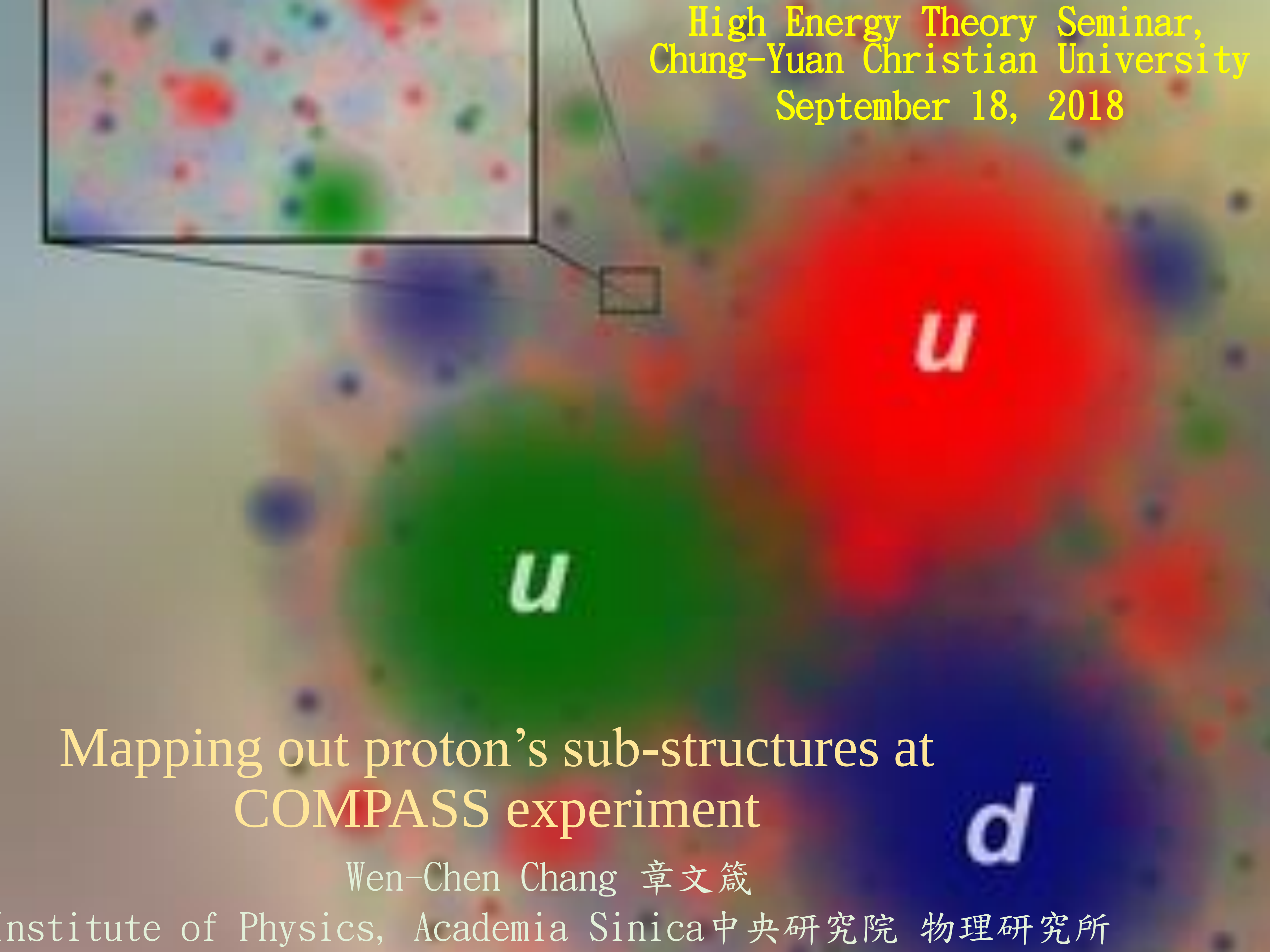


High Energy Theory Seminar,
Chung-Yuan Christian University
September 18, 2018

Mapping out proton's sub-structures at COMPASS experiment

Wen-Chen Chang 章文箴
Institute of Physics, Academia Sinica中央研究院 物理研究所

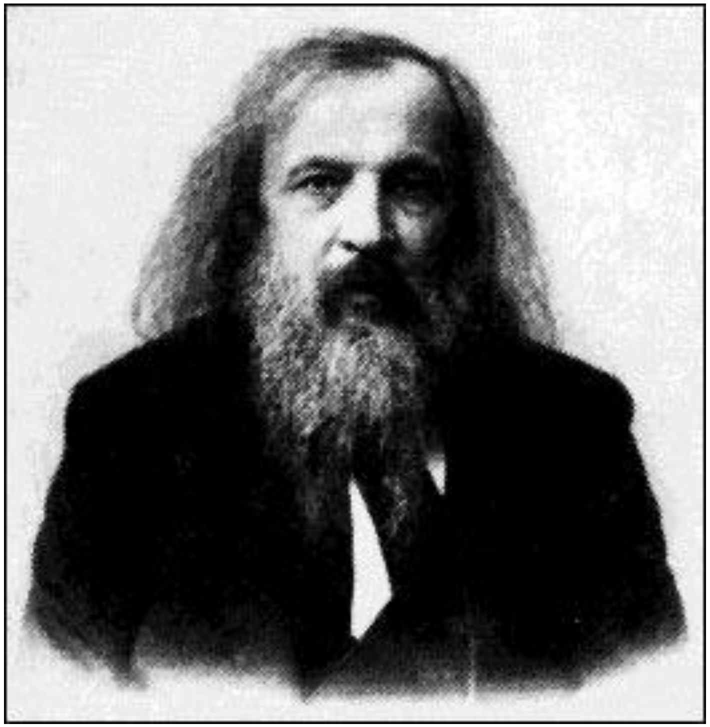
Outline

- Introduction of high energy physics (HEP)
- COMPASS experiment at CERN
  - SIDIS: transverse motions of quarks and gluons.
  - Drell-Yan: transverse motions of quarks.
  - DVCS: transverse radius of quarks.
  - 3-pion production: meson resonances.
- Summary

What is “Physics”?

- Definition of “Physics” in Encyclopædia Britannica:
  Science that deals with the structure of matter and the interactions between the fundamental constituents of the observable universe.

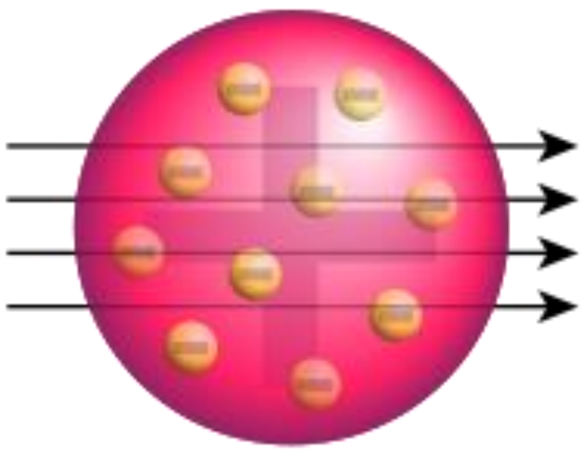
Mendeleev and Periodic Table

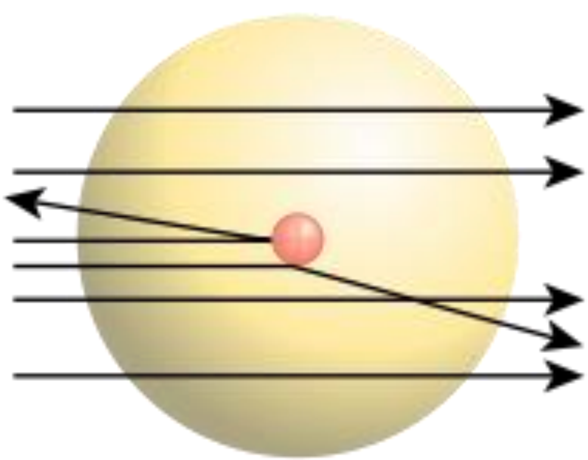


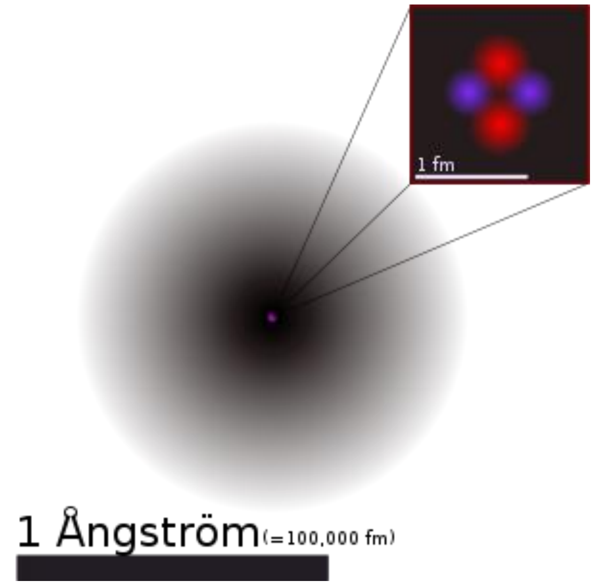
PERIODIC SYSTEM OF THE ELEMENTS IN GROUPS AND SERIES.

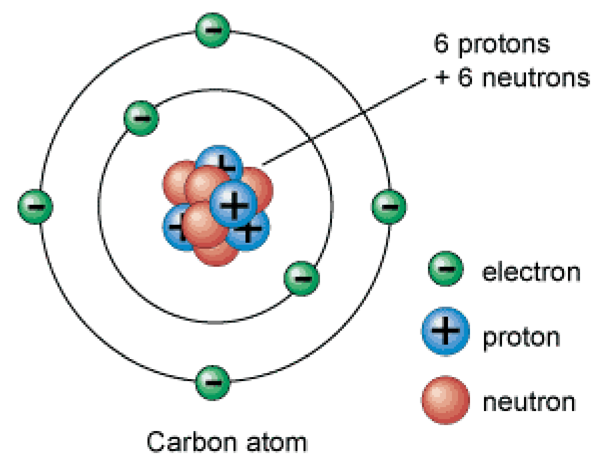
Series	GROUPS OF ELEMENTS 0	I	II	III	IV	V	VI	VII	VIII
1	—	Hydrogen H 1·008	—	—	—	—	—	—	
2	Helium He 4·0	Lithium Li 7·03	Beryllium Be 9·1	Boron B 11·0	Carbon C 12·0	Nitrogen N 14·04	Oxygen O 16·00	Fluorine F 19·0	
3	Neon Ne 19·9	Sodium Na 23·05	Magnesium Mg 24·3	Aluminium Al 27·0	Silicon Si 28·4	Phosphorus P 31·0	Sulphur S 32·06	Chlorine Cl 35·45	
4	Argon Ar 38	Potassium K 39·1	Calcium Ca 40·1	Scandium Sc 44·1	Titanium Ti 48·1	Vanadium V 51·4	Chromium Cr 52·1	Manganese Mn 55·0	Iron Fe 55·9, Cobalt Co 59, Nickel Ni 59 (Cu)
5		Copper Cu 63·6	Zinc Zn 65·4	Gallium Ga 70·0	Germanium Ge 72·3	Arsenic As 75	Selenium Se 79	Bromine Br 79·95	
6	Krypton Kr 81·8	Rubidium Rb 85·4	Strontium Sr 87·6	Yttrium Y 89·0	Zirconium Zr 90·6	Niobium Nb 94·0	Molybdenum Mo 96·0	—	Ruthenium Ru 101·7, Rhodium Rh 103·0, Palladium Pd 106·5 (Ag)
7		Silver Ag 107·9	Cadmium Cd 112·4	Indium In 114·0	Tin Sn 119·0	Antimony Sb 120·0	Tellurium Te 127	Iodine I 127	
8	Xenon Xe 128	Cesium Cs 132·9	Barium Ba 137·4	Lanthanum La 139	Cerium Ce 140	—	—	—	— — —
9		—	—	—	—	—	—	—	
10	—	—	—	Ytterbium Yb 173	—	Tantalum Ta 183	Tungsten W 184	—	Osmium Os 191, Iridium Ir 193, Platinum Pt 194·9 (Au)
11		Gold Au 197·2	Mercury Hg 200·0	Thallium Tl 204·1	Lead Pb 206·9	Bismuth Bi 208	—	—	
12	—	—	Radium Rd 224	—	Thorium Th 232	—	Uranium U 239		
HIGHER SALINE OXIDES	R	R_2O	RO	R_2O_3	RO_2	R_2O_5	RO_3	R_2O_7	RO_4
HIGHER GASEOUS HYDROGEN COMPOUNDS					RH_4	RH_3	RH_2	RH	

Rutherford experiment (1913) : Nucleus and Sub-atomic Structure

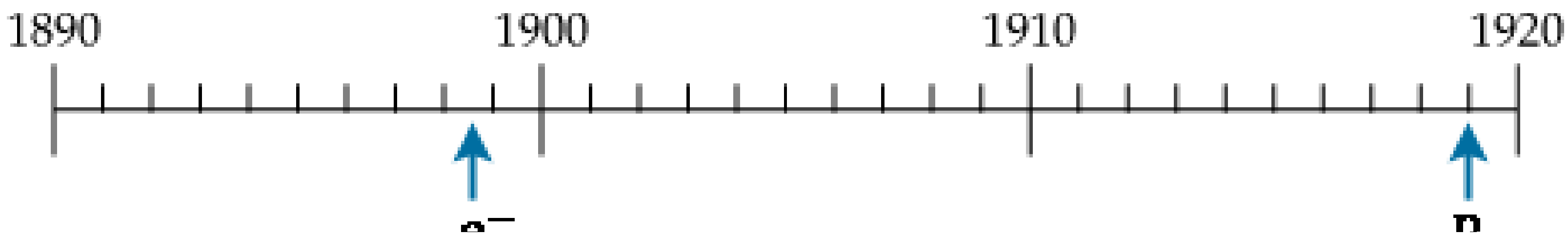






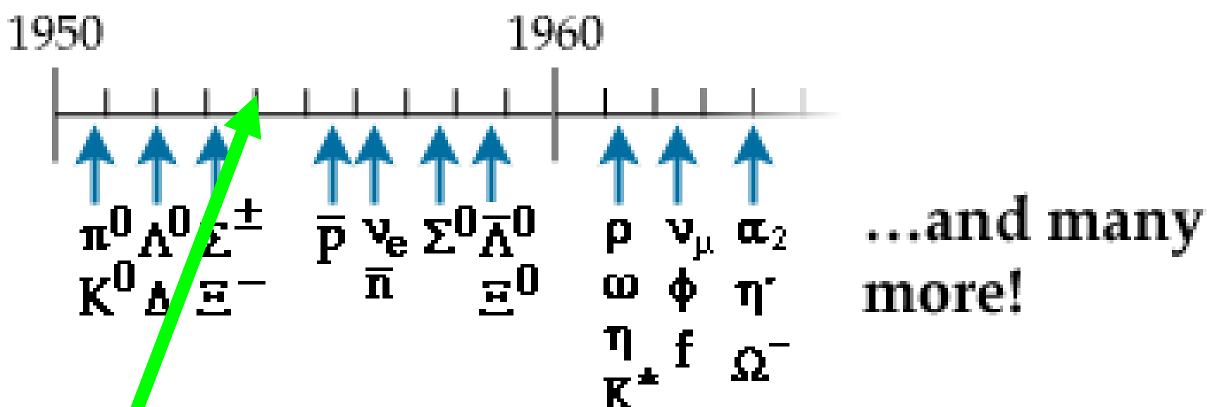


Elementary Particles Discovered: 1898 – 1964



「If I could remember the names of all these particles, I'd be a botanist.」

Enrico Fermi



1953 Donald Glaser invented the bubble chamber.
The Brookhaven Cosmotron, a 1.3 GeV accelerator, started operation.

Quark Model
(Murray Gell-Mann 1964)

Volume 8, number 3 PHYSICS LETTERS 1 February 1964

A SCHEMATIC MODEL OF BARYONS AND MESONS *

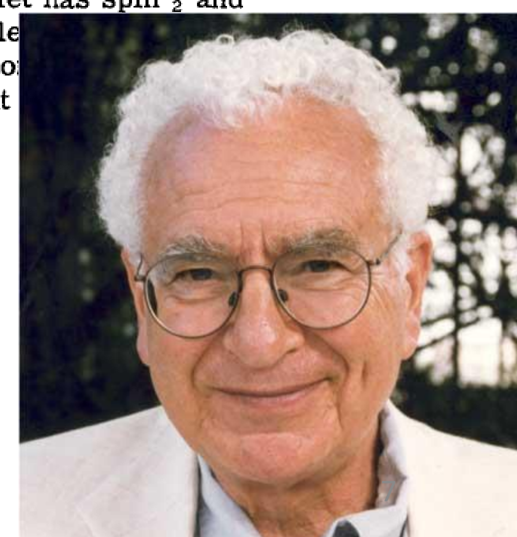
M. GELL-MANN
California Institute of Technology, Pasadena, California

Received 4 January 1964

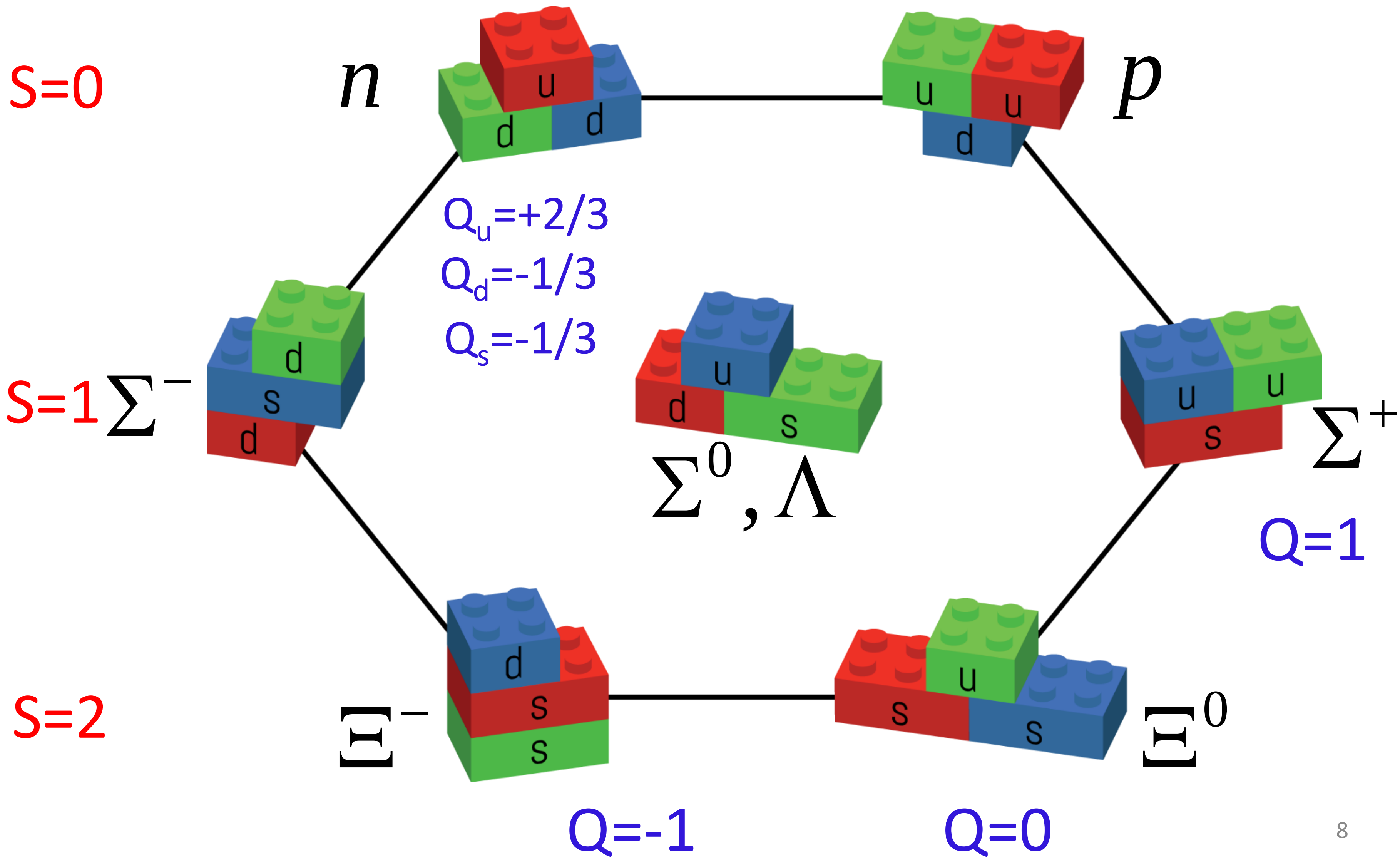
If we assume that the strong interactions of baryons and mesons are correctly described in terms of the broken "eightfold way" [1-3], we are tempted to
…ental explanation of the situa-
…sed approach is the purely dy-
…model for all the strongly in-

ber $n_t - n_{\bar{t}}$ would be zero for all known baryons and mesons. The most interesting example of such a model is one in which the triplet has spin $\frac{1}{2}$ and $z = -1$, so that the four particle…
exhibit a parallel with the lepto…
A simpler and more elegant …

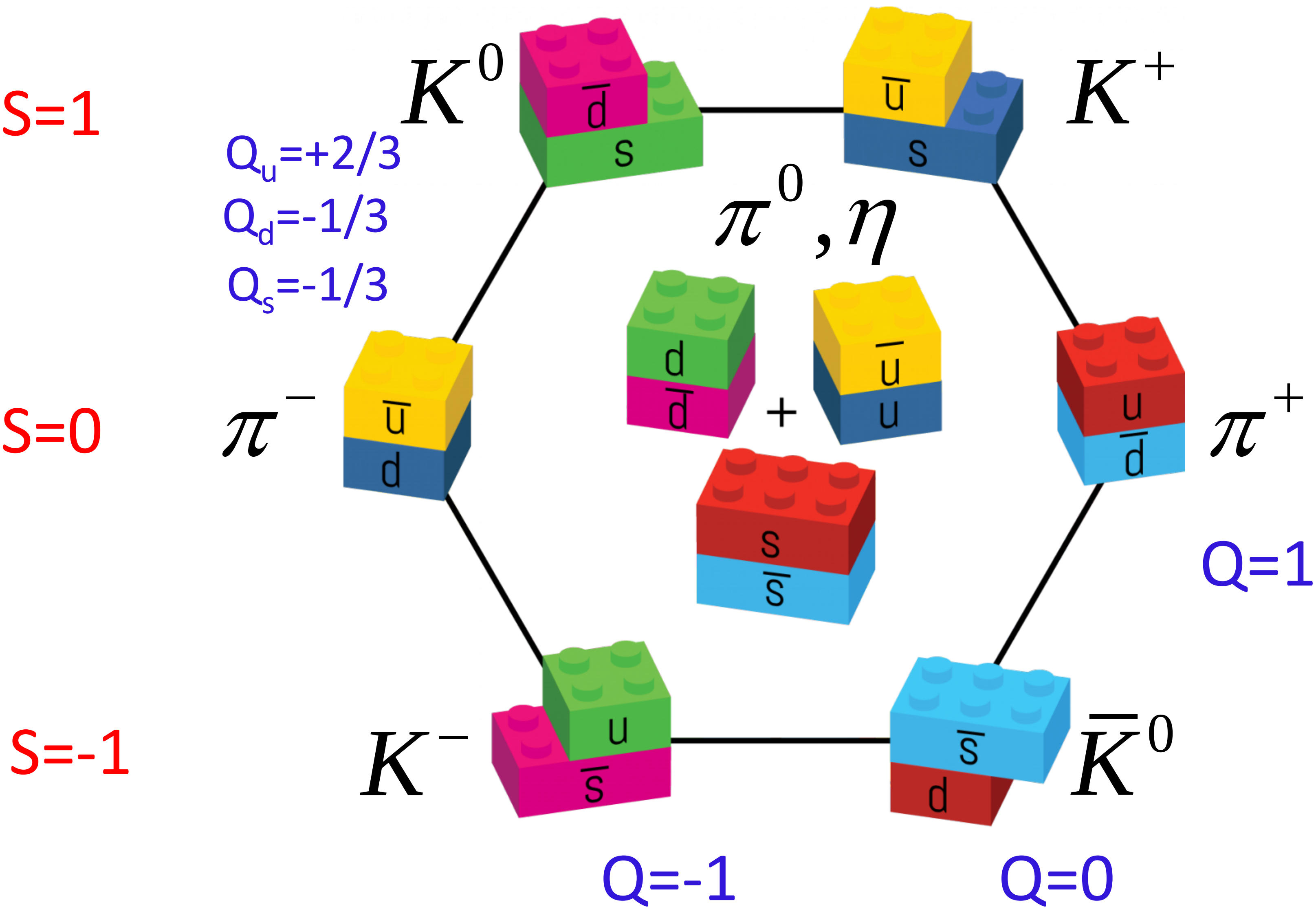
*Three types of quarks (fermions), u, d and s.
*Baryons (s=1/2, 3/2) composed of 3 quarks.
*Mesons (s=0, 1) composed of 2 quarks: a quark and an antiquark.



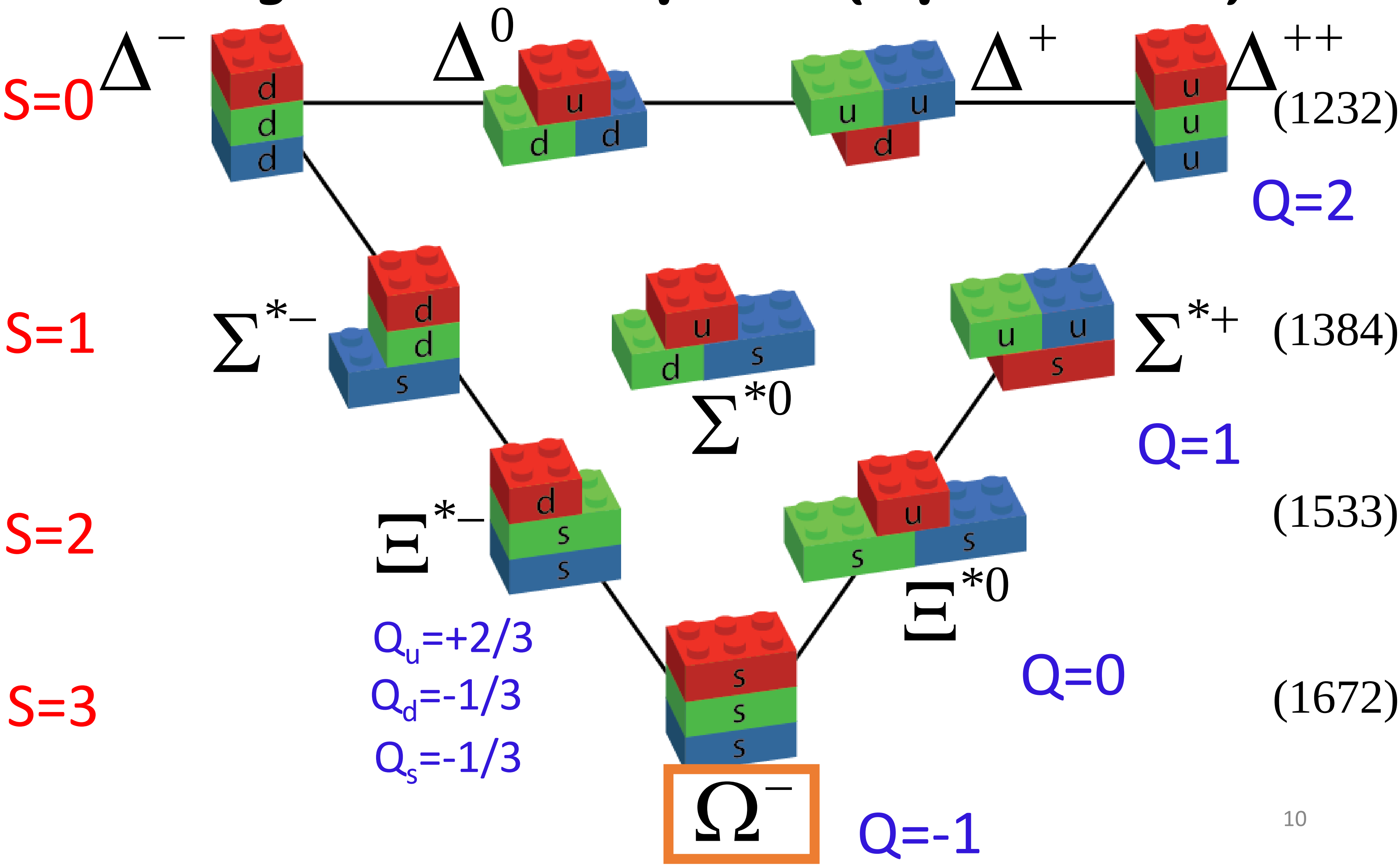
Baryon Octet (spin=1/2)



Meson Octet (spin=0)



Baryon Decuplet (spin=3/2)



OBSERVATION OF A HYPERON WITH STRANGENESS MINUS THREE*

V. E. Barnes, P. L. Connolly, D. J. Crennell, B. B. Culwick, W. C. Delaney, W. B. Fowler, P. E. Hagerty,† E. L. Hart, N. Horwitz,† P. V. C. Hough, J. E. Jensen, J. K. Kopp, K. W. Lai, J. Leitner,† J. L. Lloyd, G. W. London,‡ T. W. Morris, Y. Oren, R. B. Palmer, A. G. Prodell, D. Radojičić, D. C. Rahm, C. R. Richardson, N. P. Samios, J. R. Sanford, R. P. Shutt, J. R. Smith, D. L. Stonehill, R. C. Strand, A. M. Thorndike, M. S. Webster, W. J. Willis, and S. S. Yamamoto
Brookhaven National Laboratory, Upton, New York
(Received 11 February 1964)

It has been pointed out[1] that among the multitude of resonances which have been discovered recently, the $N_{3/2}^*(1238)$, $Y_1^*(1385)$, and $\Xi_{1/2}^*(1532)$ can be arranged as a decuplet with one member still missing. Figure 1 illustrates the position

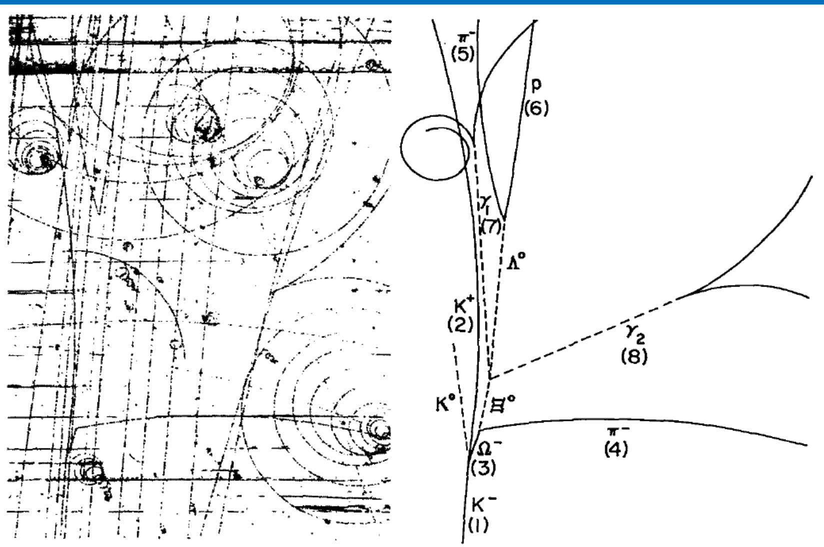


FIG. 2. Photograph and line diagram of event showing decay of Ω^-.

of such a particle.

length of ~10^6 feet. These pictures have been partially analyzed to search for the more characteristic decay modes of the Ω^-.

