Spin physics with AFTER

AFTER @ LHC

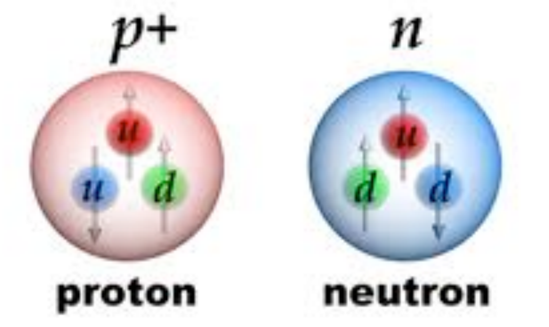
Cynthia Hadjidakis

Joint meeting LUA9-AFTER
Orsay, November 18th 2013

- Nucleon spin physics
- Physics opportunities with AFTER
- Polarizing the target

Probing the nucleon structure

Nucleon constituents:
quarks (u, d, s, ...) and
gluons



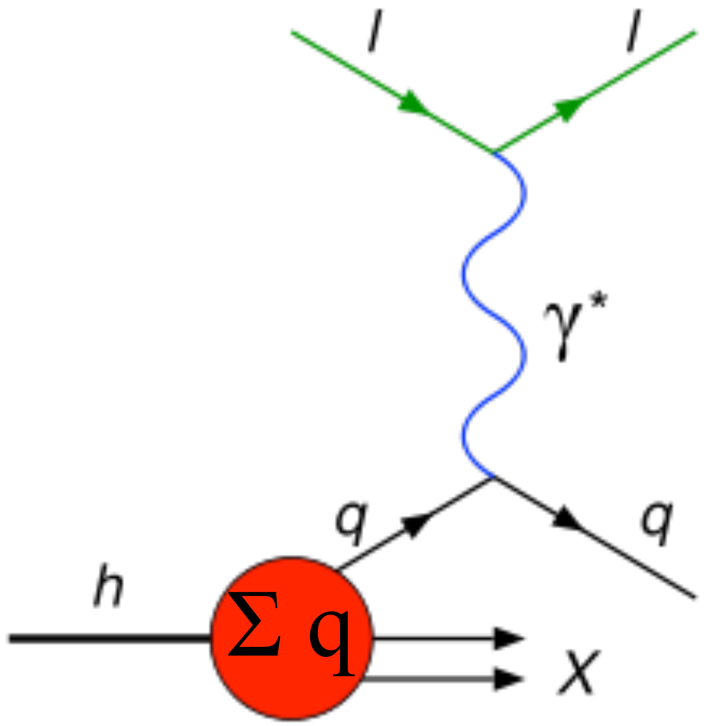
Deep inelastic scattering experiments: l p → l X
scale = Q : virtual photon energy

Drell-Yan experiments: p p → l$^+$ l$^-$ X
scale = Q : l$^+$ l$^-$ invariant mass

and also:
p p → jet
p p → W, Z
p p → Isolated photons
...

Momentum distribution function f_1 measurements
→ q(x,Q^2): parton distribution functions (pdfs)
probability to find a parton in the nucleon with a longitudinal momentum fraction x at momentum transfer Q^2

Deep Inelastic Scattering (DIS)



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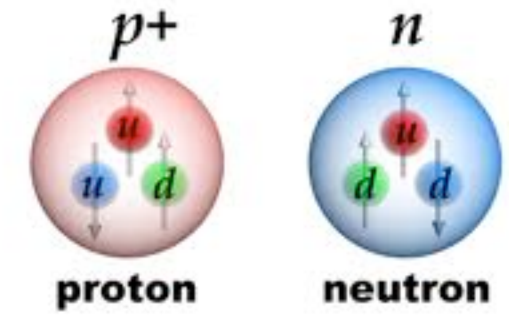

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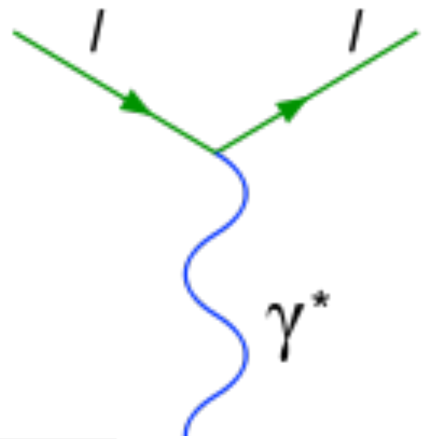

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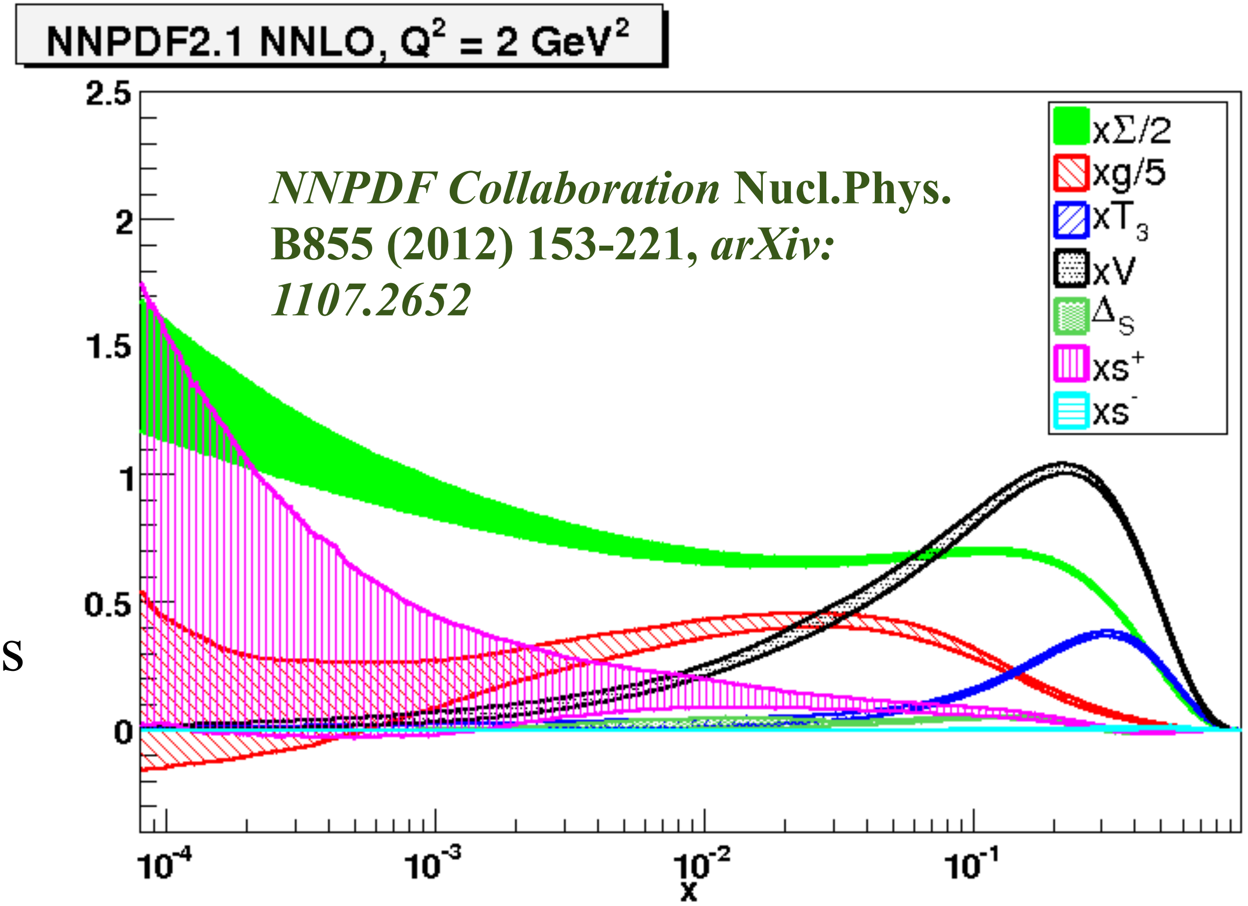

NNPDF Collaboration Nucl.Phys. B855 (2012) 153-221, *arXiv: 1107.2652*

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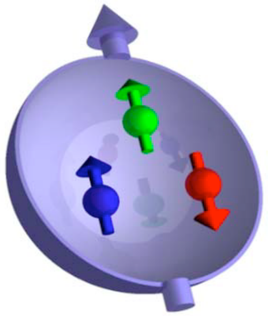
The spin puzzle of the nucleon

Nucleon spin = 1/2: how do the partons form the nucleon spin?

$$S_N = \frac{1}{2} = \frac{1}{2}\overbrace{(\Delta u_v + \Delta d_v + \Delta q_s)}^{\approx 30\%} + \overbrace{\Delta G}^{\approx 0\%} + \overset{?}{\Delta L_z^q + \Delta L_z^g}$$



total quark contribution

gluon contribution

angular momentum

Parton distribution functions

8 distributions

- three leading twist pdfs: f_1 , g_1 and h_1
  - depend on (x, Q^2)
- five Transverse Momentum Distributions (TMDs)
  - depend on (x, Q^2, k_T) with k_T the parton transverse momentum → 3-D picture of the nucleon
  - vanish when integrating over k_T
  - describe the correlations between the parton or the nucleon spin with the parton transverse momentum: spin-orbit correlations

quark polarization

nucleon polarization

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

unpolarized targets

polarized targets: measure single spin asymmetries $\Delta\sigma = \sigma^{\uparrow} - \sigma^{\downarrow}$

