Newest results from the COMPASS experiment at CERN

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on behalf of the COMPASS collaboration

EEF70 Workshop, Coimbra, Portugal, 1st – 5th September

Outline

- **Introduction**
  - COMPASS physics adressed
  - The COMPASS experiment
- **Results using hadron beams**
  - Measurement of pion polarisibility
  - Measurement of radiative widths
  - Search for spin-exotic mesons
  - Measurement of OZI violation
- **Results using muon beam**
  - Search for the Zc(3900)
  - Longitudinal spin structure of the nucleon
  - Transversity
- **COMPASS-II**
  - Deep Virtual Compton Scattering
  - Drell-Yan reactions
- **Summary & outlook**

COMPASS: The facility to study QCD

Physics with Muon & Hadron beams

The goal:

- **Study non-pertubative regime of QCD & Probe structure and dynamics of hadrons**
- **complementary methods:**

Large Q²:

Nucleon structure:

- Helicitiy, transversity PDFs
- Generalised PDFs (future)

Low Q²:

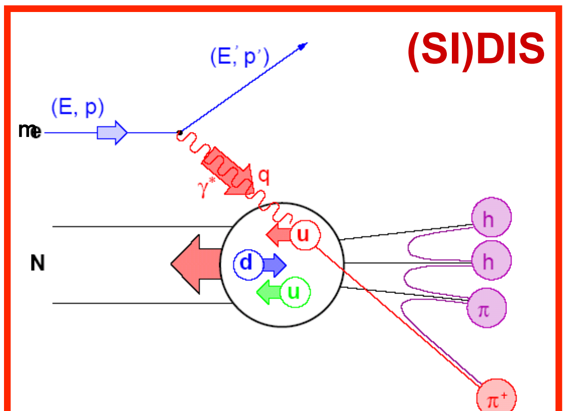
Spectroscopy

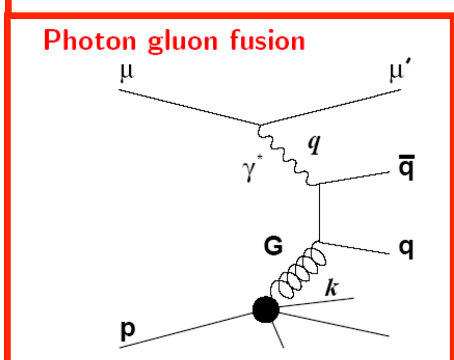
- Mass spectrum of hadrons
- Gluonic excitations (spin-exotics)

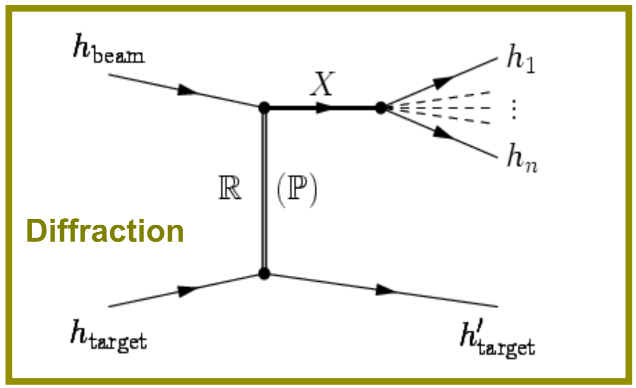
Very low Q²:

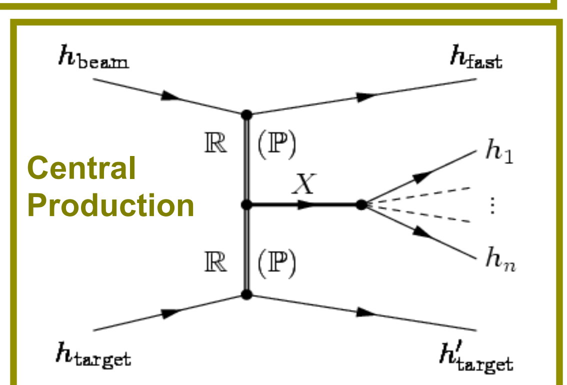
Chiral dynamics

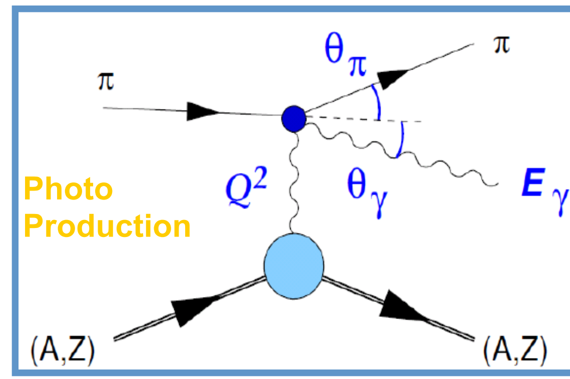
- Pion, Kaon polarisibilities
- Chiral Anomaly $F_{3\pi}$ (future)





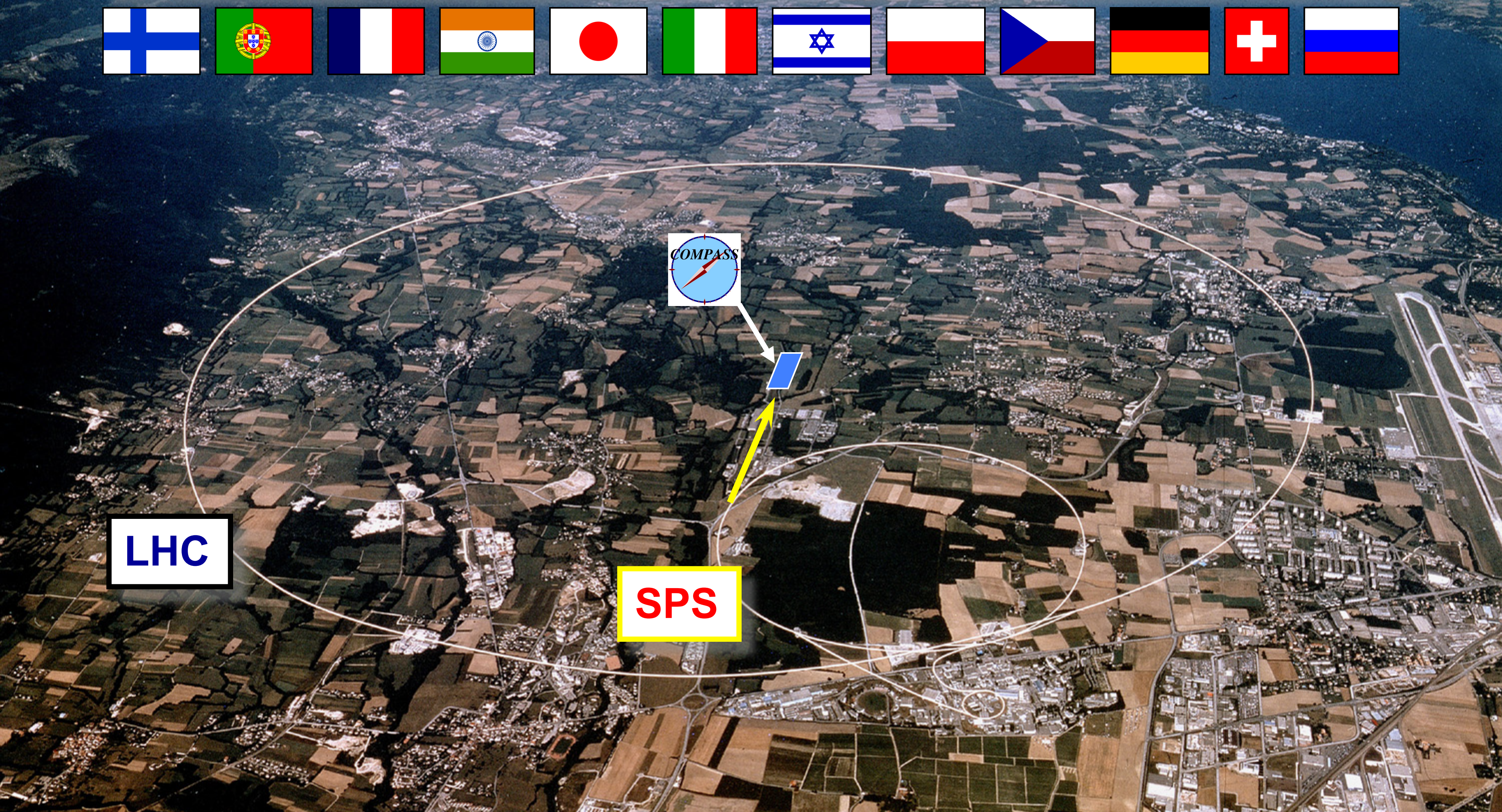






The COMPASS Experiment at CERN

COmmon Muon and Proton Apparatus for Structure and Spectroscopy



luminosity: ~ 5 x 10^{32} cm^{-2} s^{-1} , beam momentum: 160 - 200 GeV (< 400 GeV)
beam intensity: ~ 2 x 10^8 μ^+ / spill (4.8 / 9.6 s) or ~ 5 x 10^7 p^- / spill (9.6 s)

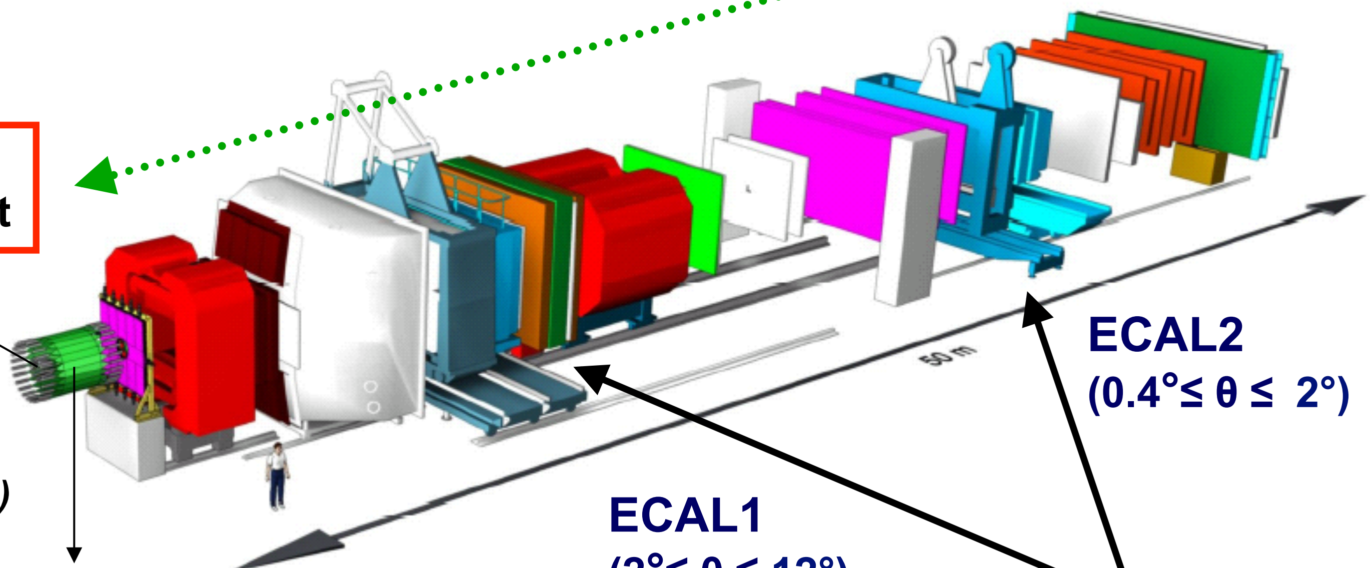
COMPASS spectrometer: Hadron setup
(2008/09) -- main changes w.r.t. muon setup

COMPASS trackers (upgraded close to beam):
SciFi, Si, MM, GEM, DC, Straw, MWPC

0.4m
liquid H_2 target

Beam

(muon or hadron)



ECAL2
($0.4° \leq \theta \leq 2°$)

ECAL1
($2° \leq \theta \leq 12°$)

Recoil detector (RPD)
to trigger on reactions
inside target

PID using
RICH & CEDARs

Electromagnetic calorimeters

(final states involving neutrals,
e.g. $\pi^0, \eta,$ or η')

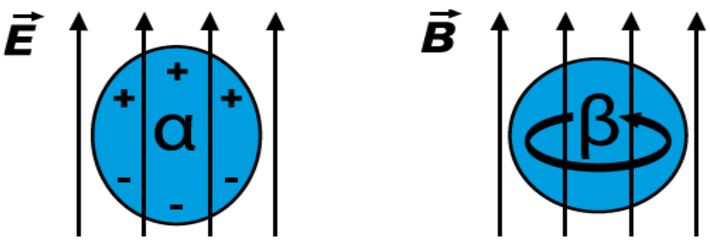
Physics with hadron beams

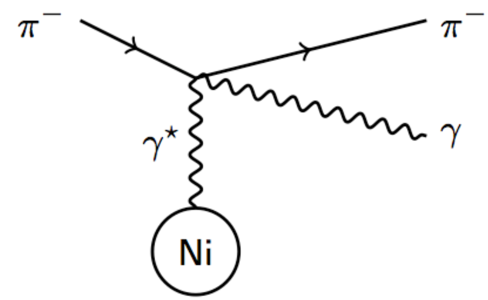
very low Q^2

Pion polarisibility

Pion in strong electromagnetic field

- Measurement of fundamental pion (kaon) polarisibilty
- Prediction by χPT: $2\alpha_\pi = \alpha_\pi - \beta_\pi = (5.7 \pm 1.0) \times 10^{-4}$ fm^3





Measurement

- Deviation of cross-section from expectation for point-like particle
- Experimentally demanding, systematics precisely to be controlled
- Assumption: $\alpha_\pi = -\beta_\pi$
- COMPASS: use pion and muon beam to measure fake-polarisibility of the muon to validate simulations

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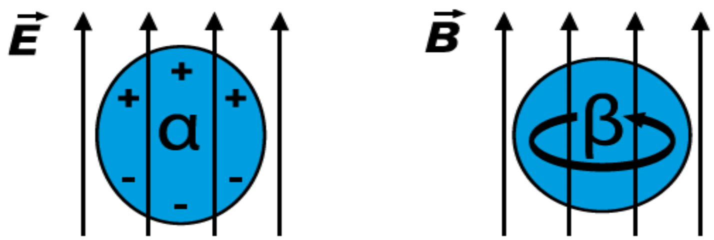

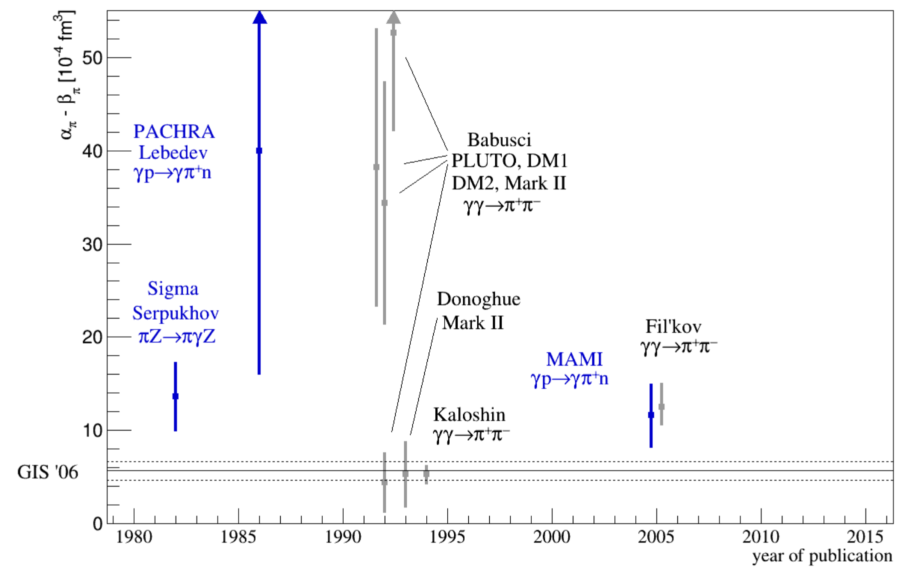

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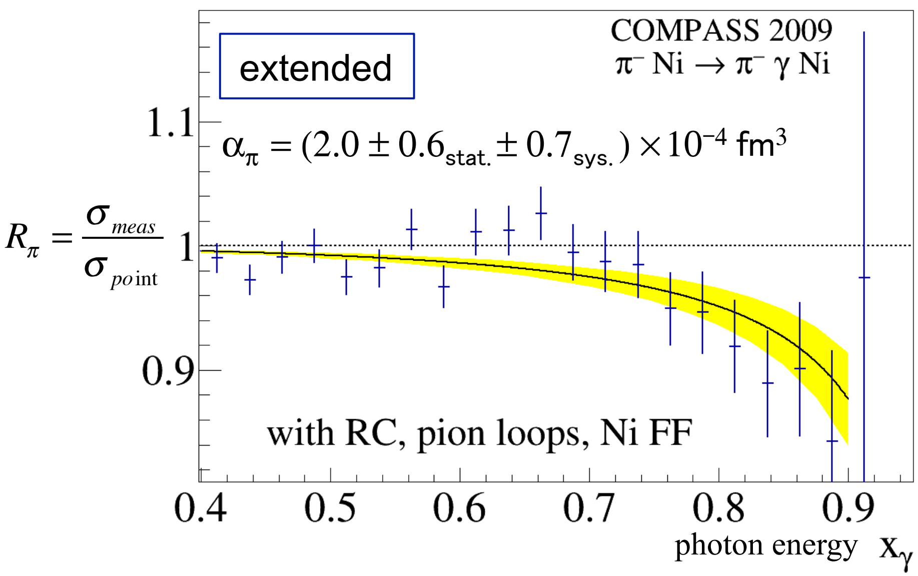
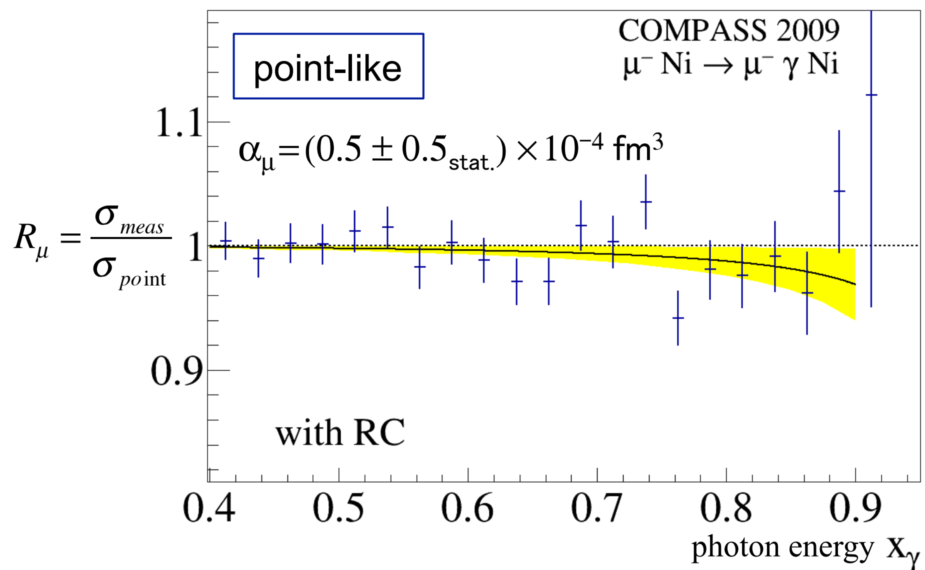
Pion polarisibility

Submitted to PRL: $\alpha_\pi = (2.0 \pm 0.6_{\text{stat.}} \pm 0.7_{\text{sys.}}) \times 10^{-4}\ \text{fm}^3$

- In tension with previous measurements
- In agreement with predictions from χPT





[hep-ex/1405.6377]

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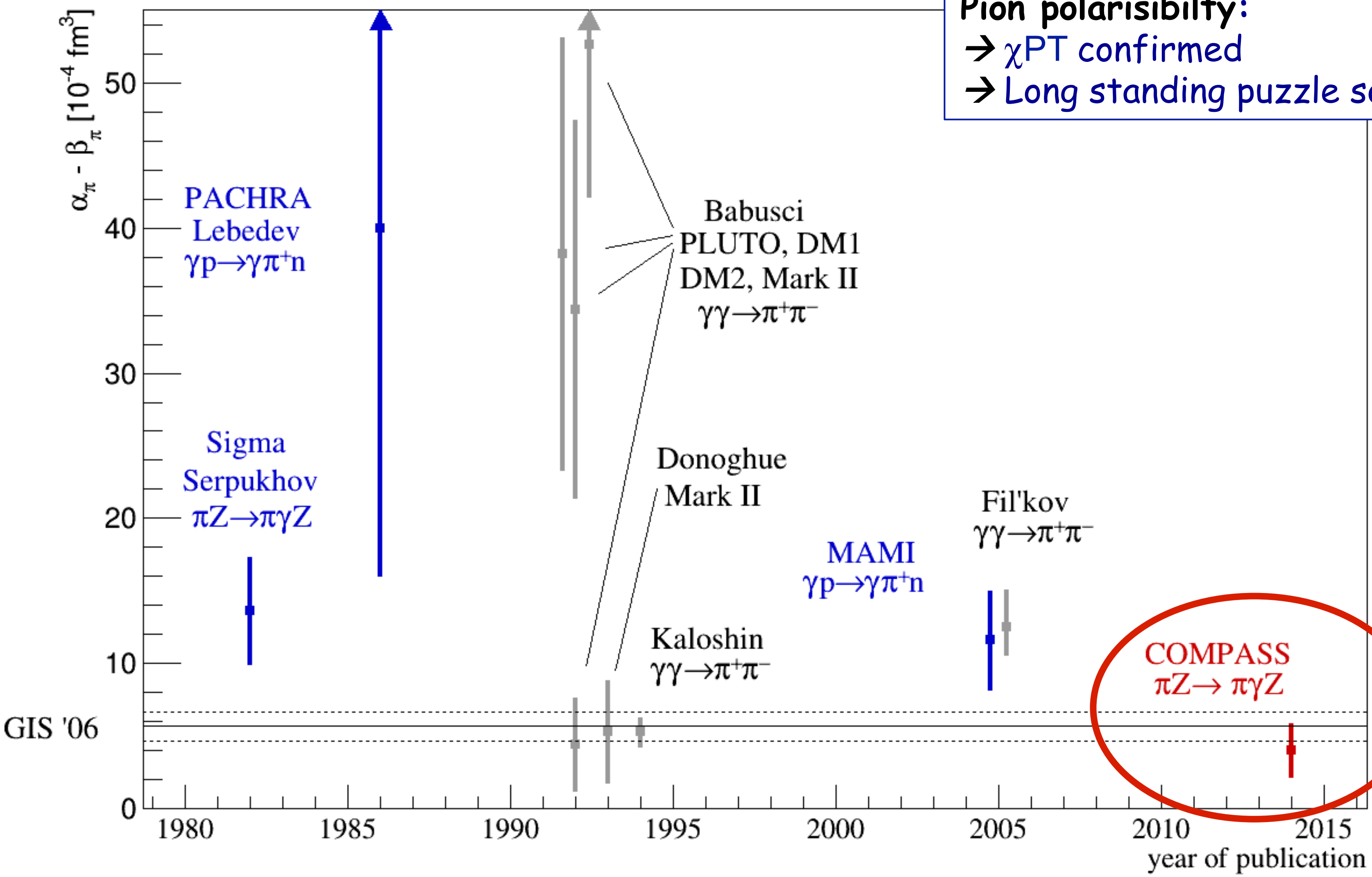
Pion polarisibilty:
→ χPT confirmed
→ Long standing puzzle solved!



