Quarkonium4AFTER:
From the theory to the experiments

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+ J. He & H. S. Shao @CERN

FCPPL Workshop
April 2015
USTC Hefei

Outline

- Energy dependence of quarkonium production at NLO
- Double J/psi at the LHC and AFTER@LHC
- AFTER@LHC
  - Internal gas target *vs* beam extraction with a bent crystal
  - Expected luminosities
  - First simulations
- Summary & Outlook

Theoretical activities I

Energy Dependence of Direct-Quarkonium Production in *pp* Collisions from Fixed-Target to LHC Energies: Complete One-Loop Analysis

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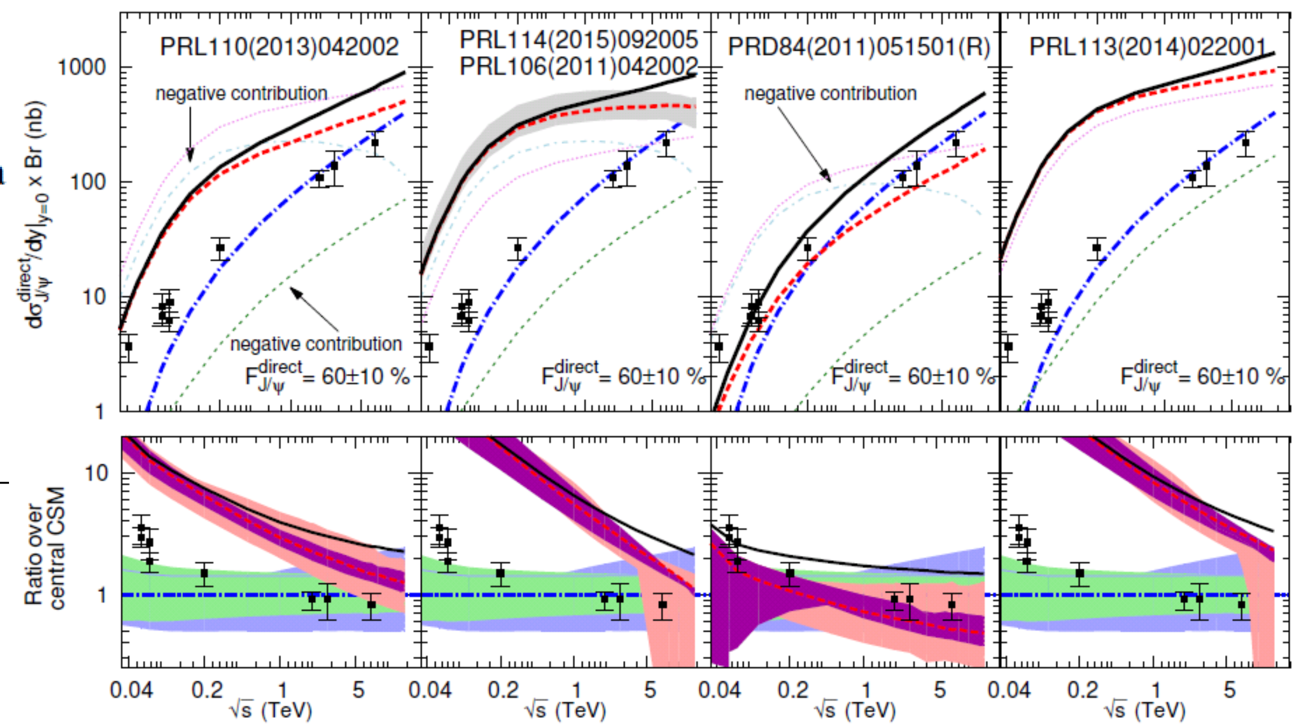
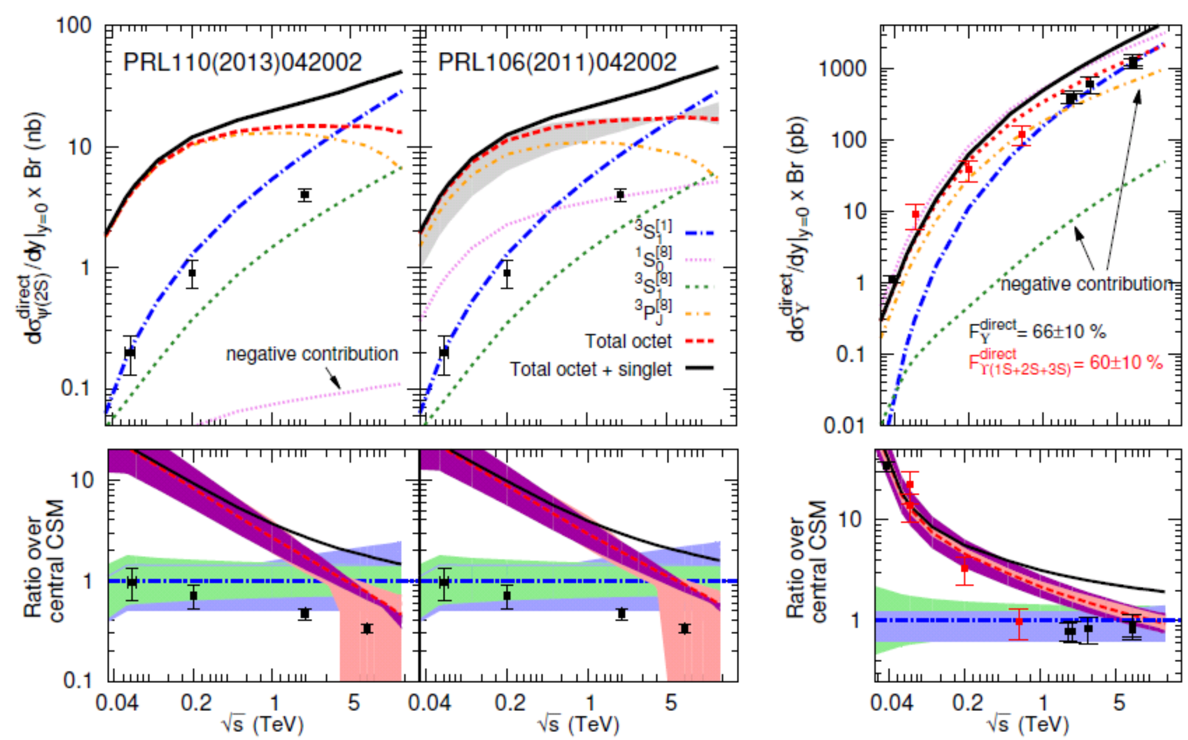
arXiv:1504.00317v1 [hep-ph] 1 Apr 2015



(a) J/ψ



(b) $\psi(2S)$ (c) $\Upsilon(1S)$

- First full one-loop analysis of the $\sqrt{s}$ dependence
- NRQCD universality challenged: Colour octet not necessarily dominant
- Theoretical issues at large $\sqrt{s}$
- Implication for heavy-ion physics: Propagation of octet vs. singlet in the QGP
- Part of Y. Feng's PhD work

Theoretical activities II

J/ψ-Pair Production at Large Momenta: Indications for Double-Parton Scatterings and Large α_s^5 Contributions