The event in question is shown in Fig. 2, and the pertinent measured quantities are given in Table I. Our interpretation of this event is

$$\begin{array}{l} K^- + p \to \Omega^- + K^+ + K^0 \\ \quad \Omega^- \to \Xi^0 + \pi^- \\ \quad\quad \Xi^0 \to \Lambda^0 + \pi^0 \\ \quad\quad\quad \pi^0 \to \gamma_1 + \gamma_2 \\ \quad\quad\quad\quad \gamma_2 \to e^+ + e^- \\ \quad\quad\quad\quad \gamma_1 \to e^+ + e^- \\ \quad\quad\quad \Lambda^0 \to \pi^- + p. \end{array} \qquad (1)$$

From the momentum and gap length measurements, track 2 is identified as a K^+. (A bubble density of 1.9 times minimum was expected for this track while the measured value was 1.7 ± 0.2.) Tracks 5 and 6 are in good agreement with the decay of a Λ^0, but the Λ^0 cannot come from the primary interaction. The Λ^0 mass as

Quark: the Eightfold Way

Physics

The Nobel Prize in Physics 1969

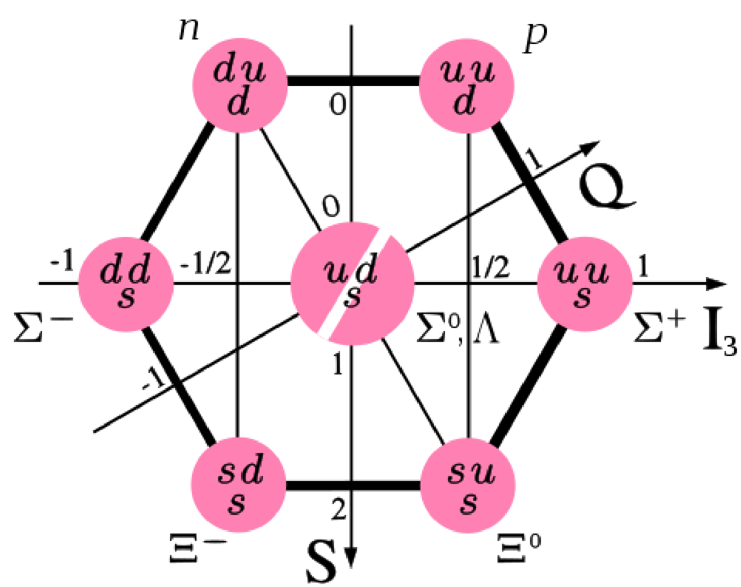
"for his contributions and discoveries concerning the classification of elementary particles and their interactions"

Murray Gell-Mann

USA

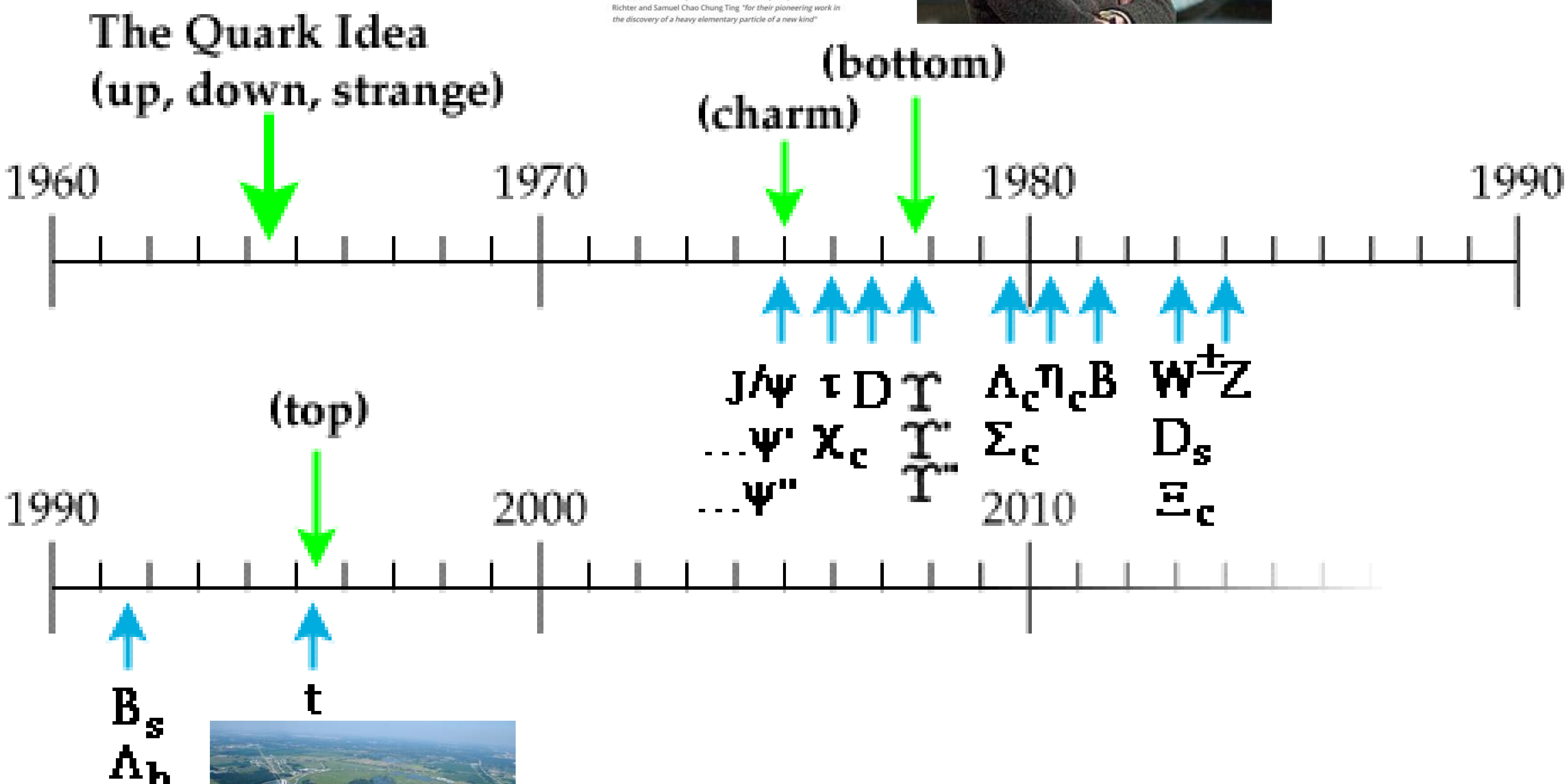
California Institute of Technology (Caltech)
Pasadena, CA, USA

b. 1929

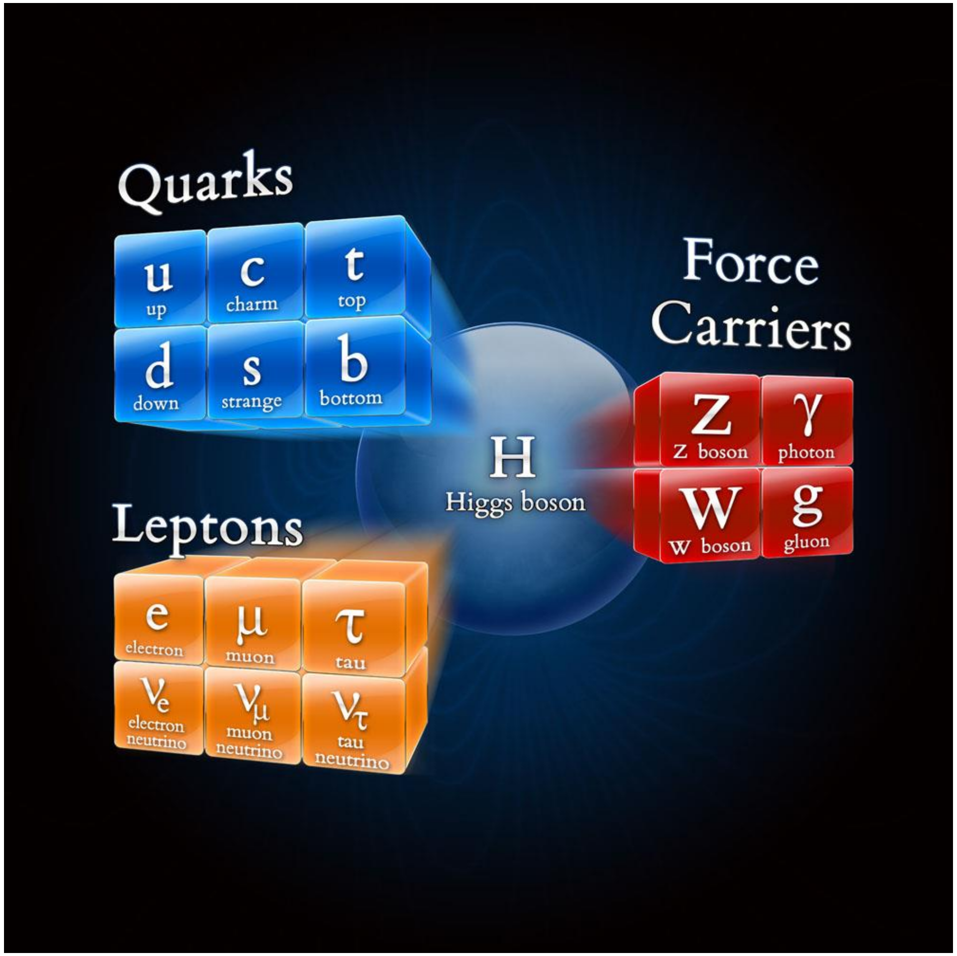


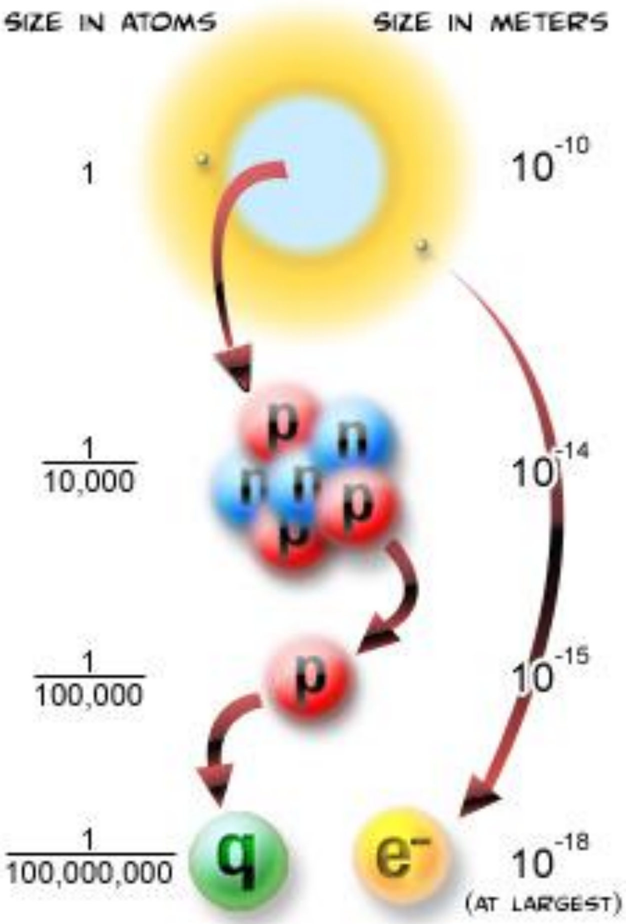
Elementary Particles Discovered: 1964 – 2010


The Nobel Prize in Physics 1976
Burton Richter, Samuel C.C. Ting
Share this: 2
The Nobel Prize in Physics 1976
Burton Richter
Prize share: 1/2
Samuel Chao Chung Ting
Prize share: 1/2
The Nobel Prize in Physics 1976 was awarded jointly to Burton Richter and Samuel Chao Chung Ting *"for their pioneering work in the discovery of a heavy elementary particle of a new kind"*

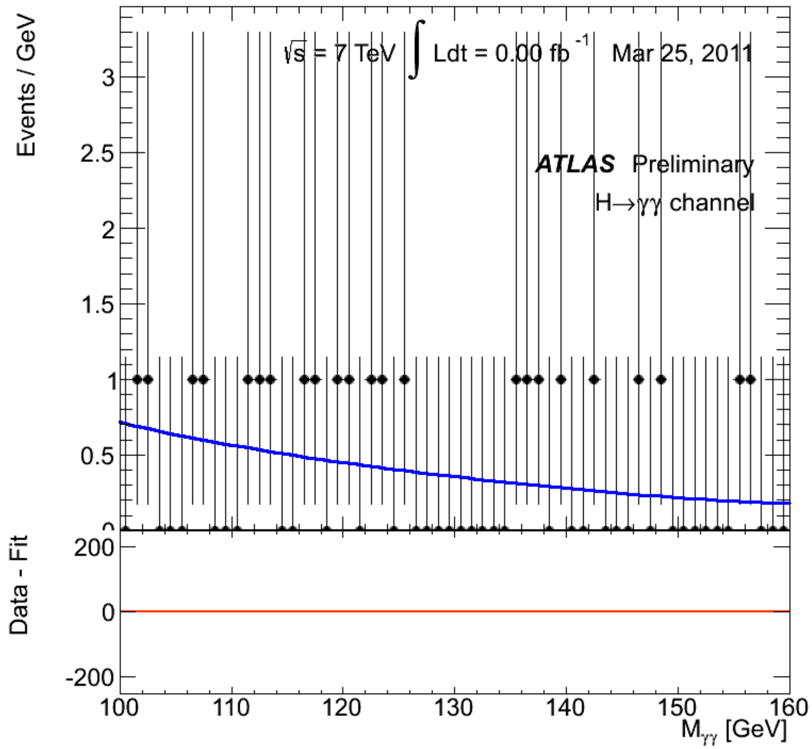


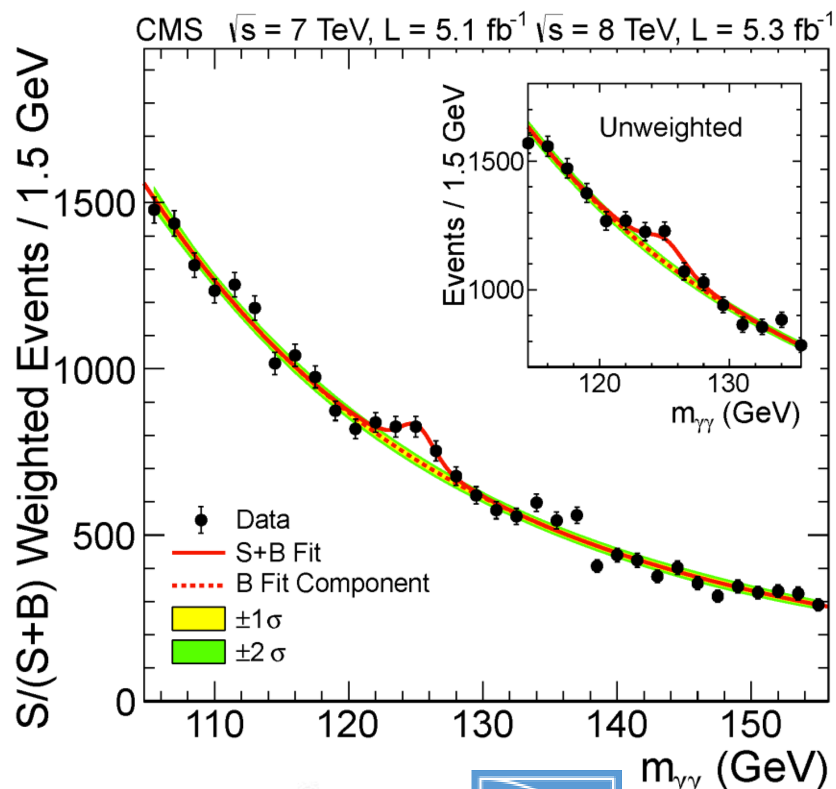
The Standard Model of High-energy Physics

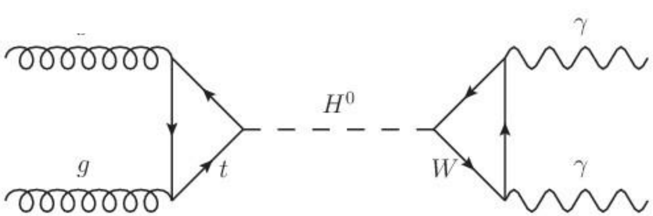




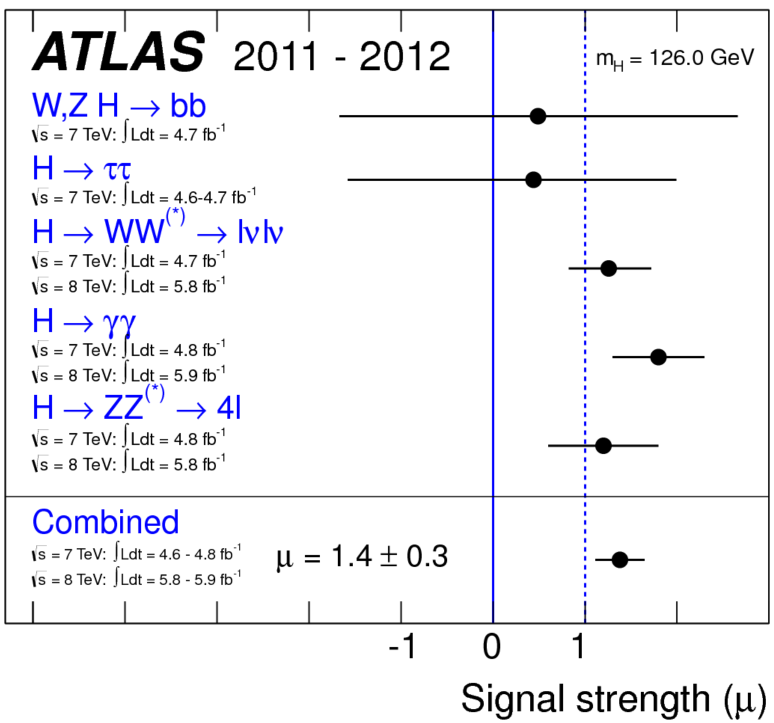
Higgs Search in two-photon decay mode

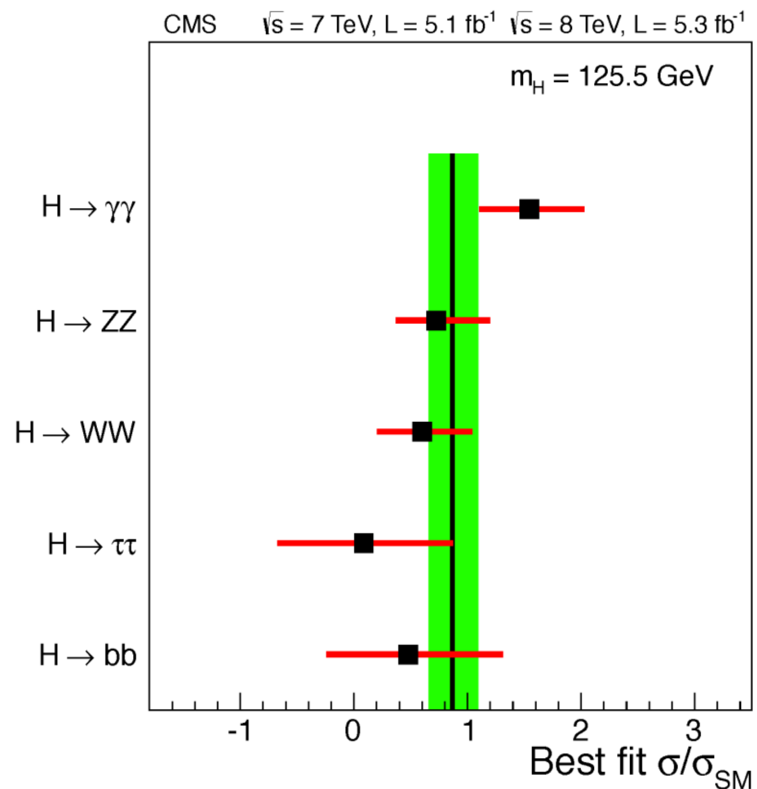






Higgs Discovery:
Announcement at CERN, July 4, 2012





The Nobel Prize in Physics 2013
François Englert, Peter Higgs

The Nobel Prize in Physics 2013

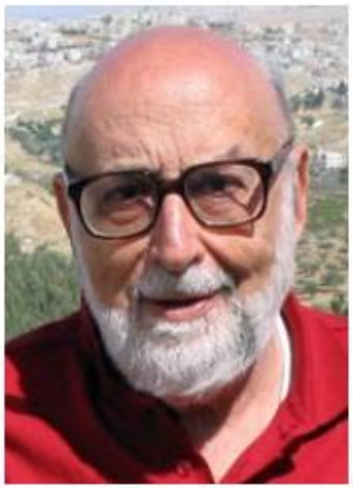


Photo: Pnicolet via Wikimedia Commons

François Englert

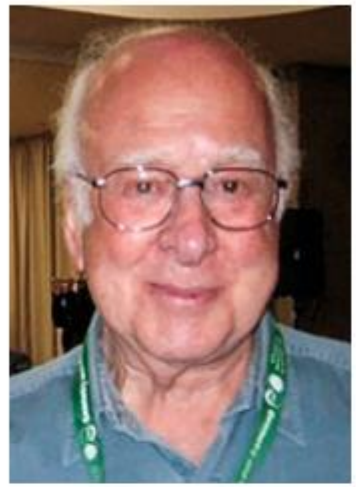


Photo: G-M Greuel via Wikimedia Commons

Peter W. Higgs

The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs *"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"*

Four Fundamental

PROPERTIES OF THE INTERACTIONS

Property \ Interaction	Gravitational	Weak (Electroweak)	Electromagnetic (Electroweak)	Strong: Fundamental	Strong: Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at: 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
Strength relative to electromag for two u quarks at: 3×10^{-17} m	10^{-41}	10^{-4}	1	60	
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

Unsolved Mysteries?

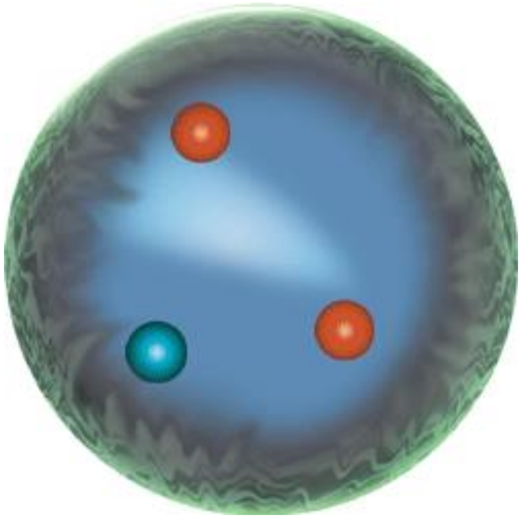
Origin of Mass

In the Standard Model, for fundamental particles to have masses, there must exist a particle called the Higgs boson. Will it be discovered soon? Is supersymmetry theory correct in predi

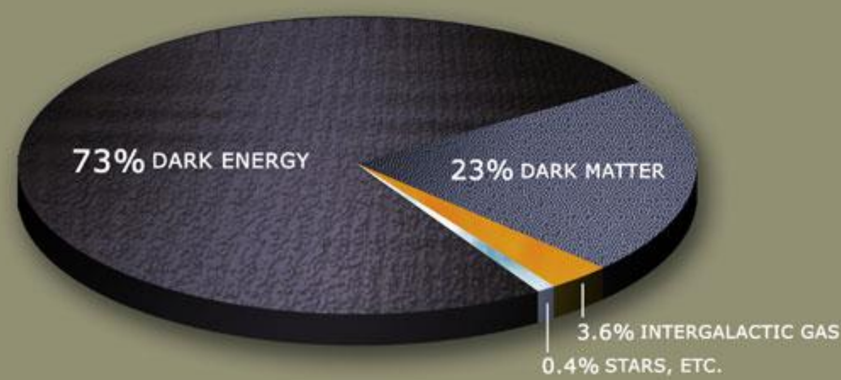
Why No Antimatter?

Matter and antimatter were created in the Big Bang. Why do we now see only matter except for the tiny amounts of antimatter that we make in the lab and observe in cosmic rays?

