CERN Academic training lecture
Physics at the AD/PS/SPS (2/4)

QCD and hadron physics: COMPASS, NA61, DIRAC

Gerhard K. Mallot /CERN

LHC
SPS
COMPASS
SHINE
NA61
DIRAC

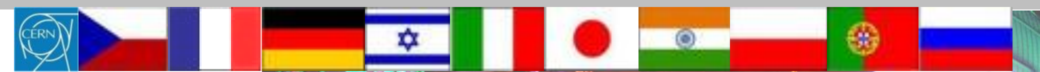
Study of non-perturbative QCD

- Properties of hadrons
  - structure functions
  - hadron spectrum
- Properties of quark matter
  - deconfinement
  - critical point
- Low energy QCD – chiral perturbation theory
  - pion/kaon polarisability
  - $\pi\pi$ scattering length

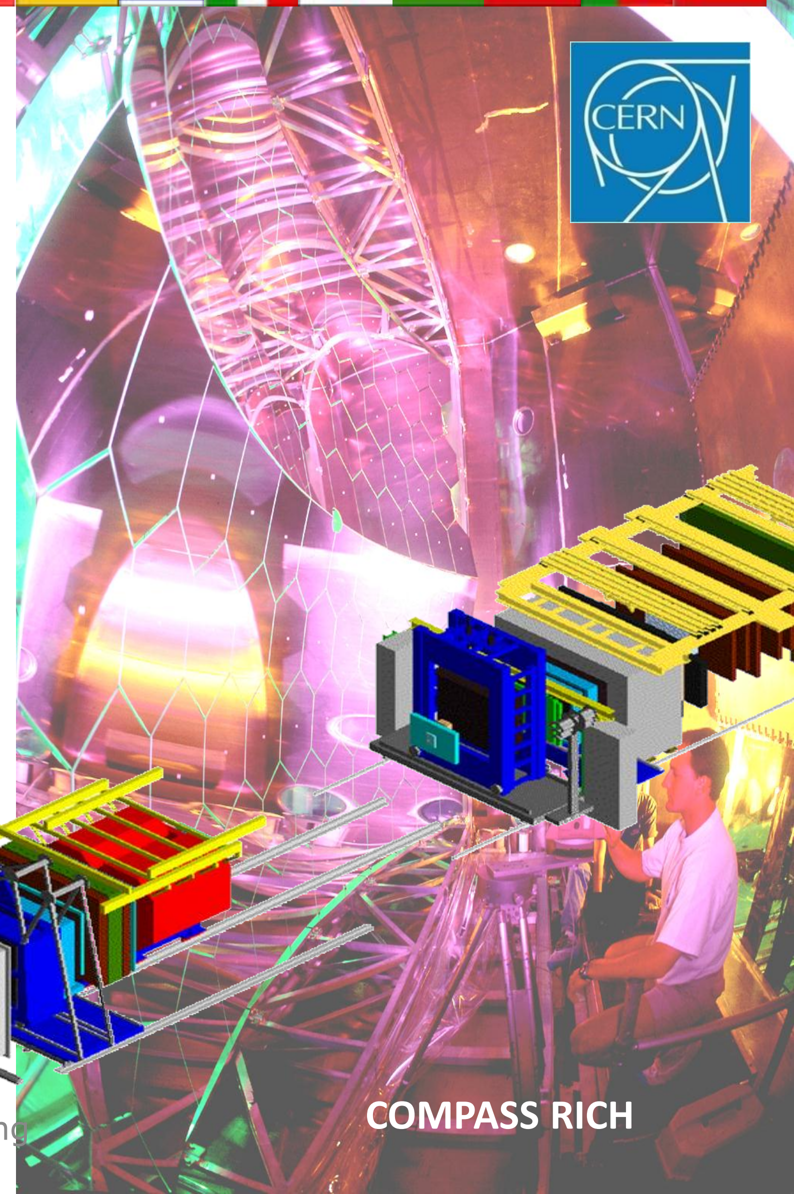
COMPASS SHINE DIRAC

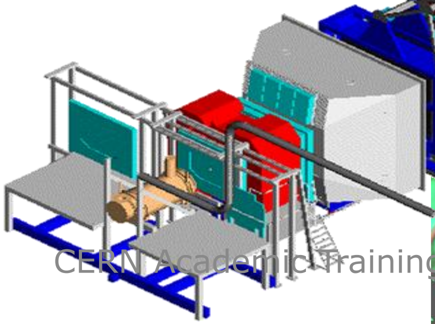
COMPASS: QCD structure of hadrons

data taking since 2002



- nucleon spin-structure (μ)
  - helicity distributions of qluons and quarks
  - transverse spin structure
  - 3D structure of the nucleon
- hadron spectroscopy (p, π, K)
  - light mesons, glue-balls
  - exotic mesons
  - polarisability of pion and kaon
- members:
  - 210 physicists,
    29 institutes,
    11 countries

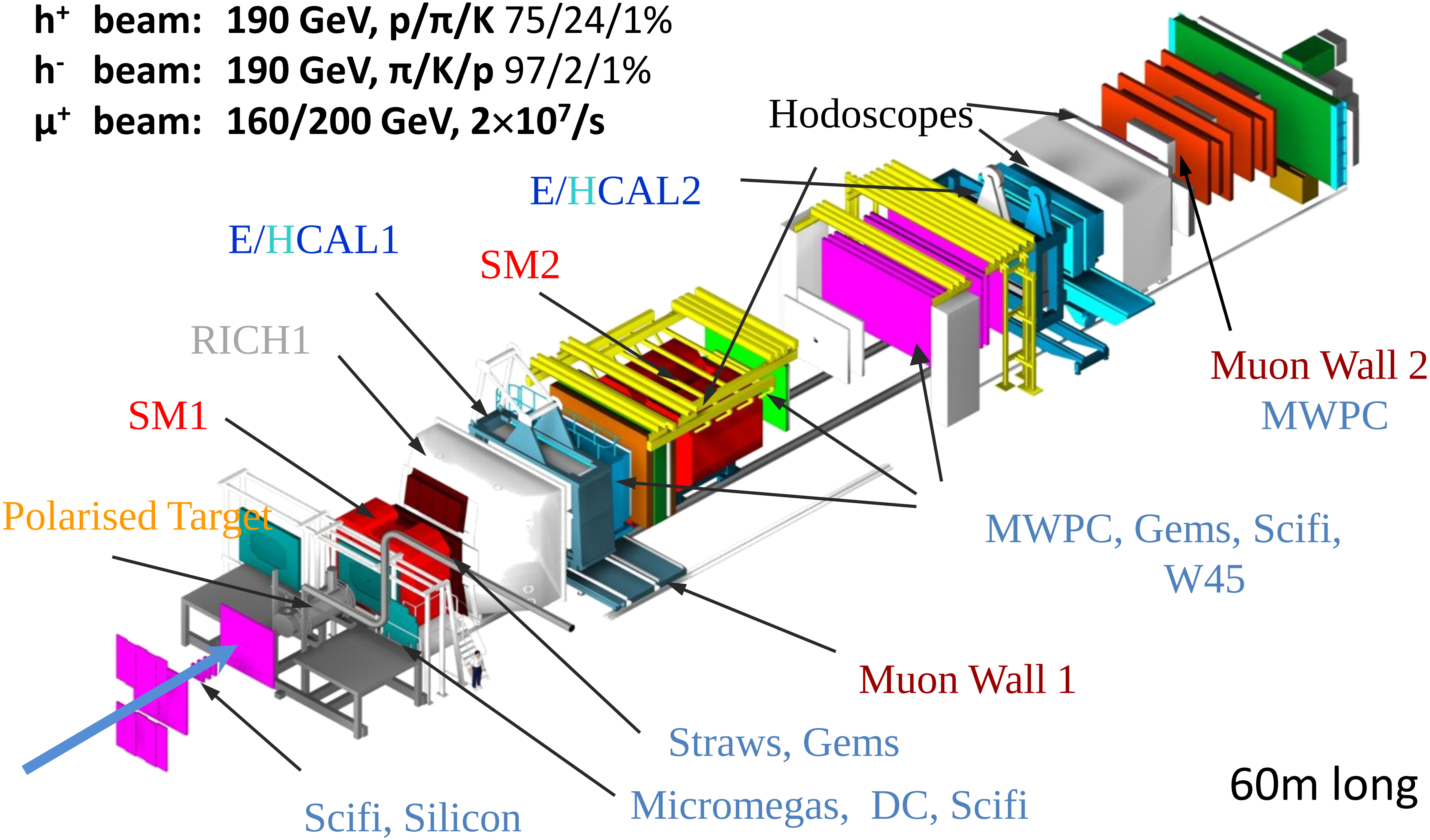





LHC
COMPASS
SHINE
NA61
SPS
DIRAC

COMPASS spectrometer

h⁺ beam: 190 GeV, p/π/K 75/24/1%
h⁻ beam: 190 GeV, π/K/p 97/2/1%
μ⁺ beam: 160/200 GeV, 2×10⁷/s



60m long

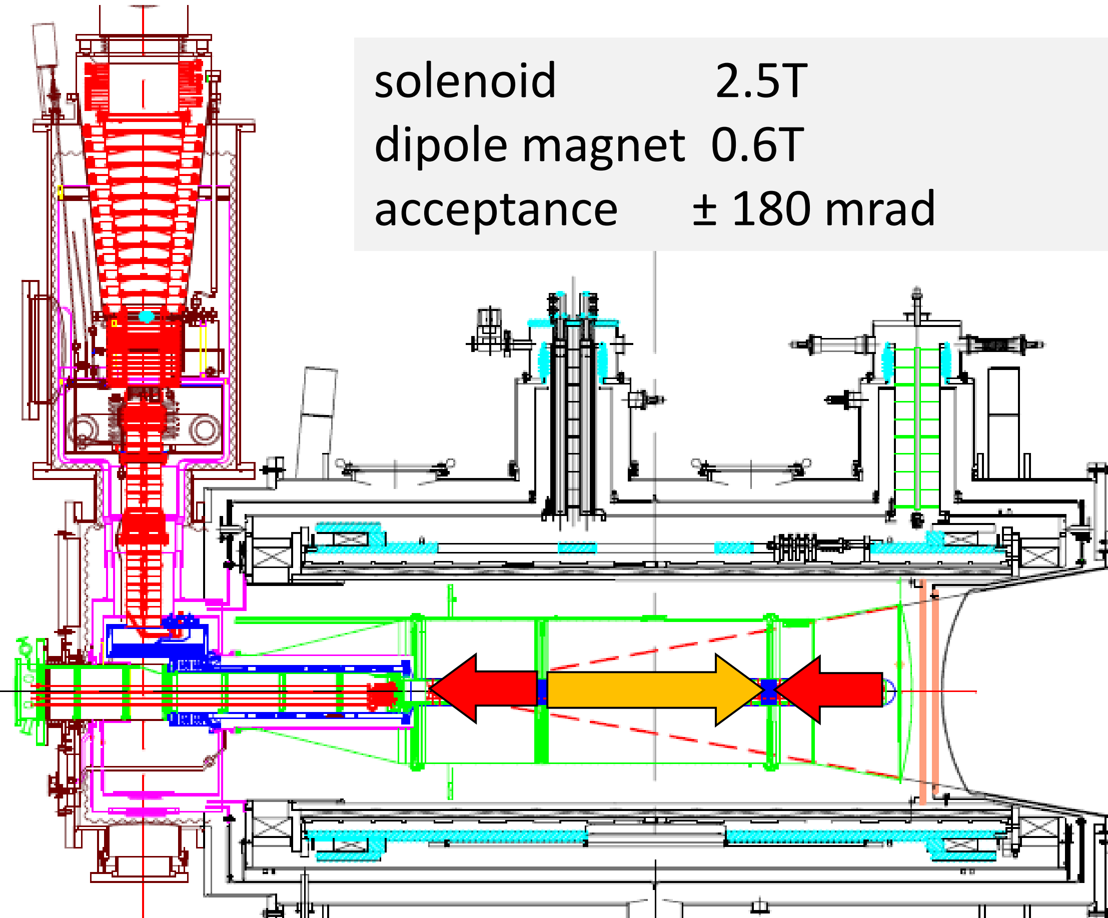
Polarized target system

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

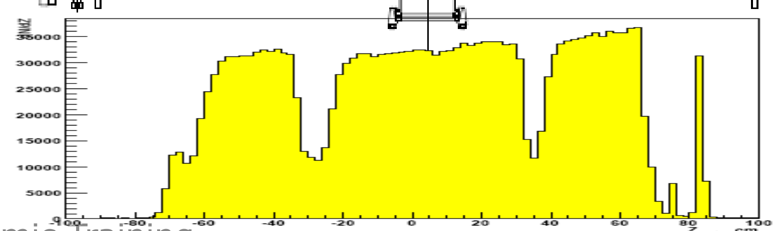
solenoid 2.5T
dipole magnet 0.6T
acceptance ± 180 mrad

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

μ



Recontructed interaction vertices

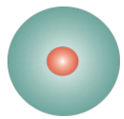


Structure: Parton Distribution Functions

Three twist-2 PDFs

$q(x)$

$f_1^q(x)$



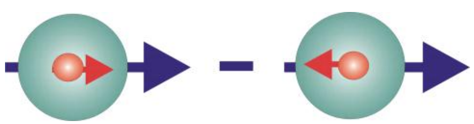
unpolarised PDF

quark/gluon with momentum *xP* in a nucleon

well known – unpolarized DIS

$\Delta q(x)$

$g_1^q(x)$



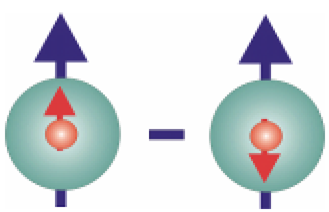
helicity PDF

quark/gluon with spin parallel to the nucleon spin in a longitudinally polarised nucleon

known – polarized DIS

$\Delta_T q(x)$

$h_1^q(x)$



transversity PDF

quark with spin parallel to the nucleon spin in a transversely polarised nucleon

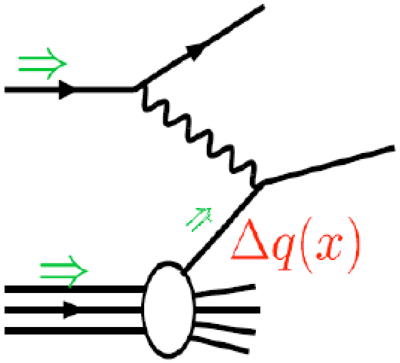
chiral odd, fairly known

Tools to study the spin structure

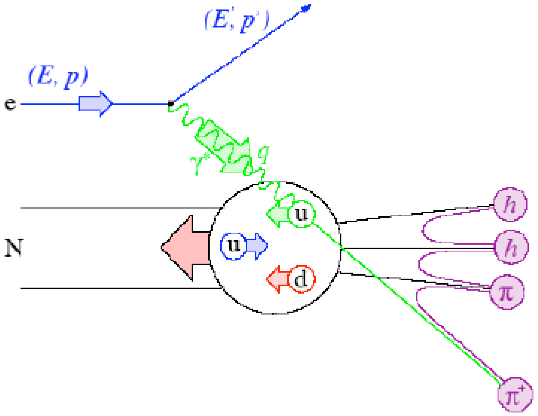
Factorization of hard interaction and fragmentation
(additional input from e^+e^-)

polarised

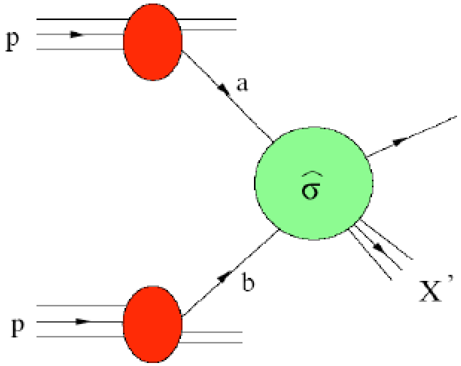
DIS



SIDIS



pp



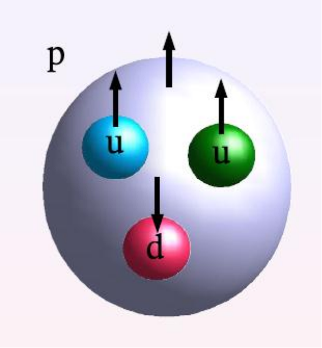
helicity structure of the nucleon

Spin: Static Quark model

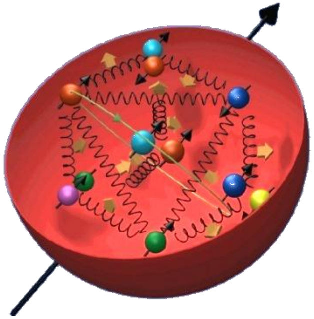
$$|p\uparrow\rangle = \frac{1}{\sqrt{18}}\Big\{2|u\uparrow u\uparrow d\downarrow\rangle - |u\uparrow u\downarrow d\uparrow\rangle - |u\downarrow u\uparrow d\uparrow\rangle + (u \leftrightarrow d)\Big\}$$

$$\Delta u = \langle p\uparrow|N_{u\uparrow} - N_{u\downarrow}|p\uparrow\rangle = \tfrac{3}{18}(10-2) = \tfrac{4}{3}$$

$$\Delta d = \langle p\uparrow|N_{d\uparrow} - N_{d\downarrow}|p\uparrow\rangle = \tfrac{3}{18}(\ 2-4) = -\tfrac{1}{3}$$



$$\Delta\Sigma = \Delta u + \Delta d = 1$$



SQM: up and down quarks carry the nucleon spin!
EMC: Quarks spins contribute little (1987/88)
ΔΣ = 0.12

Where is the proton spin?

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

small

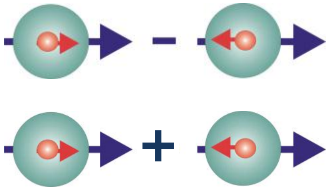
smallish,
till poorly known

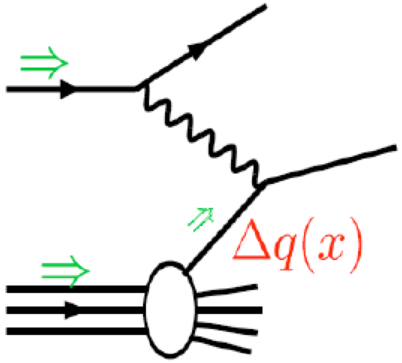
unknown

Asymmerties & SF

longitudinal double-spin x-sect. asymmetries

$$A_1(x,Q^2) = \frac{\sum_q e_q^2 \Delta q(x,Q^2)}{\sum_q e_q^2 q(x,Q^2)} = \frac{g_1(x,Q^2)}{F_1(x,Q^2)}$$





$$A_1 \simeq \frac{A_{exp}}{f\, P_\mu\, P_T\, D}$$

x: Bjorken x, fraction of nucleon momentum carried by struck quark in inf. mom. frame

f: dilution factor
D: depolarisation factor
P_μ: beam polarisation
P_T: target polarisation

Sum rules for g_1

- first moment Γ_1 of g_1 with $\Delta q = \int_0^1 \Delta q(x) \mathrm{d}x$

$$\Gamma_1 = \int_0^1 g_1(x)\mathrm{d}x \overset{proton}{=} \frac{1}{2}\left\{\frac{4}{9}\Delta u + \frac{1}{9}\Delta d + \frac{1}{9}\Delta s\right\}$$

$$\Gamma_1^{\mathrm{p}} = \frac{1}{12}\underbrace{(\Delta u - \Delta d)}_{a_3} + \frac{1}{36}\underbrace{(\Delta u + \Delta d - 2\Delta s)}_{\sqrt{3}a_8} + \frac{1}{9}\underbrace{(\Delta u + \Delta d + \Delta s)}_{a_0}$$

Neutron decay
$a_3 = |g_a/g_v|$

Hyperon decay
(3F-D)/3

$\Delta\Sigma$

- **Bjorken sum rule:**

$$\Gamma_1^{\mathrm{p}} - \Gamma_1^{\mathrm{n}} = \frac{1}{6}(\Delta u - \Delta d)$$

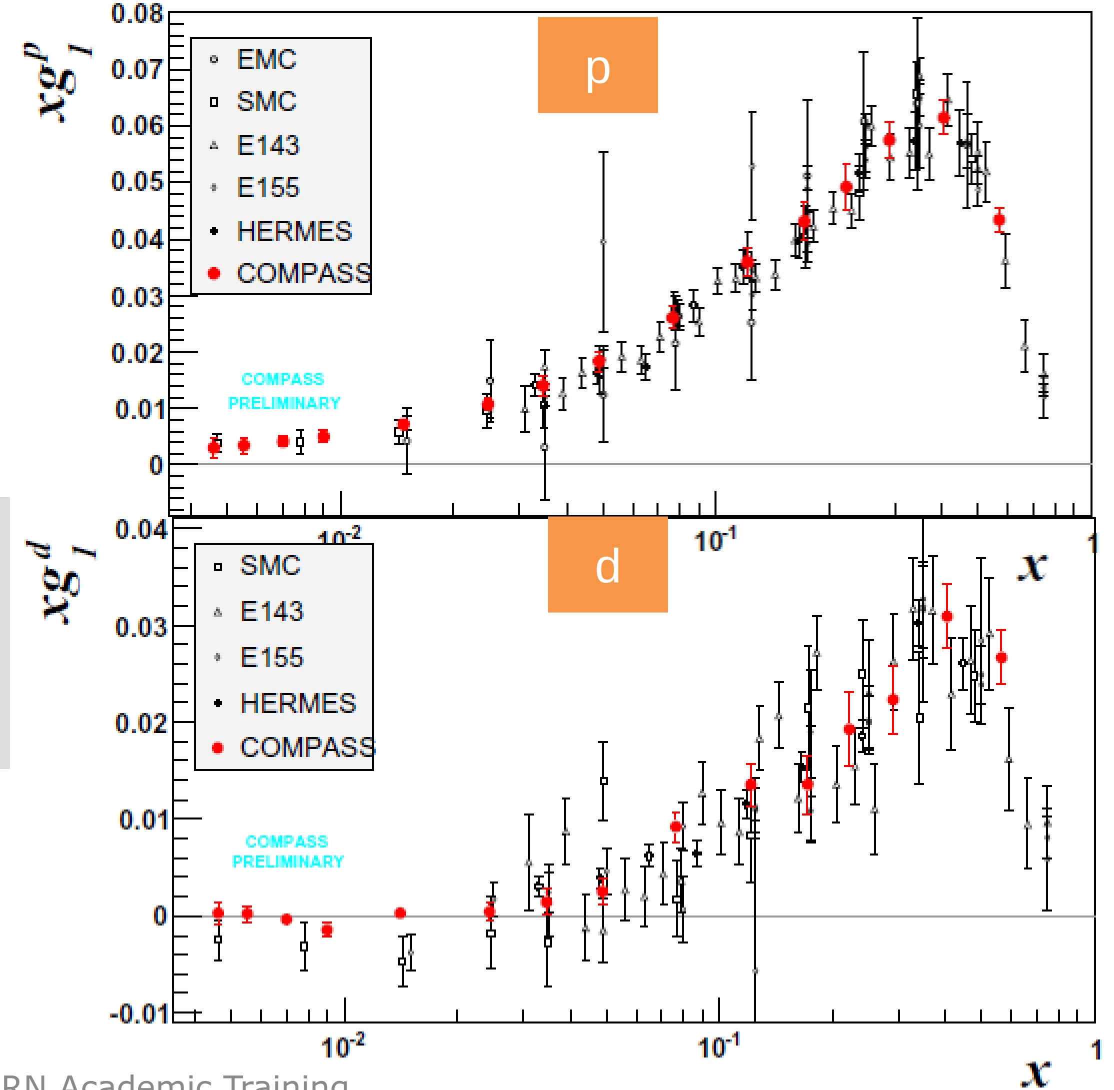
Structure function $g_1(x,Q^2)$

- very precise data
- only COMPASS for $x < 0.01$ ($Q^2 > 1$)

- deuteron data:

$\Delta\Sigma =$
$0.33 \pm 0.03 \pm 0.05$

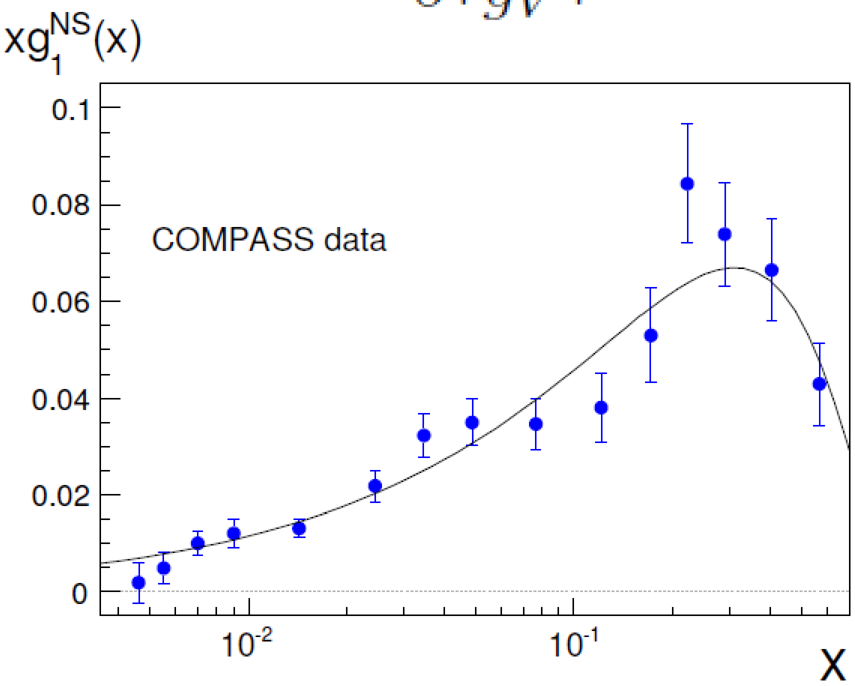
$\Delta s + \Delta\bar{s} =$
$-0.08 \pm 0.01 \pm 0.02$

