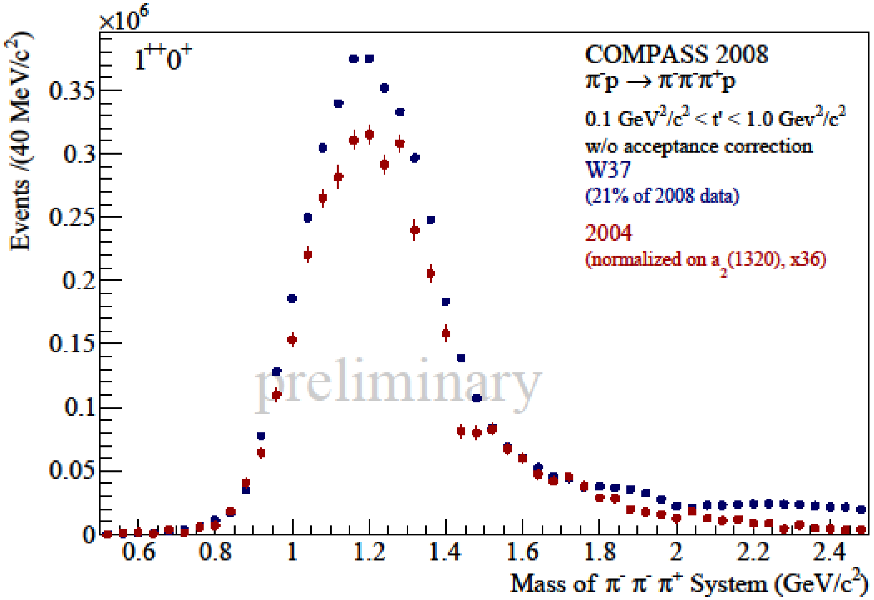
Nuclear Effect – $\pi^-\pi^-\pi^+$

- Compare intensities of $a_1(1260)$ and $\pi_2(1670)$ from **Pb** and **H_2** targets
- Normalize to intensity of $a_2(1320)$ ($J^{PC}M^{\varepsilon} = 2^{++}1^{+}$)
- Pb target: enhancement of spin projection M=1
  suppression of spin projection M=0
- Total intensity (both spin projections) roughly the same

$$J^{PC}M^{\varepsilon} = 1^{++}1^{+}$$



$$J^{PC}M^{\varepsilon} = 1^{++}0^{+}$$



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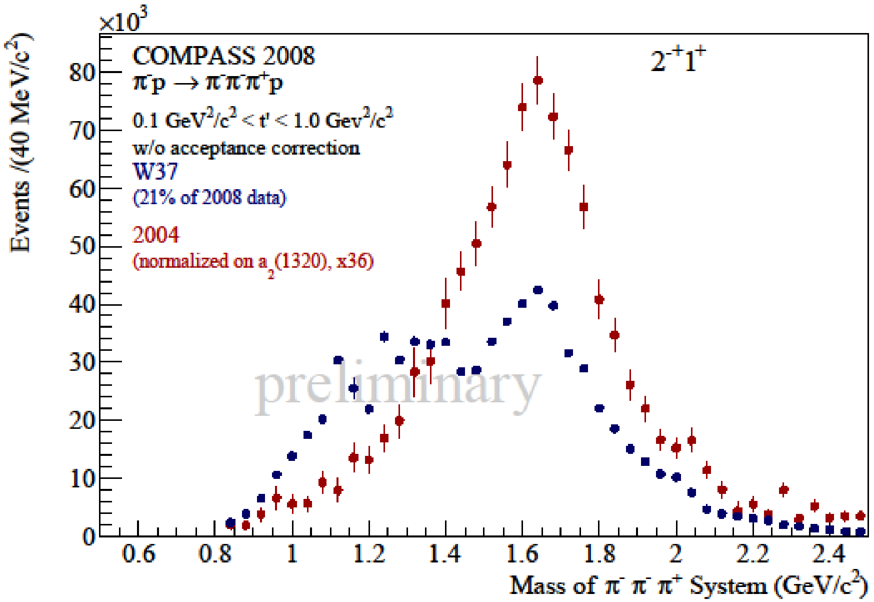
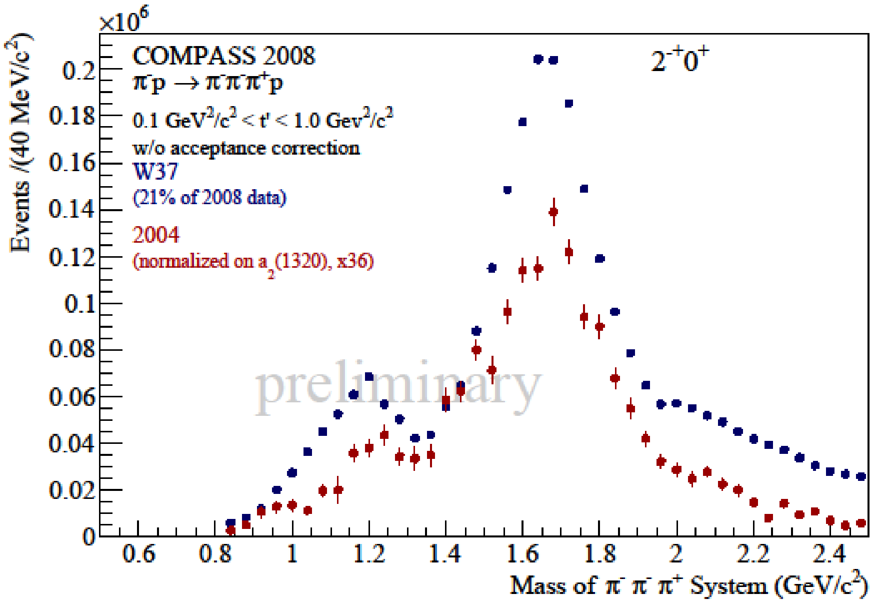


$$J^{PC}M^{\varepsilon} = 2^{-+}0^{+}$$



Multi-Particle (>3) Final States

Motivation:

- Clarify the hybrid nature of the π_1 ⇨ branching ratios to different channels

Model	$b_1\pi$	$f_1\pi$	$\rho\pi$	ηp	η'p	η(1295)p	Reference
Flux Tube, $^3P_0$	170	60	5 - 20	0 - 10	0 – 10		[Isgur et al., Close et al.]
Flux Tube, IKP m=1.6 GeV/c^2	24	5	9			2	[Isgur et al.]
Flux Tube, PSS m=1.6 GeV/c^2	59	14	8			1	[Page et al.]
L-QCD	66	15					[McNeil and Michael]

- Higher masses accessible ⇨ many disputed states: 0^{-+}, 1^{++}, 2^{-+},...

Under investigation in COMPASS:

- $\pi^-\pi^-\pi^-\pi^+\pi^+$
- $\pi^-\eta, \quad \eta \to \gamma\gamma$
  $\pi^-\eta, \quad \eta \to \pi^-\pi^0\pi^+$
- $\pi^-\eta', \quad \eta' \to \pi^-\pi^+\eta, \quad \eta \to \gamma\gamma$
  $\pi^-\eta', \quad \eta' \to \pi^-\pi^+\eta, \quad \eta \to \pi^-\pi^0\pi^+$
- $\pi^- f_1, \quad f_1 \to \pi^-\pi^+\eta, \quad \eta \to \gamma\gamma$
  $\pi^- f_1, \quad f_1 \to \pi^-\pi^+\eta, \quad \eta \to \pi^-\pi^0\pi^+$

$\pi^-\pi^-\pi^+\eta$ Final State

$\pi^-\pi^+\eta$ invariant mass

$\eta \to \pi^-\pi^+\pi^0$

$f_1(1285)$

η'

$\eta \to \gamma\gamma$

$f_1(1285)$

η'

Select η'

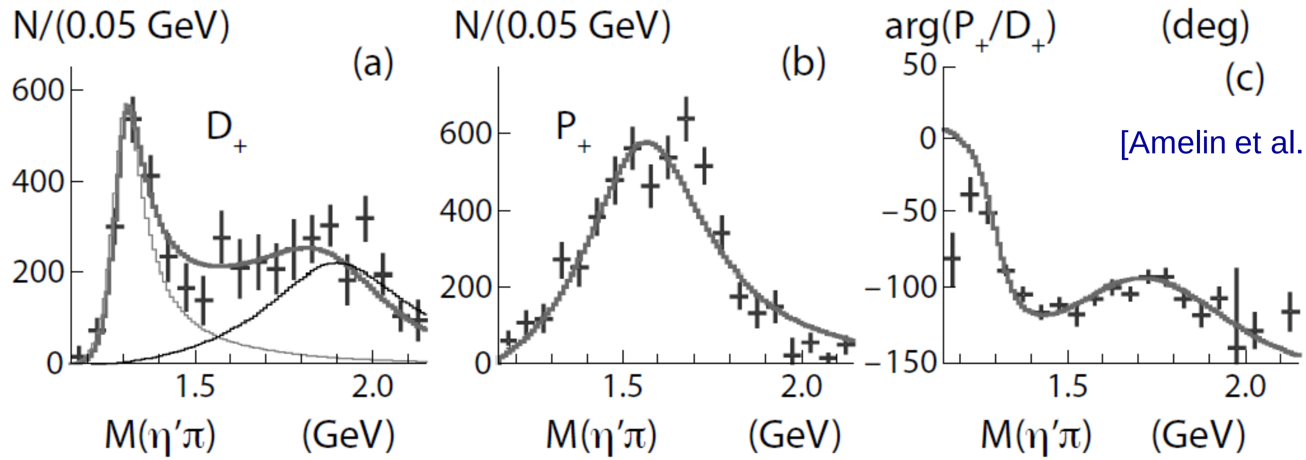
Hybrid $\pi_1(1600)$ expected in this channel

PWA - η'π final state

•Preliminary PWA

•No optimization for COMPASS (acceptance, resolution)

VES results (38 GeV pions, Be target)



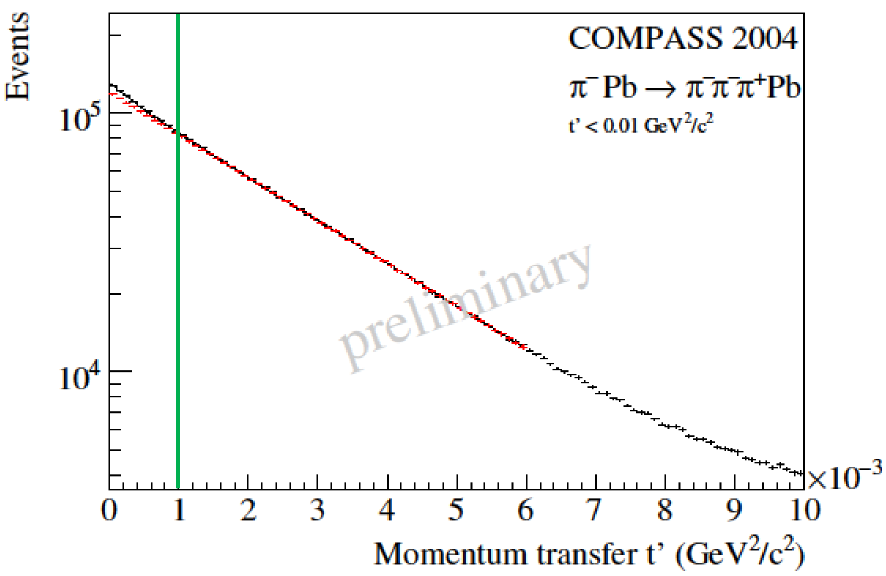
[Amelin et al., Phys. Atom. Nucl. 68, 359 (2005)]