Quark Confinement

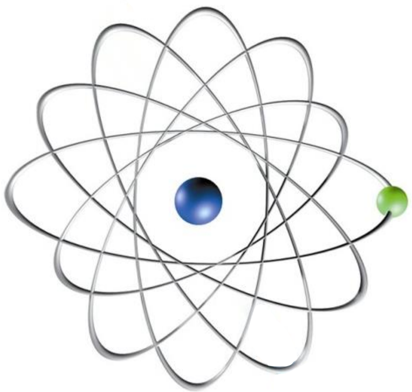


Dark Matter



Mass of Composite Systems

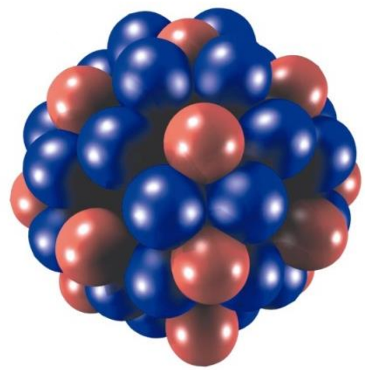
atom
10^{-10} m



$M \approx \Sigma\, m_i$

binding energy
effect $\approx 10^{-8}$

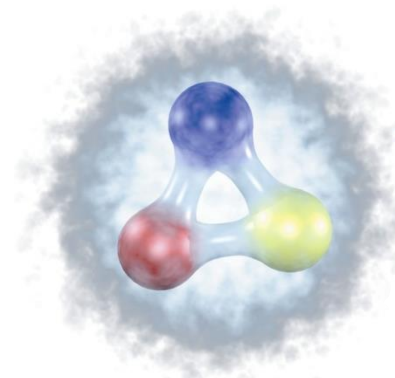
atomic nucleus 10^{-14} m



$M \approx \Sigma\, m_i$

binding energy
effect $\approx 10^{-3}$

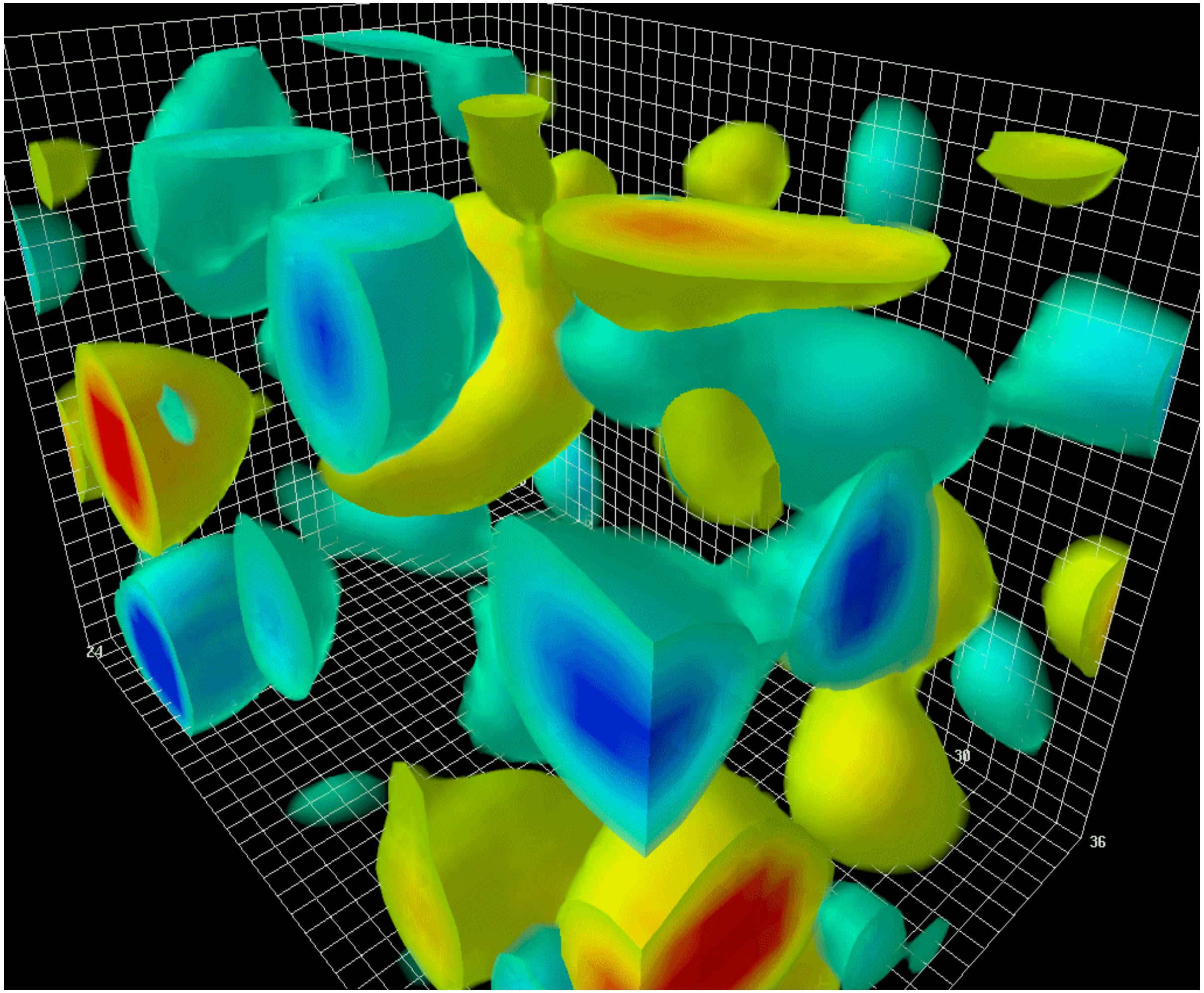
nucleon
10^{-15} m



$M \gg m_i$

nucleon: mass not determined by sum of constituent masses
$m = E/c^2$, “mass without mass“ (Wilczek)
mass given by energy stored in motion of quarks
and by energy in colour gluon fields

Topological Charge Density of Gluon Field



http://www.physics.adelaide.edu.au/theory/staff/leinweber/VisualQCD/Nobel/ChargeAPE5LQanimXs30.gif

http://www.physics.adelaide.edu.au/theory/staff/leinweber/VisualQCD/OriginMass/index.html

Quantum Chromodynamics (QCD)

Quantum Chromodynamics (QCD), the gauge field theory that describes the strong interactions of colored quarks and gluons, is the SU(3) component of the SU(3)×SU(2)×U(1) Standard Model of Particle Physics.

The Lagrangian of QCD is given by

$$\mathcal{L} = \sum_q \bar{\psi}_{q,a}(i\gamma^\mu \partial_\mu \delta_{ab} - g_s \gamma^\mu t^C_{ab} \mathcal{A}^C_\mu - m_q \delta_{ab})\psi_{q,b} - \frac{1}{4} F^A_{\mu\nu} F^{A\,\mu\nu}$$

Parameters:

m_q: quark mass

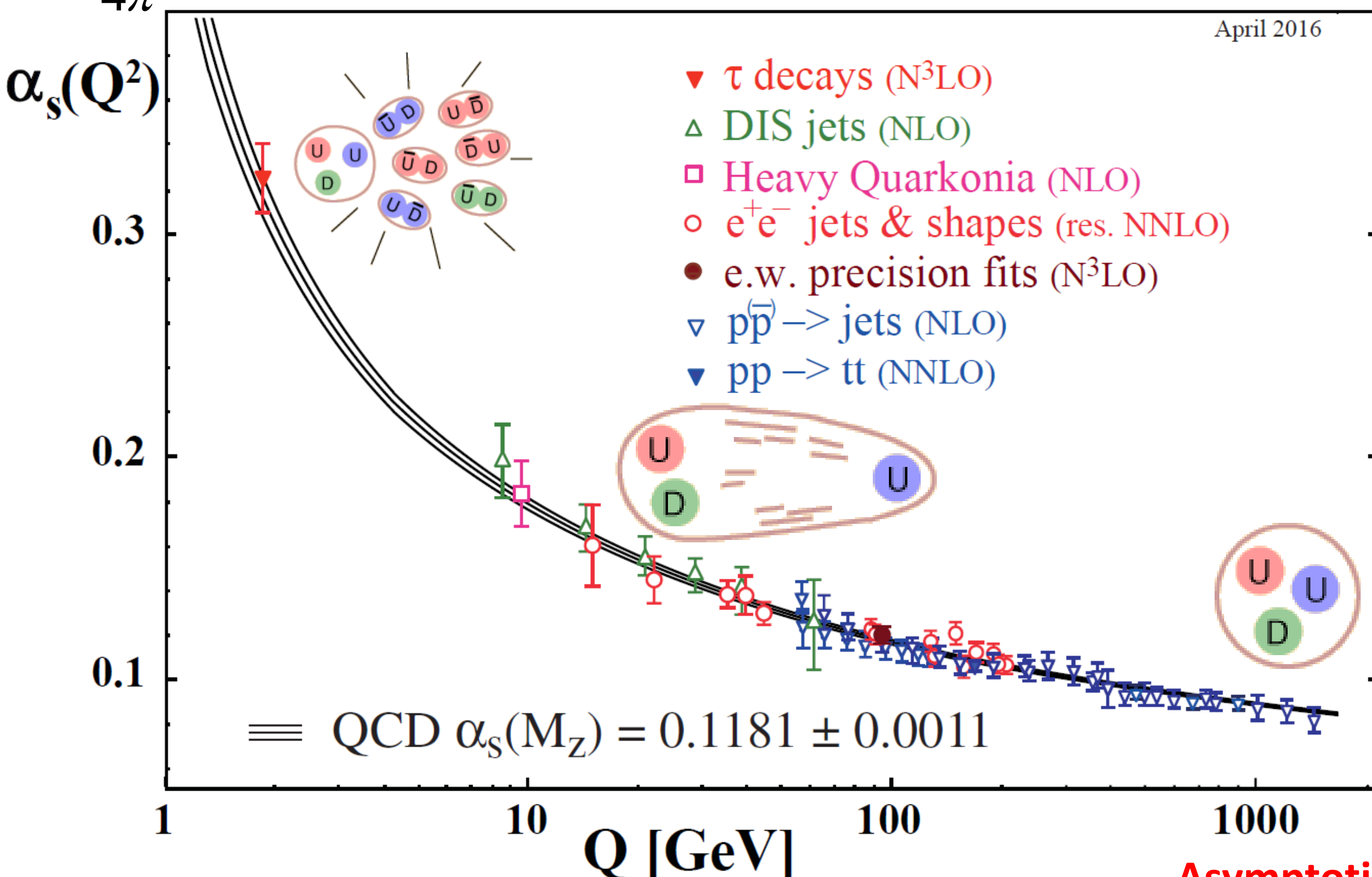
g_s:coupling constants

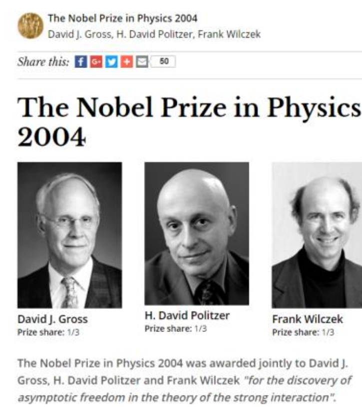
where repeated indices are summed over. The γ^μ are the Dirac γ-matrices. The $\psi_{q,a}$ are quark-field spinors for a quark of flavor q and mass m_q, with a color-index a that runs from $a = 1$ to $N_c = 3$, *i.e.* quarks come in three "colors." Quarks are said to be in the fundamental representation of the SU(3) color group.

http://pdg.lbl.gov/2017/reviews/rpp2017-rev-qcd.pdf

Properties of QCD

$\alpha_s = \frac{g_s^2}{4\pi}$ **Quark Confinement**: no isolated quarks.




The Nobel Prize in Physics 2004
David J. Gross, H. David Politzer, Frank Wilczek

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The Nobel Prize in Physics 2004

David J. Gross
Prize share: 1/3

H. David Politzer
Prize share: 1/3

Frank Wilczek
Prize share: 1/3

The Nobel Prize in Physics 2004 was awarded jointly to David J. Gross, H. David Politzer and Frank Wilczek *"for the discovery of asymptotic freedom in the theory of the strong interaction"*.

Asymptotic Freedom

http://pdg.lbl.gov/2017/reviews/rpp2017-rev-qcd.pdf

Hadron (Baryons & Mesons)

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$ Baryons are fermionic hadrons. These are a few of the many types of baryons.					
Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	antiproton	$\bar{u}\bar{u}\bar{d}$	–1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	–1	1.672	3/2

Mesons $q\bar{q}$ Mesons are bosonic hadrons These are a few of the many types of mesons.					
Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	–1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.776	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2.980	0

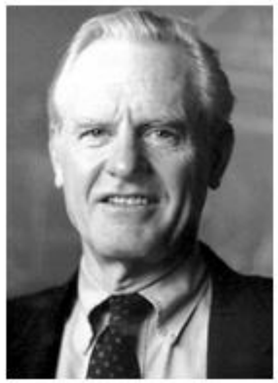
Hadron is the effective degree of freedom of all quark systems.

Deep Inelastic Scattering

The Nobel Prize in Physics 1990

Jerome I. Friedman

Prize share: 1/3



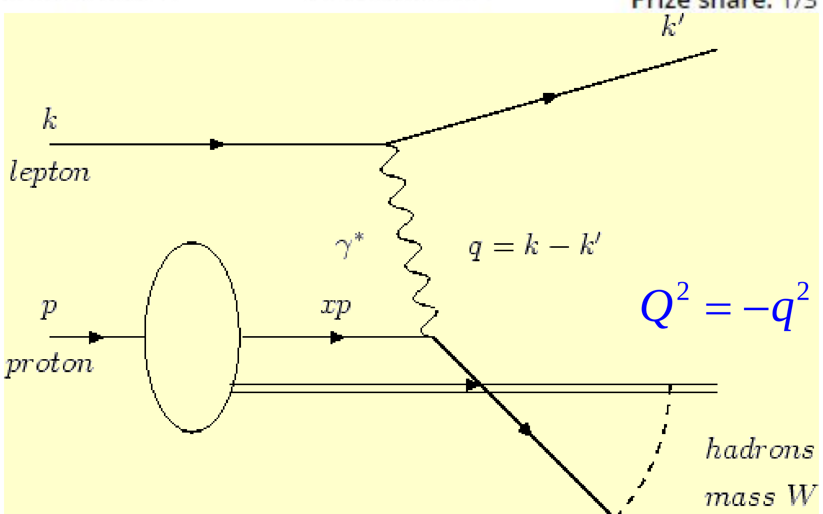
Henry W. Kendall

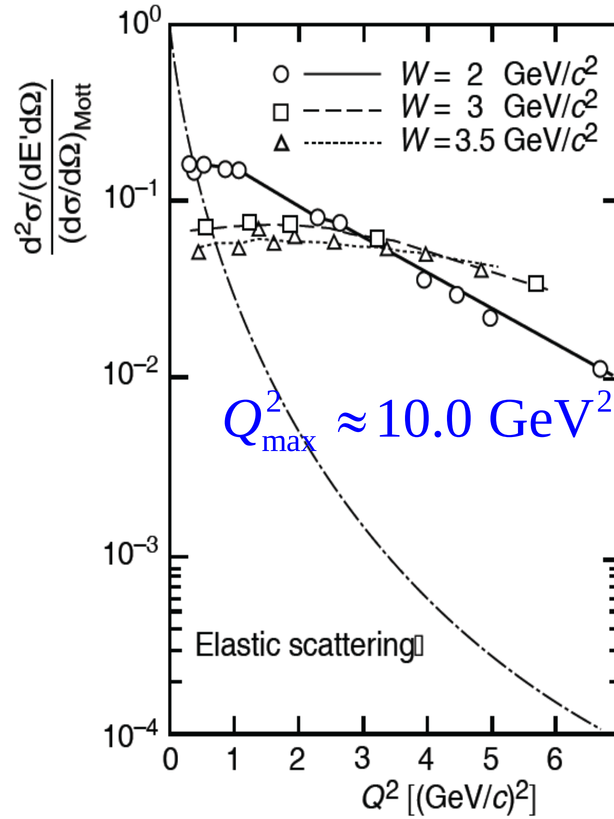
Prize share: 1/3

Photo: T. Nakashima

Richard E. Taylor

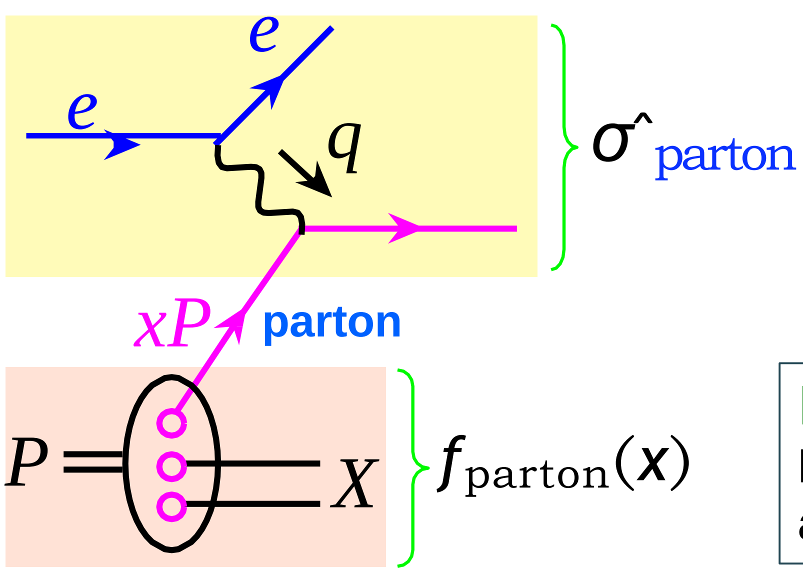
Prize share: 1/3





x: momentum fraction of struck partons

Deep-Inelastic Scattering & Factorization



Parton Distribution Functions (PDFs):
Probability density for finding a parton in a proton with momentum fraction x

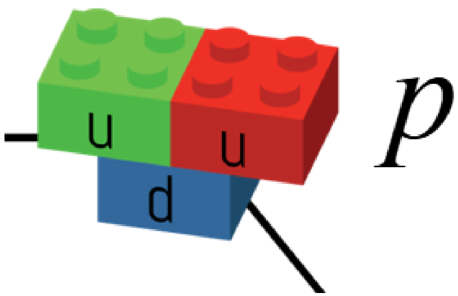
$$\sigma_{\text{proton}}(Q) = f_{\text{parton}}(x,\ Q) \otimes \hat{\sigma}_{\text{parton}}(Q)$$

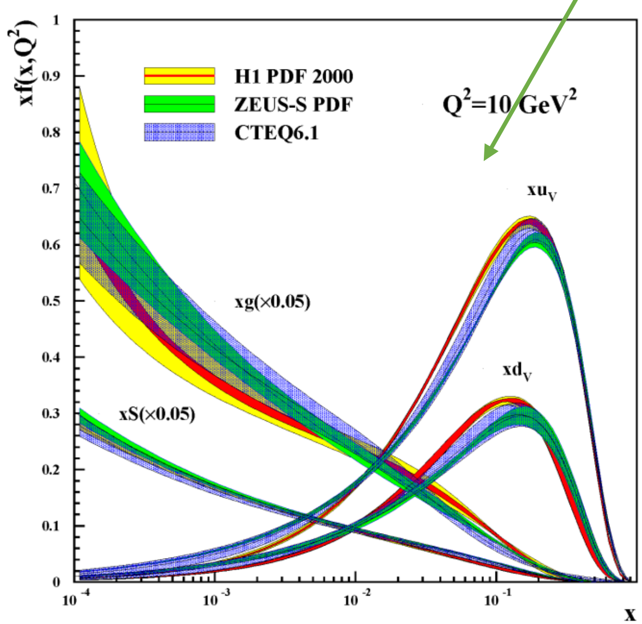
calculable

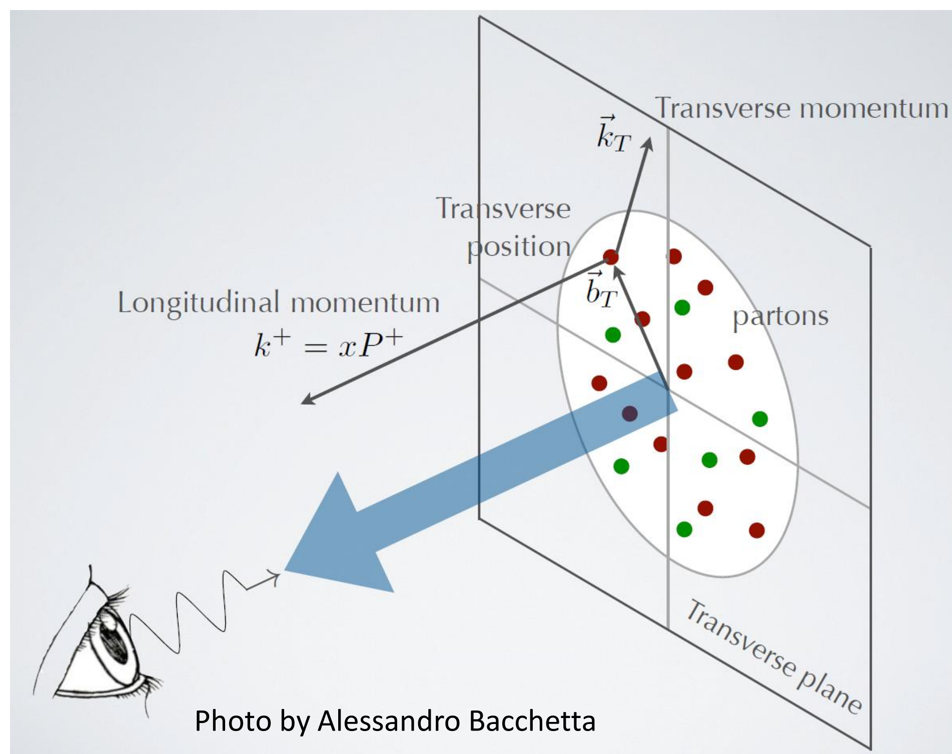
Parton Density Function

$$\sigma_{\text{proton}}(Q) = f_{\text{parton}}(x, Q) \otimes \hat{\sigma}_{\text{parton}}(Q)$$

calculable



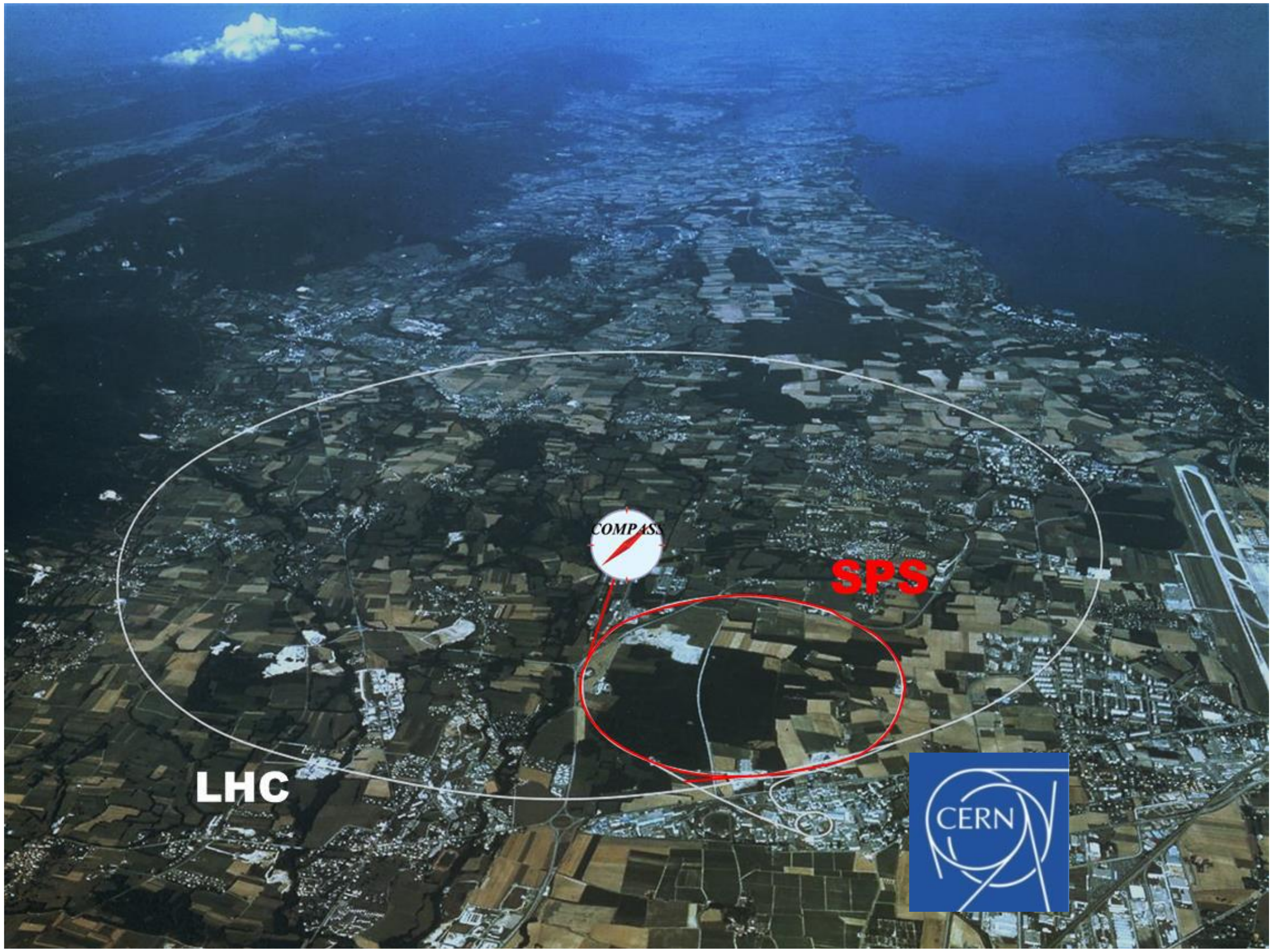




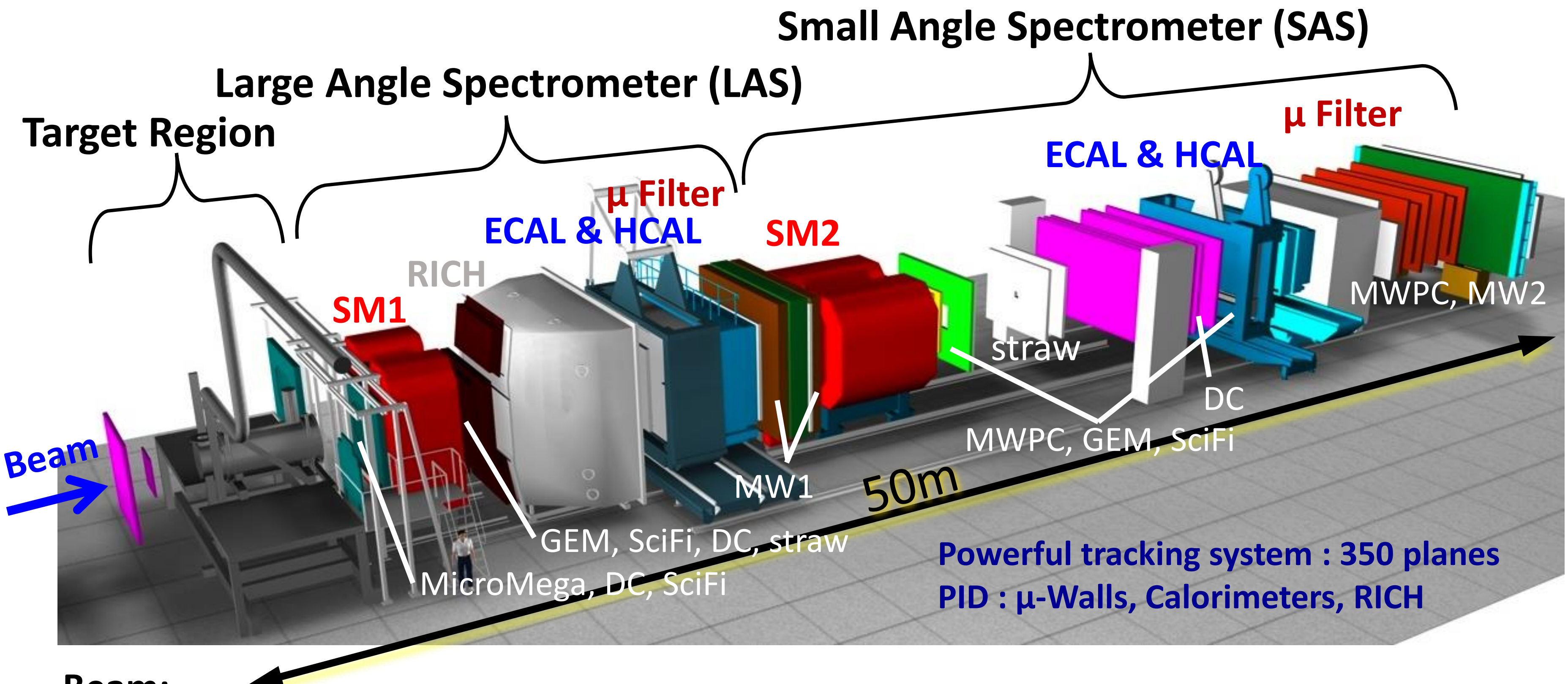
COMPASS Collaboration

(Common Muon and Proton Apparatus for Structure and Spectroscopy)

- 24 institutions from 13 countries – nearly 250 physicists
- Fixed-target experiment at SPS north area
- Physics programs:
    - Nucleon spin and partonic structures
    - Hadron spectroscopy



COMPASS Setup



Beam:

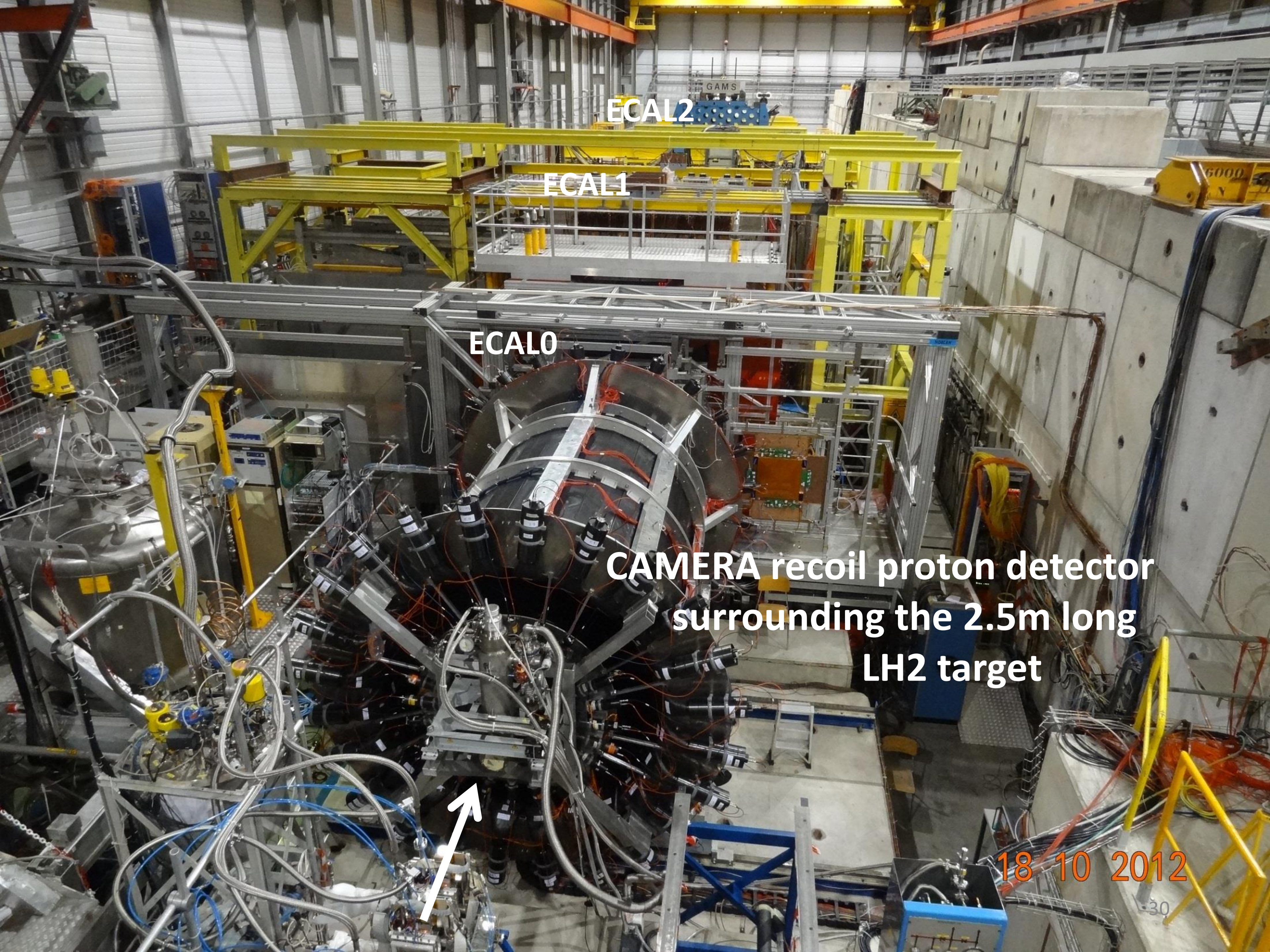
Polarized lepton beam : μ^+, μ^- 50-280 GeV/c

