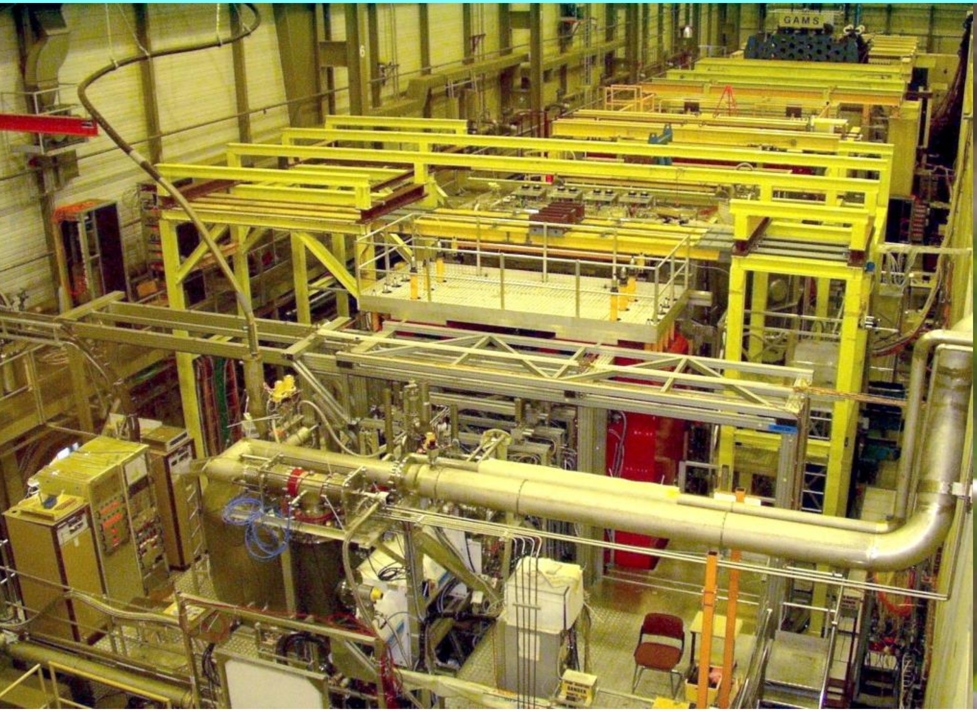
Gluons, Quarks and the Structure of the Proton



Honoring Gerhard Mallot and his Leadership & Scientific Work at CERN

M. Grosse Perdekamp, University of Illinois

Overview

- The Atomic Hypothesis and COMPASS

  Experimental study of Democritus' Hypothesis …

- Quark and Gluon Structure of the Proton

  Momentum distributions
  Spin distributions

- Large Gluon Densities and Saturation

  Studying nuclear gluon densities at low x

Richard Feynman on the Atomic Hypothesis

Feynman Lectures, Volume I; Lecture 1, "Atoms in Motion"; Section 1-2, "Matter is made of atoms"; p. 1-2

If, in some cataclysm, all of scientific knowledge were to be destroyed, and only one sentence passed on to the next generation of creatures, what statement would contain the most information in the fewest words?

I believe it is the *atomic hypothesis* that *all things are made of atoms — little particles that move around in perpetual motion, attracting each other when they are a little distance apart, but repelling upon being squeezed into one another.*

In that one sentence, you will see, there is an *enormous* amount of information about the world, if just a little imagination and thinking are applied.

From an Ancient Hypothesis to Modern Science
How do Atoms form Complex Matter?

First ideas by Greek philosophers:

Leucippus and Democritus formulated the atomic hypothesis:

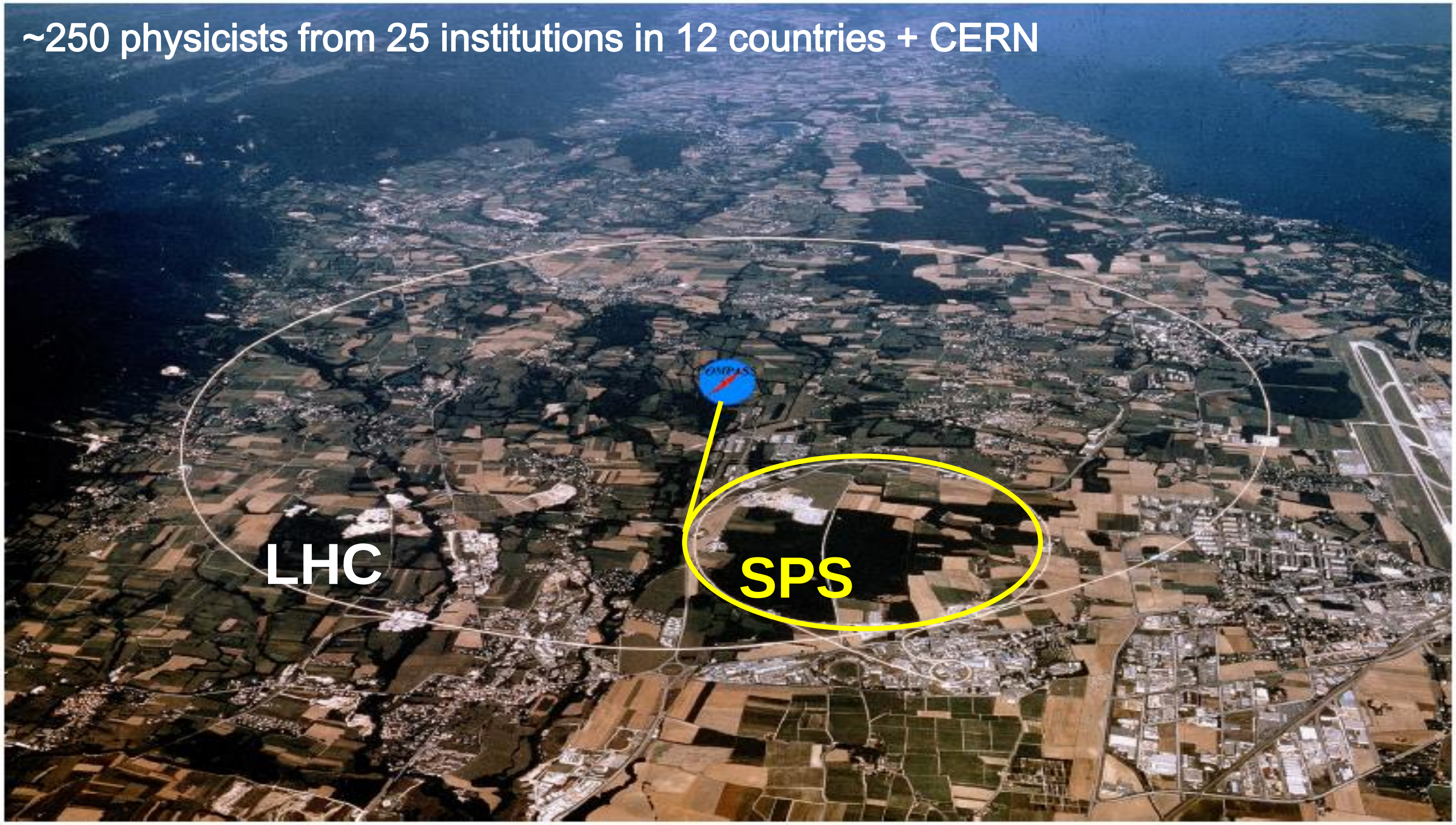
There are small particles, atoms, of which all matter is made and which cannot be divided in smaller parts.

After 80 generations, some 2400 years later:

Our experimental tools may have identified the atoms of nature and lead us to quantitative answers how these form the complex visible matter observed in nature!

COMPASS at the CERN SPS

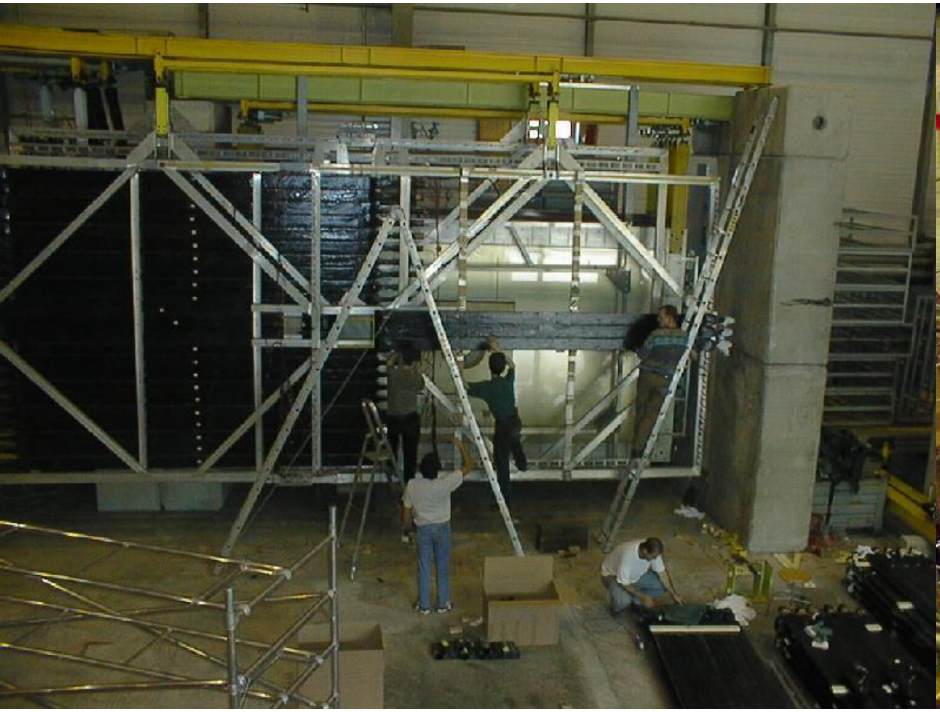
COmmon Muon Proton Apparatus for Structure and Spectroscopy

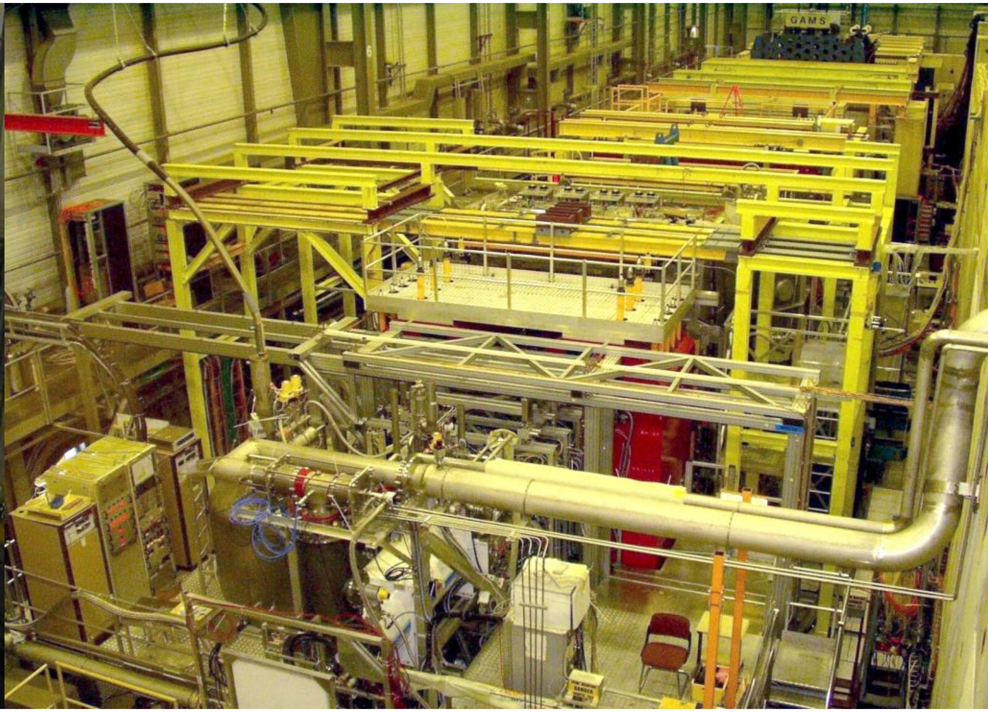


Deep Inelastic Scattering with Muons at CERN: EMC, BCDMS, NMC, SMC and COMPASS

August 1998:
Disassembling SMC Trigger Hodoscopes
for Re-configuration for COMPASS at Mainz

➔ partially used in COMPASS Detector





COMPASS at the CERN SPS

COmmon Muon Proton Apparatus for Structure and Spectroscopy

Physics Program:

Hadron Spectroscopy (p-, π-, K-beams)

- Light mesons, glue-balls, exotic mesons
- Polarisability of the pion and kaon

Nucleon Structure (μ-beam in DIS and SIDS and DY with π-beams)

- Longitudinal spin structure
- Transverse momentum and transverse spin structure
- GPDs

Leadership in COMPASS: Herding Physicists with Wide Ranging Interests!

COMPASS – Instrumentation Features

Two staged large acceptance spectrometers with high rate capability:

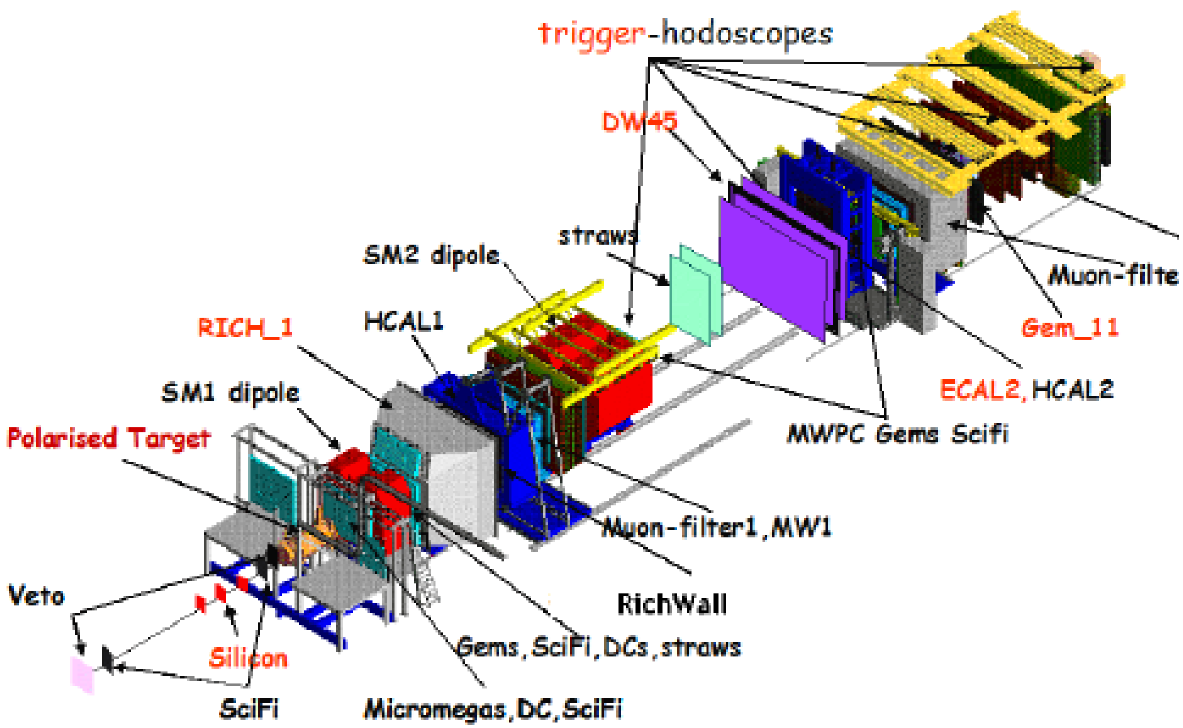
1. Large Angle Spectrometer (LAS)
2. Small Angle Spectrometer (SAS)

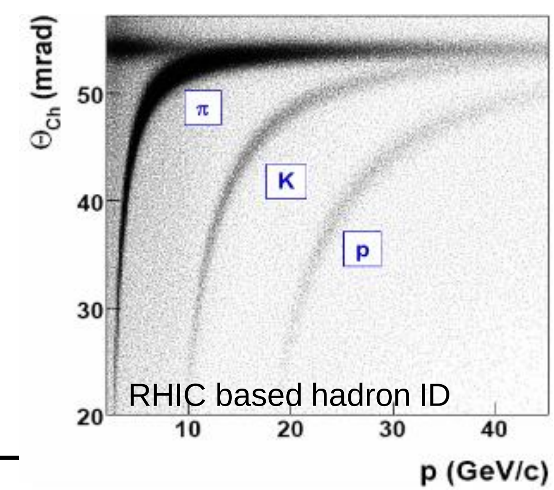
1.Muon, electron or hadron secondary beams with momenta from 20 to 250 GeV and intensities up to 10^8 particles per second.

2. Solid state polarised targets, NH_3 or ^6LiD, as well as lq H_2 target and nuclear targets.

3.Powerful tracking system – 350 planes.

