The COMPASS experiment at CERN: hadron spectroscopy and open charm results

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JINR, Dubna
On behalf of the COMPASS Collaboration

BEACH2012
Wichita

COmmon Muon and Proton Apparatus for Structure and Spectroscopy

~210 physicists
11 counties 29 Institutes

Hadron beam — **COMPASS I 2002-2011** — **Muon beam**

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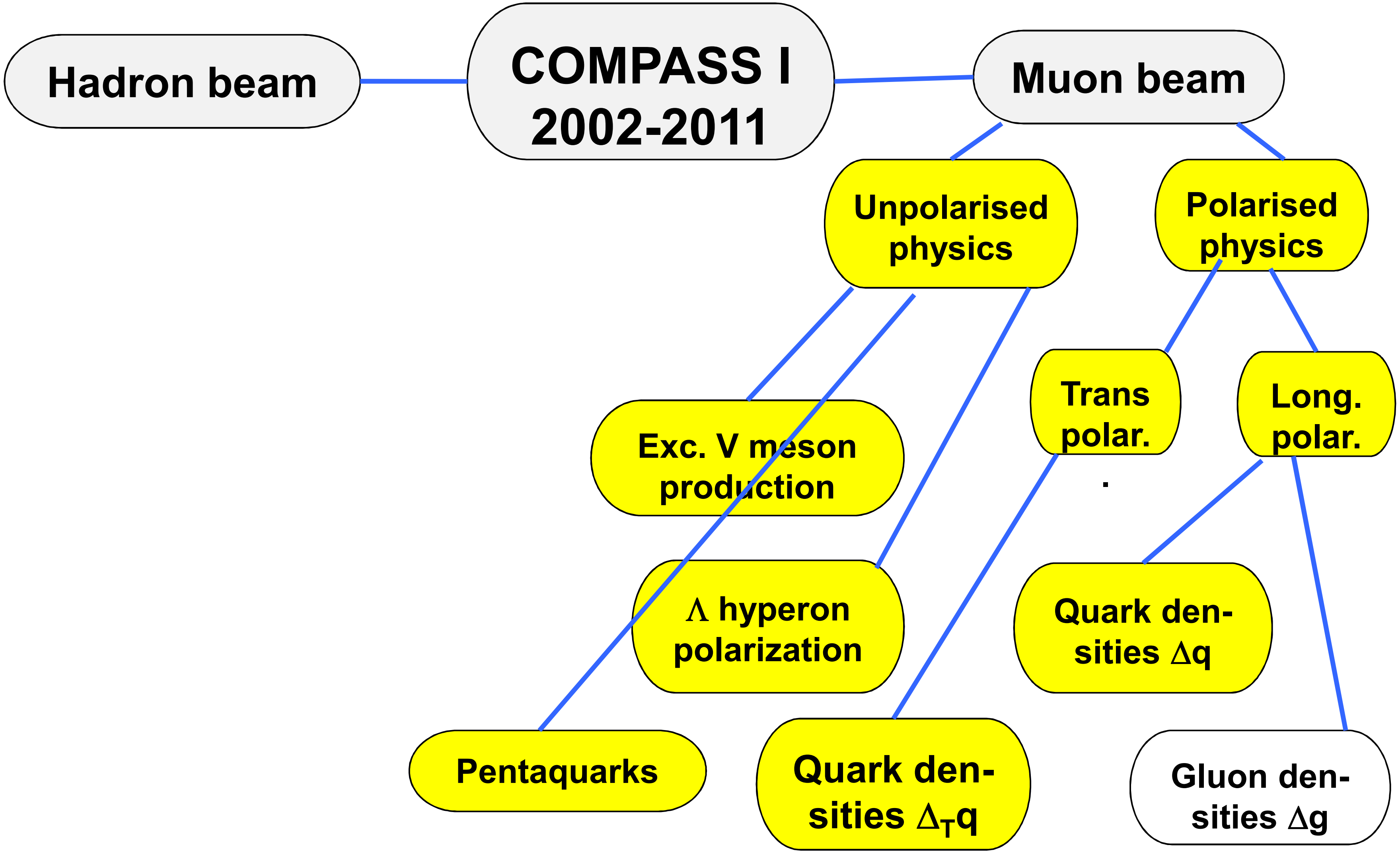

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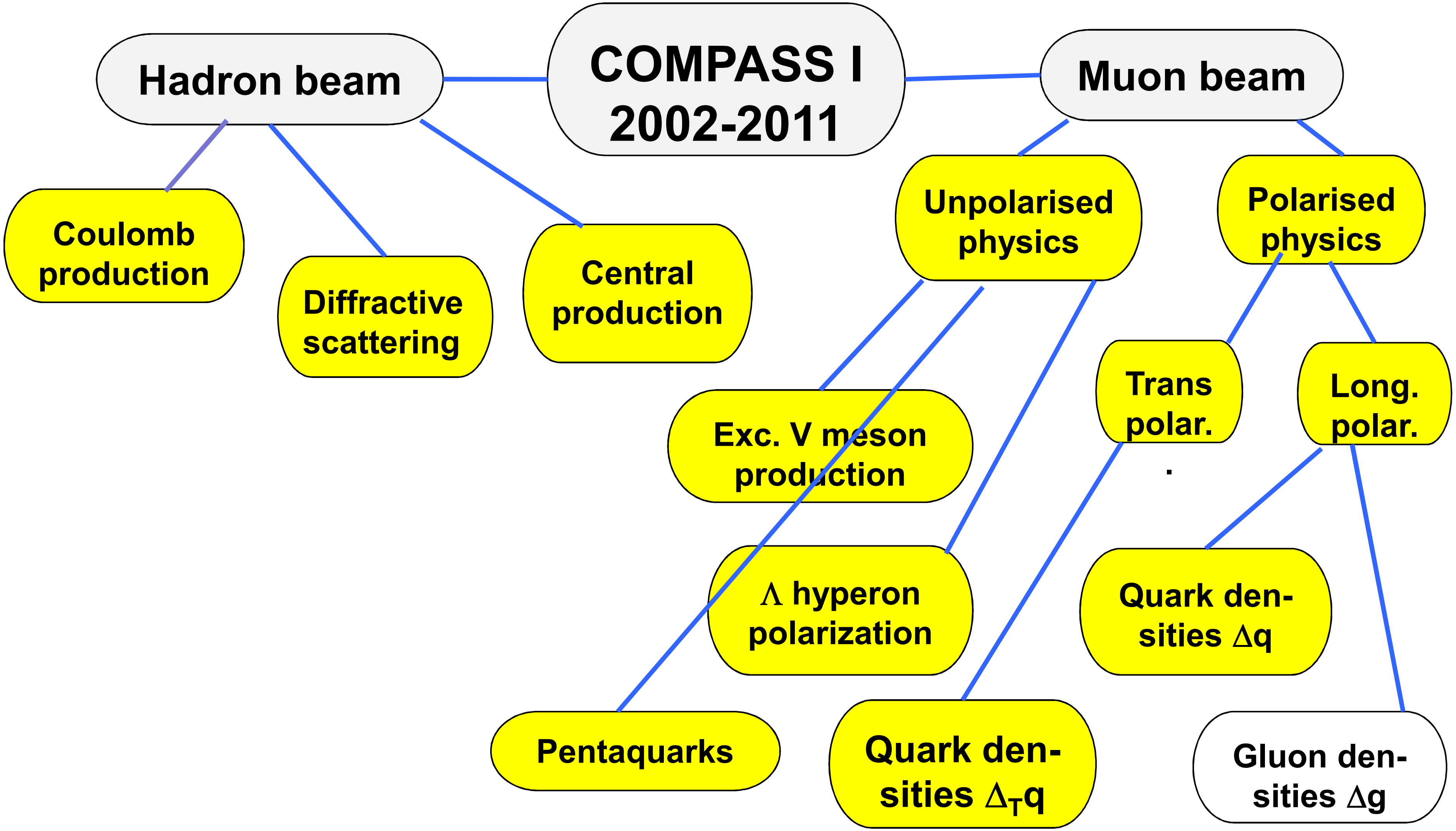

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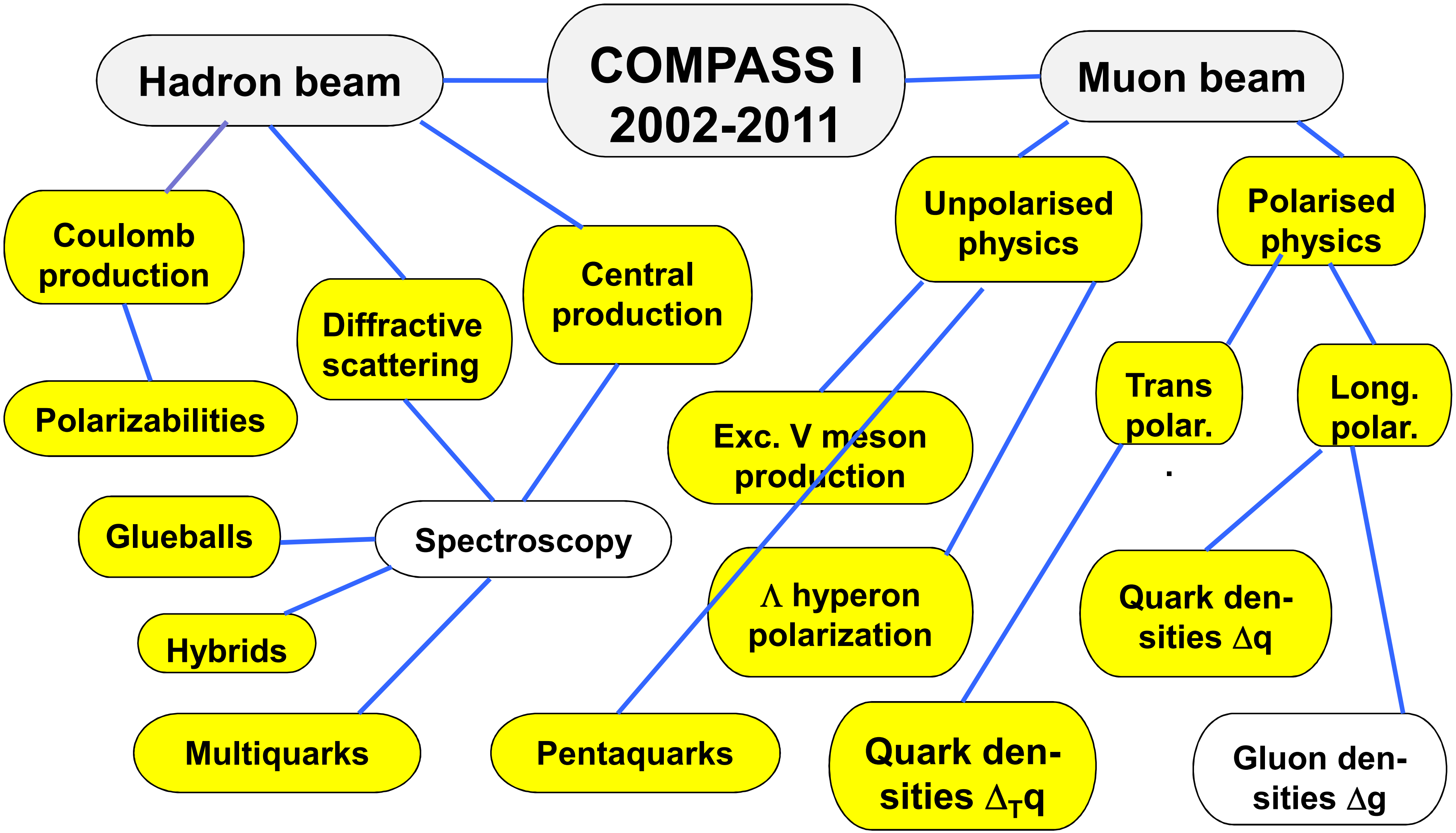
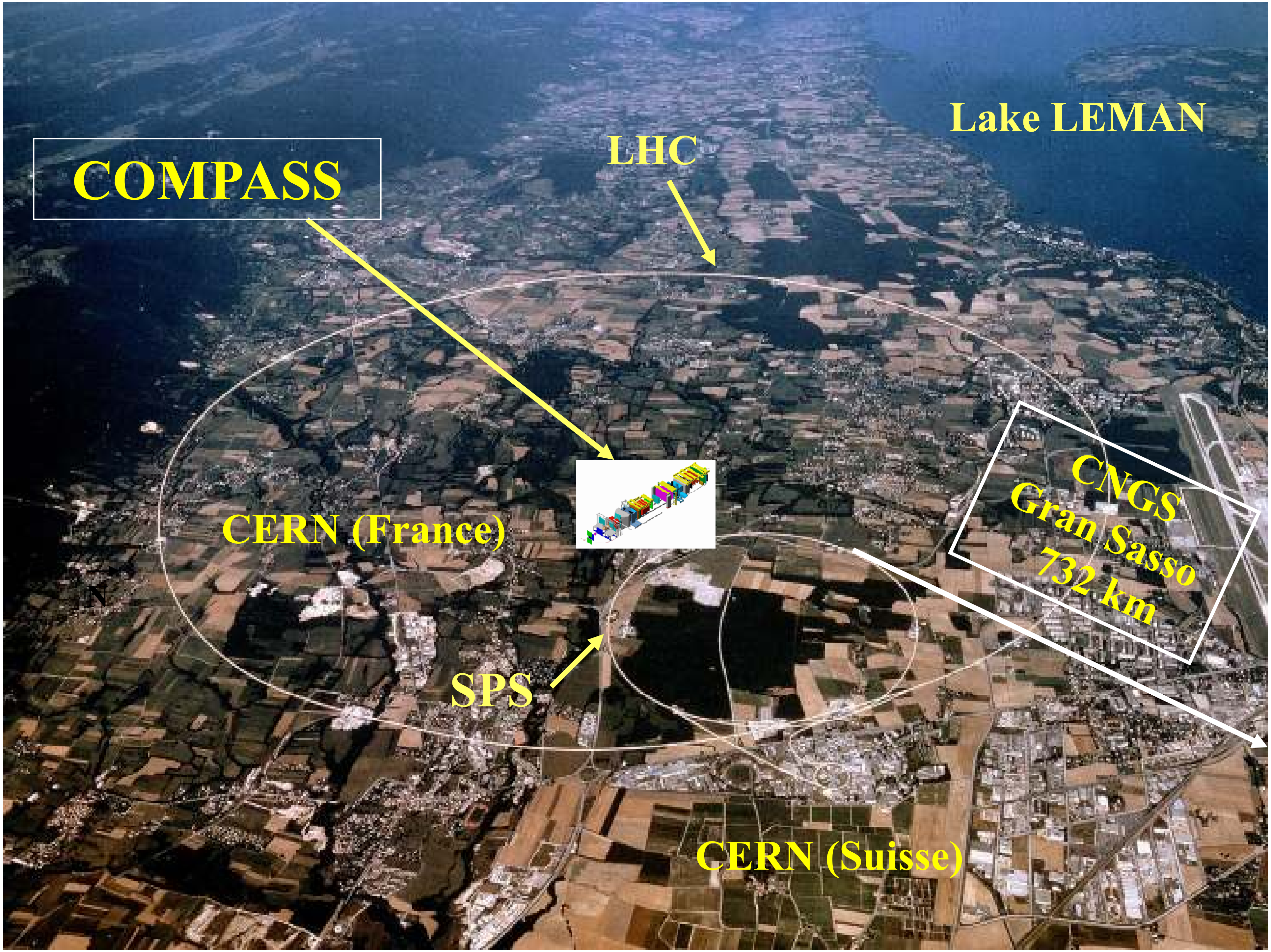
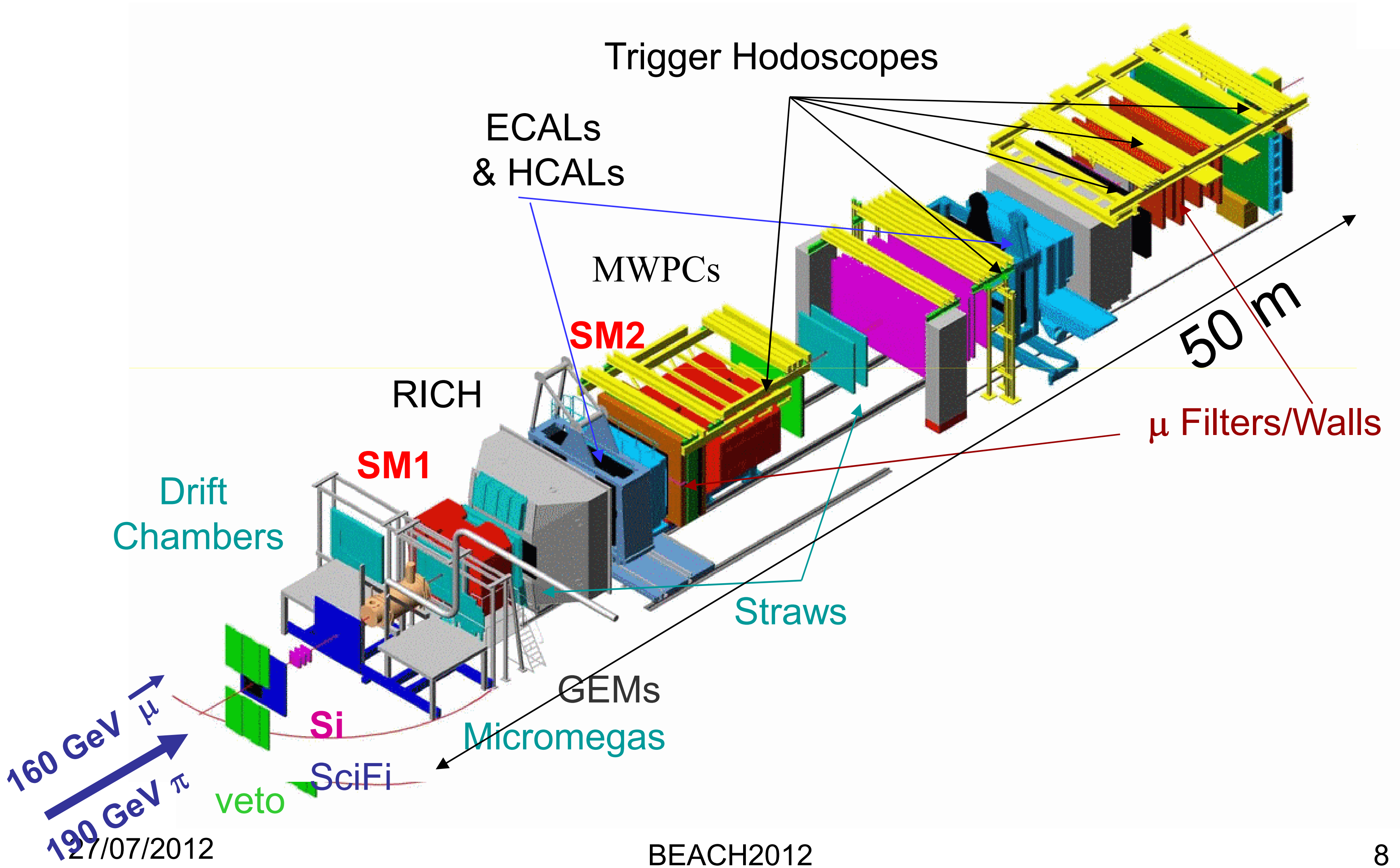



