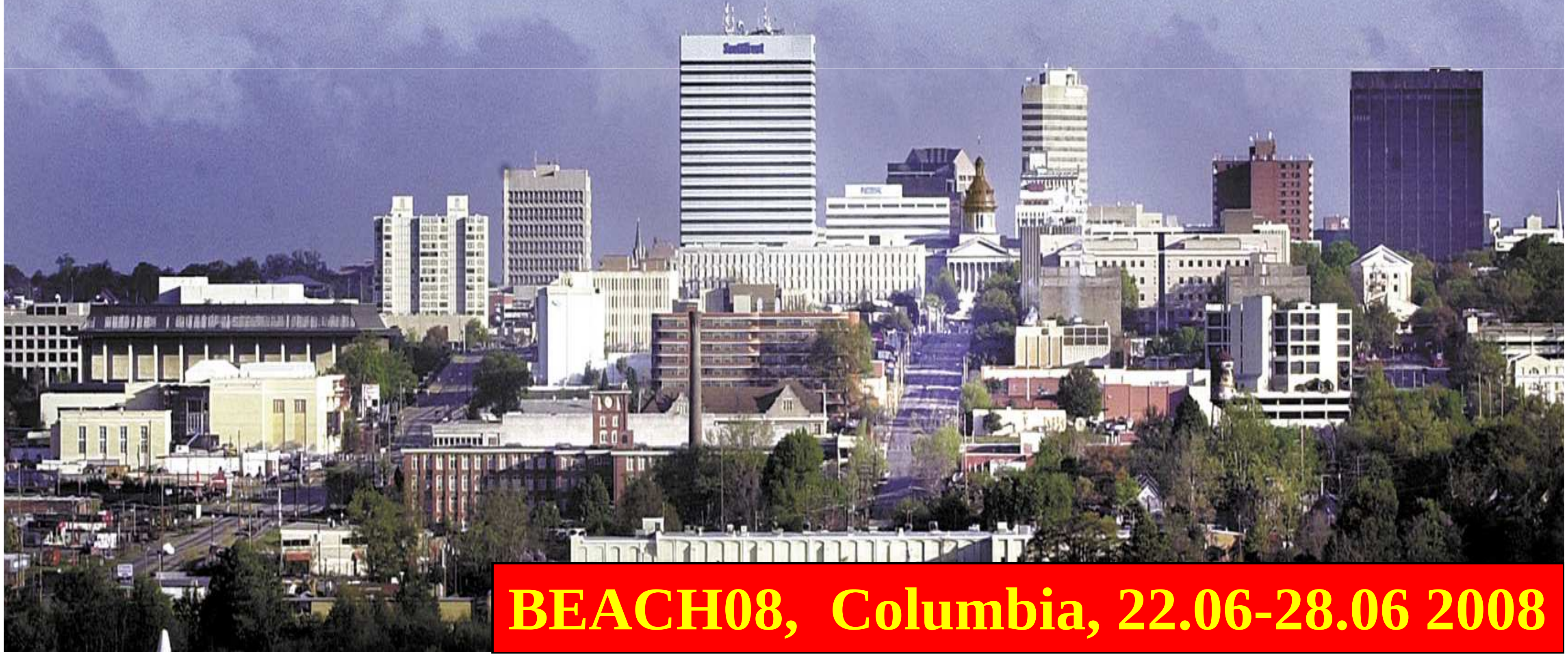
COMPASS experiment at CERN: open charm results and future hadron program

O.Kouznetsov (CEA/Saclay) on
behalf of the COMPASS Collaboration



BEACH08, Columbia, 22.06-28.06 2008


COmmon
Muon and
Proton
Apparatus for
Structure and
Spectroscopy
160 GeV polarized μ beam / 190 GeV π beam
two stage spectrometer SAS & LAS (~50 m)
HCALs, ECALs, RICH for particle ID, μ walls
Lake LEMAN
LHC
SPS
CERN (France)
CERN (Suisse)
In 2002-2004 & 2006-2007 COMPASS has recorded
about 5×10^10 events ~ 2000 TB

COMPASS

NA58 experiment at CERN

11 counties/20 Institutes/~230 physicists

Czech Republic, Finland, France, Germany, India, Israel, Italy, Japan, Poland, Portugal and Russia

Bielefeld, Bochum, Bonn, Burdwan/Calcutta, CERN, Dubna, Erlangen, Freiburg, Lisbon, Mainz, Moscow, Munich, Prage, Protvino, Saclay, Tel Aviv, Torino, Trieste, Warsaw and Yamagata

Experiment is a merge of two programmes/collaborations: HMC (muon beam) & CHEOPS (hadron beam)

Physics program of COMPASS

Detector is advantageously located at M2 SPS beam line with a variety of high intensity μ & h beams

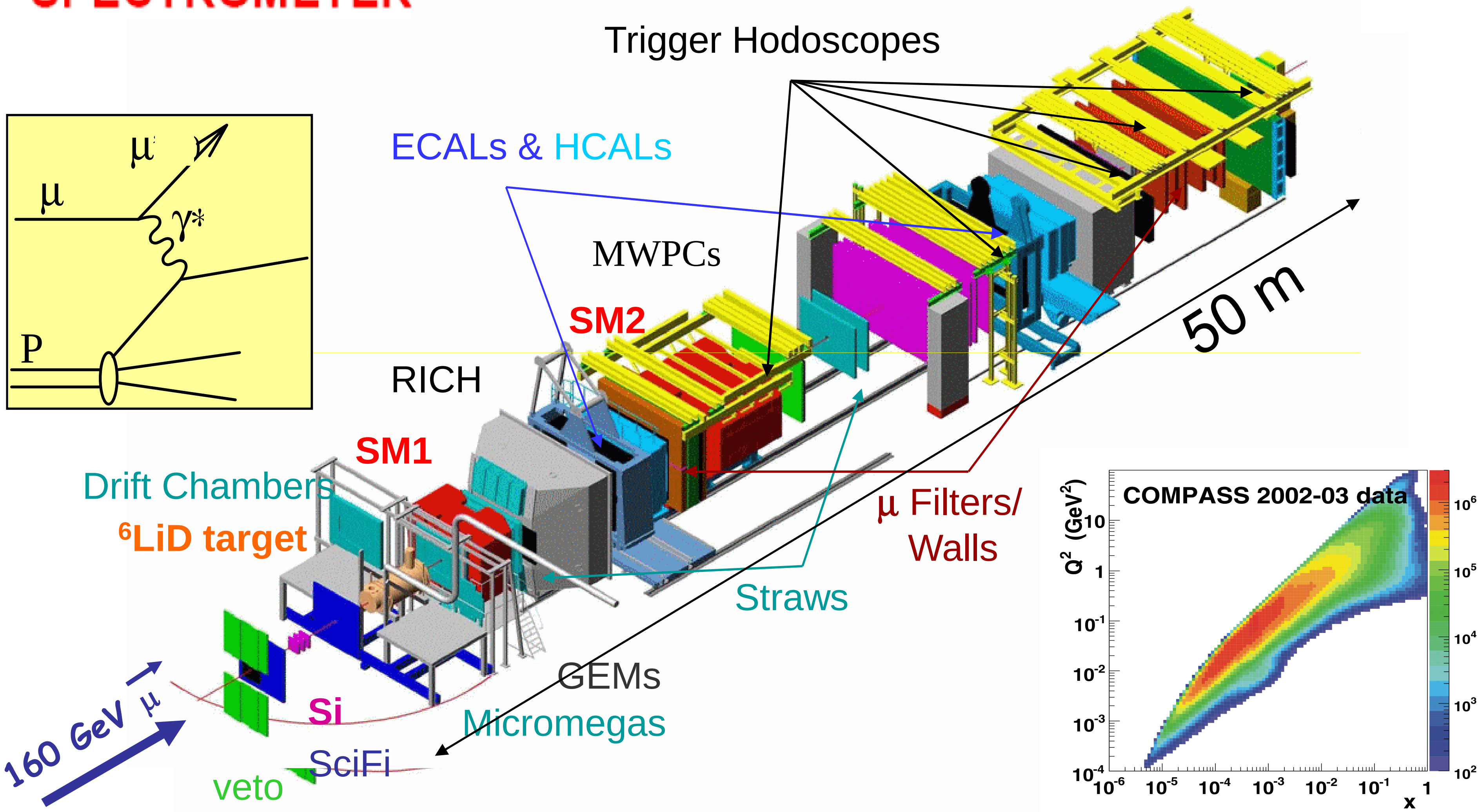
- *Runs with muon beam* (2002-2004,2006-2007)
  - Gluon polarization Δ*G/G*
  - g_1 spin structure function
  - Flavor decomposition of spin distributions
  - Transverse spin effects
  - *S*pin transfer in Λ-hyperon production
  - Vector meson production
- *Runs with hadron beams* (2008-2009)
  - Diffractive production
  - Search for new exotic states, glueballs or hybrids
  - Light meson spectroscopy
  - Production of doubly charmed baryons
  - Pion and kaon polarizabilities