4. Versatile PID – RICH, Muon Walls, Calorimeters.

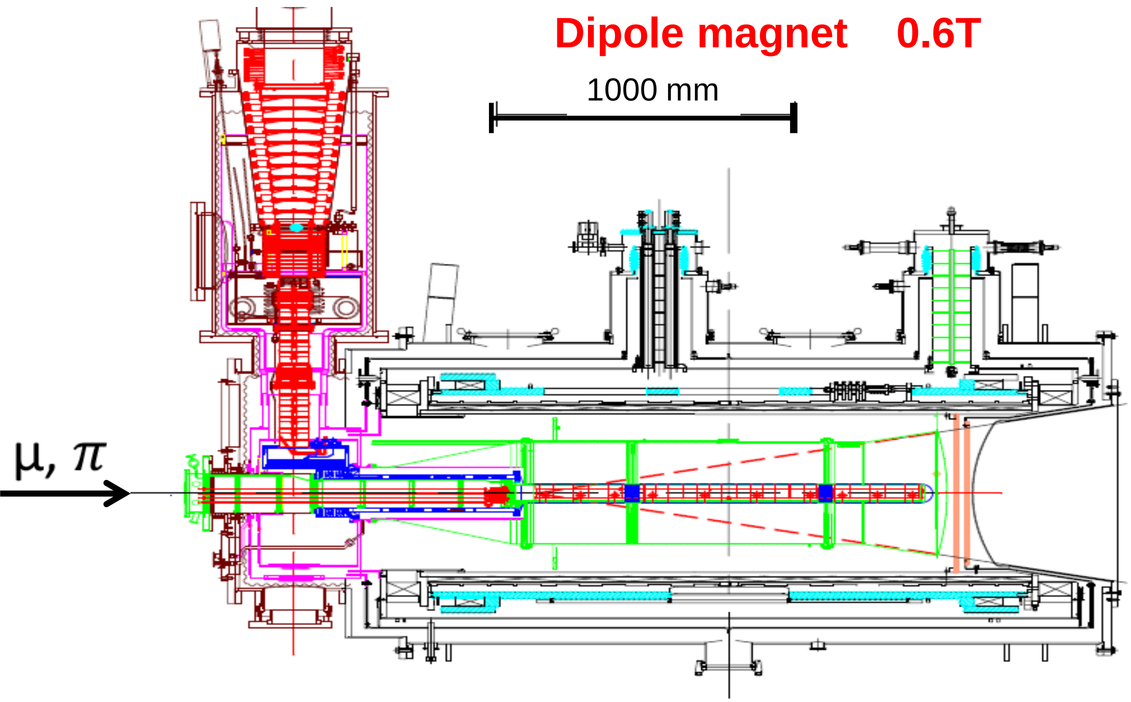




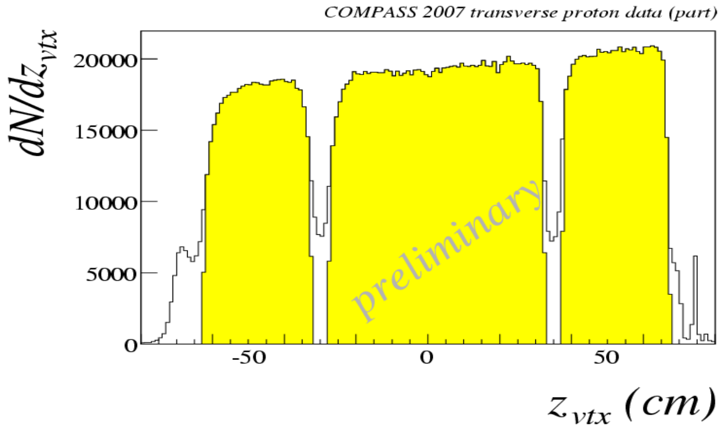
Instrumentation Features
Polarised Target

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

Solenoid 2.5T
Dipole magnet 0.6T



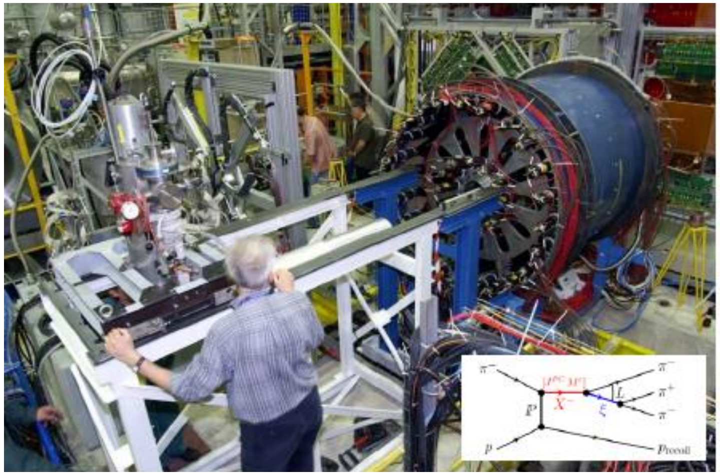
Vertex distribution for SIDIS



Opposite polarization in different target segments reversed frequently

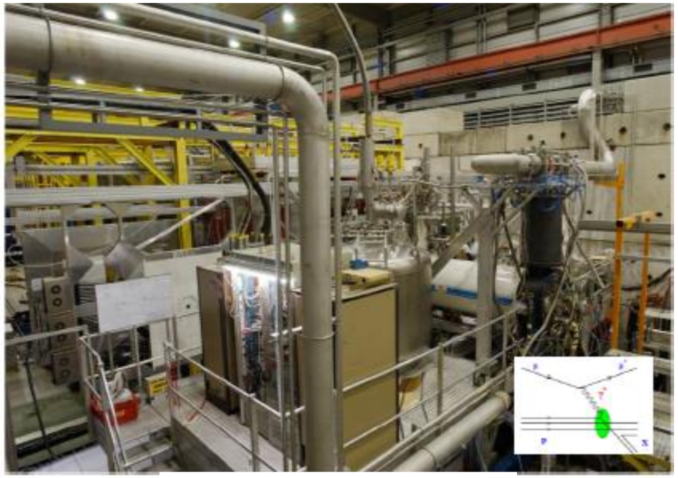
	d (^6LiD)	p (NH_3)
Polarization	**50%**	**90%**
Dilution factor	**40%**	**16%**

Versatile Apparatus - Expertise from Leading Instrumentation Groups in Europe and CERN



Hadron Spectroscopy & Polarisability

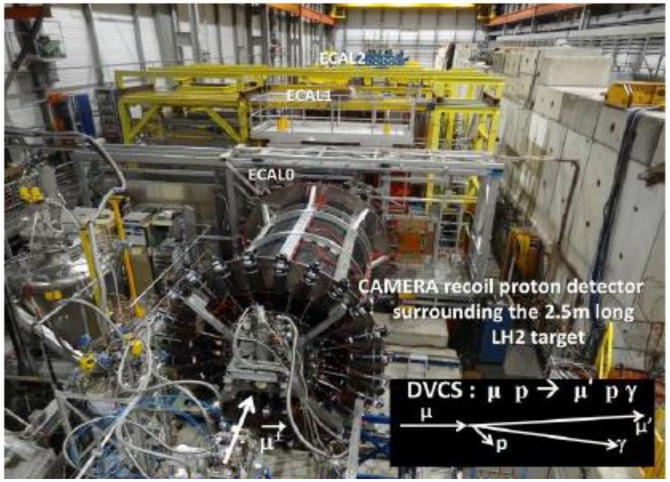
COMPASS-I 1997-2012



Polarised SIDIS

Polarised Drell-Yan

COMPASS-II 2012-2018



DVCS (GPDs) & unpolarised SIDIS

COMPASS I+II Data Sets studied and analyzed in

65 Diplom/Master - , 118 Ph.D. - and 6 Habilitation Theses

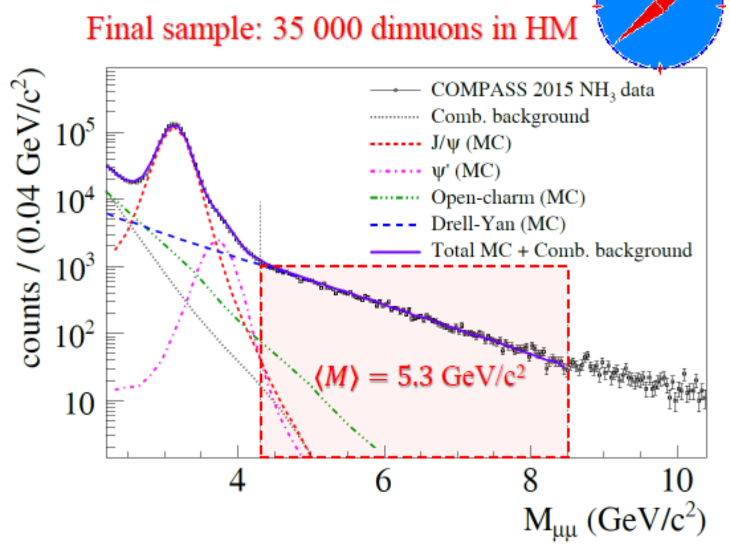
http://wwwcompass.cern.ch/compass/publications/theses

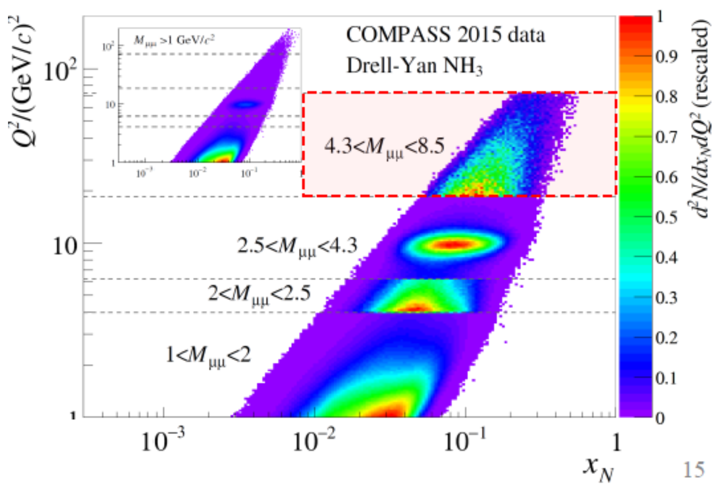
2002	Nucleon structure with	160 GeV μ	**L&T**	polarised **deuteron** target
2003	Nucleon structure with	160 GeV μ	**L&T**	polarised **deuteron** target
2004	Nucleon structure with	160 GeV μ	**L&T**	polarised **deuteron** target
2005	*CERN accelerators shut down*			
2006	Nucleon structure with	160 GeV μ	**L**	polarised **deuteron** target
2007	Nucleon structure with	160 GeV μ	**L&T**	polarised **proton** target
2008	Hadron spectroscopy			
2009	Hadron spectroscopy			
2010	Nucleon structure with	160 GeV μ	**T**	polarised **proton** target
2011	Nucleon structure with	190 GeV μ	**L**	polarised **proton** target
2012	Primakoff & DVCS / SIDIS test			
2013	*CERN accelerators shut down*			
2014	Test beam Drell-Yan process with π beam and T polarised proton target			
2015	Drell-Yan process with π beam and T polarised proton target			
2016	DVCS / SIDIS with μ beam and unpolarised proton target			
2017	DVCS / SIDIS with μ beam and unpolarised proton target			
2018	Drell-Yan process with π beam and T polarised proton target			

I (2002–2007, 2008–2012)

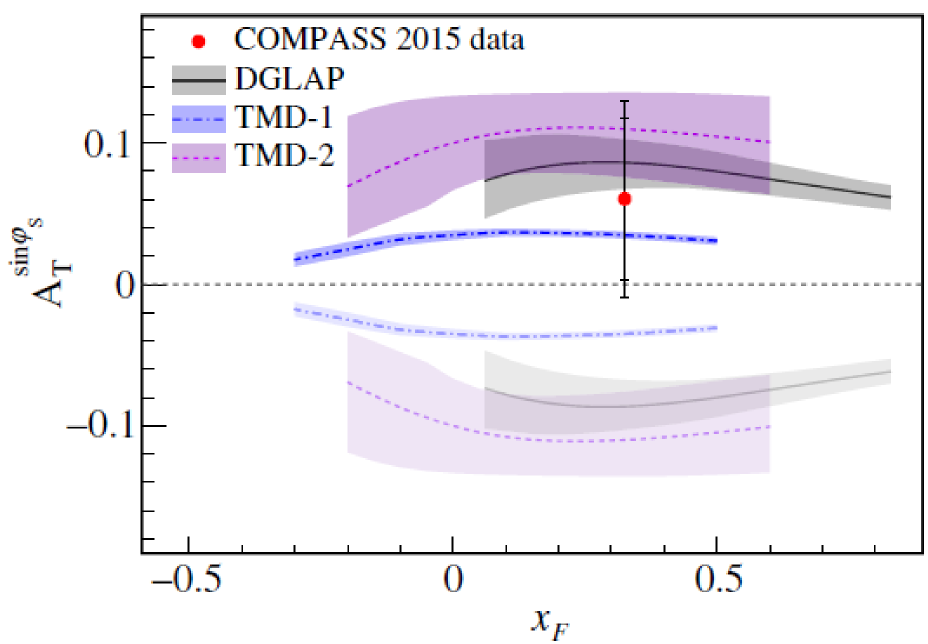
II (2015–2018)

UIUC Analysis: Measurement of Sivers Asymmetries in Drell-Yan



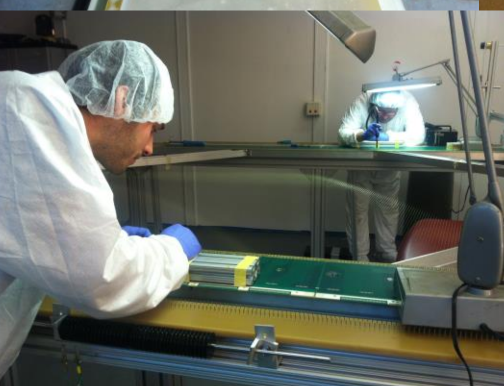


PRL 119, 112002 (2017)



COMPASS Related Instrumentation Opportunities for Student Training at UIUC → DC5

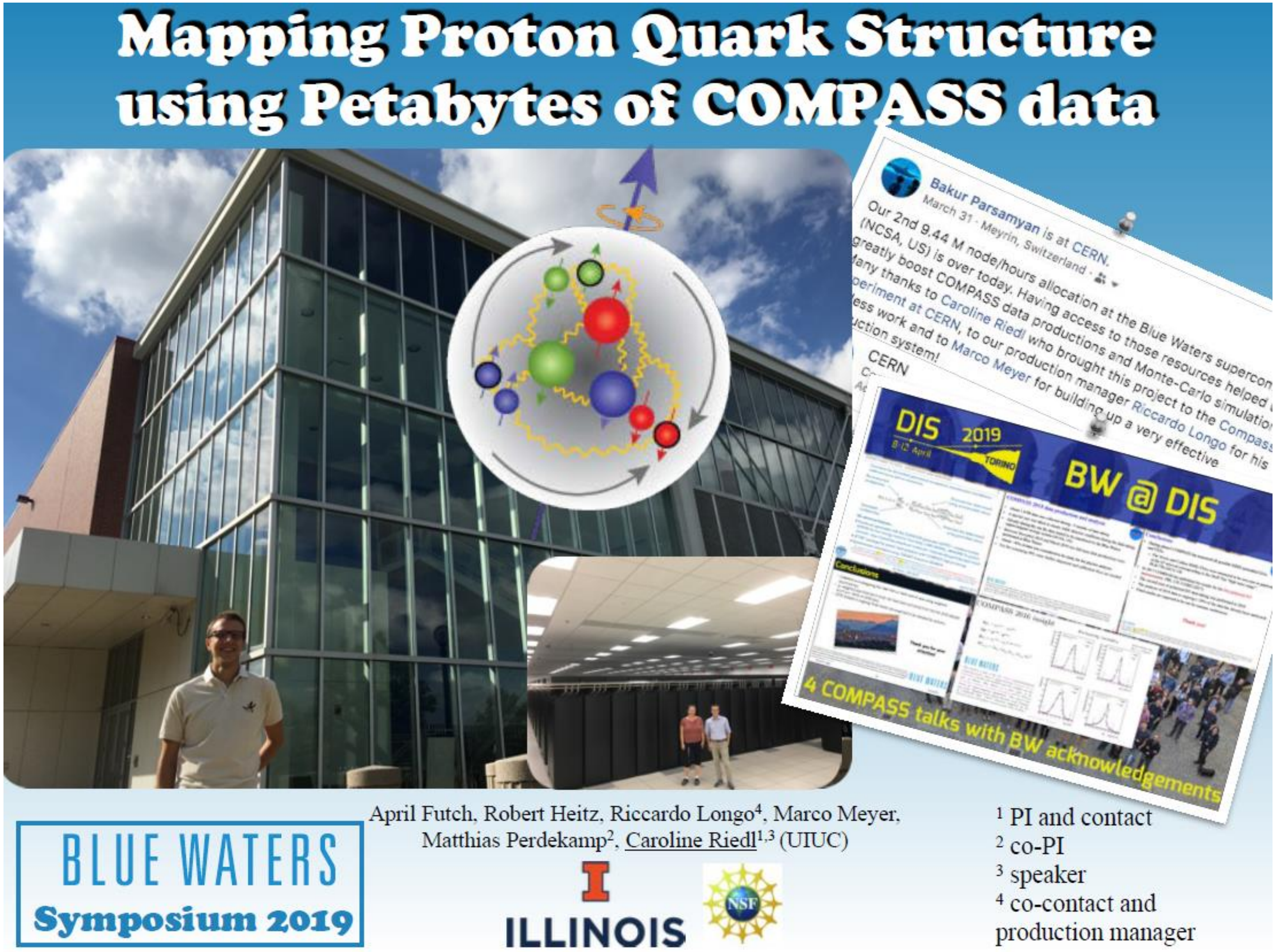






COMPASS Related Computing Opportunities for Student Training at UIUC → Blue Waters



Spin Dependent Gluon Structure of the Proton

with COMPASS

1) First measurement of the Sivers asymmetry for gluons using SIDIS data
Phys.Lett. B772 (2017) 854-864
2) Leading-order determination of the gluon polarisation from semi-inclusive deep inelastic scattering data
Eur.Phys.J. C77 (2017) no.4, 209
3) Leading and Next-to-Leading Order Gluon Polarization in the Nucleon and Longitudinal Double Spin Asymmetries from Open Charm Muoproduction
Phys.Rev. *D87 (2013) no.5, 052018*
4) Leading order determination of the gluon polarisation from DIS events with high-$p_T p_T$ hadron pairs
Phys.Lett. B718 (2013) 922-930
5) Gluon polarisation in the nucleon and longitudinal double spin asymmetries from open charm muoproduction *Phys.Lett. B676 (2009) 31-38*
6) Gluon polarization in the nucleon from quasi-real photoproduction of high-p_T hadron pairs
Phys.Lett. B633 (2006) 25-32
7) Spin asymmetries for events with high p_T hadrons in DIS and an evaluation of the gluon polarization *Phys.Rev. D70 (2004) 012002*
8) Round table on future measurements of the polarized gluon distribution in the nucleon
V.W. Hughes, S. Forte, J.C. Collins, A. De Roeck, A. Deshpande, G. Mallot, R. Arnold, G. Bunce, W.D. Nowak, E. Hughes. *SLAC-REPRINT-1996-050*

Spin Dependent Gluon Structure of the Proton

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Leading-order determination of the gluon polarisation from semi-inclusive deep inelastic scattering data
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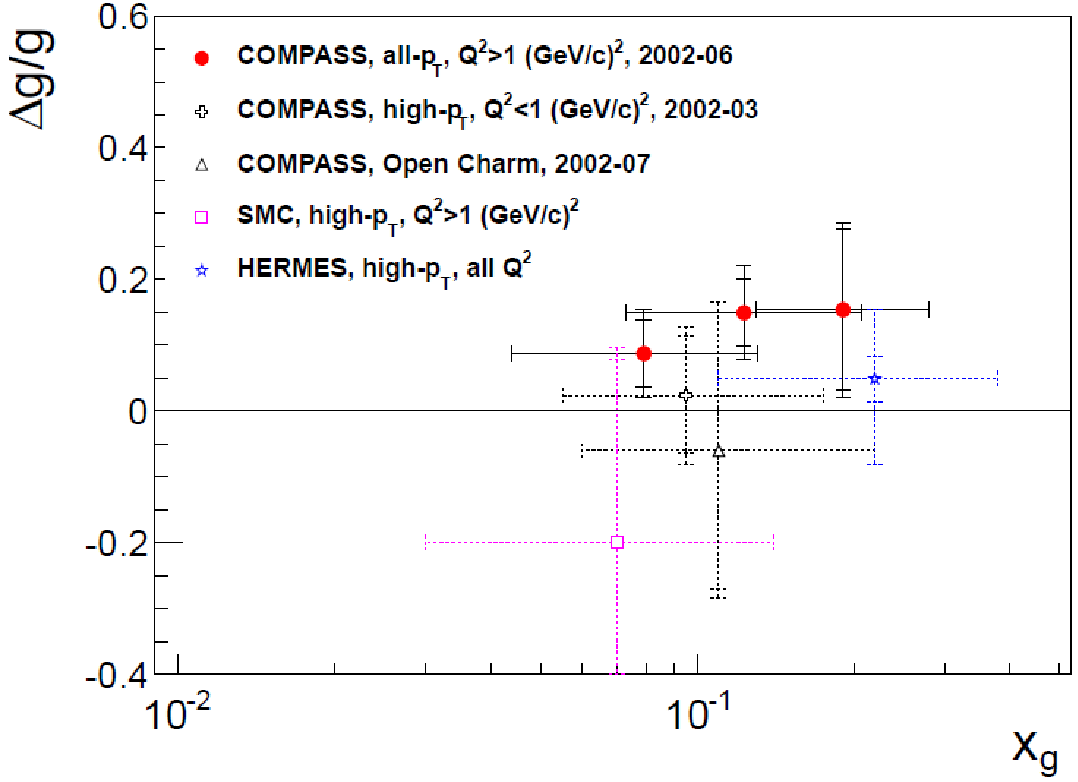

