Heavy Quarkonium Physics For A Fixed-Target ExpeRiment At the LHC (AFTER@LHC)

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WHAT IS AFTER@LHC ?

AFTER@LHC is a proposal for a multi-purpose fixed target experiment using the multi-TeV proton or heavy ion beams of the LHC at CERN

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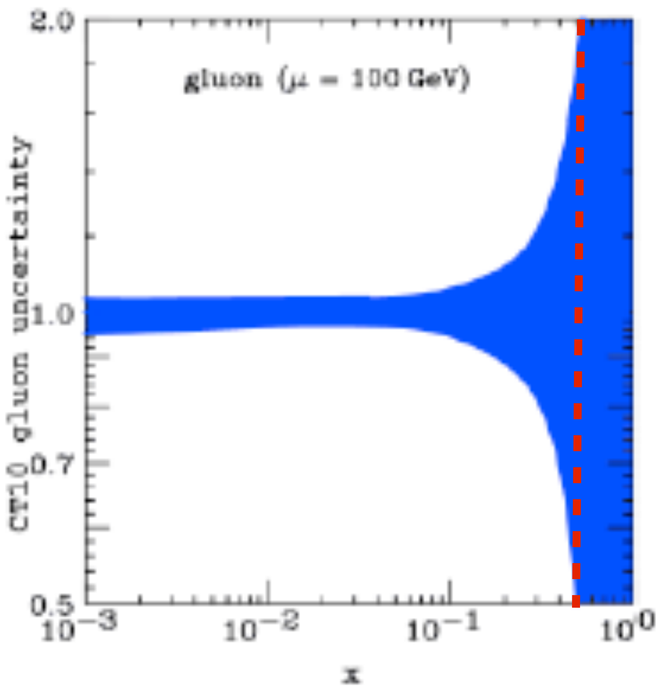
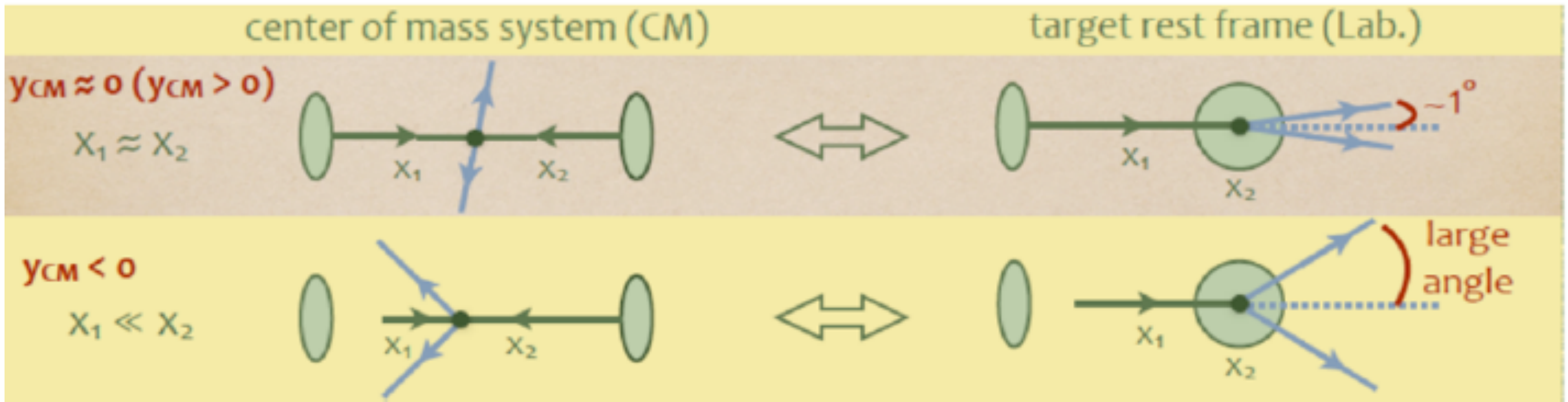
PHYSICS OPPORTUNITIES OF AFTER@LHC

- **Large-x gluon and (anti-,heavy-)quark content in nucleon & nucleus**
  - Very large PDF uncertainties for $x \gtrsim 0.5$
  - Proton charm content important to high-energy neutrino and cosmic-ray physics
  - EMC effect is an open problem; studying a possible gluon EMC effect is essential
  - Relevance of nuclear PDF to understand initial state of heavy-ion collisions
  - Search and study of rare proton fluctuations, where one gluons carries most of the proton momentum





- Backward physics fully accessible for the first time
- Access to partons with momentum fraction $x_2 \to 1$ in the target ($x_F \to -1$)

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CERN

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- **Dynamics and spin of gluons inside (un)polarised nucleons**
  - Possible missing contribution to the proton spin: orbital angular momentum
  - Test of the QCD factorisation framework
  - Determination of linearly polarised gluons in unpolarised protons
- **Heavy-ion collisions from middle to large rapidities**
  - Explore the longitudinal expansion of QGP formation with hard probes
  - Test the factorisation of cold nuclear effect from p+A to A+B collisions
  - Test azimuthal asymmetries: hydro vs. initial-state radiation

see T. Peitzmann's talk

PHYSICS OPPORTUNITIES OF AFTER@LHC

- *Physics Reports 522 (2013) 239; Few Body Syst. 53 (2012) 11-25.*

Physics Reports 522 (2013) 239–255

Contents lists available at SciVerse ScienceDirect

Physics Reports

journal homepage: www.elsevier.com/locate/physrep

Physics opportunities of a fixed-target experiment using LHC beams

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[b] Laboratoire Leprince Ringuet, Ecole polytechnique, CNRS/IN2P3, 91128 Palaiseau, France

[c] IPNO, Université Paris-Sud, CNRS/IN2P3, 91406 Orsay, France

Contents

Expression of Interest in preparation

- *Many more ideas for a fixed target experiment at LHC in a Special Issue in Advances in High Energy Physics*

Hindawi

Advances in High Energy Physics

Special Issue on
Physics at a Fixed-Target Experiment Using the LHC Beams

CALL FOR PAPERS

- ***Heavy-ion physics***
- ***Exclusive reactions***
- ***Spin physics studies***
- ***Hadron structure***
- ***Feasibility study and technical ideas***

http://after.in2p3.fr/after/index.php/Recent_published_ideas_in_favour_of_AFTER@LHC

WHY WE NEED AFTER@LHC ?

CERN

- **Advantages of a fixed-target experiment:**
  - access to large Feynman $|x_F|$
  - target versatility
  - possibility to polarize the target (study spin physics)
  - high luminosities can be achieved with either dense targets or high intensity beams
- **AFTER@LHC kinematics with utilizing LHC beams**

7 TeV proton beam on a fixed target

CMS energy:	$\sqrt{s}=\sqrt{2m_N E_p}\approx 115\ \text{GeV}$	**Rapidity shift:** $y_{CM}=0\rightarrow y_{lab}=4.8$
Boost:	$\gamma=\sqrt{s}/(2m_p)\approx 60$	

2.76 TeV Pb beam on a fixed target

CMS energy:	$\sqrt{s_{NN}}=\sqrt{2m_N E_{\text{Pb}}}\approx 72\ \text{GeV}$	**Rapidity shift:** $y_{CM}=0\rightarrow y_{lab}=4.3$
Boost:	$\gamma\approx 40$	

HOW AFTER@LHC WORKS ?

- Beam line extracted with a bent crystal
- **Dense targets:** internal gas target similar to SMOG at LHCb
- **High intensity beams:** internal wire target Kurepin, Topilskaya (Adv. High Energy Phys.'15)
- **Luminosities** in pH and pA

Target	ρ (g.cm^{-3})	A	L (μb^{-1}.s^{-1})	$\int$L (pb^{-1}.yr^{-1})
Liq H_2 (1m)	0.07	1	2000	20000
Liq D_2 (1m)	0.16	2	2400	24000
Be (1cm)	1.85	9	62	620
Cu (1cm)	8.96	64	42	420
W (1cm)	19.1	185	31	310
Pb (1cm)	11.35	207	16	160

LHC year – 9 months of running

For 1m long H_2 target

$$\int\mathcal{L} = 20\ \text{fb}^{-1}\text{yr}^{-1}$$

Large luminosities comparable to LHC, 3 orders of magnitude larger that at RHIC

- **Luminosities** in PbH and PbA

Target	ρ (g.cm^{-3})	A	L (μb^{-1}.s^{-1})	$\int$L (pb^{-1}.yr^{-1})
Liq H_2 (1m)	0.07	1	0.8	0.8
Liq D_2 (1m)	0.16	2	1	1
Be (1cm)	1.85	9	0.025	0.025
Cu (1cm)	8.96	64	0.017	0.017
W (1cm)	19.1	185	0.013	0.013
Pb (1cm)	11.35	207	0.007	0.007

Pb LHC year – 1 months of running

For 1m long H_2 target

$$\int\mathcal{L} = 0.8\ \text{pb}^{-1}\text{yr}^{-1}$$

For 1cm long Pb target

$$\int\mathcal{L} = 7\ \text{nb}^{-1}\text{yr}^{-1}$$

vs

LHC PbPb Collider: 0.5 nb^{-1}

PHYSICS HIGHLIGHT AT AFTER@LHC

- **PDF in nucleon & nucleus** (complementary to EIC, LHeC)
- **Spin physics** (QCD factorization, Boers-Mulder effect, Sivers efffect etc)
- **Heavy-ion collisions** (cold nuclear matter effect, QGP, azimuthal asymmetries)
- **Exclusive reaction** (ultra-peripheral collisions)

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- **Heavy quarkonium will play important role**
  - Large yields
  - Easy to trigger (dilepton final states)

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- **Heavy quarkonium will play important role**
  - Large yields
  - Easy to trigger (dilepton final states)

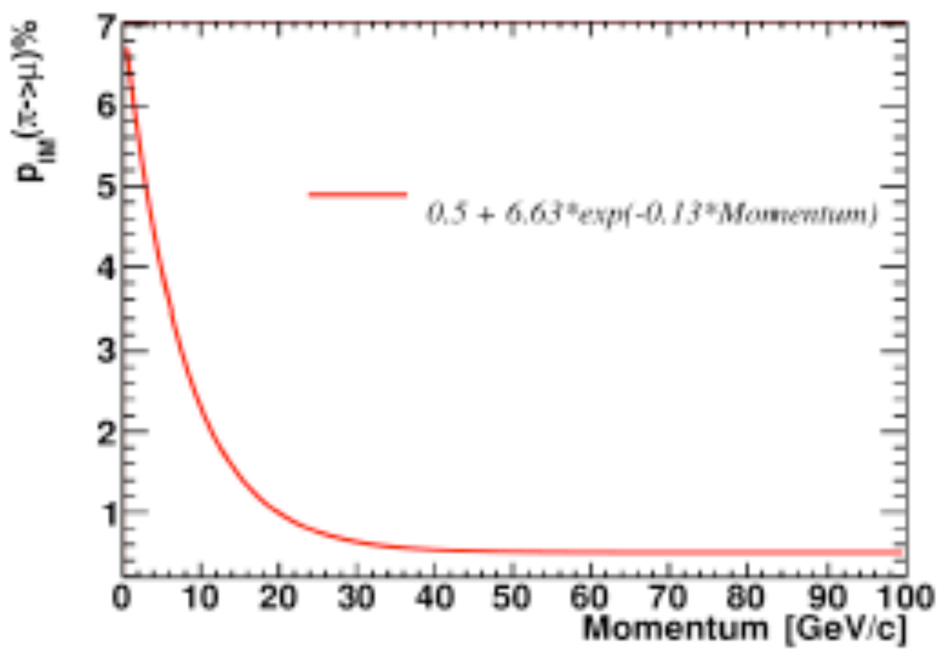
- **Selected relevant physics studies so far**
  - Feasibility studies
  - Cold nuclear matter effect in pA
  - Spin physics: single spin asymmetry
  - Double parton scatterings

FEASIBILITY STUDIES

Massacrier, Trzeciak, Fleuret, Hadjidakis, Kikola, Lansberg, HSS (Adv. High Energy Phys.'15)

- **First simulations of quarkonia at AFTER@LHC**
  - **HELAC-Onia 2.0** + **Pythia 8.1**
    HSS (Comput.Phys.Commun.'13,'16) — Sjostrand, Mrenna, Skands (Comput.Phys.Commun.'08)
  - **Signal: Quarkonium**
  - **Background**
    - Drell-Yan, open charm, open bottom, uncorrelated background
  - **Events selection**

    Single μ cuts: $2 < \eta_\mu < 5$ Minimum $p_T^\mu > 0.7$ GeV/c
  - **Reconstruction condition**
    - momentum resolution: $\Delta p/p = 0.5\%$
    - μ identification efficiency: 98%
    - *μ misidentification (with π or K) for the uncorrelated background*