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Boer-Mulders

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Sivers

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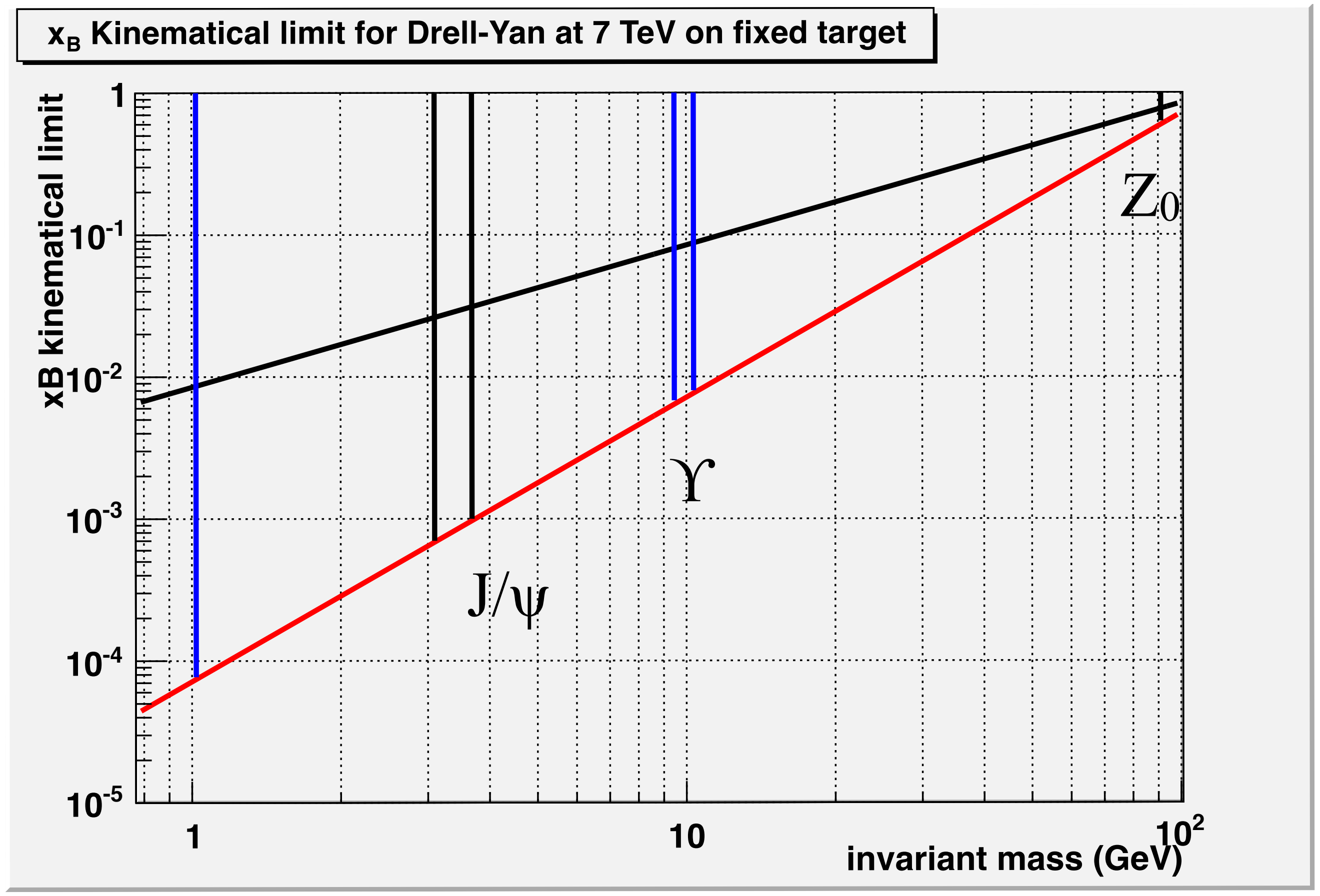
Drell-Yan kinematics with AFTER

Kinematics: 7 TeV proton beam on fixed hydrogen/deuterium target

- $\sqrt{s} = 115$ GeV and $y_{beam} = 4.8$
- $\tau = x_{beam}\, x_{target} = (M^2/\, s) = x_{min}$
- $x_{target} = x_{beam} = M/\sqrt{s}$



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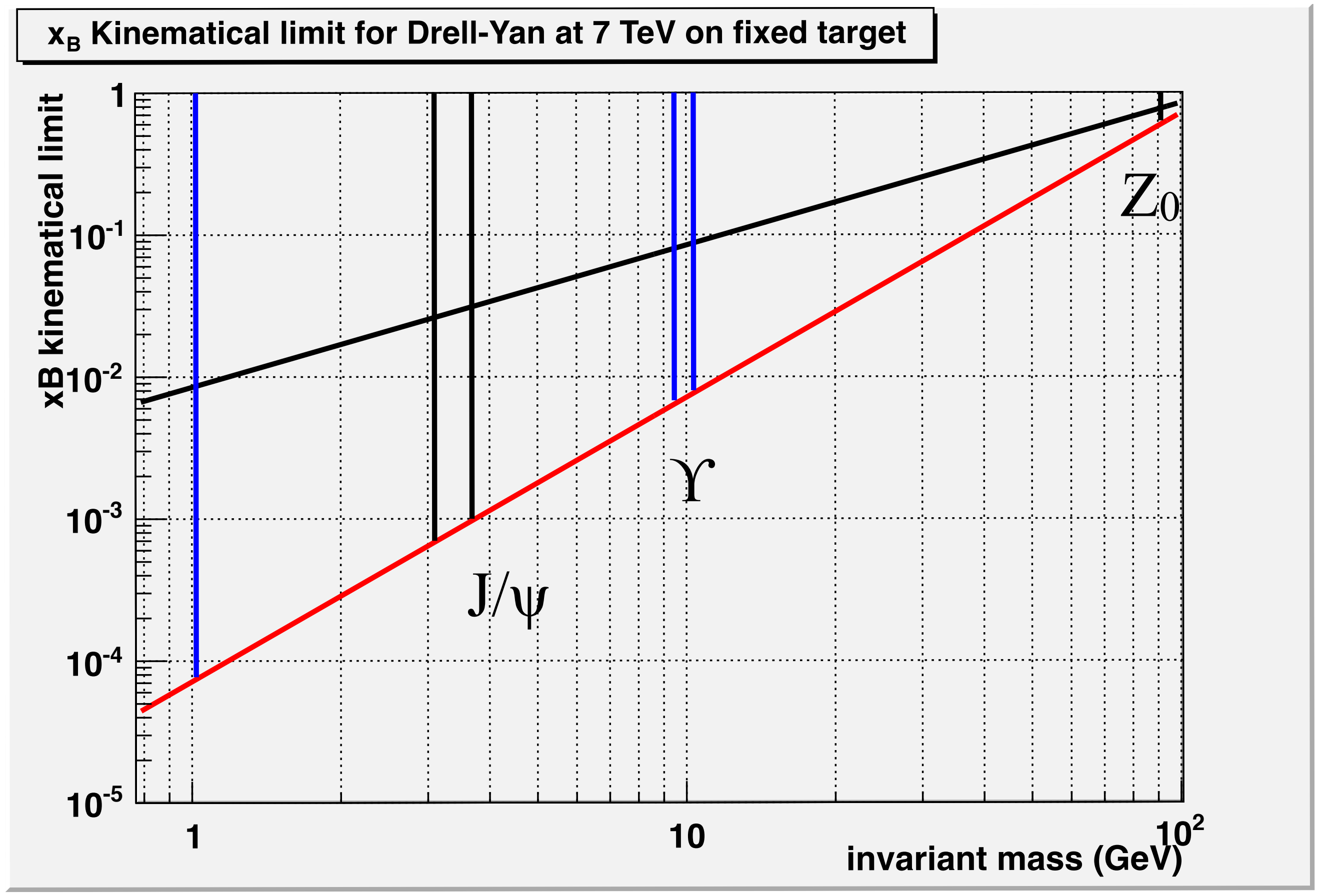
$y > 0$

x_{beam}

$x_{target} = x_{beam}$

x_{target}



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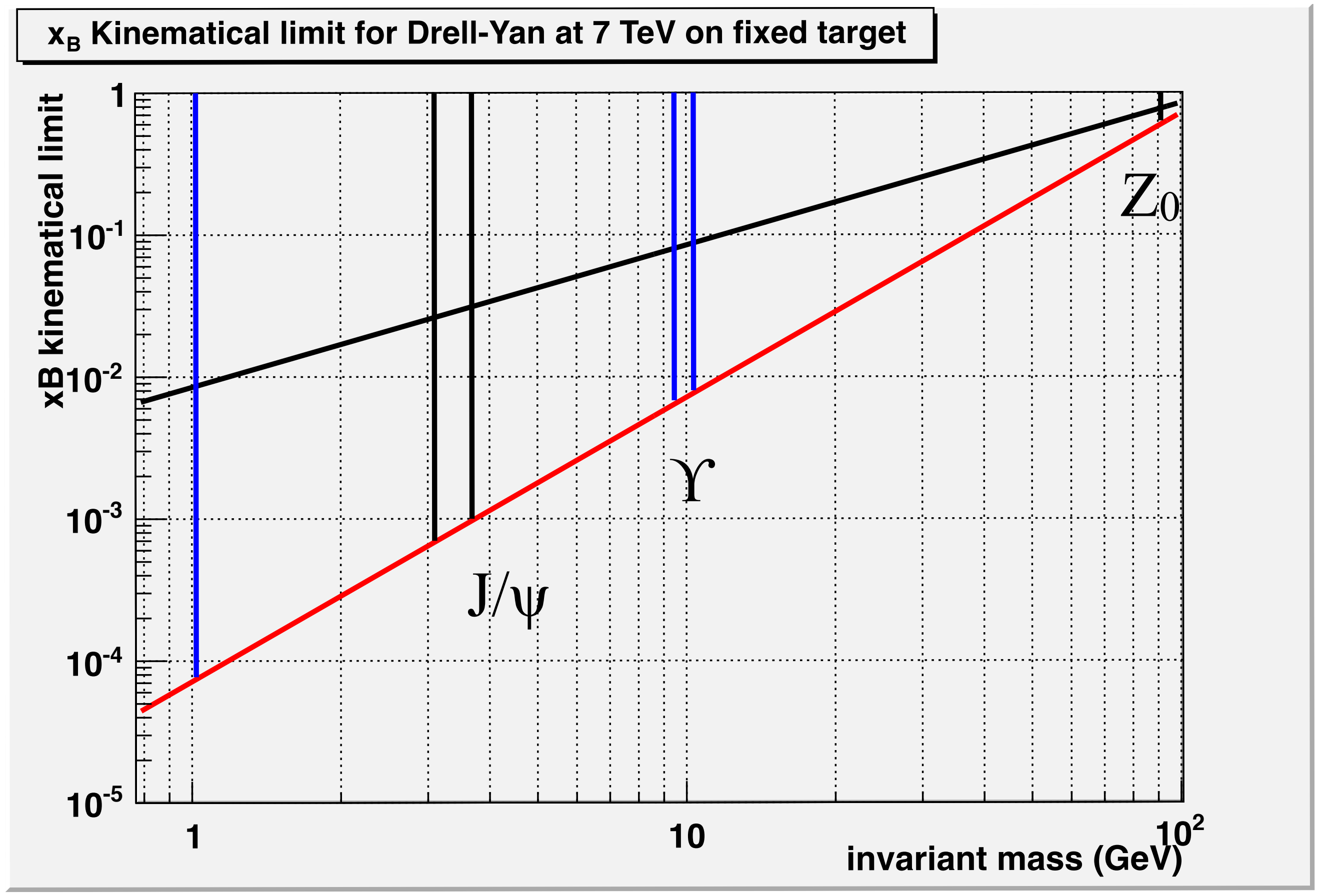