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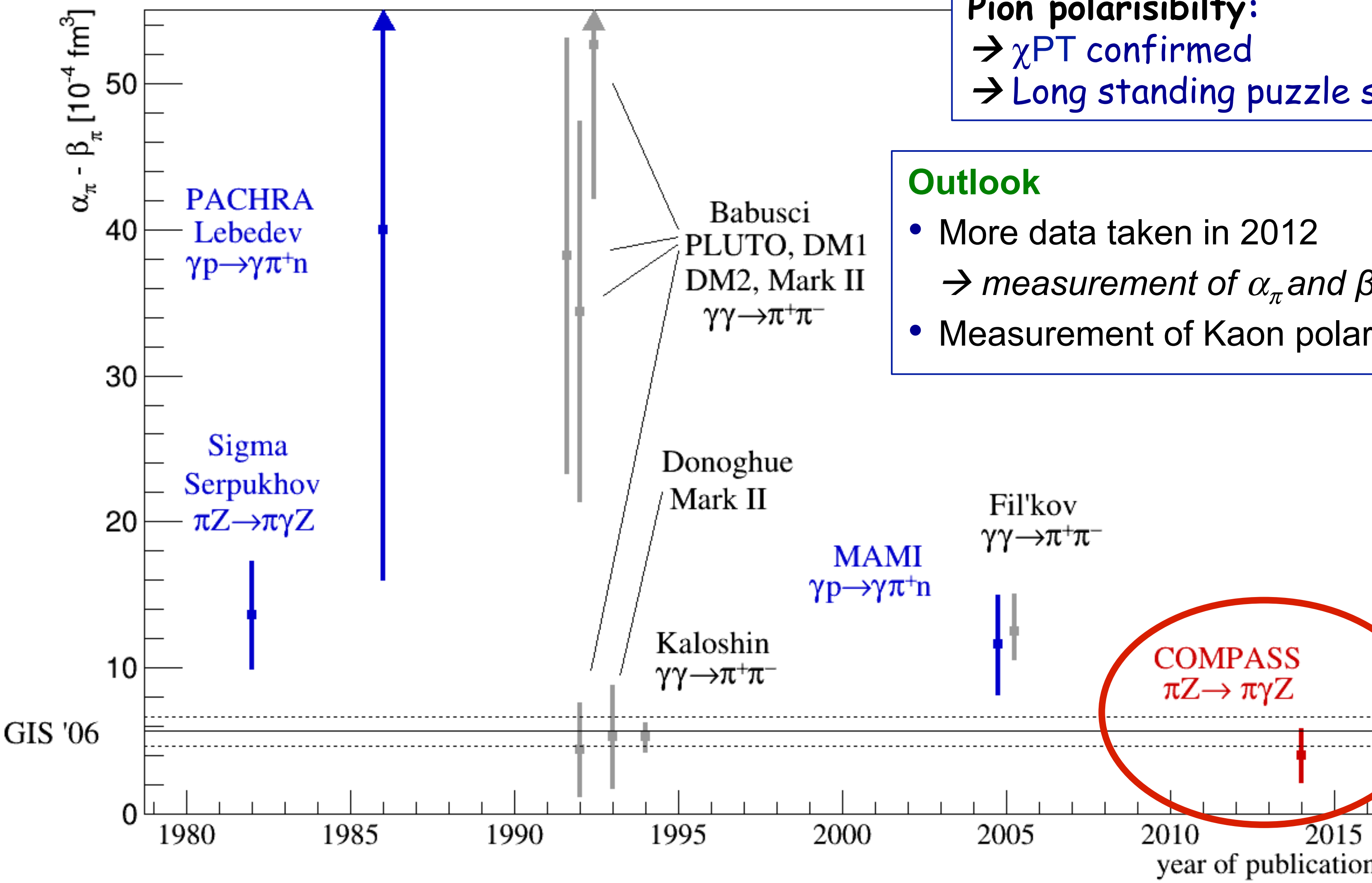

Pion polarisibilty:
→ χPT confirmed
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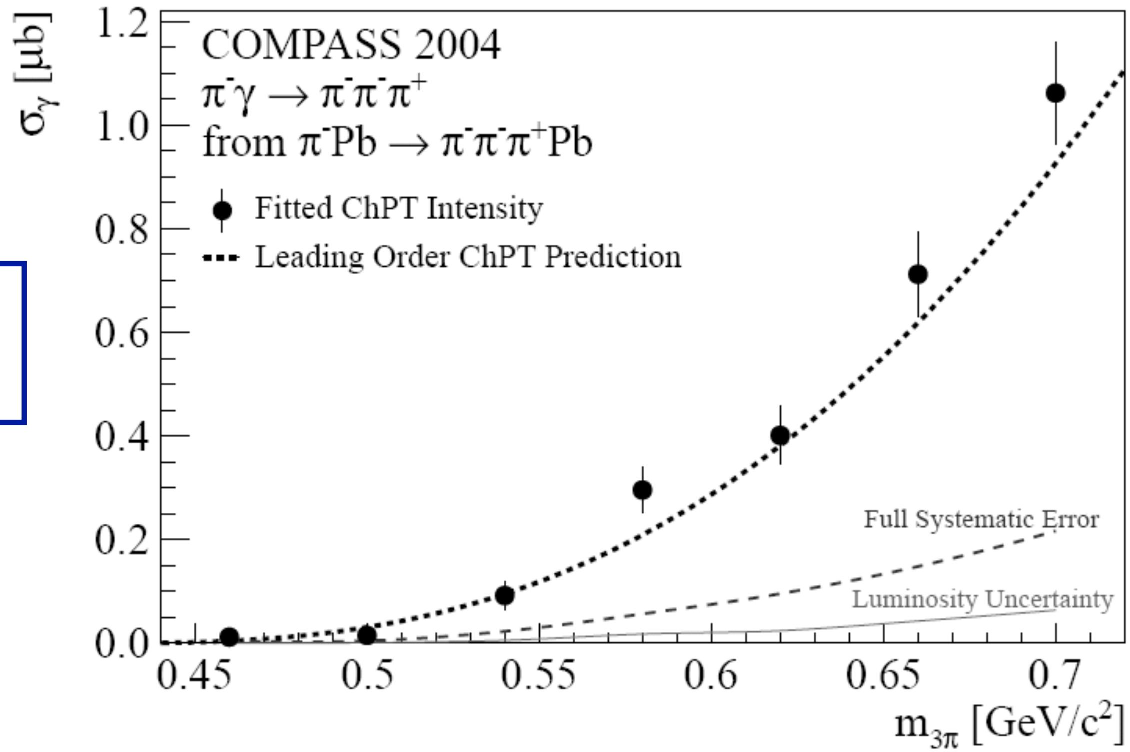
Outlook
- More data taken in 2012
  → *measurement of α_π and β_π*
- Measurement of Kaon polarisibility

Measurement of Chiral dynamics in 3π final states
(Coulomb region, very low $t' < 0.001\ GeV^2/c^2$)

PWA including amplitude from ChPT calculations substituting isobaric waves at low masses



First measurement of cross-section in this range:
- Results in agreement with LO ChPT calculations
- More data available from 2009 run (Ni target)

[hep-ex/1111.5954, PRL 108 (2012) 192001]

Measurement of radiative widths

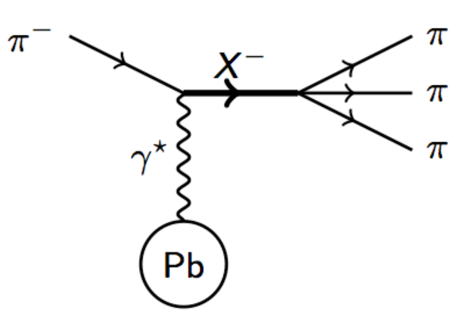
- Access to electromagnetic transitions via decay X $\to \pi\gamma$
  - $a_2(1320) \to \pi\gamma$ magnetic quadrupole moment
  - $\pi_2(1670) \to \pi\gamma$ electric quadrupole moment

- Direct measurement of $\pi\gamma$ experimentally challenging
- Inverse process: scattering of a pion off a Coulomb potential
  - quasi-real photons in the vicinity of heavy nuclei

- Cross-section for Primakoff produced X
  - $\sigma_{\text{Primakoff, X}} \sim \Gamma_0(X \to \pi\gamma)$

$$\Gamma_0(X \to \pi\gamma) = \frac{N_{X,\text{prim}}/\epsilon_X}{C_X \cdot L \cdot \text{CG} \cdot \text{BR} \cdot \epsilon_{\text{resol}}}$$

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



Identify Primakoff contribution: $\pi^- \gamma \to \pi^- \pi^- \pi^+$

- Primakoff produced states have spin projection M=1
- Cross-section for diffractively produced states

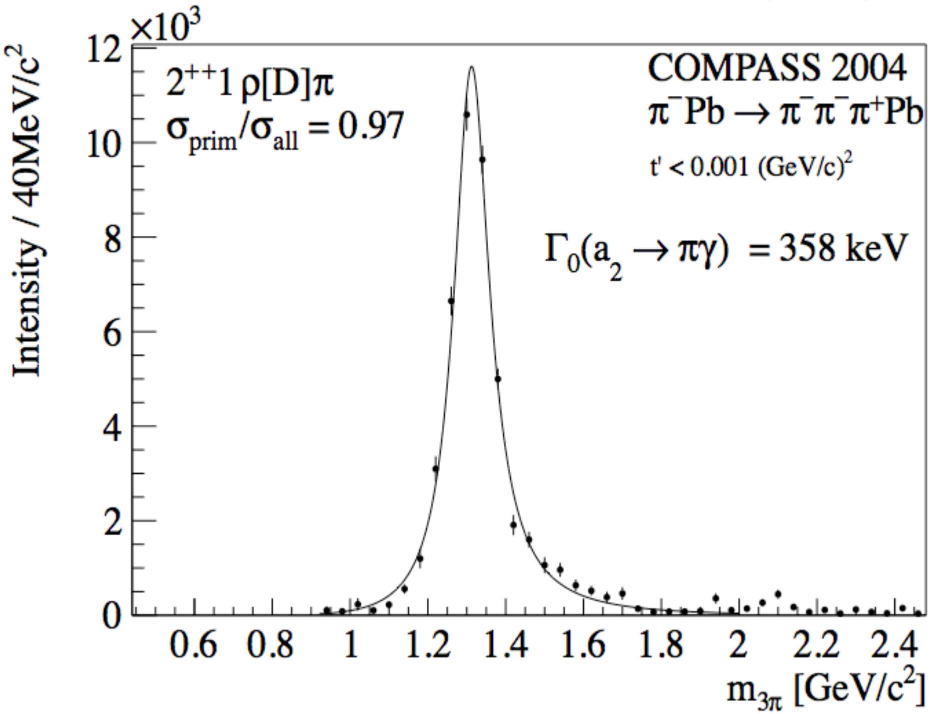
$$\sigma \sim t'^{M} e^{-bt'}$$

- at small t' states with M=1 predominantly Primakoff produced
- Partial-wave analysis to identify states with M=1
- Count number of final states to get cross-section

Measurement of radiative widths -- $a_2(1320)$
M2 transition

Theoretical predictions

- Vector Meson Dominance Model
  375 keV (Rosner, 1981)
- Relativistic Quark Model
  324 keV (Aznauryan & Ogamesyan, 1988)
- Covariant Oscillator Quark Model
  235 keV (Ishida et al., 1989)



Experimental measurements

- SELEX (2001): (284 ± 25 ± 25) keV
- E272 (1982): (295 ± 60) keV
- May et al. (1977): (460 ± 110) keV

COMPASS: (358 ± 6 ± 42) keV

EPJ A Highlight 2014

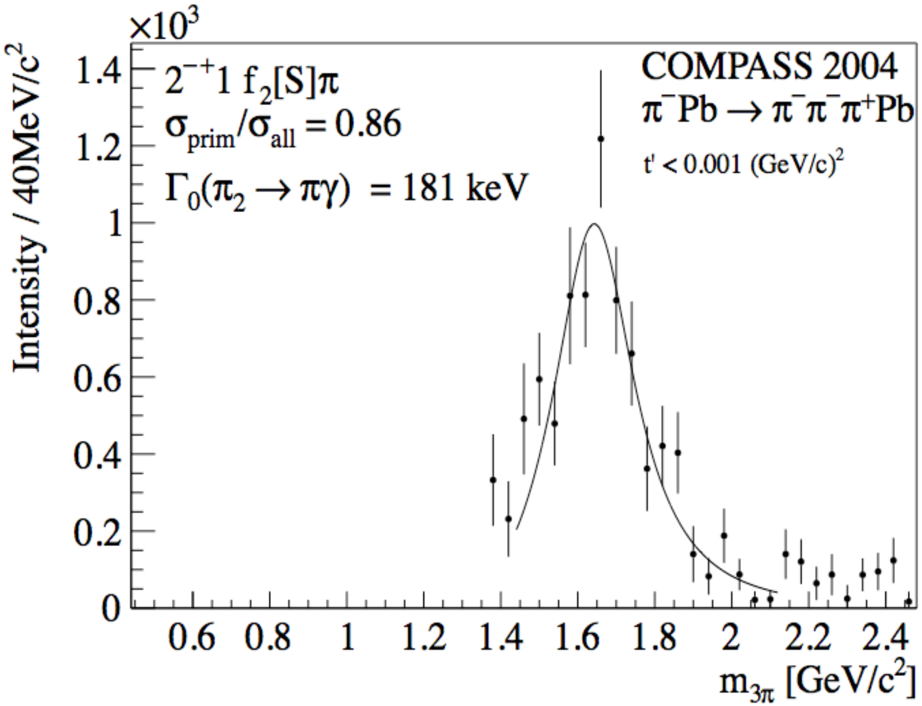
[hep-ex/1403.2644, EPJ A 50 (2014) 79]

Measurement of radiative widths -- $\pi_2(1670)$
E2 transition

Theoretical predictions
- Covariant Oscillator Quark Model

  335 keV and 521 keV

  (both Maeda et al., 2013)



Experimental measurements
- First measurement by COMPASS

COMPASS: (181 ± 11 ± 27) keV

EPJ A Highlight 2014

[hep-ex/1403.2644, EPJ A 50 (2014) 79]

Physics with hadron beams

low Q^2

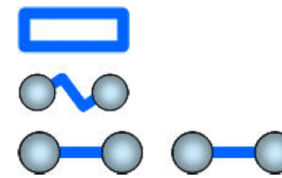
Mesons and Spin Exotic States

Constituent quark model

- color neutral $q\bar{q}$ systems
- quantum numbers $I^G J^{PC}$
- $P = (-1)^{L+1}$ $C = (-1)^{L+S}$ $G = (-1)^{I+L+1}$
- J^{PC} *multiplets:* $0^{++}, 0^{-+}, 1^{--}, 1^{+-}, 1^{++}, 2^{++}, \ldots$
- *Forbidden:* $0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, 3^{-+}, \ldots$

QCD: meson states beyond

- glueballs: gg, ggg
- hybrids: $q\bar{q}g$
- tetraquarks: $(q\bar{q})(q\bar{q})$



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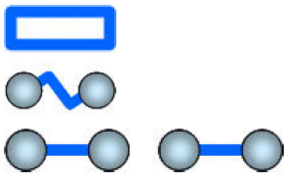

Lattice calculations:
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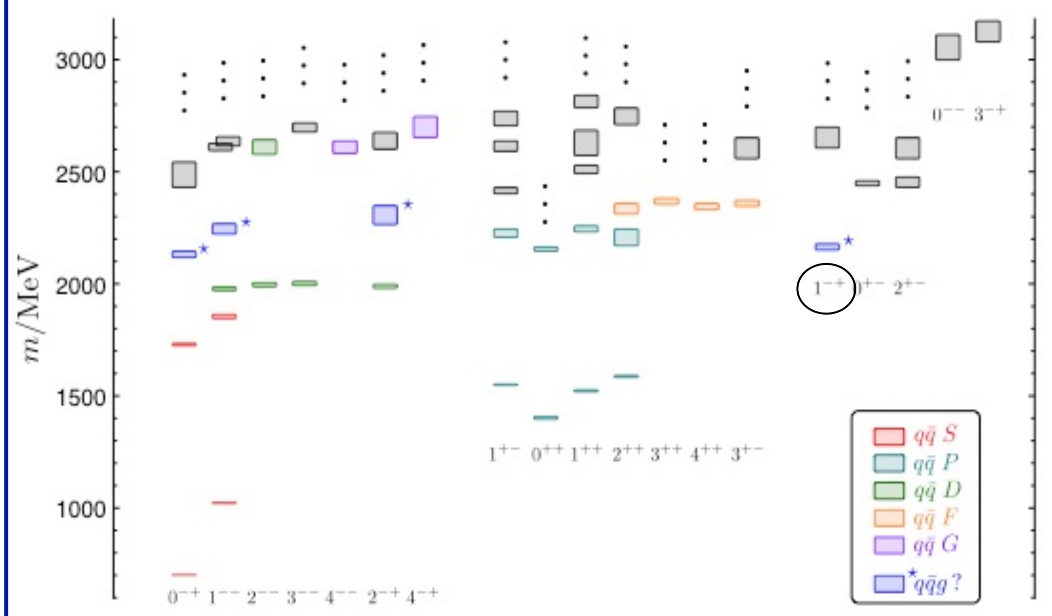
- light hybrid, exotic $J^{PC} = 1^{-+}$



J.Dudek, Phys. Rev. D84 (2011) 074023

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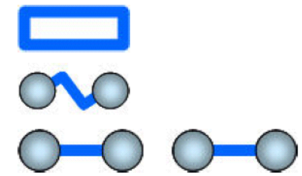

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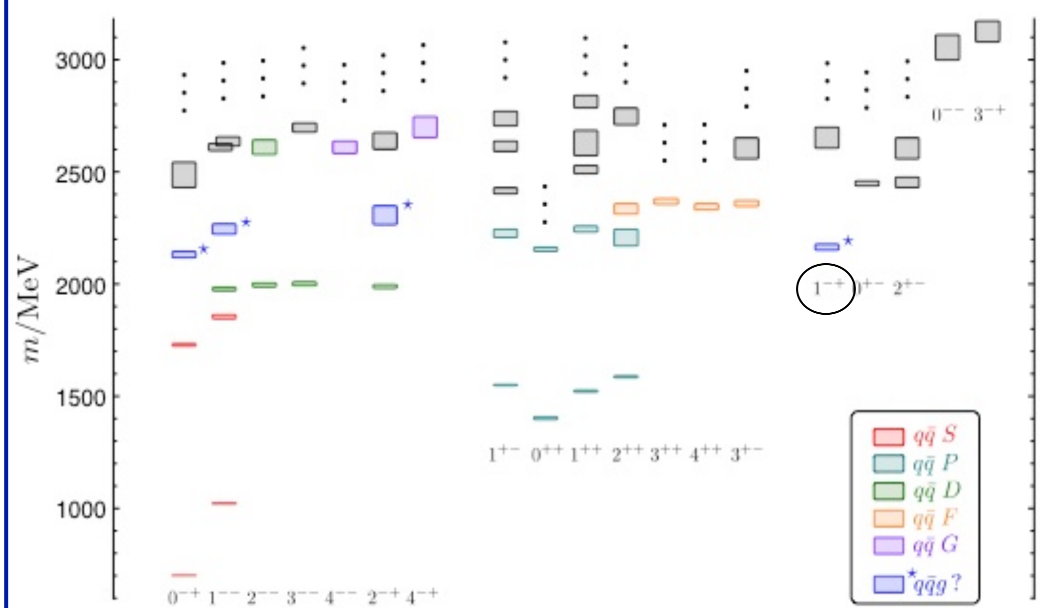
Experiment (1.3 - 2.2 GeV/c²):
hybrid candidates, exotic $J^{PC} = 1^{-+}$
- $\pi_1(1400)$: VES, E852, CB –> $\eta\pi$
- $\pi_1(1600)$: E852, VES –> $\rho\pi, \eta`\pi, f_1\pi, b_1\pi$
- $\pi_1(2000)$: E852 –> $f_1(1285)\pi$, $b_1(1235)\pi$

…. still controversial → COMPASS



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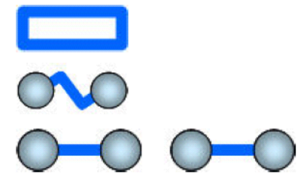

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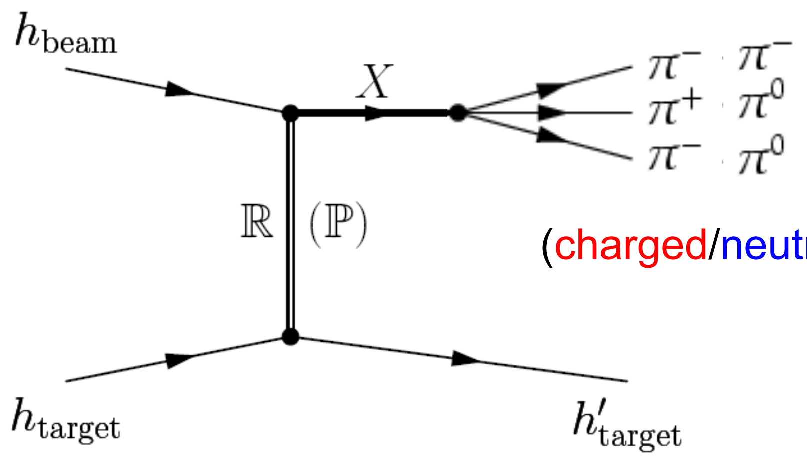
Diffractive production of e.g. 3π



(charged/neutral)

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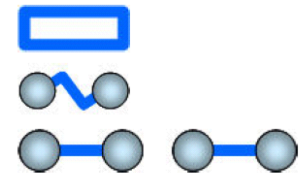

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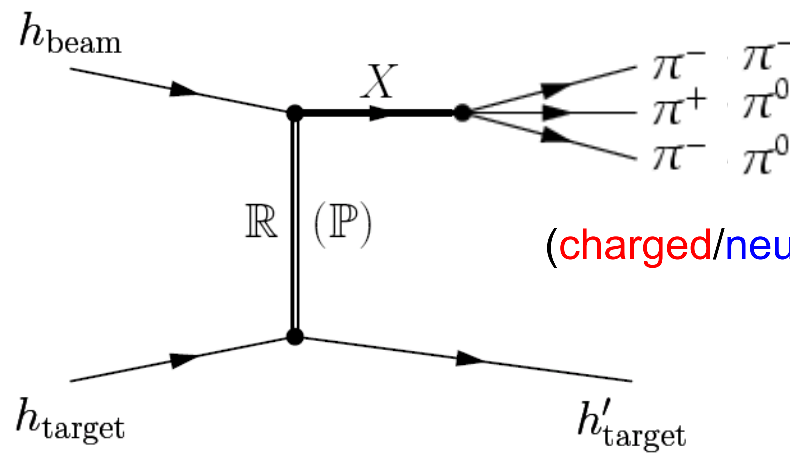


(charged/neutral)

COMPASS PWA Method

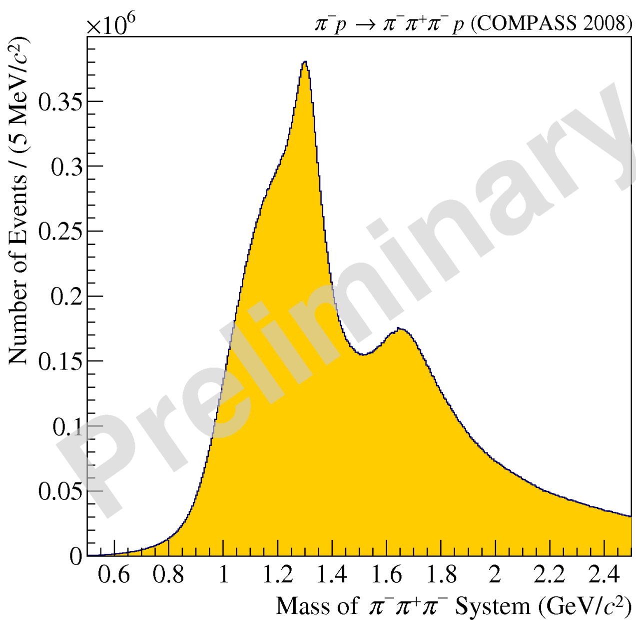
Partial wave analysis (isobar model)**:**
- **Isobars*:*** All possible, needed isobars, 88 partial-waves
- **Acceptance:** corrections included (normalisation integrals)

Step 1) PWA in mass and t' bins
- Extract production amplitudes

Step 2) χ^2 fit of mass dependence of spin density matrix:
- Applied to 1st step result
- Main partial waves chosen, parameterised by Breit-Wigner
- Non-resonant background for some waves