Polarized beam and target

TWO STAGE SPECTROMETER

COMPASS in μ run

NIM A 577(2007) 455

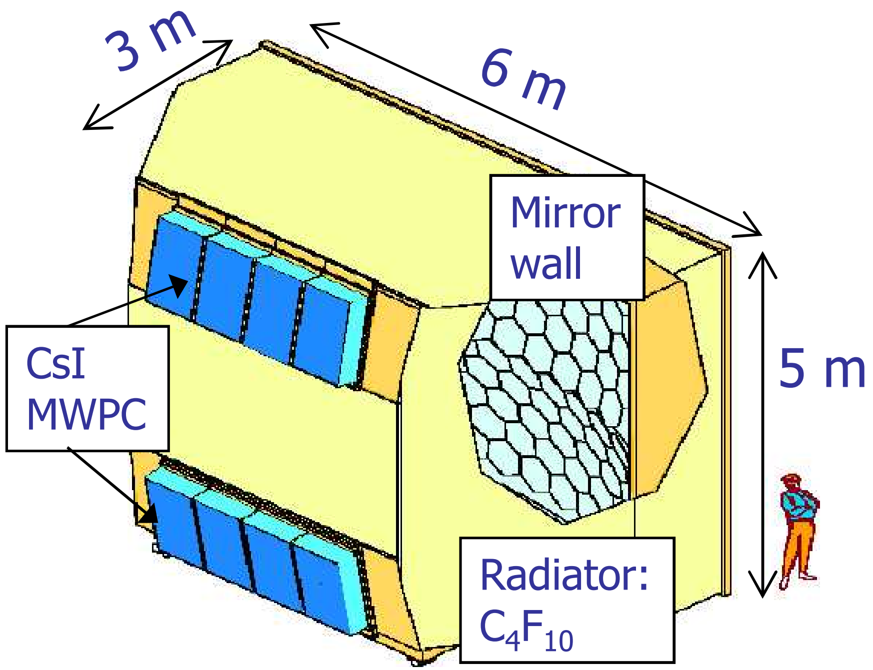


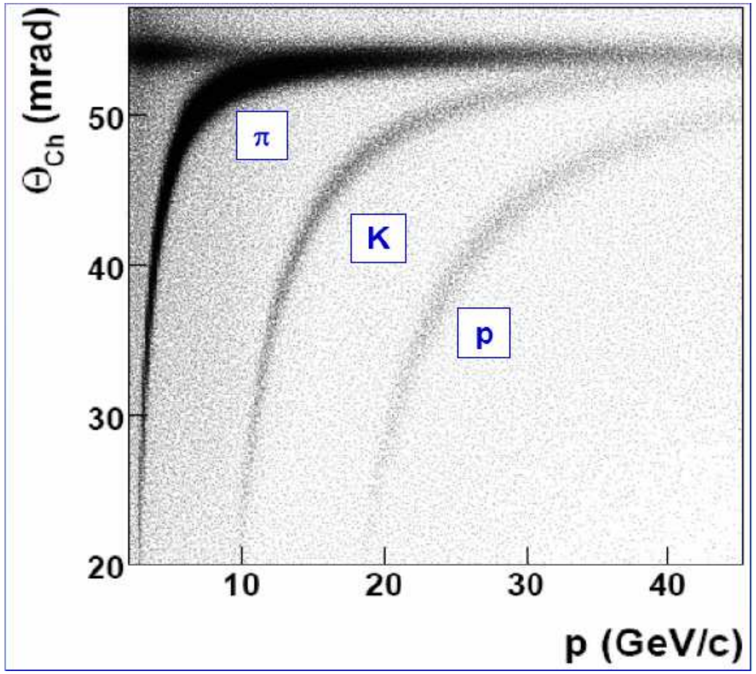
Ring Imaging Cherenkov Detector

Identification of π, K and protons

Cherenkov thresholds: π ≈ 3 GeV/c K ≈ 9 GeV/c p ≈ 17 GeV/c

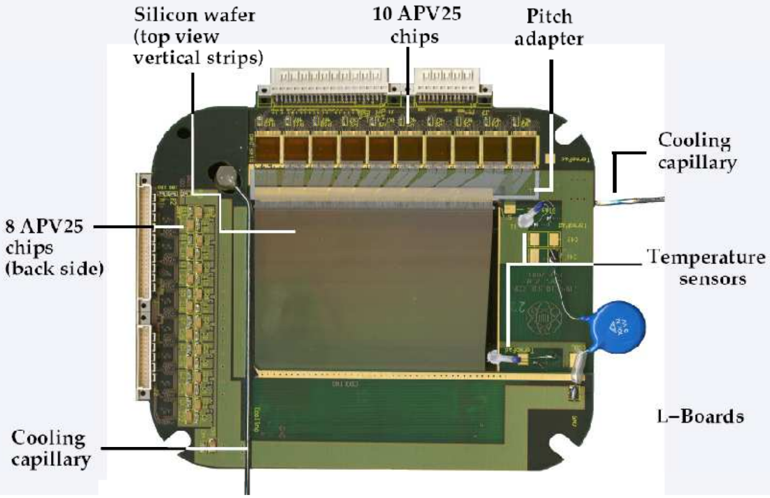
2σ π/K separation at 43 GeV/c



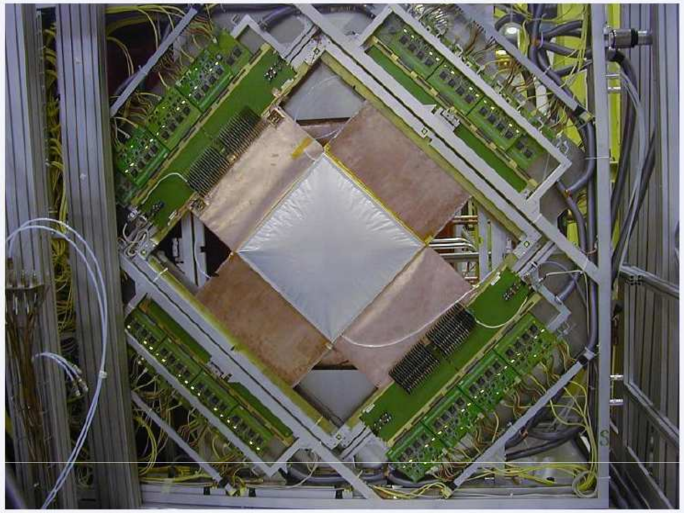


COMPASS tracking detectors

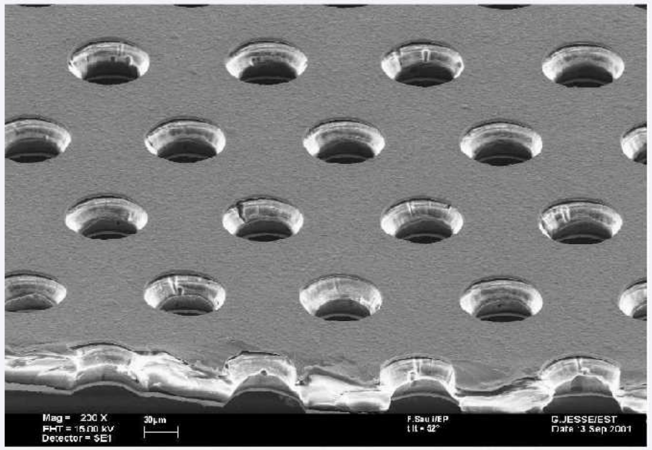
Silicon detectors (10 μm)



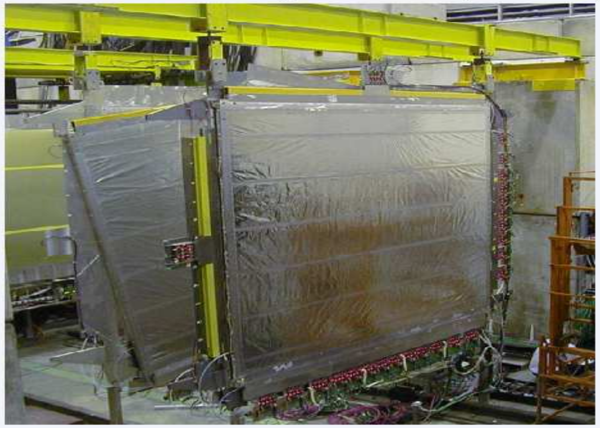
Micromegas (90 μm)



GEMs (70 μm)

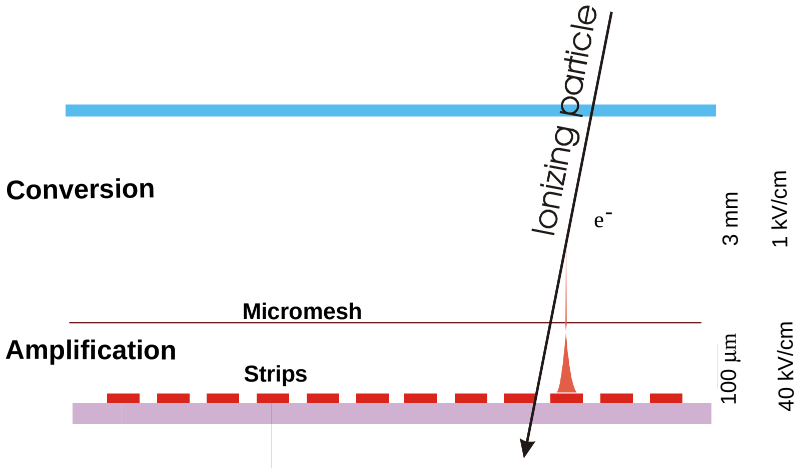


Straws (190 μm)

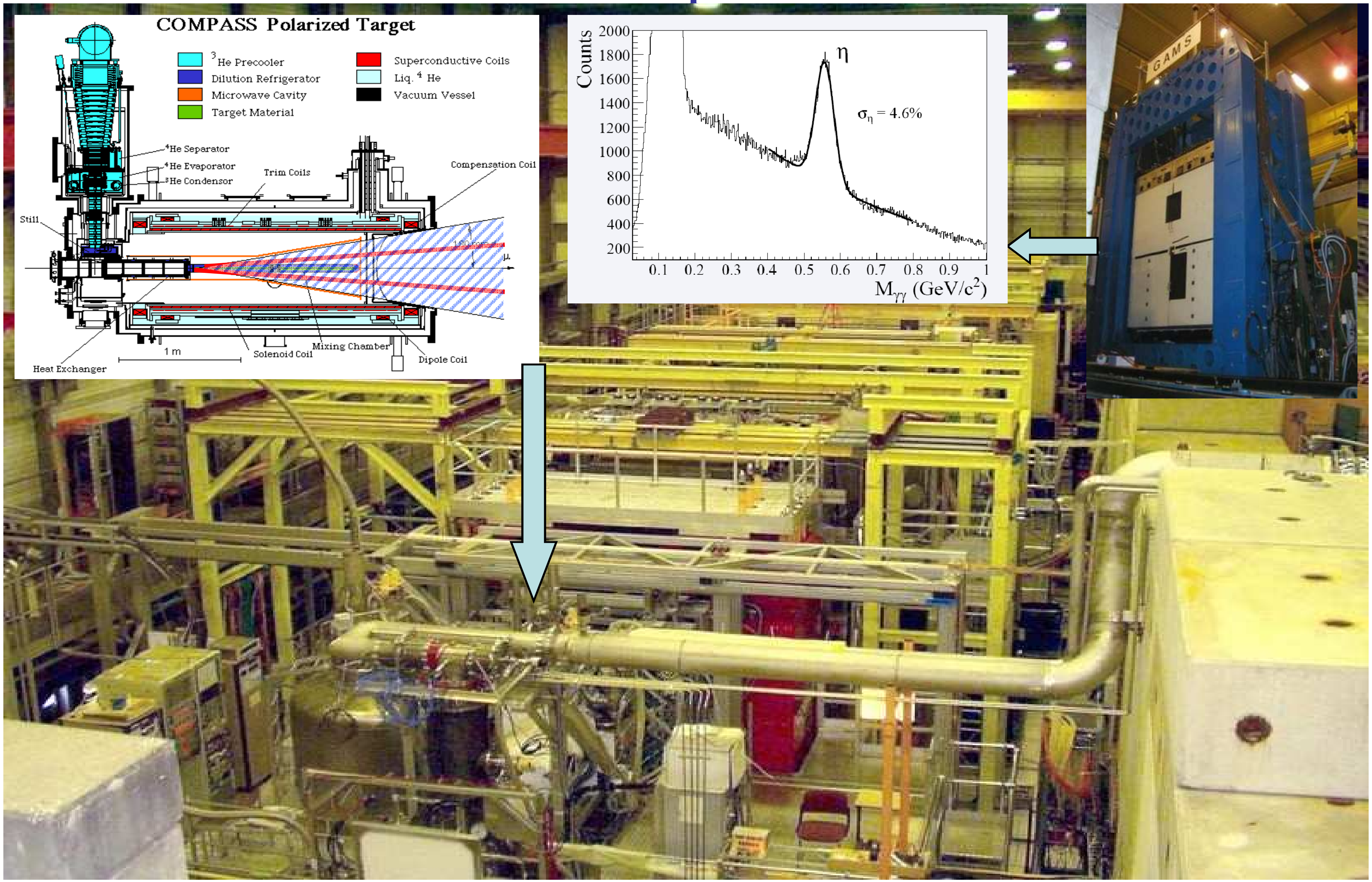


MicroMegas (Micro Mesh Gas Detector)

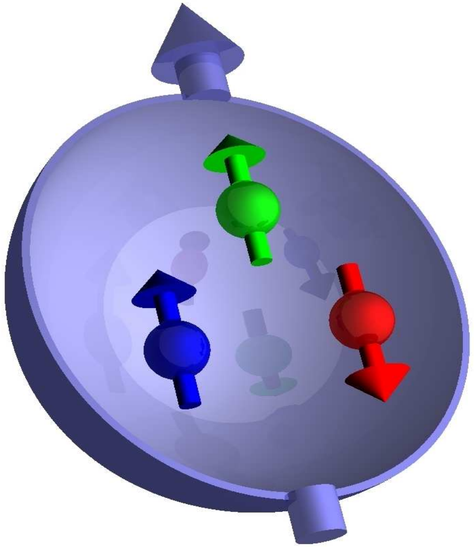
3 stations, 12 coordinates
size 40x40 cm^2
pitch 360 – 420 μm
time res. < 10 ns
space res. 70 -90 μm
efficiency > 97%
$Ne/C_2H_6/CF_4$ 80/10/10 %



COMPASS experimental hall

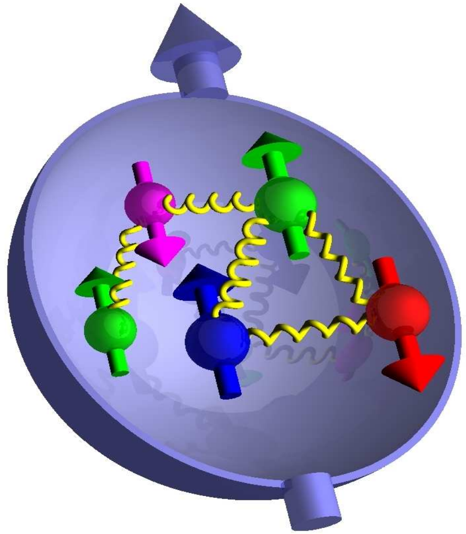


What makes up the spin of nucleon?



Naive quark model: valence quarks

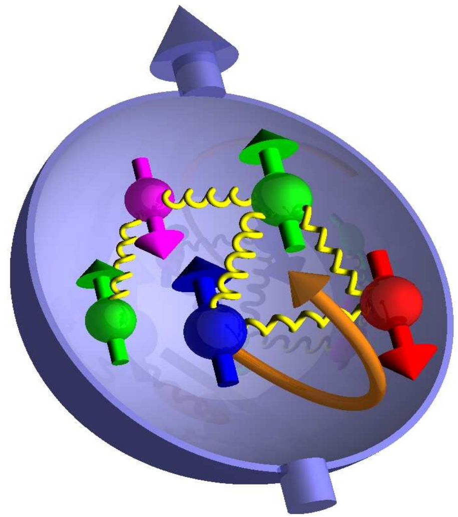
$$\frac{1}{2} = \frac{1}{2}\underbrace{\left(\Delta u_v + \Delta d_v + \Delta q_s\right)}_{\Delta\Sigma\, =\, 1\, ???}$$



QCD: …additional contributions from gluons …

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G$$

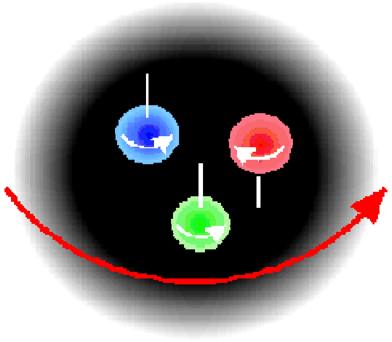
ΔG = ?



… and angular momentum

$$\frac{1}{2} = J_q + J_g$$
$$= \frac{1}{2}\Delta\Sigma + L_q$$
$$+ \quad \Delta G + L_g$$

Nucleon spin puzzle since 1988



$$\tfrac{1}{2} = \tfrac{1}{2}\Delta\Sigma + \Delta G + \langle L_z \rangle$$

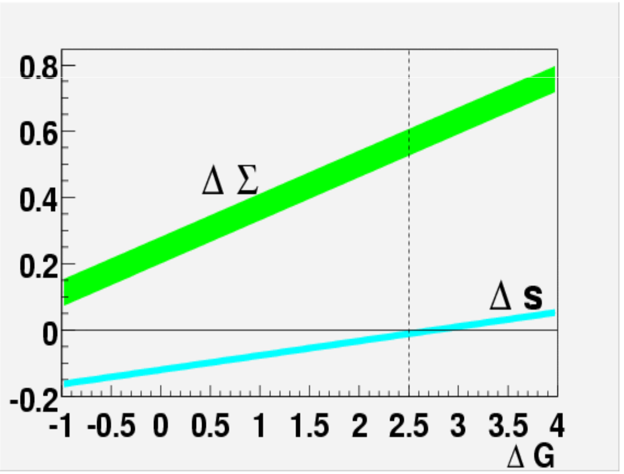
quarks — gluons — orb. mom.