Gluon Structure of the Proton

with NMC

1) Quark and gluon distributions and alpha-s from nucleon structure functions at low X
Phys.Lett. B309 (1993) 222-230

2) Inelastic J/ψ production in deep inelastic scattering from hydrogen and deuterium and the gluon distribution of free nucleons
Phys.Lett. B258 (1991) 493-498

Physics Letters B 309 (1993) 222–230
North-Holland

PHYSICS LETTERS B

Quark and gluon distributions and α_s from nucleon structure functions at low x

New Muon Collaboration

Bielefeld University, CERN, Freiburg University, Max Planck Institut für Kernphysik, Heidelberg, Heidelberg University, Mainz University, Mons University, Neuchatel University, NIKHEF-K, Saclay DAPNIA/SPP, University of California, Santa Cruz, Paul Scherrer Institute, Torino University and INFN Torino, Uppsala University, Soltan Institute for Nuclear Studies, Warsaw, Warsaw University

M Arneodo[m,1], A Arvidson[n], B Badelek[p], M Ballintijn[i], G Baum[a], J Beaufays[i,2], I G Bird[i,3], P Bjorkholm[n], M Botje[ℓ,4], C Broggini[h,5], W Bruckner[d], A Brull[c], W J Burger[ℓ,6], J Ciborowski[p], R van Dantzig[i], A Dyring[n], H Engelien[c], M I Ferrero[m], L Fluri[h], U Gaul[d], T Granier[j], D von Harrach[d,7], M van der Heijden[i,4], C Heusch[k], Q Ingram[ℓ], K Janson-Prytz[n,8], M de Jong[f], E M Kabuß[d,7], R Kaiser[c], T J Ketel[i], F Klein[f], S Kullander[n], U Landgraf[c], T Lindqvist[n], G K Mallot[f,b], C Mariotti[m,9], G van Middelkoop[i], A Milsztajn[j], Y Mizuno[d,10], J Nassalski[o], D Nowotny[d,11], J Oberski[i], A Paić[h], C Peroni[m], B Povh[d,e], R Rieger[f,12], K Rith[d,13], K Rohrich[f,14], E Rondio[o], L Ropelewski[p,3], A Sandacz[o], D Sanders[15], C Scholz[d], R Schumacher[ℓ,16], R Seitz[f], F Sever[i,17], T -A Shibata[e], M Siebler[a], A Simon[d], A Staiano[m], M Szleper[o], Y Tzamouranis[d,15], M Virchaux[j], J L Vuilleumier[h], T Walcher[f], R Windmolders[g],

NLO QCD Fit to $F_2{}^p$ and F_2d

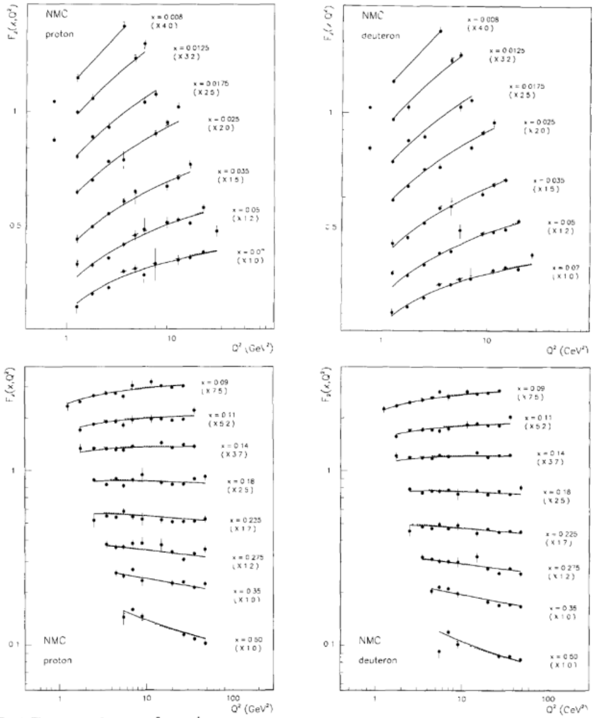

Fig 1 The structure functions F_2^p and F_2^d measured at incident muon energies of 90 and 280 GeV The 90 (280) GeV data are renormalised by 0 993 (1 011) The errors shown are statistical only The solid curves correspond to the result of the QCD fit described in section 3 The dashed curves are the result of the same fit with the higher twist contributions subtracted

Gluon Structure of the Proton

with NMC

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PHYSICS LETTERS B

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NMC – x G(x)

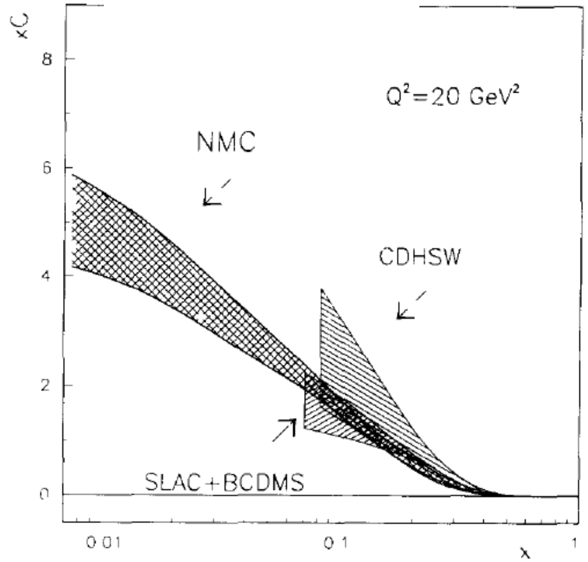
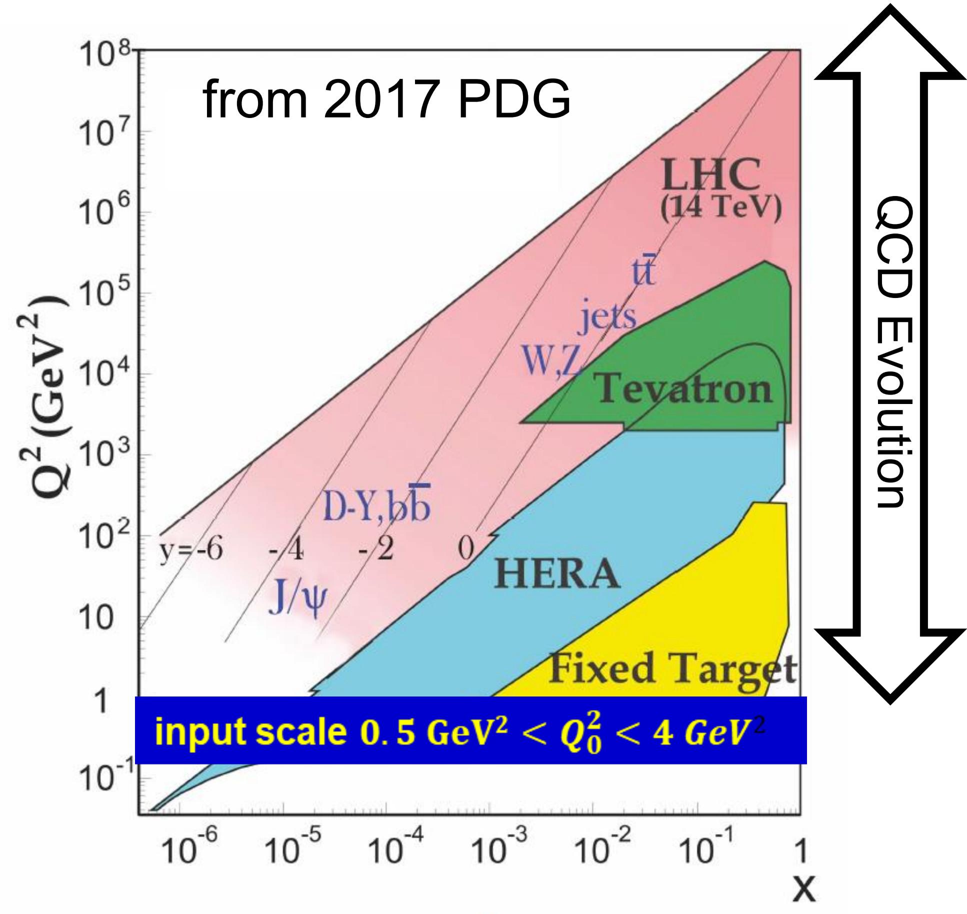


Fig 4 The gluon distribution from this analysis compared to two previous determinations in deep inelastic scattering, from the BCDMS and SLAC hydrogen and deuterium data in NLO [9] and from CDHSW iron data in LO [16]

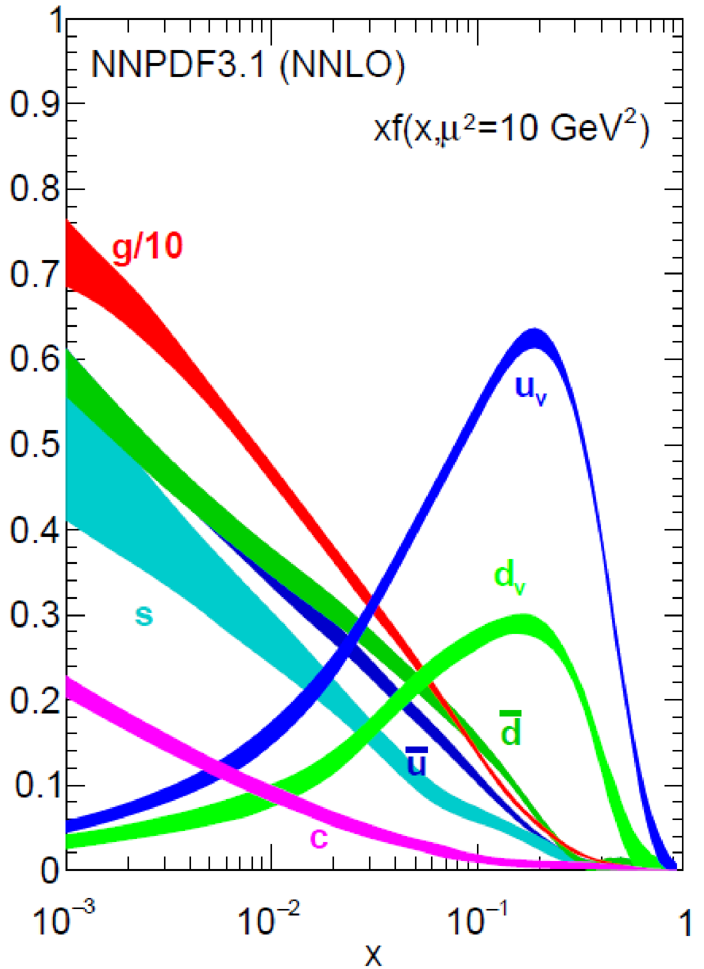
Extraction of Quark and Gluon Momentum Distributions from Modern Hard Scattering Data

- o choose parton distributions, PDFs, at input scale, Q_0^2 :
  $u(x), \bar{u}(x), d(x), \bar{d}(x), s(x), G(x), \ldots$
- o evolve pdfs to Q^2 of experimental data sets using pQCD at LO, NLO or NNLO
- o compute cross section, compare to data, compute χ^2
- o vary PDFs to minimize χ^2



Recent global fits by 6 groups
MNHT, NNPDF, CTEQ, HERA PDF, ABMP, JR

NNPDF Results for Parton Distributions



NNPDF3.1: EPJ C77 (2017) 663

Deep Inelastic Scattering

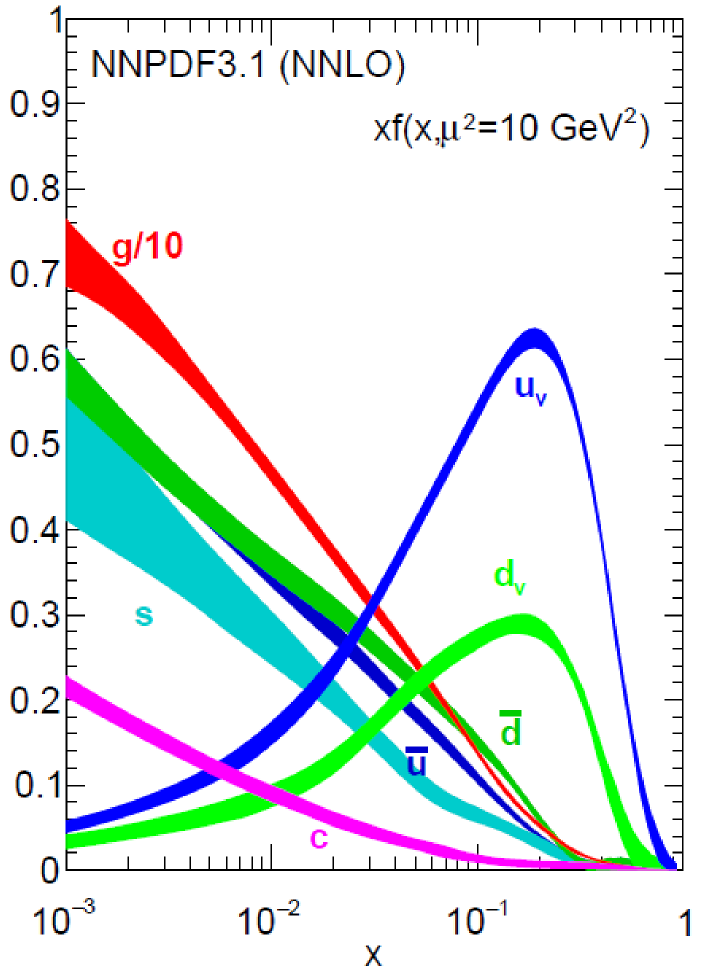
Experiment	Obs.	Ref.	$N_{\rm dat}$
NMC	F_2^d/F_2^p	[28]	260 (121/121)
	$\sigma^{\rm NC,p}$	[29]	292 (204/204)
SLAC	F_2^p	[32]	211 (33/33)
	F_2^d	[32]	211 (34/34)
BCDMS	F_2^p	[30]	351 (333/333)
	F_2^d	[31]	254 (248/248)
CHORUS	$\sigma^{CC,\nu}$	[39]	607 (416/416)
	$\sigma^{CC,\bar\nu}$	[39]	607 (416/416)
NuTeV	σ_ν^{cc}	[40, 41]	45 (39/39)
	$\sigma_{\bar\nu}^{cc}$	[40, 41]	45 (37/37)
HERA	$\sigma^p_{\rm NC,CC}$ (*)	[9]	1306 (1145/1145)
	$\sigma^c_{\rm NC}$	[38]	52 (47/37)
	F_2^b (*)	[67, 68]	29 (29/29)
EMC	[F_2^c] (*)	[69]	21 (16/16)

Tevatron + FNAL fixed target

Exp.	Obs.	Ref.	$N_{\rm dat}$
E866	$\sigma^d_{\rm DY}/\sigma^p_{\rm DY}$	[48]	15 (15/15)
	$\sigma^p_{\rm DY}$	[46, 47]	184 (89/89)
E605	$\sigma^p_{\rm DY}$	[45]	119 (85/85)
CDF	$d\sigma_Z/dy_Z$	[42]	29 (29/29)
	k_t incl jets	[87]	76 (76/76)
D0	$d\sigma_Z/dy_Z$	[43]	28 (28/28)
	W electron asy (*)	[14]	13 (13/8)
	W muon asy (*)	[13]	10 (10/9)