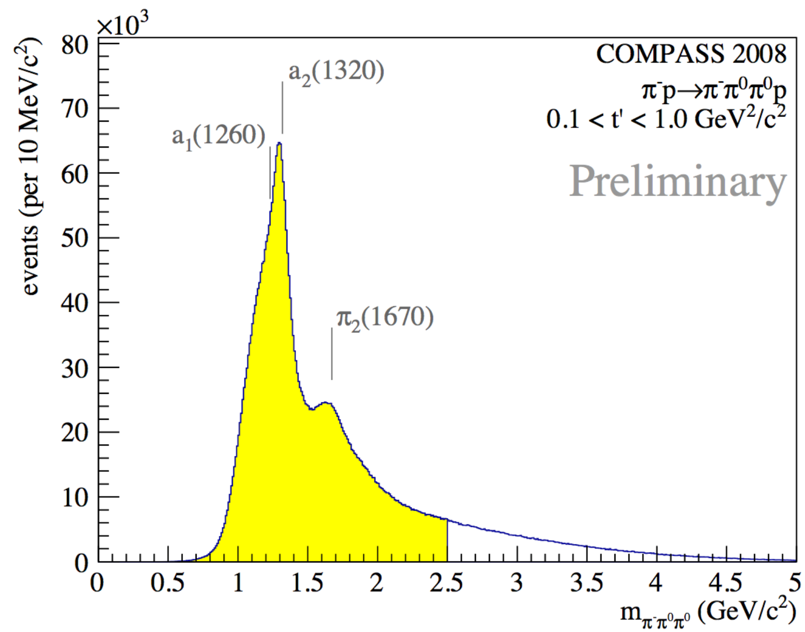
Diffractive dissociation into 3π final states
(2008 data, proton target)

Mass of outgoing 3p system – charged mode: $\pi^- p \to \pi^-\pi^+\pi^- p$



PWA: ~ 50M events

Mass of outgoing 3p system – neutral mode: $\pi^- p \to \pi^-\pi^0\pi^0 p$



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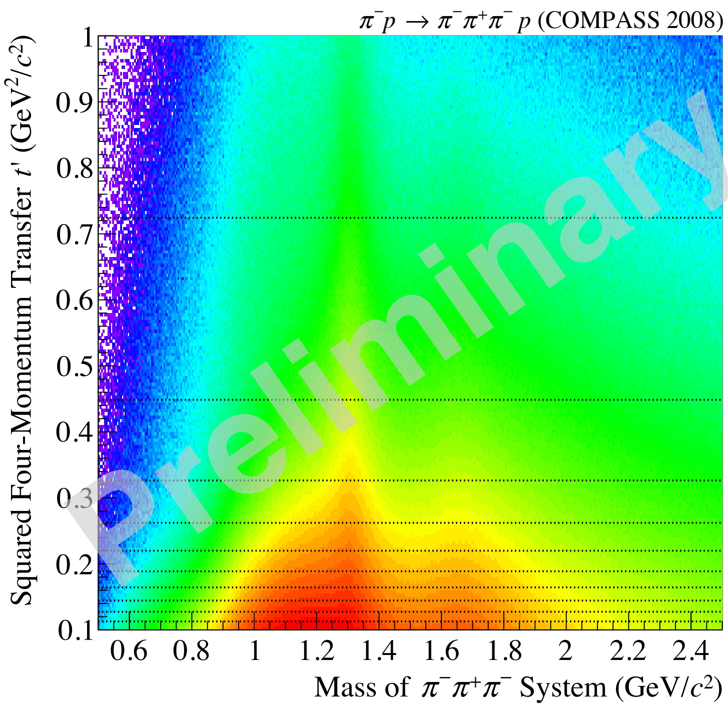

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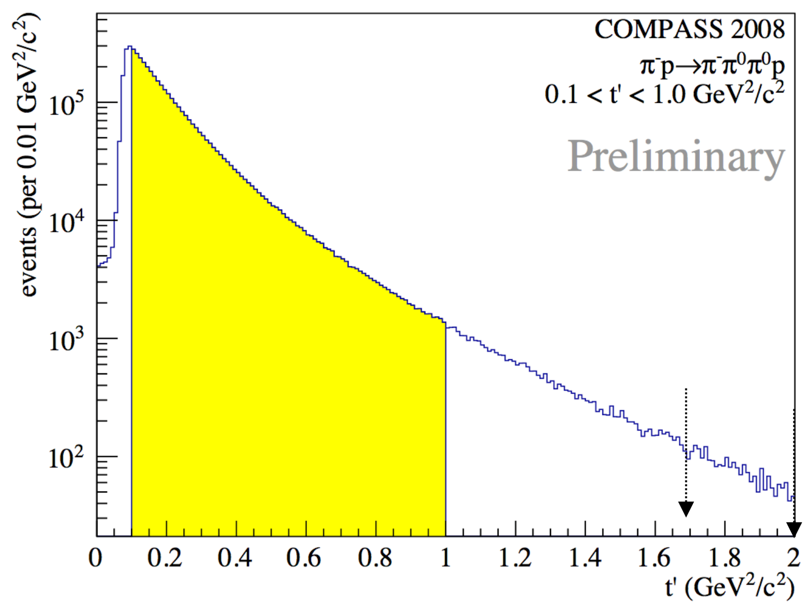
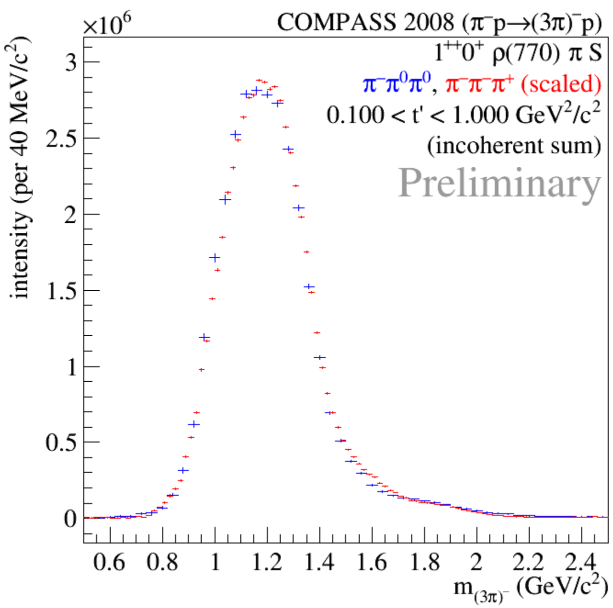


PWA: ~ 50M events
→ 400 bins in 3π mass & 11 slices of t`

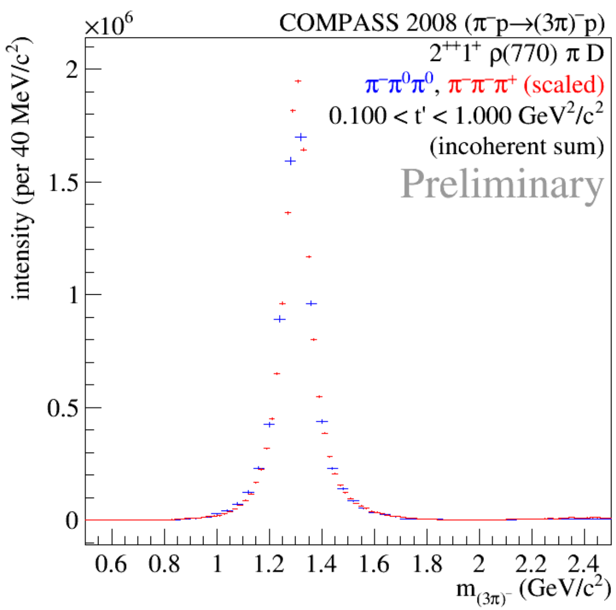
PWA: ~ 3.5M events
→ 200 bins in 3π mass & 8 slices of t`

Comparison neutral vs. charged mode
-- the 3 most prominent resonances

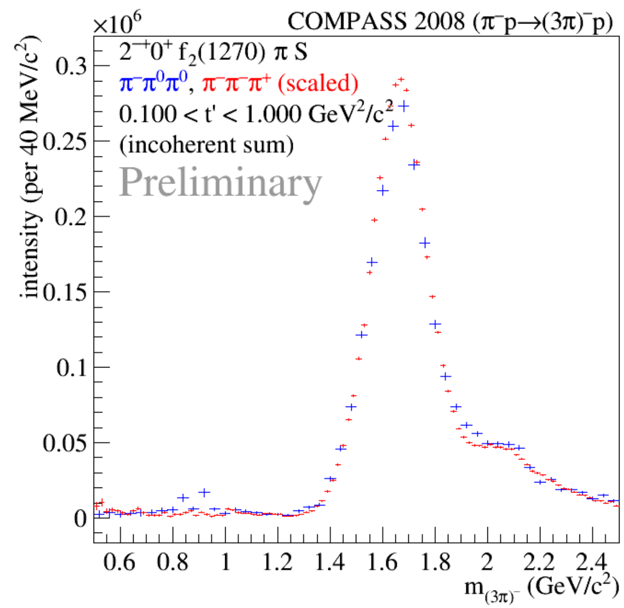
$a_1(1260) \to \rho\pi$



$a_2(1320) \to \rho\pi$



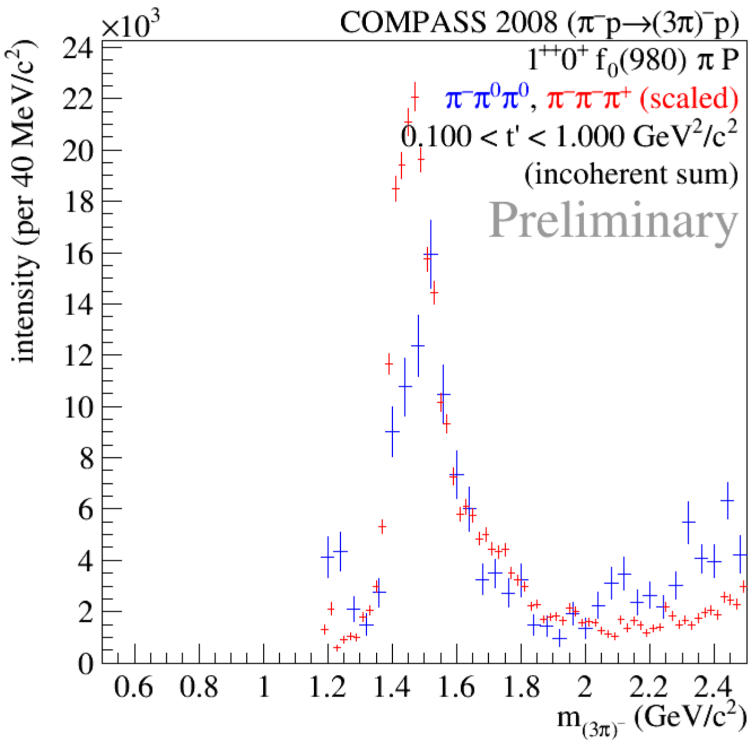
$\pi_2(1670) \to f_2\pi$



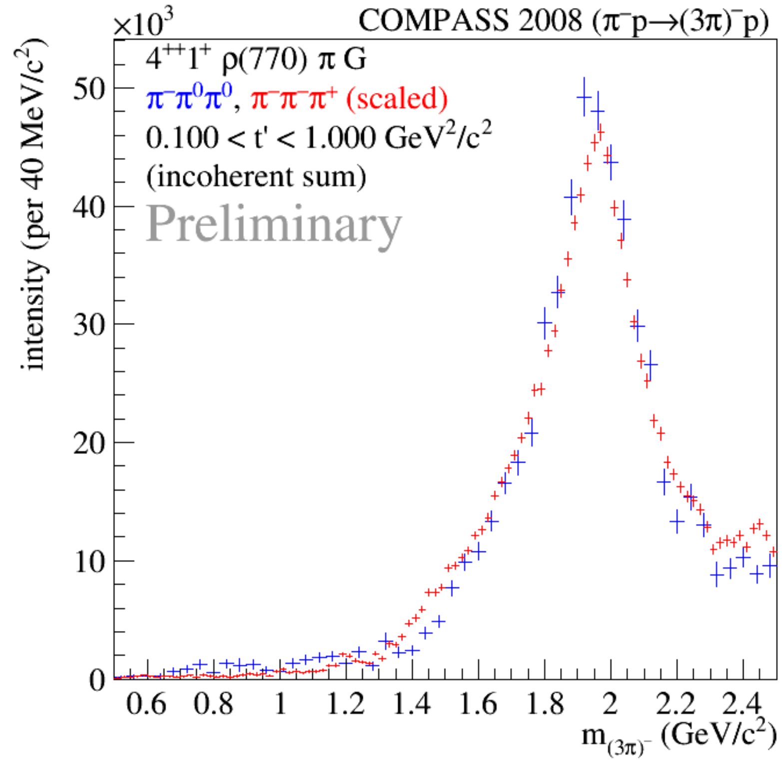
- charged mode data scaled for each plot (integral) to compare shapes
- good agreement between the two channels

Comparison neutral vs. charged mode
-- a couple of smaller waves

X(?) ->$f_0\pi$



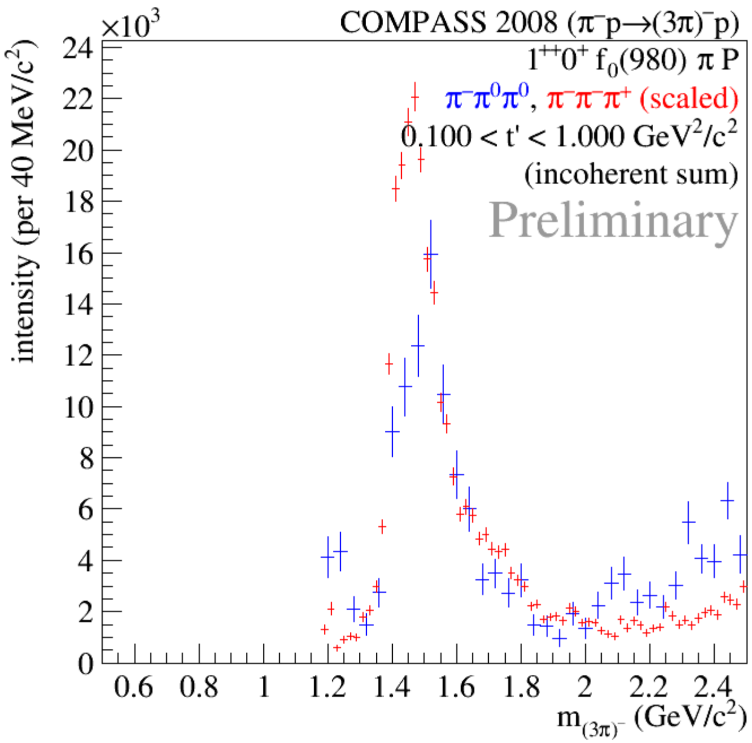
$a_4(2040)$->$\rho\pi$



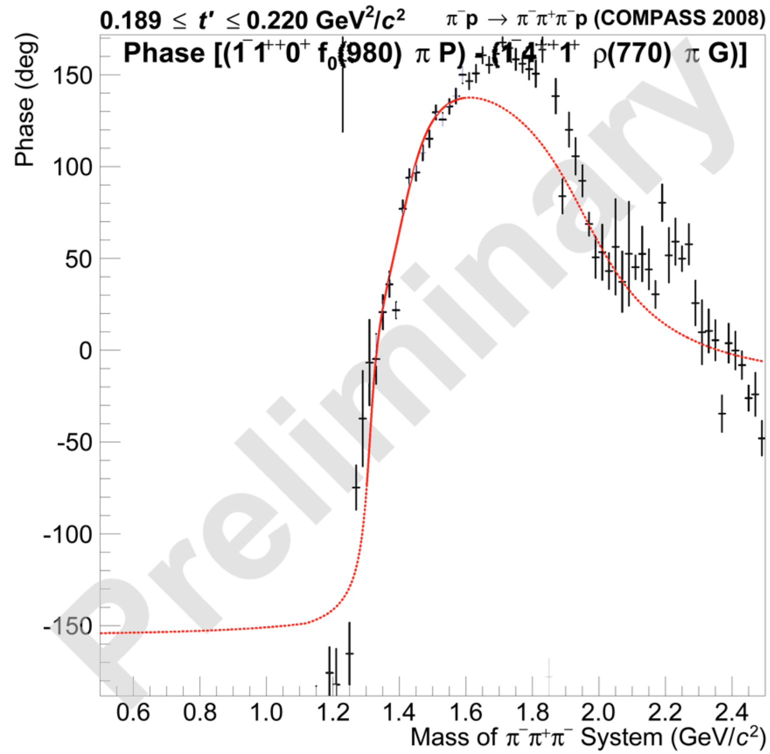
- charged mode data scaled for each plot (integral) to compare shapes
- (good) agreement between the two channels (for the 4^{++} wave)

A new axial vector resonance found?

$a_1(1420) \to f_0\pi$?

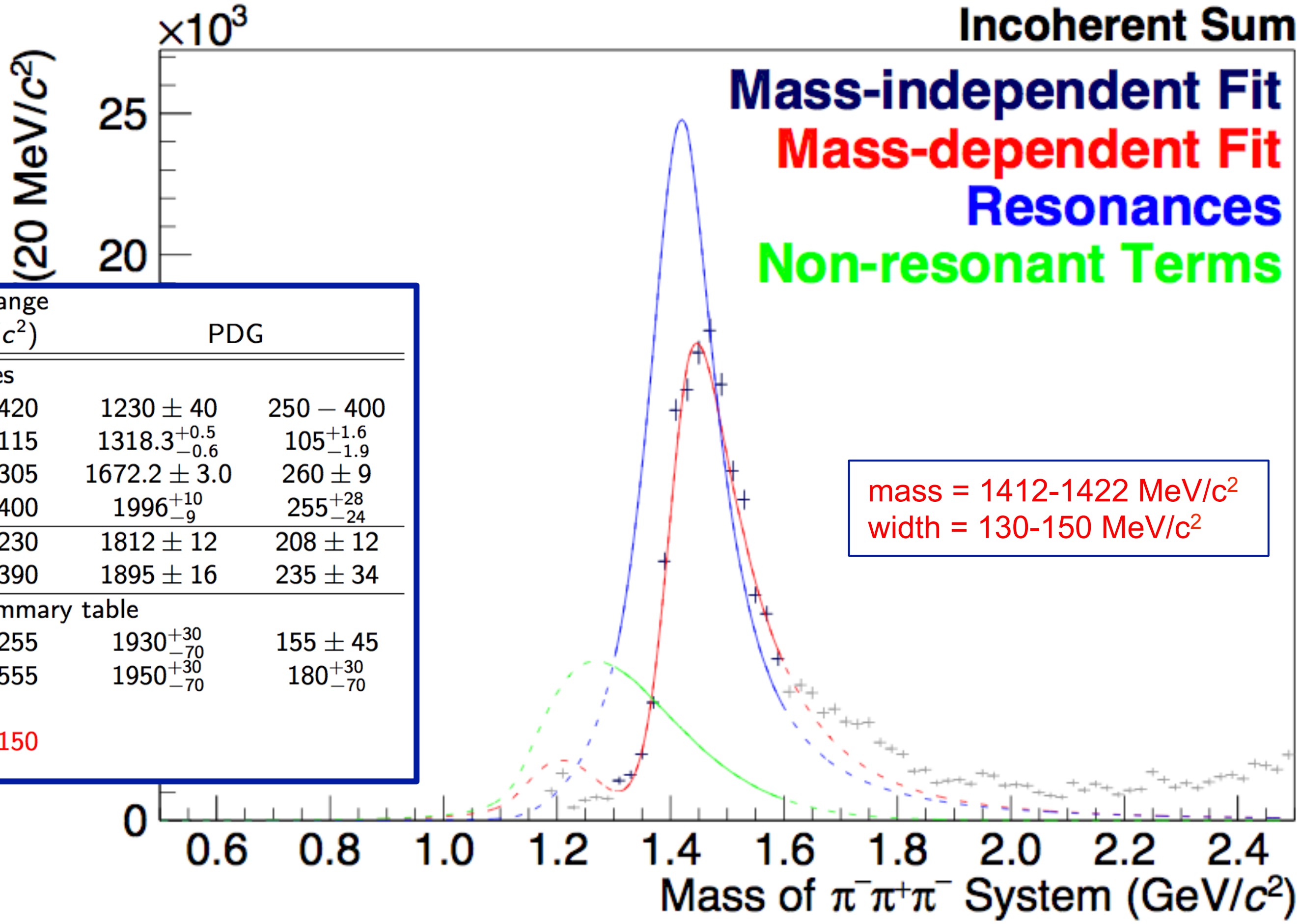


relative phase against $a_1(1260) \to \rho\pi$



- charged mode data scaled for each plot (integral) to compare shapes
- new axial vector state, coupling to $K\bar{K}$ (not seen in $\rho\pi$) → *isospin partner of $f_1(1420)$?*

A new axial vector resonance found?