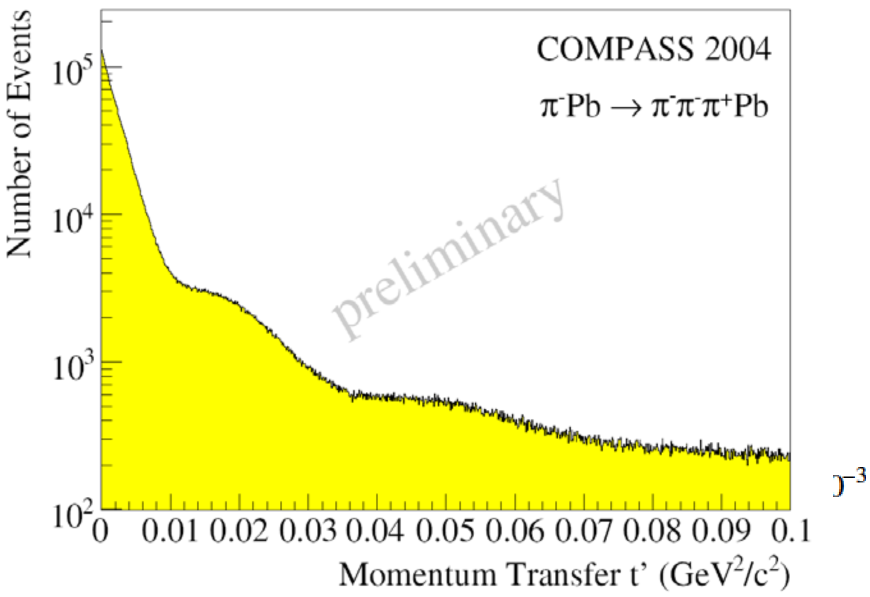
$\pi^-\pi^-\pi^+$ Final State at low t'

Coherent production on Pb nucleus

Contributions at very low t':

- Diffraction: $\sigma(t') \propto e^{-b_{\text{Diff}} t'}, \quad b_{\text{Diff}} \approx 400\left(\text{GeV}/c\right)^{-2}$
- Photoprod.: $\sigma(t') \propto e^{-b_{\text{Prim}} t'}, \quad b_{\text{Prim}} \approx 2050\left(\text{GeV}/c\right)^{-2}$



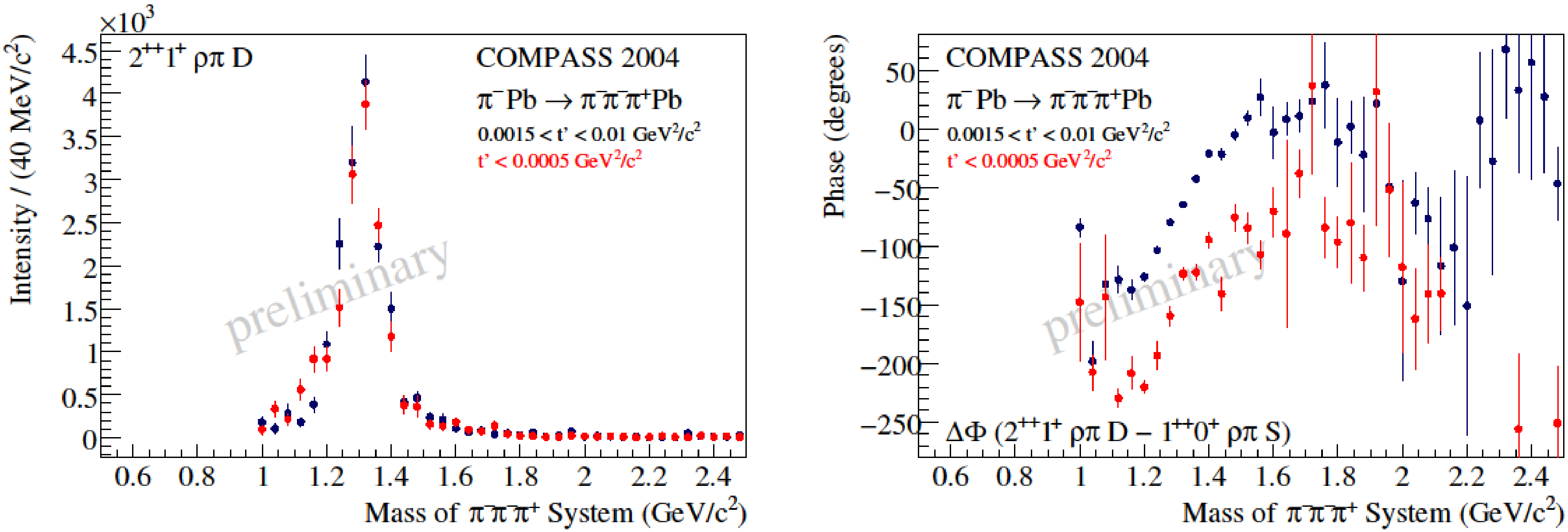


- Fit of 2 exponentials for $t' < 0.006\ \text{GeV}^2/c^2$
- Steep fall-off for photoproduced events dominated by experimental resolution
- Statistical subtraction of diffractive contribution