NNPDF Results for Parton Distributions

Precise Collider Data ➔ good sensitivity for PDFs



NNPDF3.1: EPJ C77 (2017) 663

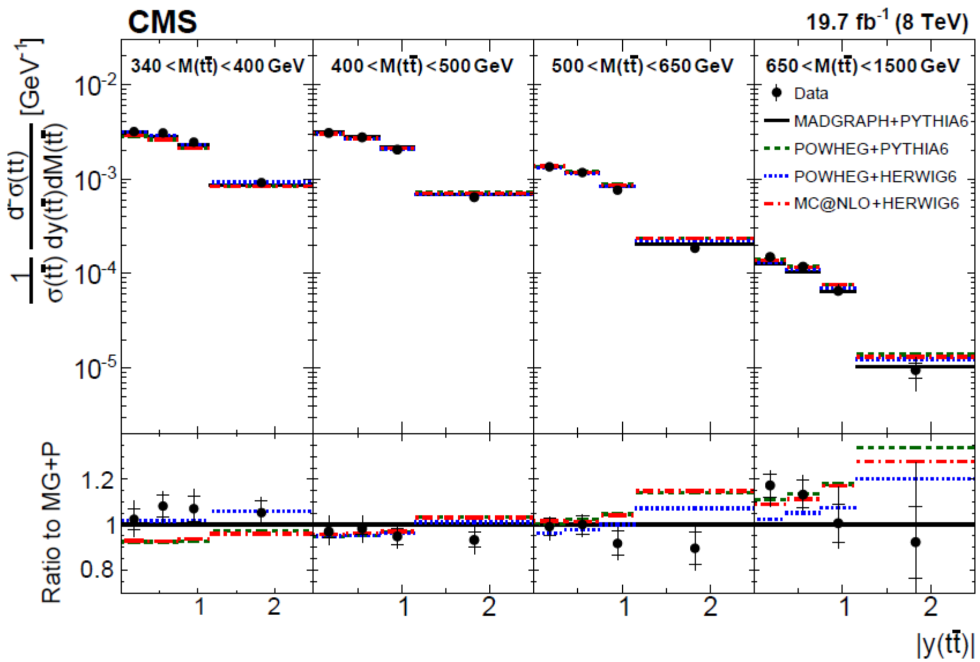
LHC experiments

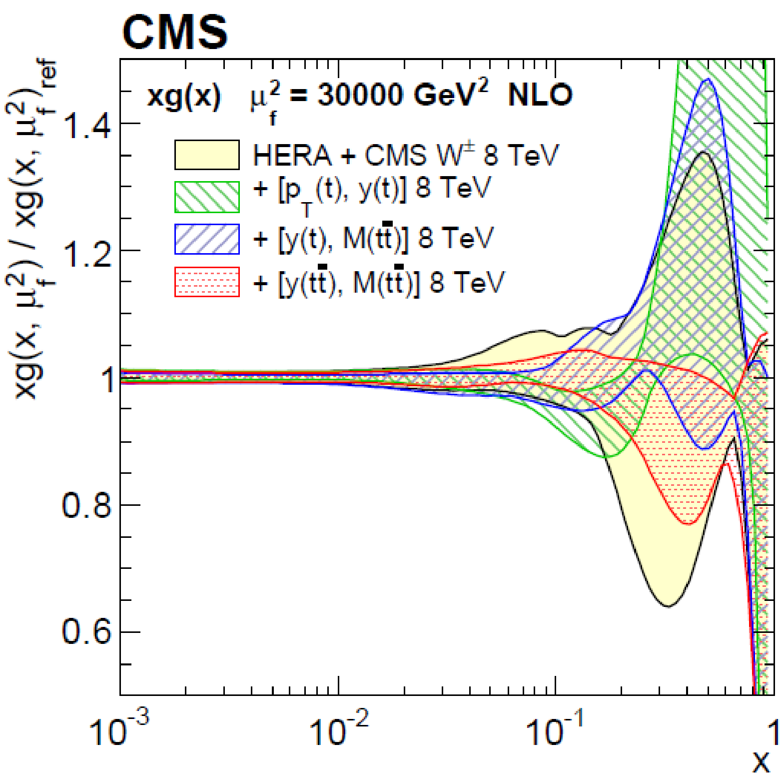
Exp.	Obs.	Ref.	N_{dat}
ATLAS	W, Z 2010	[49]	30 (30/30)
	W, Z 2011 (*)	[72]	34 (34/34)
	high-mass DY 2011	[50]	11 (5/5)
	low-mass DY 2011 (*)	[77]	6 (4/6)
	[Z p_T 7 TeV (p_T^Z, y_Z)] (*)	[78]	64 (39/39)
	Z p_T 8 TeV (p_T^Z, M_{ll}) (*)	[71]	64 (44/44)
	Z p_T 8 TeV (p_T^Z, y_Z) (*)	[71]	120 (48/48)
	7 TeV jets 2010	[57]	90 (90/90)
	2.76 TeV jets	[58]	59 (59/59)
	7 TeV jets 2011 (*)	[76]	140 (31/31)
	$\sigma_{tot}(t\bar{t})$	[74, 75]	3 (3/3)
	$(1/\sigma_{t\bar{t}})d\sigma(t\bar{t})/y_t$ (*)	[73]	10 (10/10)
CMS	W electron asy	[52]	11 (11/11)
	W muon asy	[53]	11 (11/11)
	$W + c$ total	[60]	5 (5/0)
	$W + c$ ratio	[60]	5 (5/0)
	2D DY 2011 7 TeV	[54]	124 (88/110)
	[2D DY 2012 8 TeV]	[84]	124 (108/108)
	$W^{\pm}$ rap 8 TeV (*)	[79]	22 (22/22)
	Z p_T 8 TeV (*)	[83]	50 (28/28)
	7 TeV jets 2011	[59]	133 (133/133)
	2.76 TeV jets (*)	[80]	81 (81/81)
	$\sigma_{tot}(t\bar{t})$	[82, 88]	3 (3/3)
	$(1/\sigma_{t\bar{t}})d\sigma(t\bar{t})/y_{t\bar{t}}$ (*)	[81]	10 (10/10)
LHCb	Z rapidity 940 pb	[55]	9 (9/9)
	$Z \to ee$ rapidity 2 fb	[56]	17 (17/17)
	$W, Z \to \mu$ 7 TeV (*)	[85]	33 (33/29)
	$W, Z \to \mu$ 8 TeV (*)	[86]	34 (34/30)

CMS, EPJ C77 (2017) 459
Double Differential $t\bar{t}$ Production Constrains G(x)

Example: $\frac{1}{\sigma(t\bar{t})}\frac{d^2\sigma(t\bar{t})}{dy(t\bar{t})dM(t\bar{t})}$

Additional cross section in CMS QCD analysis:
$[p_T(t), y(t)], [y(t), M(tt)], [y(tt), M(tt)]$

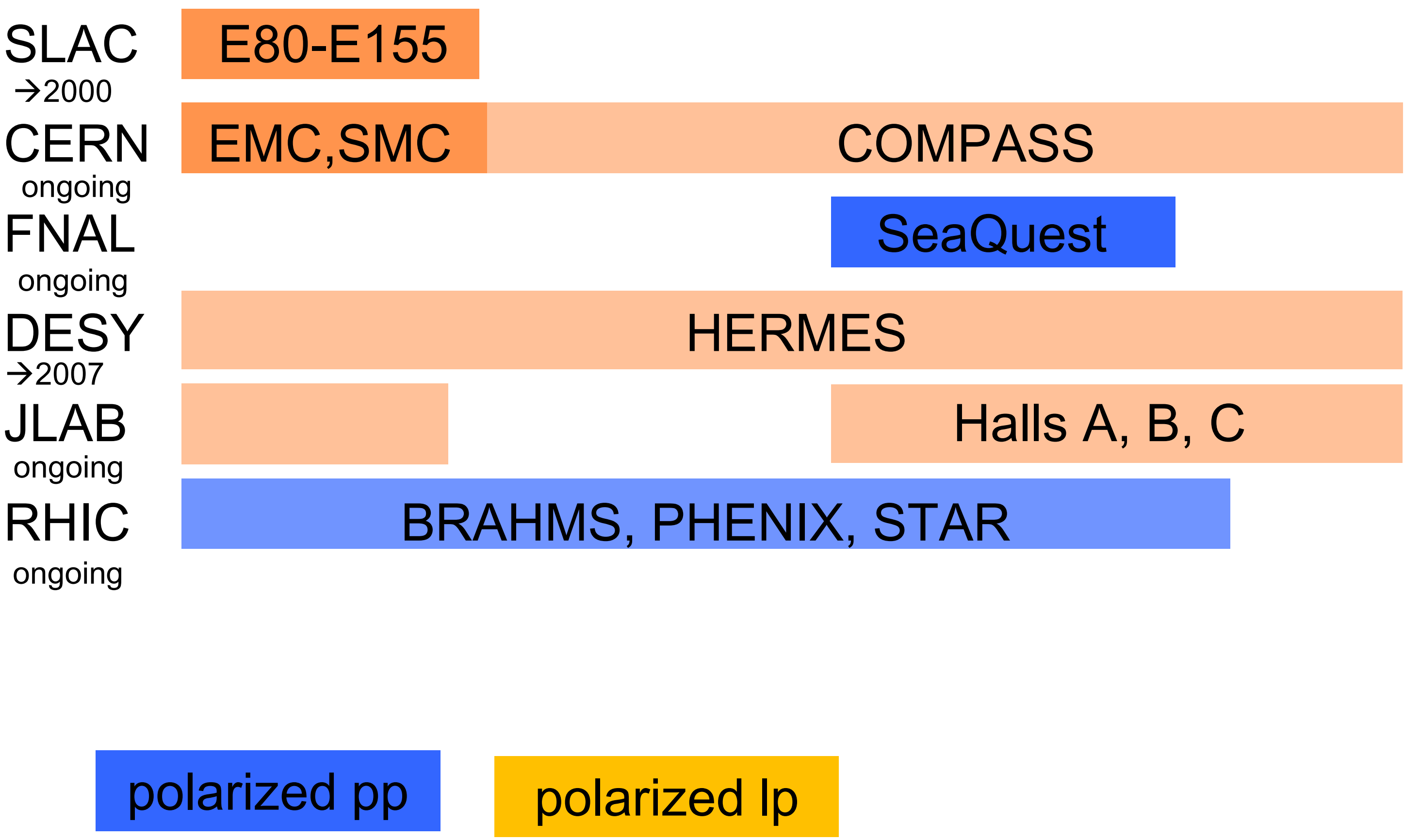




$t\bar{t}$ data constrain $G(x,\mu_f^2)$ for *x>0.05*

Nucleon Spin Structure: 40 Years of Experiment

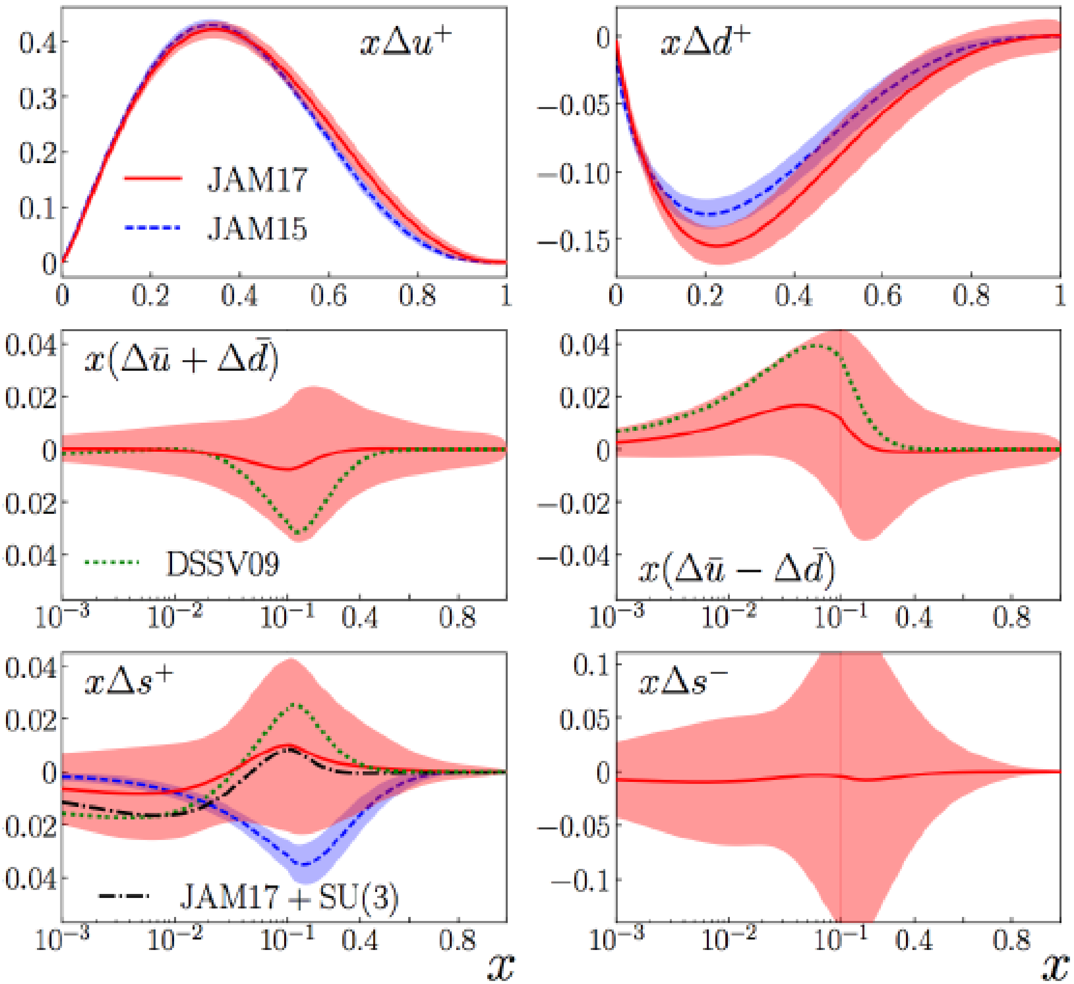
Quark Spin – Gluon Spin – Transverse Spin – GPDs



Quark and Gluon Helicity Distributions from

•NNPDF

J.J. Ethier *et al.* (JAM Collaboration), PRL 119, 132001 (2017)



Up and down quark helicity distributions are known.

Large uncertainties for sea-quarks.

Quark Spin

$\Delta\Sigma = 0.36 \mp 0.09$

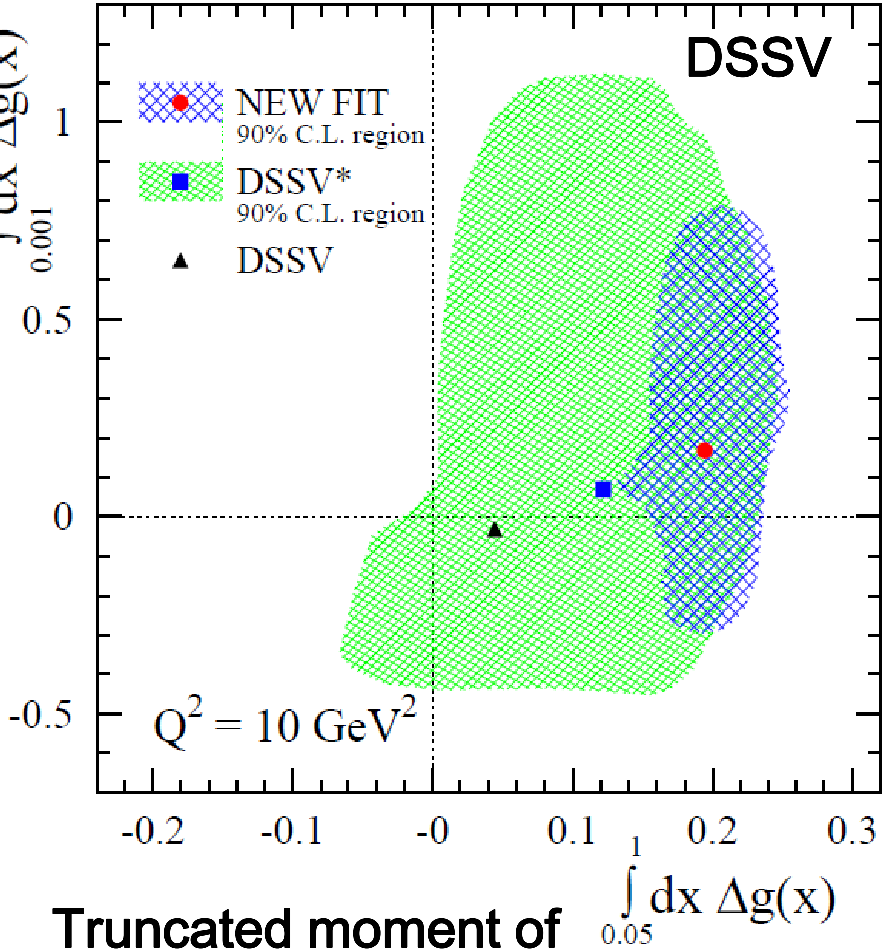
Δs = -0.03 ∓ 0.1

$Q^2 = 1\ GeV^2$

DIS and SIDIS at Jlab 12 GeV!

Knowledge of Truncated Moments of ΔG and ΔΣ(Q²)in Valence- and Sea-Regions

Phys.Rev.Lett. 113 (2014) 012001



Truncated moment of ΔG(x) for sea between 0.001 < x < 0.05

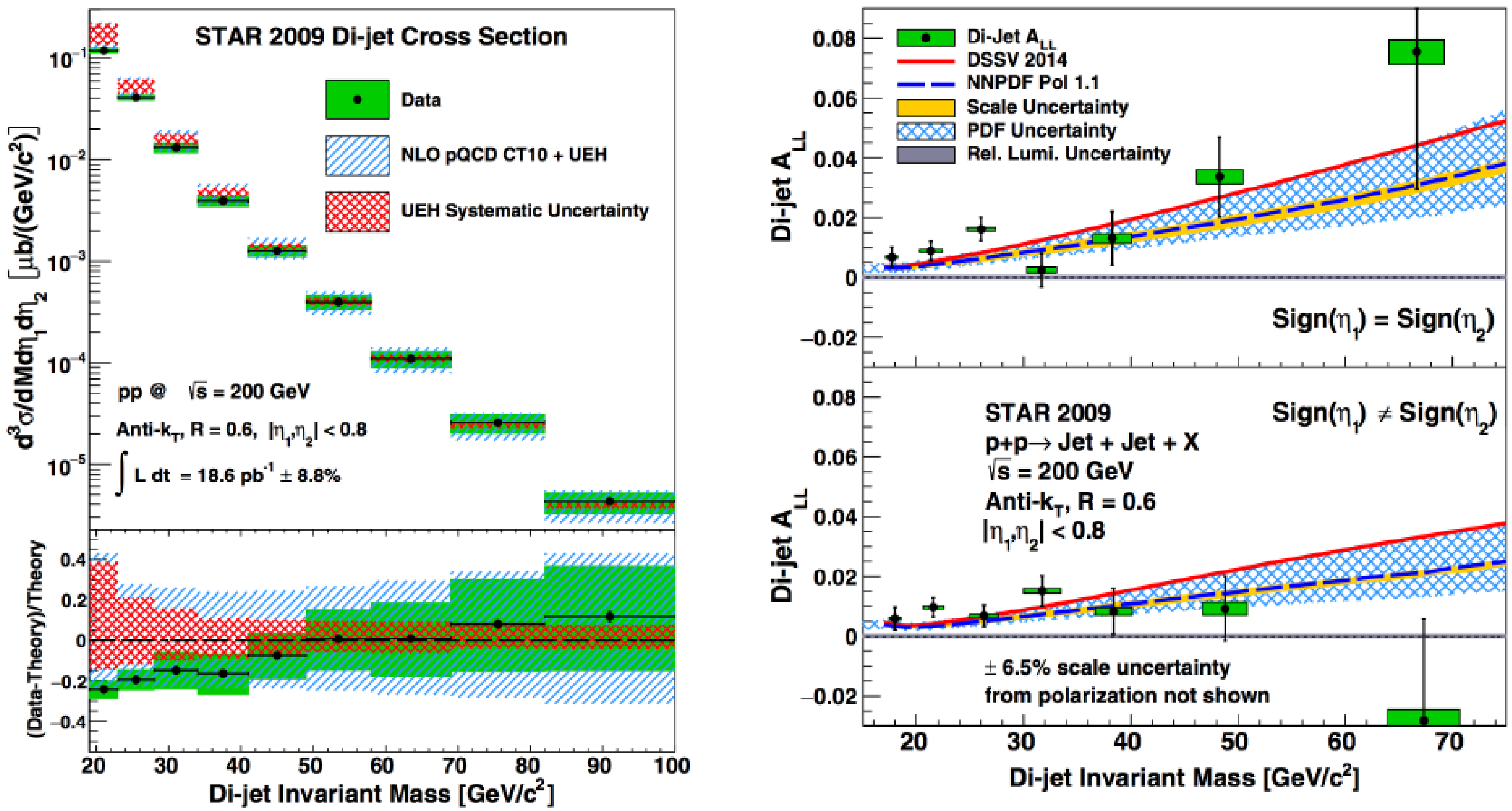
Truncated moment of ΔG(x) for valence region 0.05 < x < 1

Within errors large gluon spin contributions possible at low x!

