Hadron structure studies at AFTER@LHC

Andrea Signori

7th APS-**GHP** workshop

on behalf of the **AFTER@LHC study group**

http://after.in2p3.fr

Jefferson Lab

Outline of the talk

- **AFTER@LHC**

- **TMD physics**

- **Intrinsic charm**

Outline of the talk

- **AFTER@LHC**

- **TMD physics** ⟸ my expertise and field of contribution to the AFTER study group

- **Intrinsic charm**

AFTER @ LHC

References:

- Brodsky, Fleuret, Hadjidakis, Lansberg : DOI: 10.1016/j.physrep.2012.10.001
- Physics at A Fixed Target Experiment using the LHC beams:
  http://after.in2p3.fr/after/images/d/d6/Special_Issue-AHEP-AFTER.pdf

  and references therein

- EOI for AFTER@LHC (work in progress)

AFTER @ LHC

Important features :

novel energy range
between RHIC and fixed targ

- high luminosity (exploits LHC beam)
- explore high-x and backward rapidity region (thanks to the boost)
- target polarization
- vary the atomic mass of the target

Which are useful to ... :

- advance our understanding of the high-x partonic content of nucleons&nuclei
- explore 3D structure of (un)polarized hadrons in momentum space
- get new insights into heavy ion physics

AFTER @ LHC

1D structure in momentum space :

- improve (g, heavy quarks) PDFs at high-x ==> crucial for BSM searches!
- constrain "intrinsic" charm effects ==> important for particle and astroparticle physics (neutrino flux from cosmic rays)

- provide data for nuclear PDF studies
- new insights into the EMC effects ?

3D structure in momentum space :

- investigation of (un)polarized TMD PDFs via spin asymmetries
- inputs to the proton spin puzzle ?
- tests for generalized universality of TMDs

Two proposals

Inject gas into the beam ... :
“A polarized gas target inside the LHC beam”

C. Barschel, P. Lenisa, A. Nass, and E. Steffens, Adv.Hi.En.Phys. (2015) 463141

... or extract the beam :
“LHC beam extracted by a bent crystal”

E. Uggerhøj, U.I Uggerhøj, NIM B 234 (2005) 31, Rev. Mod. Phys. 77 (2005) 1131

- no observed decrease for the LHC performance
- both currently under investigation at LHC and (unpolarized) gas option already tested (Smog, limited test)

- luminosity can be **3 orders of magnitude higher** than **RHIC** 200 GeV !
  order of 10-1 fb/yr

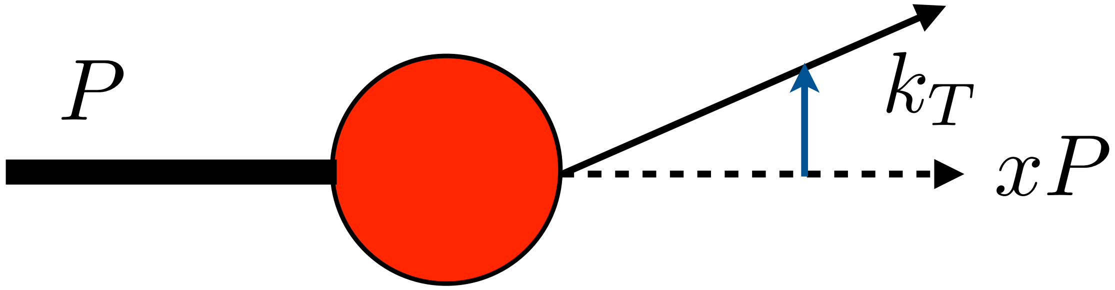
TMDs and spin physics

References:

- Liu, Lorcé : **Few Body Syst. 57 (2016) no.6, 379-384**
- Bacchetta : **Eur.Phys.J. A52 (2016) no.6, 163**
- Kanazawa, Koike, Metz, Pitonyak : **Adv.High Energy Phys. 2015 (2015) 257934**
- Anselmino, D'Alesio, Melis : **Adv.High Energy Phys. 2015 (2015) 475040**
- AFTER study group : this week
  and references therein

- EOI for AFTER@LHC (work in progress)

Quark TMD PDFs



$$\Phi_{ij} \sim \text{F.T.}\ \langle PS|\ \bar{\psi}_j(0)\ U_{[0,\xi]}\ \psi_i(\xi)\ |PS\rangle_{|\text{LF}}$$

$$f_1^q(x, k_T^2)$$

involve all 3 components:

richer than 1D PDFs

Bacchetta, Mulders
Phys.Rev. D62 (2000) 114004

unpolarized quark in unpolarized proton → f_1

unpolarized quark in transversely polarized proton → $f_{1T}^{\perp}$

quark pol.

nucleon pol.

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

Twist-2 TMDs

Why ..?

- TMDs in unpolarized protons :
  to improve the description of LHC observables

  * BM for quarks and gluons

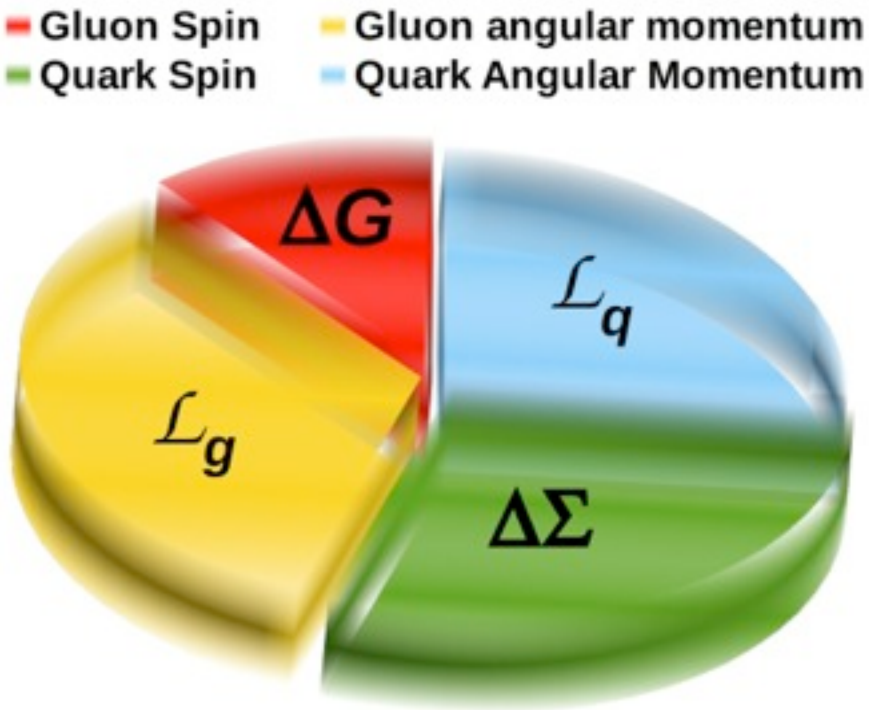
  * unp W± prod => important for flavor decomposition of unp quark TMDs

- TMDs in **polarized** protons :
  to address the **OAM** of partons
  (e.g. the **Sivers** case)

the **experimental handle** is a **spin asymmetry** :

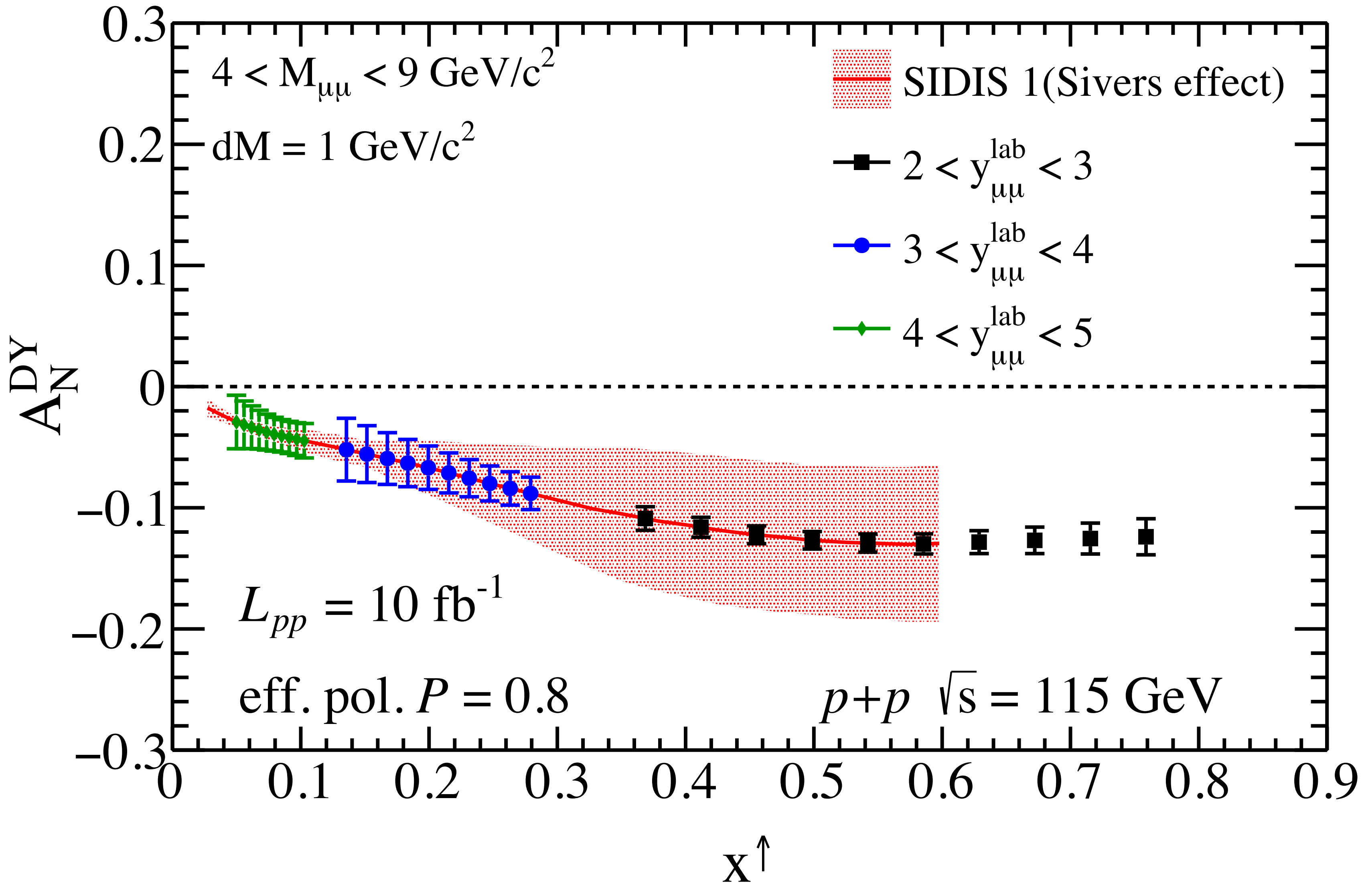
$$\boxed{A_N \sim \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}}}$$

the arrow represent the direction of the transverse spin of the target



A_N in Drell-Yan

AFTER@LHC - projections



proton target

LHCb like detector

cite Anselmino and our FBS paper

specific azimuthal modulation of AN

test the generalized universality of the Sivers

clean TMD fact. interpretation

sudakov suppression not a problem

Jefferson Lab

Gluon-induced A_N

multiple probes available, for example :

quarkonia
(Yuan, PRD 78 (2008) 014024; Schaefer, J. Zhou, PRD (2013))

B - D meson production
(M. Anselmino, et al. PRD 70 (2004) 074025)

photon, photon-jet, di-photon production
(A. Bacchetta, et al., PRL 99 (2007) 212002; J.W. Qiu, et al., PRL 107 (2011) 062001)

J/Psi + photon production
(W. den Dunnen, J.P.L., C. Pisano, M. Schlegel, PRL 112, 212001 (2014))

and more ...