Hadron beam : π^+, π^+, K^+, K^-, p

Target:

Polarized NH_3 and ^6LiD target

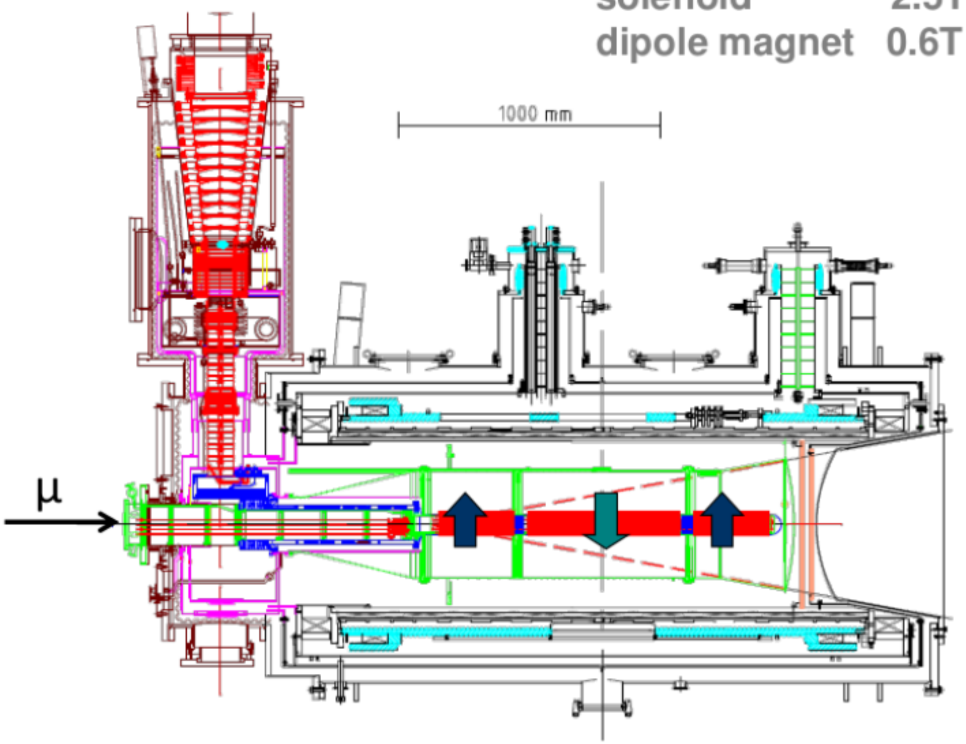
Liquid hydrogen target

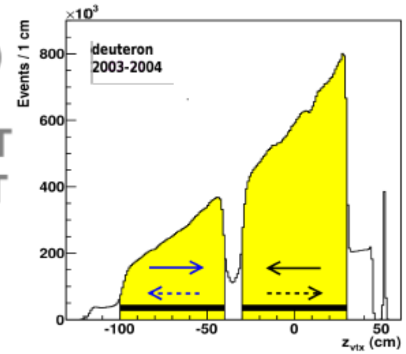

ECAL2
ECAL1
ECAL0
CAMERA recoil proton detector
surrounding the 2.5m long
LH2 target
18 10 2012
GAMS

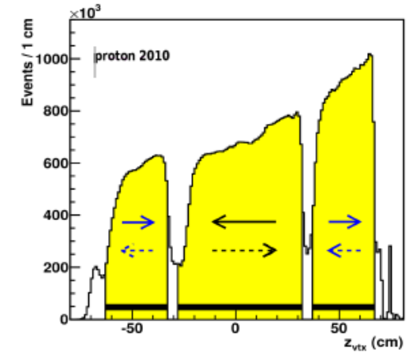
Polarized Target

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

solenoid	2.5T
dipole magnet	0.6T



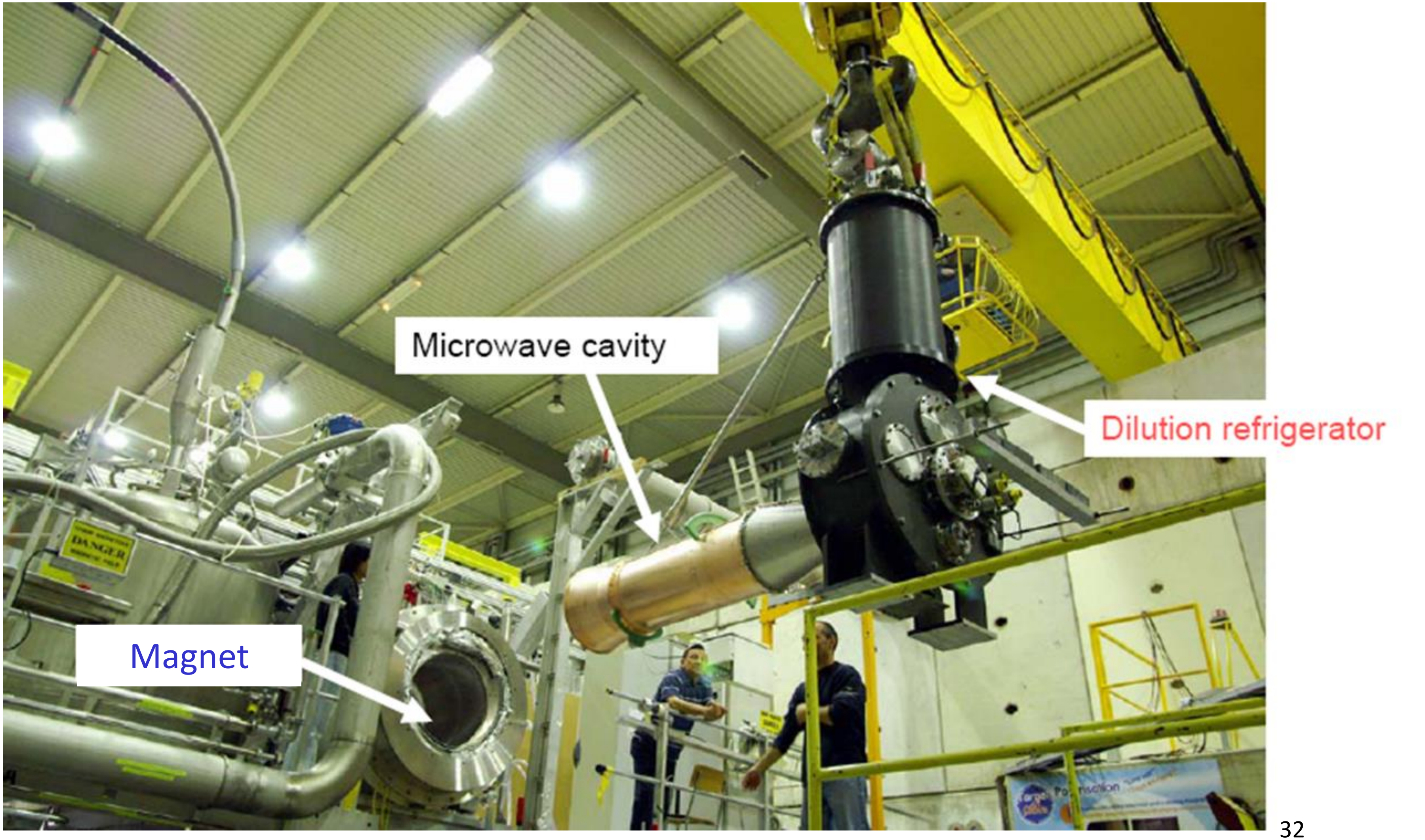




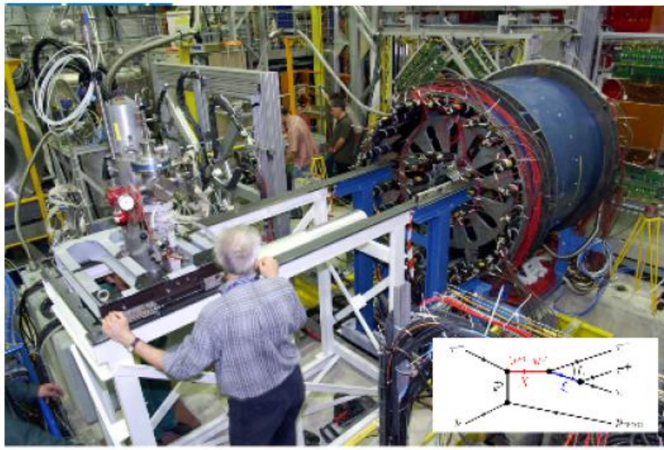
'deuteron' - Li^6D 2 cells
'proton' - NH^3 3 cells

	Li^6D	NH^3
polarisation	50%	90%
dilution	40%	16%

Polarized Target



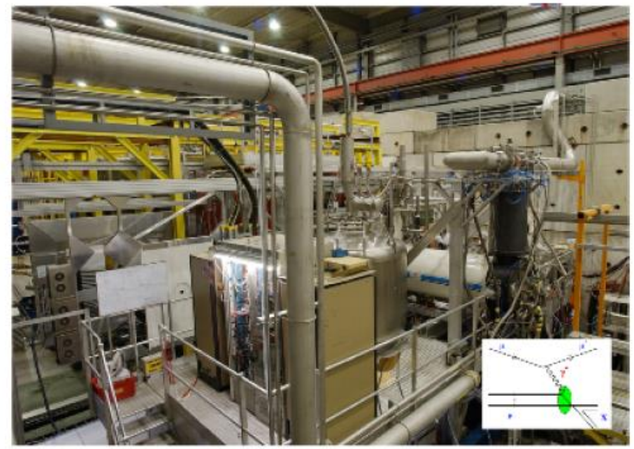
COMPASS physics
Commom **M**uon **P**roton **A**pparatus for **S**tructure and **S**pectroscopy



Hadron Spectroscopy & Chiral Dynamics

COMPASS-I
1997-2011

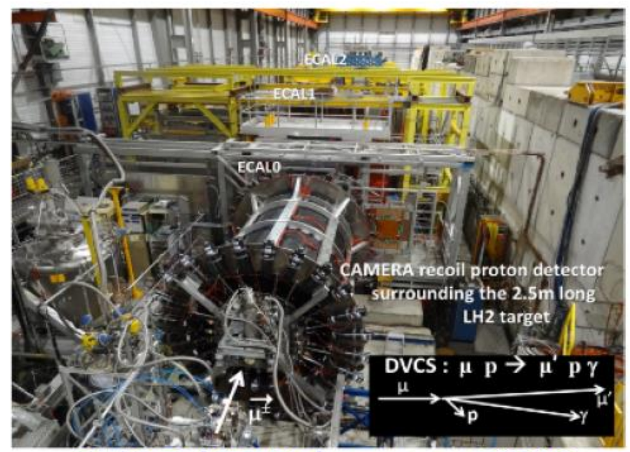
*** extension ***
& 2021



Polarised SIDIS

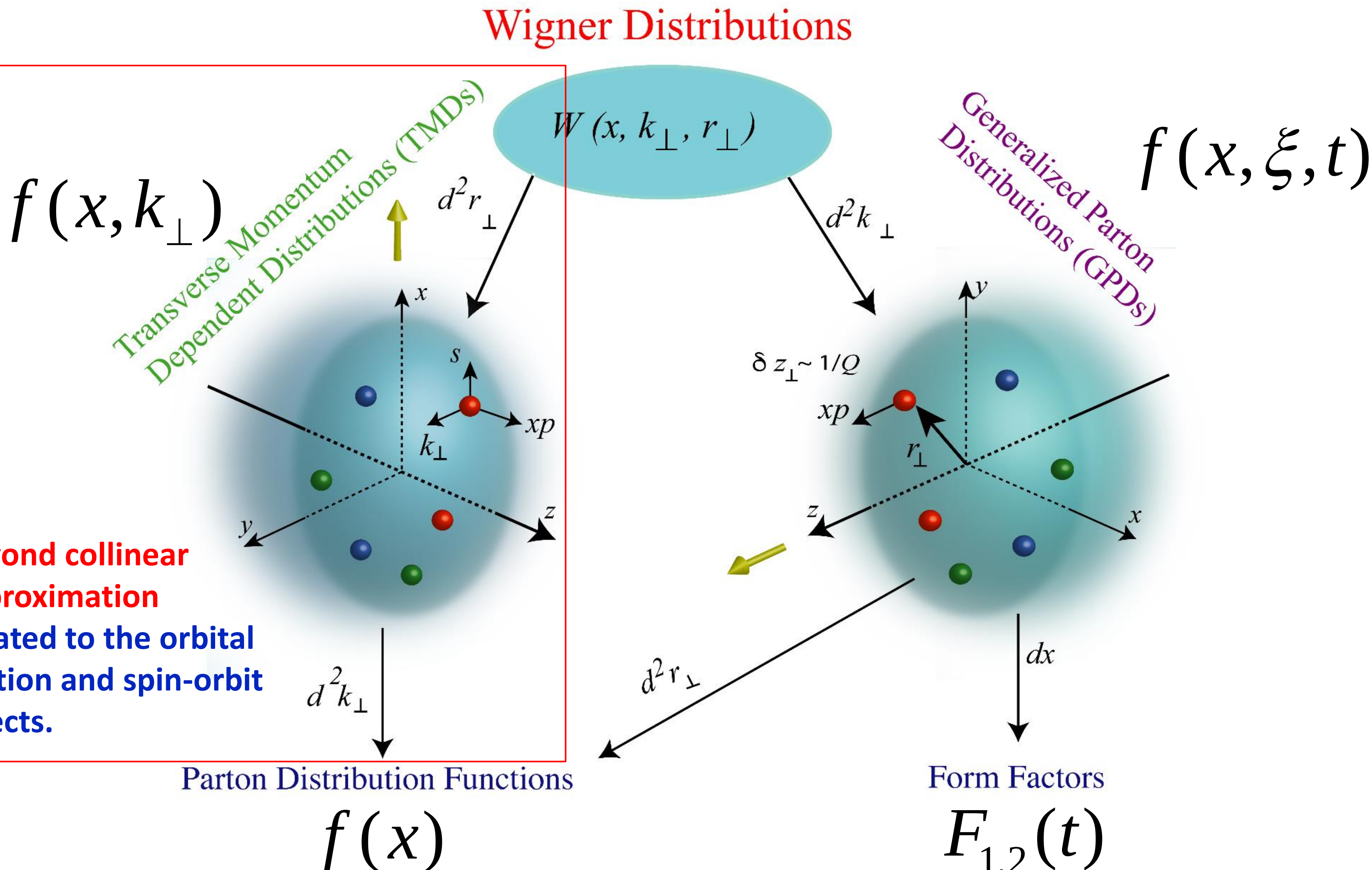
Polarised Drell-Yan

COMPASS-II
2012-2020



DVCS (GPDs) + unp. SIDIS

Multi-dimensional Partonic Structures



- **Beyond collinear approximation**
- **Related to the orbital motion and spin-orbit effects.**

http://www.int.washington.edu/PROGRAMS/17-3/

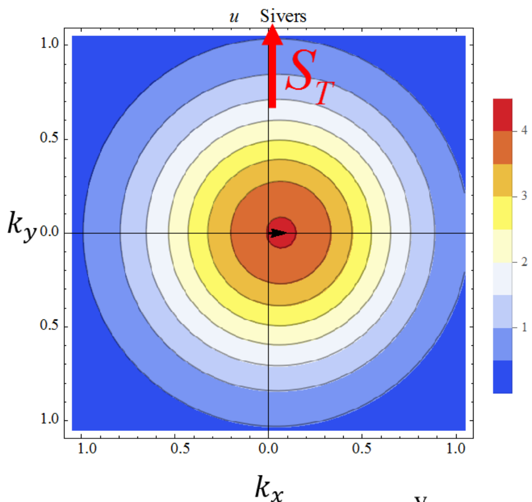
Leading-Twist Transverse-momentum Dependent **Parton Density Function** (TMDs)

- spin of the nucleon
- spin of the parton
- k_T of the parton

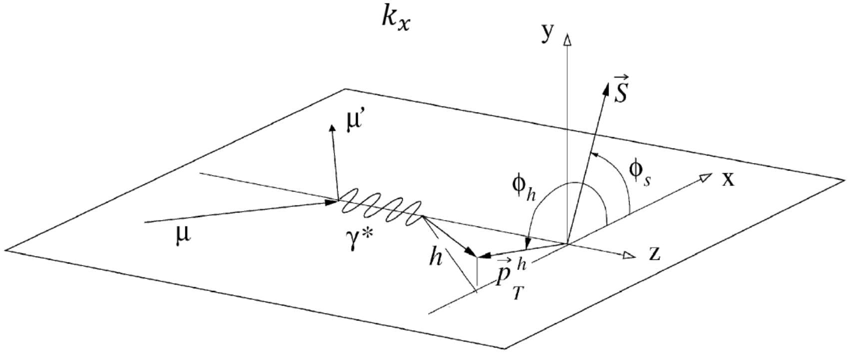
Nucleon \ Quark	U	L	T
U	number density $f_1^{q,g}(x, k_T^2)$		Boer-Mulders $h_1^{\perp q,g}(x, k_T^2)$
L		Helicity $g_{1L}^{q,g}(x, k_T^2)$	worm-gear L $h_{1L}^{\perp q,g}(x, k_T^2)$
T	Sivers $f_{1T}^{\perp q,g}(x, k_T^2)$	Kotzinian-Mulders worm-gear T $g_{1T}^{\perp q,g}(x, k_T^2)$	Transversity $h_1^{q,g}(x, k_T^2)$ Pretzelosity $h_{1T}^{\perp q,g}(x, k_T^2)$

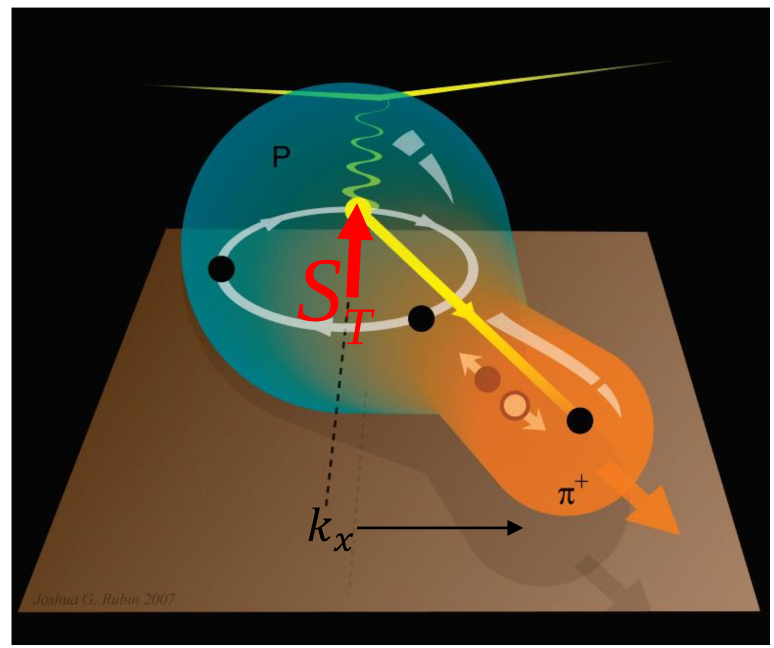
Sivers Asymmetry A_{Siv} in SIDIS (Left-Right Asymmetry w.r.t. S_T)

$$f_{q/p\uparrow}(x,\overrightarrow{k_T},\overrightarrow{S_T}) = f_{q/p}(x,k_T^2) - \frac{1}{M_N} f_{1T}^{\perp q}(x,k_T^2)\overrightarrow{S_T}\cdot(\hat{p}_N \times \overrightarrow{k_T})$$



The orbital motion of an u quark inside a proton causes positive-charged pions (u$\bar{d}$) to fly off predominantly to beam-left.





$$A_T^h \equiv \frac{d\sigma(\vec{S}_T) - d\sigma(-\vec{S}_T)}{d\sigma(\vec{S}_T) + d\sigma(-\vec{S}_T)} = \left|\vec{S}_T\right| \cdot [D_{NN} \cdot A_{Coll} \cdot \sin(\phi_h + \phi_S - \pi) + A_{Siv} \cdot \sin(\phi_h - \phi_S)]$$

Polarization-dependent Terms: Transverse Spin Asymmetry (TSA)

A_{UT}

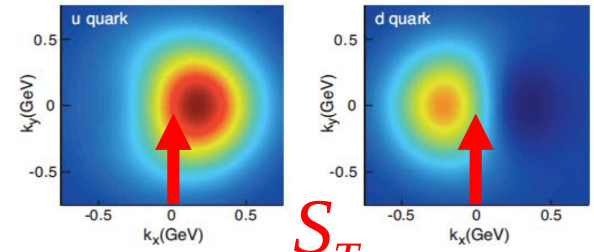
$$A_{UT} = \frac{F_{UT}}{F_{UU}} = \frac{1}{fS_T}\frac{N^{\uparrow} - N^{\downarrow}}{N^{\uparrow} + N^{\downarrow}}$$

f: dilution factor due to non-polarizable content of the target

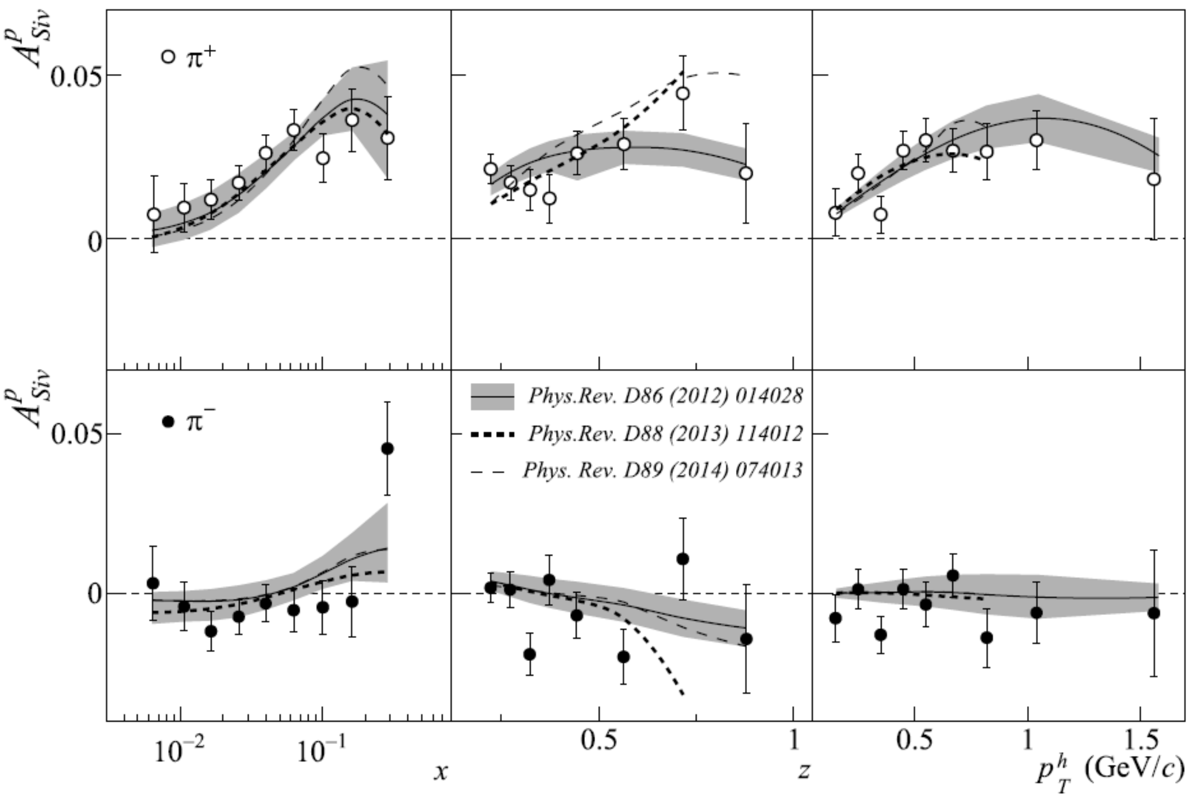
S_T: polarization degree of nucleon transverse spin

- **Advantage**: most of the systematics due to instrumental artifacts cancel.
- **Disadvantage**: unpolarized structure function F_{UU} has to be well known.

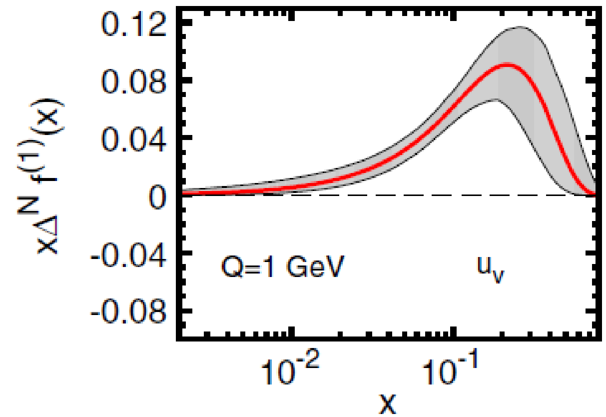
Nonzero Sivers Asymmetries from SIDIS

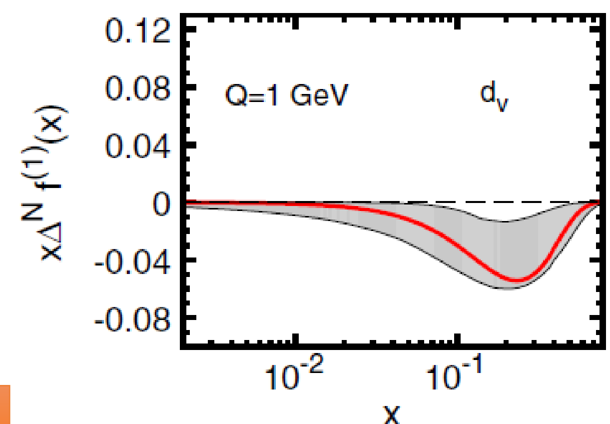


COMPASS, PLB 744 (2015) 250



Sivers Functions



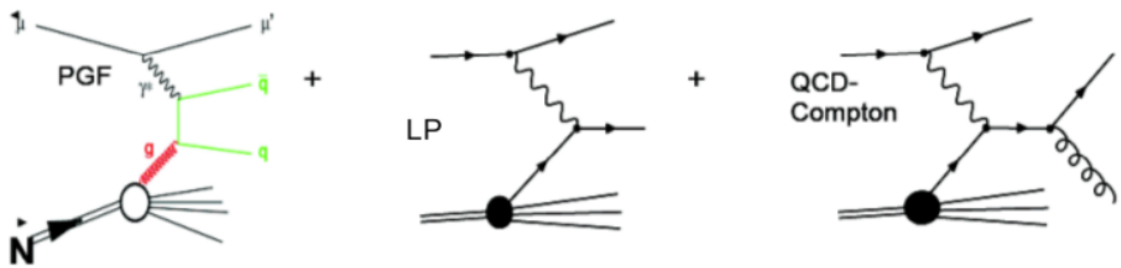


Signals of Sivers functions of valence quarks from SIDIS.
How about Sivers functions of gluons?

PRD 86, 014028 (2012)
[arXiv:1204.1239]

Feynman Diagrams of $\gamma^* N$ Scattering

photon-gluon fusion (PGF) | Leading process (LP)- main DIS process | QCD Compton



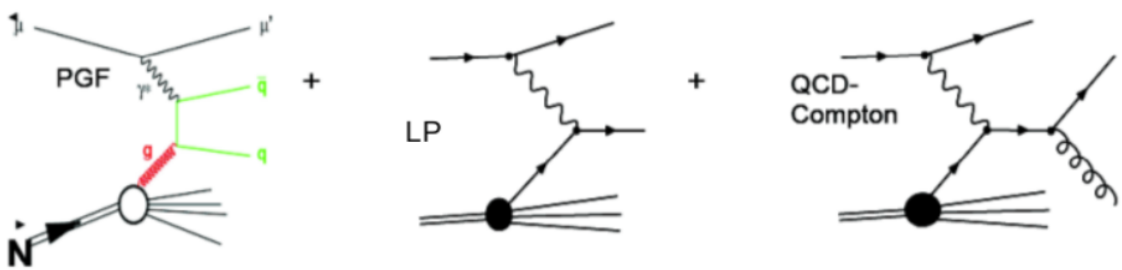
3 processes in the single photon exchange approximation describe well the unpolarised data

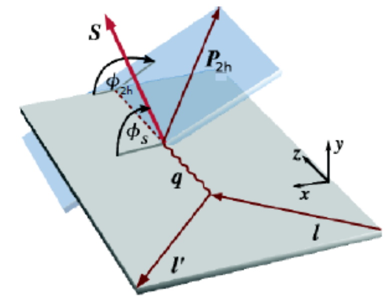
With the use of neural network trained on MC simulation it is possible to extract

the asymmetries of the three processes simultaneously.

