Search for gluon saturation effects in p-Pb collisions at the LHC with ALICE

Workshop on Nuclear Parton Distribution Functions, Annecy
February 22th 2010

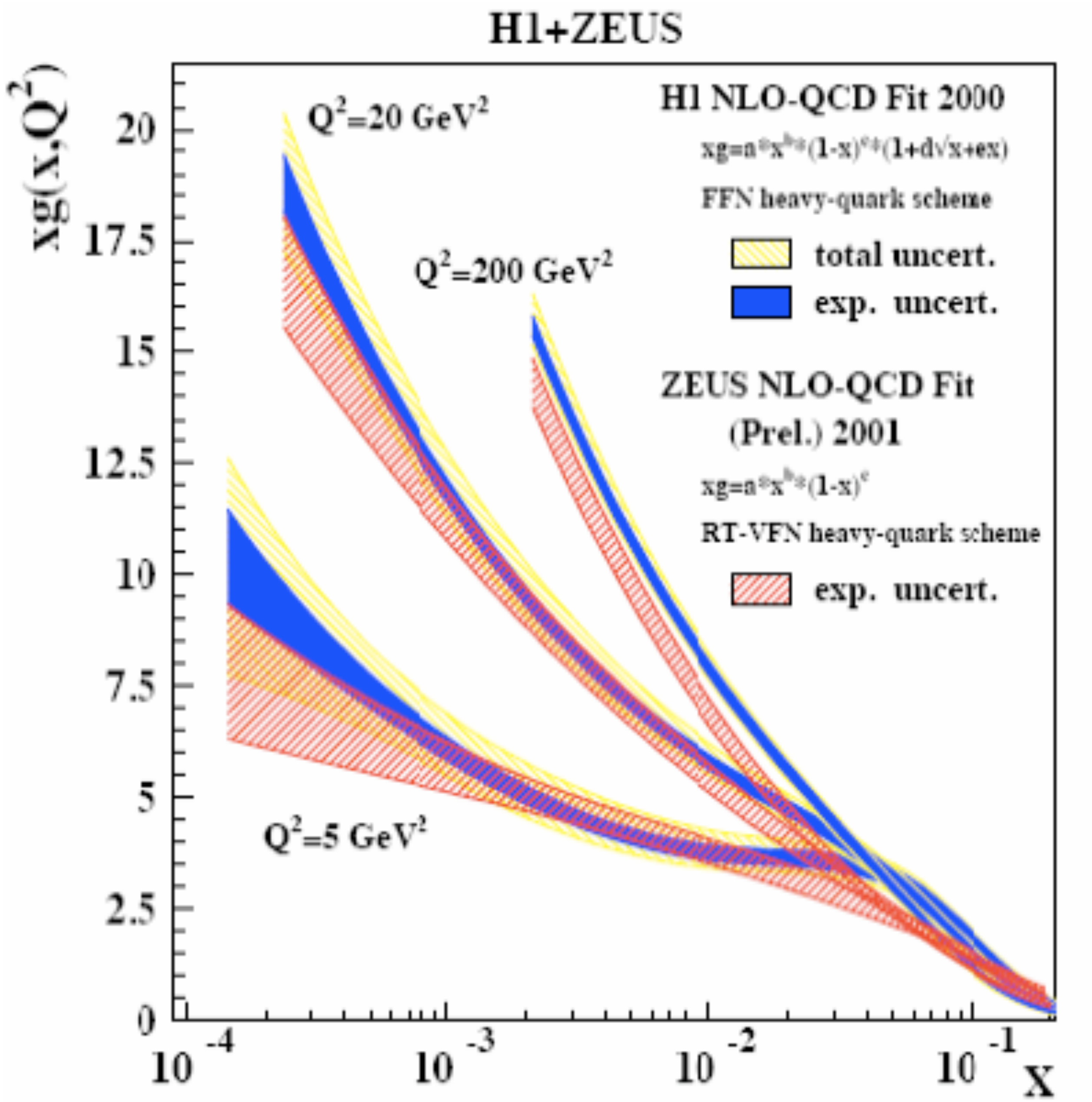
Cynthia Hadjidakis

• Small-x physics and gluon saturation effects: the Colour Glass Condensate

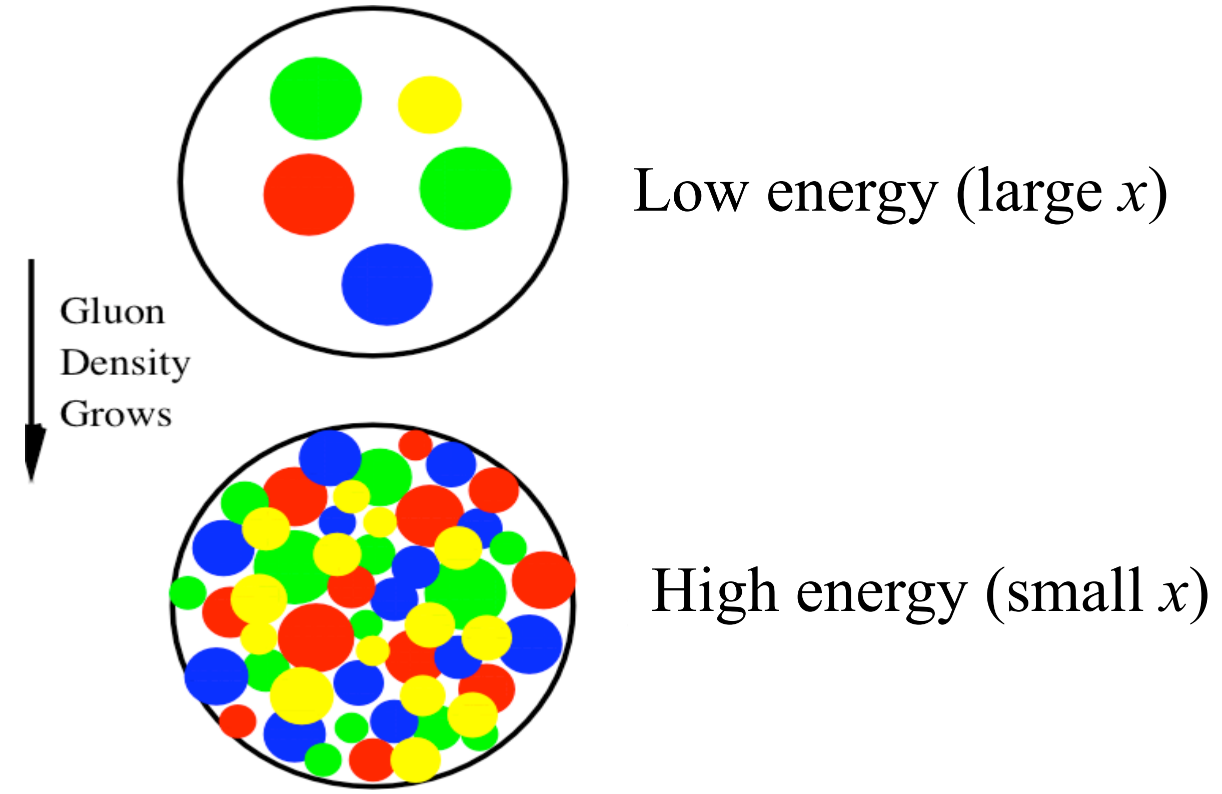
• Study of heavy flavour production at the LHC with the ALICE Forward Muon Spectrometer in p-Pb collisions

High energy physics and saturation effects

DIS measurements at HERA

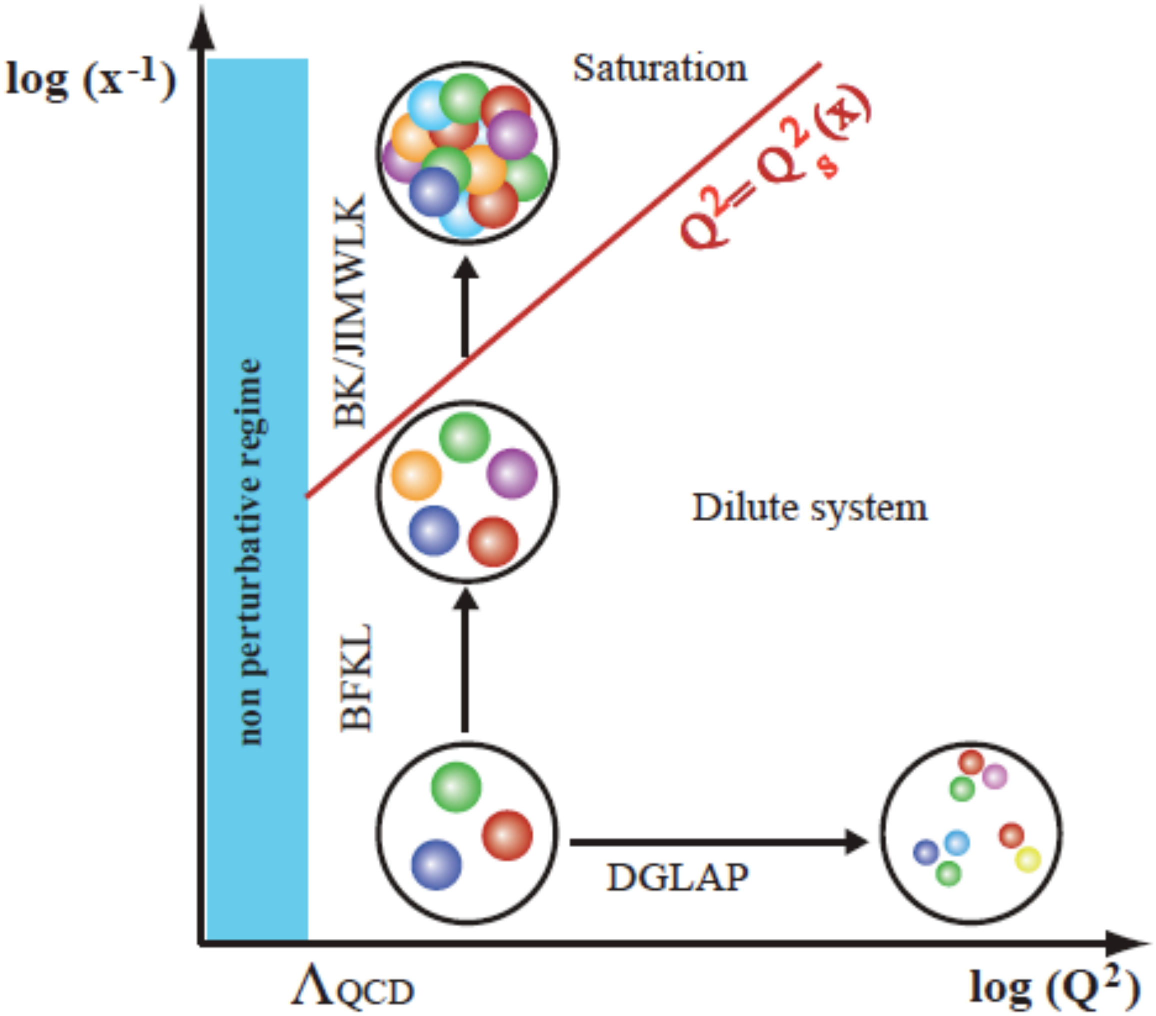


Small-x rise of $xg(x)$: saturation of the gluon density



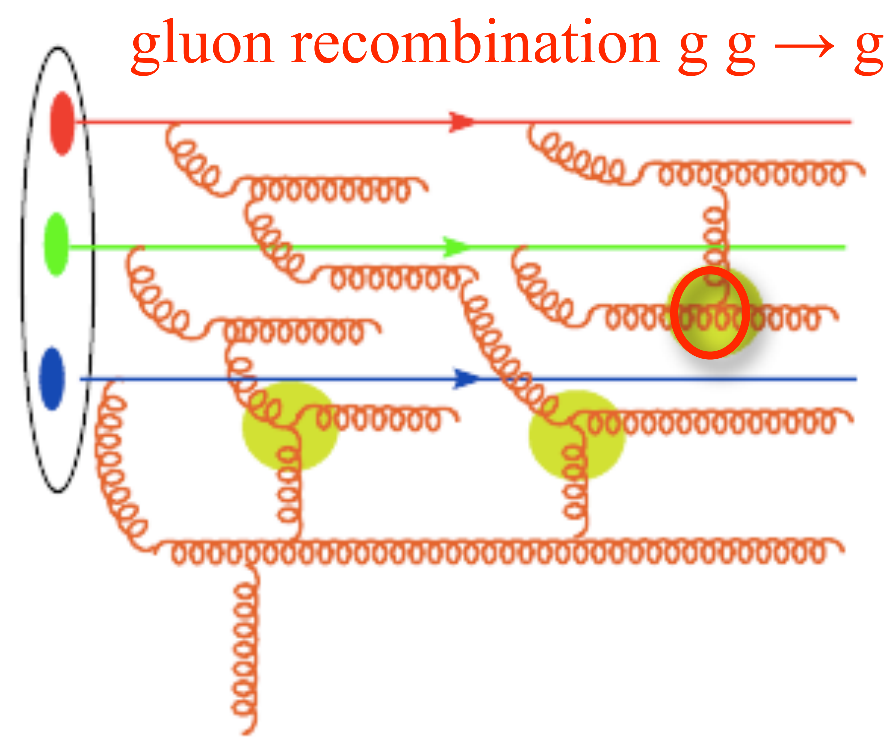
High energy physics and saturation effects

Nucleon structure: x and Q^2 evolution



Saturation regime at low x and Q^2

Gribov, Levin, Ryskin, Phys.Rept.100,1983
Mueller, Qiu, Nucl.Phys.B268,1986
Blaizot, Mueller, Nucl.Phys.B289,1987



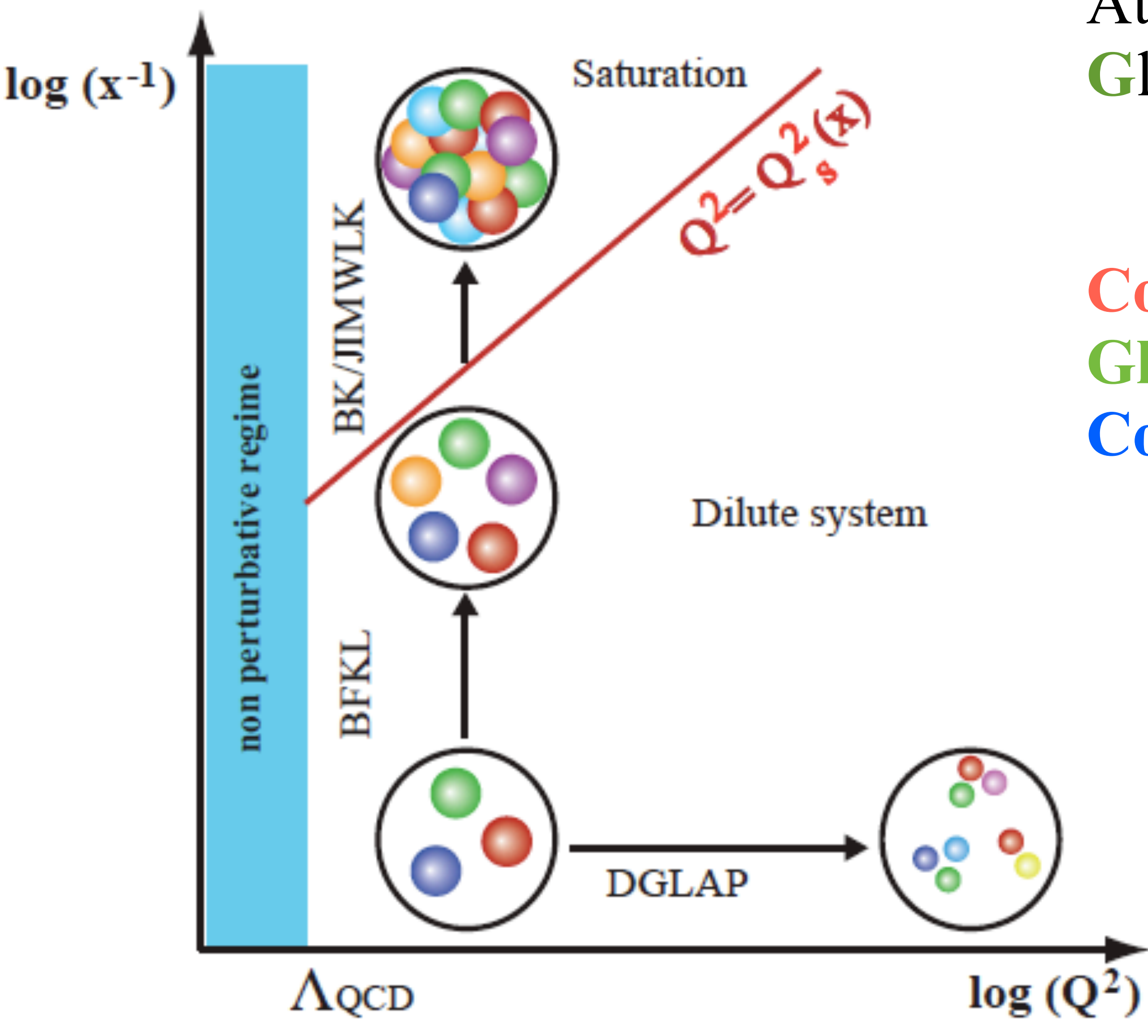
x-evolution

Large-x, linear → BFKL
Balitsky, Fadin, Kuraev, Lipatov

Small-x, non linear → JIMWLK/BK
Jalilian-Marian, Iancu, McLerran, Weigert, Leonidov, Kovner
Balitsky, Kovchegov