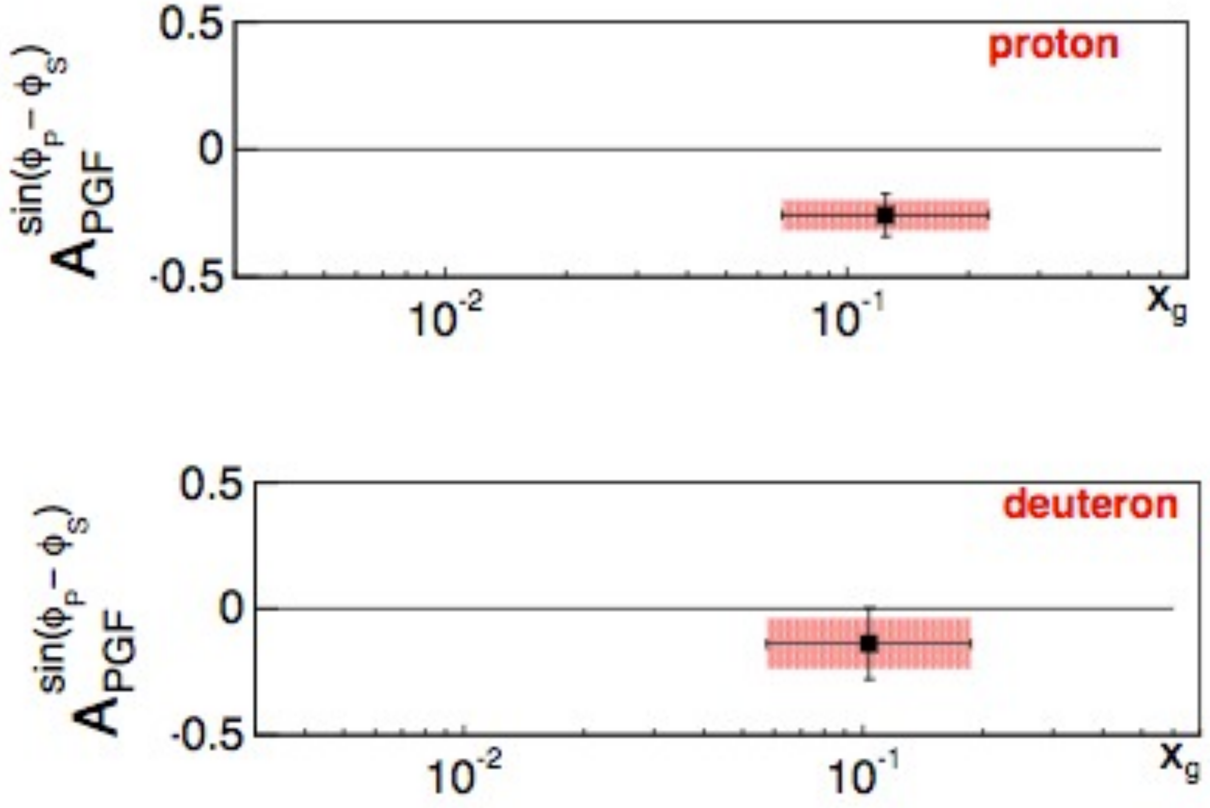
All these measurements can be done with AFTER@LHC with the very high precision

Gluon Sivers effect - news

$$e\ p \to e\ h_1\ h_2\ X$$

photon-gluon fusion channel

arXiv 1701.02453
COMPASS collaboration

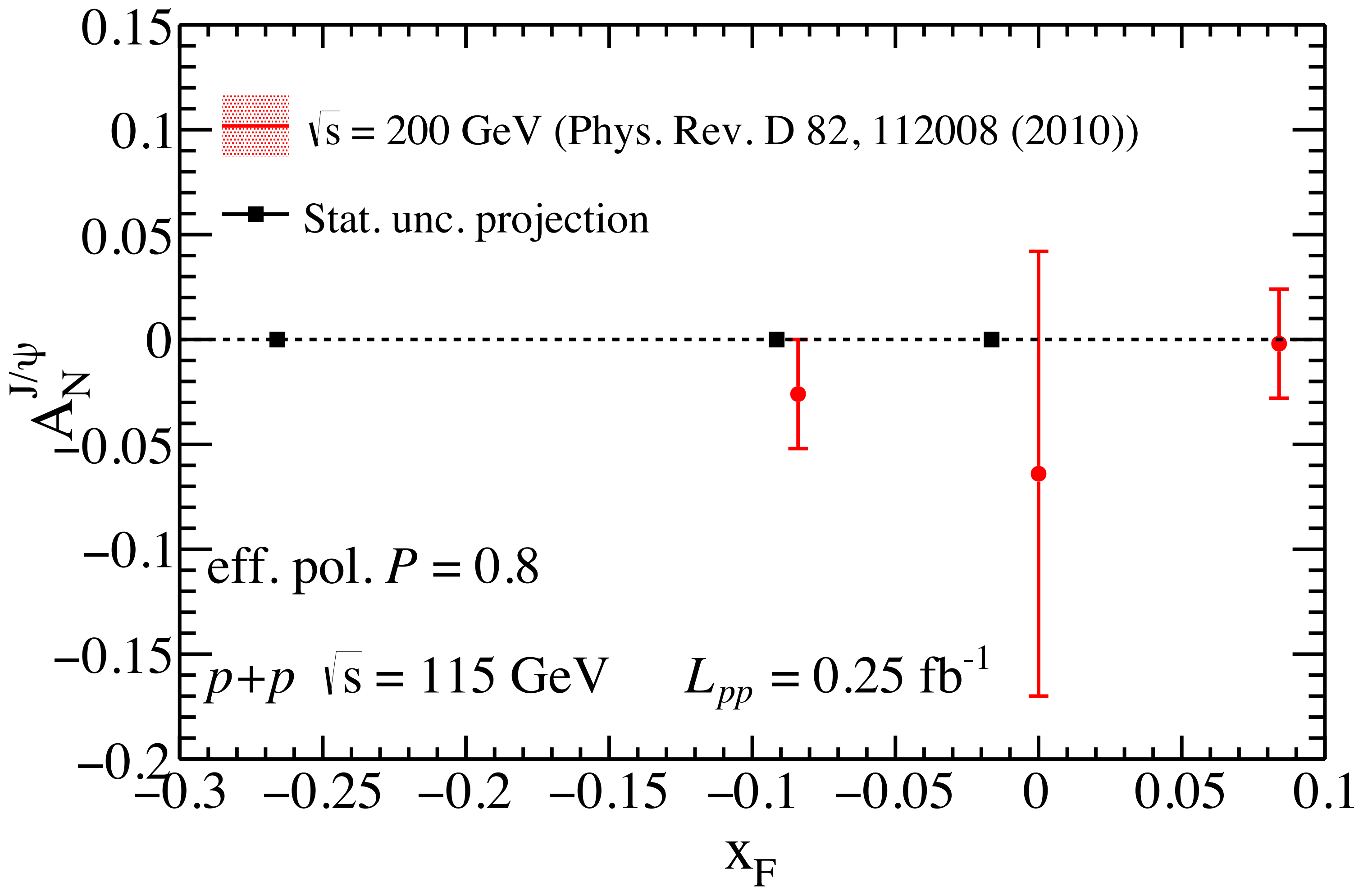


first hints of a non-zero gluon Sivers effect
(COMPASS data + Monte Carlo input)

A_N in J/Ψ production

cite our FBS paper

AFTER@LHC - projections



LHCb like detector

comparison to STAR (RHIC)

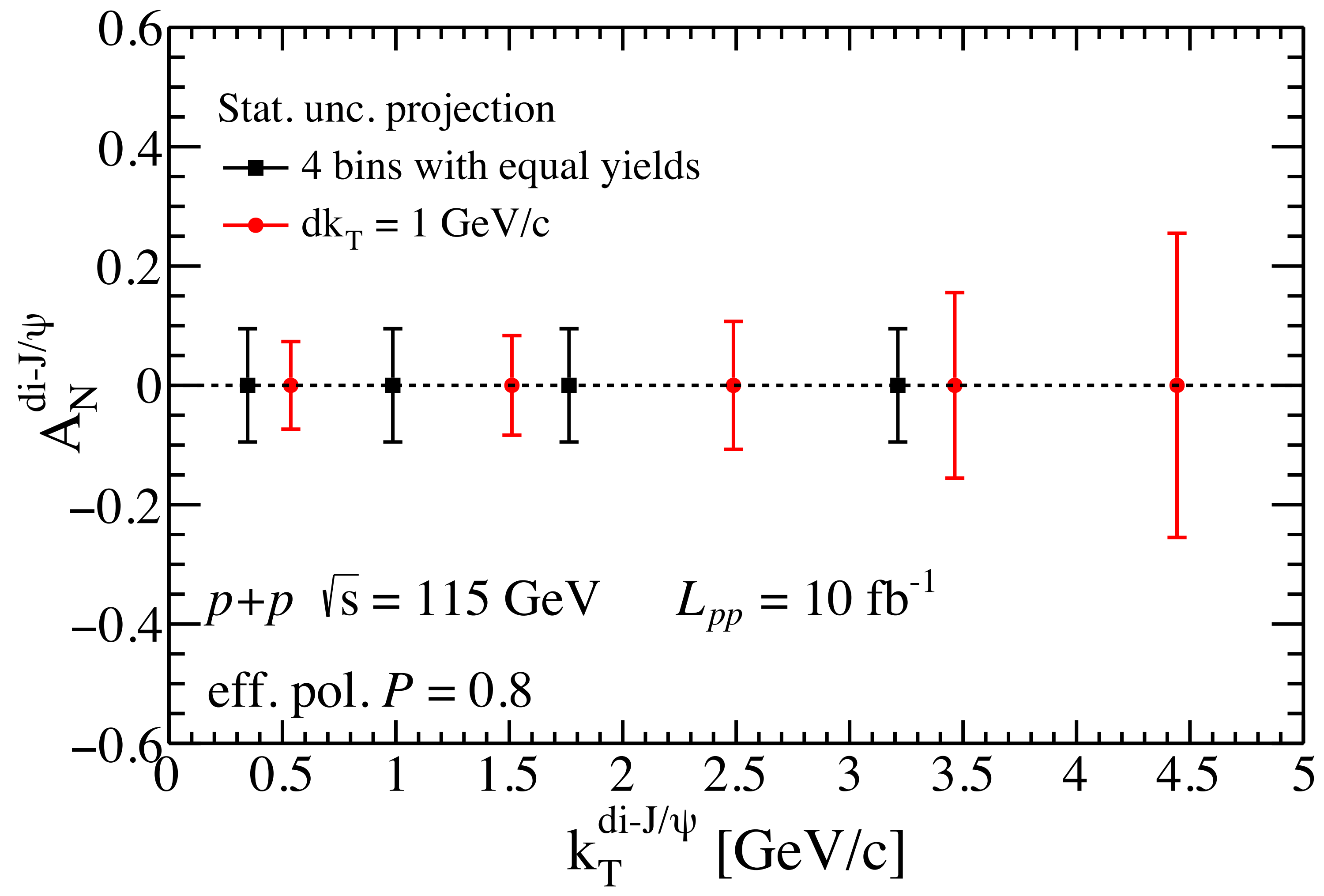
small errors: important for pheno!