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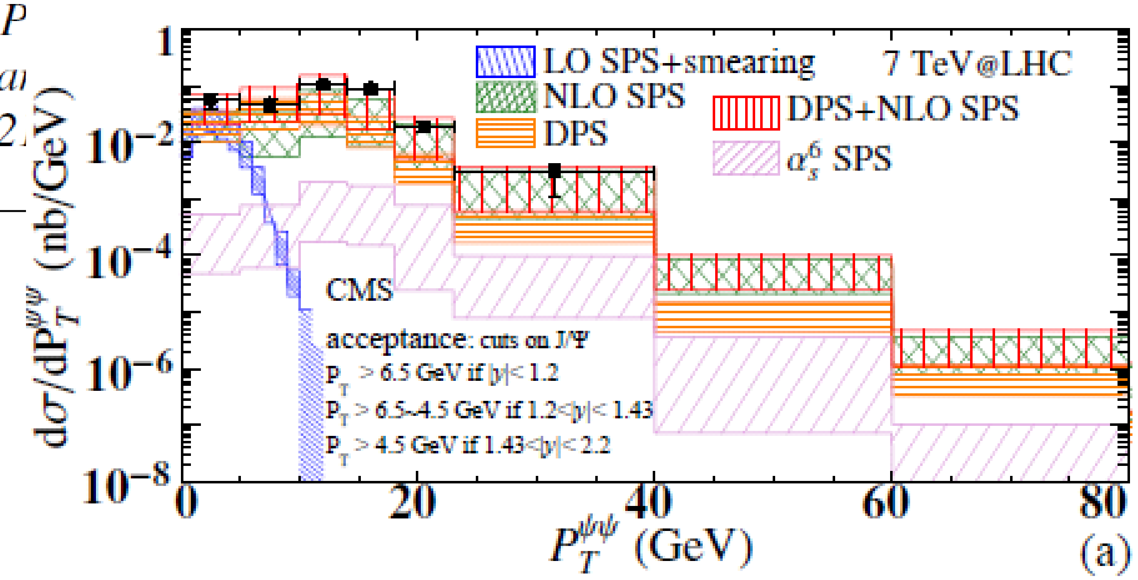
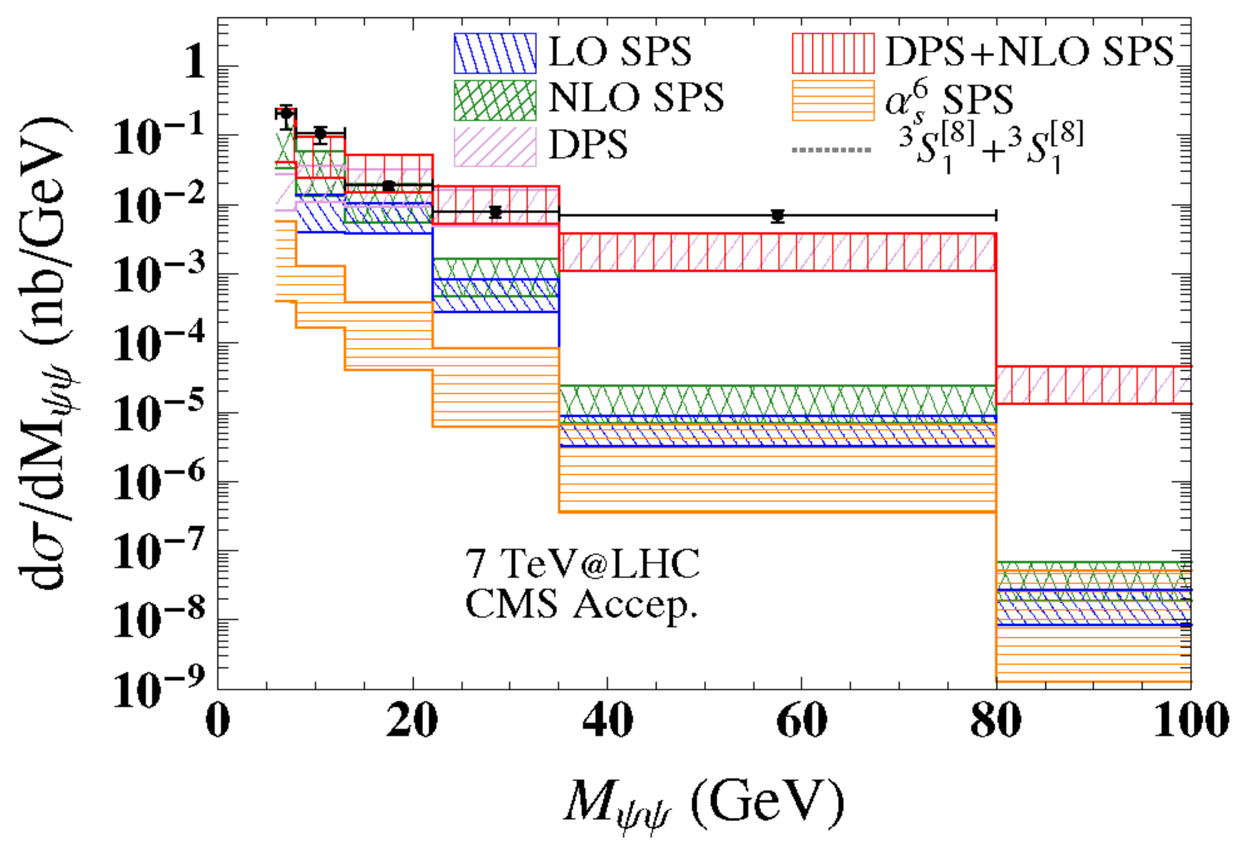
arXiv:1410.8822v1 [hep-ph] 31 Oct 2014



- Solution of order-of-magnitude discrepancy with the CMS data by introducing double-parton scattering
- Derivation of relations to test DPS dominance involving quarkonium excited states (J/ψ+χ, J/ψ+ ψ')
- Computation of the first part of the NNLO (α_s^6)'s contributions



Theoretical activities III

Double quarkonium production at a fixed-target experiment at the LHC (AFTER@LHC)

