The France-Stanford Center for Interdisciplinary Studies

Quarkonium physics at a fixed-target experiment with the proton and lead LHC beams

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with F. Fleuret (LLR), S.J. Brodsky (SLAC), C. Hadjidakis (IPN), . . .

Part I

A fixed-target experiment using the LHC beam(s): generalities

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Target	ρ (g.cm^{-3})	A	$\mathcal{L}$ (μb^{-1}.s^{-1})	$\mathcal{L}$ (pb^{-1}.y^{-1})
Liq. H_2	0.07	1	21	210
Liq. D_2	0.16	2	24	240
Be	1.85	9	60	600
Cu	8.96	64	40	400
W	19.1	185	30	300
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- Using **NA51**-like 1.2m-long liquid H_2 & D_2 targets, $\mathcal{L}_{H_2/D_2} \simeq 20$ fb$^{-1}y^{-1}$
- For comparison, PHENIX recorded lumi for
  Run9 pp at 200 GeV: 16 pb^{-1} & Run8 *d*Au at 200 GeV : 0.08 pb^{-1}

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Target	ρ (g.cm^{-3})	A	$\mathcal{L}$ (mb^{-1}.s^{-1})=$\int\mathcal{L}$ (nb^{-1}.yr^{-1})
Liq. H_2	0.07	1	**28**
Liq. D_2	0.16	2	**34**
Be	1.85	9	**84**
Cu	8.96	64	**56**
W	19.1	185	**42**
Pb	11.35	207	**22**

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- For comparison, Phenix recorded lumi for Run10
  AuAu at 200 GeV: 1.3 nb^{-1} & AuAu at 62 GeV: 0.11 nb^{-1}

Part II

AFTER as a quarkonium observatory in *pp*

(constraining the glue at large x in the proton)

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  - Yet, very sensitive on $g(x, Q^2)$ where it is not well known

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  - a study of direct J/ψ yield (χ_c only measured in *pp* by CDF and PHENIX)
  - a study of direct $\Upsilon(nS)$ (χ_b only measured in *pp* by CDF (1 point))
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  - adapted triggers (Big issue for CMS and ATLAS)

A Fixed Target ExpeRiment: A quarkonium observatory

- Interpolating the world data set:

Target	$N_{J/\Psi}$ (y^{-1}) $N_{J/\Psi} = A\mathcal{L}\sigma_{\Psi}$	N_{Υ} (y^{-1}) $N_{\Upsilon} = A\mathcal{L}\sigma_{\Upsilon}$
	(with branching and per unit of rapidity)	
Liq. H^2 (1m)	$0.6\ 10^9$	10^6
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Be	$0.2\ 10^9$	$2.7\ 10^5$
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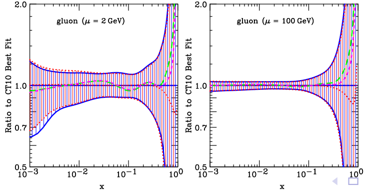
- AIM/HOPE: Extract $g(x, Q^2)$ with Q^2 as low as 10 GeV^2
  from $x = 10^{-3}$ up to $\simeq$ one



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- Absolutely complementary to eRHIC (and LHeC)
  whose focus would be low-*x*.

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Target	$N_{J/\Psi}$ (y^{-1}) $N_{J/\Psi} = A\mathcal{L}\sigma_\Psi$	N_Υ (y^{-1}) $N_\Upsilon = A\mathcal{L}\sigma_\Upsilon$
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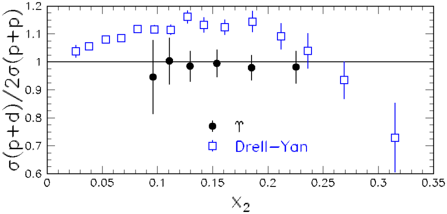
- AIM/HOPE: Extract $g(x, Q^2)$ with Q^2 as low as 10 GeV^2
  from $x = 10^{-3}$ up to $\simeq$ one
- Absolutely complementary to eRHIC (and LHeC)
  whose focus would be low-*x*.
- Use of *pp* vs *pd* $\rightarrow$ access to the
  gluon content in the neutron in a wide *x* domain

cf. E866, Phys. Rev. Lett. 100 062301 (2008)