interpretation : coll tw3 or Sivers TMD

we know TMD fact doesn't hold in general in pp -> hadrons

A_N in di - J/Ψ production

AFTER@LHC - projections



LHCb like detector

cite our FBS paper

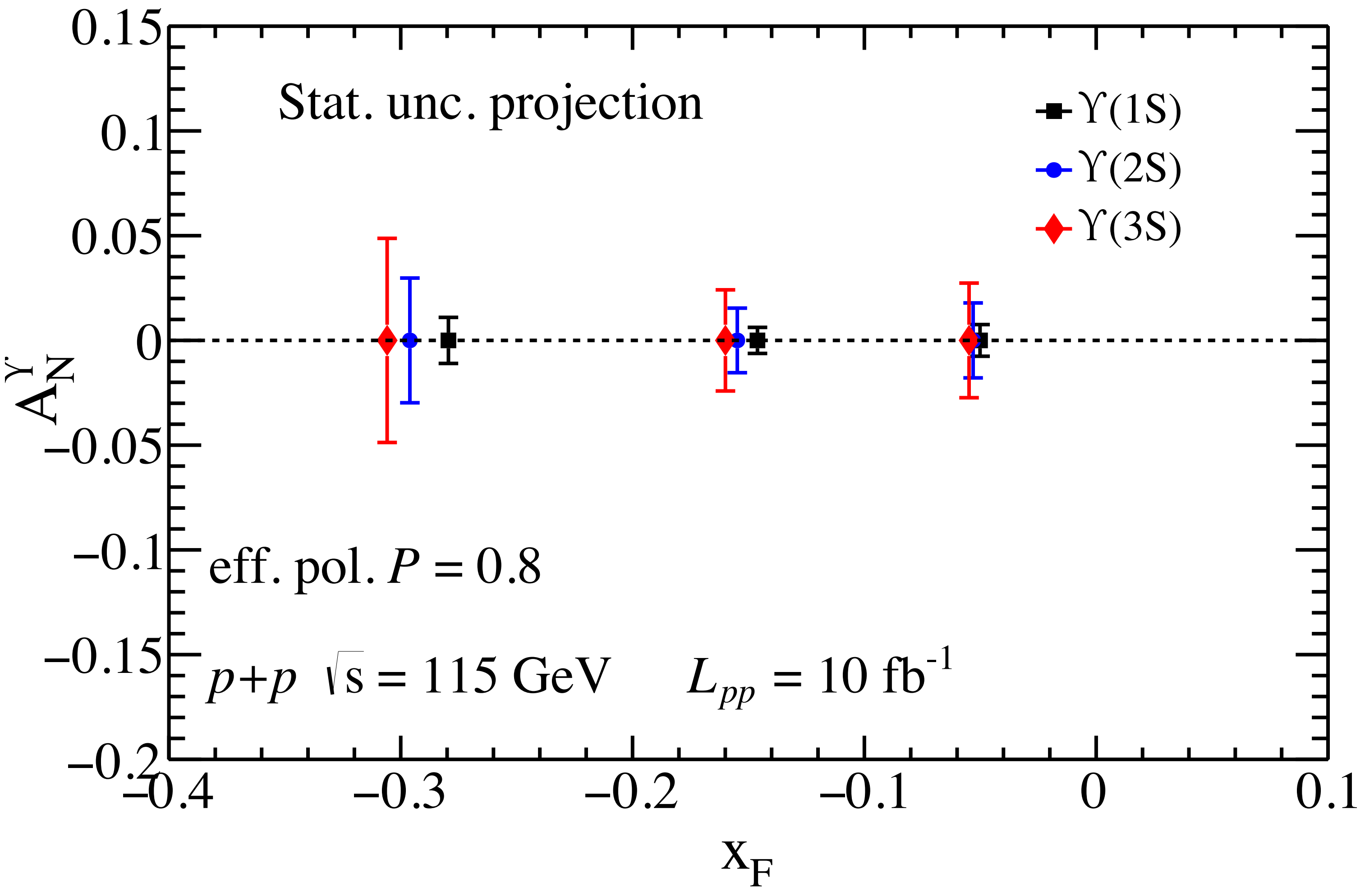
small errors: important for pheno!

interpretation : coll tw3 or Sivers TMD

Jefferson Lab

A_N in Υ production

AFTER@LHC - projections



LHCb like detector

cite our FBS paper

small errors: important for pheno!

interpretation : coll tw3 or Sivers TMD

IC - Intrinsic Charm

References:

- Hobbs : arXiv:1612.05686
- Brodsky, Kusina, Lyonnet, Schienbein, Spiesberger, Vogt: **Adv.High Energy Phys. 2015 (2015) 231547**
  and references therein

- Expression of interest (EOI) for AFTER@LHC (work in progress)

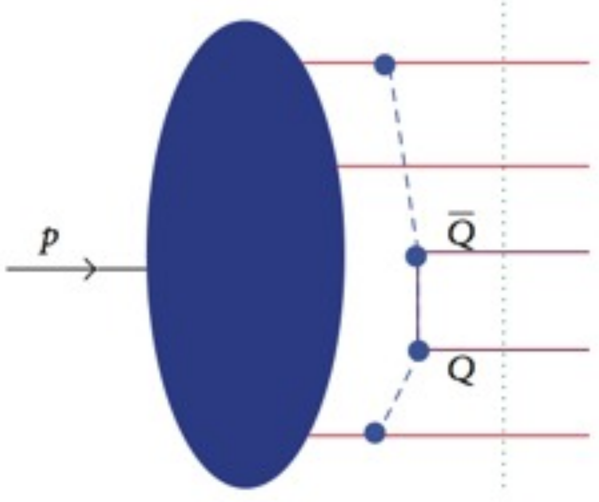
Intrinsic sea quarks in the proton

a component of non-perturbative origin
to the sea quark content of the proton

[...] Two distinct types of quark and gluon contributions to the nucleon sea [...]: "intrinsic" and "extrinsic".

"**Intrinsic**" sea quarks are multi-connected to the valence quarks of the nucleon

In contrast, "**extrinsic**" sea quarks are generated from the QCD hard bremsstrahlung and gluon splitting
In this case, the sea quark structure is associated with the *internal composition of gluons, rather than the proton itself*.



$|uud Q\bar{Q}\rangle$

Brodsky, Ma
hep-ph/9707408

$$\langle N|\bar{Q}Q|N\rangle - \langle 0|\bar{Q}Q|0\rangle$$

IC - why & where

measurements consistent (to different extents) with the hypothesis of IC :

EMC measurements of the large x F_{2c} in muon DIS off iron
EMC collaboration : **Nucl.Phys. B213 (1983) 31-64**
Harris, Smith, Vogt: Nucl.Phys. B461 (1996) 181-196

the first and
“most discussed”

lattice calculation : MILC collaboration (IC & IS) **Phys.Rev. D88 (2013) 054503**

A number of **open charm observables** (e.g. Lambda and D production)
in hadroproduction at CERN and Fermilab - cite Review vogt

J/Psi production from **pA events in fixed-target mode** at CERN **Phys.Lett. B246 (1990) 217-220**

check the pA ref.

double J/Psi production from πA events (NA3 - CERN) **Phys.Lett. B349 (1995) 569-575**

Global analyses of PDFs (?)

more ... see the review

Essentially we need more data : **AFTER@LHC** can be helpful in this respect

Models for IC

BHPS model
(Brodksy et al.)

Generalization of BHPS
(Pumplin)

Meson-cloud model
(Paiva et al.)
(Steffens et al.)
(Hobbs et al.)

“sea-like” approach
(CTEQ 07/08)

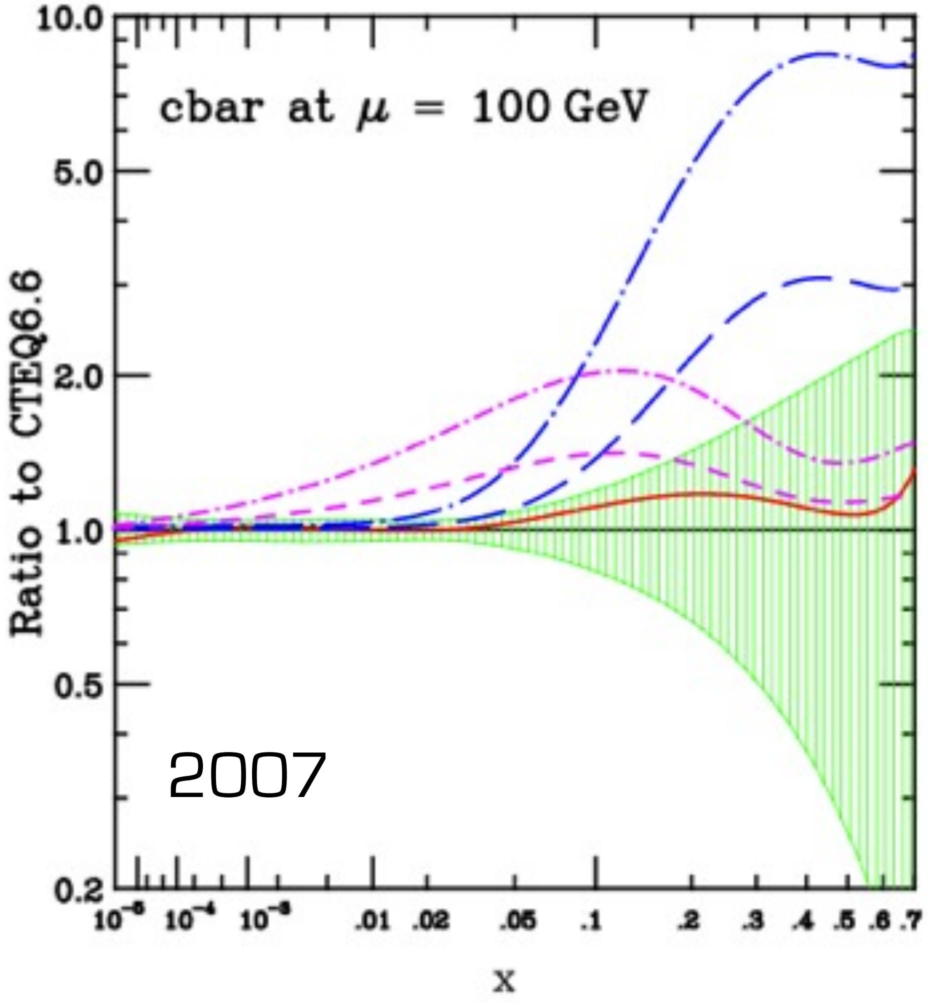
for a detailed overview see :

Adv.High Energy Phys. 2015 (2015) 231547

Global fits of PDFs & IC

The first global analysis of proton PDFs including IC :
CTEQ Phys.Rev. D75 (2007) 054029 , Phys.Rev. D78 (2008) 013004

Ratio of anticharm distributions with and without IC contribution
to anticharm PDF in CTEQ 6.6.
Green: uncertainty with radiative charm.
Other colors: impact of different IC models.



2007

CTEQ - TEA global analysis Phys.Rev. D89 (2014) no.7, 073004

sensitivity to IC - different assumptions and different results

(mention the numbers for average x IC)

2014

fact: distributions in transverse momentum and y for W±/Z can be affected
but effect is comparable to PDF uncertainties

Global fits of PDFs & IC

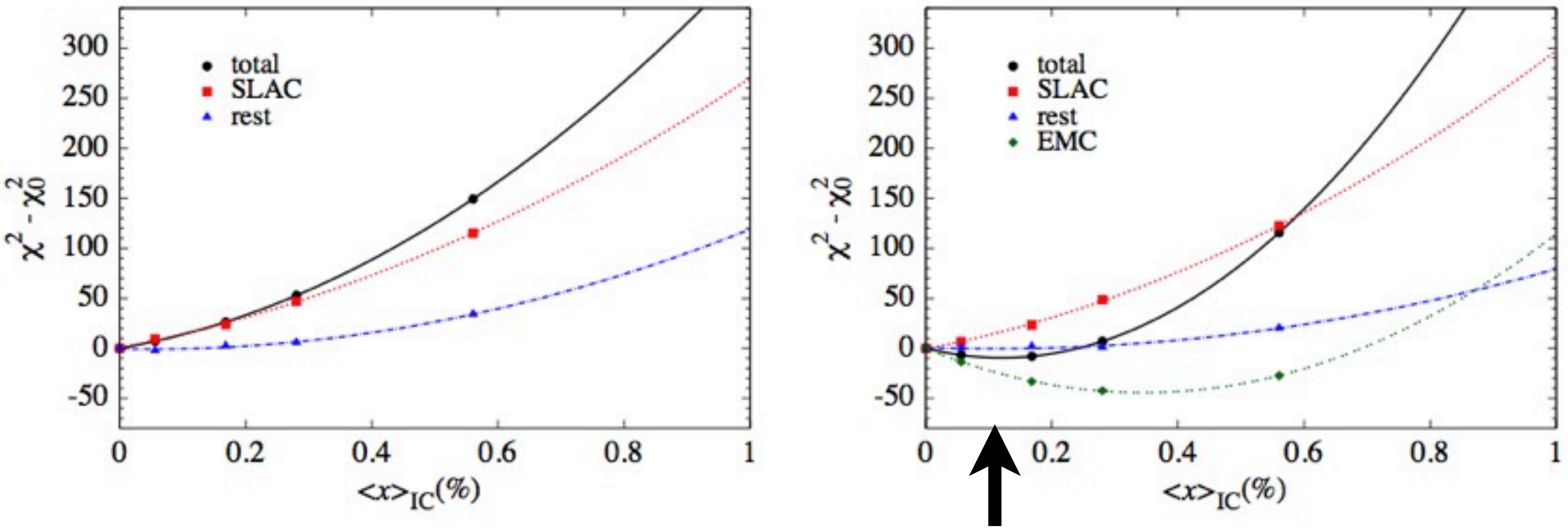
2015 J.Delgado, Hobbs, Londergan, Melnitchouk Phys.Rev.Lett. 114 (2015) no.8, 082002

updated formalism including higher twist effect, target mass corrections, nuclear effects

without EMC data : <xic> = 0, <0.1% at 5 sigma

including EMC data : <xic> = 0.15 ± 0.09%

$$F_2^c = F_2^{c\bar{c}} + F_2^{IC}$$



EMC data is in tension with the other data sets

demand for additional exp. measurements!