Lake LEMAN
LHC
COMPASS
CNGS
Gran Sasso
732 km
CERN (France)
SPS
CERN (Suisse)
N

TWO STAGE SPECTROMETER

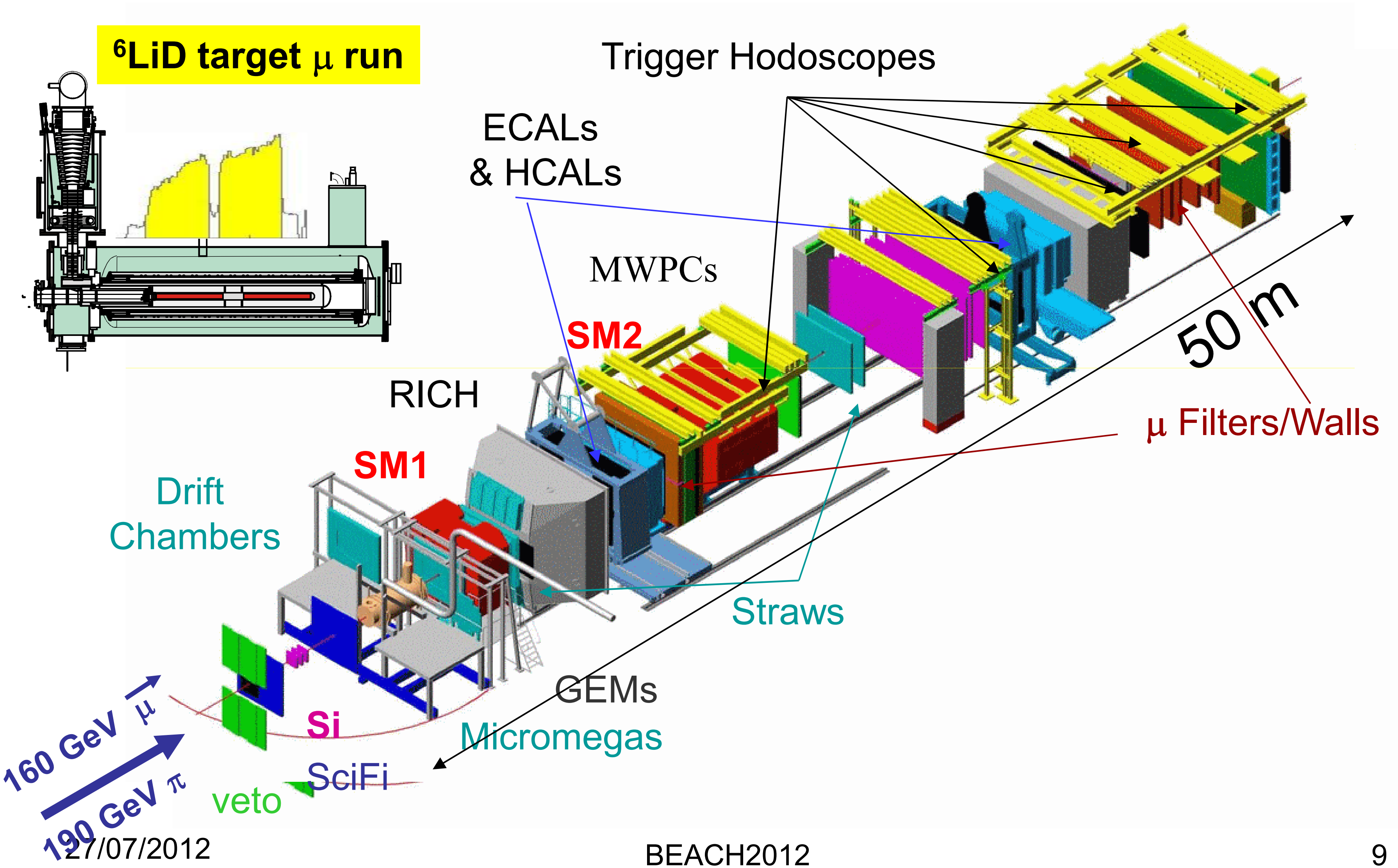
COMPASS in μ run
NIM A 577(2007) 455



TWO STAGE SPECTROMETER

COMPASS in μ run

NIM A 577(2007) 455



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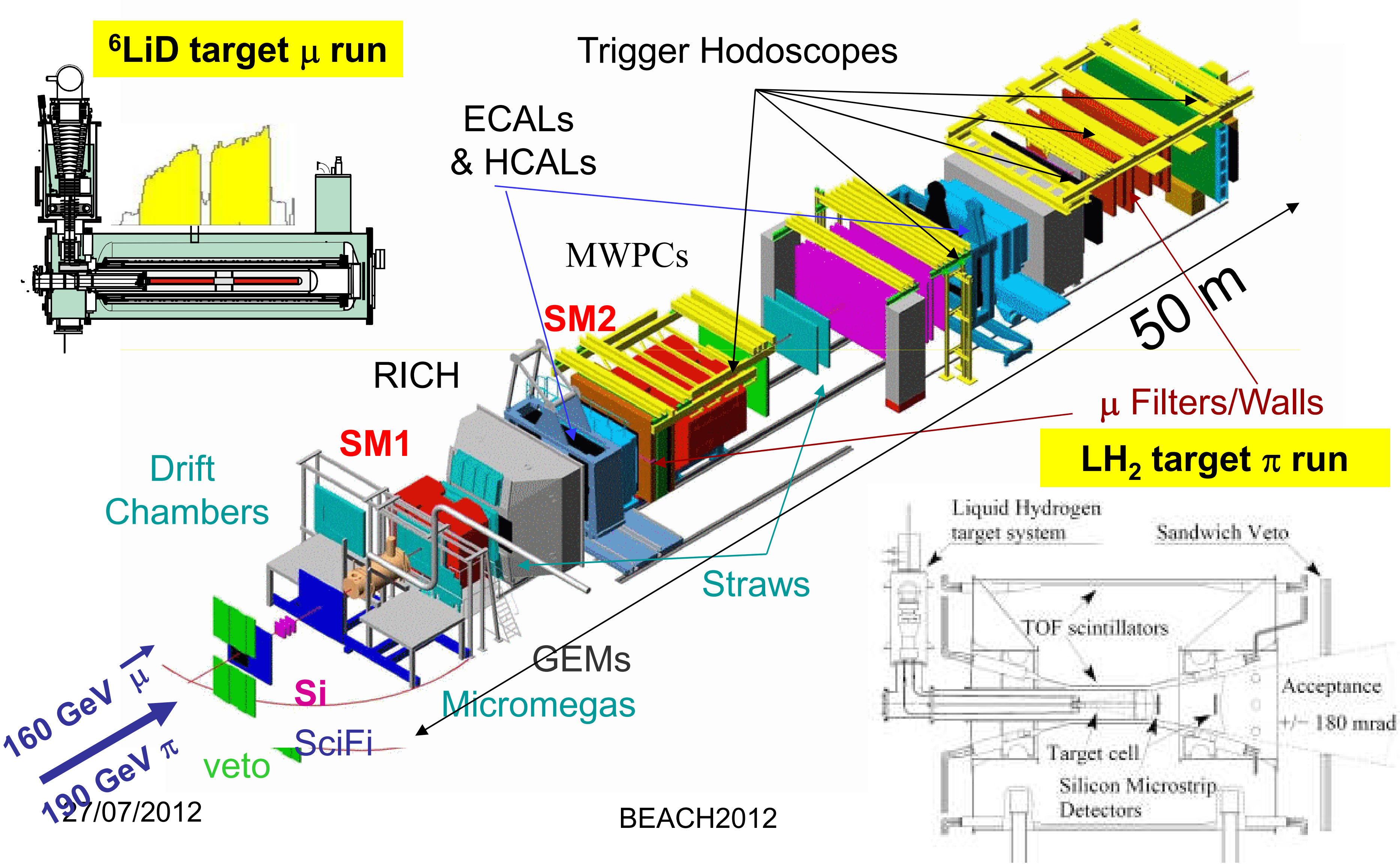

Outline

Data taken

2002-2004	:160 GeV μ on ^{6}LiD **L,T**
2006	:160 GeV μ on ^{6}LiD **L**
2007	:160 GeV μ on NH_3 **T**
2010	:160 GeV μ on NH_3 **T**
2011	:200 GeV μ on NH_3 **L**

Part I: nucleon spin structure

Charmed D mesons & a gluon contribution to the nucleon spin

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Search for exotic states in diffractive dissociation and central production

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2112, SPS/LHC shutdown, 2014, 2015, 2016

Part I: nucleon spin structure

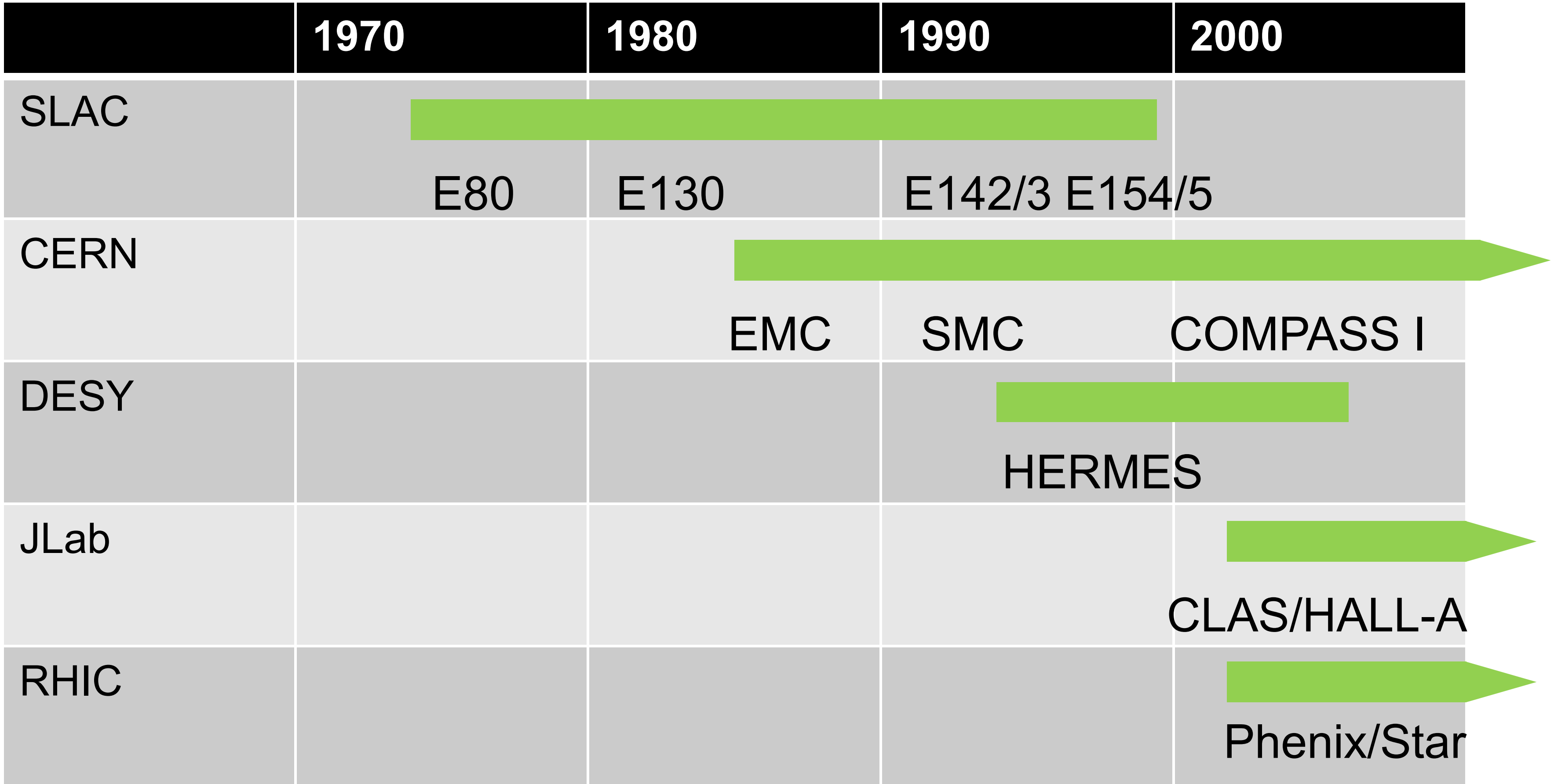
Charmed D mesons & **a gluon contribution** to the nucleon spin

Part II: hadron reactions

Search for exotic states in diffractive dissociation and central production

Conclusion & COMPASS-II proposal

Part I: nucleon spin structure



- A worldwide effort since decades

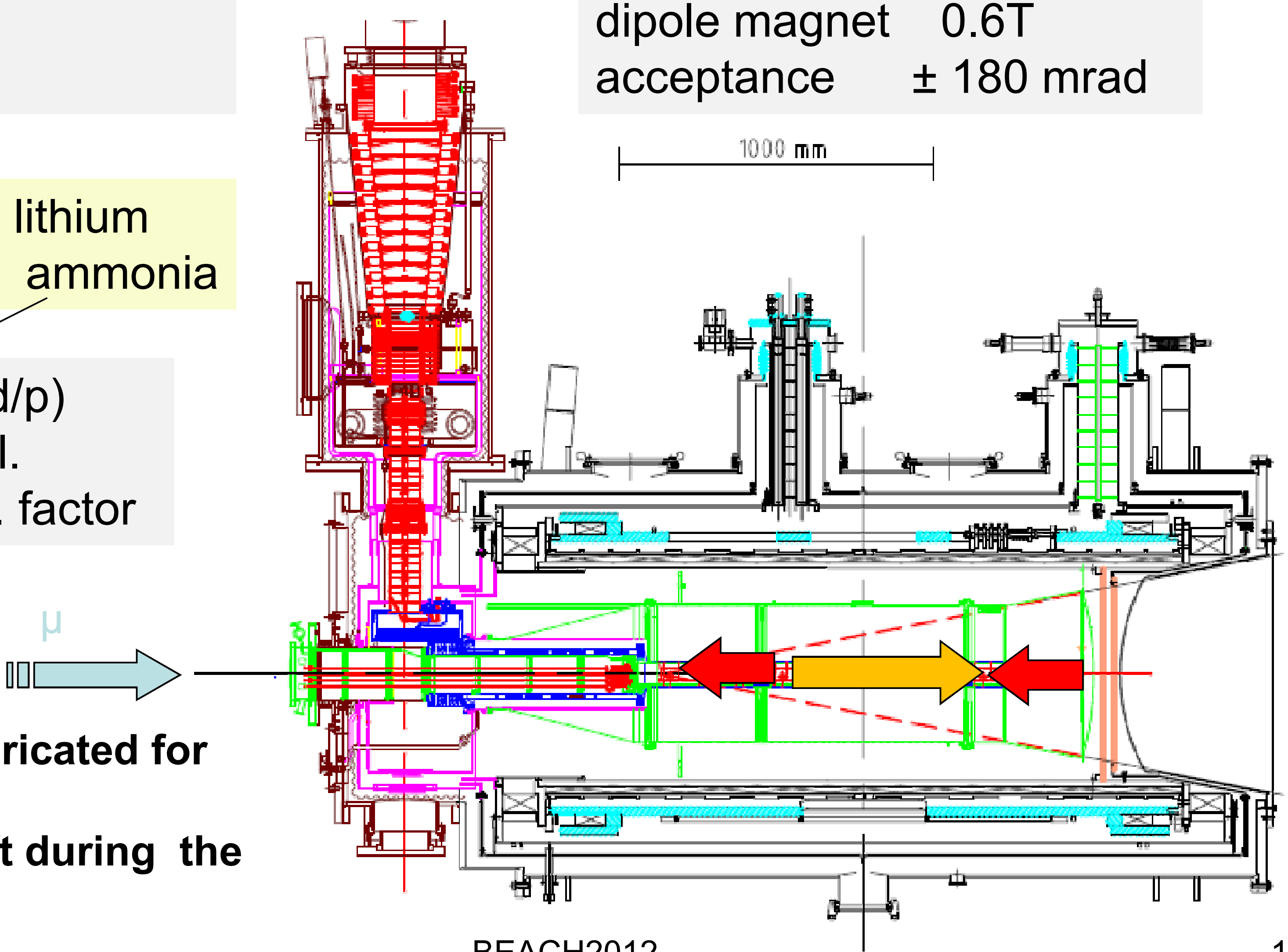
Key apparatus: polarised target

$^3He - {^4He}$ dilution refrigerator (T~50mK)