A Fixed Target ExpeRiment: A quarkonium observatory

Glue in the neutron and in the deuteron

E866 opened the way: $g_n(x, Q^2 \simeq 100\text{GeV}^2) \simeq g_p(x, Q^2 \simeq 100\text{GeV}^2)$



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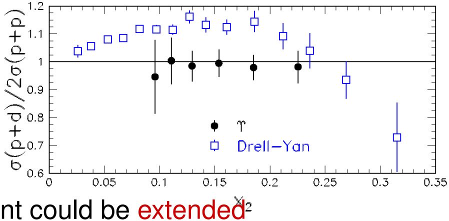

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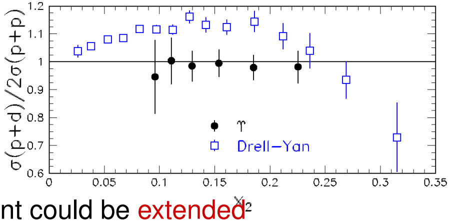

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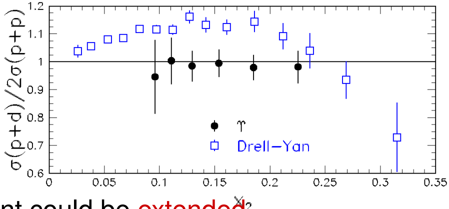

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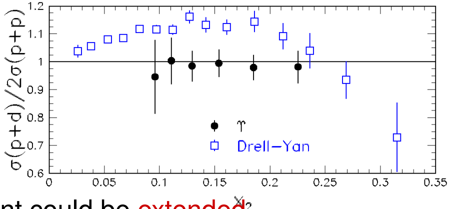

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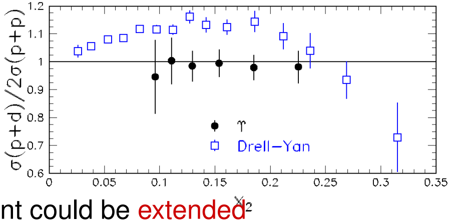

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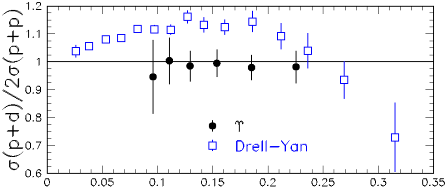

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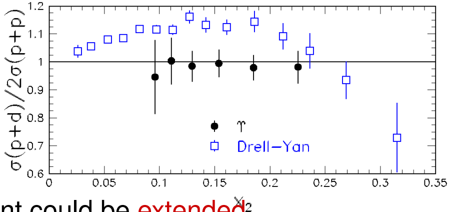

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- Momentum distribution of these gluons "shared" between n and p ?

Part III

AFTER as a quarkonium observatory in *pA*

(Precision analysis of Cold Nuclear Matter Effects)

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  - In general one should be careful with factorization breaking effects:

This calls for different measurements to (in)validate factorization

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  - not to mention ratio with open charm, Drell-Yan, etc ...

Part IV

Heavy-ion physics with AFTER in *PbA* collisions

(the quest for sequential quarkonium suppression)

A Fixed Target ExpeRiment: a quarkonium observatory in *PbA*

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- the possibilities for $c\bar{c}$ recombination
  - Open charm studies are difficult where recombination matters most
    i.e. at low P_T
  - Only indirect indications –from the y and P_T dependence of R_{AA}–
    that recombination may be at work
  - CNM effects may show a non-trivial y and P_T dependence too !
  - not clear what v_2 tells us

A Fixed Target ExpeRiment: a quarkonium observatory in *PbA*

- The excellent capabilities in *pA* should help
  - to reduce the CNM uncertainties
  - to measure their dependence in y and P_T

Rough estimation of the yield: $2 \times 10^7 J/\psi$, $10^4 \Upsilon$ per year (10^6 sec)

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- last but not least, excited states would be studied
  - $\psi(2S)$ thanks to the statistics and the resolution
  - χ_c thanks the excellent colorimetry in high-multiplicity environment
    cf. the CALICE detector using particle flow techniques
  - and maybe ... for the very first time the η_c

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Part V

Spin Physics with AFTER

(the quest for gluon spin contributions)

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  the possibility of polarising the target

see COMPASS, HERMES, CLAS, ...