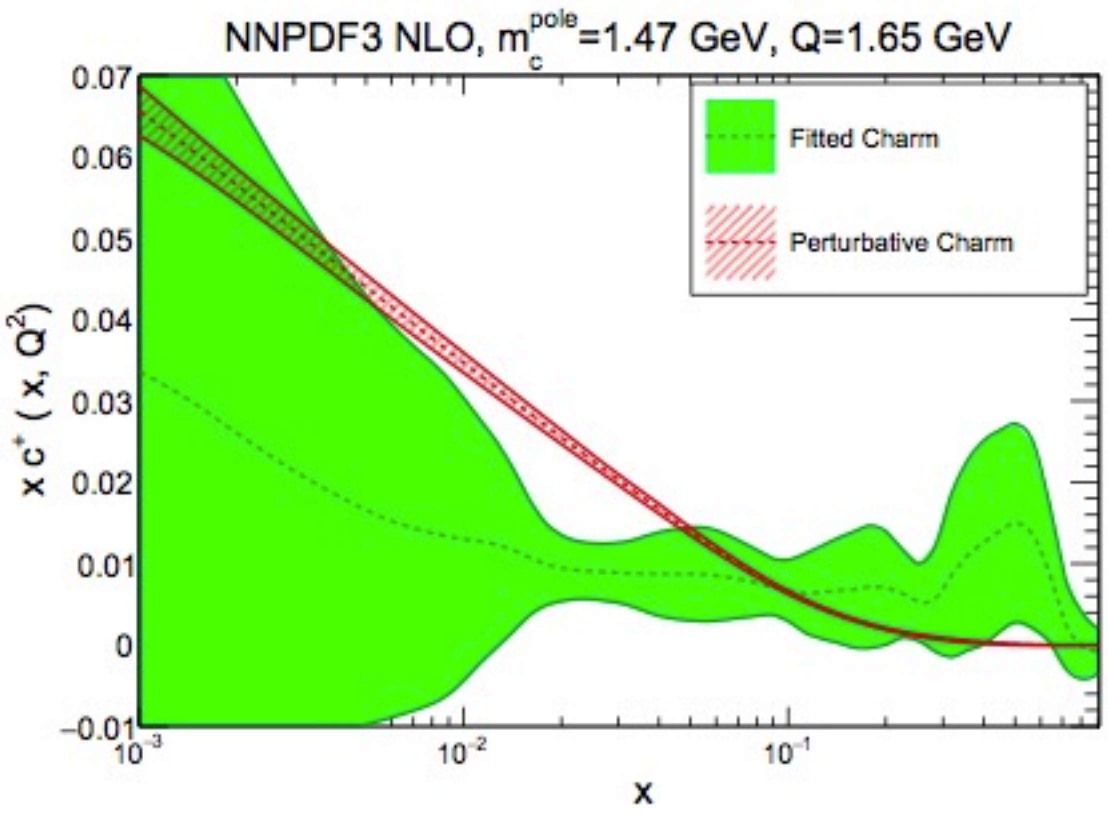
Global fits of PDFs & IC

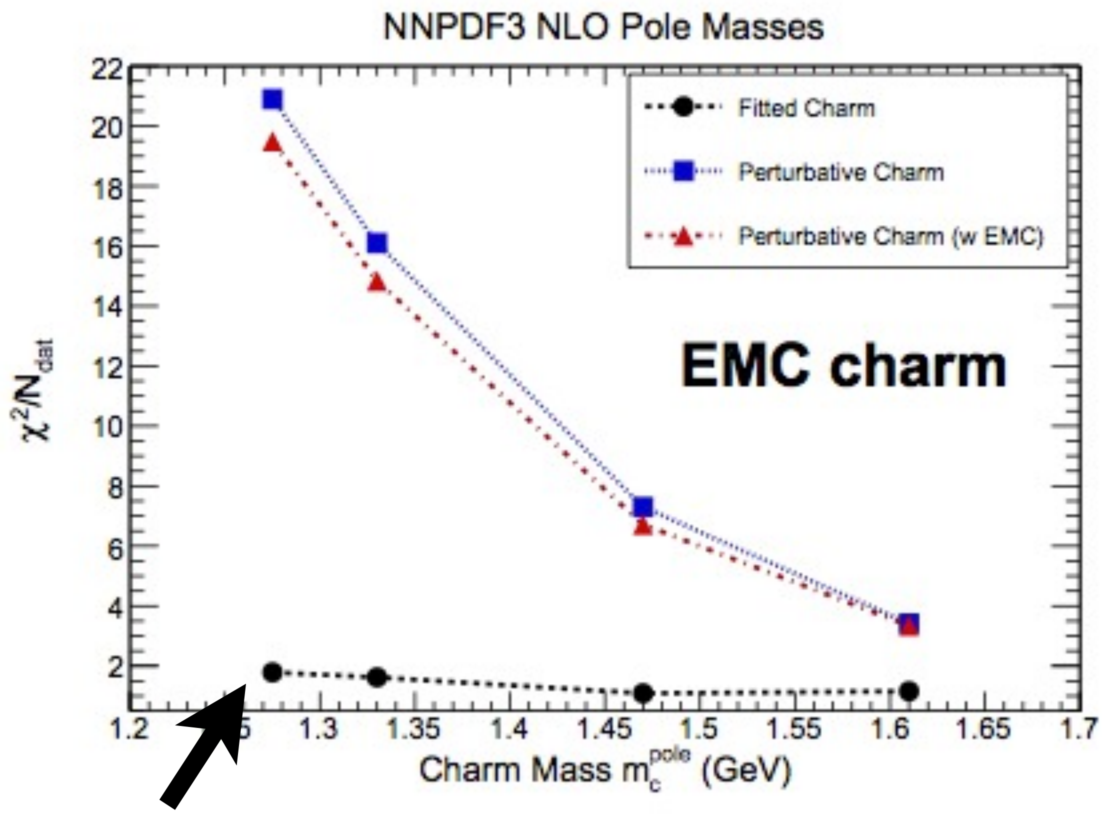
2016 NNPDF analysis with EMC data

Eur.Phys.J. C76 (2016) no.11, 647

$$F_2^c = F_2^{pert} + F_2^{fitted}$$

<x_ic> = 0.7 ± 0.3 %





No other data set behaves in this way

Essentially we need more data : AFTER@LHC can be helpful in this respect

The role of AFTER@LHC

provide **additional experimental input**
with **high luminosity** for processes
sensitive to charm quarks
at **high-x**, such as:

- inclusive charm-hadron production

- photon + charm-jet production

- EW boson production

- Z + c production (at LHC)

The role of AFTER@LHC

provide **additional experimental input**
with **high luminosity** for processes
sensitive to charm quarks
at **high-x**, such as:

- inclusive charm-hadron production

- photon + charm-jet production

- EW boson production

cite review Vogt

- Z + c production (at LHC)

Phys.Rev. D93 (2016) no.7, 074008

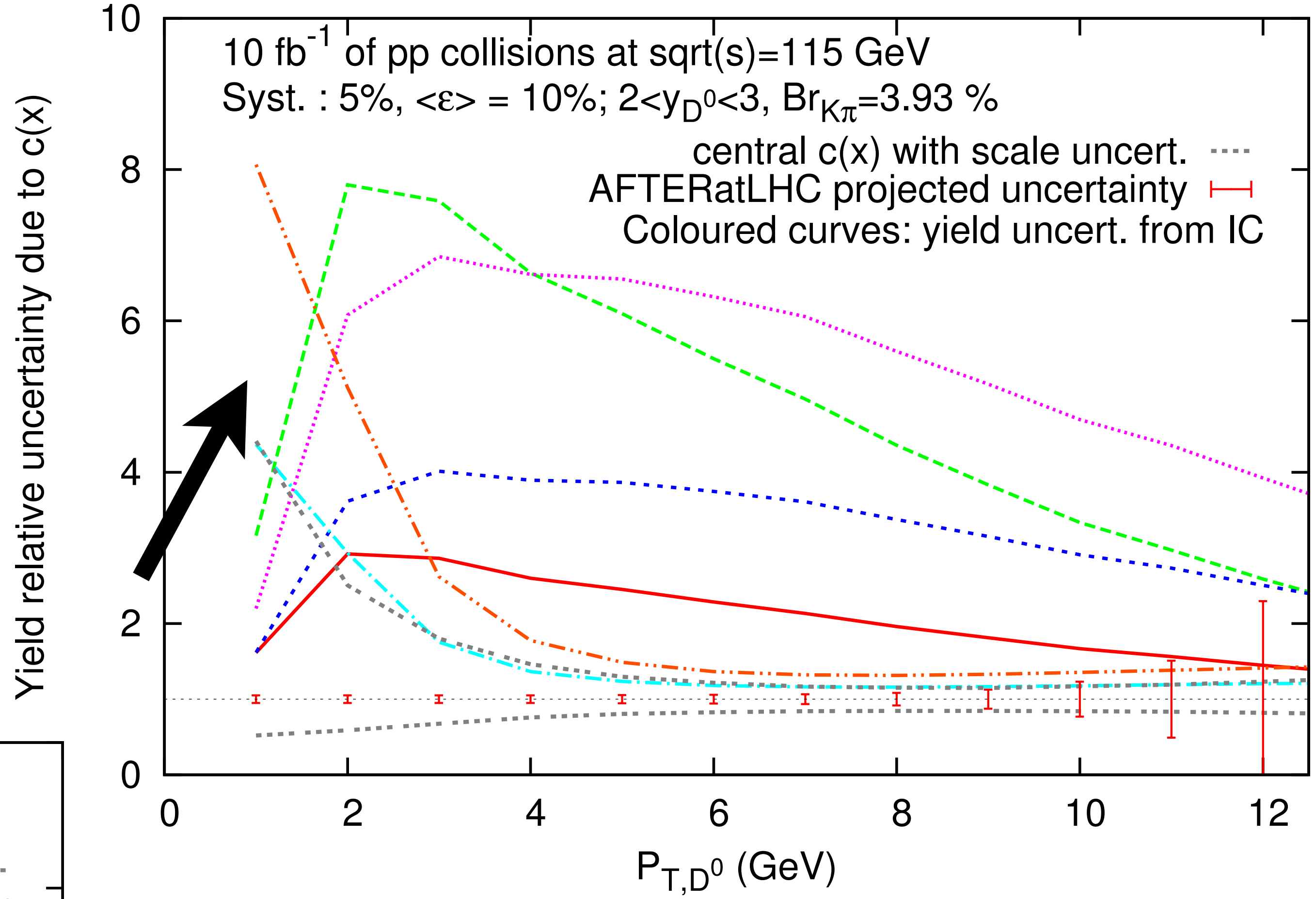
cite MIT talk

in general, effects are more evident
at high transverse momenta
or forward rapidities

