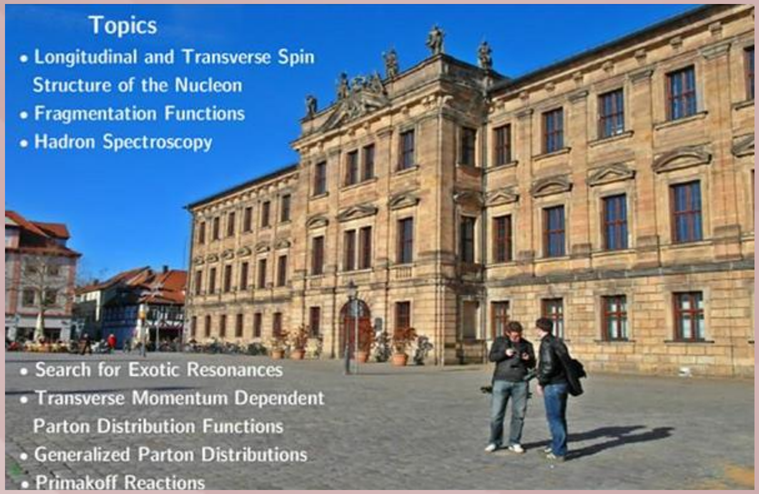
Highlights of the Workshop

Franco Bradamante



IWHSS 2013

International Workshop on Hadron Structure and Spectroscopy

Erlangen, 22-24 July 2013

Thanks to Wolfgang Eyrich

and to all the speakers

- very good talks
- a huge amount of material
- a good show of the variety of physics which can be done at COMPASS

and apologies to

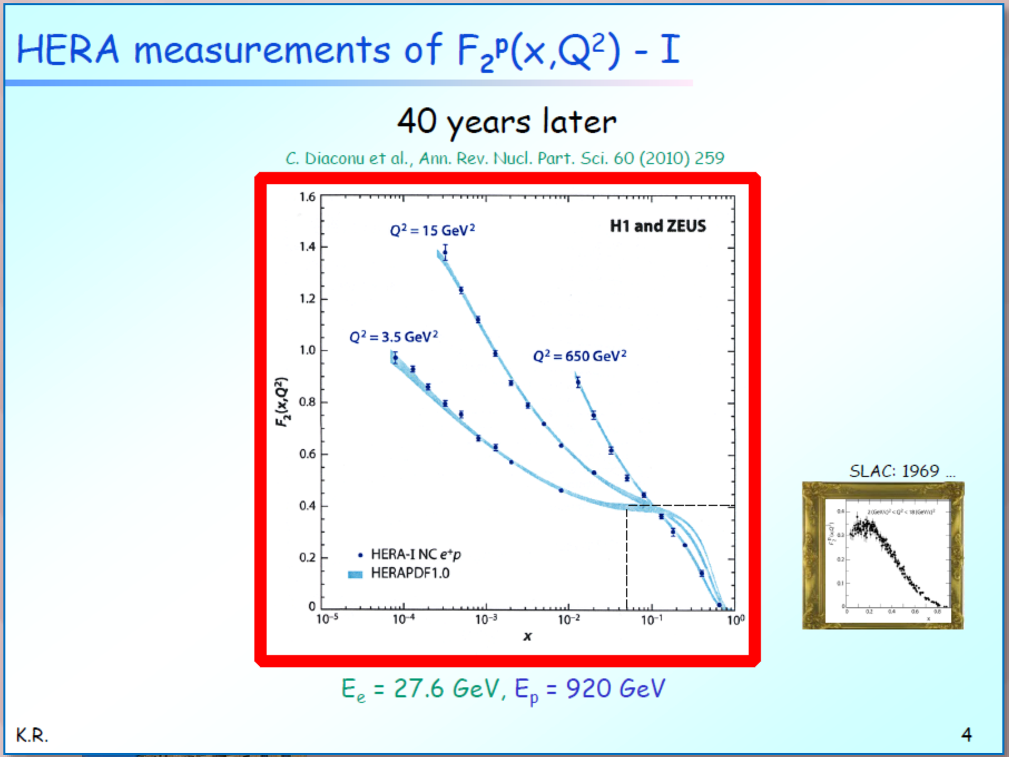
Volker Burkert	JLAB 12
Andrea Ferrero	COMPASS II
Klaus Peters	FAIR
Alexander Nagaytsev	NICA

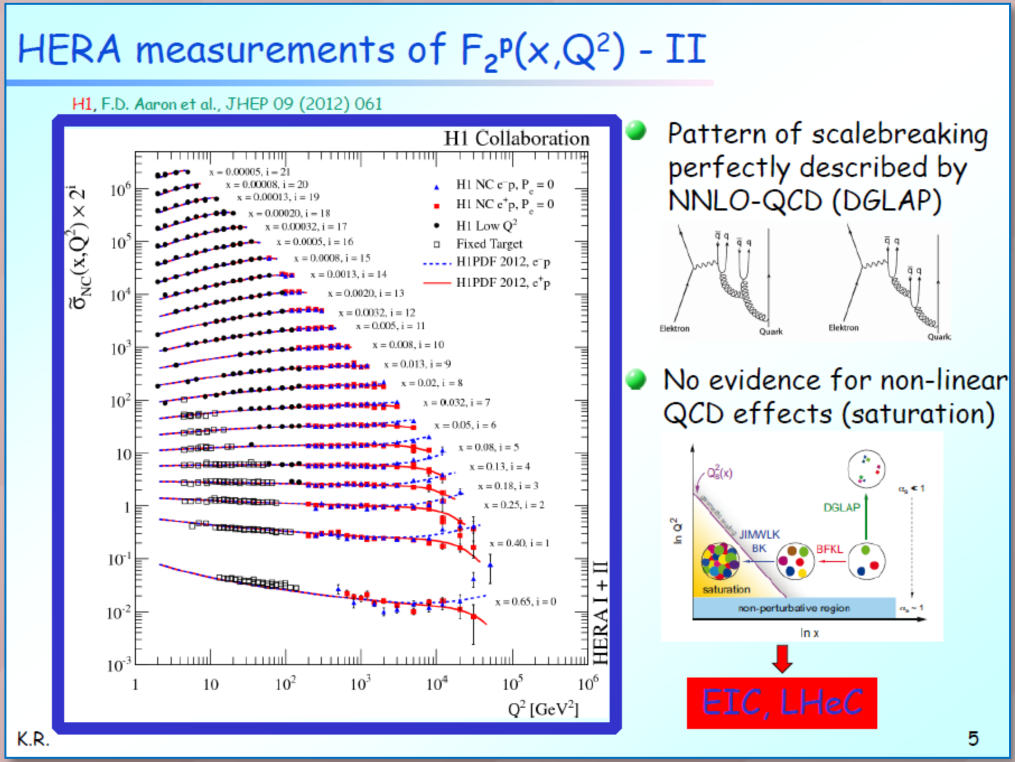
opening lecture:

beautiful review of DIS by K. Rith …

… mostly everything!

in particular the achievements of the HERA Collinder





More Accomplishments from HERA collider

C. Diaconu et al., Ann. Rev. Nucl. Part. Sci. 60 (2010) 259

- QCD tests, $\alpha_s(Q^2)$, Jet production
- Charm and beauty production
- Diffraction
- DVCS
- Searches for new physics
- ⋮

<u>But unfortunately</u>

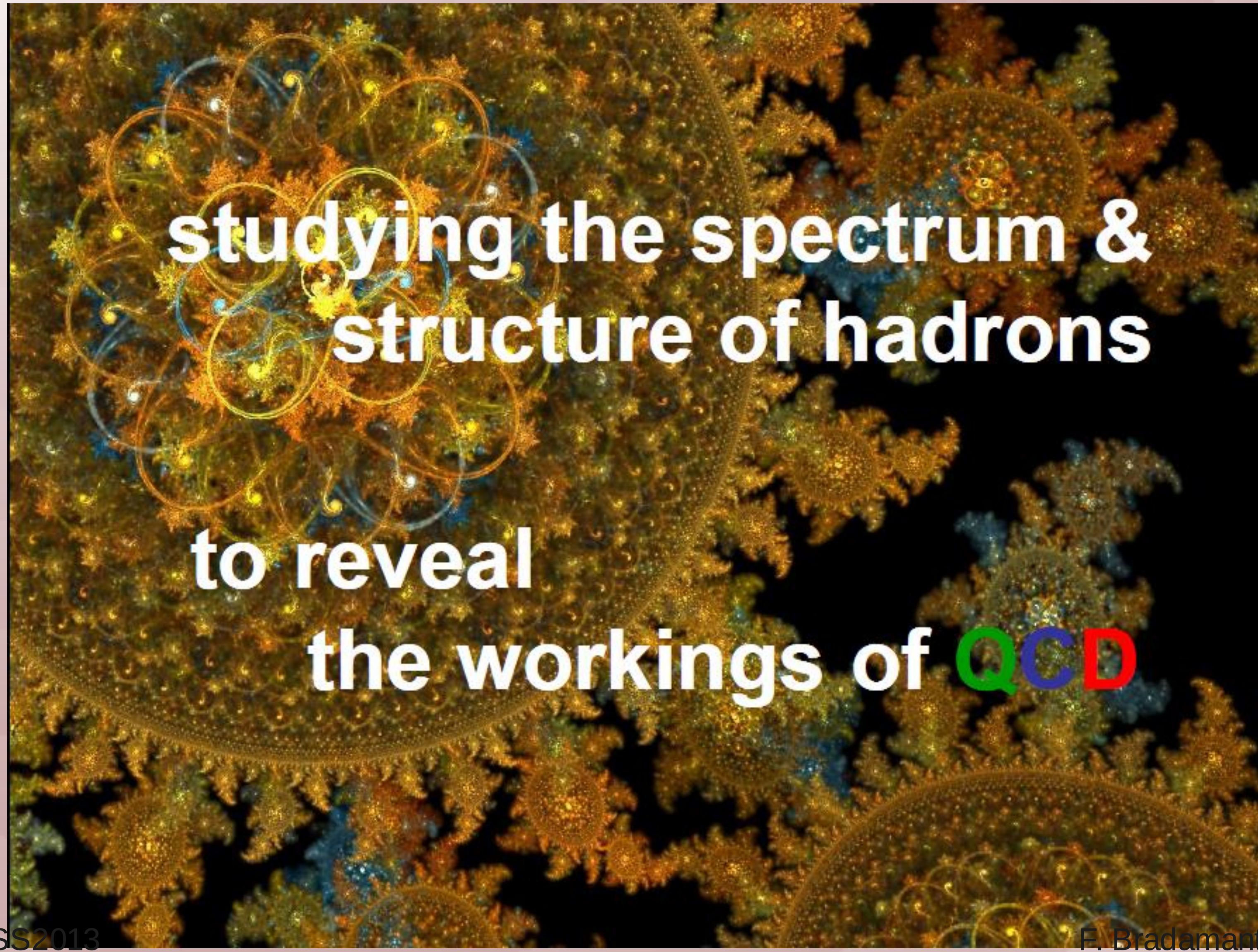
- no ed
- no eA → EIC, LHeC
- no $\vec{e}\vec{p}$

K. Rith

K.R.

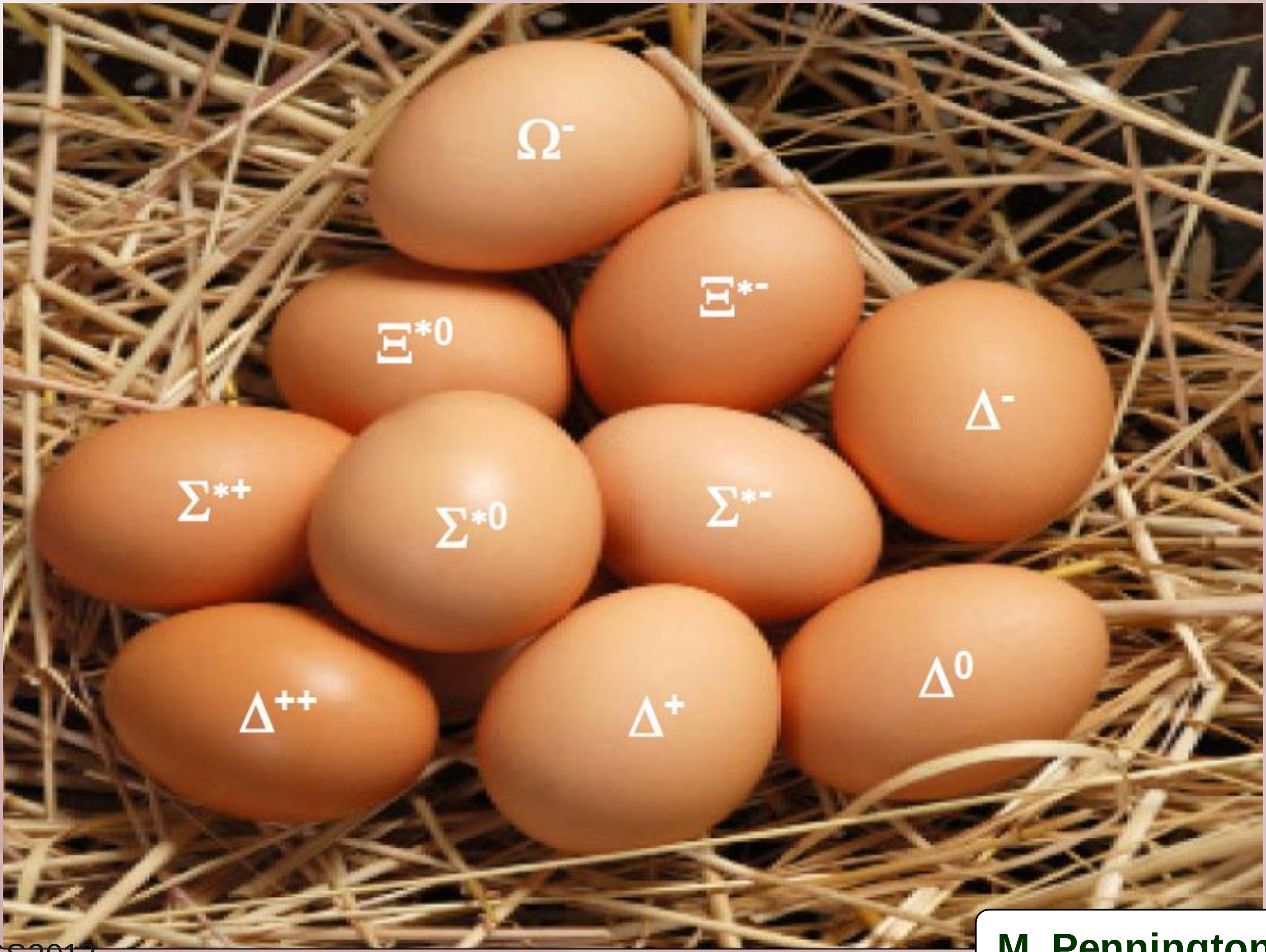
spectroscopy

magnificent talk by M. Pennington



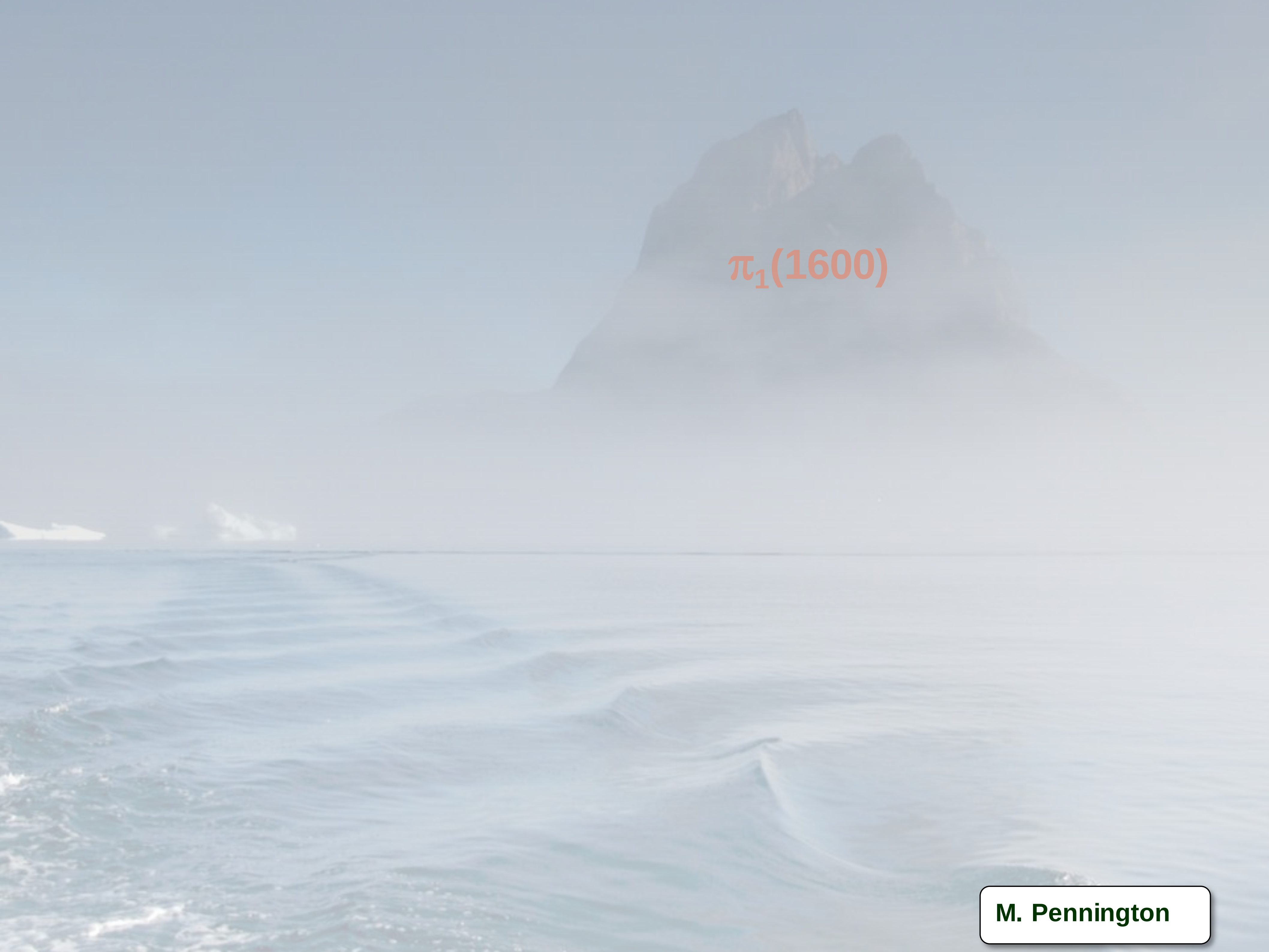
spectroscopy

the eight-fold way …



M. Pennington

spectroscopy


$\pi_1(1600)$
M. Pennington


$\pi_1(1600)$
M. Pennington

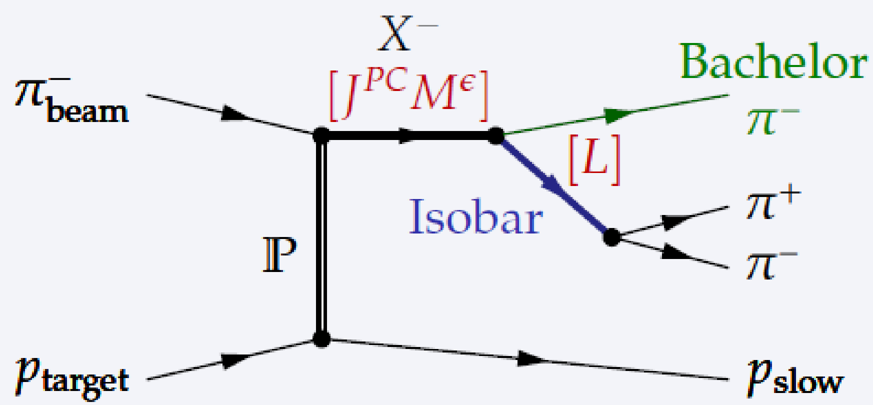

$\pi_1(1600)$
M. Pennington

spectroscopy

B. Gruber

PWA of $\pi^- p \to \pi^- \pi^+ \pi^- p_{\text{slow}}$

COMPASS



- 190 GeV/c negative hadron beam: 97 % π^-, 2 % K^-, 1 % $\bar{p}$
- Liquid hydrogen target
- Recoil proton p_{slow} measured by RPD
- Kinematic range $0.1 < t' < 1.0\,(\text{GeV}/c)^2$