Achilli et al. (JINST'13)

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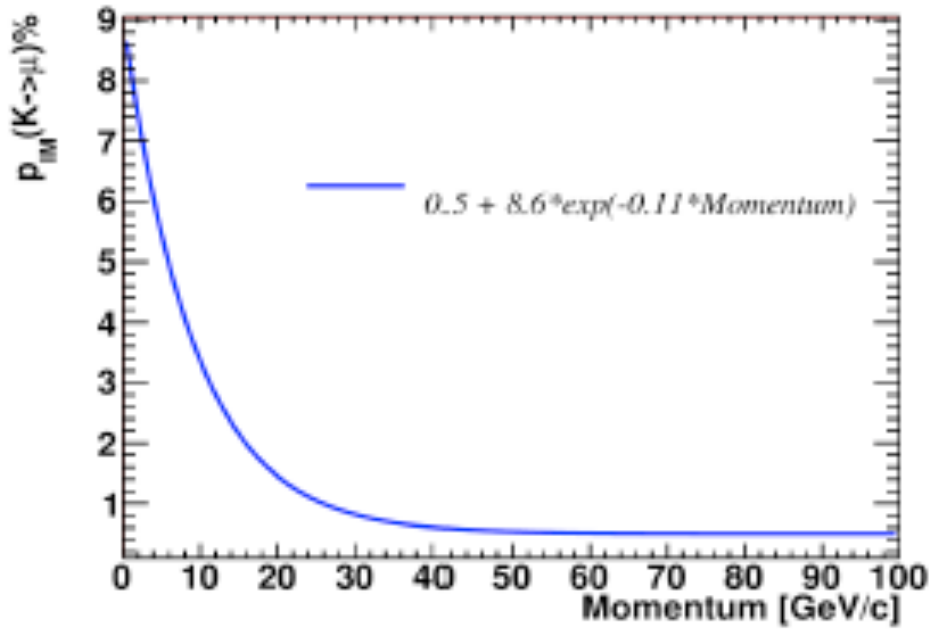

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- **Signal simulations: a data-driven way**
  - **Quarkonium production amplitude in crystal ball function**

Kom, Kulesza, Stirling (PRL'11)

$$\overline{|\mathcal{A}_{gg\to\mathcal{Q}+X}|^2} = \begin{cases} K\exp(-\kappa\frac{p_T^2}{M_\mathcal{Q}^2}) & \text{when } p_T \leq \langle p_T\rangle \\ K\exp(-\kappa\frac{\langle p_T\rangle^2}{M_\mathcal{Q}^2})\left(1+\frac{\kappa}{n}\frac{p_T^2-\langle p_T\rangle^2}{M_\mathcal{Q}^2}\right)^{-n} & \text{when } p_T > \langle p_T\rangle \end{cases}$$

Model independent !

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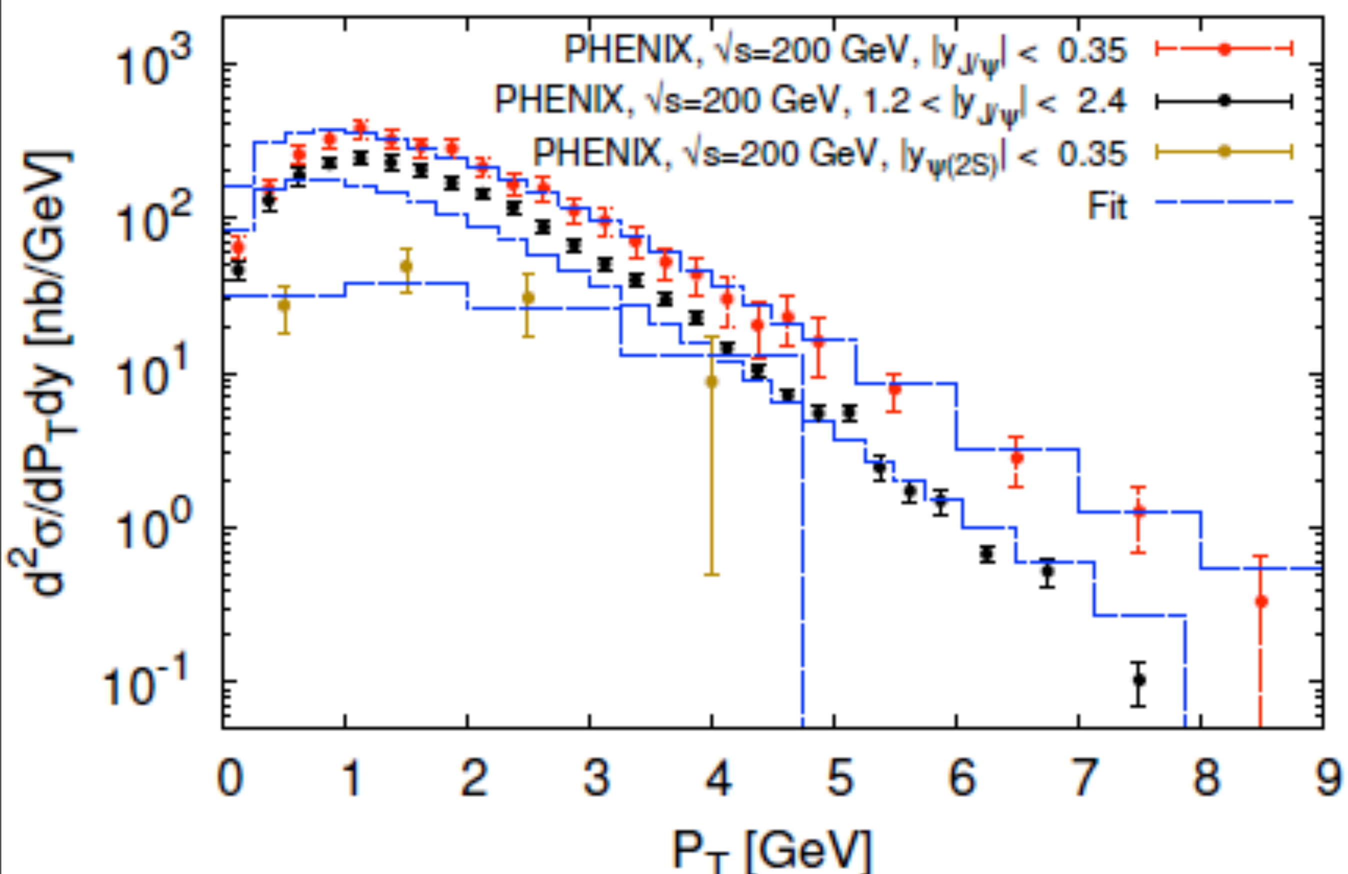

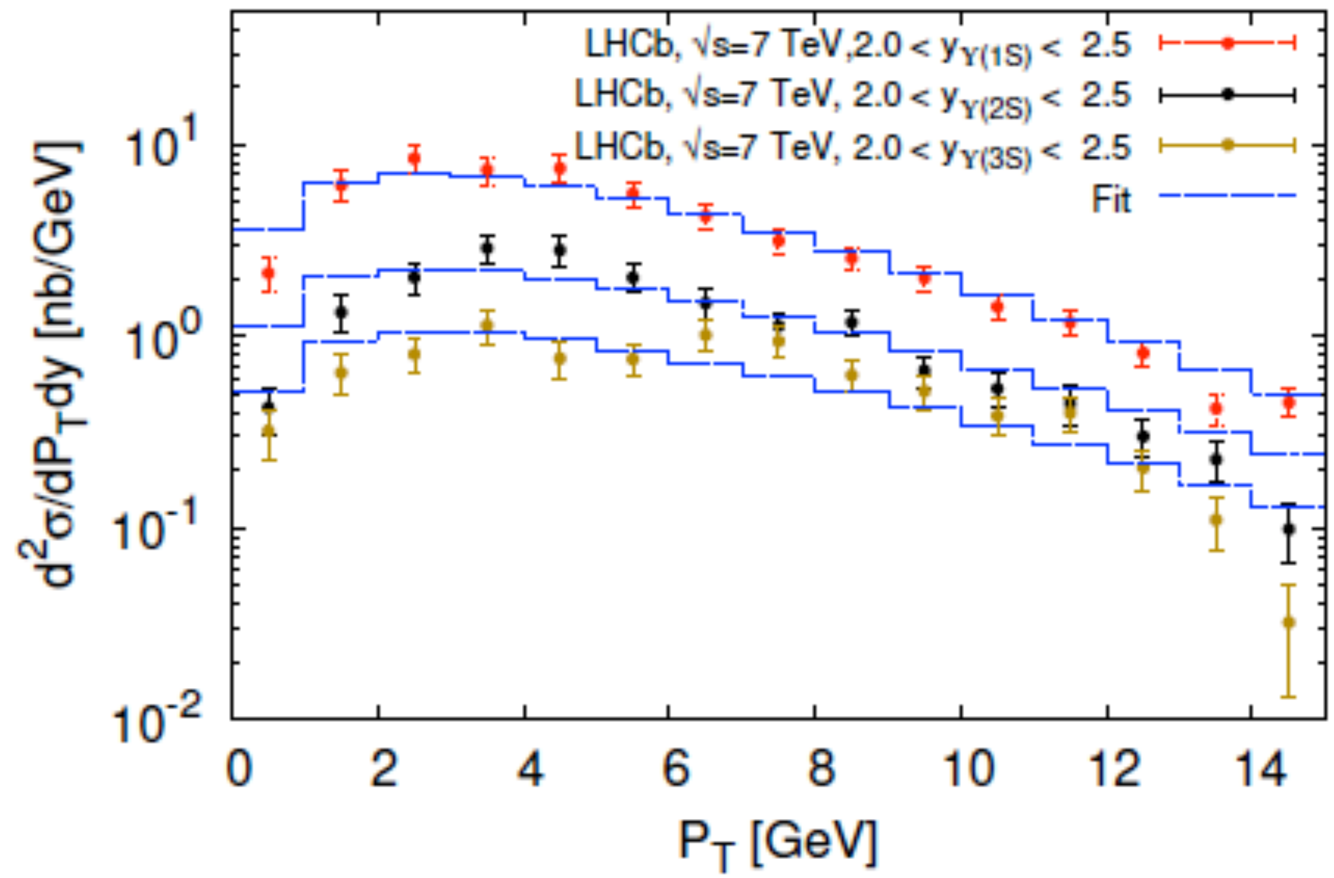

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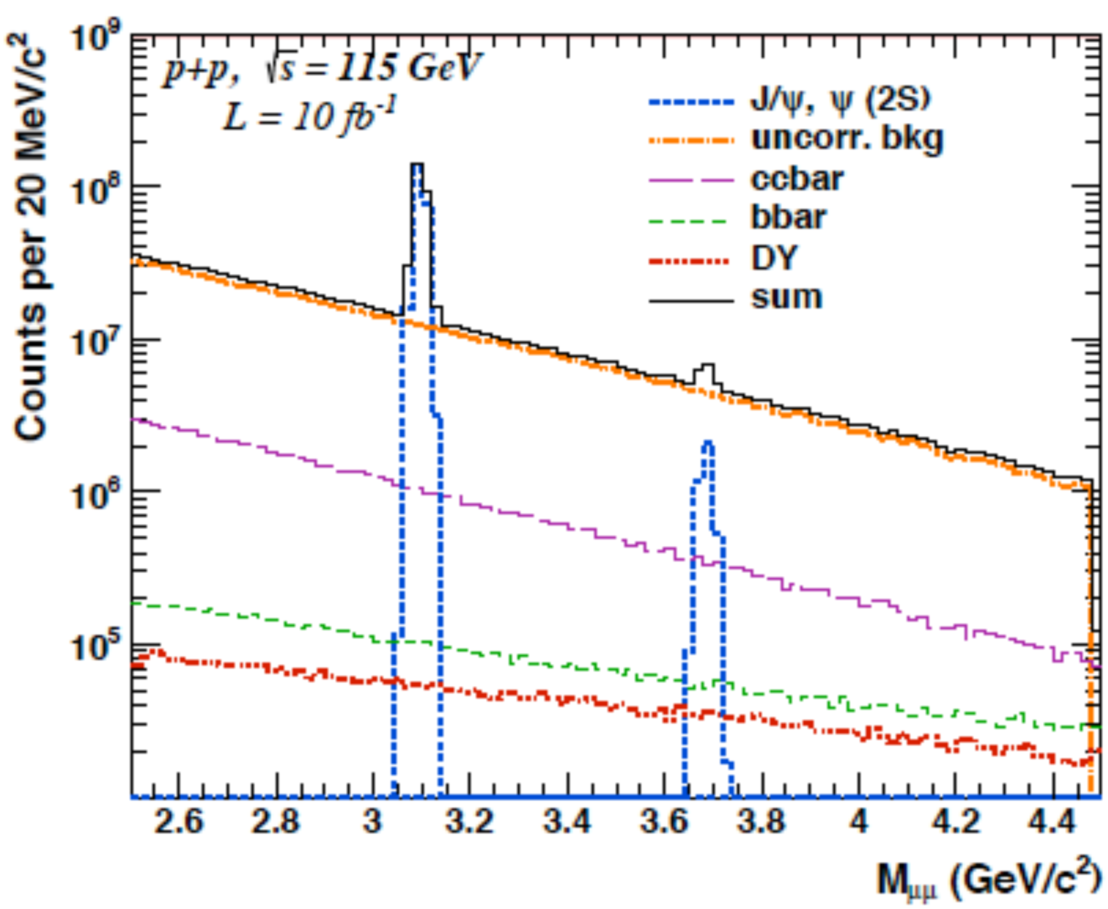