D^0 meson production at AFTER

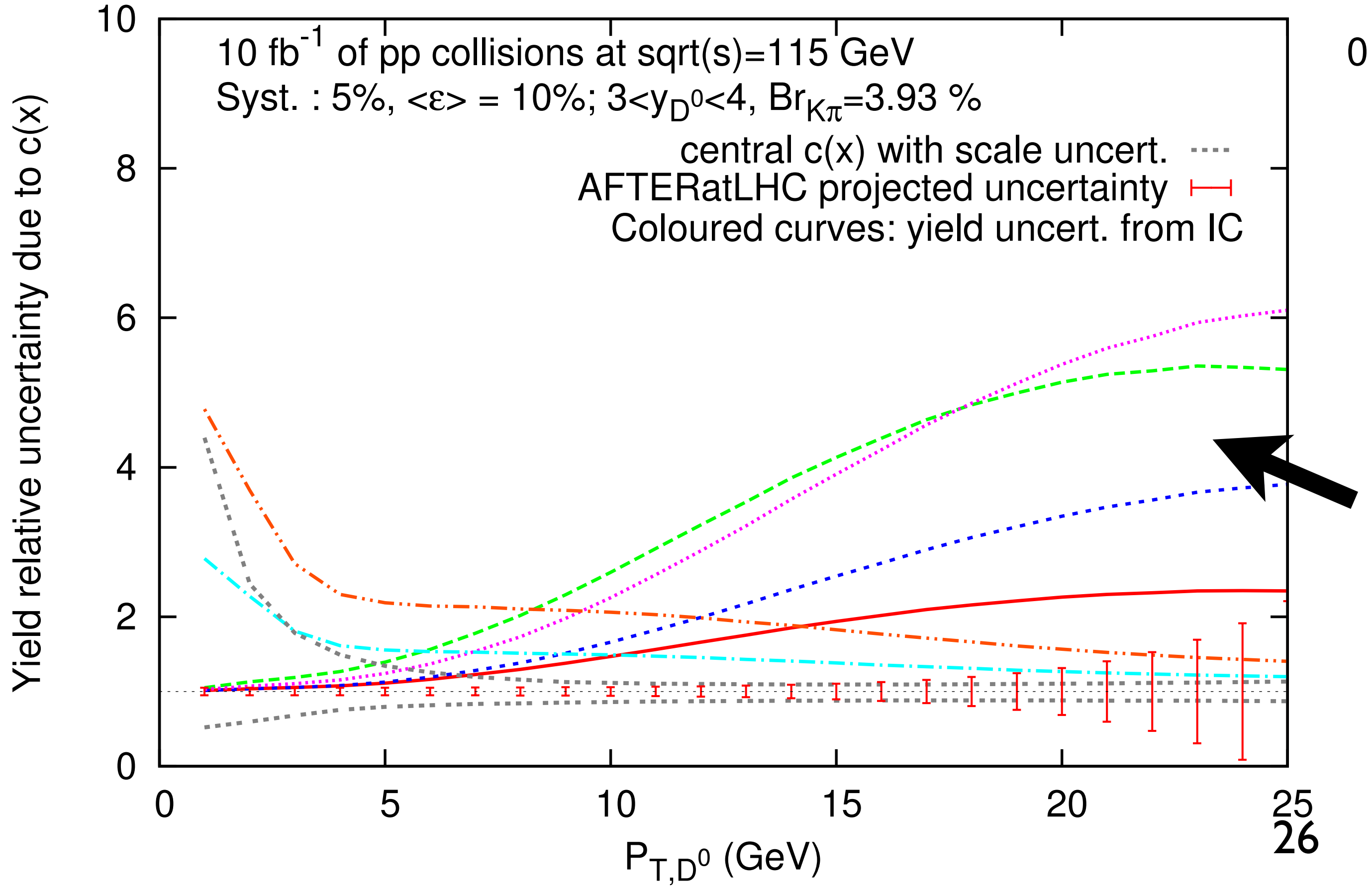
uncertainties on the number of produced D0 generated from different models for IC, normalized to the number of produced D0

systematical **5% uncertainties** assumed, considering LHCb-like performance



backward rapidity (CM)

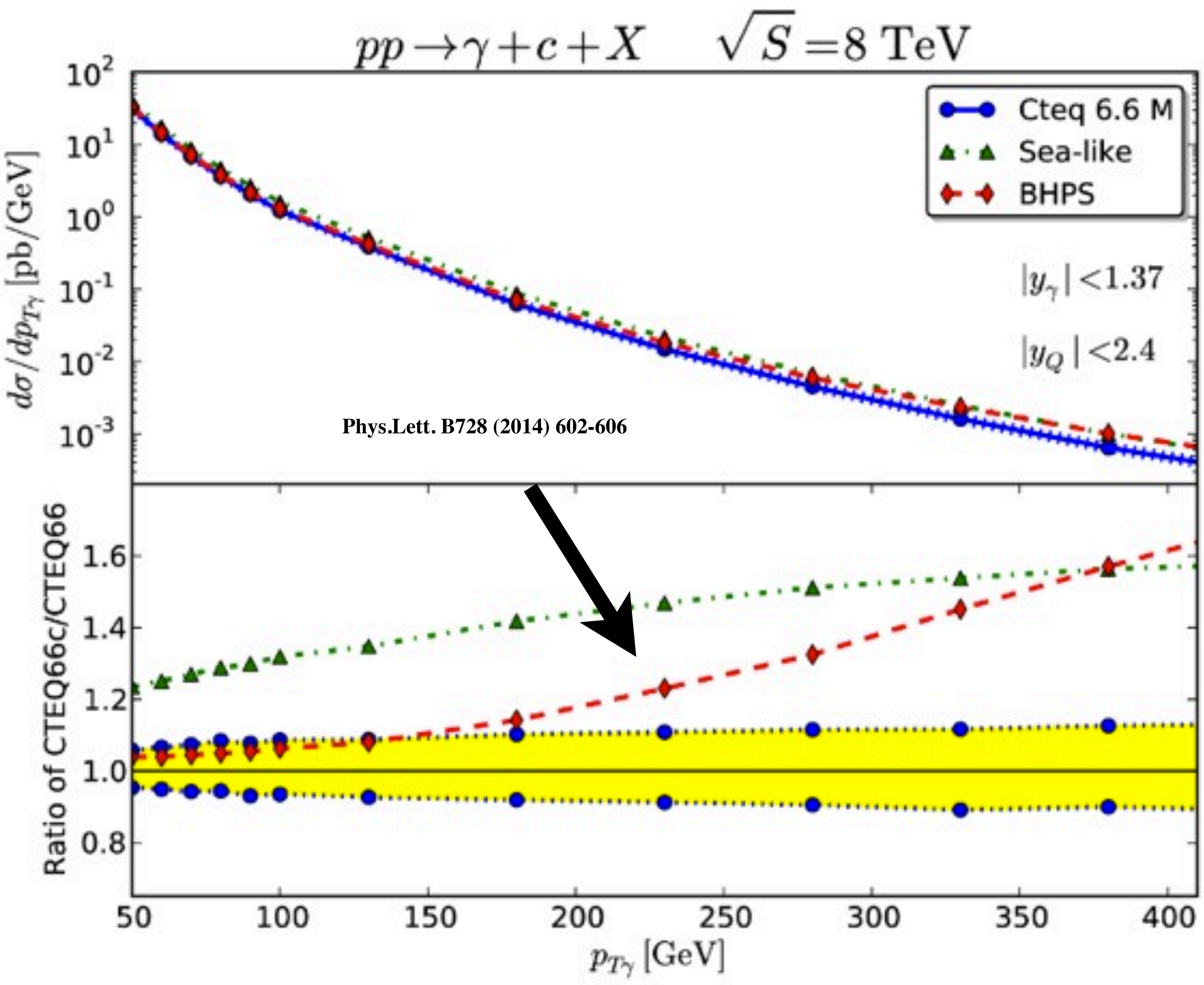
better top right for uncertainty
better bottom left for alpha with high pT
(less theo unc from pQCD)
Both would be better



more forward rapidity (CM)

γ + c production at LHC

backup slide ?



QCD predictions at NLO based on CTEQ6.6M (solid blue line), BHPS CTEQ6c2 (dashed red line) and sea-like CTEQ6c4 (dash-dotted green line).

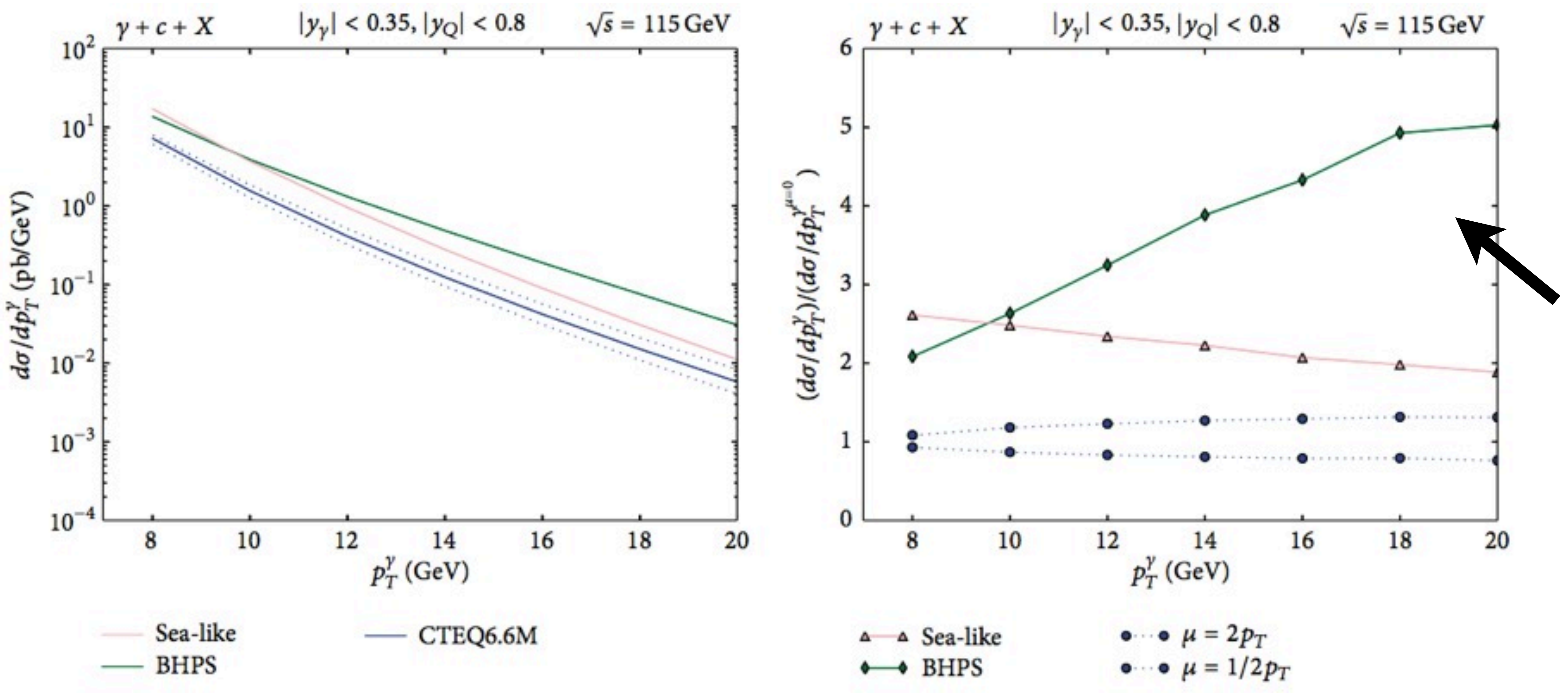
The ratio of the cross sections with respect to the CTEQ6.6M (solid blue line) distribution (bottom).

effect of IC in the proton can be visible at LHC at very high transverse photon momentum

the cross section decreases fast with t.m., so this measurement is limited by statistics

Jefferson Lab

γ + c production at AFTER



At AFTER the impact of IC
would be relevant at lower t.m.,
with higher cross section
with respect to the LHC

Conclusions

AFTER: general considerations

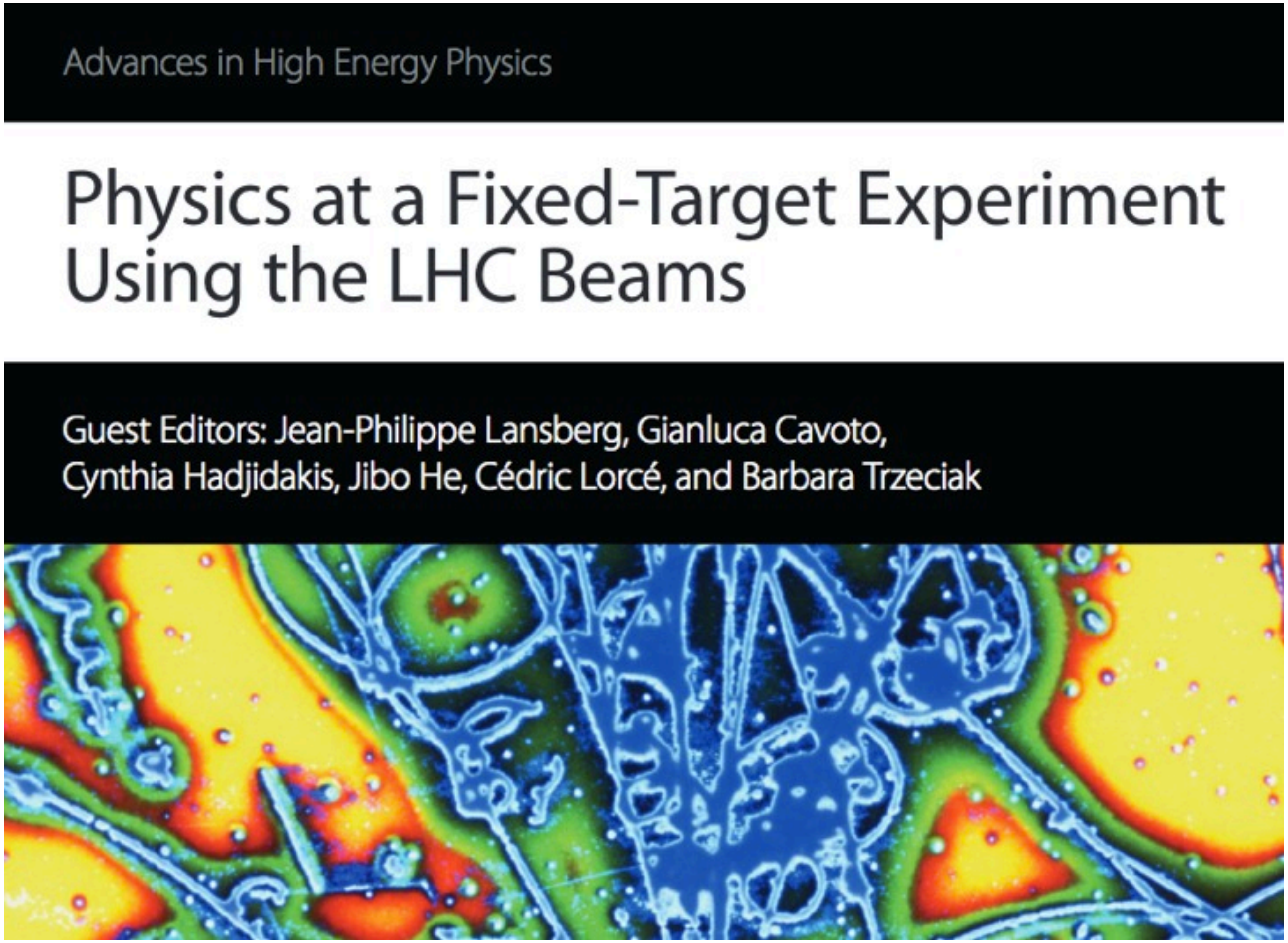
Spin asymmetry studies provide new insights into the proton spin puzzle (via TMD factorization and/or twist-3 formalism)