Deuterated lithium ammonia

$^6LiD/NH_3$ (d/p)
50/90% pol.
40/16% dil. factor

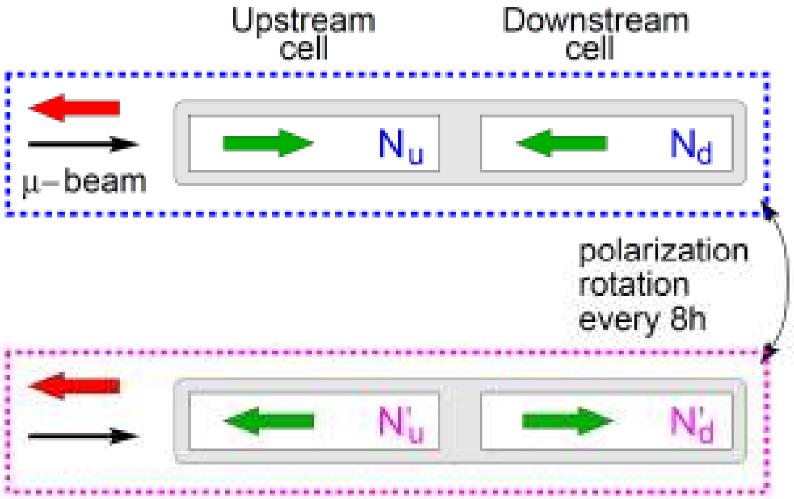
solenoid 2.5T
dipole magnet 0.6T
acceptance ± 180 mrad



biggest /fabricated for SMC coll.
Special shift during the data taking

Measurement of asymmetry

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



- **flux normalization:**

$$A_{\exp} = \frac{N_u - N_d}{N_u + N_d}$$

- **acceptance difference:**
  Polarisation rotation

- **take average asymmetry:**

$$\Rightarrow A_{\exp} = \frac{A + A'}{2} = \frac{1}{2}\left(\frac{N_u - N_d}{N_u + N_d} + \frac{N'_d - N'_u}{N'_u + N'_d}\right)$$

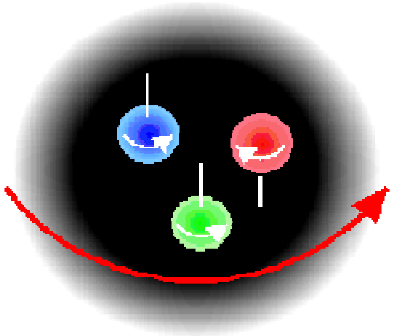
$\Rightarrow$ minimization of bias

- **experimental asymmetry**

$$A_{\exp} = p_{\mu}\, p_{T}\, f\, A_{\parallel}$$

p_{μ}, p_{T} beam and target polarisation
f dilution factor

Nucleon spin puzzle since 1988



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

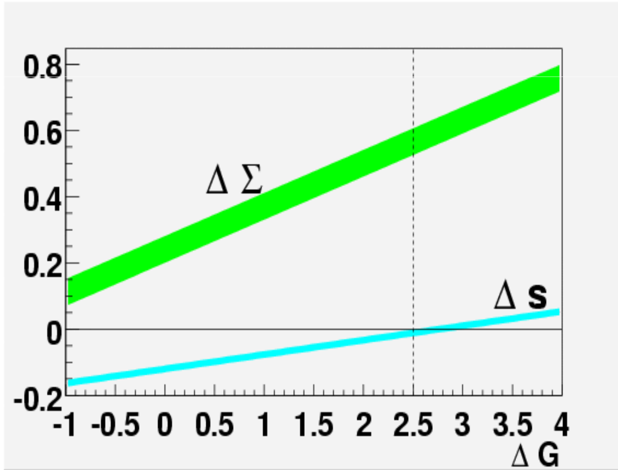
quarks — gluons — orb. mom.

"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 ($a_0 \neq \Delta\Sigma$)

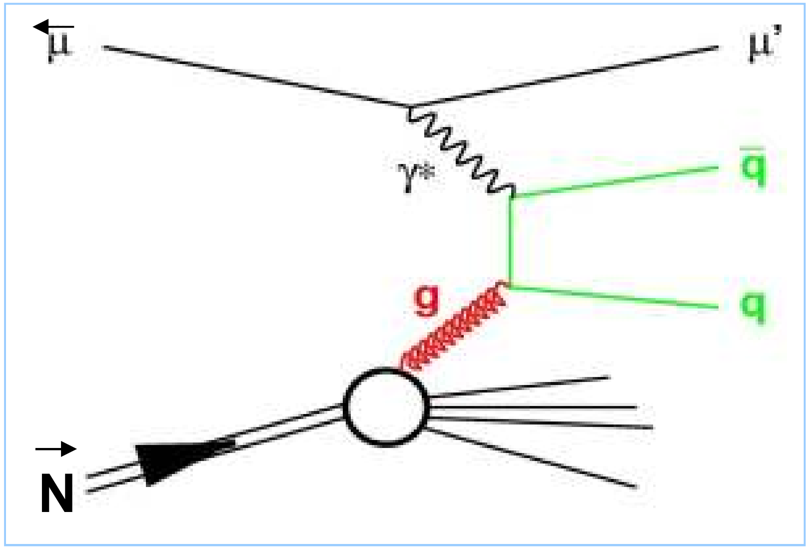
a_0 ($= \Delta\Sigma$) is measured to be ~0.30-0.35 instead of expected 0.6



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

Gluon polarisation Δg/g from μ *N* scattering

Photon Gluon Fusion (PGF)



$A_{]]} = R_{PGF} <a_{LL}> <\Delta g/g> + A_{bkg}$

Spin asymmetry of cross sections for longitudinal polarizations of beam and target, parallel and antiparallel

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

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

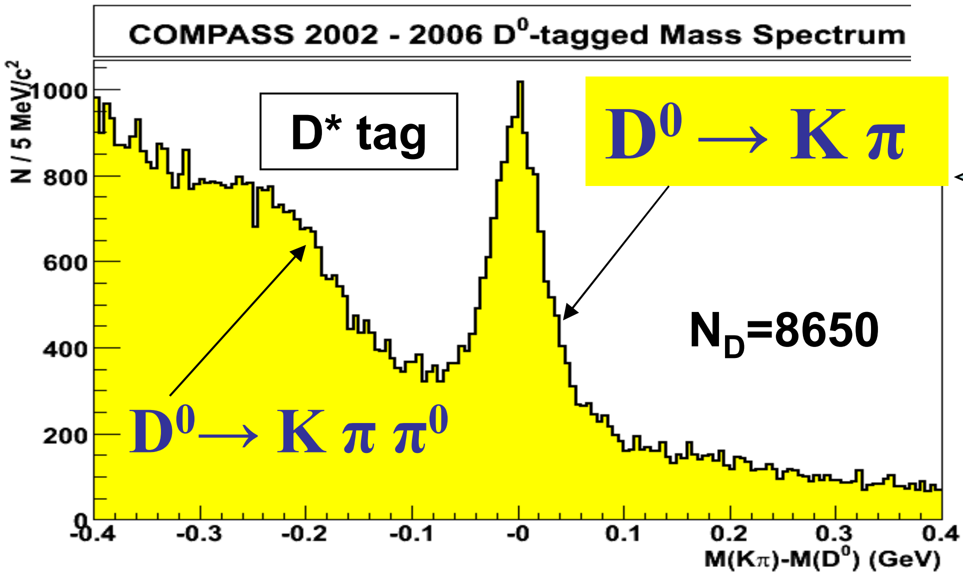
→ easy to get a statistics

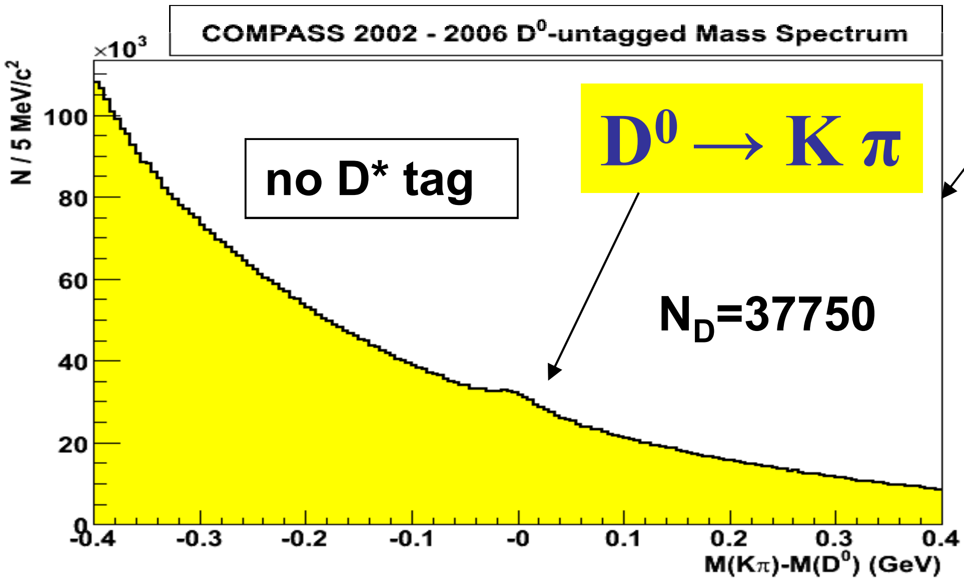
→ but physical background

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

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

Open charm (example)





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

BR ≈ 68%

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

BR ≈ 4%

only

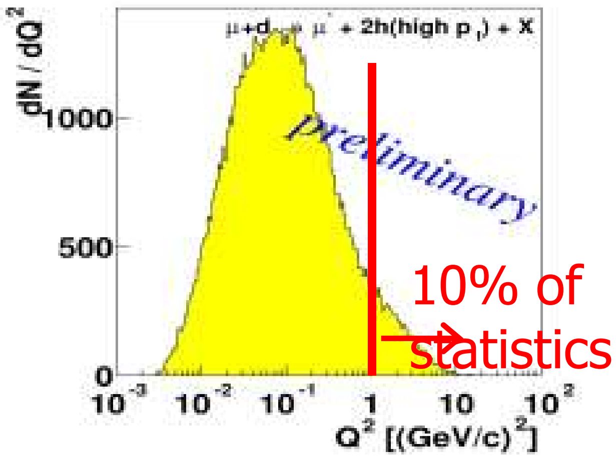
Also were used:

D^0 ➔ $K\pi\pi\pi$

D^0 ➔ $K\pi\pi^0$ (no π^0 rec)

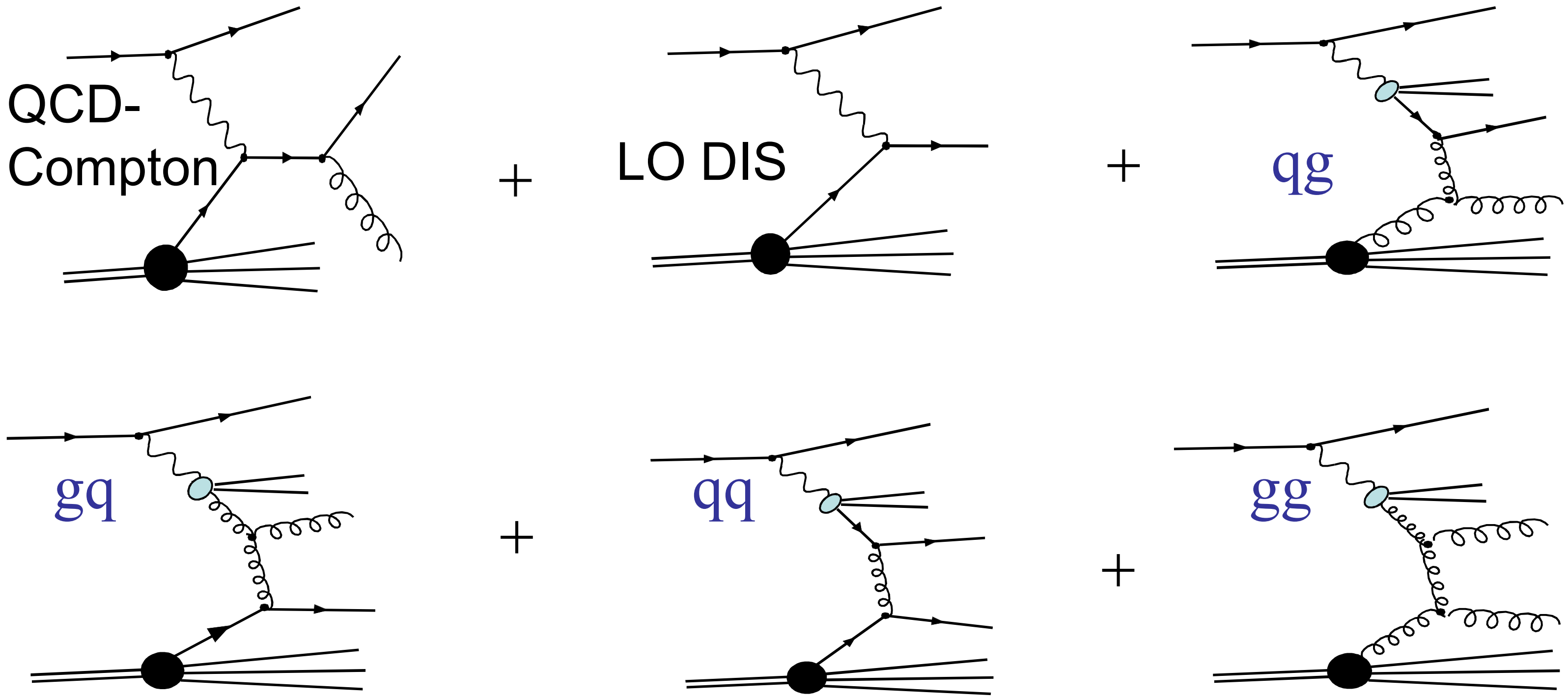
D^0 ➔ $K_{sub}\pi$ (no K ID)

Total number:
86250 D^0 mesons

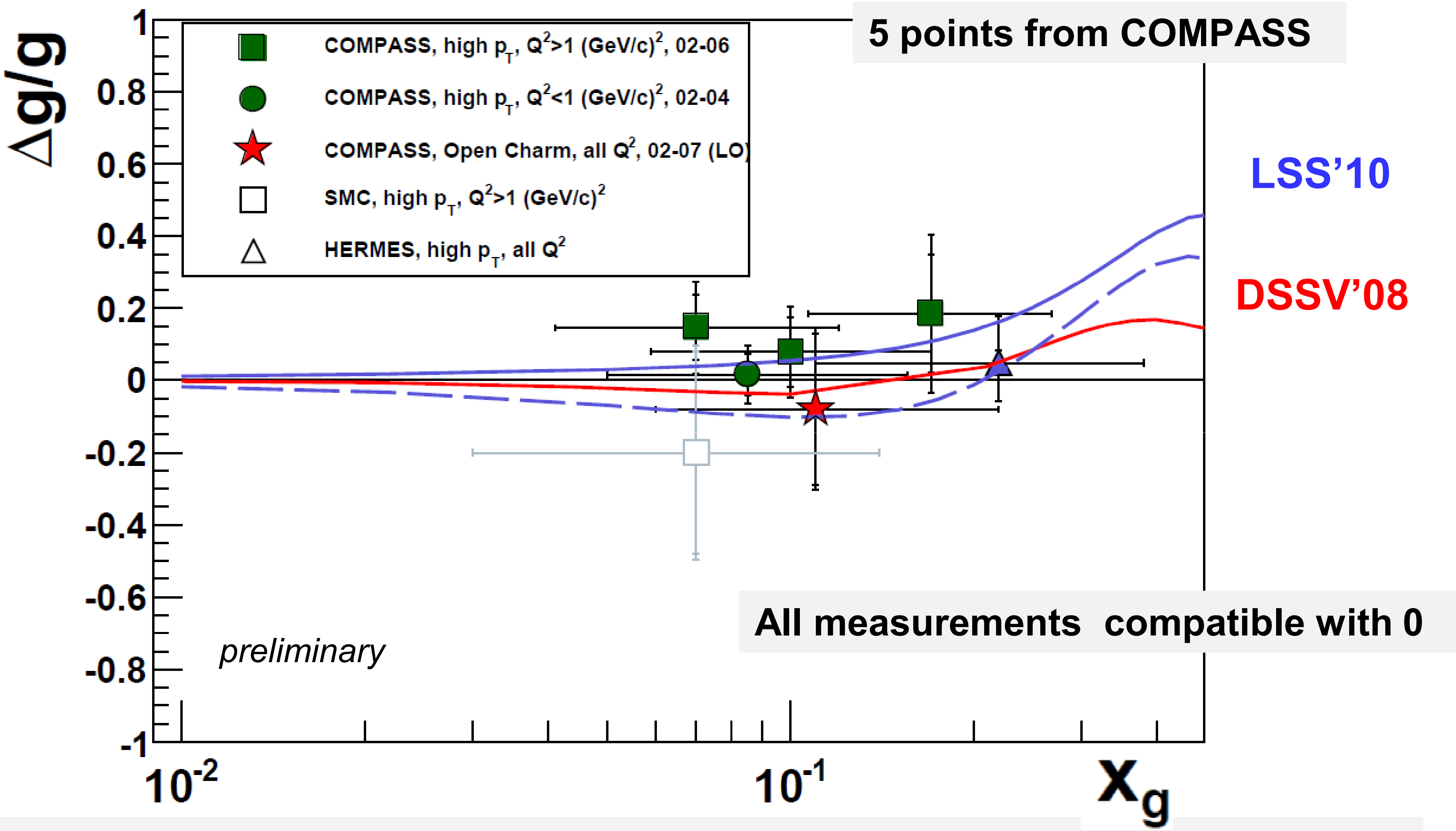


high p_T hadron pairs

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



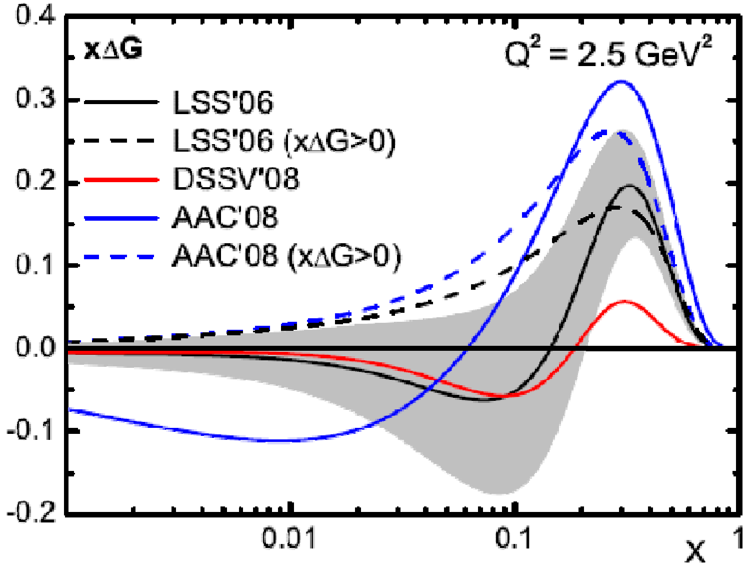
World direct measurements on $\Delta g/g$ in LO