$$\int_{0.05}^{1} \Delta G(x) \approx 0.2 \mp 0.05℃$$

$$\int_{0.001}^{0.05} \Delta G(x) \approx 0.13 + 1.1 - 0.3$$

Constraining $\Delta G(x)$: First $A_{LL}^{jet}(M_{jet})$



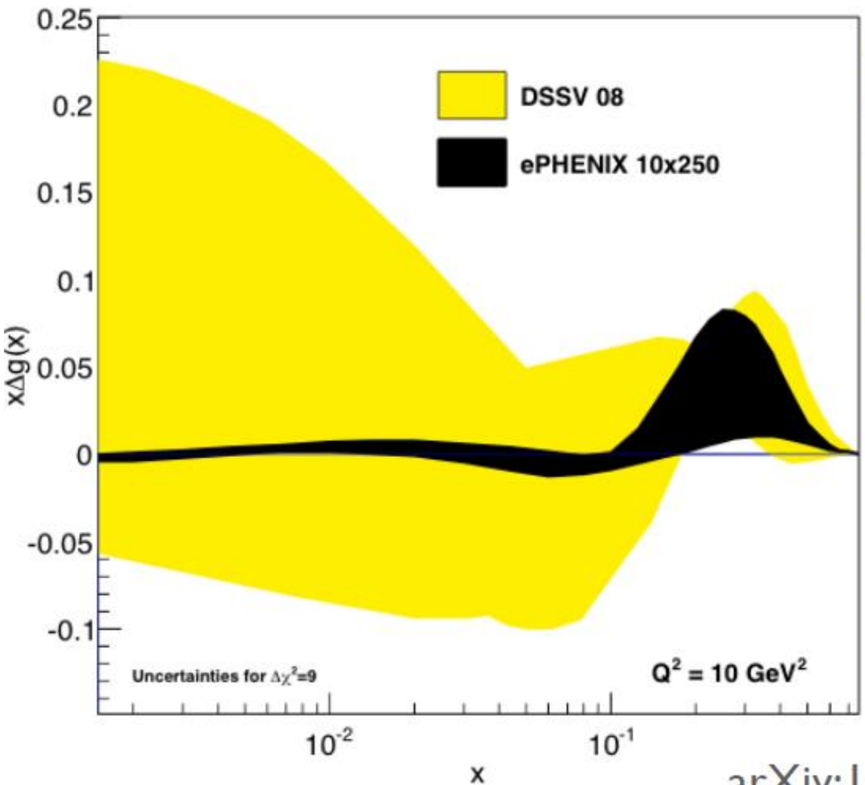
Consistent with analyses that find $\int_{0.05}^{1} \Delta G(x) \approx 0.2$ for x>0.05

L. Adamczyk *et al.*, STAR, Phys. Rev. D 95, 071103 (2017).

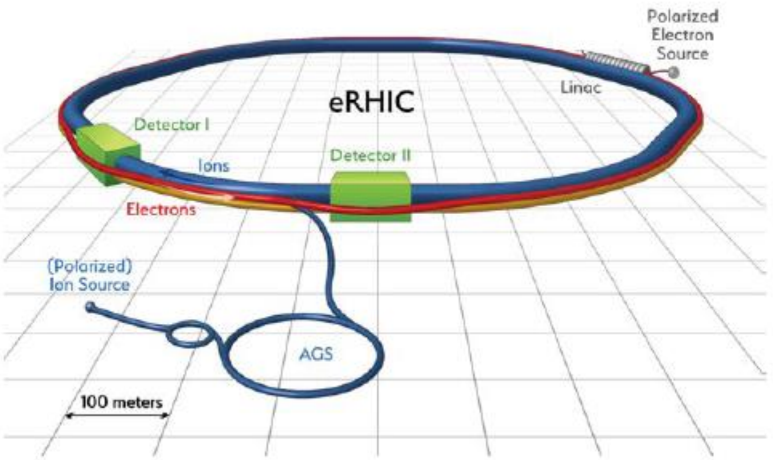
EIC – Impact on low x Extrapolation for $\Delta G(x)$

Future Electron-Ion Collider

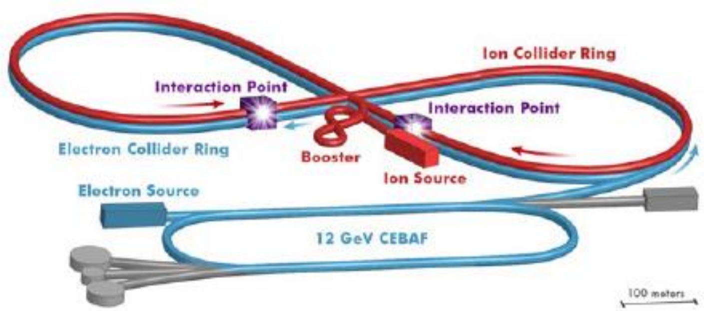
$\Delta G(x)$ reduction of uncertainties



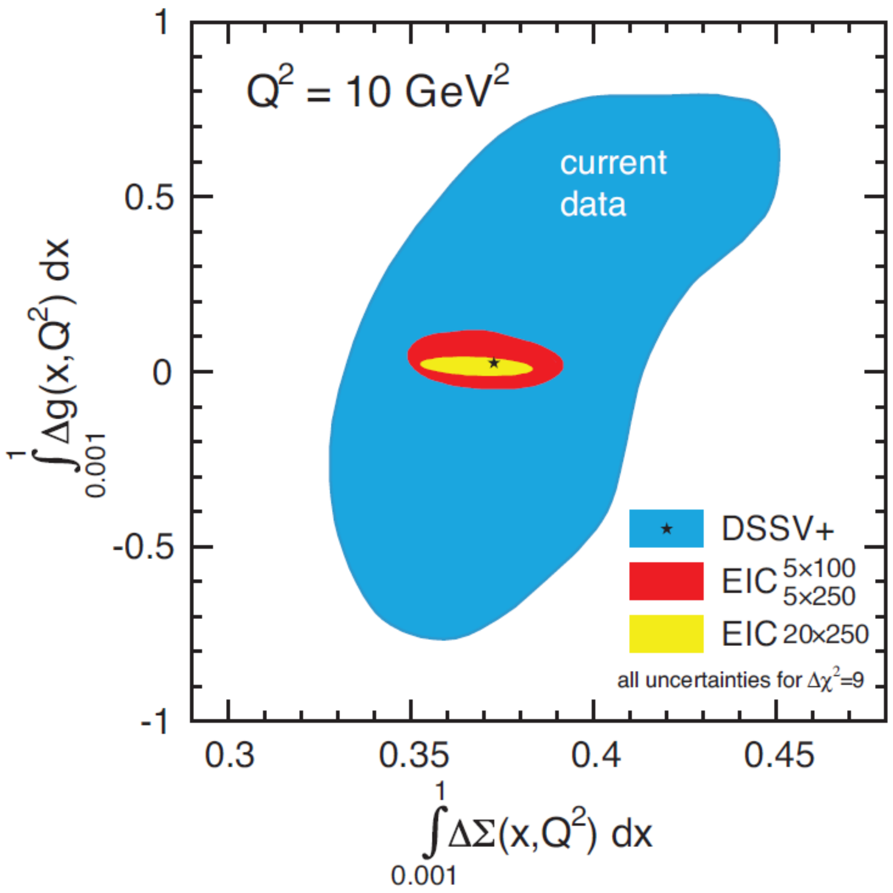
arXiv:I



Not to scale



Impact of EIC on Gluon- and Quark-Spin Contributions.



Will constrain orbital contribution:

$$L_Z = \frac{1}{2} - \frac{1}{2}\Delta\Sigma - \Delta G$$

A-Dependence of Proton Structure

NMC (my first publication as a student with GKM)

The Structure Function ratios $F_2(Li) / F_2(D)$ and $F_2(C) / F_2(D)$ at small x
Nucl.Phys. B441 (1995) 12-30

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH   CERN PPE 95-32

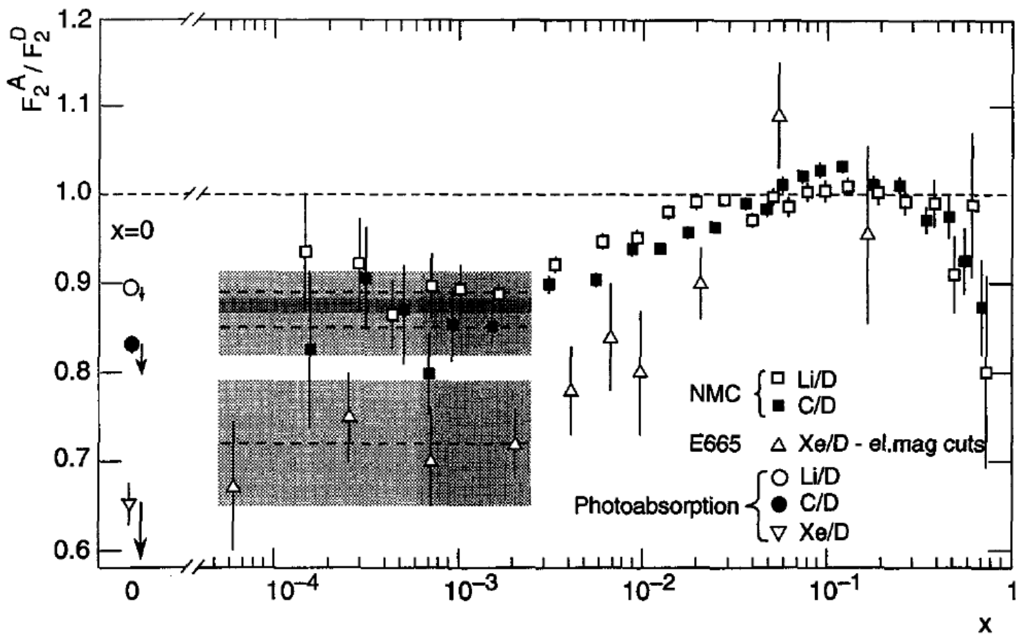
THE STRUCTURE FUNCTION RATIOS
$F_2^{\mathrm{Li}}/F_2^{\mathrm{D}}$ AND $F_2^{\mathrm{C}}/F_2^{\mathrm{D}}$ AT SMALL x

THE NEW MUON COLLABORATION (NMC)

*Bielefeld University[1+], Freiburg University[2+], Max-Planck Institut für Kernphysik, Heidelberg[3+], Heidelberg University[4+], Mainz University[5+], Mons University[6], Neuchâtel University[7], NIKHEF-K[8++], Saclay DAPNIA/SPP[9**], University of California, Los Angeles[10], University of California, Santa Cruz[11], Paul Scherrer Institut[12], Torino University and INFN Torino[13], Uppsala University[14], Soltan Institute for Nuclear Studies, Warsaw[15*], Warsaw University[16*]*

M. Arneodo[13a)], A. Arvidson[14], B. Badełek[14,16], M. Ballintijn[8c)], G. Baum[1], J. Beaufays[8b)], I.G. Bird[3,8c)], P. Björkholm[14], M. Botje[12d)], C. Broggini[7e)], W. Brückner[3], A. Brüll[2f)], W.J. Burger[12g)], J. Ciborowski[8,16], R. van Dantzig[8], A. Dyring[14], H. Engelien[2h)], M.I. Ferrero[13], L. Fluri[7], U. Gaul[3], T. Granier[9], M. Grosse-Perdekamp[2i)], D. von Harrach[3j)], M. van der Heijden[8d)], C. Heusch[11], G. Igo[10], Q. Ingram[12], K. Janson-Prytz[14k)], M. de Jong[8], E.M. Kabuß[3j)], R. Kaiser[2], H.J.Kessler[2], T.J. Ketel[8], F. Klein[5], S. Kullander[14], U. Landgraf[2], T. Lindqvist[14], G.K. Mallot[5], C. Mariotti[13l)], G. van Middelkoop[8], A. Milsztajn[9], Y. Mizuno[3m)], A. Most[3], A. Mücklich[3], J. Nassalski[15], D. Nowotny[3n)], J. Oberski[8], A. Paić[7], C. Peroni[13], B. Povh[3,4], R. Rieger[5o)], K. Rith[3p)], K. Röhrich[5q)], E. Rondio[15], L. Ropelewski[16], A. Sandacz[15], D. Sanders[r)], C. Scholz[3n)], R. Seitz[5u)], F. Sever[1,8s)], T.-A. Shibata[4], M. Siebler[1], A. Simon[3t)], A. Staiano[13], M. Szleper[15], Y. Tzamouranis[3r)], M. Virchaux[9], J.L. Vuilleumier[7], T. Walcher[5], C. Whitten[10], R. Windmolders[6], A. Witzmann[2], F. Zetsche[3k)]

26   *NMC Collaboration/Nuclear Physics B 441 (1995) 12–30*



Why Study Nuclear Effects in Nucleon Structure in Particular the Nuclear Gluon Distribution $G_A(x)$?

General interest:

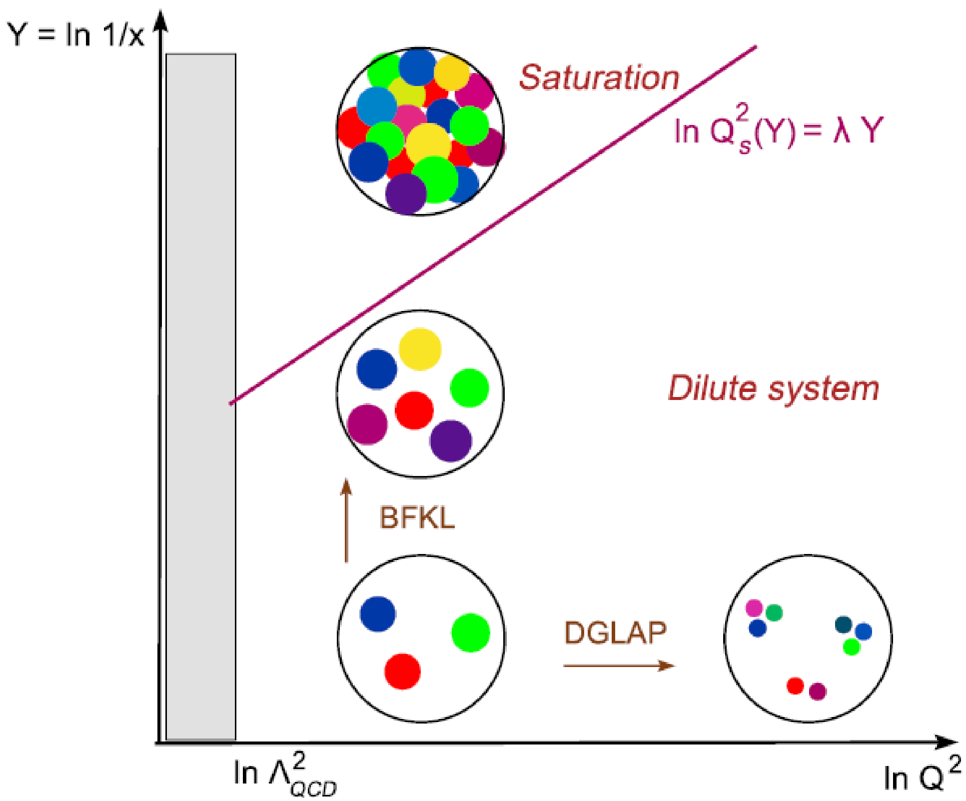
- Extend Understanding of QCD into the non-perturbative regime of high field strengths and large gluon densities.
- Search for universal properties of nuclear matter at low x and high energies.

Heavy Ion Collisions:

- Understand the initial state to obtain quantitative description of the final state in HI-collisions.
- Establish theoretical framework to describe initial state of HI-collisions based on measurements of $G_A(x)$ in p/d-A or e-A.

Saturation → The Color Glass Condensate

F. Gelis, E. Iancu, J. Jalilian-Marian, R. Venugopalan
Ann. Rev. Nucl. Part. Sci. 60 (2010) 463 and references therein



CGC: an effective field theory:

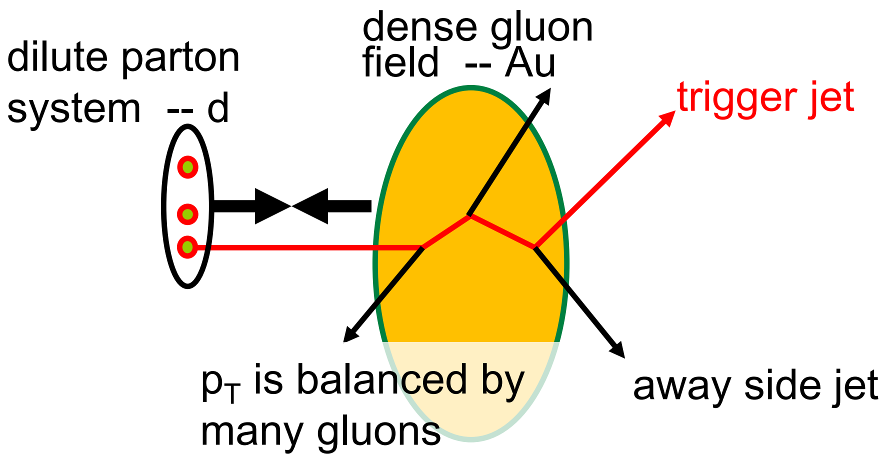
Small-x gluons are described as the color fields radiated by fast color sources at higher rapidity. This EFT describes the saturated gluons (slow partons) as a Color Glass Condensate.

The EFT provides a gauge invariant, universal distribution, $W(\rho)$:

> $W(\rho)$ ~ probability to find a configuration ρ of color sources in a nucleus.

The evolution of $W(\rho)$ is described by the JIMWLK equation.

Probing for Gluon Saturation Effects with Jet-Jet Correlations in d+Au or p+Pb



Idea:

Presence of dense gluon field in the heavy nucleus leads to scattering of multiple gluons and parton can distribute its energy to many scattering centers

→ Mono-jet signature !