Generally, the effects of IC are larger at colliders with a lower center-of-mass energy and for hard processes with moderate factorization scales. Therefore, a high luminosity fixed target experiment like AFTER@LHC operating at a center-of-mass energy 115 GeV would be ideally suited to constrain IC effects.

Backup

Special issue

http://www.hindawi.com/journals/ahep/si/354953/



Advances in High Energy Physics

Physics at a Fixed-Target Experiment Using the LHC Beams

Guest Editors: Jean-Philippe Lansberg, Gianluca Cavoto, Cynthia Hadjidakis, Jibo He, Cédric Lorcé, and Barbara Trzeciak

Further references

Feasibility study and technical ideas

Feasibility studies for quarkonium production at a fixed-target experiment using the LHC proton and lead beams (AFTER@LHC) by L. Massacrier, B. Trzeciak, F. Fleuret, C. Hadjidakis, D. Kikola, J.P.Lansberg, and H.S. Shao arXiv:1504.05145 [hep-ex]. Adv.Hi.En.Phys. (2015) 986348

A Gas Target Internal to the LHC for the Study of pp Single-Spin Asymmetries and Heavy Ion Collisions by C. Barschel, P. Lenisa, A. Nass, and E. Steffens. Adv.Hi.En.Phys. (2015) 463141

Quarkonium production and proposal of the new experiments on fixed target at LHC by N.S. Topilskaya, and A.B. Kurepin. Adv.Hi.En.Phys. (2015) 760840

Generalities

Physics Opportunities of a Fixed-Target Experiment using the LHC Beams
By S.J. Brodsky, F. Fleuret, C. Hadjidakis, J.P. Lansberg. [arXiv:1202.6585 [hep-ph]]. Phys.Rept. 522 (2013) 239.
C.

Further references

Spin physics

Transverse single-spin asymmetries in proton-proton collisions at the AFTER@LHC experiment by K.Kanazawa, Y. Koike, A. Metz, and D. Pitonyak. [arXiv:1502.04021 [hep-ph]. Adv.Hi.En.Phys. (2015)257934.

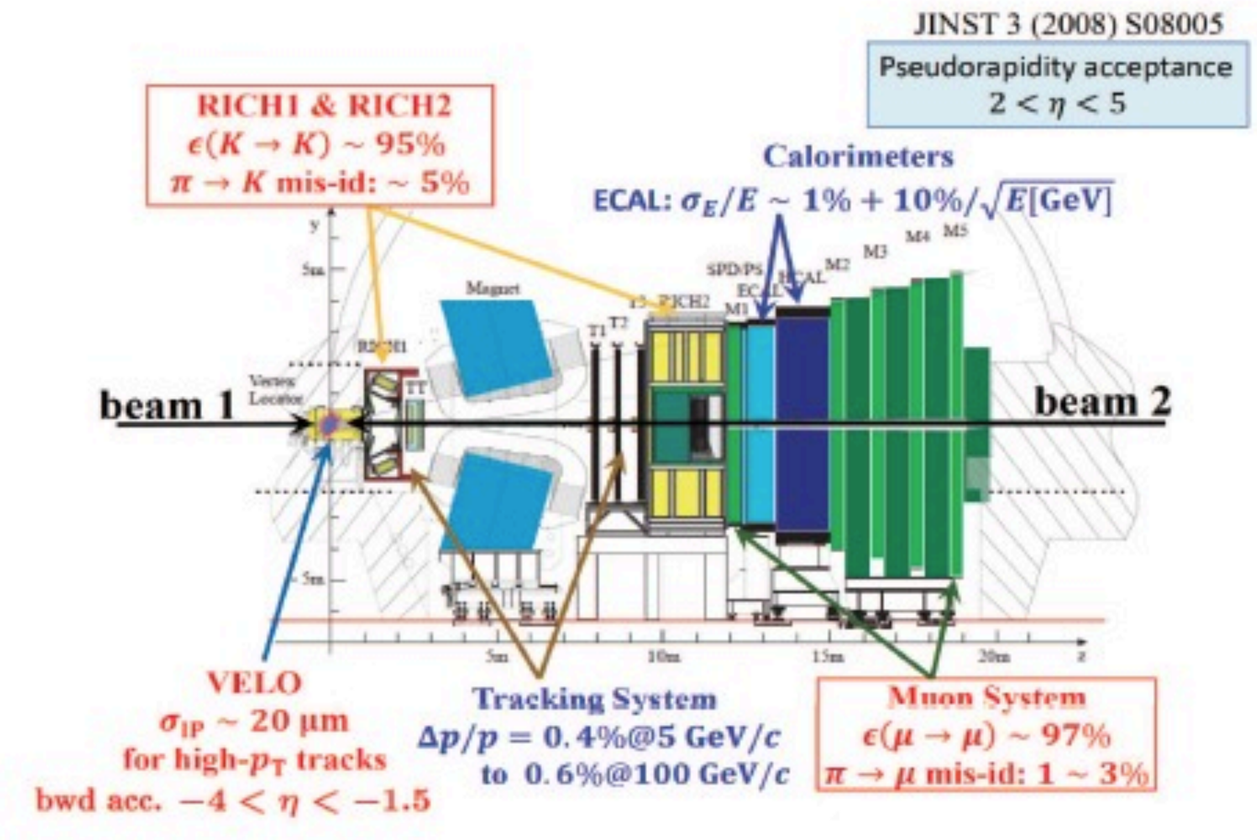
Transverse single-spin asymmetries in proton-proton collisions at the AFTER@LHC experiment in a TMD factorisation scheme by M. Anselmino, U. D'Alesio, and S. Melis. [arXiv:1504.03791 [hep-ph]]. Adv.Hi.En.Phys. (2015) 475040.

The gluon Sivers distribution: status and future prospects by D. Boer, C. Lorcè, C. Pisano, and J. Zhou. [arXiv:1504.04332 [hep-ph]]. Adv.Hi.En.Phys. (2015) 371396

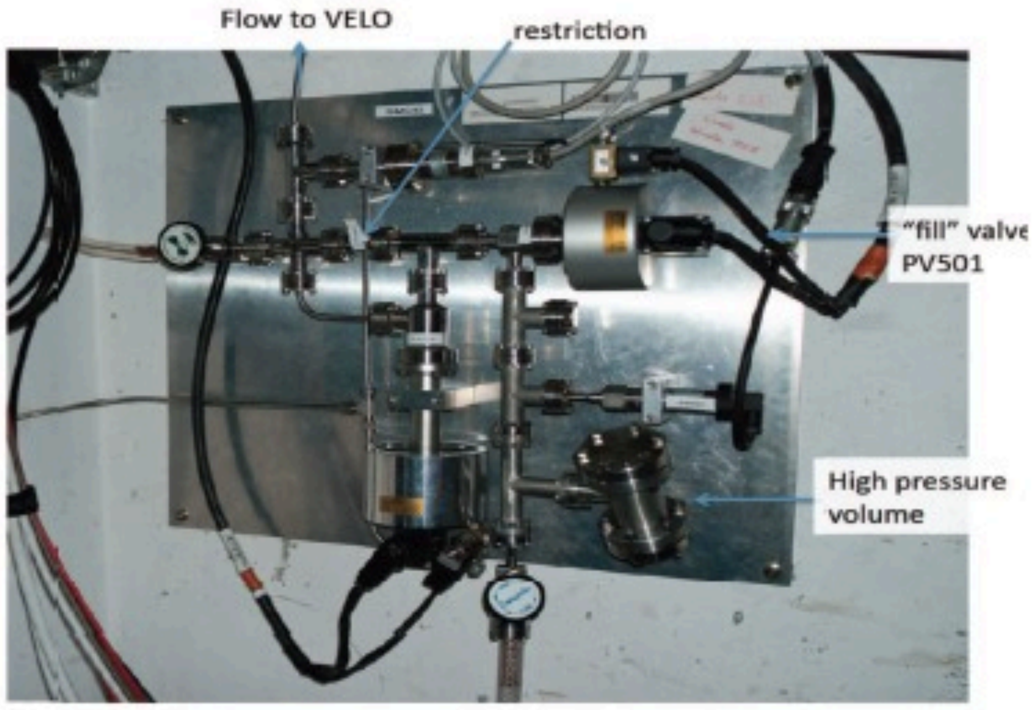
Azimuthal asymmetries in lepton-pair production at a fixed-target experiment using the LHC beams (AFTER) By T. Liu, B.Q. Ma. Eur.Phys.J. C72 (2012) 2037.

Polarized gluon studies with charmonium and bottomonium at LHCb and AFTER By D. Boer, C. Pisano. Phys.Rev. D86 (2012) 094007

Internal gas target - Smog



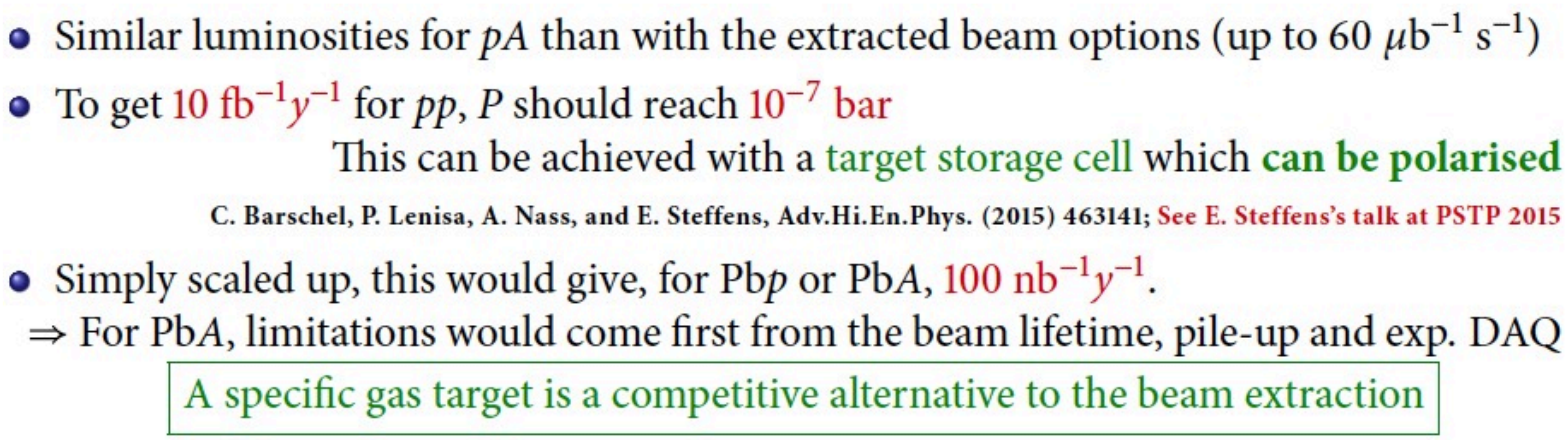
SMOG: System for Measuring Overlap with Gas



➜ injection of Ne-gas into VELO

- Initially: low density Ne-gas injected into LHCb Vertex Locator [LHCb-CONF-2012-034]
- Short pilot runs: 2012 pNe at $\sqrt{s_{NN}}$ = 87 GeV & 2013 PbNe at $\sqrt{s_{NN}}$ = 54 GeV
- 12 hours of pNe and 8 hours pHe (09/2015); 3 days of pAr in (10/2015)
- 1 week of PbAr (12/2015)
- Noble gases favoured
- Target unpolarised with the current SMOG system
- SMOG test : no decrease of LHC performances observed

Internal gas target - Smog



- Similar luminosities for pA than with the extracted beam options (up to 60 $\mu\mathrm{b}^{-1}\,\mathrm{s}^{-1}$)
- To get 10 $\mathrm{fb}^{-1}y^{-1}$ for pp, P should reach 10^{-7} bar

This can be achieved with a target storage cell which **can be polarised**

C. Barschel, P. Lenisa, A. Nass, and E. Steffens, Adv.Hi.En.Phys. (2015) 463141; See E. Steffens's talk at PSTP 2015

- Simply scaled up, this would give, for Pbp or PbA, 100 $\mathrm{nb}^{-1}y^{-1}$.