Partial Wave Analysis

Two clearly separated regions: **$t' < 0.5 \cdot 10^{-3}$ GeV²/c²**

$0.0015 < t' < 0.01$ GeV²/c²



$a_2(1320)$ (M=1) present in both t'-ranges ⇨ different production mechanisms

Diffraction $\sigma(t') \propto t' e^{-bt'}$ vanishes for t'→0

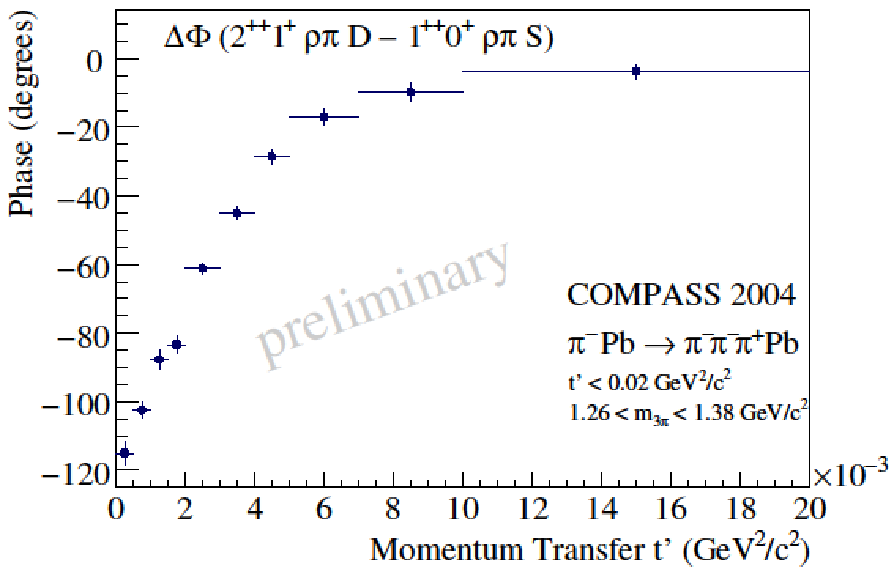
Photoproduction $\sigma(t') \propto e^{-b_{\mathrm{Prim}} t'}$

Phase difference $a_2(1320)$ - $a_1(1260)$: offset for two t'-regions!

Phase Difference a_2-a_1

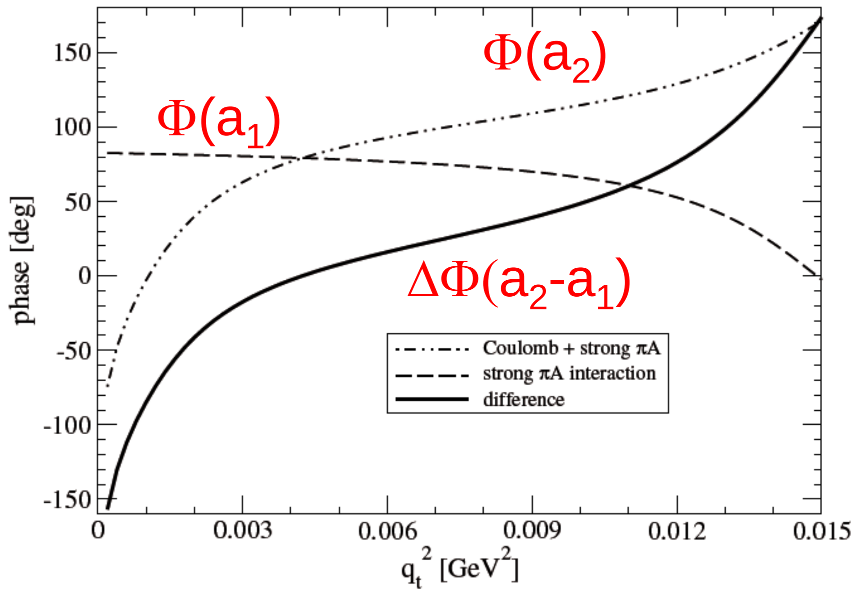
PWA in t' bins for single mass bin $1.26 < m_{3\pi} < 1.38\ GeV/c^2$ (a_2 region)

Experiment



Theory

[G. Faeldt et al., Phys. Rev. C 79 014607 (2009)]
Plot by N. Kaiser, TUM



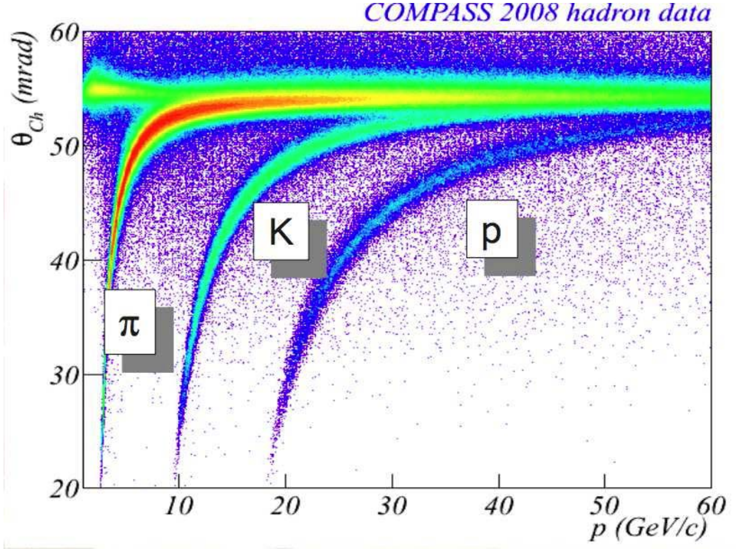
⇨ smooth transition from a_2 photoproduction to diffractive production with increasing t'