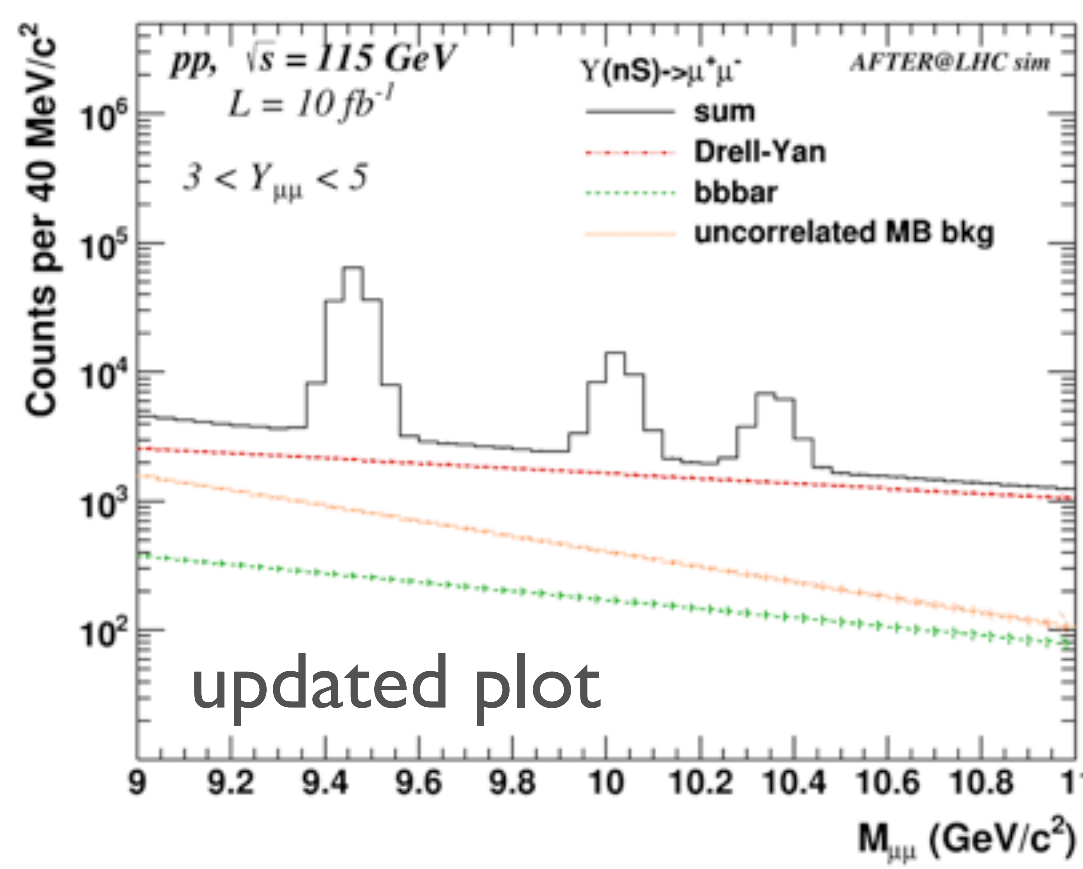

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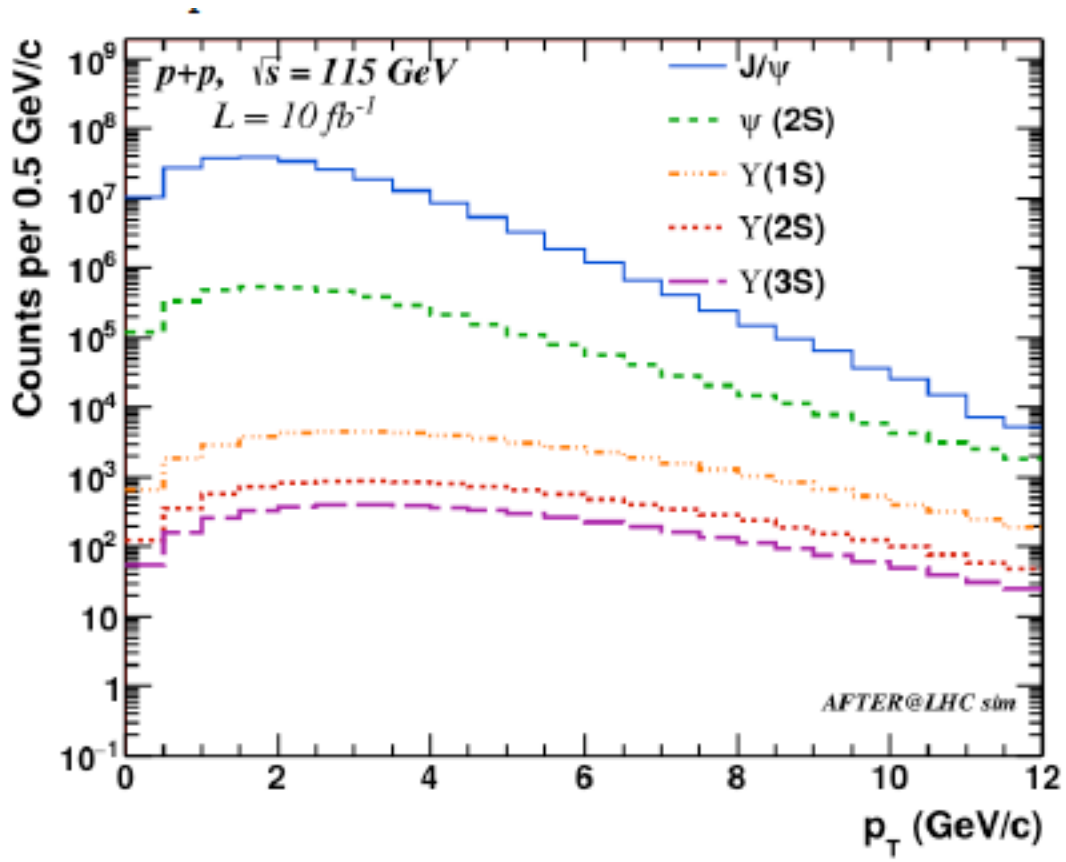
  - **Fit double differential distributions of the pp data**
  - **Simulations with background**
    - Good separation of different quarkonium states
  - **Differential distributions**

→ J/ψ and ψ(2S) signals can be studies up to p_T~ 15 GeV/c, Υ(nS) up to ~ 10 GeV/c

→ All quarkonium states can be measured down to 0 GeV/c



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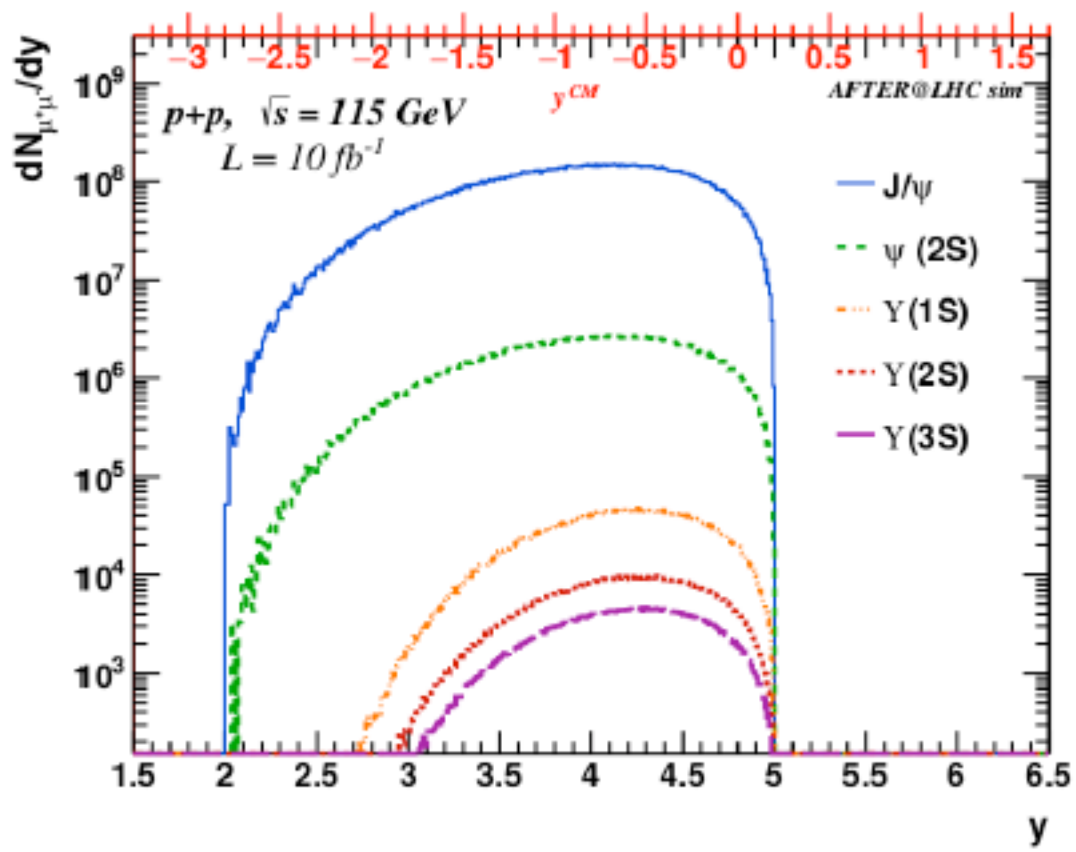
➔ All quarkonium states can be measured down to 0 GeV/c

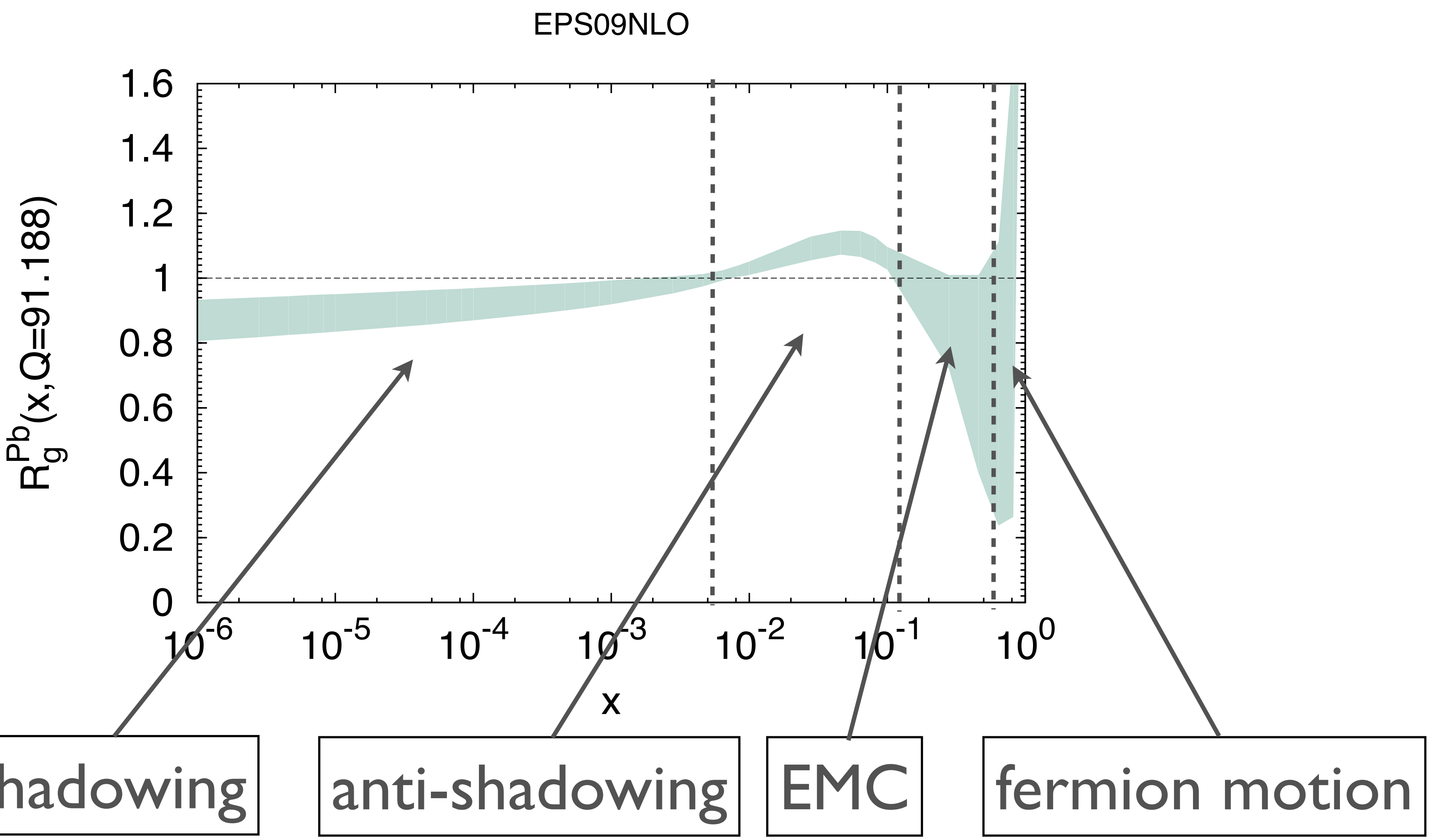
➔ Study is limited to the rapidity range of $2 < y < 5$ ($2 < \eta_\mu < 5$)