⇒ For PbA, limitations would come first from the beam lifetime, pile-up and exp. DAQ

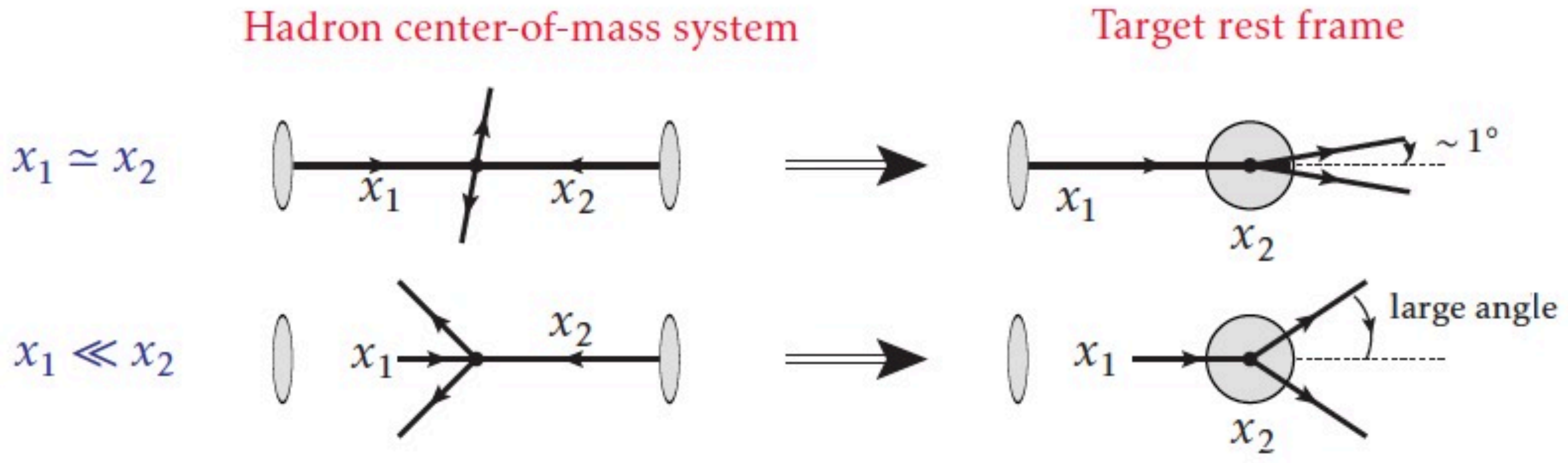
A specific gas target is a competitive alternative to the beam extraction

Frames and rapidities

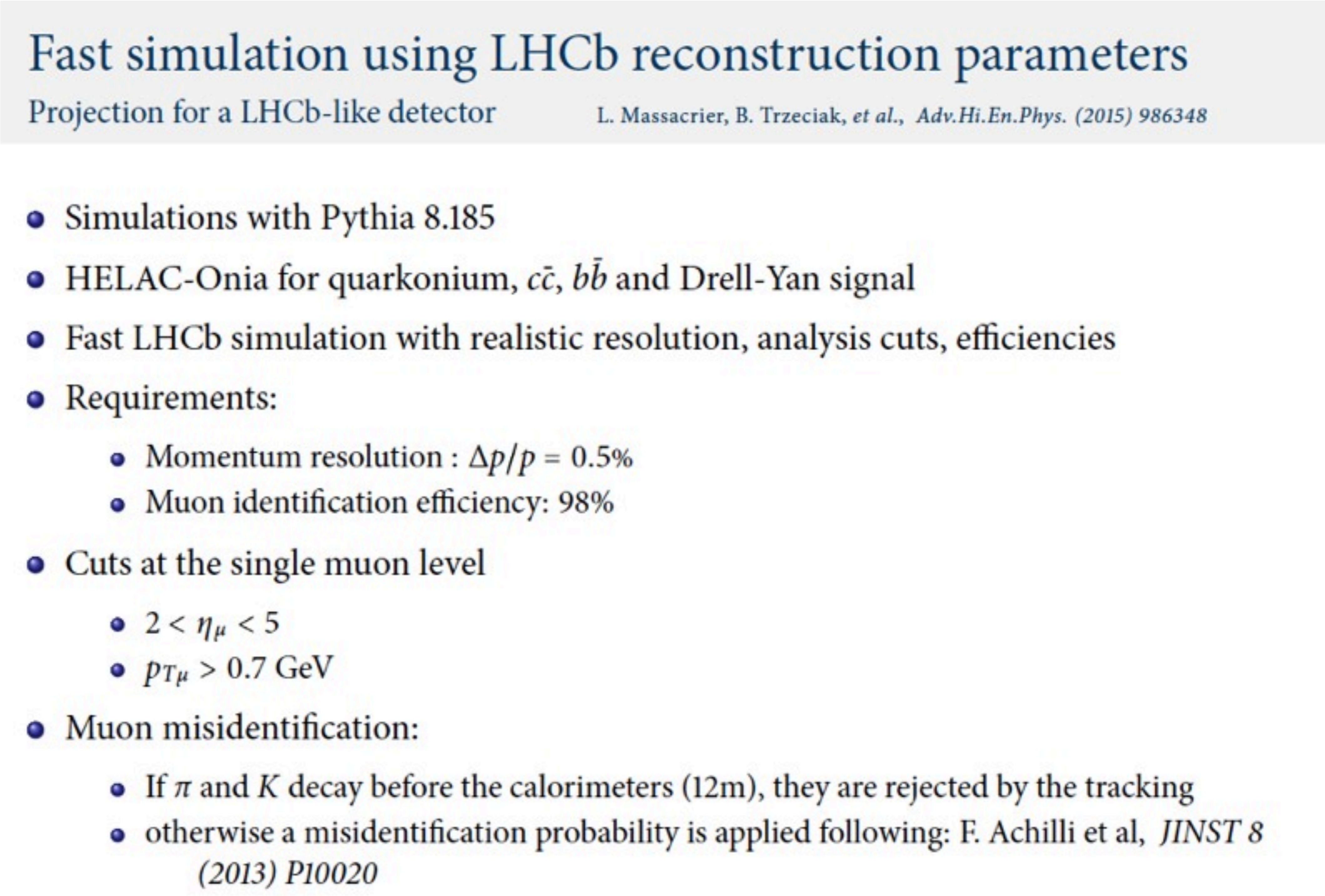
Boost effect: LHCb becomes a backward detector

- Because of the boost $y_{CM} = 0 \Rightarrow y_{Lab} \simeq 4.8$
- The pseudo-rapidity coverage of LHCb, $2 \leq \eta \leq 5$, approximately translates to a rapidity coverage in the *CM* of roughly $-2.8 \leq y_{CM} \leq 0.2$
- ALICE muon arm: $2.5 \leq \eta \leq 4 \Rightarrow -2.3 \leq y_{CM} \leq -0.8$

· **access to partons with momentum fraction $x \rightarrow 1$ in the target**



Simulation setup



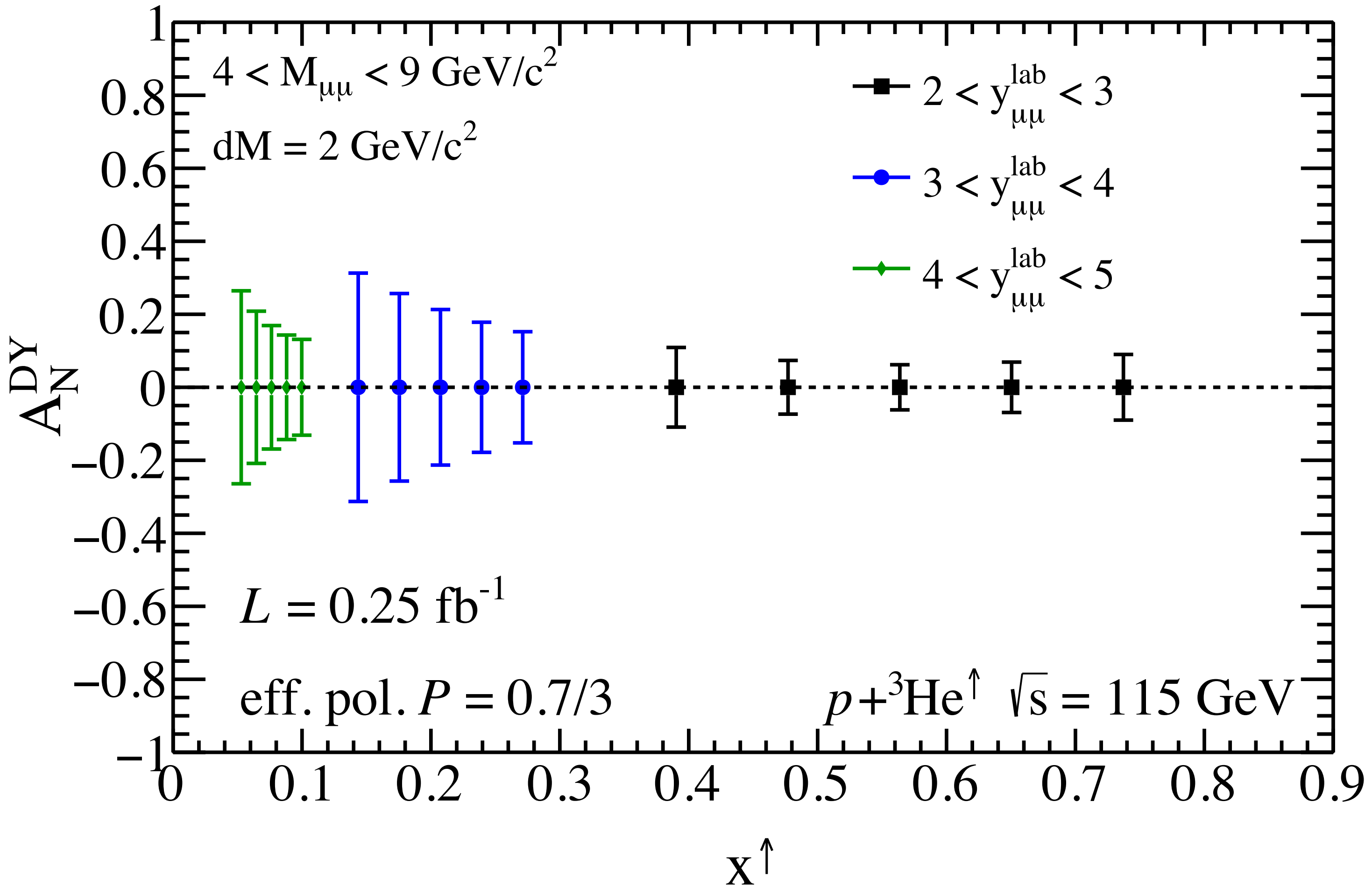
Fast simulation using LHCb reconstruction parameters

Projection for a LHCb-like detector L. Massacrier, B. Trzeciak, *et al.*, *Adv.Hi.En.Phys. (2015) 986348*