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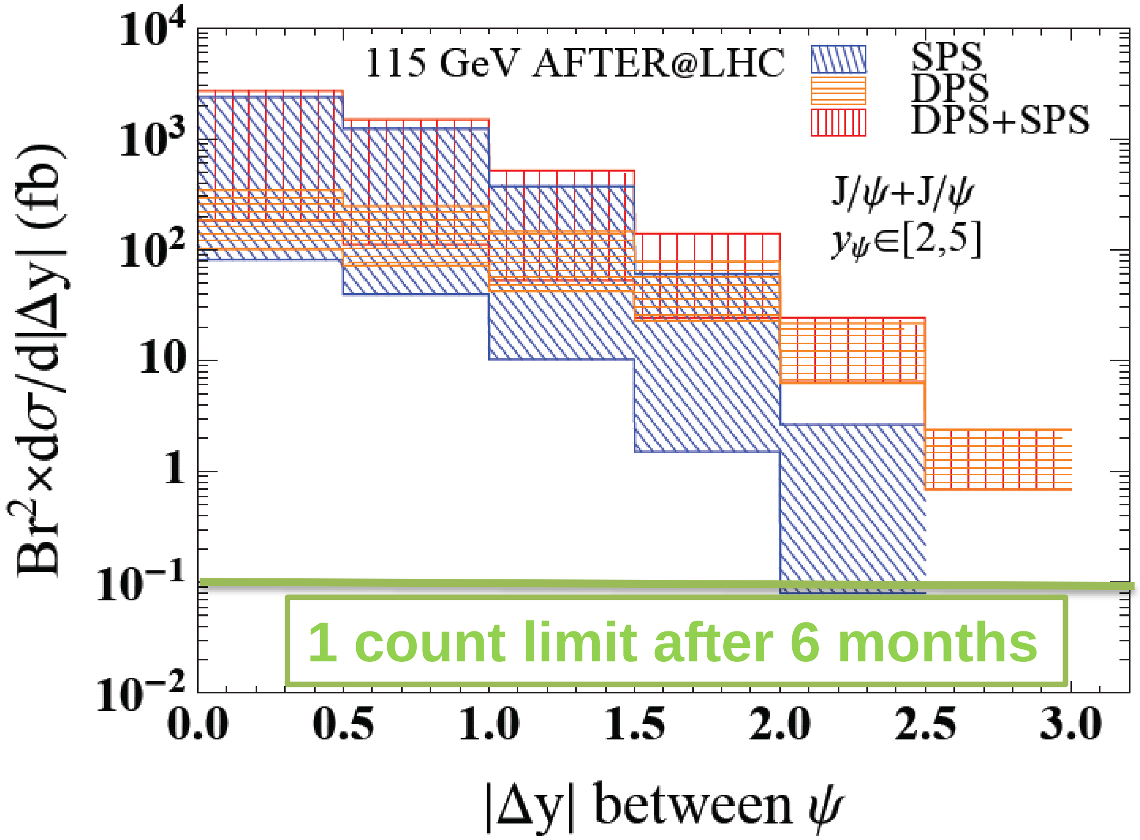
To be submitted to arXiv

(Dated: March 19, 2015)

We present predictions for double quarkonium production in the kinematical region relevant for the proposed fixed-target experiment by using the LHC beams (dubbed as AFTER@LHC) . These include all spin-triplet S-wave charmonium and bottomonium pairs, i.e. $\psi(n_1S) + \psi(n_2S)$, $\psi(n_1S) + \Upsilon(m_1S)$ and $\Upsilon(m_1S) + \Upsilon(m_2S)$ with $n_1, n_2 = 1, 2$ and $m_1, m_2 = 1, 2, 3$. We calculate the contributions from double-parton scatterings and single-parton scatterings. With an integrated luminosity of 20 fb^{-1} to be collected at AFTER@LHC, we find that the yeilds for double charmonium production are large enough for differential distribution measurements. We discuss some differential distributions for $J/\psi + J/\psi$ production, which can help to study the physics of both double-parton and single-parton scatterings in a new energy range.

- Double quarkonium production measurable at AFTER@LHC
- Enough statistics for ψ+ψ to look for DPS at '*low*' energies
- Can be complemented with ψ+*D*
- Can also probe the charm content in the proton

S.J. Brodsky, J.P. Lansberg Phys.Rev.D81:051502,2010



Status report on AFTER@LHC
& Connections with SMOG@LHCb

AFTER@LHC : A Fixed Target ExpeRiment @ LHC for hadron, heavy-ion and spin physics

- **3 main physics objectives :**
  - Advance our understanding of the **large-*x*** gluon, antiquark and heavy-quark content in the nucleon & nucleus
  - Dynamics and **spin** of **gluons** inside (un)polarised nucleons
  - **Heavy-ion collisions** towards large rapidities

- **Various ways to collide LHC beams on fixed targets :**
  - Beam line extracted with a bent crystal
  - Beam "splitted" with a bent crystal

  } **To be tested by (L)UA9, 2 crystals installed**

  - Internal wire target
  - Internal gas target *à la* SMOG-LHCb

  } **Low stat. data already collected by LHCb**

- **Submission of an Expression of Interest to the LHCC in Fall 2015**
  - Identify *pro's* and *con's* of these 4 fixed-target modes
  - Simulations of the **detector performances**
  - Phenomenology and benchmarking of **key observables**
  - Novel theoretical ideas

Beam extraction using a bent crystal

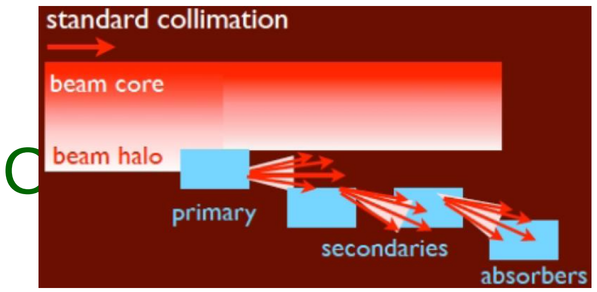
- Beam collimation @LHC: amorphous collimator, inefficiency of 0.2% (3.5 TeV p beam)
  - Expected bent crystal inefficiency: 0.02%

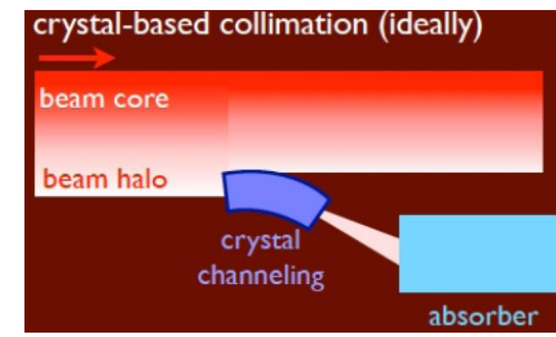
  UA9: test @SPS on the crystal with proton and ion beams

  LUA9 (beam bending experiment using crystal): approved by LHCC

  *2 bent crystals **already installed** in IR7 during LS1*

  2015/2016 first tests with beams





- **Proton beam extraction:**
  - Single or multi-pass extraction efficiency of 50%
  - LHC beam loss ~ 10^9 p^+ s^{-1} - extracted beam : ***5 x 10^8 p^+ s^{-1}***
  - Extremely small emittance: beam size (in the extraction direction) 950m after the extraction: 0.3mm

- **Ion beam extraction**
  - Successfully tested at the SPS, should also work at the LHC (P. Ballin et al, NIMB 267 (2009) 2952)