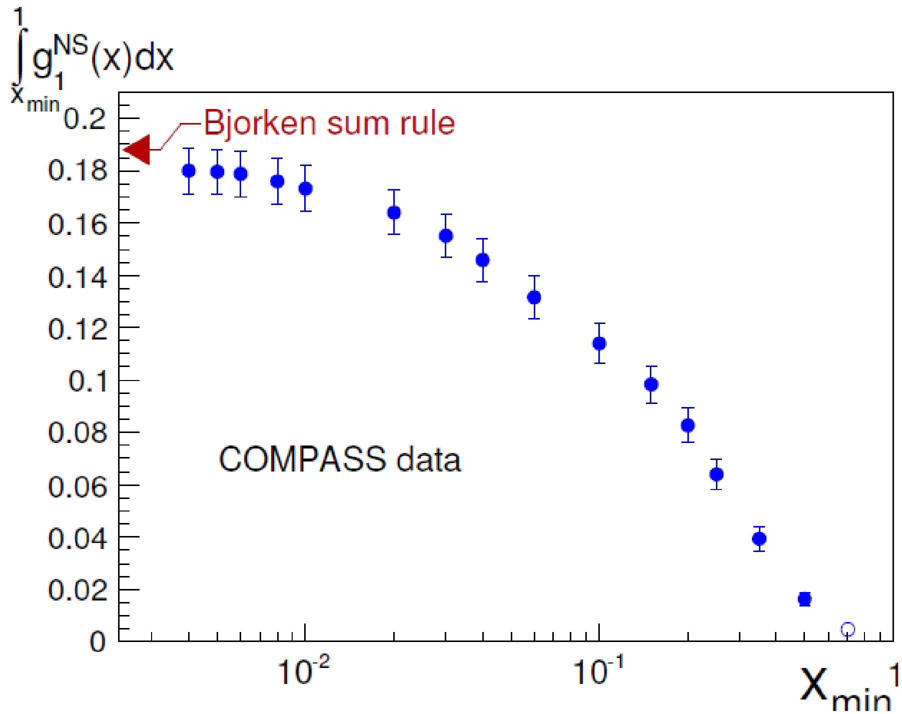


Bjorken sum rule

$$\Gamma_1^{NS}(Q^2) = \frac{1}{6}\left|\frac{g_A}{g_V}\right| C_1^{NS}(Q^2)$$

$$g_1^{NS}(x, Q^2) = g_1^p(x, Q^2) - g_1^n(x, Q^2)$$



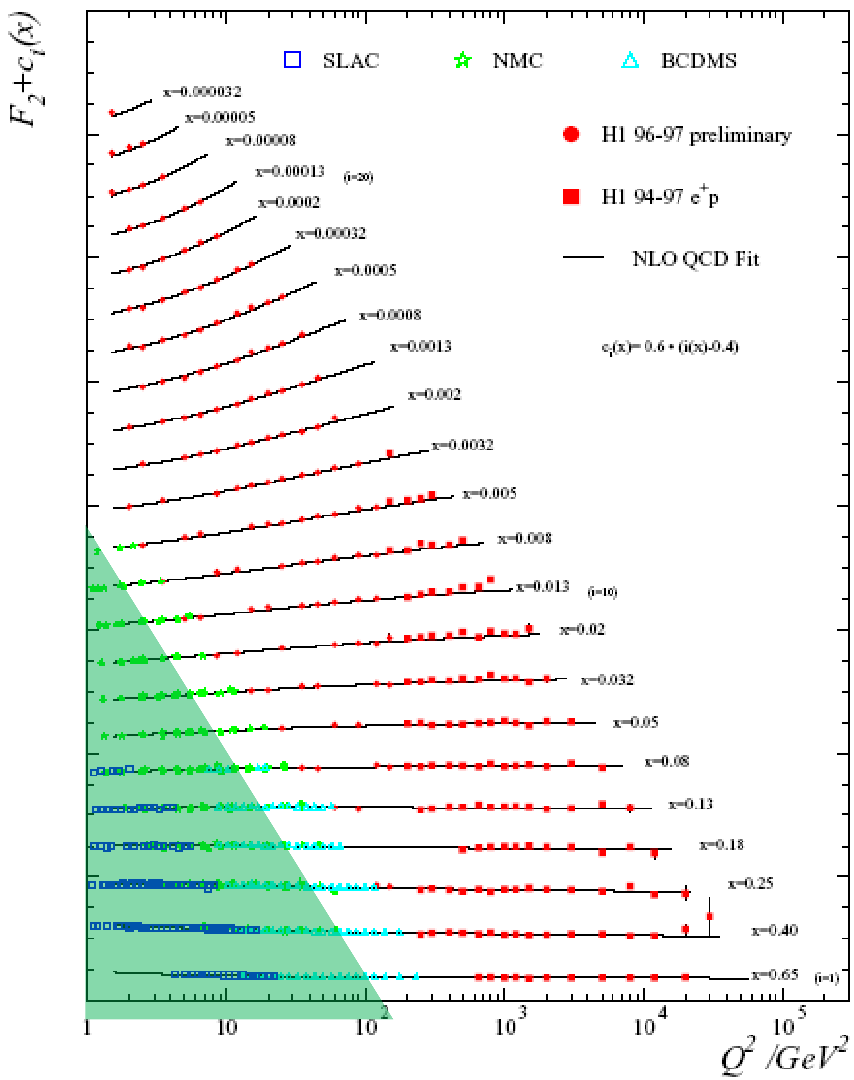


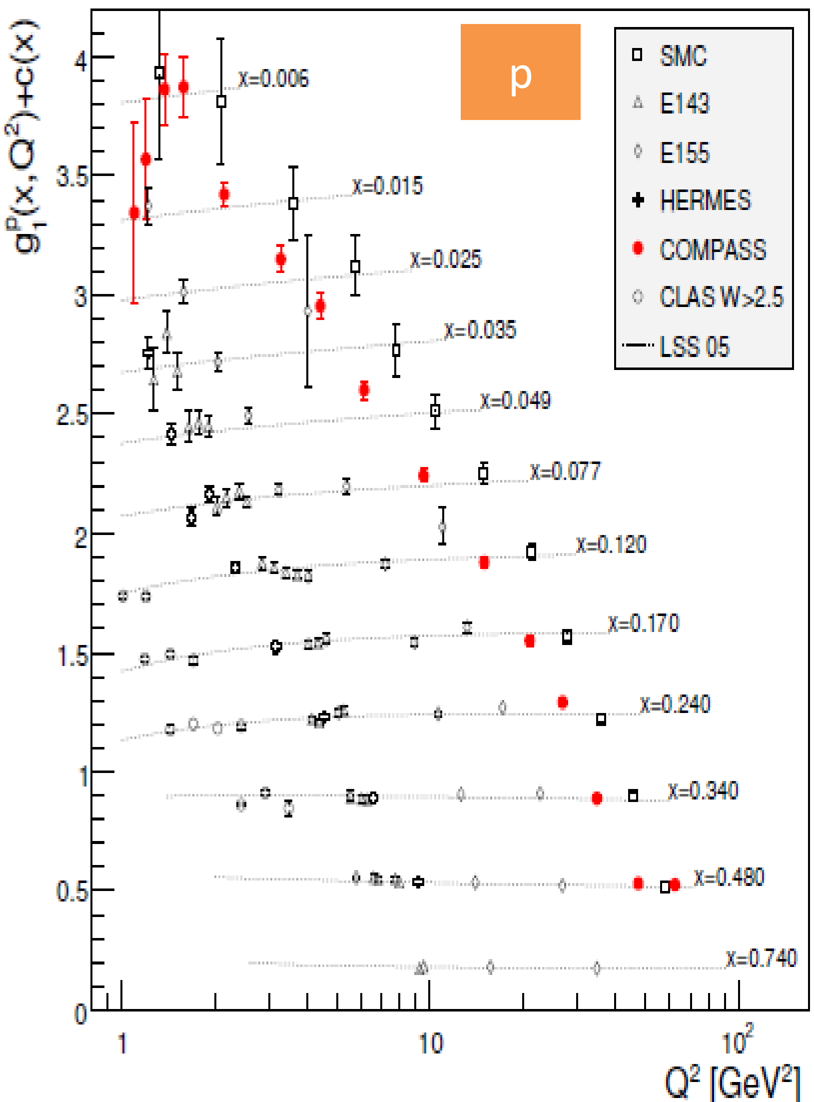
$$|g_A/g_V| = 1.28 \pm 0.07(\mathrm{stat.}) \pm 0.10(\mathrm{syst.})$$

PLB 690 (2010) 466

$$|g_A/g_V| = 1.269$$ from neutron β decay

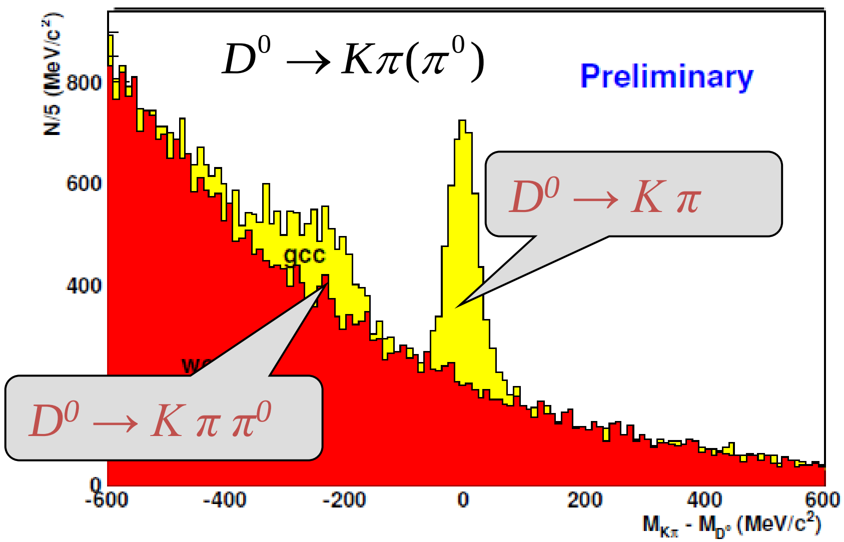
$F_2(x,Q^2)$ + $g_1(x,Q^2)$ −

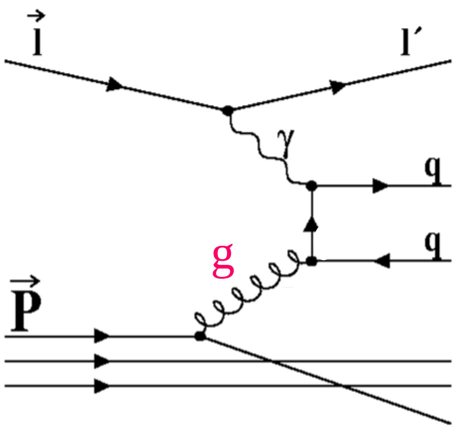

$F_2+c_i(x)$
SLAC
NMC
BCDMS
H1 96-97 preliminary
H1 94-97 e^+p
NLO QCD Fit
$c_i(x) = 0.6 \cdot (i(x)-0.4)$
Q^2 /GeV^2


p
SMC
E143
E155
HERMES
COMPASS
CLAS W>2.5
LSS 05
$g_1^p(x,Q^2)+c(x)$
Q^2 [GeV^2]

Gluon polarisation from PGF

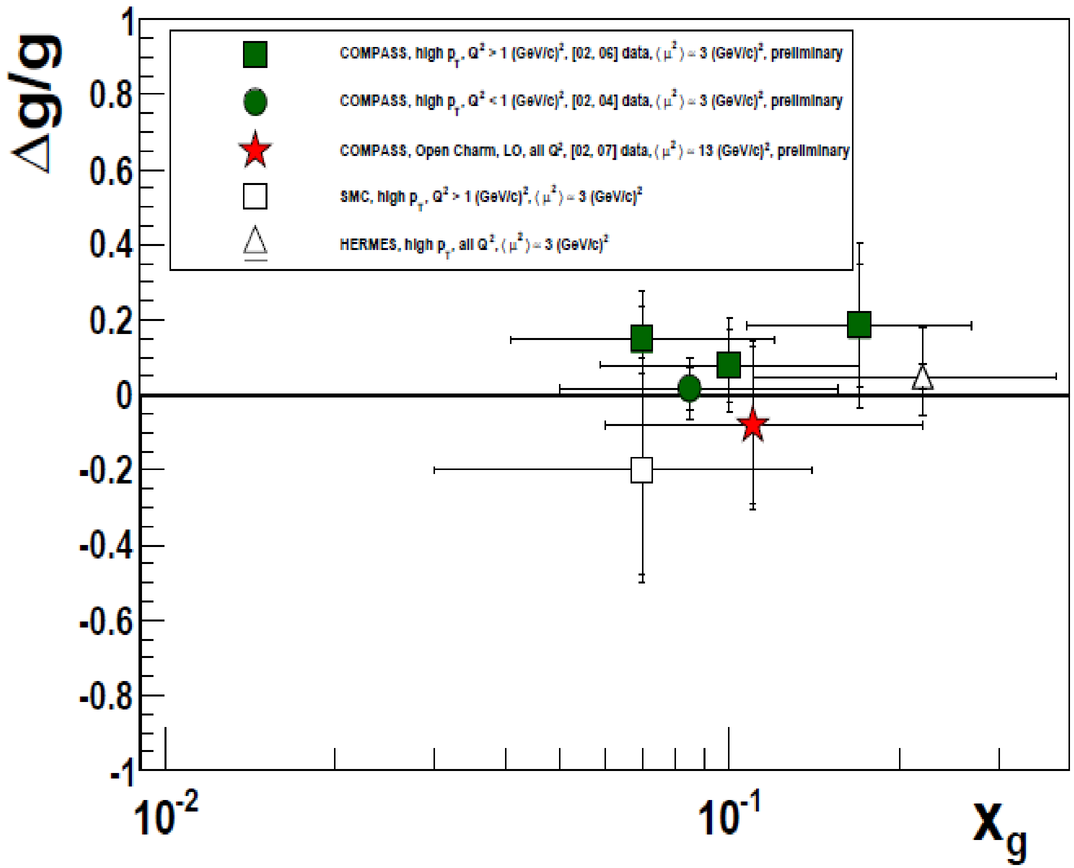
- open charm: single D meson
  cleanest process wrt physics background





- high-p_T hadron pairs with $Q^2 > 1$ GeV²
  high-p_T hadron pairs with $Q^2 < 1$ GeV²
  Single hadron production $Q^2 < 0.1$ GeV²

$\Delta g/g$ from PGF (LO)



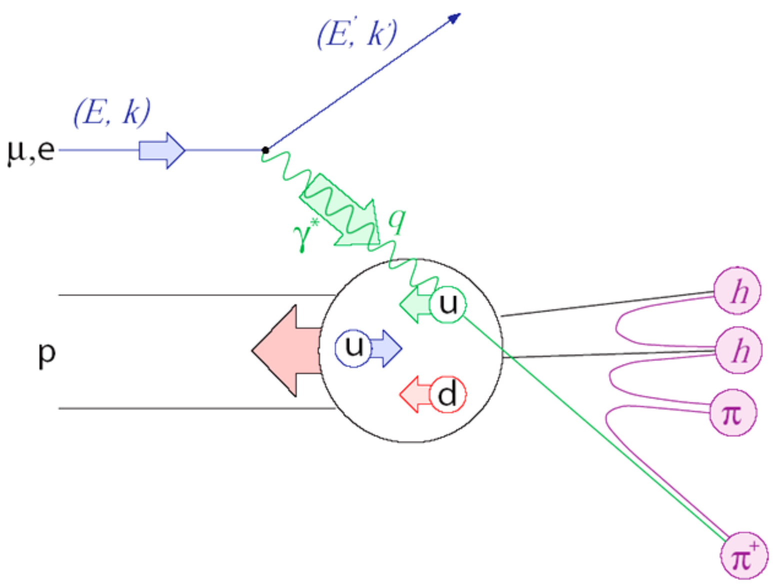
- The gluon polarisation is rather small
- confirmed by polarised *pp* at RHIC

X-sect. asymmetries

$$\frac{A_{\rm exp}}{f\ P_\mu\ P_T\ D} \simeq A_1$$

- Inclusive scattering

$$A_1 = \frac{\sum_q e_q^2 g_1^q(x,Q^2)}{\sum_q e_q^2 f_1^q(x,Q^2)}$$



- Semi-inclusive scattering

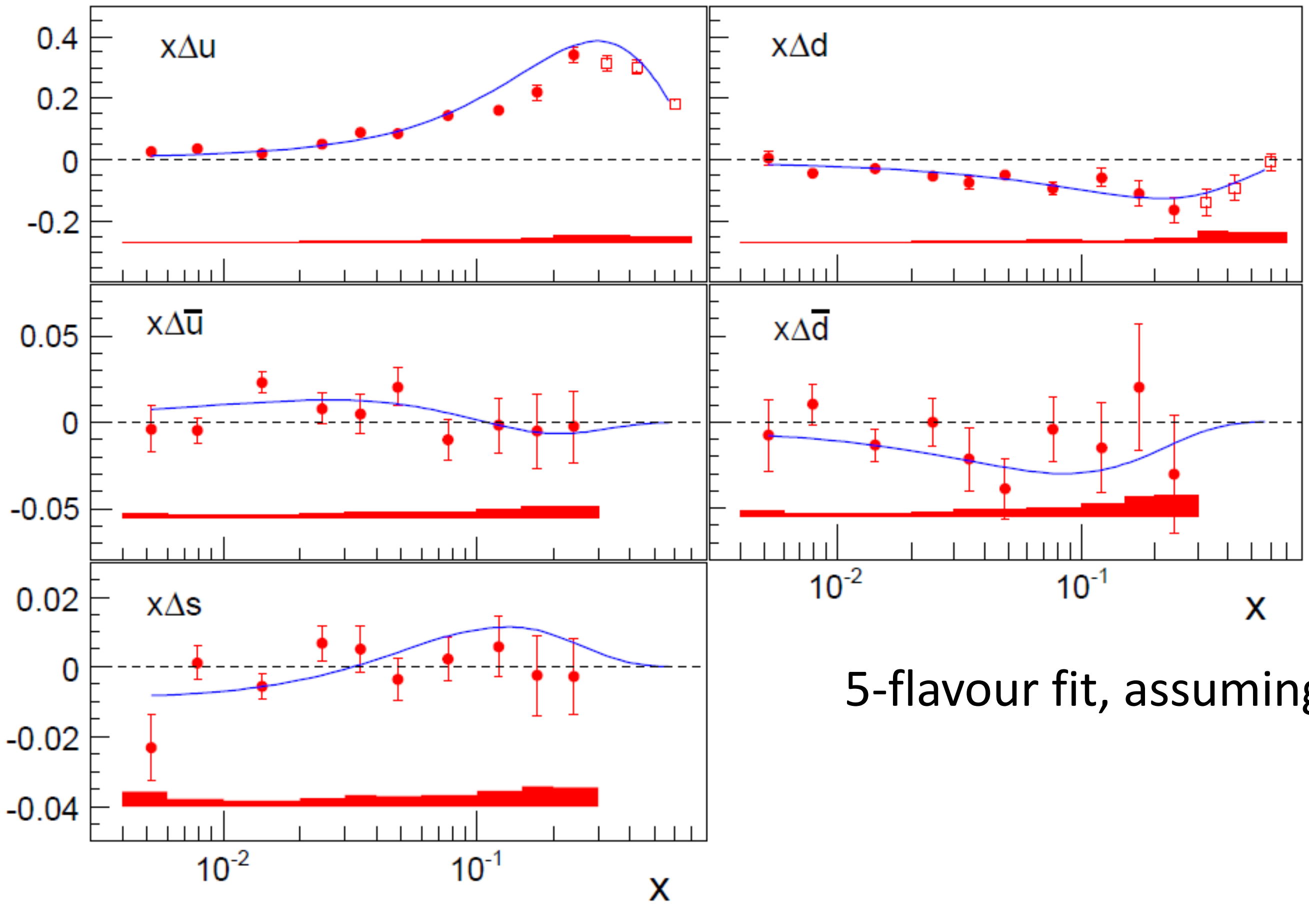
$$A_1^h = \frac{\sum_q e_q^2 g_1^q(x,Q^2) D_{1q}^h(z,Q^2)}{\sum_q e_q^2 f_1^q(x,Q^2) D_{1q}^h(z,Q^2)}$$

$$z = E_h/\nu$$

Flavour distributions

LO analysis of 5p+5d asymmetries, DSS FF
Line: NLO DSSV not including these data

PLB693 (2010) 227
PRD80 (2009) 034030



5-flavour fit, assuming $\Delta s = \Delta\bar{s}$

Transverse spin structure

TMD parton distributions

- 8 intrinsic-transverse-momentum dependent PDFs at leading twist
- Azimuthal asymmetries with different angular modulations in the hadron and spin azimuthal angles, Φ_h and Φ_s
- Vanish upon integration over k_T except f_1, g_1, and h_1

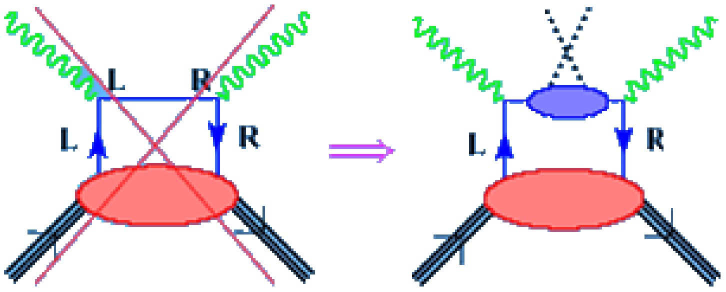
quark polarization \ nucleon polarization	U	L	T
U	f_1 number density		$f_{1T}^{\perp}$
L		g_1 helicity	g_{1T}
T	$h_1^{\perp}$	$h_{1L}^{\perp}$	h_1 transversity; $h_{1T}^{\perp}$

Boer–Mulders

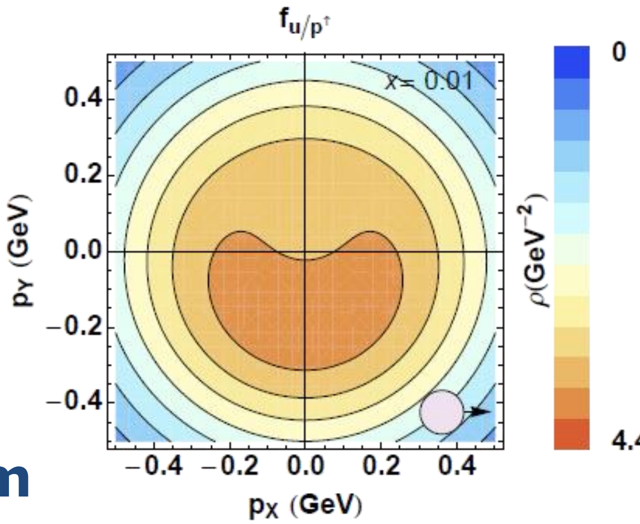
	aka
Sivers	$\Delta_0^T q$
Transversity	$\Delta_T q$

chiral odd

SSA: transversity (Collins) and Sivers



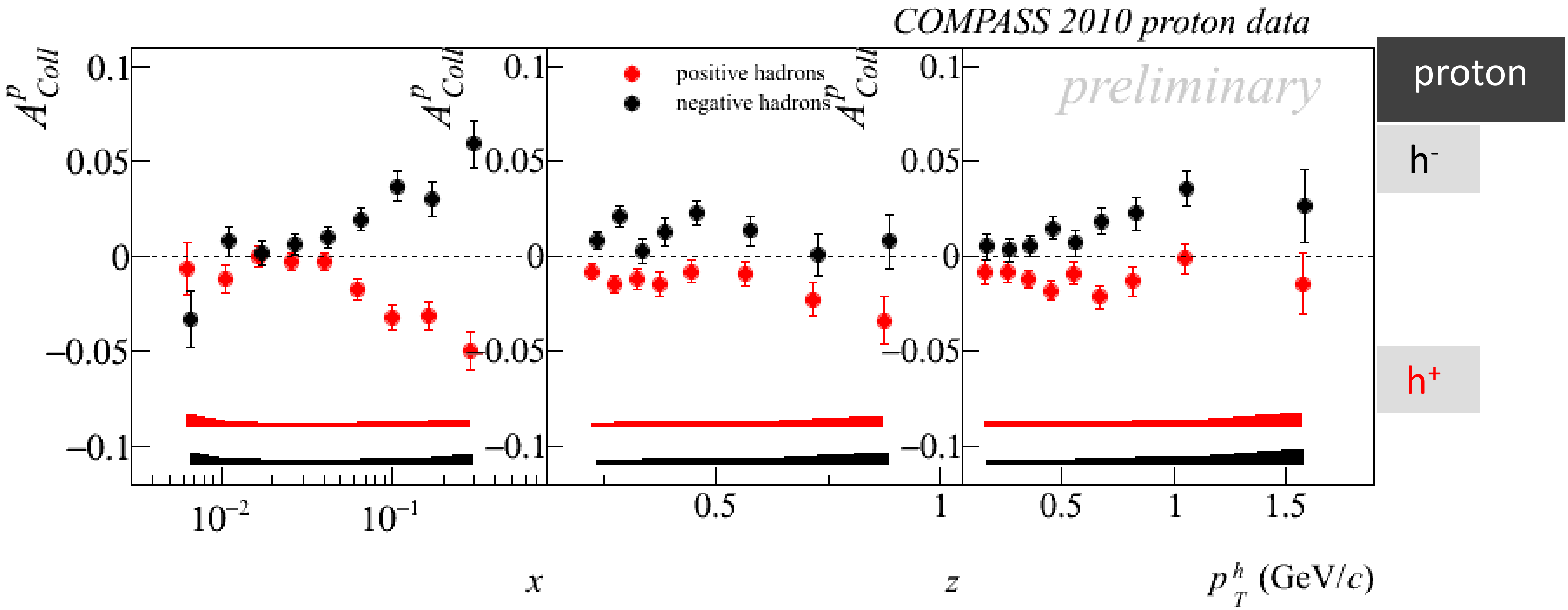
- transversity
  - chiral odd, can be measured in SIDIS (not in incl. DIS)
  - leads to an azimuthal asymmetry if the chiral-odd Collins fragmentation function is non-zero



- Sivers function
  - leads to a azimuthal asymmetry
  - naive T-odd
  - final/initial state interaction
  - should change sign for SIDIS/DY
  - related to **orbital angular momentum**

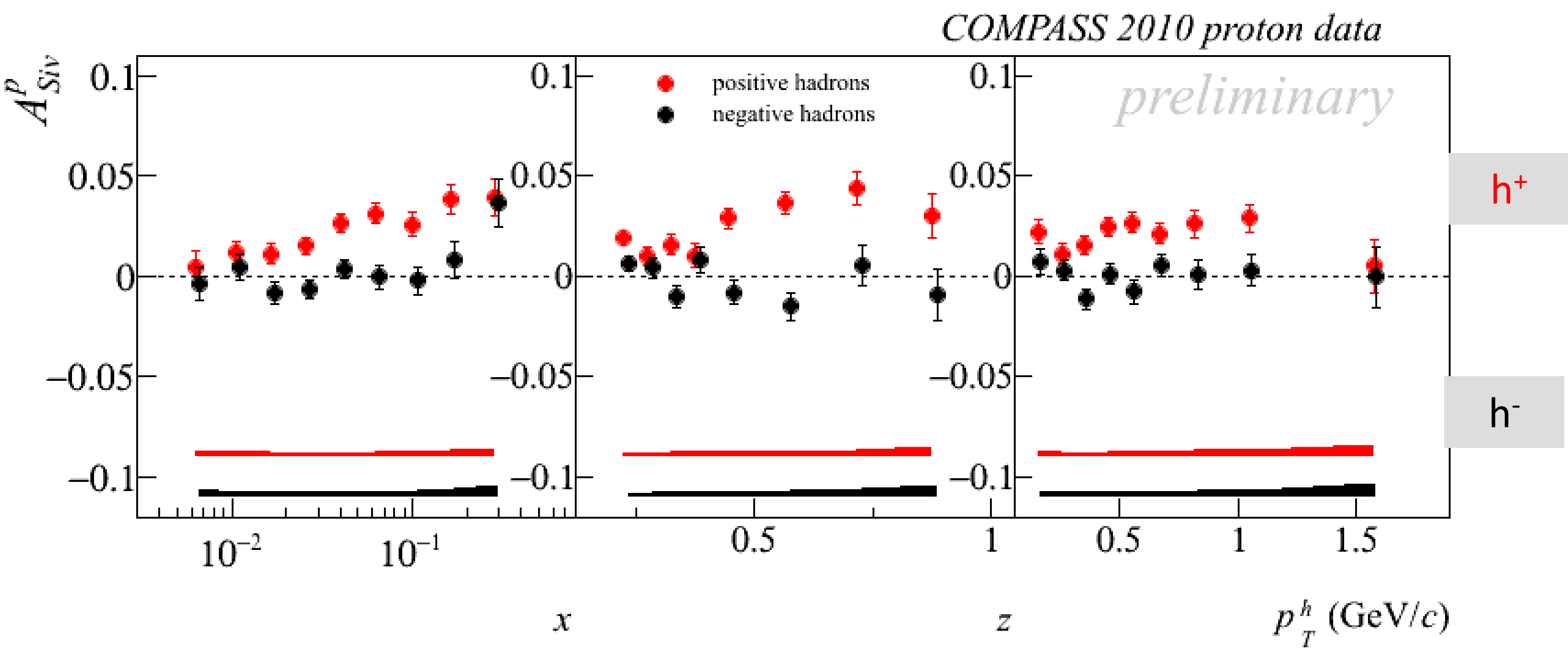
Collins Asymmetries

- large asymmetry for proton ~10%
- zero deuteron result important ⇒ opposite sign of u and d



Proton Sivers Asymmetry

- compatible with zero for the deuteron
- non-zero asymmetry for pos. hadrons



COMPASS-II

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN–SPSC–2010–014
SPSC-P-340
May 17, 2010

- Generalized Parton Distributions (GPD):
  simultaneously SIDIS on proton: (2012), 2015/16, ...
- TMD in $\pi^- + p^\uparrow$ Drell-Yan: 2014, ...
- Pion (and kaon) polarizabilities 2012

COMPASS-II Proposal

Approved December 2010, first measurements 2012

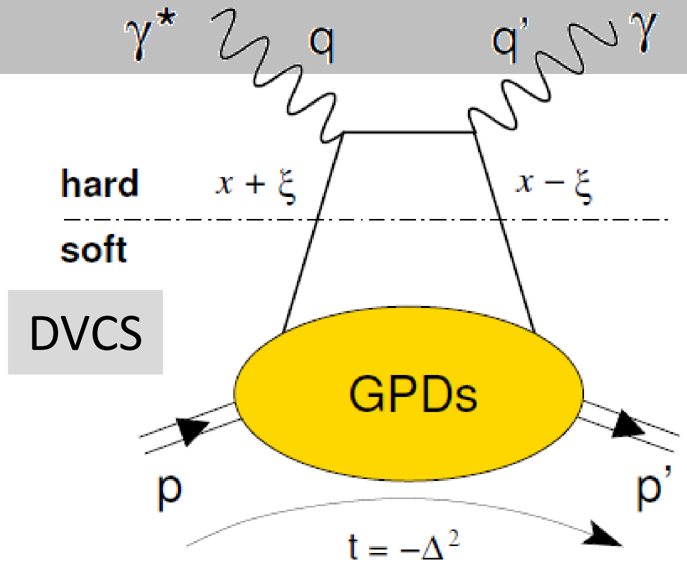
The COMPASS Collaboration

wwwcompass.cern.ch/compass/proposal/compass-II_proposal/compass-II_proposal.pdf

GPD's

$H(x, \xi, t, Q^2); \quad Q^2$ large, t small

$H^f, E^f, \tilde{H}^f, \tilde{E}^f$ with $f = q, g$



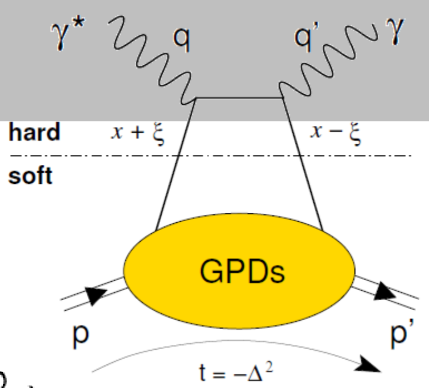
- *H (E)* for nucleon helicity (non)conservation
- PDFs and elastic FF as limiting cases
- $H, \tilde{H} \rightarrow f_1, g_1$ for $\xi \rightarrow 0$;
- Correlating transverse spatial and longitudinal momentum DoF
- tools: DVCS, HEMP (vector & pseudoscalar)

Total orbital momentum:

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

X.-D. Ji, PRL 78 (1997) 610

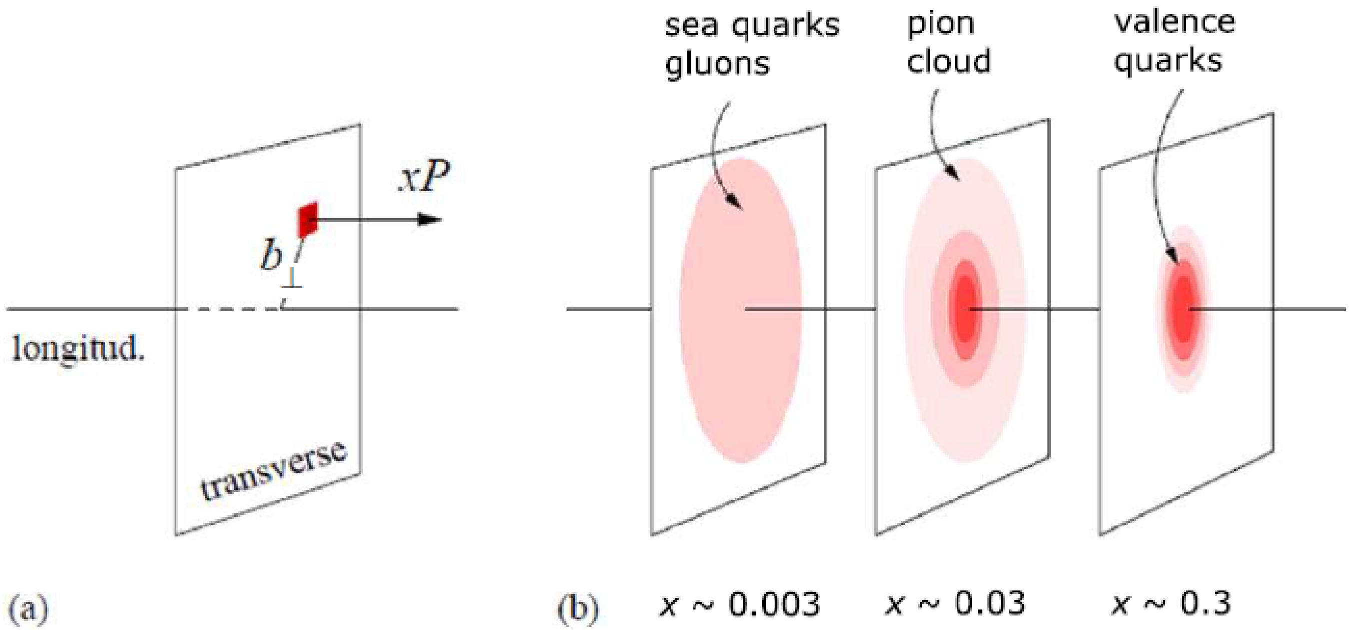
`Tomography'



- $\xi=0 \rightarrow t = -\Delta_T^2$, no long. transfer

$$q^f(x, \boldsymbol{b}_\perp) = \int \frac{d^2\boldsymbol{\Delta}_\perp}{(2\pi)^2} \exp(-i\boldsymbol{\Delta}_\perp \cdot \boldsymbol{b}_\perp) H^f(x, 0, -\boldsymbol{\Delta}_\perp^2)$$

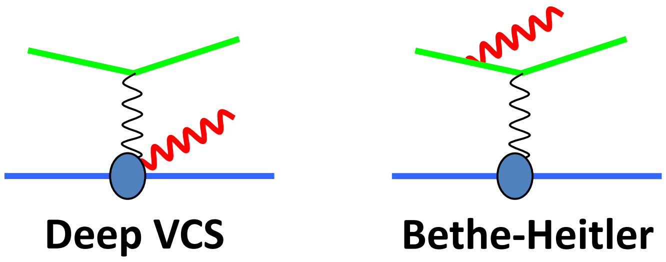
- Transverse size as function of longitudinal momentum fraction



adapted from JLAB 12 GeV CDR

DVCS

- DVCS can be separated from BH and constrain the GPD *H* e.g. using cross-sections for different μ beam charge & spin (**e_μ** & **P_μ**)



- Note: $\mu^\pm$ have opposite polarisation at COMPASS

$$d\sigma^{\mu p \to \mu p \gamma} = d\sigma^{BH} + d\sigma_0^{DVCS} + P_\mu d\Delta\sigma^{DVCS} + e_\mu \mathrm{Re}\, I + P_\mu e_\mu \mathrm{Im}\, I$$

Charge & Spin difference and sum:

$$\mathcal{S} = d\sigma^{\overleftarrow{+}} + d\sigma^{\overrightarrow{-}} = 2(d\sigma^{BH} + d\sigma_0^{DVCS} + \mathrm{Im}\, I)$$

$$\mathcal{D} = d\sigma^{\overleftarrow{+}} - d\sigma^{\overrightarrow{-}} = 2(d\sigma_0^{DVCS} + \mathrm{Re}\, I)$$

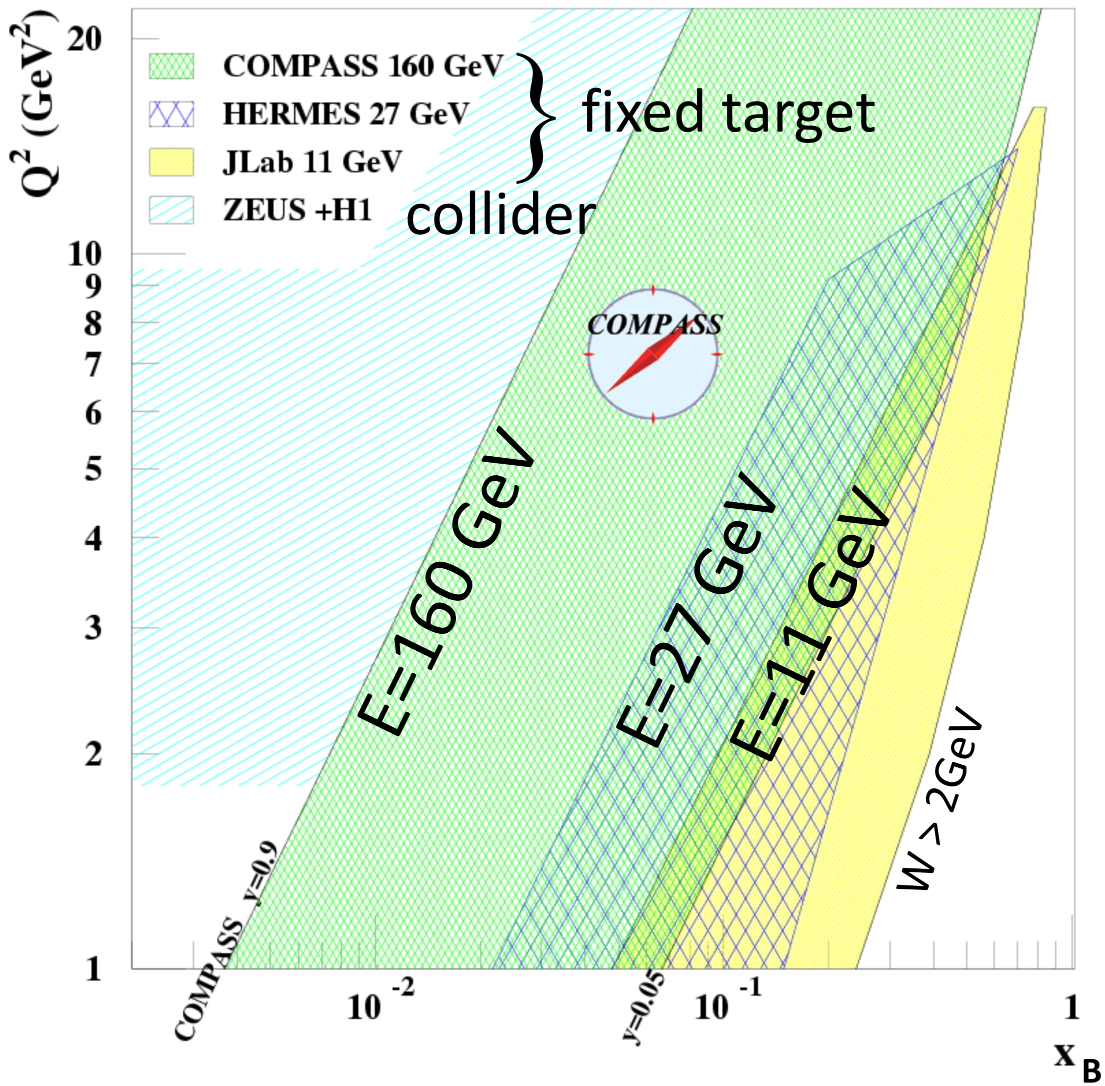
Im and Re related to

$$H(x = \xi, \xi, t)$$

$$\mathcal{P} \int dx\, H(x, \xi, t)/(x - \xi)$$

DVCS

- DVCS is the cleanest process to determine GPDs
- need a world-wide effort
- global analysis over large kinematic range mandatory
- COMPASS-II: from HERA to JLAB 12 GeV kinematics

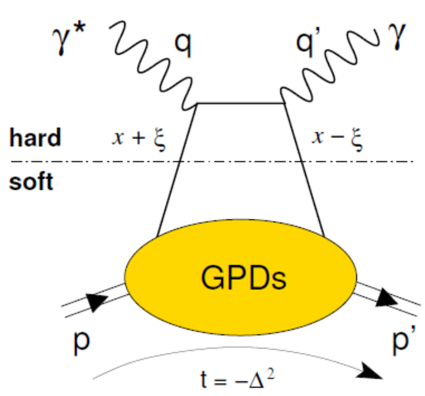


transverse proton size

- The distance $\langle r_\perp^2 \rangle$ between struck quark and spectator c.m. given by *t*-slope of DVCS cross-section σ_0 (as function of x_{Bj}, LO)

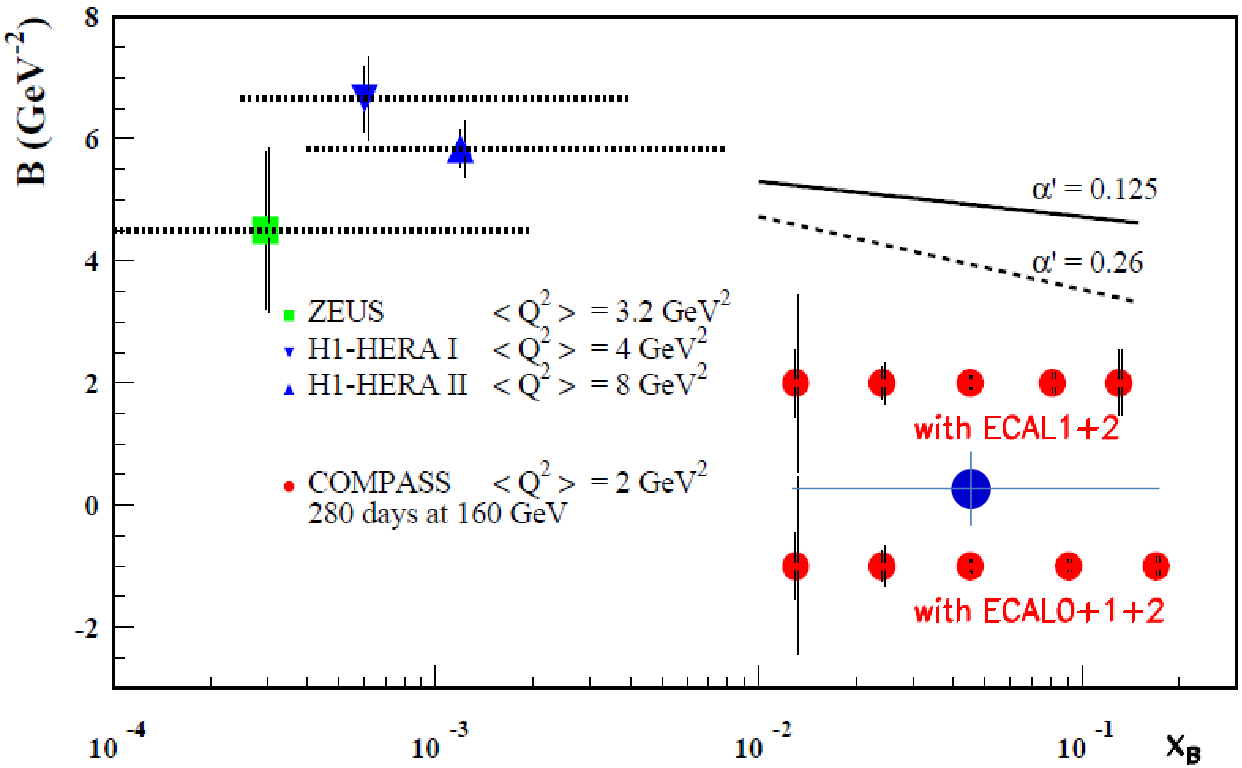
$$\frac{d\sigma_0^{DVCS}}{dt} \propto \exp(-B(x_B)|t|) \qquad \langle r_\perp^2(x_B)\rangle \approx 2B(x_B)$$

- Reminder $\mathcal{S} = 2(d\sigma^{BH} + d\sigma_0^{DVCS} + Im\, I)$
- Subtract BH from $\mathcal{S}$, integrate over $\phi \rightarrow \sigma_0$
- H1 found 0.65 ± 0.02 fm at $x_{Bj} \approx 10^{-3}$
- Parametrisation $B(x_B) = B_0 + 2\alpha' \log \frac{x_0}{x_B}$



projected t-slope & transv. size

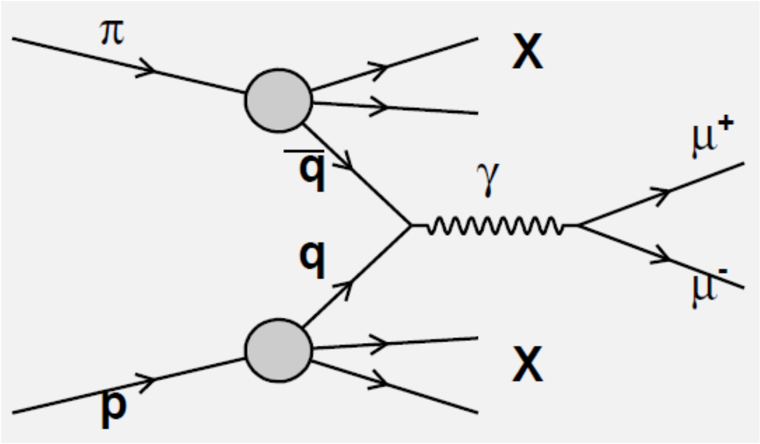
- COMPASS-II projection, 2 years of data taking ●, pilot run 2012 ●
- x_B region unique to COMPASS
- transition from HERA → HERMES/JLab



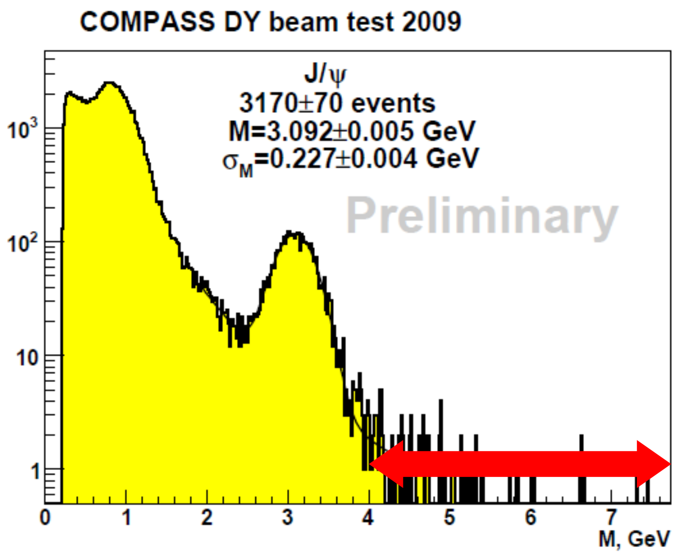
$$\langle r_\perp^2(x_B)\rangle \approx 2 \cdot B(x_B)$$

Drell–Yan Process

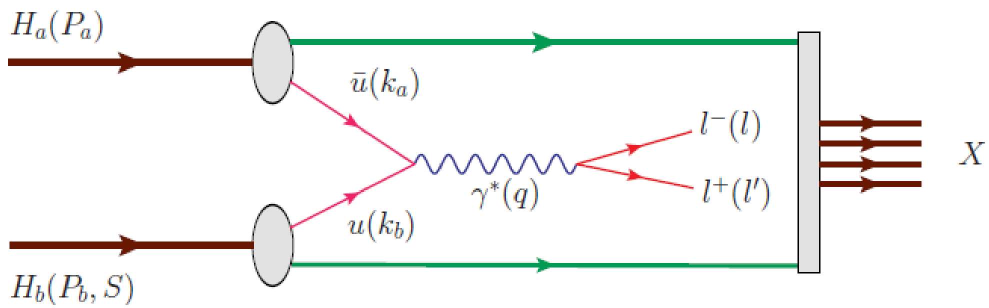
- No fragmentation function involved
- Convolution of two PDFs
- Best: pol. antiproton–proton (long-term)
- Simpler: negative pion on pol. proton (short-term)
- Pion valence anti-u annihilates with proton u



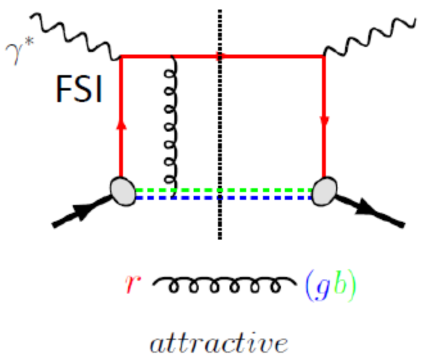
$$\sigma^{DY} \propto f_{\bar{u}|\pi^-} \otimes f'_{u|p}$$

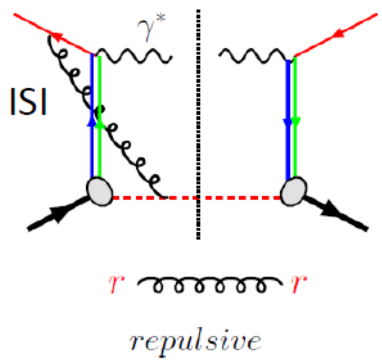


Restricted universality in SIDIS and pol. DY



T-odd TMD





`gauge link changes sign for T-odd TMD', restricted universality of T-odd TMDs

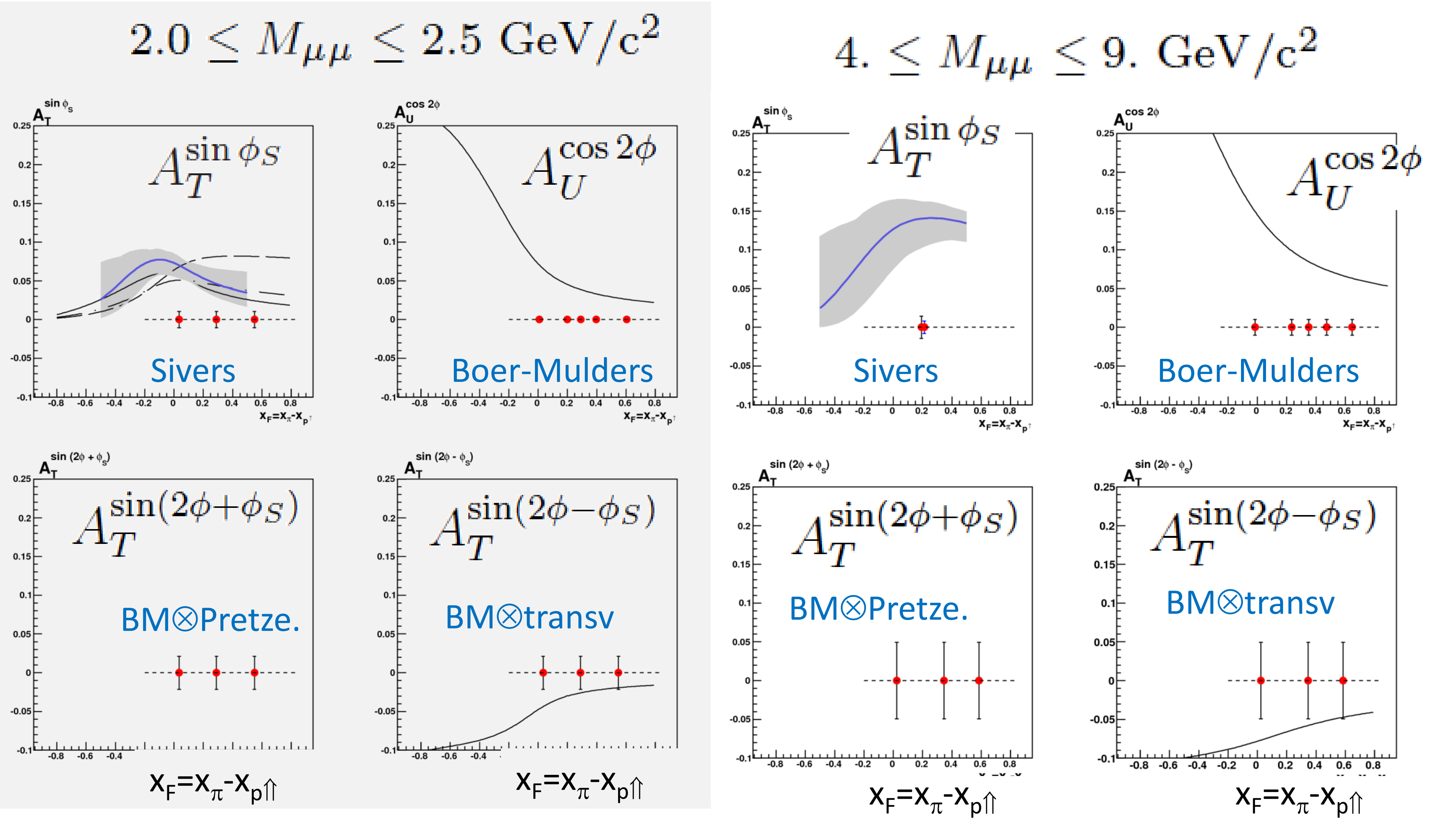
J.C. Collins, PLB536 (2002) 43

$$f_{1T}^{\perp}\Big|_{DY} = -f_{1T}^{\perp}\Big|_{DIS} \quad \text{and} \quad h_1^{\perp}\Big|_{DY} = -h_1^{\perp}\Big|_{DIS}$$

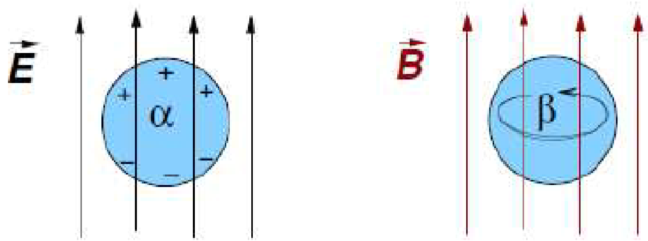
Sivers

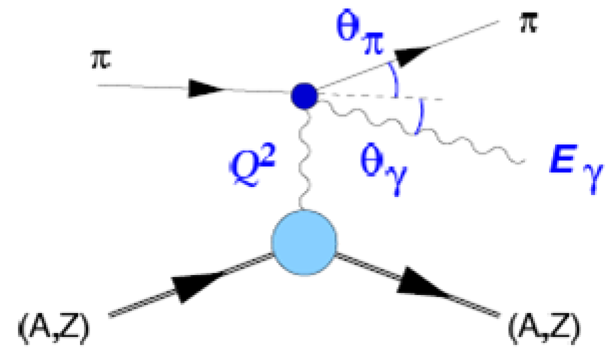
Boer-Mulders

Projected measurement



COMPASS hadron programme: Tests of χPT



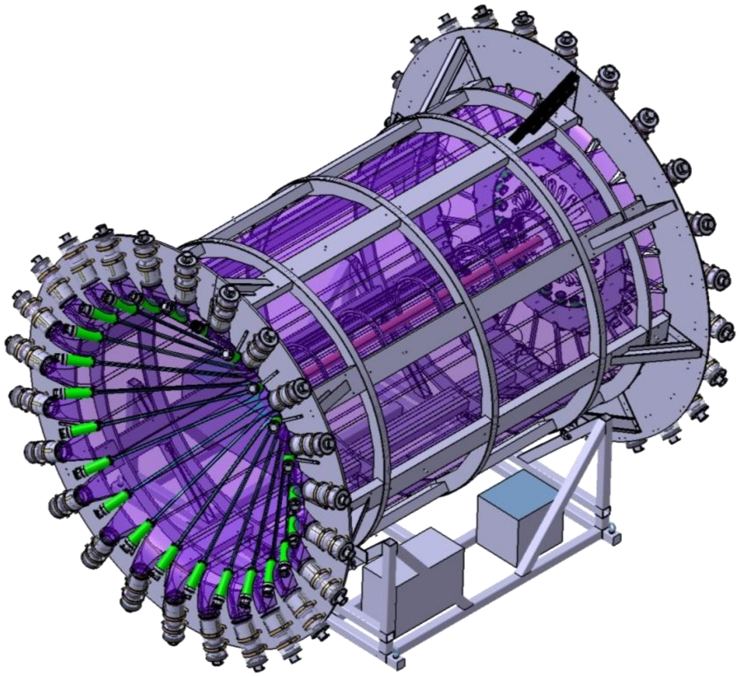


- Pion (and kaon) polarisability via Primakoff scattering
- control measurement with muons
- present exp. situation confused

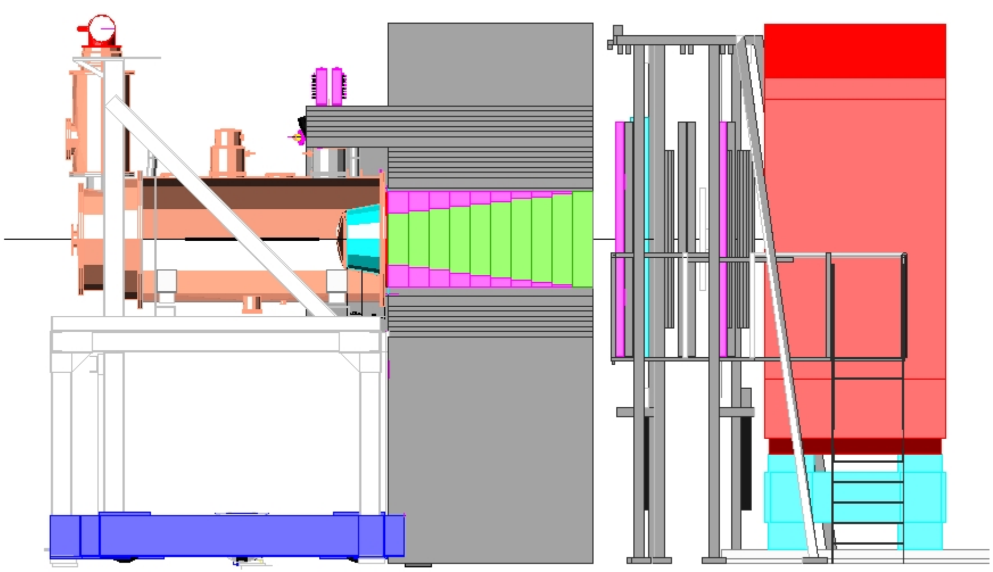
	$\alpha_\pi - \beta_\pi$ $(10^{-4}\ \mathrm{fm}^3)$	$\alpha_\pi + \beta_\pi$ $(10^{-4}\ \mathrm{fm}^3)$	$\alpha_2 - \beta_2$ $(10^{-4}\ \mathrm{fm}^3)$
2-loop ChPT prediction	5.7 ± 1.0	0.16 ± 0.10	16
COMPASS sensitivity	$\pm\, 0.66$	$\pm\, 0.025$	$\pm\, 1.94$

COMPASS-II major new equipment

- CAMERA recoil for GPD
- ECAL0, RICH upgrade



- Hadron absorber for DY



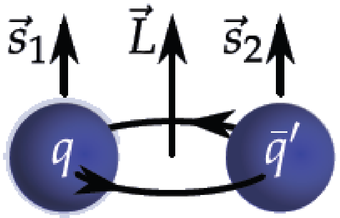
Mesons

- quantum numbers in CQM

$$S=0,1;\ \vec{J}=\vec{L}+\vec{S};\ P=(-1)^{L+1};\ C=(-1)^{L+S}$$

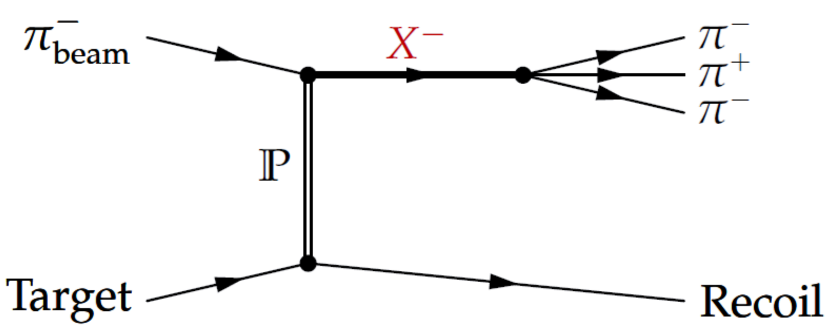
- forbidden (exotic QN's)

$$J^{PC}=0^{--},0^{+-},1^{-+},2^{+-},3^{-+},\ldots$$



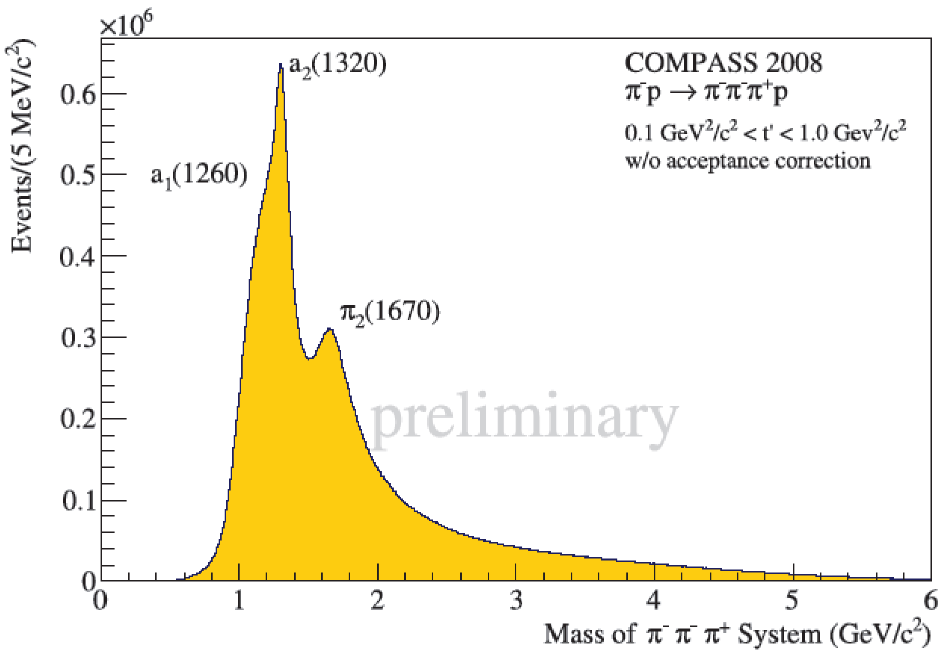
- more states in QCD:
  hybrids $|q\bar{q}g\rangle$, glueballs $|gg\rangle$, multiquark states $|q^2\bar{q}^2\rangle$