- Simulations with Pythia 8.185
- HELAC-Onia for quarkonium, $c\bar{c}$, $b\bar{b}$ and Drell-Yan signal
- Fast LHCb simulation with realistic resolution, analysis cuts, efficiencies
- Requirements:
  - Momentum resolution : $\Delta p/p$ = 0.5%
  - Muon identification efficiency: 98%
- Cuts at the single muon level
  - $2 < \eta_{\mu} < 5$
  - $p_{T\mu} > 0.7$ GeV
- Muon misidentification:
  - If π and K decay before the calorimeters (12m), they are rejected by the tracking
  - otherwise a misidentification probability is applied following: F. Achilli et al, *JINST 8 (2013) P10020*

A_N in Drell-Yan - neutron

AFTER@LHC - projections



LHCb like detector

He3 target

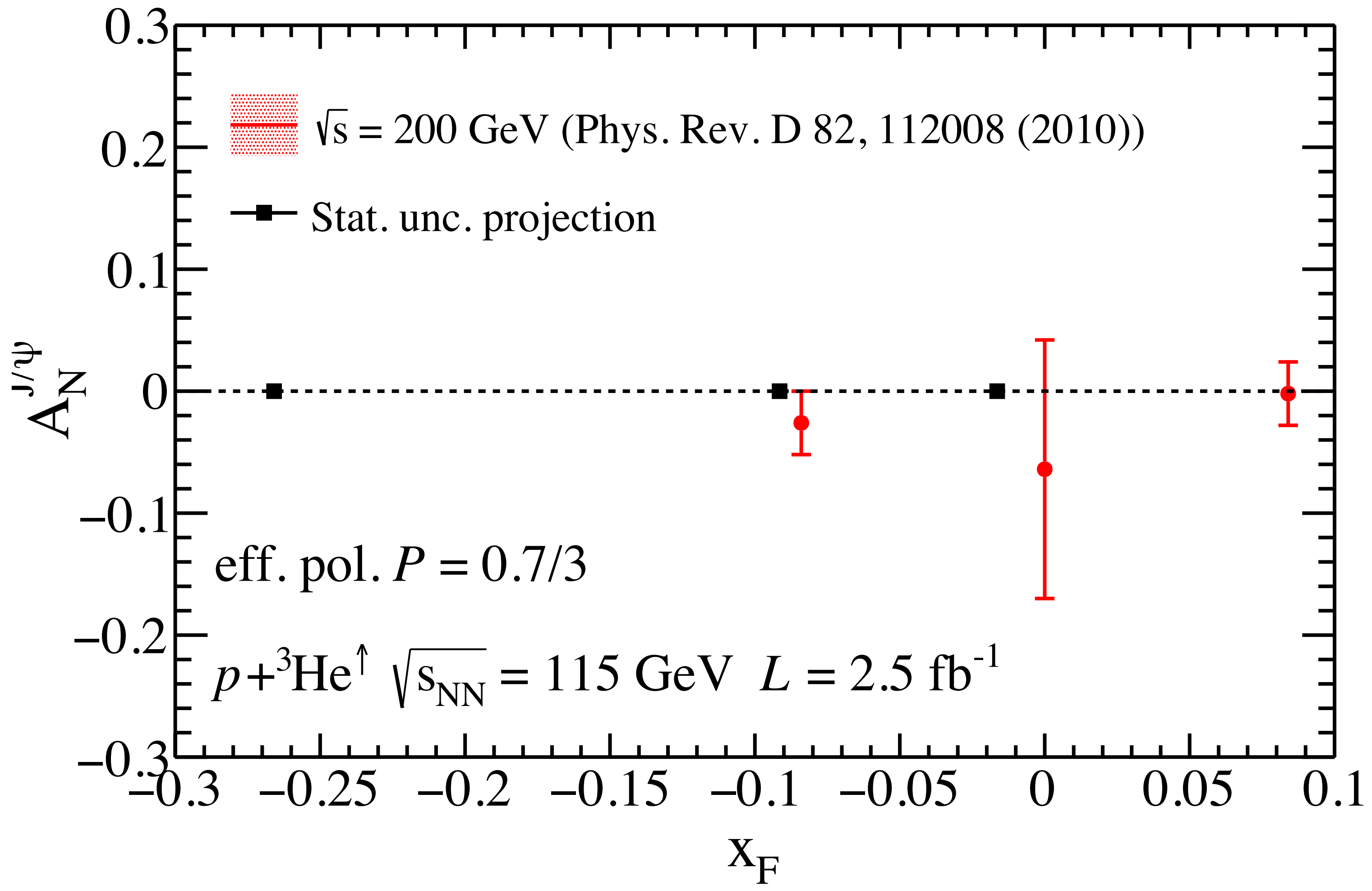
important for neutron studies :
Sivers function in a neutron

specific azimuthal modulation of AN

A_N in J/Ψ production

cite our new paper

AFTER@LHC - projections

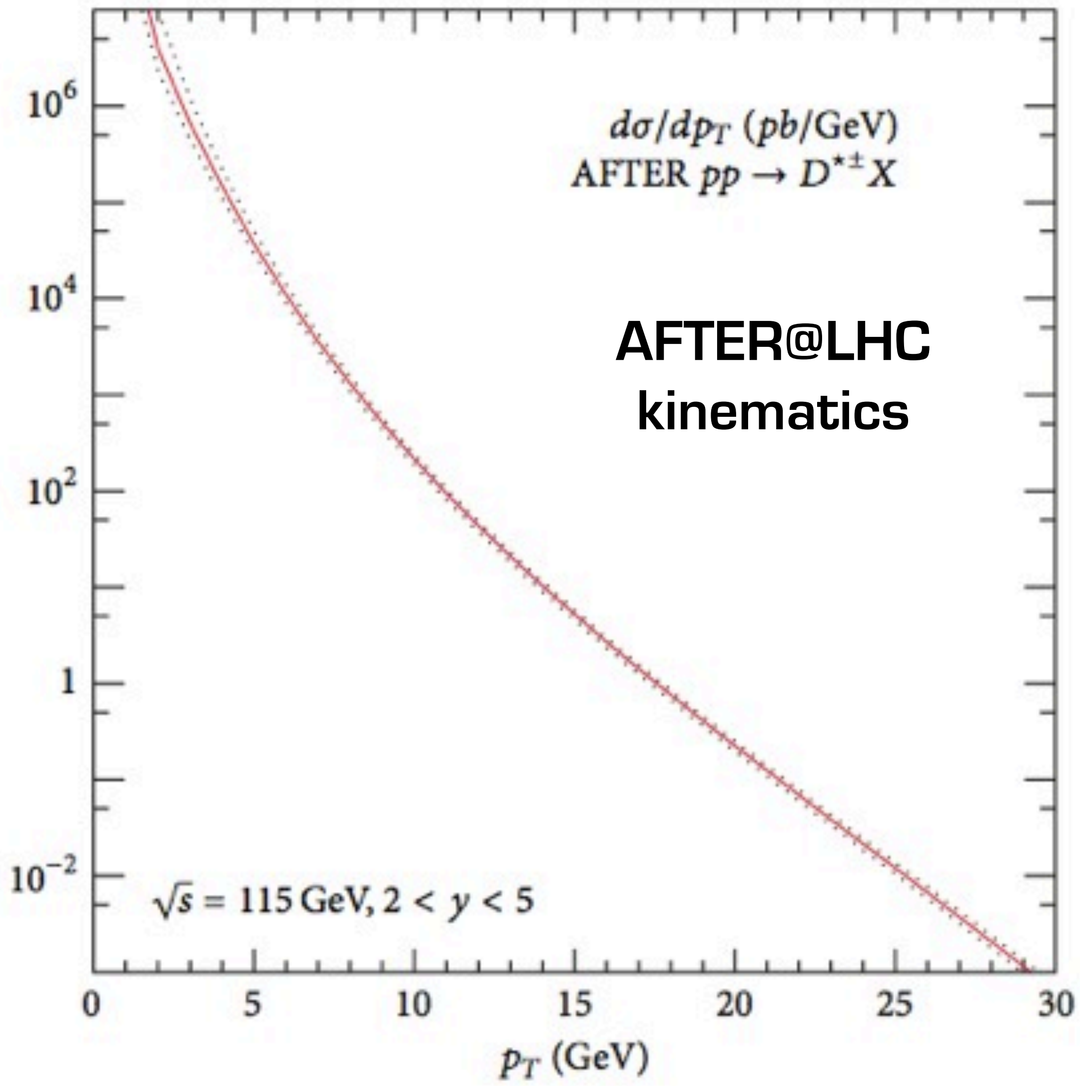


LHCb like detector

comparison to STAR (RHIC)

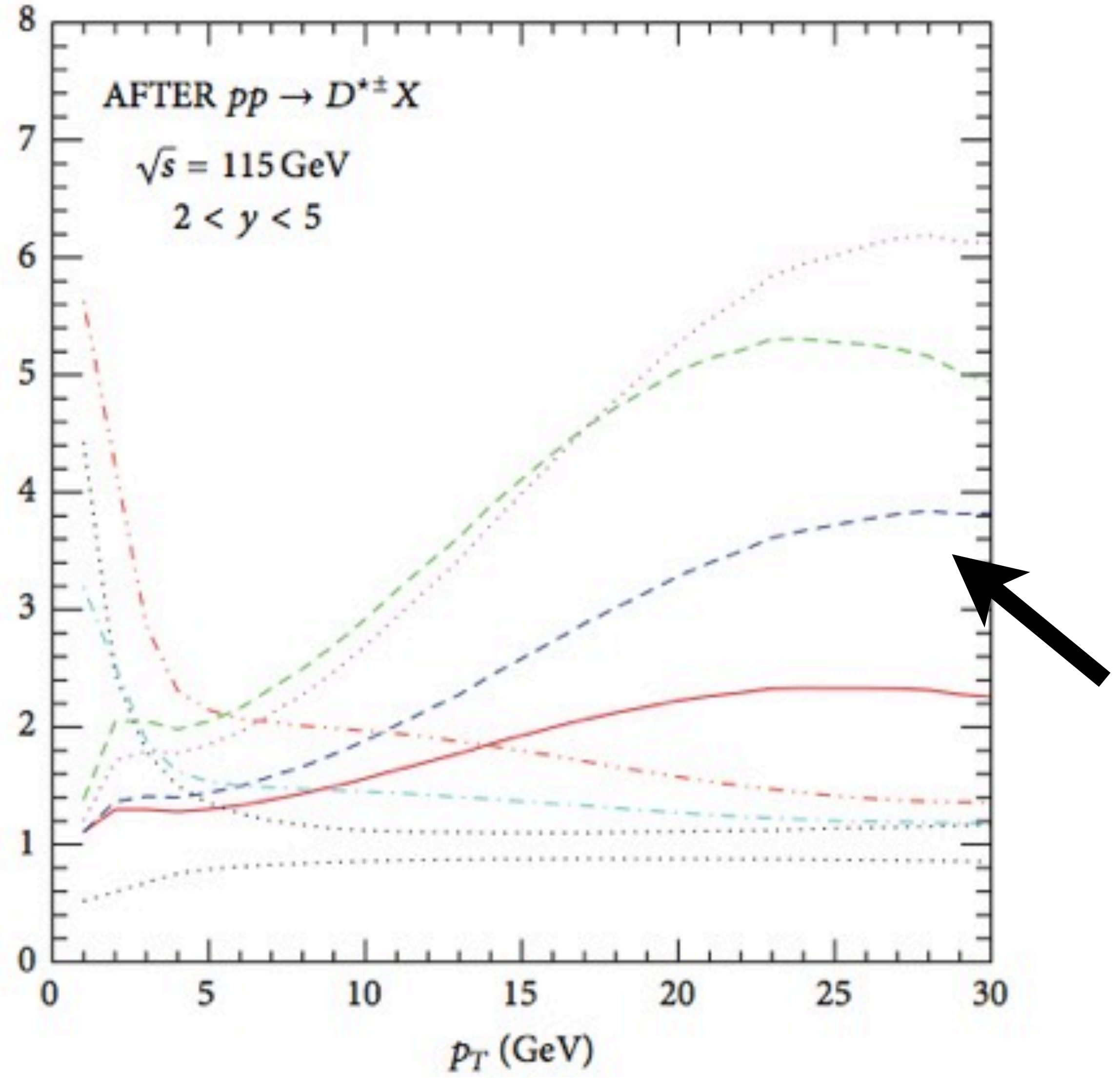
target: He3 : neutron studies

$D^{\pm/*}$ meson production at AFTER



AFTER@LHC kinematics

cross section without IC



ratio of cross sections with different CTEQ6.6 PDF members (= different IC models) to cross section w/o IC