Method presented in the $\Delta g/g$ extraction paper: COMPASS, acc EPJC, hep-ex/1609.06062

Neural Network to disentangle individual contributions





$$\mathbf{P} = \mathbf{p}_1 + \mathbf{p}_2$$
$$\phi = \phi_P - \phi_S$$
$$t = ud, c, ud', c'.$$

$$N_t = \alpha_t \left(1 + \beta_t^G A_{PGF}^{\sin\phi}(\vec{x}) + \beta_t^L A_{LP}^{\sin\phi}(\vec{x}) + \beta_t^C A_{QCDC}^{\sin\phi}(\vec{x})\right)$$

α_t - generalised acceptance of cell t

$$\beta^G = R_{PGF} f P_T \sin\phi,$$
$$\beta^L = R_{LP} f P_T \sin\phi,$$
$$\beta^C = R_{QCDC} f P_T \sin\phi.$$

$R_{PGF}, R_{LP}, R_{QCDC}$ - from neural network trained on MC data

$$\vec{x} = \left\{x_{Bj}, Q^2, p_{T1}, p_{T2}, p_{L1}, p_{L2}\right\}$$

Event Selection

Kinematic cuts

- DIS cuts: $Q^2 > 1(\mathrm{GeV}/c)^2$; $0.003 < x_{Bj} < 0.7$; $0.1 < y < 0.9$;
- $W > 5\mathrm{GeV}/c^2$;
- $z_1, z_2 > 0.1$;
- $z_1 + z_2 < 0.9$;
- $p_{T1} > 0.7\mathrm{GeV}/c$; $p_{T2} > 0.4\mathrm{GeV}/c$ - optimised to enhance PGF fraction and ϕ_g, ϕ_P correlation in MC.

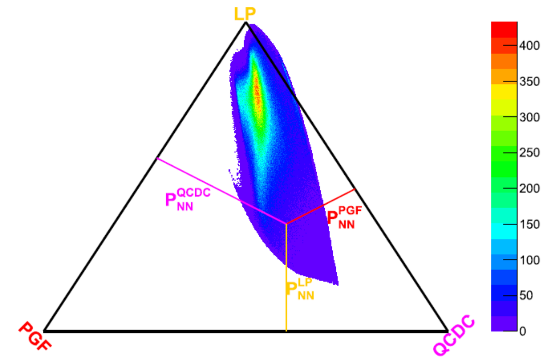
MC events for Neural Network Training

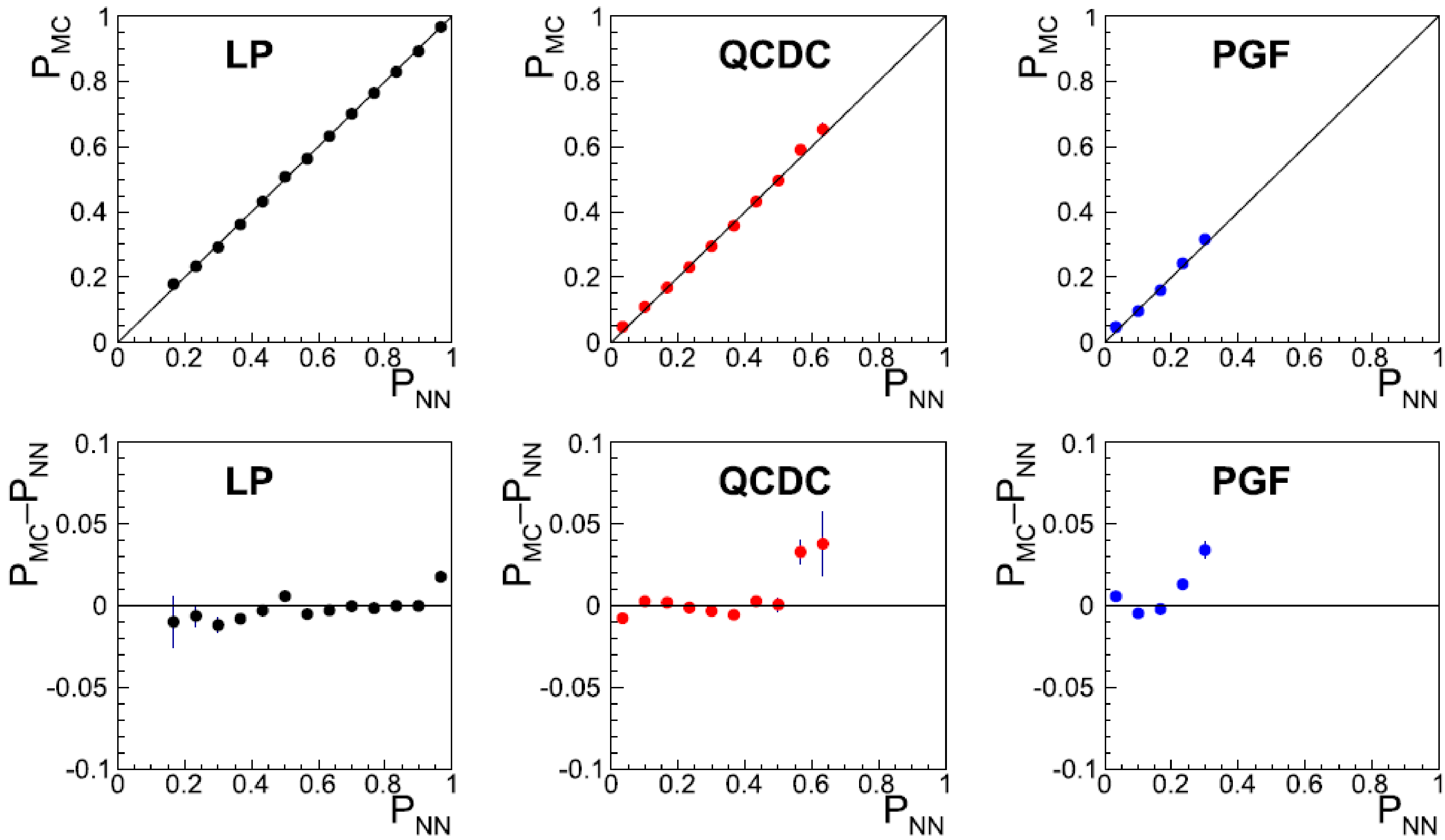
Full chain MC with LEPTO generator, GEANT with COMPASS setup and reconstruction package

- MSTW08 PDFs
- Parton Shower on
- F_L on
- FLUKA for secondary interactions

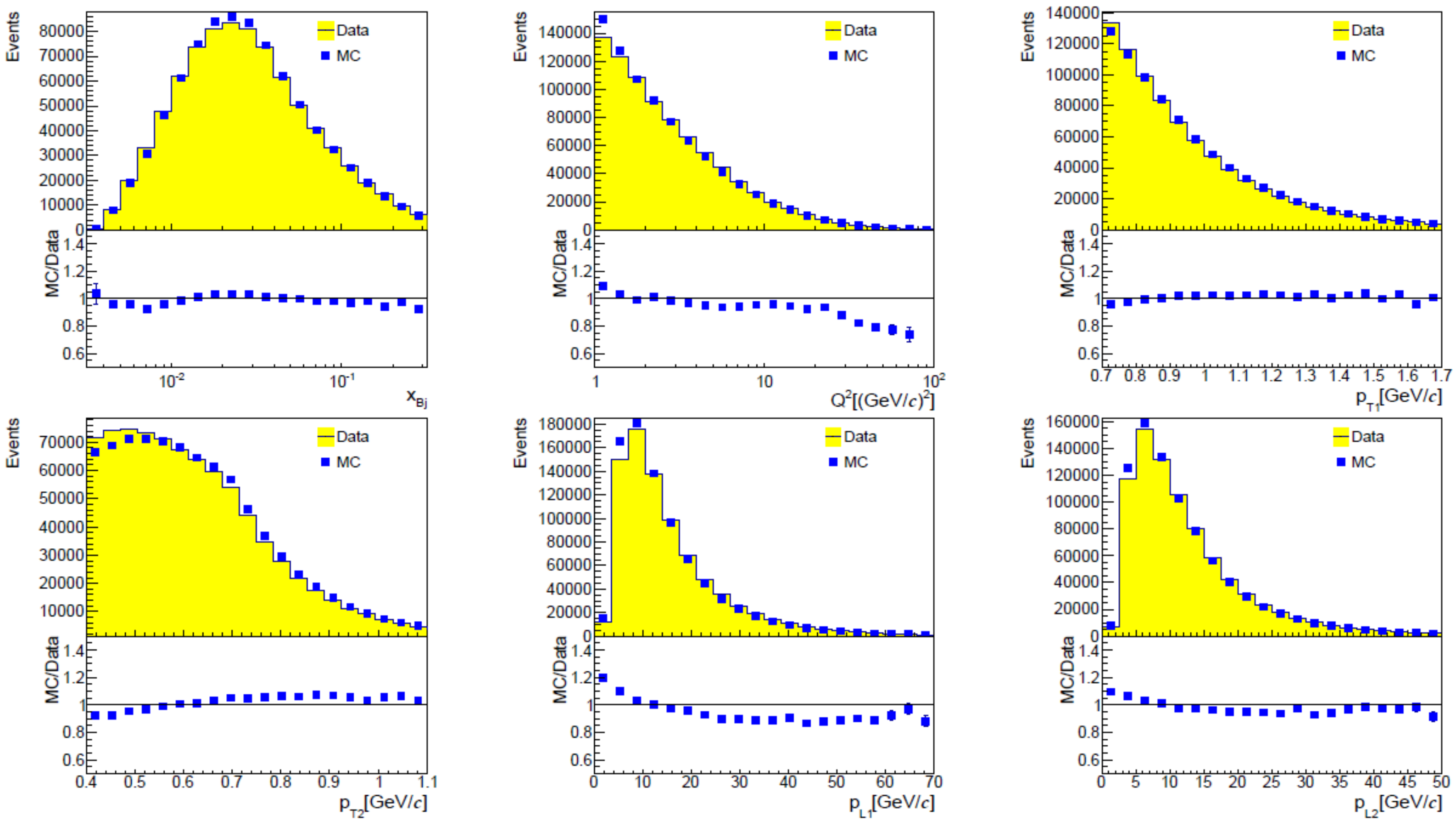
6 kinematic variables as an input of NN: $p_{T1}, p_{T2}, p_{L1}, p_{L2}, Q^2, x_{Bj}$
good agreement between MC and data for distribution of these variables needed

NN MC Training



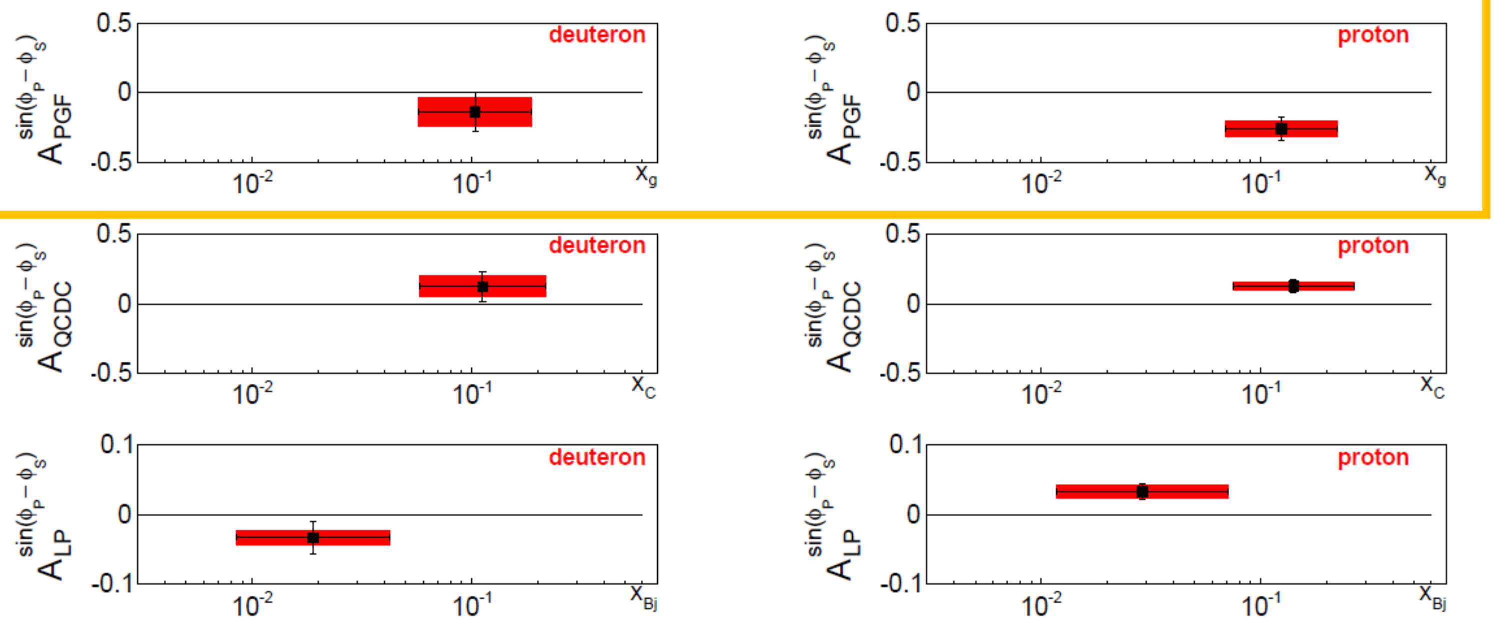


MC vs. Proton Data



Sivers 2-h Asymmetries

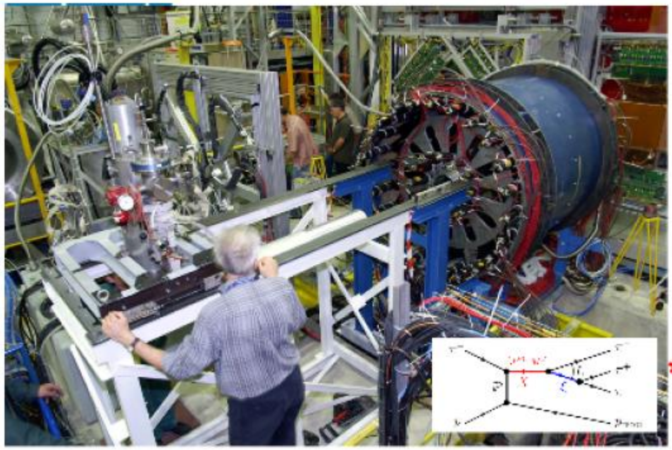
Sivers



Results

- Gluon Sivers contribution for proton: $A_{PGF,p}^{\sin(\phi_P-\phi_s)} = -0.26 \pm 0.09(stat.) \pm 0.06(syst.)$
- Gluon Sivers contribution for deuteron: $A_{PGF,d}^{\sin(\phi_P-\phi_s)} = -0.14 \pm 0.15(stat.) \pm 0.10(syst.)$
- Limited precision on deuteron. More data needed.
- The results for the LP compatible with single hadron measurements.
- COMPASS, PLB 772 (2017) 854, hep-ex/1701.02453

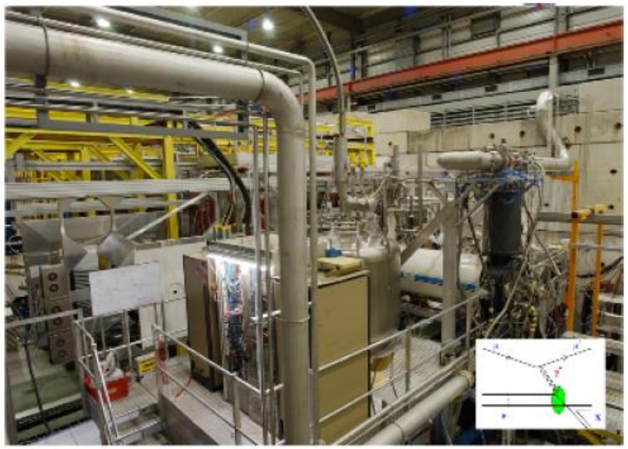
COMPASS physics
Commom **M**uon **P**roton **A**pparatus for **S**tructure and **S**pectroscopy



Hadron Spectroscopy & Chiral Dynamics

COMPASS-I
1997-2011

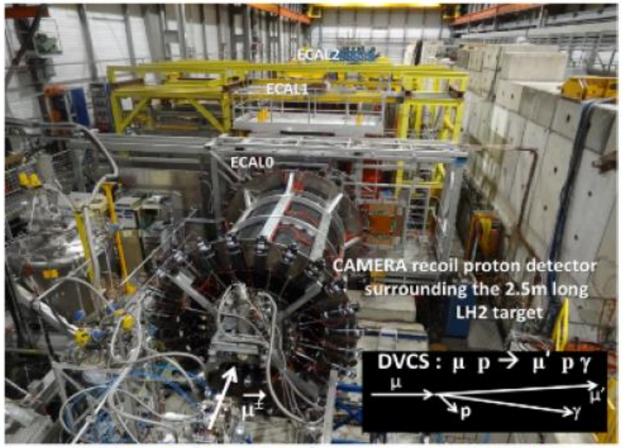
*** extension ***
& 2021



Polarised SIDIS

Polarised Drell-Yan

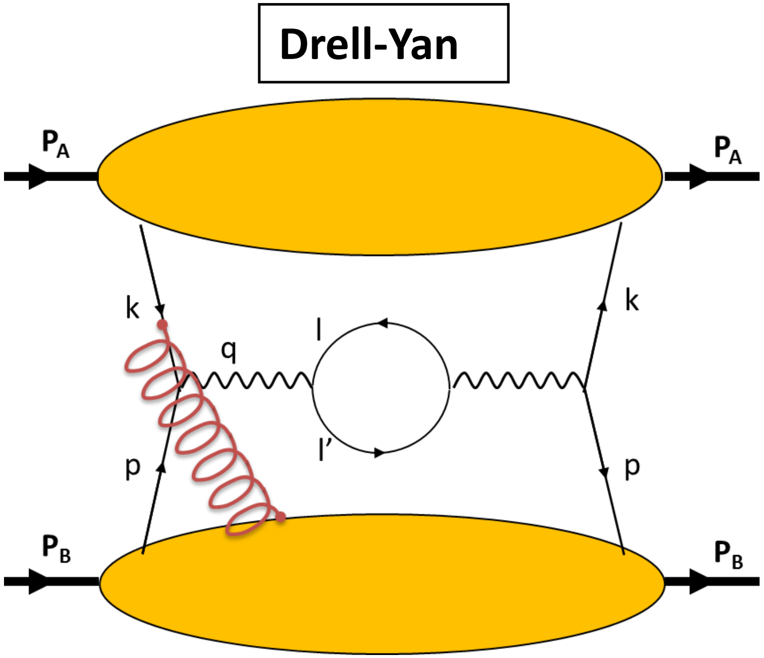
COMPASS-II
2012-2020

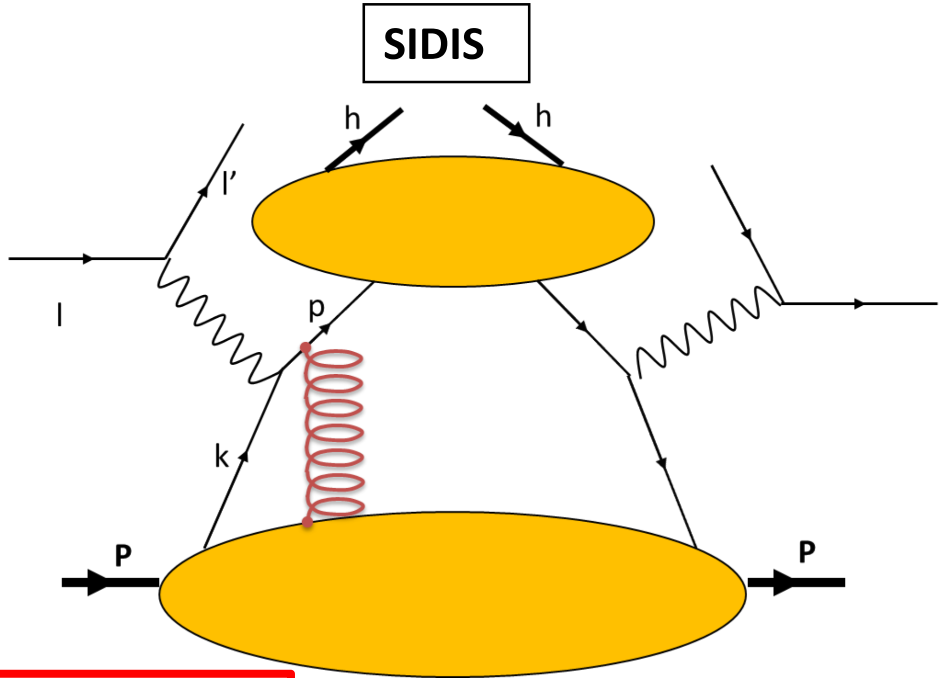


DVCS (GPDs) + unp. SIDIS

Non-Universality of Sivers Functions

J.C. Collins, Phys. Lett. B 536 (2002) 43
A.V. Belitsky, X. Ji, F. Yuan, Nucl. Phys. B 656 (2003) 165
D. Boer, P.J. Mulders, F. Pijlman, Nucl. Phys. B 667 (2003) 201
Z.B. Kang, J.W. Qiu, Phys. Rev. Lett. 103 (2009) 172001





$$\text{Sivers}\,|_{DY} = -\text{Sivers}\,|_{SIDIS}$$

- QCD gluon gauge link (Wilson line) in the initial state (DY) vs. final state interactions (SIDIS).
- ***Fundamental predictions from TMD physics will be tested.***

COMPASS-II Transversely Polarized Drell-Yan Program

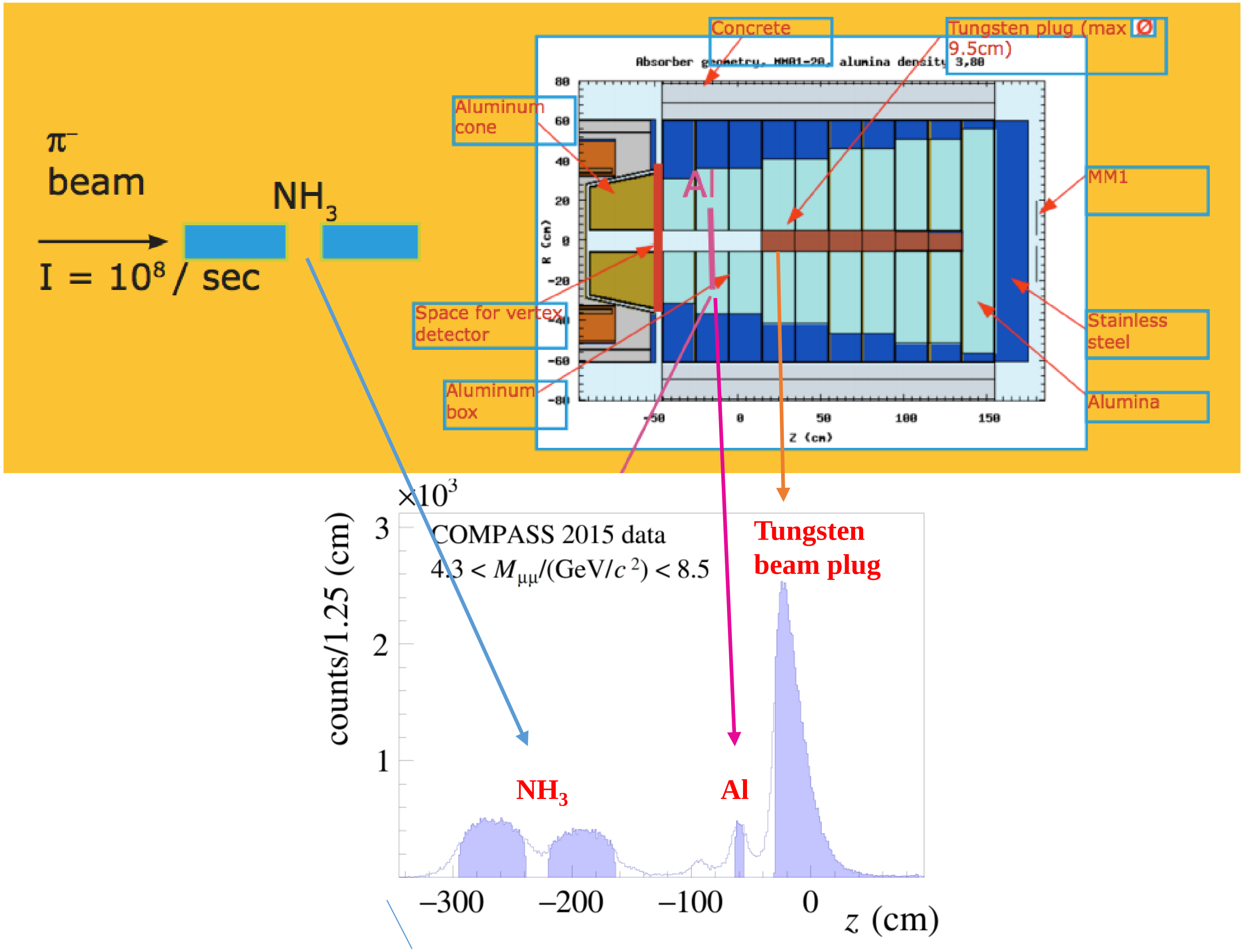
- Schedules:
  - 2014 Oct – Dec: commission Drell-Yan runs
  - 2015: first year of transversely polarized Drell-Yan runs with 190 GeV π^- beam

PRL **119,** 112002 (2017) PHYSICAL REVIEW LETTERS week ending 15 SEPTEMBER 2017

First Measurement of Transverse-Spin-Dependent Azimuthal Asymmetries in the Drell-Yan Process

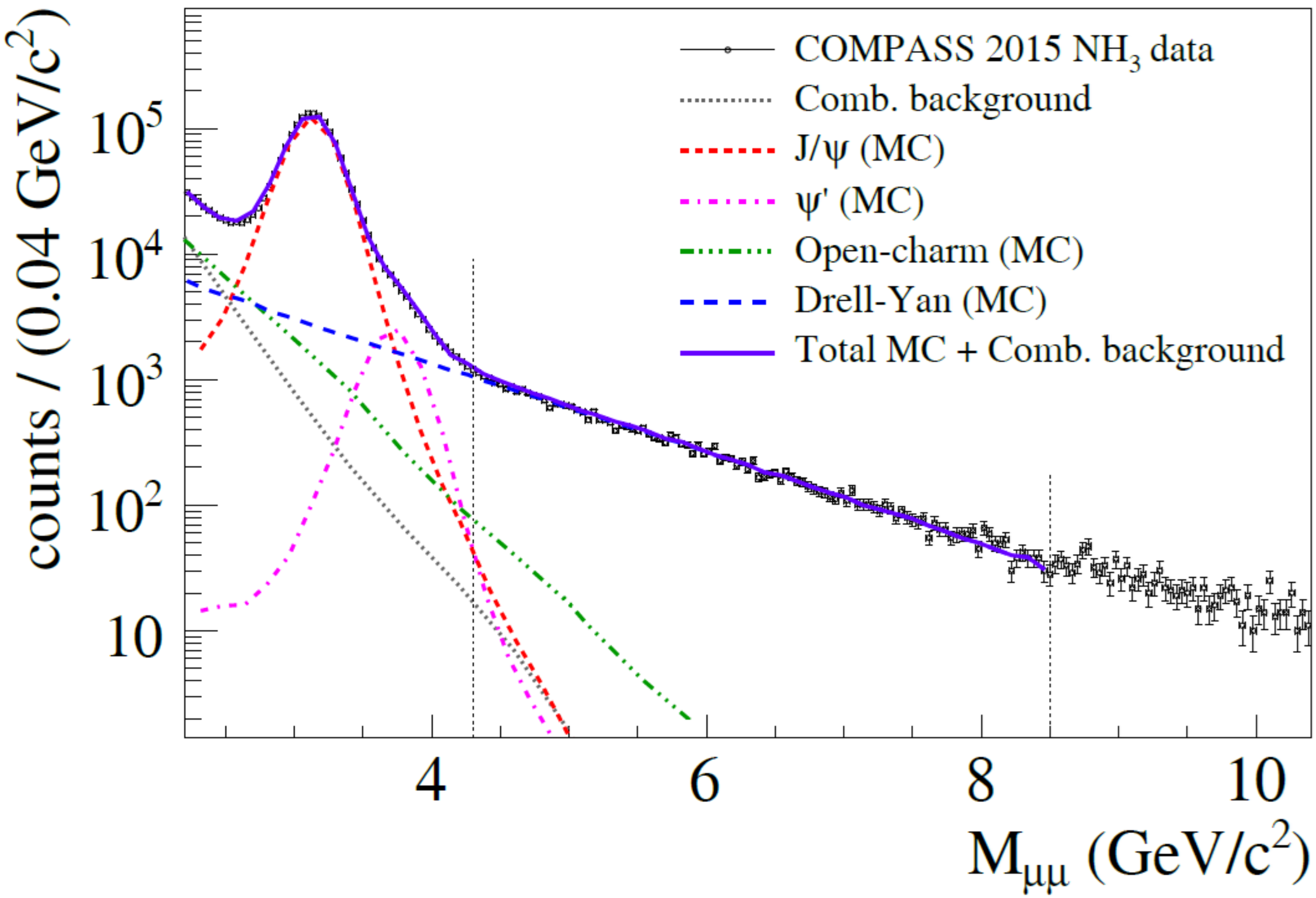
M. Aghasyan,[24] R. Akhunzyanov,[7] G. D. Alexeev,[7] M. G. Alexeev,[25] A. Amoroso,[25,26] V. Andrieux,[27,20] N. V. Anfimov,[7] V. Anosov,[7] A. Antoshkin,[7] K. Augsten,[7,18] W. Augustyniak,[28] A. Austregesilo,[15] C. D. R. Azevedo,[1] B. Badełek,[29] F. Balestra,[25,26] M. Ball,[3] J. Barth,[4] R. Beck,[3] Y. Bedfer,[20] J. Bernhard,[12,9] K. Bicker,[15,9] E. R. Bielert,[9] R. Birsa,[24] M. Bodlak,[17] P. Bordalo,[11,b] F. Bradamante,[23,24] A. Bressan,[23,24] M. Büchele,[8] W.-C. Chang,[21] C. Chatterjee,[6] M. Chiosso,[25,26] I. Choi,[27] S.-U. Chung,[15,c] A. Cicuttin,[24,d] M. L. Crespo,[24,d] S. Dalla Torre,[24] S. S. Dasgupta,[6]