spectroscopy

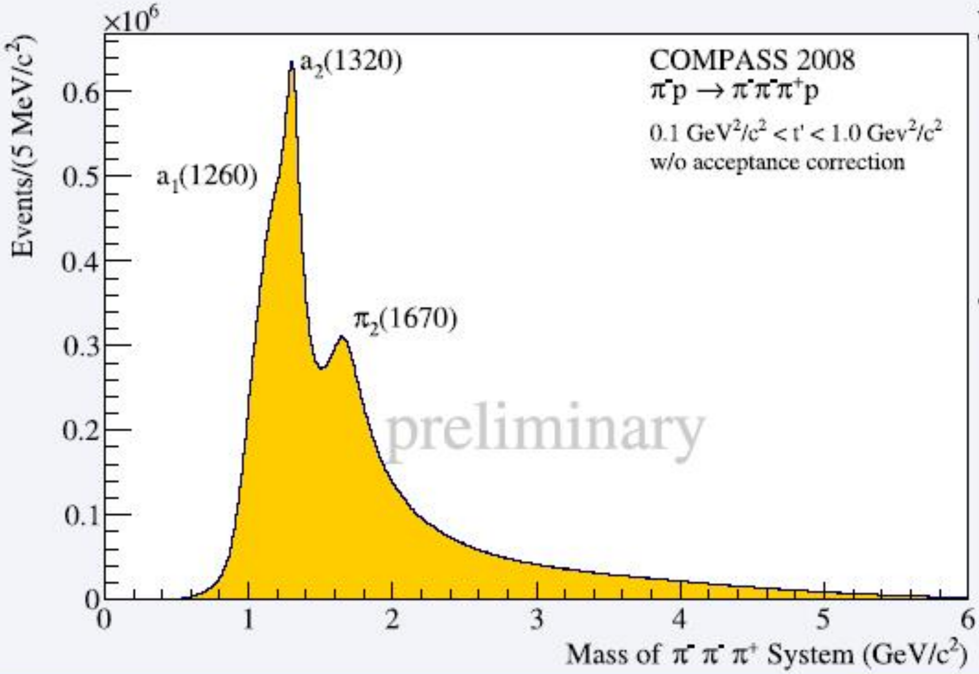
B. Gruber

PWA of $\pi^- p \to \pi^- \pi^+ \pi^- p_{\text{slow}}$

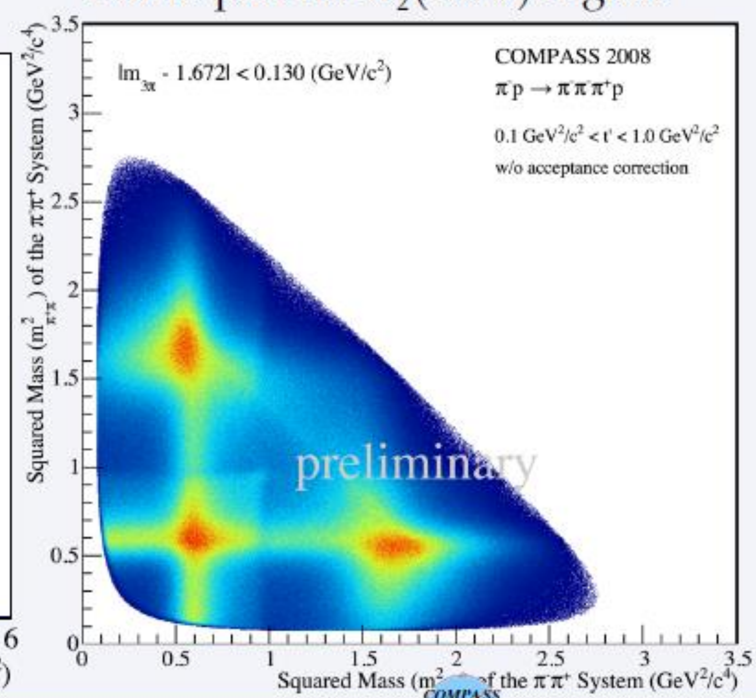
World's largest diffractive 3π data set: ≈50 M exclusive events

- Challenging analysis
  - Needs precise understanding of apparatus
  - Model deficiencies become visible

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



Dalitz plot for $\pi_2(1670)$ region

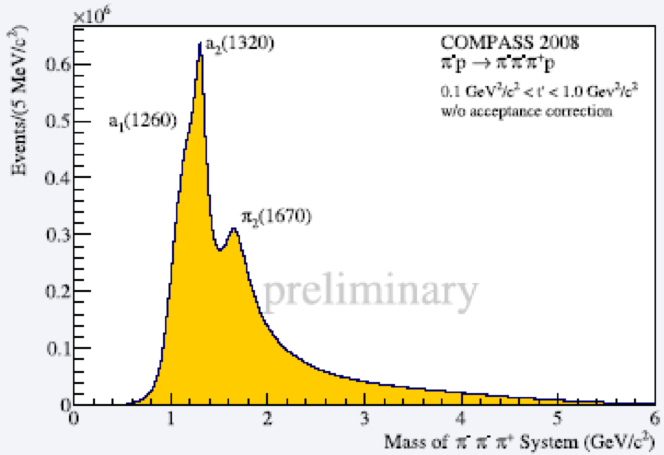


spectroscopy

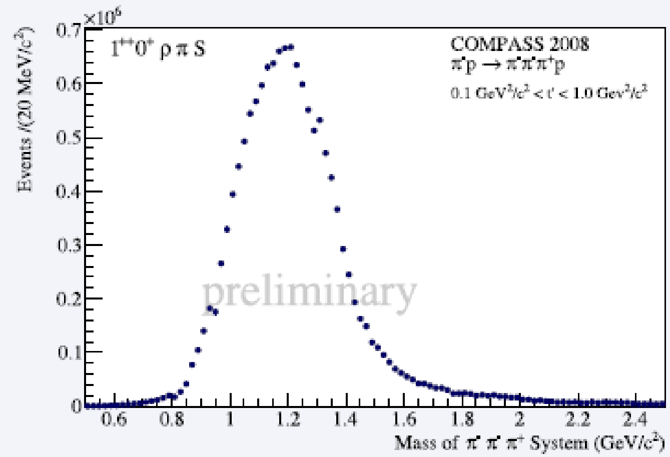
B. Gruber

PWA of $\pi^- p \to \pi^-\pi^+\pi^- p_{\text{slow}}$

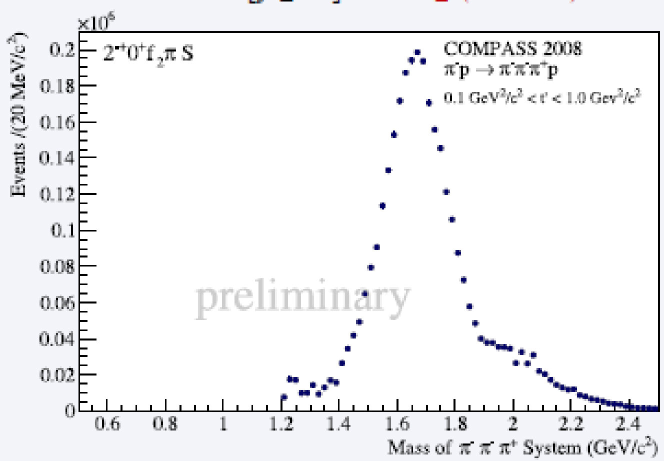
$\pi^-\pi^+\pi^-$ invariant mass spectrum



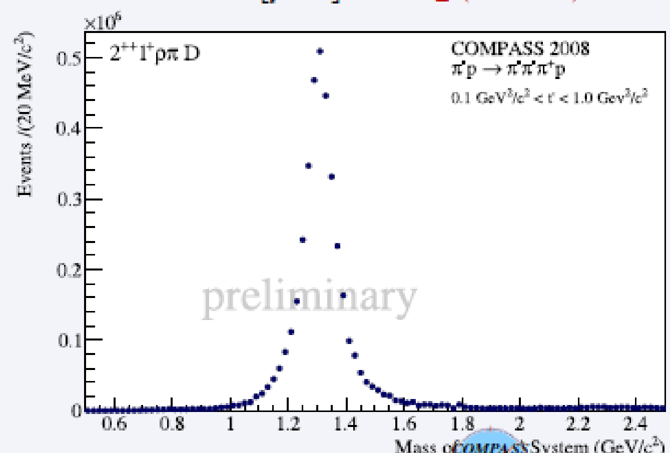
$1^{++}\,0^+\,[\rho\pi]S$: $a_1(1260)$



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



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



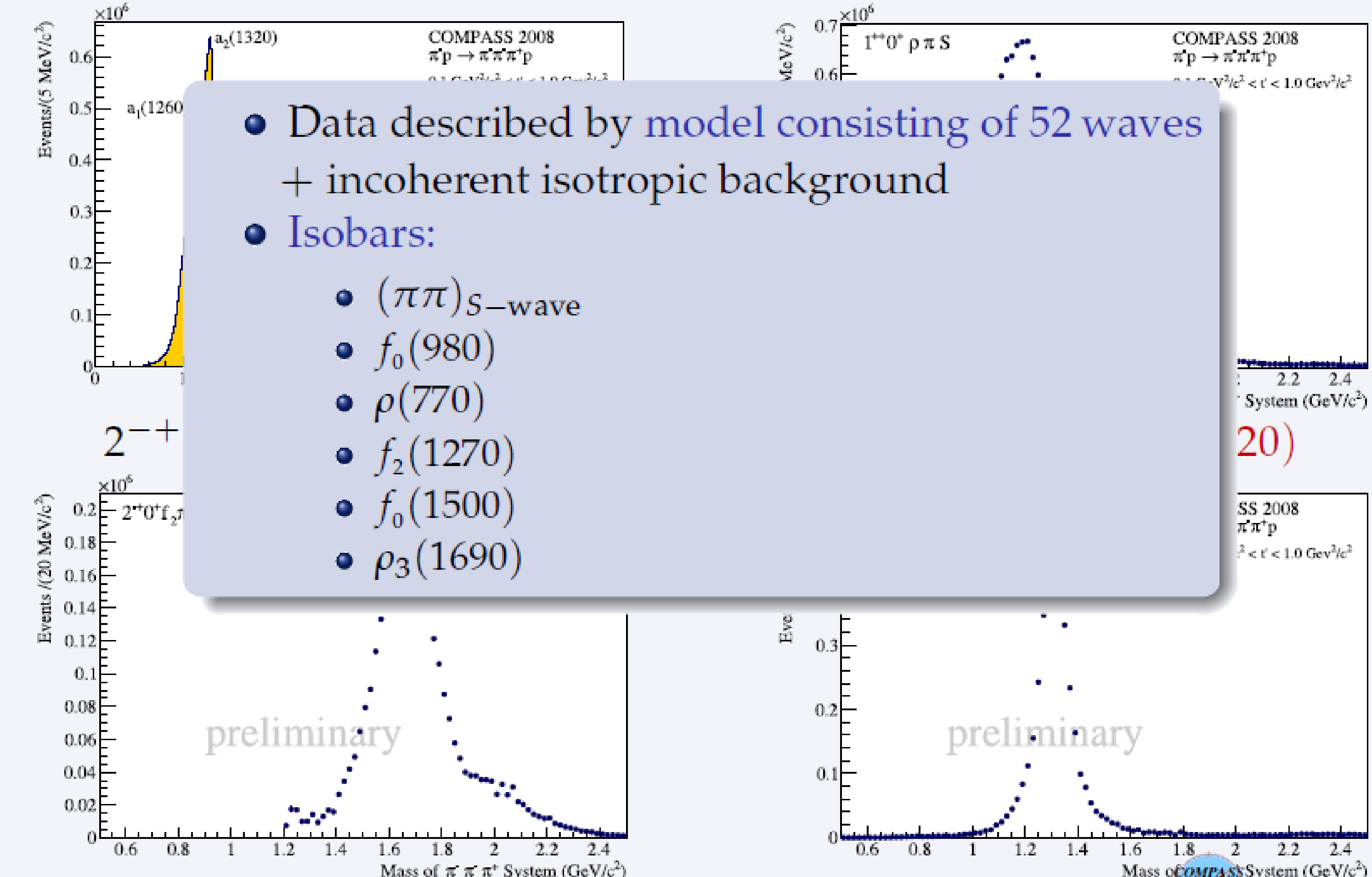
spectroscopy

B. Gruber

PWA of $\pi^- p \rightarrow \pi^- \pi^+ \pi^- p_{slow}$

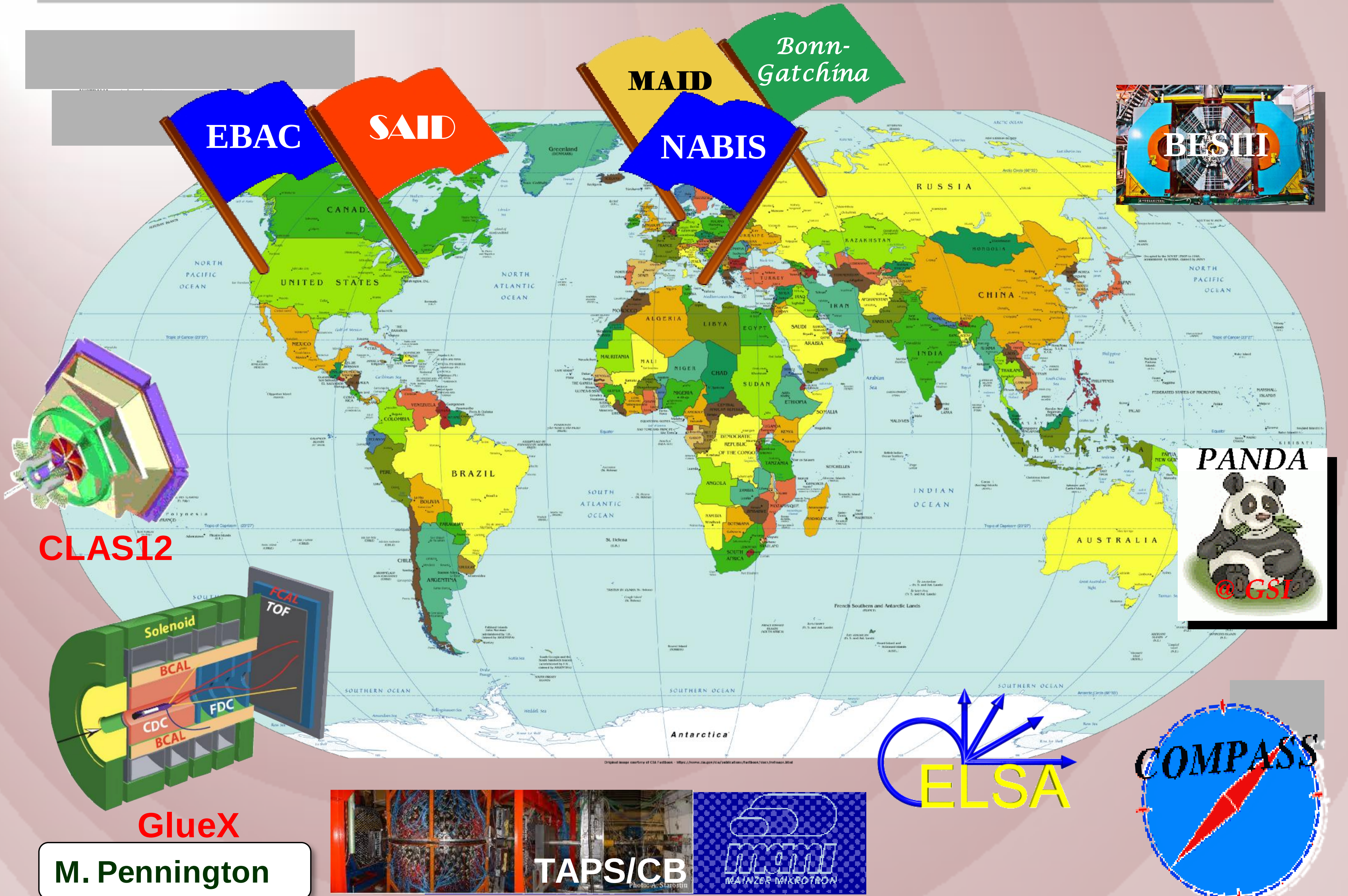
$\pi^- \pi^+ \pi^-$ invariant mass spectrum