⇨ possibility to cleanly separate photoproduction from diffraction

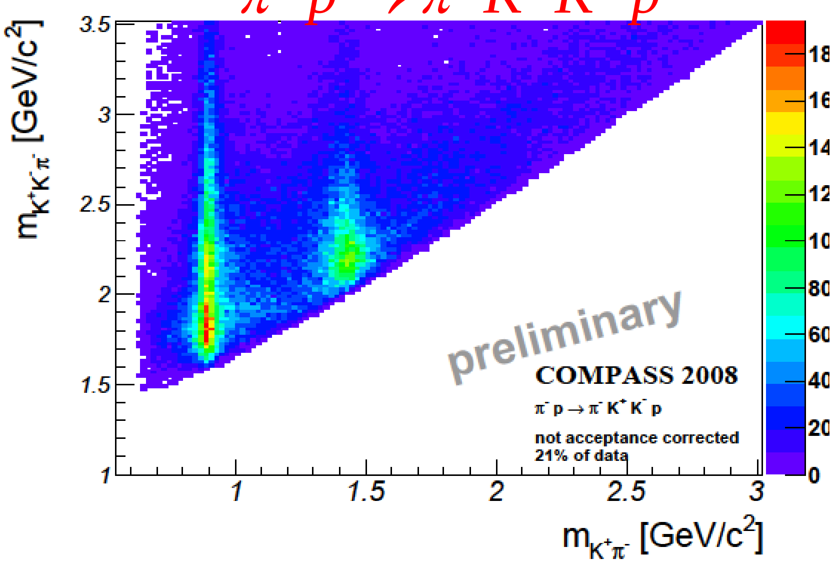
⇨ determination of radiative width of $a_2(1320)$, $\pi_2(1670)$

Kaonic Final States

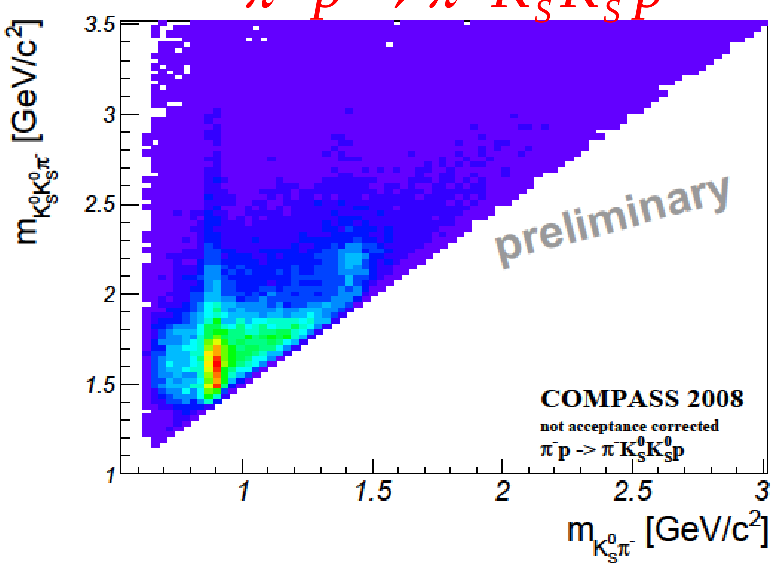
- Access to exotics, glueballs
- Clarify flavor content of resonances
- $K^{\pm}$ ⇨ RICH particle identification
- K_S ⇨ $\pi^+\pi^-$ decay
- K beam ⇨ CEDAR tagging
  - ⇨ extend knowledge on K spectrum



$\pi^- p \to \pi^- K^+ K^- p$



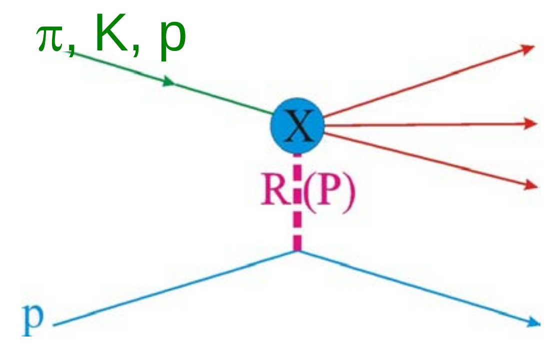
$\pi^- p \to \pi^- K_S^0 K_S^0 p$

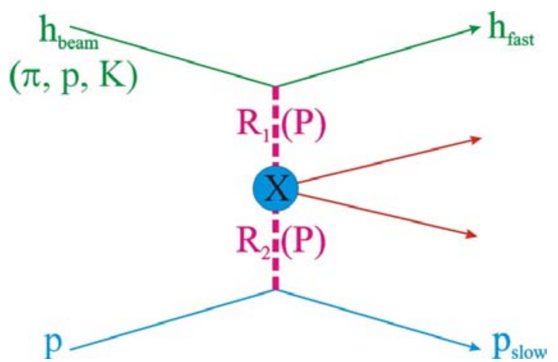


Diffractive states at 1.7 GeV/c² and 2.2 GeV/c², decaying to K*(892) and K*(1430)