$Q^2_s(x)$ defines the scale below which the gluon density saturates

Colour Glass Condensate



At small-x, hadronic matter can be described by the **C**olour **G**lass **C**ondensate (CGC) model

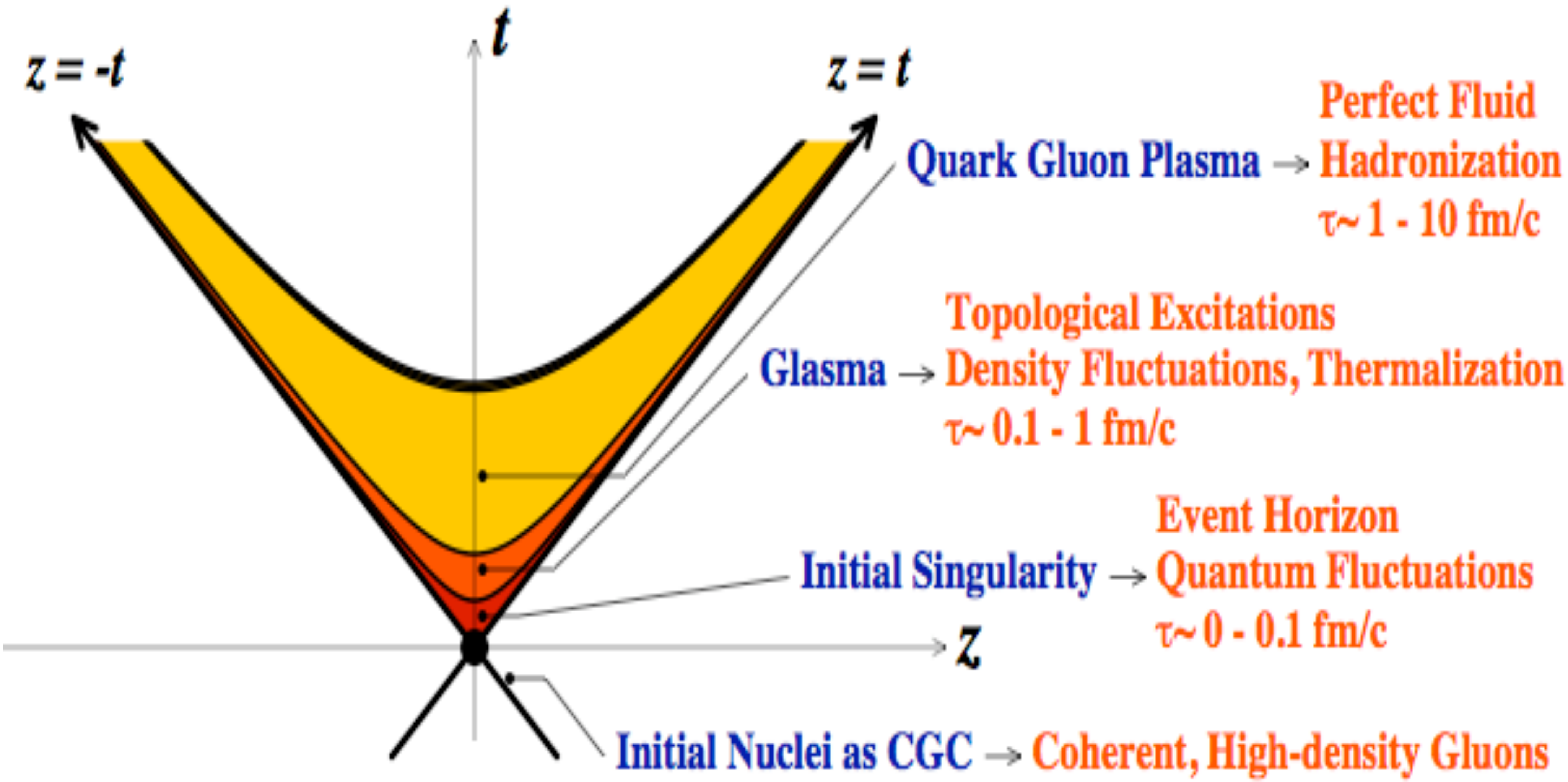
McLerran, Venugopalan, Iancu, Leonidov, Mueller, ...

Colour gluons are coloured
Glass fast partons as "frozen" sources of soft gluons
Condensate high gluon occupancy

If large Q^2_s : weakly coupled QCD-based theory but not necessarily perturbative → CGC is a classical effective theory

$Q^2_s \propto x^{-0.3} A^{1/3}$ → saturation for low x (high $\sqrt{s}=1/x$), large A
→ $Q^2_{s,LHC} = 3\ Q^2_{s,RHIC}$
→ $Q^2_{s,Pb} = 6\ Q^2_{s,p}$
if 2→1 kinematics (gg→QQbar) → $Q^2_s\,(y=3) = 4\ Q^2_s\,(y=0)$

CGC as initial state of heavy ion collisions



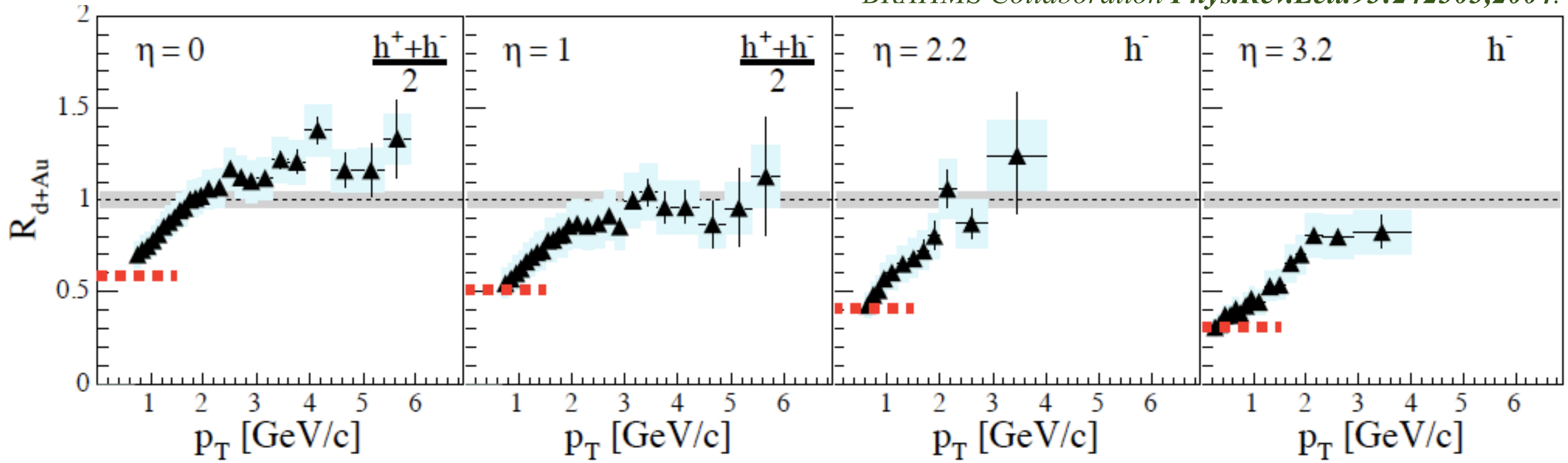
CGC framework can describe heavy ion collisions up to $\tau = 1/Q_s$

Understanding initial state will help to separate hot from cold nuclear matter effects in heavy ion collisions → p-A collisions

d-Au collisions at RHIC

$$R_{dAu} \equiv \frac{1}{\langle N_{coll} \rangle} \frac{d^2N^{d+Au}/dp_T d\eta}{d^2N^{p+p}_{inel}/dp_T d\eta}.$$

BRAHMS Collaboration ***Phys.Rev.Lett.93:242303,2004***.



At forward rapidity and low p_T (small-*x* partons probed in the nucleus), R_{d+Au} decreases

→ not explained by pQCD NLO calculations and shadowing

→ signature for a possible onset of gluon saturation at RHIC energies

But... Q^2_s =1-2 GeV^2 @ RHIC: saturation regime close to non perturbative regime

Search for saturation effects at LHC with ALICE

ALICE requirements for the forthcoming 5 years at LHC

ALICE PPR Vol. 1

Collision system	$\sqrt{s_{NN}}$(TeV)	L_0 ($cm^{-2}s^{-1}$)	Run time (s)	σ_{geom} (b)
p-p	7 / 14	3.10^{30} *	5.10^{7}	0.07
Pb-Pb	2.76 / 5.5	5.10^{26}	2.10^{6}	7.7
p-Pb	8.8	1.10^{29}	1.10^{6}	1.9
Ar-Ar	6.3	1.10^{29}	1.10^{6}	2.7

(*ATLAS/CMS L_0= 10^{34} - LHCb L_0 = 10^{32})

- p-Pb and Pb-Pb collisions at LHC (Q^2_s =3-5 GeV^2): definitive tests of the CGC picture
- p-Pb better system to test the saturation regime (no Quark Gluon Plasma)
- Understanding of cold nuclear matter effect in pPb is crucial to understand QGP probes in Pb-Pb collisions

- **Many observables for studying saturation effects**

In p-p, p-Pb and Pb-Pb: multiplicities, R_{pA} and R_{AA} for forward and/or low p_T production, long range correlation in rapidity, ...

→ Forward heavy flavour production in p-p and p-Pb

p-Pb collisions at LHC

- p-Pb collisions, LHC single magnet ring with two-beam aperture imposes:

  $\sqrt{s} = \sqrt{(Z_1 Z_2/A_1 A_2)} \times 2p_p$ TeV → for p-Pb $\sqrt{s} = 8.8$ TeV

  $\Delta y = 0.5 \ln (Z_1 A_2/Z_2 A_1)$ → for p-Pb = 0.47

  → y- and $\sqrt{s}$-dependence extrapolation needed when comparing p-Pb / p-p

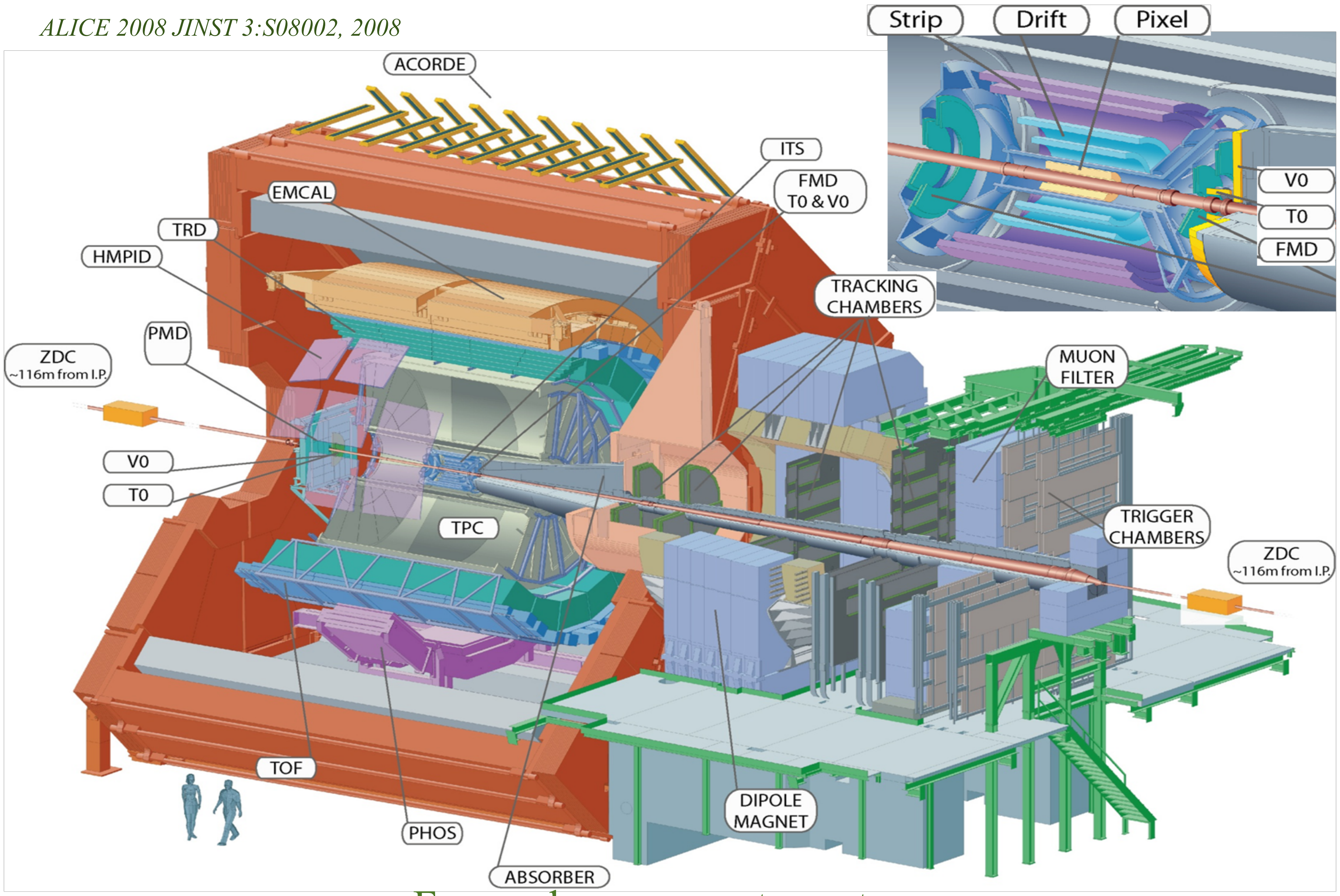
- Running with d-Pb would be better...