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



- Data described by model consisting of 52 waves + incoherent isotropic background
- Isobars:
  - $(\pi\pi)_{S-\text{wave}}$
  - $f_0(980)$
  - $\rho(770)$
  - $f_2(1270)$
  - $f_0(1500)$
  - $\rho_3(1690)$

Global working : Amplitude Analyses & Spectroscopy



M. Pennington

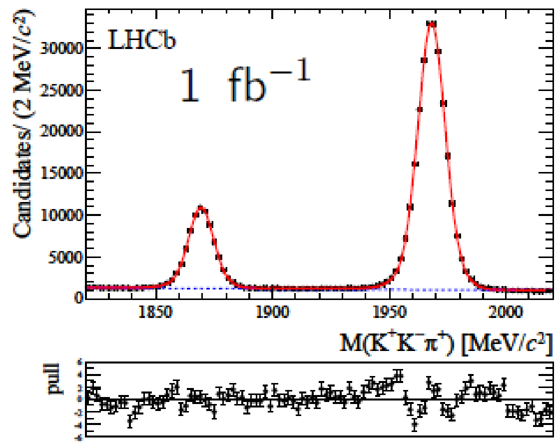
M. Kreps

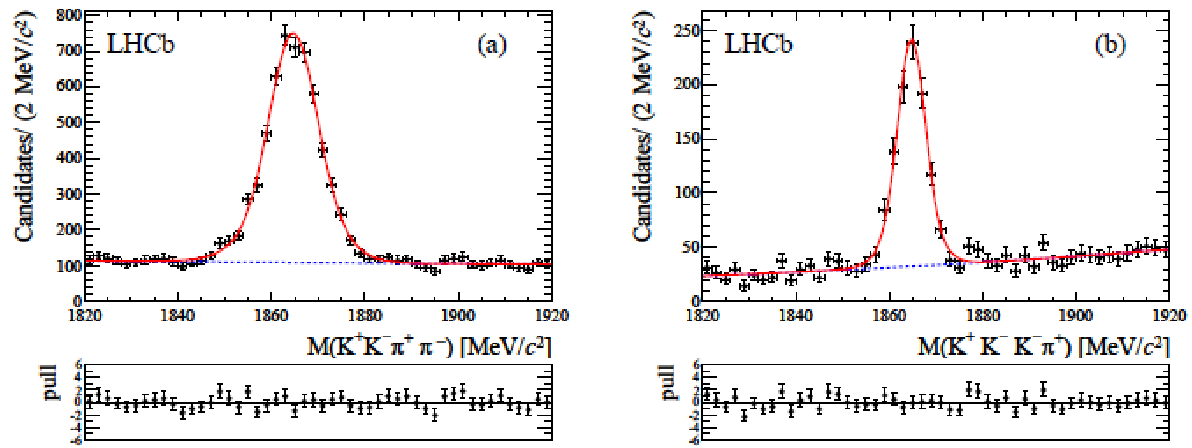
Ground state $D_{(s)}$ mesons

THE UNIVERSITY OF WARWICK

JHEP 06 (2013), 065

- Huge samples available at LHCb
- Dominant systematic uncertainty from momentum and energy loss calibration
- Smaller Q value of the decay $\Rightarrow$ smaller sensitivity to momentum calibration
- Have large samples of other particles to calibrate momentum



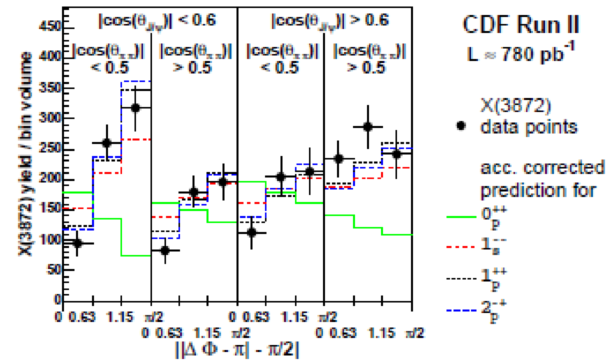


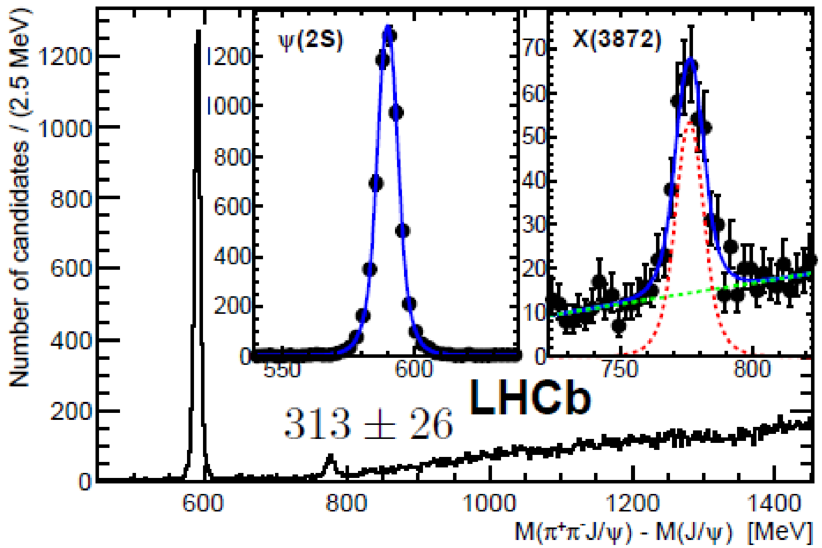
M. Kreps

$X(3872)$ quantum numbers

THE UNIVERSITY OF WARWICK

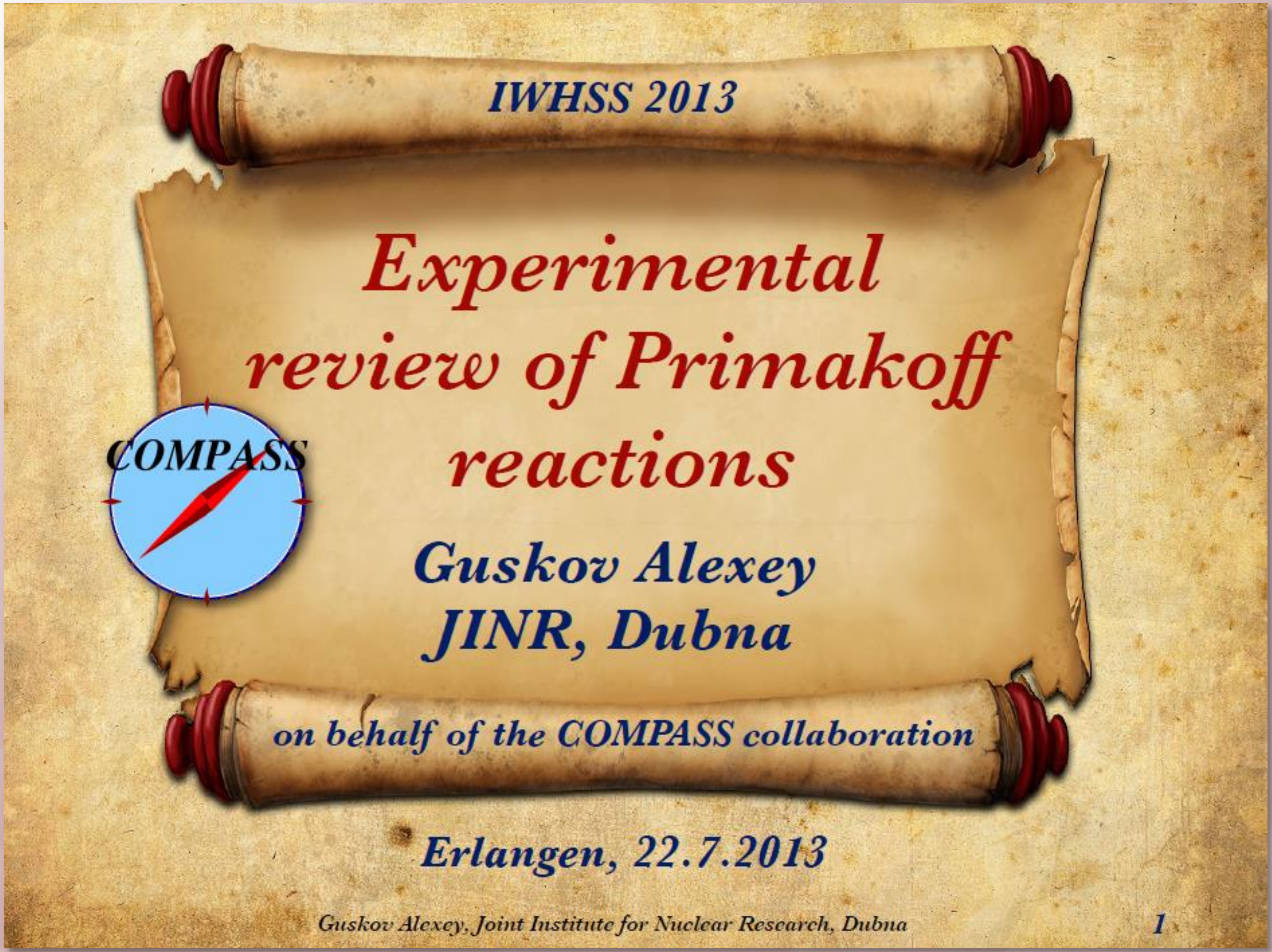
- Its 10 years since observation of $X(3872)$
- Triggered renewed interest to $c\bar{c}$ states
- Lot of speculations what $X(3872)$ is
- Determination of quantum numbers important
  - Not all hypotheses work with any J^{PC}
  - Restricts its position in spectrum
- In 2006 CDF restricted J^{PC} to 1^{++} or 2^{-+}
- BABAR favours 2^{-+} from observation of $X(3872) \to J/\psi\,\omega$



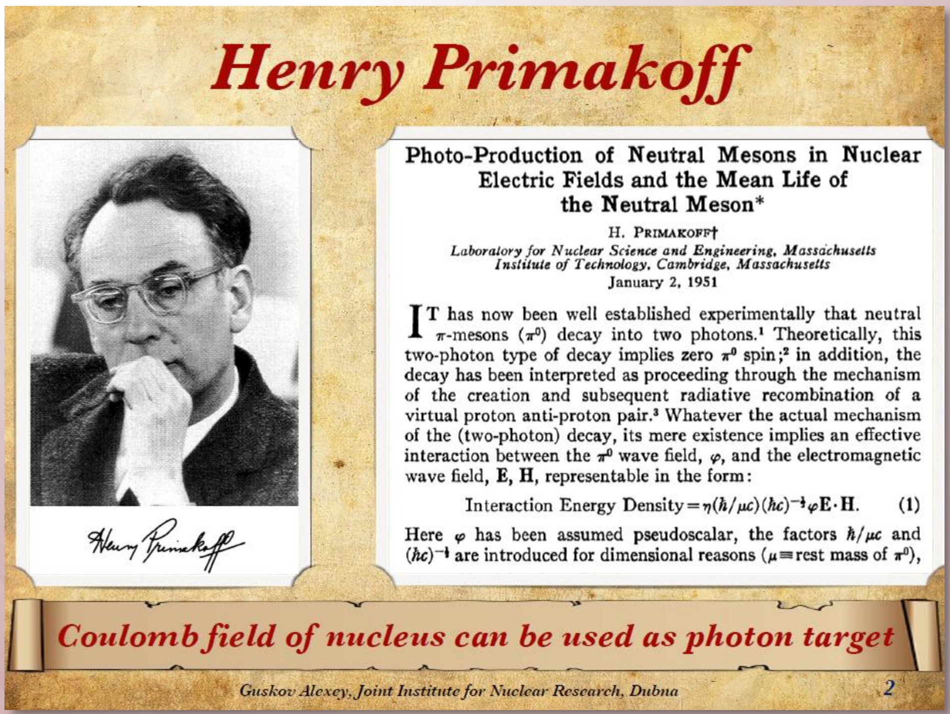


PRL 110, 222001

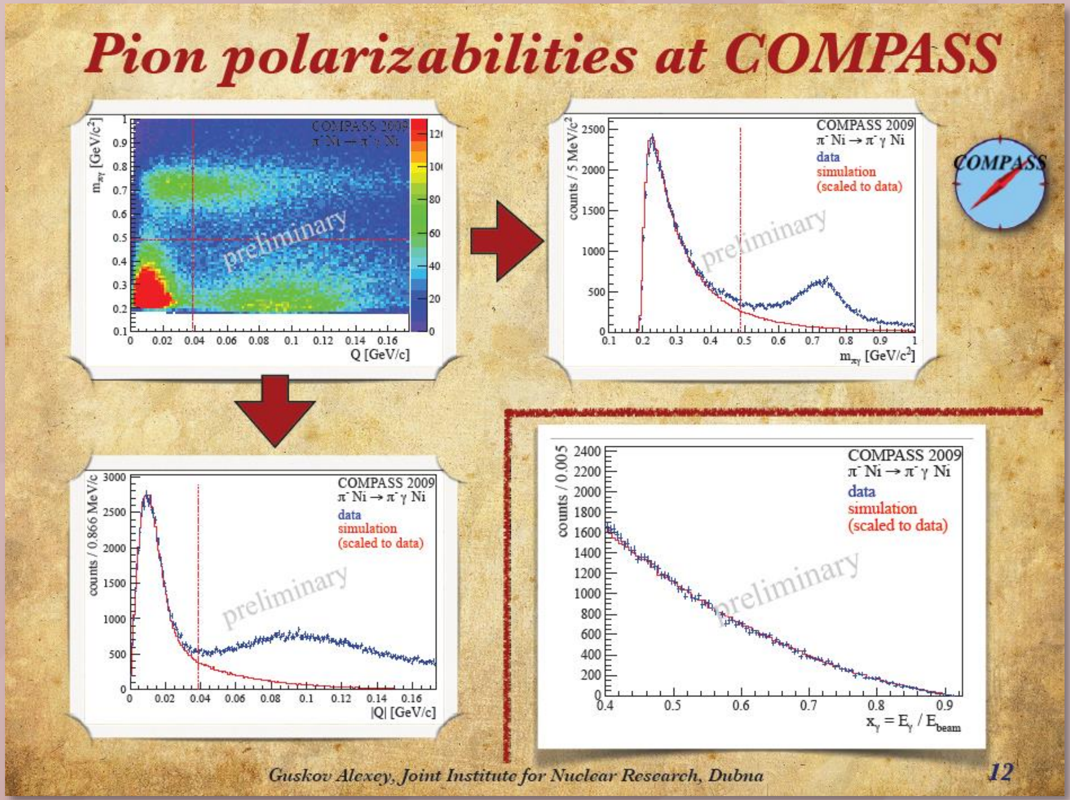
Primakoff reactions



Primakoff reactions



history



present

future: COMPASS
JLab

a hot issue

Unpolarised SIDIS:

- Multiplicities
- Fragmentation Functions
- k_T distributions
- p_T distributions
- Azimuthal Modulations

$$\cos \phi \, , \cos 2\phi$$

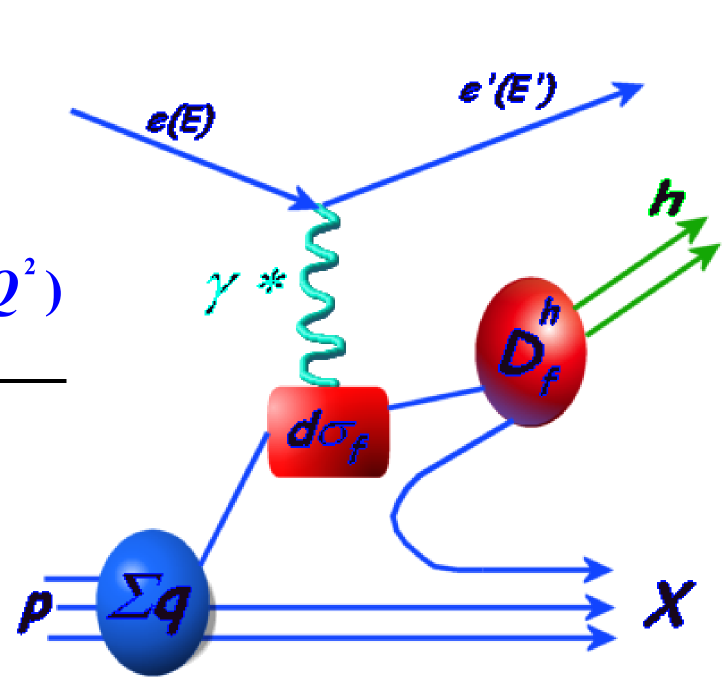
E.-C. Aschenauer
K. Kurek
M. Stratmann
G. Schnell
M. Radici
M. Boglione
B. Parsamyan

and connections with unpolarised Drell-Yan

Multiplicities and Fragmentation Functions

E.-C. Aschenauer

New results from COMPASS and hermes



$$\frac{dN^h(z,p_t,x,Q^2,\phi)}{N^e(x,Q^2)} = \frac{\sum_f e_f^2 \int_0^1 dx q_f(k_t,x,Q^2) D_f^h(z,p_t,Q^2)}{\sum_f e_f^2 \int_0^1 dx q_f(k_t,x,Q^2)}$$

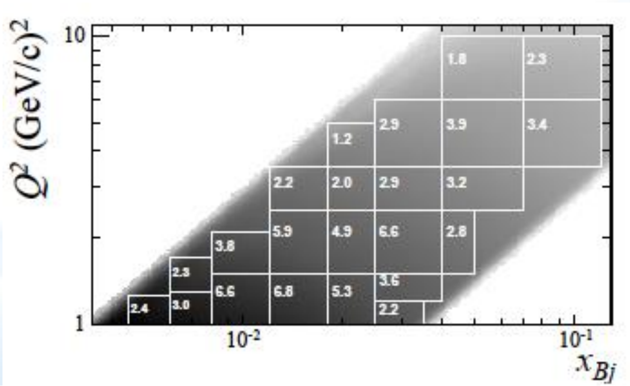
General Cuts applied:

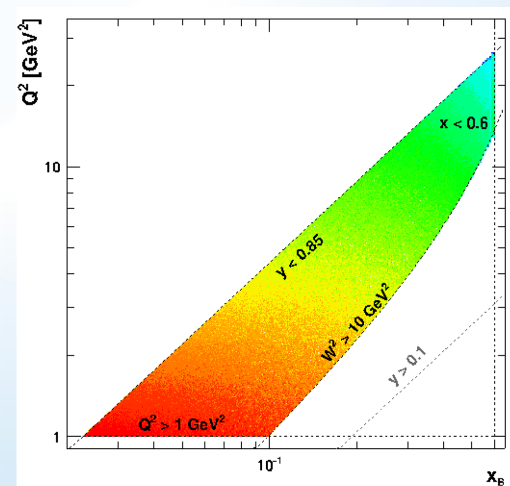
COMPASS:

Q^2>1GeV
0.1<y<0.9,
5 GeV <W<17 GeV,
0.003<x<0.7
0.2<z<0.85
h^+h^-: arXiv:1305.7317
π,K: Talk at DIS

HERMES:

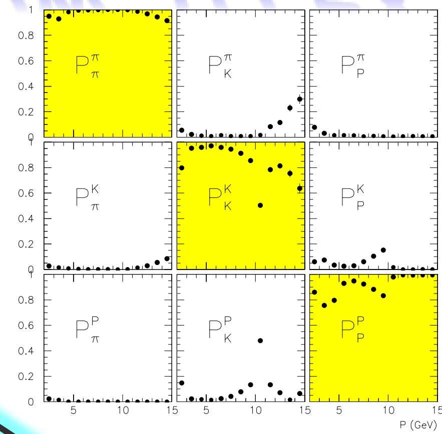
Q^2>1GeV
0.1<y<0.85,
10 GeV <W^2
0.2<z<0.85
PRD87 (2013) 074029



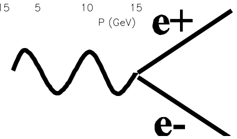


HOW TO EXTRACT MULTIPLICITIES

unpolarised raw data

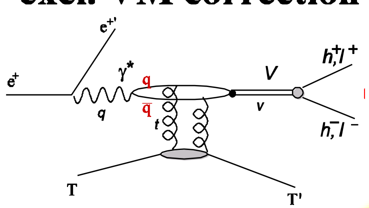


- RICH PID unfolding
- trigger efficiency correction
- charge-sym. bkg correction



experimental multiplicities in acceptance

excl. VM correction

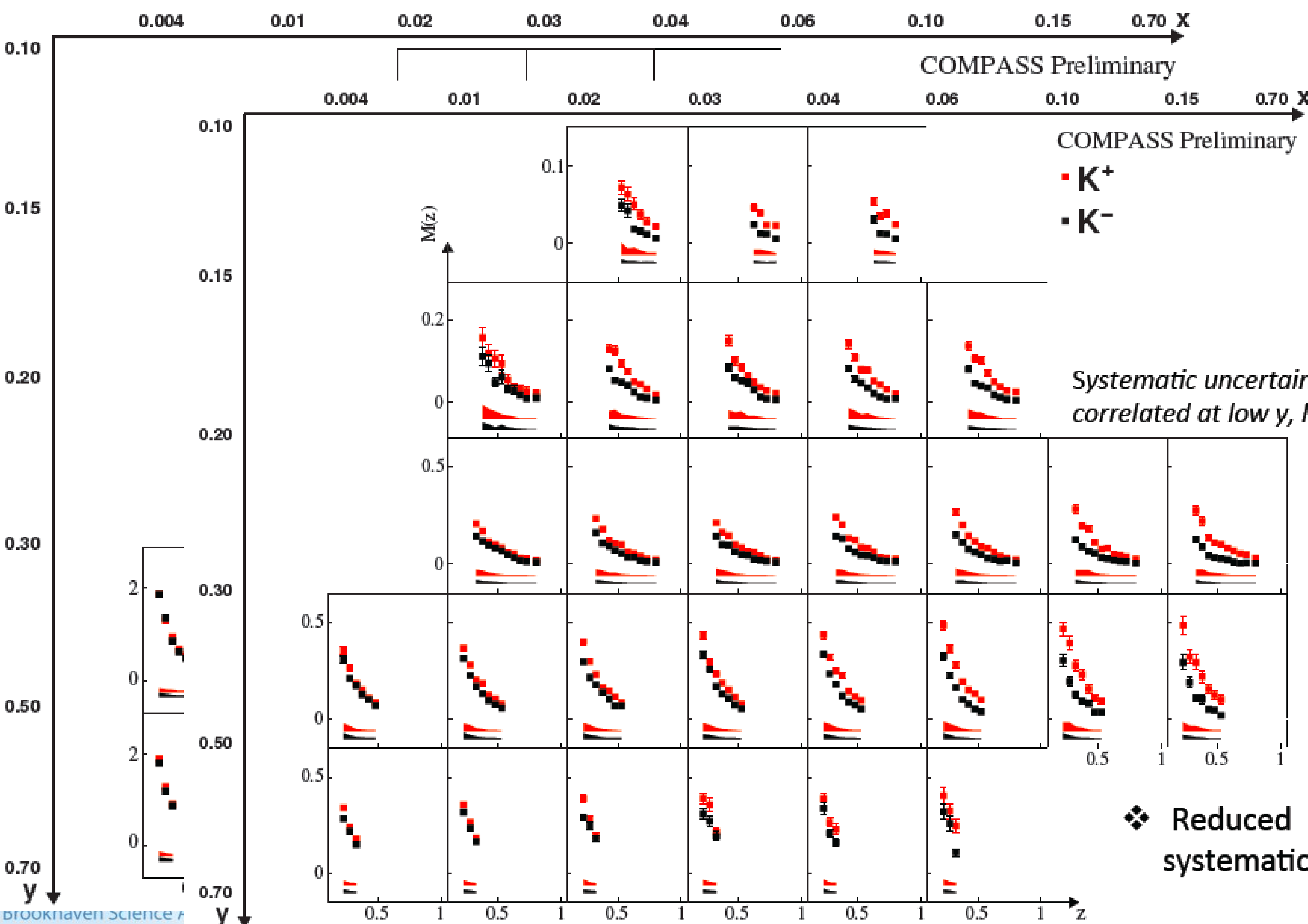


Unfolding for Detector Smearing and QED Radiative Effects

MC based corrections

Born level multiplicities

RESULTS



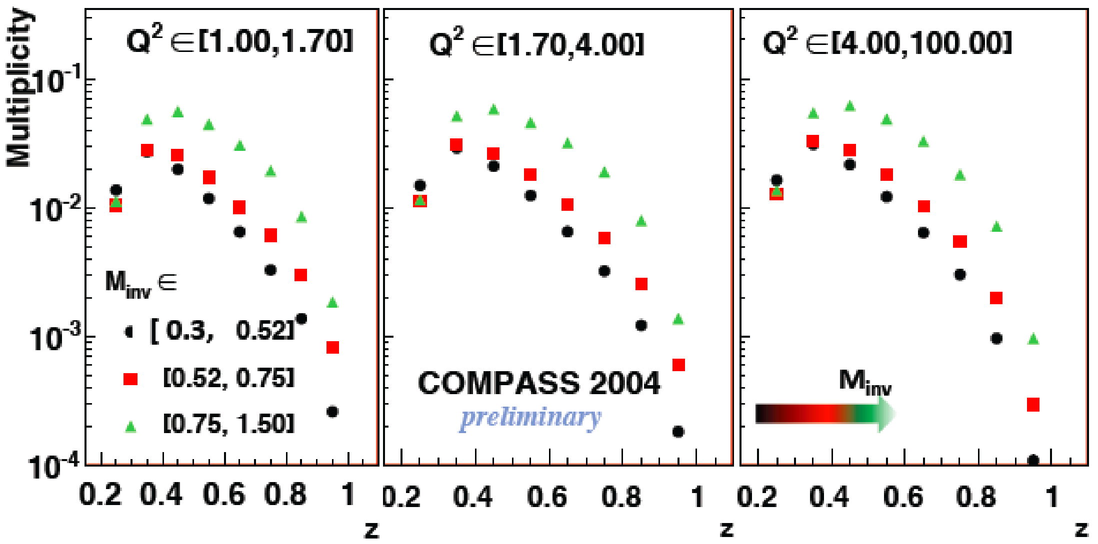
Systematic uncertainty fully correlated at low y, low z

❖ Reduced systematic errors

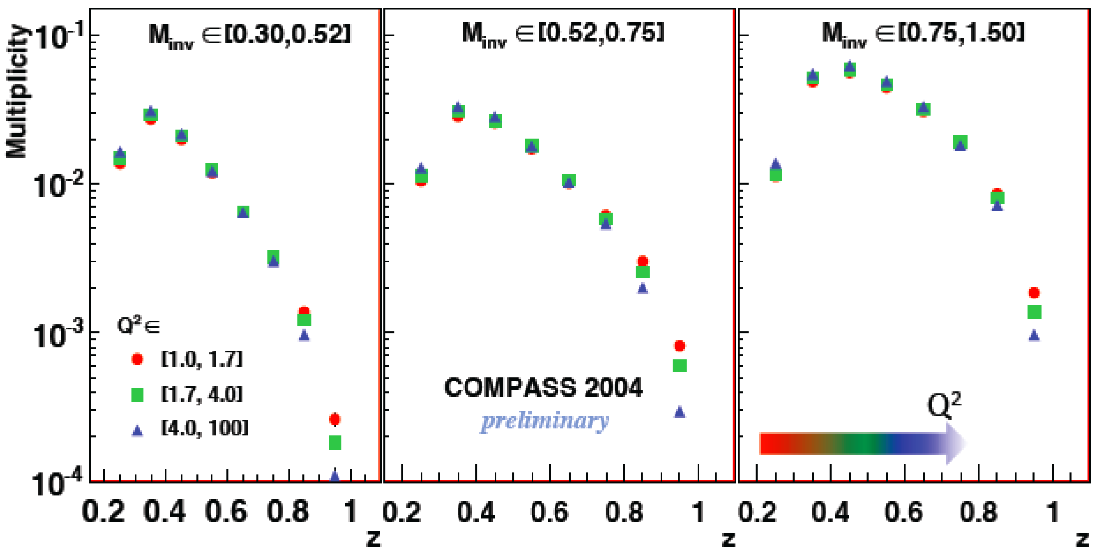
HADRON PAIR MULTIPLICITIES

CUTS:

Q^2>1GeV; 0.1<y<0.9, 5 GeV <W<17 GeV; 0.003<x<0.7



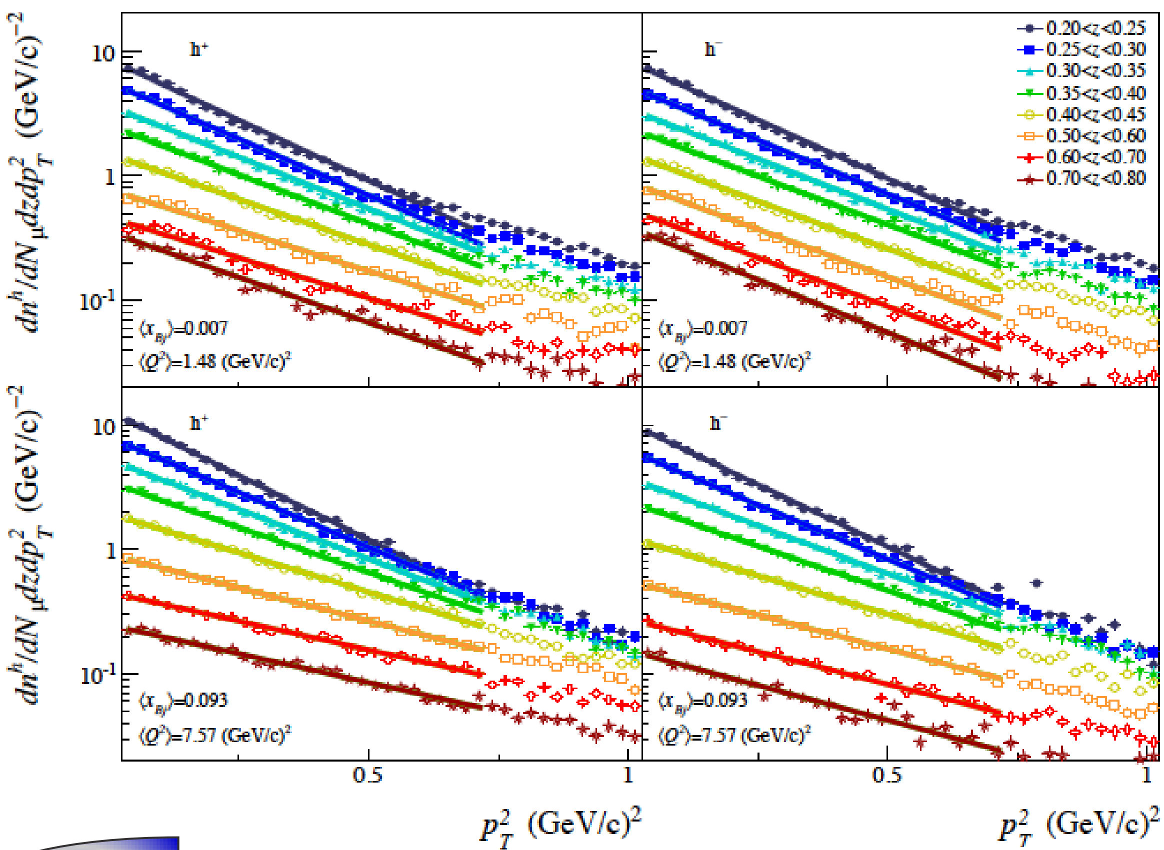
$$z = z_{h^+} + z_{h^-}$$



- First measurement in simultaneous (x,Q^2,M_{inv}) bins
- Non negligible dependence upon M_{inv} and z
- Weak Q^2 dependences
- Lepto reproduces dependences
- Input for fits to extract

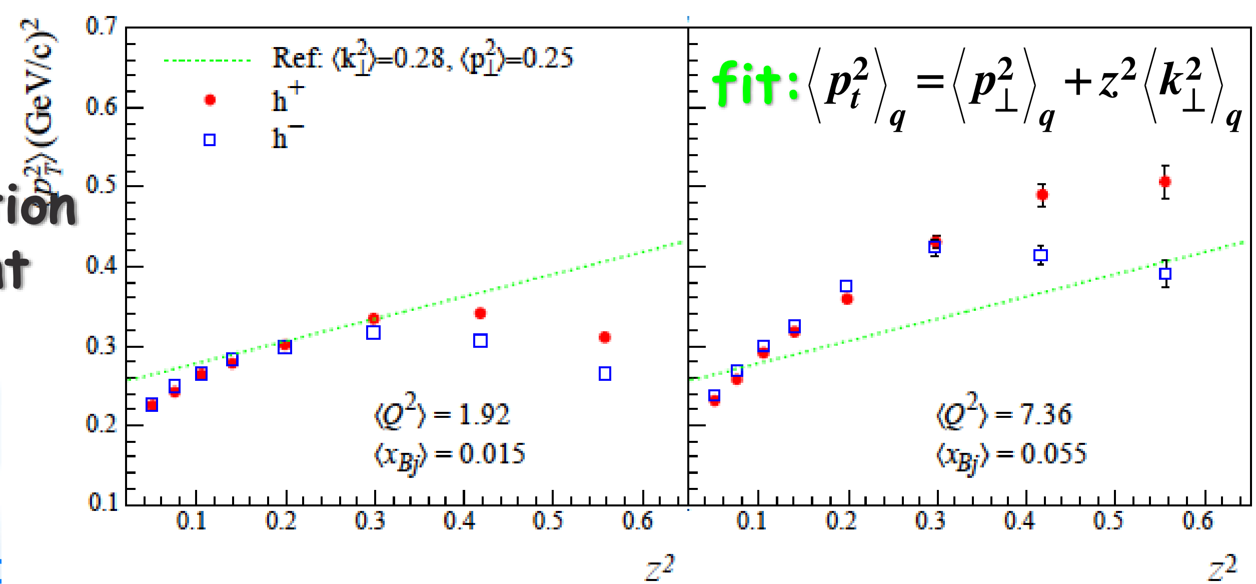
$$D_q^{h^+h^-}(z,Q^2,M_{inv})$$

RESULTS



very precise multidimensional data (x, Q^2, p_t, z)

- fit is not a good representation
- need to account for different underlying sub-processes
- neglects other dependences



Multiplicities and Fragmentation Functions

E.-C. Aschenauer

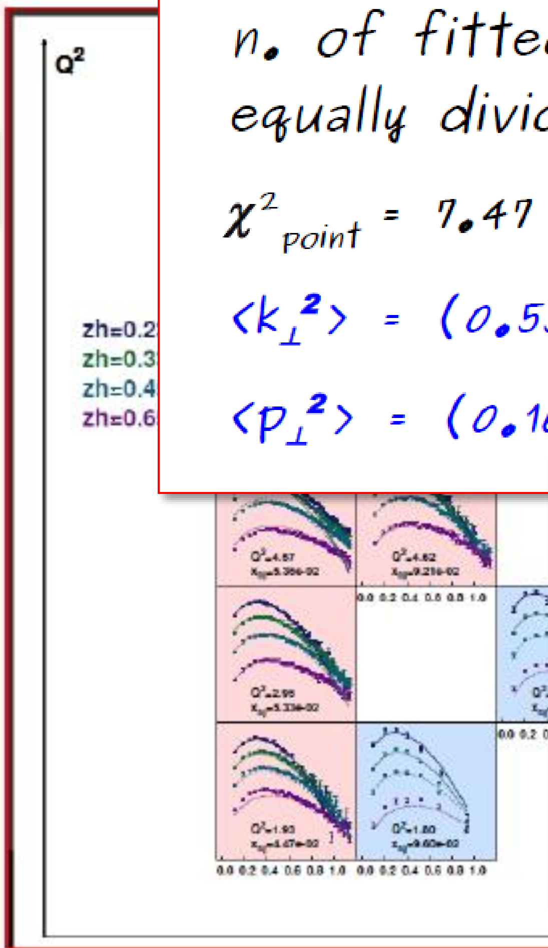
M. Boglione

Extracting the unpolarized TMD

Gaussian w

- HERMES +

M. Boglione



- HERMES + COMPASS fit

Very preliminary
Anselmino, Boglione, Gonzalez, Melis

cuts: $Q^2 > 1.68$, $z < 0.7$, $P_T/Q < 1$, $x > 0.08$

n. of fitted data points: 2873 (almost equally divided between HERMES and COMPASS)

$\chi^2_{point} = 7.47$

$\langle k_\perp^2 \rangle = (0.55 \pm 0.21)\ GeV^2$

$\langle p_\perp^2 \rangle = (0.16 \pm 0.03)\ GeV^2$

Any sign of Q^2 evolution ?