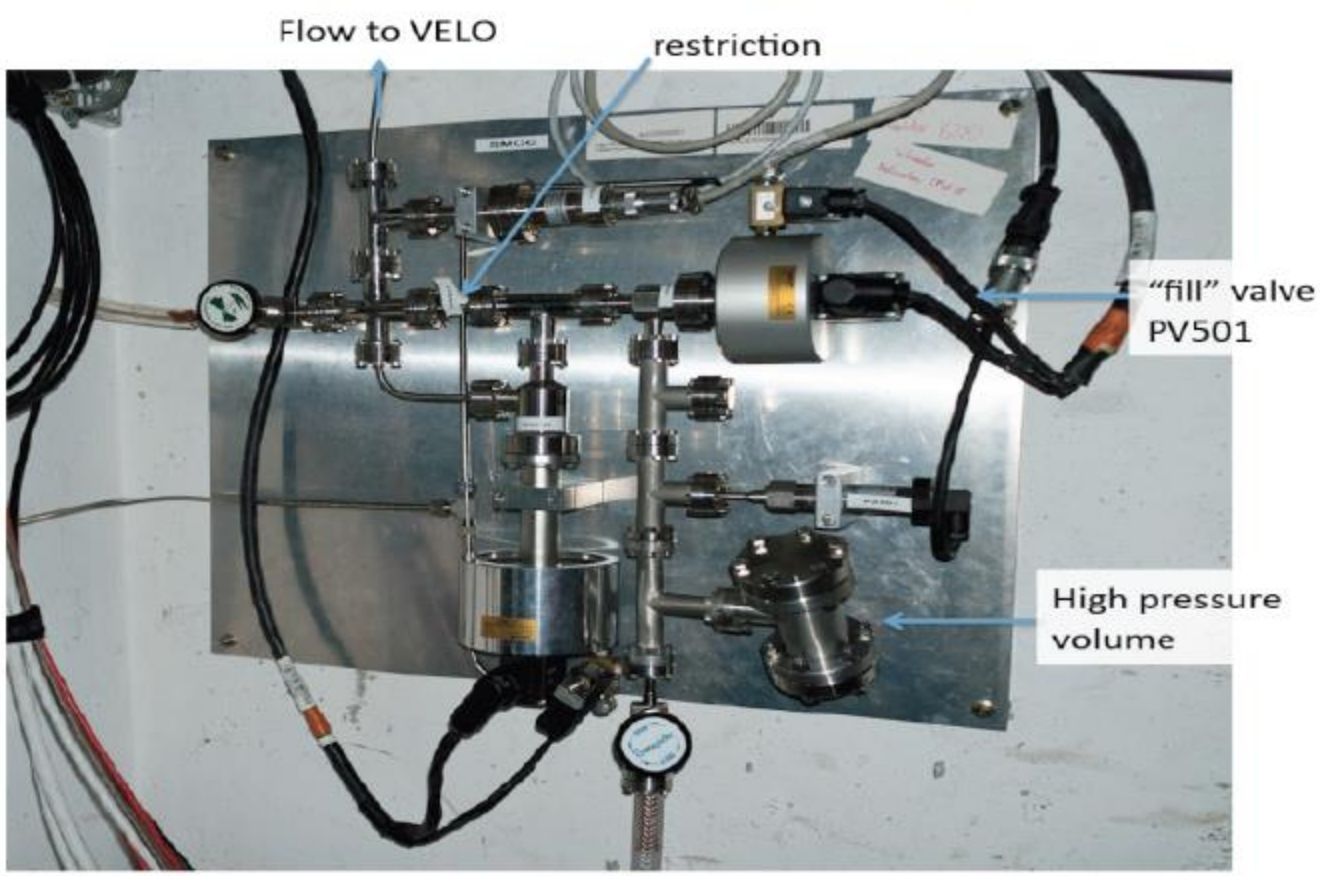
Deflecting the beam halo at 7σ distance to the beam

No loss in the LHC beam

Internal gas target: SMOG@LHCb

Another way to the fixed-target mode

SMOG: System for Measuring Overlap with Gas



➜ injection of Ne-gas into VELO

- Low density Ne-gas injected into VELO in LHCb
- pNe pilot run at $\sqrt{s_{NN}}$ **= 87 GeV** in **2012**
- PbNe pilot run at $\sqrt{s_{NN}}$ **= 54 GeV** in **2013**

LHCb−CONF−2012−034

- Noble gases favored (Ne, Xe, Ar, …)
- As for now, target polarization is not possible with SMOG
- Luminosity limit to be checked
- Internal gas target can be polarized, would be another system wrt SMOG

SMOG is the ideal test ground for AFTER@LHC

Luminosities and quarkonium yields

Instantaneous luminosity (integrated over 10^7 sec. for p or 10^6 sec. for Pb)

Extraction

Φ extracted beam = 5×10^8 $p^+ s^{-1}$

(50% of the beam loss)

$$\phi_{\mathrm{beam}} \times (\rho \times l \times N_A) / A$$

Gas target

Φ Full beam = 2×10^{18} $p^+ s^{-1}$

$$\phi_{\mathrm{beam}} \times \left(\frac{\mathcal{N}_A}{22400} \times \mathrm{P} \times \ell\right)$$

Beam	Flux (s^{-1})	Target	$\sqrt{s_{NN}}$ (GeV)	Thickness (cm)	ρ $(g.cm^{-3})$	A	$\mathcal{L}$ $(\mu b^{-1}.s^{-1})$	$\int \mathcal{L}$ $(pb^{-1}.y^{-1})$	$\mathrm{Br}_{\ell\ell} \frac{dN_{J/\psi}}{dy}\Big\vert_{y=0}$ (y^{-1})	$\mathrm{Br}_{\ell\ell} \frac{dN_{\Upsilon}}{dy}\Big\vert_{y=0}$ (y^{-1})
p	5×10^8	Liquid H	115	100	0.068	1	2000	20000	4.0×10^8	8.0×10^5
p	5×10^8	Liquid D	115	100	0.16	2	2400	24000	9.6×10^8	1.9×10^6
p	5×10^8	Pb	115	1	11.35	207	16	160	6.7×10^8	1.3×10^6
Pb	2×10^5	Liquid H	72	100	0.068	1	0.8	0.8	3.4×10^6	6.9×10^3
Pb	2×10^5	Liquid D	72	100	0.16	2	1	1	8.0×10^6	1.6×10^4
Pb	2×10^5	Pb	72	1	11.35	207	0.007	0.007	5.7×10^6	1.1×10^4

Beam	Flux (s^{-1})	Target	$\sqrt{s_{NN}}$ (GeV)	Usable gas zone (cm)	Pressure (Bar)	A	$\mathcal{L}$ $(\mu b^{-1}.s^{-1})$	$\int \mathcal{L}$ $(pb^{-1}.y^{-1})$	$\mathrm{Br}_{\ell\ell} \frac{dN_{J/\psi}}{dy}\Big\vert_{y=0}$ (y^{-1})	$\mathrm{Br}_{\ell\ell} \frac{dN_{\Upsilon}}{dy}\Big\vert_{y=0}$ (y^{-1})
p	3×10^{18}	perfect gas	115	100	10^{-9}	A	10	100	$2 \times 10^6 \times A$	$4 \times 10^3 \times A$
Pb	5×10^{14}	perfect gas	72	100	10^{-9}	A	0.001	0.001	$4.25 \times 10^3 \times A$	$8.6 \times A$