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- Double Transverse Spin Asymmetries probe transversity
- The beam may become transversely polarised during the crystal extraction

  M. Ukhanov, Nucl. Instrum. Meth. A 582 (2007) 378.

  $\rightarrow$ to be experimentally checked ...

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Transverse Single Spin Asymmetry and quarkonia

Information on the $\mathcal{Q}$ production mechanisms can also obtained in:
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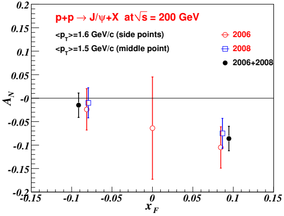

PHENIX, PRD 82, 112008 (2010)

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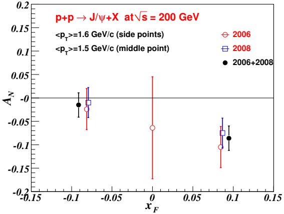

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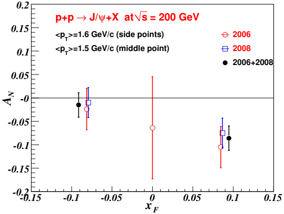

PHENIX, PRD 82, 112008 (2010)

- At $x_F > 0$, the gluon from the $p^{\uparrow}$ has a larger x_B
- It knows more about the proton spin than at low x_B → SSA grows

Spin Asymmetries and quarkonia

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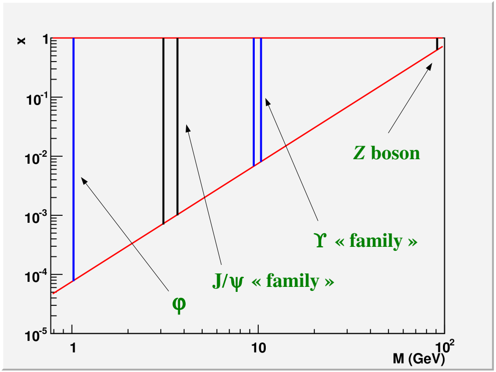
- Of course, transverse SSA can be studied in parallel for other mesons (*D*, *B*, ...)
- In general, the backward region is the most favourable allowing for measurements in the large *x* region of the polarised nucleon

Part VI

More with AFTER

(Drell-Yan, jet and W/Z)

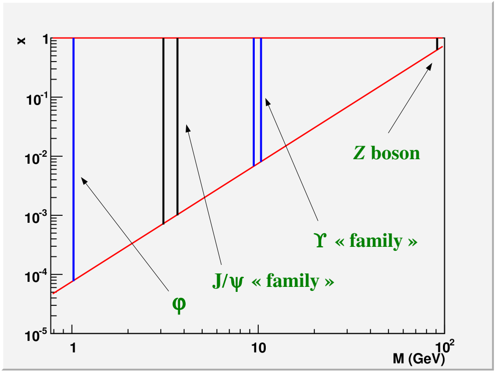
➟ Region in x probed by dilepton production as function of $M_{\ell\ell}$



A Fixed Target ExpeRiment

A dilepton observatory

- Region in x probed by dilepton production as function of $M_{\ell\ell}$
  - → Above $c\bar{c}$: $x \in [10^{-3}, 1]$
  - → Above $b\bar{b}$: $x \in [9 \times 10^{-3}, 1]$



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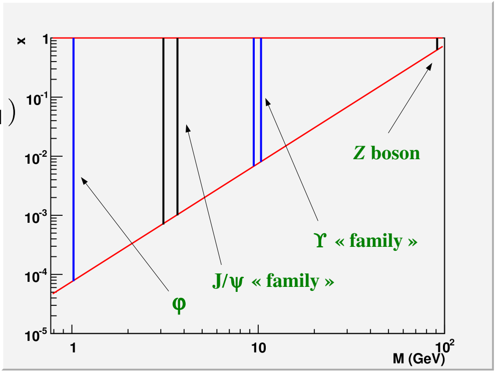