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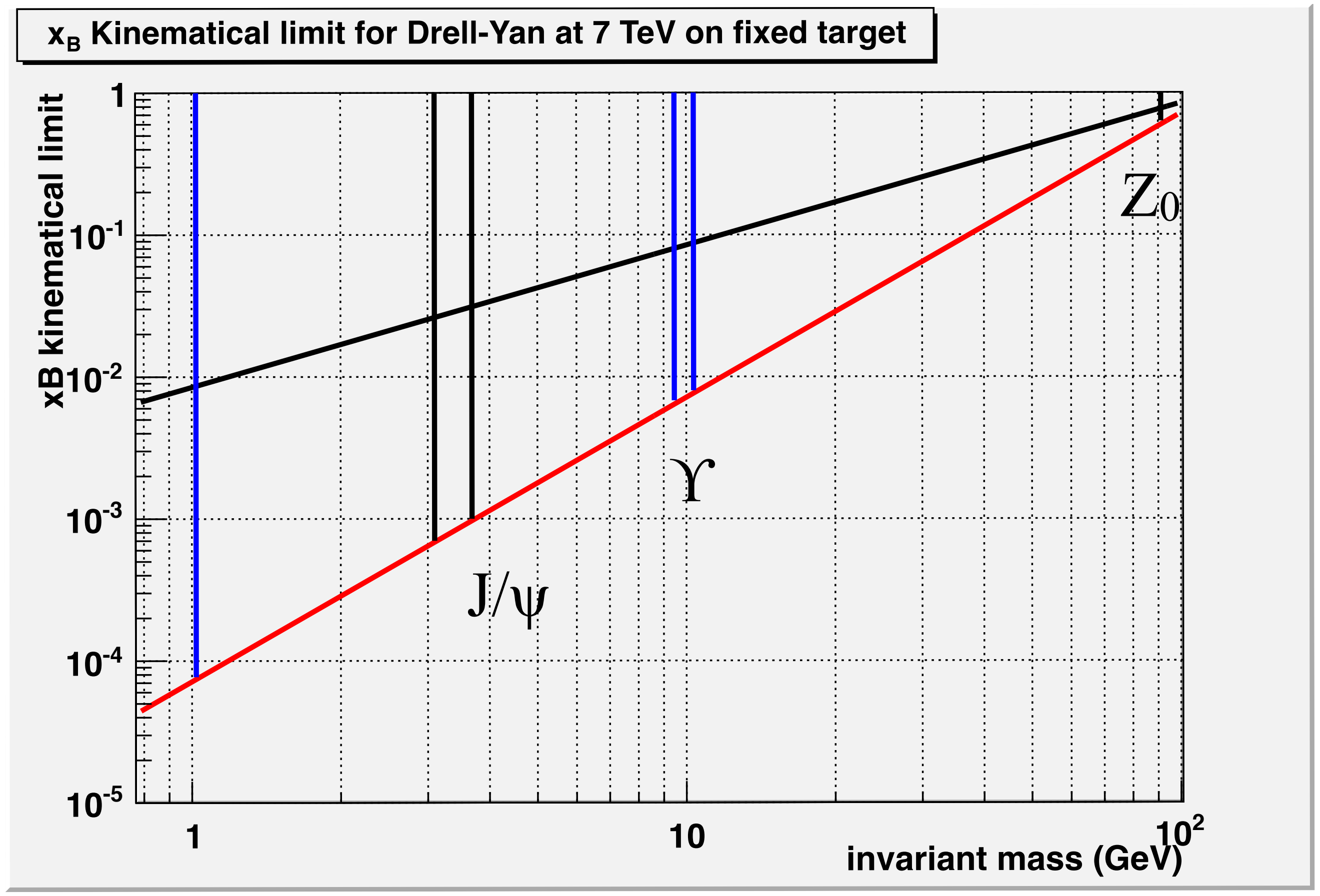
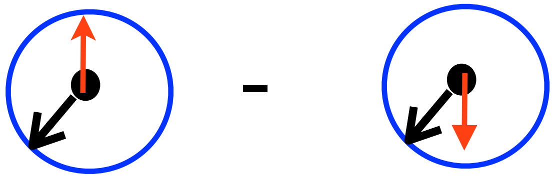


Rapidity boost: good condition to access backward rapidity region and large target x_{target} and low $x_F = x_{beam} - x_{target} \rightarrow -1$: target-rapidity region

Unpolarized target: Boer-Mulders effect

Boer-Mulders effect: correlation between the **parton $\mathbf{k_T}$** and **its spin** (in an **unpolarized nucleon**)



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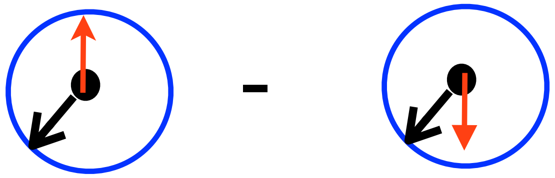
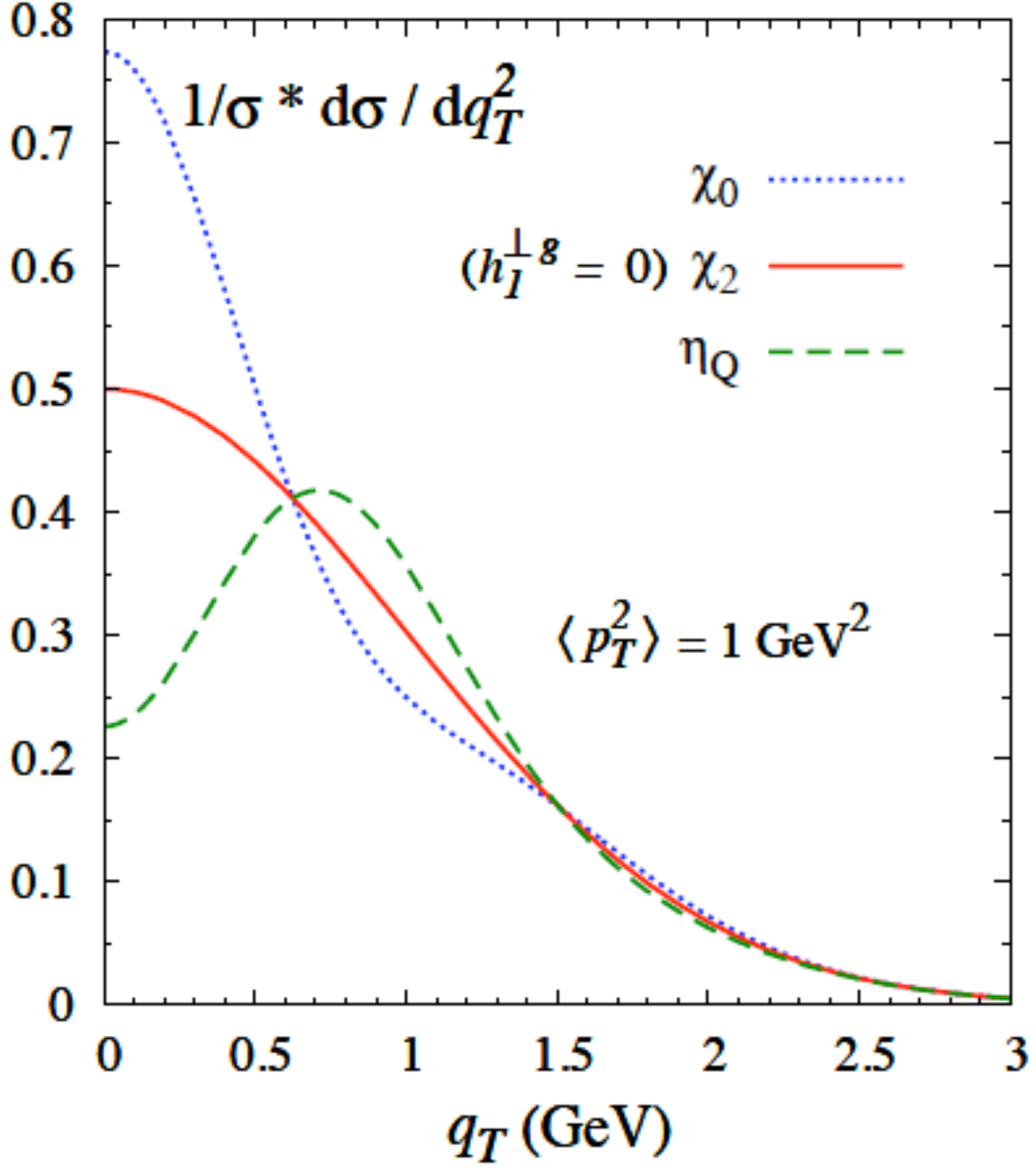


Double-node structure of transverse-momentum distributions predicted for scalar and pseudoscalar quarkonia → give access to the Boer-Mulders TMD pdf for gluons

Boer and Pisano Phys.Rev. D86 (2012) 094007



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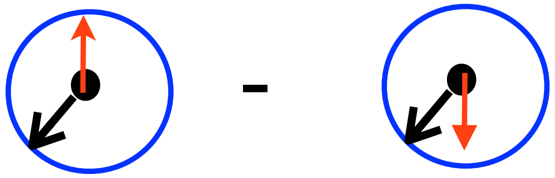

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- **Experimental probes @ AFTER**

- large quarkonium yields expected: scalar and pseudoscalar quarkonia: χ_{c0}, χ_{b0}, η_c, η_b
- PID and modern calorimetry