...

More work ...

More parameters ...

Multiplicities and Fragmentation Functions

E.-C. Aschenauer

M. Boglione

M. Stratmann

M. Stratmann

take away message

global QCD analyses of fragmentation functions ongoing

- pion FFs rather well constrained
- uncertainties for kaon FFs still large

many new data sets will lead to much improved sets

e^+e^-

- BELLE and BaBar add precision data at different scale than LEP
- possible tension between BELLE and BaBar

e/μ p

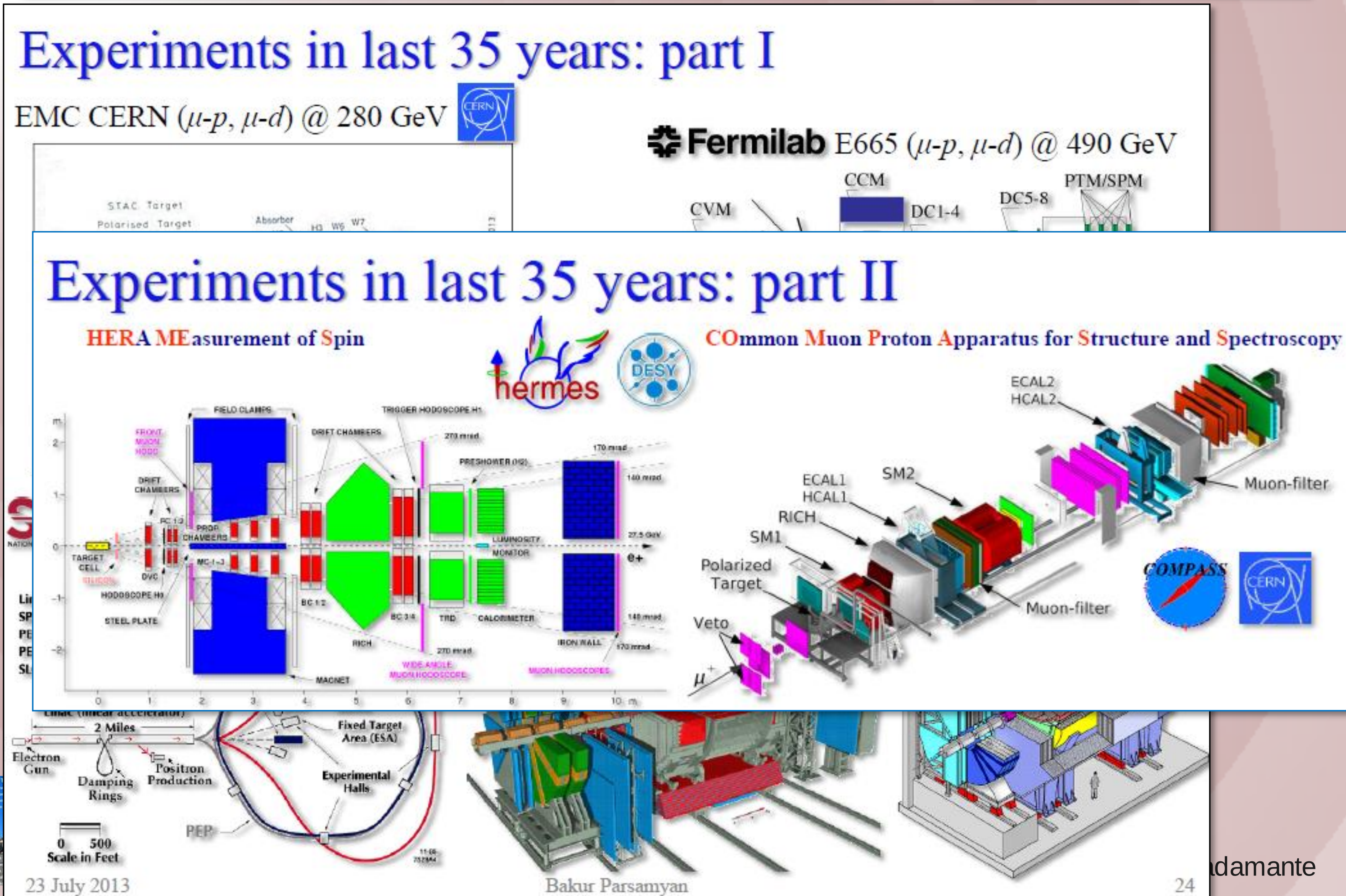
- COMPASS and HERMES pion results fit very well together
- will start with kaons as soon as COMPASS results become available

pp

- new RHIC and first LHC results in the fit
- some normalization issue with ALICE

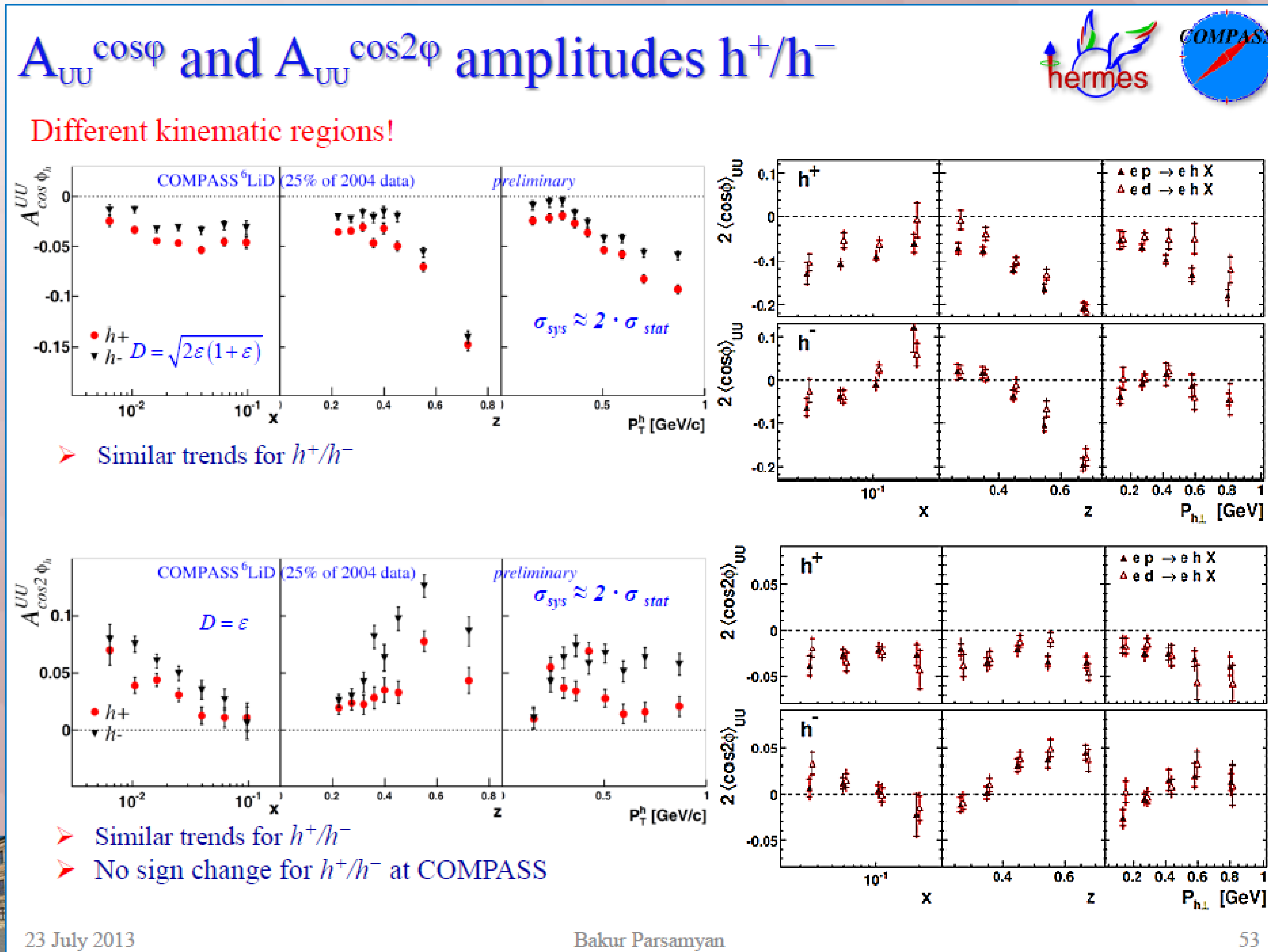
azimuthal asymmetries in unpolarised SIDIS

B. Parsamyan



azimuthal asymmetries in unpolarised SIDIS

B. Parsamyan



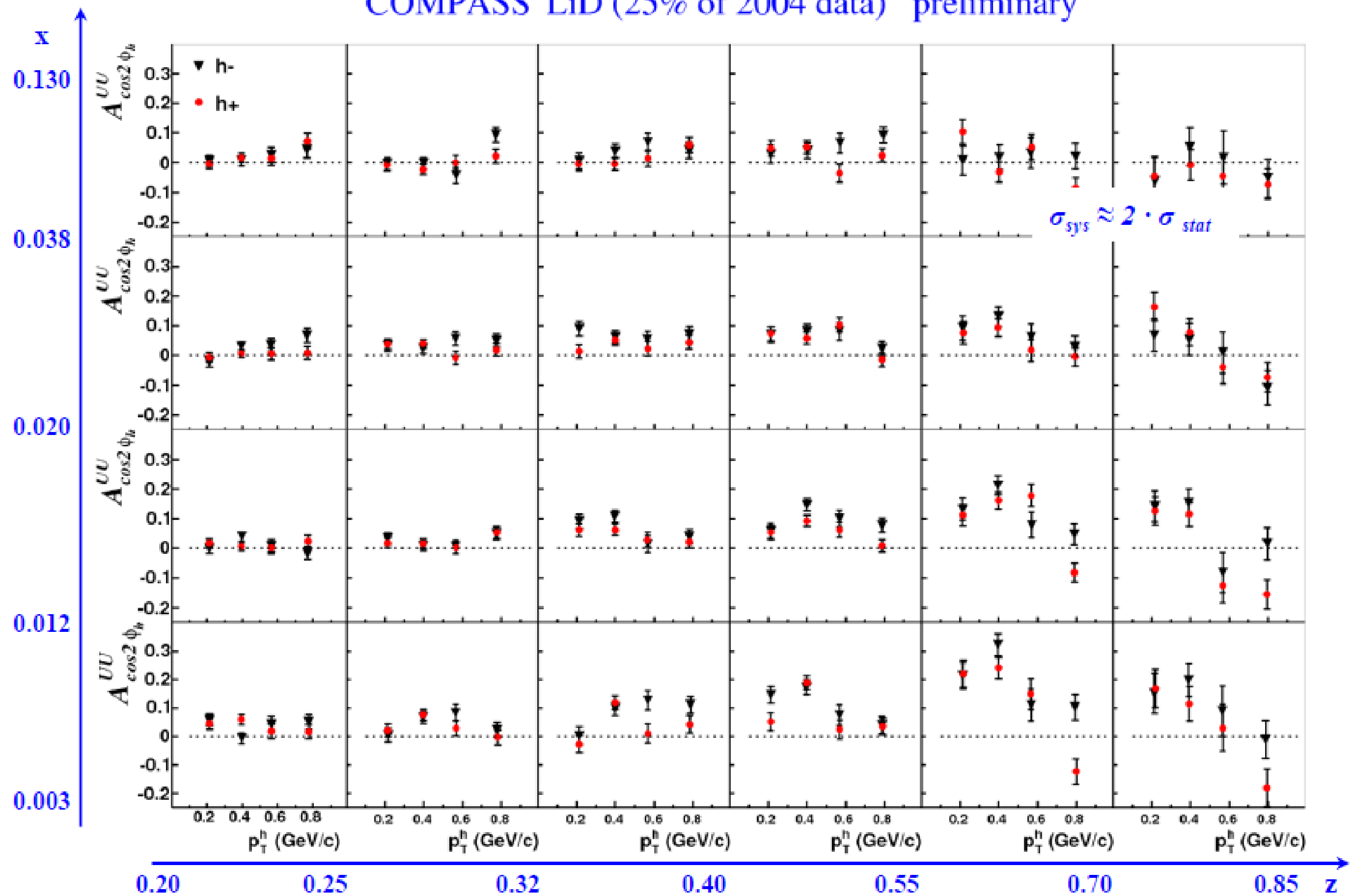
ante

azimuthal asymmetries in unpolarised SIDIS

B. Parsamyan

$A_{UU}^{\cos 2\varphi_h}$ - asymmetry (P_{hT} - dependence)

COMPASS ^{6}LiD (25% of 2004 data) preliminary



P_{hT} trend not discribed by the models arises in large z and low x region

23 July 2013 Bakur Parsamyan 51

longitudinal spin structure of the nucleon

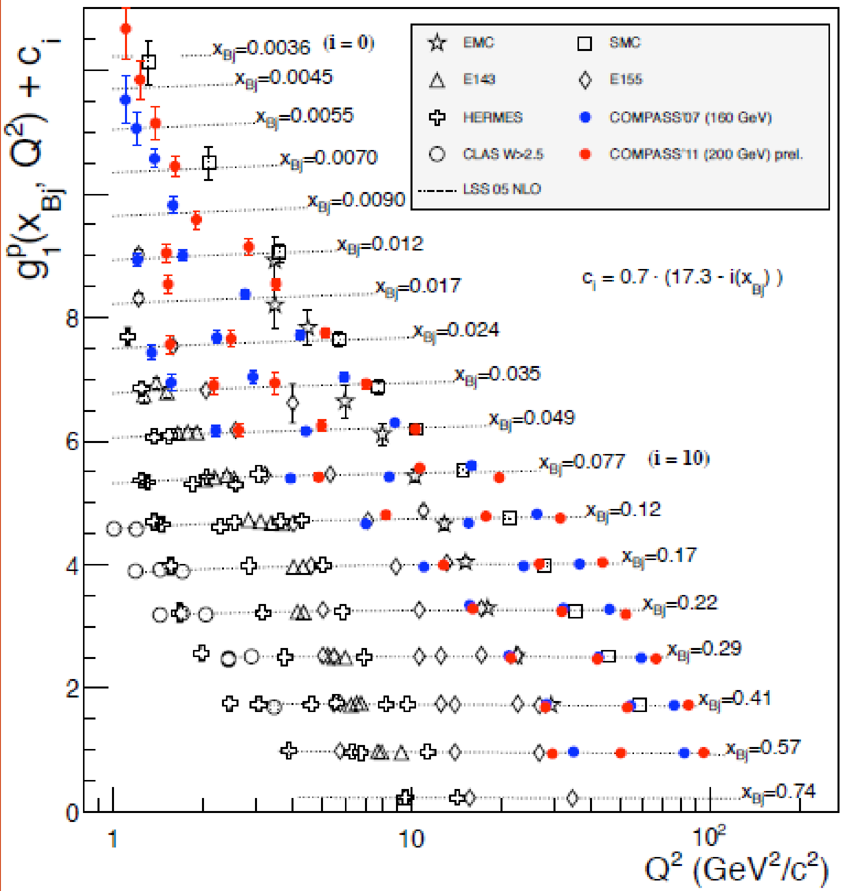
K. Rith
K. Kurek
C. Lorce
F. Ringer

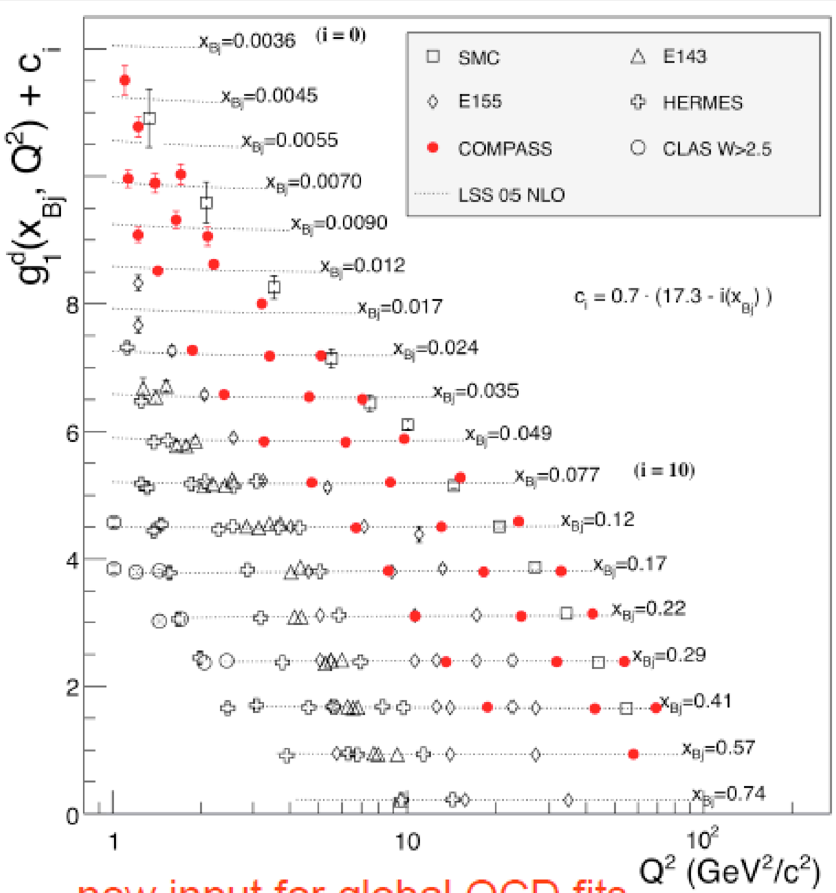
review
of longitudinal spin physics

K. Kurek

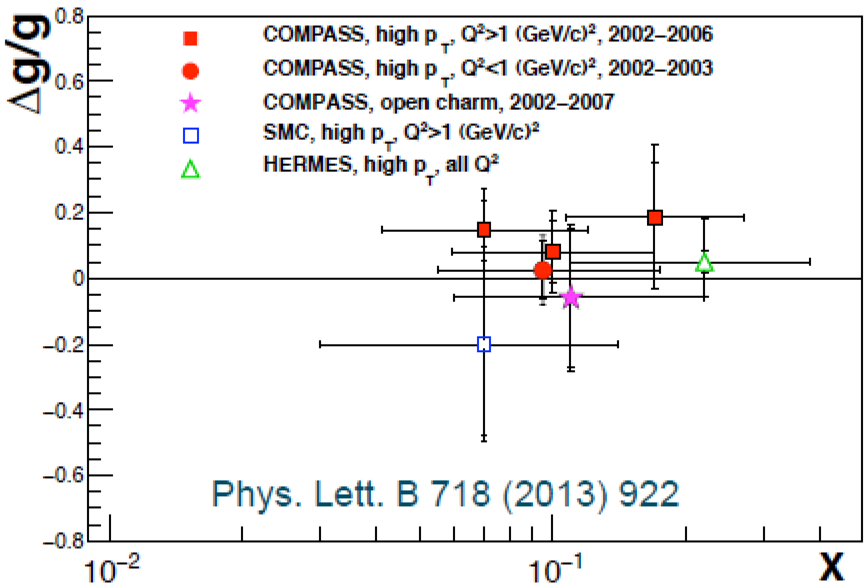
World data for proton and deuteron g_1 structure function