  $\Delta y = 0.1$ → almost same acceptance than symmetric systems
  Nucleon probe (average of proton and neutron)

  ...but requires a LHC upgrade (additional beam injection source) not foreseen

ALICE experiment

ALICE 2008 JINST 3:S08002, 2008



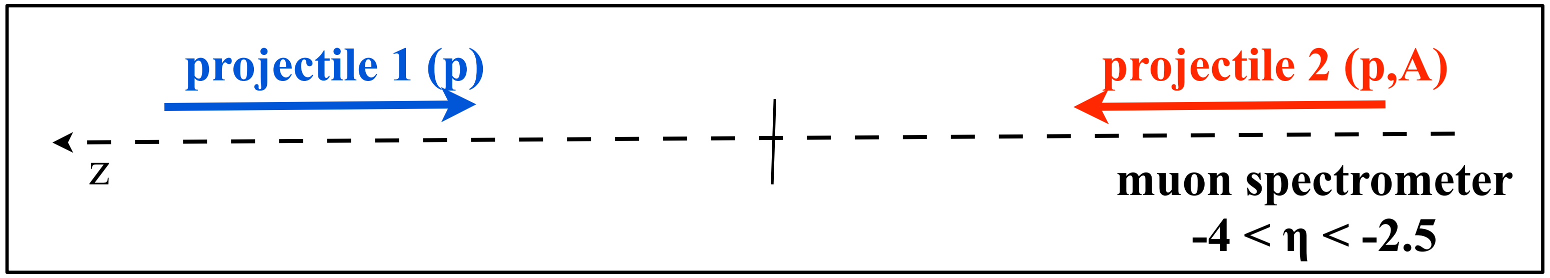
Forward muon spectrometer

$-4 < \eta < -2.5$

Inner Tracking System

vertex determination

CGC model for forward heavy flavour production



Fujii, Gelis, Venugopalan ***Nucl.Phys.A780,2006***

$$\frac{dN^{pPb}_{Q\overline{Q}}}{dyd^2\boldsymbol{p}_t} = f_g^{(p)}(x_1) \otimes \varphi(x_2) \otimes \frac{dN^{\mathrm{sat}}_{\mathrm{gg}\to Q\overline{Q}}}{dyd^2\boldsymbol{p}_t}$$

✦ gg→ QQbar production
evaluated in a strong background colour field (multiple scattering effects)

In p-p (p-Pb) at forward rapidity → partons probed: $x_2 \ll x_1$

✦ projectile 1 = dilute system = $f_g(x_1)$ CTEQ6 gluon p.d.fs

✦ projectile 2 = dense system = $\varphi(x_2)$ CGC gluon distr. in a saturated nucleus

- initial condition @ $x_0 = 10^{-2}$ using McLerran-Venugopalan (MV) model
  - multiple scattering effect due to dense system (both initial gluons and QQbar pair).
  - saturation scale (Q^2_s) determined @ $x_0 = 10^{-2}$
- small-x evolution according to Balitsky-Kovchegov (BK) equation (valid for $x < x_0$)

Model parameter estimation

- saturation scale Q^2_s :
  - evaluated from $dN^{h+/-}/dy|_{y=0}$ @ RHIC in Au-Au collisions: $Q_s{}^2{}_{,Au} = 2$ GeV^2

    Krasnitz, Nara, Venugopalan Nucl.Phys.A727:427-436,2003.

  - $Q_{s,A}{}^2$ is only A-dependent
    - A-dependence from the color charge density: $g^4\mu_B{}^2 = (B/A)^{1/3}\, g^4\mu_A{}^2$ with $g^4\mu_A{}^2 \propto Q_{s,A}{}^2 / (1+\ln(Q_{s,A}{}^2/\Lambda^2{}_{QCD}))$
    - $Q_{s,A}{}^2$ can be defined for any A. In particular, $Q_{s,p}{}^2 = 0.17$ GeV^2

  $\rightarrow$ constant thickness of projectile 2 assumed $\equiv$ most central collisions

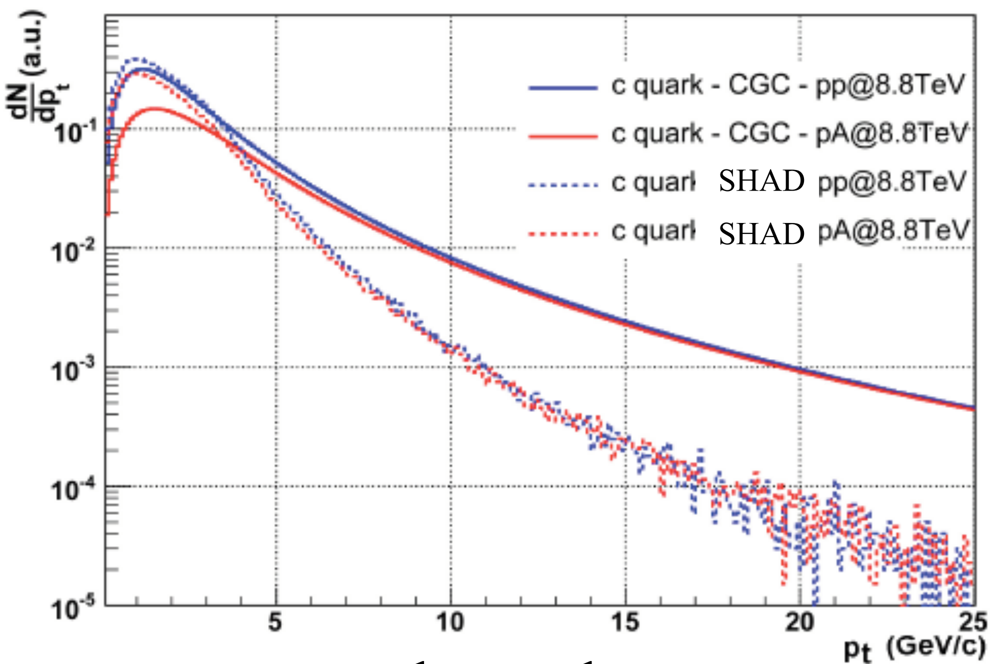
- quark mass $m_c = 1.2$ GeV

- coupling constant α_s ... not running but fixed: effective way to account for NLO correction in α_s
  - from HERA data (y-dependence of F_2): $\alpha_s = 0.15$

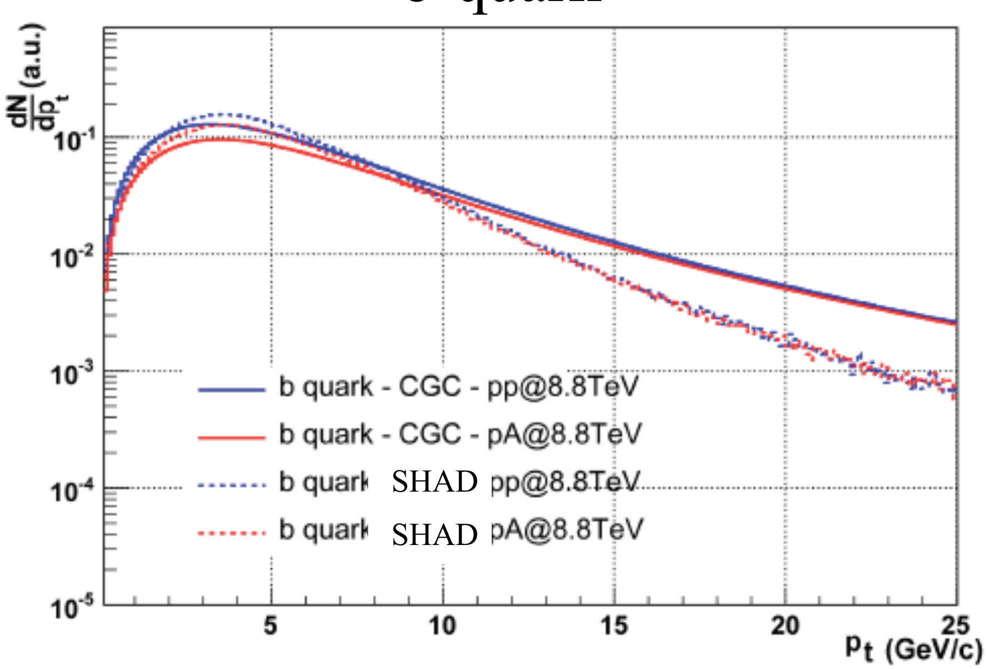
Open heavy flavour at forward rapidity

Open heavy flavour production at forward rapidity

c-quark

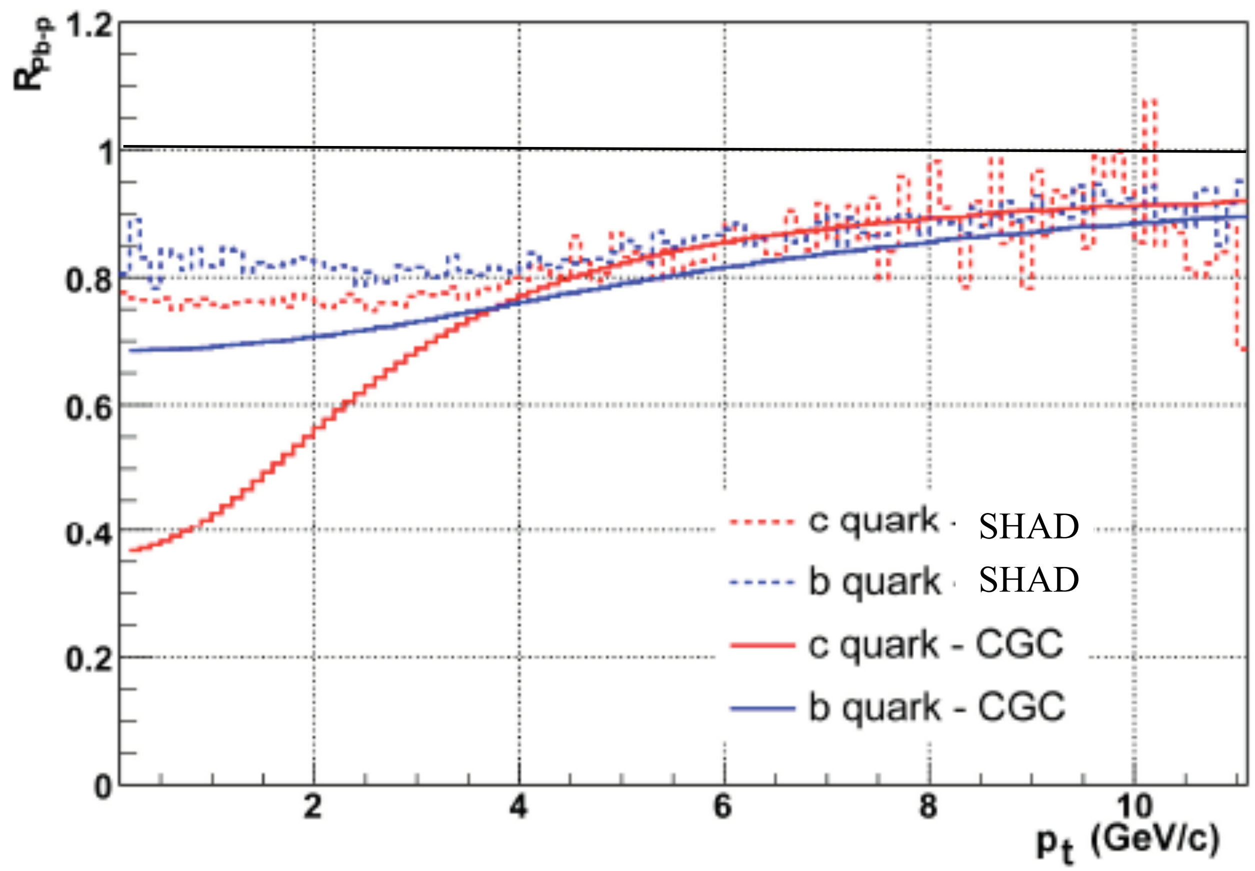


b-quark



A. Charpy et al. ALICE-INT-2009-043

$R_{p\text{-}Pb}$ for c- and b-quarks @ $\sqrt{s}$ = 8.8 TeV

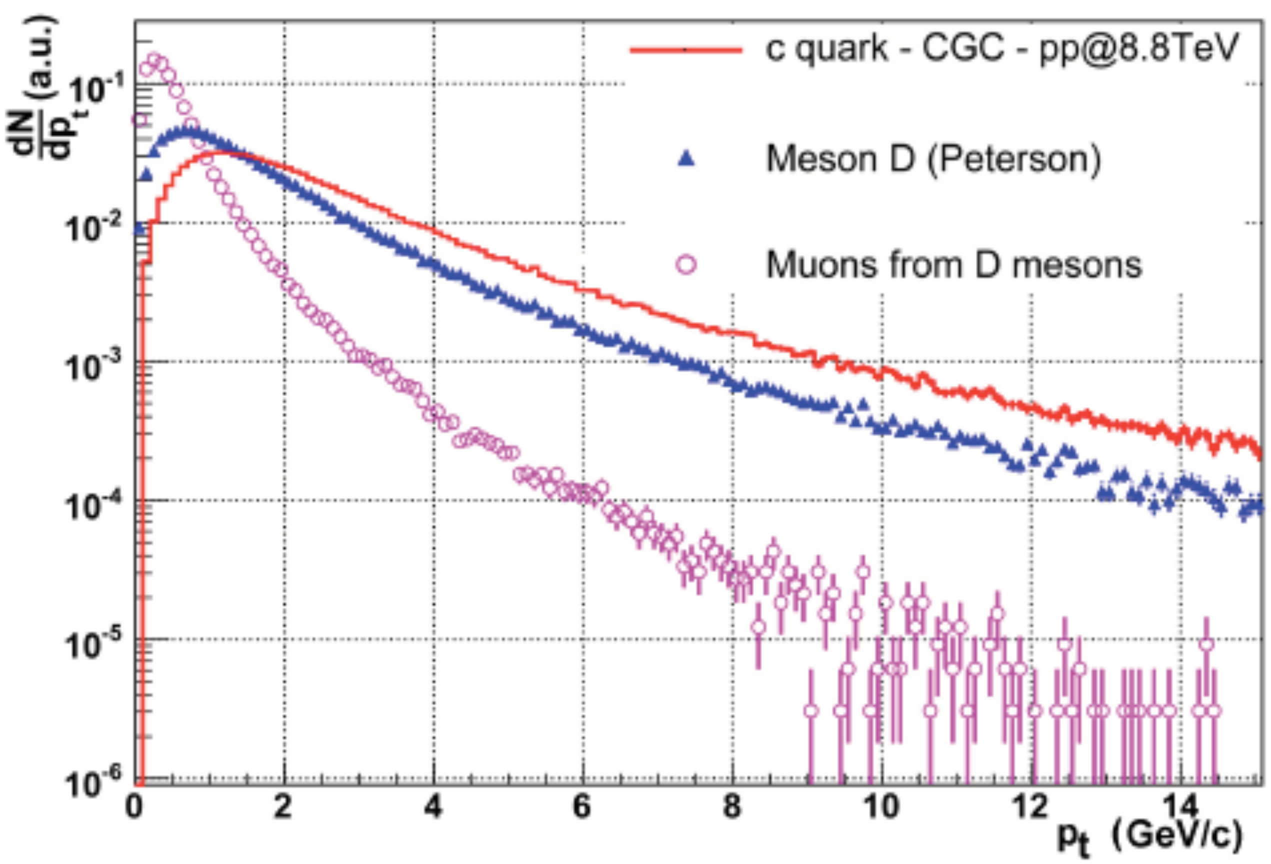


- SHAD = PYTHIA-MNR tuned to NLO pQCD with nuclear shadowing (EKS98)

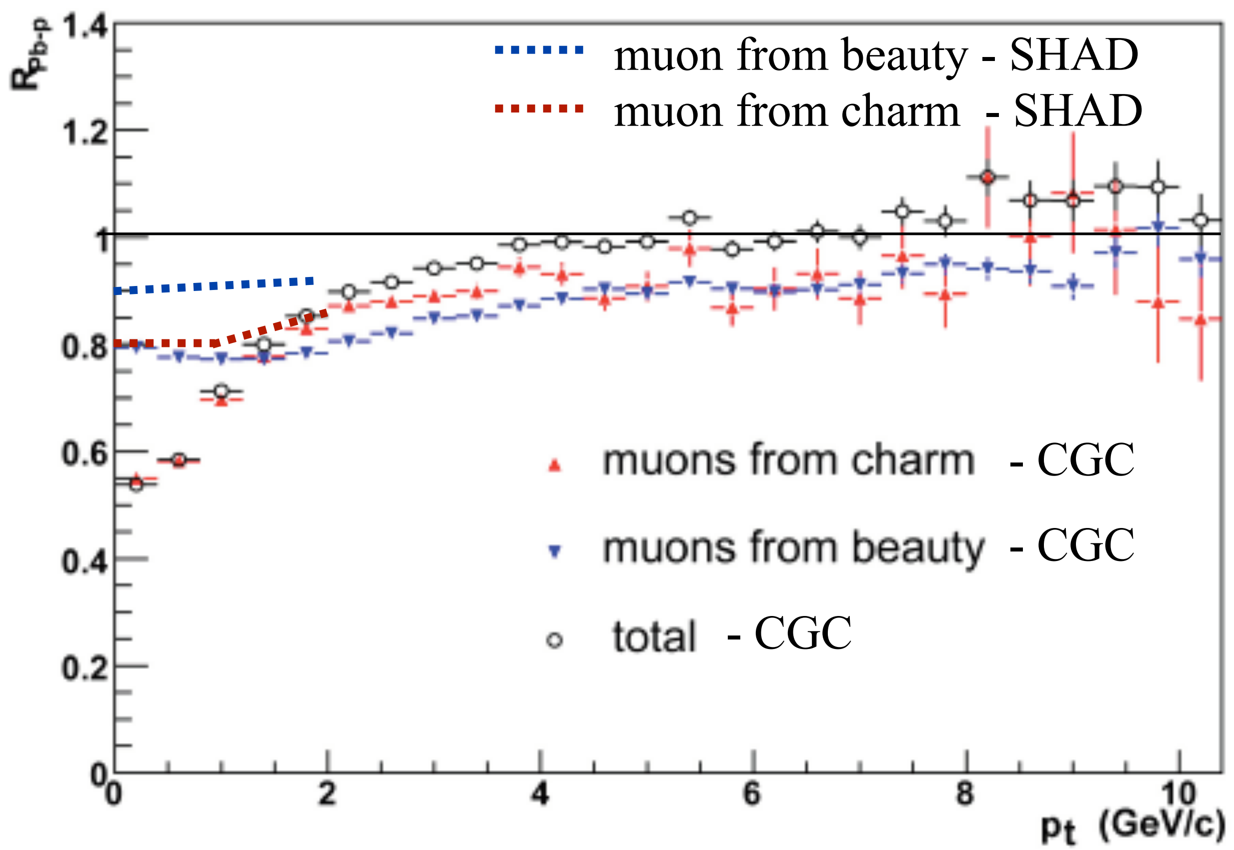
→ Gluon saturation effects important for c-quark at p_T<4 GeV/c