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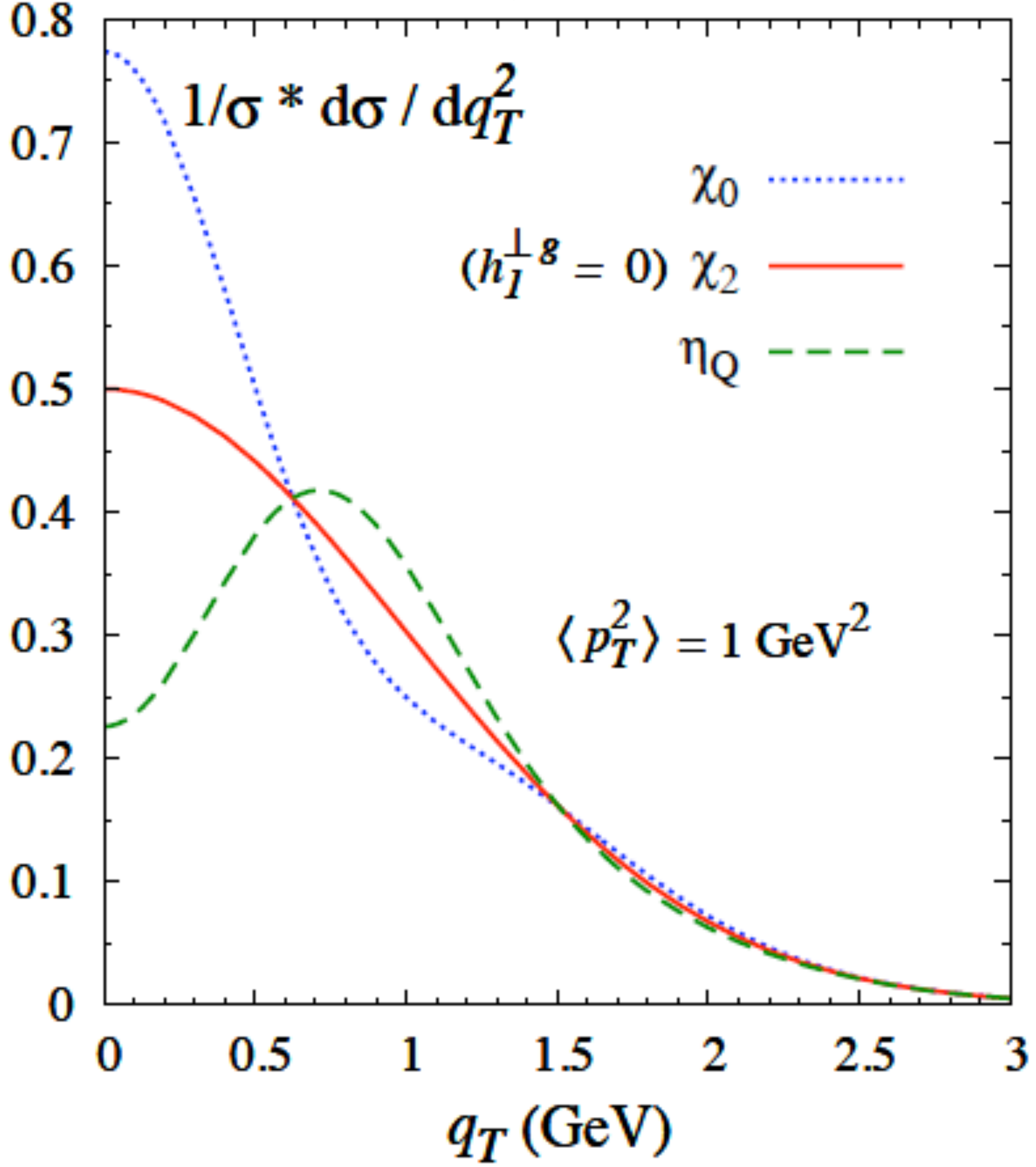
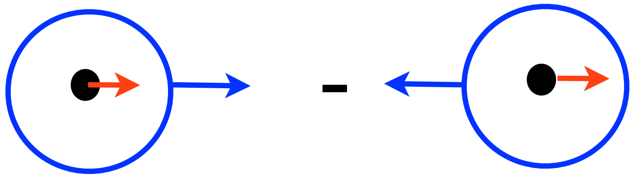
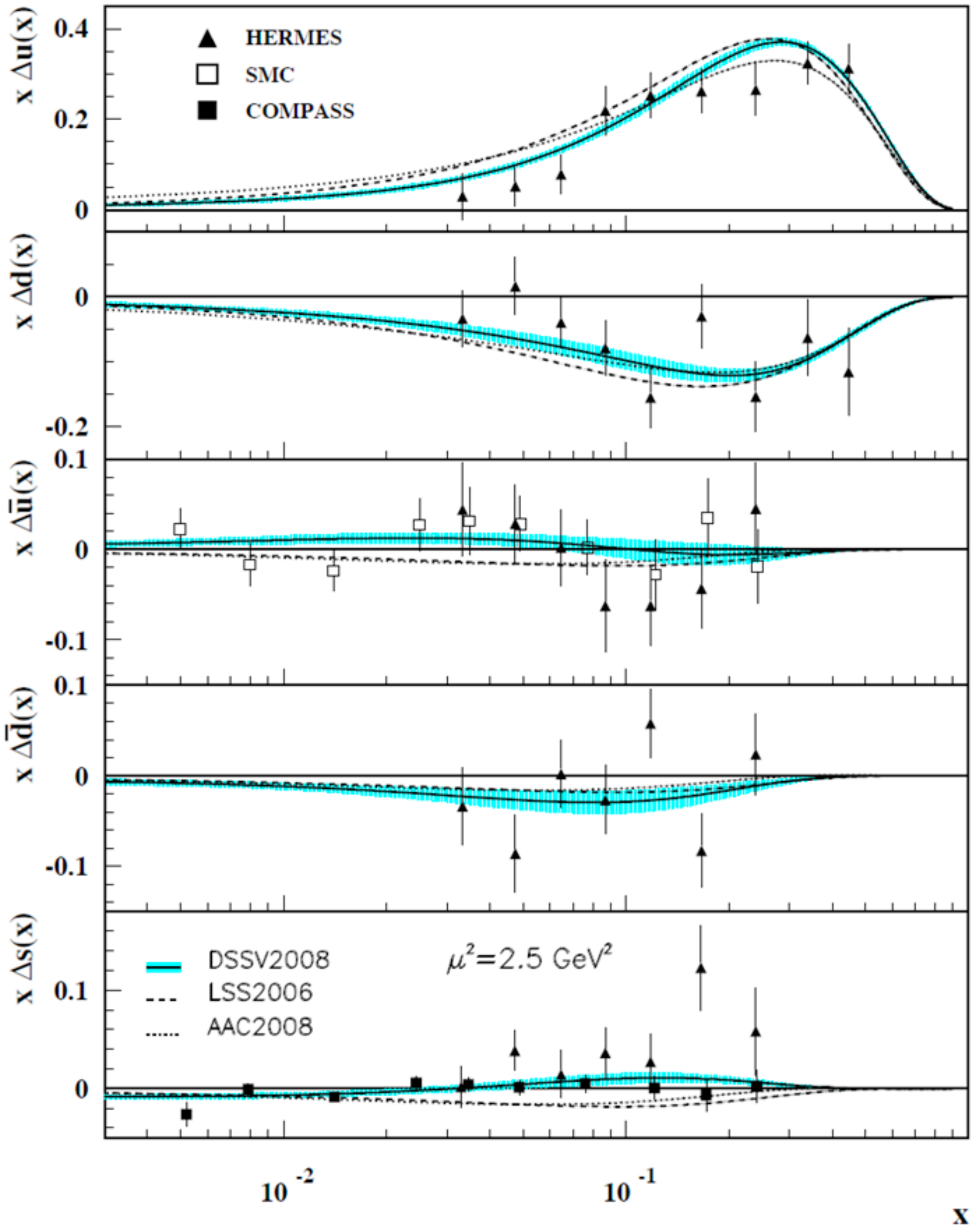


Longitudinal polarized target: helicity distr.

parton helicity distribution in a **longitudinally polarized nucleon**:





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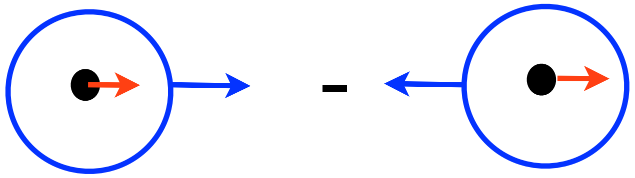
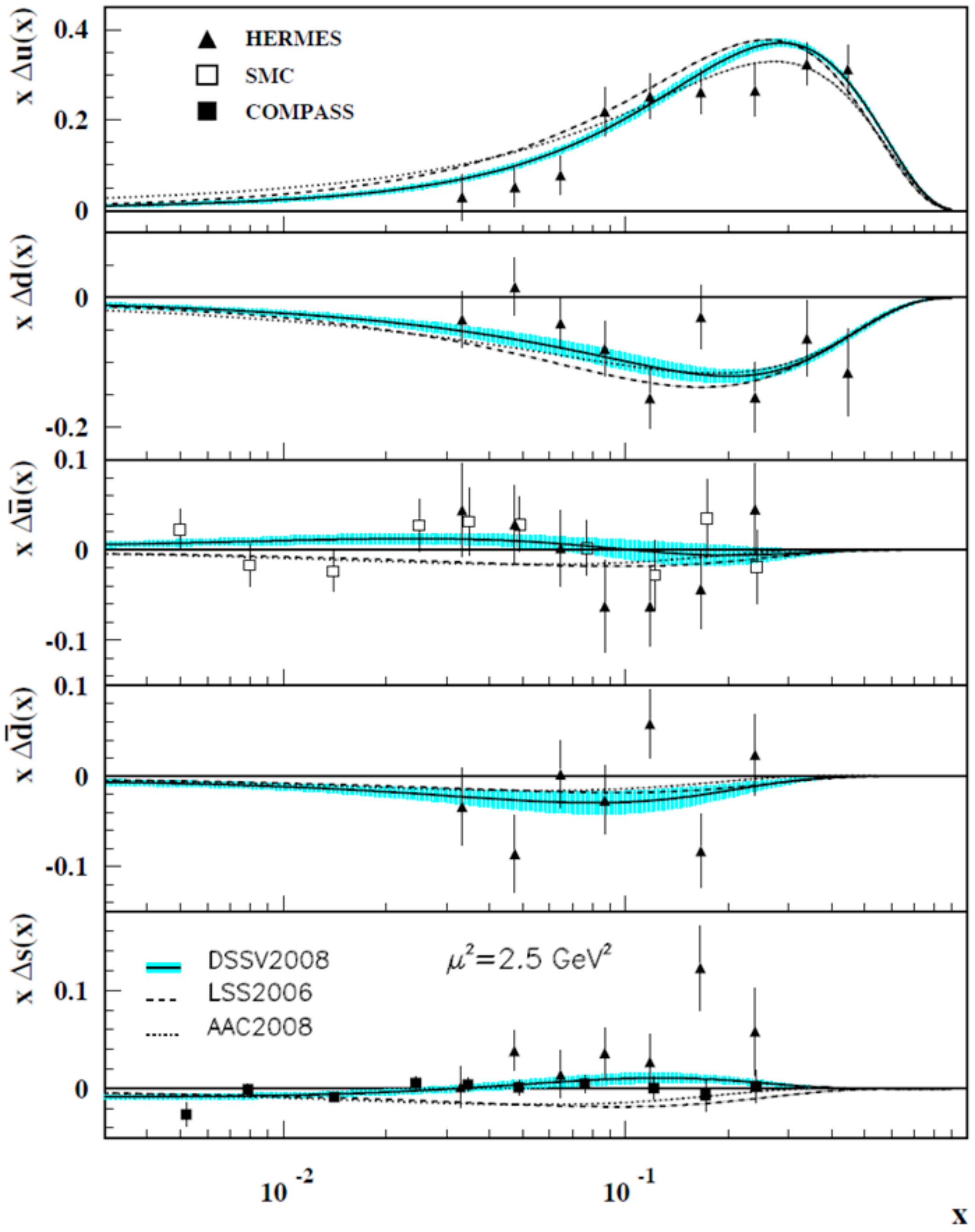


- **Experimental probes @ AFTER**
  - $W^{+/-}$ → individual helicity distribution of quark and anti-quark



Transversaly polarized target: Sivers effect

Sivers effect in a **transversaly polarized nucleon**:
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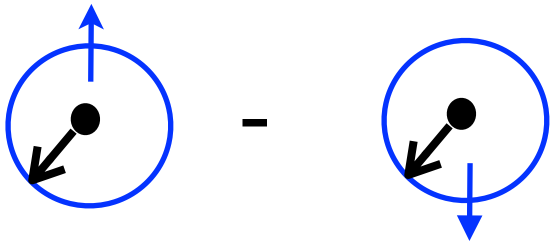

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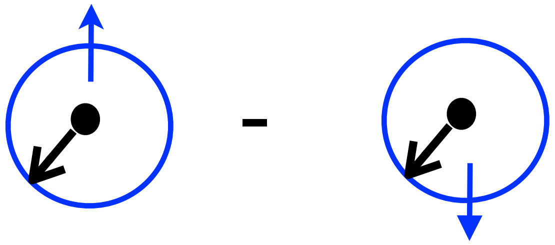

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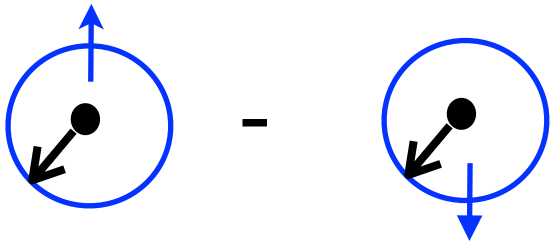