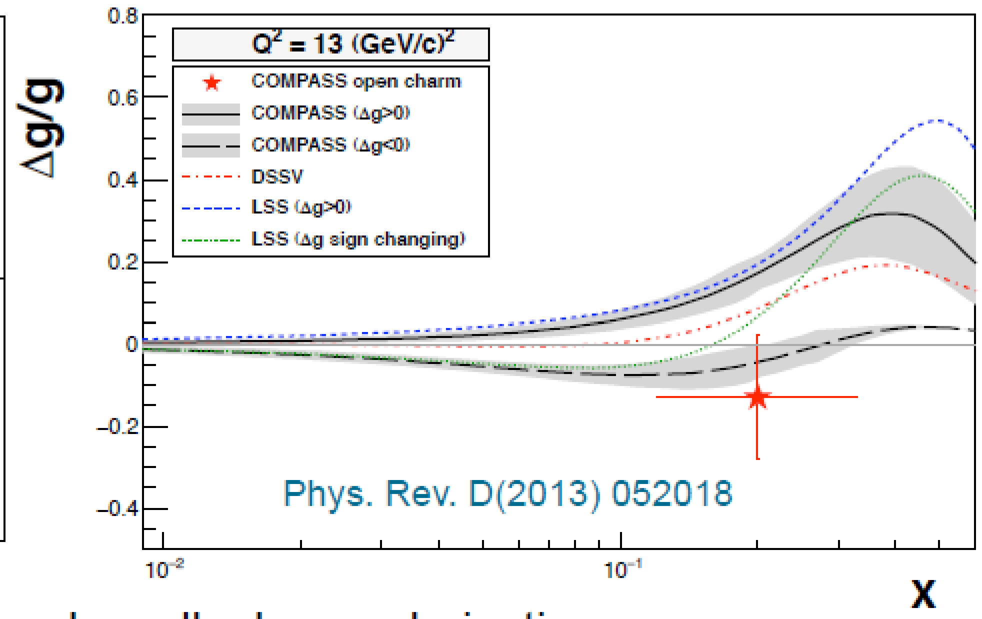
COMPASS proton data 2011@200 GeV included





new input for global QCD fits

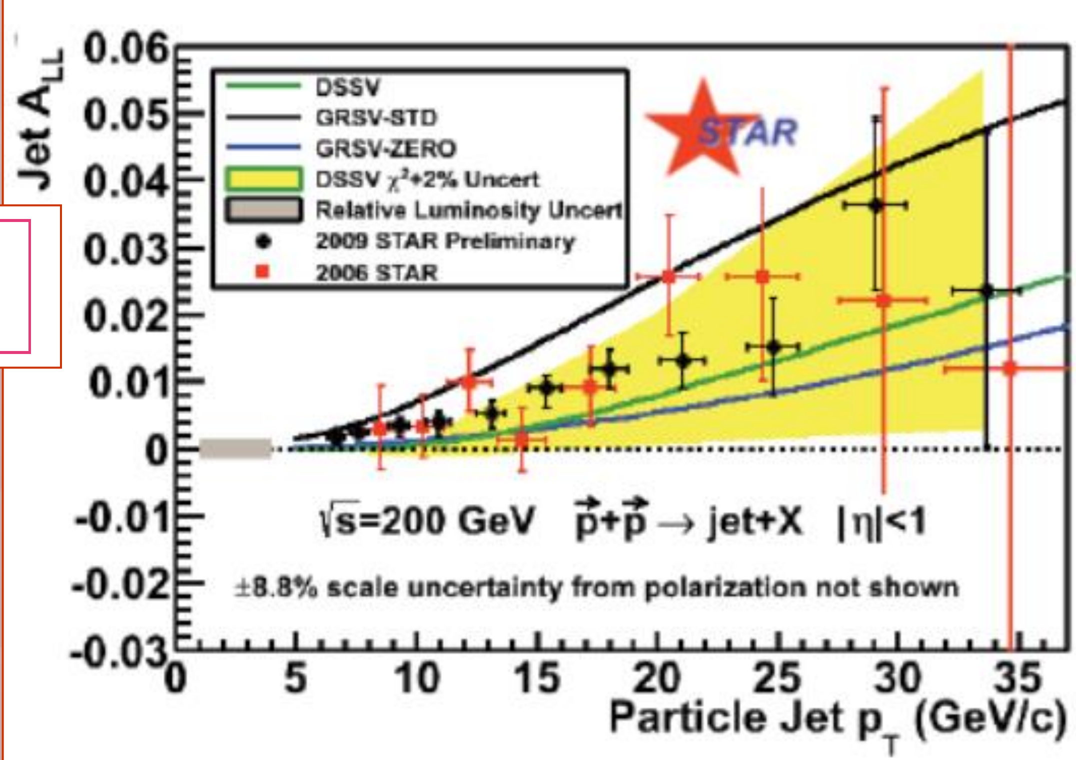




LO: all data consistent and point toward small gluon polarisation

K. Kurek

$$DSSV++: \int_{0.05}^{0.2} \Delta g(x)dx = 0.10^{+0.06}_{-0.07}$$



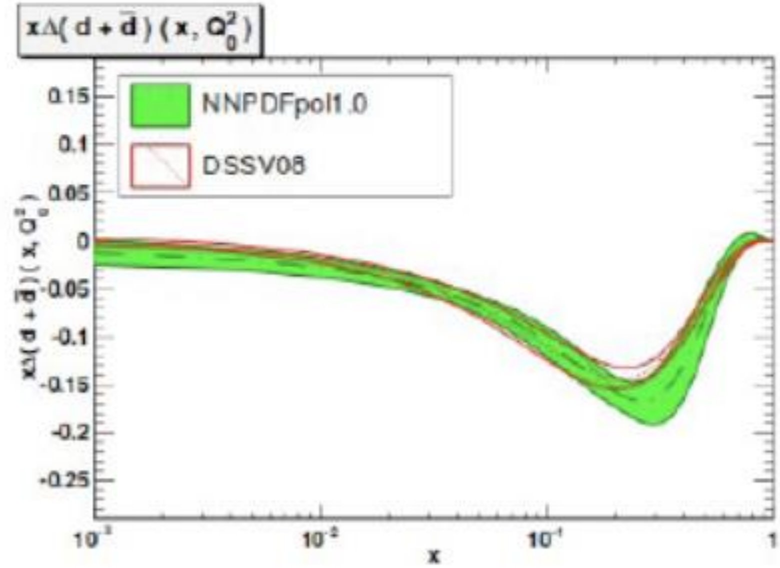
IWHSS2013

K. Kurek

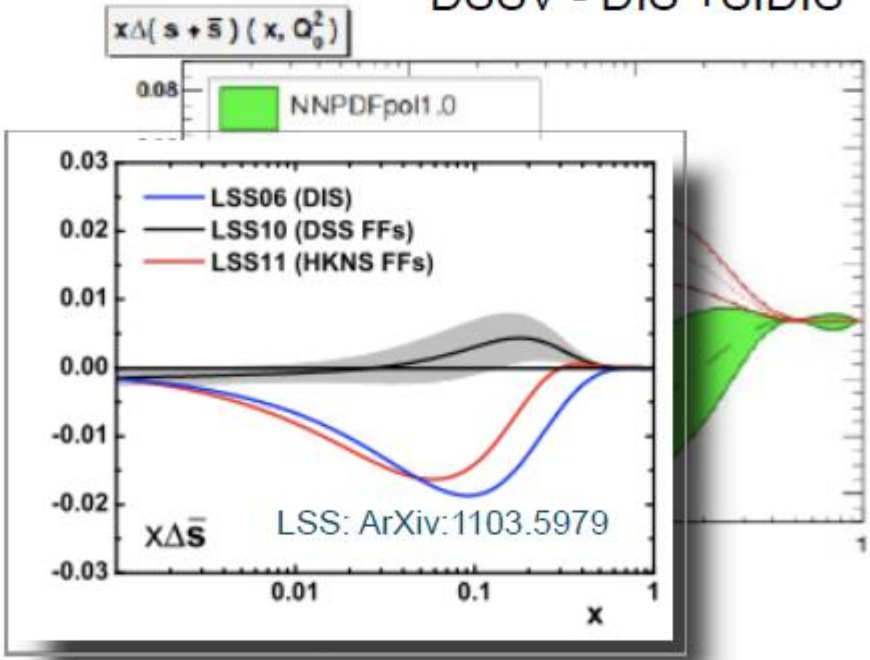
Δs puzzle

The lesson:
Important piece of information:
precise measurement of FFs

NNPDF - only DIS
DSSV - DIS +SIDIS



NNPDF, R.D.Ball et al. arXiv: 1303.7236



The proton spin decomposition: observability and interpretation

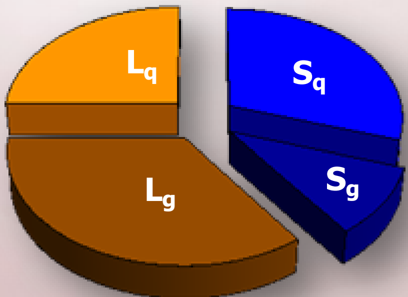
C. Lorcé

The decompositions in a nutshell

Canonical

$\vec{p} = \frac{\partial L}{\partial \vec{v}}$

[Jaffe-Manohar (1990)]



$$\vec{S}_q = \frac{1}{2}\int \mathrm{d}^3r\,\psi^\dagger\vec{\Sigma}\psi$$
$$\vec{L}_q = \int \mathrm{d}^3r\,\psi^\dagger\vec{r}\times(-i\vec{\nabla})\psi$$
$$\vec{S}_g = \int \mathrm{d}^3r\,\vec{E}^a\times\vec{A}^a$$
$$\vec{L}_g = \int \mathrm{d}^3r\,E^{ai}\vec{r}\times\vec{\nabla}A^{ai}$$

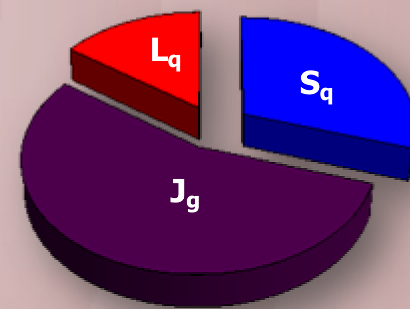
Gauge non-invariant!

Kinetic

$\vec{\pi} = m\vec{v} = \vec{p} + g\vec{A}$

[Ji (1997)]

$\vec{D} = \vec{\nabla} + ig\vec{A}$

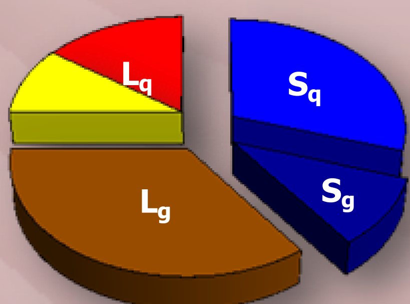


$$\vec{S}_q = \frac{1}{2}\int \mathrm{d}^3r\,\psi^\dagger\vec{\Sigma}\psi$$
$$\vec{L}_q = \int \mathrm{d}^3r\,\psi^\dagger\vec{r}\times(-i\vec{D})\psi$$
$$\vec{J}_g = \int \mathrm{d}^3r\,\vec{r}\times(\vec{E}^a\times\vec{B}^a)$$

$$\vec{\mathsf{L}}_{\text{pot}} = \int \mathrm{d}^3r\,\rho^a\,\vec{r}\times\vec{A}^a_{\text{phys}}$$
$$\rho^a = g\psi^\dagger t^a\psi = (\vec{\mathcal{D}}\cdot\vec{E})^a$$

[Chen *et al.* (2008)]

$A = A_{\text{pure}} + A_{\text{ph}}$

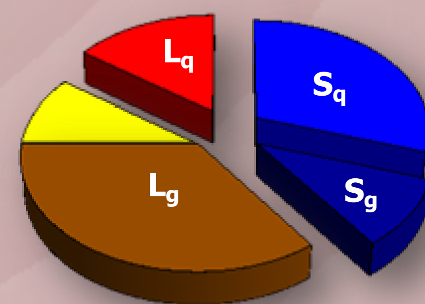


$$\vec{\mathsf{S}}_q = \frac{1}{2}\int \mathrm{d}^3r\,\psi^\dagger\vec{\Sigma}\psi$$
$$\vec{\mathsf{L}}_q = \int \mathrm{d}^3r\,\psi^\dagger\vec{r}\times(-i\vec{D}_{\text{pure}})\psi$$
$$\vec{\mathsf{S}}_g = \int \mathrm{d}^3r\,\vec{E}^a\times\vec{A}^a_{\text{phys}}$$
$$\vec{\mathsf{L}}_g = \int \mathrm{d}^3r\,E^{ai}\vec{r}\times\vec{\mathcal{D}}_{\text{pure}}A^{ai}_{\text{phys}}$$

Gauge-invariant extension (GIE)

tsu (2010)]

$A = A_{\text{pure}} + A_{\text{phys}}$



$$\vec{S}_q = \frac{1}{2}\int \mathrm{d}^3r\,\psi^\dagger\vec{\Sigma}\psi$$
$$\vec{L}_q = \int \mathrm{d}^3r\,\psi^\dagger\vec{r}\times(-i\vec{D})\psi$$
$$\vec{\mathcal{S}}_g = \int \mathrm{d}^3r\,\vec{E}^a\times\vec{A}^a_{\text{phys}}$$
$$\vec{\mathcal{L}}_g = \left[\int \mathrm{d}^3r\,\vec{r}\times(\vec{E}^a\times\vec{B}^a) - \int \mathrm{d}^3r\,\vec{E}^a\times\vec{A}^a_{\text{phys}}\right]$$

$$\int \mathrm{d}^3r\,\vec{r}\times[(\vec{A}^a_{\text{phys}}\times\vec{\mathfrak{D}}_{\text{pure}})\times\vec{E}^a]$$

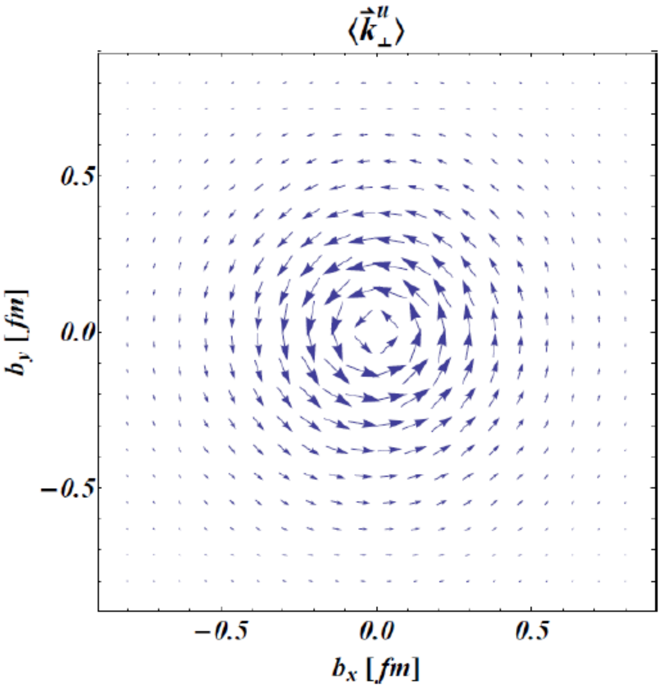
[C.L. (2013)]

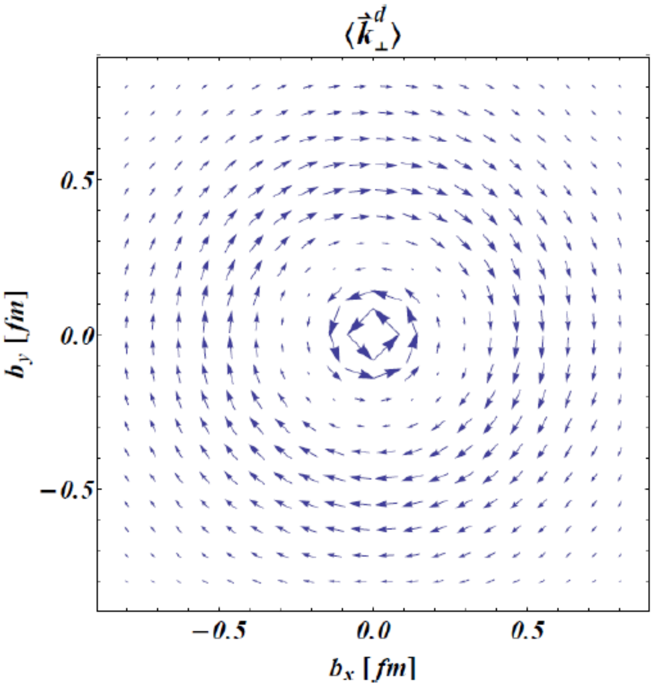
The orbital motion in a light-front quark model

[C.L., Pasquini, Xiong, Yuan (2012)]

Average transverse quark momentum in a longitudinally polarized nucleon

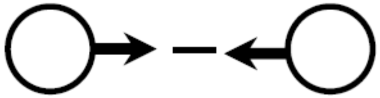
$$\langle\vec{k}_\perp\rangle(\vec{b}_\perp) = \int \mathrm{d}x\,\mathrm{d}^2k_\perp\,\vec{k}_\perp\,\rho_{++}^{[\gamma^+]}(x,\vec{k}_\perp,\vec{b}_\perp)$$