"past" — "present" — "future" — experiments

Measurement of ΔG is important for two reasons:

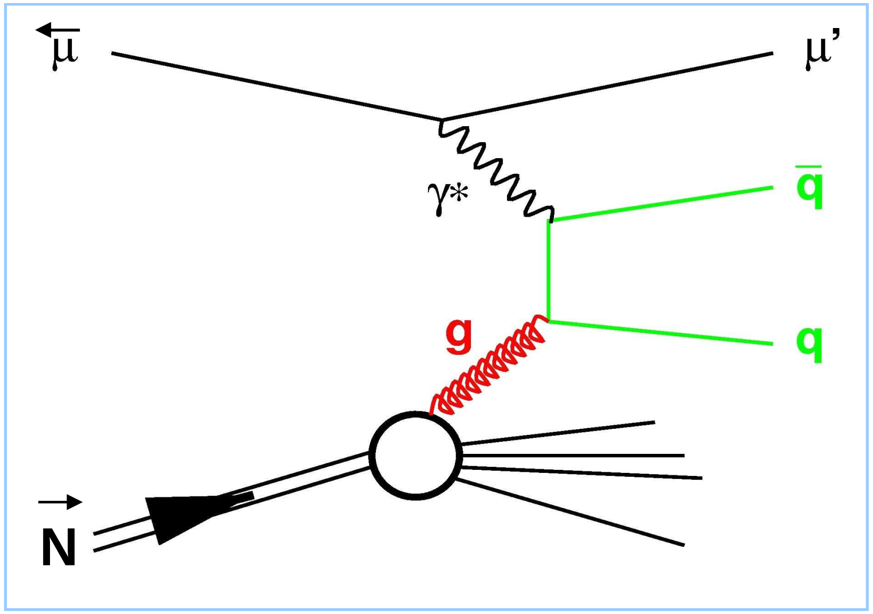
- as an element of nucleon spin puzzle
- possible role of axial anomaly in the a_0 interpretation ($a_0 \neq \Delta\Sigma$)

a_0 (= ΔΣ) is measured to be ~0.30-0.35 instead of expected 0.6



$$a_0 = \Delta\Sigma - \frac{3\alpha_s}{2\pi}\Delta G$$

Photon Gluon Fusion (PGF)



Open Charm

$$\gamma^{*}g \rightarrow c\bar{c} \rightarrow D^{0}X$$

→ clean channel

→ but experimentally difficult

$\sigma \approx 100$ nb… limited statistics

High-pT Hadron Pairs

$$\gamma^{*}g \rightarrow q\bar{q} \rightarrow h\bar{h}$$

→ easy to get a statistics

→ but physical background

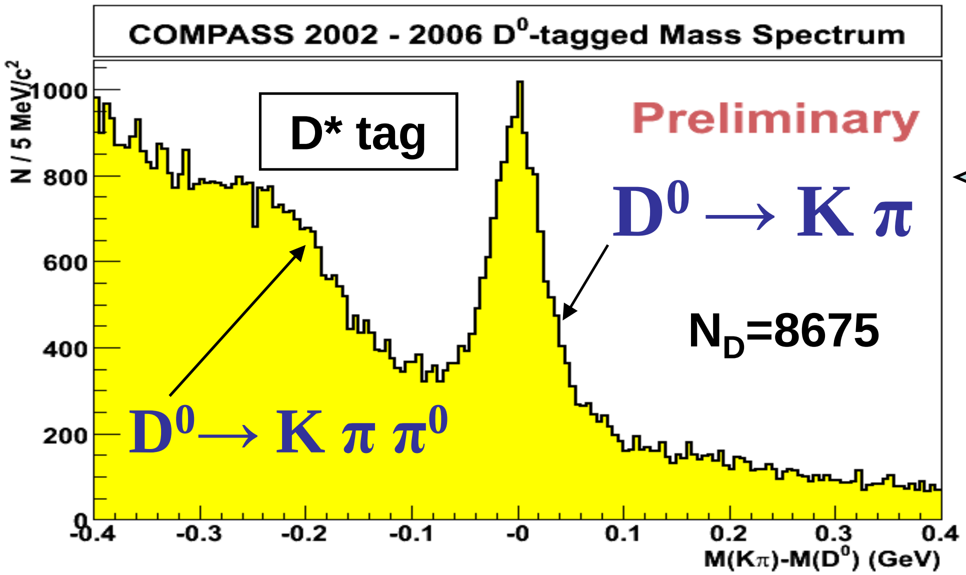
2 cases $Q^2 < 1$ GeV^2 (90% stat)

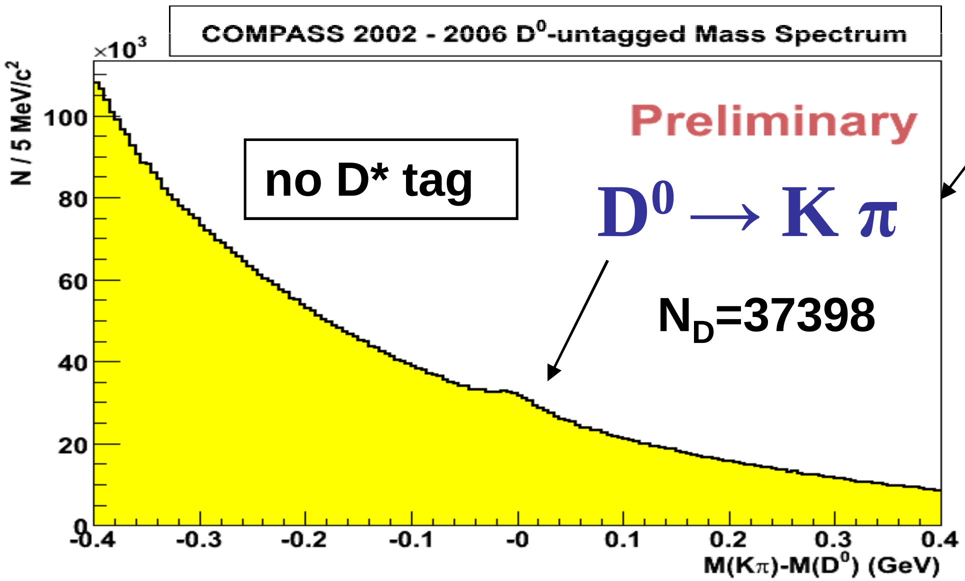
& $Q^2 > 1$ GeV^2 (10% stat)

cross-section asymmetry A||

$$A_{||} = \frac{\sigma^{\Uparrow\downarrow} - \sigma^{\Uparrow\uparrow}}{\sigma^{\Uparrow\downarrow} + \sigma^{\Uparrow\uparrow}}$$

Open charm





$$D^{*+} \to D^0 \pi^+_{soft}$$

BR ≈ 68%

$$D^0 \to K^- \pi^+$$

BR ≈ 4%

only

- golden channel, weak MC dependence
- small statistics, no vertex detector → no primary/secondary vertex separation

Open charm

Gluon polarization $\Delta G/G$ is extracted from the measured double spin asymmetry A_{exp} of the D^0 cross-section

$$A_{\rm exp} = p_\mu \, p_{\rm T} \, f \, a_{\rm LL} \, \frac{S}{S+B} \, \frac{\Delta G}{G}$$

using the analysing power (a_{LL}), target polarisation (p_T) , beam polarisation (p_μ) , dilution factor (f) and signal purity $S/(S+B)$

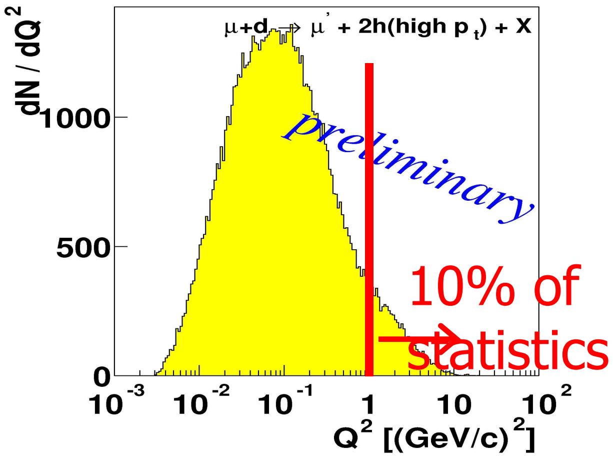
$$\delta\left(\frac{\Delta G}{G}\right) \propto 1 \Big/ \sqrt{\frac{S}{S+B} \times S}$$

$S/(S+B)$ was parameterized (Σ) as a function of kinematical variables and the RICH response; it's given event-by-event

Event weight: $w = p_\mu \, f \, a_{LL} \, \Sigma$

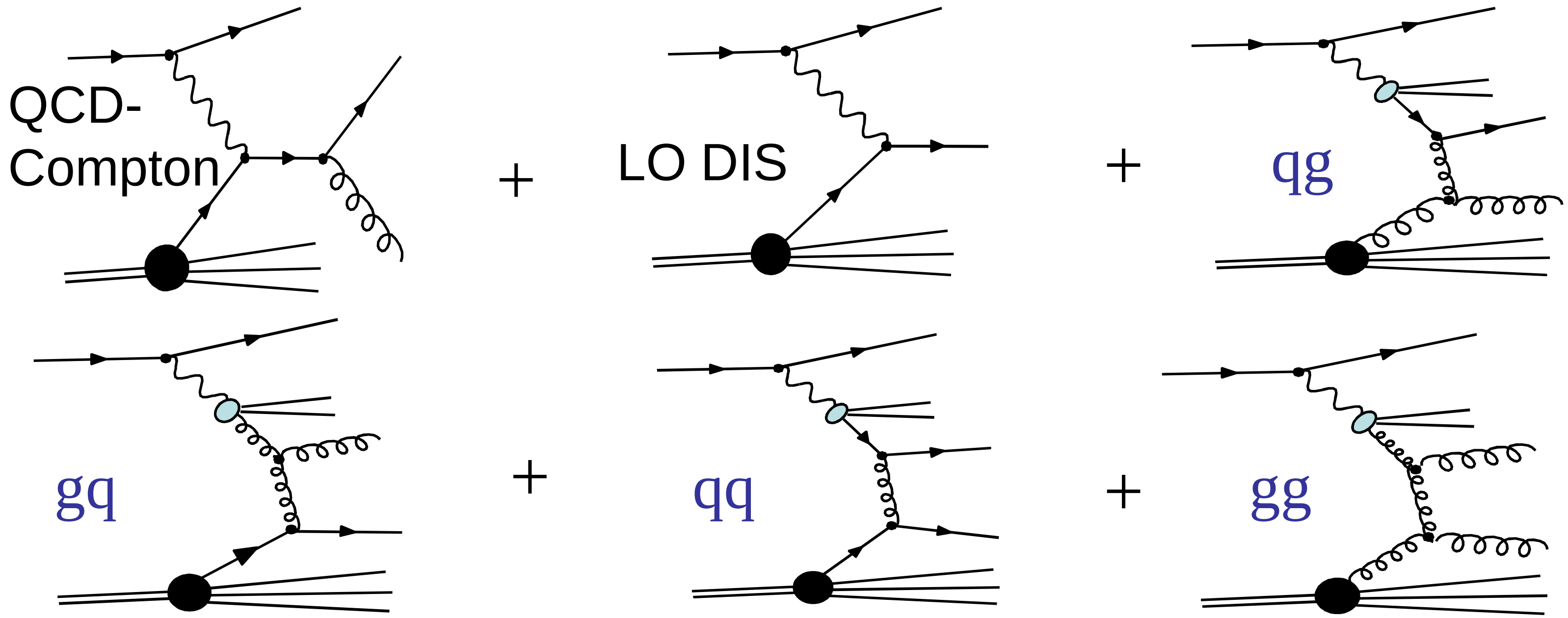
Preliminary (2002-2006) result:

$\Delta G/G = -0.49 \pm 0.27\ (\text{stat}) \pm 0.11\ (\text{syst})$



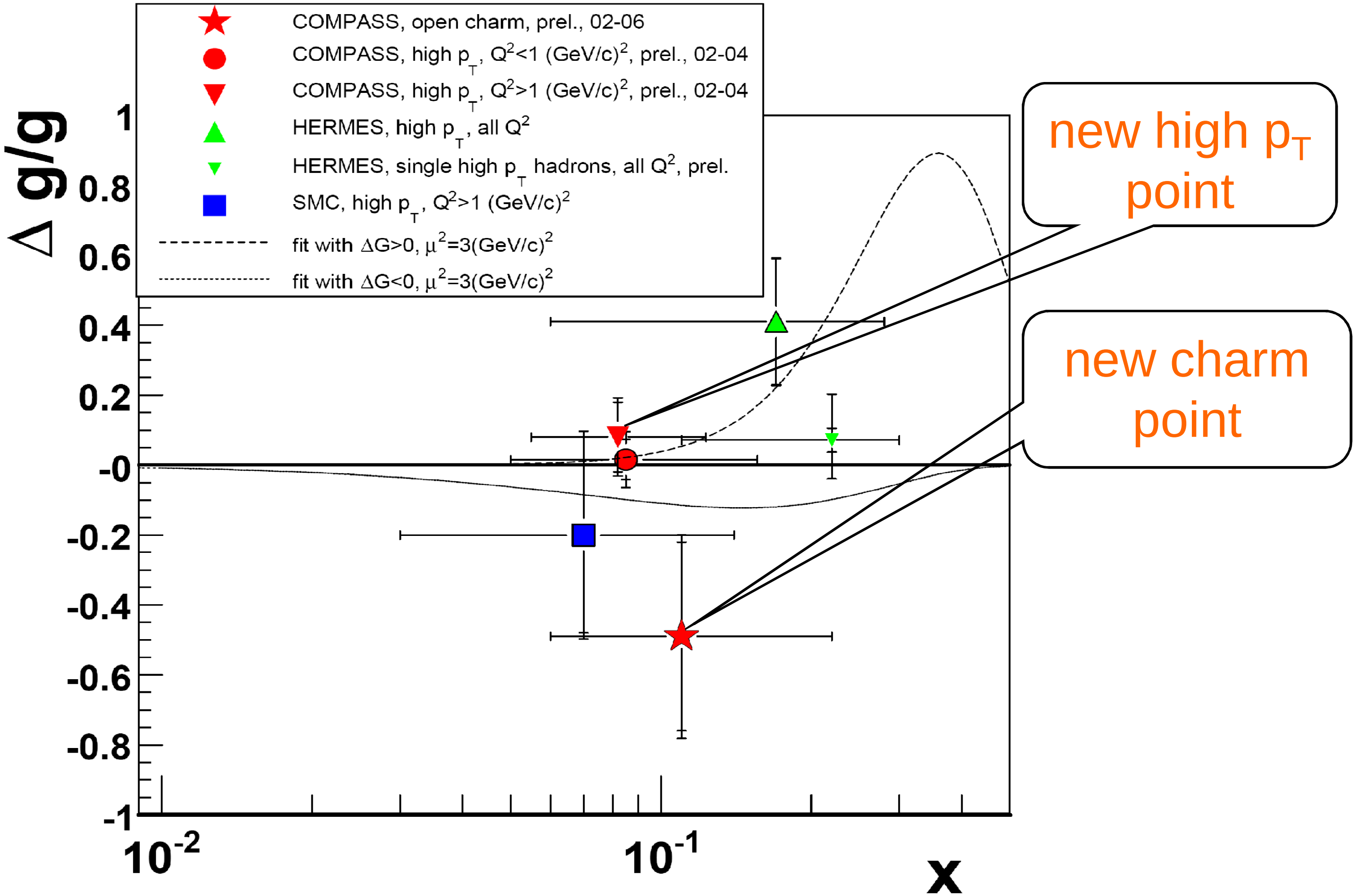
high p_T hadron pairs

- considerably higher statistics **...** but physical background, resolved photons processes (last 4) are important only for low Q^2



New analysis for Q^2>1 GeV^2 was done using 2002-2004 data .