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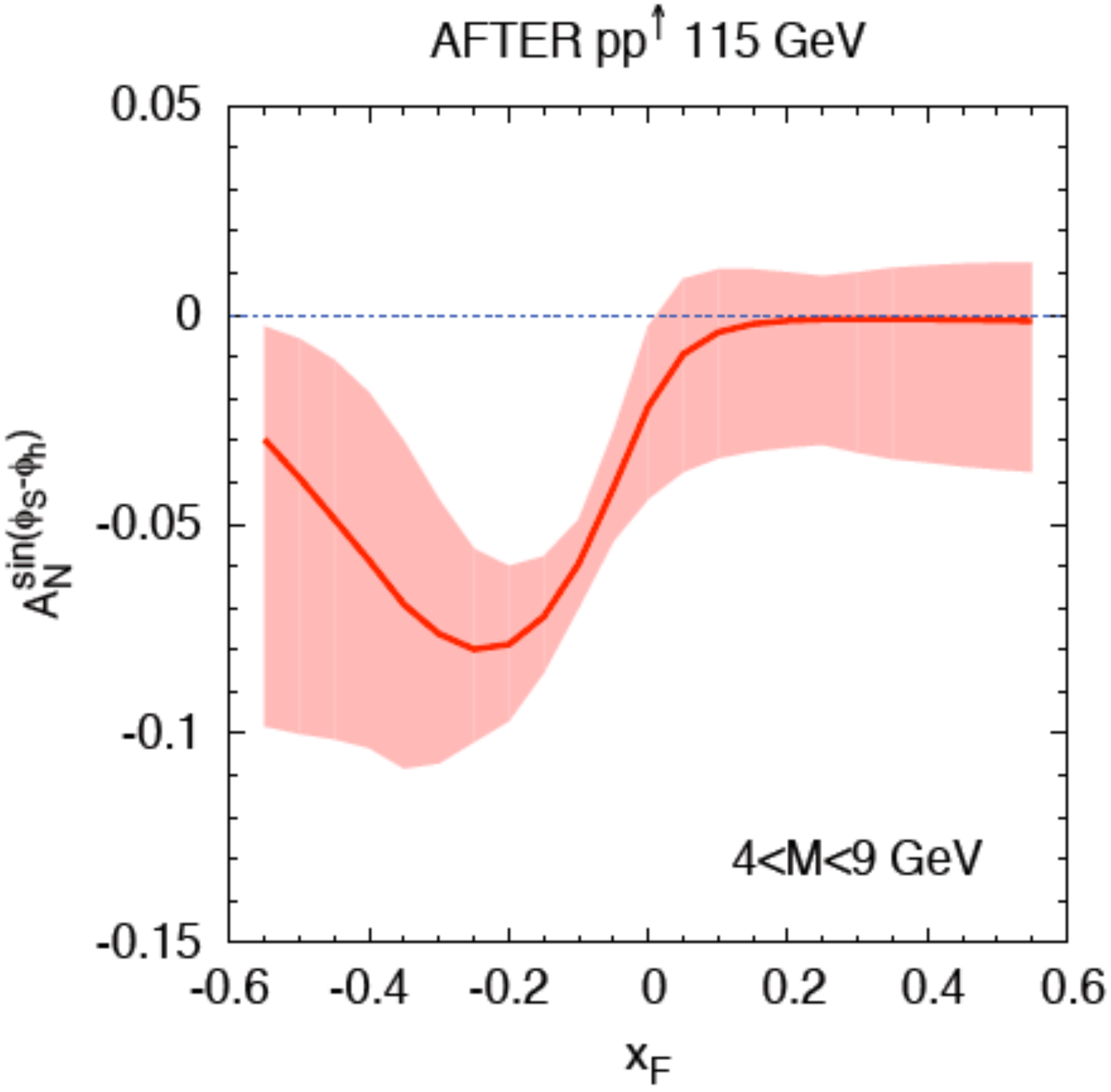
M. Anselmino Trento 2013



see also T. Liu and B.Q. Ma Eur.Phys.J. C72 (2012) 2037

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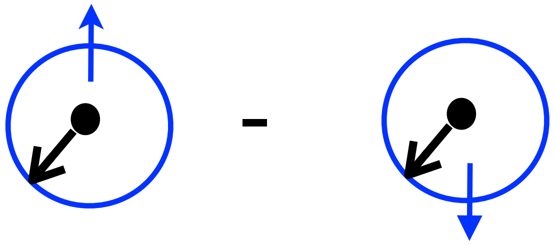

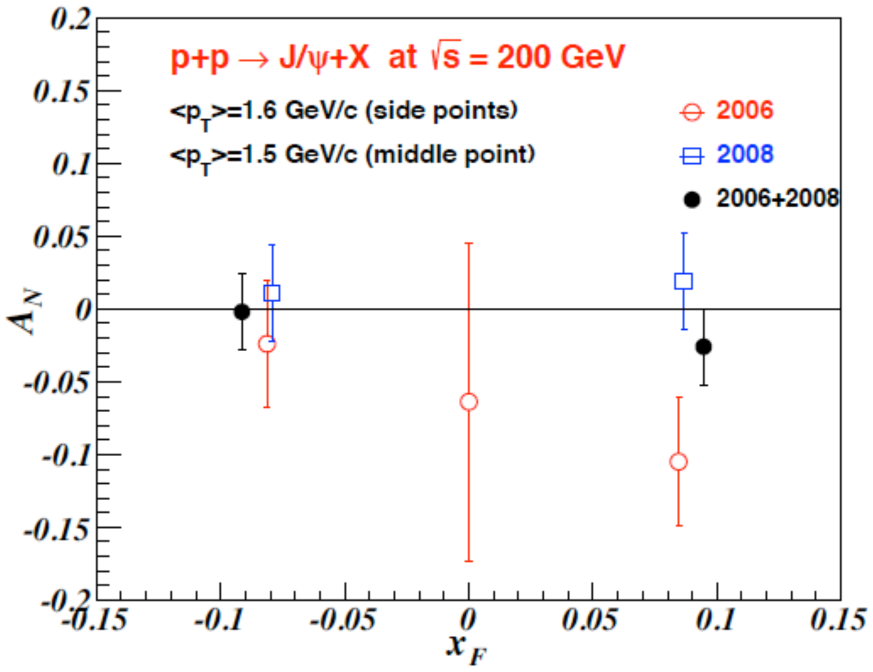

Non-zero gluon Sivers function produce a finite SSA for color-single J/ψ

Yuan PRD 78 (2008) 014024

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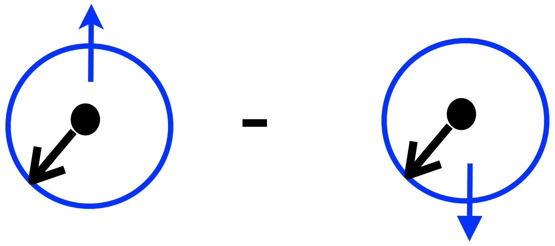

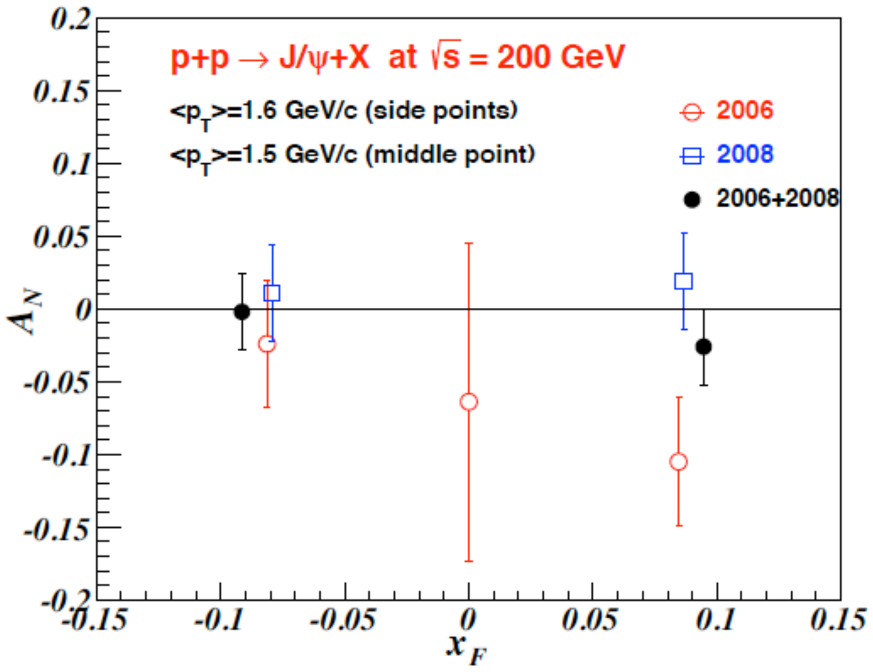

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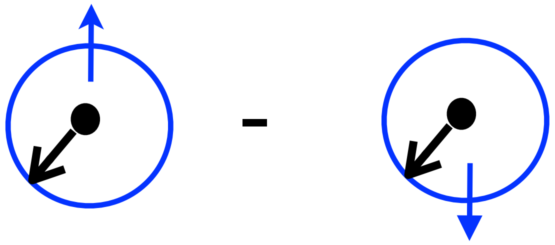