D. Kharzeev, E. Levin, L. McLerran, Nucl.Phys.A748:627-640,2005

Experimental signature:

Angular correlation between hadrons in opposing hemispheres

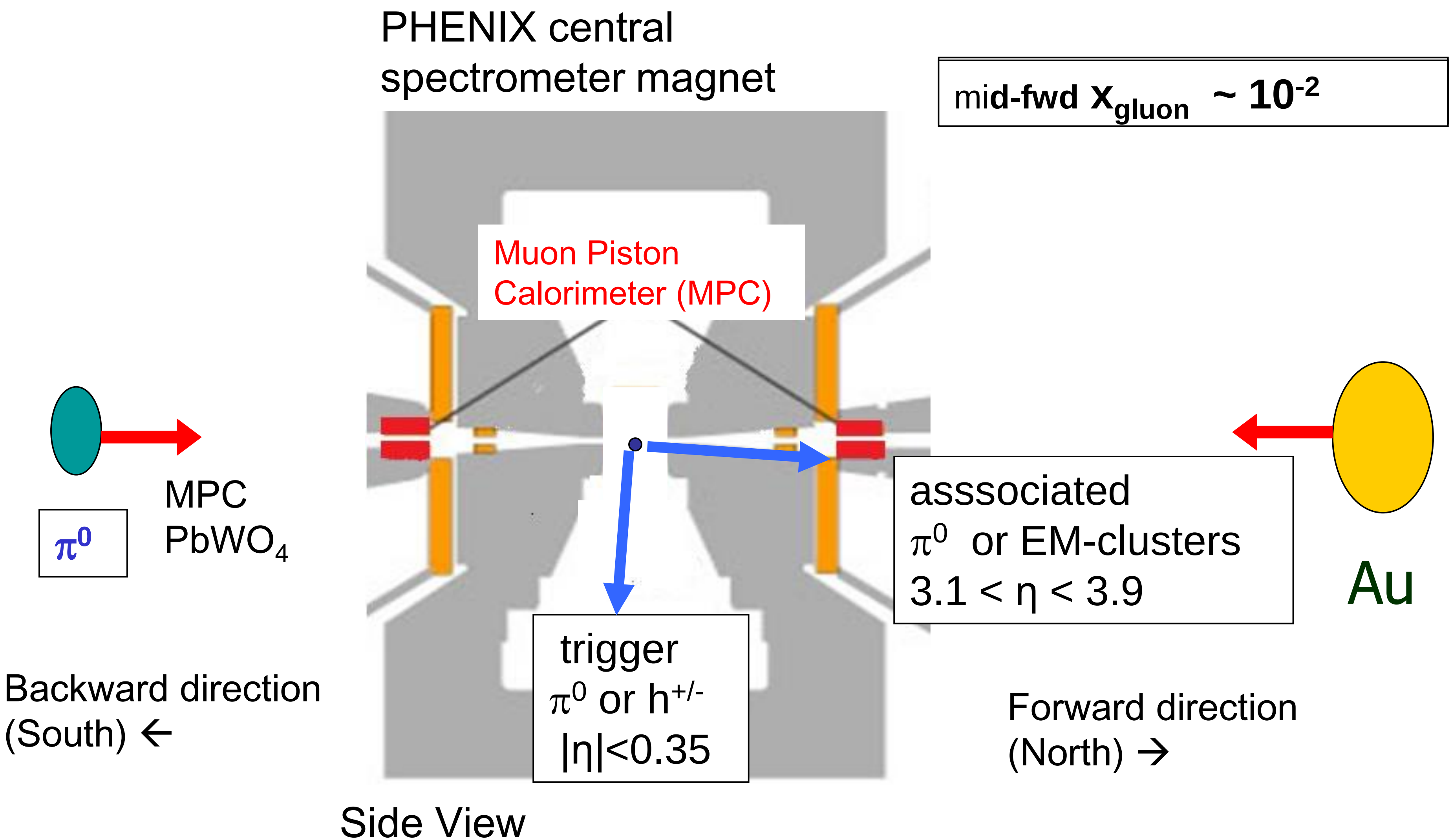
→ widening of correlation width of d-Au/p-Pb compared to pp

→ reduction in associated yield of hadrons on the away site

Effects large at low x

→ measurements at forward rapidity

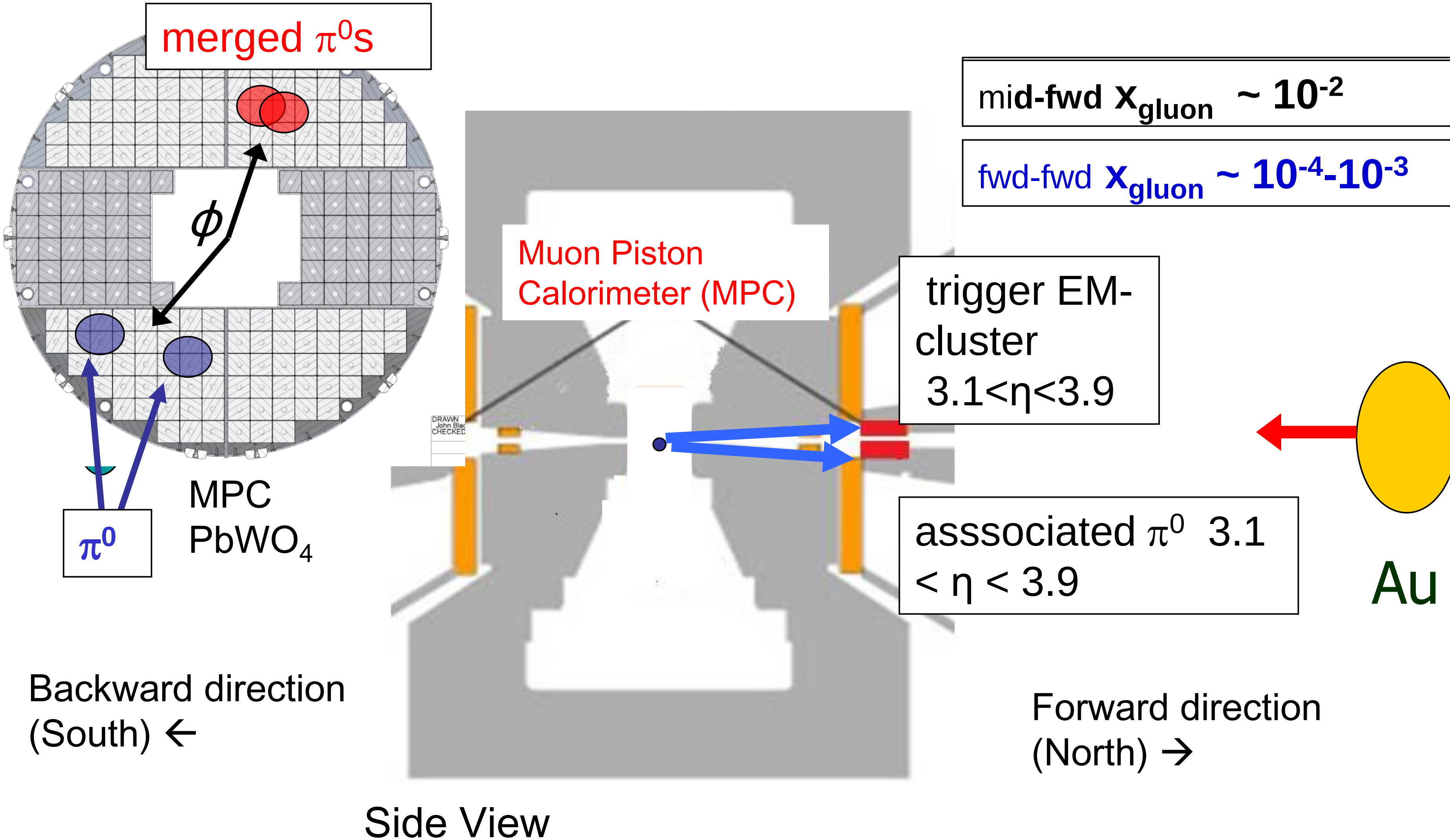
At RHIC (without forward jet detection) Measurement of di-Hadron Correlations



At RHIC (without forward jet detection) Measurement of di-Hadron Correlations

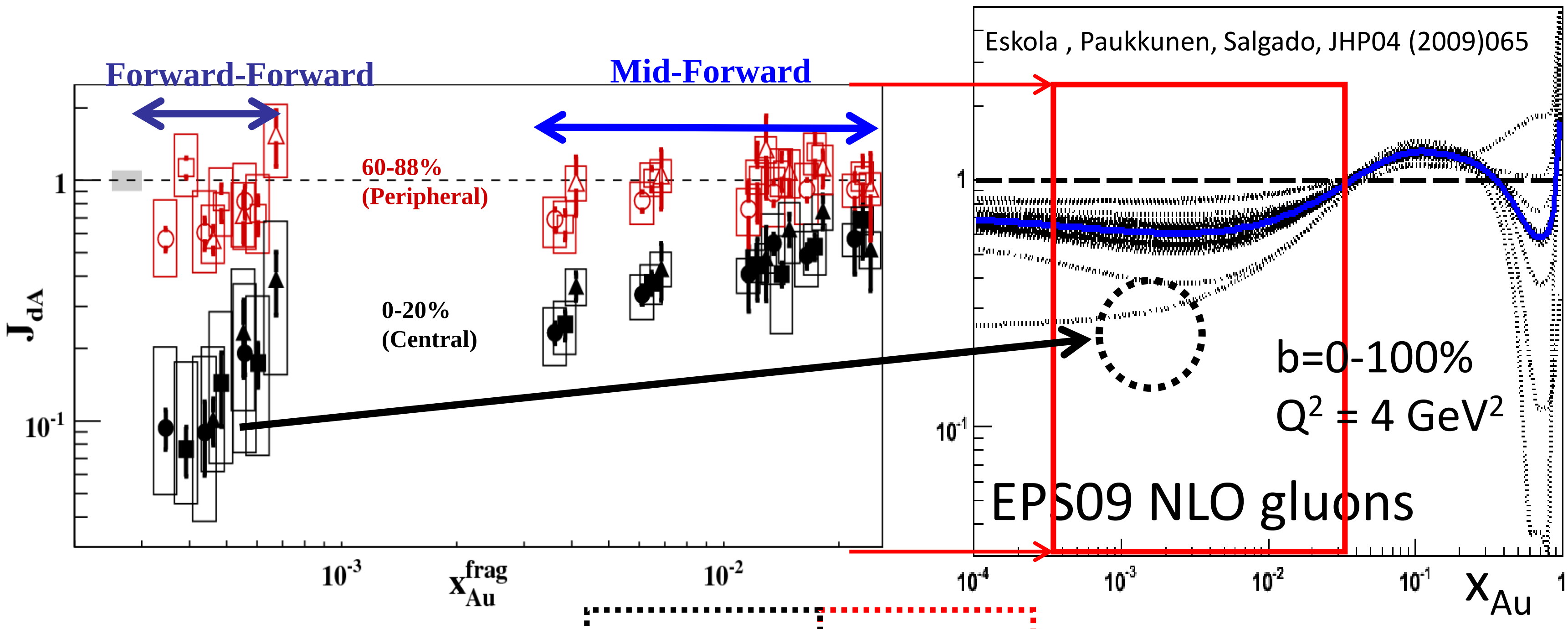
mid-fwd x_{gluon} ~ 10^{-2}

fwd-fwd x_{gluon} ~ 10^{-4}-10^{-3}



Leading Order $J_{dA} \sim R_G^{Au}$

$$R_G^{Au}(x,Q^2) = \frac{xG_{Au}(x,Q^2)}{AxG_p(x,Q^2)}$$



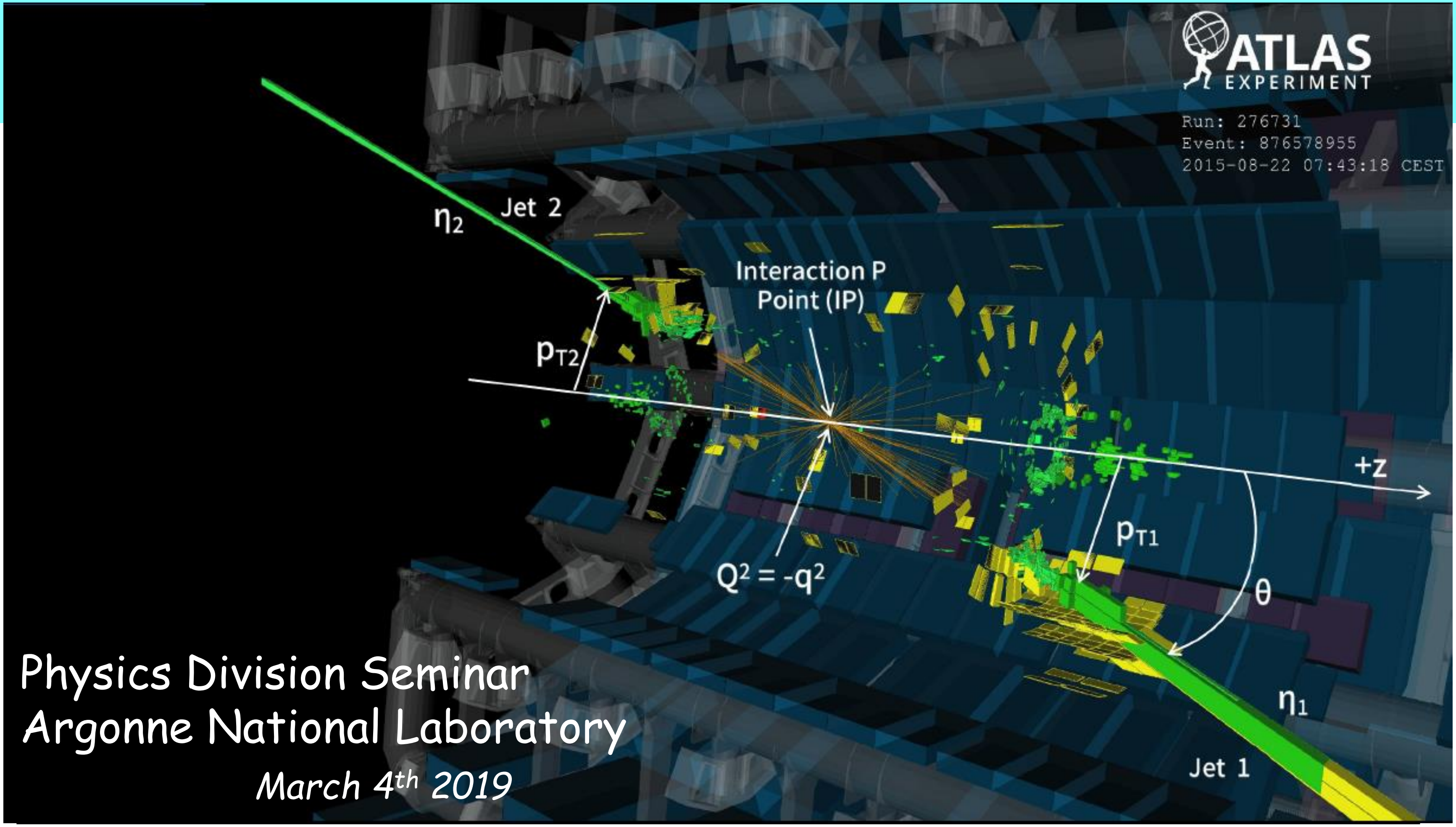
$$J_{dA} = \frac{\sigma_{dAu}^{pairs} / \sigma_{dAu}}{\langle N_{coll} \rangle \sigma_{pp}^{pairs} / \sigma_{pp}} \propto \frac{f_d^a(x_d) \otimes f_{Au}^b(x_{Au}) \otimes \hat{\sigma}^{ab\to cd} \otimes D(z_c, z_d)}{f_p^a(x_p) \otimes f_p^b(x_p) \otimes \hat{\sigma}^{ab\to cd} \otimes D(z_c, z_d)}$$

High x, mostly quarks
Weak effects expected

Low x, mostly gluons $\rightarrow J_{dA} \sim R_G^{Au}$

Probing the Gluon Distribution at Low x in p-Pb with Forward di-Jet Measurements in ATLAS

M. Grosse Perdekamp, UIUC

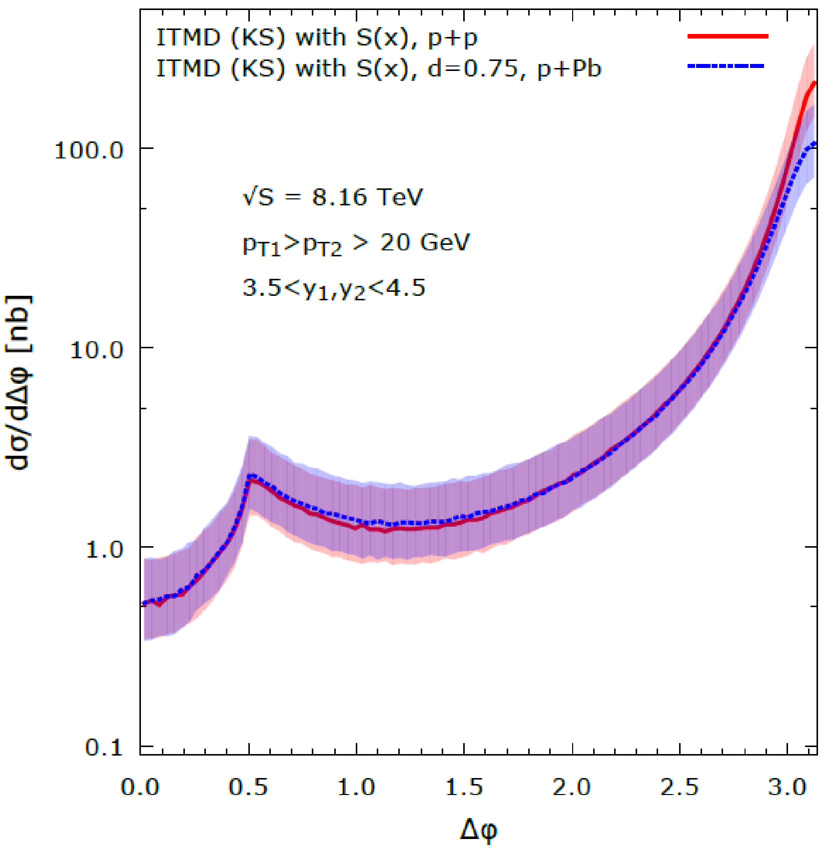


Physics Division Seminar
Argonne National Laboratory
March 4th 2019

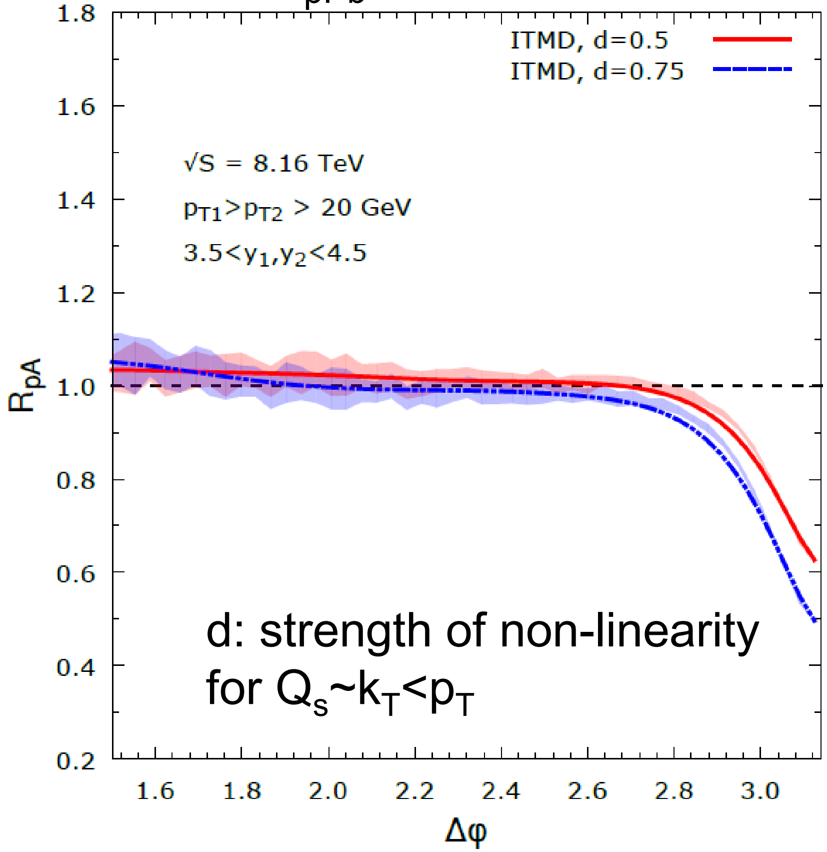
Expectations for LHC: Forward di-jet production in p+Pb collisions in the small-x improved TMD factorization framework

A. van Hameren, P. Kotko, K. Kutak, C. Marquet, E. Petreska and S. Sapeta, JHEP 1612 (2016) 034,
Erratum: JHEP 1902 (2019) 158

Di-Jet Yield vs ΔΦ



Di-Jet R_{pPb} vs ΔΦ



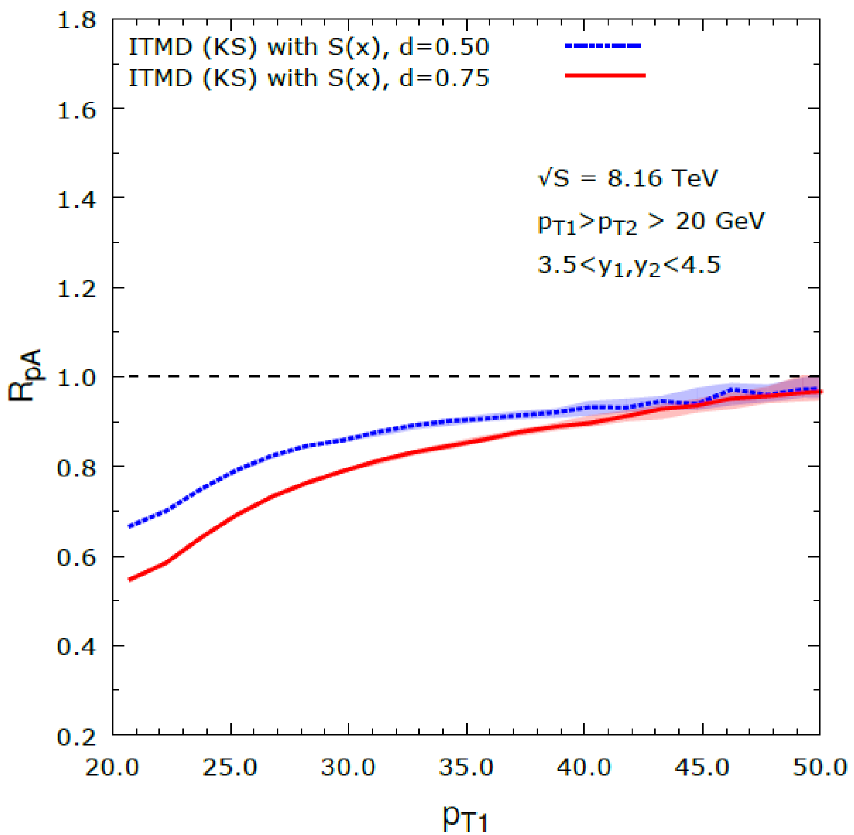
d: strength of non-linearity for $Q_s \sim k_T < p_T$

Using TMD factorization yields sensitivity to non-linearities (saturation)!