➔ J/ψ and ψ(2S) signals can be studies in the whole range, lowest y for ϒ(nS) is ~ 2.5-3



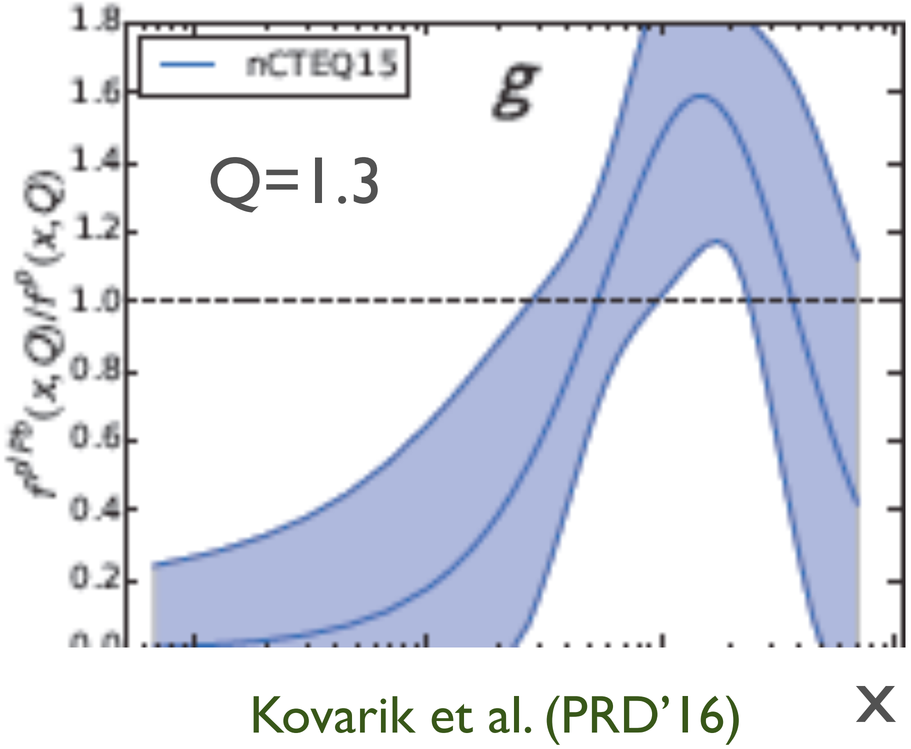
COLD NUCLEAR MATTER EFFECTS

- **Nuclear effects on PDF**

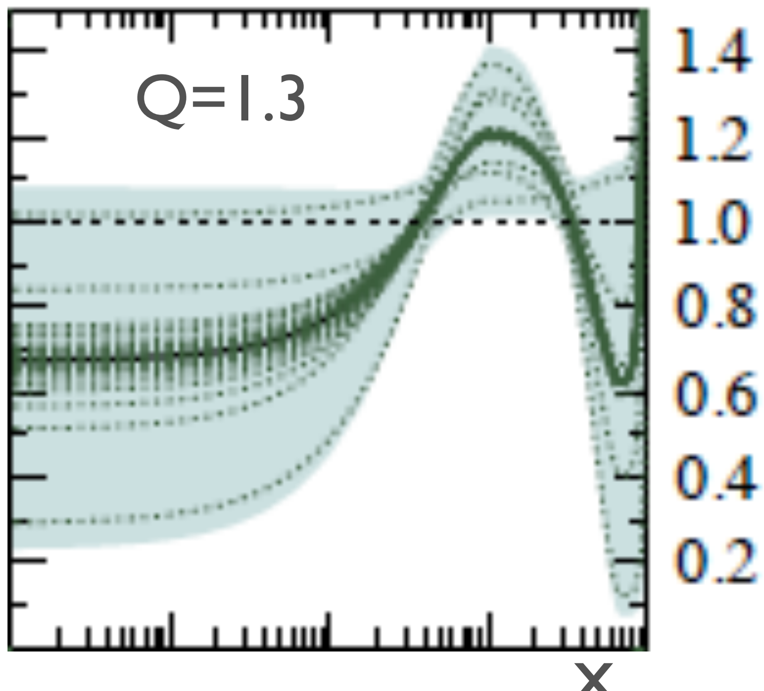


COLD NUCLEAR MATTER EFFECTS

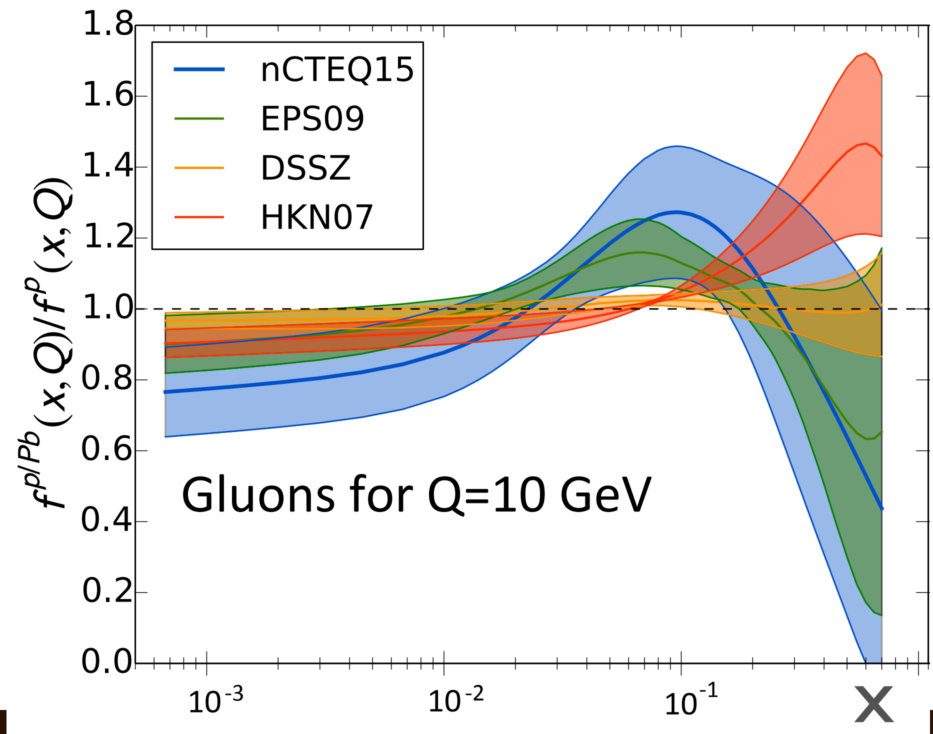
- **Nuclear effects on PDF**
  - **Quite large uncertainties even in modern nuclear PDF**



Kovarik et al. (PRD'16)



Eskola, Paukkunen, Salgado (JHEP'09)



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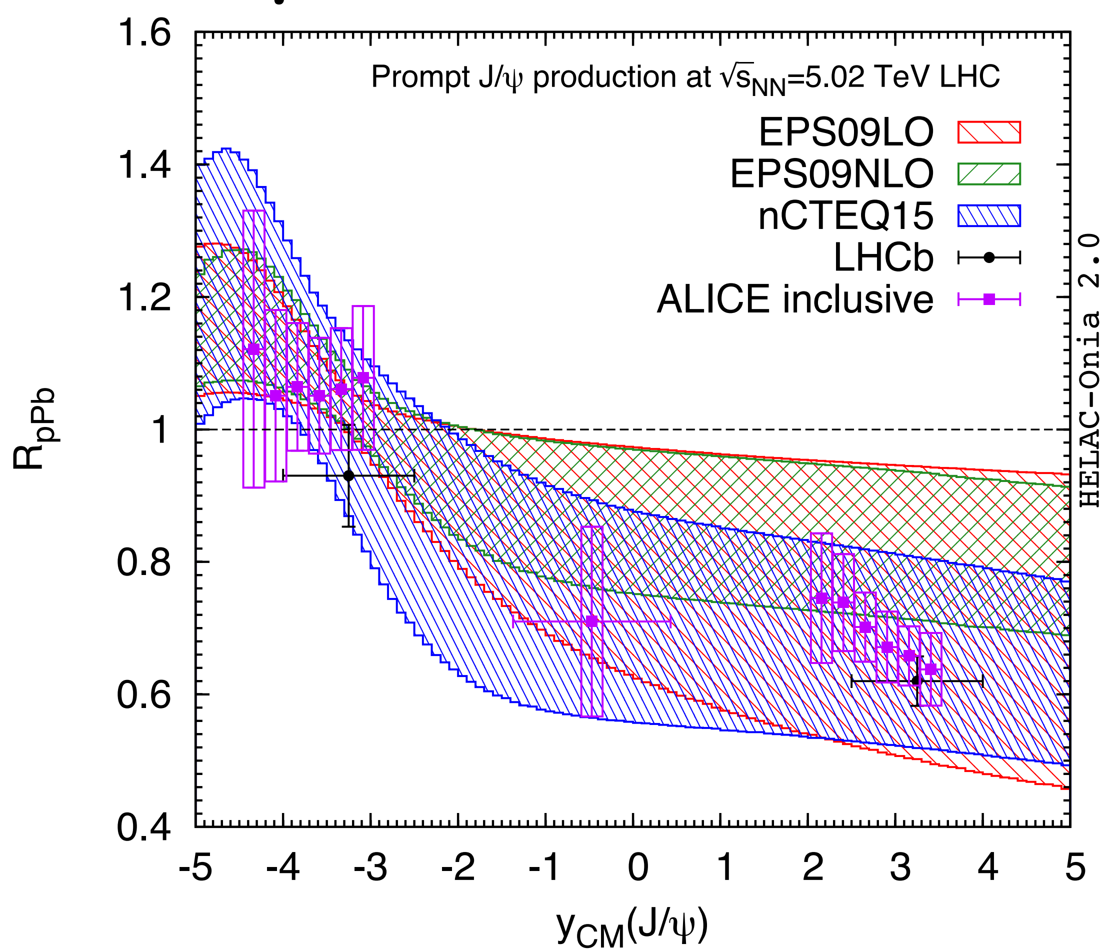
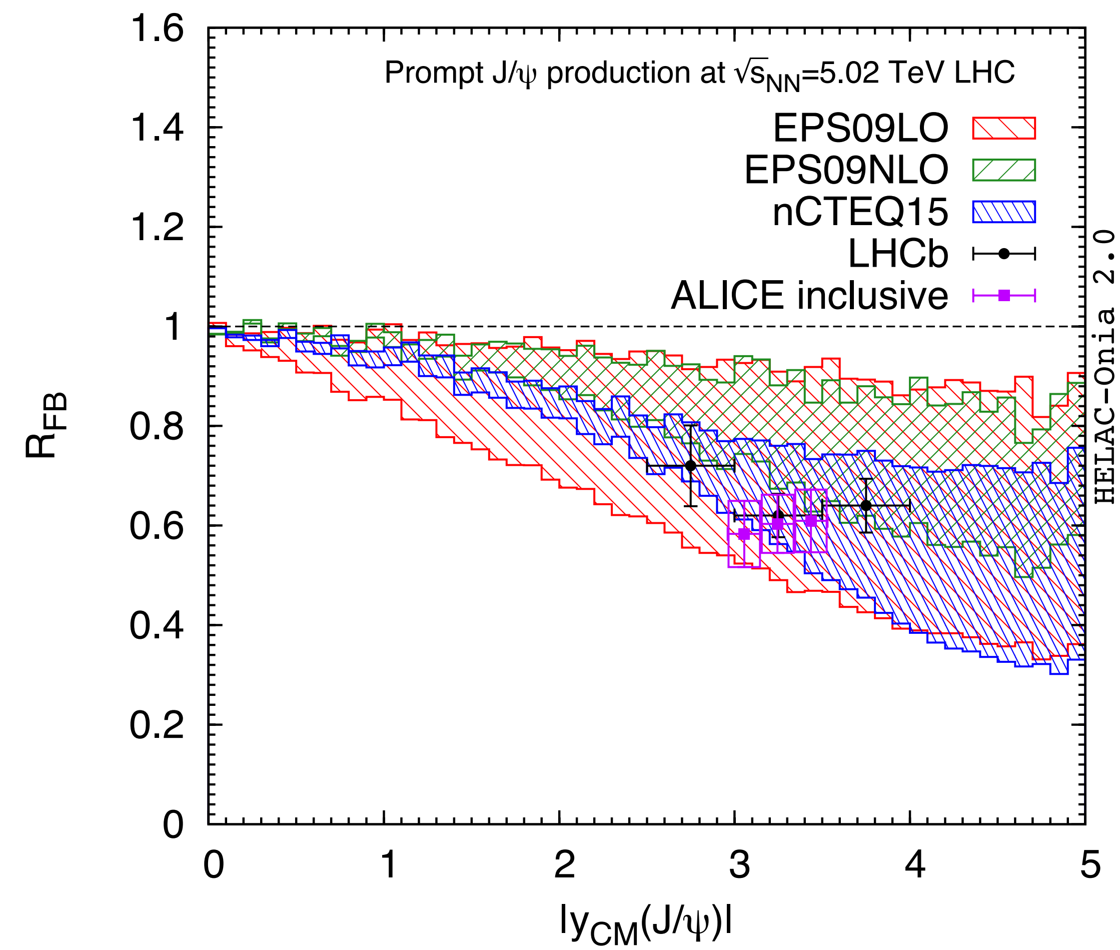
  - **Not a precise test for the LHC collider data**