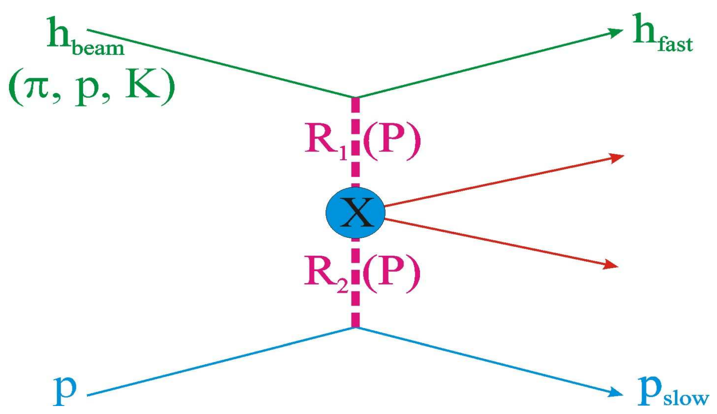
ΔG/G measurements



QCD fits → $|\Delta G| \approx 0.2-0.3$ as direct measurements point to a small value of ΔG ….. axial anomaly contribution is small → $a_0 \approx \Delta\Sigma$

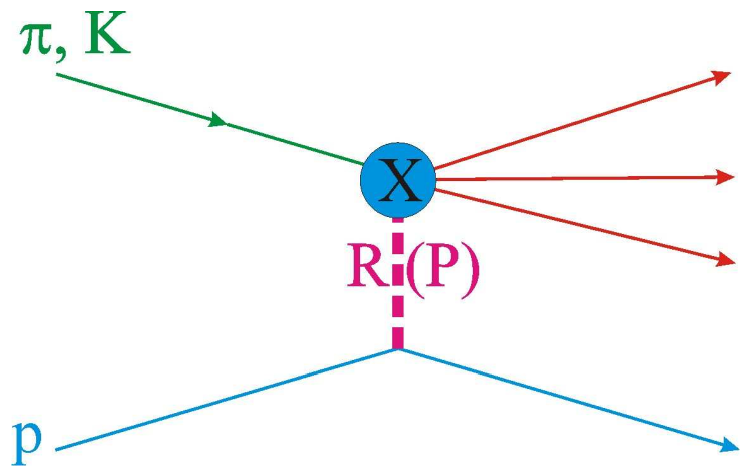
In 2008 COMPASS will collect data from two production mechanisms with the same apparatus using p, π and K projectiles

Central production



Large rapidity gap between scattered beam and X
Beam particle looses ~10% of its energy
Particles at large angles
Possible source of glueballs

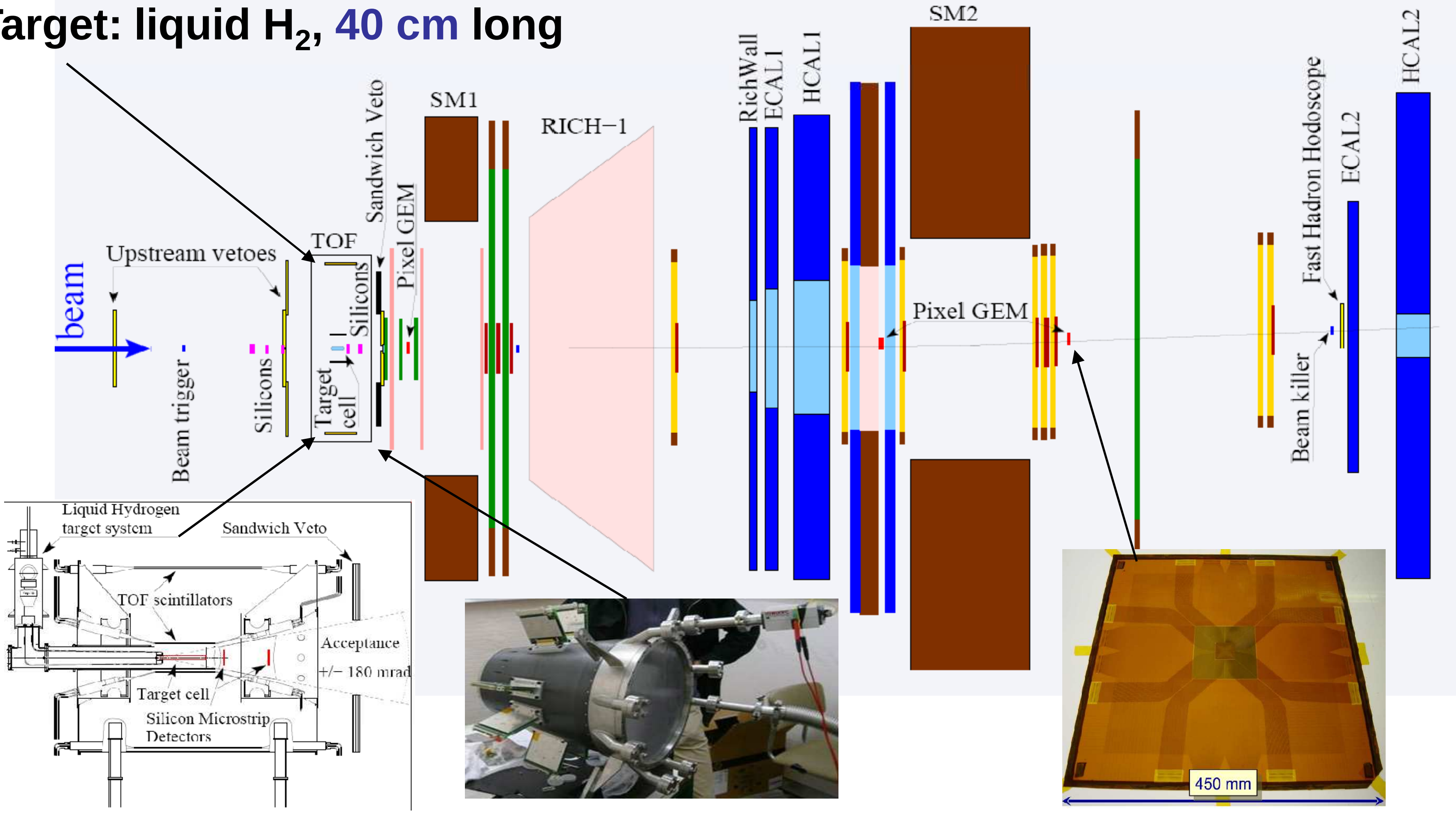
Diffractive scattering



Forward kinematics
Large cross-section (~mb)
Need to separate particles at very small angles
Study of J^{PC}-exotic mesons

Beam: 190 GeV positive/negative hadrons
Negative: 96% π, 3.5% K, 0.5% p
Positive: 75% K, 25% π
Beam intensity: $5{\cdot}10^6$ had/s
Luminosity: 0.15 pb^{-1} /day
Target: liquid H_2, 40 cm long

COMPASS in 2008

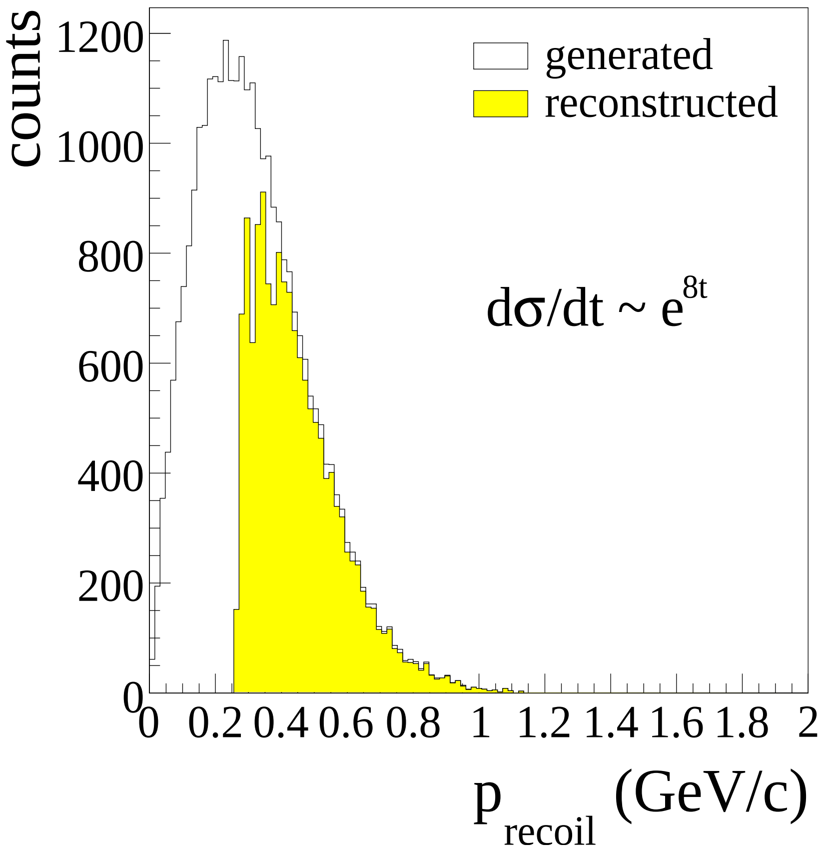


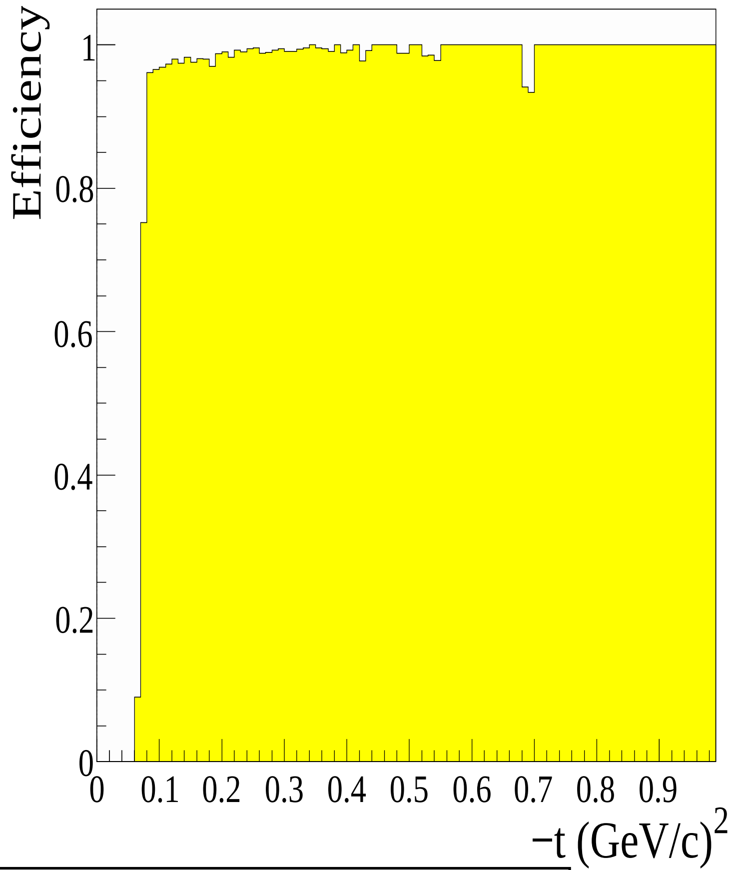
GEM−based beam tracking

Detection of target recoil protons

Simulated recoil protons from diffractive π−*p* scattering

Full acceptance for −*t* > 0.06 (GeV/*c*)2





Efficiency ~100% for P>290 MeV/c

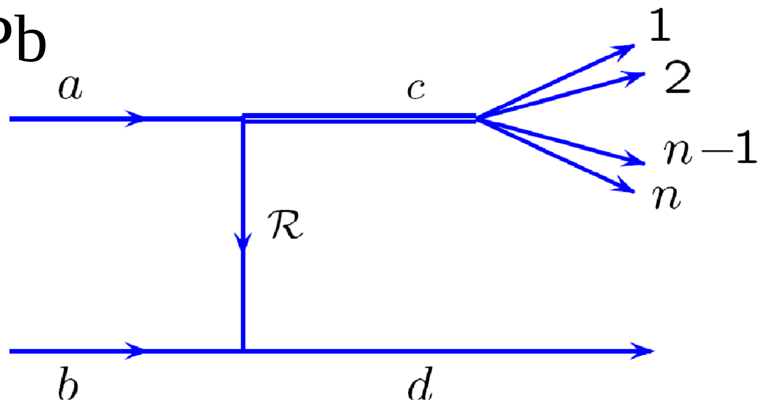
3π Events from Diffractive Dissociation at COMPASS