Data with Proton Beam

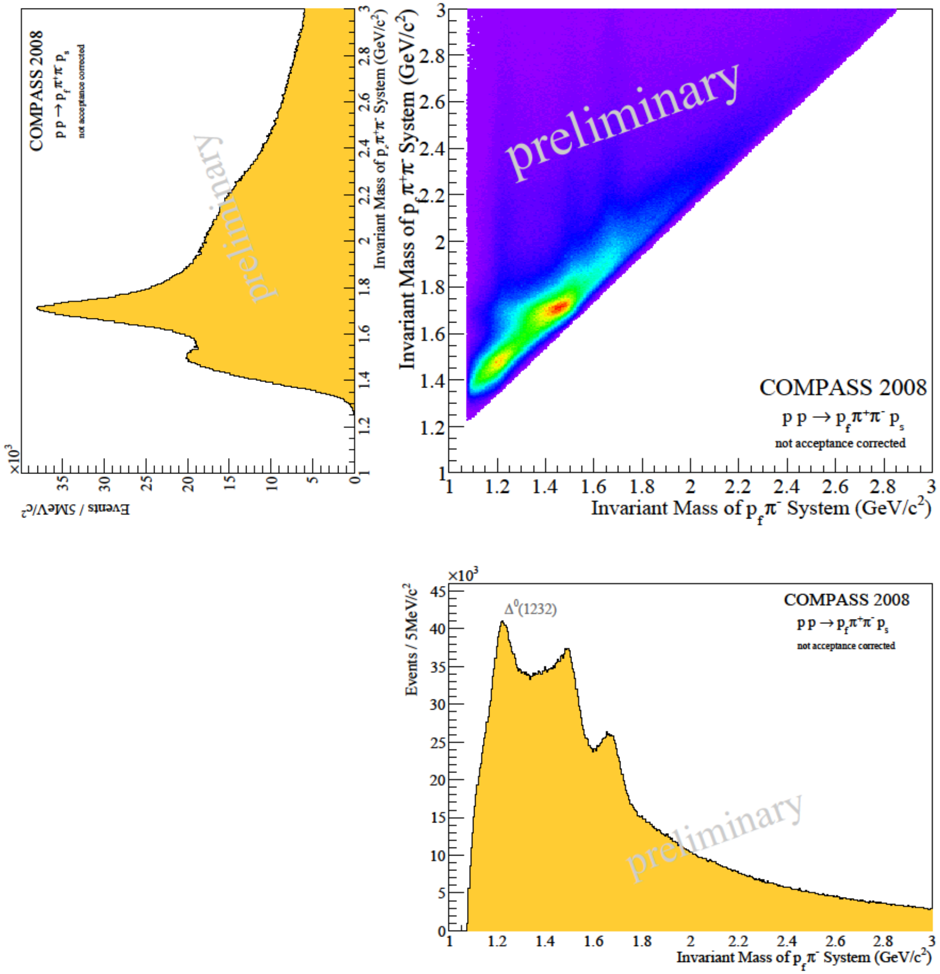
- Beam: 190 GeV/c, 71.5% p, 25.5% π, 3.0% K
- CEDARs tagging protons
- Trigger: Recoil proton
- ~10% of total 2008/2009 statistics
- Baryon spectroscopy:
  - $pp \rightarrow p_f \pi^+ \pi^- p_s$
  - $pp \rightarrow p_f K^+ K^- p_s$
- Central Production
  - $pp \rightarrow p_f \pi^+ \pi^- p_s$
  - $pp \rightarrow p_f \pi^+ \pi^- \pi^+ \pi^- p_s$
  - $pp \rightarrow p_f K\bar{K} p_s$