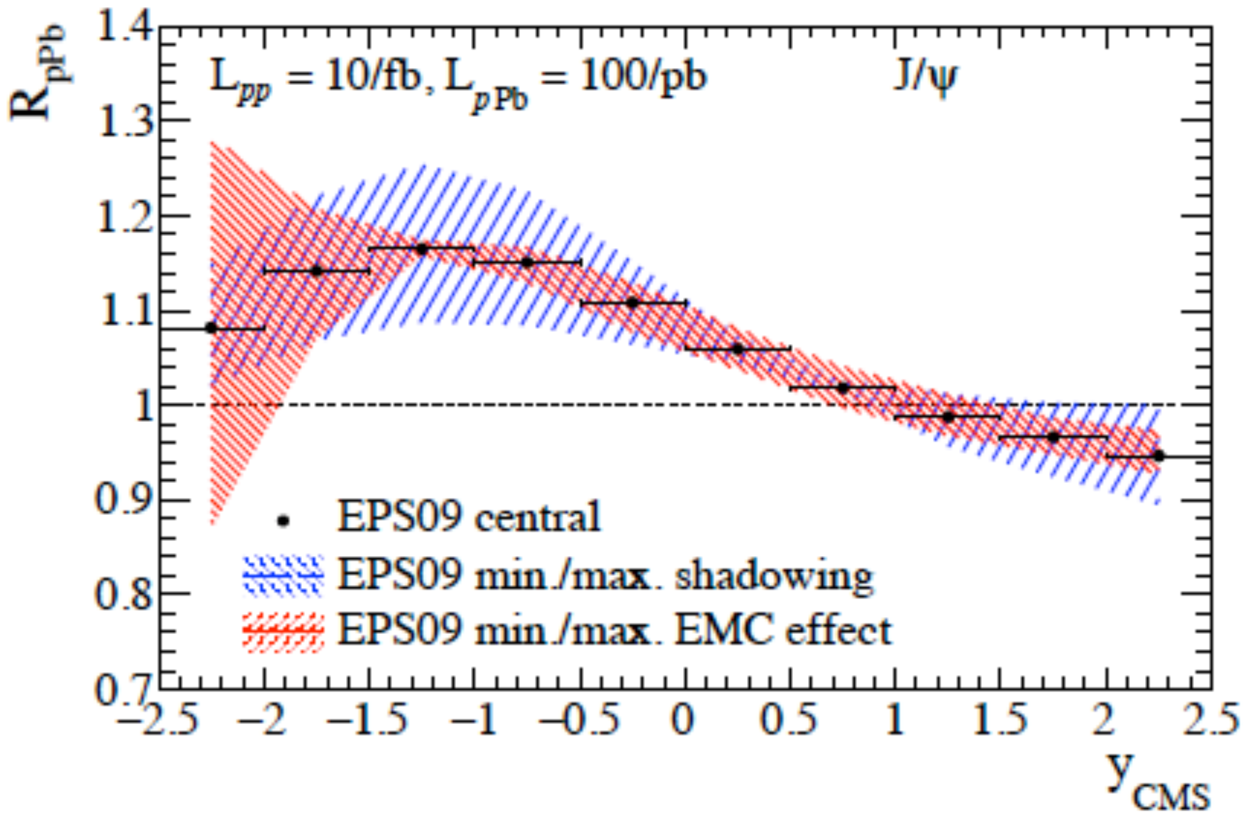


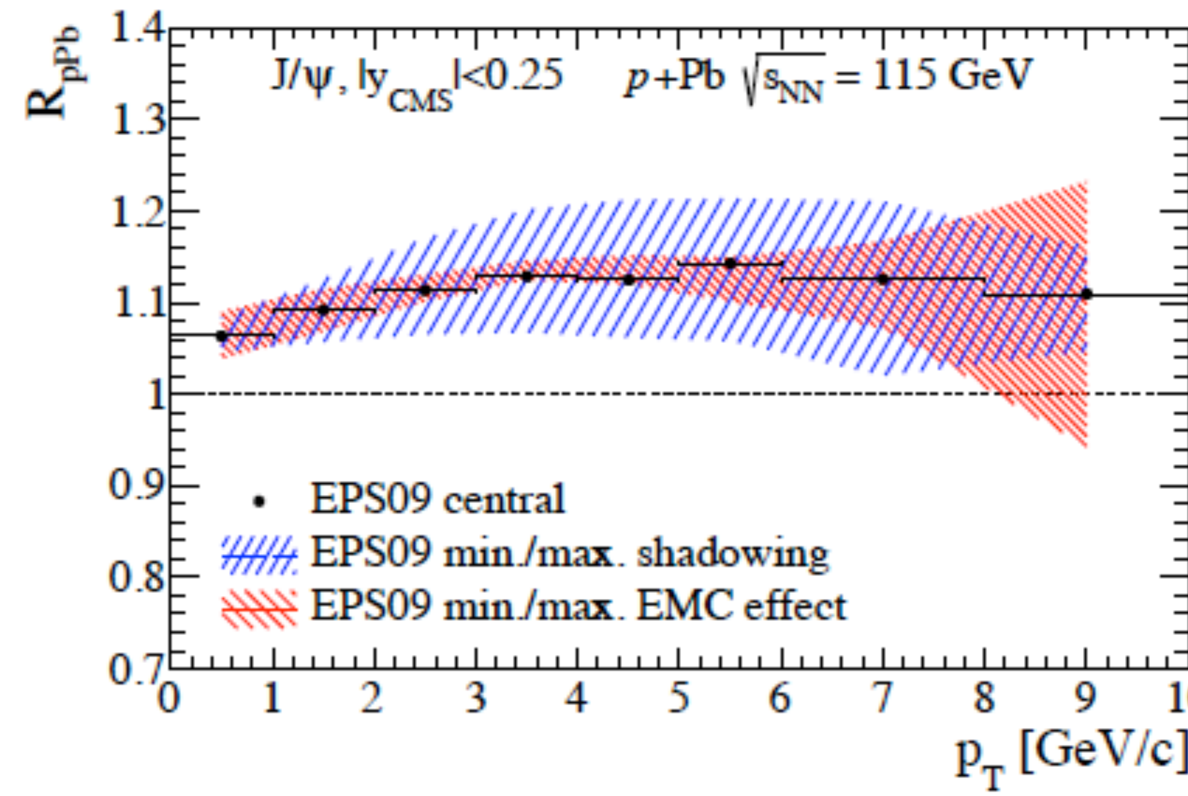


Lansberg, HSS (in prep.)

COLD NUCLEAR MATTER EFFECTS

- **Nuclear effects on PDF**
  - **Quite large uncertainties even in modern nuclear PDF**
  - **Not a precise test for the LHC collider data**
  - **Quarkonium help to constrain both small x (PbH) and large x (pPb)**
    - Combination of measurements of quarkonium for $-3<y_{CM}<0$ will allow to pin down the existence of a possible gluon EMC and antishadowing effect





Massacrier, Trzeciak, Fleuret, Hadjidakis, Kikola, Lansberg, HSS (Adv. High Energy Phys.'15)

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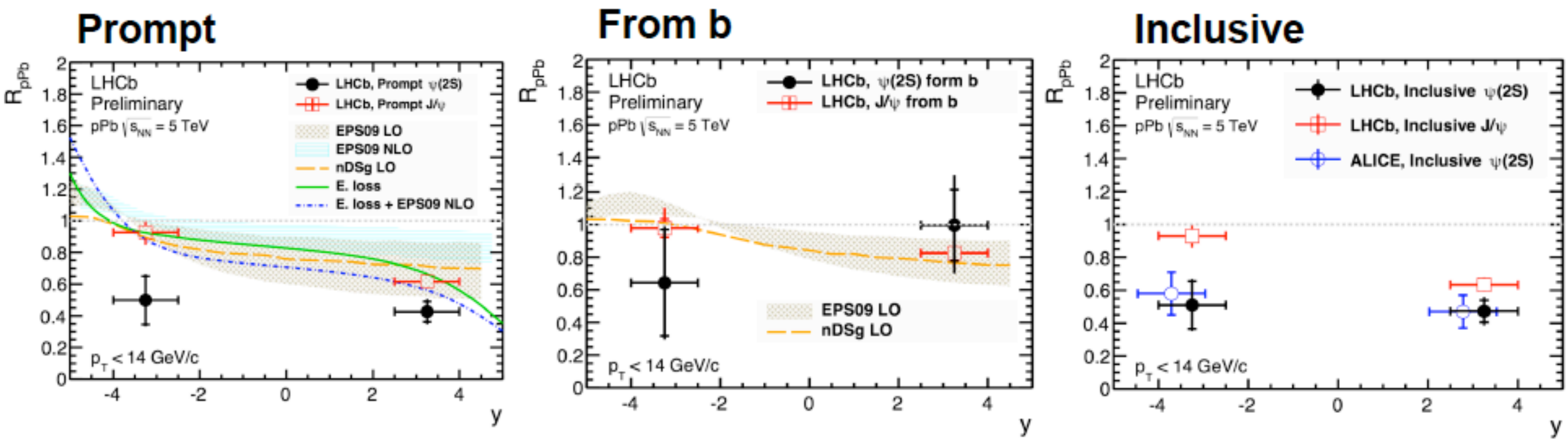
    - Combination of measurements of quarkonium for $-3<y_{CM}<0$ will allow to pin down the existence of a possible gluon EMC and antishadowing effect
- **Other cold nuclear matter effects**
  - Larger suppression for excited quarkonium in the backward
  - Other mechanism at play, e.g. comovers Ferreiro (PLB'15) ? see B. Schmidt's talk