Fragmentation and decay into muons

open charm



$R_{p\text{-}Pb}$ for single muons from open charm

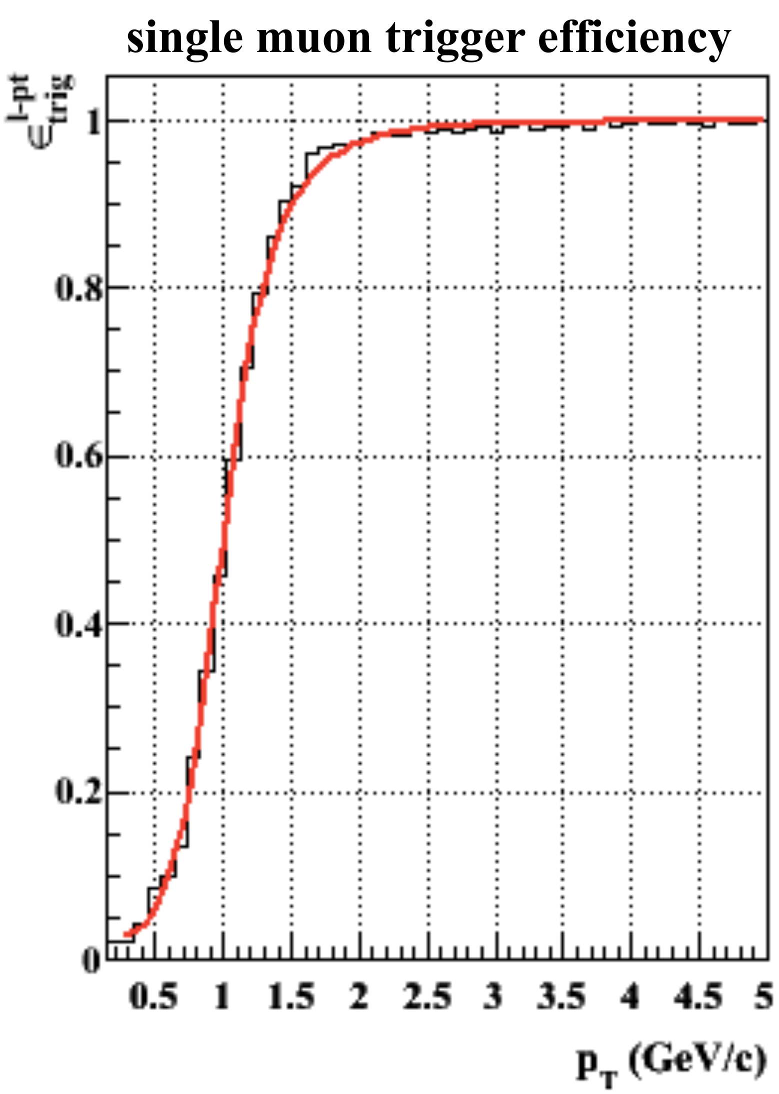


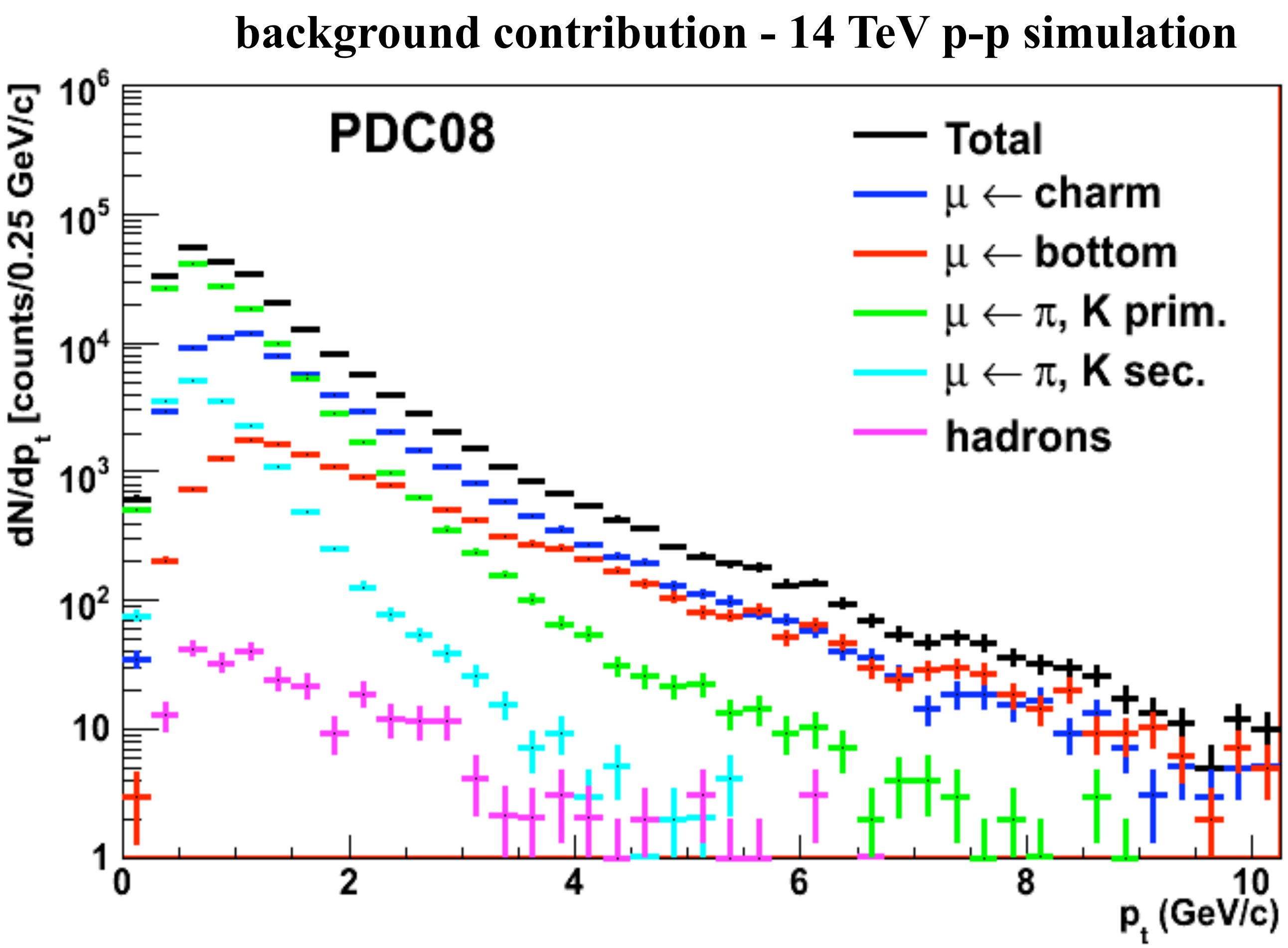
→ Fragmentation and decay into muons soften the p_T spectrum

→ Gluon saturation effects (30%) for muons from c-quark at p_T<2 GeV/c

Single muon detection in the Muon Spectrometer

Forward Muon Spectrometer
- $-4 < \eta < -2.5$
- $p > 4$ GeV/c (muon absorber and filter)





→ Muon trigger efficiency decreases at low p_T

→ Large background contribution from π and K at $p_T < 1.5$ GeV/c

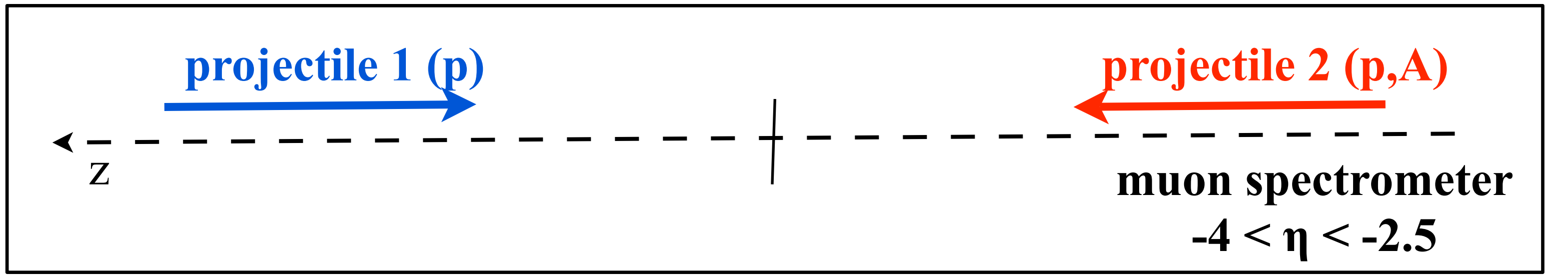
Open heavy flavour in the Muon Spectrometer → challenging channel to study saturation effect

J/ψ production at forward rapidity

Why J/ψ ?

- More suppressed in p-Pb collisions (more sensitive to multiple scattering)
- Simpler to measure experimentally

J/ψ production at forward rapidity



✦ projectile 1 = dilute system = $f_g(x_1)$ CTEQ6 gluon p.d.fs + **k_T kick**

J/ψ $p_T = 0 \rightarrow$ gluon k_T not negligible

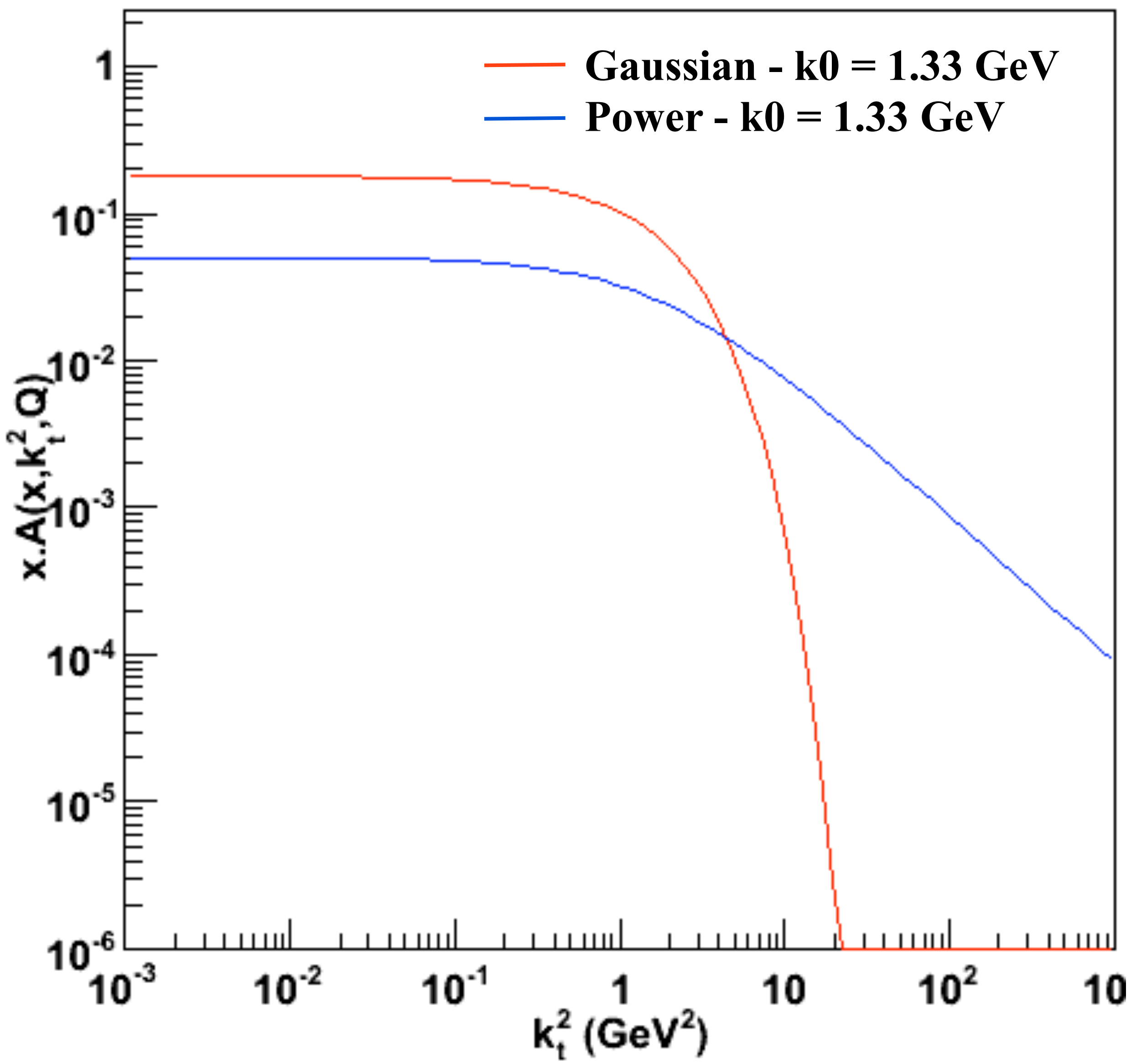
Unintegrated gluon p.d.f:

- Gaussian

$x.A(x,k^2_t,Q^2) = x.G(x,Q^2)\ \exp(-k_t^2/k_0^2)$

- Power

$x.A(x,k^2_t,Q^2) = x.G(x,Q^2)\ /\ (k_t^2 + k_0^2)$



→ effect important on R_{pPb} J/ψ for $p_T < 2.5$ GeV

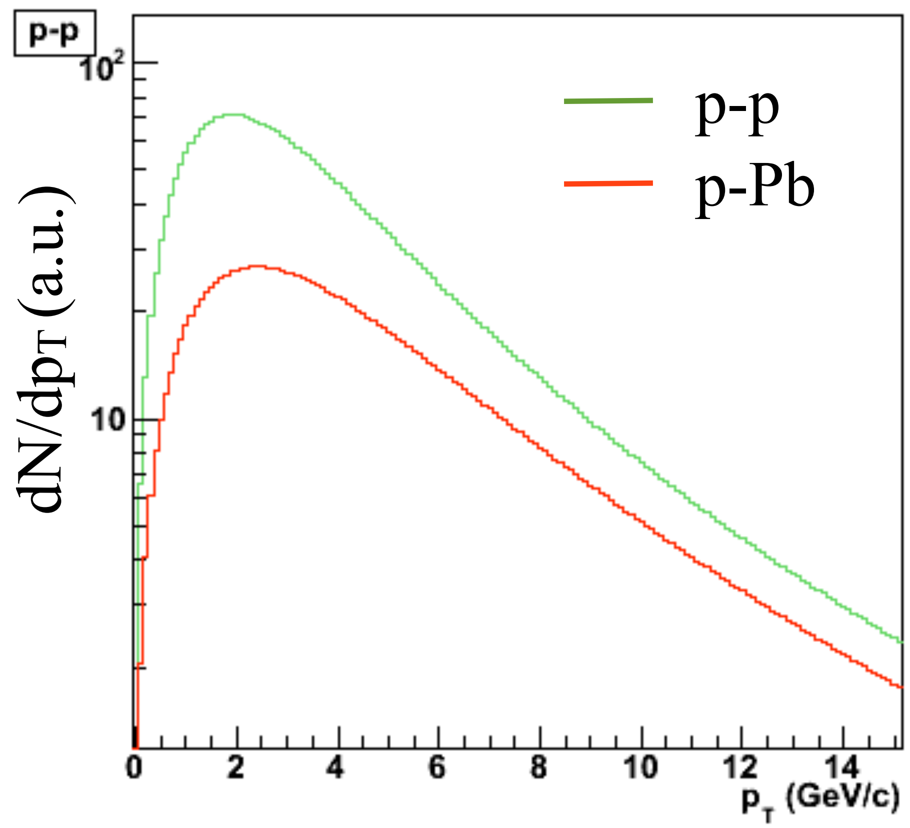
→ Power k_T-dependence is preferred: results on nuclear modification factor in qualitative agreement with