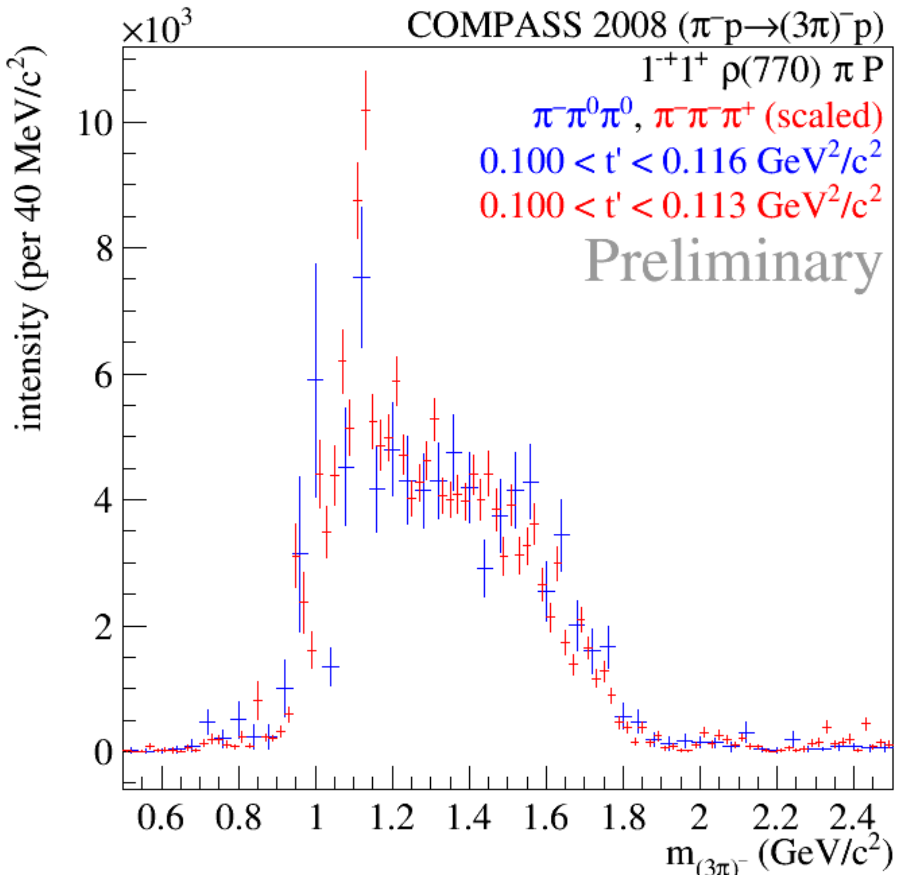


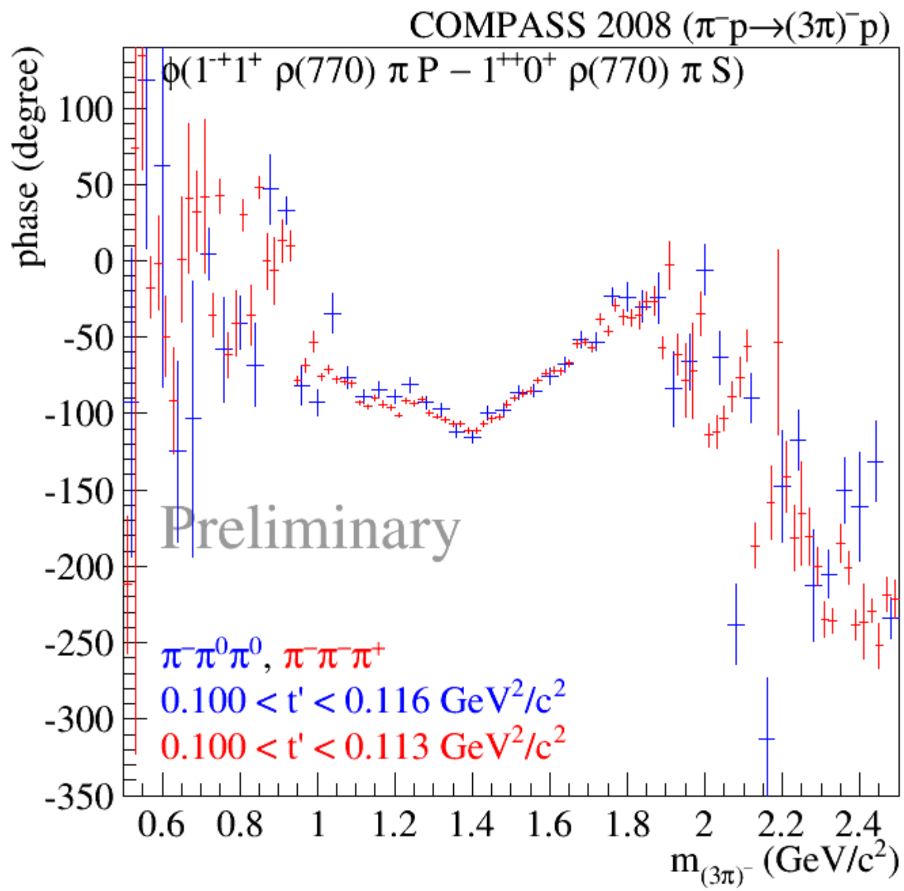
	J^{PC}	mass range (MeV/c^2)	width range (MeV/c^2)	PDG	
major waves					
a_1 (1260)	1^{++}	1260 – 1290	360 – 420	1230 ± 40	250 – 400
a_2 (1320)	2^{++}	1312 – 1315	108 – 115	$1318.3^{+0.5}_{-0.6}$	$105^{+1.6}_{-1.9}$
π_2 (1670)	2^{-+}	1635 – 1663	265 – 305	1672.2 ± 3.0	260 ± 9
a_4 (2040)	4^{++}	1928 – 1959	360 – 400	1996^{+10}_{-9}	255^{+28}_{-24}
π (1800)	0^{-+}	1790 – 1807	212 – 230	1812 ± 12	208 ± 12
π_2 (1880)	2^{-+}	1900 – 1990	210 – 390	1895 ± 16	235 ± 34
states not in PDG summary table					
a_1 (1930)	1^{++}	1920 – 2000	155 – 255	1930^{+30}_{-70}	155 ± 45
a_2 (1950)	2^{++}	1740 – 1890	300 – 555	1950^{+30}_{-70}	180^{+30}_{-70}
a_1 (1420)	1^{++}	1412 – 1422	130 – 150		

[S.Paul, MENU 2013]

- charged mode data scaled for each plot (integral) to compare shapes
- new axial vector state, coupling to KK (not seen in ρπ) → *isospin partner of f_1(1420)?*

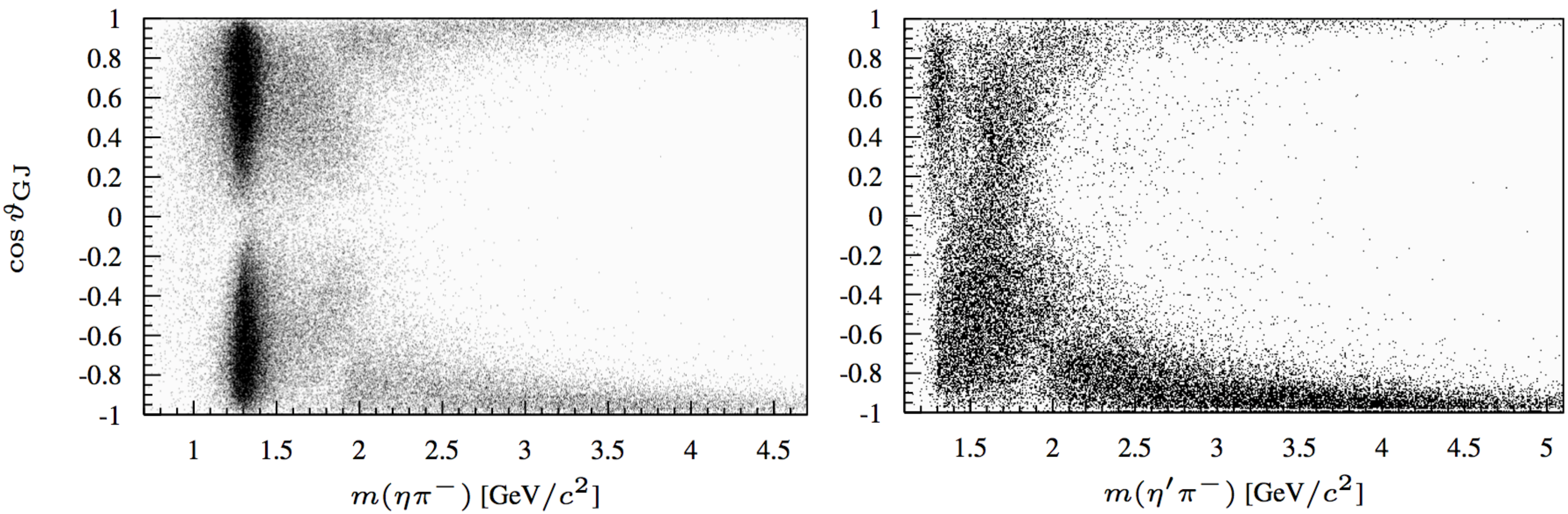
Spin exotic 1^{-+} wave





- charged mode data scaled for each plot (integral) to compare shapes
- good agreement between the two channels, differences depending on t'
- Deck contribution amplitude to be included → *describe large background*

Different channel for the search:
$\pi^- + p \rightarrow \pi^-\eta' / \pi^-\eta + p$

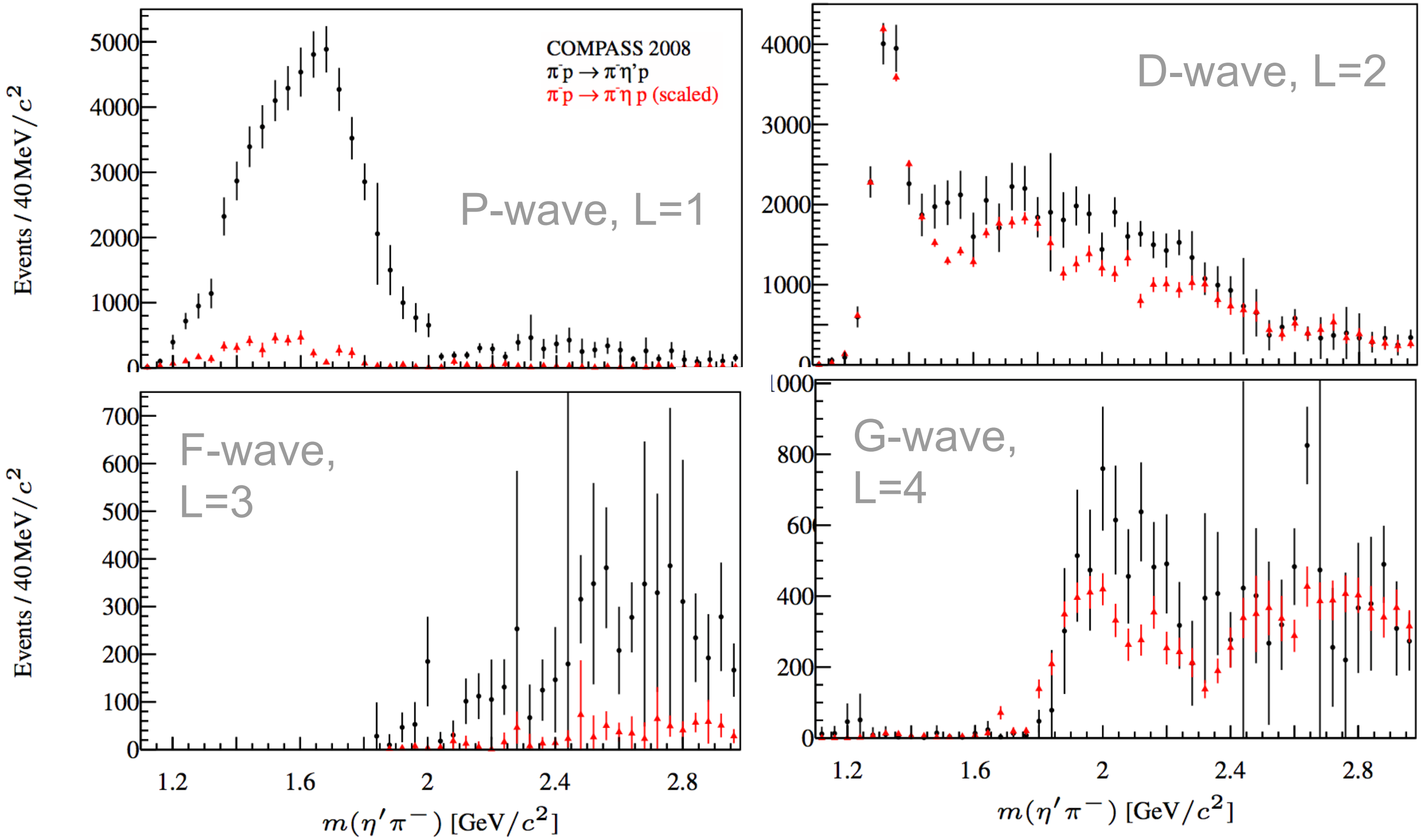


→ Both channels similar, different interference effects

[hep-ex/1408.4286, submitted to PLB]

Different channel for the search:
$\pi^- + p \rightarrow \pi^-\eta' / \pi^-\eta + p$

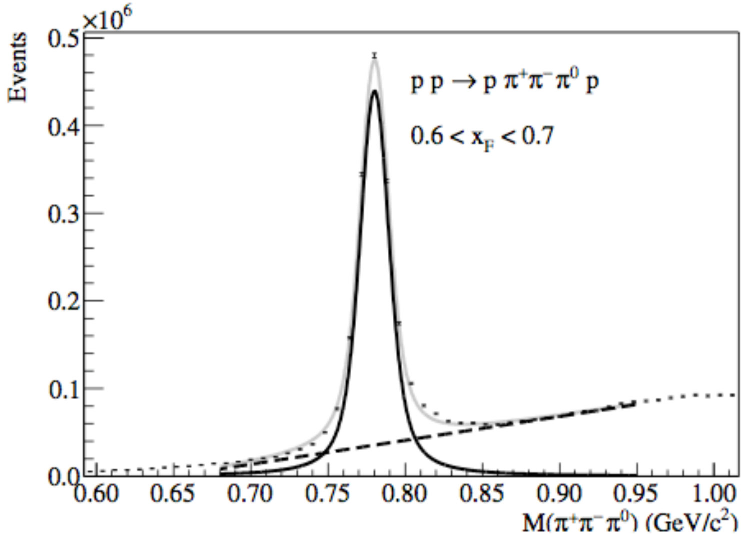
corrected for phase-space:

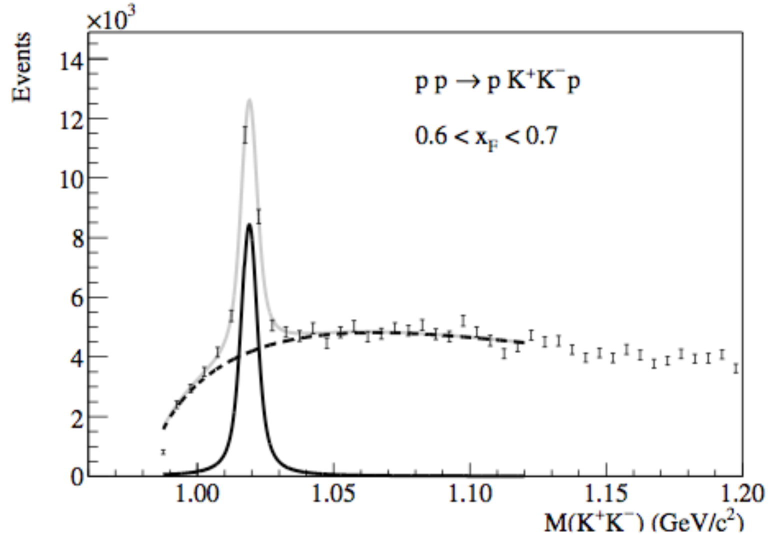


→ Even-L partial-waves: similar intensity distributions in η and η'
→ Odd-L partial-waves, in particular the P wave, are suppressed in ηπ by factor 5-10

[hep-ex/1408.4286, submitted to PLB]

Measurement of OZI violation



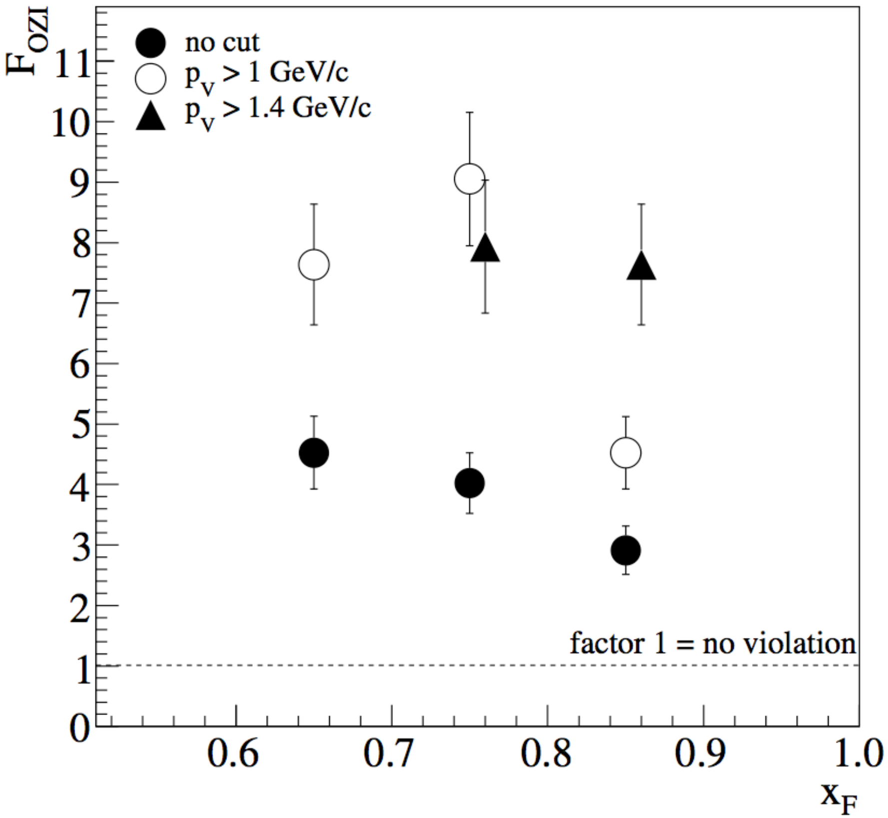


- clear ω and ϕ peaks on top of background
- fit of acceptance corrected mass spectra in bins of x_F
- fit signal and background → *ratio of cross-sections*

$$R_{\phi/\omega} = \frac{d\sigma(pp \to p\phi p)/dx_{\mathrm{F}}}{d\sigma(pp \to p\omega p)/dx_{\mathrm{F}}}$$

[NPB 886 (2014) 1078, hep-ex/1405.6376]

Measurement of OZI violation



$$F_{\rm OZI} = R_{\phi/\omega} / \tan^2 \delta_{\rm V}$$

OZI rule prediction: $\tan^2 \delta_{\rm V} = 0.0042$

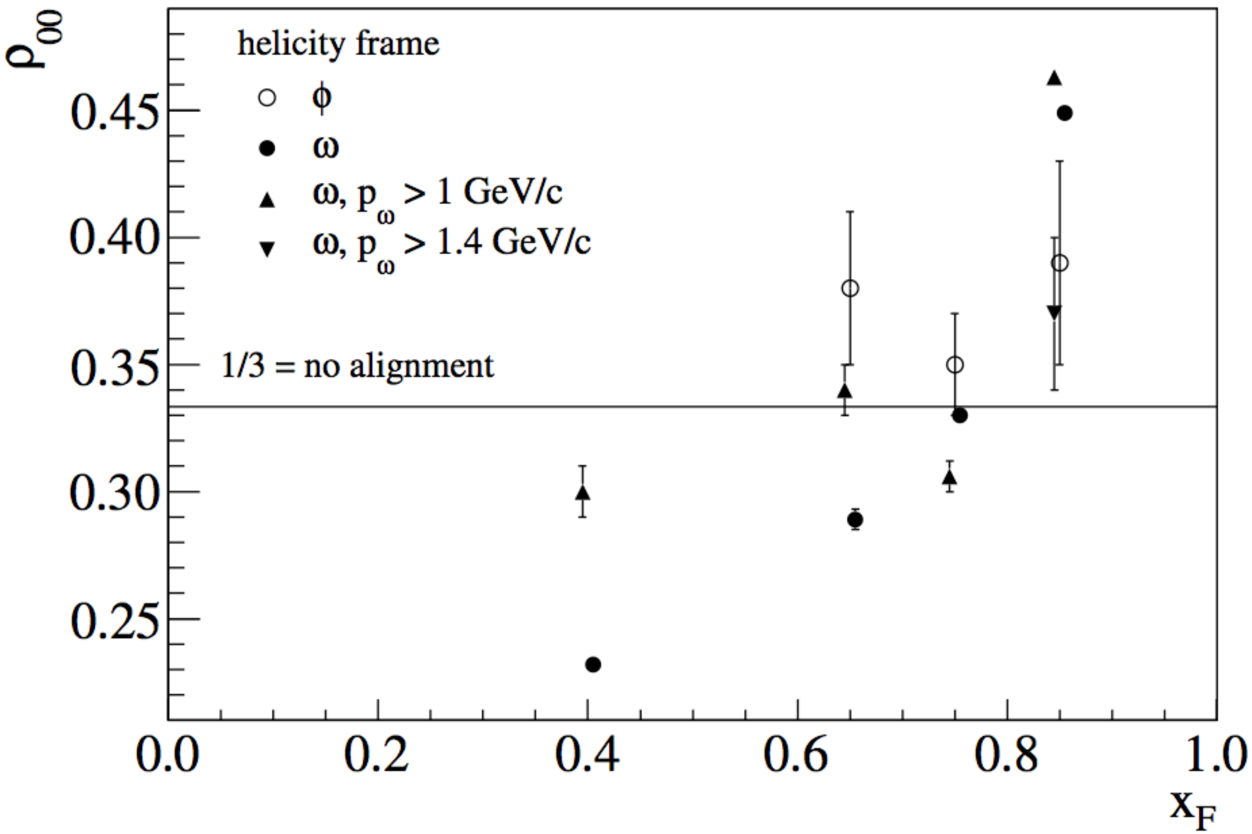
- OZI violation observed
  - factor 4, dependence on x_F
- Comparison with other experiements
  - larger F_{OZI} expected
  - ω cross-section resonantly enhanced?
- Cut on vector meson momentum p_V for both channels to get rid of pω resonances *(present in low mass resonance region $M_{p\omega}$)*

=> OZI violation of factor 8 & independent of x_F

Violation value F_{OZI}=8 in agreement with results by SPHINX collaboration

[NPB 886 (2014) 1078, hep-ex/1405.6376]

Measurement of OZI violation

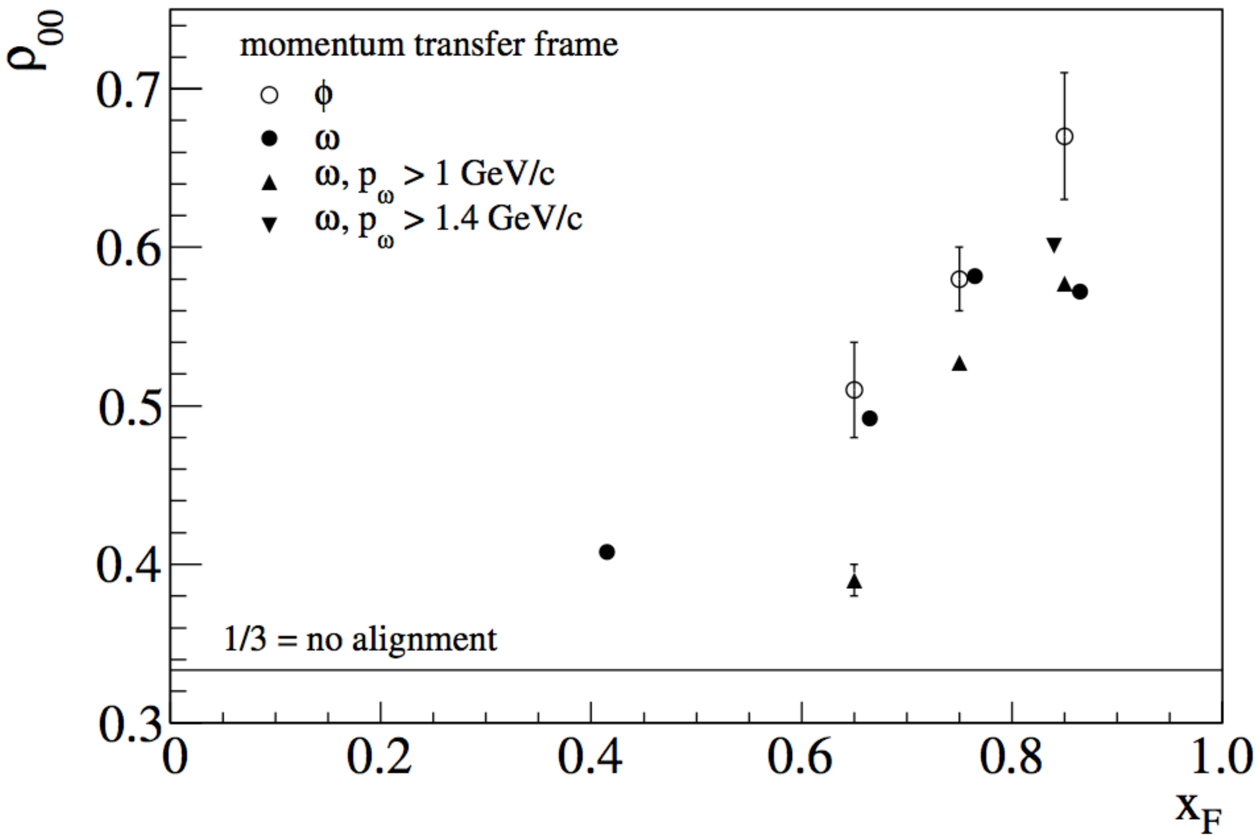


- observed x_F dependence
  - production mechanism?
  - study spin alignment
- choose helicity frame
  - diffractive resonant production
- after cuts ω & ϕ similarly (not) aligned
  - expected for no resonances produced

→ *Other reference frame?*

[NPB 886 (2014) 1078, hep-ex/1405.6376]

Measurement of OZI violation



- momentum transferframe
  - central production
- alignment observed for ω & ϕ
  - same order & x_F dependence
  - central production of both ω (at higher masses) & ϕ