Large luminosities comparable to LHC - with 1 m long $H_2(D_2)$ target

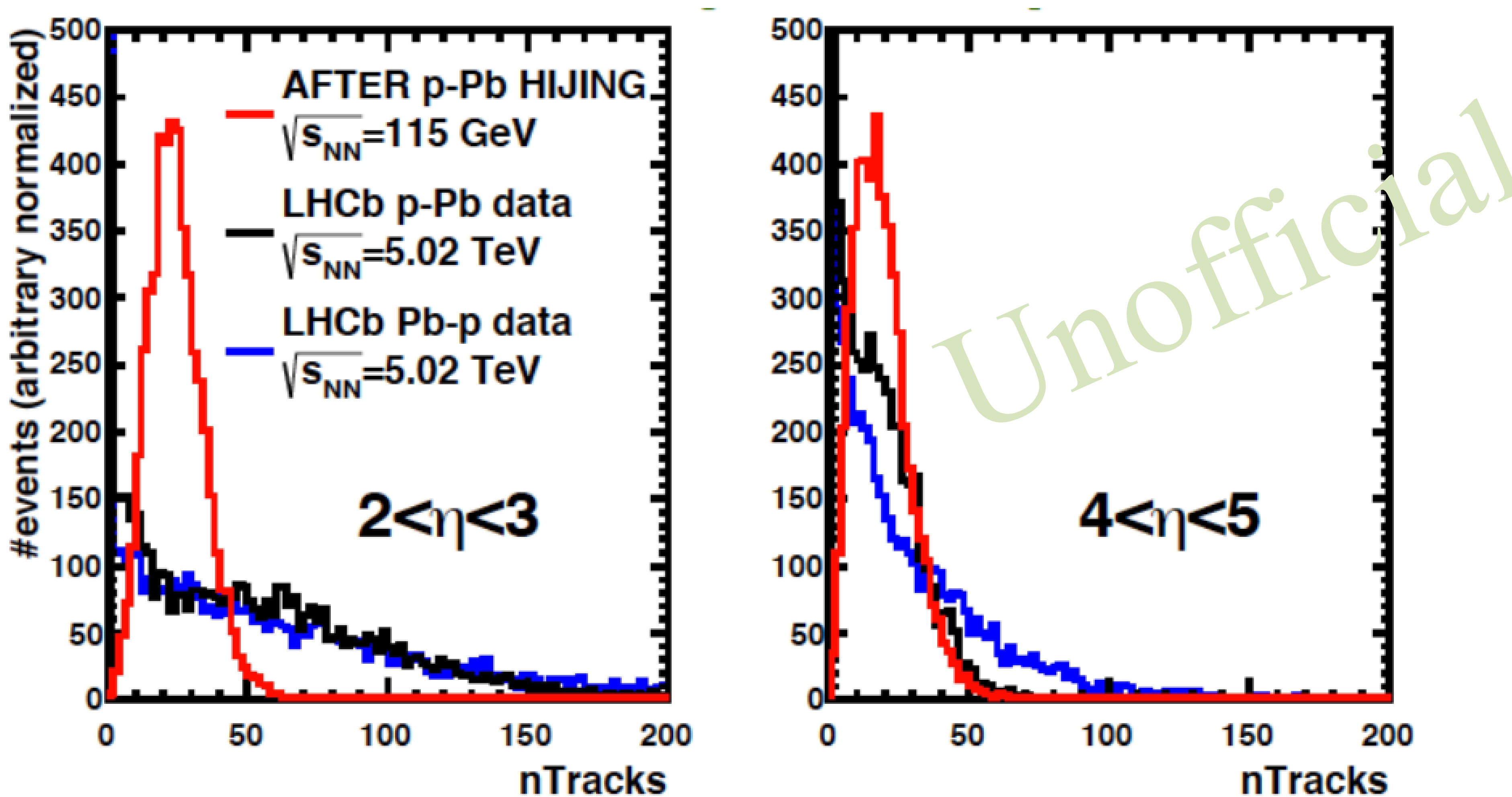
$\rightarrow$ 3 orders of magnitude larger than at RHIC

Gas Target needs pressure of 2 x 10^{-7} bar to compete with the extraction

Fast simulations

7 TeV proton beam on a Pb target
$\sqrt{s_{NN}}$ = 115 GeV

Z. Yang, AFTER workshop les Houches, January 2014



- Probability of high track multiplicity is lower in the fixed target mode than in the collider mode, at LHCb acceptance 2 < η < 5
- Boost should not be an issue – no problem for LHCb-like detector to cope with seen multiplicity

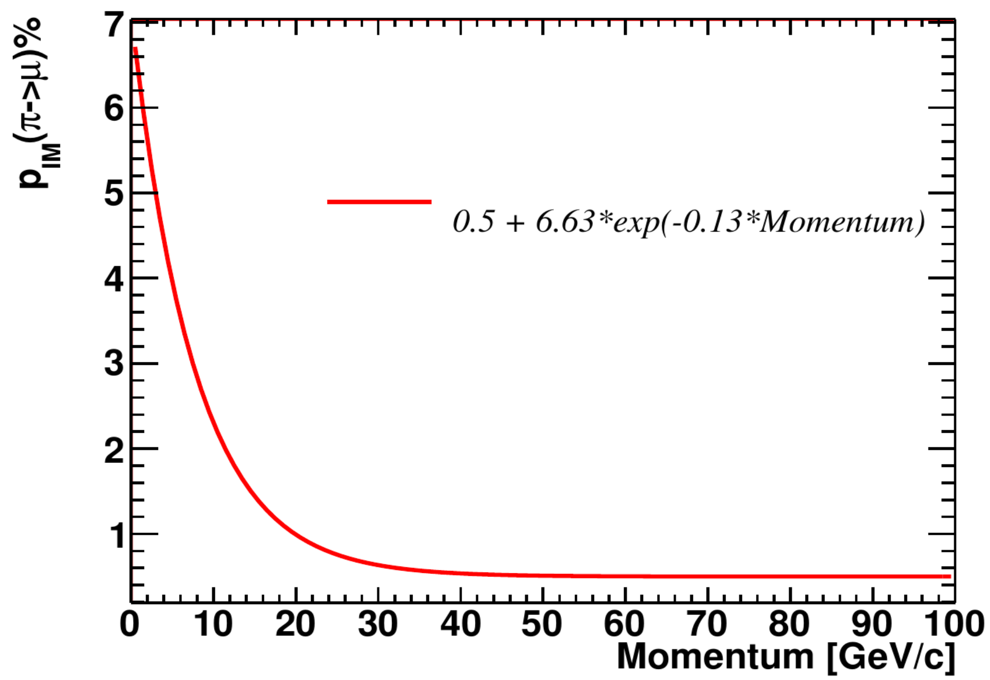
Quarkonium fast simulations, pp at $\sqrt{s}$ = 115 GeV