Dimuon Vertex Distributions (2015 Trans.-pol. Drell-Yan Runs)



COMPASS, PRL 119 (2017) 112002

Dimuon Invariant-mass Distributions (2015 Trans.-pol. Drell-Yan Runs)



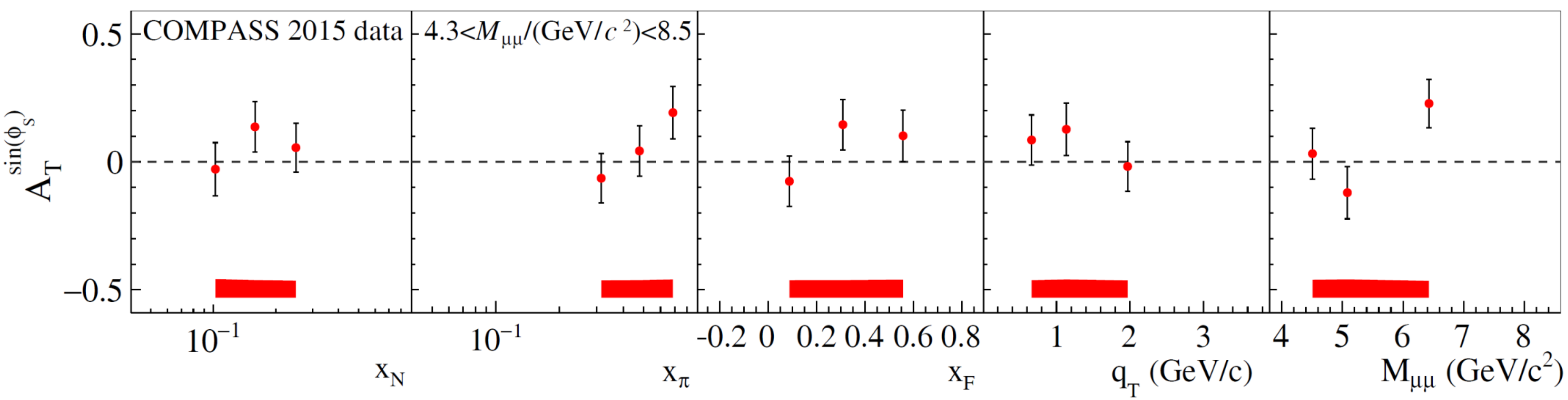
COMPASS, PRL 119 (2017) 112002

Transverse Spin Asymmetries in Trans.-pol. Drell-Yan: Sivers

$$\frac{d\sigma^{LO}}{d^4q d\Omega} = \frac{\alpha_{em}^2}{Fq^2}\hat{\sigma}_U^{LO}$$

$$A_T^{\sin\phi_s} \propto \text{Density } f_1|_\pi \otimes \text{Sivers } f_{1T}^{\perp}|_p$$

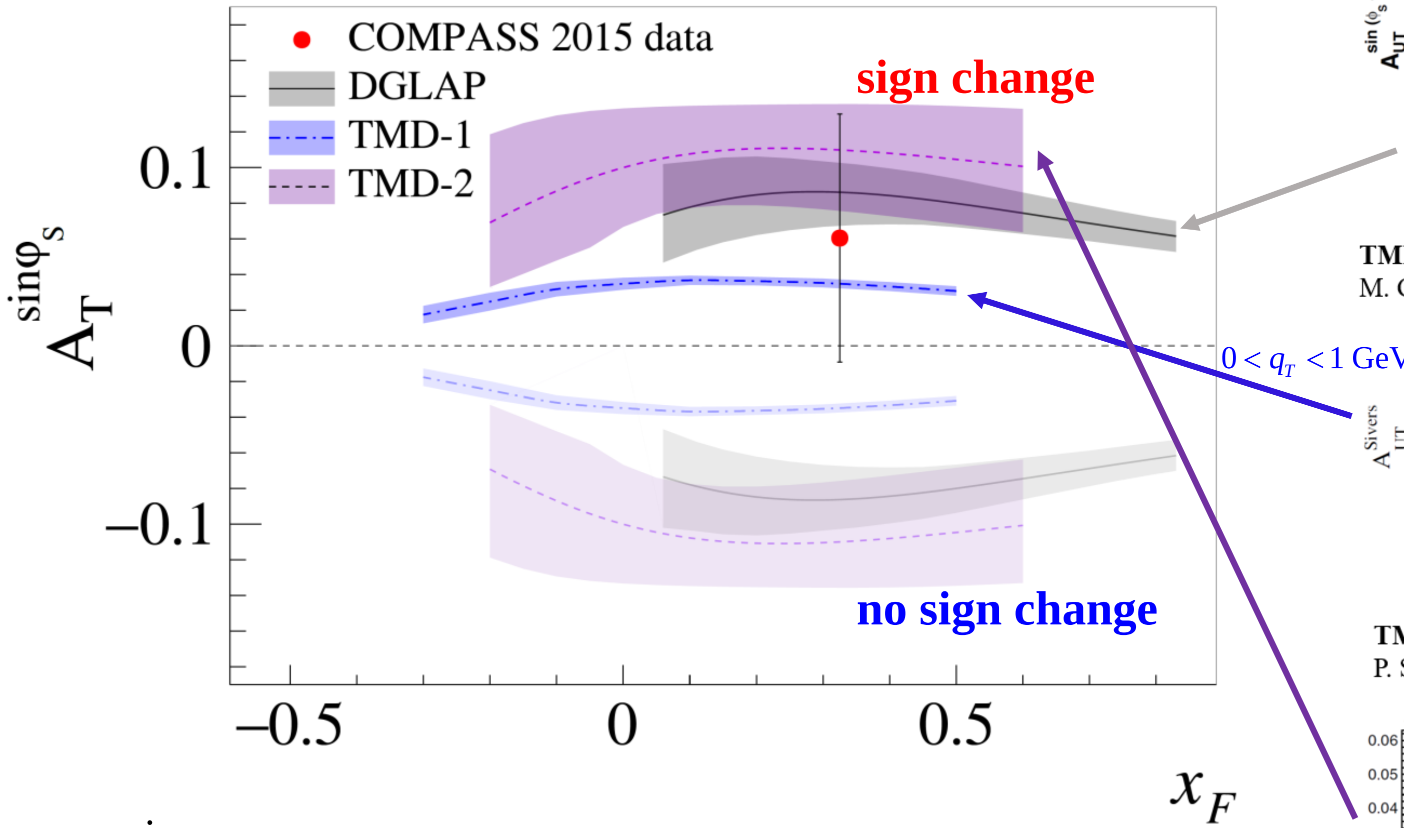
$$\left\{ \left(1 + D_{[\sin^2\theta]}^{LO} A_U^{\cos 2\varphi} \cos 2\varphi\right) + \left|\vec{S}_T\right| \left[A_T^{\sin\varphi_S} \sin\varphi_S + D_{[\sin^2\theta]}^{LO} \left(A_T^{\sin(2\varphi-\varphi_S)} \sin(2\varphi - \varphi_S) + A_T^{\sin(2\varphi+\varphi_S)} \sin(2\varphi + \varphi_S) \right) \right] \right\}$$



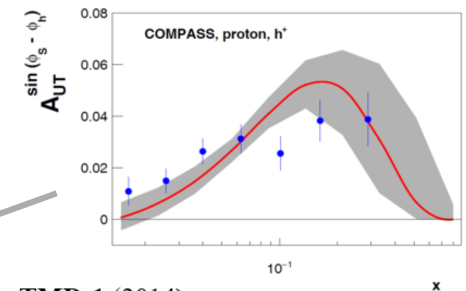
COMPASS, PRL 119 (2017) 112002

Sivers Asymmetry in Drell-Yan: Hint of Sign Change!

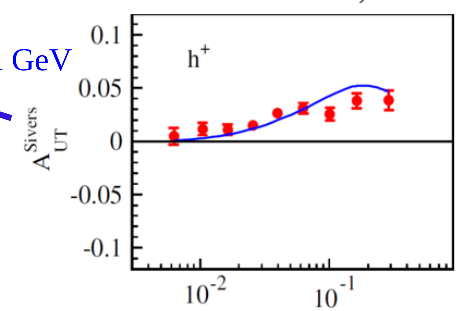
COMPASS, PRL 119 (2017) 112002



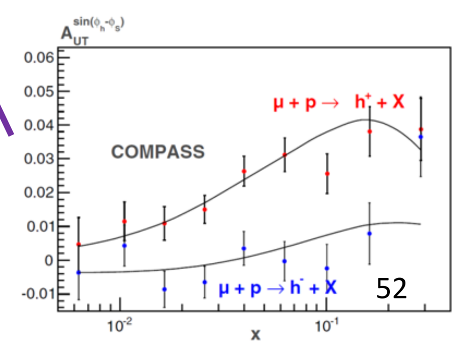
DGLAP (2016)
M. Anselmino et al., **arXiv:1612.06413**



TMD-1 (2014)
M. G. Echevarria et al. **PRD89,074013**



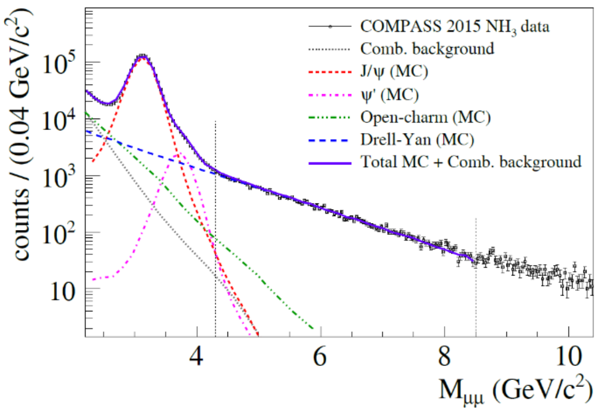
TMD-2 (2013)
P. Sun, F. Yuan, **PRD88, 114012**

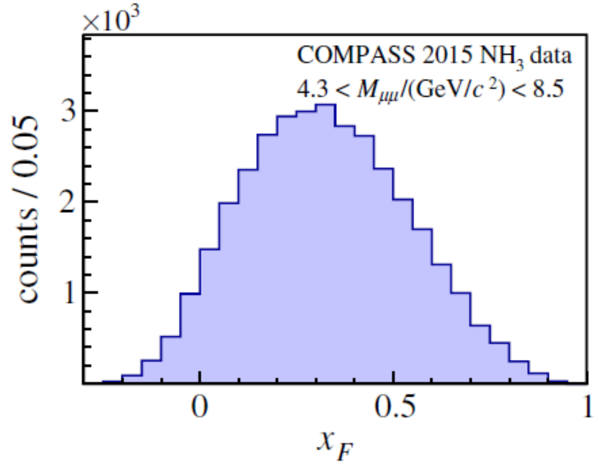


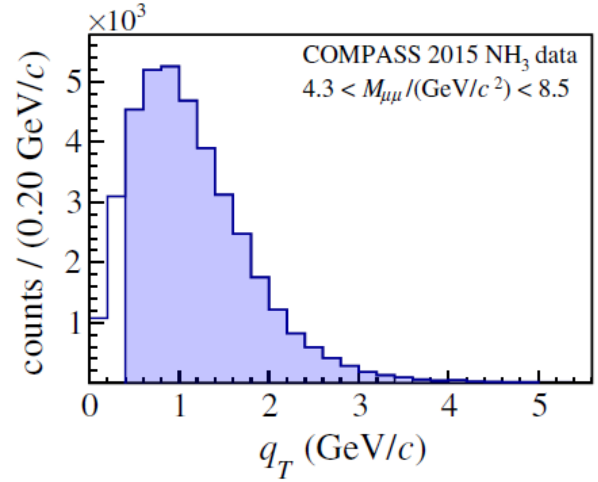
$$A_T^{\sin\varphi_s} = 0.060 \pm 0.057(stat.) \pm 0.040(sys.)$$

2018: Polarized Drell-Yan program (improved statistics errors of Sivers asymmetries are expected).

Unpolarized Cross Sections: Pion PDFs and Sudakov FFs

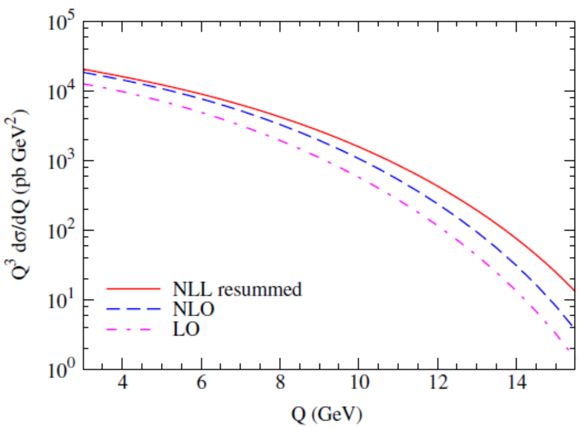


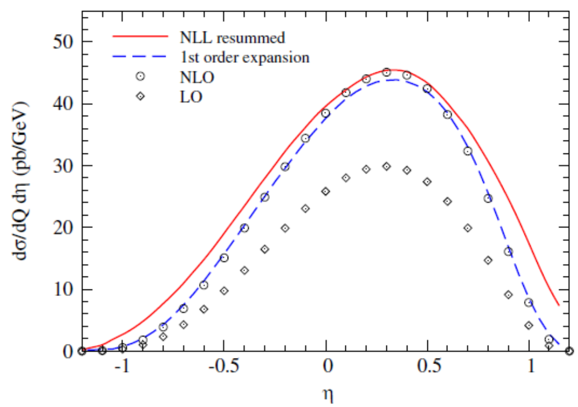


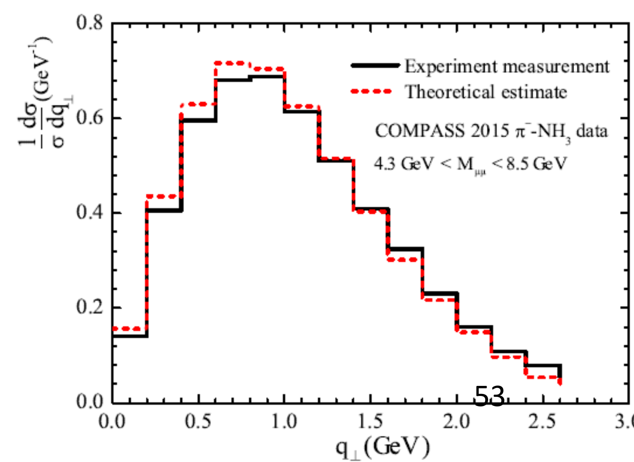


Aicher *et al.*, PRD 83 (2011) 114023

Wang *et al.*, JHEP08(2017)137

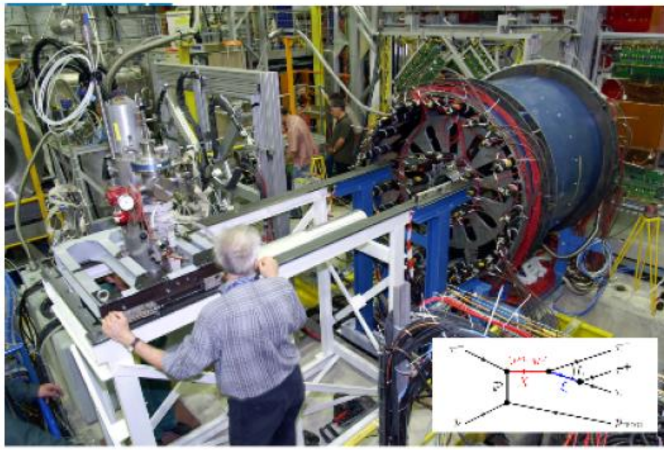






COMPASS physics

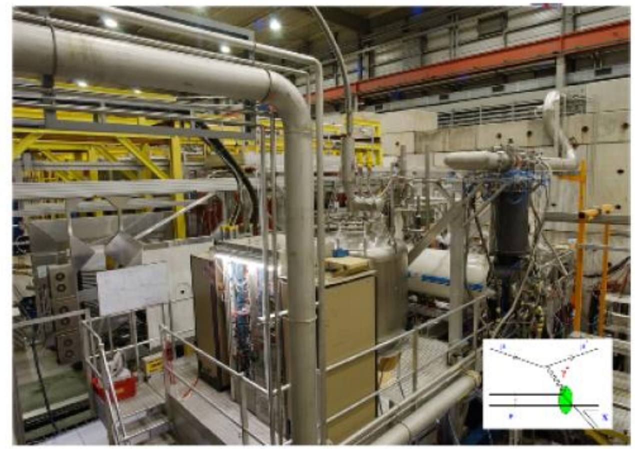
Commom **M**uon **P**roton **A**pparatus for **S**tructure and **S**pectroscopy



Hadron Spectroscopy & Chiral Dynamics

COMPASS-I
1997-2011

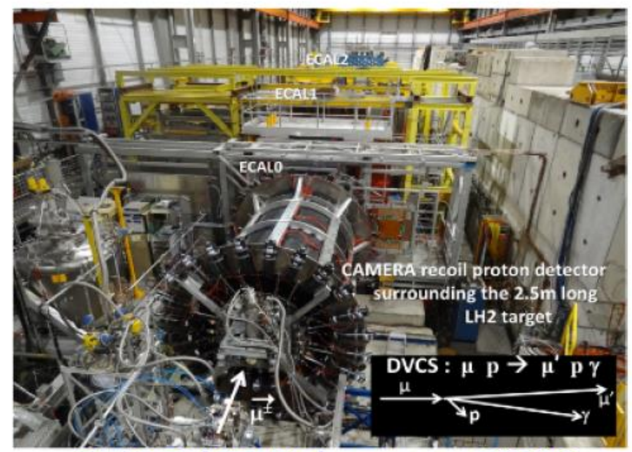
*** extension ***
& 2021



Polarised SIDIS

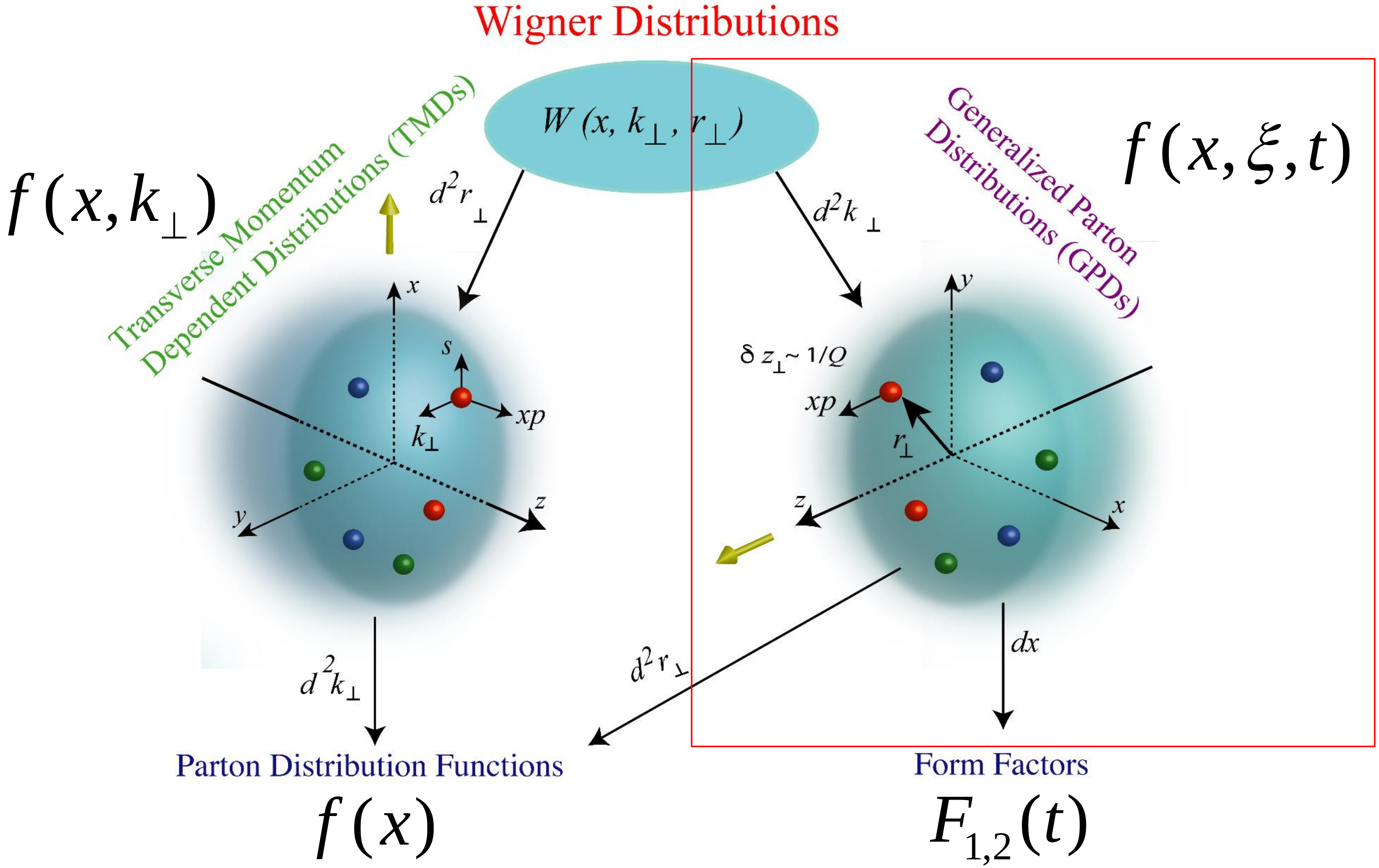
Polarised Drell-Yan

COMPASS-II
2012-2020



DVCS (GPDs) + unp. SIDIS

Multi-dimensional Partonic Structures

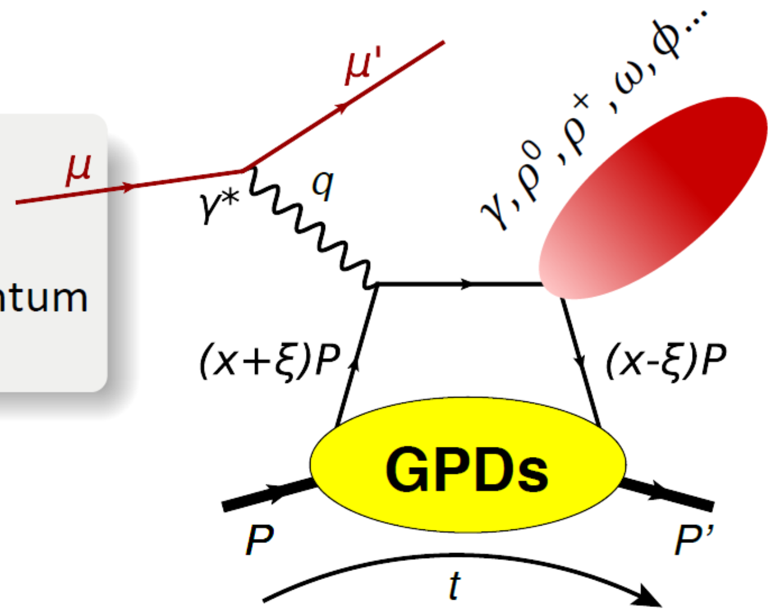


http://www.int.washington.edu/PROGRAMS/17-3/

DVCS and Exclusive pi0

Introduction to GPDs

GPDs provide a **“3D”** description of the nucleon by encoding **CORRELATIONS** between momentum and position of partons



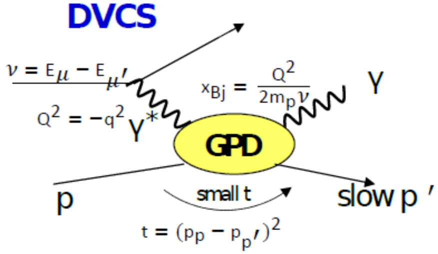
Definition of variables:

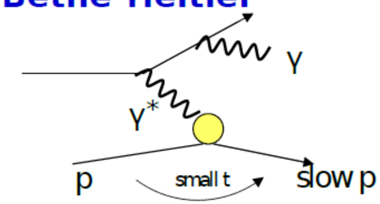
- q: exchanged photon four-momentum
- x: average long. momentum - NOT ACCESSIBLE
- ξ: long. mom. difference $\simeq x_B/(2-x_B)$
- t: four-momentum transfer

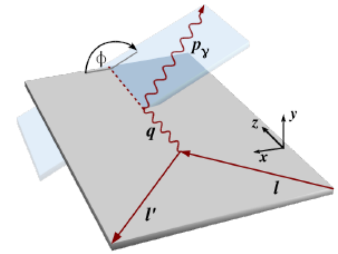
For proton target:

- 4 chiral-even GPDs: $\mathbf{H}\ \ \widetilde{\mathbf{H}}\ \ \mathbf{E}\ \ \widetilde{\mathbf{E}}$
- 4 chiral-odd (“transversity”) GPDs: $\mathbf{H_T}\ \ \widetilde{\mathbf{H}}_\mathbf{T}\ \ \mathbf{E_T}\ \ \widetilde{\mathbf{E}}_\mathbf{T}$

Extraction of DVCS

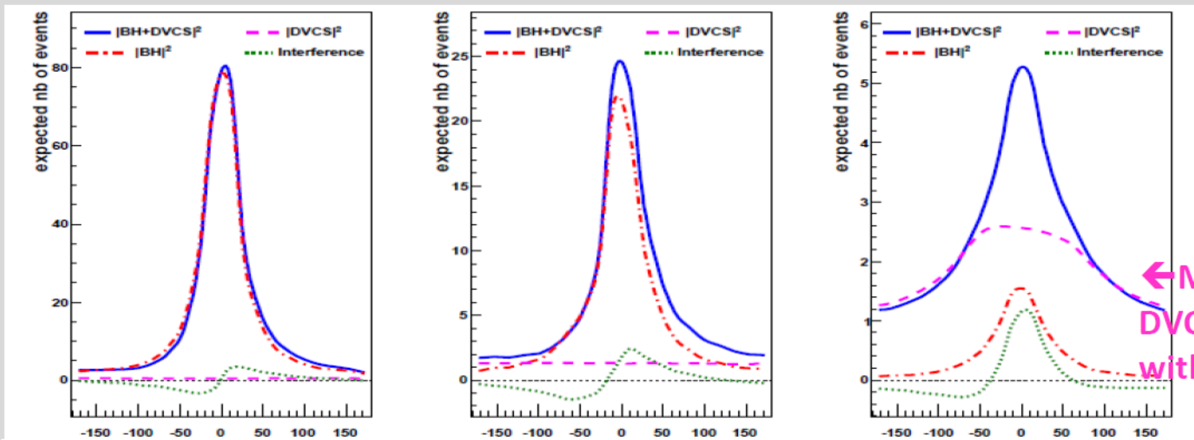






$d\sigma \propto |T_{DVCS}|^2 + |T_{BH}|^2 +$ interference term

bilinear combination of GPDs — known to 1 % — linear combination of GPDs



Monte-Carlo Simulation for COMPASS set-up with only ECAL1+2

← Missing DVCS acceptance without ECAL0

$0.005 < x_B < 0.01$ — $0.01 < x_B < 0.03$ — $0.03 < x_B$

BH dominates

excellent reference yield

study of Interference

→ Re T^{DVCS} or Im T^{DVCS}

DVCS dominates

study of $d\sigma^{DVCS}/dt$

→ Transverse Imaging

Transverse Nucleon Imaging

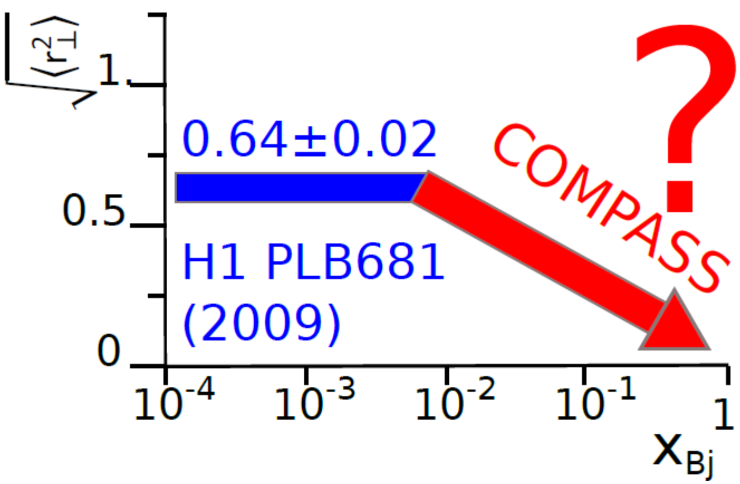
Beam Charge and Spin **SUM**:

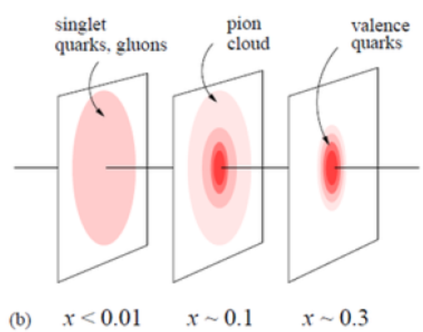
$$\mathbf{S_{CS,U}} \equiv \mathbf{d\sigma(\mu^{+\leftarrow}) + d\sigma(\mu^{-\rightarrow}) \propto d\sigma^{BH} + d\sigma^{DVCS}_{unpol} + Ks^{Int}_{1}} \sin\phi$$

Integration over ϕ and BH **subtraction** → $\mathbf{d\sigma^{DVCS}/d|t| \sim exp(-B|t|)}$

$$< b_\perp^2(x_B) > \approx 2B(x_B)$$

$b_\perp$ → distance between struck parton and baricenter of momentum

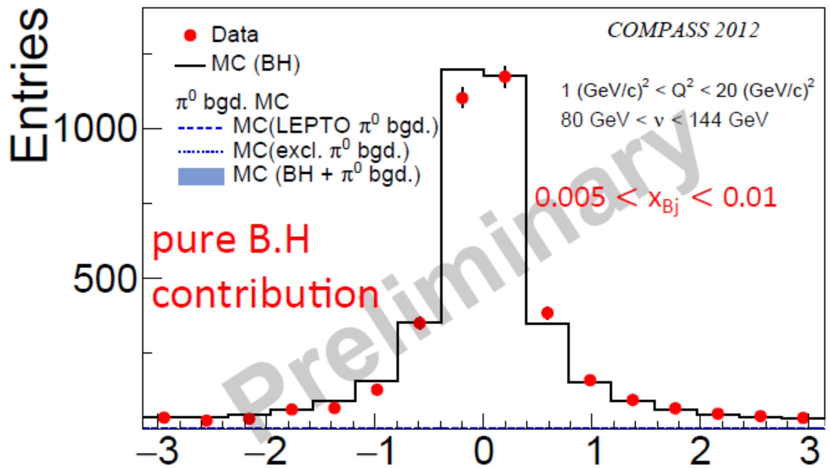


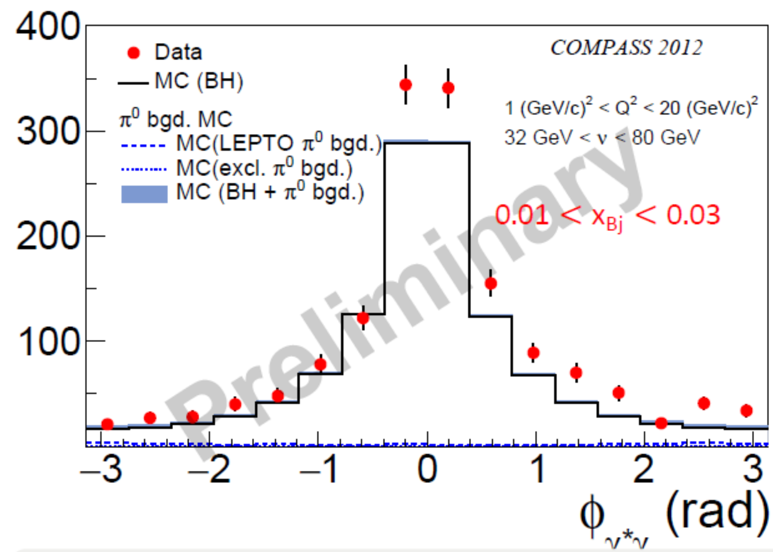


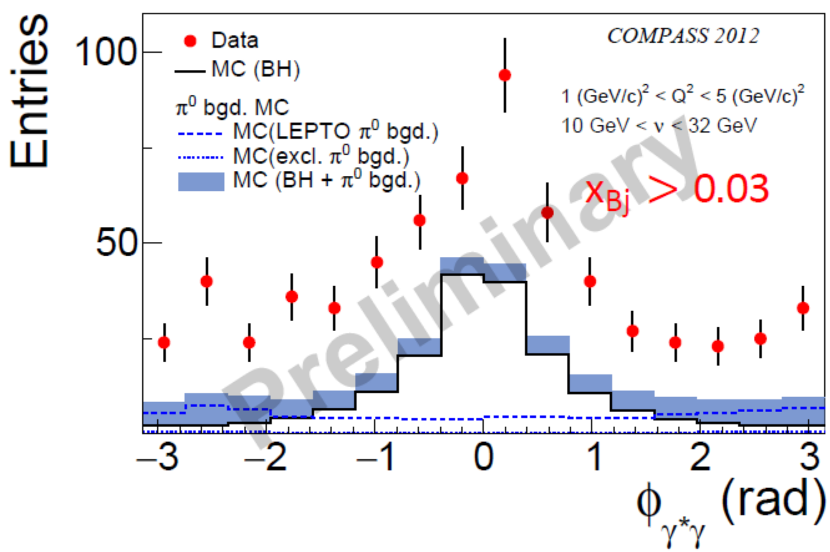
Ansatz at small $\mathbf{x_B}$:
$\mathbf{B(x_B) \simeq B_0 + 2\alpha' ln(x_0/x_B)}$
(inspired by Regge phenomenology)

Exclusive γ Azimuthal Distributions for DVCS

Kinematically constrained vertex fit applied



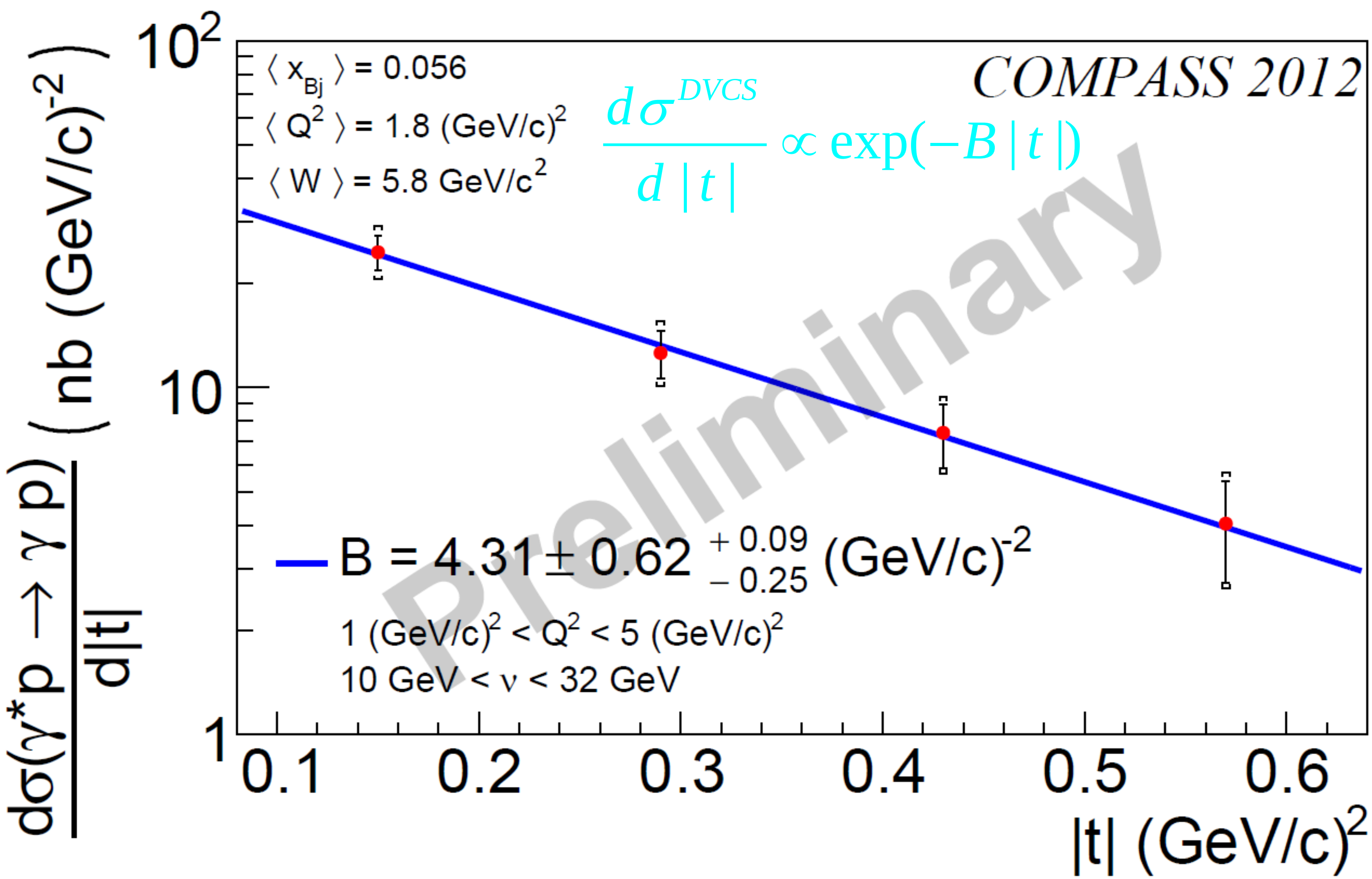




- BH Monte Carlo normalization based on integrated luminosity
- BH process dominant at small x_{Bj}
- π^0 background contributing at large x_{Bj}
- **clear excess of DVCS at large x_{Bj}**

DVCS x-section and t-slope extraction

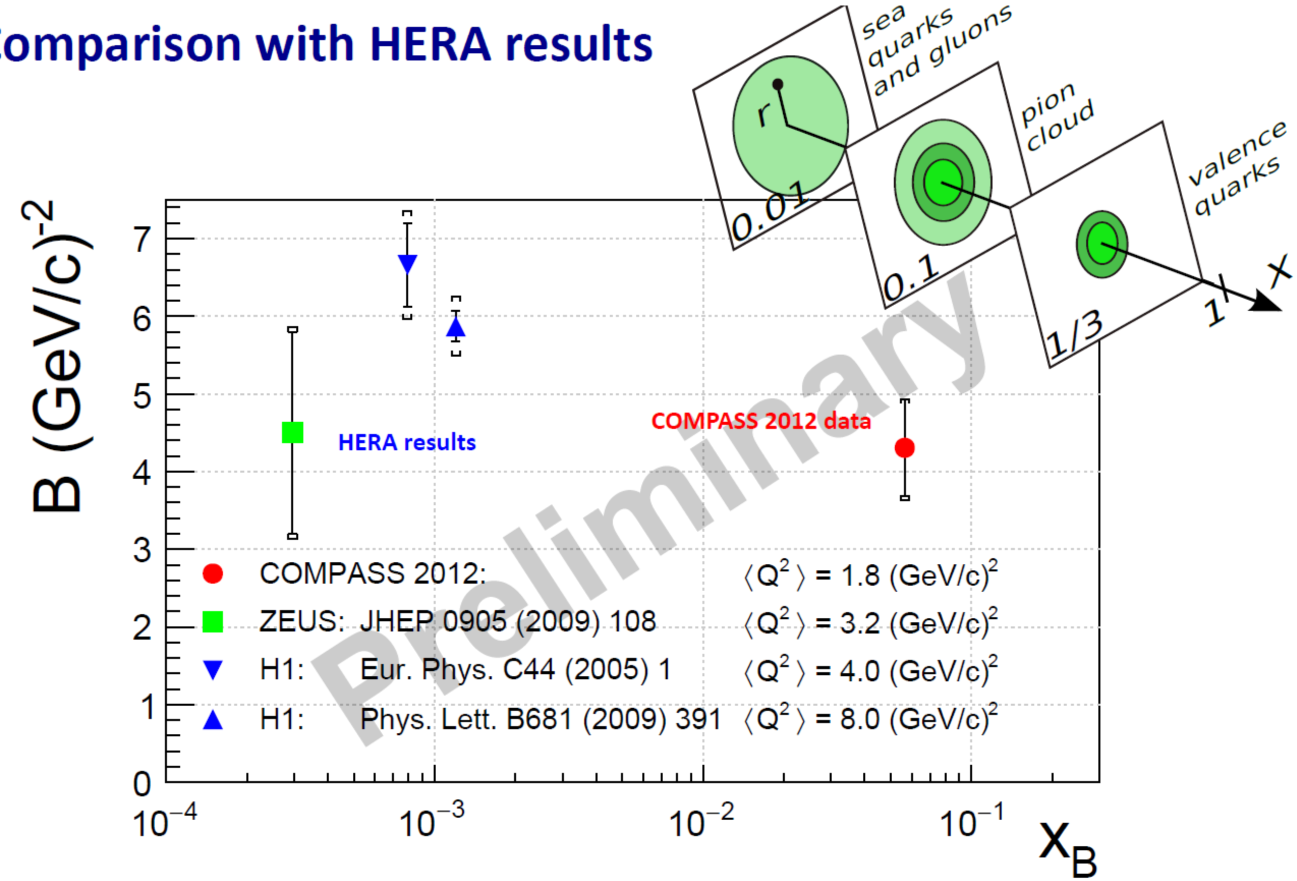
Kinematically constrained vertex fit applied

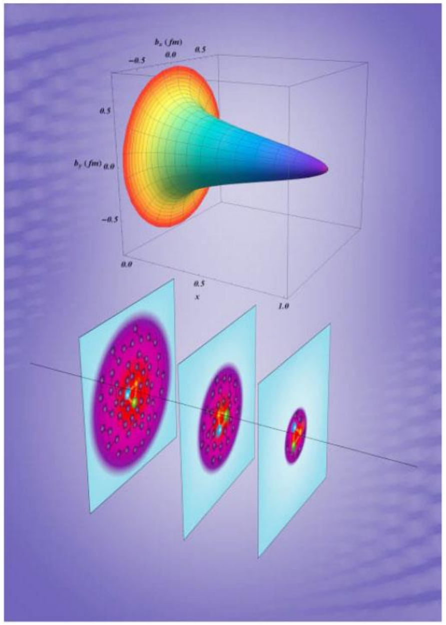


COMPASS, hep-ex/1802.02739

Quark density and transverse radius as a function of *x*

Comparison with HERA results





$$\sqrt{\langle r_\perp^2 \rangle} = (0.58 \pm 0.04_{\text{stat}} {}^{+0.01}_{-0.02}\big|_{\text{sys}})\ \text{fm}$$

COMPASS, hep-ex/1802.02739

COMPASS physics

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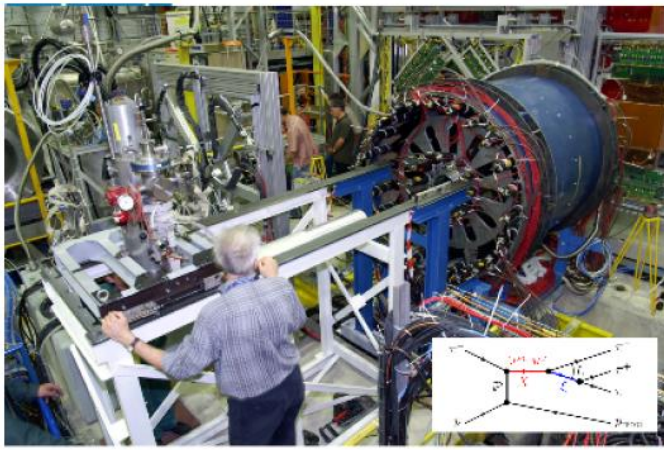

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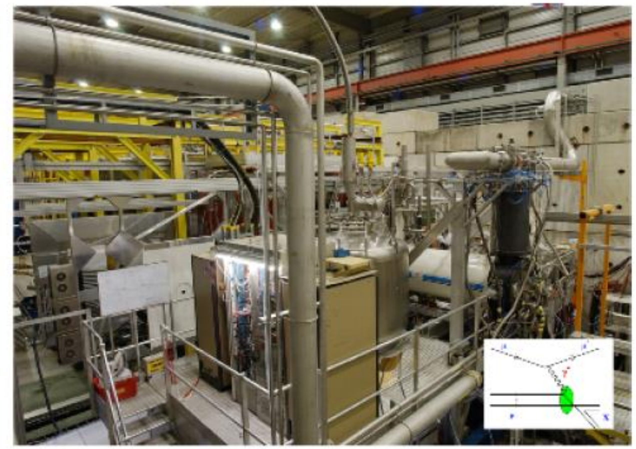

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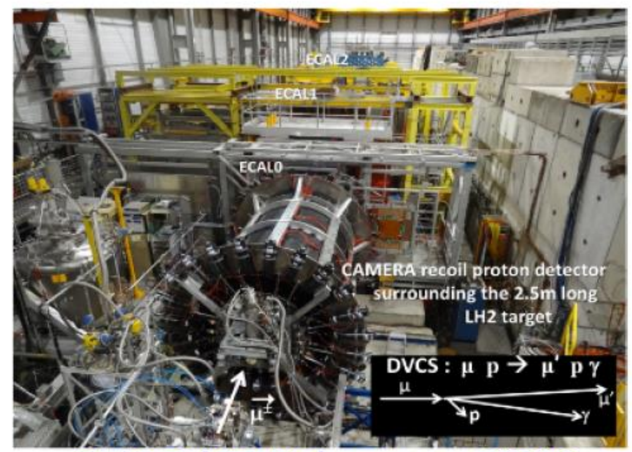
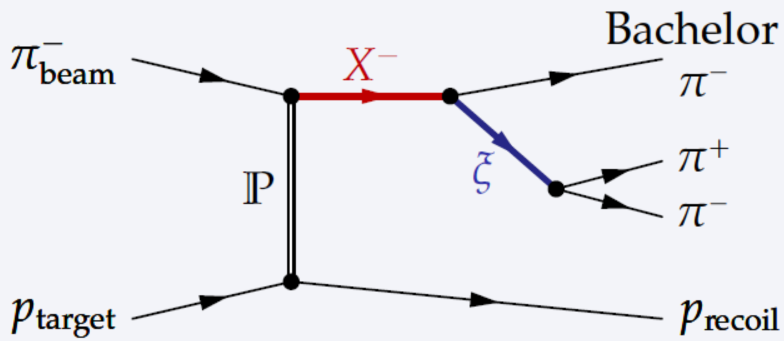


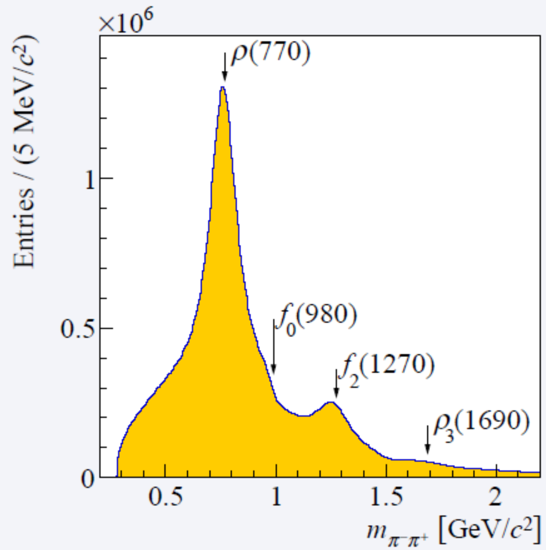
DVCS (GPDs) + unp. SIDIS

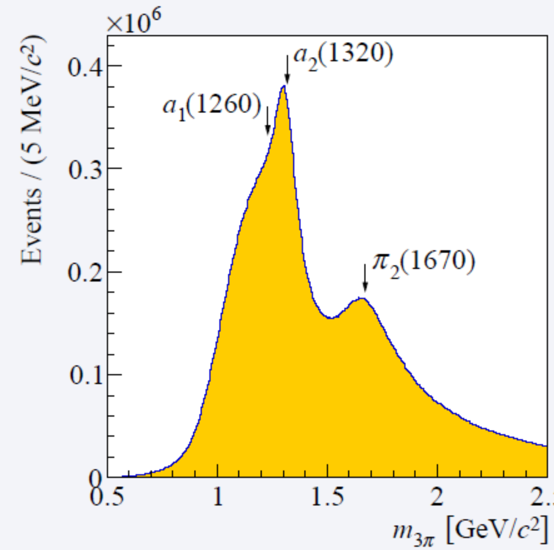
Meson Production in Diffractive Dissociation

Example: $\pi^-\pi^-\pi^+$ final state

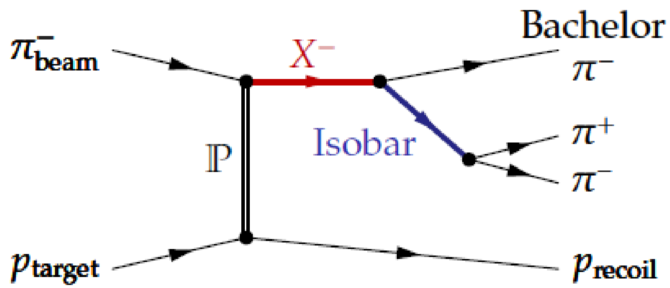
C. Adolph *et al.*, PRD **95** (2017) 032004







Decay of X via intermediate $\pi^-\pi^+$ resonances = "isobars"



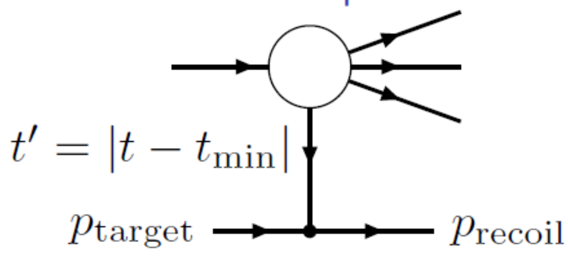
2π resonances 3π resonances

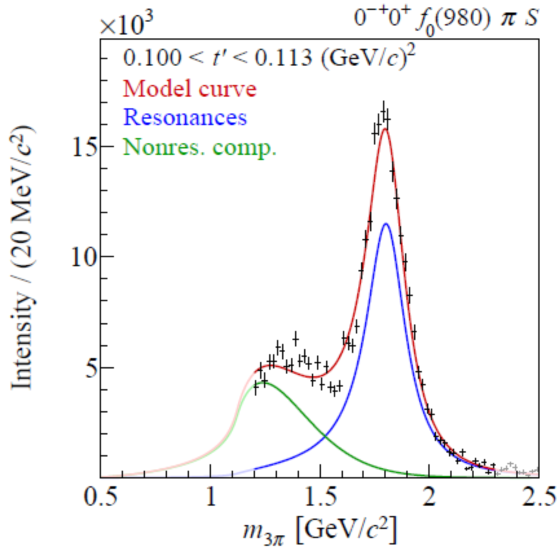
Partial wave	Relative intensity	Resonances	Nonresonant component Eq.	$m_{3\pi}$ fit range [GeV/c^2]
$0^{-+}0^+ f_0(980)\pi S$	2.4 %	$\pi(1800)$	(29)	1.20 to 2.30
$1^{++}0^+ \rho(770)\pi S$	32.7 %	$a_1(1260)$ [Eq. (24)], $a_1(1640)$	(27)	0.90 to 2.30
$1^{++}0^+ f_0(980)\pi P$	0.3 %	$a_1(1420)$	(29)	1.30 to 1.60
$1^{++}0^+ f_2(1270)\pi P$	0.4 %	$a_1(1260)$ [Eq. (24)], $a_1(1640)$	(29)	1.40 to 2.10
$1^{-+}1^+ \rho(770)\pi P$	0.8 %	$\pi_1(1600)$	(27)	0.90 to 2.00
$2^{++}1^+ \rho(770)\pi D$	7.7 %	$a_2(1320)$ [Eq. (25)], $a_2(1700)$	(27)	0.90 to 2.00
$2^{++}2^+ \rho(770)\pi D$	0.3 %		(29)	1.00 to 2.00
$2^{++}1^+ f_2(1270)\pi P$	0.5 %		(29)	1.00 to 2.00
$2^{-+}0^+ \rho(770)\pi F$	2.2 %	$\pi_2(1670)$, $\pi_2(1880)$, $\pi_2(2005)$	(27)	1.20 to 2.10
$2^{-+}0^+ f_2(1270)\pi S$	6.7 %		(27)	1.40 to 2.30
$2^{-+}1^+ f_2(1270)\pi S$	0.9 %		(29)	1.40 to 2.30
$2^{-+}0^+ f_2(1270)\pi D$	0.9 %		(29)	1.60 to 2.30
$4^{++}1^+ \rho(770)\pi G$	0.8 %	$a_4(2040)$	(29)	1.25 to 2.30
$4^{++}1^+ f_2(1270)\pi F$	0.2 %		(29)	1.40 to 2.30
Intensity sum	56.8 %			

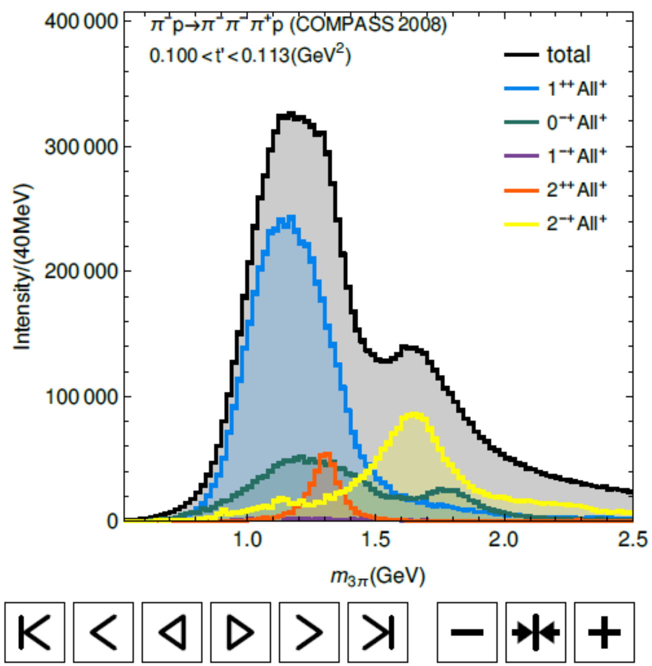
Interpretation of the partial waves

[arXiv:1802.05913]

Fit of the resonance parameters







Fit model

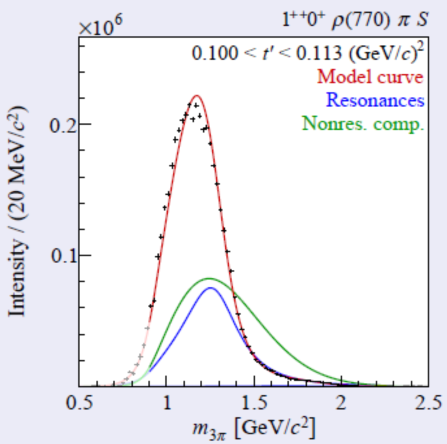
- Signal(BW) and Background ($p^L e^{-p}$)
  $T(m_{3\pi}, t') = c(t')\text{BW}(m_{3\pi}) + \text{BG}(m_{3\pi}, t')$
- The main big fit:
  - 14 interfering waves $\times$ 11 t'-slices simultaneously.
  - 722 parameters, 76500 data points.