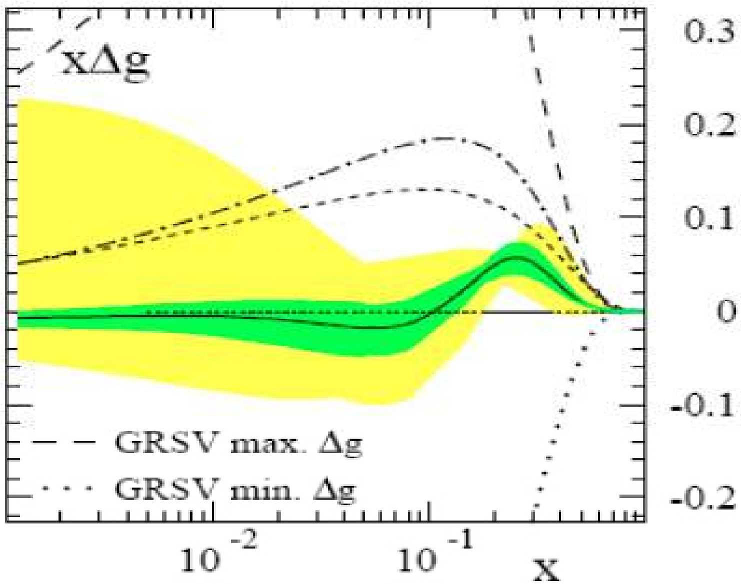
QCD fits → $|\Delta G| \approx 0.2 - 0.3$ as direct measurements point to a small value of ΔG ….. axial anomaly contribution is small → $a_0 \approx \Delta\Sigma$

Accessing ΔG: QCD fits to world data (DIS, SIDIS)

From Leader, Spin-2008



From DSSV, PRL 101, 2008



LSS-06 : Phys. Rev. D73, 2006 AAC'06 : Phys. Rev. D74, 2006 DSSV-08: Phys. Rev. Lett. 101, 2008

ΔG(x) may be: positive, negative, or sign-changing!

QCD analysis shows small first moment of Δg ➔ **|ΔG|** ≈ 0.2-0.3

ΔG~ 2.5 is needed to restore ΔΣ~0.6.

Summary for Part I

- The worlds result for direct measurements of the gluon polarisation $\Delta g/g$

➔ major contribution of COMPASS

➔ indicates a small value of ΔG (the first moment of Δg)

- confirmed by polarised *pp* at RHIC
- global QCD analysis of g_1 data confirms a small value of ΔG: $|\Delta G|= 0.2\text{-}0.3$
- "spin crisis” is unsolved yet
- Next step: a contribution of the angular orbital momentum of quarks and gluons in nucleon spin decomposition

Part II: Hadron reactions

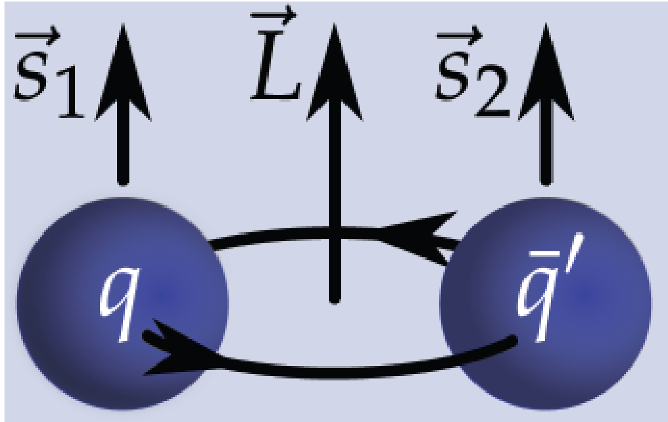
2004 190 GeV π^-, μ on Pb (short run)
2008 190 GeV π^- on LH_2
2009 190 GeV p,π^+,π^- on LH_2, Pb, Ni, W

Beam intensity: $5\cdot10^6$ had/s
Negative: 96% π, 3.5% K
Positive: 75% p, 25% π

A large amount of data were collected with hadron beam in 2008/2009 (10 – 100 times world statistics).

π^- p → $\pi^+ \pi^- \pi^-$ and $\pi^0\pi^0 \pi^-$ (2008/2009 data)
π^- p → 5π-final state at low four-momentum transfer (2004 data)
π^- p → $\eta\pi$ and $\eta'\pi$ (2008/2009 data)
$\pi^+ \pi^-$ in central production $pp \to p_{fast}\pi^+\pi^-p_{slow}$ (2009 data)
Spectroscopy using initial/final states with strangeness

Mesons in the Constituent Quark Model



Spin-parity rules for bound $q\bar{q}'$ system

Quark spins couple to total intrinsic spin
S = 0 (singlet) or 1 (triplet)
Relative orbital angular Momentum $\vec{L}$
and total spin $\vec{S}$ couple to
meson spin $\vec{J} = \vec{S} + \vec{L}$
Parity P = $(-1)^{L+1}$
Charge conjugation C = $(-1)^{L+S}$
Forbidden ➔ J^{PC} = 0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, 3^{-+}, . . .

QCD allows for states beyond the CQM

Hybrids $q\bar{q}g$, glueballs gg, ggg, multi-quark states $q\bar{q}q\bar{q}$

"Exotic" mesons have quantum numbers forbidden for $q\bar{q}'$
Particularly interesting: J^{PC}-exotic states

From old experiments: hybrids with $J^{PC} = 1^{-+}$

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

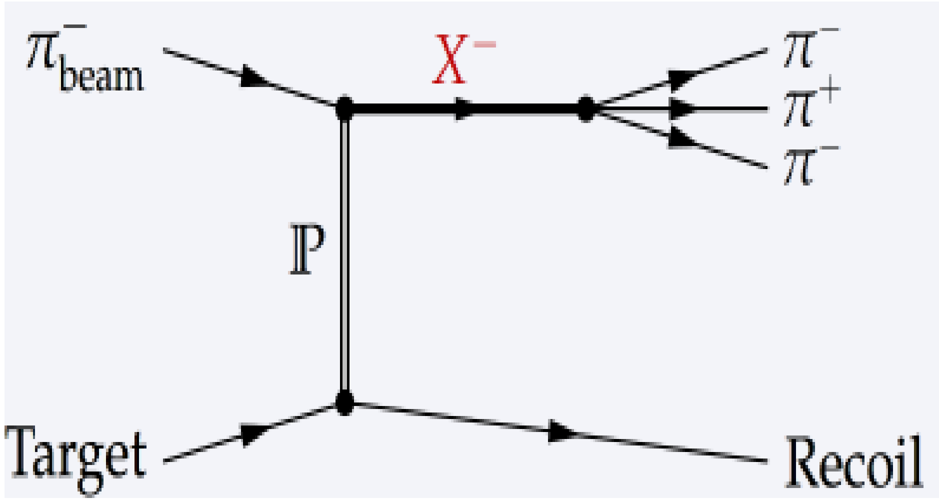
- **π_1(1400)**
  - $\pi^- N \rightarrow \eta\pi^- N$ (E852, VES)
  - $\bar{p}n \rightarrow \pi^-\pi^0\eta$ (Crystal Barrel)
  - $\bar{p}p \rightarrow 2\pi^0\eta$ (Crystal Barrel)
- **π_1(1600)**
  - $\pi^- N \rightarrow \rho\pi N$ (E852, VES)
    $\rightarrow \eta'\pi N$
    $\rightarrow f_1(1285)\pi N$
    $\rightarrow b_1(1235)\pi N$
  - $\bar{p}p \rightarrow b_1(1235)\pi\pi$ (Crystal Barrel)
- **π_1(2000)**
  - $\pi^- N \rightarrow f_1(1285)\pi N$ (Crystal Barrel)
    $\rightarrow b_1(1235)\pi N$

resonant nature controversial...

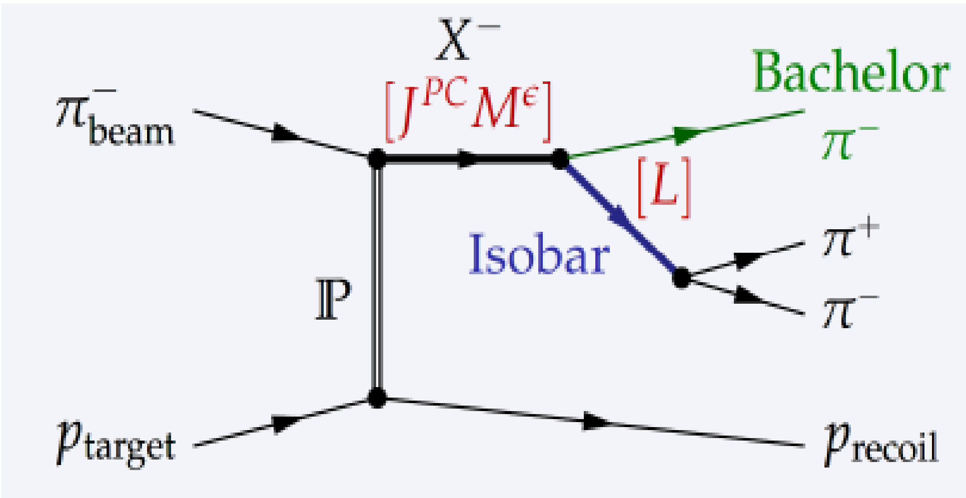
The identification of exotics demands complete information on all neighbouring states and thus requires in particular:

- Reconstruction of final states containing both neutral and charged particles
- Observation of the same meson resonance in several different channels
- Production of resonances in different reactions

Difractive dissociation: $\pi^- p \rightarrow \pi^- \pi^- \pi^+ p$



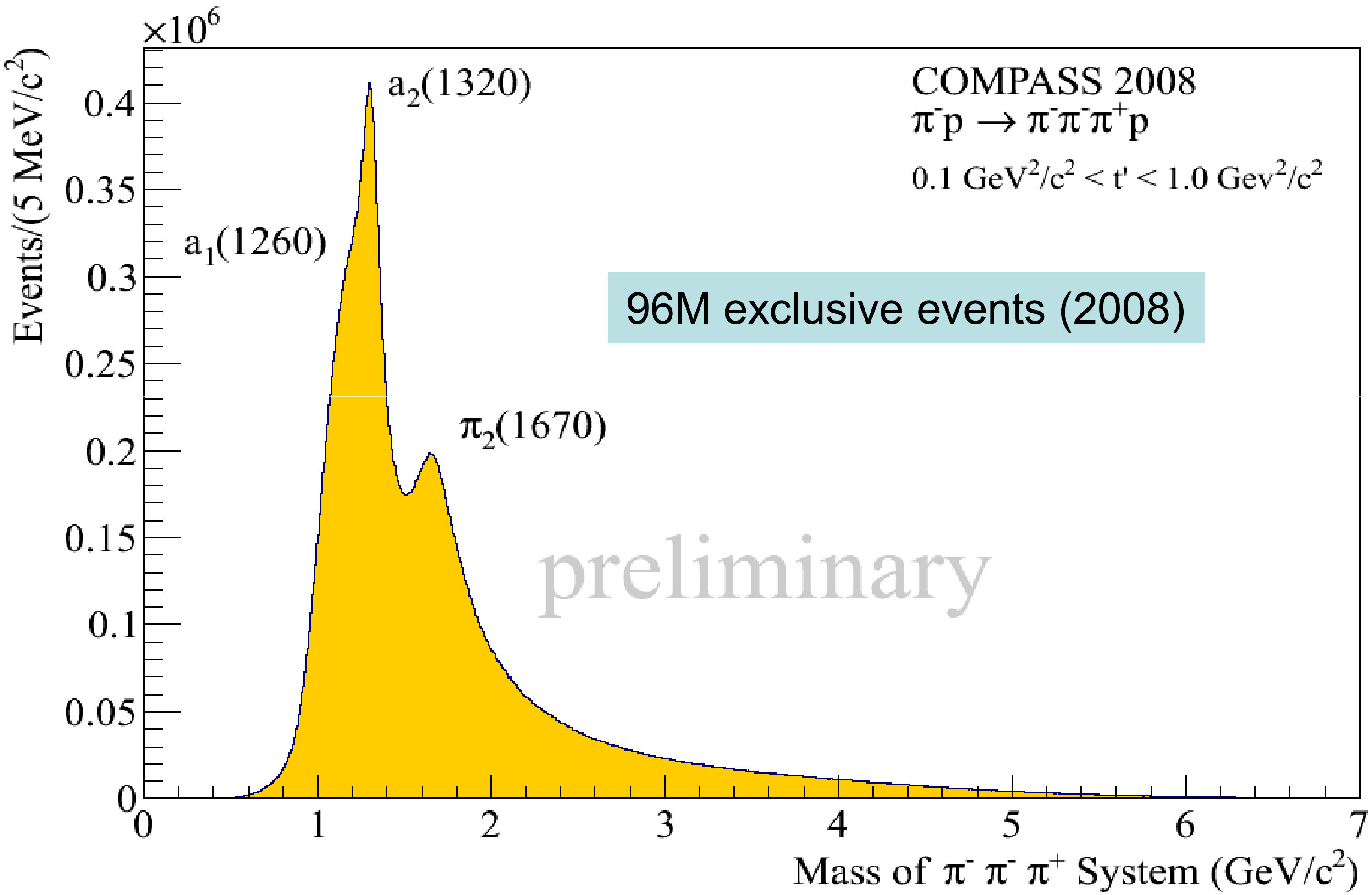
Soft scattering of beam hadron off nuclear target (remains intact);
Beam particle is excited into some intermediate state X
X decays into n-body final state



Partial-Wave Analysis (PWA)

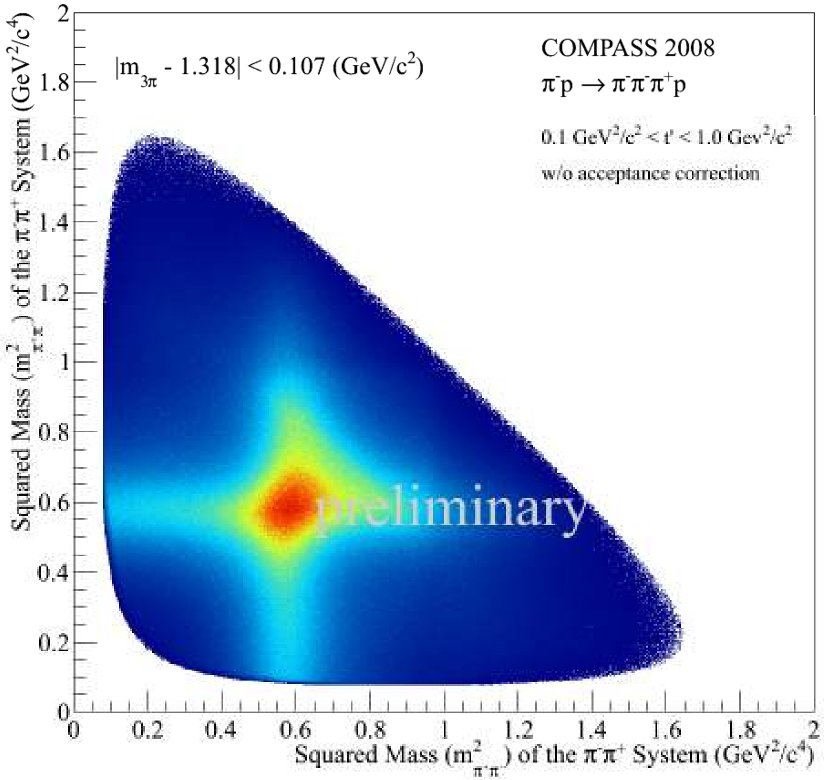
Isobar model: X^- decay is chain of successive two-body decays
"Wave": unique combination of isobar and quantum numbers
Fit of spin-density matrix for major waves with Breit-Wigner