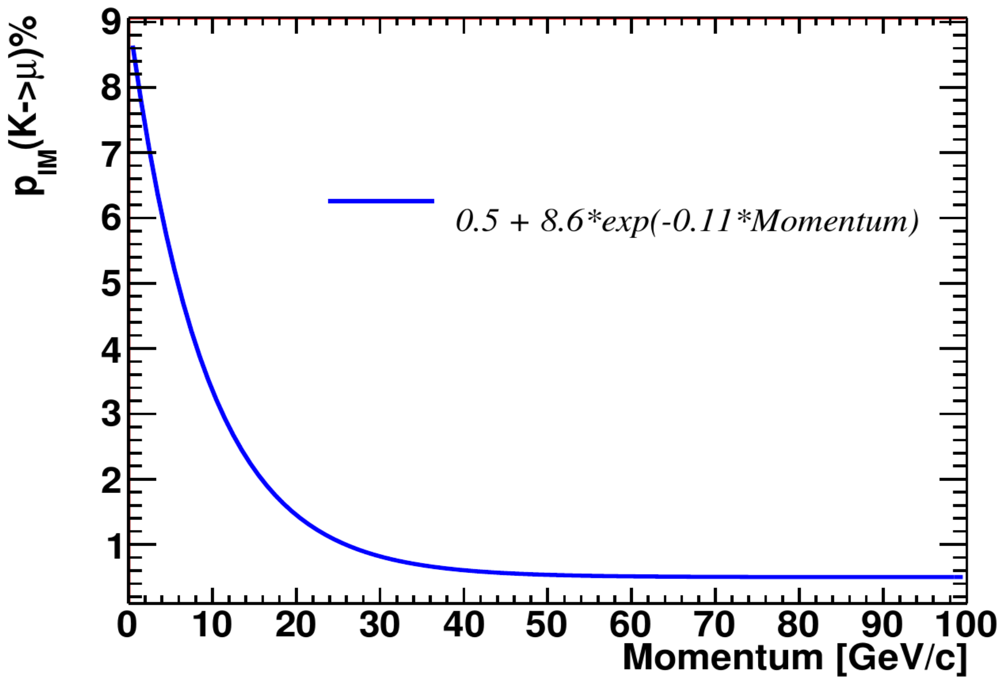
PYTHIA 8.185
Fast simulations with LHCb reconstruction parameters

- **Requirements:**
  Momentum resolution: $\Delta p/p$ = 0.5%
  μ identification efficiency: 98%

- **Single μ cuts:**
  $2 < \eta_\mu < 5$
  $p_T^\mu > 0.7$ GeV/c

- **μ misidentification:**
  π/K decays before 12m, rejected
  π/K decays after 12m, probability is applied