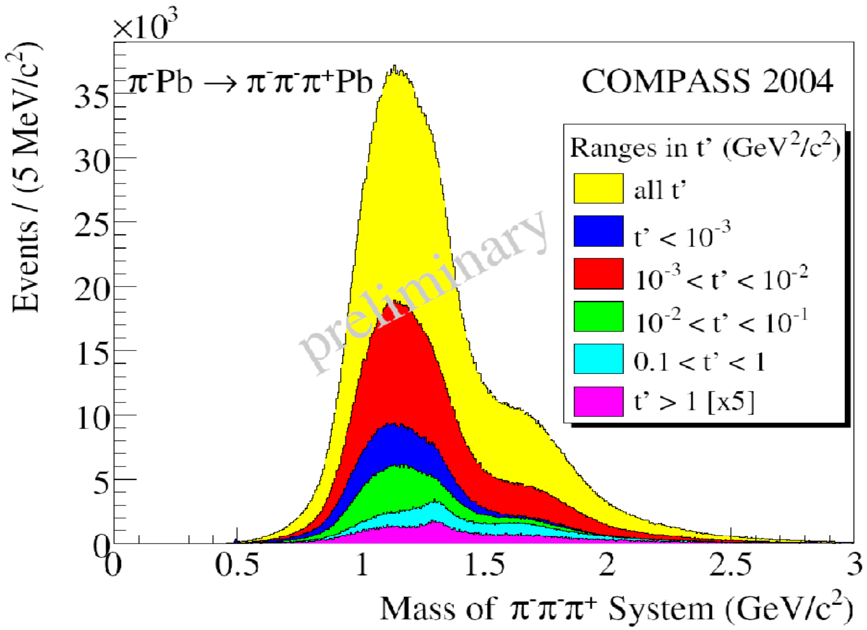
2004 pilot run: $\pi^- + \mathrm{Pb} \to \pi^-\pi^-\pi^+ + \mathrm{Pb}$

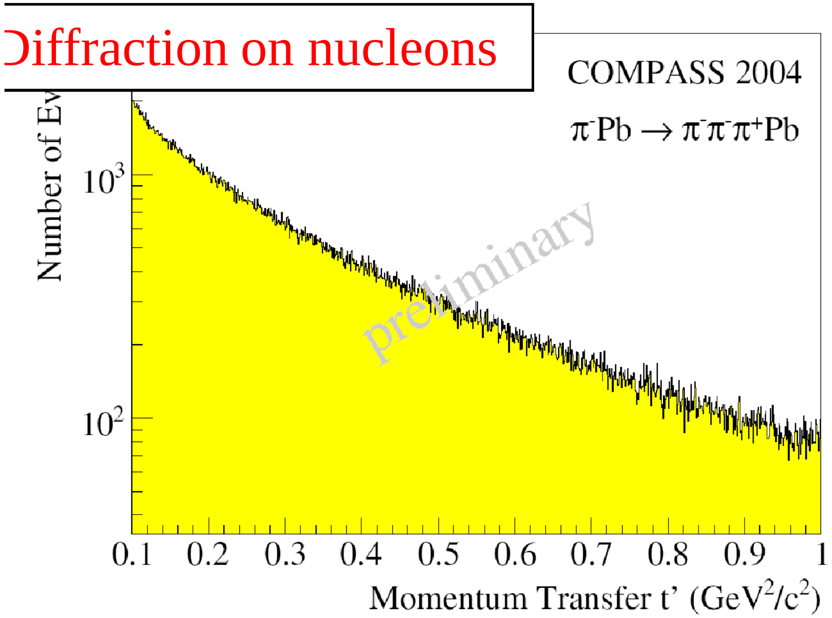
Exclusivity ⇨ target stays intact

Momentum transfer

$$-t = -(p_a - p_c)^2$$

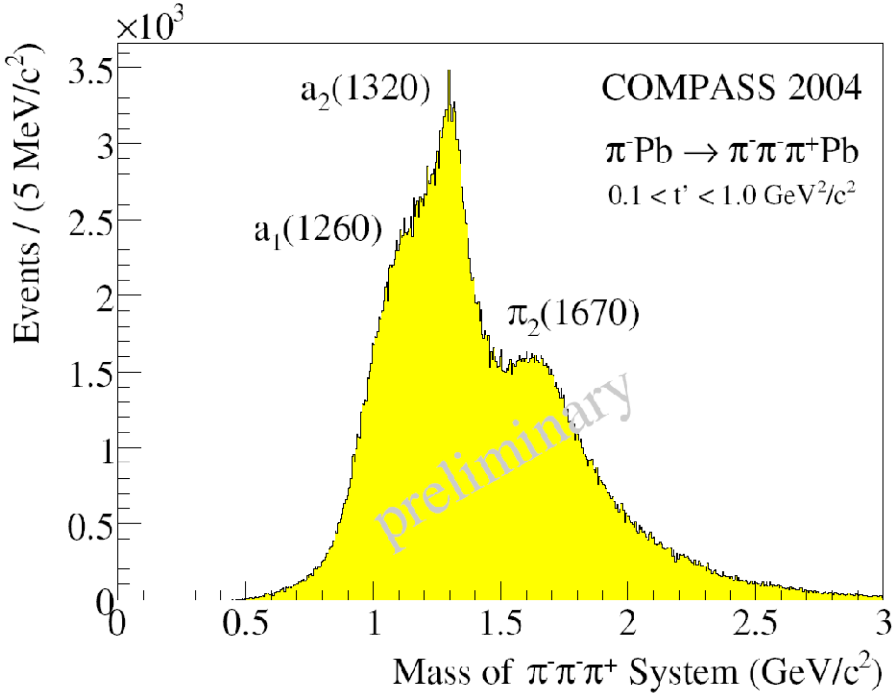


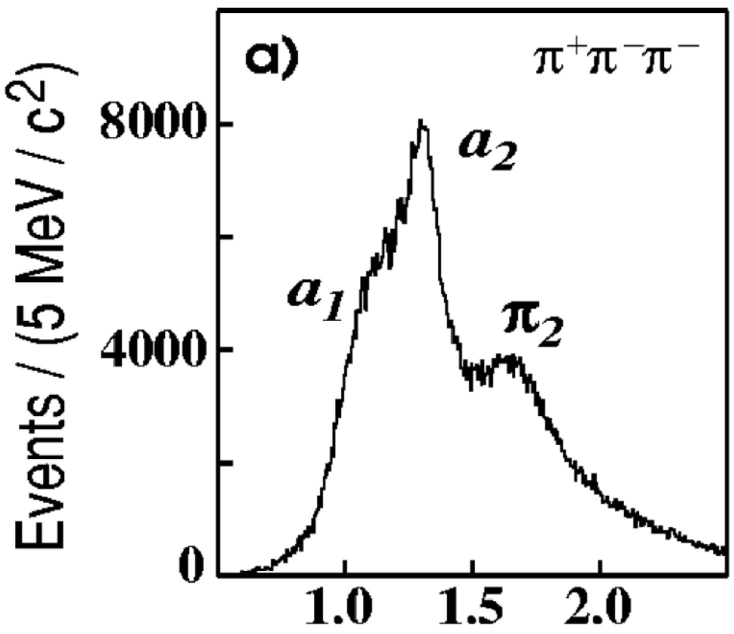




Invariant Mass of 3π System

Well-known $a_1(1260)$, $a_2(1320)$, $\pi_{2(}1670)$ states come out correctly



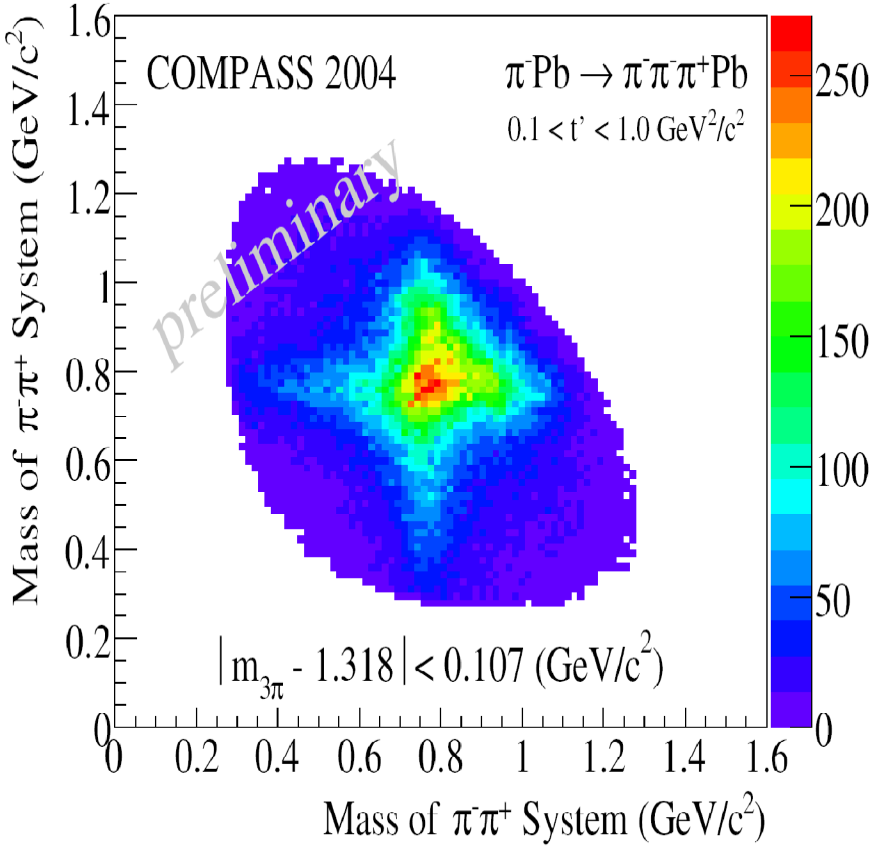


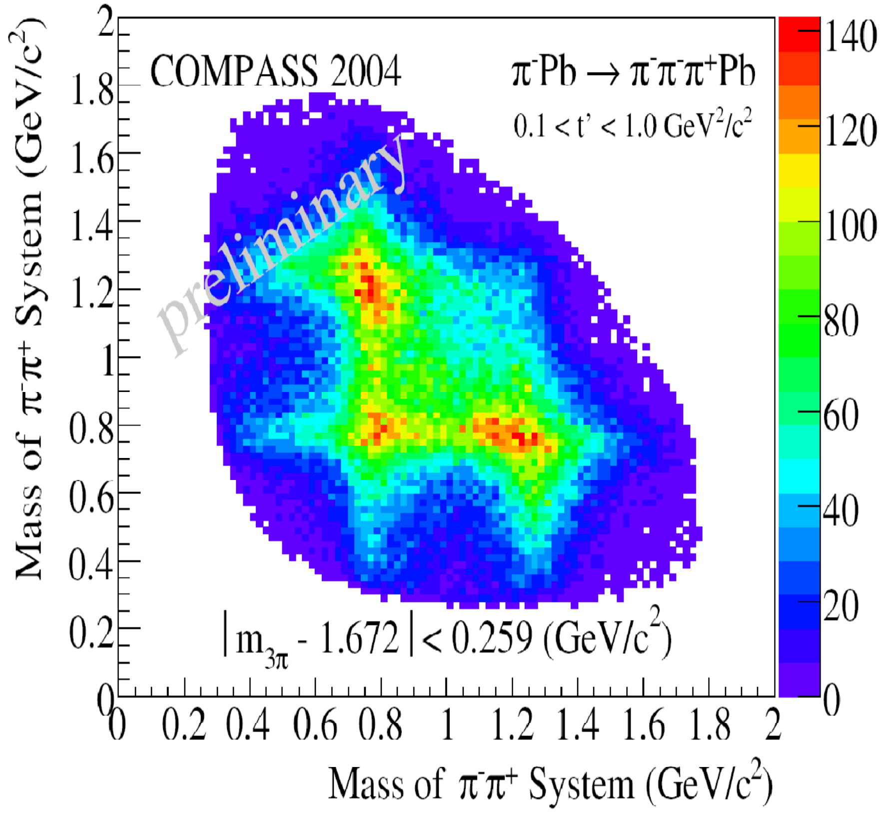
COMPASS: p_π=190 GeV/c
4M events in 3 days (full t-range)
450k events in BNL-E852 t-range

BNL-E852: p_π =18 GeV/c
250k events ⇨ $\pi_1(1600)$ but
its existence still questionable

Mass of $\pi^+\pi^-$ combinations from 3π events

$$a_2(1320) \rightarrow \rho\pi \qquad \pi_2(1670) \rightarrow \rho\pi\,,\, f_2\pi$$