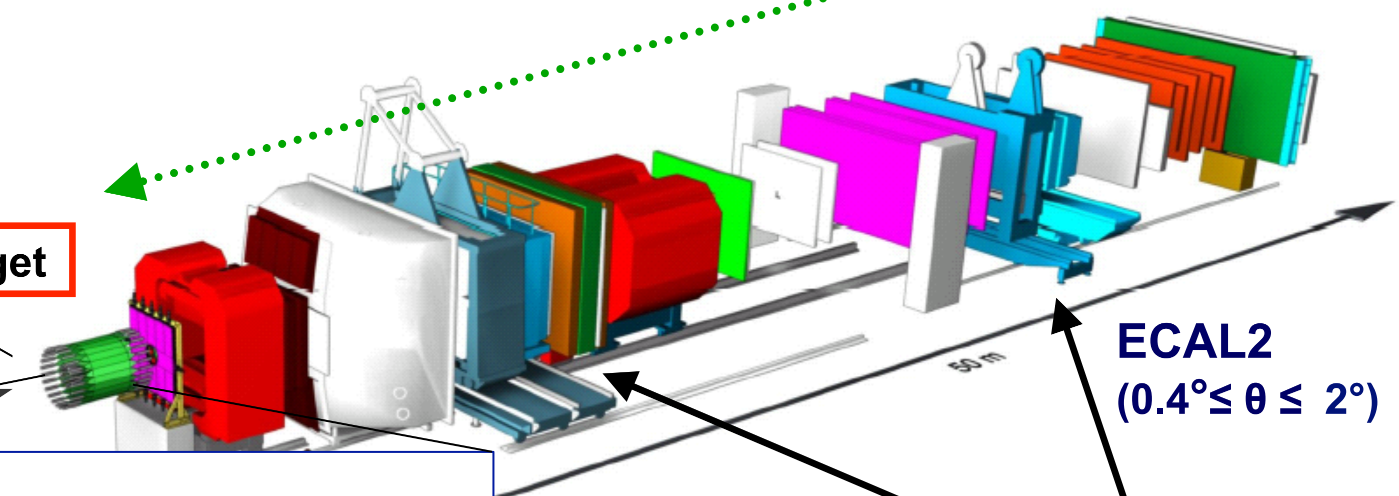
=> OZI violation should be studied in non-diffractive region, contributions from different production mechanisms, F_{OZI} = 8 observed for ω vs. ϕ production

[NPB 886 (2014) 1078, hep-ex/1405.6376]

Physics with muon beams
Large Q^2

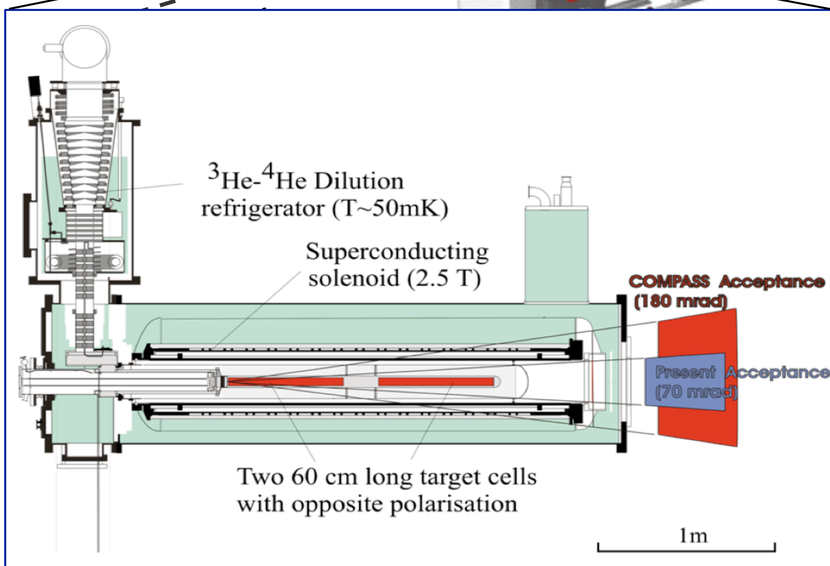
COMPASS spectrometer: Muon setup

COMPASS trackers (upgraded close to beam):
SciFi, Si, MM, GEM, DC, Straw, MWPC



polarised target

muon beam



ECAL2
(0.4°≤ θ ≤ 2°)

ECAL1
(2°≤ θ ≤ 12°)

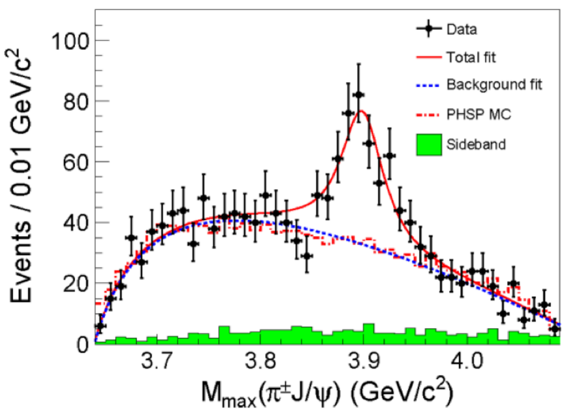
Electromagnetic calorimeters

(final states involving neutrals, e.g. $\pi^0, \eta,$ or η')

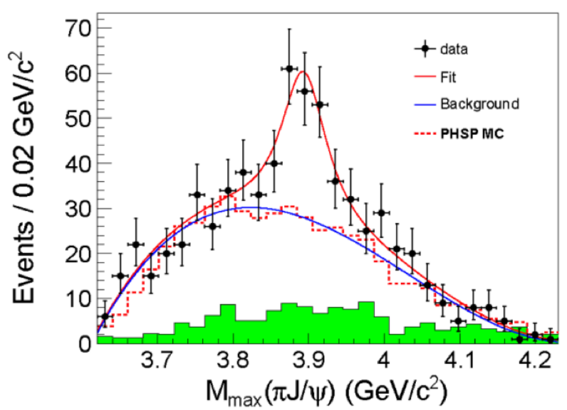
Search for charmonium-like (exotic) state $Z_c(3900)$

Highlight in 2013:

- Discovery of charged $c\bar{c}$ state
- $e^+e^- \rightarrow \pi^+\pi^- J/\psi$ ($\sqrt{s} = 4.26$ GeV), decay: $Z_c(3900) \rightarrow J/\psi\, \pi^\pm$



BESIII, arXiv:1303.5949

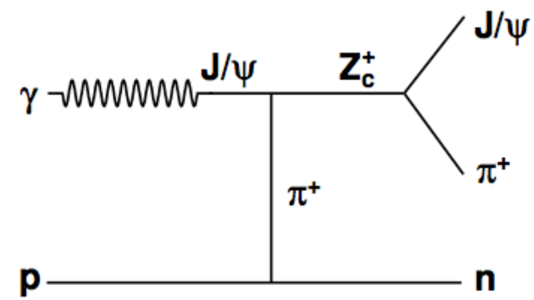


Belle, arXiv:1304.0121

COMPASS:

- Photon may behave like a J/ψ (VMD model)

  → $Z_c(3900)$ production via interaction of incoming photon with virtual charged pion (target nucleon)



→ sizable cross-section

[14] Q.-Y. Lin et al., Phys. Rev. D 88, 114009 (2013),

- Exclusive production channel:

exclusively produced

$$\mu^+ N \rightarrow \mu^+ Z_c^\pm(3900)\, N \rightarrow \mu^+ J/\psi \pi^\pm N \rightarrow \mu^+\mu^+\mu^-\pi^\pm N$$

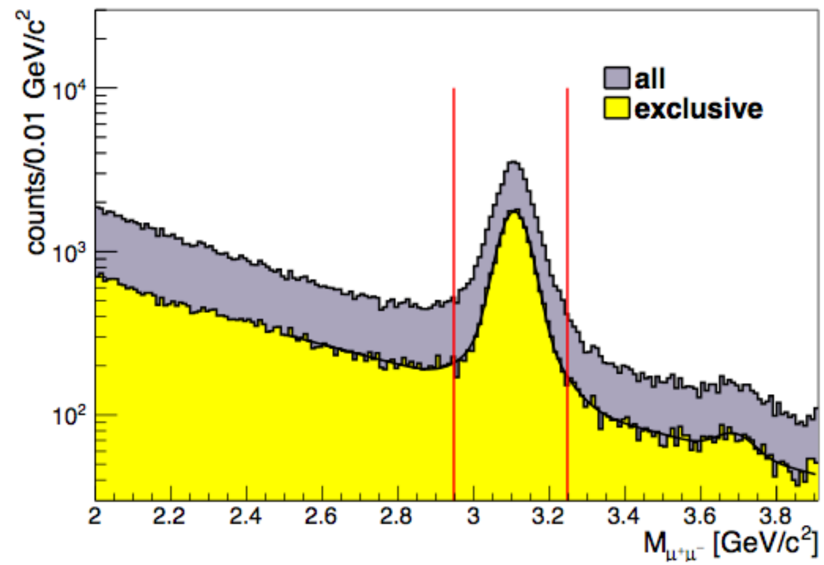
[hep-ex/1407.6186, submitted to PLB]

Search for charmonium-like (exotic) state $Z_c(3900)$

Selection of exclusive $\mu^+ J/\psi\, \pi^\pm$ sample

- vertex, exactly 3 outgoing muons, 1 pion
- mass cut on $J/\psi(\rightarrow \mu^+\mu^-)$
- energy balance
- momentum cut for $\pi^\pm$ (>2GeV/c)

  → *reduce bkgrd of pomeron exchange*

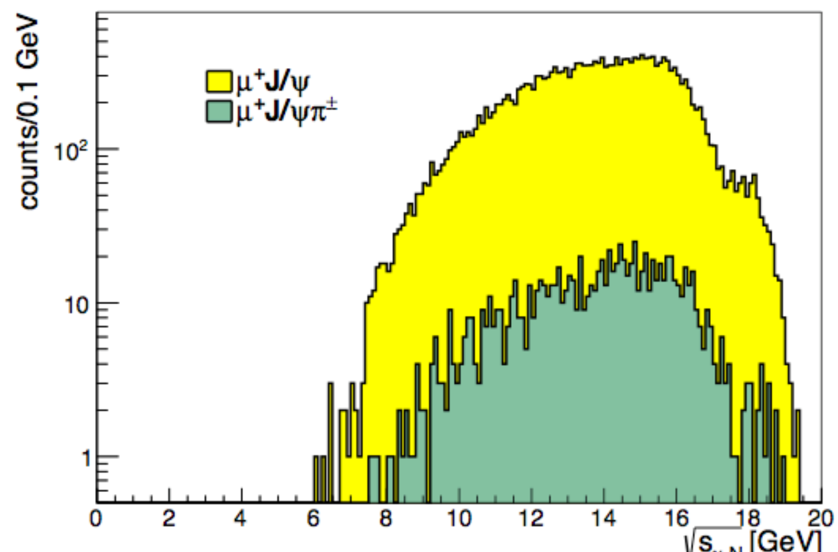


Selection of exclusive $\mu^+ J/\psi$ sample

- $\mu^+ N \rightarrow \mu^+ J/\psi\, N$ *(incoherent excl. prod.)*
- used for absolute normalisation

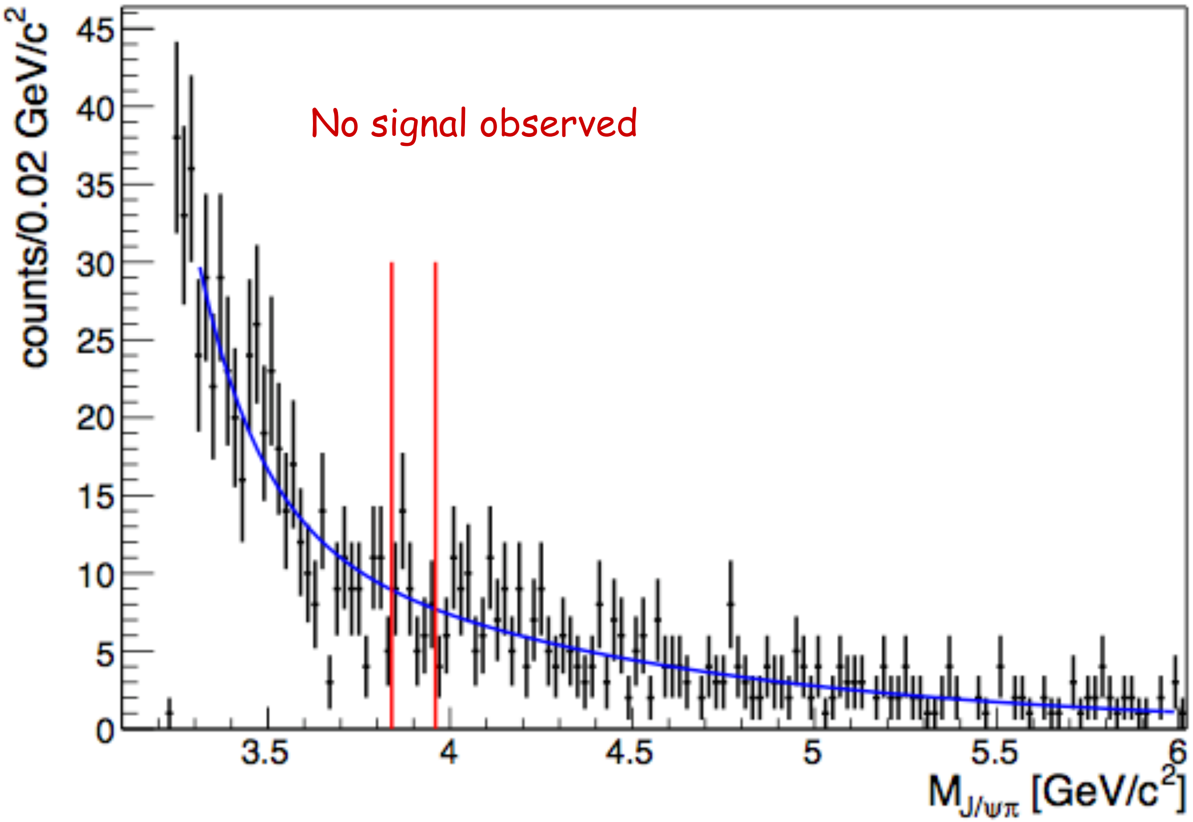
  (cross-section $\sigma_{\gamma N \rightarrow J/\psi N}$ from NA14)
- same selection criteria

→ *Ratio of acceptances for both samples equals about the acceptance for the additional pion (~0.5)*



[hep-ex/1407.6186, submitted to PLB]

Search for charmonium-like (exotic) state $Z_c(3900)$



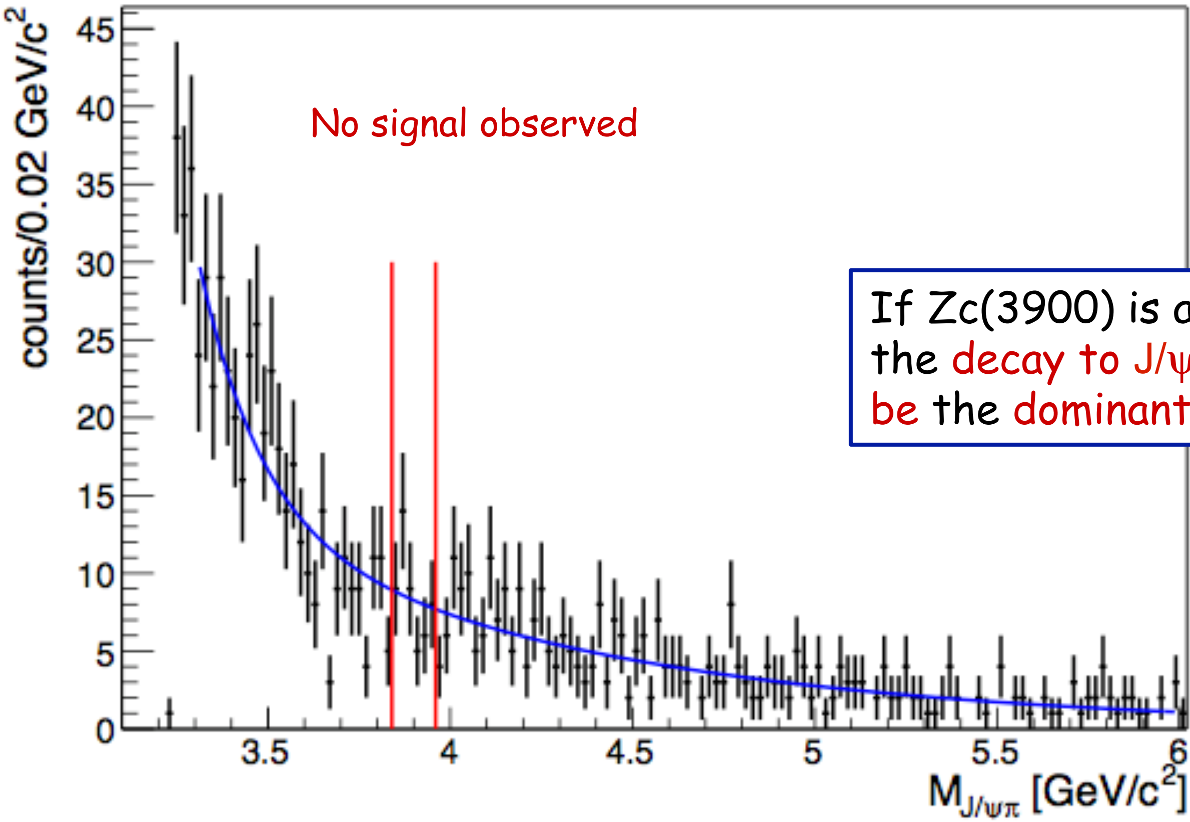
$$\left.\frac{BR(Z_c^{\pm}(3900) \to J/\psi\pi^{\pm}) \times \sigma_{\gamma\ N \to Z_c^{\pm}(3900)\ N}}{\sigma_{\gamma\ N \to J/\psi\ N}}\right|_{\langle\sqrt{s_{\gamma N}}\rangle = 13.8\ \text{GeV}} < 3.7 \times 10^{-3}$$

NA14

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

[hep-ex/1407.6186, submitted to PLB]

Search for charmonium-like (exotic) state $Z_c(3900)$



If Zc(3900) is a resonance, the decay to $J/\psi\,\pi^\pm$ cannot be the dominant one ...

$$\frac{BR(Z_c^\pm(3900) \to J/\psi\pi^\pm) \times \sigma_{\gamma\, N \to Z_c^\pm(3900)\, N}}{\sigma_{\gamma\, N \to J/\psi\, N}}\Bigg|_{\langle\sqrt{s_{\gamma N}}\rangle = 13.8\text{ GeV}} < 3.7 \times 10^{-3}$$

NA14

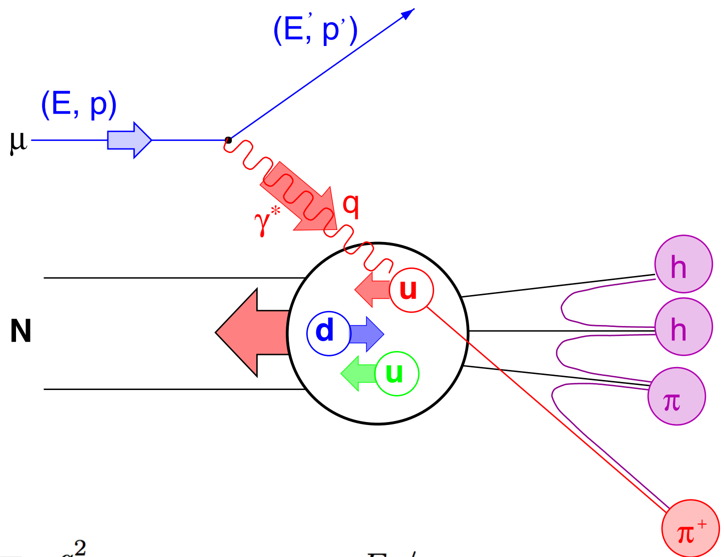
$$BR(Z_c^\pm(3900) \to J/\psi\pi^\pm) \times \underbrace{\sigma_{\gamma\, N \to Z_c^\pm(3900)\, N}}\Big|_{\langle\sqrt{s_{\gamma N}}\rangle = 13.8\text{ GeV}} < 52\text{ pb}$$

sizeable [14]

[hep-ex/1407.6186, submitted to PLB]

The Nucleon in the Quark Parton Model

(Semi-Inclusive) Deep Inelastic Scattering:



$Q^2 = -q^2$

$\nu = E - E'$

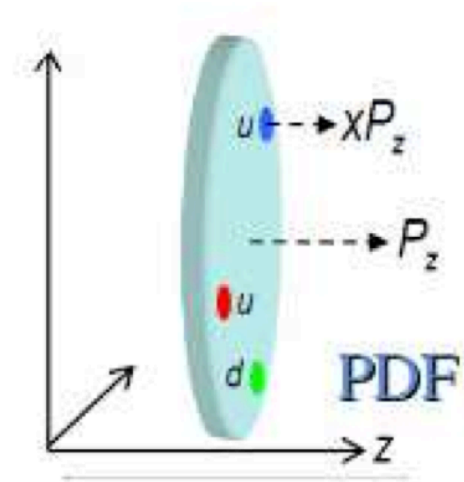
$x = Q^2/2M\nu$

$z = E_h/\nu$

p_T^h : transverse momentum

$q(x) = q(x)^+ + q(x)^-$ + quark ↑↑ nucleon

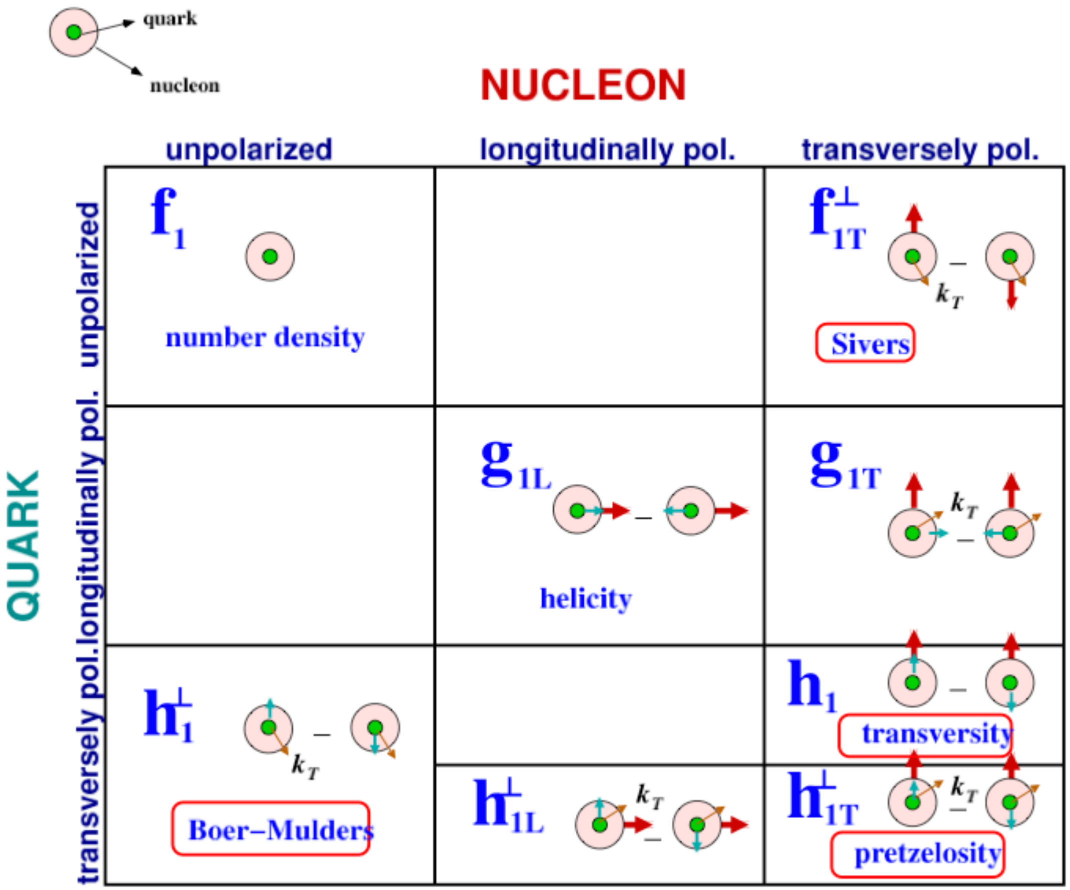
$\Delta q(x) = q(x)^+ - q(x)^-$ − quark ↓↑ nucleon



Parton Distribution Functions in DIS

- due to the longitudinal momentum (in z direction), the nucleon is Lorentz-boosted
- the intrinsic transverse quark momentum k_T is neglected in this 1-D picture