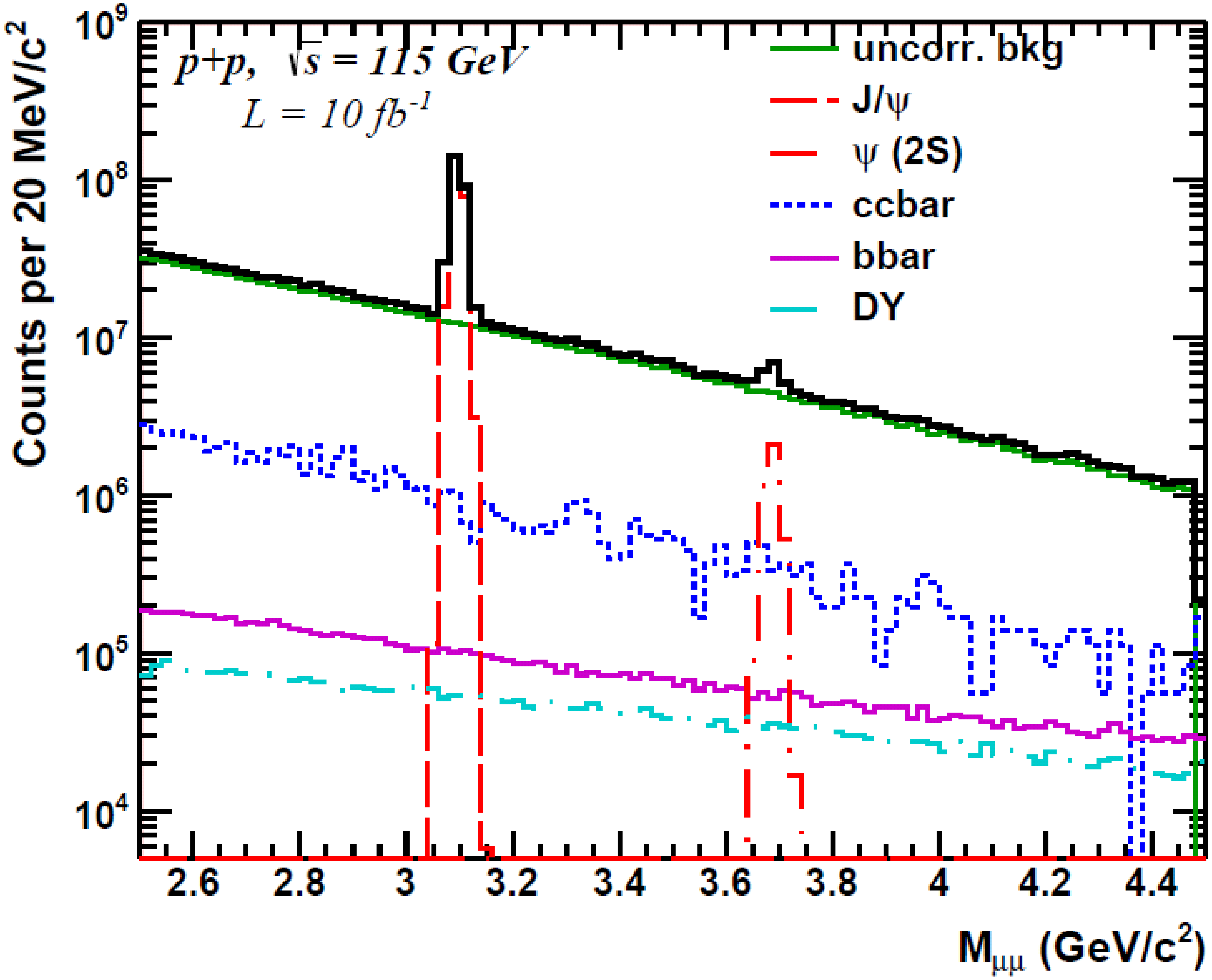


F. Achilli et al, arXiv:1306.0249

ψ signal simulation with full background

J/ψ / $\psi(2S) \rightarrow \mu^+ \mu^-$

$\int L = 10\ fb^{-1}$, **0.5 year of data taking with 1m H_2 target**

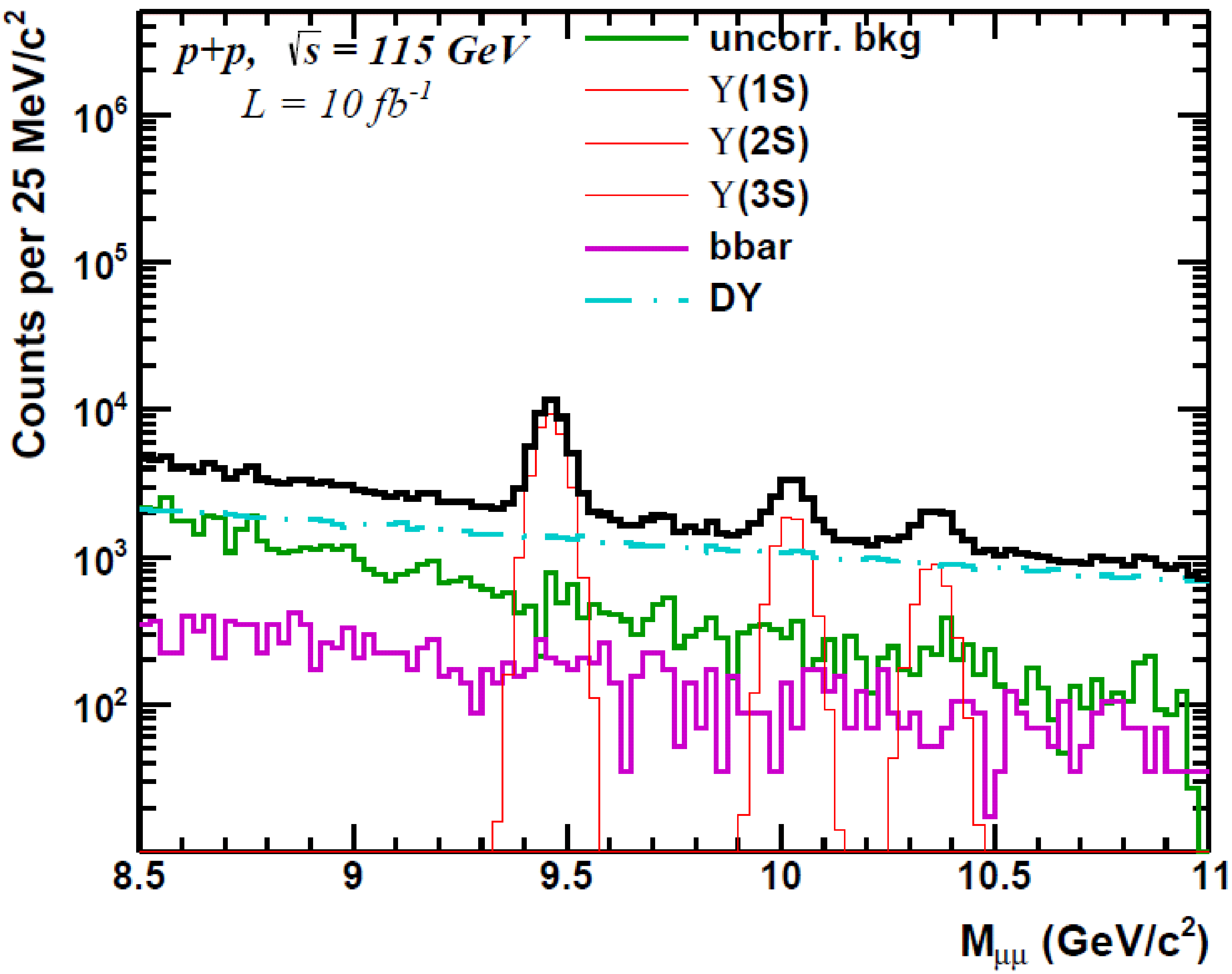


Dominant source of background is uncorrelated background

Υ signal simulation with full background

Υ(nS) → μ⁺ μ⁻

∫L = 10 fb^{-1} , **0.5 year of data taking with 1m H_2 target**

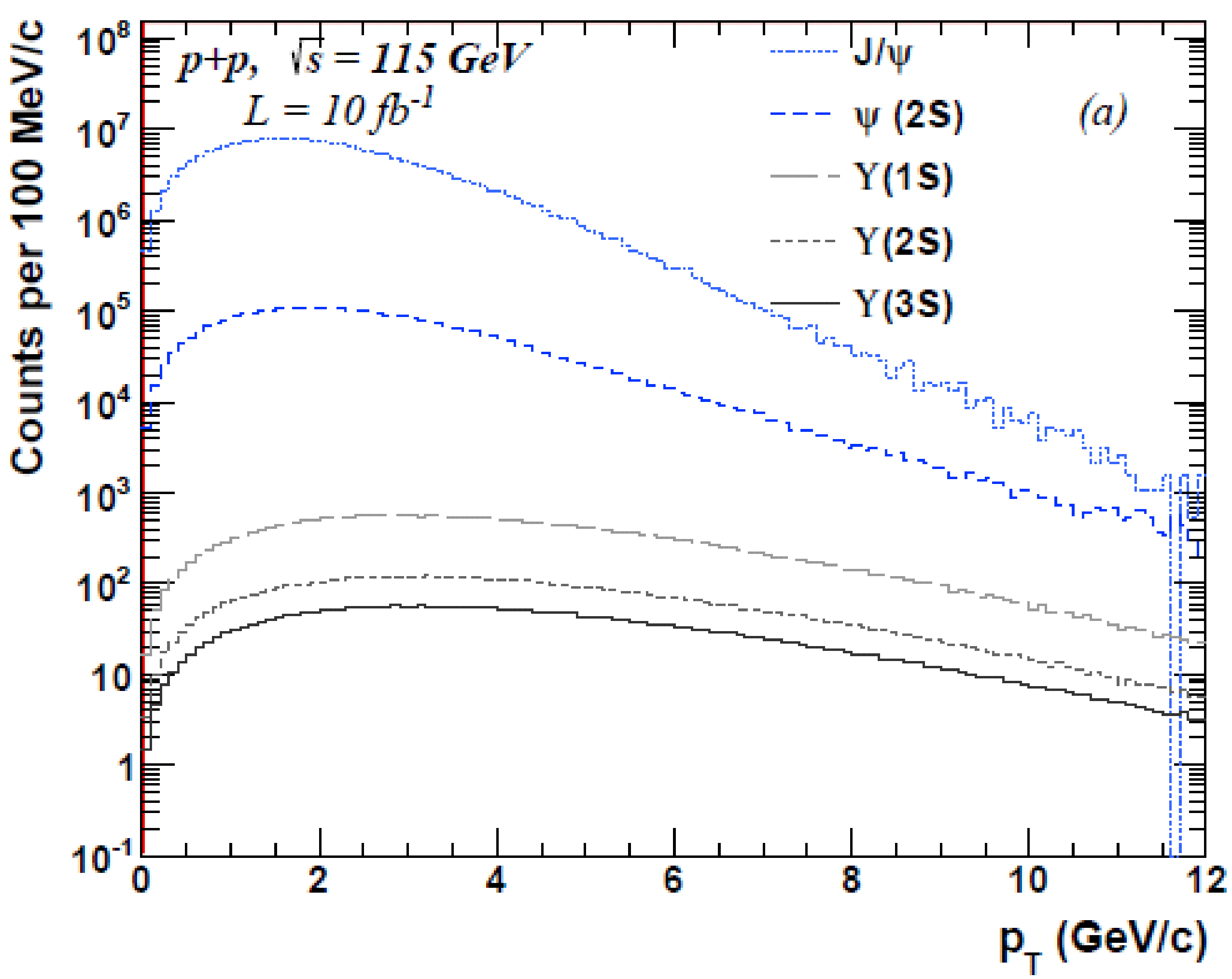


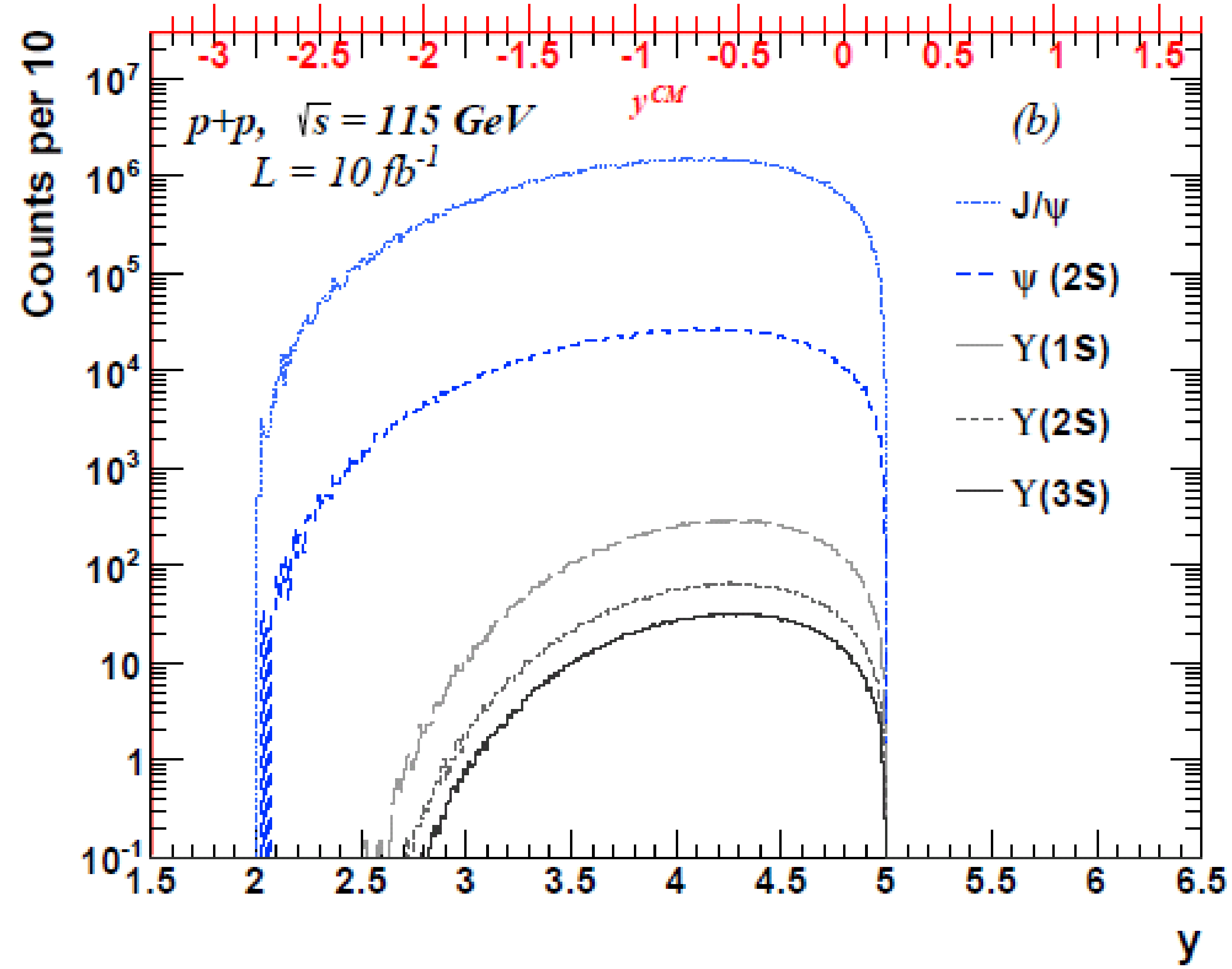
Dominant source of background is DY

Quarkonium acceptance and p_T reach

L = 10 fb^{-1} , **0.5 year of data taking with 1m H_2 target**

$2 < \eta_\mu < 5$





- J/ψ p_T~15 GeV/c with 1 year data
- x_T ~ 0.25
- Equivalent p_T reach to RHIC@500 GeV
- Same p_T reach expected for pA

- $-2.8<y^{CM}< 0.2$ for J/ψ
  Limited only by cuts on μ
- Even wider rapidity range
  with larger acceptance detector

Outlook

- Special issue in Advances in High Energy Physics on AFTER
  - **submission deadline April 17, 2015**
  - (6 editors e.g. J.P. Lansberg, C. Hadjidakis, J.He)
- 12-15 papers to be published
  (including Franco-Chinese works)
- **Expression of interest to the LHCC expected in Fall 2015:**
  2 AFTER workshops in 2015 to prepare
  (in Warsaw (June) and Black Forest (September))
- Application Xu Guangqi IPN-THU

Website: after.in2p3.fr

Advances in High Energy Physics

Hindawi

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

CALL FOR PAPERS

Fixed-target experiments (FTE) have brought essential contributions to particle and nuclear physics. They have led to particle discoveries (Ω, J/ψ, ...) and evidence for the novel dynamics of quarks and gluons in heavy-ion collisions. In accessing high x_F and in offering options for (un-) polarised proton and nuclear targets, they have also led to the observation of surprising QCD phenomena. They offer specific advantages compared to collider experiments: access to high x_F, high luminosities, target versatility, and polarisation.