- Diffractive dissociation:

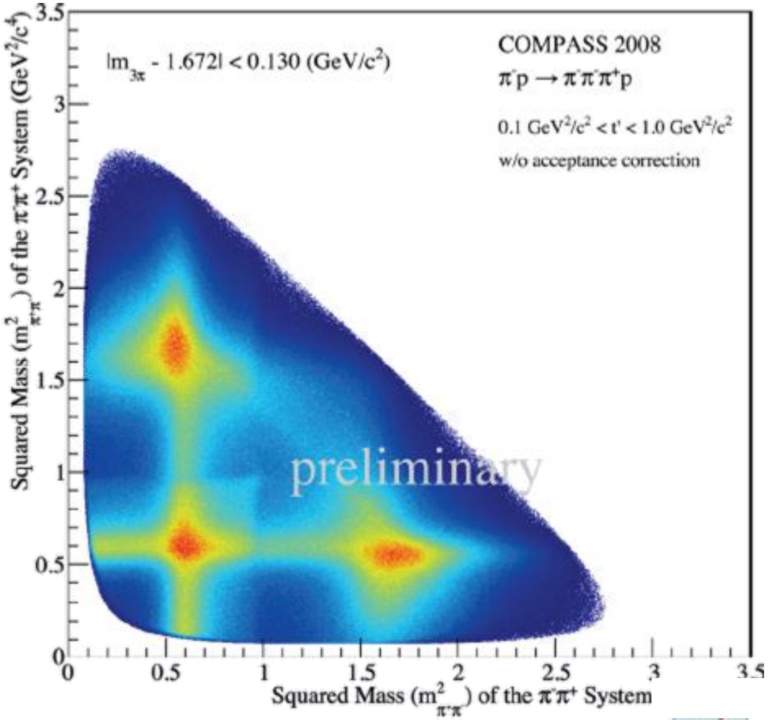


1. Example: $\pi^- p \rightarrow \pi^- \pi^+ \pi^- p$

- sample with 96 Mevents

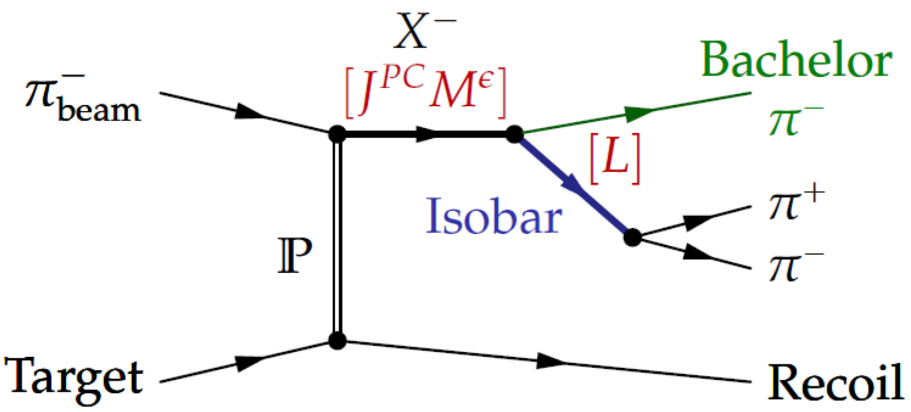


around π_2 region



$\pi^- p \rightarrow \pi^- \pi^+ \pi^- p$

- Isobar model:

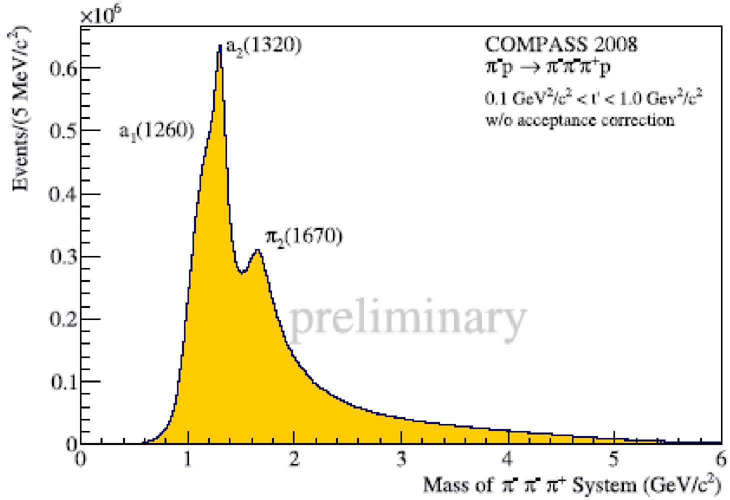


X decay is chain of successive two-body decays

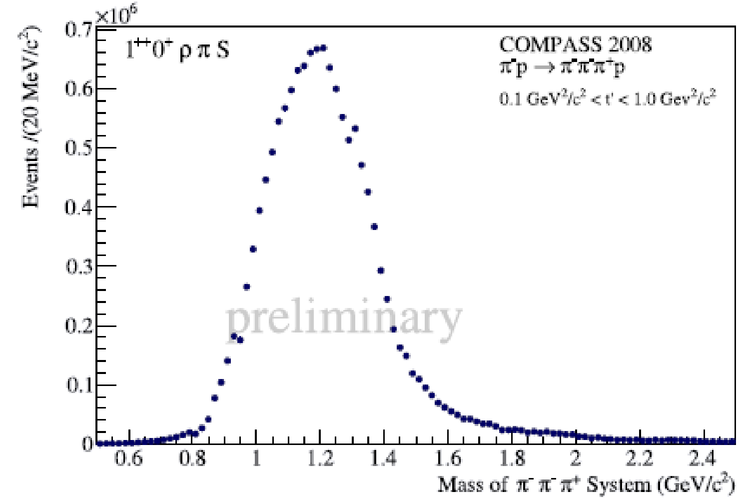
- Analysis:
  - Partial wave analysis (PWA) in mass bins with up to 53 waves
  - fit of spin-density matrix for major waves with Breit-Wigner

Major waves

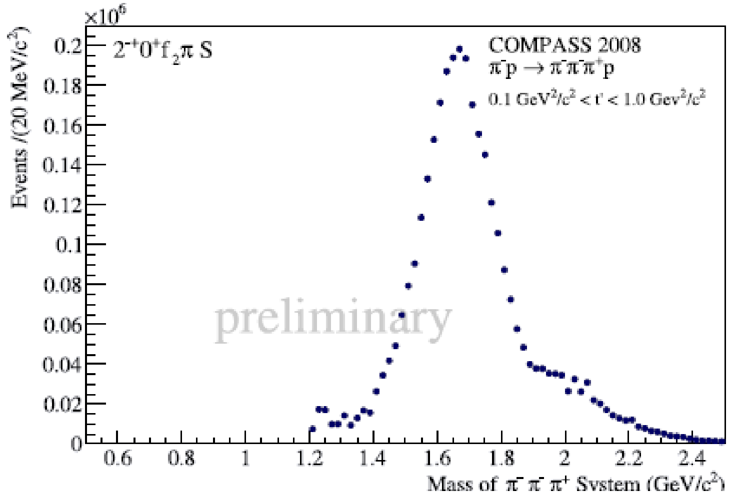
$\pi^- \pi^+ \pi^-$ invariant mass spectrum



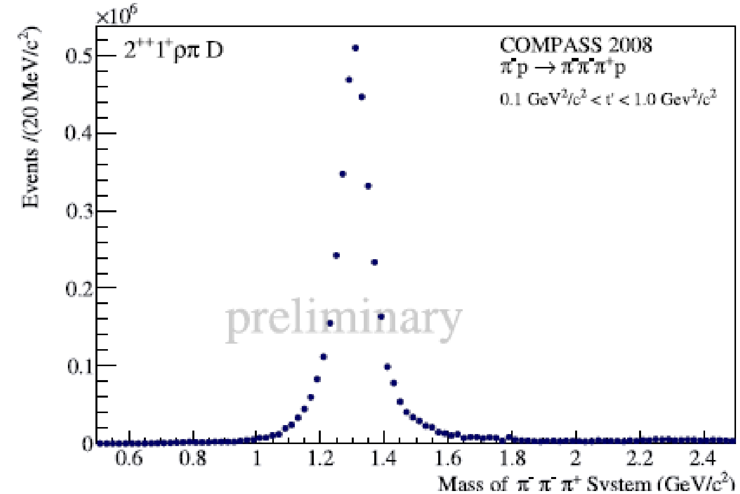
$1^{++}\,0^+\,[\rho\pi]S : a_1(1260)$



$2^{-+}\,0^+\,[f_2\pi]S : \pi_2(1670)$



$2^{++}\,1^+\,[\rho\pi]D : a_2(1320)$



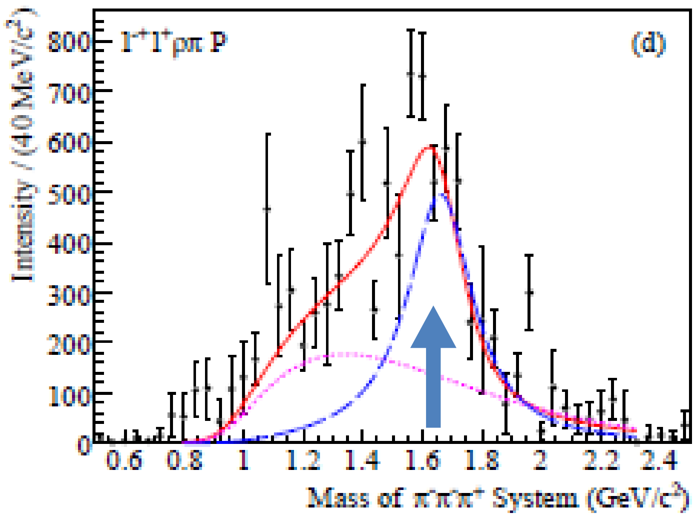
Exotic $J^{PC}=1^{-+}$ wave [$\pi_1(1600)$]

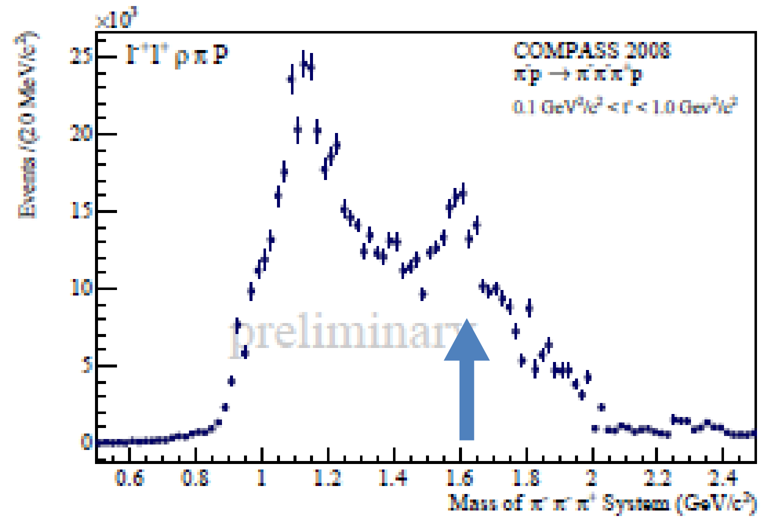
2004 **Pb**

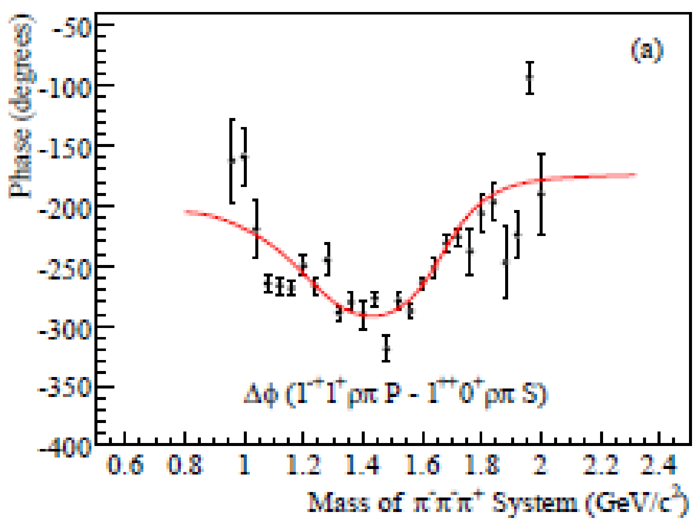
`work in progress'

2008 **p**

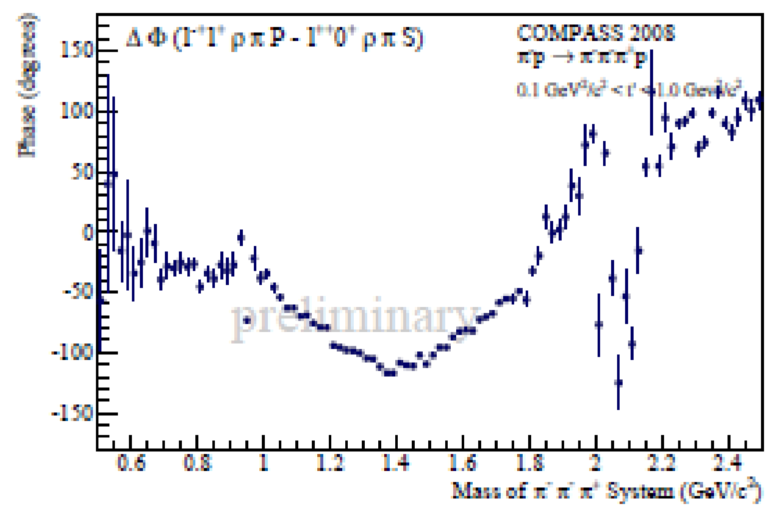
Phys. Rev. Lett. 104, 241803 (2010)



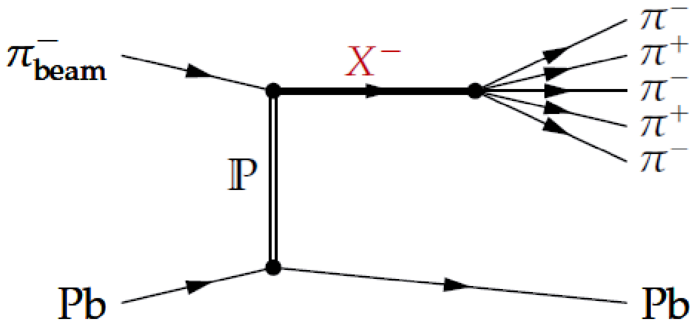




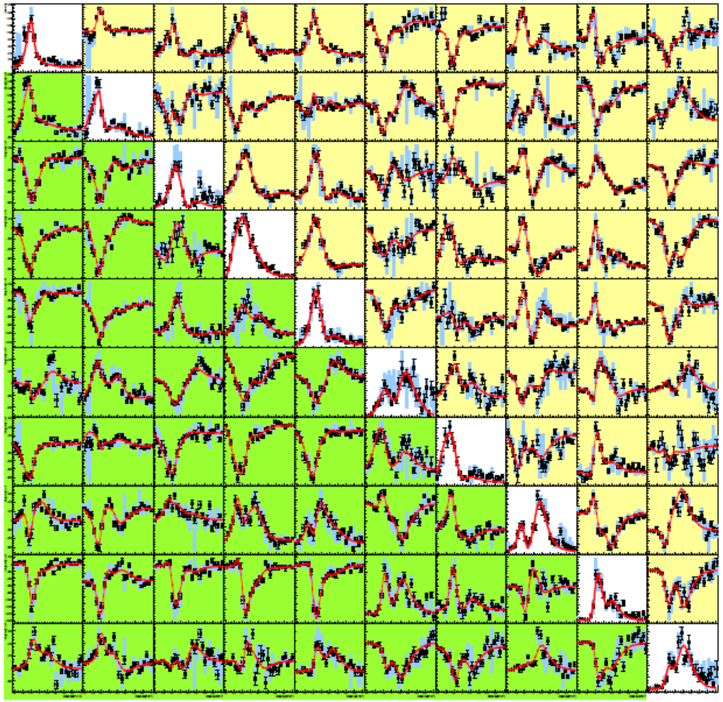
phase motion wrt a_1



2. Example: $\pi^- Pb \rightarrow \pi^- \pi^+ \pi^- \pi^+ \pi^- Pb$

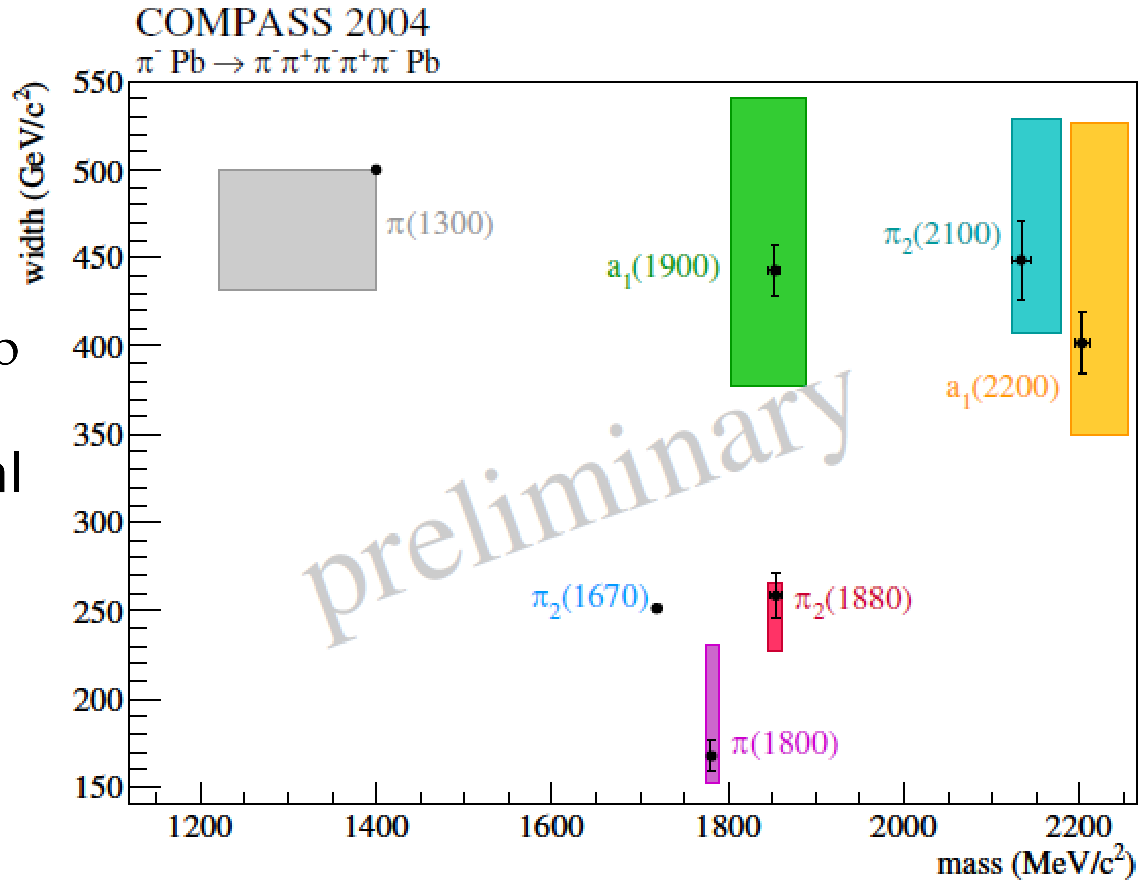


- 5 pion final state
- access to higher mass region ~ 2 GeV
- large number of possible waves
- spin density sub-matrix →
- first 5-body final-state PWA
- work in progress, still simple model



Resonances in $\pi^- Pb \rightarrow \pi^- \pi^+ \pi^- \pi^+ \pi^- Pb$

- Known states: $\pi_2(1670)$; $\pi(1800)$
- Elusive: π_2 (1880) in $a_1\rho$ and $a_2\rho$
- Two 1^{++} resonances
- Possible $\pi_2(2200)$ signal



Boxes show systematic uncertainties from wave set variations, symbols values obtained in best fit

Further analysis

Huge data set:

- neutral channels involving: π^0, η, η'
- glue balls searches in $pp \rightarrow p_{\mathrm{fast}}\pi^+\pi^-p_{\mathrm{slow}}$
- different t ranges
- OZI rule
- etc, ...

We are only at the beginning of the harvest

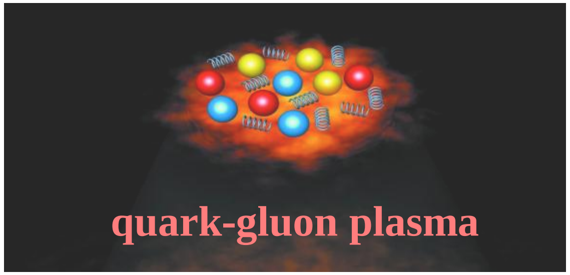
SHINE (NA61)

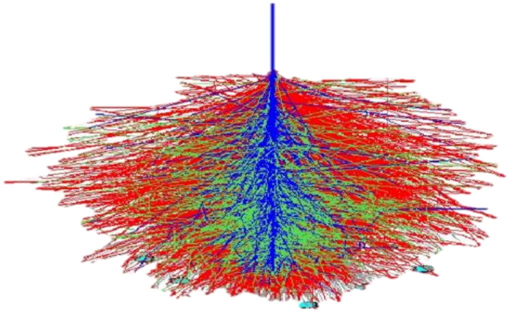
Threefold programme:

- search for the critical point in strongly interacting matter & precision study of onset of deconfinement (A+A, p+A, p+p)

- hadron production for neutrino experiments (T2K target) (p+C, π^+C, long target)

- hadron production hadron production for cosmic rays (Pierre Auger, Kaskade) (p+C, π^+C)





slides adapted from M. Gazdzicki & Z. Fodor


LHC
SHINE
NA61
COMPASS
SPS
DIRAC

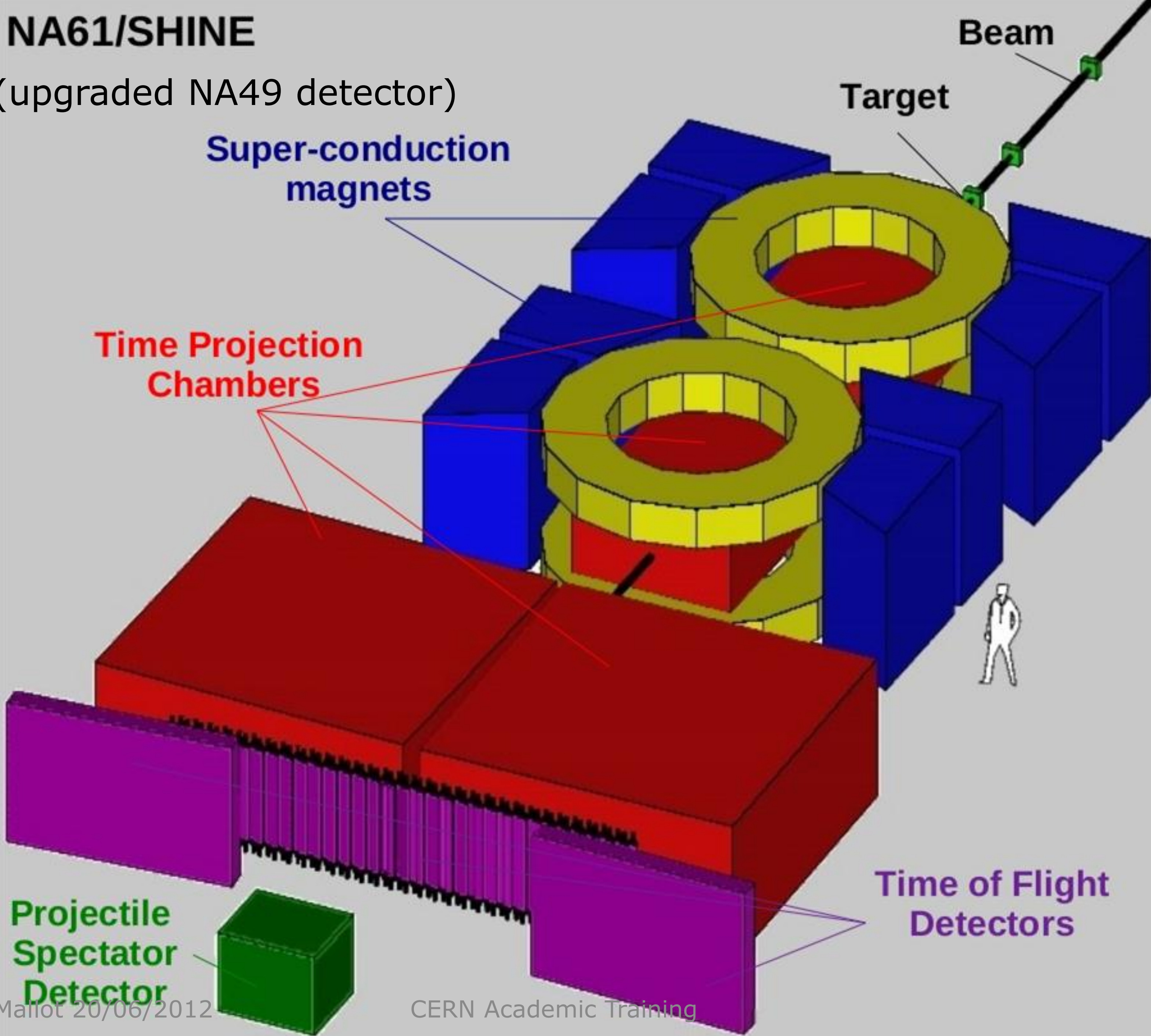
NA61:

136 physicists from 27 institutes and 14 countries:

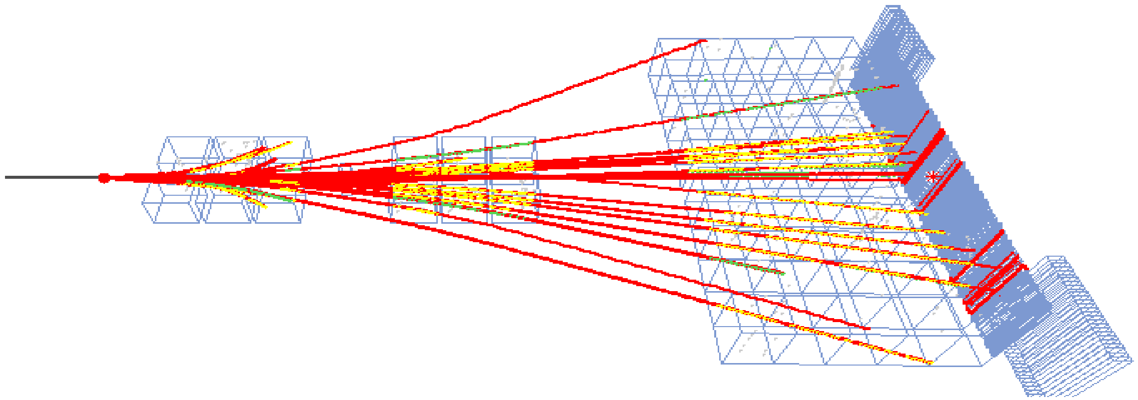
University of Athens, Athens, Greece
University of Belgrade, Belgrade, Serbia
University of Bergen, Bergen, Norway
University of Bern, Bern, Switzerland
KFKI IPNP, Budapest, Hungary
Jagiellonian University, Cracow, Poland
Joint Institute for Nuclear Research, Dubna, Russia
Fachhochschule Frankfurt, Frankfurt, Germany
University of Frankfurt, Frankfurt, Germany
University of Geneva, Geneva, Switzerland
Forschungszentrum Karlsruhe, Karlsruhe, Germany
Institute of Physics, University of Silesia, Katowice, Poland
Jan Kochanowski Univeristy, Kielce, Poland
Institute for Nuclear Research, Moscow, Russia
University of Nova Gorica, Nova Gorica, Slovenia
LPNHE, Universites de Paris VI et VII, Paris, France
Faculty of Physics, University of Sofia, Sofia, Bulgaria
St. Petersburg State University, St. Petersburg, Russia
State University of New York, Stony Brook, USA
KEK, Tsukuba, Japan
Soltan Institute for Nuclear Studies, Warsaw, Poland
Warsaw University of Technology, Warsaw, Poland
University of Warsaw, Warsaw, Poland
Univeristy of Wroclaw, Wroclaw, Poland
Universidad Tecnica Federico Santa Maria, Valparaiso, Chile
Rudjer Boskovic Institute, Zagreb, Croatia
ETH Zurich, Zurich, Switzerland