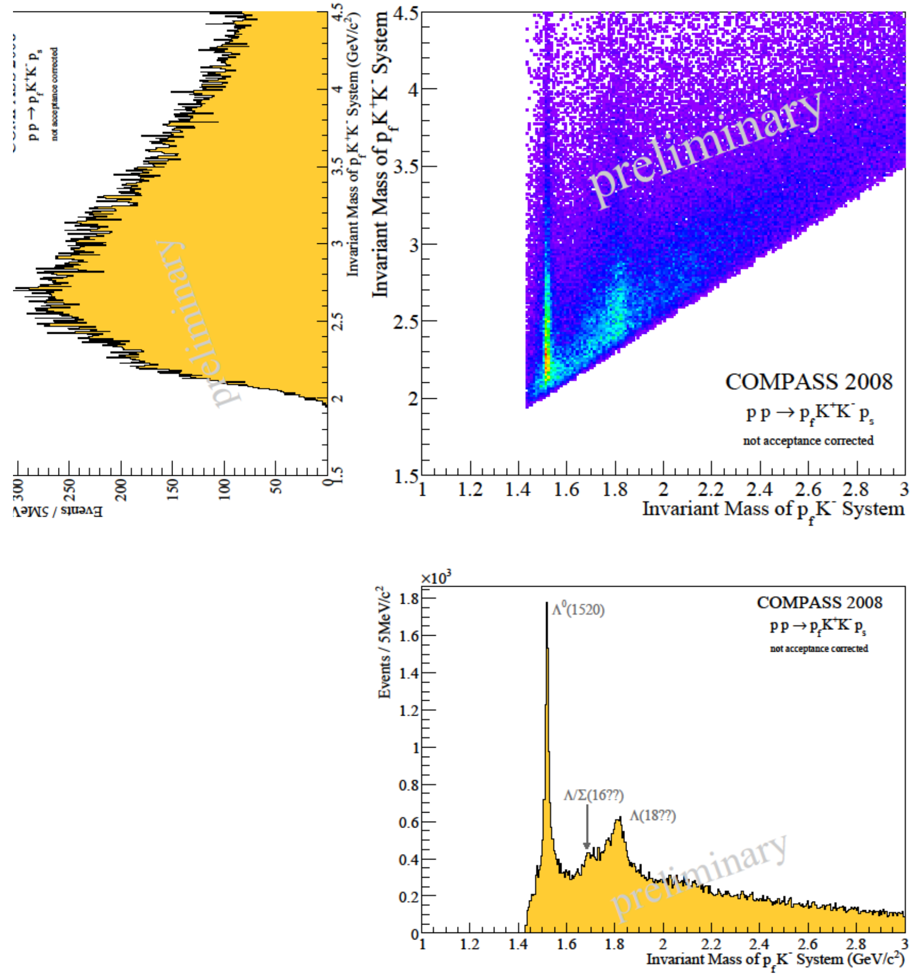


Baryon Spectroscopy

$pp \rightarrow p_f \pi^+ \pi^- p_s$



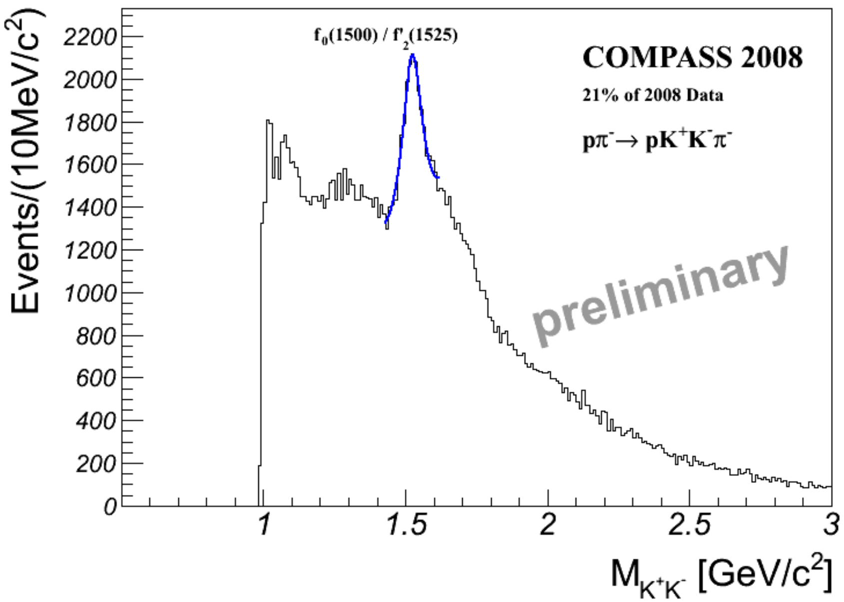
$pp \rightarrow p_f K^+ K^- p_s$



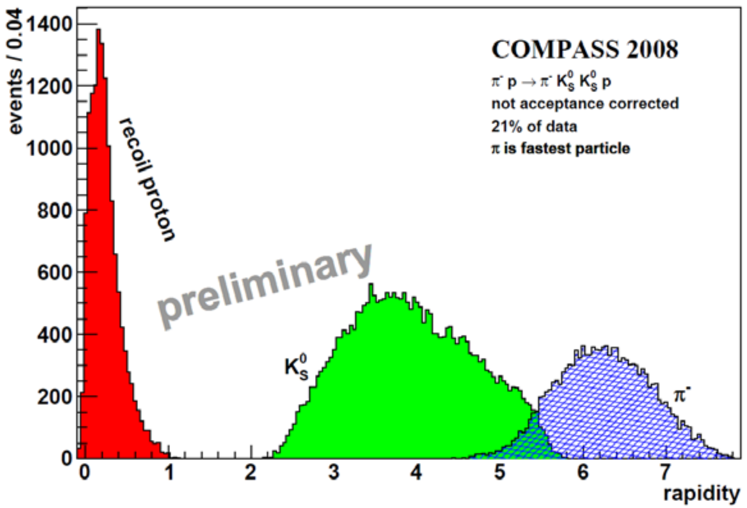
- final states containing charged and neutral particles
- Masses up to ~3 GeV/c^2 accessible

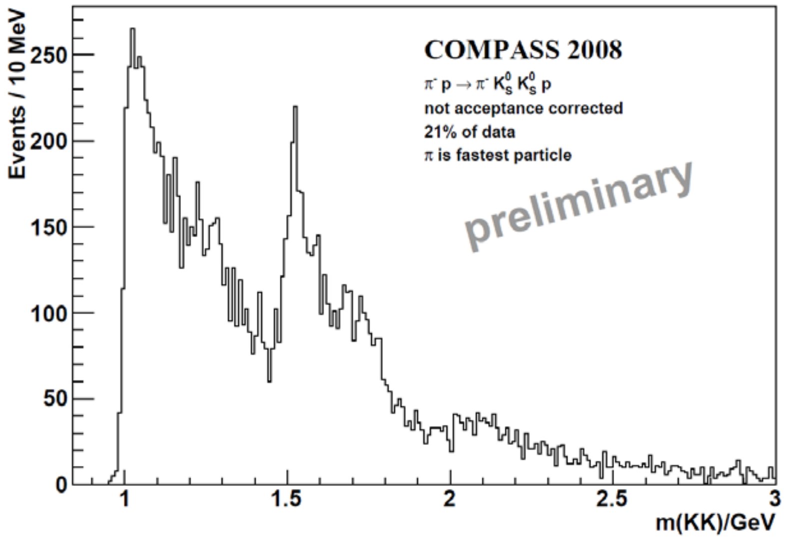
Central Production

$\pi^- p \rightarrow \pi_f K^+ K^- p_s$



$\pi^- p \rightarrow \pi_f K_S^0 K_S^0 p_s$





Conclusions

- High statistics: 10 × world data sample on diffractive and central production
- High and uniform acceptance for charged and neutral final states
- Clear **π_1(1600)** signal in $\pi^-\pi^-\pi^+$ for Pb target
- Signal also seen for H_2 target in $\pi^-\pi^-\pi^+$, $\pi^-\pi^0\pi^0$, $\eta'\pi$, $f_1\pi$
- Nuclear effect: production of M=1 states enhanced for larger A
- Kaonic final states ⇨ resonance coupling to strangeness
- Kaon beam ⇨ study Kaon spectrum
- Proton beam
  - central production of (glue-rich) states
  - baryon resonances
- PWA: two different programs: Illinois-Protvino-Munich, BNL-Munich