The LHC 7 TeV protons on targets release a c.m.s. energy close to 115 GeV (72 GeV with Pb), in a range never explored so far, significantly higher than that at SPS and not far from RHIC. The production of quarkonia, DY, heavy flavours, jets, and γ in pA collisions can be studied with statistics previously unheard of and in the backward region, $x_F < 0$, which is uncharted. High precision QCD measurements can also obviously be carried out in pp and pd collisions with H_2 and D_2 targets. With the 50 TeV protons of the future circular collider (FCC), the c.m.s. energy could reach 300 GeV for original studies of W and Z boson, and perhaps H^0, production in pp and pA collisions.

With the LHC Pb beam, one can study the quark-gluon plasma (QGP) from the viewpoint of the nucleus rest frame after its formation. Thanks to modern technologies, studies of, for instance, direct γ and quarkonium P-waves production in heavy-ion collisions can be envisioned.

Polarising the target allows one to study single-spin correlations including the Sivers effect, hence, the correlation between the parton k_T and the nucleon spin.

We intend to publish a special issue on the physics at such a FTE using the LHC or FCC beams. The editors welcome original research articles and review articles from both theorists and experimentalists.

Potential topics include, but are not limited to:

- Heavy-quark and gluon content at large x
- TMDs and single-spin asymmetries
- Heavy-flavour studies in pA and AA collisions at FTEs
- W, Z, and H^0 production near threshold
- Target polarisation
- Secondary beams
- Simulation tools for high-energy physics
- Beam collimation and extraction with bent crystals
- Machine feasibility and radiological aspects
- Connection between UHECR studies and FTEs

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Friday, 12 June 2015

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Impact Factor 2.6

Summary

- Many physics opportunities with a fixed target experiment using LHC p and Pb beams
- Novel testing ground for QCD in the high-x frontier with AFTER@LHC
- Extensive spin program with a polarized target
- Using dense targets high luminosities can be achieved
- Target versatility: hydrogen, deuteron, nucleus – nuclear effects and QGP
- First fast simulations performed

- BACKUP

Physics Highlights: AFTER @ LHC

✓ ***Physics Reports 522 (2013) 239***

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Physics opportunities of a fixed-target experiment using LHC beams

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