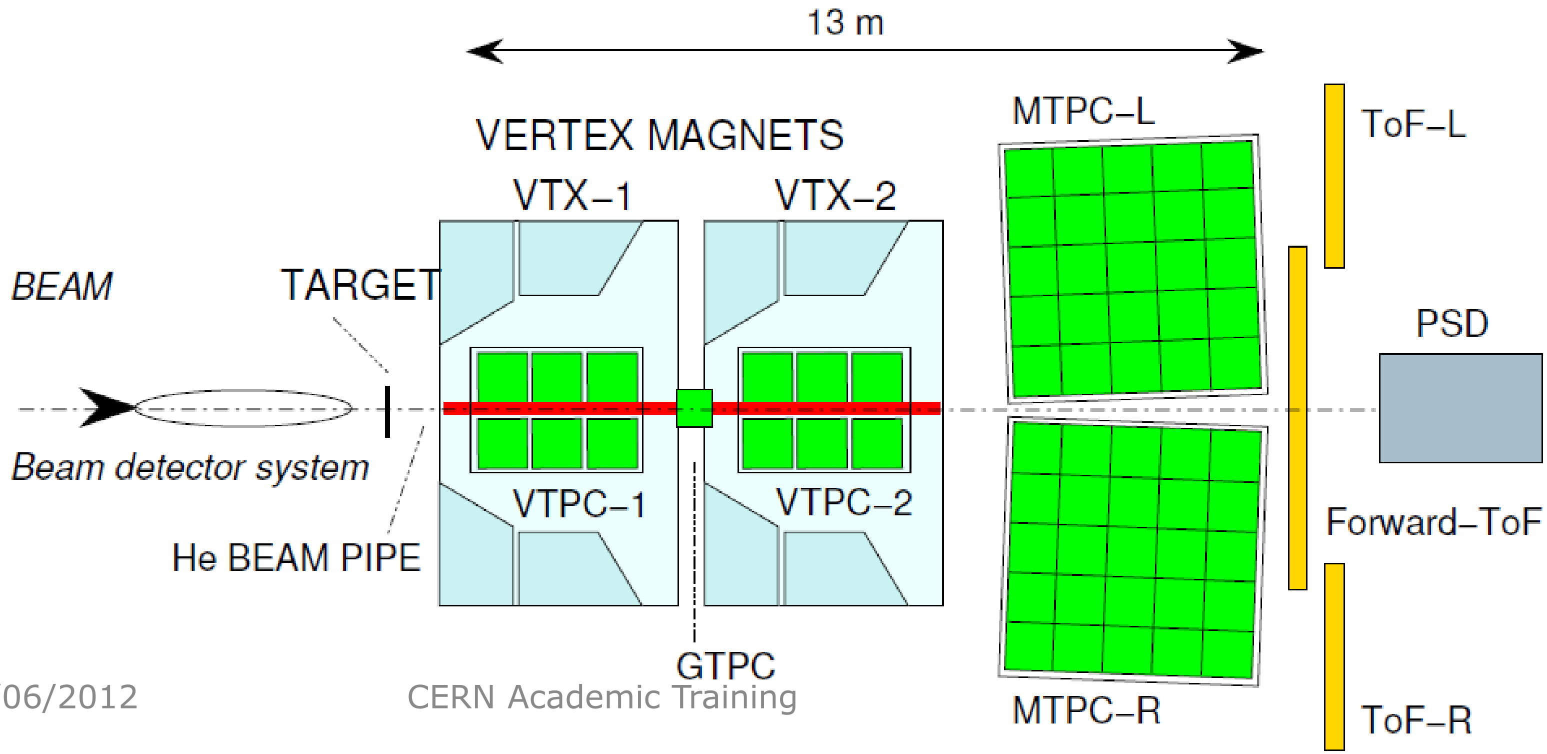
NA61/SHINE

(upgraded NA49 detector)



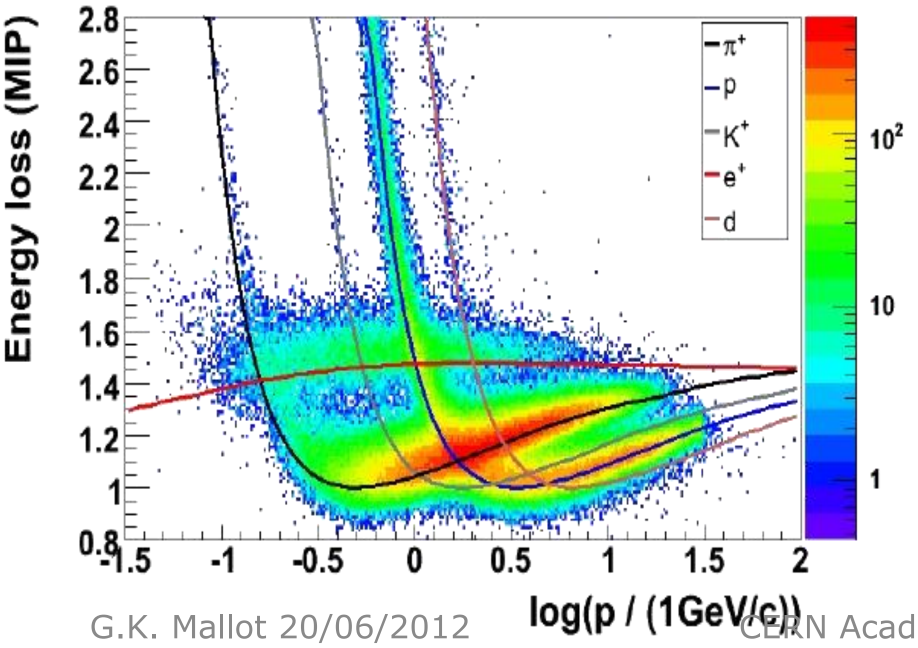
NA61 spectrometer

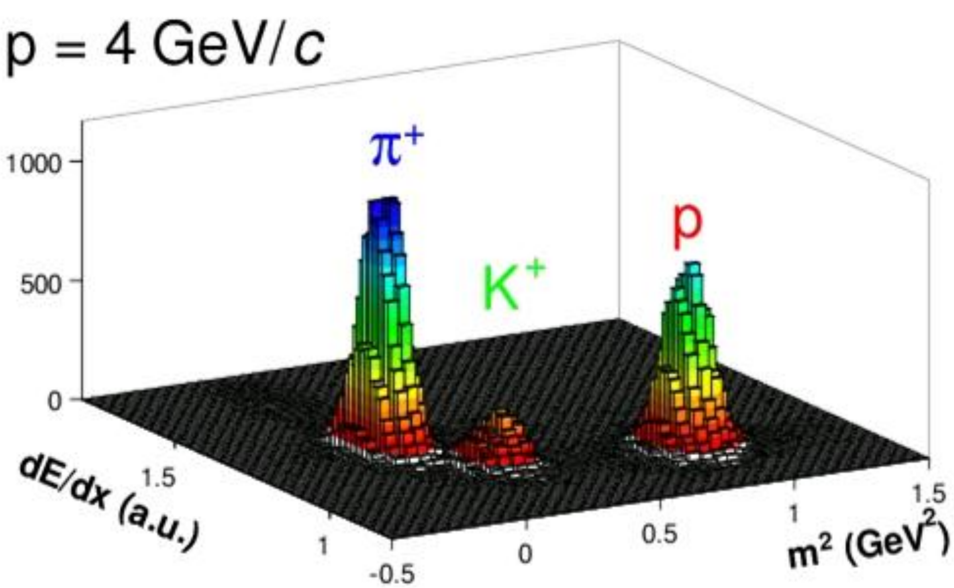




Particle identification

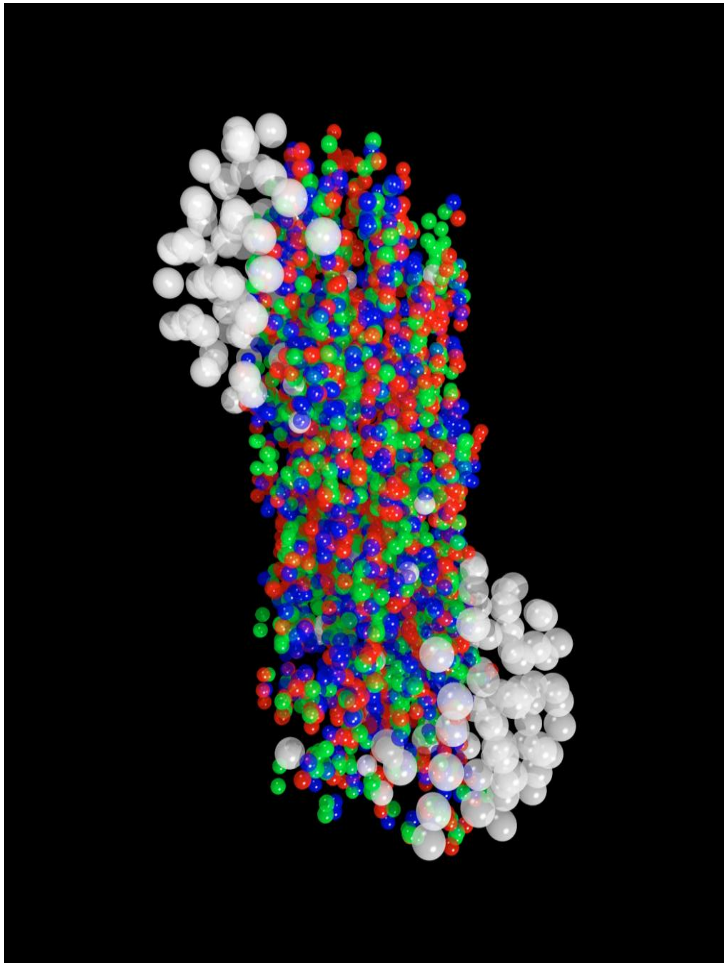
- Momentum measured with 2 superconducting magnets and TPCs (1.5 and 1.2 T)
- Energy loss measurements in the TPCs
- Time-of-flight counters at low *p*





Onset of deconfinement

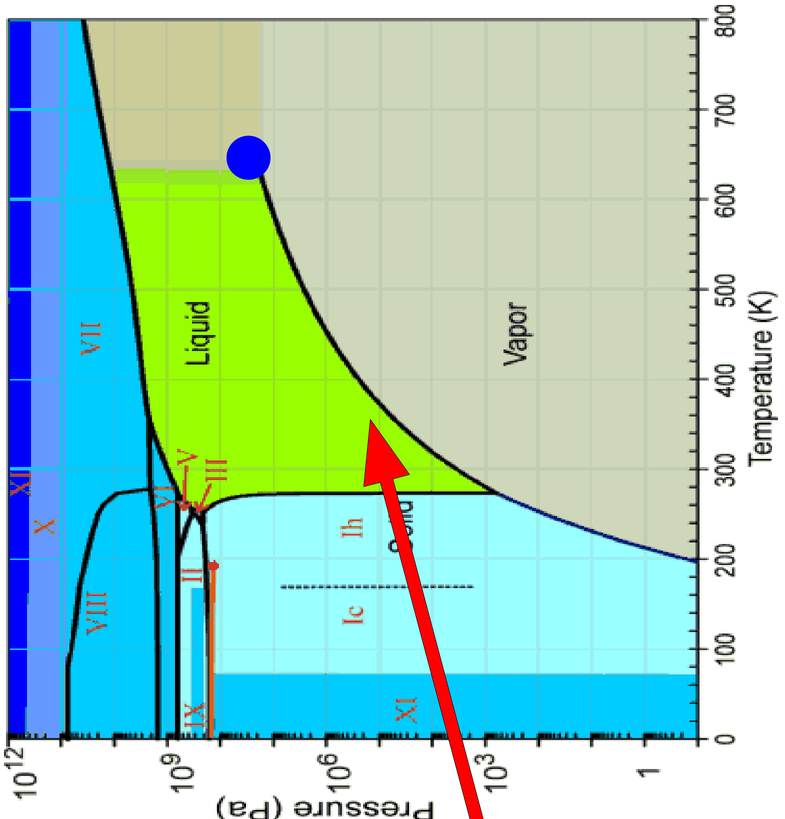
- Phase transition from hadron gas to Quark-Gluon-Plasma
- Equilibrium of early state (fire ball) reflected in produced hadron multiplicities
- Rapid changes of energy dependence of hadron production (discovery NA49)
- Described by statistical model of the early stage SMES
- Endpoint (critical point) of phase boundary in SPS range!



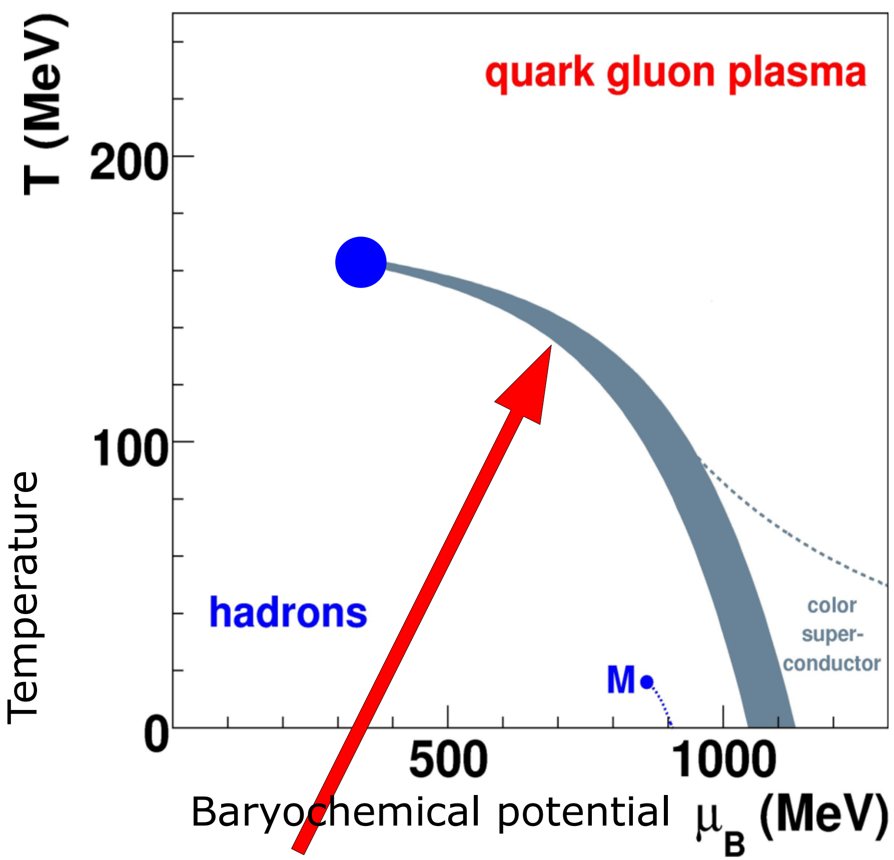
Pb-Pb collision (UrQMD)

EM and strong phase diagrams

water



strongly interacting matter

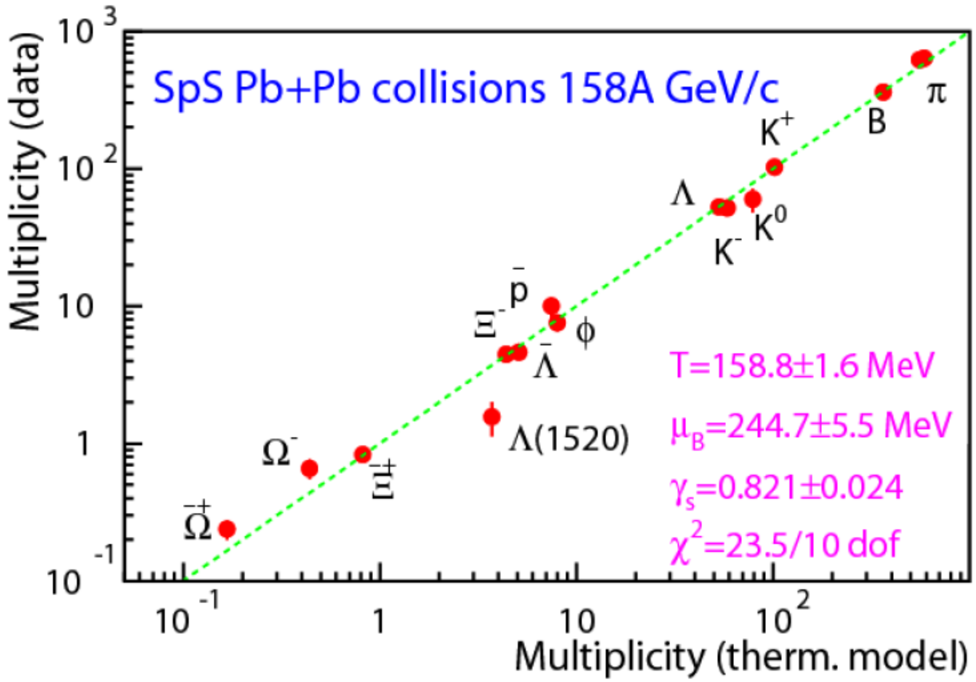


1^{st} order phase transition

critical point

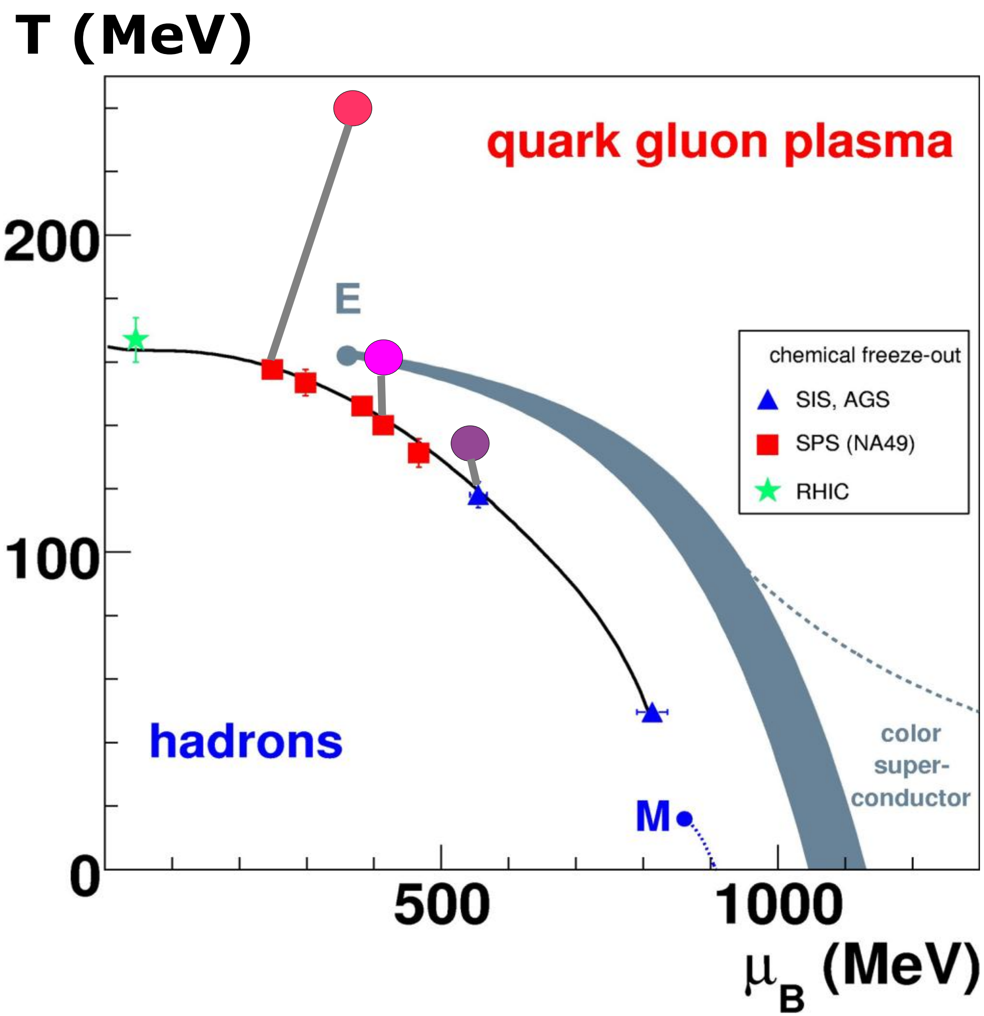
Hadron multiplicities

- Fit chemical freeze-out temperature T and chemical potential μ_B (Hadron gas model)



$$\langle n_i \rangle = \frac{(2J_i + 1)\, V}{(2\pi)^3} \int d^3p \, \frac{1}{\gamma_s^{-S_i} exp[(E_i - (\mu_B + \mu_S + \mu_Q))/T] \pm 1}$$

Onset of deconfinement



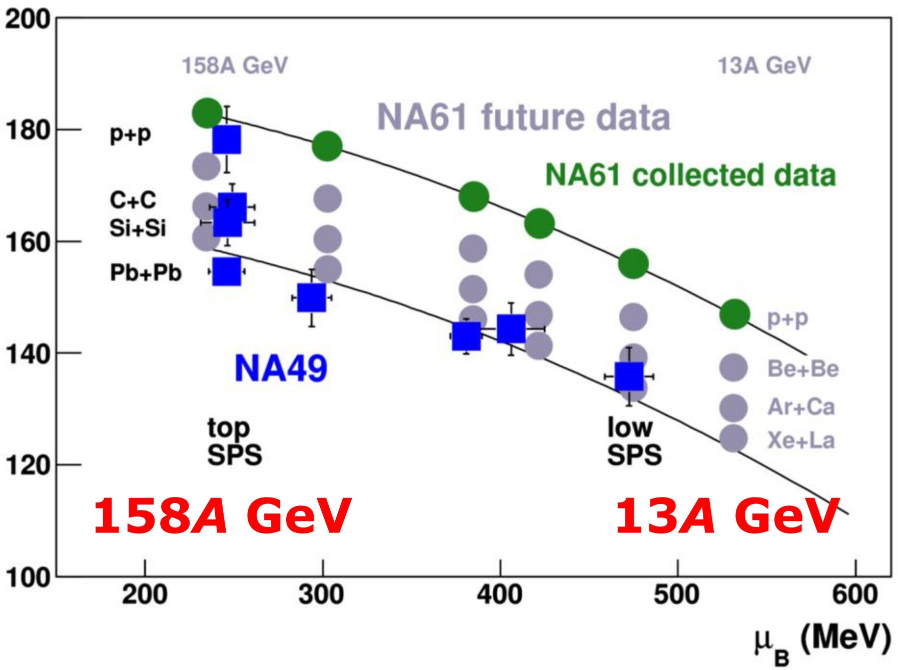
early-stage fire ball

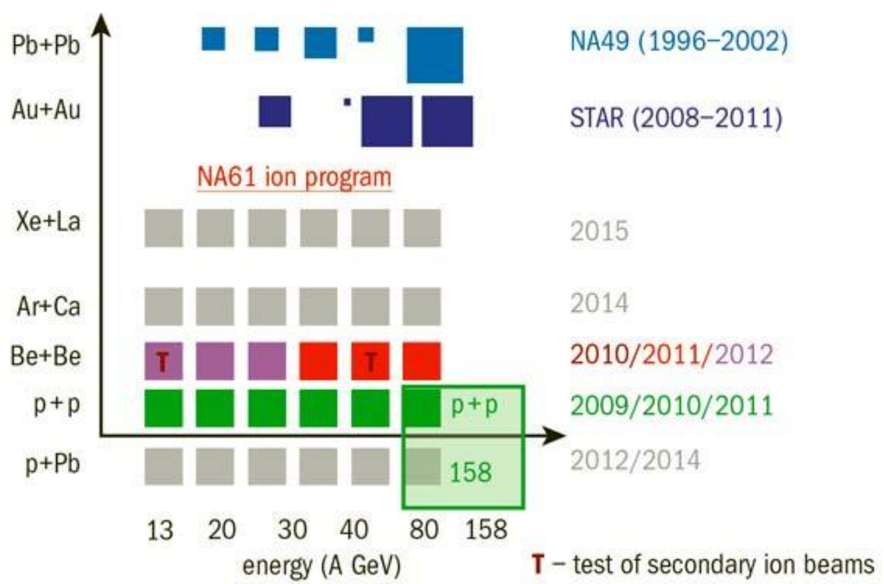
chemical freeze-out

- SPS energies in region of hypothetical critical point E
- With increasing energy crossing transition region, onset of deconfinement
- Critical point search by freeze-out point close to it
- 2D scan in system size and energy needed to study CP

2D scan in size and energy

- SPS energies 13*A*-158*A* GeV
- from p+p to Pb+Pb (system size)

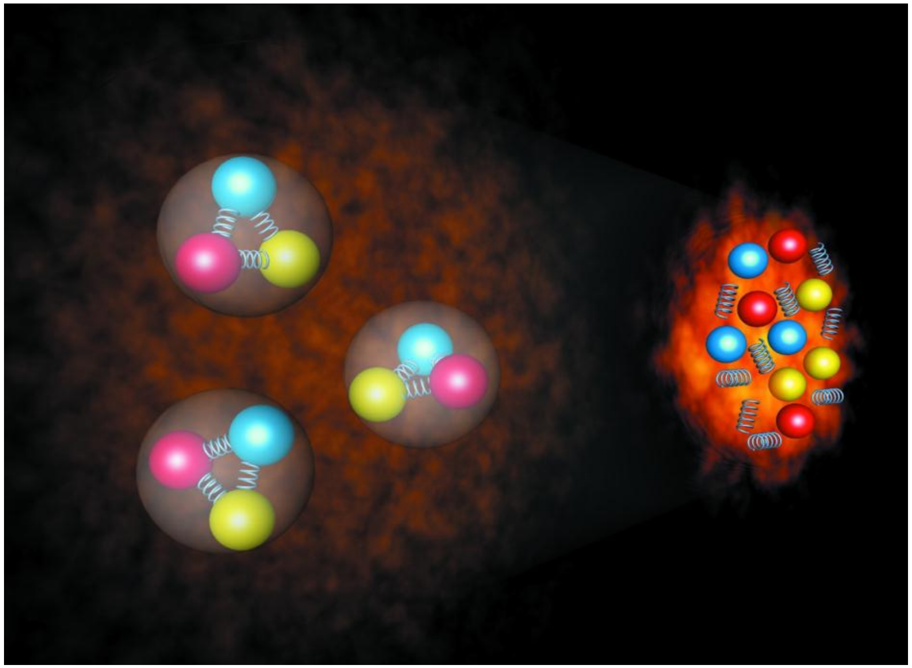




Beccatini, Manninen, Gaździcki, PRC73, 044905 (2006)