Fujii, Gelis, Venugopalan ***Nucl.Phys.A780,2006***

Model for J/ψ production

✦ Colour Evaporation Model

$$\frac{dN_{J/\psi}}{dY\,d^2\boldsymbol{P}_\perp} \underset{CEM}{=} F_{J/\psi} \int_{4m_c^2}^{4m_D^2} dM^2 \, \frac{dN_{\text{ccbar}}}{dY\,d^2\boldsymbol{P}_\perp dM^2}$$

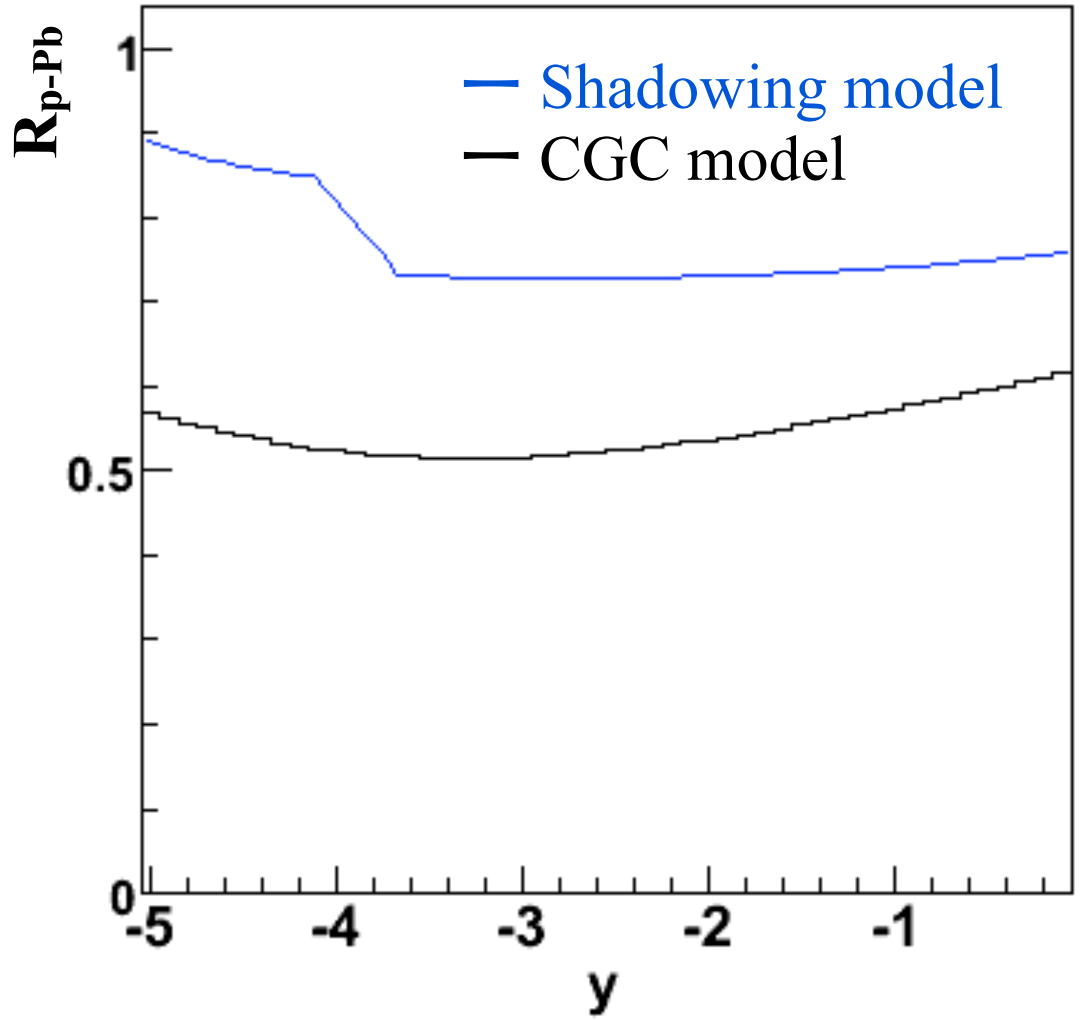


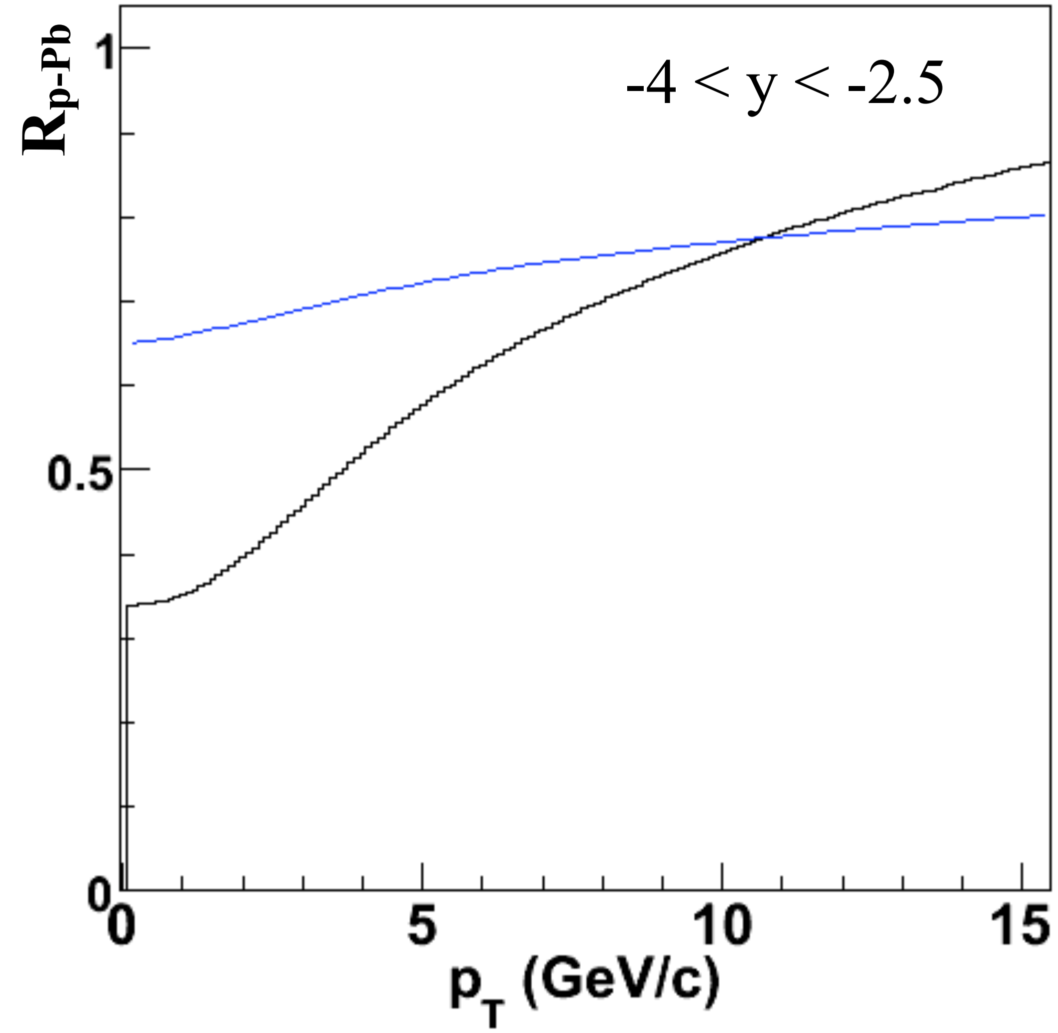
Quarkonium production mechanism not well understood... and does not cancel out in nuclear modification ratio

Ferreiro et al. Phys.Lett.B680:50-55,2009

J/ψ assumed to be formed outside of the nucleus (LHC energy) → no absorption effect

$R_{p\text{-}Pb}$ for J/ψ production



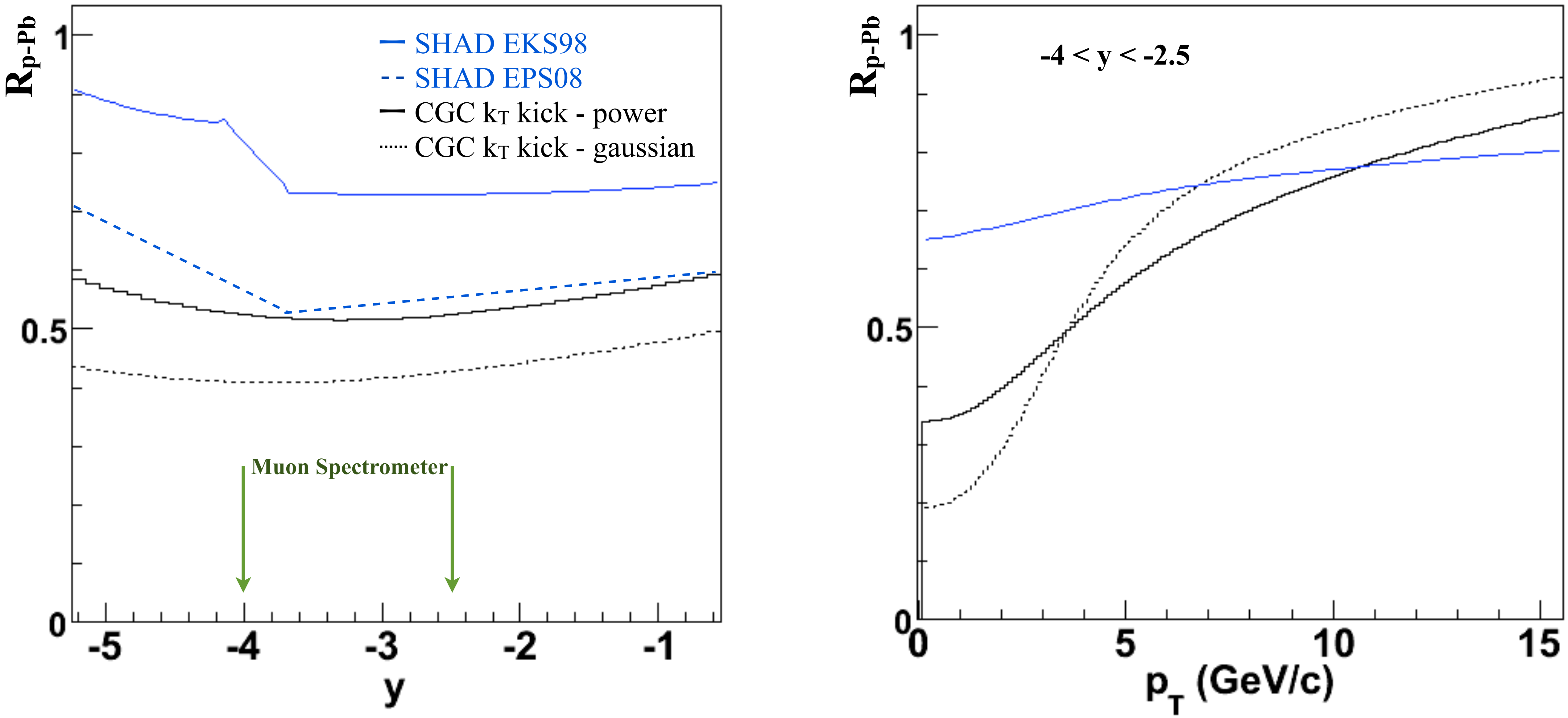


Shadowing model *Smbat Grigoryan*

- cross section: energy dependence from CEM model and p_T dependence from a parameterization from CDF data
- shadowing: EKS98 and LO kinematics (gg→J/ψ) for p_T-dependence: $x_{1,2} = m_t/\sqrt{s}\,\exp(\pm y)$

... including some of the model uncertainties

- Shadowing model: EPS08 used as lower bound of EKS98
- CGC model: at low p_T main uncertainty = k_T dependence of p.d.f for projectile 1

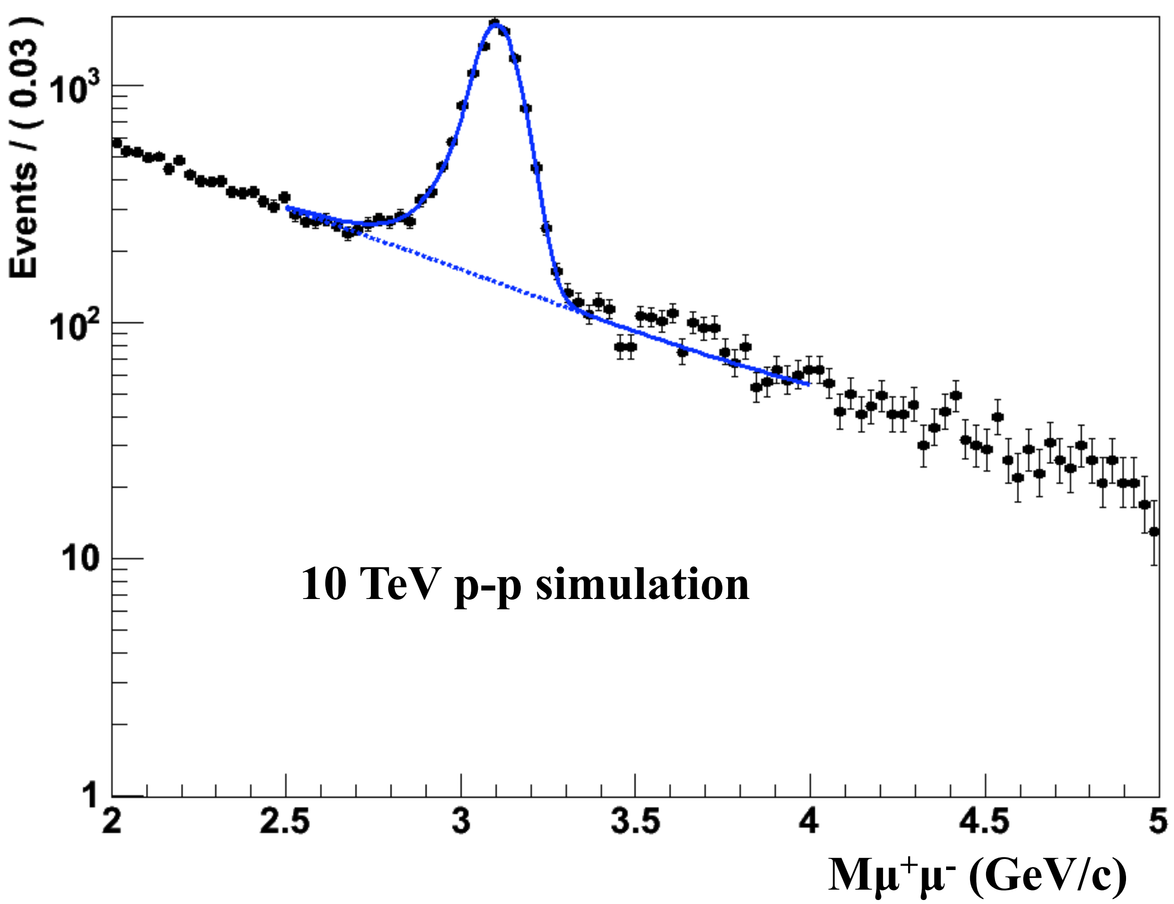


$R_{p\text{-}Pb}$ in Muon Spectrometer acceptance: CGC model = [0.40-0.55] / Shadowing = [0.55-0.75]