Difractive dissociation: $\pi^- p \rightarrow \pi^- \pi^- \pi^+ p$

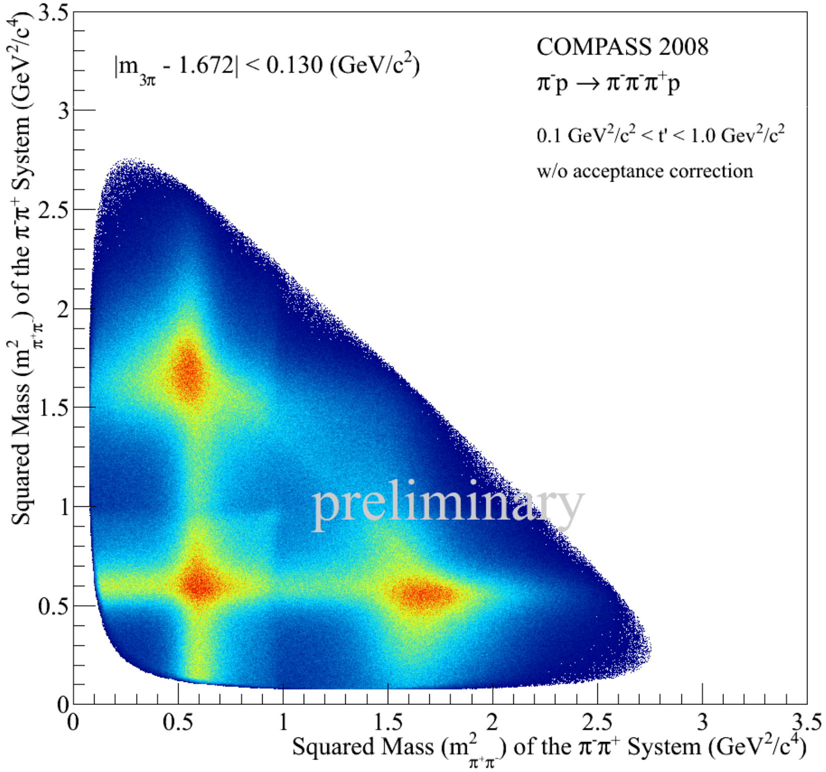


Difractive dissociation: $\pi^- p \rightarrow \pi^- \pi^- \pi^+ p$

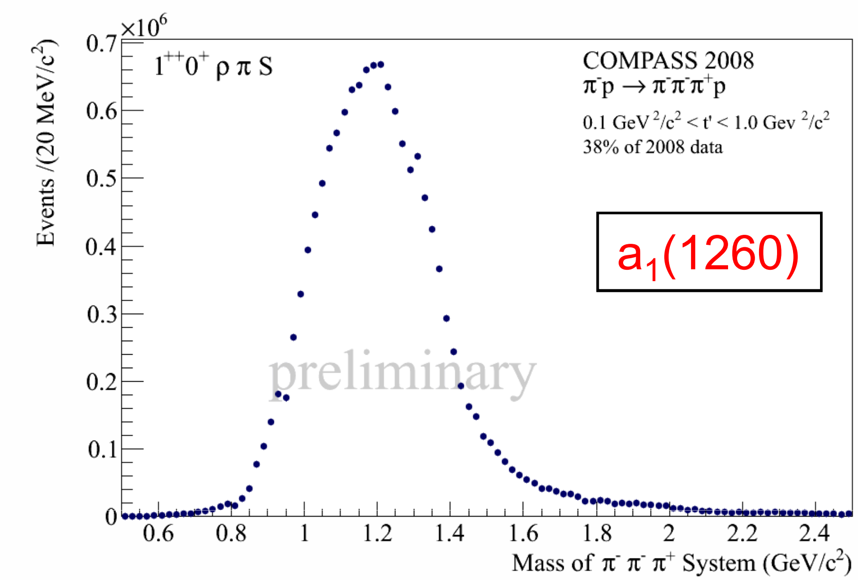
Left: Dalitz plot for $a_2(1320)$, events selected by $\pm \Gamma_0$ around a_2 mass.
Right: Dalitz plot for $\pi_2(1670)$ with $\pm 0.5\Gamma_0$

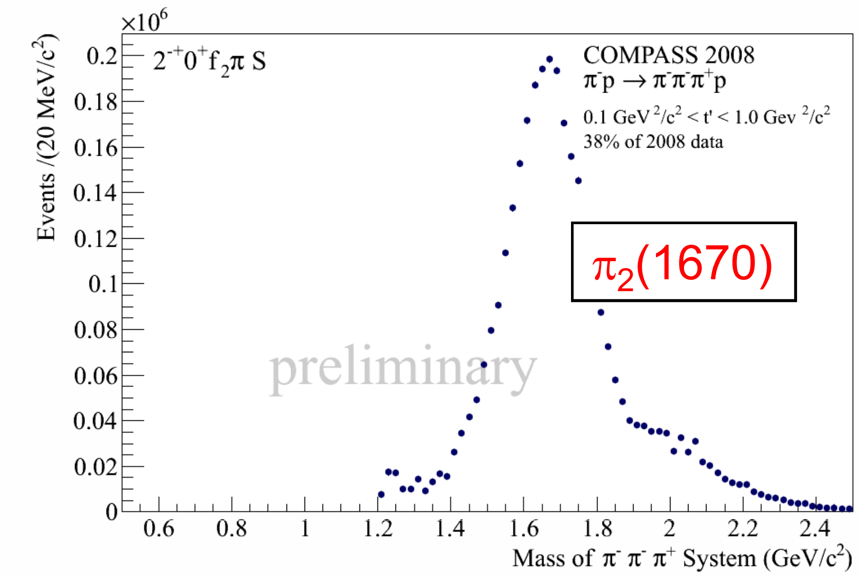


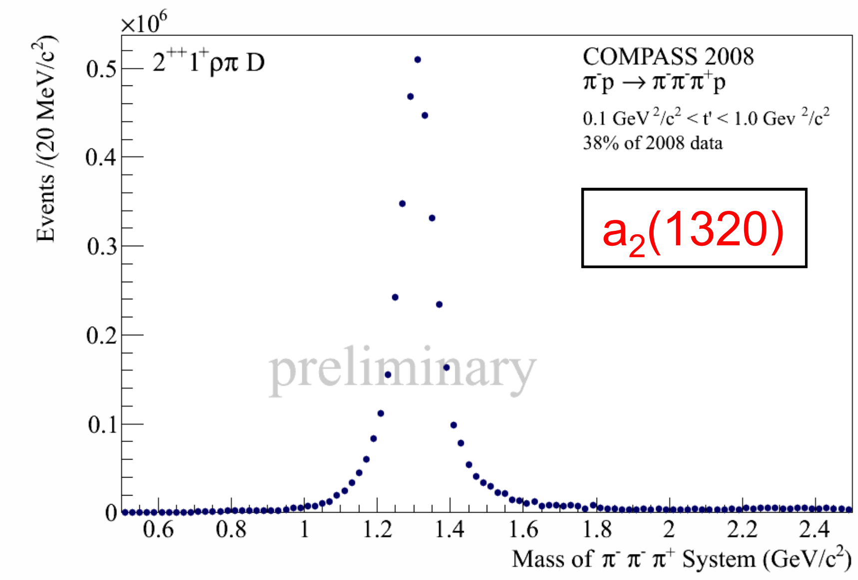
ACH

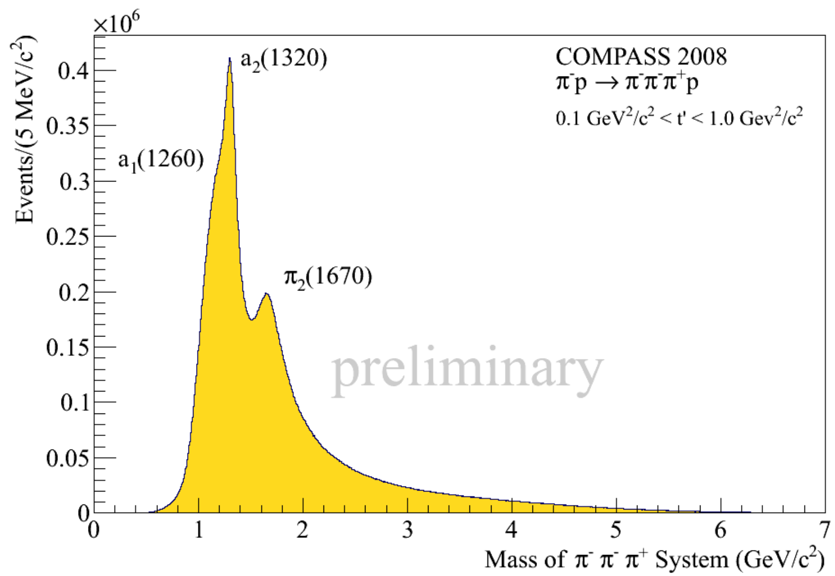


Intensities of Major Waves



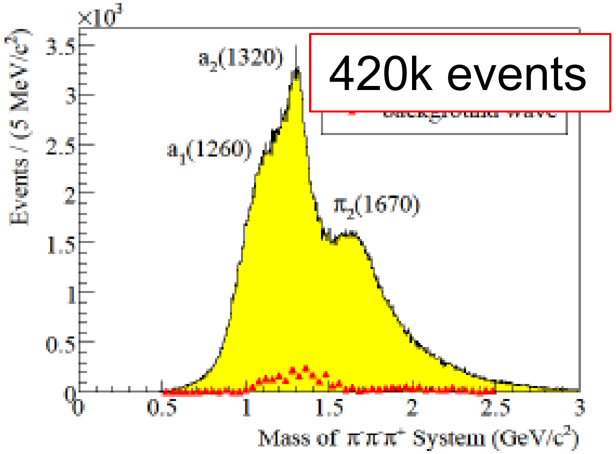






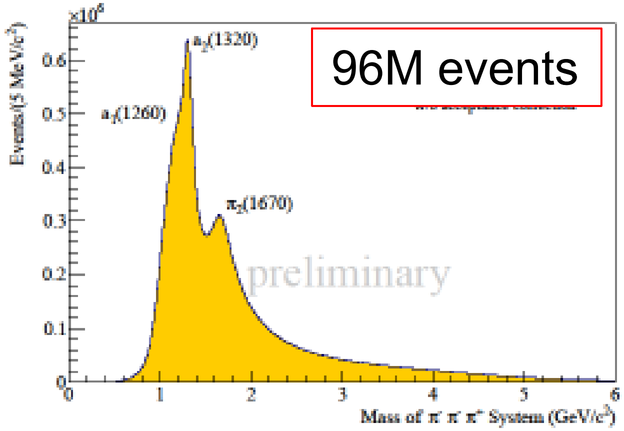
Diffractive dissociation: 3π final states

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



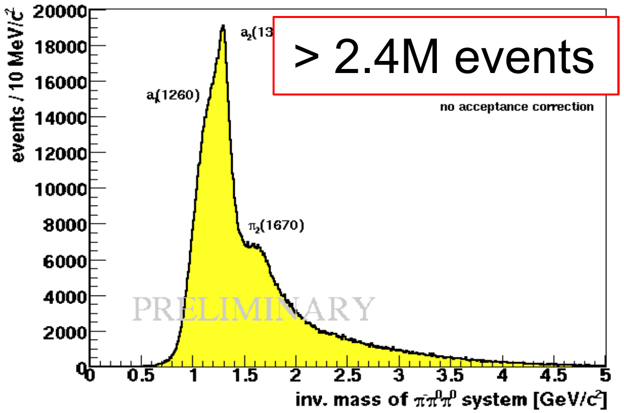
- Target: 3 mm Pb
- Trigger: Multiplicity
- No RPD

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



- Target: 40 cm LH_2
- Trigger: Recoil proton
- RPD

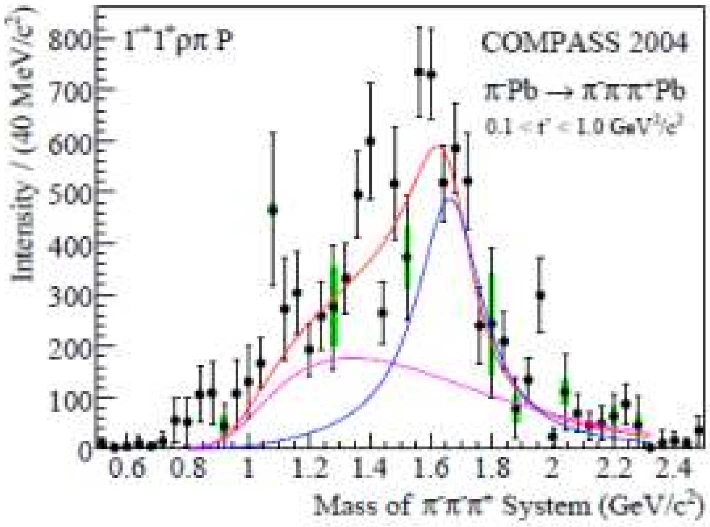
$\pi^- \, \mathrm{p} \rightarrow \pi^-\pi^0\pi^0 \, \mathrm{p}$

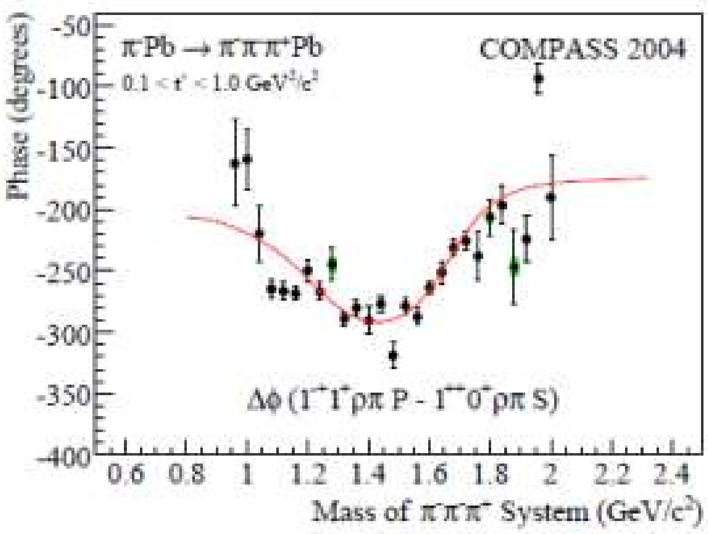


- Cross-check:
  - tracking vs
  - ECAL

Search for exotic $J^{PC}=1^{-+}$ in all 3 samples

Diffractive pion dissociation (2004 data, Pb target)





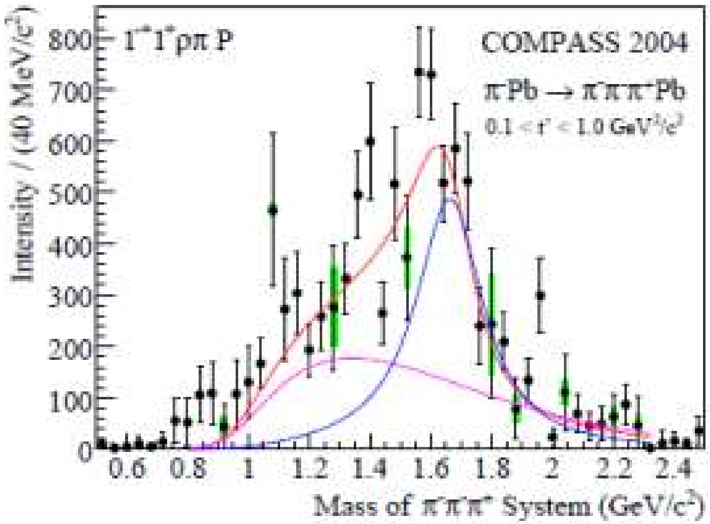
COMPASS, Phys. Rev. Lett. 104 (2010) 241803

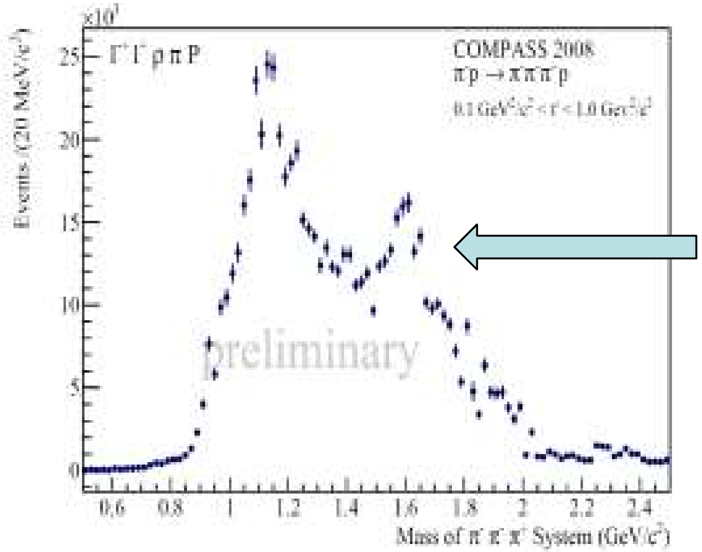
PWA analysis of 420000 events
mom transfer 0.1 < *t'*< 1 (GeV/c)^2
quasi-free nucleons in Pb
$a_1(1260)$, $a_2(1320)$ and $\pi_2(1670)$ are clearly visible

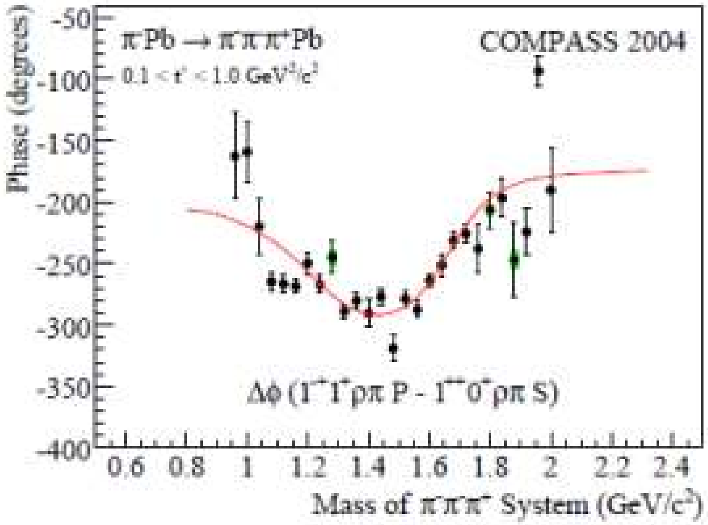
Significant spin exotic $J^{PC} = 1^{-+}$ wave