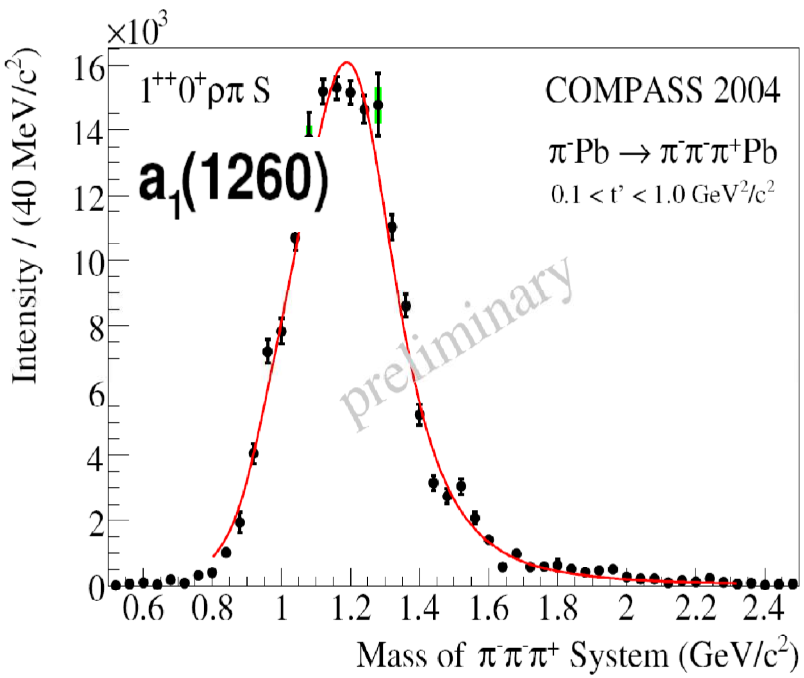


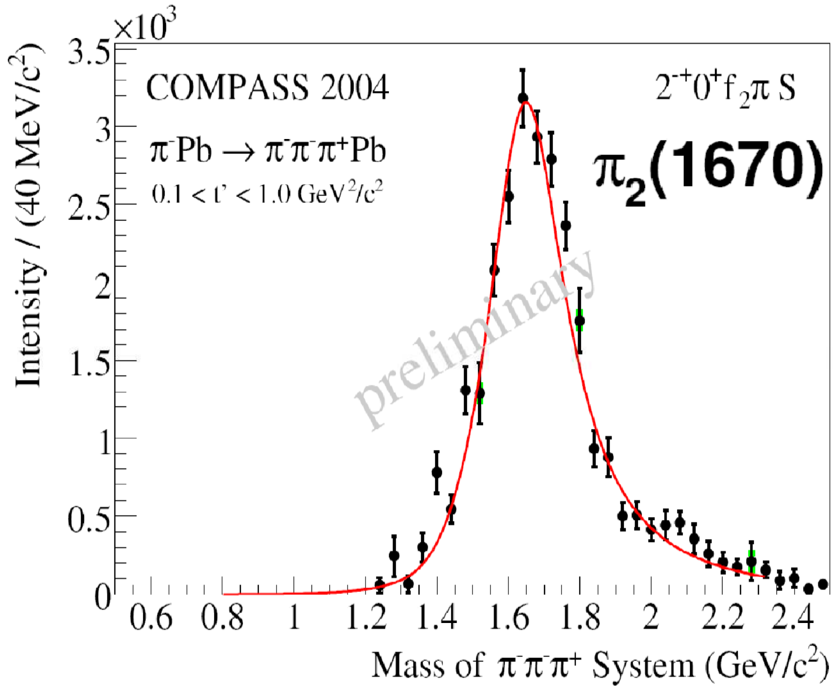


Partial Wave Analysis

Notation of Partial Waves: $J^{PC}M^{\epsilon}[\ldots]L$

- Spin J, parity P, C-parity C, spin projection M, reflectivity ϵ, decay particles $[\ldots]$ and their relative orbital angular momentum L
- E. g.: $\pi_2(1670)$: $2^{-+}1^{+}[f_2\pi]S$, $2^{-+}0^{+}[\rho\pi]P$, $a_2(1320)$: $2^{++}1^{+}[\rho\pi]D$
- Intensity is a coherent and incoherent ($\epsilon = \pm 1$, flat) sum of partial waves



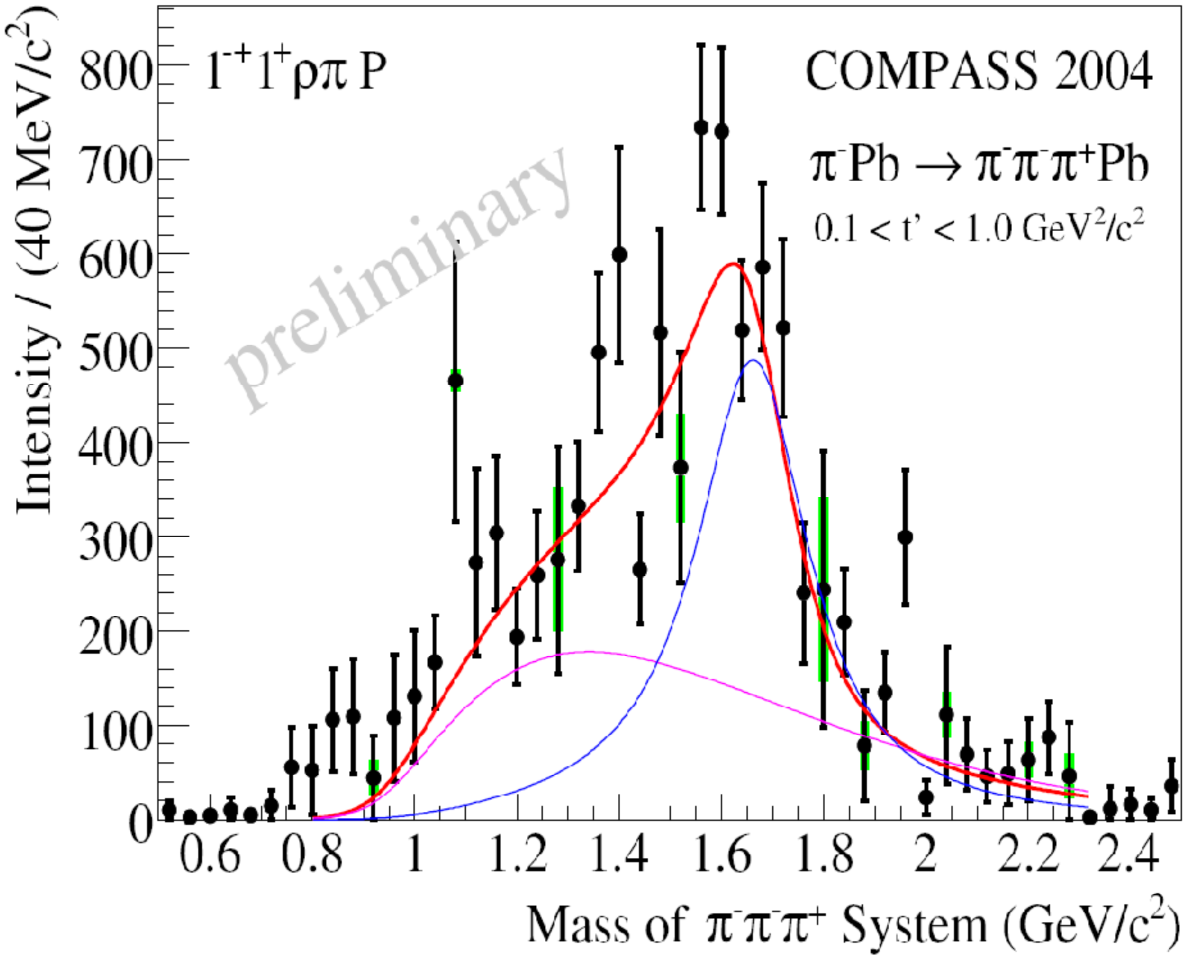


COMPASS results compared to PDG values

State	(GeV)	COMPASS ± stat ± syst	PDG
$a_1(1260)$	M	1.256 ± 0.006 + 0.007 - 0.017	1.230 ± 0.040
	Γ	0.366 ± 0.009 + 0.028 - 0.025	0.250 to 0.600
$a_2(1320)$	M	1.321 ± 0.001 + 0.000 - 0.007	1.3183 ± 0.0006
	Γ	0.110 ± 0.002 + 0.002 - 0.015	0.107 ± 0.005
$\pi_1(1600)$	M	1.660 ± 0.010 + 0.000 - 0.064	$1.653^{+0.018}_{-0.015}$
	Γ	0.269 ± 0.021 + 0.042 - 0.064	$0.225^{+0.045}_{-0.028}$
$\pi_2(1670)$	M	1.659 ± 0.003 + 0.024 - 0.008	1.6724 ± 0.0032
	Γ	0.271 ± 0.009 + 0.022 - 0.024	0.259 ± 0.009
$\pi(1800)$	M	1.785 ± 0.009 + 0.012 - 0.006	1.812 ± 0.014
	Γ	0.208 ± 0.022 + 0.021 - 0.037	0.207 ± 0.013
$a_4(2040)$	M	1.884 ± 0.013 + 0.050 - 0.002	2.001 ± 0.010
	Γ	0.295 ± 0.024 + 0.046 - 0.019	0.313 ± 0.031

Exotics: π_1(1600) in COMPASS

preliminary



Breit-Wigner parameters for π_1(1600)

$$M = \left(1.660 \pm 0.010 ^{+0.000}_{-0.064}\right) \mathrm{GeV}/c^2$$

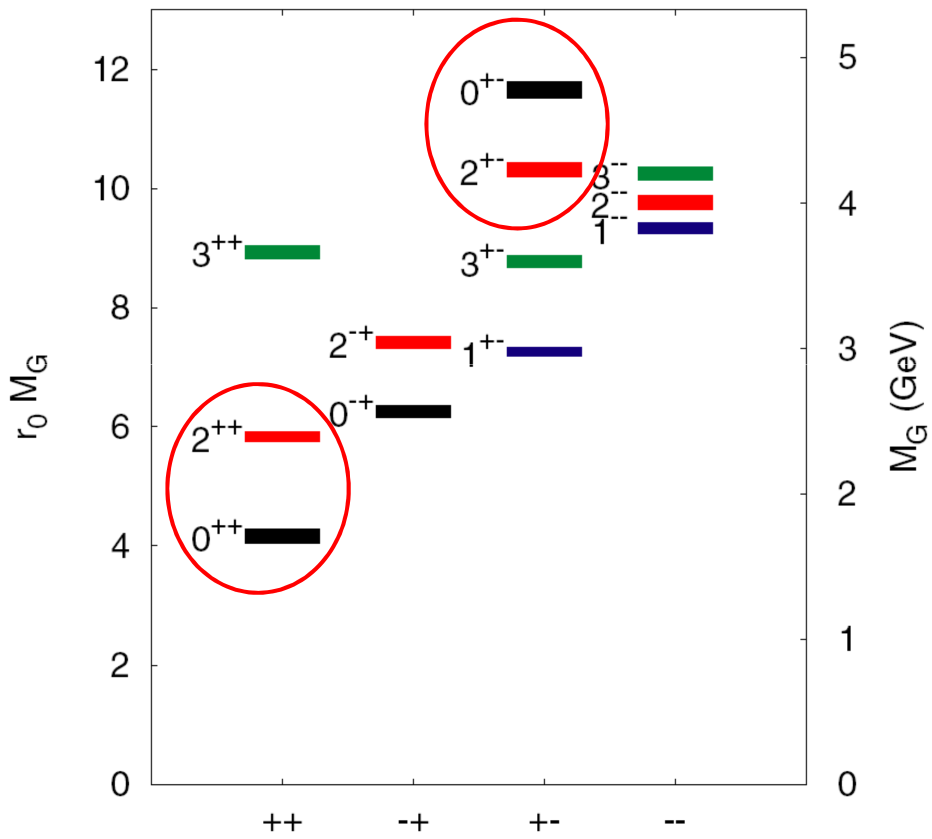
$$\Gamma = \left(0.269 \pm 0.021 ^{+0.042}_{-0.064}\right) \mathrm{GeV}/c^2$$

Light exotics

Experiment	Exotic	J^{PC}	Mass [MeV/c^2]		Width [MeV/c^2]		Decay
E852	$\pi_1(1400)$	1^{-+}	1359	${}^{+16}_{-14}\ {}^{+10}_{-24}$	314	${}^{+31}_{-29}\ {}^{+9}_{-66}$	$\eta\pi$
Crystal Barrel	$\pi_1(1400)$	1^{-+}	1400	$\pm20\pm20$	310	$\pm50\ {}^{+50}_{-30}$	$\eta\pi$
Crystal Barrel	$\pi_1(1400)$	1^{-+}	1360	±25	220	±90	$\eta\pi$
Obelix	$\pi_1(1400)$	1^{-+}	1384	±28	378	±58	$\rho\pi$
E852	$\pi_1(1600)$	1^{-+}	1593	$\pm8\ {}^{+29}_{-47}$	168	$\pm20\ {}^{+150}_{-12}$	$\rho\pi$
E852	$\pi_1(1600)$	1^{-+}	1597	$\pm10\ {}^{+45}_{-10}$	340	$\pm40\pm50$	$\eta'\pi$
Crystal Barrel	$\pi_1(1600)$	1^{-+}	1590	±50	280	±75	$b_1\pi$
Crystal Barrel	$\pi_1(1600)$	1^{-+}	1555	±50	468	±80	$\eta'\pi$
E852	$\pi_1(1600)$	1^{-+}	1709	$\pm24\pm41$	403	$\pm80\pm115$	$f_1\pi$
E852	$\pi_1(1600)$	1^{-+}	1664	$\pm8\pm10$	185	$\pm25\pm28$	$\omega\pi\pi$
E852	$\pi_1(2000)$	1^{-+}	2001	$\pm30\pm92$	333	$\pm52\pm49$	$f_1\pi$
E852	$\pi_1(2000)$	1^{-+}	2014	$\pm20\pm16$	230	$\pm32\pm73$	$\omega\pi\pi$
E852	$h_2(1950)$	2^{+-}	1954	±8	138	±3	$\omega\pi\pi$
COMPASS	$\pi_1(1600)$	1^{-+}	1660	±10	269	±21	$\rho\pi$

Glueballs mass spectrum

Lattice calculation



[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 candidates:

- $f_0(1500)$ (Crystal Barrel, WA102)

  $J^{PC}=0^{++}$ ⇨ mixing with isoscalar mesons!