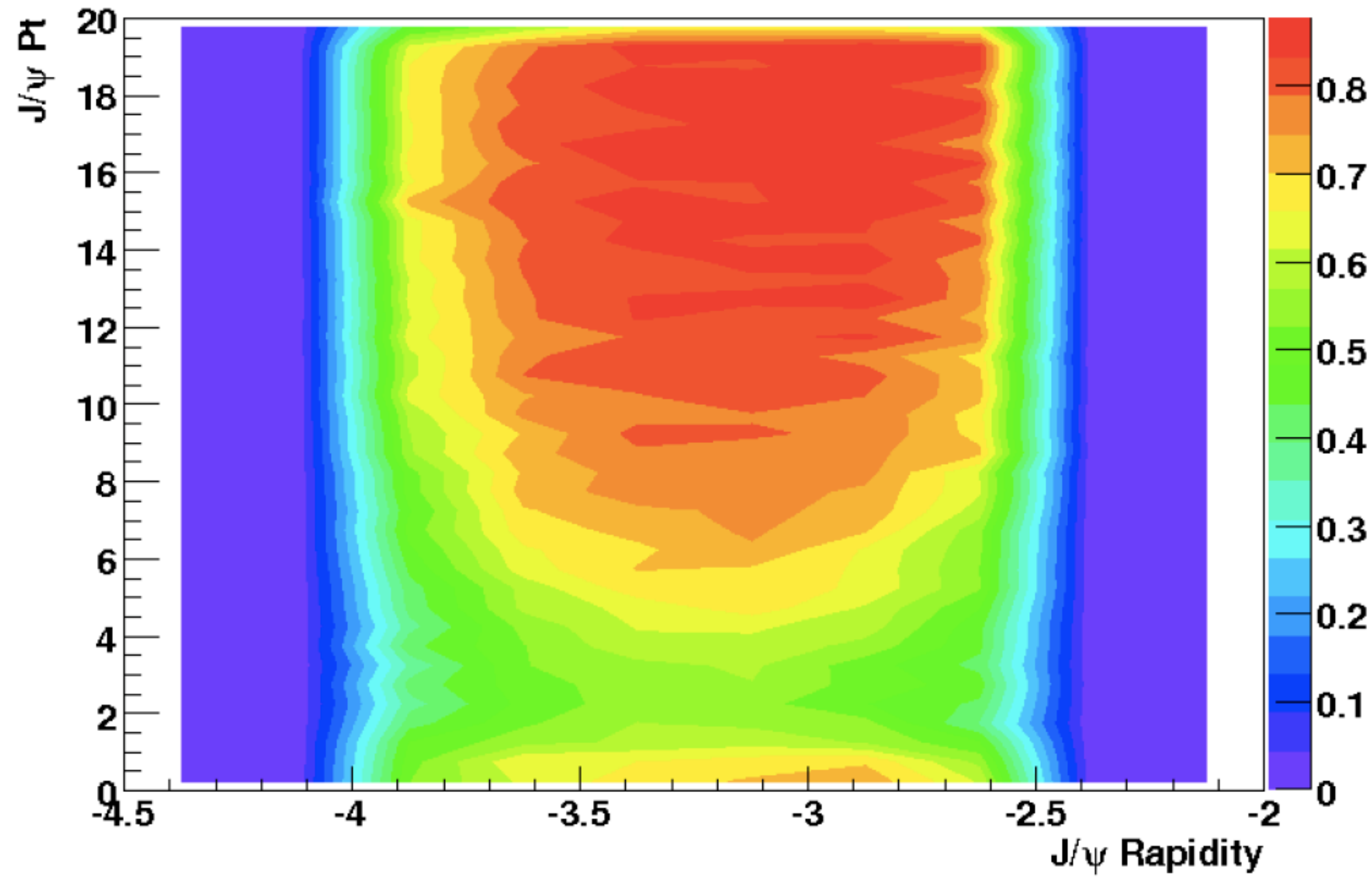
Sharper p_T-dependence for CGC model but large model uncertainties

J/ψ measurement at forward rapidity

Background subtraction: J/ψ → $\mu^+ \mu^-$



J/ψ efficiency



→ invariant mass fit allows an estimation of the background

→ J/ψ reconstructed in the Muon Spectrometer down to low $p_T \simeq 0$

J/ψ measurement promising channel

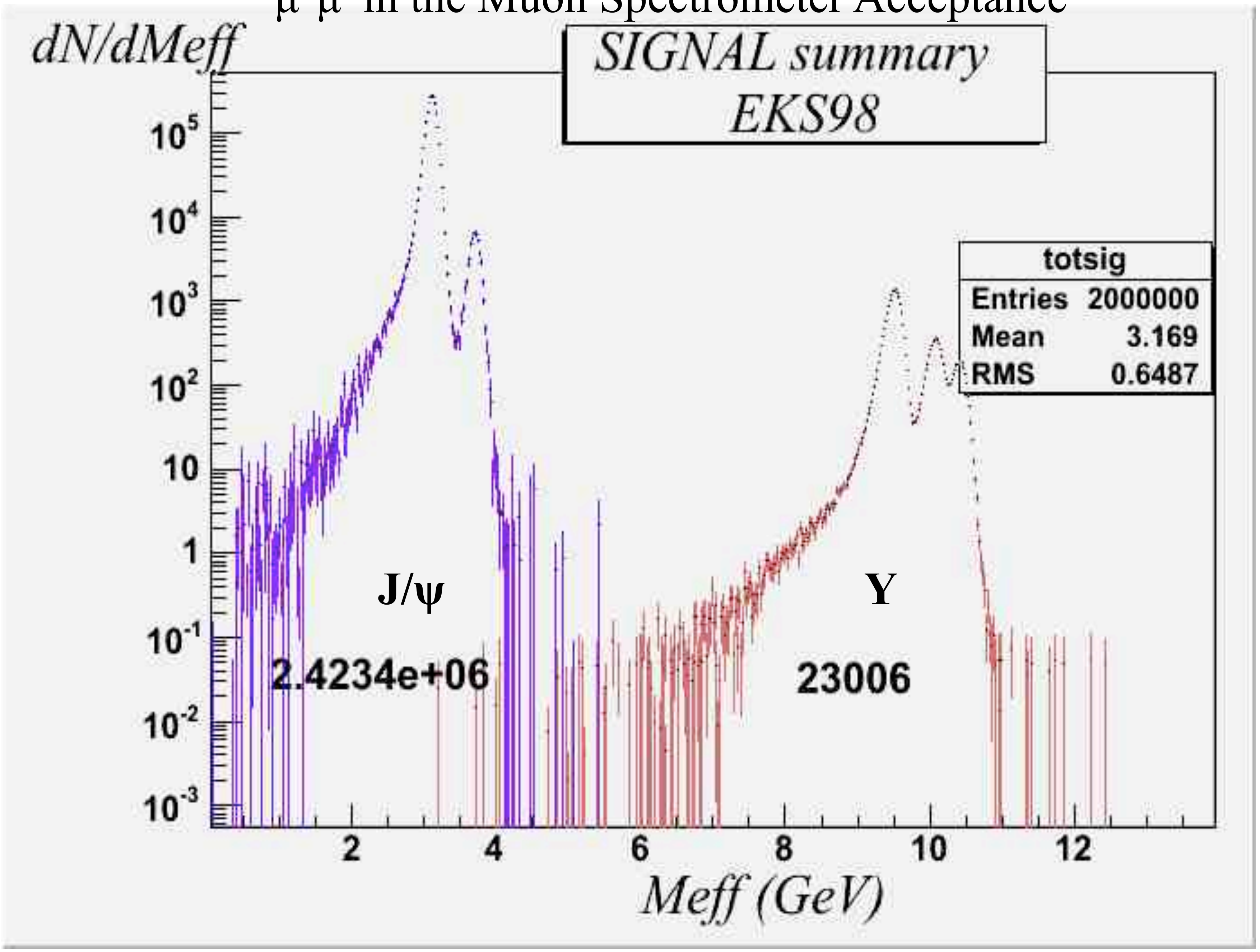
Expected yield in p-Pb collisions

ALICE PPR Vol. 2

Running scenario:
Time $t = 10^6$ s (1 month)
Luminosity $L = 1.1\ 10^{29}\ \mathrm{cm^{-2}\ s^{-1}}$

cross sections (EKS98)
$\sigma_{Jpsi} = 0.4$ mb
$\sigma_{Upsilons} = 3.5\ \mu$b

$\mu^+\mu^-$ in the Muon Spectrometer Acceptance

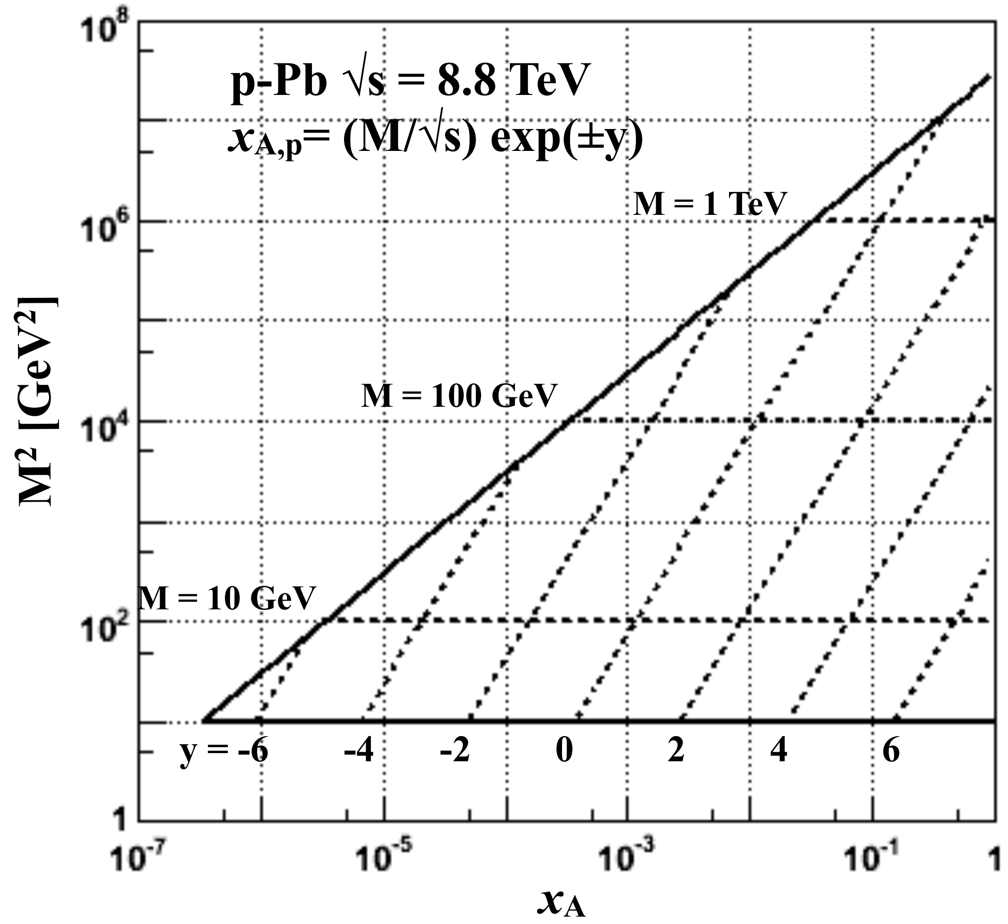


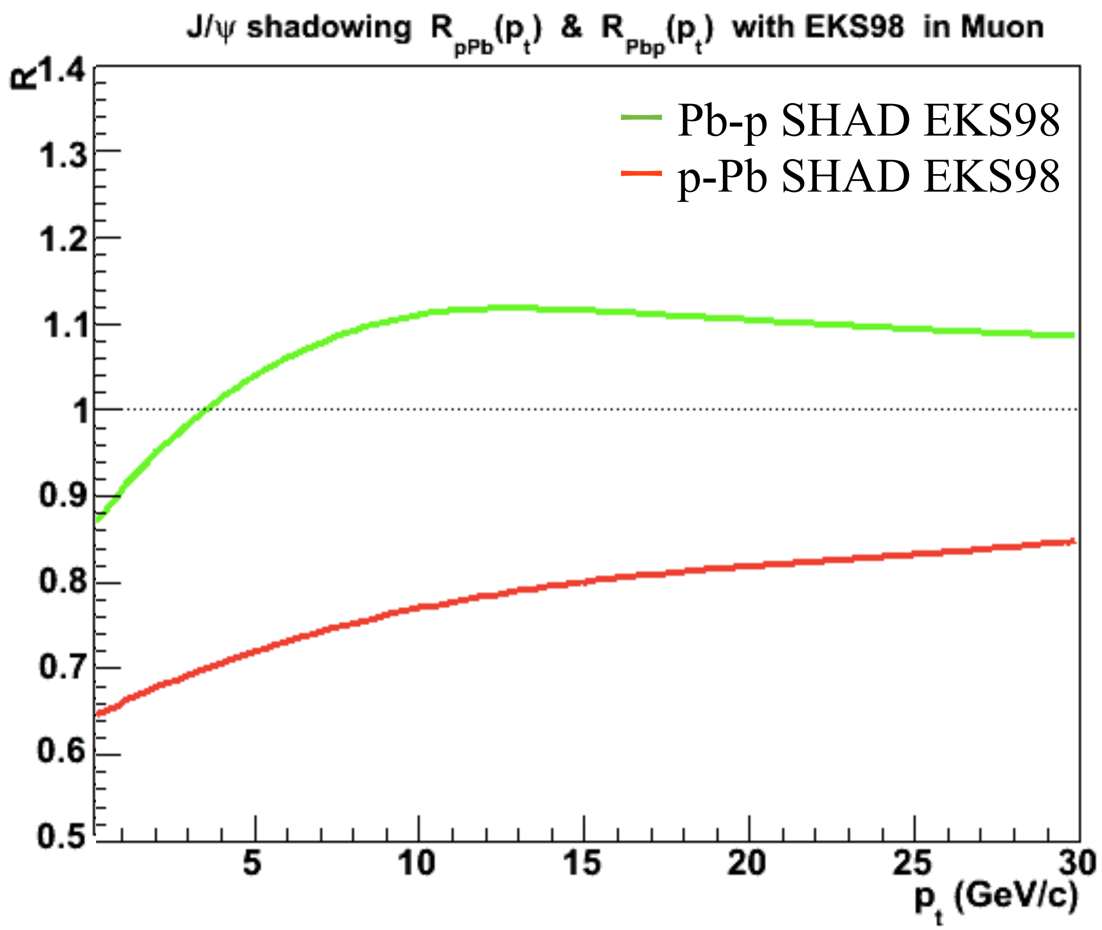
2 muons detection efficiency (60%) with 1 GeV/c p_T trigger

→ for one month of p-Pb collisions: $N_{J/\psi} = 1.5\ 10^6$ and $N_{\Upsilon} = 1.4\ 10^4$

$R_{p\text{-}Pb}$ y-dependence: central barrel and Pb-p collisions

In p-Pb, at forward rapidity, saturation effect dominates Cronin effect (multiple scattering of gluons and of QQbar pair).
Cronin effect may be visible at mid-rapidity (central barrel y=[-0.9,0.9] with $J/\psi \rightarrow e^+e^-$), and backward rapidity (Pb-p collisions in the Muon Spectrometer)