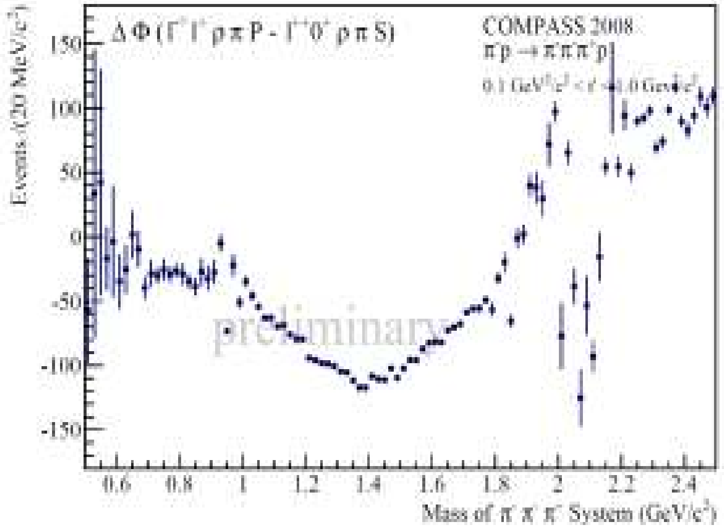
- $M = 1660 \pm 10^{+0}_{-64}$ MeV/c²
  $\Gamma = 269 \pm 21^{+42}_{-64}$ MeV/c²
- consistent with $\pi_1(1600)$
- Neglible leakage from other waves

2004 data Pb target vs 2008 proton target

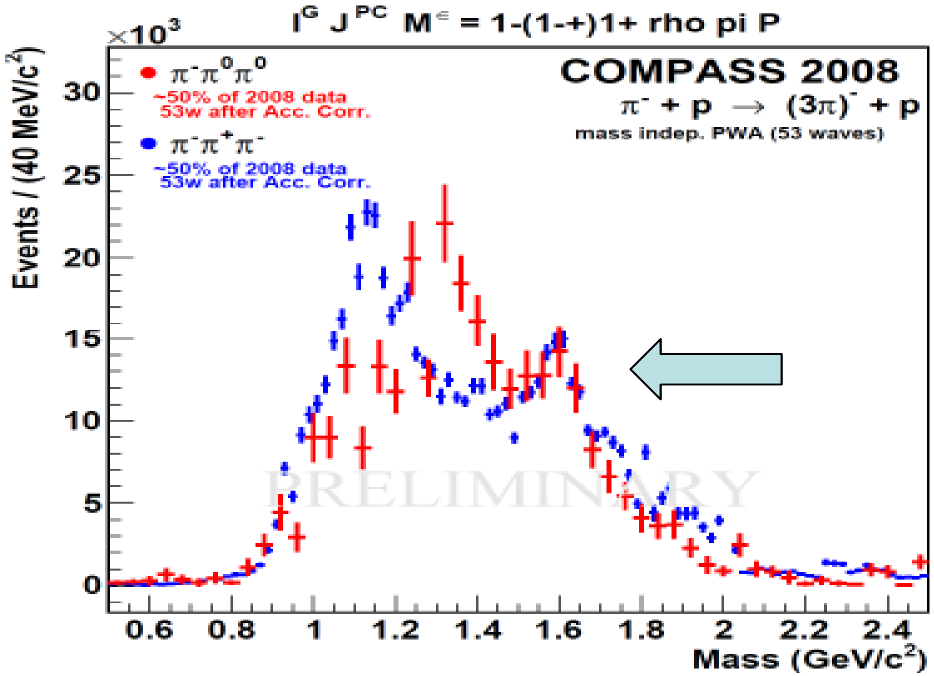








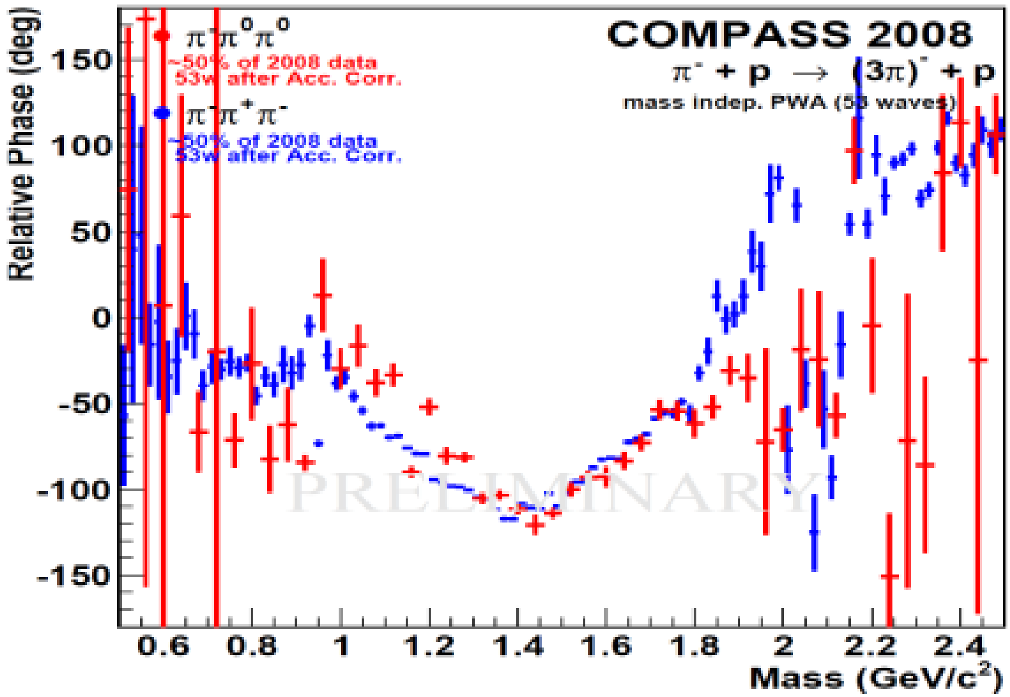
2008 proton target: $\pi^+ \pi^- \pi^-$ vs $\pi^0\pi^0 \pi^-$

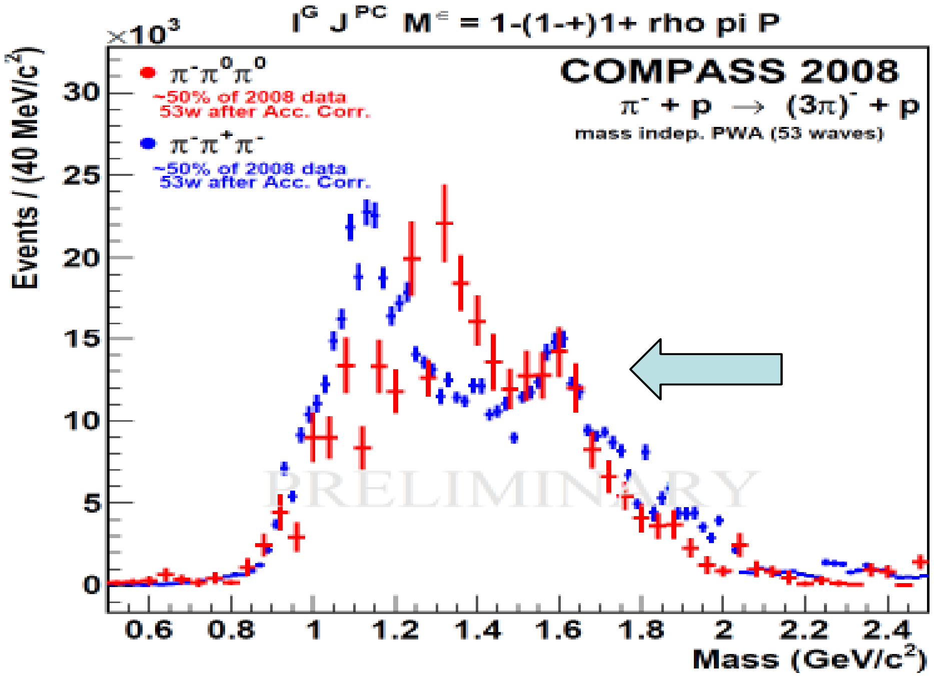


Peak at 1.67 GeV/c^2

Phase motion indicates resonant behavior

Structure at 1.2 GeV/c^2 unstable w.r.t. fit model





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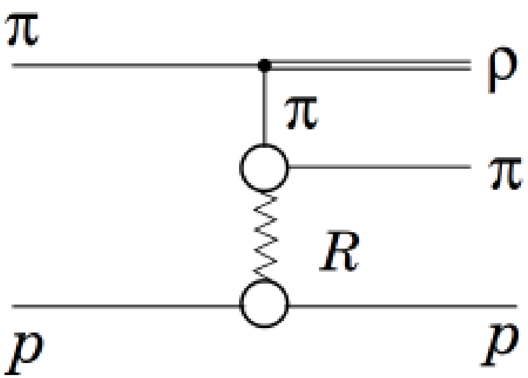
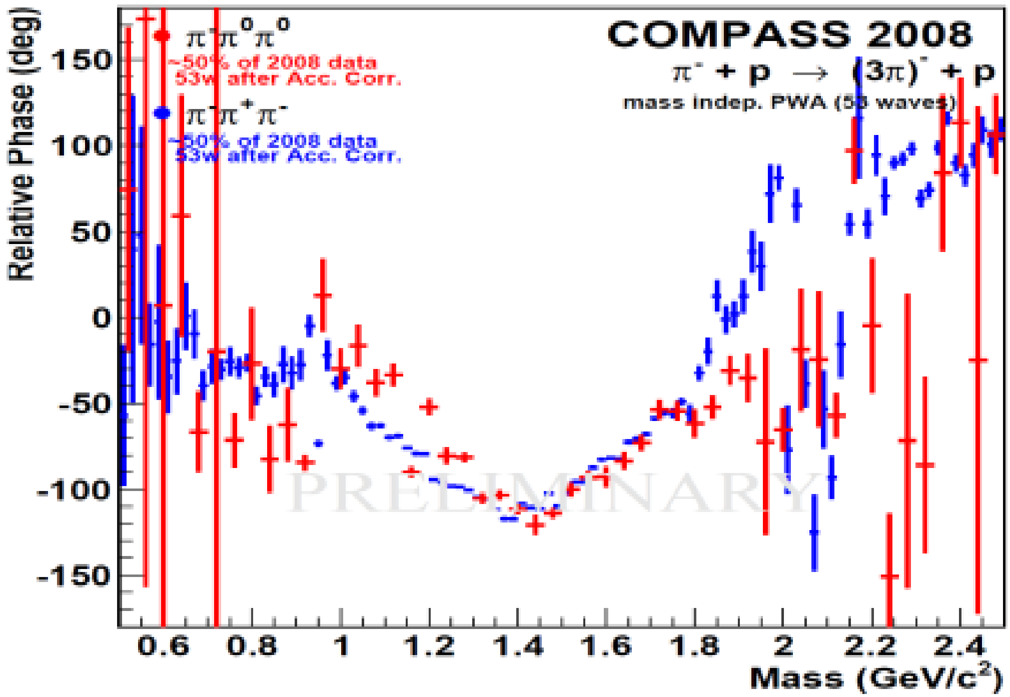
Structure at 1.2 GeV/c^2 unstable w.r.t. fit model

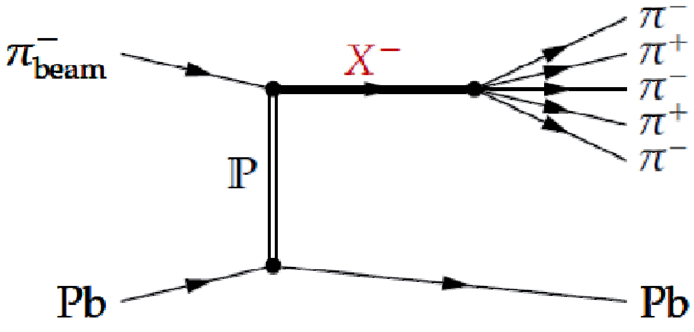
Non-resonant background to be understood (Deck effect)





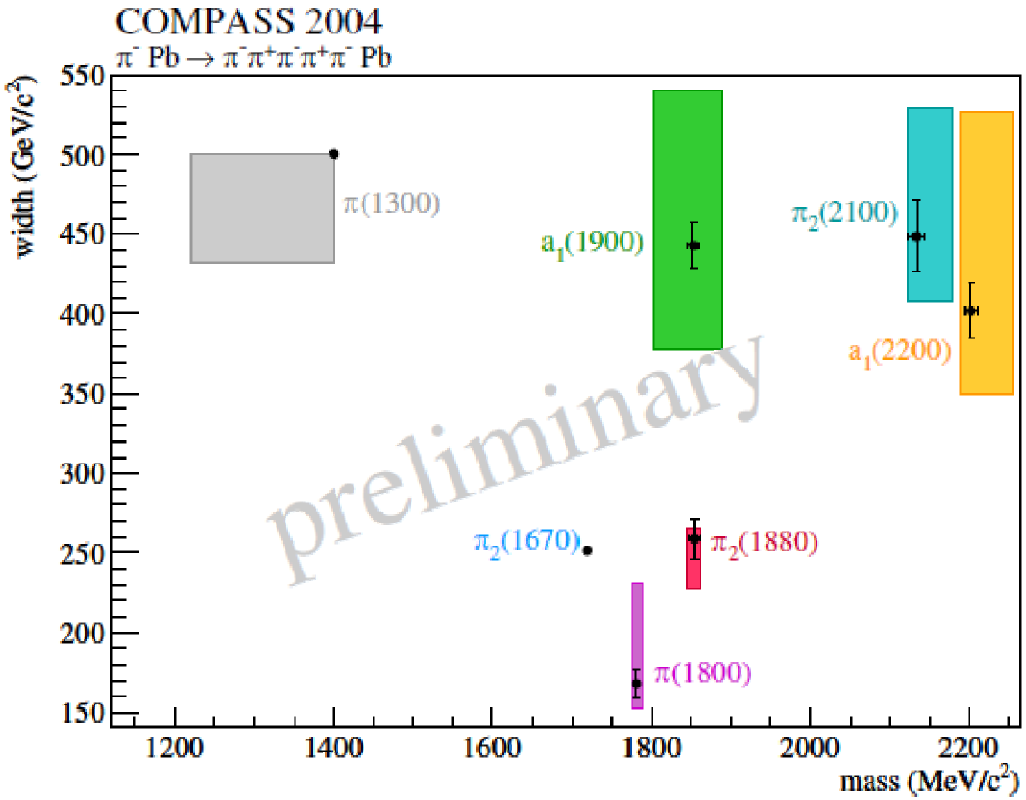
27/07/2012

$\pi^- Pb \to \pi^- \pi^+ \pi^- \pi^+ \pi^- Pb$



Light-meson frontier: access to mesonic states in 2 GeV/c^2 region

Little information from previous experiments

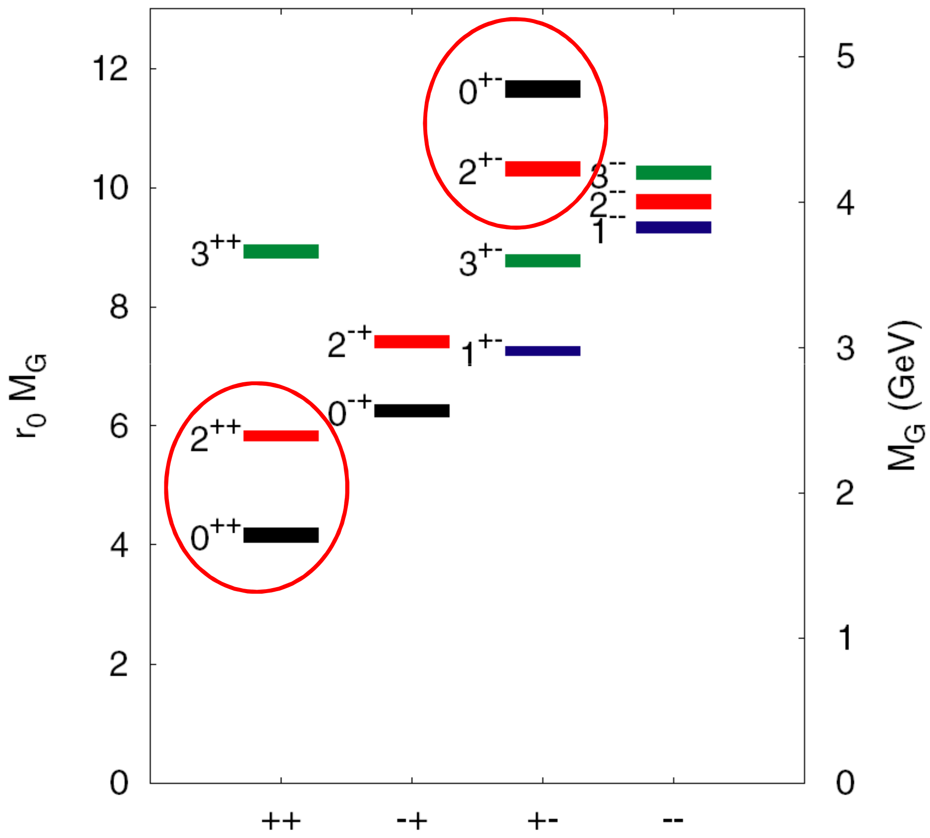


Known states:
$\pi_2(1670)$; $\pi(1800)$

Possible $\pi_2(2200)$ signal

Glueballs

Quenched L-QCD prediction



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

Lightest glueballs:

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

Experimental candidates:

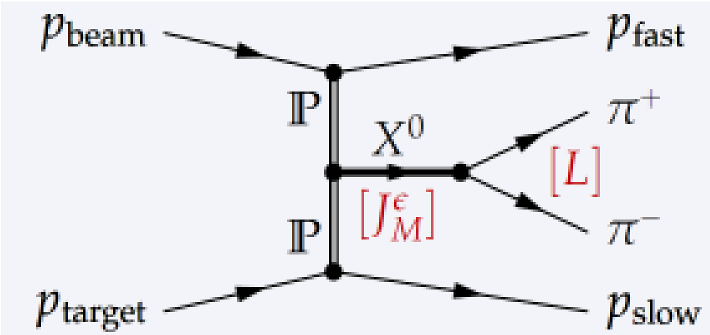
- $f_0(1500)$ (Crystal Barrel, WA102)