Nucleon spin structure

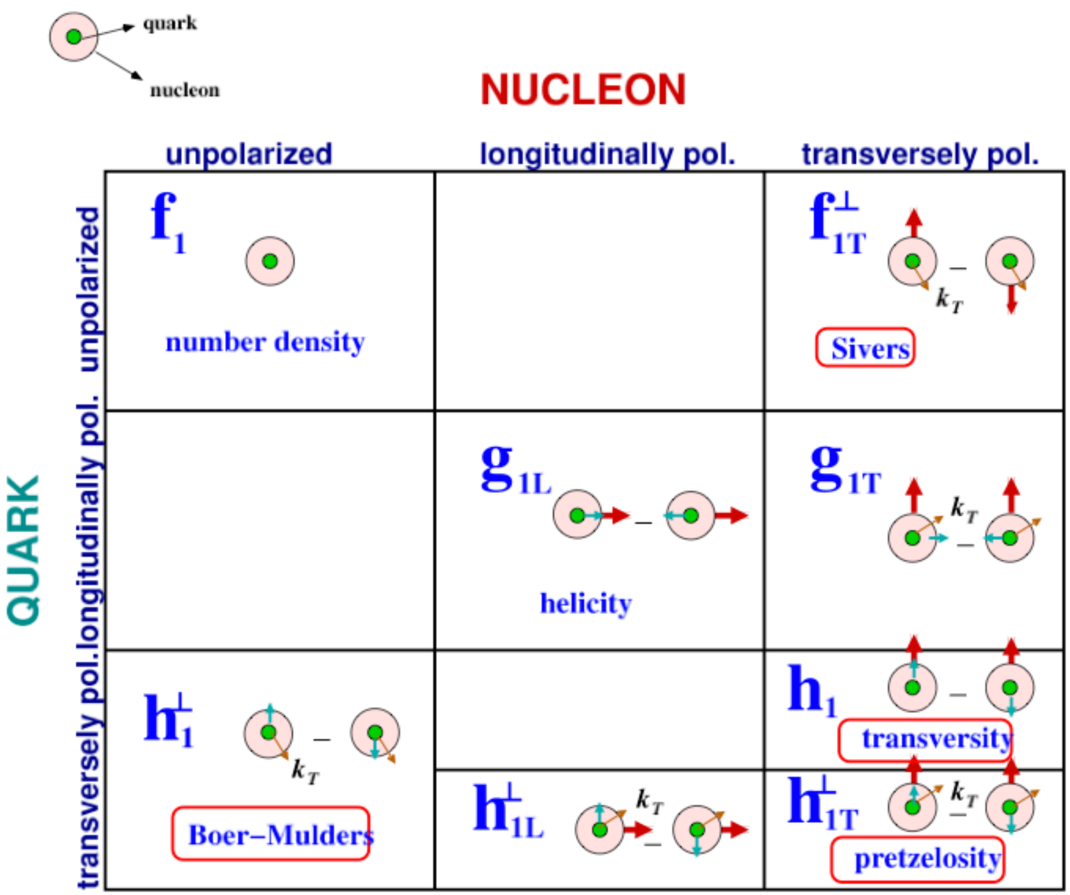


Structure functions:

- incl. e/mu scattering experiments
  - ➢ quark parton model, quarks
- More detailed understanding
  - ➢ spin degrees of freedom
  - ➢ intr. transverse momentum k_T
- 3 survive integration over k_T:
  → *f_1, g_1 and h_1*

→ *Study structure of nucleon*

Nucleon spin structure



Spin-dependent distribution g_1:

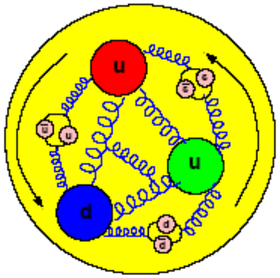
- parton (quarks & gluons) helicity distributions Δq(x)
- access to quark & gluon polarisation
- measured in Deep Inelastic Scattering

→ *How the nucleon spin ½ is built from quarks and gluons*

The spin of the nucleon

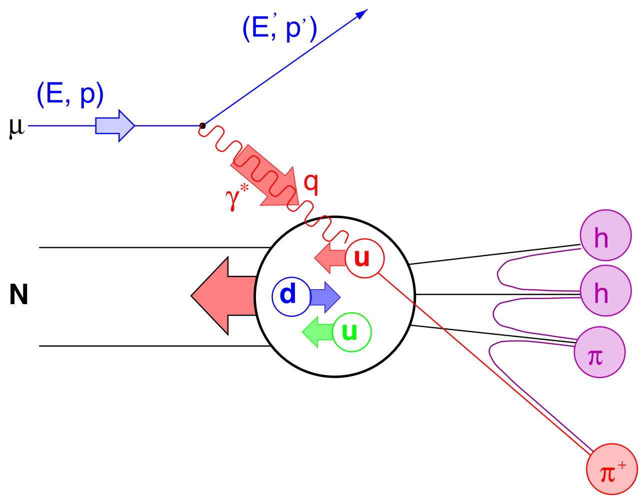
$$S_N = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$

accessible via

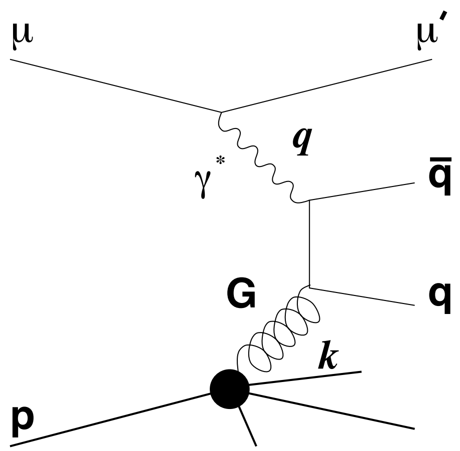


$\Delta\Sigma,\ \Delta s$	inclusive DIS
$\Delta u, \Delta d, \Delta s$	semi-inclusive DIS
ΔG	PGF in DIS
L_q	DVCS

(SI)DIS:



PGF in DIS:



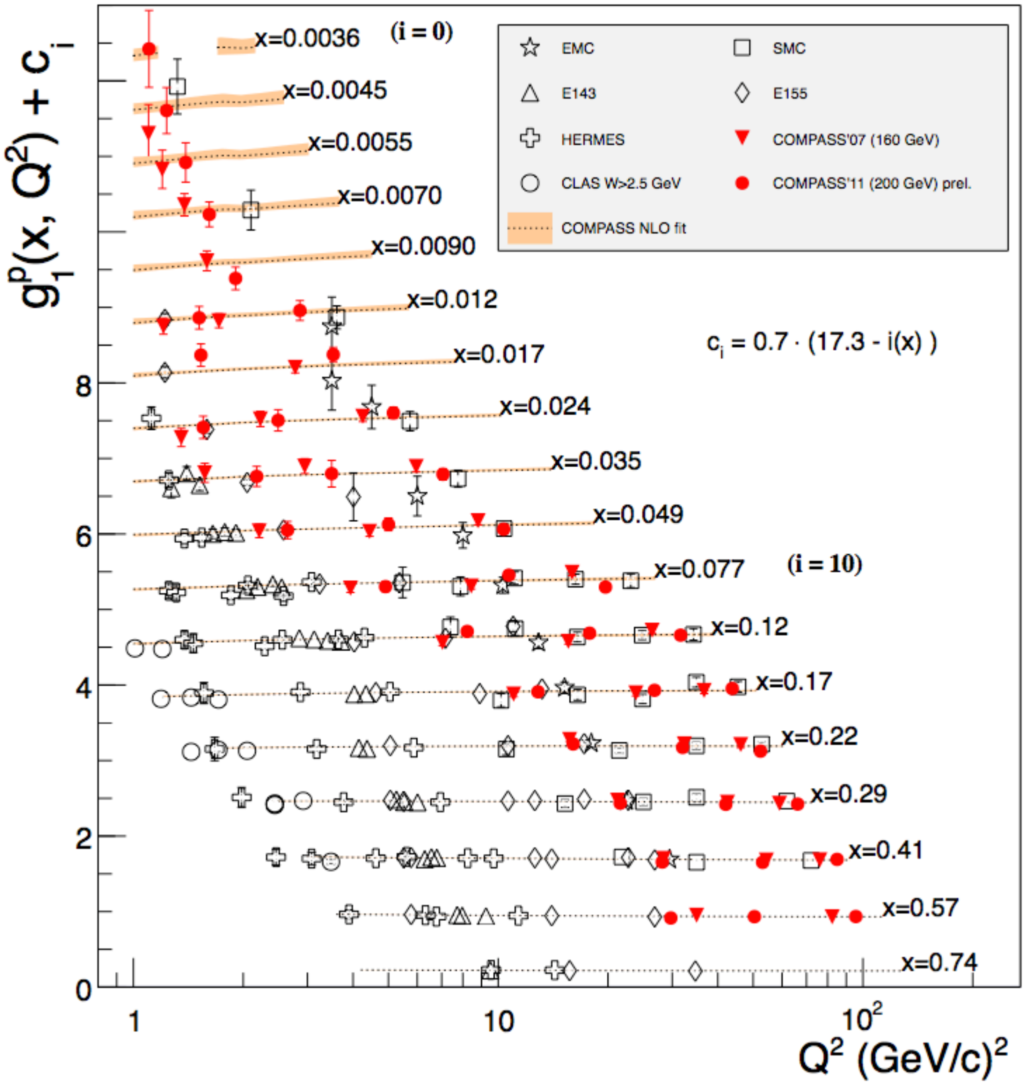
Nucelon structure – longitudinal polarisation

Longitudinal spin structure function:

$$g_1(x,Q^2) \stackrel{LO}{=} \frac{1}{2}\sum_q e_q^2 \Delta q(x,Q^2)$$

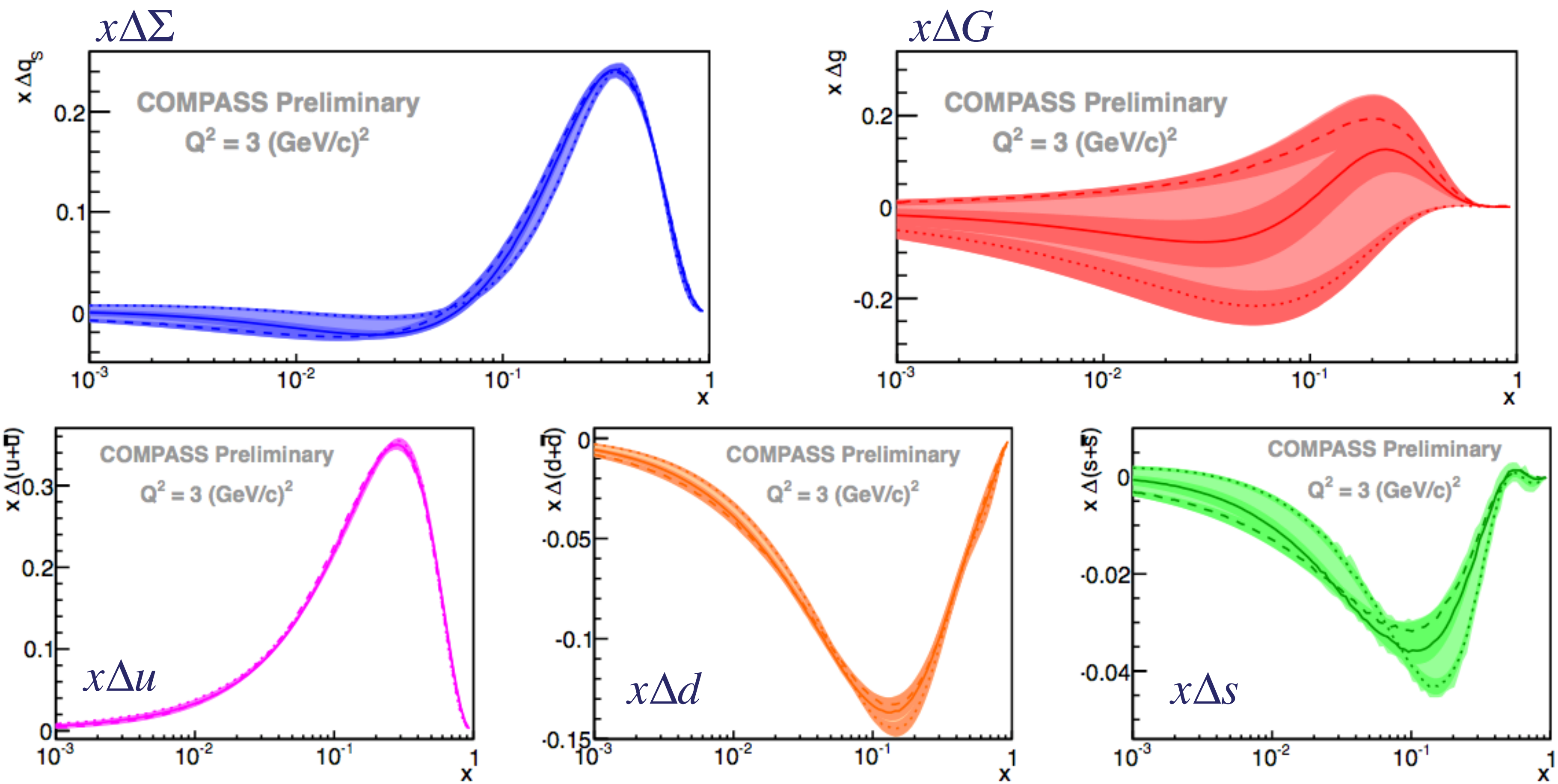
- COMPASS 2011 (200 GeV)
- COMPASS 2007 (160 GeV)
- COMPASS fit at NLO
- New data point at very low x
- New input for global QCD fit

→ *Indirect extraction of ΔG/G*



[M.Wilfert, DIS 2014]

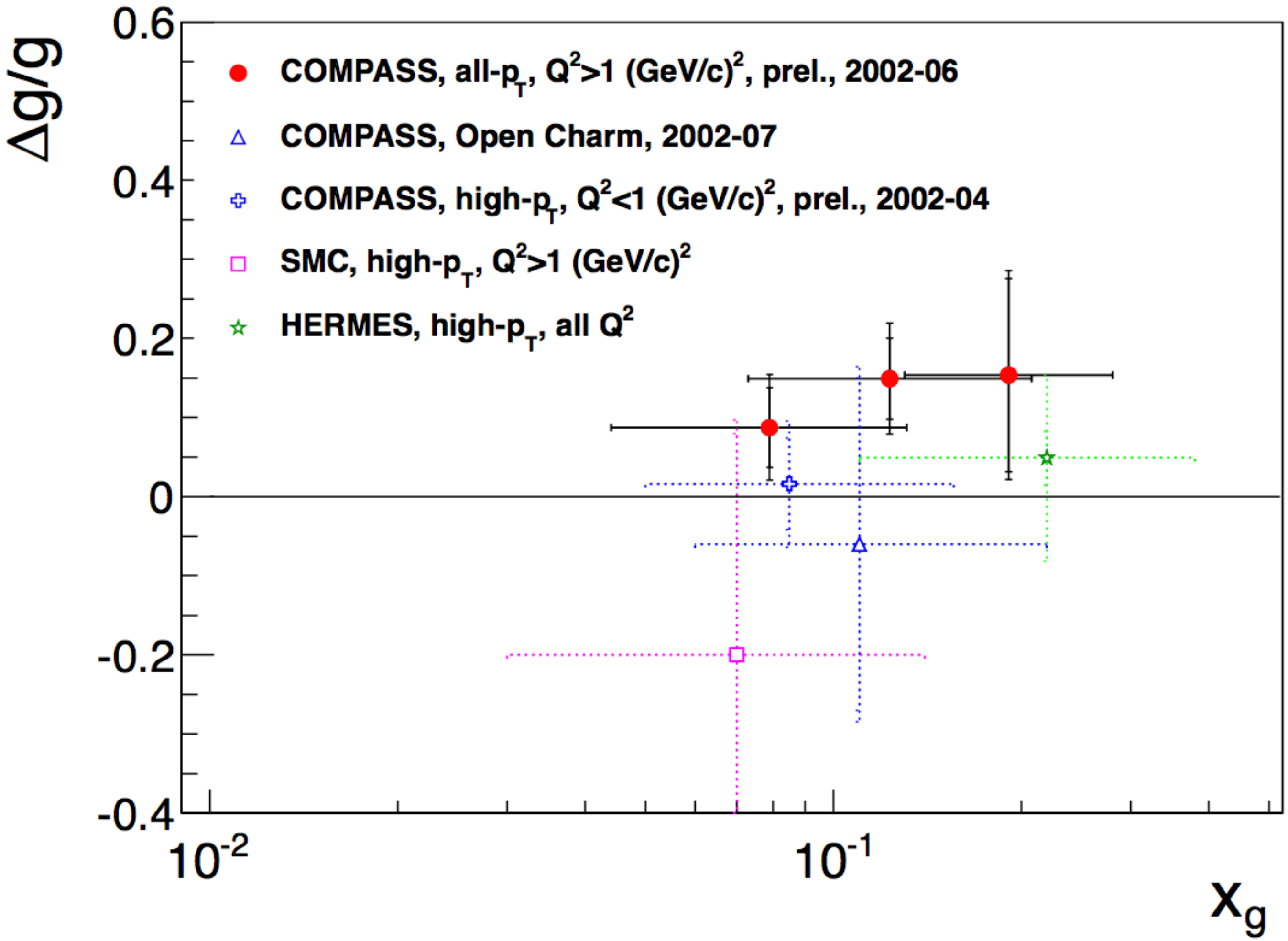
Polarised parton distributions



- Small sensitivity to light sea and gluon polarisation
- Quark polarisation $\Delta\Sigma = \int \Delta q_{Si}(x)\,dx \approx 0.3$
- Gluon polarisation $\Delta G = \int \Delta g(x)\,dx$ → not well constrained

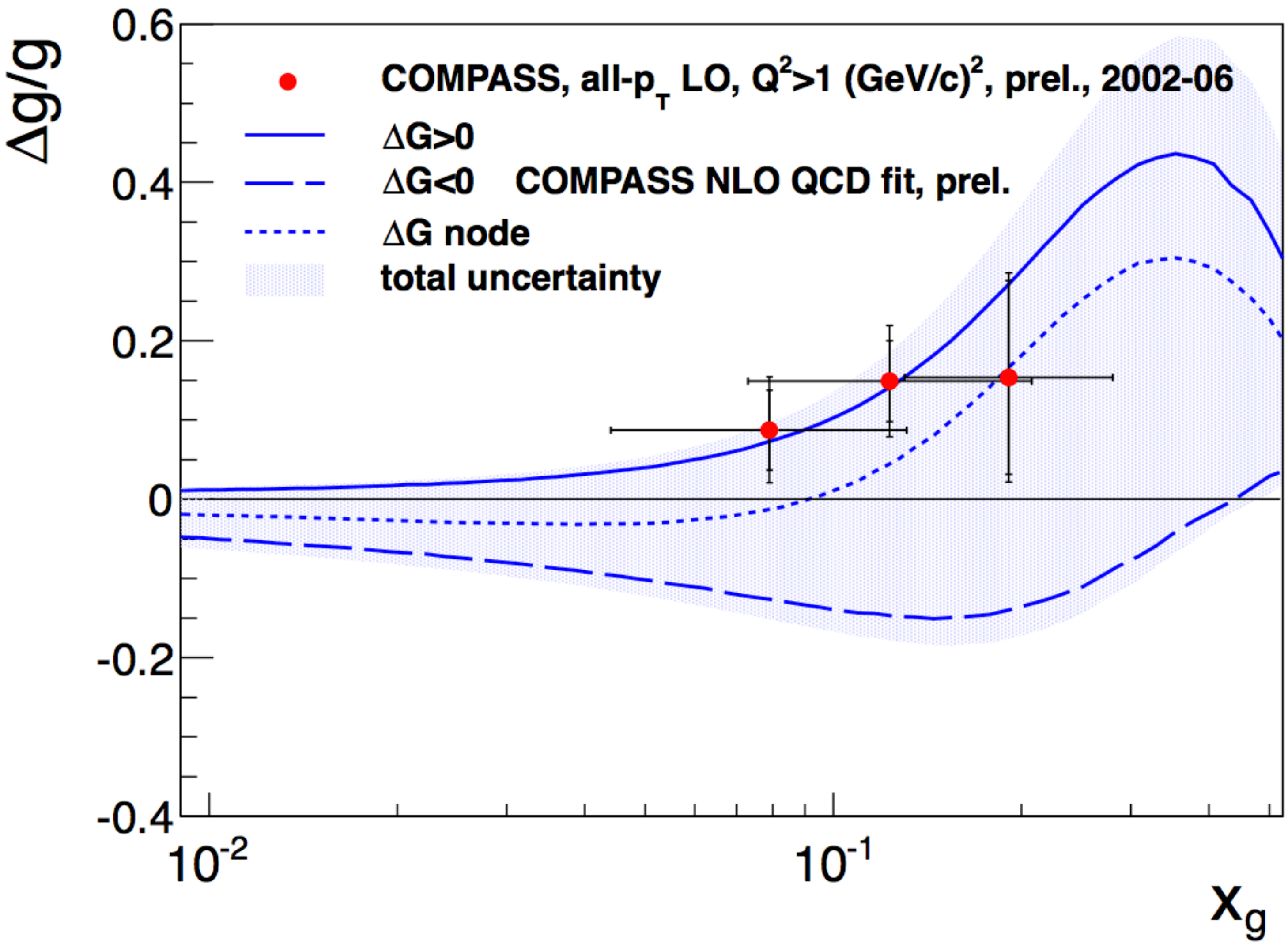
[M.Wilfert, DIS 2014]

The world ΔG/G data



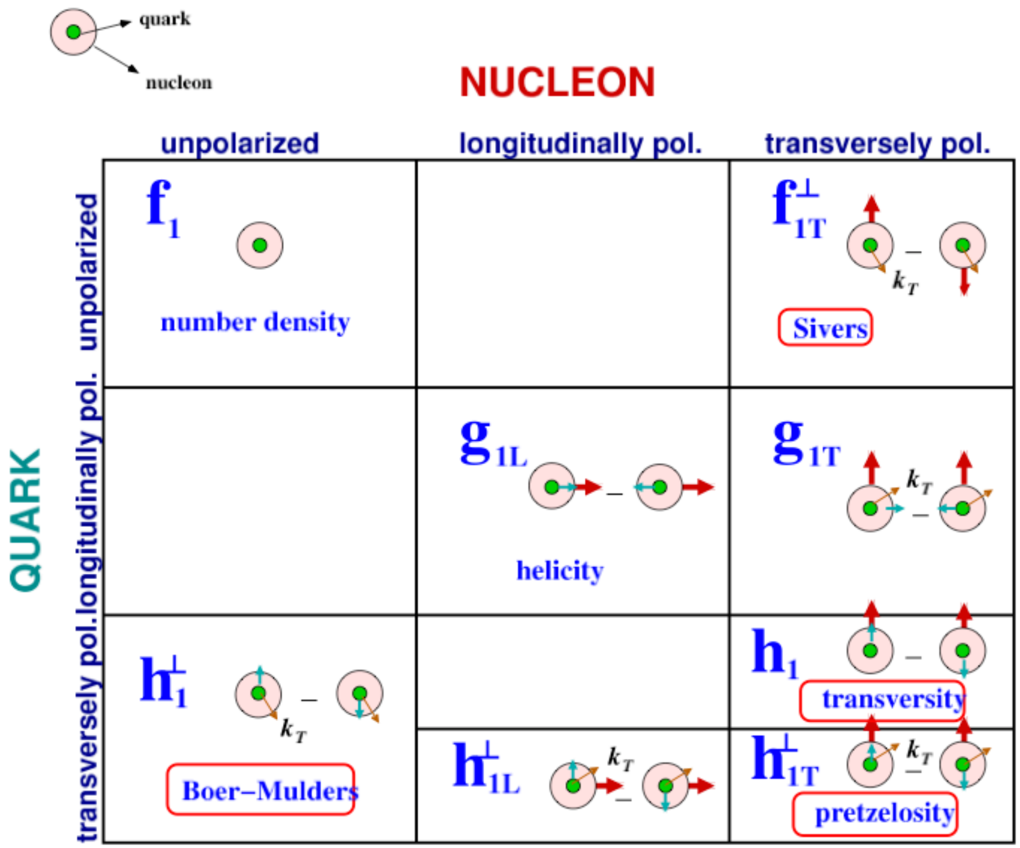
→ $\Delta g/g$ small and positive

Comparison of new results and NLO QCD fits



[M.Stolarski, DIS 2014]

Nucleon spin structure -- Transversity



How to access transversity:

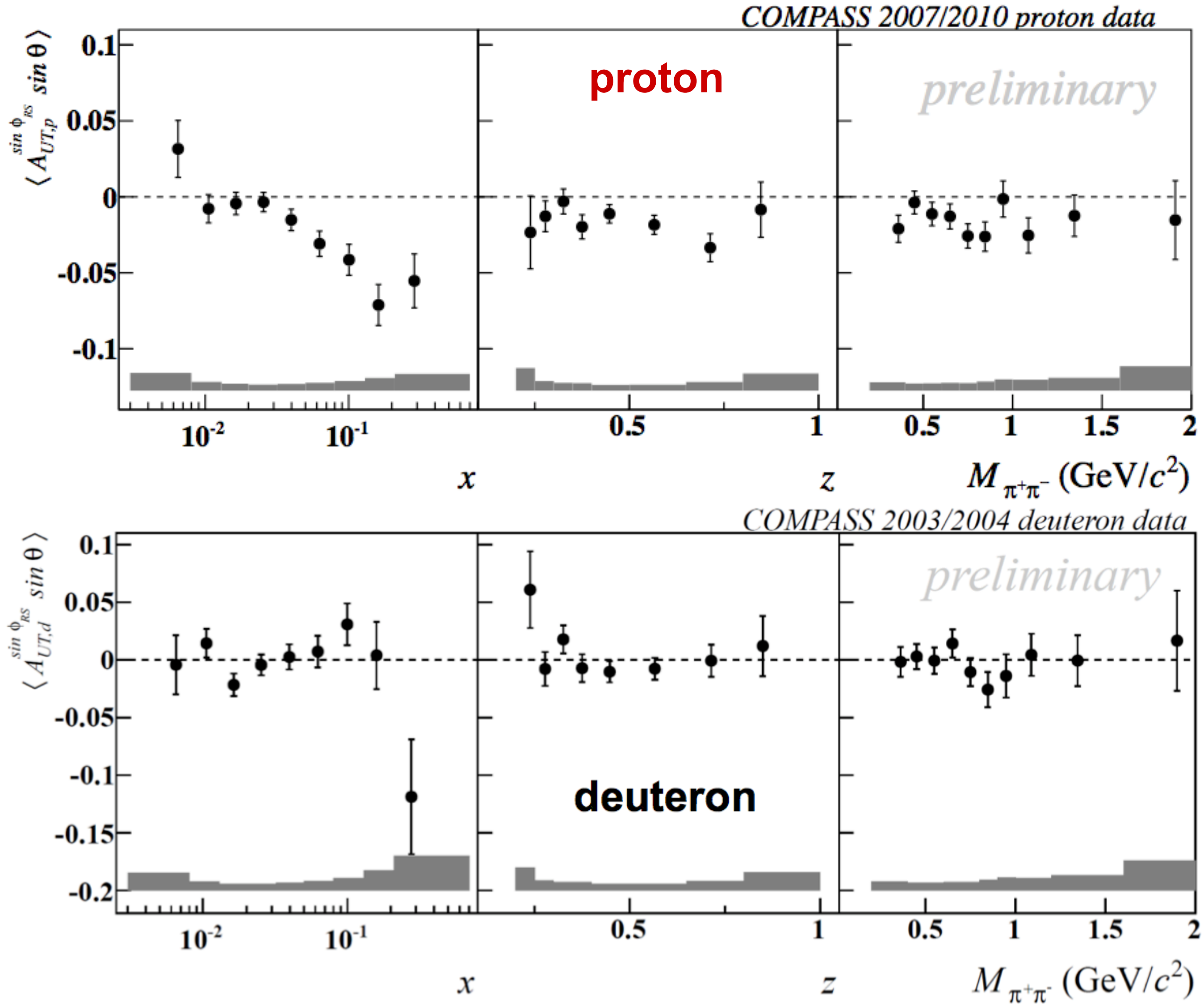
- not measurable in DIS as quark helicity must flip => SIDIS
- three methods:
  - azimuthal asymmetry of single hadrons
    → ~ **h_1 x Collins FF**
  - azimuthal asymmetry of hadron pairs
    → ~ **h_1 x H_1**
  - spin transfer of e.g. Λ hyperons
    → ~ **h_1 x D_Λ**
- Collins FF and H_1 measurable in e^+e^- collisions => *Belle*

Nucleon structure – transverse polarisation

SIDIS results:

di-hadron asymmetries for $\pi^+\pi^-$

→ *mainly valence quark effects*

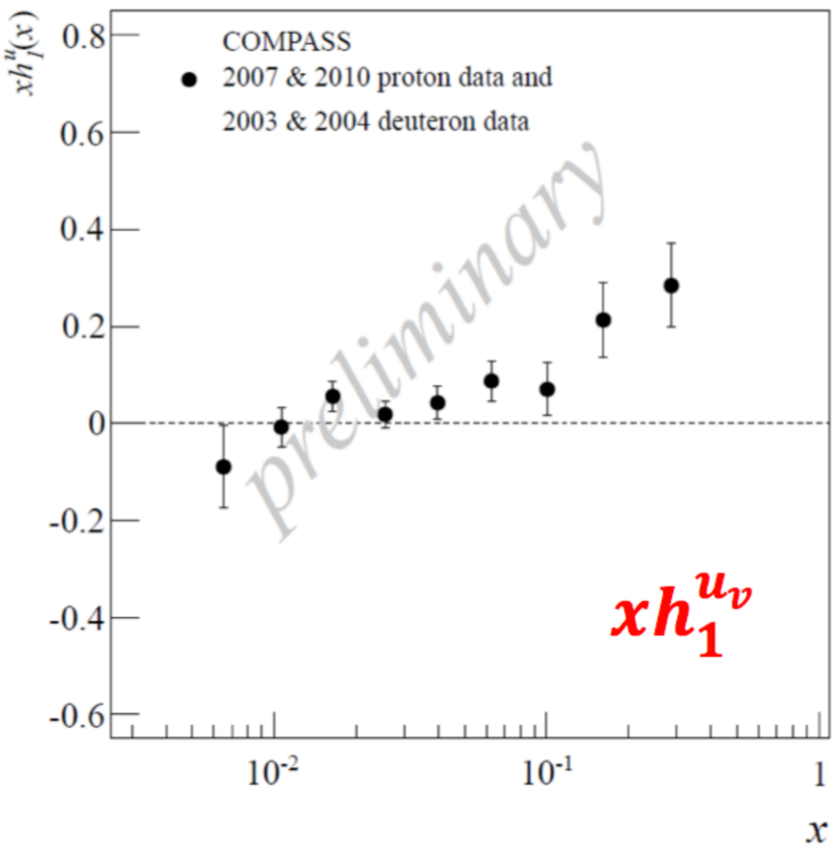


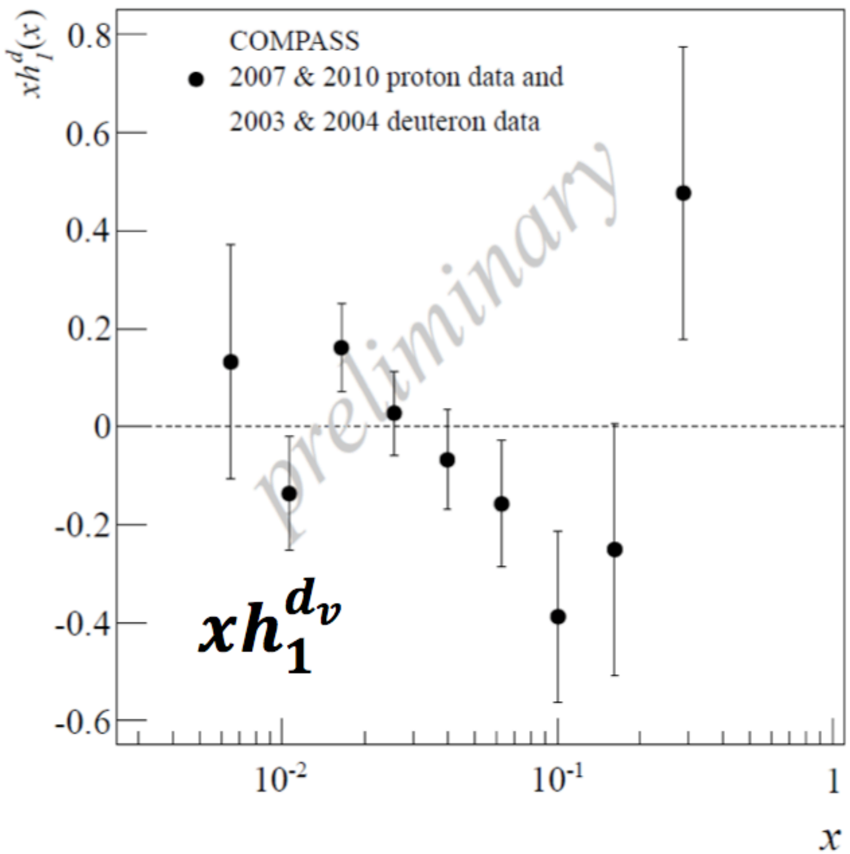
[C.Braun, DIS 2014]

Nucleon structure – transverse polarisation

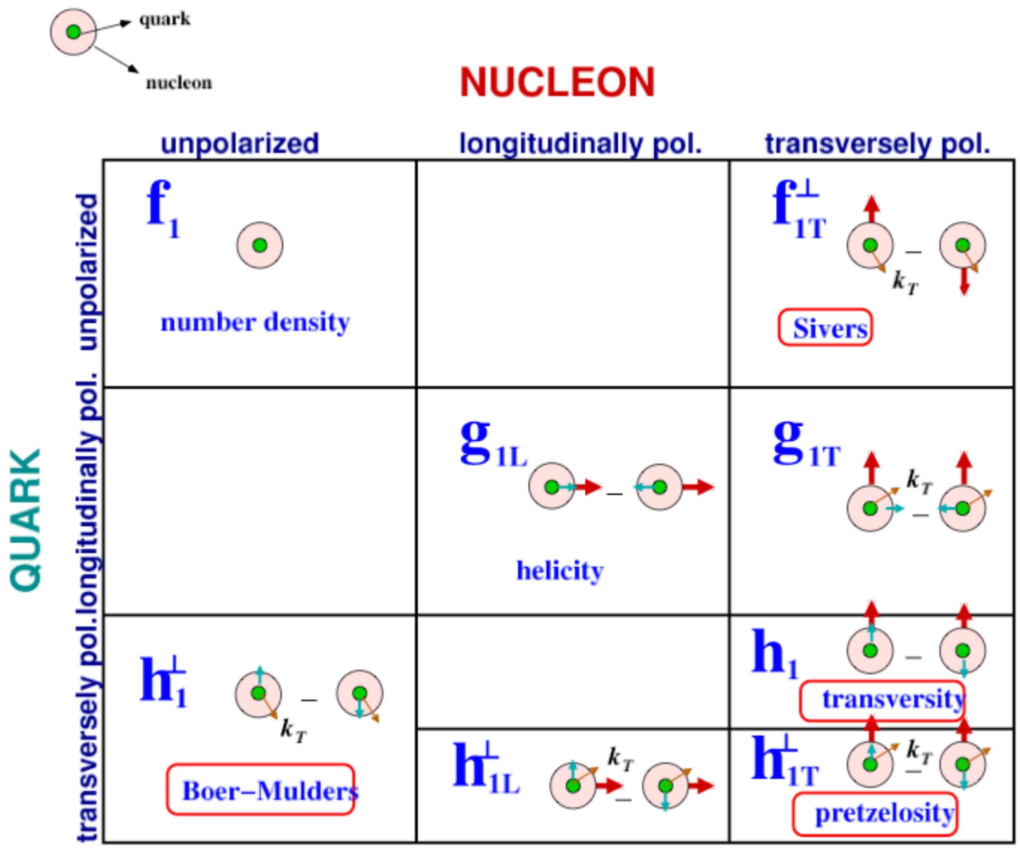
Transversity results, measured in each x bin from pion pair asymmetry on p and d
(assumption: sea quark contribution negligible)

Flavour separation





Transverse Momentum Distributions (TMDs)



Sivers function:

- correlation of quark k_T and nucleon transverse spin

Sivers and BM functions T-odd
→ *process dependent*

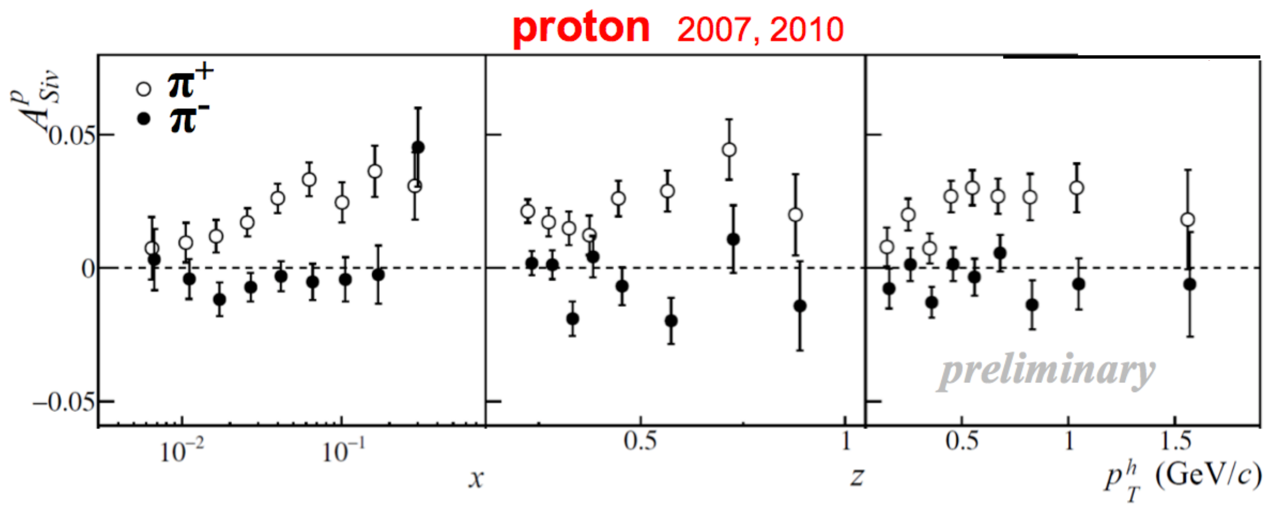
Boer-Mulders function:

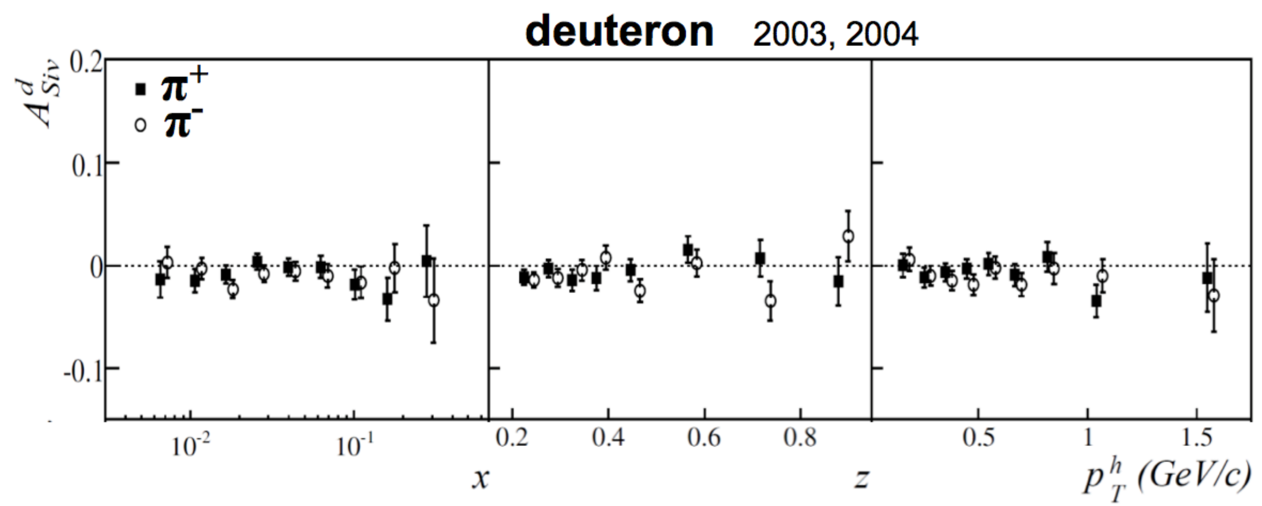
- correlation of quark k_T and transverse quark spin in unpolarised nucleon

Nucleon structure – transverse polarisation

SIDIS results on TMD observables,
some examples, here:

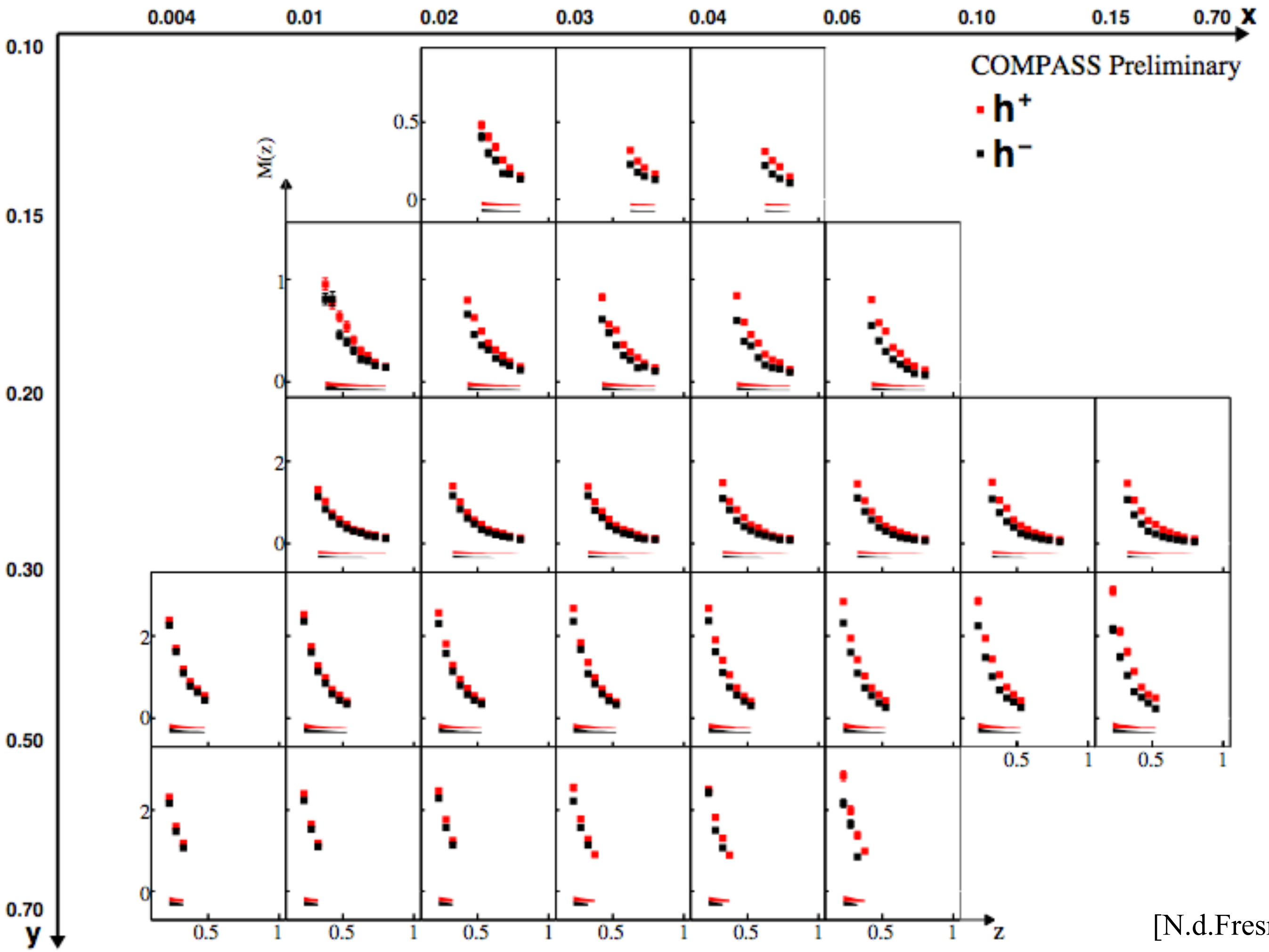
Sivers asymmetry





Nucleon structure – Towards unpolarised FF

- π^+ multiplicities vs. z in (x,y) bins
- π^- multiplicities vs. z in (x,y) bins

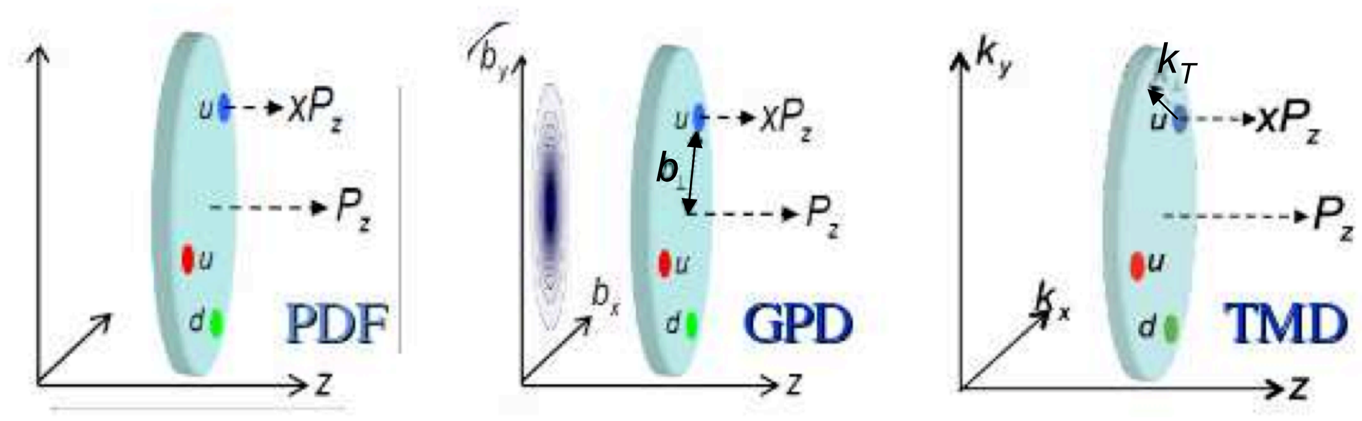


[N.d.Fresne, DIS 2014]

Next step: Multiplicites for kaons and di-hadrons measured as well, soon to come ...