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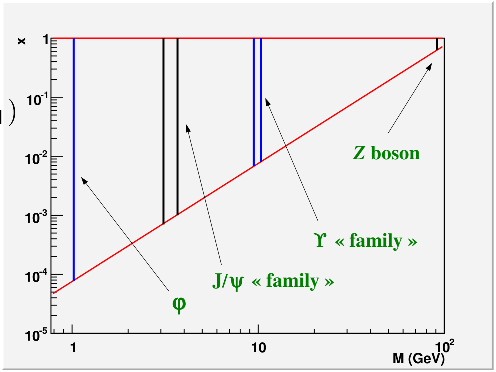
→ sea-quark asymetries via p and d studies

- at large(est) x: backward ("easy")

- at small(est) x: forward (need to stop the (extracted) beam)



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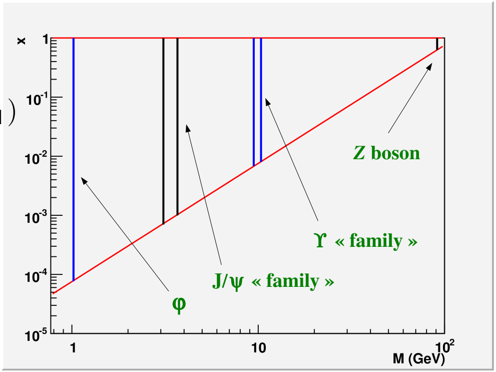
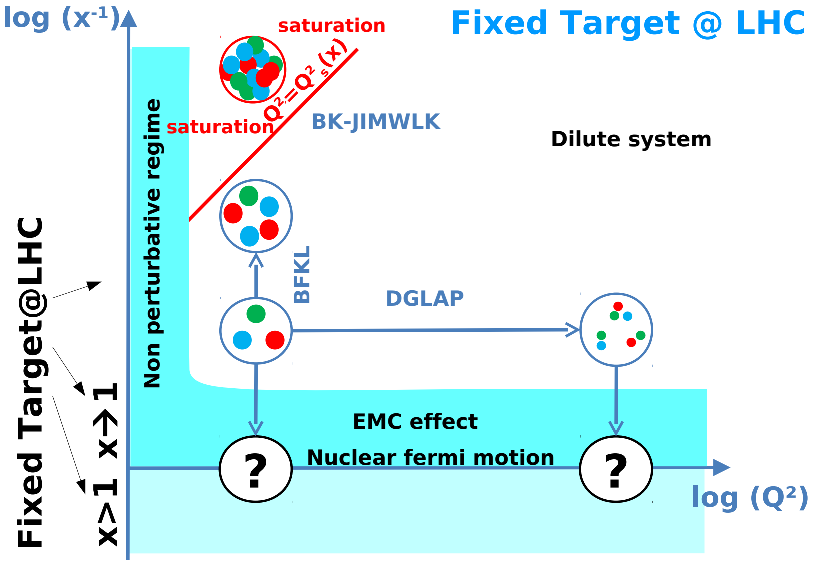


➟ To do: to look at the rates to see how competitive this will be

Overall



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Fixed Target @ LHC
$Q^2=Q^2_s(x)$
saturation
BK-JIMWLK
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Non perturbative regime
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x>1
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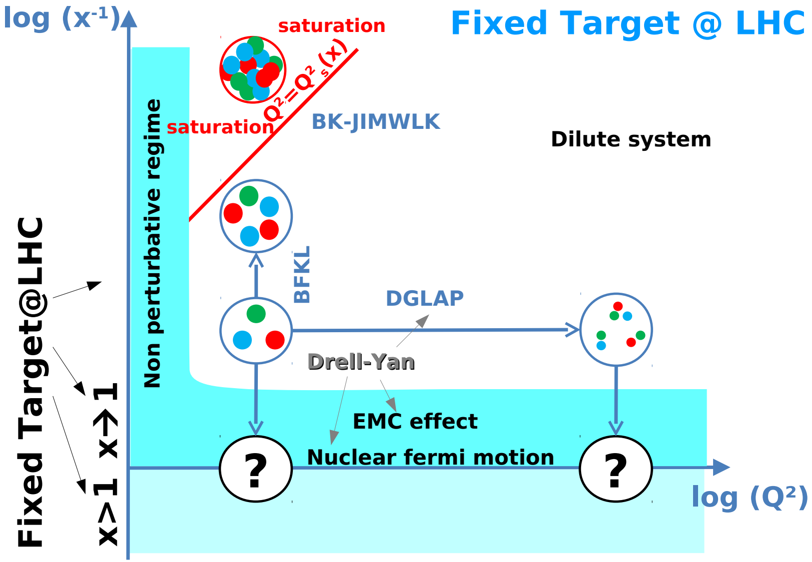