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

Higher masses:

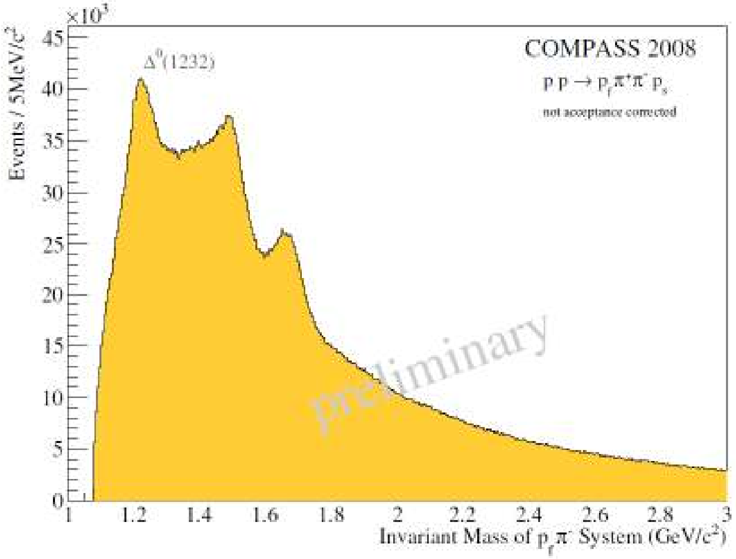
- exotic: $J^{PC} = 2^{+-}, 0^{+-}$
- $M \sim 4.3\ \text{GeV}/c^2$

Central production pp $\rightarrow$ $p_{fast}\pi^+\pi^- p_{slow}$

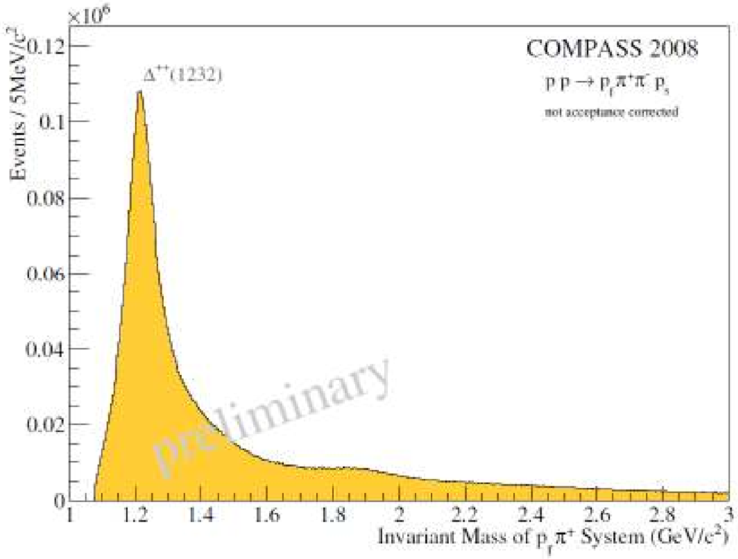


Selection of central events: cut $m(p_{fast}\pi^{\pm}),m(p_{slow}\pi^{\pm})$ > 1.5 GeV/c^2

Invariant mass $p_{fast}\pi^-$

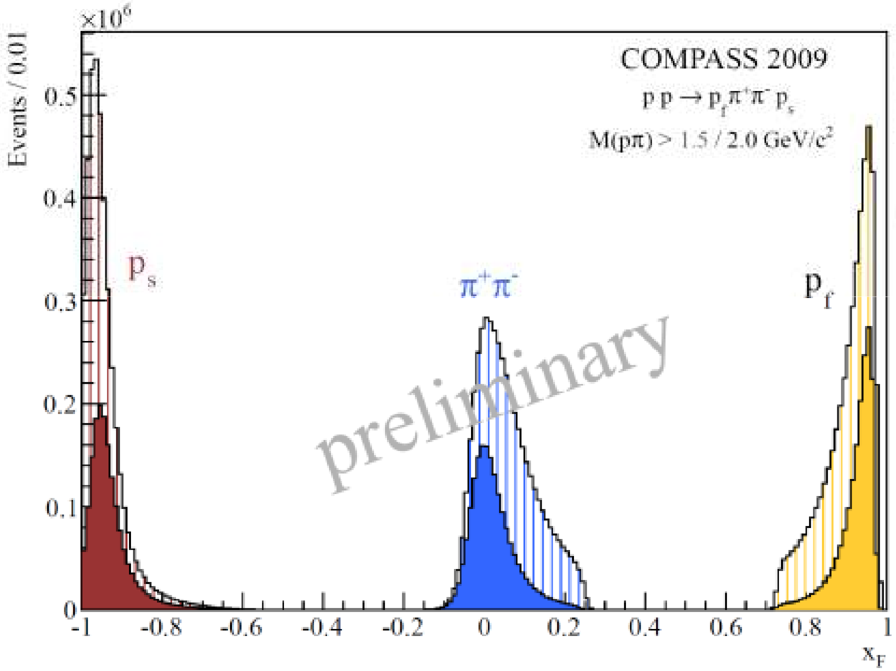


Invariant mass $p_{fast}\pi^+$

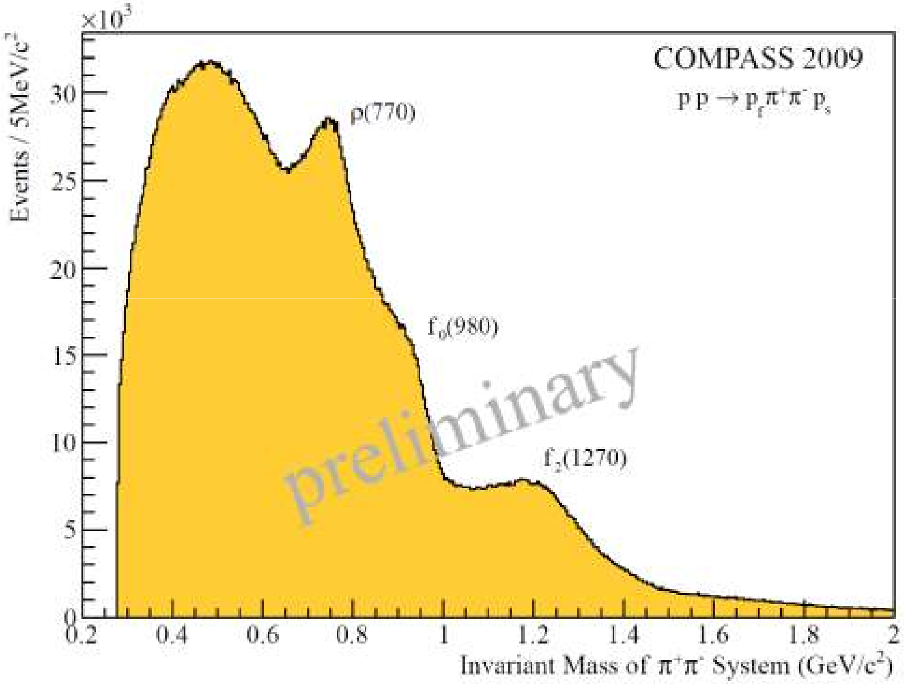


$pp \rightarrow p_{fast}\pi^{+}\pi^{-}p_{slow}$

x_F distribution



$\pi^{+}\pi^{-}$ invariant mass



Analysis similar to previous experiments (WA102)
Comparable results

Final states with strangeness: π & K beams

Glueball candidates decaying into KK

$f_0(1380)$,$f_0(1500)$: qq mixing with gg ?

Hybrid candidates decaying into KKπ

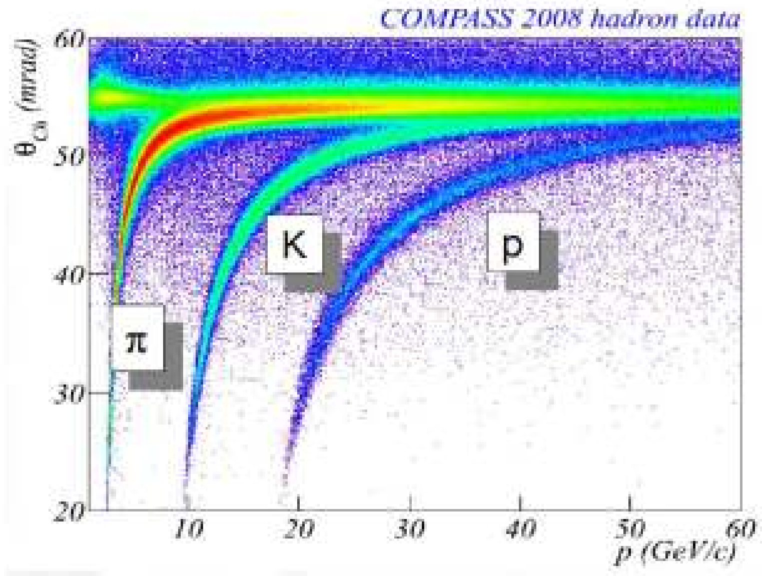
$\pi(1800)$: usual 3^1S_0 or Hybrid?

K from beam identified by CEDAR

K^+K^- identified by RICH: 10 GeV/c< P_K < 30 GeV/c

$$\pi^- p \rightarrow K^+ K^- \pi^- p,$$
$$\pi^- p \rightarrow K_s^0 K_s^0 \pi^- p,$$
$$\pi^- p \rightarrow K_s^0 K_L^0 \pi^- p,$$
$$K^- p \rightarrow K^- \pi^- \pi^+ p,$$

....



Summary for Part II

COMPASS has excellent potential to contribute for hybrids, glueballs , multi-quark states searches in diffractive dissociation & central production

Evidence for these QCD allowed states still not beyond doubt

A large amount of data were collected with hadron beam in 2008/2009 (10 – 100 times world statistics)

- Already observed the spin exotic wave $\pi_1(1600)$ in data from 2004 run
- The same analysis of 2008 data ($\pi^+ \pi^- \pi^-$ and $\pi^0\pi^0 \pi^-$) is still in progress
- Search for glueballs in central production has been started
- Measures charged and neutral channels: Independent consistency check. Measures kaonic final states

COMPASS II

COMPASS-II was approved by the CERN Research Board: Dec. 1, 2010.

COMPASS II

2012, SPS/LHC shutdown, 2014, 2015, 2016

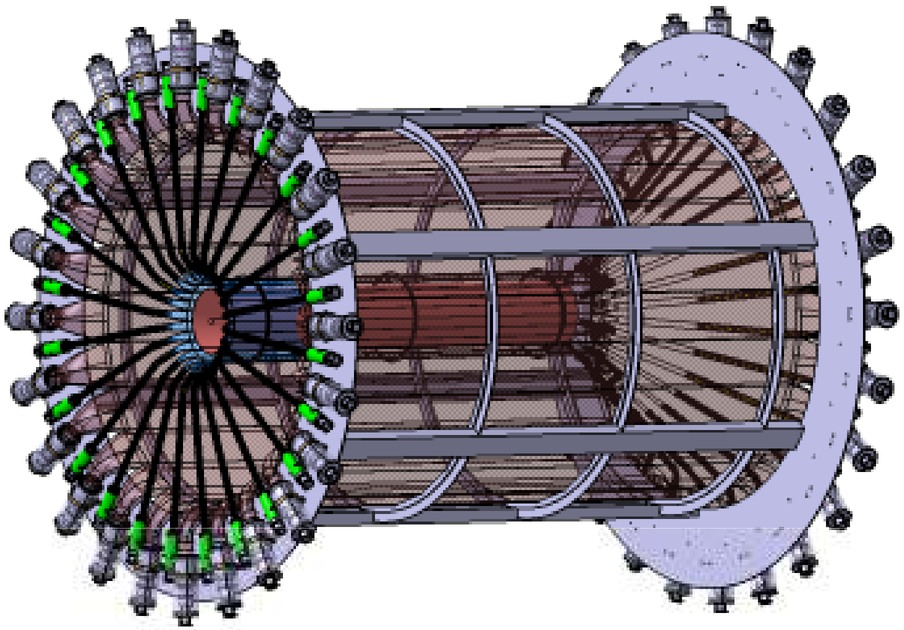
DVSC & DVMP
Study Generalised Parton distributions

Unpolarized SIDIS
Fragmentation Functions, s-PDFs, TMDs

Drell-Yan
Universality of TMDs

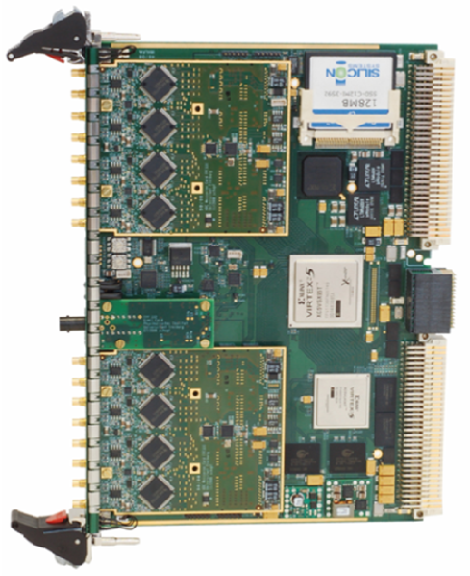
Primakoff
Polarizabilities of π and K

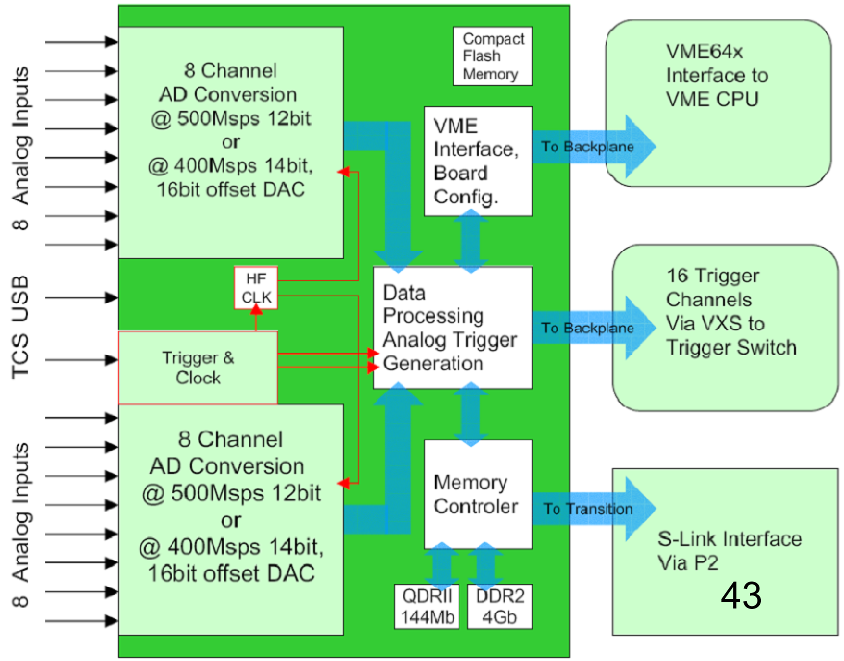
Recoil proton detector for 2.5 m long LH_2 target (Saclay/Freiburg)



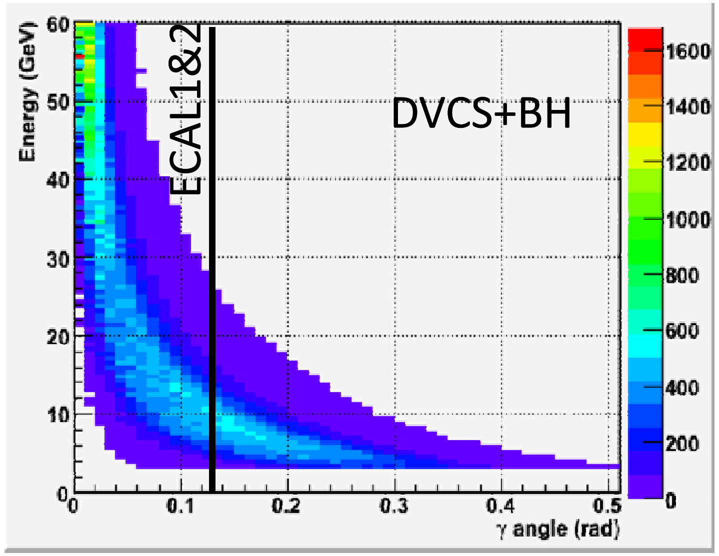
- 4 m long scintillator slabs
- ~ 300 ps timing resolution
- 30º prototype tested successfully

Gandalf Project:
1 GHz digitalisation of the PMT signal to cope with high rate





New large-angle electromagnetic calorimeter ECAL0 (Dubna)



Requirements

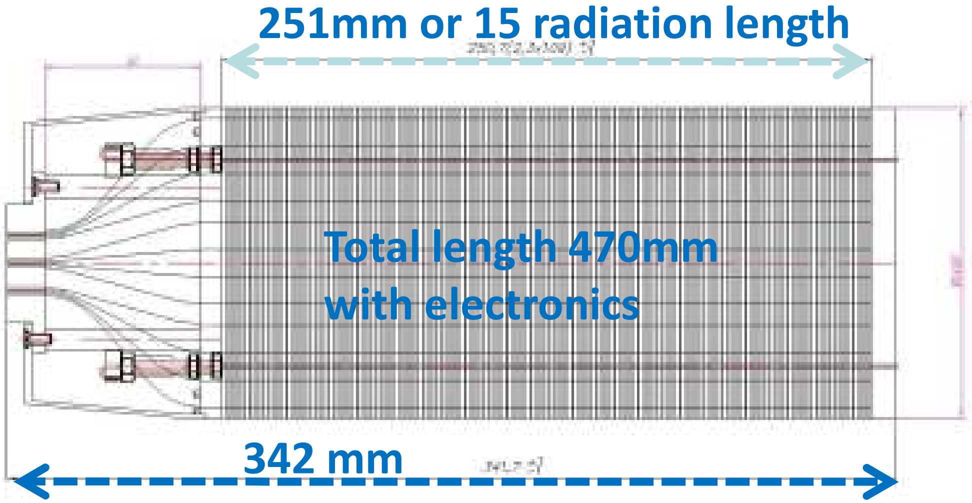
- Photon energy range 0.2- 30 GeV
- Size: 360cm x 360cm ;
- Granularity 4x4 – 6x6 cm^2
- Energy resolution < 10.0%/√E (GeV)
- Thickness < 50 cm,
- Insensitive to the magnetic field.