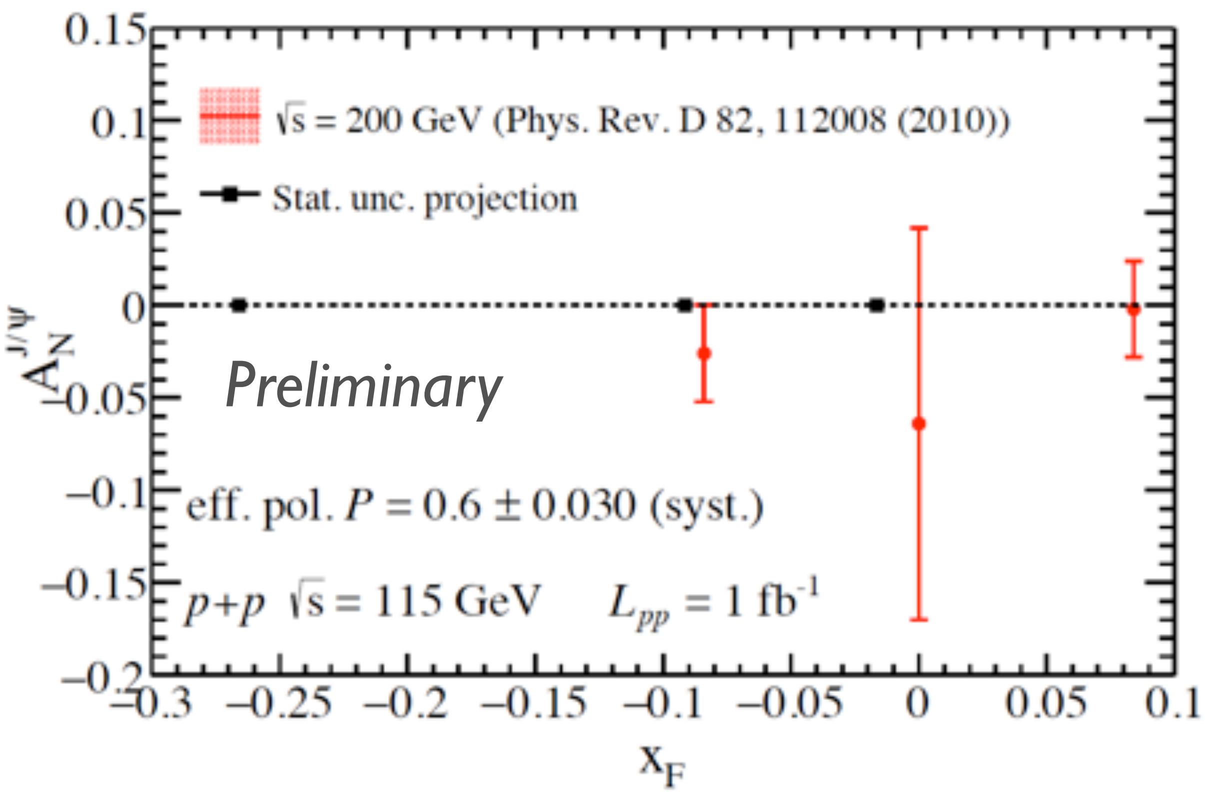
Thursday, August 25, 16

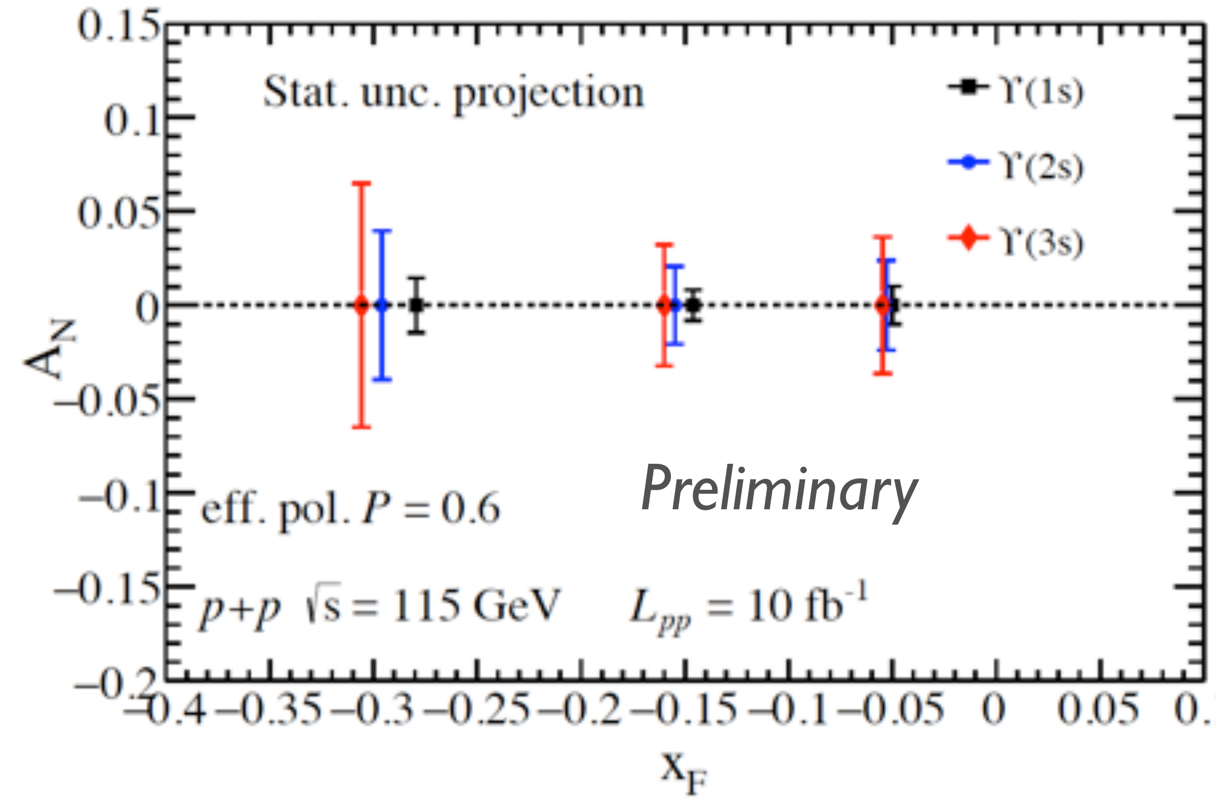
SPIN PHYSICS: SINGLE SPIN ASYMMETRY

- Polarized target allows to study spin physics
  - Gluon PDF in polarized proton $g_{p\uparrow}(x,k_T) \overset{?}{=} g_{p\downarrow}(x,k_T)$ (Sivers effect)
  - Much larger Feynman $|x_F|$ achievable compared with PHENIX
  - Much smaller stat. uncertainty (permille level)
  - First opportunity to observe single spin asymmetry in Upsilon
  - The precise verification of sign change of the Sivers function
  - SIDIS data (current only) vs more data (Drell-Yan, quarkonium etc)

Single Spin Asymmetry

$$A_N = \frac{1}{P}\frac{\sigma^\uparrow - \sigma^\downarrow}{\sigma^\uparrow + \sigma^\downarrow}$$

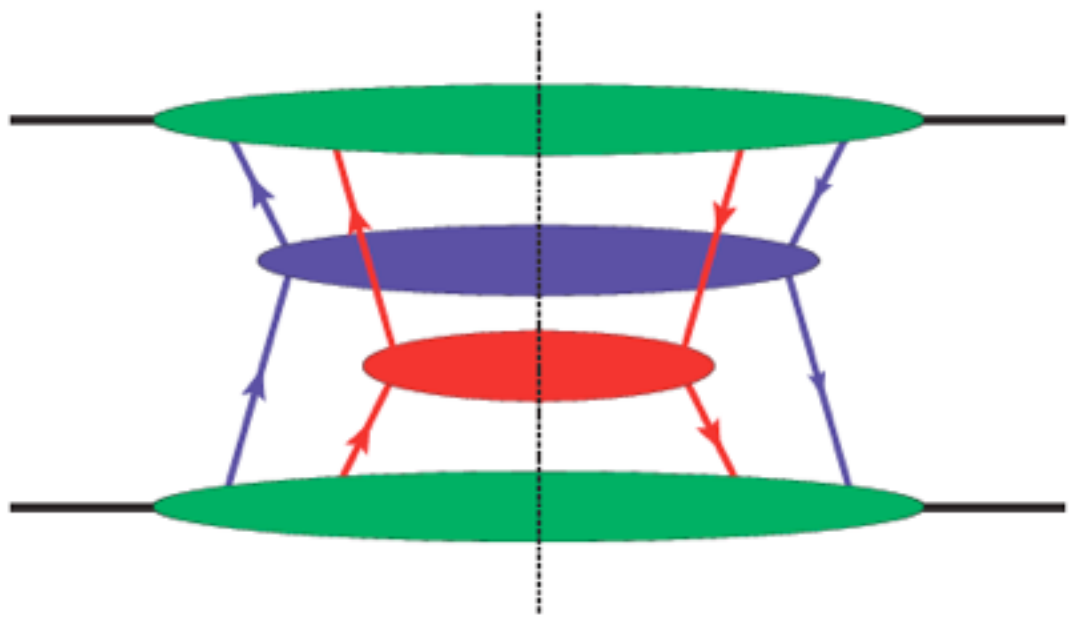




Expression of Interest in preparation

DOUBLE PARTON SCATTERINGS

- **Double Parton Hard Scatterings**
  - **An important production mode of particles in high-energy coll.**



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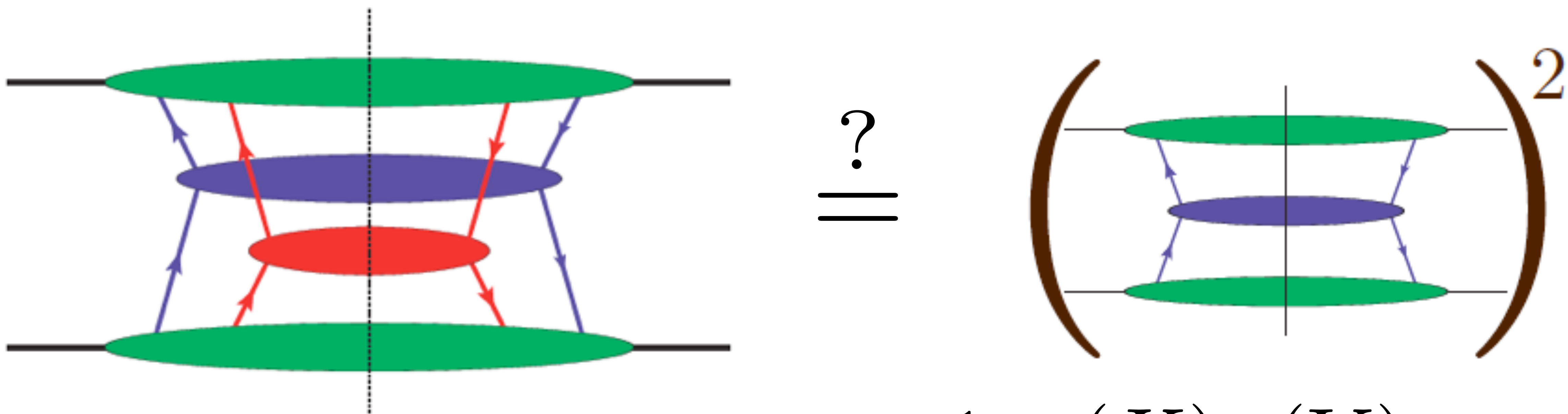
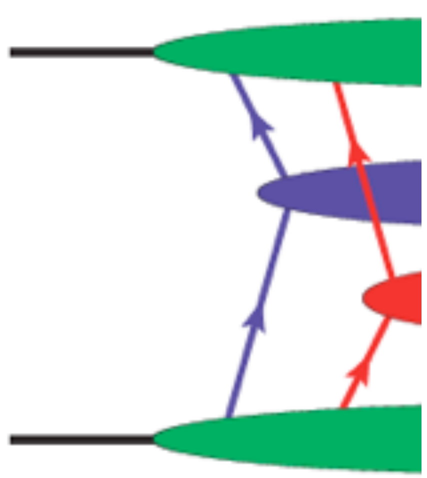