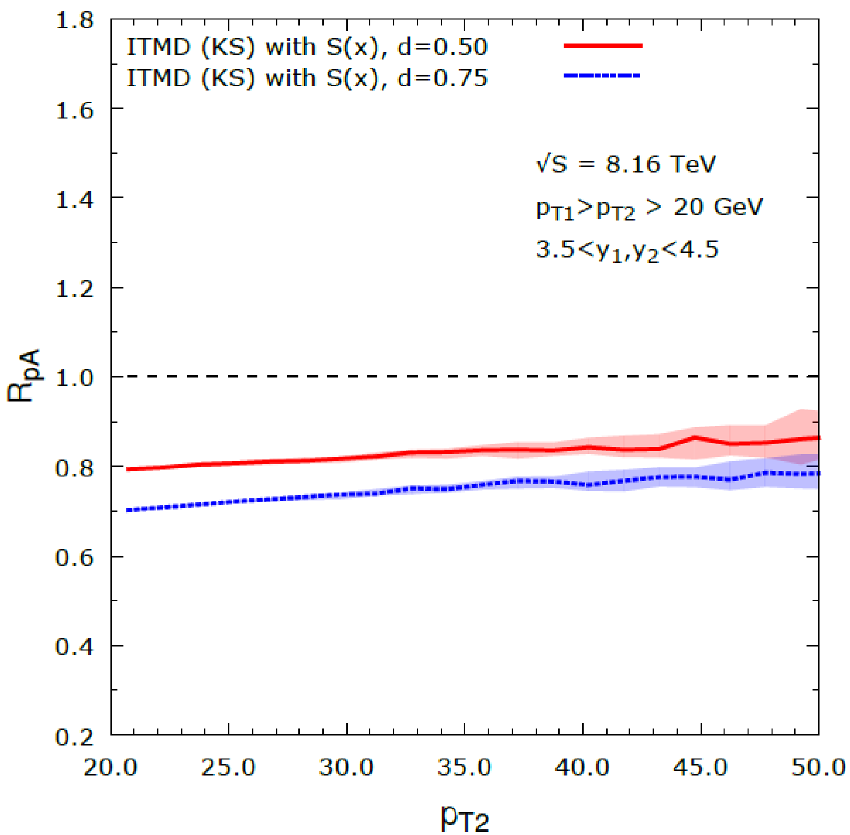
Expectations for LHC: Forward di-jet production in p+Pb collisions in the small-x improved TMD factorization framework

A. van Hameren, P. Kotko, K. Kutak, C. Marquet, E. Petreska and S. Sapeta, JHEP 1612 (2016) 034,
Erratum: JHEP 1902 (2019) 158

$R_{pA}(\Delta\Phi=0)$ vs Trigger Jet p_T

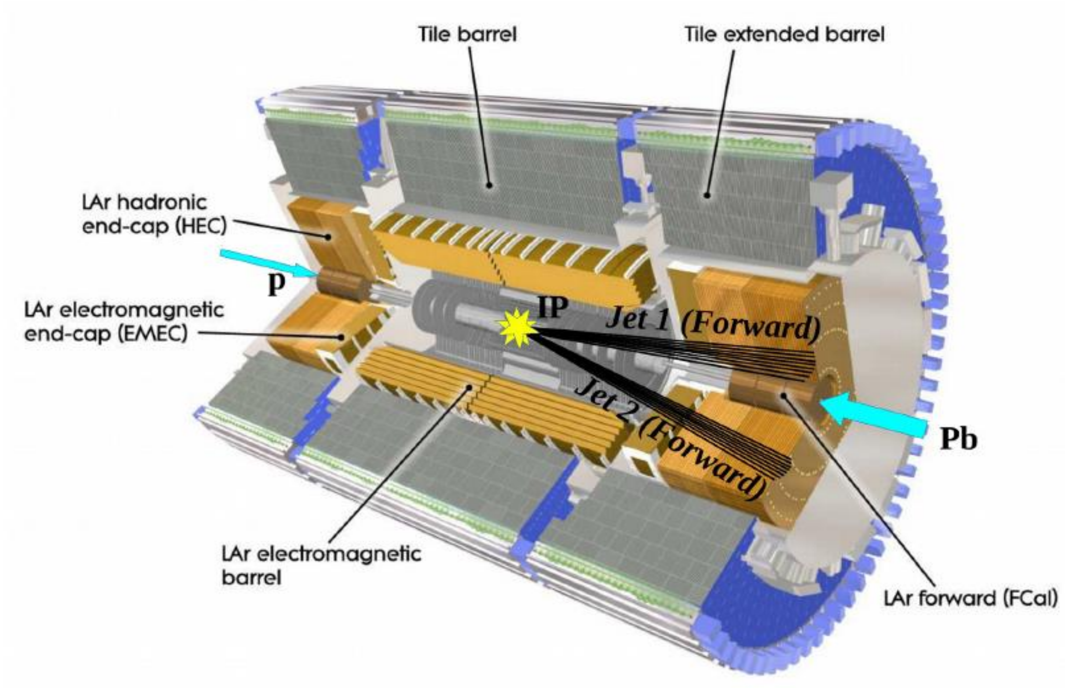


$R_{pA}(\Delta\Phi=0)$ vs Associate Jet p_T



ATLAS Calorimeter Systems as Input to Jet Reconstruction in Heavy Ion Collisions

- Composed of Liquid Argon (LAr) and Tungsten scintillating calorimeters.
- Used to detect energy deposits from particles.
- Use calorimeter info as input to HI jet reconstruction.



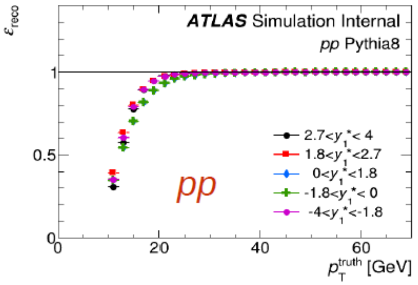
Probing low x:

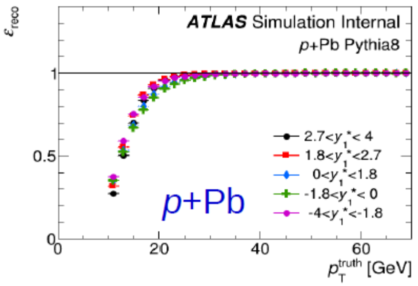
p_T^{Jet}>28 GeV (for jet reconstruction efficiencies and energy resolution)

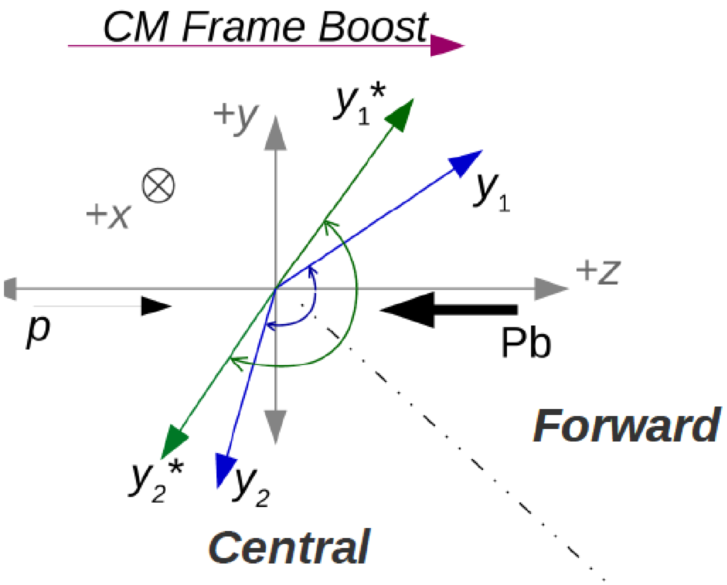
- **Given two jets with**
  - $p_{T,1} \sim p_{T,2} \sim$ 28 GeV
- **Forward-Forward Jets**
  - $y^*_1 \sim y^*_2 \sim 4$
  - $x_2 \sim 1.5 \times 10^{-4}$
- **Forward-Central Jets**
  - $y^*_1 \sim 4$, $y^*_2 \sim 0$
  - $X_2 \sim 4.1 \times 10^{-3}$
- **Central-Central Jets**
  - $y^*_1 \sim y^*_2 \sim 0$
  - $x_2 \sim 8.0 \times 10^{-3}$

- Preferable to use forward-forward dijets to probe lowest x_2 of the pPb ion.

Jet reconstruction efficiencies



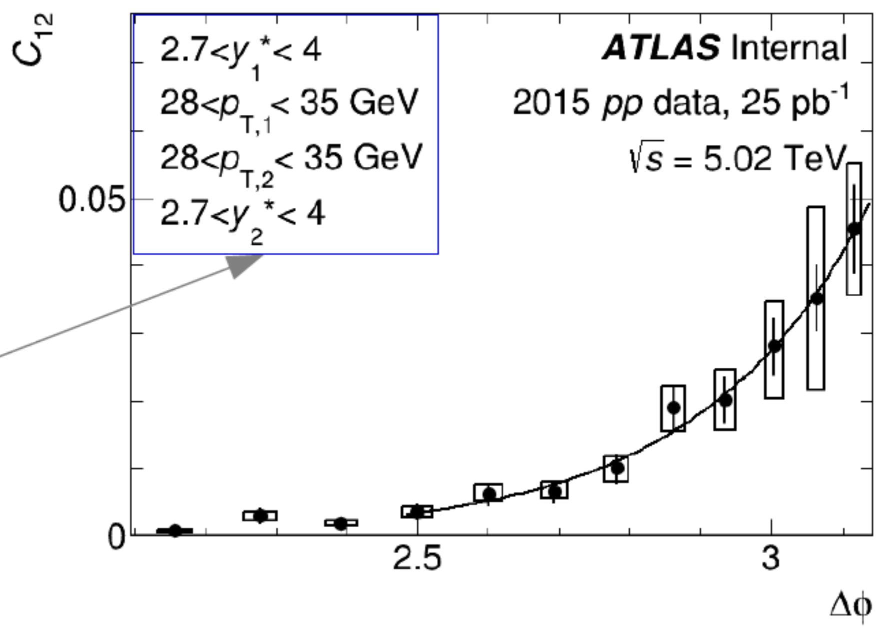




Azimuthal Angular Jet Yields

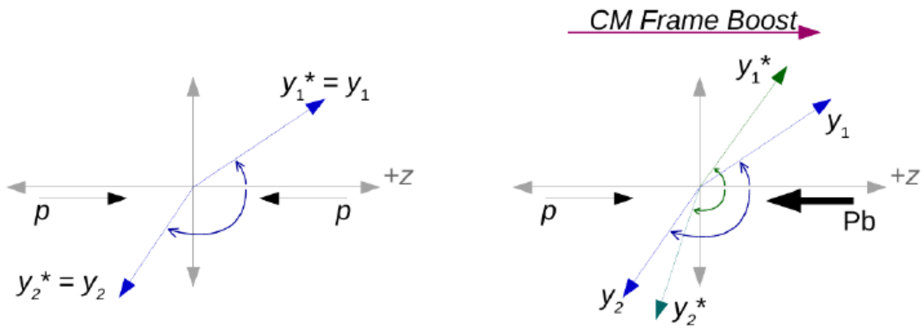
$$C_{12}(p_{T,1}, p_{T,2}, y_1^*, y_2^*) = \frac{1}{N_1}\frac{dN_{12}}{d\Delta\phi}$$

- Use two highest p_T jets in an event. N_{12}
- Construct $\Delta\varphi$ distributions.
  - Normalize by number of highest p_T jets N_1
  - In combinations of ($p_{T,1}$, $p_{T,2}$, y_1^*, y_2^*)
- Result – $C_{12}(p_{T,1}, p_{T,2}, y_1^*, y_2^*)$



Binning in Trigger Jet $p_{T,1}$, Associated Jet $p_{T,2}$ and rapidity

- Leading (highest pT) jet in the event.
  - Required to be in most forward direction
  - proton-going
  - $2.7 < y_1^* < 4.0$
- Rapidity and momentum ranges motivated by triggers.



Bins in $p_{T,1}$[GeV]	Bins in $p_{T,2}$[GeV]	Bins in y_2^*
$28 < p_{T,1} < 35$	$28 < p_{T,2} < 35$	$2.7 < y_2^* < 4.0$
$35 < p_{T,1} < 45$	$35 < p_{T,2} < 45$	$1.8 < y_2^* < 2.7$
$45 < p_{T,1} < 90$	$45 < p_{T,2} < 90$	$0.0 < y_2^* < 1.8$
		$-1.8 < y_2^* < 0.0$
		$-4.0 < y_2^* < -1.8$

Observables

$$C_{12}(p_{\mathrm{T},1}, p_{\mathrm{T},2}, y_1^*, y_2^*) = \frac{1}{N_1}\frac{\mathrm{d}N_{12}}{\mathrm{d}\Delta\phi}$$

azimuthal di-jet yield

$$C_{12} = \frac{1}{N_1}\frac{\mathrm{d}N_{12}}{\mathrm{d}\Delta\phi}$$

Fit →

$$C_{12}(\Delta\Phi) = \int_{-\infty}^{\infty} \mathrm{d}\delta \frac{e^{-\delta^2/2\sigma^2}}{\sqrt{8\pi\sigma^2\tau^2}} e^{-|\Delta\Phi-\delta|/\tau}$$

↓ *Integrate*

$$I_{12} = \frac{1}{N_1}\frac{\mathrm{d}N_{12}}{\mathrm{d}y_1^*\mathrm{d}y_2^*\mathrm{d}p_{\mathrm{T},1}\mathrm{d}p_{\mathrm{T},2}}$$

conditional di-jet yield

↓ *Extract Width*

$$W_{12} = \mathrm{RMS}(C_{12}) = \sqrt{2\tau^2 + \sigma^2}$$

width of di-jet yield

↓ *Ratio*

$$\rho_I^{\mathrm{pPb}} = \frac{I_{12}^{p+\mathrm{Pb}}}{I_{12}^{pp}}$$

conditional di-jet yield ratio between pPb and pp

↓ *Ratio*

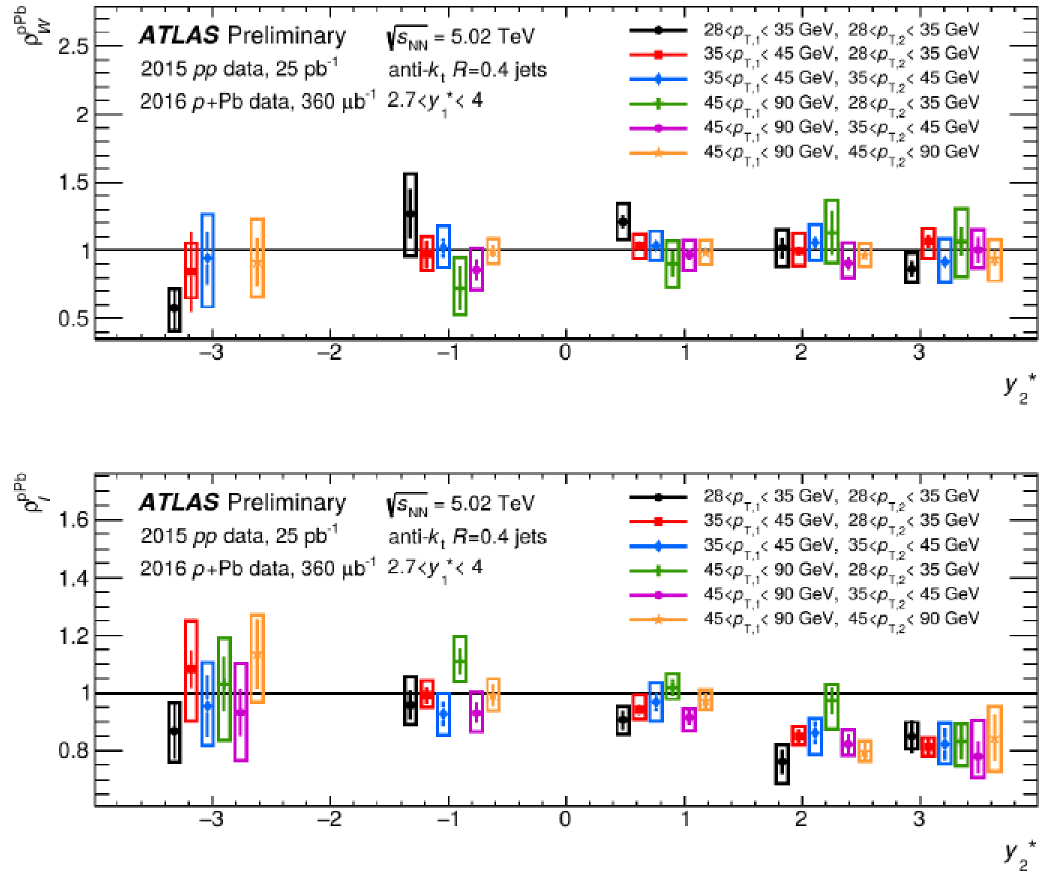
$$\rho_W^{\mathrm{pPb}} = \frac{W_{12}^{p+\mathrm{Pb}}}{W_{12}^{pp}}$$

Results ρ^{W}_{pPb} and ρ^{I}_{pPb}

$$\rho_W^{\mathrm{pPb}} = \frac{W_{12}^{p+\mathrm{Pb}}}{W_{12}^{pp}}$$

$$\rho_I^{\mathrm{pPb}} = \frac{I_{12}^{p+\mathrm{Pb}}}{I_{12}^{pp}}$$

- Ratios of widths (top) are consistent with unity.
- Ratios of yields (bottom) show suppression up to 20% in two most forward, proton-going direction bins.