F_{14}

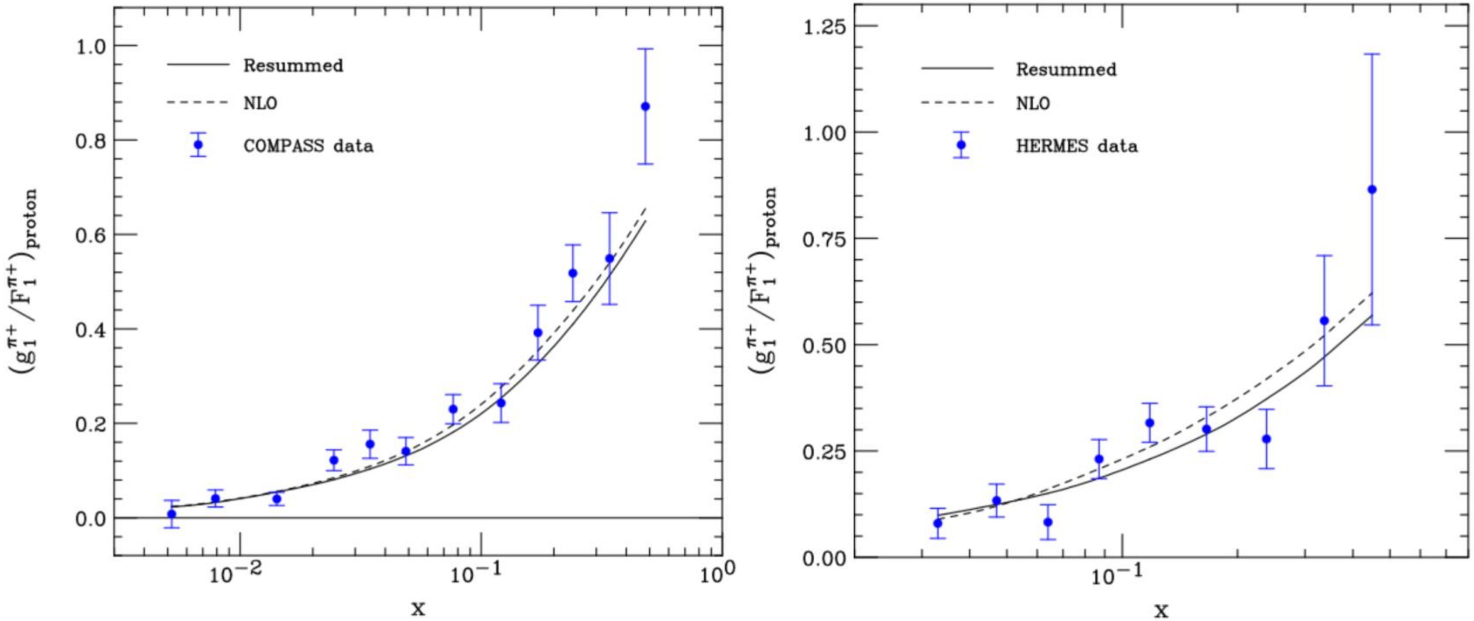
« Vorticity »



QCD resummation for semi-inclusive hadronproduction processes

F. Ringer

Semi-inclusive DIS asymmetries A_1^h



proton target $0.2 < z < 0.8$

using MRST'02/DSSV PDFs and DSS FFs

EBERHARD KARLS UNIVERSITÄT TÜBINGEN

recent progress in lattice QCD

V. Drach

Our laboratory

BlueGene/Q :Ju

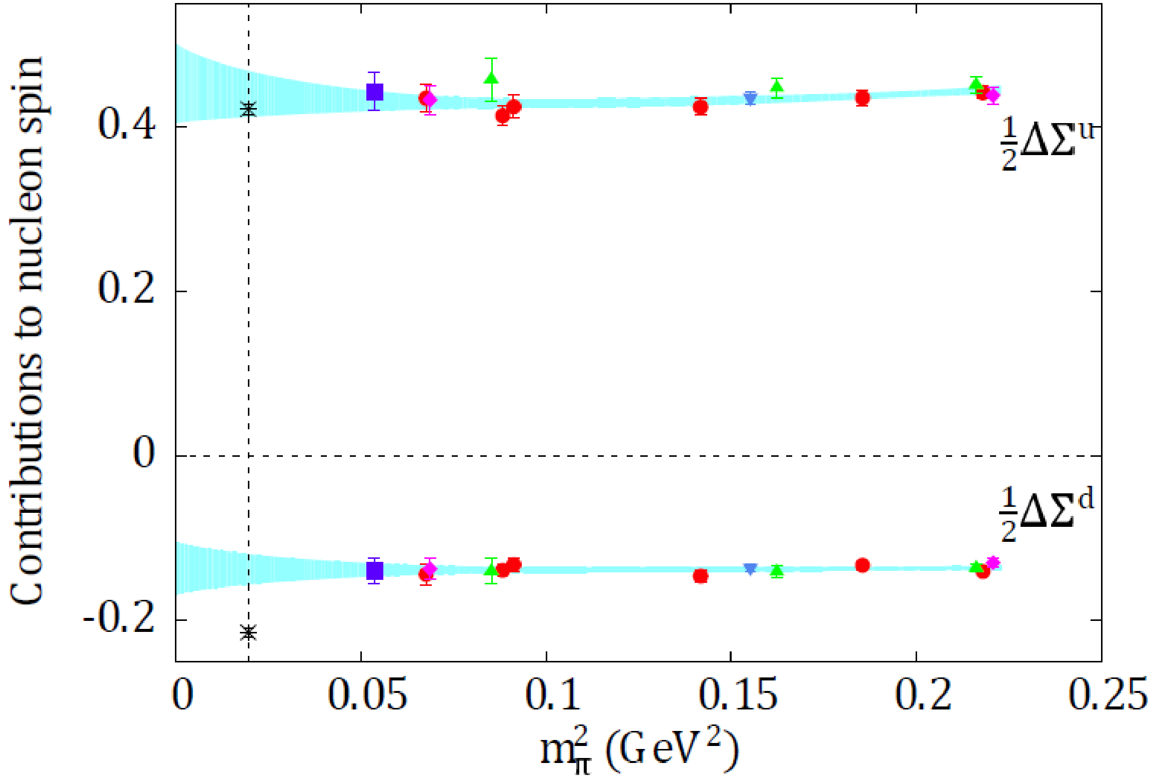
(7$^{\text{th}}$ biggest com

to solve the (cla

($N_{\text{d.o.f}} \sim 12 \times V$

$\Delta\Sigma^q$

Unquenched but neglect disconnected insertion



Physical points are from the HERMES 2007 analysis. [ETM, 1303.5979]

DVCS and GPDs

K. Rith

V. Drach

…

H. Moutard

Review of some recent developments on Deeply Virtual Compton Scattering

H. Moutard

Review of some recent developments on Deeply Virtual Compton Scattering

From QCD first principles to experimental data.

Very good theoretical control, but not easy to implement!

- **All-order proof of factorization** of DVCS amplitude.
  Collins and Freund, Phys. Rev. **D59**, 074009 (1999)
- Hard scattering kernel computed at **next-to-leading order** at leading twist.
  Belistky and Müller, Phys. Lett. **B417**, 129 (1998)
- Evolution equations computed at **next-to-leading order**.
  Belitsky *et al.* , Nucl. Phys. **B574**, 347 (2000) and ref. therein
- Finite-t and target mass corrections computed at **leading order**: kinematic power corrections to **twist 4 accuracy**.
  Braun *et al.* , Phys. Rev. Lett. **109**, 242001 (2012)

GPD "measurements" ?

- **Already achieved**: experimentally constrained models.
- Next step: **Measured transverse plane images**.

H. Moutard

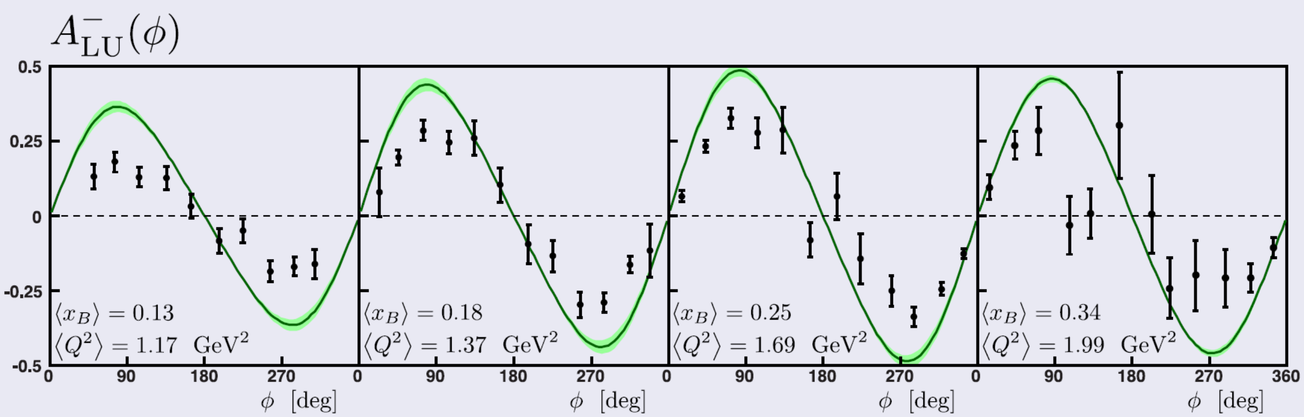
Review of some recent developments on Deeply Virtual Compton Scattering

Recent developments on DVCS

Goloskokov-Kroll (GK) model on DVCS.

No parameter of the GK model **was tuned** to analyse DVCS.

Beam Spin Asymmetry, CLAS



Kroll *et al.* , Eur. Phys. J C**73** (2013) 2278

H. Moutard

Review of some recent developments on Deeply Virtual Compton Scattering

CEA - Saclay

Conclusions.

The importance of spacelike and timelike Compton scattering at COMPASS.

- **Large NLO "corrections"** to DVCS amplitude.
- **Larger** for TCS. **Measurement of TCS at COMPASS**?
- Measurements of DVCS and TCS provide tests of **factorization** and of the **QCD understanding** of these reactions through the size of NLO corrections.
- Need global GPD fits to **separate quarks and gluon** contributions and **accurately** interpret extracted data.
- DVCS measurements at COMPASS will provide an interesting **cross-check of HERMES DVCS data**.
- **COMPASS DVCS experiment may provide a way to constrain gluon GPDs!**

Drell-Yan

…

C. Riedl

Review of Drell-Yan experiments

M. Radici

Theoretical overview of transverse spin physics in SIDIS and Drell-Yan

C. Riedl
Review of Drell-Yan experiments

Selected Drell-Yan experiments of the past

1970 — Brookhaven AGS, p-U, 29 GeV

First measurement: *Observation of Massive Muon Pairs in Hadron Collisions*

1979 — FNAL CIP, $\pi^{\pm}$, Be/Cu/W, 80, 225, 252 GeV

CER... Ome... $\pi^{\pm}$, K... p... Cu/... 40 G...

198...

criedl@illinois.edu - Review of Dre...

IWHSS2...

Future Drell-Yan experiments

- Programs for future Drell-Yan measurements:
  nucleon-nucleon at
  - SeaQuest (Fermilab)
  - RHIC (Brookhaven)
  - J-PARC (KEK)
  - IHEP (Protvino)
  - JINR (Dubna)

  anti(p)-nucleon at
  - FAIR (GSI)

  pion-nucleon at
  - COMPASS (CERN)

  Only existing meson plan!

The story of the DY E-XYZ and NA* experiments will be continued

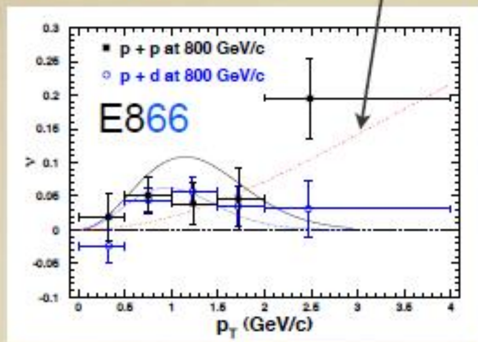
- Past measurements exclusively considered the unpolarized cross section, future ones also aim for polarization measurements.
  - transversely polarized DY: spin-dependent TMDs
  - longitudinally polarized DY: quark helicity

More details on FAIR in K. Peter's talk @ this workshop
More details on JINR in I. Savin's and A. Nagaytsev's talk
The RHIC Spin program, arXiv:1304.0079

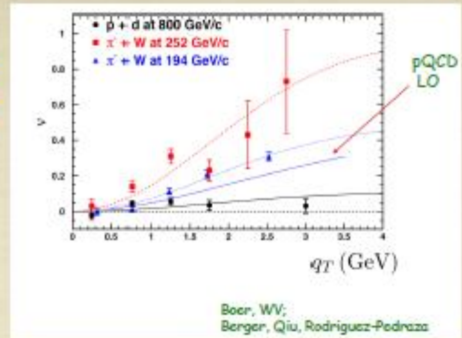
M. Radici

Theoretical overview of transverse spin physics in SIDIS and Drell-Yan

NLO pQCD partly accounts for ν_{pp}, but not for ν_{pD} and $\nu_{\pi N}$



E866
E615
NA10



situation complicated from higher twists:

Drell-Yan: $\mu \to W_{UU}^{\cos\phi} = \frac{1}{Q} f_1 \otimes f_1 + \frac{1}{Q} h_1^{\perp} \otimes h_1^{\perp}$ $\quad \nu \to W_{UU}^{\cos 2\phi} = h_1^{\perp} \otimes h_1^{\perp} + \frac{1}{Q^2} f_1 \otimes f_1$

Cahn effect $\qquad$ Cahn effect

SIDIS: $F_{UU}^{\cos\phi} = \frac{1}{Q} f_1 \otimes D_1 + \frac{1}{Q} h_1^{\perp} \otimes H_1^{\perp} + \ldots$ $\quad F_{UU}^{\cos 2\phi} = h_1^{\perp} \otimes H_1^{\perp} + \frac{1}{Q^2} f_1 \otimes D_1$

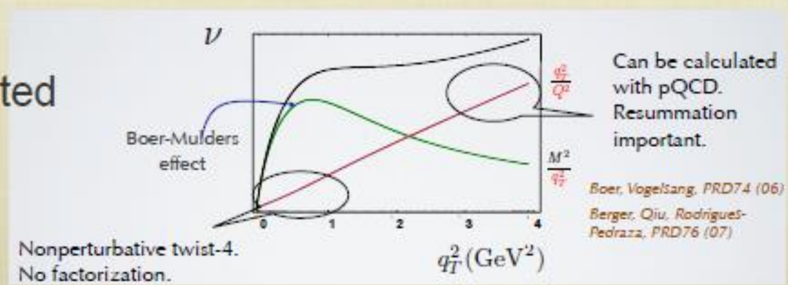
found very large, confirmed by recent data

hermes P.R. D87 (13)

COMPASS Sbrizzai Transversity 2011

very complicated

Bacchetta talk DY@ECT*12



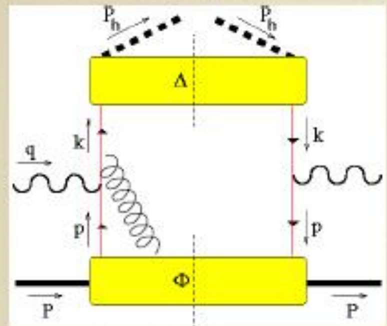
⇨ talk Parsamyan

M. Radici

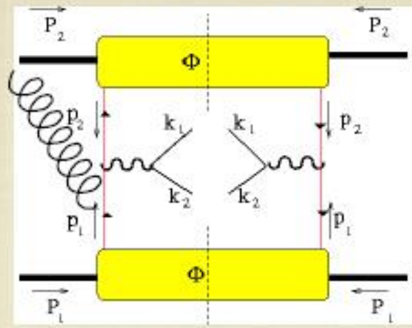
Theoretical overview of transverse spin physics in SIDIS and Drell-Yan

process dependence of naïve T-odd function:
the sign change between SIDIS and Drell-Yan

SIDIS



Drell-Yan



"Final" residual color interactions "Initial"

<u>QCD prediction to be tested:</u> $\text{Sivers}\Big|_{\text{SIDIS}} = -\text{Sivers}\Big|_{\text{D-Y}}$

*Collins, PL B**536** (02)*

it is not just checking TMD factorization,
it motivates a polarized Drell-Yan measurement..

transverse spin and momentum structure of the nucleon

K. Rith

G. Schnell

Experimental review of transverse spin physics

M. Radici

Theoretical overview of transverse spin physics in SIDIS and Drell-Yan

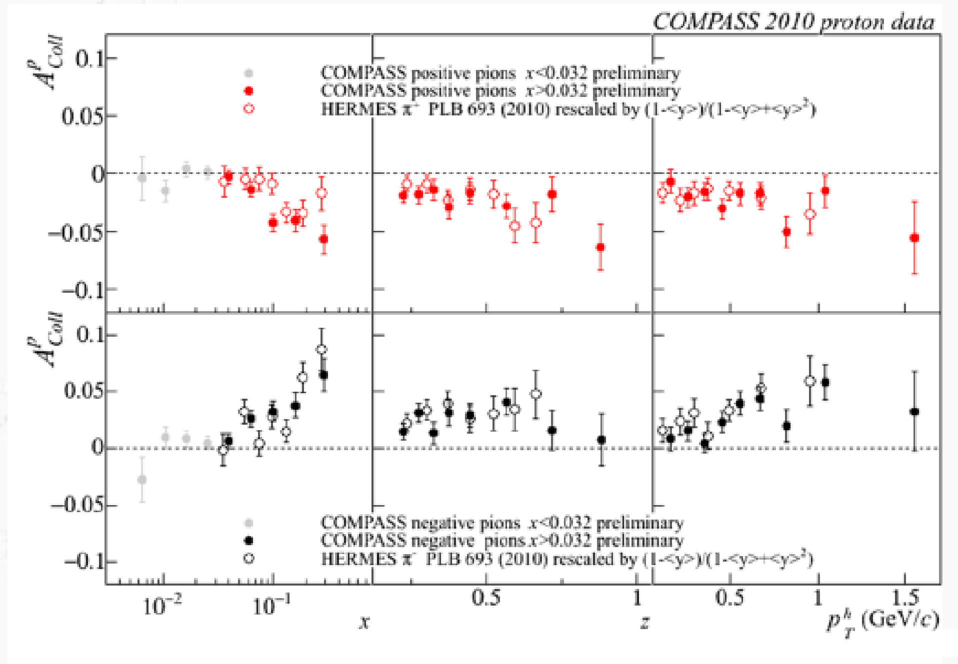
M. Boglione

Transverse momentum distributions – Q2 evolution

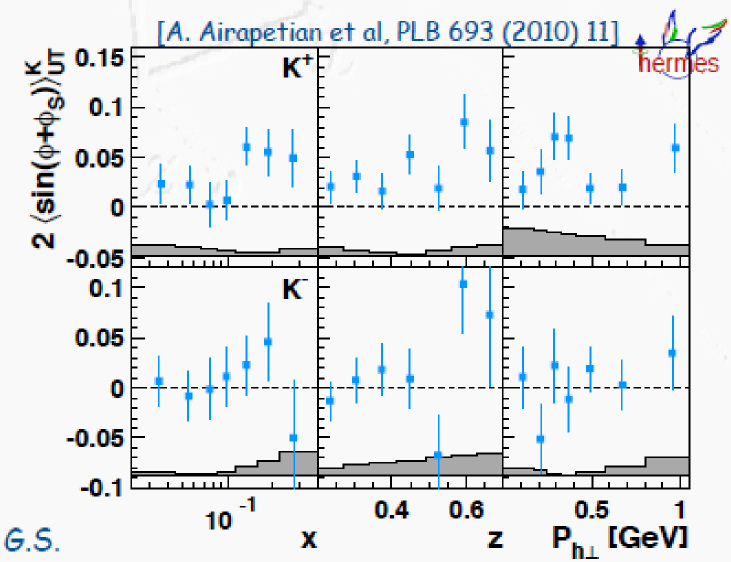
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