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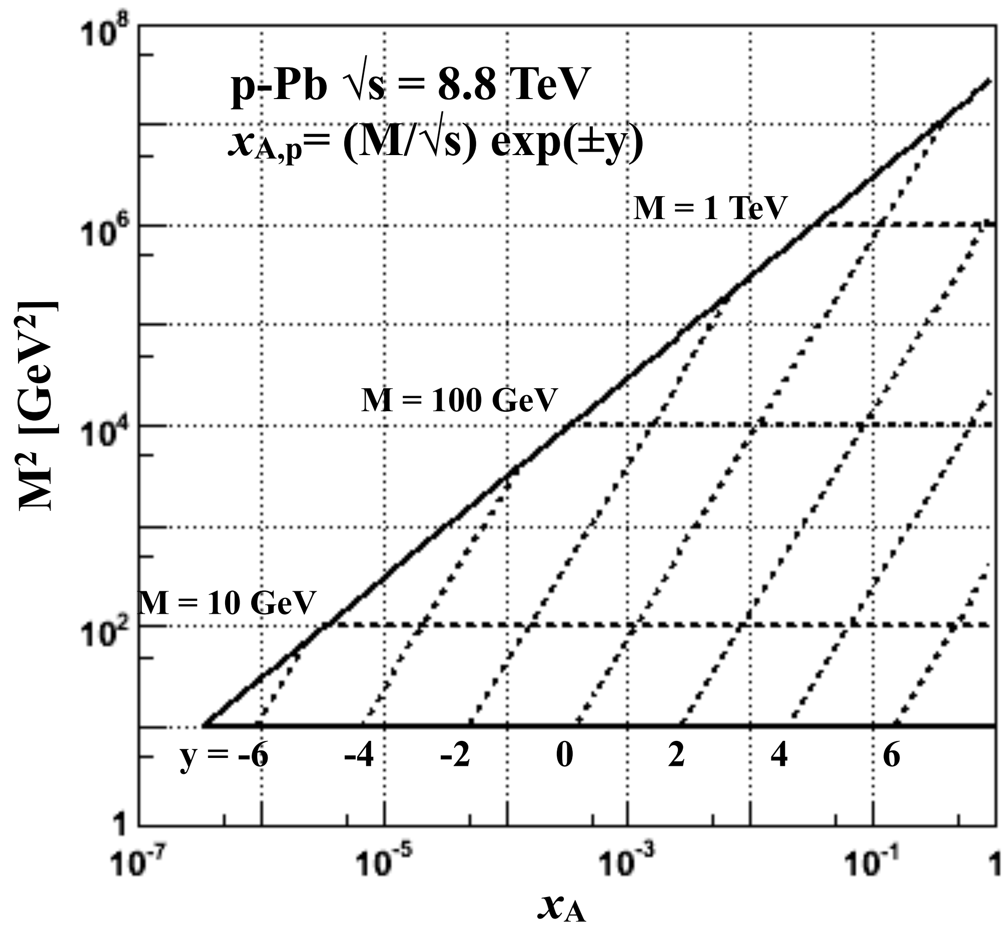
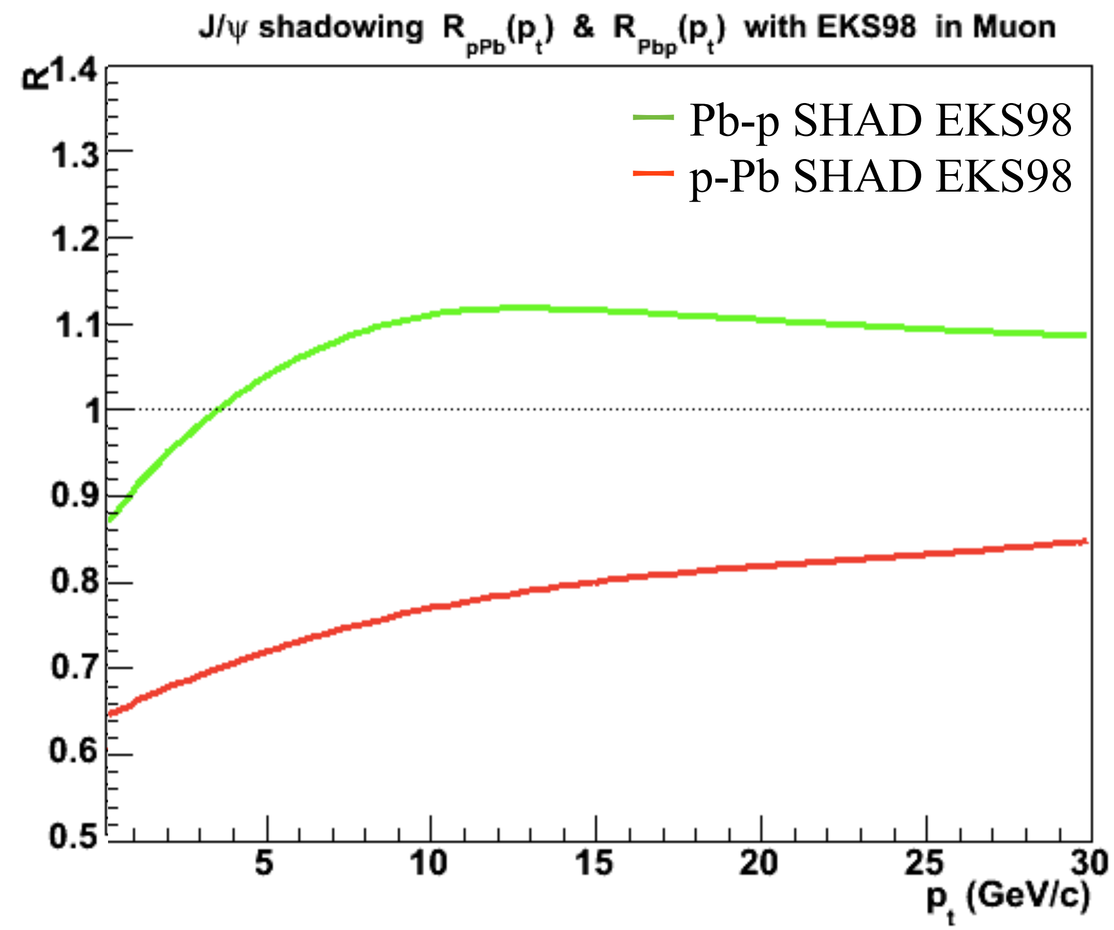




→ CGC model not valid in Pb-p collisions in the Muon Spectrometer acceptance (at y = 4, $x_A \simeq 10^{-2}$ and $x_p \simeq 10^{-5}$): need a more complex model with projectile and target described by the CGC

→ Expected yield in Pb-p (SHAD-EKS98): 20% more J/ψ / 6% more Υ in Pb-p than p-Pb in the Muon Spectrometer acceptance: 10^6s to share between p-Pb and Pb-p collisions

Overview

Small-x physics
- Colour Glass Condensate framework developed to describe high density gluon system
- Onset of gluon saturation seen in the forward region @ RHIC
- RHIC → LHC with $\sqrt{s}$ 30 times larger : definitive tests of the CGC picture

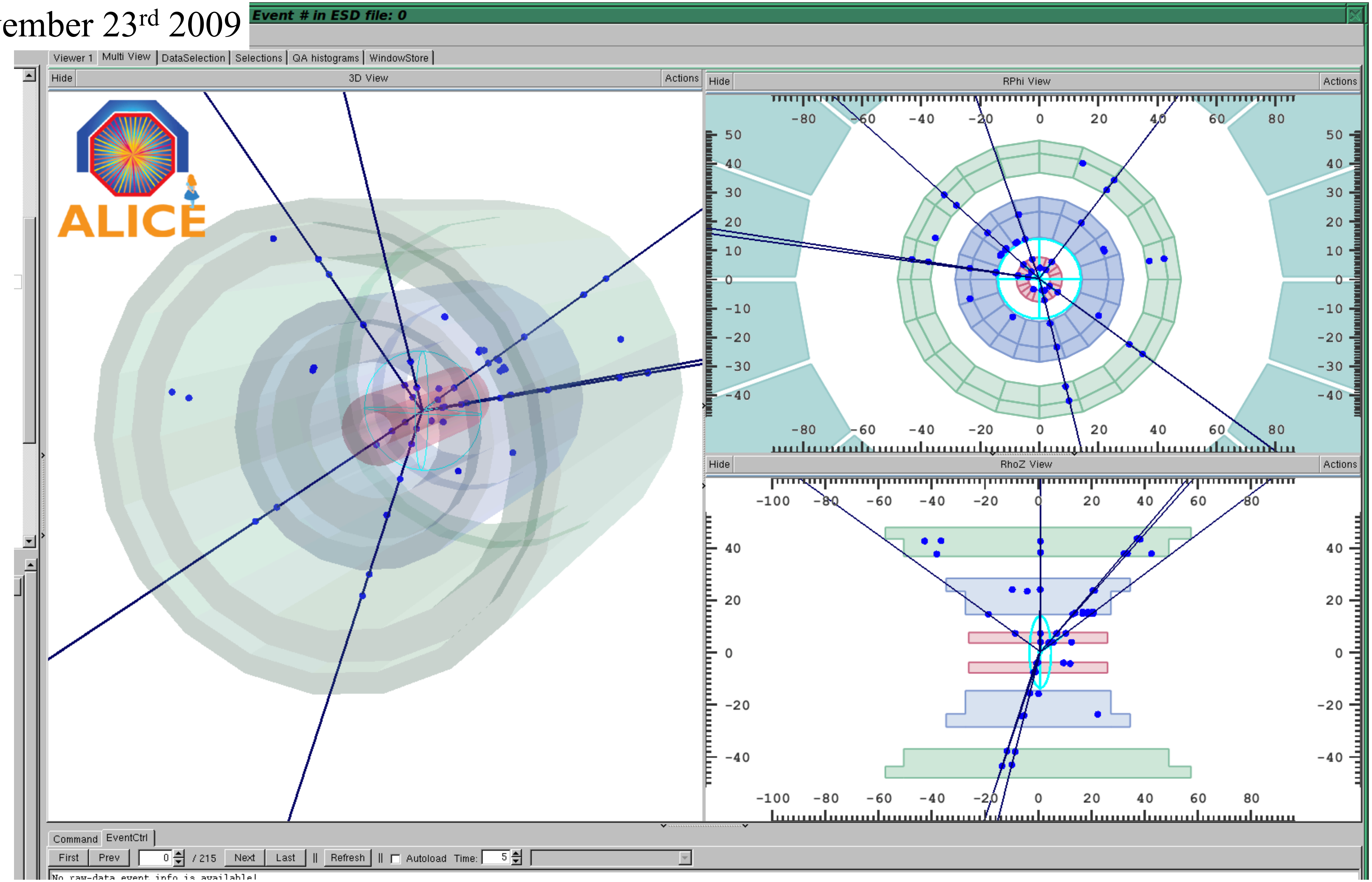
Heavy flavour production at the LHC with the ALICE Forward Muon Spectrometer as a tool to measure gluon saturation effect in p-p and p-Pb collisions
- Single muon production challenging measurement
- J/ψ production promising measurement

First data for ALICE in p-p collisions @ $\sqrt{s}$ = 900 GeV

p-p collisions in 2010 @ $\sqrt{s}$ = 7 TeV for few months of data taking
- large statistics up to p_T = 12 GeV/c for single muons
- 10k J/ψ up to p_T = 10 GeV/c

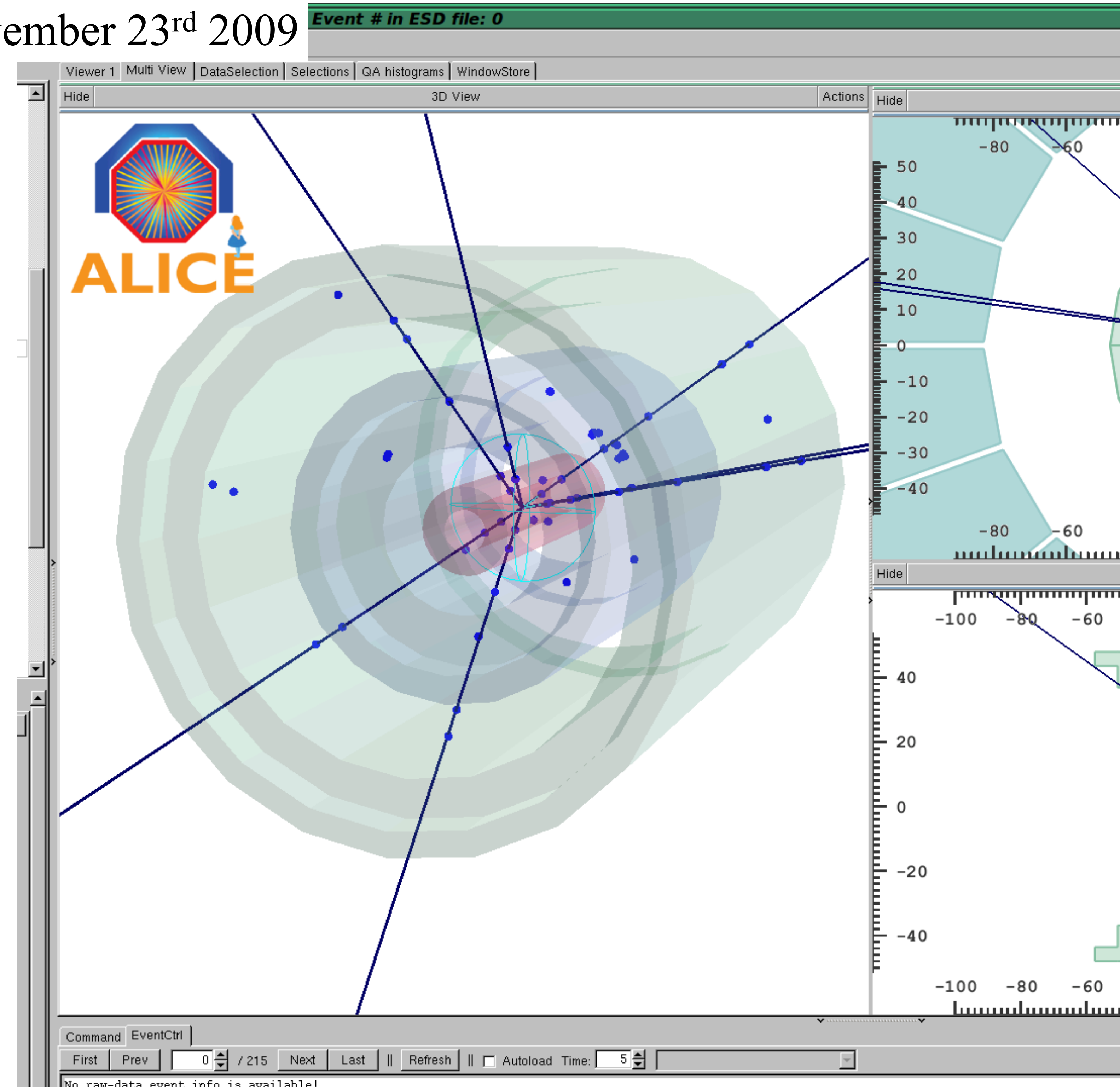
First p-p collisions @ 900 GeV !!

November 23rd 2009



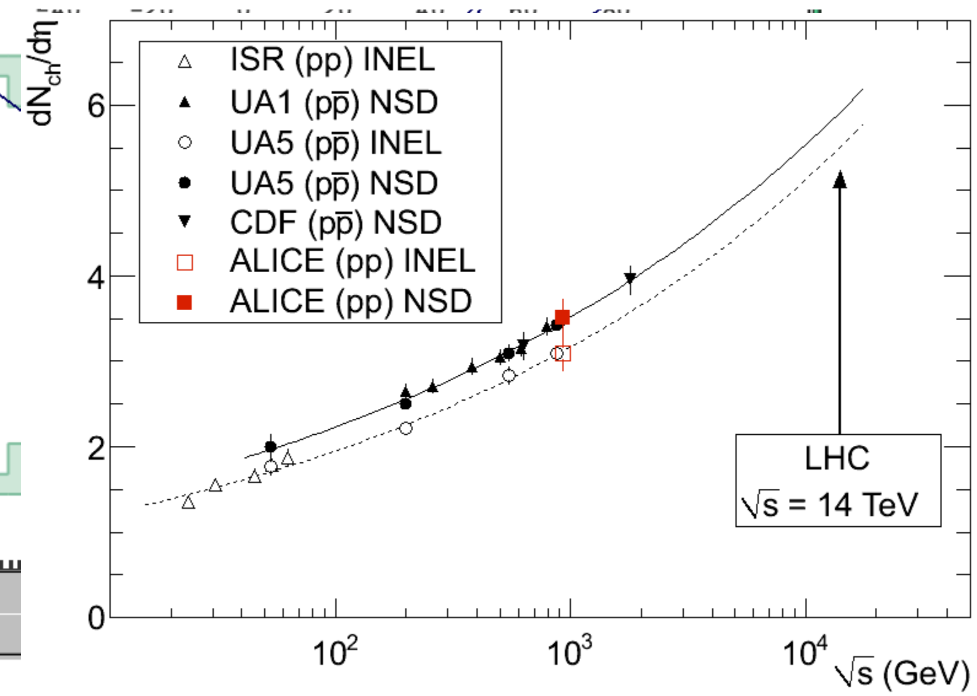
First p-p collisions @ 900 GeV !!