COMPASS phase II

Motivation: Improve the 1-dimensional picture of the nucleon

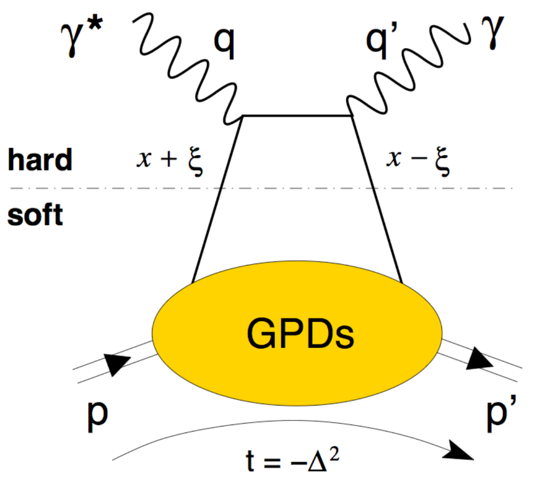


- **Generalised Parton Distributions (GPDs)**
  - ➢ longitudinal momentum structure plus transverse spatial structure
    → *accessible in exclusive reactions like DVCS or HEMP*
- **Transverse Momentum Dependent distributions (TMDs)**
  - ➢ dynamic picture using intrinsic transverse momenta of partons
    → *accessible in SIDIS and Drell-Yan process*
- **Flavour separation and fragmentation in SIDIS**
  - ➢ strange quark distribution and fragmentation functions

Generalised Parton Distributions (GPDs)

Access GPD through DVCS process

- generalised parton distributions for quarks and gluons
  $H^f, E^f, \tilde{H}^f, \tilde{E}^f \, (x, \xi, t)$
- limits:
  - $q(x) = H(x,0,0)$
  - $F(t) = \int dx\, H(x, \xi, t)$
- GPDs contained in Compton form factor



Ji's sumrule:

$$J^f = \frac{1}{2} \lim_{t \to 0} \int_{-1}^{1} dx \; x \; \left[H^f(x,\xi,t) + E^f(x,\xi,t)\right]$$

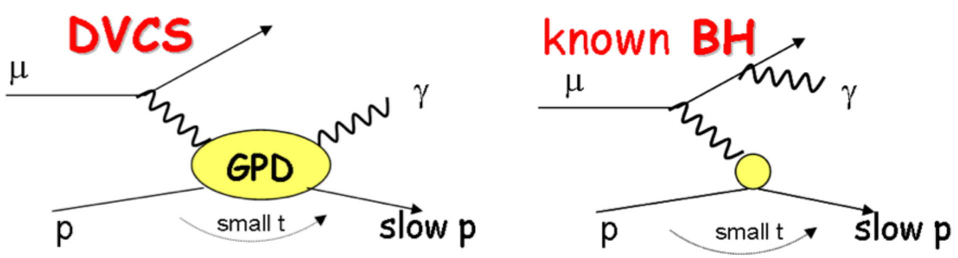
J^f: total angular momentum contribution of quark f

- unpolarised hydrogen target => GPD H
- transversely polarised target => GPD E

Measurement of GPD H via DVCS

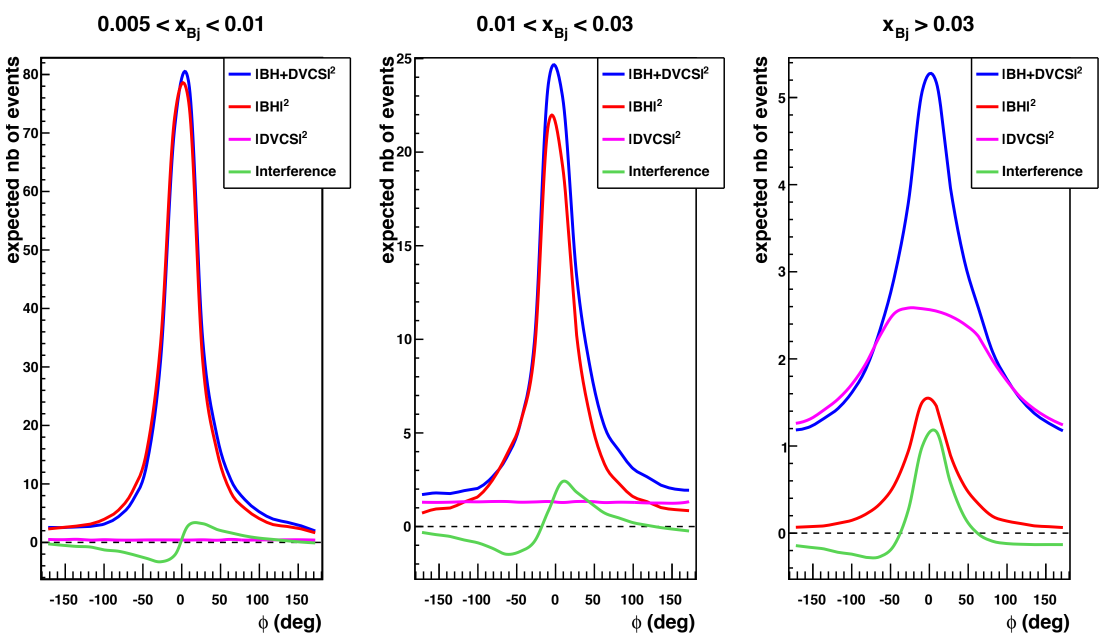
$$\mu^{\pm} p \longrightarrow \mu^{\pm} \gamma p$$

- competing: DVCS and BH
  → *measurement with μ^+ and μ^-*
- yields Re(H) and Im(H)



Monte-Carlo simulation:

- BH dominant at low x_{Bj}
- DVCS signal at higher x_{Bj}



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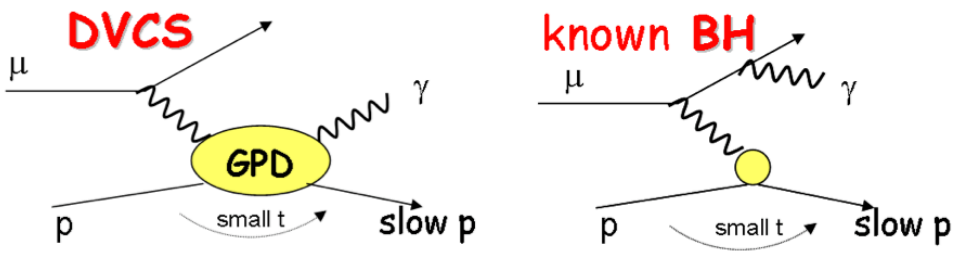

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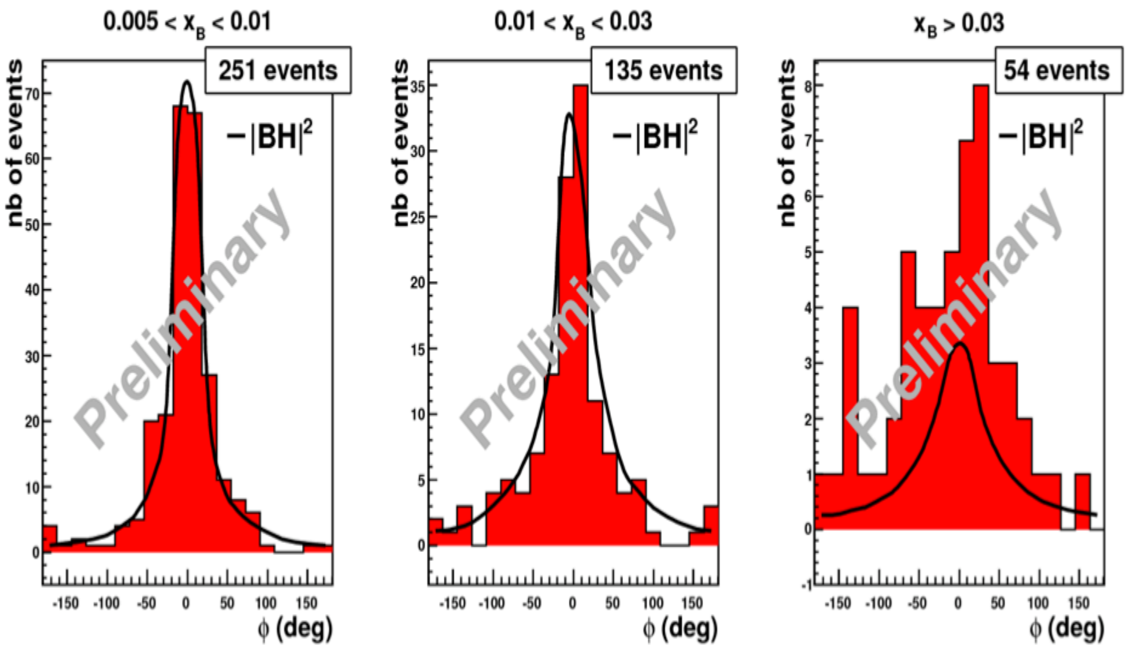
Monte-Carlo simulation:
- BH dominant at low x_{Bj}
- DVCS signal at higher x_{Bj}

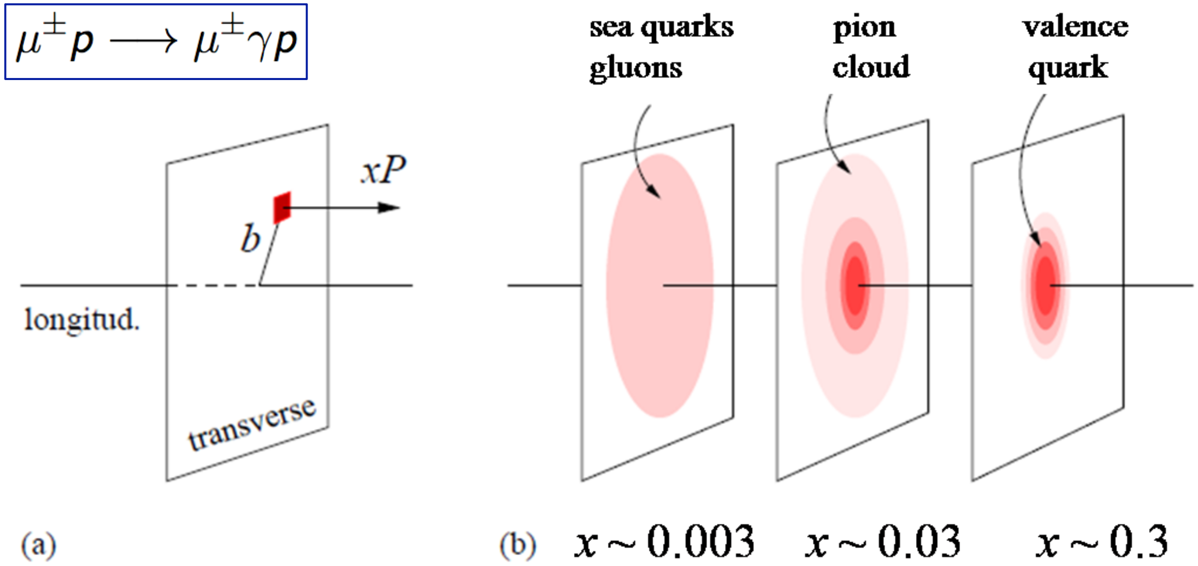
Real data analysis:
- 2009 feasibility test measurement
  (few days, short 40cm target)

→ *clear DVCS signal*



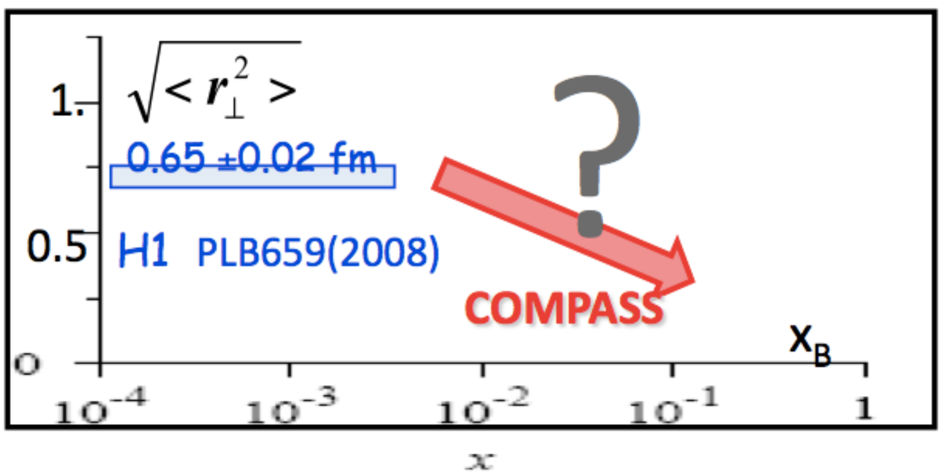
Nucleon tomography

$\mu^{\pm} p \longrightarrow \mu^{\pm} \gamma p$



$\mathbf{b}_{\perp}$: distance to center of momentum

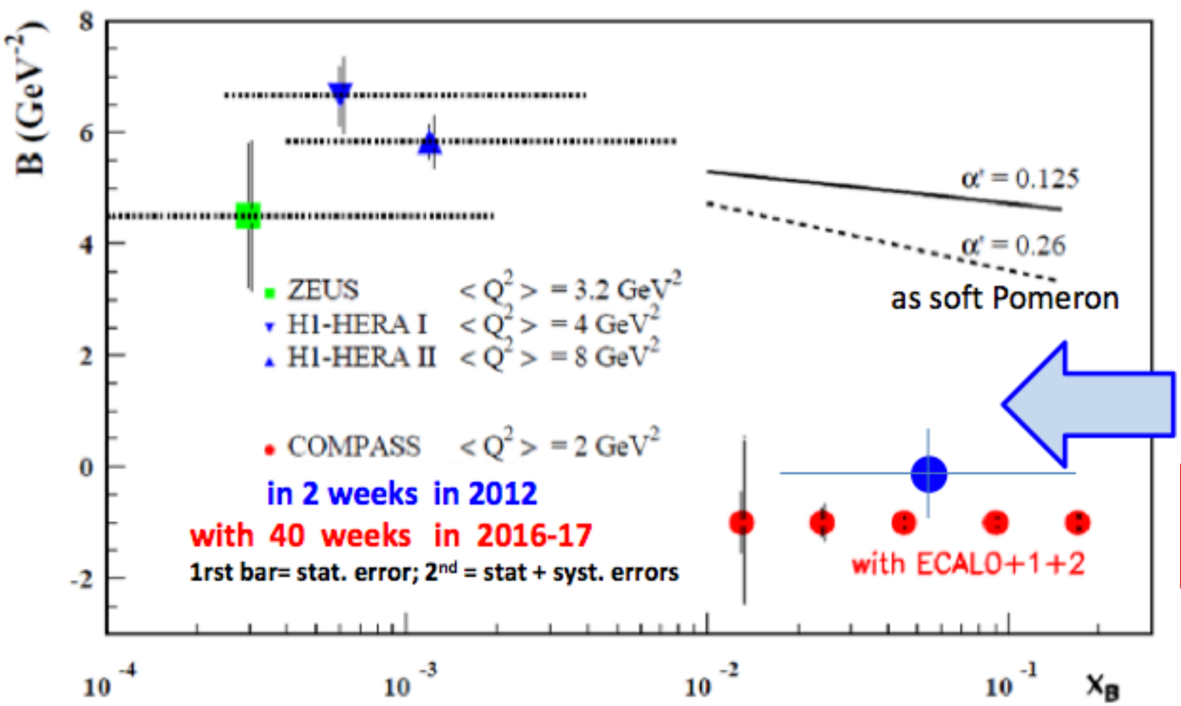
- $r_{\perp}$: transverse size of the nucleon
- $r_{\perp} = b_{\perp}/(1-x)$
- extraction mostly model independent



Transverse imaging – projection for t-slope

$\mu^{\pm} p \longrightarrow \mu^{\pm} \gamma p$ *(also accessible via HEMP)*

- Differential cross-section ~ exp(-B|t|): $d\sigma^{DVCS}/d|t| \propto \exp(-B|t|)$ with $B(x) \sim 1/2 \langle r_{\perp}^2(x) \rangle$
- Ansatz at small x_{Bj}: $x \approx x_{Bj}$, $B(x_{Bj}) = B_0 + 2\alpha' \ln \frac{x_0}{x_{Bj}}$



DVCS test in 2012

projections for 2 years of data
ε_{global} = 10%, L = 1222 pb^{-1}

- 2012: 2 weeks of data taking with nearly complete set-up

  → *1/20 of proposal statistics*

Measurement of TMDs via polarised Drell-Yan

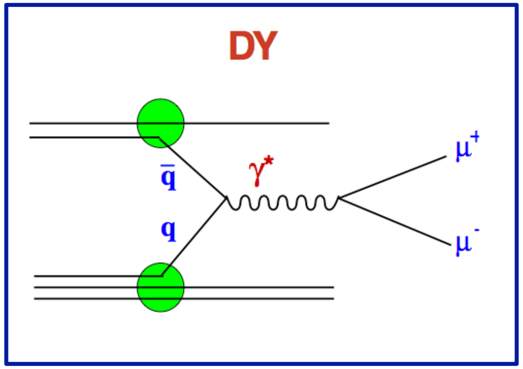
$\pi^- p^\uparrow \rightarrow \mu^+ \mu^- X$

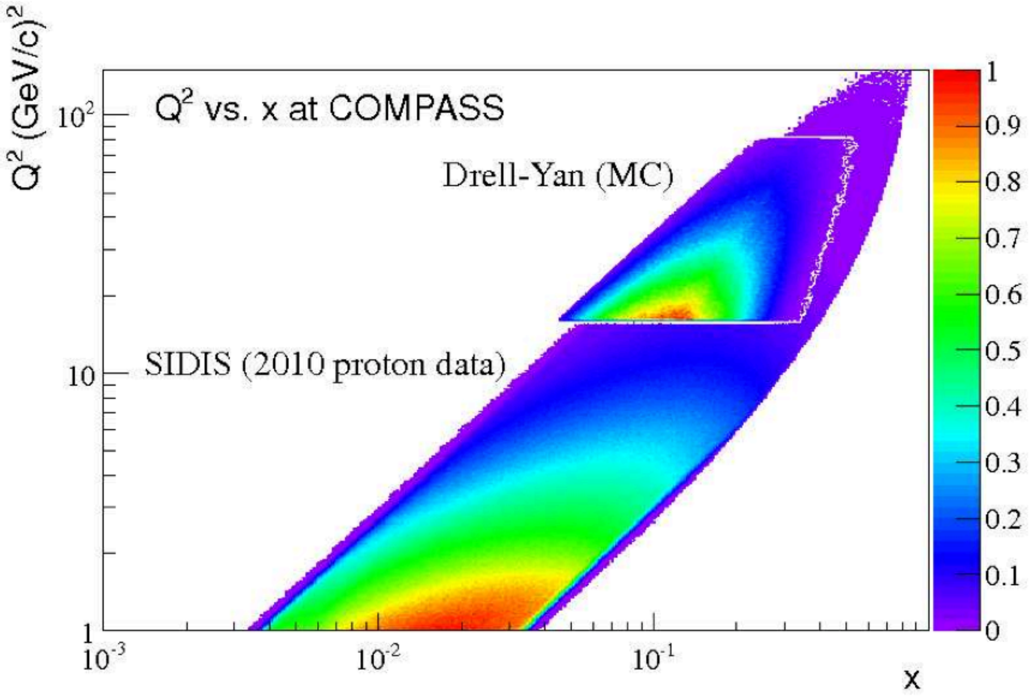
- DY: We measure lepton pair ($\mu^+\mu^-$)
  from $q\bar{q}$ annihilation
  → *important: hadron absorber*

- ideal DY experiment: $p\bar{p}$

- good compromise: $\pi^- p$
  → *annihilation of valence (anti-) quarks from π^- and from polarised proton*

- good acceptance at COMPASS in the valence quark region!

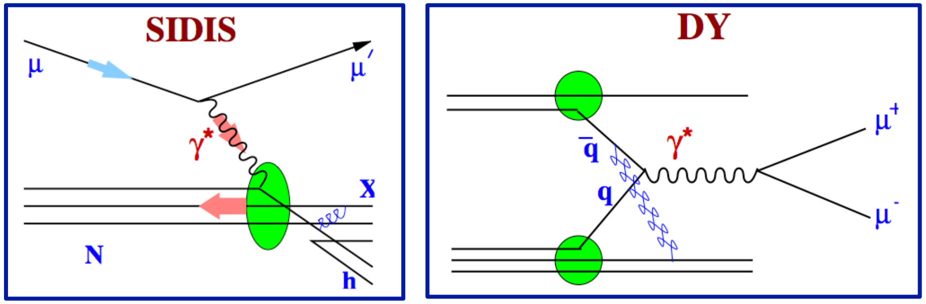




Measurement of TMDs via polarised Drell-Yan -- (non-) universality of TMDs

$$\pi^- p^\uparrow \rightarrow \mu^+ \mu^- X$$

Final state interaction | Initial state interaction



- DY: Access to 4 azimuthal modulations:
  - Boer-Mulders, Sivers, pretzelosity and transversity PDFs
- COMPASS: Access TMDs by azimuthal asymmetries in both:
  - Drell-Yan: TMD x TMD
  - SIDIS: TMD x FF
- Parasitic measurement of Boer-Mulders asymmetry in SIDIS
- Boer-Mulders and Sivers TMDs are T-odd, thus the prediction:

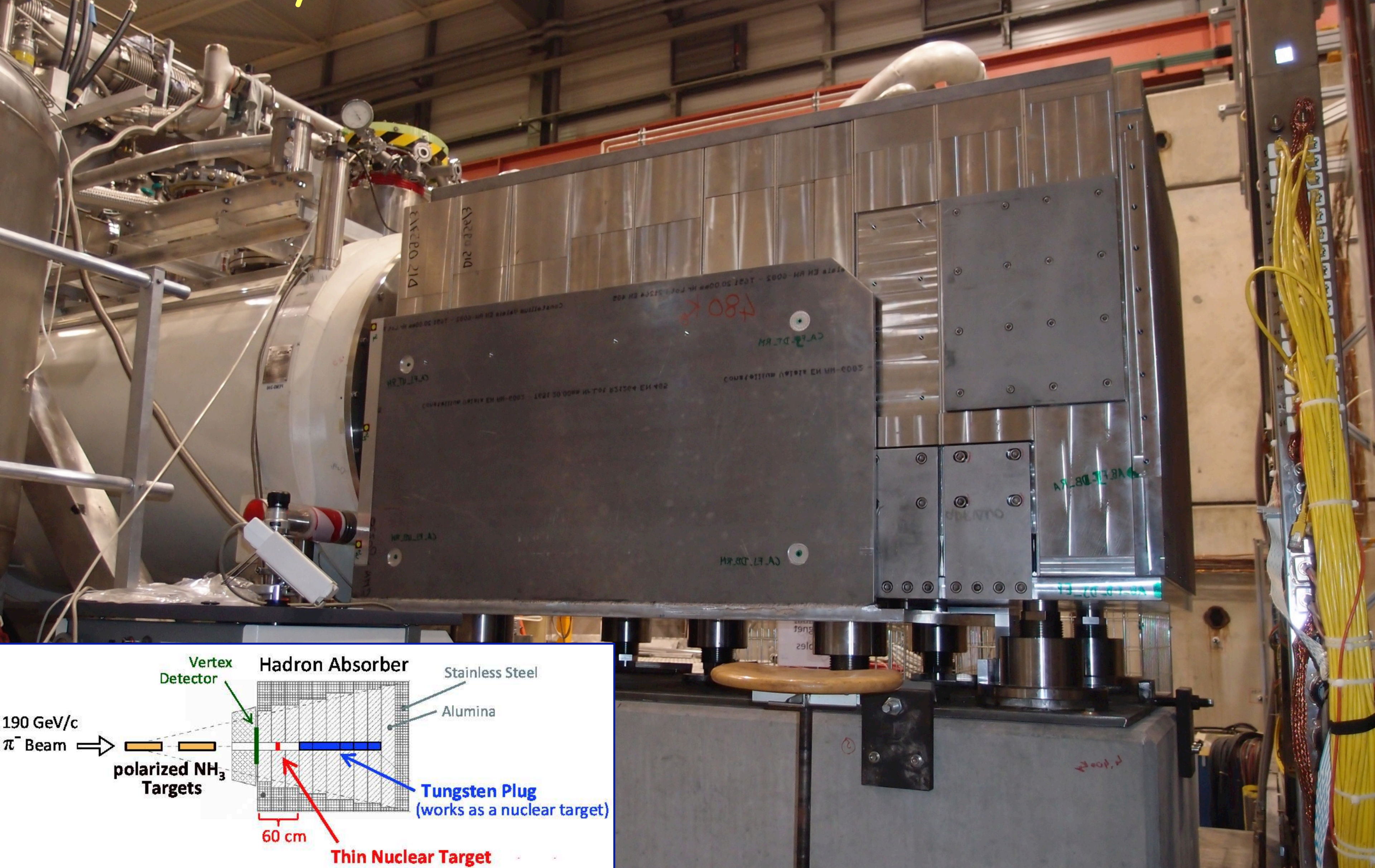
$$f_{1T}^{\perp}(SIDIS) = -f_{1T}^{\perp}(DY)$$

$$h_{1}^{\perp}(SIDIS) = -h_{1}^{\perp}(DY)$$

Fundamental test of universality and validation of TMD approach:
=> Change of sign in DY vs. SIDIS

Target region for Drell-Yan measurement

July 2014: Absorber for 2014 test installed



Summary & conclusions

Results from hadron beam data

- First precise measurement of pion polarisibility
- New path to radiative meson excitations
- High potential for light mesons spectroscopy & spin-exotic search
- New measurement of OZI violation

Results from muon beam data

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  - GPDs *(1D → 3D picture of the nucleon)*
  - Drell-Yan *(fundamental check of Sivers fctn.)*

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COMPASS is the facility to study QCD -- nucleon structure and spectroscopy