Collins amplitudes

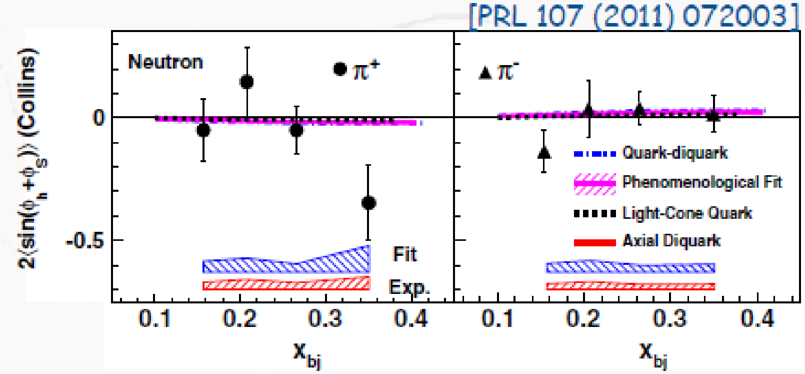
- wealth of new results:
  - COMPASS
    [PLB 692 (2010) 240, PLB 717 (2012) 376]
  - HERMES
    [PLB 693 (2010) 11]
  - Jefferson Lab
    [PRL 107 (2011) 072003]



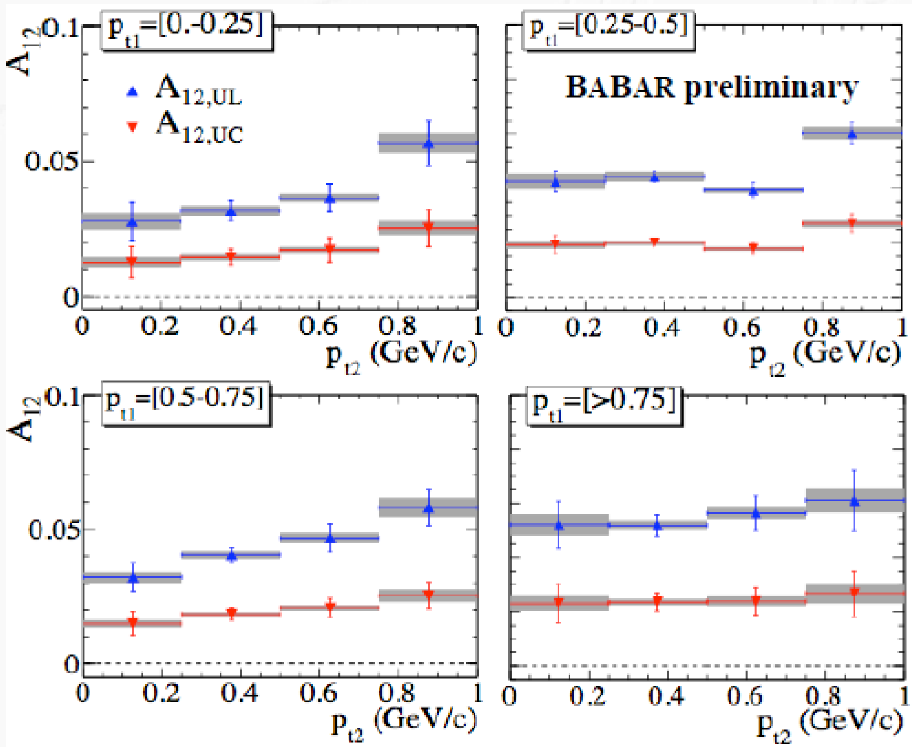
[A. Airapetian et al, PLB 693 (2010) 11]

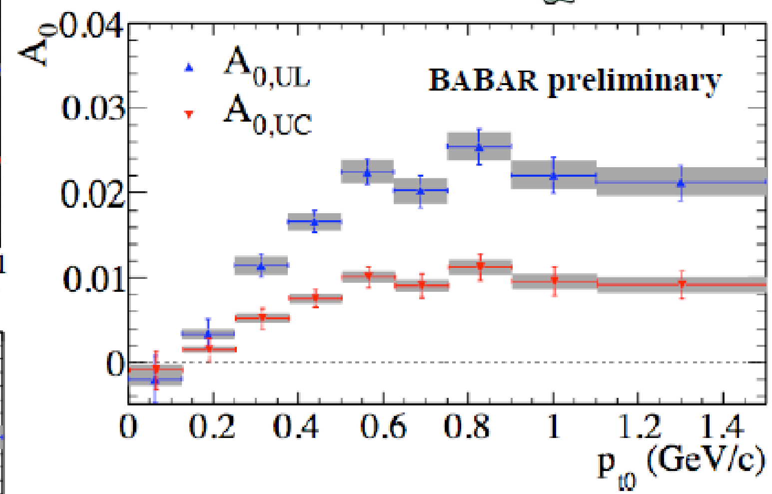


[PRL 107 (2011) 072003]



Collins FF from e^+e^-



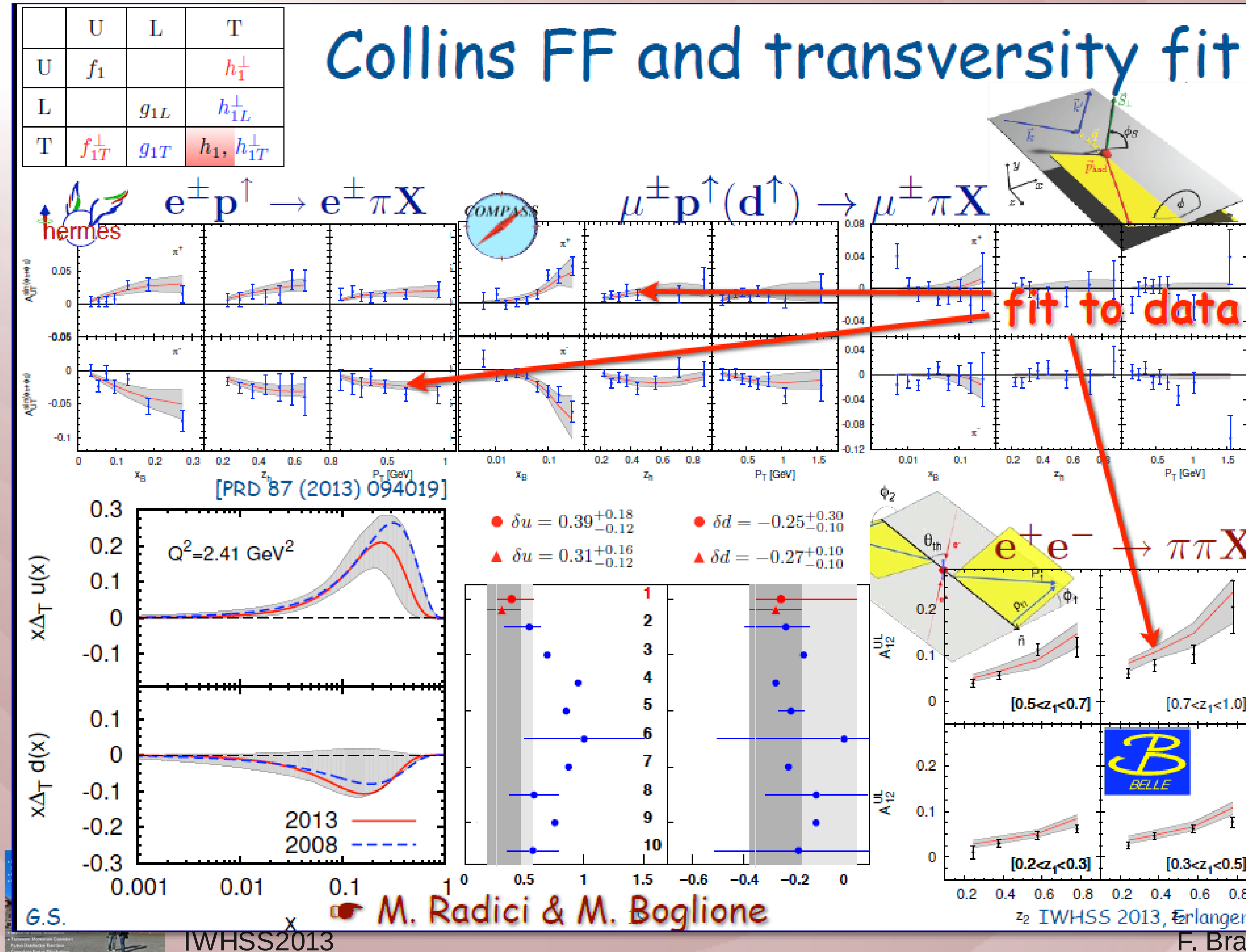


FIRST MEASUREMENT of Collins asymmetries *vs.* p_t in e^+e^- annihilation at Q^2~110 $(GeV/c)^2$ (time-like region)

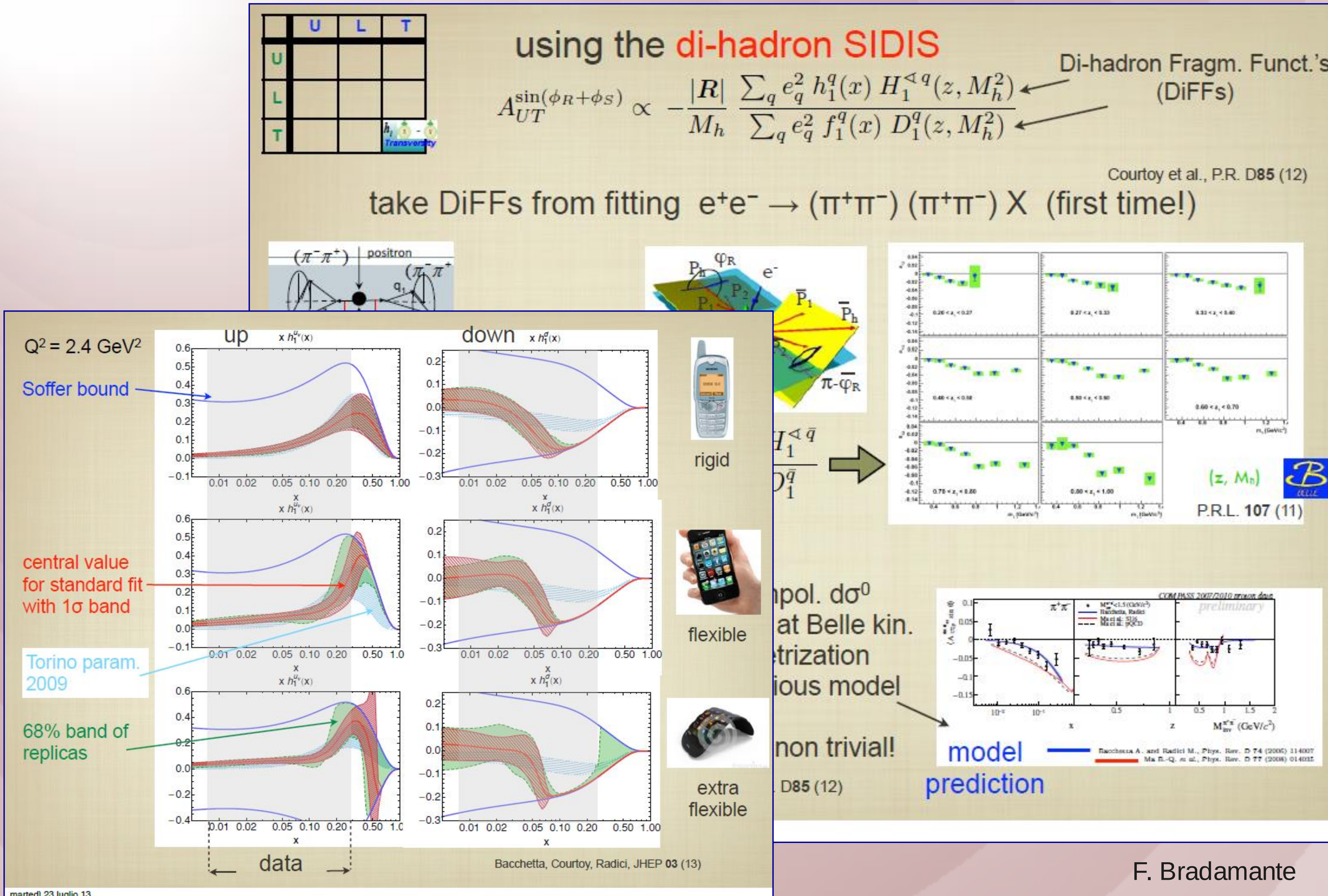
- **nonzero A^{UL} and A^{UC}**
  - ⇒ only modest dependence on (p_{t1}, p_{t2})
  - ⇒ $A^{UC} < A^{UL}$; complementary information on $H_1^{\perp, fav}$ and $H_1^{\perp, dis}$
  - ⇒ $A_0 < A_{12}$, but interesting structure in p_t

slide taken from [I. Garzia, DIS 2013]

G. Schnell - Experimental review of transverse spin physics



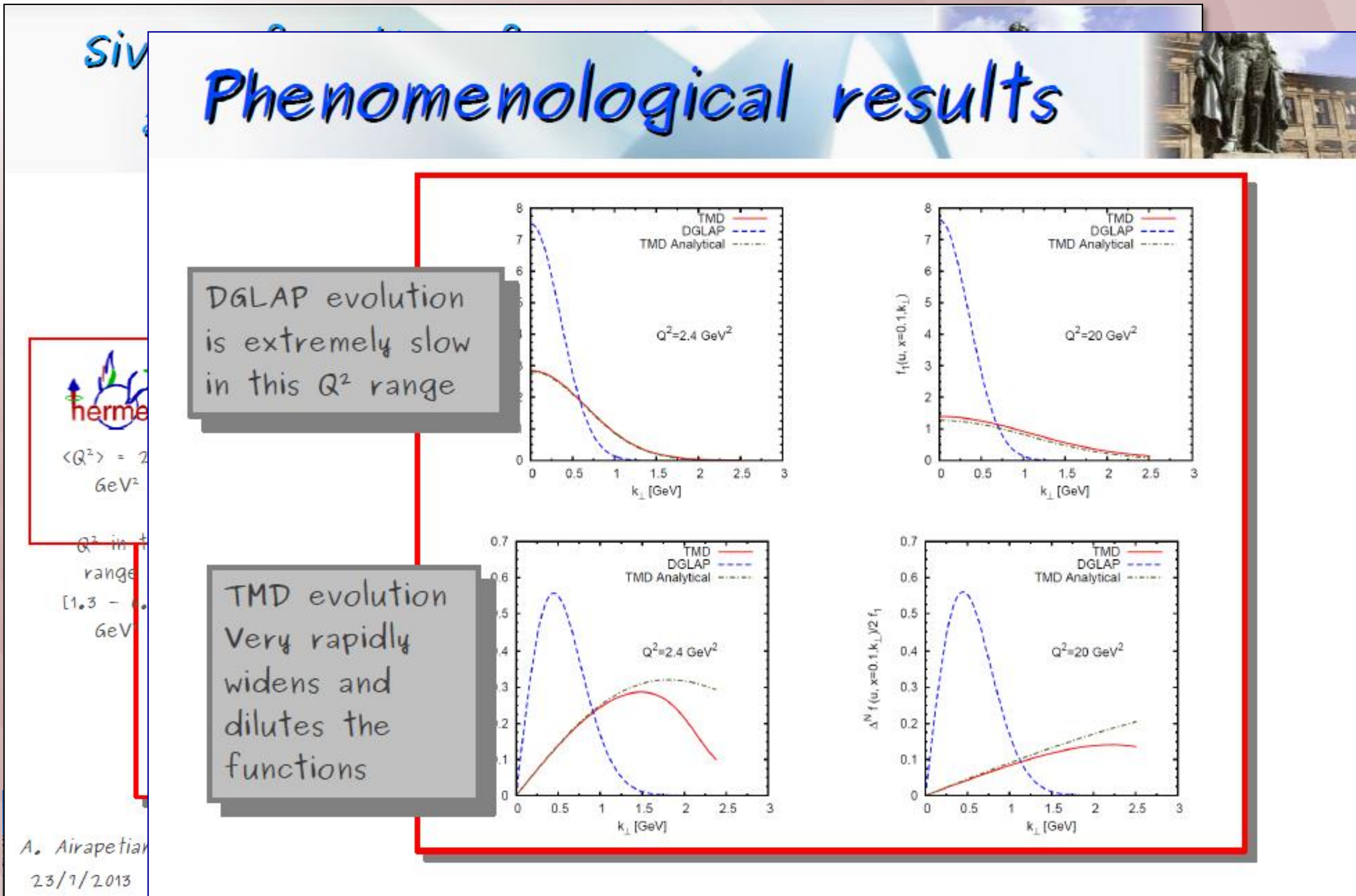
M. Radici - Theoretical overview



F. Bradamante

M. Boglione - Transverse momentum distributions

Q^2 evolution



thank you for your participation

and for your patience

and see you next year

in Crimea !