Signals of deconfinement

hadrons mixed

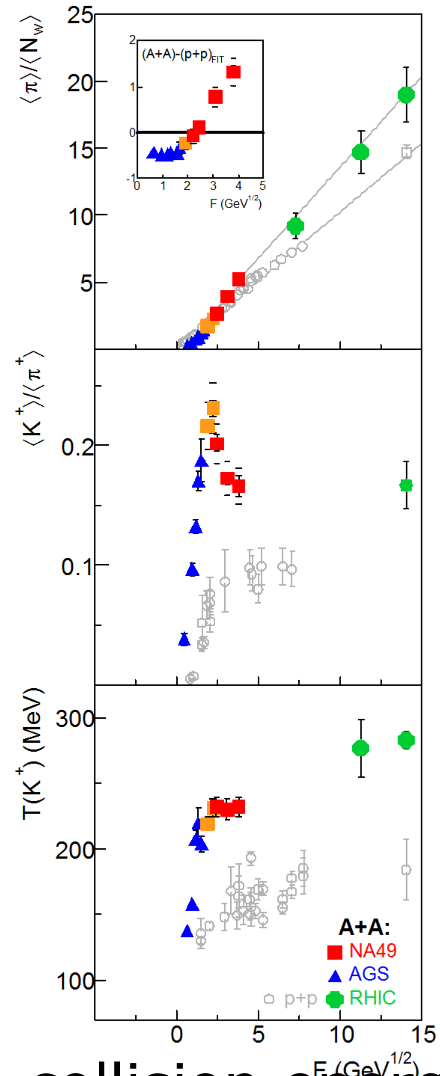


AGS SPS RHIC

collision energy

AGS SPS RHIC

hadronic observables



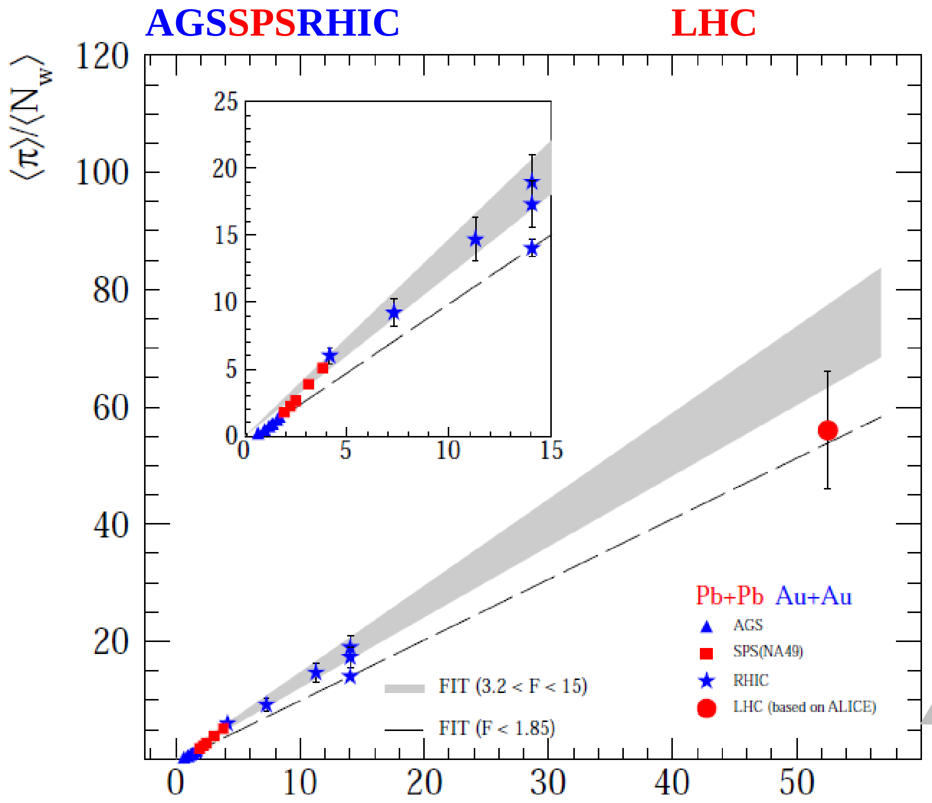
Kink

Horn

Step

collision energy

The kink in pion multiplicity



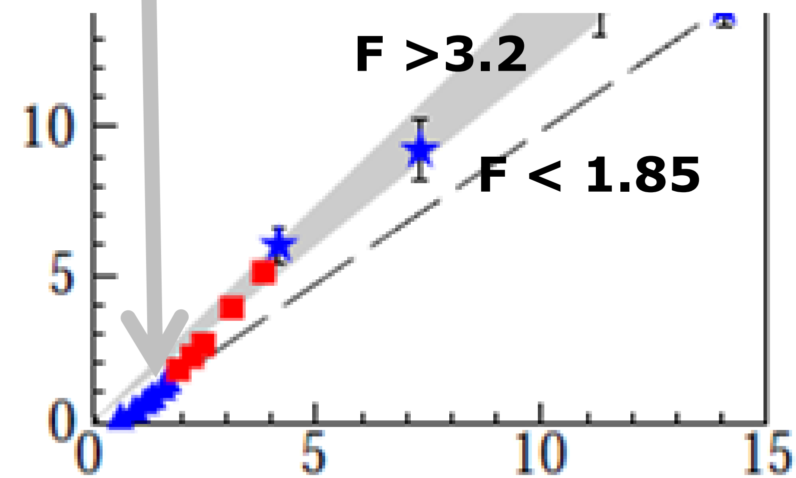
Deconfinement

↓

Increased entropy production

↓

Steepening of the increase of pion production

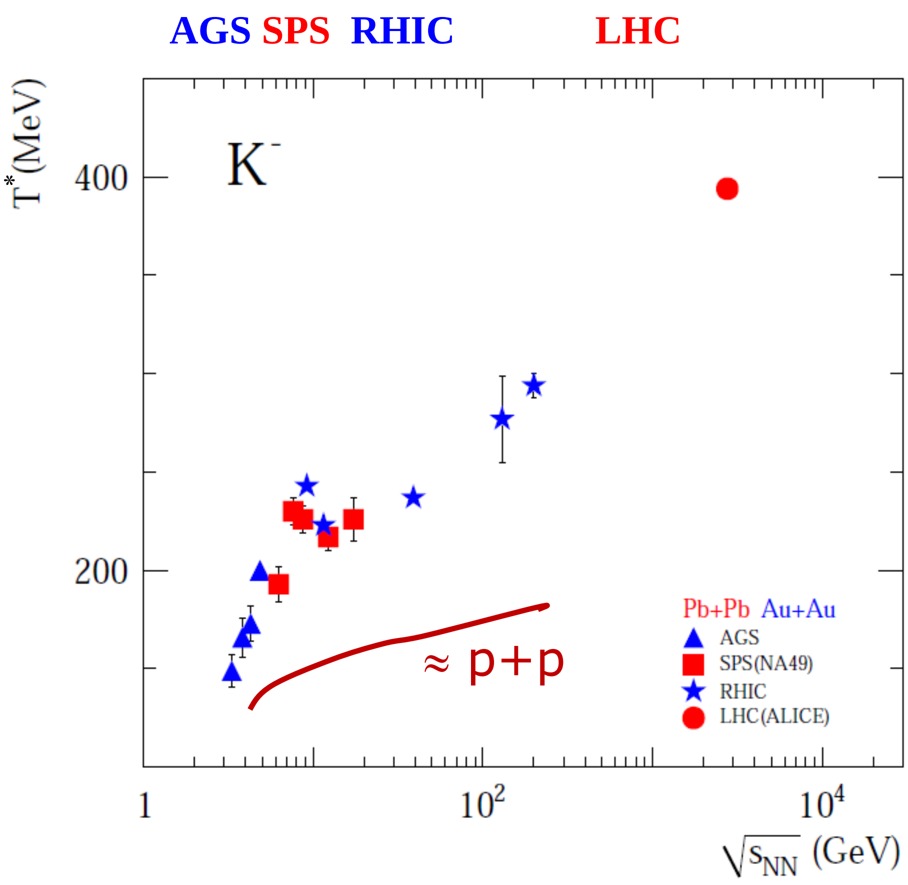


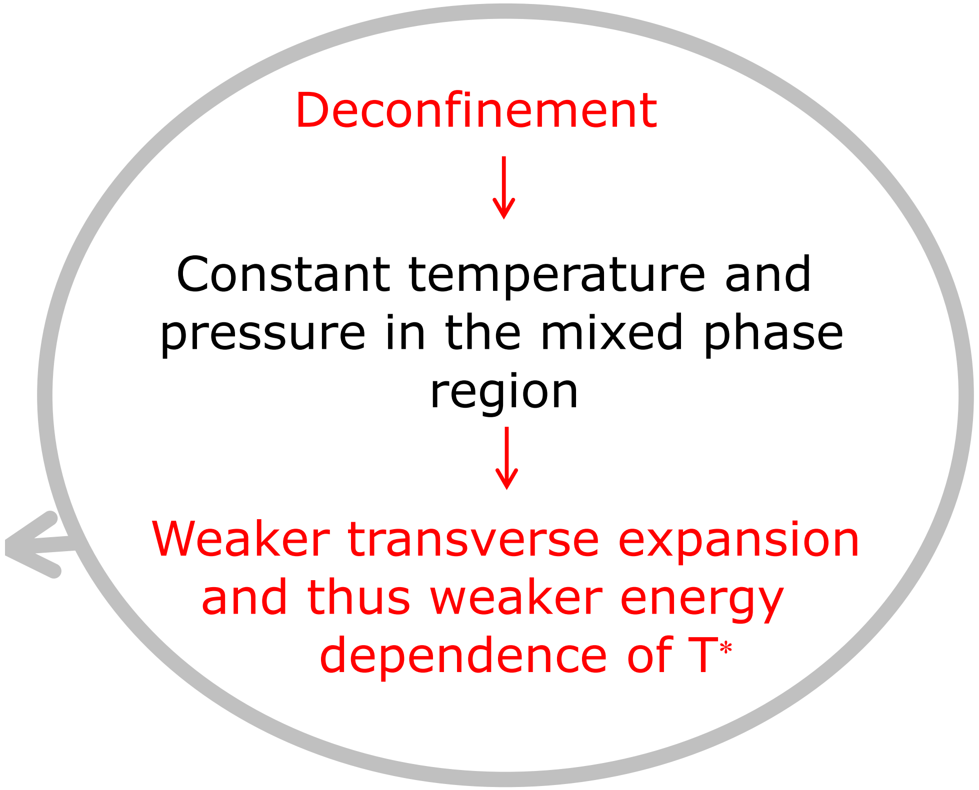
$$F \approx s_{NN}^{\frac{1}{4}}$$

$\langle \pi \rangle$ pion multiplicity

$\langle N_W \rangle$ number of interacting nucleons

The step in m_T slopes



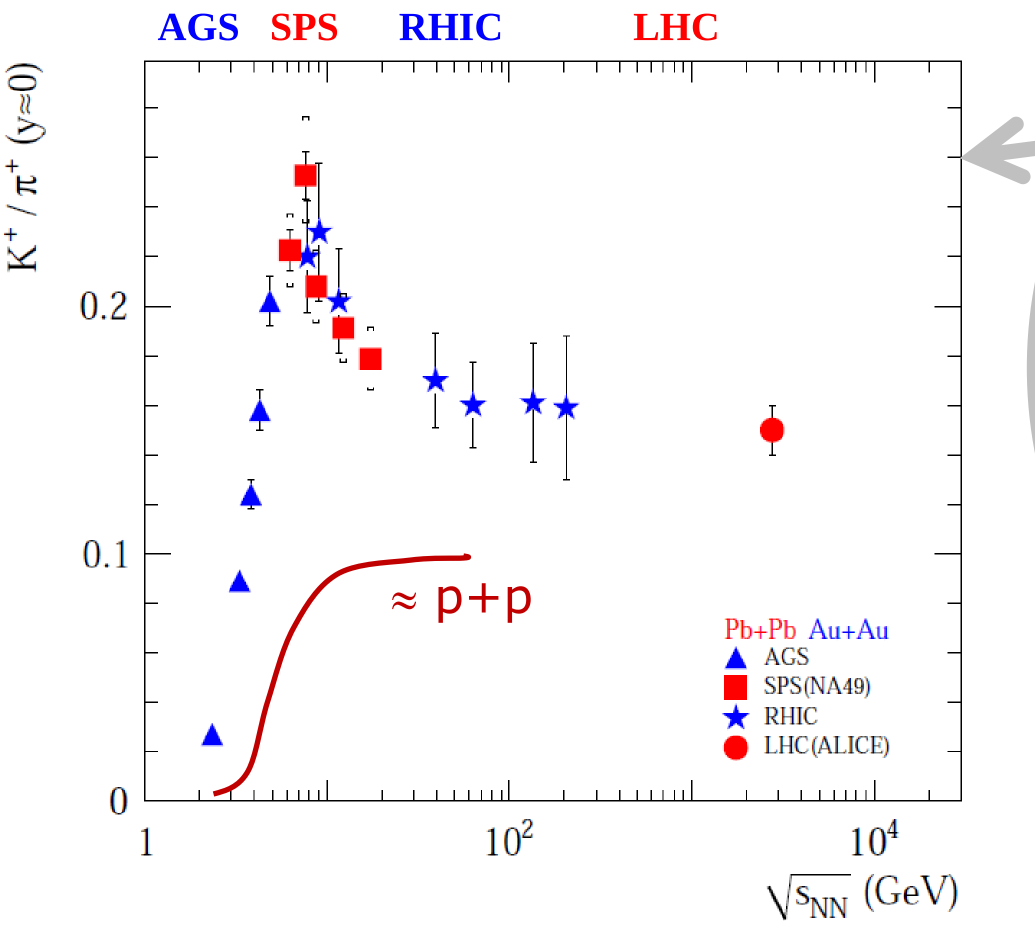


$$m_T = (m^2 + p_T^2)^{1/2}$$

$$\frac{dN}{m_T dm_T} \cong C \exp\left(-\frac{m_T}{T^*}\right)$$

T^* – inverse slope parameter of transverse mass spectra

The horn in strangeness yield



Deconfinement

↓

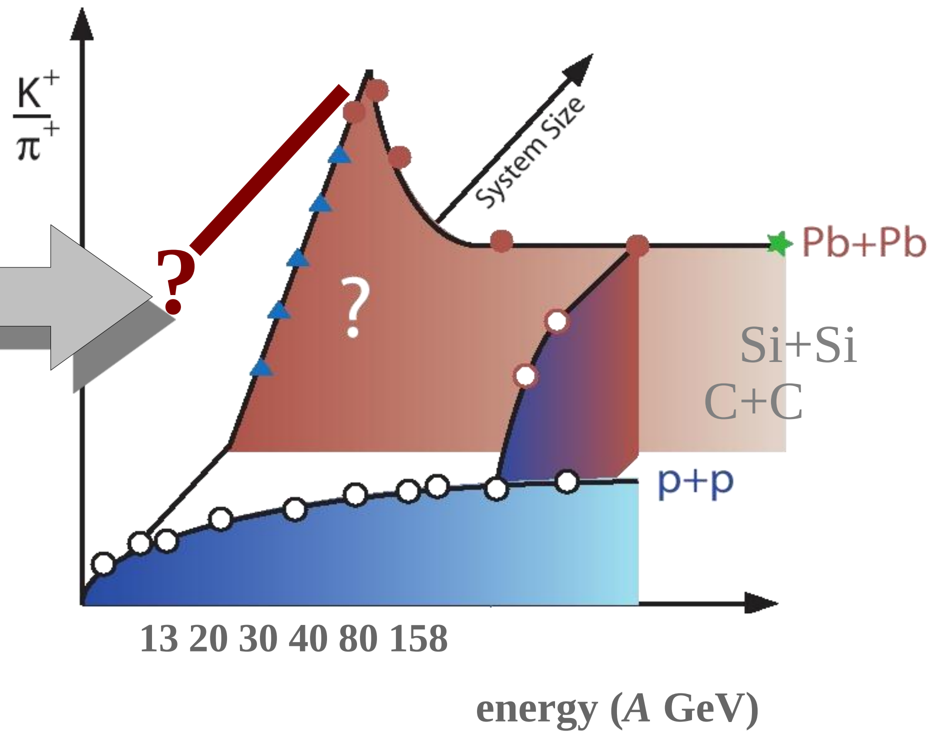
Decrease of masses of strangeness carriers and the number ratio of strange to non-strange degrees of freedom

↓

A sharp maximum in the strangeness to pion ratio

Systematic study of the onset of deconfinement

study transition with light nuclei

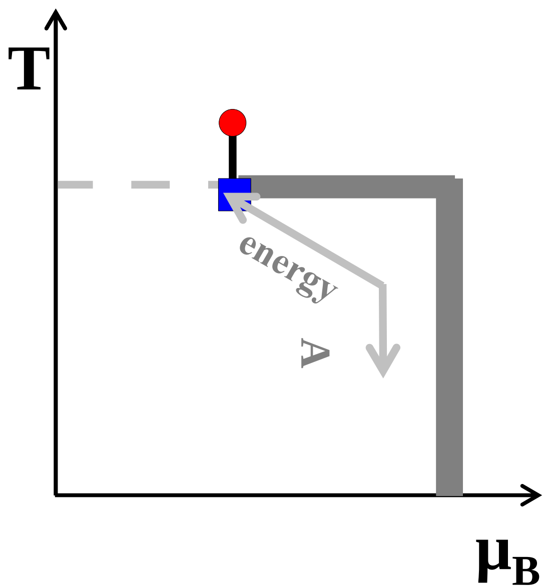


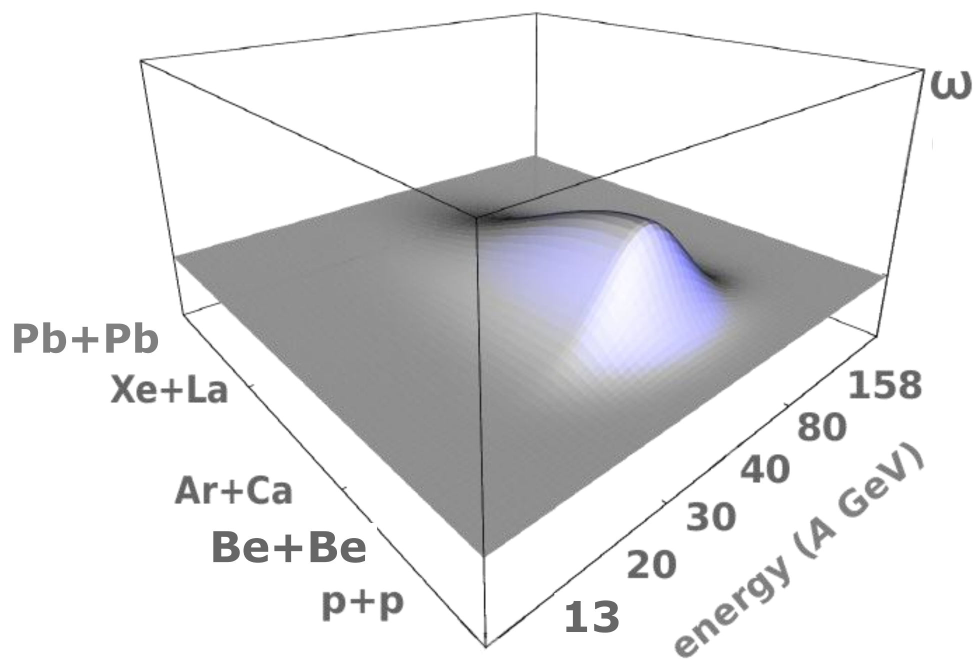
Search for the critical point

- Signal: increased fluctuations due to long-range correlations, e.g. in multiplicities (ω), particle ratios, ...

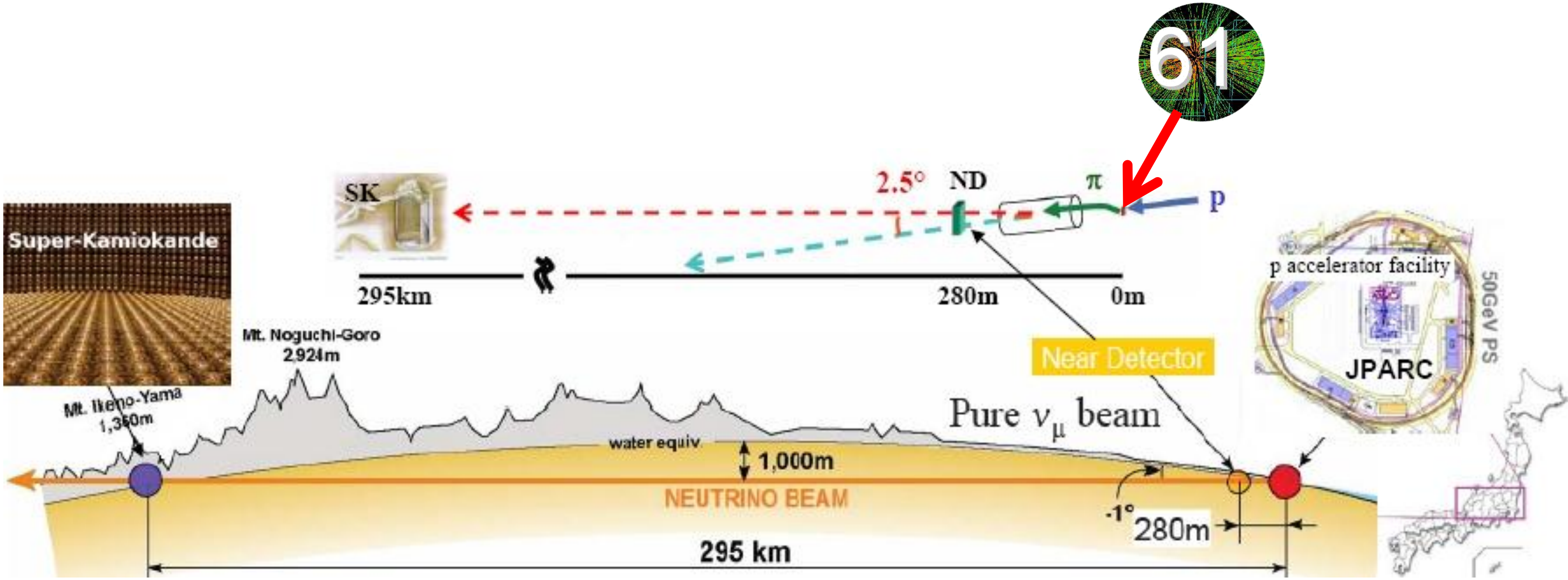
$$\omega = \frac{\langle N^2 \rangle - \langle N \rangle^2}{\langle N \rangle}$$

- Hill of fluctuations for freeze-out close to CP
- 2D scan in not too small systems with E > 30*A* GeV
- Discovery potential





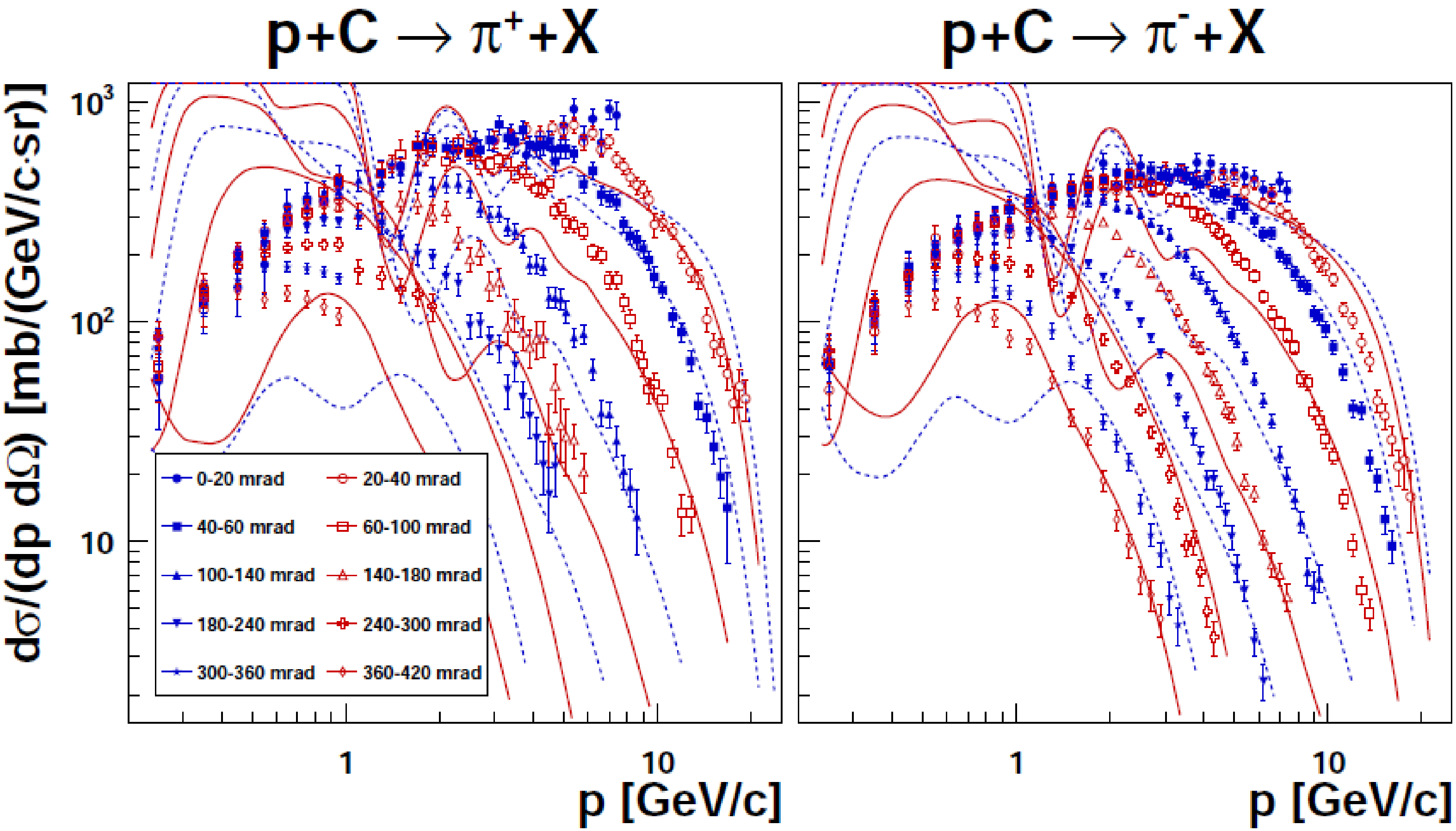
Hadron production data for T2K



- High precision data on pion and kaon production on the T2K target needed to get the initial neutrino flux

Precise data for T2K

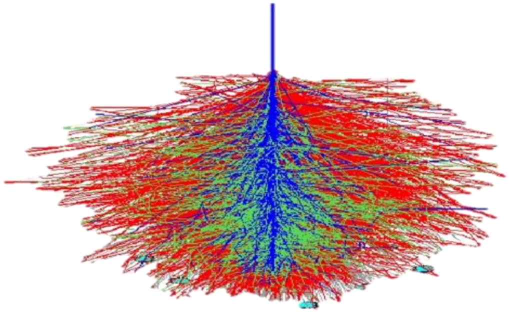
Inclusive π^+ spectra in p+C at 31 GeV/c

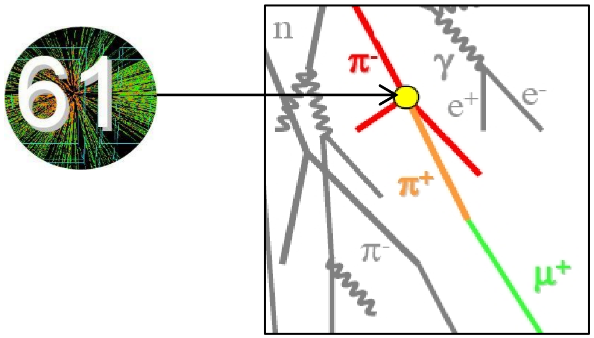


comparison to Gheisha2002

Extensive air showers

- e.g. Pierre Auger Observatory
- last interaction before muoproduction in SPS range
- important input



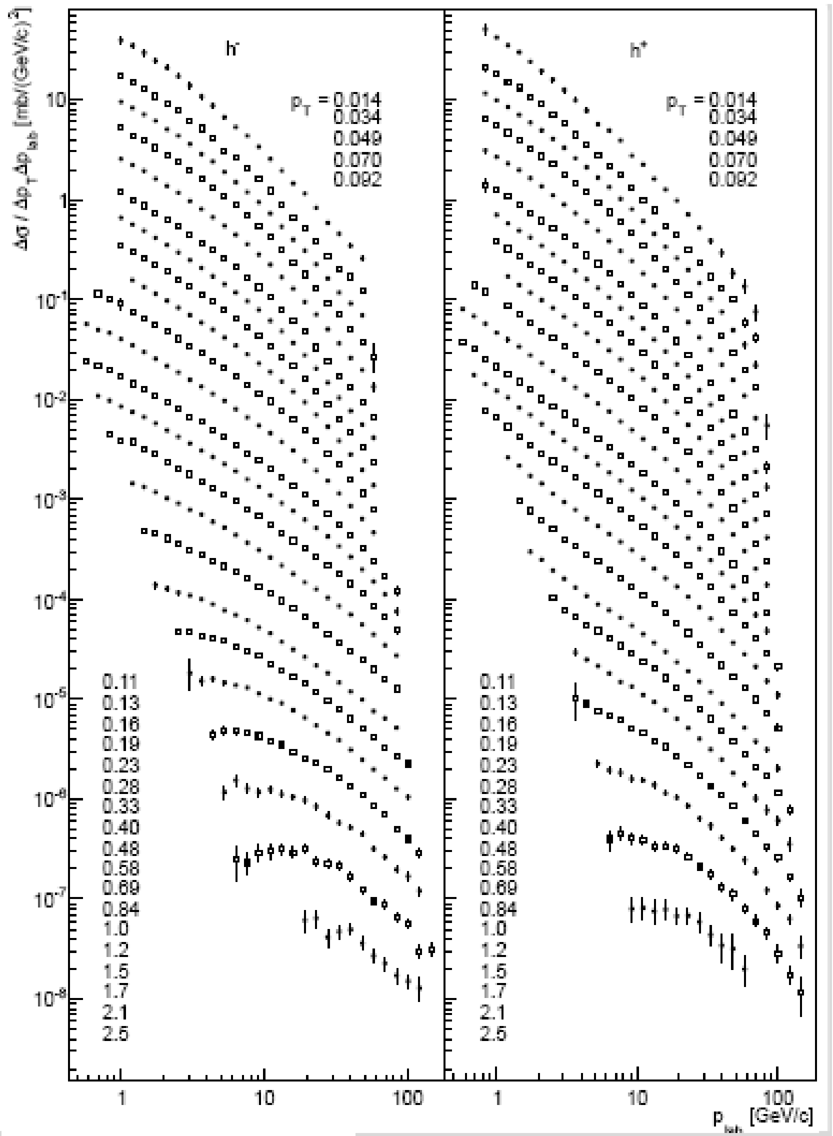


Precise spectra in π+C for PAO

Results at 350 GeV/c

also for 158 GeV/c

- Differential inclusive cross section for charged hadron production.
- Error bars: total uncertainty
- Data points are successively divided by
  - 6.0 up to $p_T = 0.034$ GeV/c,
  - 2.5 up to $p_T = 0.11$ GeV/c,
  - 2.0 up to $p_T = 0.33$ GeV/c,
  - 1.5 up to $p_T = 0.84$ GeV/c,
- no rescaling for $p_T = 0.014$ GeV/c and $p_T \geq 1$ GeV/c



SHINE summary

- The onset of deconfinement (OD) and the likely location of the critical point (CP) are at SPS energies
- Precise mapping of OD and potential discovery of CP
- Important supporting measurements for neutrino and cosmic ray experiments