Outlook

- Production of large-statistics Monte Carlo sample
- Production mechanism ⇨ study t-dependence
- Optimization of wave set for H_2 / Pb / Ni data ⇨ genetic algorithm
- Improvement of model
  - Deck amplitude
  - Rescattering effects
- Development of PWA for baryons and central production
- **Future data taking** ⇨ addendum to COMPASS II proposal
  - higher beam energy / beam energy scan
  - dedicated trigger for neutral channels and higher masses

COMPASS Future Plans

2009	2010	2011	2012	2013	2014	2015	2016

Spectroscopy — p,π,K beam

Transversity — μ beam: Collins, Sivers

DIS / SIDIS — μ beam: Δq at low x, high precision

π, K beam — **p, K Polarizability**

μ beam — **GPDs: DVCS, HEMP**

π beam — **Transversity: Drell-Yan**

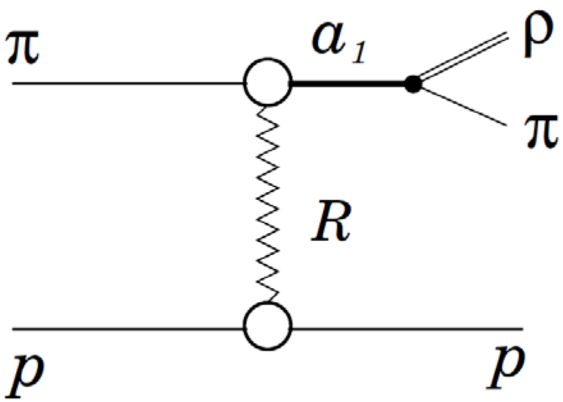
...

p beam — **Spectroscopy**

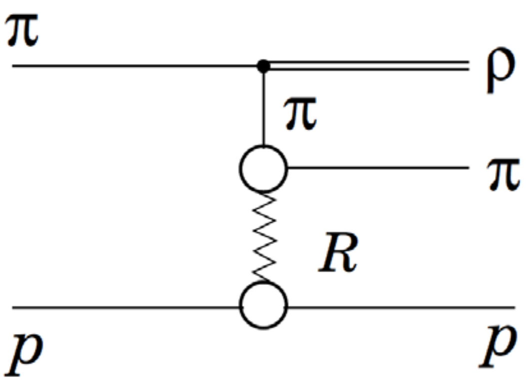
Spare Slides

Deck Effect

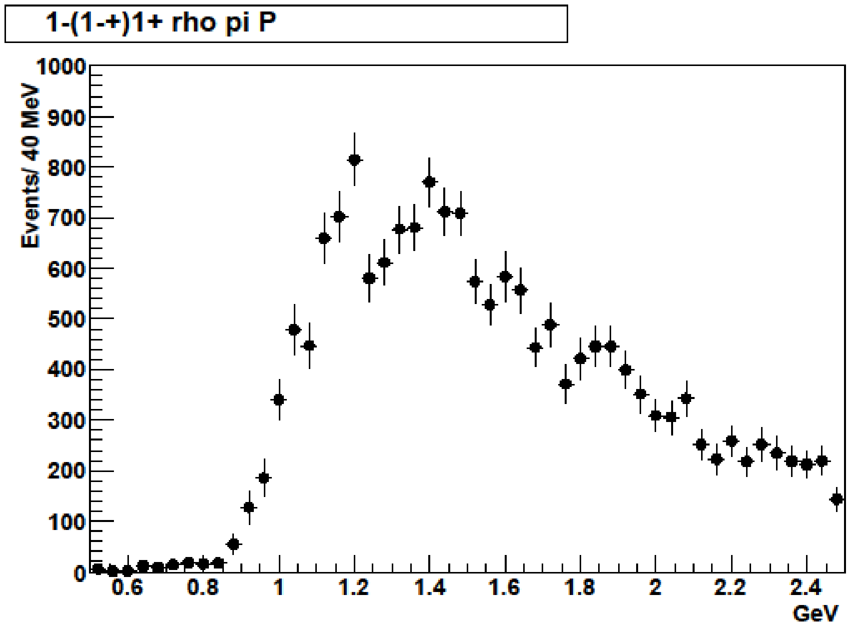
Resonant production



Non-resonant production

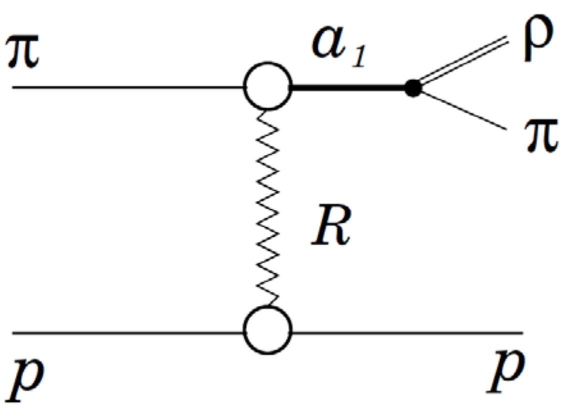


- Generate pure Deck-like events
- Pass through Monte Carlo & PWA
- Examine exotic wave



Deck Effect

Resonant production



Non-resonant production