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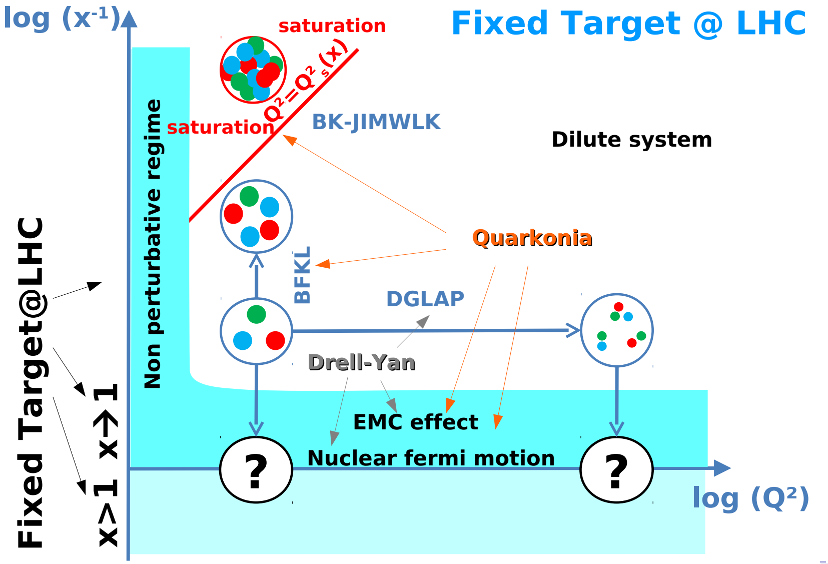

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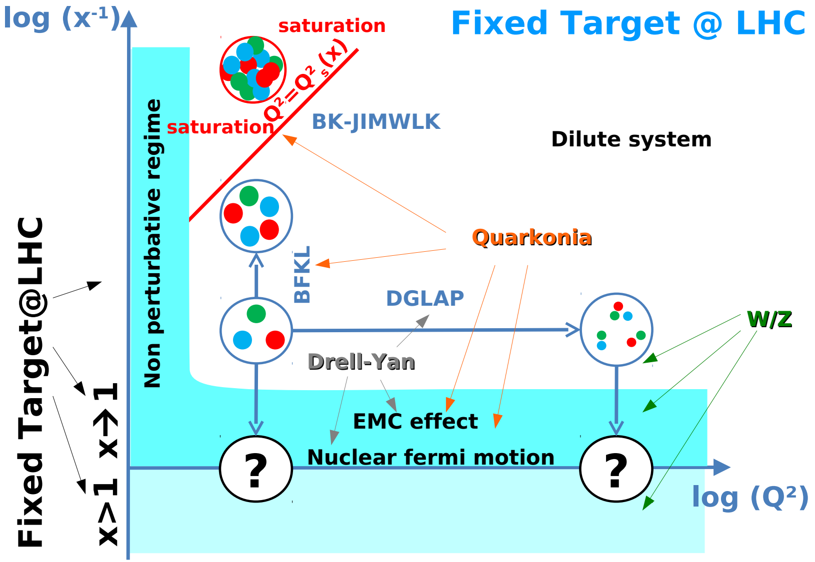