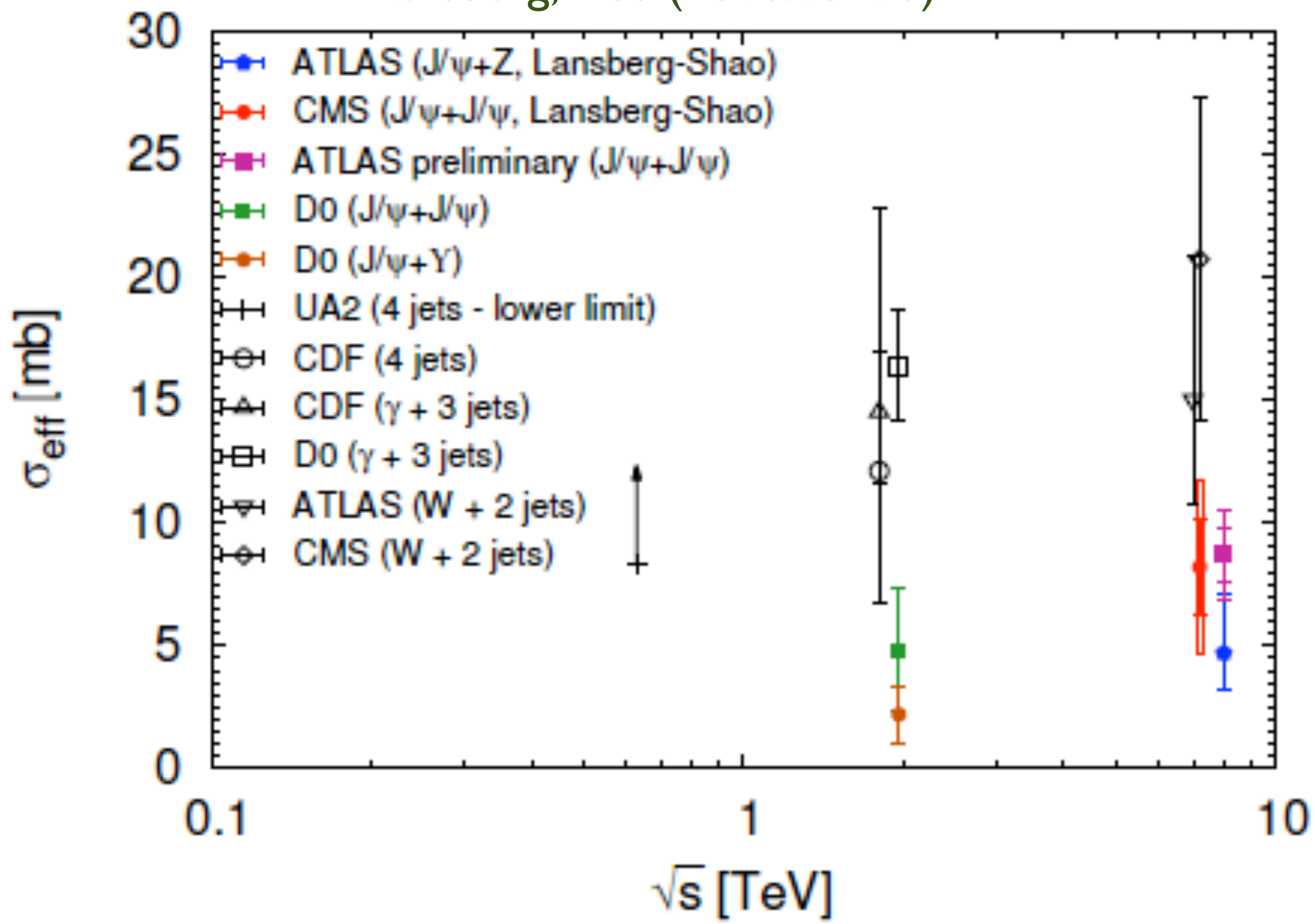
$$\sigma^{\rm DPS}(X+Y) \stackrel{?}{=} \frac{1}{m}\frac{\sigma(X)\sigma(Y)}{\sigma_{\rm eff}}$$

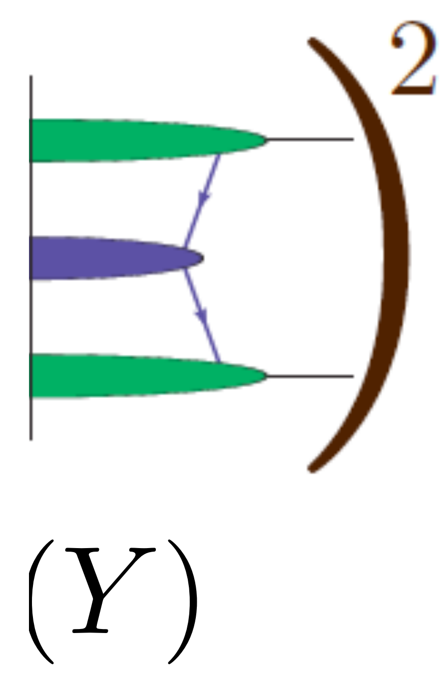
DOUBLE PARTON SCATTERINGS

- **Double Parton Hard Scatterings**
  - **An important production mode of particles in high-energy coll.**
  - **How to quantify its size ?**
  - **Universal $\sigma_{\rm eff}$?** see I. Belyaev, D. Bertsche's talks
    - process independent ?
    - energy independent ?
    - initial flavor independent ? gluon = quark ?



Lansberg, HSS (1608.03198)





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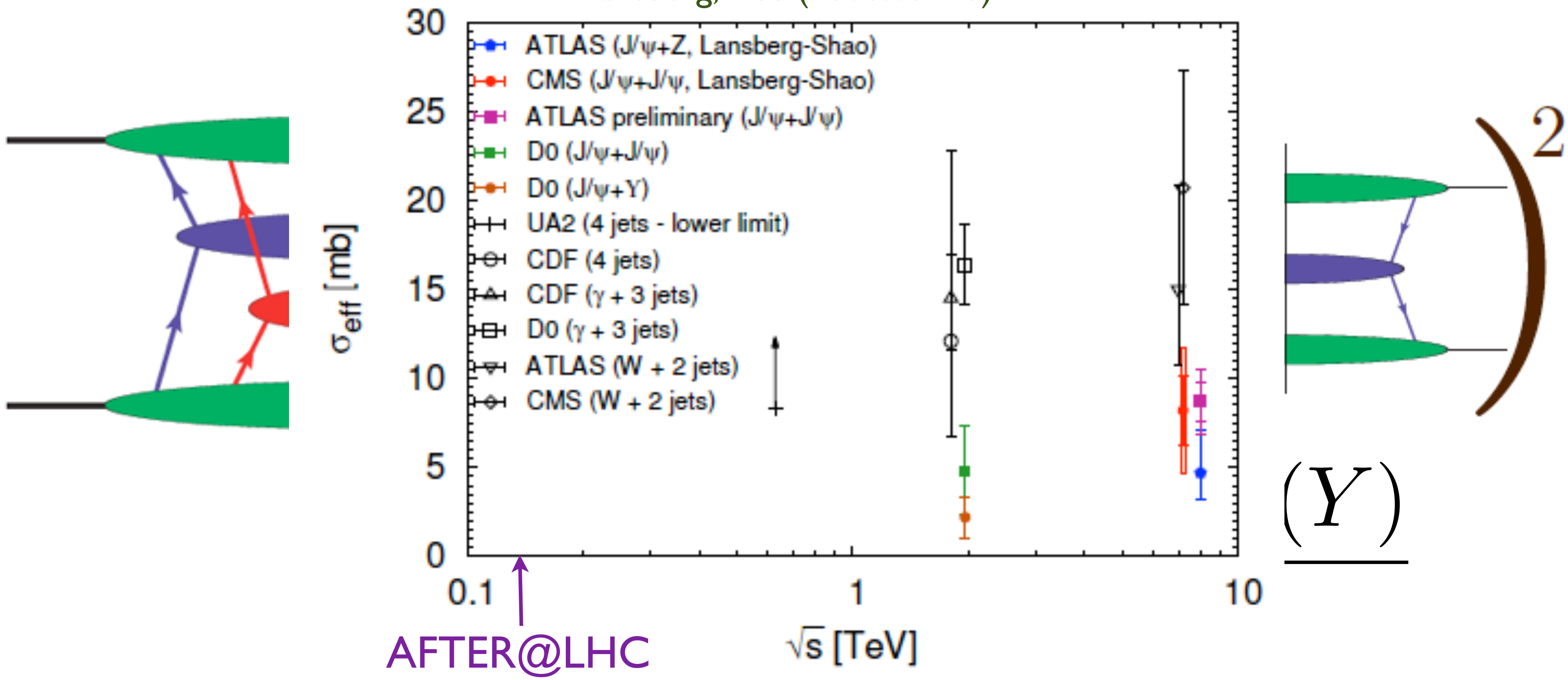
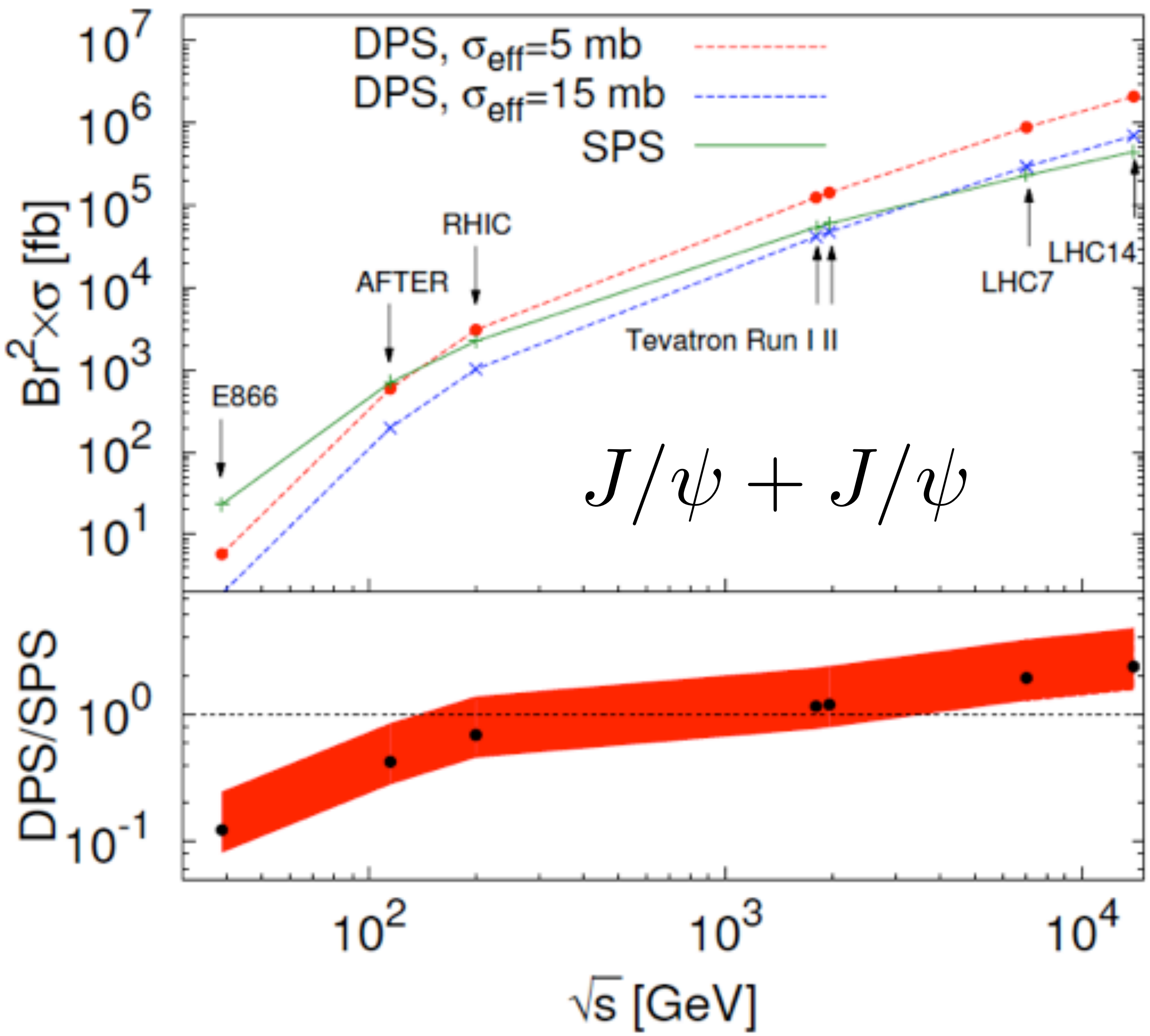
Lansberg, HSS (1608.03198)



DOUBLE PARTON SCATTERINGS

Lansberg, HSS (NPB'15)

- **Double Quarkonium Production at AFTER@LHC**
  - **First opportunity to measure it at $\sqrt{s}$ ~100 GeV due to high luminosity**



DOUBLE PARTON SCATTERINGS

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- **Double Quarkonium Production at AFTER@LHC**
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    - Other processes are not even observed yet in the LHC collider mode

$\sigma(pp \to \mathcal{Q}_1 + \mathcal{Q}_2 + X) \times \mathcal{B}(\mathcal{Q}_1 \to \mu^+\mu^-)\mathcal{B}(\mathcal{Q}_2 \to \mu^+\mu^-)$ in units of fb at $\sqrt{s} = 115$ GeV,

	$J/\psi + J/\psi$	$J/\psi + \psi(2S)$	$\psi(2S) + \psi(2S)$
$\sigma_{\rm DPS}$	590^{+730}_{-210}	$19^{+23}_{-6.7}$	$0.15^{+0.18}_{-0.052}$
$\sigma^{\rm CSM}_{\rm SPS}$	700^{+3600}_{-560}	85^{+440}_{-68}	$2.5^{+13}_{-2.0}$