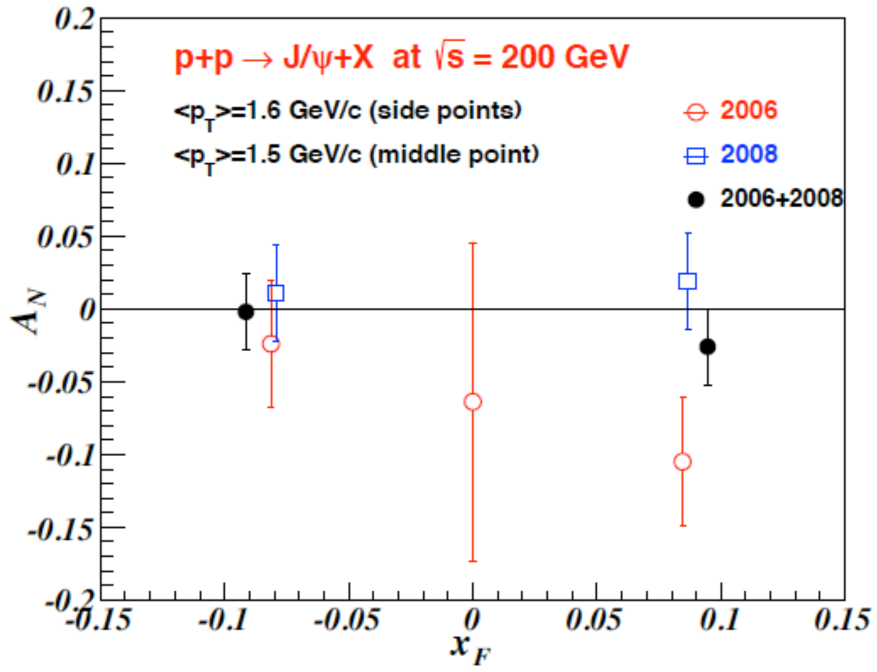

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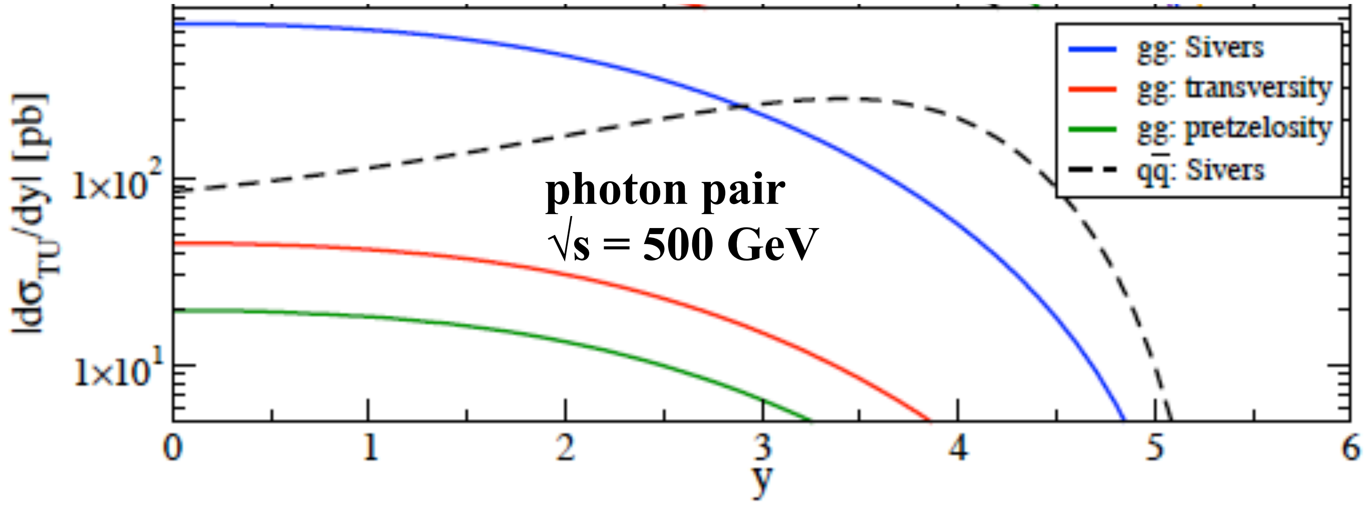
J.W. Qiu, M. Schlegel and W. Vogelsang PRD 78 (2008) 014024



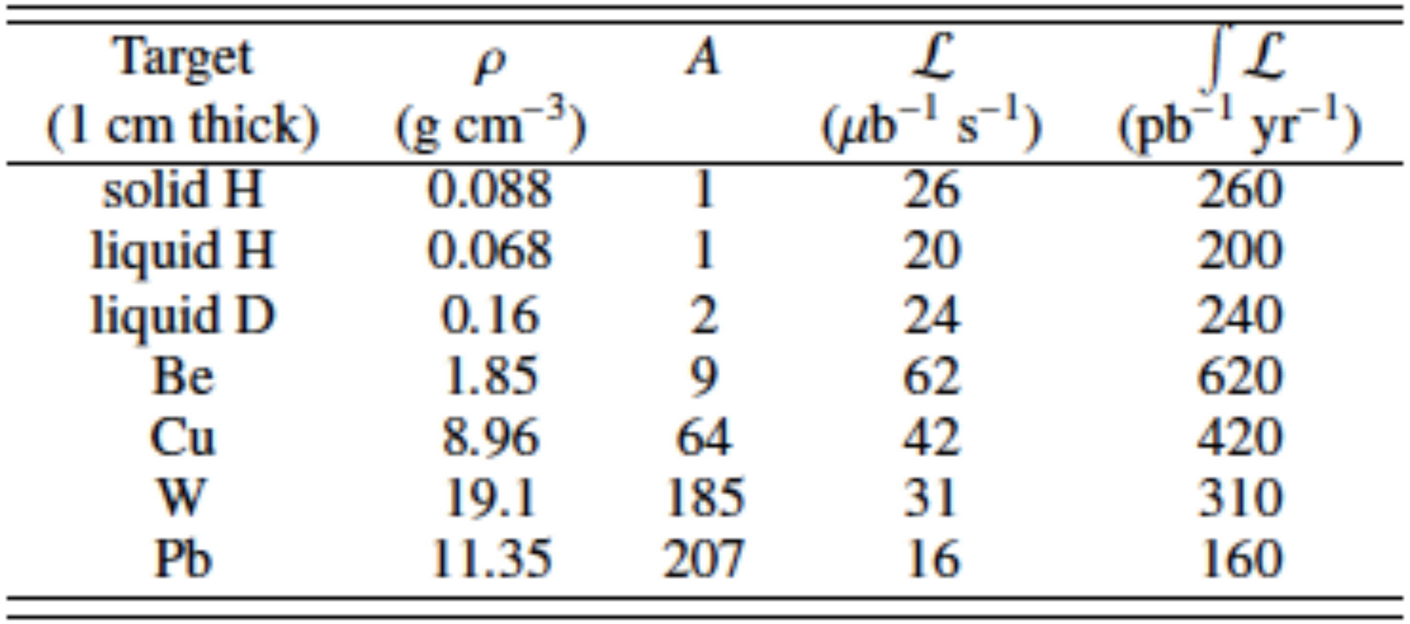
Luminosities in pp @ 115 GeV

- **Intensity: $N_{beam} = 5.10^8$ protons.s^{-1}**
  - Beam: 2808 bunches of 1.15×10^{11} p = 3.2×10^{14} p
  - Bunch: Each bunch passes IP at the rate: ~11 kHz
  - Instantaneous extraction: IP sees 2808 x 11000~3.10^7 bunches passing every second → extract ~16 protons in each bunch at each pass
  - Integrated extraction: Over a 10h run: extract ~5.6% of the protons stored in the beam

- **Instantaneous Luminosity**

  $L = N_{beam} \times N_{Target} = N_{beam} \times (\rho \times \mathbf{e} \times N_A)/A$
  - $N_{beam} = 5 \times 10^8$ p^+/s
  - **e** (target thickness) = 1 cm

- **Integrated luminosity**
  - 9 months running/year
  - 1 year ~ 10^7 s

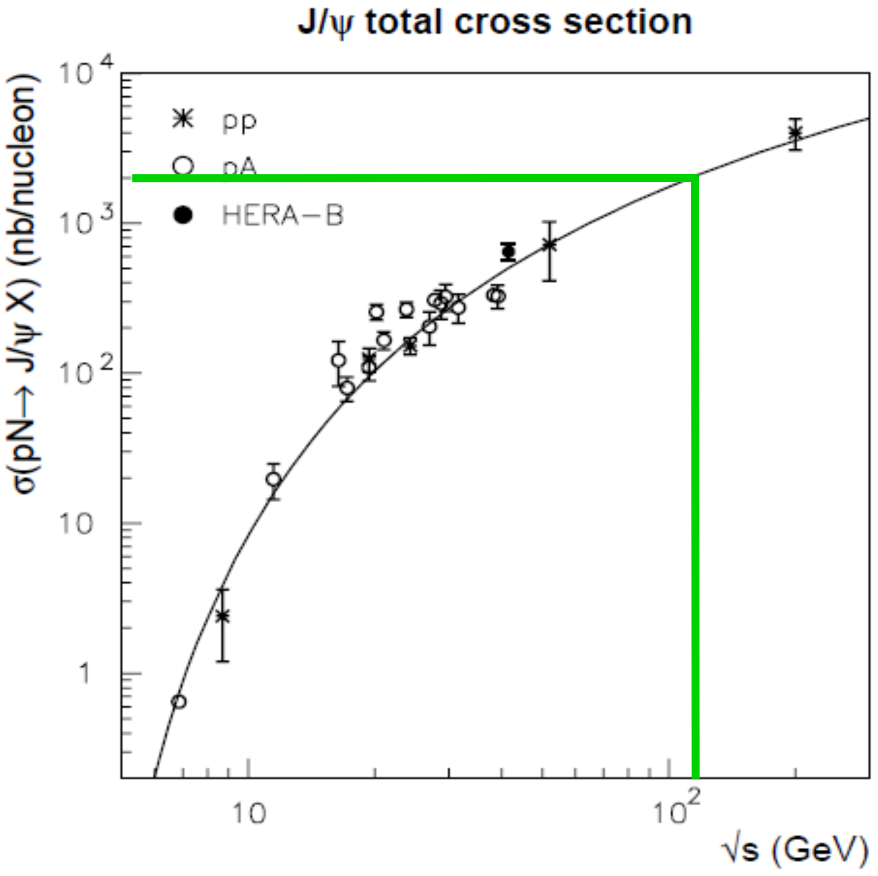


Target (1 cm thick)	ρ (g cm^{-3})	A	$\mathcal{L}$ (μb^{-1} s^{-1})	$\int \mathcal{L}$ (pb^{-1} yr^{-1})
solid H	0.088	1	26	260
liquid H	0.068	1	20	200
liquid D	0.16	2	24	240
Be	1.85	9	62	620
Cu	8.96	64	42	420
W	19.1	185	31	310
Pb	11.35	207	16	160

⇒ Large luminosity in pH and pD ~ 0.2 /fb/yr for a 1 cm thick target

⇒ Larger luminosity with 50 cm or 1 m H2 or D2 target (1 m ↔ 20 /fb/yr = LHC in 2012)

Quarkonium yields in pp @ 115 GeV



In pp

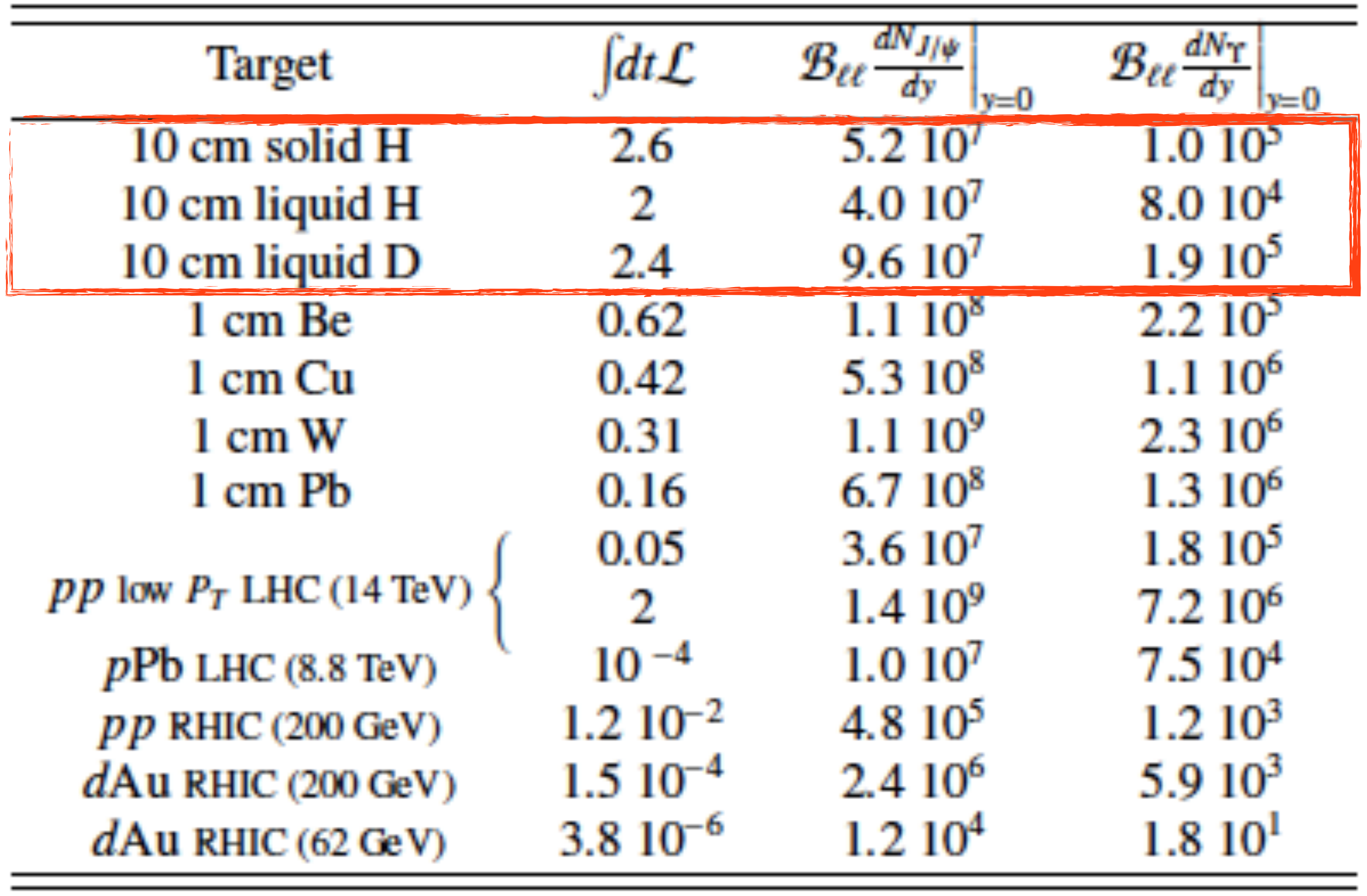
⇒ RHIC @ 200 GeV x 100 with 10 cm thick H target