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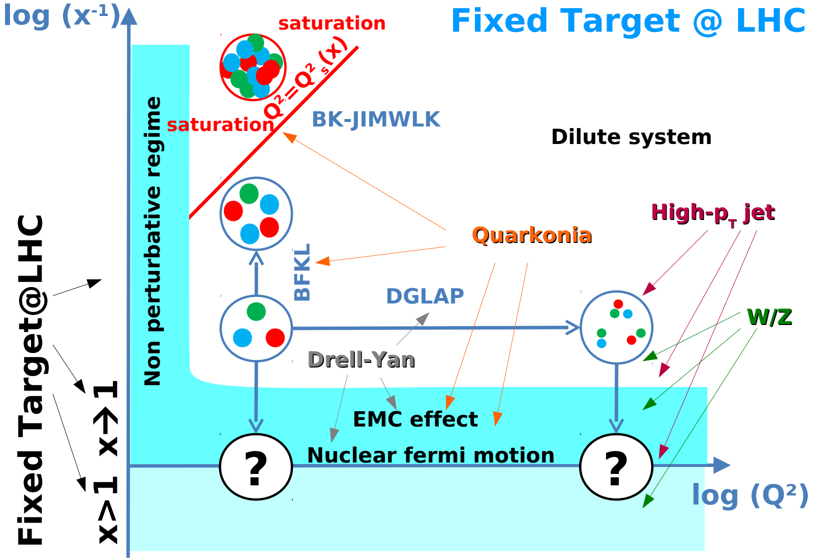

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Part VII

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- Planned LHC long shutdown ($<$ 2020 ?) could be used to install the extraction system
- Very good complementarity with electron-ion programs

Part VIII

Backup slides

Beam extraction

- **Beam extraction @ LHC**

… there are extremely promising possibilities to extract 7 TeV protons from the circulating beam by means of a bent crystal.

… The idea is to put a bent, single crystal of either Si or Ge (W would perform slightly better but needs substantial improvements in crystal quality) at a distance of $\simeq 7\sigma$ to the beam where it can intercept and deflect part of the beam halo by an angle similar to the one the foreseen dump kicking system will apply to the circulating beam.

… ions with the same momentum per charge as protons are deflected in a crystal with similar efficiencies

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NIM B Beam Interactions with Materials & Atoms
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Strong crystalline fields – a possibility for extraction from the LHC

E. Uggerhøj, U.I. Uggerhøj *
Department of Physics and Astronomy, University of Aarhus, Ny Munkegade, Aarhus C DK-8000, Denmark

Received 9 September 2004; received in revised form 6 January 2005
Available online 24 February 2005

If the crystal is positioned at the kicking section, the whole dump system can be used for slow extraction of parts of the beam halo, the particles that are anyway lost subsequently at collimators.

Need for a quarkonium observatory

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PHYSICAL REVIEW D VOLUME 37, NUMBER 5 1 MARCH 1988

Structure-function analysis and ψ, jet, W, and Z production: Determining the gluon distribution

A. D. Martin
Department of Physics, University of Durham, Durham, England

R. G. Roberts
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W. J. Stirling
Department of Physics, University of Durham, Durham, England

(Received 27 July 1987)

We perform a next-to-leading-order structure-function analysis of deep-inelastic μN and νN scattering data and find acceptable fits for a range of input gluon distributions. We show three equally acceptable sets of parton distributions which correspond to gluon distributions which are (1) “soft,” (2) “hard,” and (3) which behave as $xG(x) \sim 1/\sqrt{x}$ at small x. J/ψ and prompt photon hadroproduction data are used to discriminate between the three sets. Set 1, with the “soft”-gluon distribution, is favored. W, Z, and jet production data from the CERN collider are well described but do not distinguish between the sets of structure functions. The precision of the predictions for σ_W and σ_Z allow the collider measurements to yield information on the number of light neutrinos and the mass of the top quark. Finally we discuss how the gluon distribution at very small x may be directly measured at DESY HERA.