LHC
SHINE
NA61
COMPASS
SPS
DIRAC

DIRAC

DIRAC Collaboration

CERN
Geneva, Switzerland

Czech Technical University
Prague, Czech Republic

Institute of Physics ASCR
Prague, Czech Republic

Nuclear Physics Institute ASCR
Rez, Czech Republic

INFN-Laboratori Nazionali di Frascati
Frascati, Italy

University of Messina
Messina, Italy

KEK
Tsukuba, Japan

Kyoto University
Kyoto, Japan

Kyoto Sangyou University
Kyoto, Japan

Tokyo Metropolitan University
Tokyo, Japan

IFIN-HH
Bucharest, Romania

JINR
Dubna, Russia

SINP of Moscow State University
Moscow, Russia

IHEP
Protvino, Russia

Santiago de Compostela University
Santiago de Compostela, Spain

Bern University
Bern, Switzerland

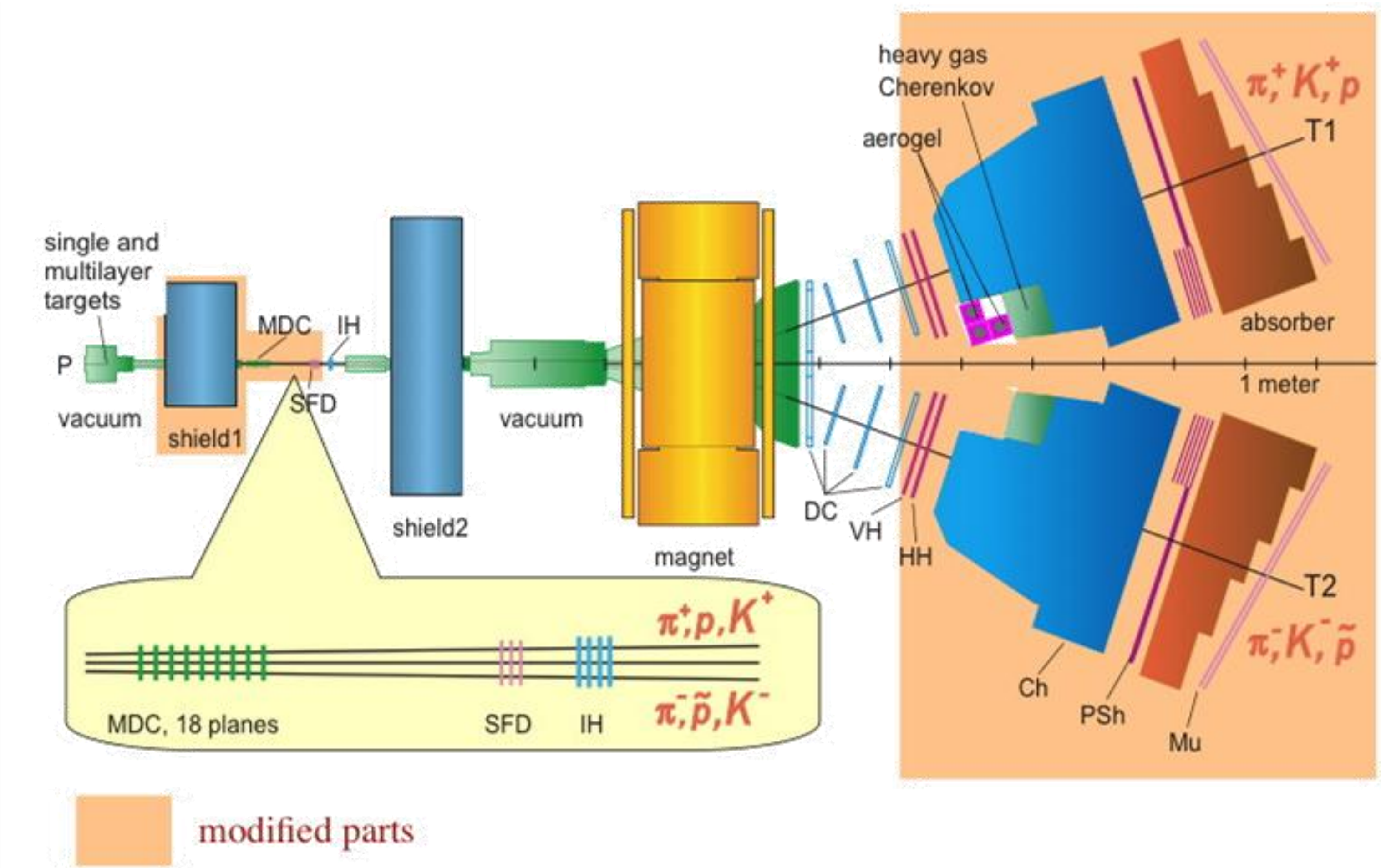
Zurich University
Zurich, Switzerland

7 countries, 17 Institutes, ~ 60 members

Introduction

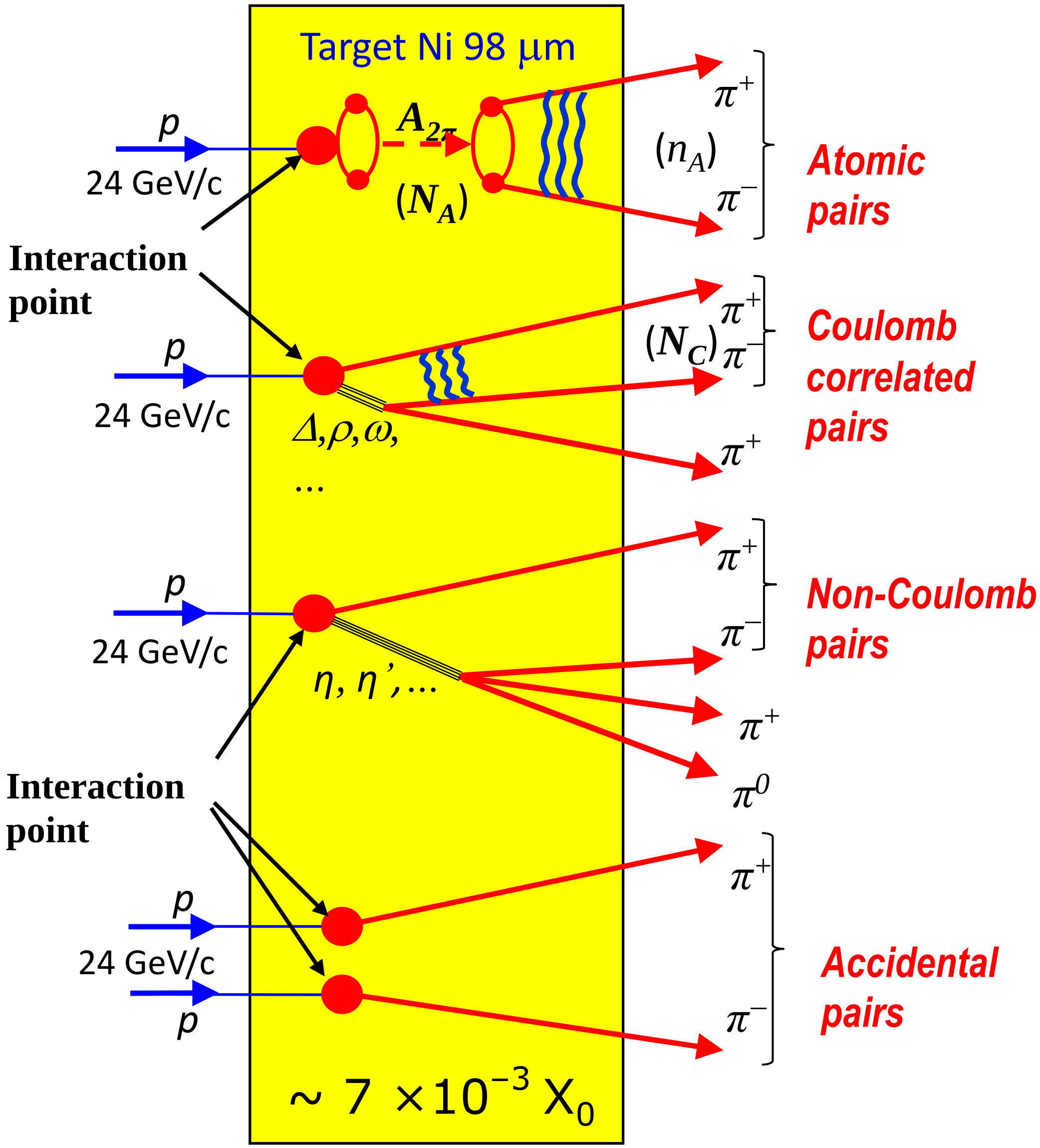
- electromagn. bound mesonic atoms
  - e.g. $\pi^-\pi^+$ pionium ($A_{2\pi}$) and πK ($A_{\pi K}$)
- ideal to study QCD at very low energies
  - confinement region
- strong interaction
  - broadens and shifts atomic s-state levels
  - dominate lifetime
- $\pi\pi$ interaction well known
  - $A_{2\pi}$ lifetime $\rightarrow$ fundamental $\pi\pi$ scattering length
  - $\pi\pi$ approx. chiral symmetry SU(2)
  - πK extension to SU(3), role of strange quark

Dirac dimeson spectrometer



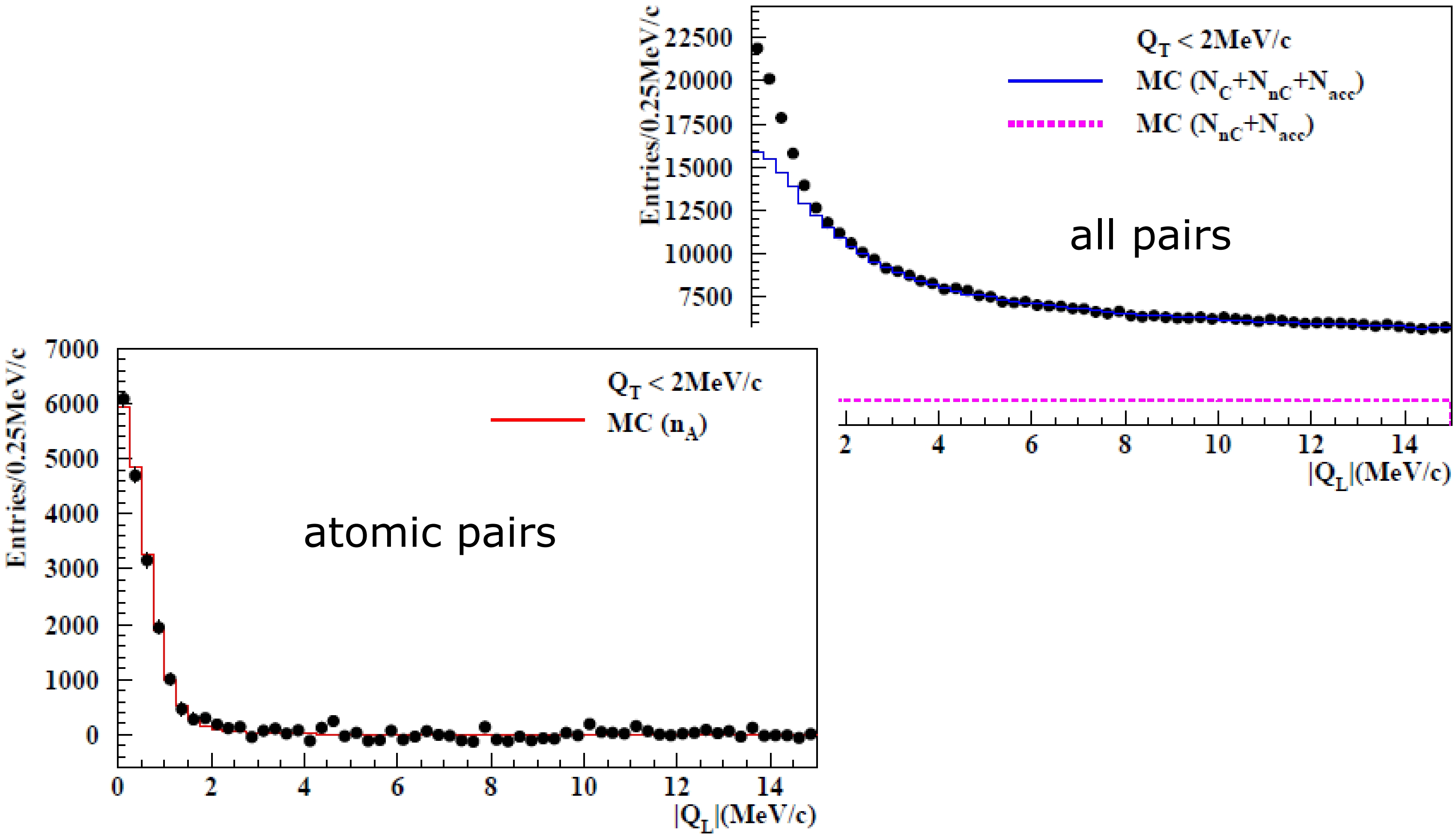
MDC - *microdrift gas chambers,* **SFD** - *scintillating fiber detector,* **IH** – *ionization hodoscope.* **DC** - *drift chambers ,* **VH** – *vertical hodoscopes,* **HH** – *horizontal hodoscopes,* **Ch** – *nitrogen Cherenkov ,* **PSh** - *preshower detectors ,* **Mu** - *muon detectors*

$A_{2\pi}$ observation



- $A_{2\pi}$ lifetime given by breakup probability n_A/N_A
- $N_A = k \times N_C$; k calc.
- n.C. and acc. pairs subtracted using $\pi\pi$ relative momentum, reso. ~ 0.5 MeV/c
- total n_A
  2001-2003: 21000
  2008-2010: 24000

Longitudinal momentum ππ pairs



$A_{2\pi}$ lifetime and scattering length

- Lifetime provides difference of S-wave of isoscalar and isotensor scattering length $|a_0 - a_2|$
- DIRAC lifetime and s.l. in (in $1/m_\pi$) (2001−2003)

$$\tau = \left(3.15^{+0.20}_{-0.19}\Big|_{\rm stat}\ {}^{+0.20}_{-0.18}\Big|_{\rm syst}\right) \times 10^{-15}\ \mathrm{s}$$

$$|a_0 - a_2| = \left(0.2533^{+0.0080}_{-0.0078}\Big|_{\rm stat}\ {}^{+0.0078}_{-0.0073}\Big|_{\rm syst}\right)$$

Phys.Lett. B704 (2011) 24-29

- theory

$$\tau = (2.9 \pm 0.1) \cdot 10^{-15}\ \mathrm{s}$$

$$a_0 - a_2 = (0.265 \pm 0.004)$$

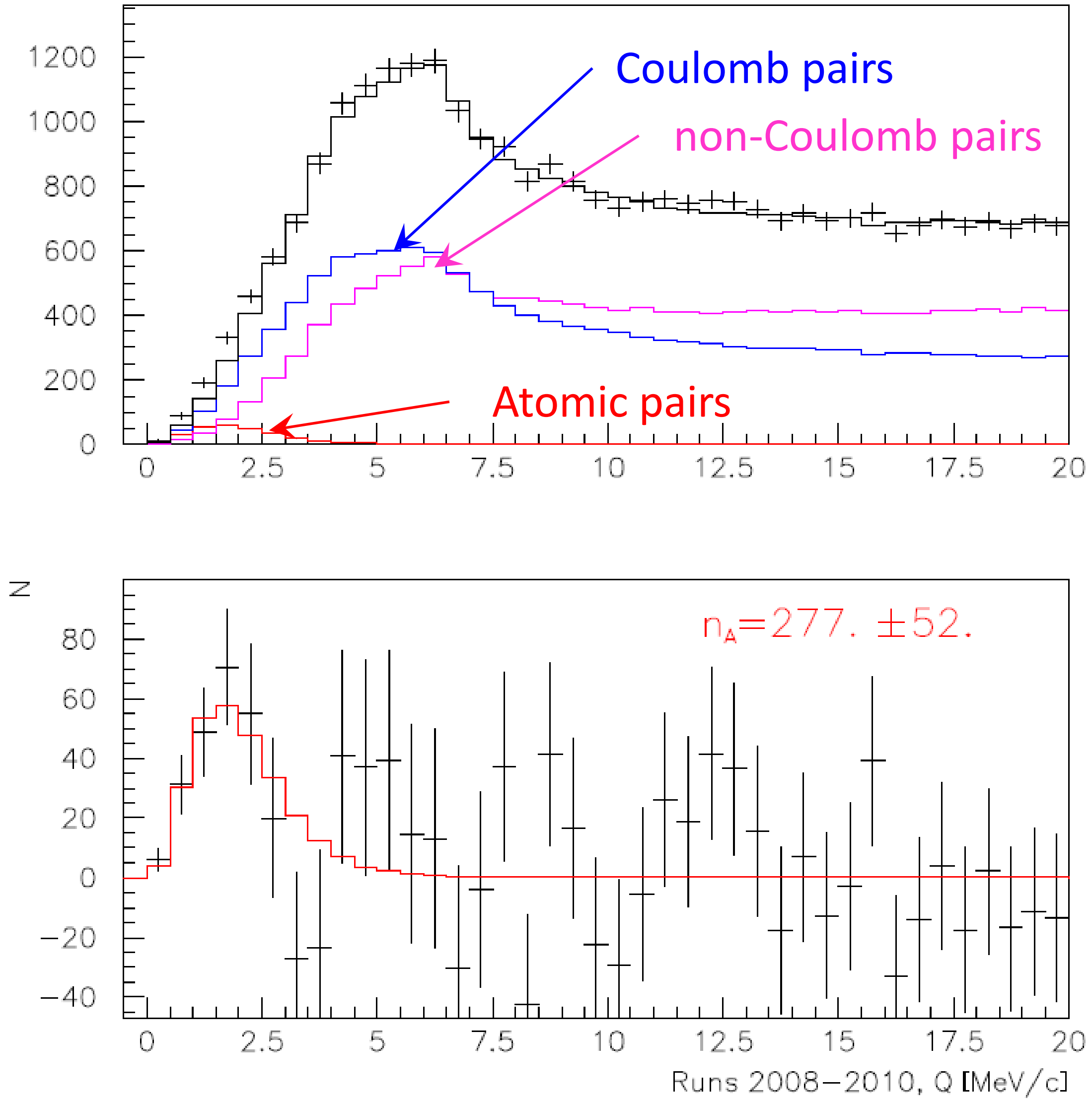
- NA48

$$a_0 - a_2 = 0.2639 \pm 0.0020 \pm 0.0015$$ K_{e4} & $K_{3\pi}$

EPJ C70 (2010) 635

III. The status of π^-K^+ and π^+K^- atoms

A. Benelli, V. Yazkov

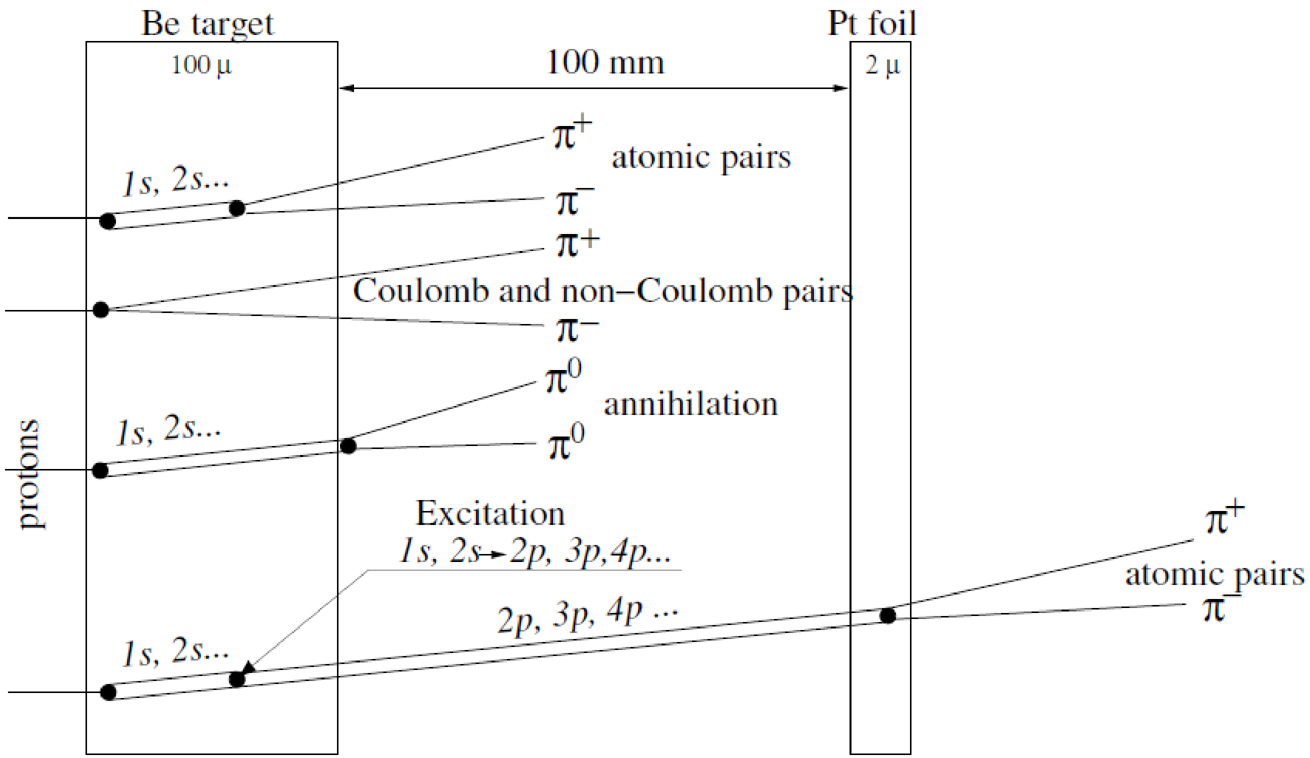


Run 2008-2010, statistics with low and medium background (⅔ of all statistics). Point-like production of all particles. The e^+e^- background was not subtracted.

Q – relative momentum in the πK c.m.s.

Possible measurement $2a_0+a_2$

- lamb shift in $A_{2\pi}$ in sensitive to $2a_0+a_2$
- long-lived $\Delta^{str}_{2s-2p} = -\frac{\alpha^3 m_\pi}{8}\frac{1}{6}(2a_0 + a_2) + \cdots$
- separate a_0 and a_2 also from NA48 K_{e4}



Summary

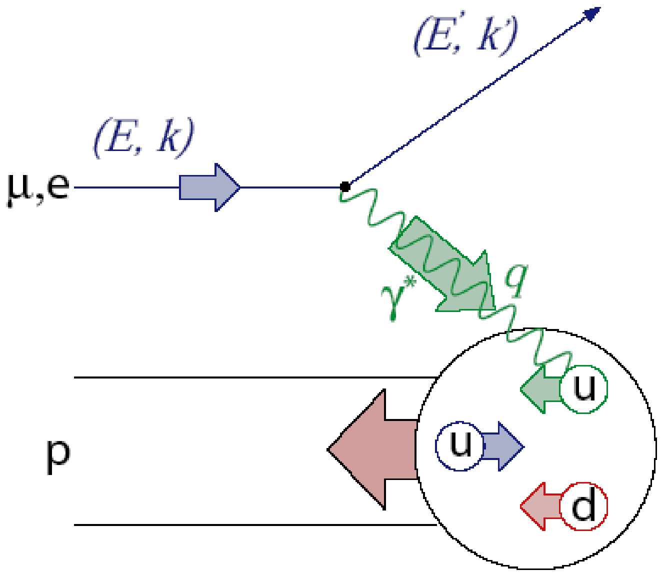
- CERN has a rich programme on QCD and hadron physics with a large community
- Unique and indispensable
- Excellent prospects for the future

Thank you!

Special thanks for slides to B. Grube, F. Haas, M. Gazdzicki, Z. Fodor, L. Nemenov and others

Backup

Deep Inelastic Scattering



$$Q^2 = -(k-k')^2 \overset{lab}{=} 4EE' \sin^2\frac{\vartheta}{2}$$

$$P \cdot q \overset{lab}{=} M\nu = M(E-E')$$

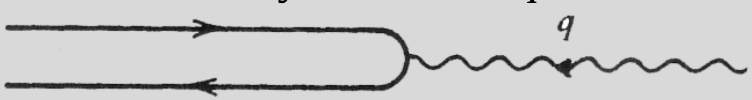
$$P \cdot k \overset{lab}{=} ME$$

$$x \overset{lab}{=} \frac{Q^2}{2M\nu} = \frac{-q^2}{2P \cdot q}$$

$$y \overset{lab}{=} \frac{\nu}{E} = \frac{P \cdot q}{P \cdot k}$$

$$0 \leq x, y \leq 1$$

Bjorken-*x*: fraction of longitudinal momentum carried by the struck quark in infinite-momentum frame (Breit)



Sum Rules

Bjorken sum rule

PR 148 (1966) 1467

$$\Gamma_1^p - \Gamma_1^n = \frac{1}{6} g_a$$

if wrong $\Rightarrow$ QCD wrong, "worthless equation", needs neutron measurement

Ellis-Jaffe sum rule

PR D9 (1974) 1444

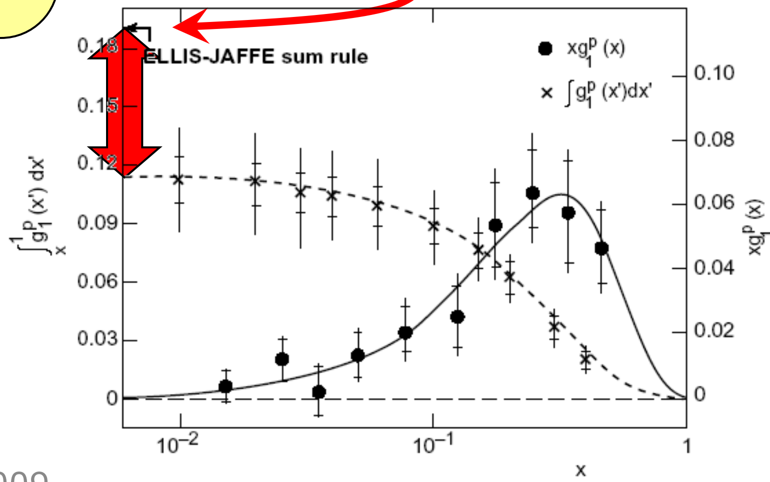
$$\Gamma_1^p = \frac{1}{12} g_a + \frac{5}{36}\sqrt{3} a_8 + \frac{1}{3}\Delta s \Rightarrow \Delta\Sigma \simeq 0.6$$

formulated for $\Delta s=0$, unpolarised strange quarks

Consequences of violation:

$$\begin{aligned} \Delta s &= -0.19 \pm 0.06 \\ \Delta\Sigma &= 0.12 \pm 0.17 \end{aligned}$$

EMC 1987



Measurable asymmetries

$$A_{meas} = P_t P_b f A$$

P_b*, *P_t beam and target polarisations,

f target dilution factor = polarisable N/total N

note: linear in error: $f=1/2$ => requires 4 times statistics

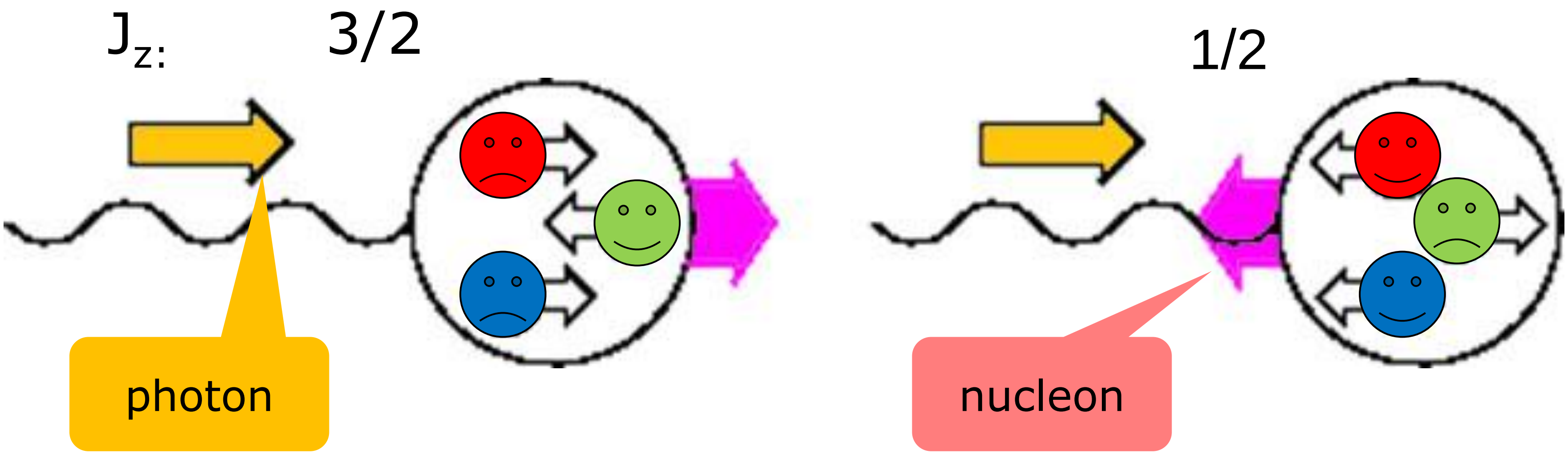
$$g_1 \simeq \frac{A_\parallel}{D} F_1 \simeq \frac{A_\parallel}{D} \frac{F_2}{2x}$$

huge rise of ***$F_2/2x$*** at small ***x***

D depolarisation factor, kinematics, polarisation transfer from polarised lepton to photon, ***$D \approx y$***