Higher masses:

- exotic: $J^{PC} = 2^{+-}, 0^{+-}$
- $M \sim 4.3\,\mathrm{GeV}/c^2$

Expected event rates (run 2008)

- 190 GeV/c hadron beam $\mathcal{L}$=0.15 pb^{-1}/day
- Diffractive scattering: $\pi^- p \to \pi_1(1600)\, p,\ \pi_1(1600) \to \pi^+\pi^-\pi^-$
    - $\sigma(\pi_1)\times BR(\pi_1\to\pi^+\pi^-\pi^-)$=0.6 μb
    - ε(DAQ)×ε(reco)=5%

⇨ $4.5\cdot10^3$ ev./day

- Goal for 2008: $1.6\cdot10^5$ π_1(1600) events in ~35 day
- Central production: $\pi^- p \to \pi^- f_0(1500)\, p,\ f_0(1500) \to \eta\eta \to 4\gamma$
    - σ(f0)×BR($f_0\to\eta\eta\to4\gamma$)=1.5 μb·5%·15%=11nb
    - ε(DAQ)×ε(reco)=2%

⇨ 30 ev./day

- Goal for 2008: $2\cdot10^3$ $f_0\to\eta\eta$ events in ~60 days

$f_0 \to 2\pi^+ 2\pi^-$

⇨ $2.5\cdot10^3$ ev./day

- Goal for 2008: $1\cdot10^5$ $f_0 \to 2\pi^+\, 2\pi^-$ events in ~60 days

Conclusions

Data taking with μ beam: 2002-2004, 2006-2007

Direct measurements results indicate small **ΔG** around ***x* ≈ 0.1;**

- QCD analysis of g_1 shows the first moment of |**ΔG|** ≈ 0.2-0.3;

ΔG>0 and ΔG<0 solutions describe data equally well

	ΔΣ		ΔG		<Lz>
1/2 =	**1/2 × 0.3**	**+**	**0.35**	**+**	**0.0**
1/2 =	**1/2 × 0.3**	**+**	**0.0**	**+**	**0.35**
1/2 =	**1/2 × 0.3**	**-**	**0.35**	**+**	**0.7**

but direct measurements cannot yet discriminate between them

Pilot run with π beam: 2004 (3 days)

- **Diffractive reactions** being studied: 3π
- Major partial waves are correctly reconstructed
- Statistics 2×higher than BNL-E852 in 1 year

Looking forward to many new results from 2008 hadron run

Backup slides

Data taking…

Up to 2008 COMPASS has collected data for program with a polarised muon beam

- beam momentum/polarisation: 160 GeV/c /~80%
- beam intensity: $2x10^8$ μ+/spill (4.8s/16.2s)
- luminosity: ~5 $x10^{32}$ cm^{-2} s^{-1}
- up to 2006 ^{6}LiD target (~ 50% polarized deuterons)
- in 2007 NH_3 target (~ 90% polarized protons)
- **recorded about 5×10^{10} events ~ 2000 TB**

2004: a short pilot run for hadron program

2008: hadron run with 190 GeV π^- beam for diffractive and central production is going on

Nucleon spin decomposition

Proton spin sum rule:

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_z$$

Total quark spin (cf singlet axial charge a_0)

$$\Delta\Sigma = \Delta u + \Delta d + \Delta s$$

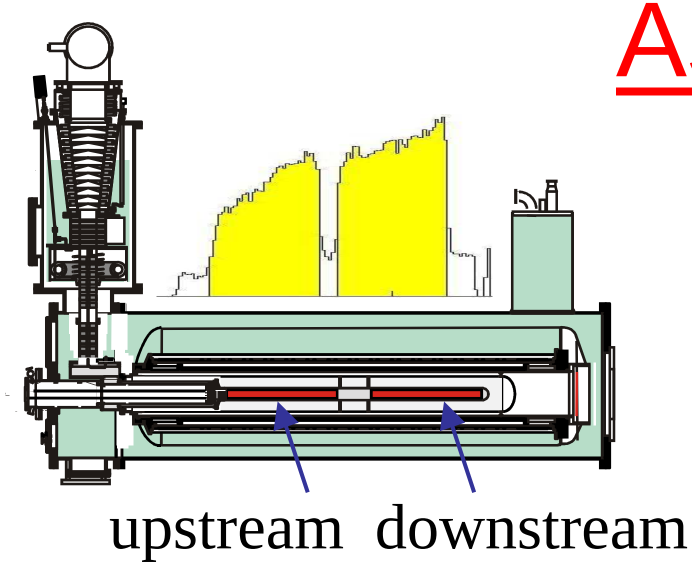
Net quark spin contributions Δq

Net strange quark spin Δs

Net gluon spin ΔG

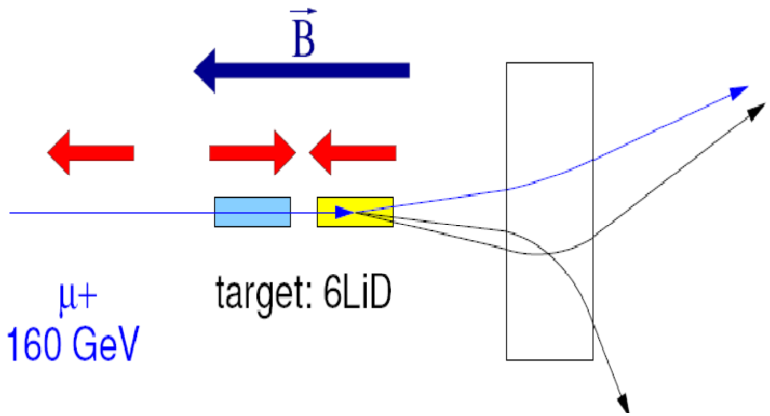
Orbital angular momentum L_z

Asymmetry measurement



two oppositely polarized 60 cm long target cells: upstream (u), downstream (d)
cells polarization reversal every 8 hours
counting rate asymmetry in two target cells gives the **cross-section asymmetry** $A_{\|}$

$$A_{\|} = \frac{\sigma^{\Uparrow\downarrow} - \sigma^{\Uparrow\uparrow}}{\sigma^{\Uparrow\downarrow} + \sigma^{\Uparrow\uparrow}} \quad \Rightarrow \quad \frac{A_{\|}}{D} = \frac{1}{P_T P_B f D} \, \frac{1}{2} \left(\frac{N_u^{\uparrow\downarrow} - N_d^{\uparrow\uparrow}}{N_u^{\uparrow\downarrow} + N_d^{\uparrow\uparrow}} + \frac{N_d^{\uparrow\downarrow} - N_u^{\uparrow\uparrow}}{N_d^{\uparrow\downarrow} + N_u^{\uparrow\uparrow}} \right)$$



target polarisation $P_T \approx 0.50$
dilution factor $f \approx 0.40$
beam polarisation $P_B \approx 0.80$
depolarisation factor $D \approx 0.60$

Measurements of the gluon polarization

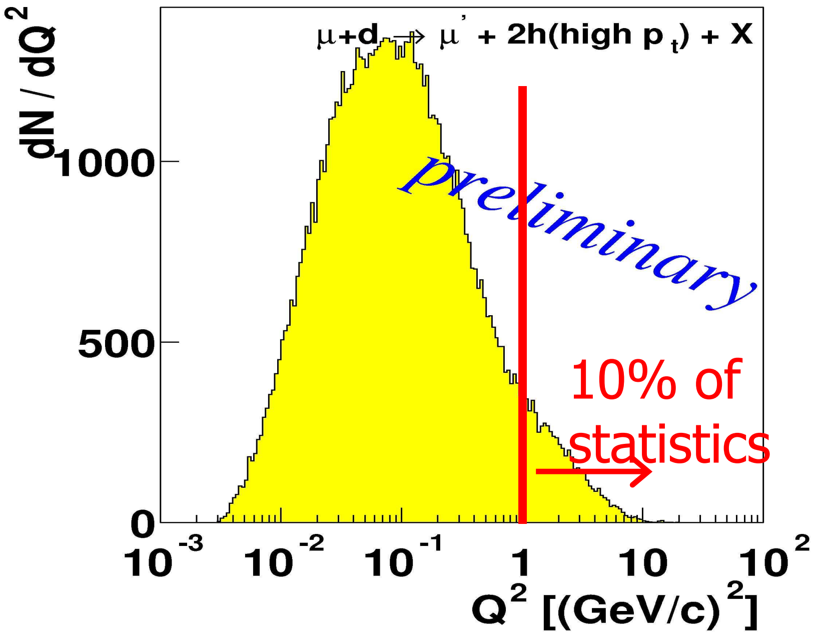
two approaches: direct and indirect &
three methods & four measurements

1. Double spin asymmetry of the OPEN CHARM cross-section in high energy μD scattering (first direct method)

2. Double spin asymmetry of the high-pt HADRON PAIRS in high energy μD DIS: $Q^2 > 1$ GeV^2 (second direct method)

3. Double spin asymmetry of the high-pt HADRON PAIRS in high energy μD scattering: $Q^2 < 1$ GeV^2 (second direct method)

4. Measurement of g1 of the deuteron and QCD fit of all the world data (indirect method)



high p_T hadron pairs

PGF contribution enhancement

$p_T > 0.7$ GeV/c

$p_{T1}^2 + p_{T2}^2 > 2.5$ (GeV/c)^2

x_F, $z > 0.1$

$m(h_1,h_2) > 1.5$ GeV/c^2

$Q^2 < 1$ GeV^2	←	analysis	→	$Q^2 > 1$ GeV^2
90%	←	*statistics from total*	→	*10%*
50%	←	*resolved photons contribution*	→	*----*
QCD-C, LO	←	*another background*	→	*QCD-C, LO*
PYTHIA	←	*MC generator used*	→	*LEPTO*

Gluon polarization: direct measurements

- open charm: 2002-2006

$\Delta G/G = -0.49 \pm 0.27$ (stat) ± 0.11 (syst)

$<x> \sim 0.11$, $<\mu^2> \sim 13\ GeV^2$

- high-p_T pairs, $Q^2 > 1 GeV^2$: 2002–2004

$\Delta G/G = 0.08 \pm 0.10$ (stat) ± 0.05(syst)

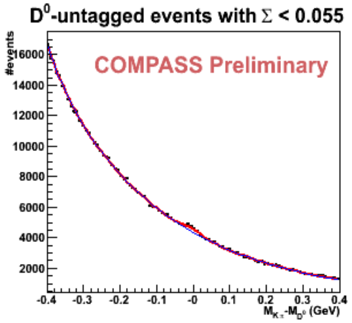
$<x> = 0.082$, $\mu^2 \sim 3\ GeV^2$

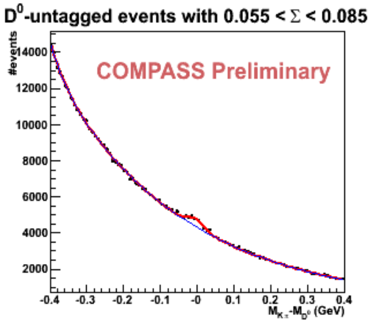
- high-p_T pairs, $Q^2 < 1 GeV^2$: 2002–2004

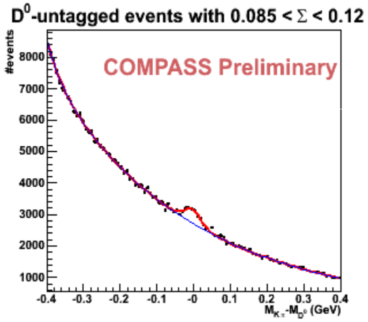
$\Delta G/G = 0.016 \pm 0.058$ (stat) ± 0.055 (syst)