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Z. Phys. C – Particles and Fields 38, 473–478 (1988)

J/ψ Production at large transverse momentum at hadron colliders

E.W.N. Glover[1]*, A.D. Martin[2], W.J. Stirling[2]

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[2] Physics Department, University of Durham, Durham, DH1 3LE, England

Received 7 October 1987

Abstract. We calculate J/ψ hadroproduction and emphasize the importance of the J/ψ signal as a measure of $b\bar{b}$ production via the decay $B \to \psi X$ and of the gluon structure function at low x via χ hadroproduction followed by $\chi \to \psi\gamma$ decay. We compare with UA1 data and data at ISR energies and make predictions for ψ production at TEVATRON energies.

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PHYSICAL REVIEW D VOLUME 48, NUMBER 11 1 DECEMBER 1993

ψ production in $\bar{p}N$ and $\pi^- N$ interactions at 125 GeV/c and a determination of the gluon structure functions of the $\bar{p}$ and the π^-

C. Akerlof,[4] H. Areti,[3,*] M. Binkley,[2] S. Conetti,[3,†] B. Cox,[2,†] J. Enagonio,[2]
He Mao,[5] C. Hojvat,[2] D. Judd,[2,‡] S. Katsanevas,[1] R. D. Kephart,[2] C. Kourkoumelis,[1] P. Kraushaar,[4,§]
P. Lebrun,[3,*] P. K. Malhotra,[2,∥] A. Markou,[1] P. O. Mazur,[2] D. Nitz,[4] L. K. Resvanis,[1] D. Ryan,[3]
T. Ryan,[3,¶] W. Schappert,[3,**] D. G. Stairs,[3] R. Thun,[4] F. Turkot,[2] S. Tzamarias,[1,††] G. Voulgaris,[1]
R. L. Wagner,[2] D. E. Wagoner,[2,‡] W. Yang,[2] and Zhang Nai-jian[5]

(E537 Collaboration)

[1] *University of Athens, Athens, Greece*
[2] *Fermi National Accelerator Laboratory, Batavia, Illinois 60510*
[3] *McGill University, Montreal, Quebec, Canada H3A 2T8*
[4] *University of Michigan, Ann Arbor, Michigan 48109*
[5] *Shandong University, Jinan, People's Republic of China*

(Received 9 February 1993)

We have measured the cross section for production of ψ and ψ' in $\bar{p}$ and π^- interactions with Be, Cu, and W targets in experiment E537 at Fermilab. The measurements were performed at 125 GeV/c using a forward dimuon spectrometer in a closed geometry configuration. The gluon structure functions of the $\bar{p}$ and π^- have been extracted from the measured $d\sigma/dx_F$ spectra of the produced ψ's. From the $\bar{p}$W data we obtain, for $\bar{p}$, $xG(x)=(2.15\pm0.7)[1-x]^{(6.83\pm0.5)}[1+(5.85\pm0.95)x]$. In the π^- case, we obtain, from the W and the Be data separately, $xG(x)=(1.49\pm0.03)[1-x]^{(1.98\pm0.06)}$ (for π^-W), $xG(x)=(1.10\pm0.10)[1-x]^{(1.20\pm0.20)}$ (for π^-Be).

More on quarkonium as a probe...

- New observables involving quarkonia are needed to pin down the production mechanism **see e.g. JPL, talk at Quarkonium Production, Vienna, 18-21 April 2001**

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Double J/ψ production: a probe of gluon polarization?

S.P. Baranov[1], H. Jung[2]

[1]P.N.Lebedev Physical Institute, Moscow 117924, Russia
[2]III. Physikalisches Institut, Lehrstuhl B, RWTH Aachen, Germany

Received: 5 July 1994/Revised version: 5 October 1994 Z. Phys. C 66, 647–651 (1995)

Abstract. We consider the process of direct simultaneous production of two J/ψ particles and discuss the possibility that it can be used as a tool to measure the gluon polarization in the colliding particles.

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PHYSICAL REVIEW D VOLUME 49, NUMBER 9 1 MAY 1994

Associated $J/\psi + \gamma$ production as a probe of the polarized gluon distribution

M. A. Doncheski*
Department of Physics, University of Wisconsin, Madison, Wisconsin 53706

C. S. Kim
Department of Physics, Yonsei University, Seoul 120, Korea
(Received 15 March 1993)

Associated production of J/ψ and a γ has recently been proposed as a clean probe of the gluon distribution. The same mechanism can be used to probe the polarized gluon content of the proton in polarized proton-proton collisions. We study $J/\psi + \gamma$ production at both polarized fixed target and polarized collider energies.