Prototype under studies

Shaschlyk module with AMPD readout

new shashlyk modules for tests in 2011

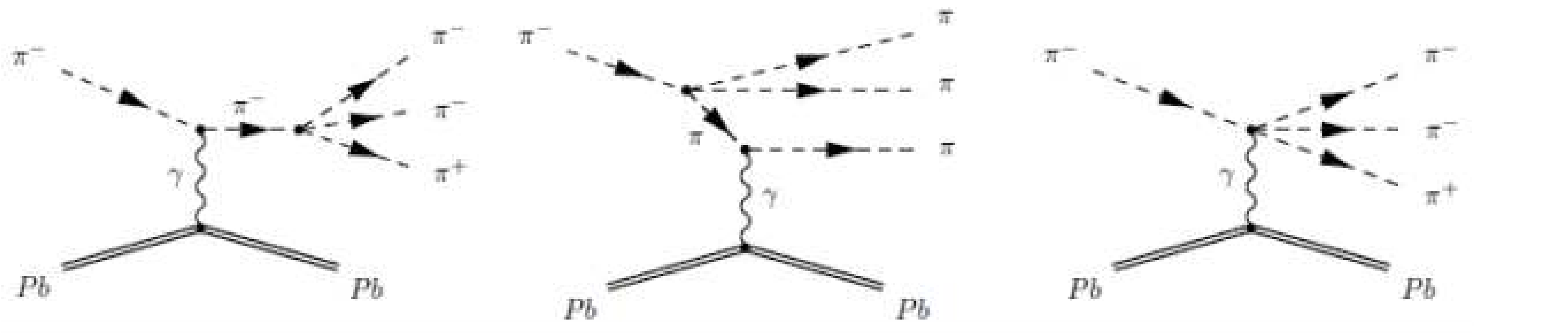
109 plates made of Sc 0.8 mm /Pb 1.5 mm



Avalanche Micropixel Photo Diodes

3 x 3 mm^2, density of pixels 40 000/mm^2

First Measurement of Chiral Dynamics in $\gamma\pi^- \to \pi^-\pi^-\pi^+$

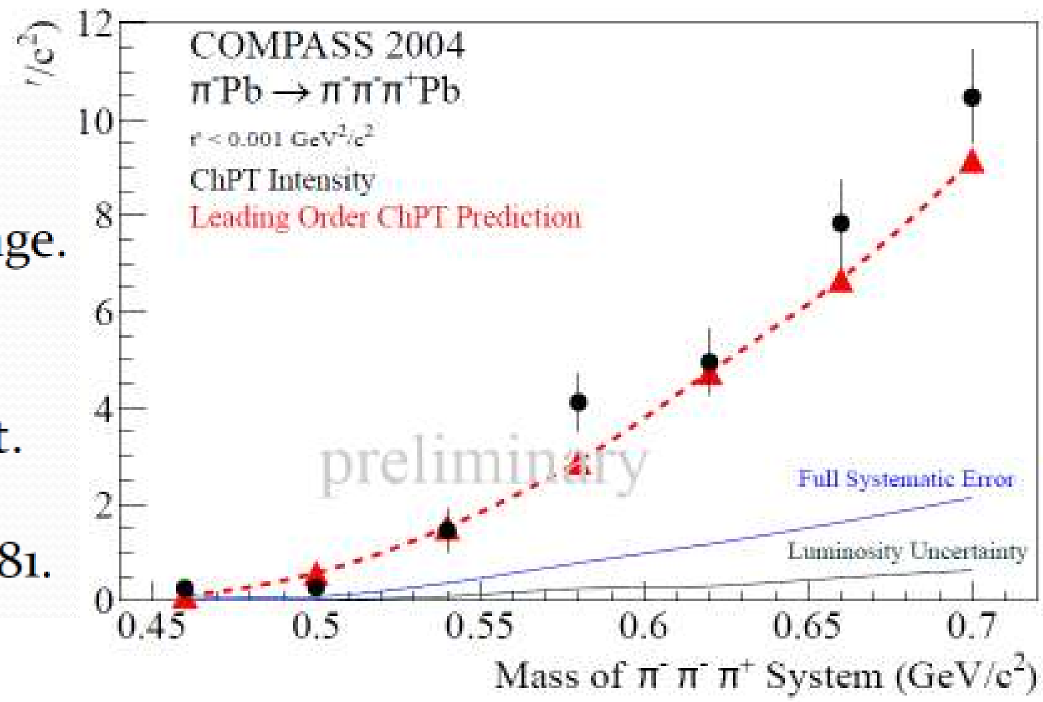


Low momentum transfer:

Contribution from photon exchange.

Low masses:

Only pions produced → ChPT test.
Results compared to LO ChPT predictions from EPJA 36 (2008) 181.



PRL 108, 192001 (2012)

Testing ChPT

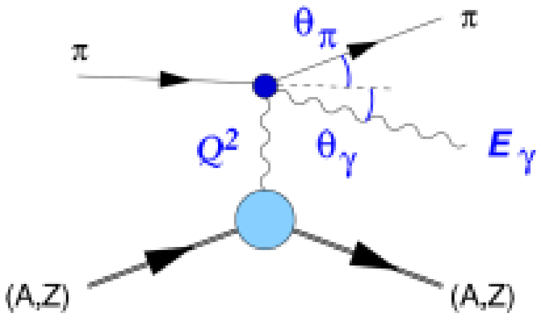
$$\pi^- Z \rightarrow \pi^- Z \gamma$$

2-loop chiral prediction

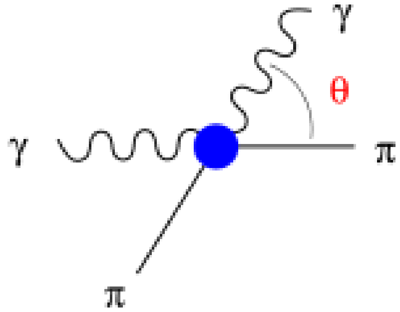
$$\alpha_\pi - \beta_\pi = (5.7 \pm 1.0) 10^{-4}\ \text{fm}^3$$

$$\alpha_\pi - \beta_\pi \text{ from } 4 \text{ to } 14 \cdot 10^{-4}\ \text{fm}^3$$

measurments



Primakoff



Inverse Compton

$$\frac{d\sigma_{\pi\gamma}}{d\Omega_{cm}} = \left[\frac{d\sigma_{\pi\gamma}}{d\Omega_{cm}}\right]_{point-like} + C\,\frac{s - m_\pi^2}{s^2}\,\mathcal{P}(\alpha_\pi, \beta_\pi)$$

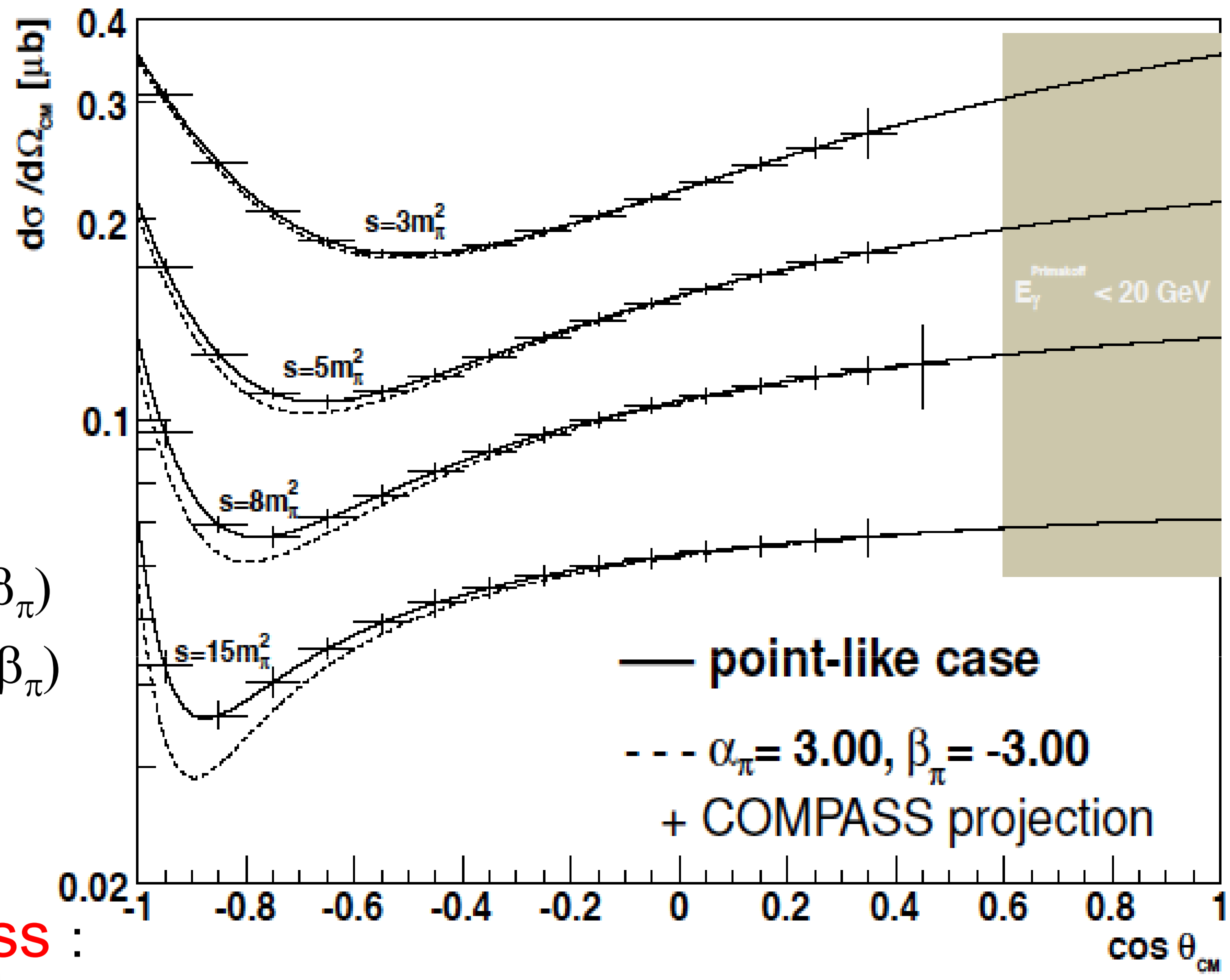
Polarizability:

$$\mathcal{P} = (1 - \cos\theta_{cm})^2\,(\alpha_\pi - \beta_\pi) + (1 + \cos\theta_{cm})^2\,(\alpha_\pi + \beta_\pi)\,\frac{s^2}{m_\pi^4} + (1 - \cos\theta_{cm})^3\,(\alpha_2 - \beta_2)\,\frac{(s - m_\pi^2)^2}{24s}$$

Pion polarisability measurements

COMPASS features

- Energy: 190 GeV
- High-I pion beam
- Muon beam = ref.
- For'd anlgles: $(\alpha_\pi+\beta_\pi)$
- Back'd angles $(\alpha_\pi-\beta_\pi)$

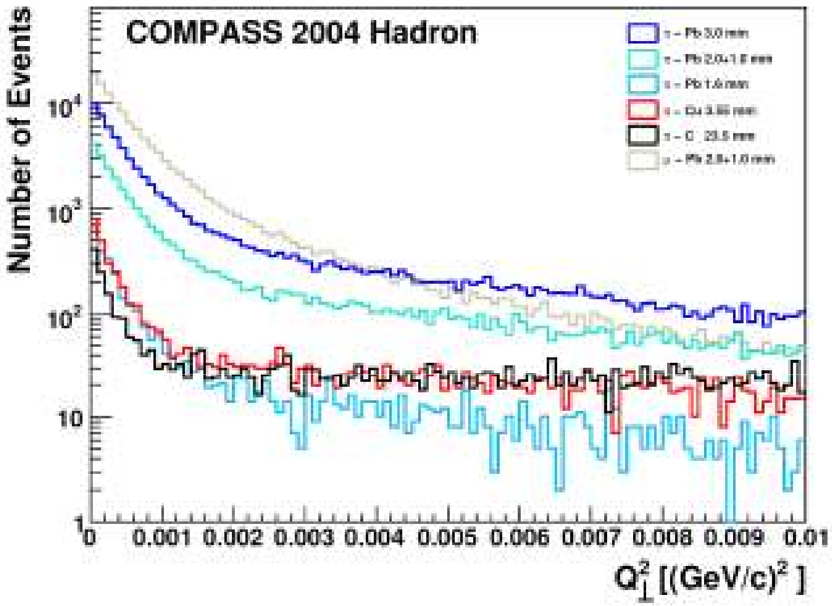


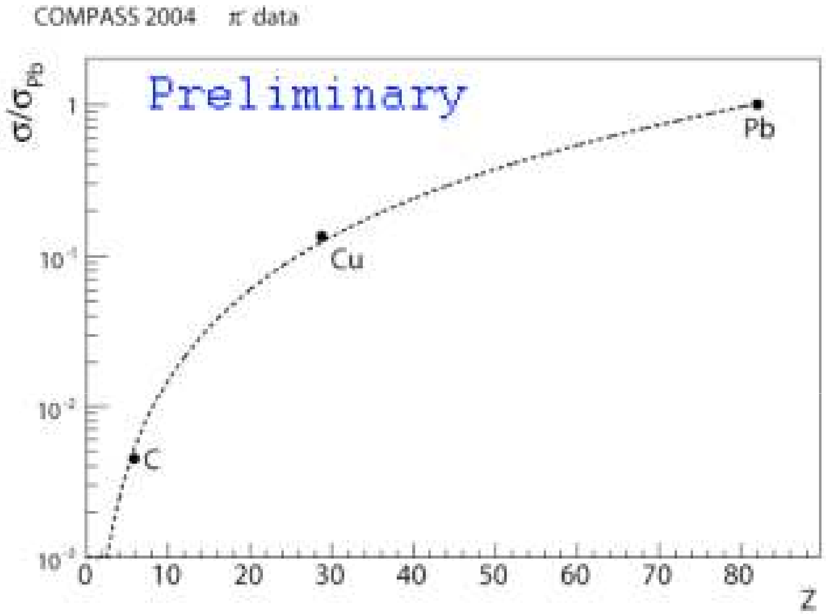
Unique at Compass :

- kaon component in hadron beam: kaon polarisability accessible
- availability of a muon beam (point like) for comparison/systematics
- switching between pion and muon beam within few hours possible

Projections for polarisabilities

Two Primakoff test runs were performed in 2004 & 2009





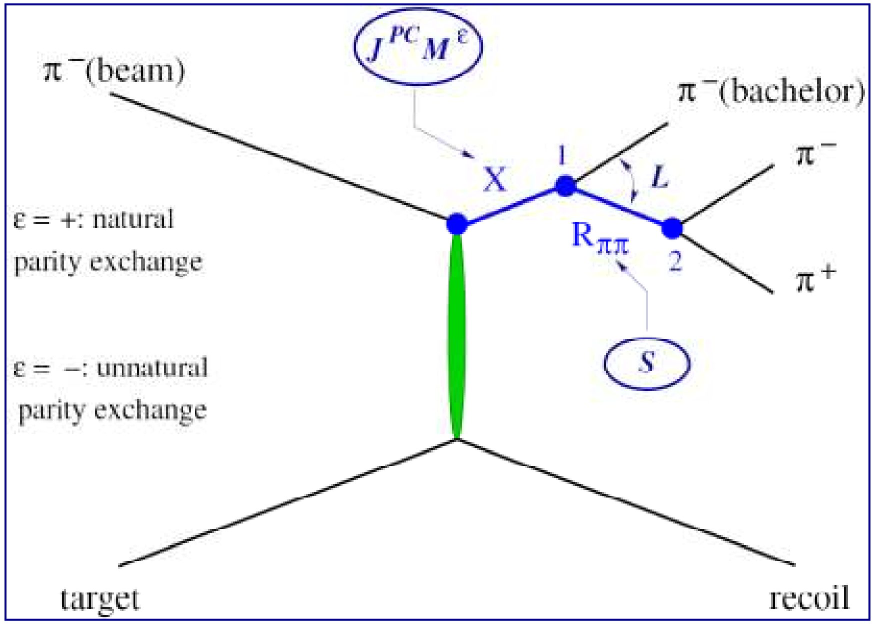
- expected precision of the new measurement:

in 120 d 90 d with π, 30 d of μ beam	$\alpha_\pi - \beta_\pi$ $(10^{-4}\ \mathrm{fm}^3)$	$\alpha_\pi + \beta_\pi$ $(10^{-4}\ \mathrm{fm}^3)$	$\alpha_2 - \beta_2$ $(10^{-4}\ \mathrm{fm}^5)$
2-loop ChPT prediction	5.70 ± 1.0	$.016 \pm 0.10$	16
COMPASS sensitivity	± 0.66	± 0.25	± 1.94

Partial Wave Analysis

Isobar model:

- X decays via sequence of 2-body decays
- Intermediate resonances: isobars
- Partial wave: $\chi = J^{PC}M^{\varepsilon}[isobar\ R]L$
- 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: $m, \{\theta_{GJ}, \phi_{GJ}, m_R, \theta_H, \phi_H\} \equiv \tau$
  - contain angular distributions and isobar parameterizations



Reflectivity basis: linear combinations

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

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

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