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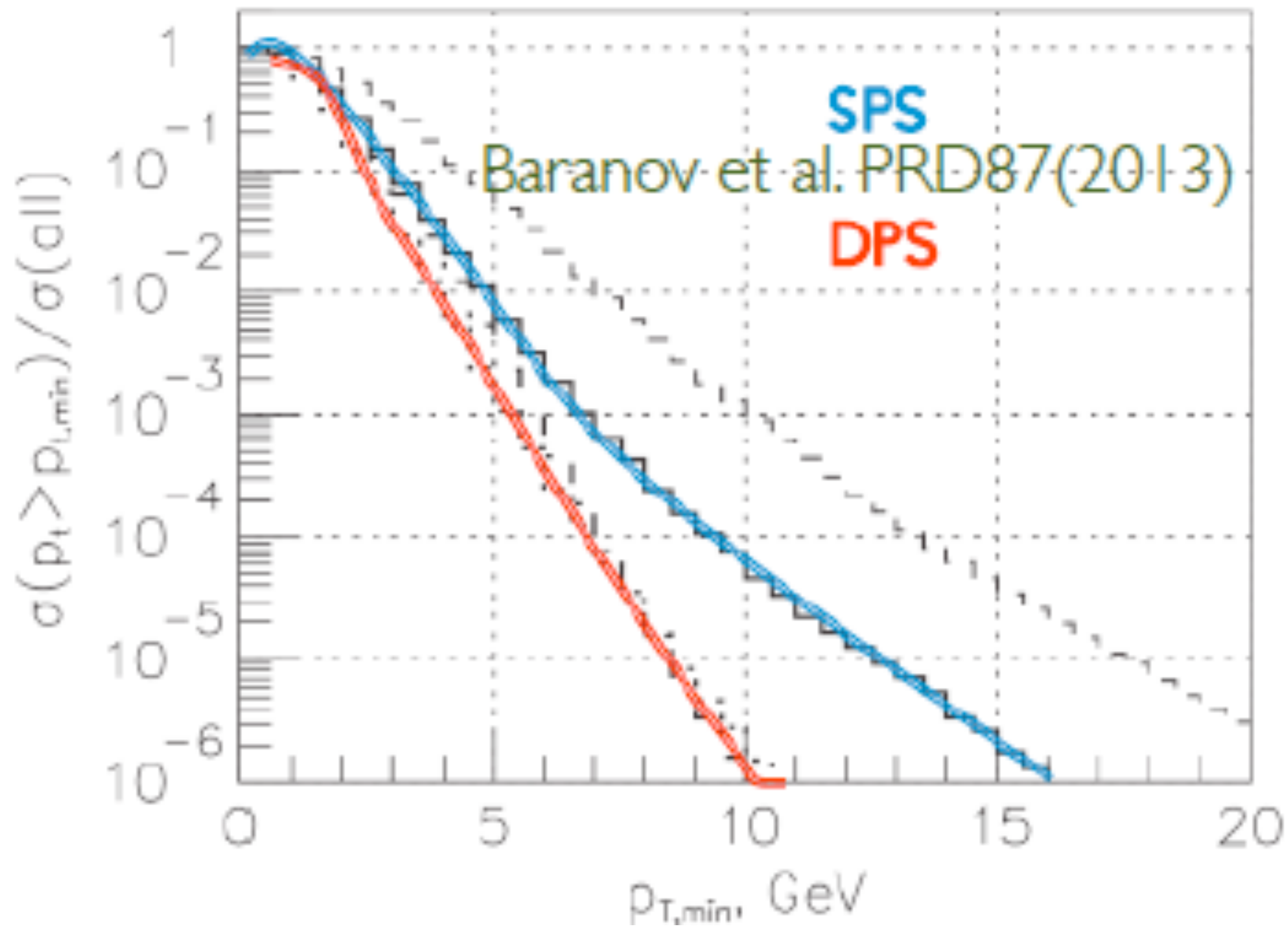
  - **Maintain the maximal DPS with p_T down to 0**



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DOUBLE PARTON SCATTERINGS

Lansberg, HSS (NPB'15)

- **Double Quarkonium Production at AFTER@LHC**
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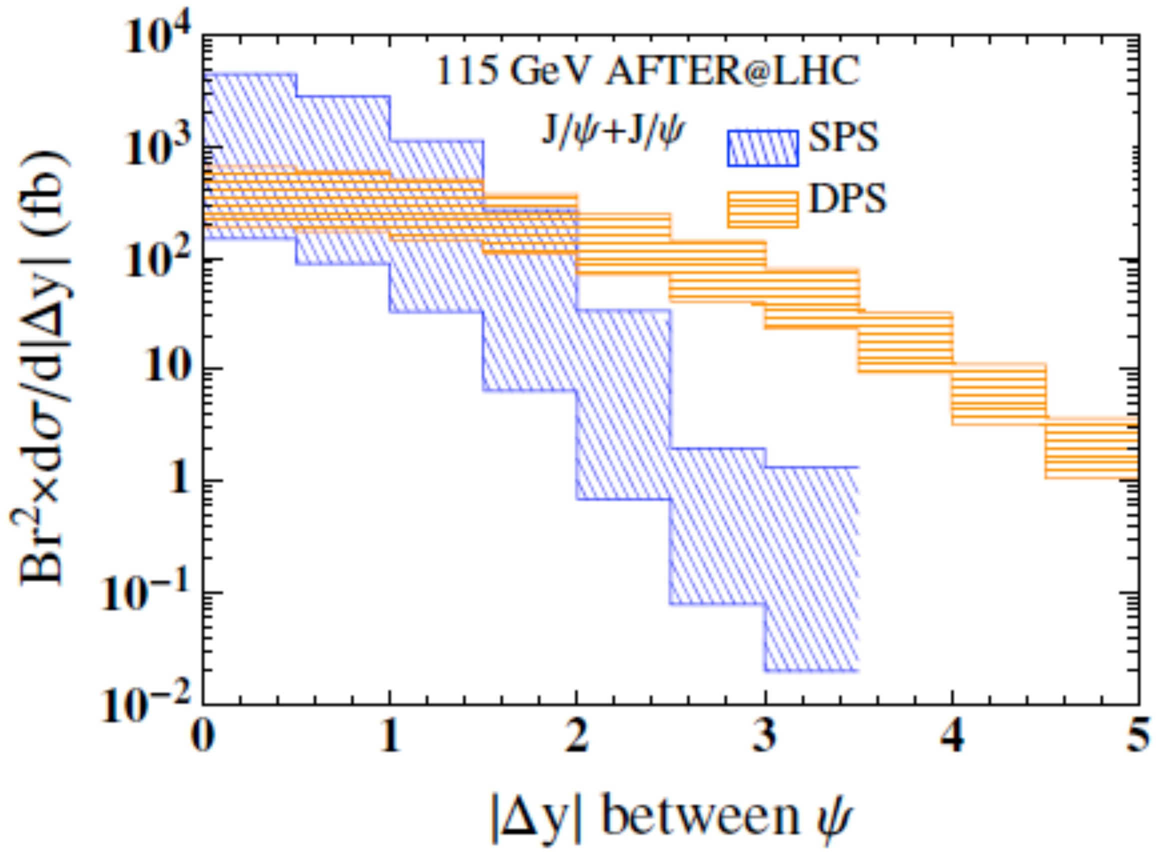
  - **Only double charmonium is feasible**
    - Other processes are not even observed yet in the LHC collider mode
  - **Maintain the maximal DPS with p_T down to 0**
  - **Much hope to separate SPS vs DPS via kinematical distributions**



SUMMARY

- Many physics opportunities with AFTER@LHC
- Novel testing ground for QCD in the high-x frontier with AFTER@LHC
- Very high luminosities can be achieved and target versatility
- Heavy quarkonium will play an important role at AFTER@LHC
- Many ideas in favour of AFTER@LHC published
- First feasibility study performed
- New opportunities for studying nuclear effect, spin, DPS etc
- Expression of Interest in preparation

Vielen Danken !

Thank you for your attention !

Back Up

LUMINOSITIES: INTERNAL GAS TARGET

- **Luminosities** in pH and pA with internal gas target

Beam	Target	Usable gas zone (cm)	Pressure (Bar)	L ($\mu b^{-1}.s^{-1}$)	$\int L$ ($pb^{-1}.yr^{-1}$)
p	Perfect gas	100	10^{-9}	10	100

With pressure of 10^{-6} mbar - 3 times SMOG – one gets 100 pb^{-1} yr^{-1}

- **Luminosities** in PbH and PbA with internal gas target

Beam	Target	Usable gas zone (cm)	Pressure (Bar)	L ($\mu b^{-1}.s^{-1}$)	$\int L$ ($pb^{-1}.yr^{-1}$)
Pb	Perfect gas	100	10^{-9}	0.001	0.001

$$P = 10^{-6}\ mbar$$

BEAM EXTRACTION WITH BENT CRYSTAL

Motivated for collimation purposes

Standard collimation today → Crystal-based collimation
- UA9 (@SPS)
- LUA9 (@LHC)

→ To beam extraction
- CRYSBEAM (@SPS then LHC)
- AFTER@LHC

W. Scandale et al., JINST 6 T10002 (2011)

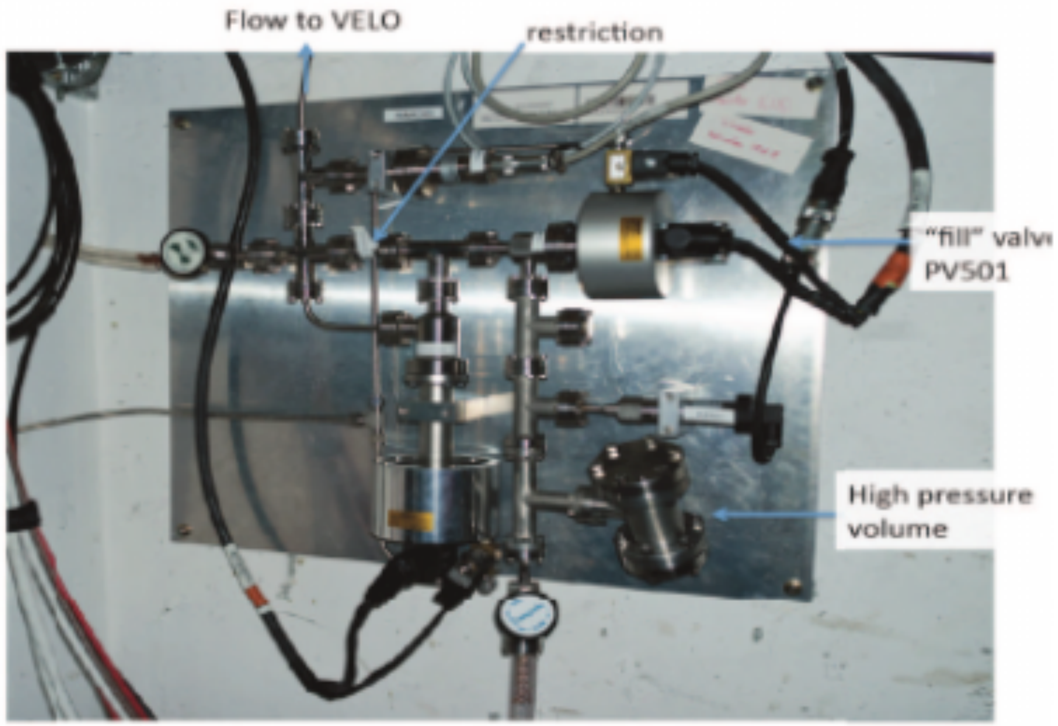
Beam "split" with a bent crystal

- ✗ beam collimation at LHC using bent crystals is studied by the UA9 collaboration
- ✗ UA9 test @SPS of the crystal with proton and ion beams
- ✗ LUA9 (beam bending experiment at LHC using crystal)
  - 2 bent crystals installed in IR7 during LS1, 2015/2016 tests with beams
- ✗ proton beam extraction: single or multi-pass extraction efficiency, 50%
- ✗ expected extracted p beam: 5×10^8 p/s (LHC beam loss: $\sim 10^9$ p/s)
- ✗ expected extracted Pb beam: 2×10^5 Pb/s

INTERNAL GAS TARGET WITH SMOG

Motivated for precise luminosity determination

SMOG: System for Measuring Overlap with Gas



➜ injection of Ne-gas into VELO

- Low density noble gas injected into VELO in LHCb
- Short pNe pilot run at 87 GeV (2012)
- Short PbNe pilot run at 54 GeV (2013)
- He, Ne and Ar gas injected (2015)
- pNe, pAr run at 110 GeV (2015)
- 1.5 week of PbAr at 69 GeV (2015)

Limitations so far:

- Only noble gas
- Target polarization is not possible with SMOG

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