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Pair production of J/ψ as a probe of double parton scattering at LHCb

C. H. Kom* and W. J. Stirling†
Cavendish Laboratory, J.J. Thomson Avenue, Cambridge CB3 0HE, United Kingdom

A. Kulesza‡
Institute for Theoretical Particle Physics and Cosmology, RWTH Aachen University D-52056 Aachen, Germany
(Dated: May 24, 2011)

We argue that the recent LHCb observation of J/ψ–pair production indicates a significant contribution from double parton scattering, in addition to the standard single parton scattering component. We propose a method to measure the double parton scattering at LHCb using leptonic final states from the decay of two prompt J/ψ mesons.

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Institute for Theoretical Particle Physics and Cosmology, RWTH Aachen University D-52056 Aachen, Germany
(Dated: May 24, 2011)

We argue that the recent LHCb observation of J/ψ–pair production indicates a significant contribution from double parton scattering, in addition to the standard single parton scattering component. We propose a method to measure the double parton scattering at LHCb using leptonic final states from the decay of two prompt J/ψ mesons.

- Double J/ψ, $J/\psi+\gamma$, $J/\psi+D$, ... can of course be studied with AFTER

A Fixed Target ExpeRiment

One exotic illustration of the potentialities:

Ultra-peripheral collisions

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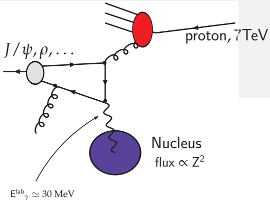
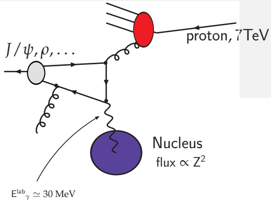
Ultra-peripheral collisions



Inelastic photoproduction of J/ψ via UPC*

A Fixed Target ExpeRiment

One exotic illustration of the potentialities: Ultra-peripheral collisions



Inelastic photoproduction of J/ψ via UPC*

Thanks to the boost: $W^{max}_{\gamma+p}$ for a coherent photon emission (Z^2 fact.) can be as high as 25 GeV !

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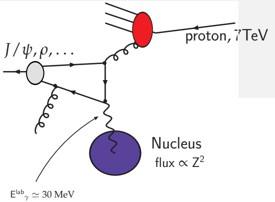

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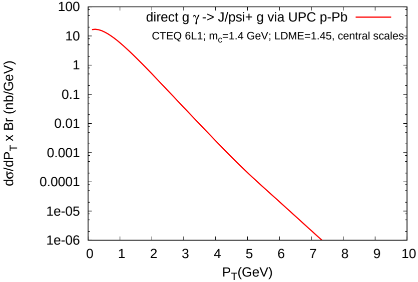

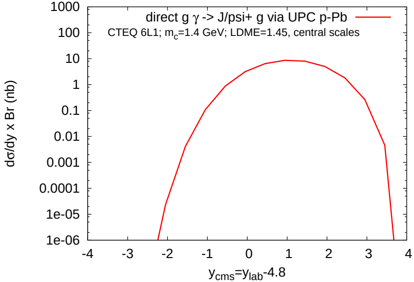

Disclaimer: these numbers suppose a dedicated trigger and are preliminary

A photon-proton collider at the LHC ?

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- True also for diffractive J/ψ photoproduction
- Handle on gluons (not sure though that one can compete in some way with EICs)

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ZEITSCHRIFT FÜR PHYSIK C

Diffractive J/ψ photoproduction as a probe of the gluon density

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Abstract. We use perturbative QCD, beyond the leading $\ln Q^2$ approximation, to show how measurements of diffractive J/ψ production at HERA can provide a sensitive probe of the gluon density of the proton at small values of Bjorken x. We estimate both the effect of the relativistic motion of the c and $\bar{c}$ within the J/ψ and of the rescattering of the $c\bar{c}$ quark pair on the proton. We find that the available data for diffractive J/ψ photoproduction can discriminate between the gluon distributions of the most recent sets of partons.