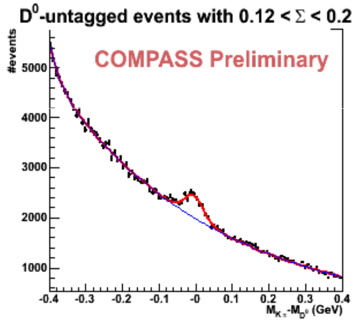
$<x> = 0.085$, $\mu^2 = 3\ GeV^2$

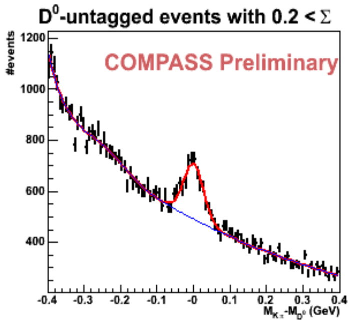
Signal purity: Σ parametrisation



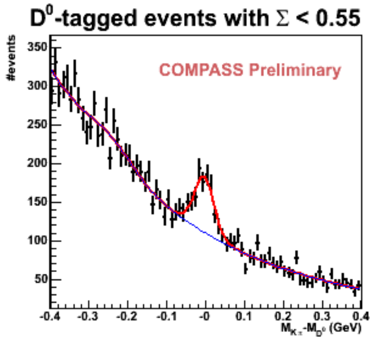


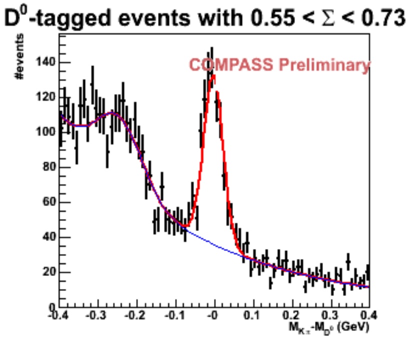


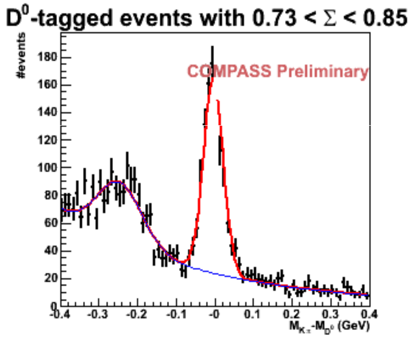


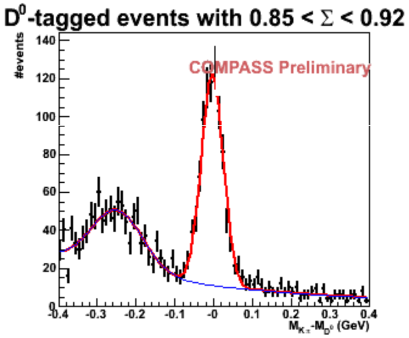


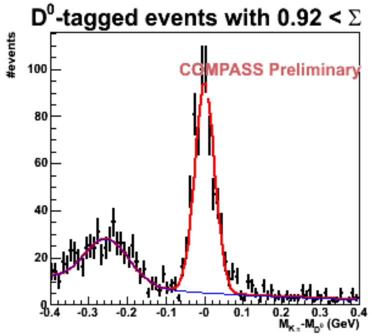
$D^0 \rightarrow K\,\pi$
no D* tag





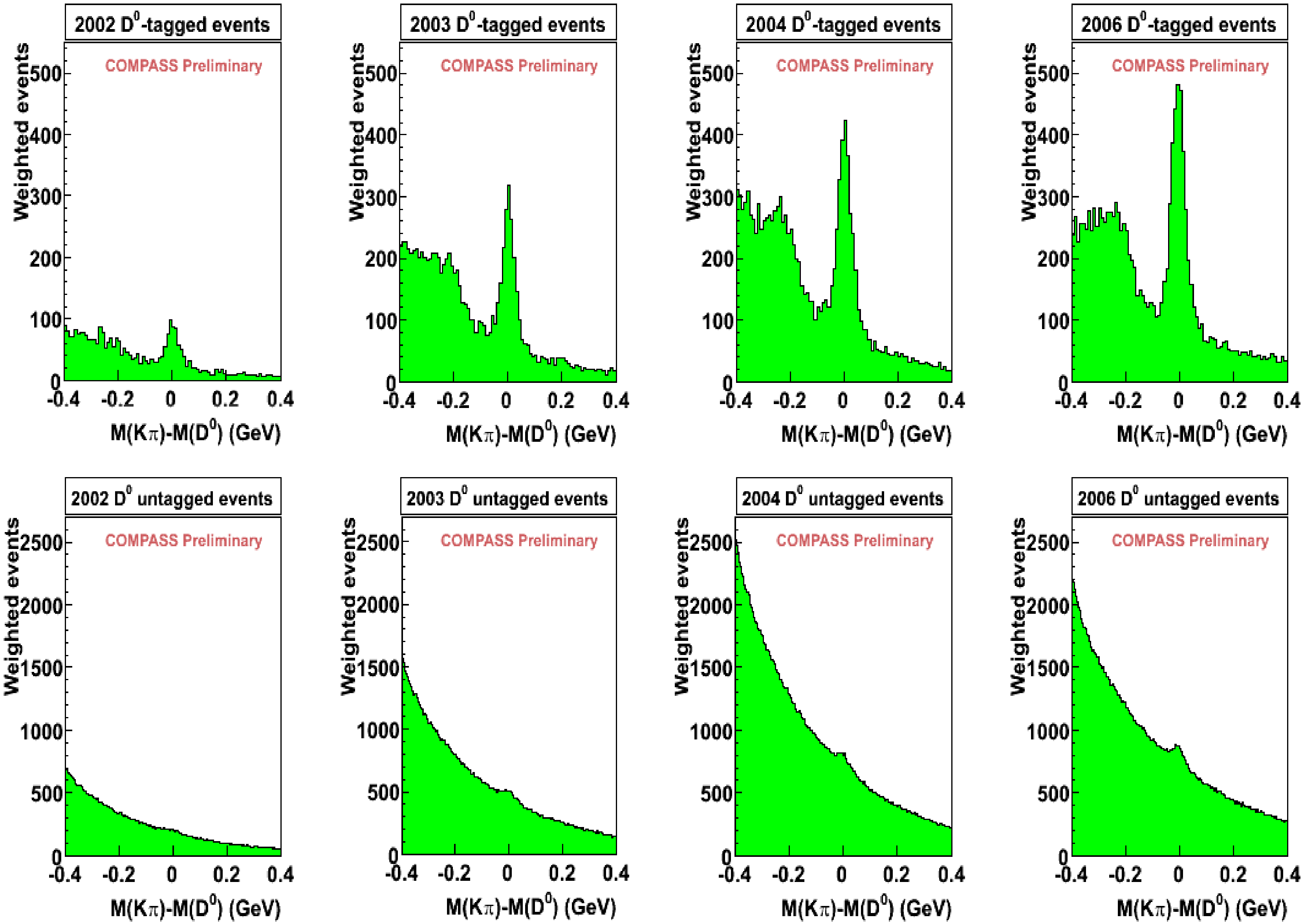






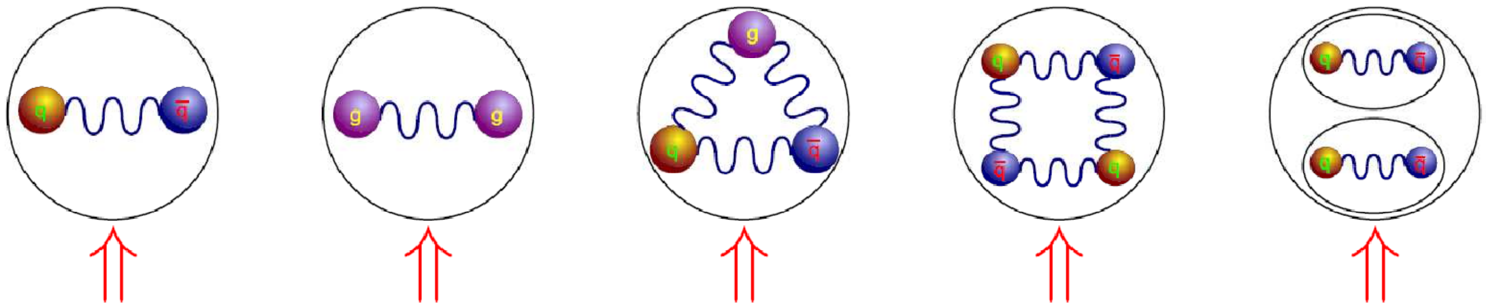
$D^0 \rightarrow K\,\pi$
D* tag

Weighted mass spectra



Mesons beyond the NQM

- COMPASS will start the meson spectroscopy program in 2008 → glueballs and hybric



- The NQM only predicts mesons composed of $q\bar{q}$
- However, gluons carry color charge and can appear as valence constituents:
  - Glueballs: states with only valence gluons (gg, ggg)
  - Hybrids: $q\bar{q}$-systems with one additional valence gluon
- quarks can also form $q\bar{q}q\bar{q}$ bound states and meson-meson molecules
- non-$q\bar{q}$ mesons can have exotic J^{PC} combinations:

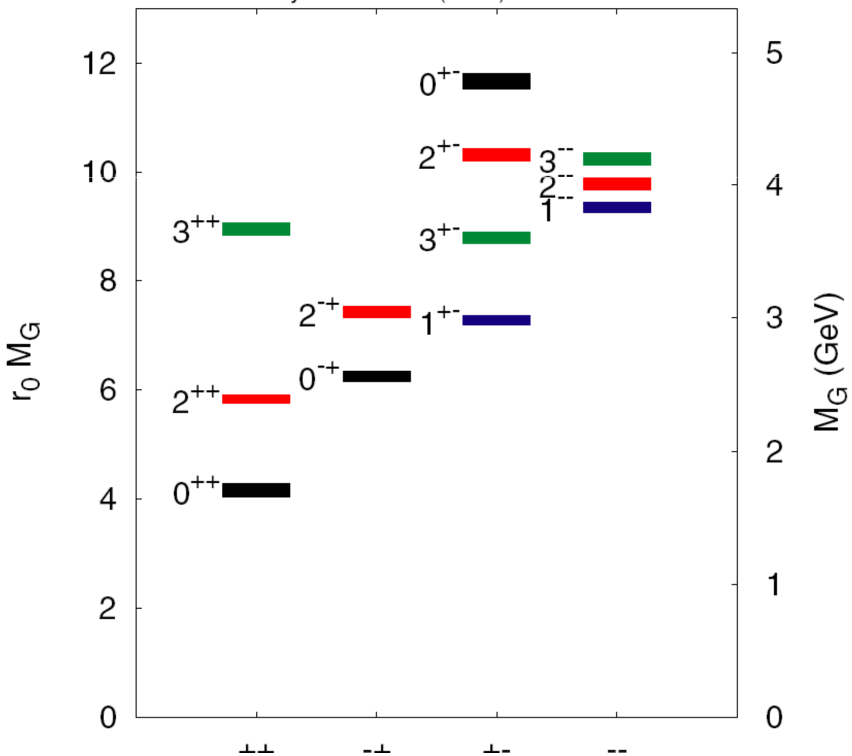
$$J^{PC} = 0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, \ldots$$

- The unabiguous experimental identification of such states represents a fundamental test of non-perturbative QCD

Glueballs mass spectrum

Lattice calculations (numerical solution of the QCD Lagrangian over a space-time grid) provide the most accurate predictions for the glueballs spectrum

C. Morningstar and M. Peardon,
Phys. Rev. D 73 (2006) 014516



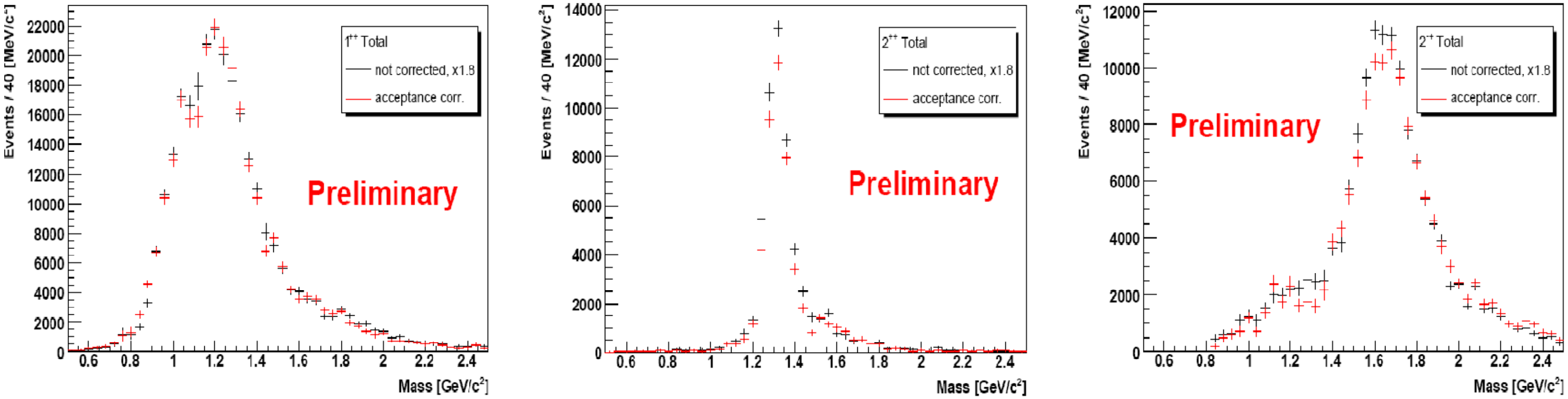
- Lower mass glueballs:
  - $J^{PC} = 0^{++}$ scalar
    $M \sim 1700$ MeV/c^2
  - $J^{PC} = 2^{++}$ tensor
    $M \sim 2400$ MeV/c^2
- The light glueballs have conventional J^{PC}

mixing with nearby $q\bar{q}$ mesons

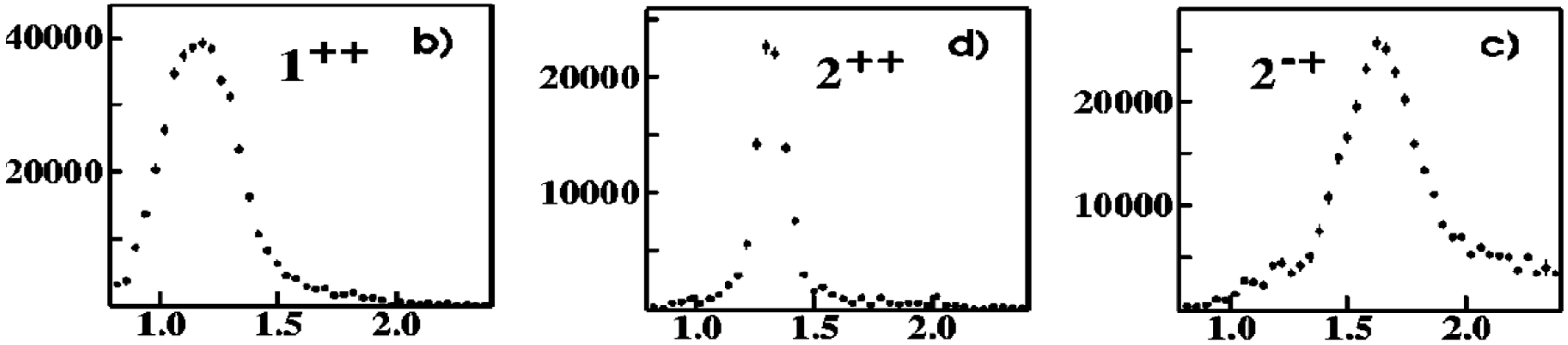
- The lightest exotic glueball (2^{+-}) is above 4 GeV/c^2

PWA results

Major partial waves are correctly reconstructed, acceptance distorsions almost absent



COMPASS 2004 hadron run (preliminary)



BNL 1994 run (PRD 65, 072001 (2002))