⇒ Comparable to LHCb (PPR nominal) if 1m H target

⇒ Large statistics for detailed studies on quarkonium production (different quarkonium states, ...)

Inclusive pp cross-sections

$B_{ll}\, d\sigma/dy|_{y=0}$ @ 115 GeV
J/ψ = 20 nb
Υ = 40 pb



Target	$\int dt\mathcal{L}$	$\mathcal{B}_{\ell\ell}\frac{dN_{J/\psi}}{dy}\Big\|_{y=0}$	$\mathcal{B}_{\ell\ell}\frac{dN_{\Upsilon}}{dy}\Big\|_{y=0}$
10 cm solid H	2.6	5.2 10^7	1.0 10^5
10 cm liquid H	2	4.0 10^7	8.0 10^4
10 cm liquid D	2.4	9.6 10^7	1.9 10^5
1 cm Be	0.62	1.1 10^8	2.2 10^5
1 cm Cu	0.42	5.3 10^8	1.1 10^6
1 cm W	0.31	1.1 10^9	2.3 10^6
1 cm Pb	0.16	6.7 10^8	1.3 10^6
pp low P_T LHC (14 TeV)	0.05	3.6 10^7	1.8 10^5
	2	1.4 10^9	7.2 10^6
*p*Pb LHC (8.8 TeV)	10^{-4}	1.0 10^7	7.5 10^4
pp RHIC (200 GeV)	1.2 10^{-2}	4.8 10^5	1.2 10^3
*d*Au RHIC (200 GeV)	1.5 10^{-4}	2.4 10^6	5.9 10^3
*d*Au RHIC (62 GeV)	3.8 10^{-6}	1.2 10^4	1.8 10^1

Luminosity per year in fb^{-1}

Polarizing the hydrogen target

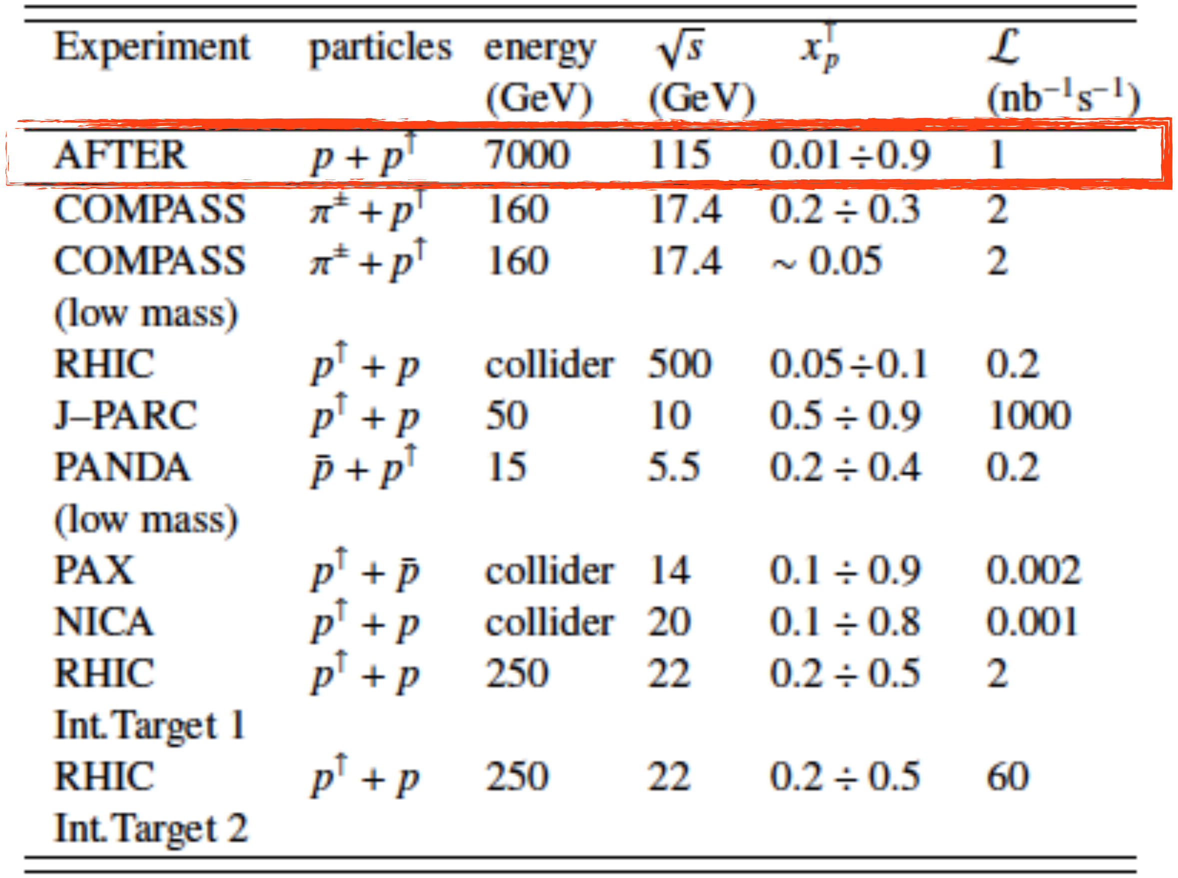
- **Instantaneous Luminosity**

$L = N_{beam} \times N_{Target} = N_{beam} \times (\rho \times e \times N_A)/A$

– N_{beam}=5 x 10^8 p^+/s

– **e** (target thickness) = 50 cm

$x_p^\uparrow$ range corresponds to Drell-Yan measurements



Experiment	particles	energy (GeV)	$\sqrt{s}$ (GeV)	$x_p^\uparrow$	$\mathcal{L}$ ($nb^{-1}s^{-1}$)
AFTER	$p + p^\uparrow$	7000	115	$0.01 \div 0.9$	1
COMPASS	$\pi^\pm + p^\uparrow$	160	17.4	$0.2 \div 0.3$	2
COMPASS (low mass)	$\pi^\pm + p^\uparrow$	160	17.4	~ 0.05	2
RHIC	$p^\uparrow + p$	collider	500	$0.05 \div 0.1$	0.2
J–PARC	$p^\uparrow + p$	50	10	$0.5 \div 0.9$	1000
PANDA (low mass)	$\bar{p} + p^\uparrow$	15	5.5	$0.2 \div 0.4$	0.2
PAX	$p^\uparrow + \bar{p}$	collider	14	$0.1 \div 0.9$	0.002
NICA	$p^\uparrow + p$	collider	20	$0.1 \div 0.8$	0.001
RHIC Int.Target 1	$p^\uparrow + p$	250	22	$0.2 \div 0.5$	2
RHIC Int.Target 2	$p^\uparrow + p$	250	22	$0.2 \div 0.5$	60

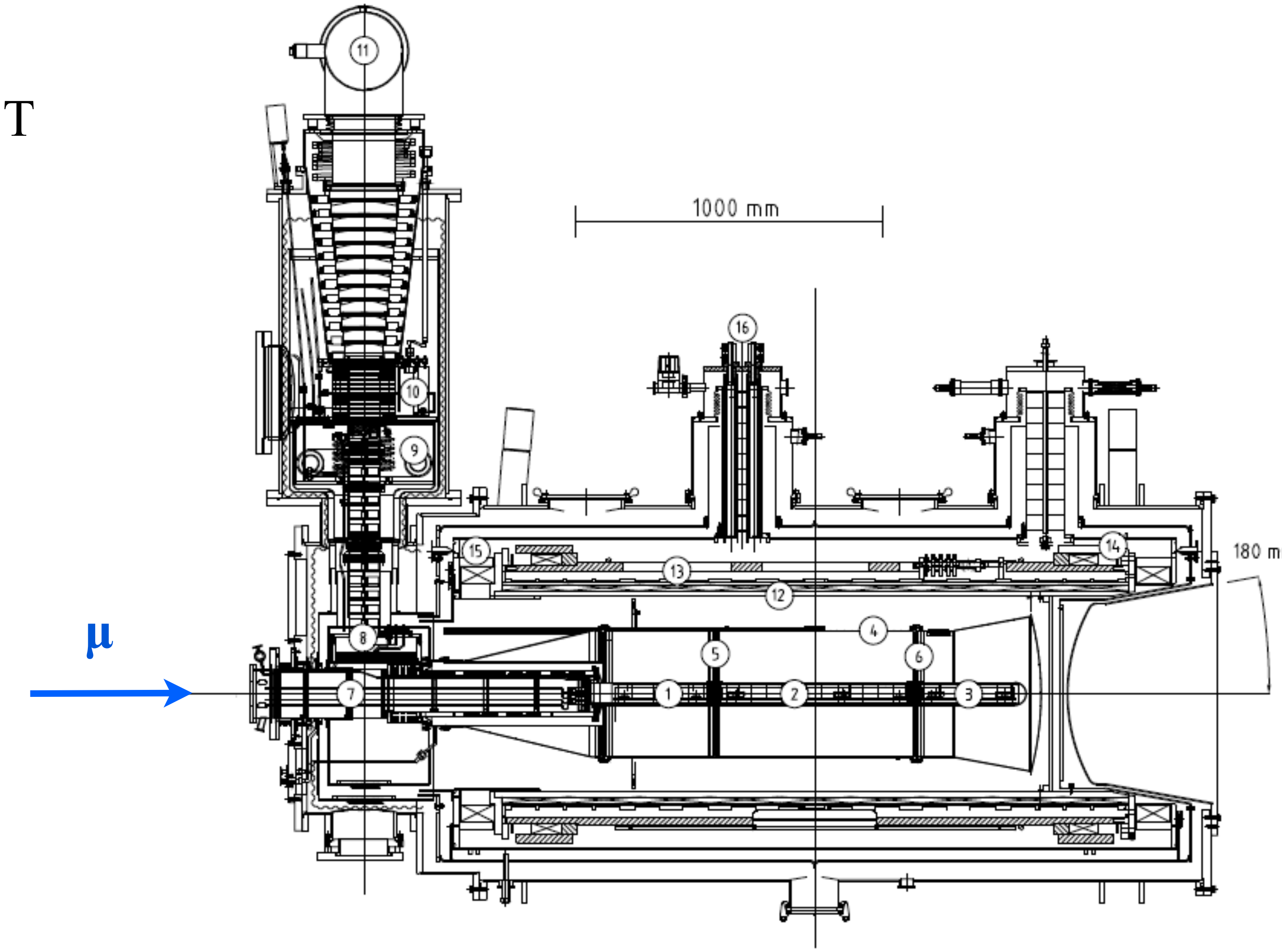
⇒ AFTER provides a competitive luminosity to study target spin related measurements