Even big ***g_1*** at small ***x*** causes very small asymmetries

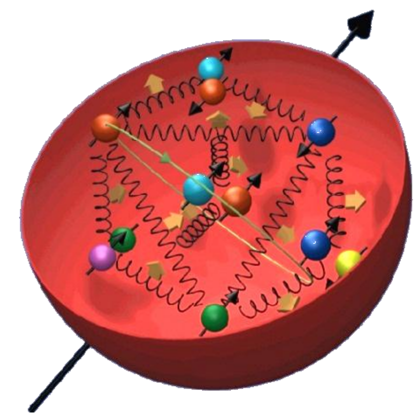
Photoabsorption & Spinstructure



- Measure cross-section asymmetry

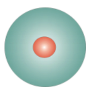
$$\frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}}$$

- Need polarised beam & target (for longitudinal spin structure)



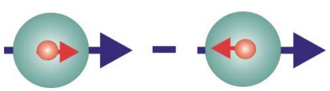
Asymmerties & SF

spin-averaged structure function:



$$F_2(x) = x \sum_i e_i^2 \left\{ q_i^+(x) + q_i^-(x) \right\}$$

spin-dependent structure function:



$$g_1(x) = \frac{1}{2} \sum_i e_i^2 \left\{ q_i^+(x) - q_i^-(x) \right\}$$

inclusive scattering:

$$\Delta q = q^+ - q^-$$

$$A_1 = \frac{\sum_q e_q^2 \Delta q(x, Q^2)}{\sum_q e_q^2 q(x, Q^2)} \qquad \frac{A_{\text{exp}}}{f\, P_\mu\, P_T\, D} \simeq A_1$$

COMPASS-II schedule

2012	Primakoff scattering:	Polarizabilities of p and K
	DVCS pilot run:	*t*-slope, transverse size
2013	Accelerator shutdown	
2014	Drell-Yan:	Universality of TMDs
2015−2016	DVCS and DVMP:	Study GPDs, “nucleon tomography”
	Unpolarized SIDIS:	FF, strangeness PDF, TMDs

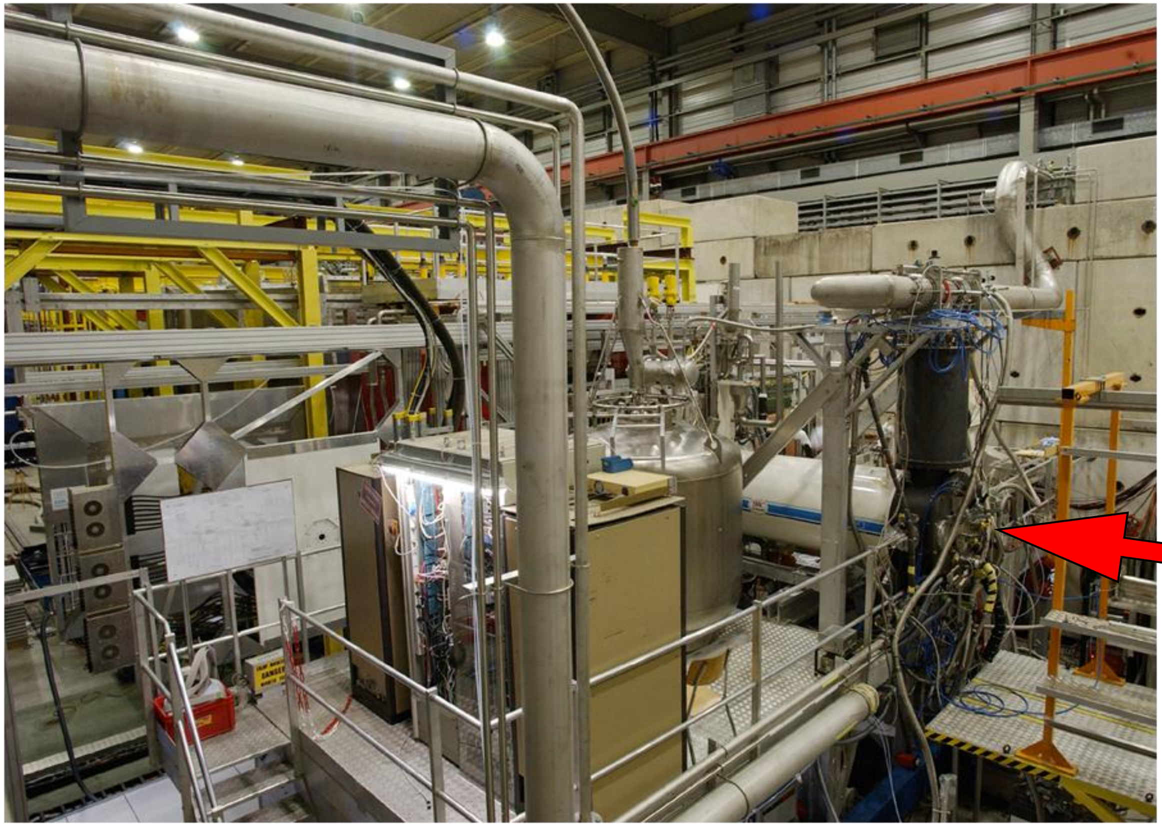
... DVCS and HEMP with transversely polarised target

... further spectroscopy measurements

Polarized target system

COMPASS Spectrometer

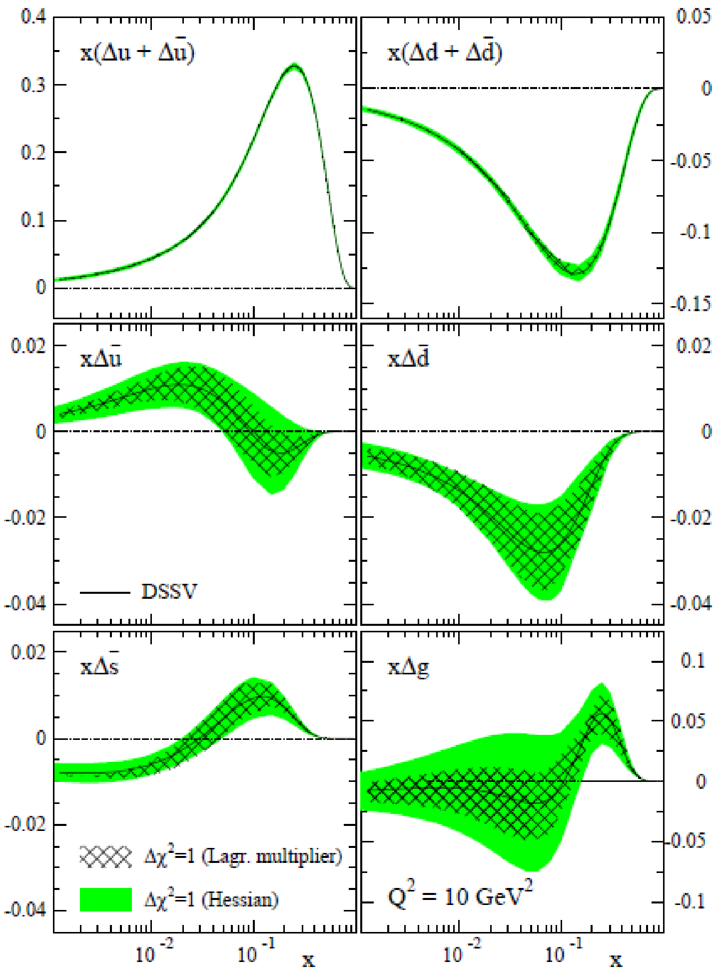
Polarised target



- $^6LiD/NH_3$
- 50/90% polarisation
- 50/16% dilution fact.
- 2.5 T
- 50 mK

μ

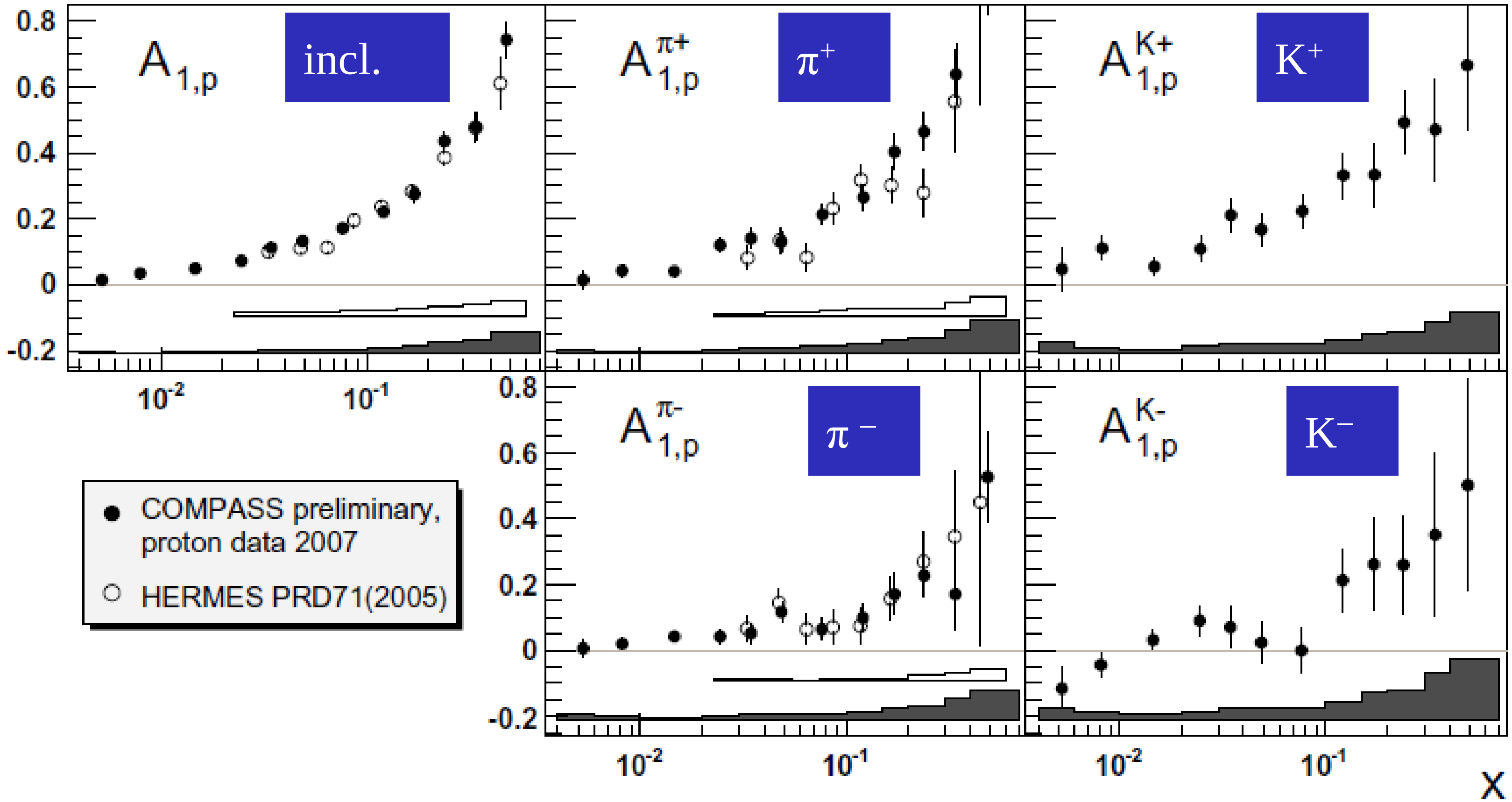
QCD Fits



Marco Stratmann (tomorrow)

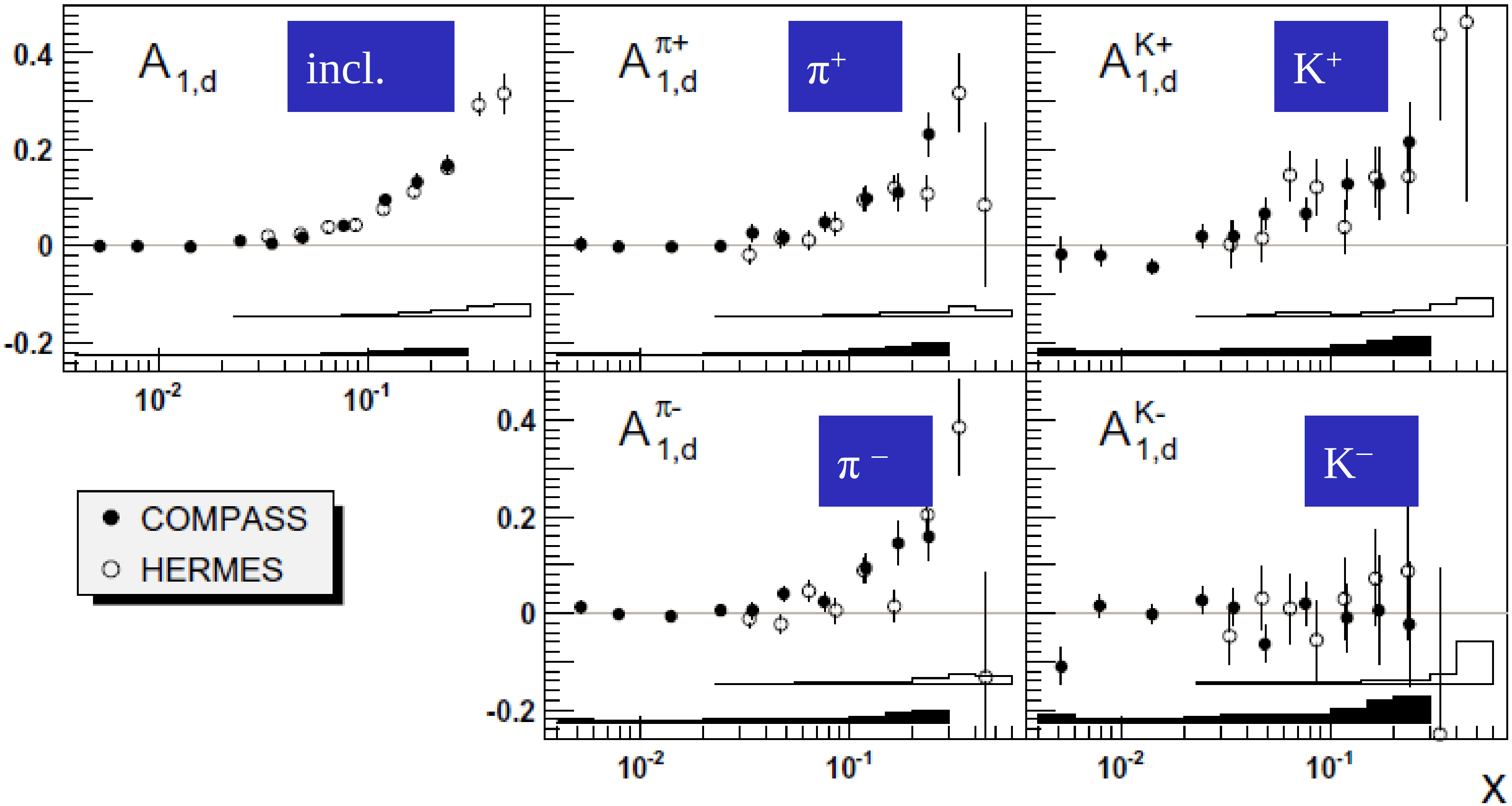
Incl. & semi-incl. A_1

- proton

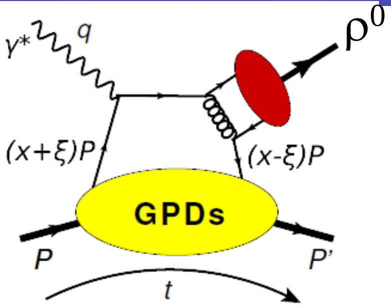


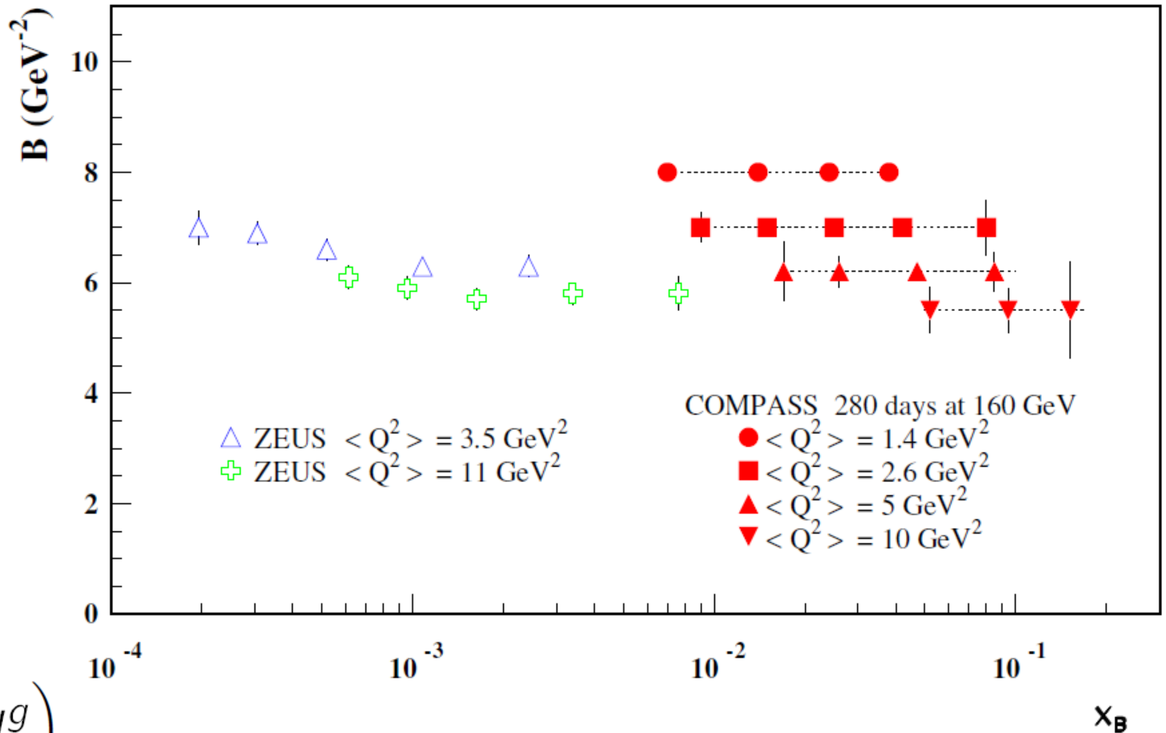
Incl. & semi-incl. A_1

- deuteron



t-slope for ρ^0 production





also ϕ, ω, ..

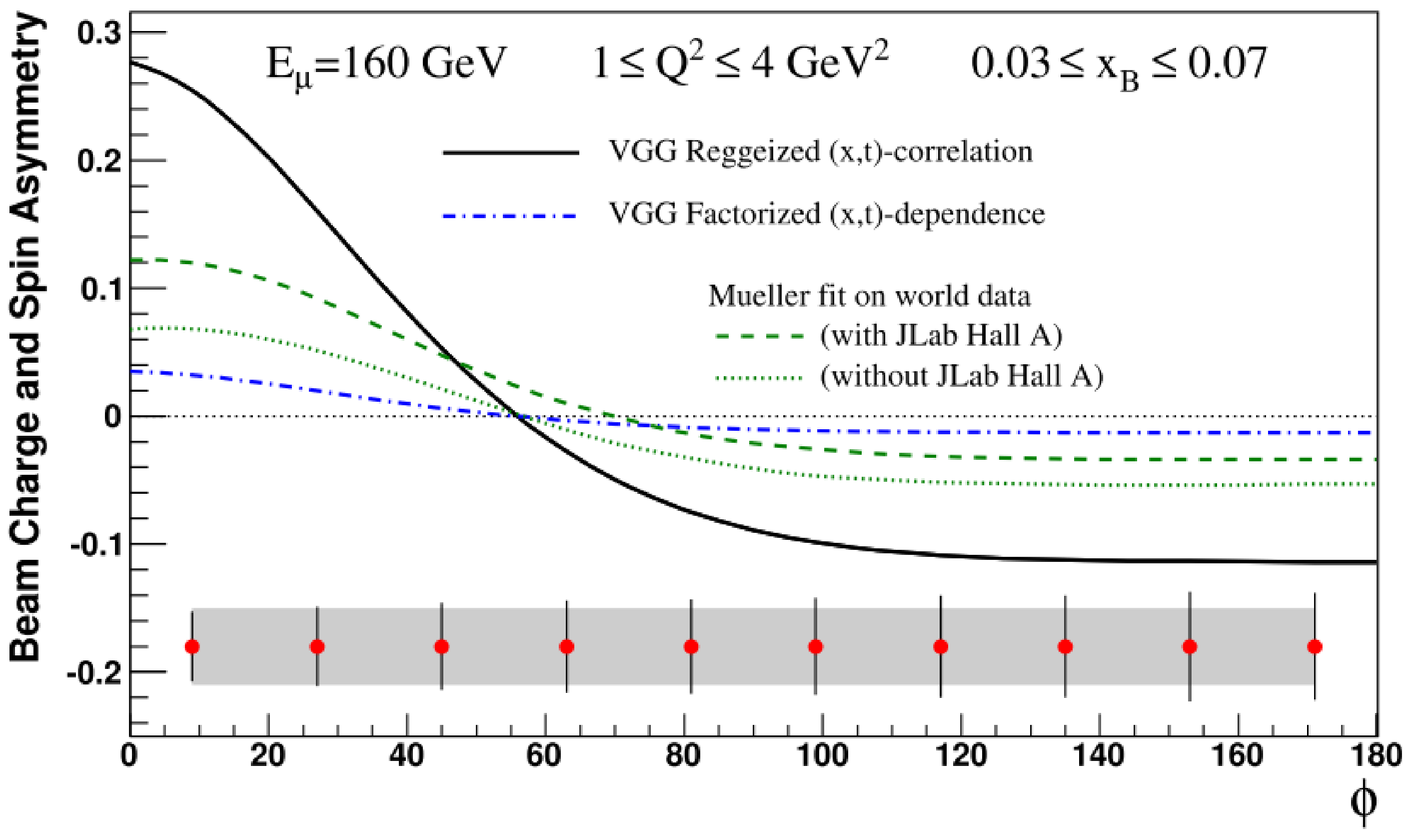
$$H_{\rho^0} = \frac{1}{\sqrt{2}}\left(\frac{2}{3}H^u + \frac{1}{3}H^d + \frac{3}{8}H^g\right)$$

$$H_{\omega} = \frac{1}{\sqrt{2}}\left(\frac{2}{3}H^u - \frac{1}{3}H^d + \frac{1}{8}H^g\right)$$

$$H_{\phi} = -\frac{1}{3}H^s - \frac{1}{8}H^g$$

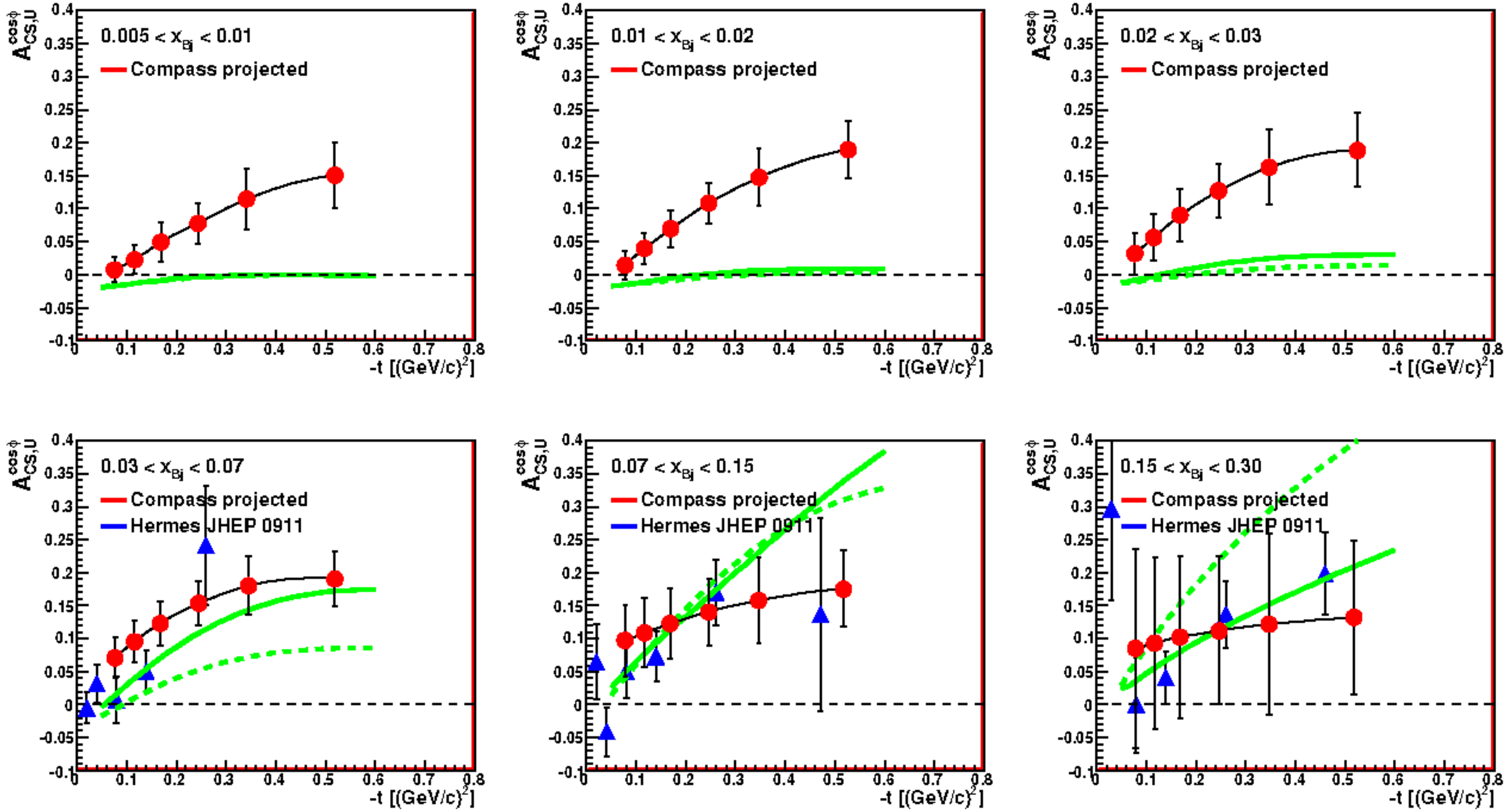
Wollny, Wed 15:15

Proj. charge & spin asymmetry



Beam charge-and-spin asym.

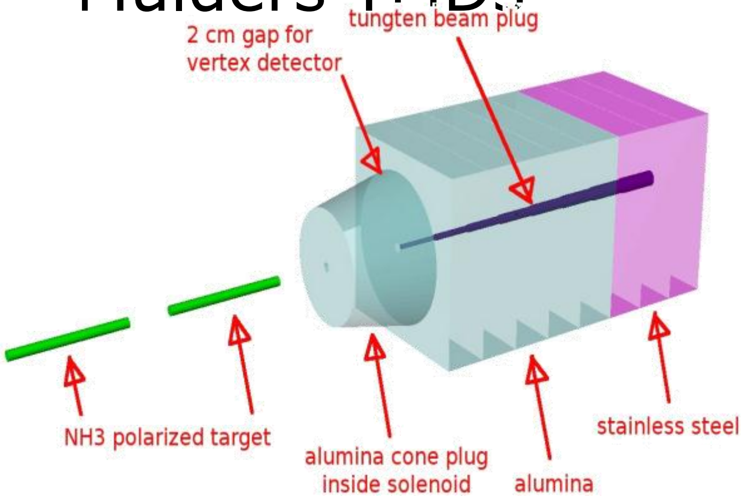
amplitude of cos ϕ modulation as fctn of -*t*

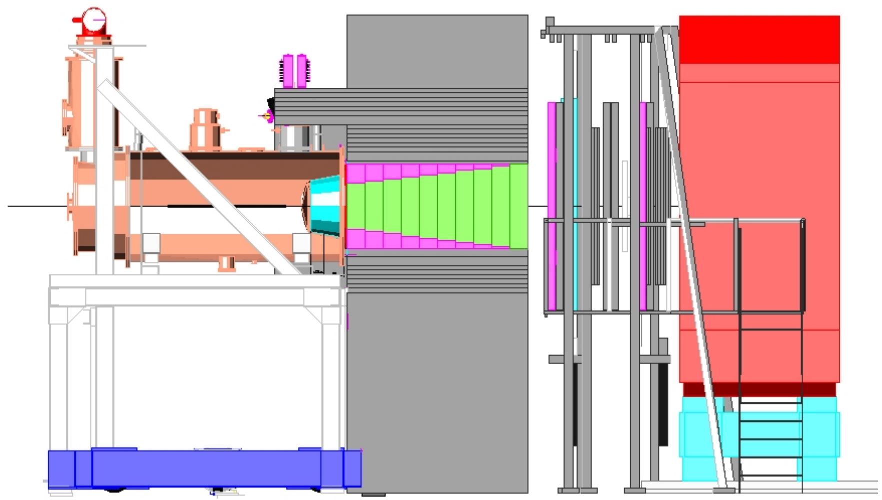


fits by Kumericki, Mueller

COMPASS-II Polarised Drell-Yan

- COMPASS-II: 190 GeV/c π^- beam on transversely pol. proton target
- π^- valence u-antiquark picks nucleon's u quark in valence region (u-quark dominance)
- Access to transversity , the T-odd Sivers and Boer-Mulders TMDs





Target region for DY