Mass and width of the resonances

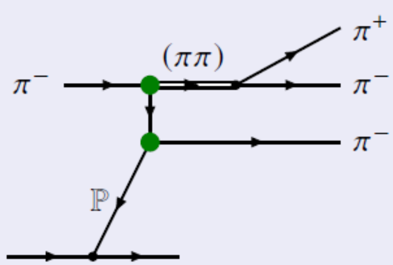
[arXiv:1802.05913]

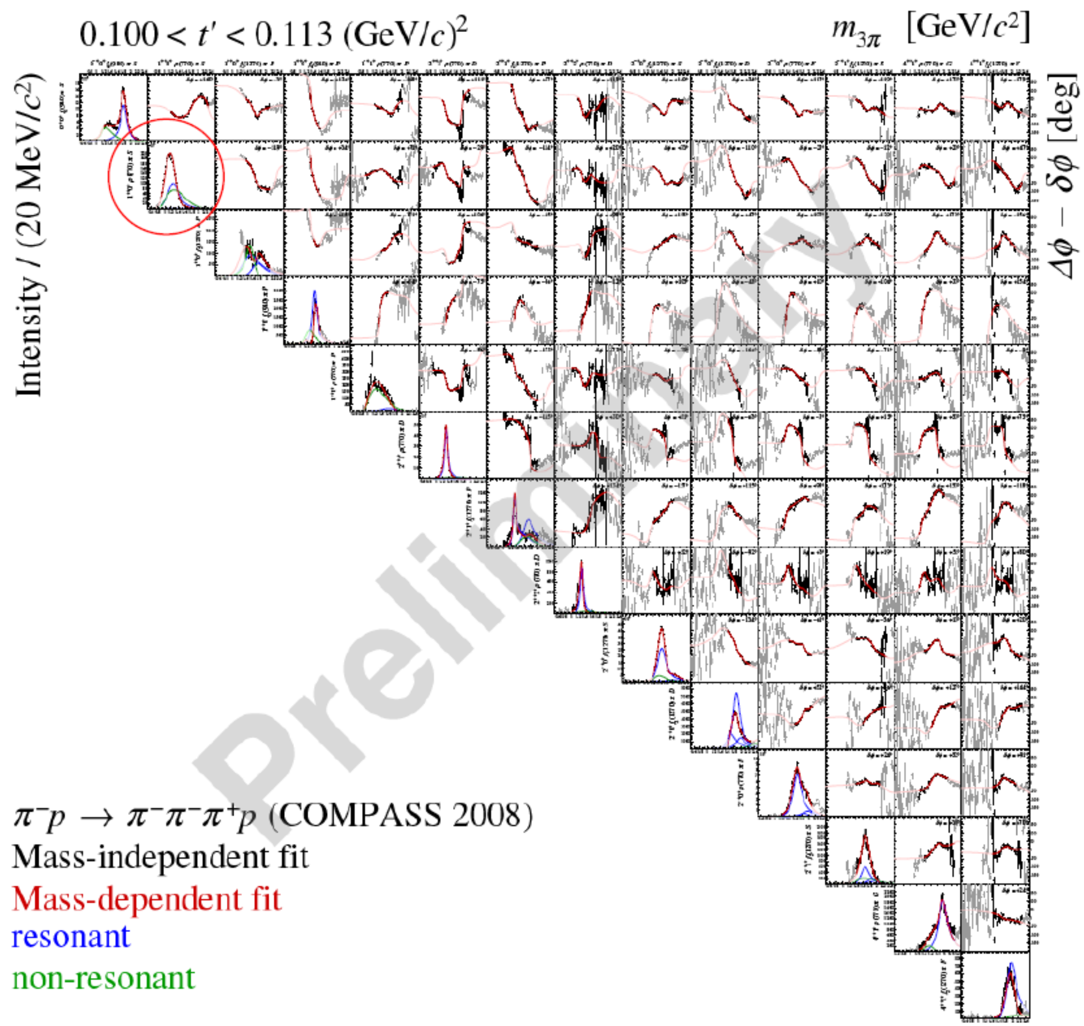
The main mass-dependent fit

Axial vector 1^{++}



- Non-resonant background





$\pi^- p \to \pi^-\pi^-\pi^+ p$ (COMPASS 2008)

Mass-independent fit

Mass-dependent fit

resonant

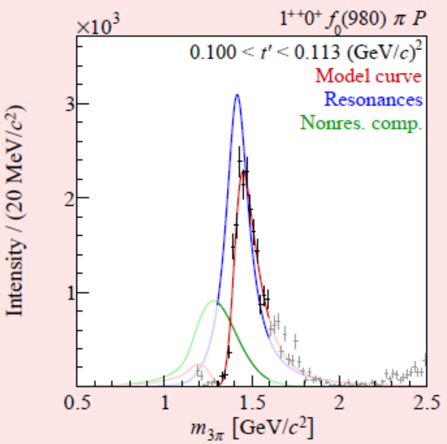
non-resonant

Mass and width of the resonances

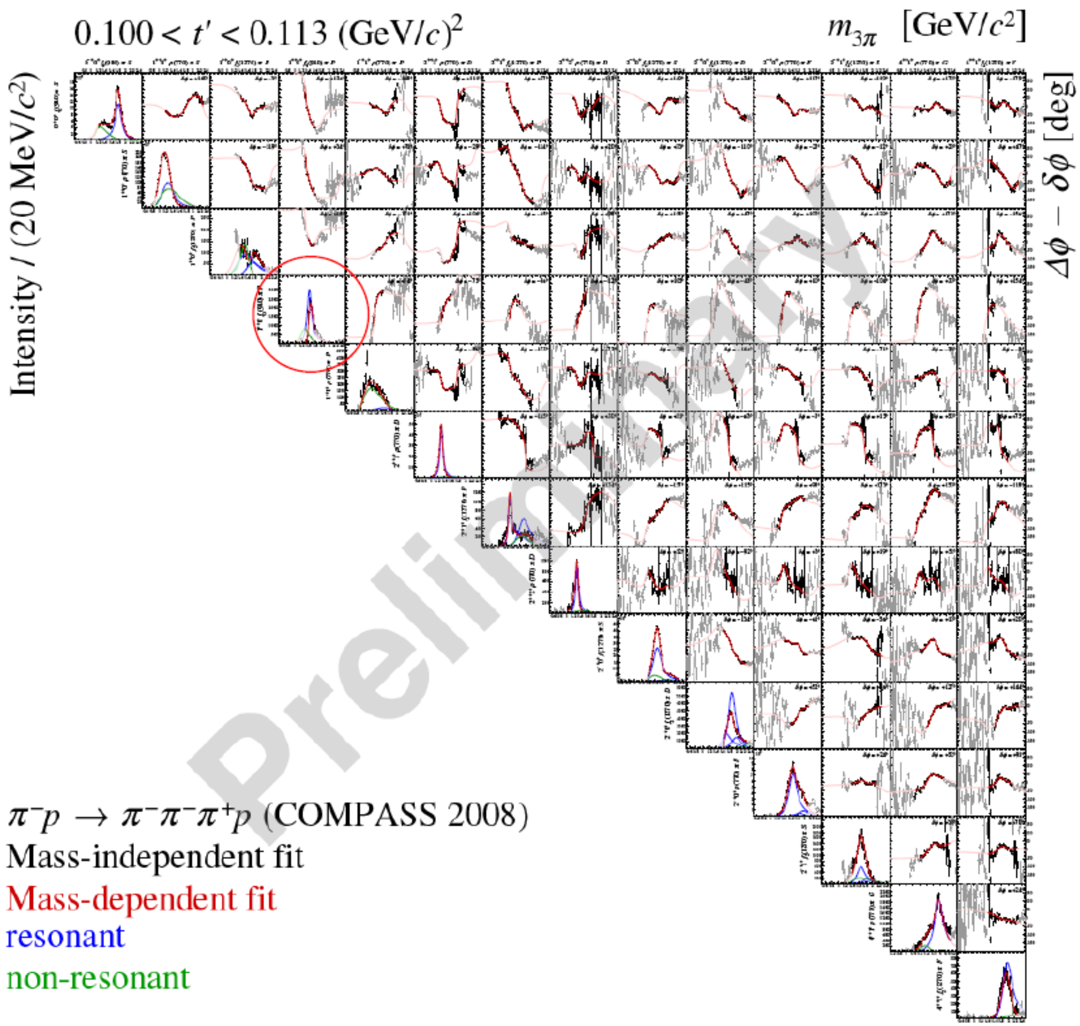
[arXiv:1802.05913]

The main mass-dependent fit

Axial “?” 1^{++}



- Exotic candidate!



$\pi^- p \to \pi^-\pi^-\pi^+ p$ (COMPASS 2008)

Mass-independent fit

Mass-dependent fit

resonant

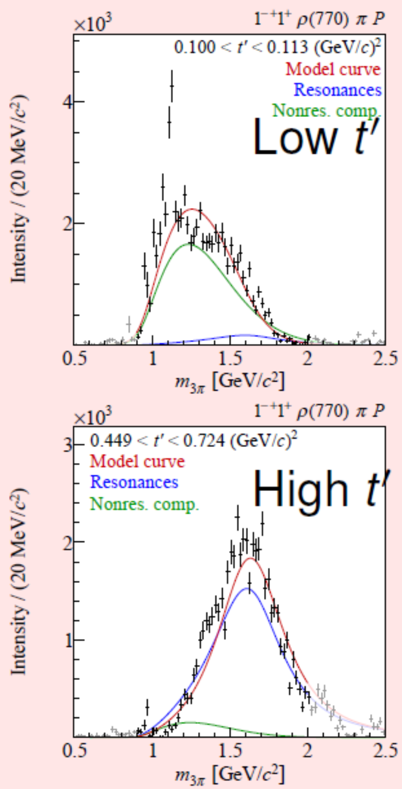
non-resonant

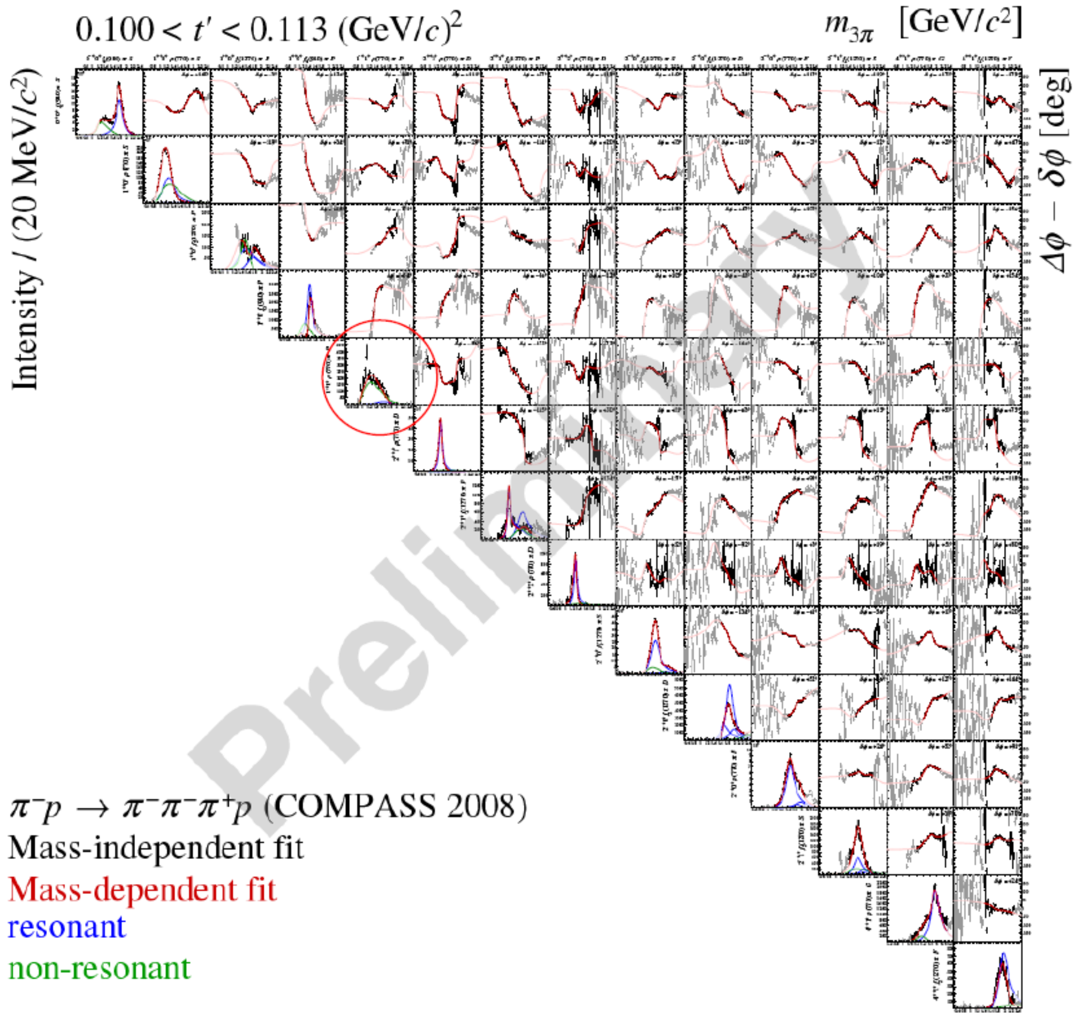
Mass and width of the resonances

[arXiv:1802.05913]

The main mass-dependent fit

Non-$q\bar{q}$ 1^{-+}



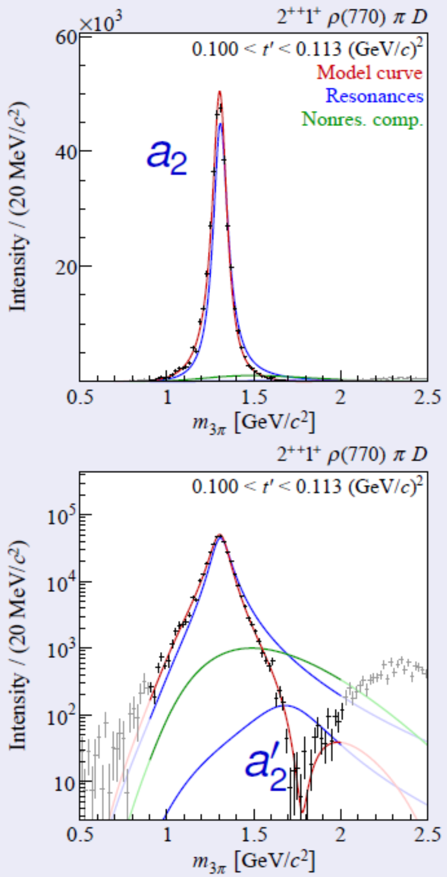


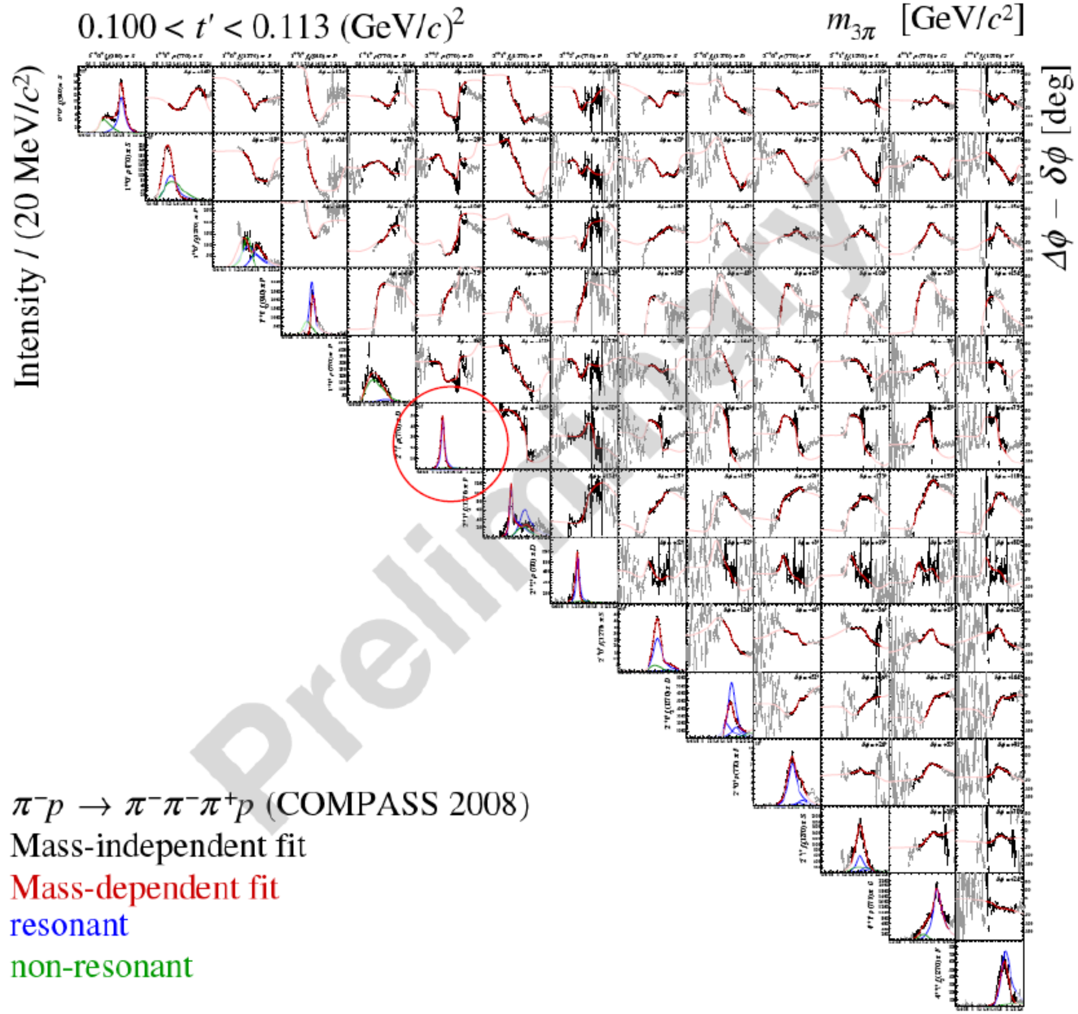
Mass and width of the resonances

[arXiv:1802.05913]

The main mass-dependent fit

Tensors 2^{++}



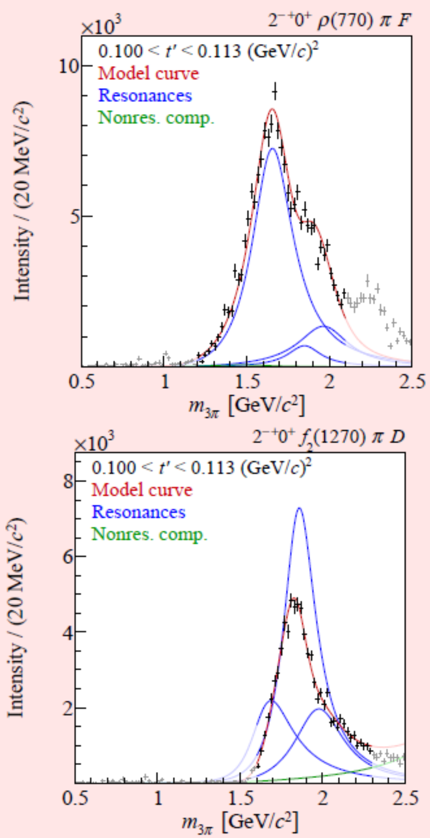


Mass and width of the resonances

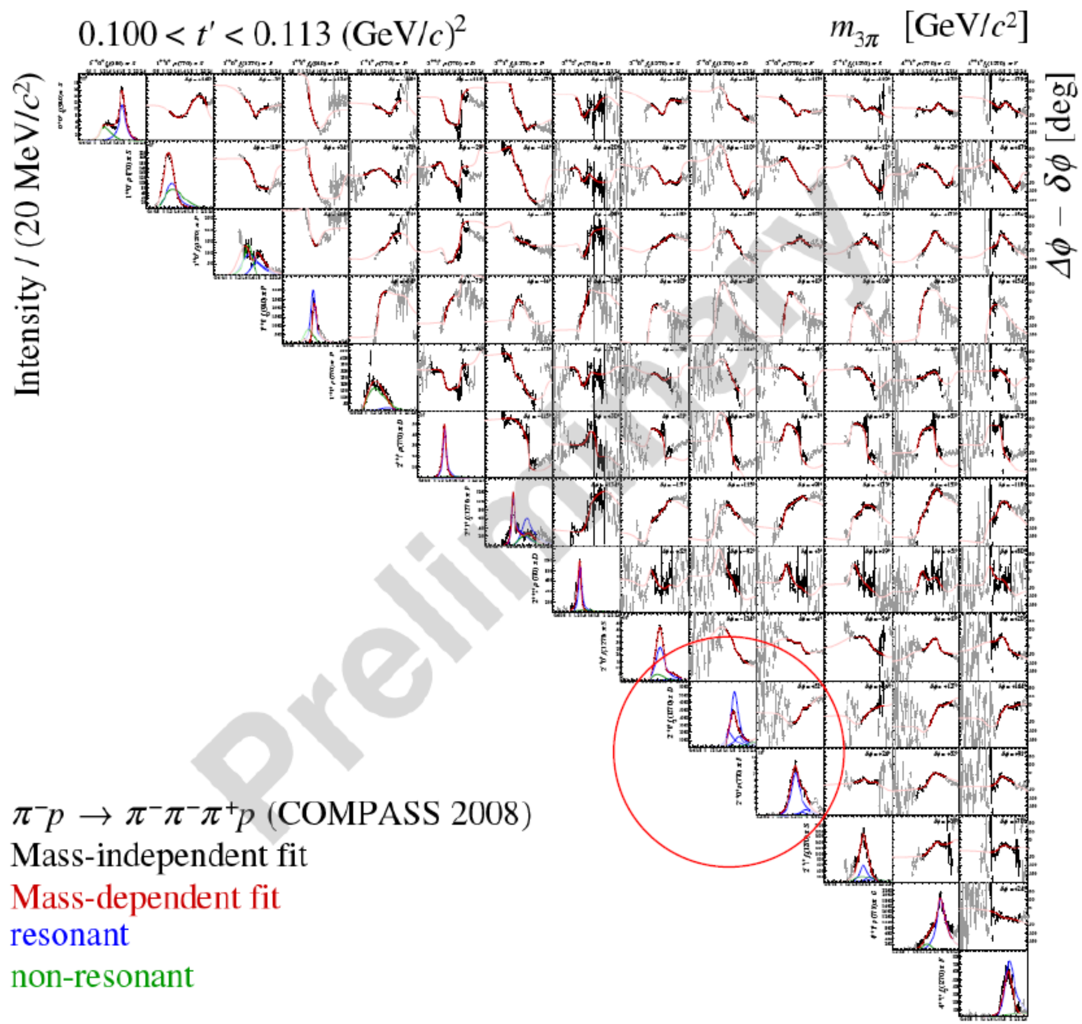
[arXiv:1802.05913]

The main mass-dependent fit

Axial tensors 2^{-+}



- three resonances!

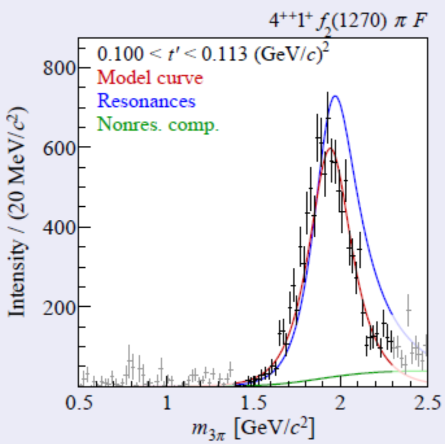


Mass and width of the resonances

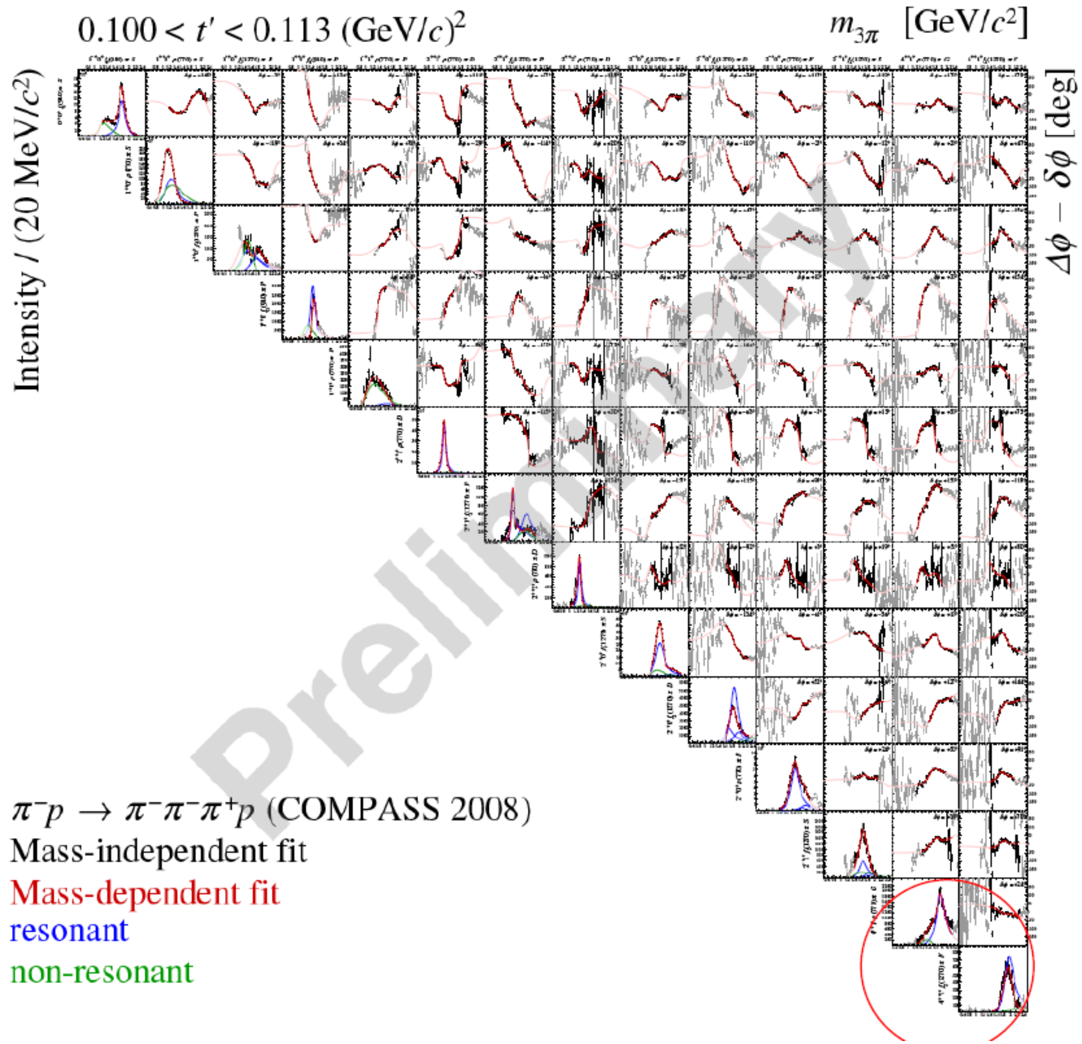
[arXiv:1802.05913]

The main mass-dependent fit

Spin-4 4^{++}



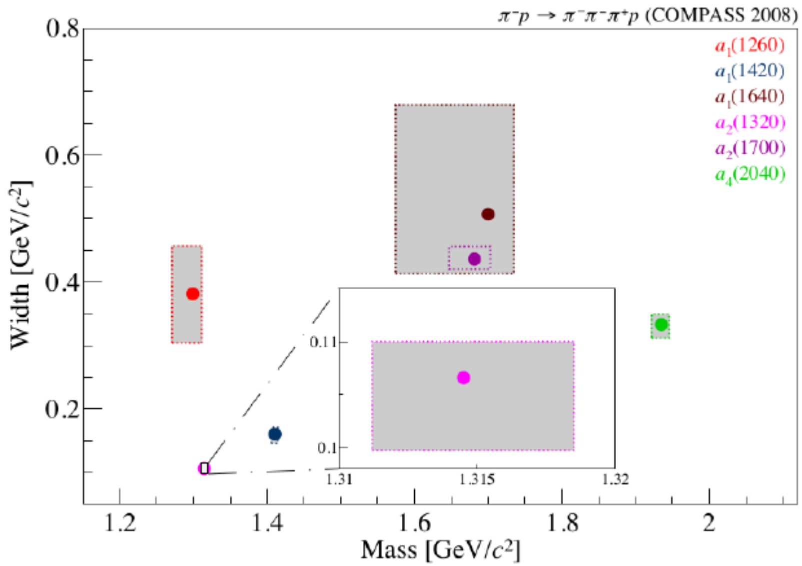
- Clean signal of the high spin state



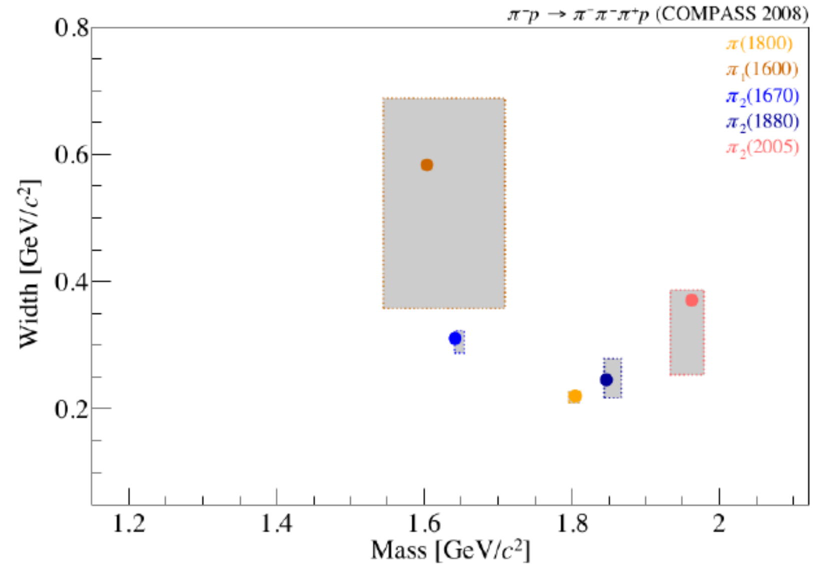
Resonance parameters

The most precise measurement of the Breit-Wigner parameters

a_n resonances



π_n resonances



- Dots show the value in the main fit
- Gray boxes indicate systematic uncertainty
  - Omitting waves
  - Modification of resonance models
  - Variation of the non-resonance parameters
  - Modification of the χ^2 function (partially including correlations)

Future Plan

- Short-term future 2021/22
  (addendum to the COMPASS-II proposal)
  - complete the COMPASS transverse spin program:
    one year of running with transversely polarised deuteron target
  - Proton radius with high-energetic muon beam
- Longer-term future: a new proposal for a multi-purpose setup >2025
  - radiofrequency-separated kaon beam for strange-meson spectroscopy, kaon- and antiproton-induced Drell-Yan, kaon-photon reactions
  - DVCS with muon beam on polarised target with recoil detection
  - measurements with antiproton beams: spectroscopy, cross sections
  - Letter of Intent is currently being drafted and discussed within the "Physics beyond colliders" initiative of the "European Strategy for Particle Physics" https://arxiv.org/abs/1808.00848

Summary

- Proton is a fundamental particle composed of quarks interacting with an exchange of gluons.
- Through the DIS and Drell-Yan processes, COMPASS experiment try to extend our understanding of proton's substructure from 1d to multi-dimensional.