⇒ Complementary x_p range with other spin physics experiments

Target experimental setup: COMPASS example

- Specifications
  - Superconducting solenoid : 2.5 T
    - 16 trim coils
    - Field homogeneity: 10^{-4}
  - Dipole magnet (long. or transverse): 0.5 T
  - Temperature: ~50 mK (frozen)
  - Materials: NH_3, ^6LiD
  - Dilution factor: ~0.4

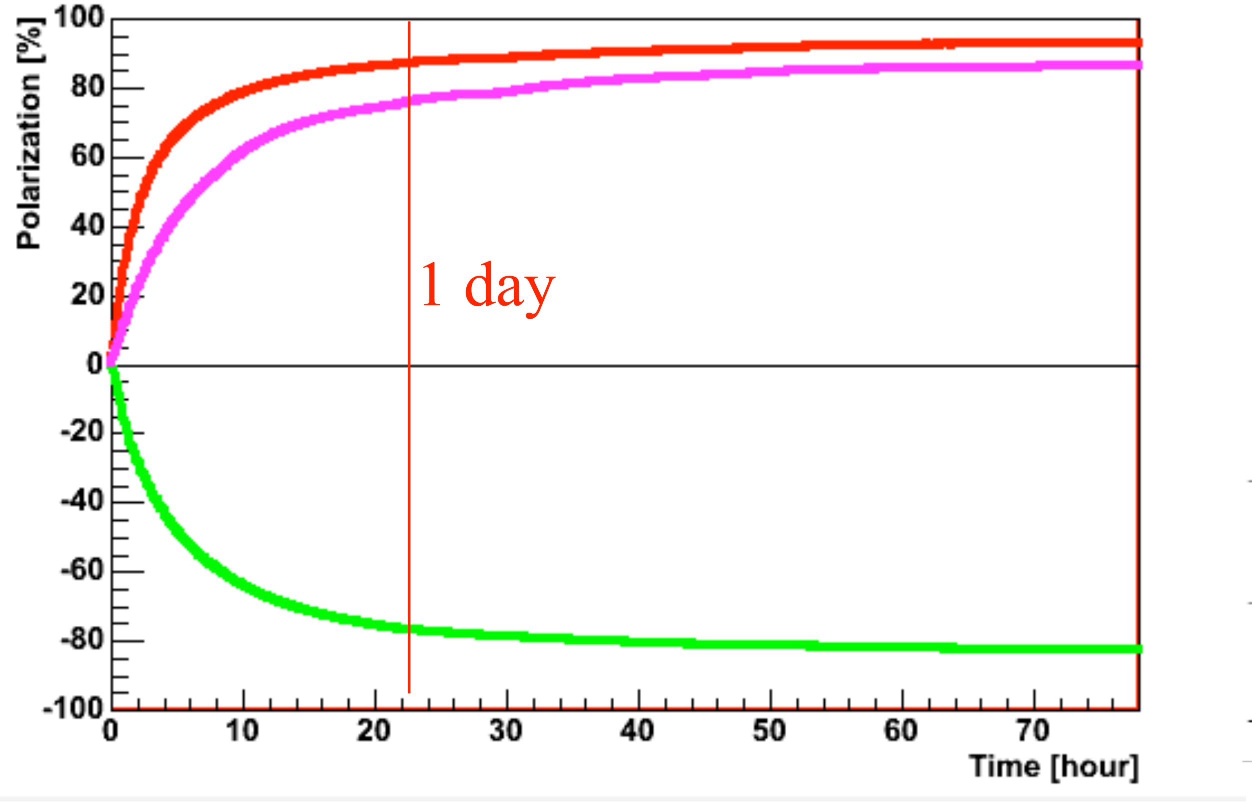
- Performances
  - Polarization: >90%, >50%
  - Field reversal: 8h, 24h



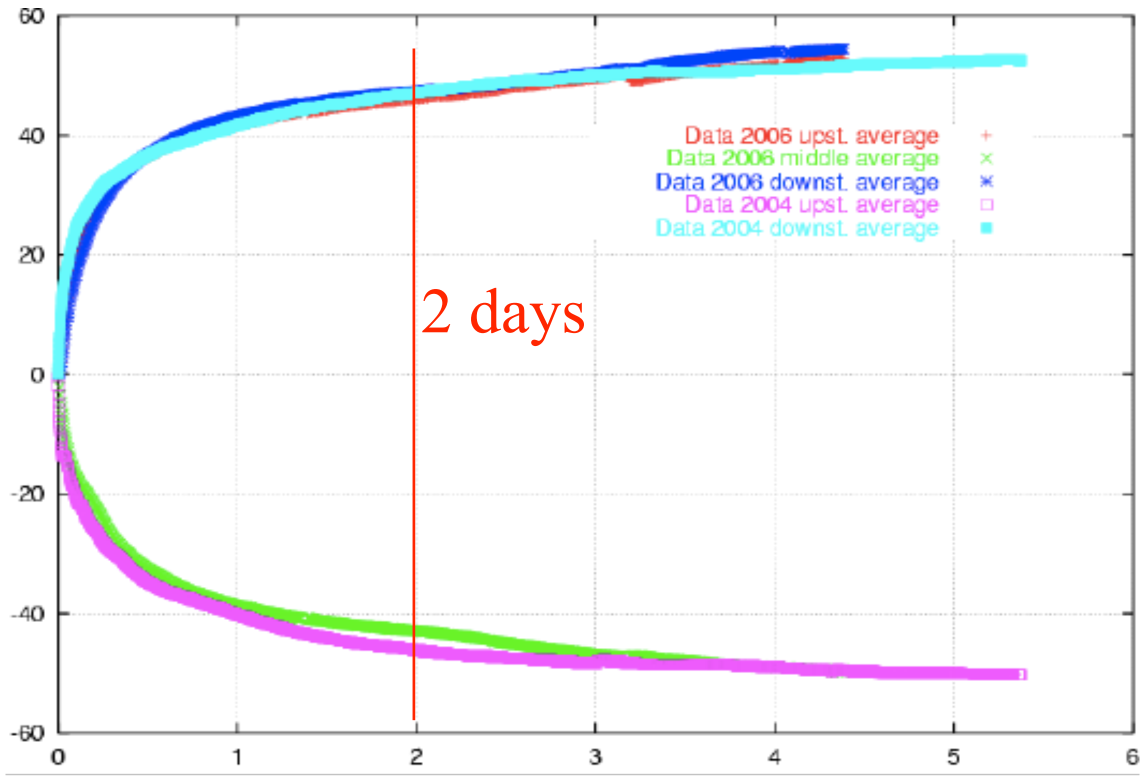
Space constraints for the polarized targets

Target experimental setup: COMPASS example

NH_3 material



^{6}LiD material



time relaxation ~ 1000 hours

Conclusion

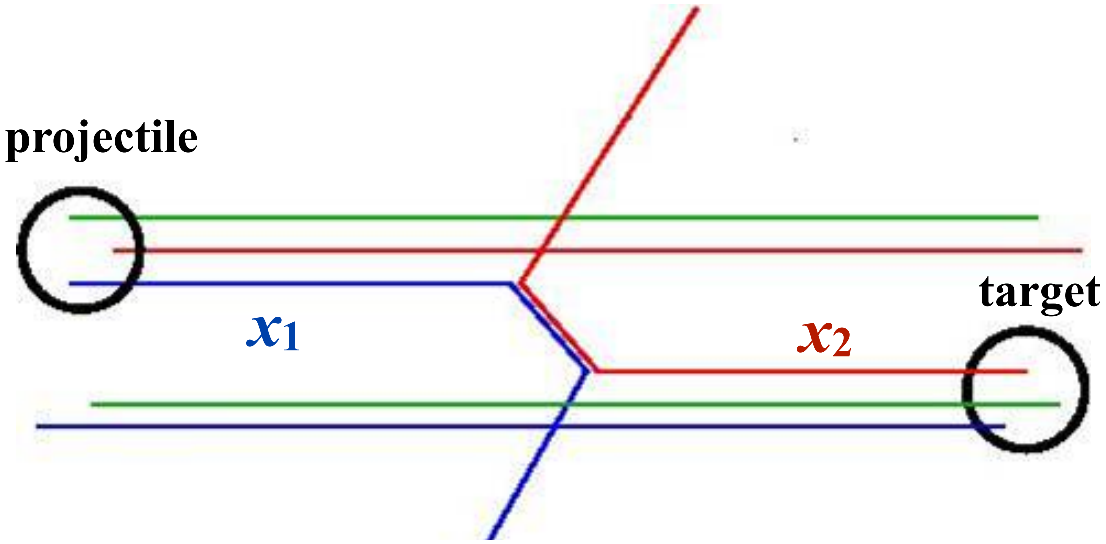
- LHC proton continuous extraction with bent crystal on a fixed (polarized or not) target offers many spin physics opportunities

- High boost and large luminosities provide access to large and very large parton *x* measurements for quarks and gluons: QCD laboratory at large *x*

- Space and time constraints for the polarized targets

Rapidity boost in a fixed target mode

- **Very high boost:**
  - With 7 TeV beam
    $\gamma = \sqrt{s}/(2m_p) = 61.1$ and $\mathbf{y_{CMS} = 4.8}$
  - With 2.76 TeV beam
    $\gamma = 38.3$ and $\mathbf{y_{CMS} = 4.3}$
- $y_{lab} = y_{CM} + \mathbf{y_{CMS}}$
  forward region: $y_{CM}>0$
  backward region: $y_{CM}<0$
- $\eta = -\ln\tan\theta/2$ (= y for massless particles)
  - With 7 TeV beam
    $y_{CM} = 0 \Leftrightarrow \theta \sim 16$ mrad (0.9°)



For a 2 → 1 process (e.g. gg→QQbar)

$$x_{1,2} = M/\sqrt{s}\, e^{\pm y_{CM}}$$

y_{CM} : QQbar CMS rapidity
M : QQbar mass

- $y_{lab} = 4.8 \leftrightarrow y_{CM} = 0 \rightarrow x_1 = x_2$
- **backward region:** $y_{CM} < 0 \rightarrow x_1 < x_2$
- $y_{lab}(J/\Psi) \sim 1.2 \rightarrow x_2 = 1$
- $y_{lab}(\Upsilon) \sim 2.4 \rightarrow x_2 = 1$

Good condition to access large target x_2 and low $x_F = x_1 - x_2 \rightarrow -1$: target-rapidity region