Dijet azimuthal correlations and conditional yields in pp and p+Pb collisions at $\sqrt{s_{NN}}$=5.02TeV with the ATLAS detector *Phys.Rev. C100 (2019) no.3, 034903*

Next Steps

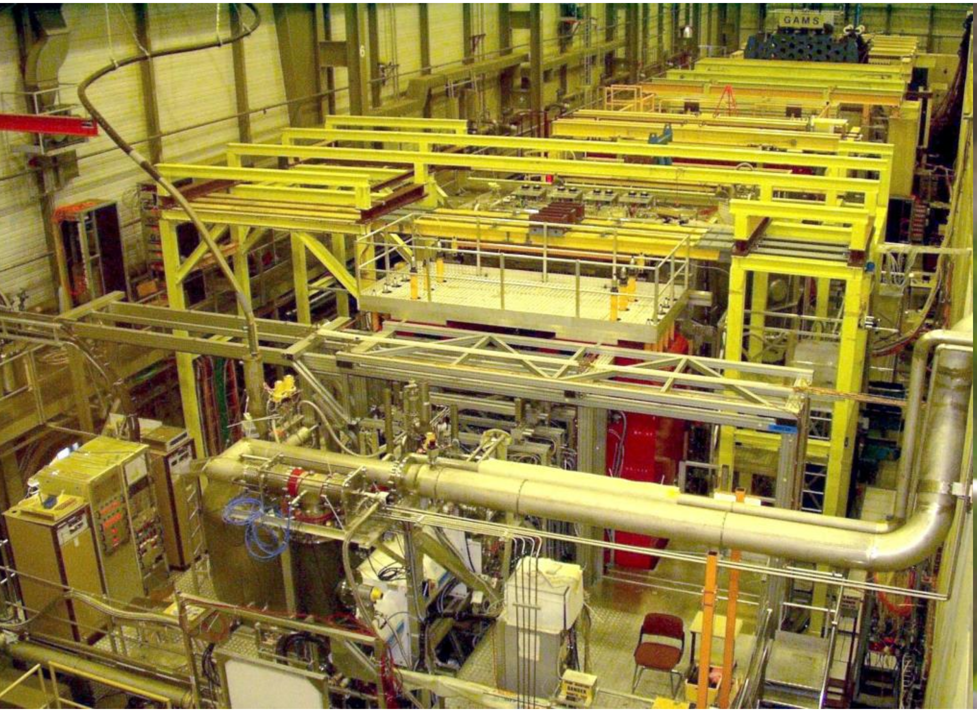
- Consistent with newly updated calculations:

  Broadening and saturation effects in dijet azimuthal correlations in p-p and p-Pb collisions at √=s= 5.02 TeV
  Andreas van Hameren, Piotr Kotko, Krzysztof Kutak, Sebastian Sapeta (Cracow, INP)
  Phys.Lett. B795 (2019) 511-515

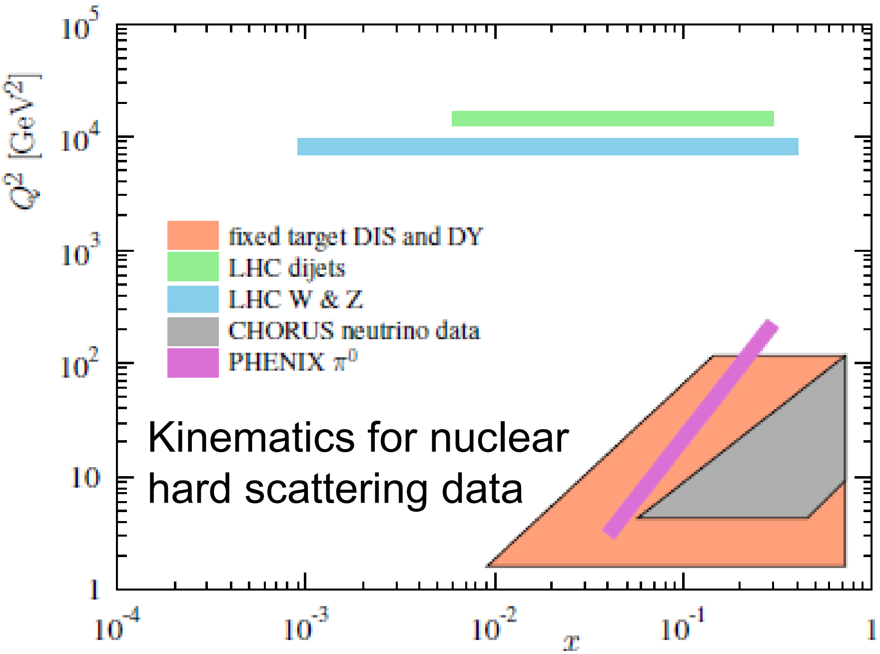
- Determine centrality dependence and R_{pPb} for single jets to determine J_{pPb}. Latest pPb run has sufficient statistics.

- Study possibility to perform correlation measurement between a forward Jet and a forward hadron in the ZDC, tagging the lowest x-possible in pPb and pp.

Thank you!!



Modification of Nucleon Structure in Nuclei



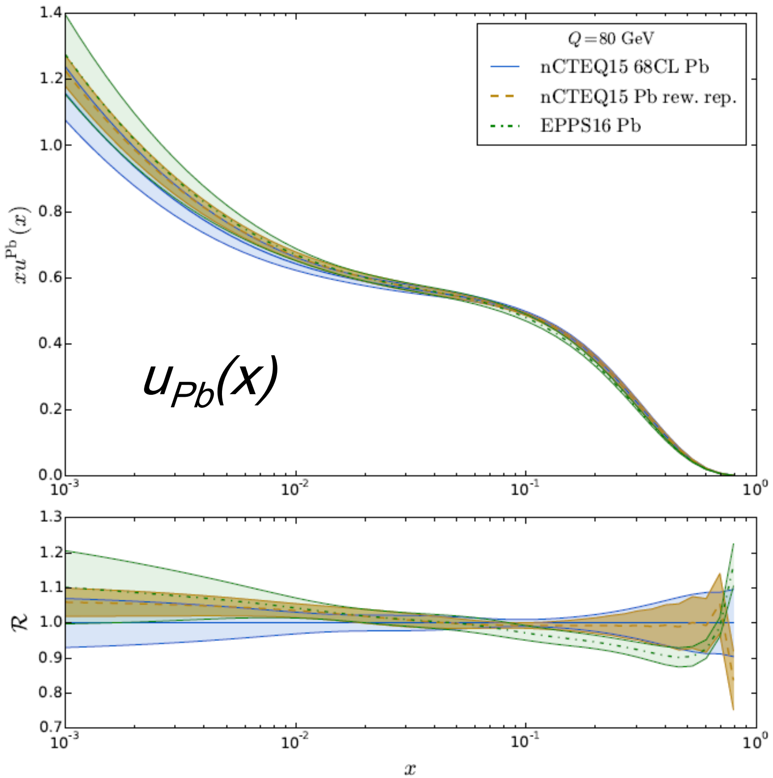
Recent nuclear PDF fits:

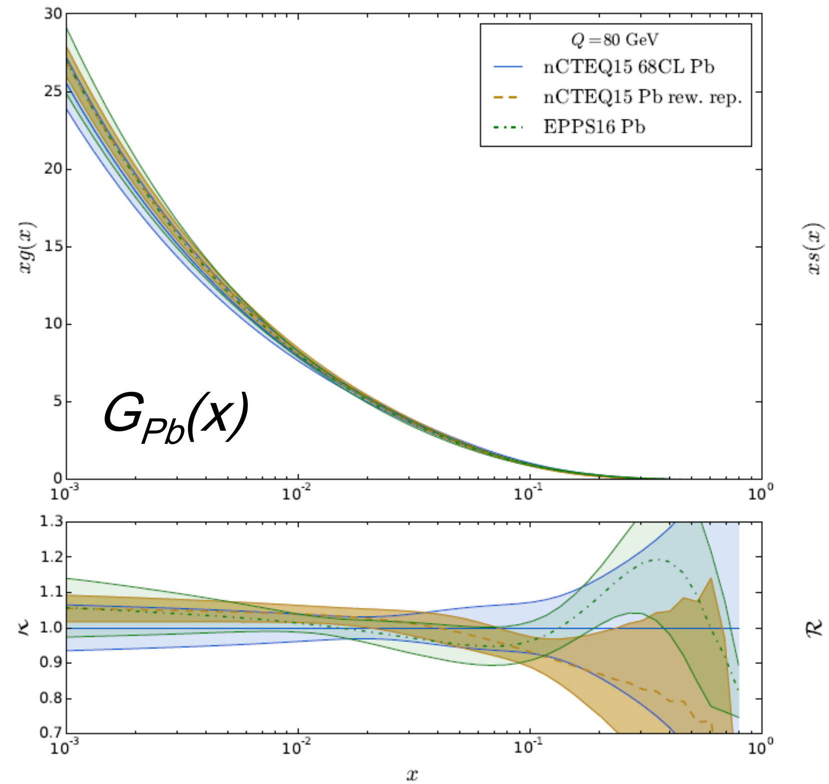
nCTEQ: Phys.Rev. D93 (2016) 085037
EPPS16: EPJ C77 (2017) 163 [arXiv:1612.05741]

LHC pPb and PbPb data

		Observable
pPb	ATLAS	$d\sigma(Z \to \ell^+\ell^-)/dy_Z$ [1]
		$d\sigma(W^+ \to \ell^+\nu)/dy_{\ell+}$ [2]
		$d\sigma(W^- \to \ell^-\bar{\nu})/dy_{\ell-}$ [2]
	CMS	$d\sigma(Z \to \ell^+\ell^-)/dy_Z$ [3]
		$d\sigma(W^+ \to \ell^+\nu)/dy_{\ell+}$ [4]
		$d\sigma(W^- \to \ell^-\bar{\nu})/dy_{\ell-}$ [4]
	LHCb	$\sigma(Z \to \ell^+\ell^-)$ [5]
	ALICE	$\sigma(W^+ \to \ell^+\nu)$ [6]
		$\sigma(W^- \to \ell^-\bar{\nu})$ [6]
PbPb	ATLAS	$1/\sigma_{tot} d\sigma/dy_Z$ [7]
		A_ℓ [8]
	CMS	$1/\sigma_{tot} d\sigma/dy_Z$ [9]
		A_ℓ [10]

Impact of LHC *pPb* and *PbPb* data on $u_{Pb}(x)$ and $G_{Pb}(x)$: nCETQ vs EPPS16



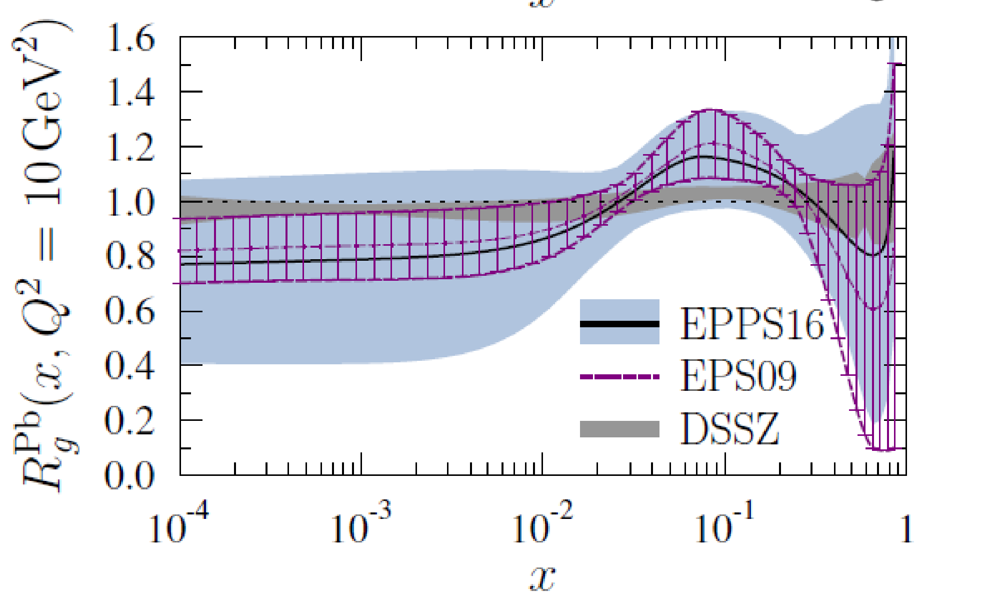


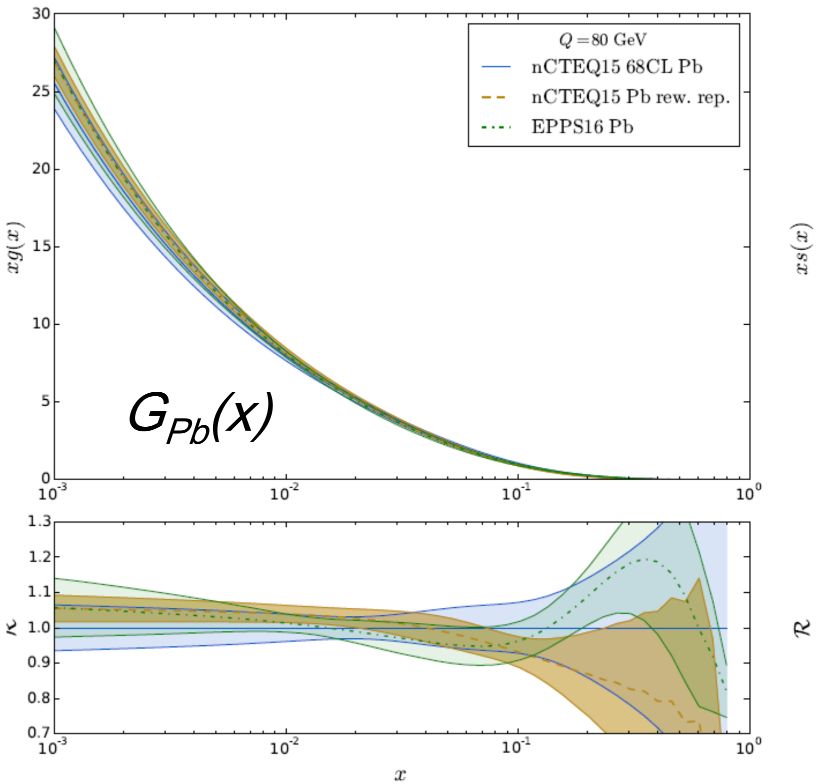
nCTEQ: Phys.Rev. D93 (2016) 085037
EPPS16: EPJ C77 (2017) 163 [arXiv:1612.05741]

LHC data in agreement with fixed target and RHIC data. More HI data taking to come …

Impact of LHC *pPb* and *PbPb* data on $u_{Pb}(x)$ and $G_{Pb}(x)$: nCETQ vs EPPS16

Gluon: Nuclear Modification Factor $R_g^{Pb}(x)$





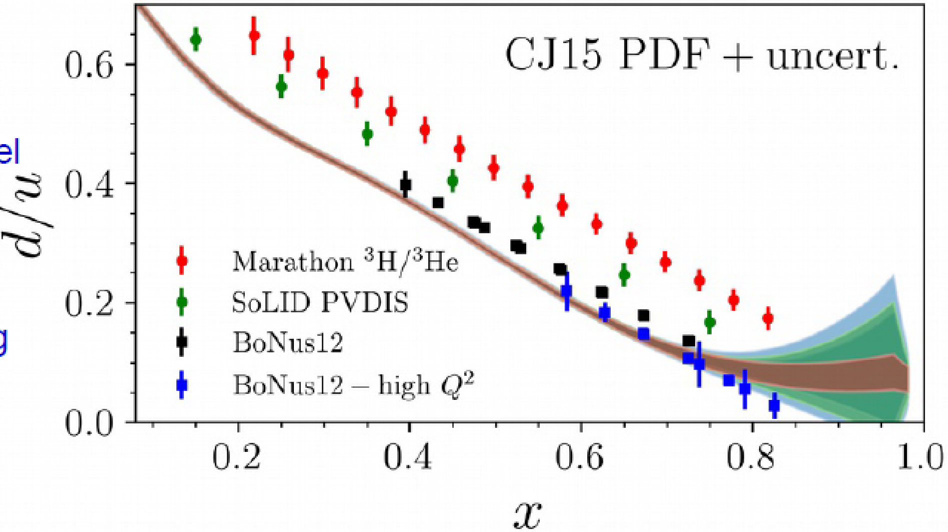
nCTEQ: Phys.Rev. D93 (2016) 085037
EPPS16: EPJ C77 (2017) 163 [arXiv:1612.05741]

LHC data in agreement with fixed target and RHIC data. More HI data taking to come …

Jefferson Laboratory: *d(x)/u(x)* at high x in DIS

- JLAB 12 GeV program includes dedicated experiments to improve structure functions and d/u ratio at high x
  - Hall C: precision F_2 for ep and ed scattering
  - MARATHON: ^3H and ^3He, nuclear corrections cancel in ratio
  - BONuS12: effective free neutron target in ed scattering with proton tag
  - SoLID PVDIS: u/d from parity-violating ep scattering
- Fitting group CJ at JLAB, focussing on the use of high-x data in PDFs

Projected precision on u/d from future 12 GeV JLAB experiments



CJ15 PDFs: Phys.Rev. D93 (2016) 114017 [arXiv:1602.03154]
BONuS 5 GeV: Phys.Rev. C89 (2014) 045206, add: Phys.Rev. C90 (2014) 059901[arXiv:1402.2477]
MARATHON: https://www.jlab.org/exp_prog/proposals/10/PR12-10-103.pdf
SoLID PVDIS: https://www.jlab.org/exp_prog/proposals/10/PR12-10-007.pdf
Hall C precision F2: https://www.jlab.org/exp_prog/proposals/10/PR12-10-002.pdf

Parallel session talks:
BONuS12: WG7(261) 18.4. 10:24
JLAB 12GeV: WG7(255) 18.4. 16:54

from Stefan Schmitt, DIS 2018 in Kobe, Japan