November 23rd 2009



First ALICE publication: charged-particle pseudorapidity density at √s=900 GeV

ALICE collaboration EPJC 65 (2010),111



First p-p collisions @ 900 GeV !!

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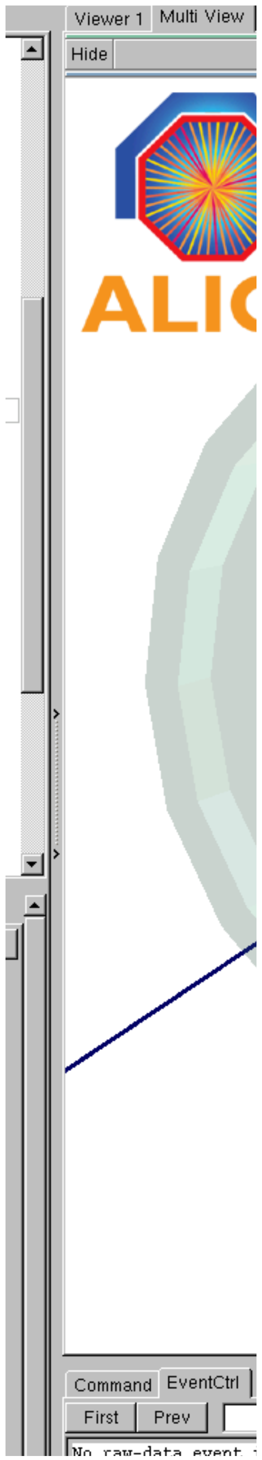
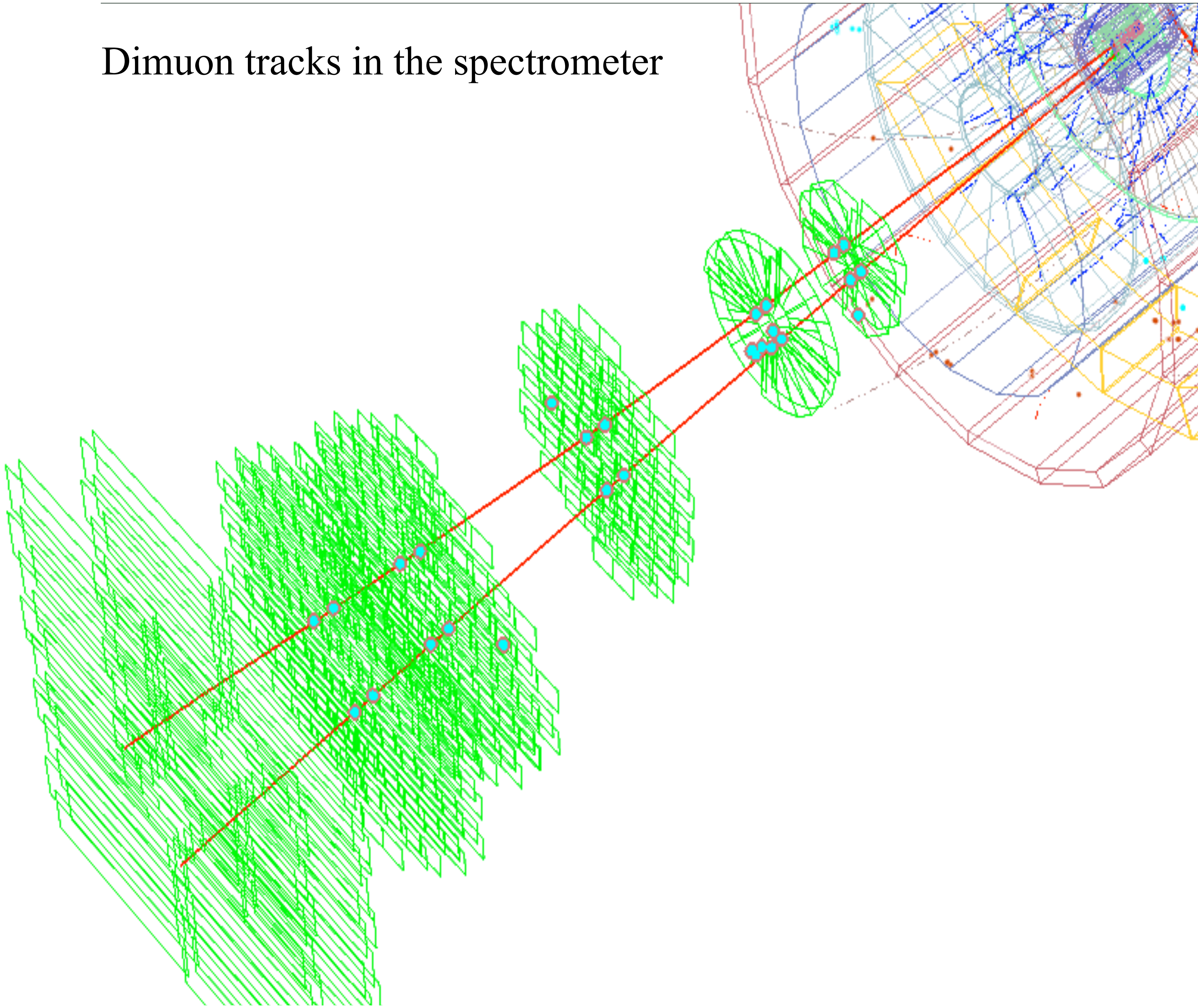
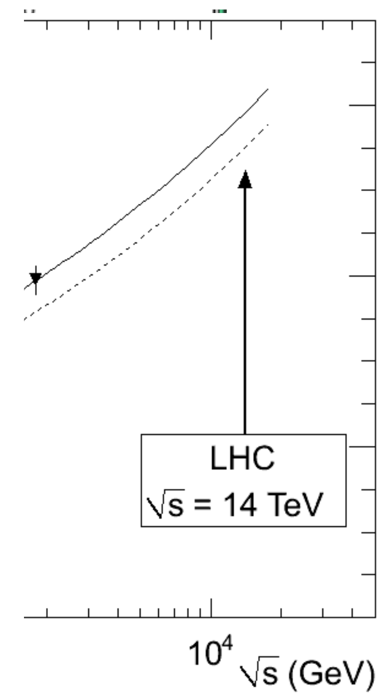


Dimuon tracks in the spectrometer



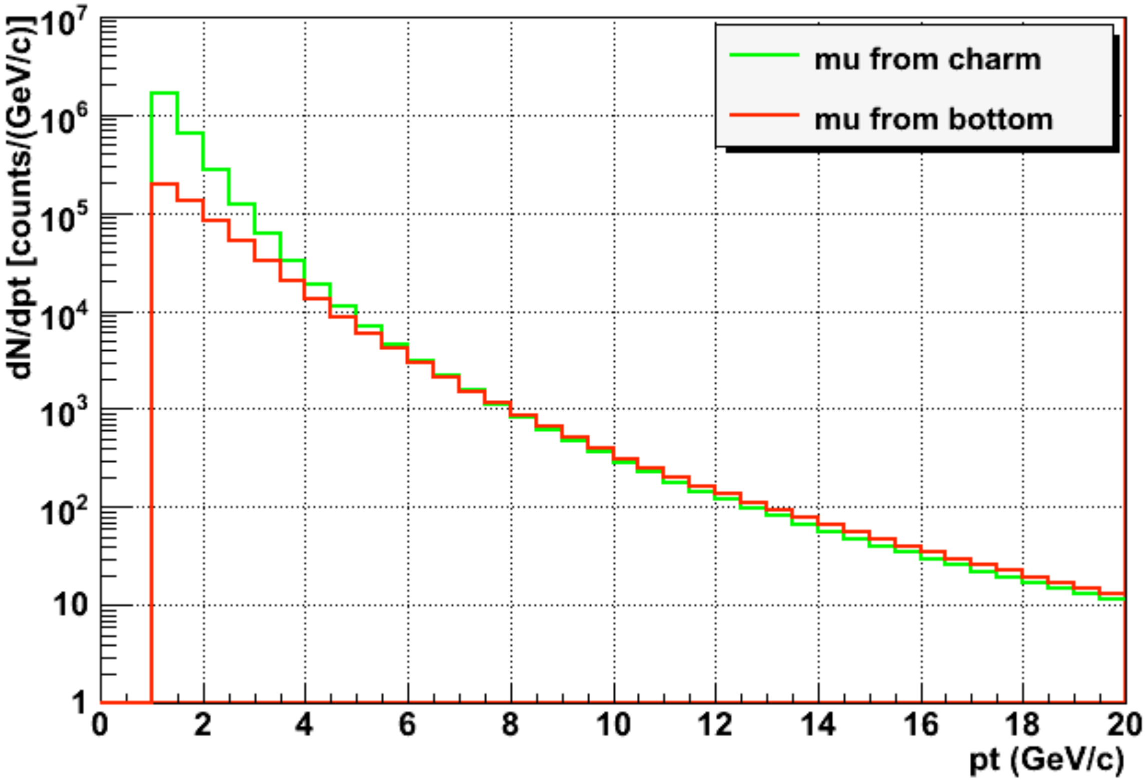
harged-particle
s=900 GeV
65 (2010),111



Forthcoming p-p collisions @ 7 TeV

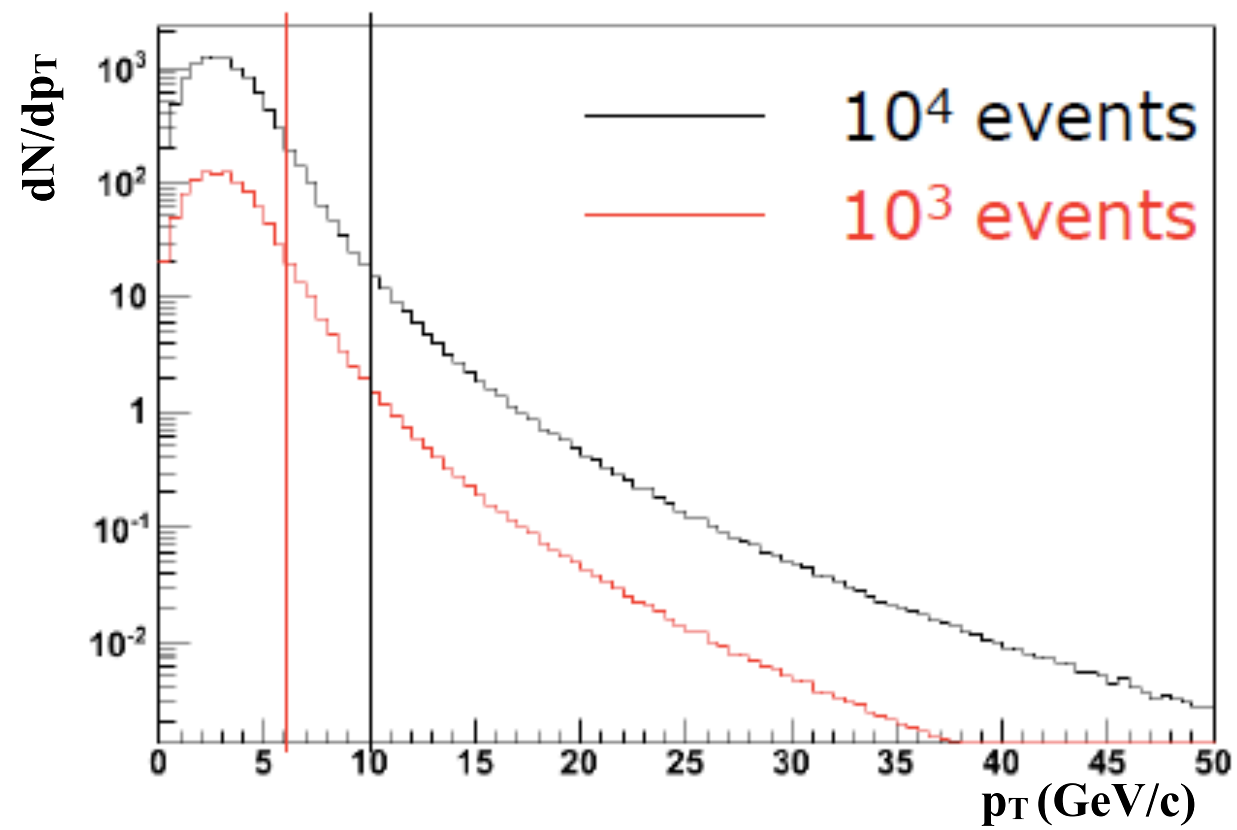
Statistics and p_T reach at 7 TeV for 3 months of data taking
with $L_0 = 2.3\ 10^{29}\ cm^{-2}s^{-1}$ and ε_{LHC}=12%

single muons



large statistics up to $p_T \sim 12$ GeV/c

J/ψ



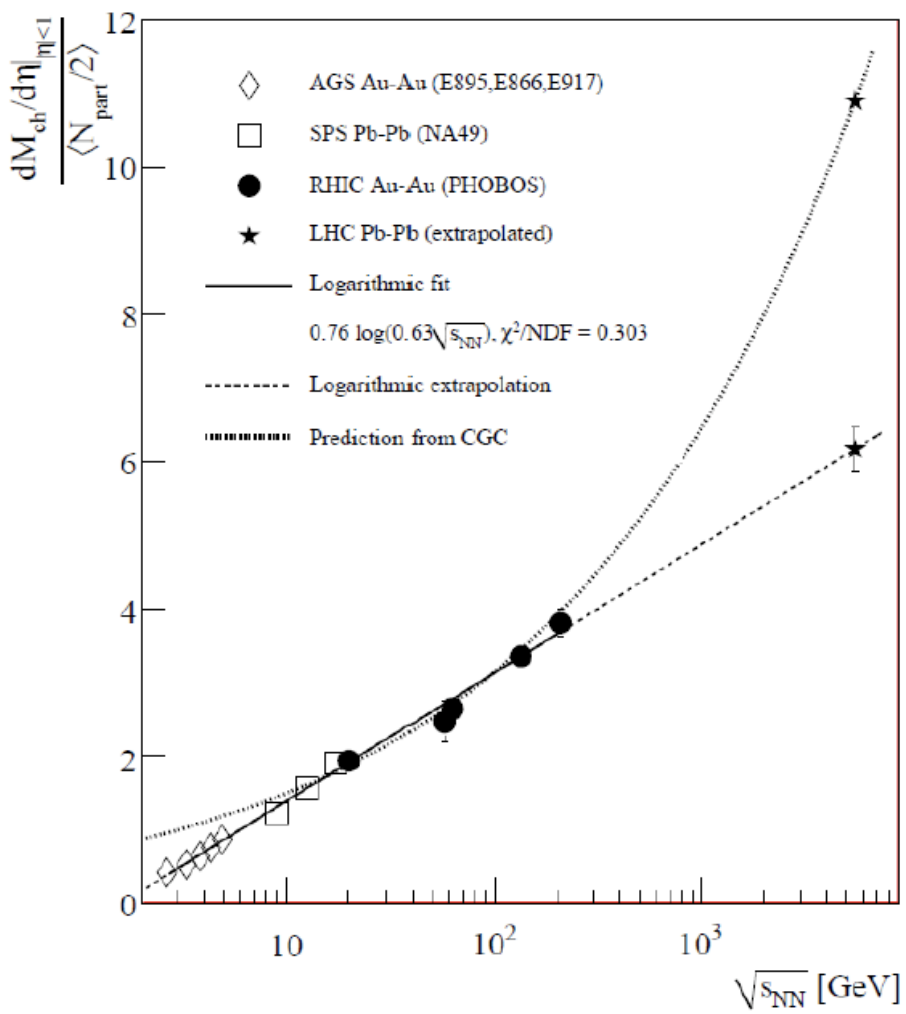
10k J/ψ expected
reach in $p_T \sim 10$ GeV/c

LHC calendar

2010 - 2011 p_p = 3.5 TeV (p-p $\sqrt{s}$ = 7 TeV / Pb-Pb $\sqrt{s}$ = 2.76 TeV)
Shutdown end of 2011 to step up in beam energy

Back-up slides

Multiplicity measurements at RHIC



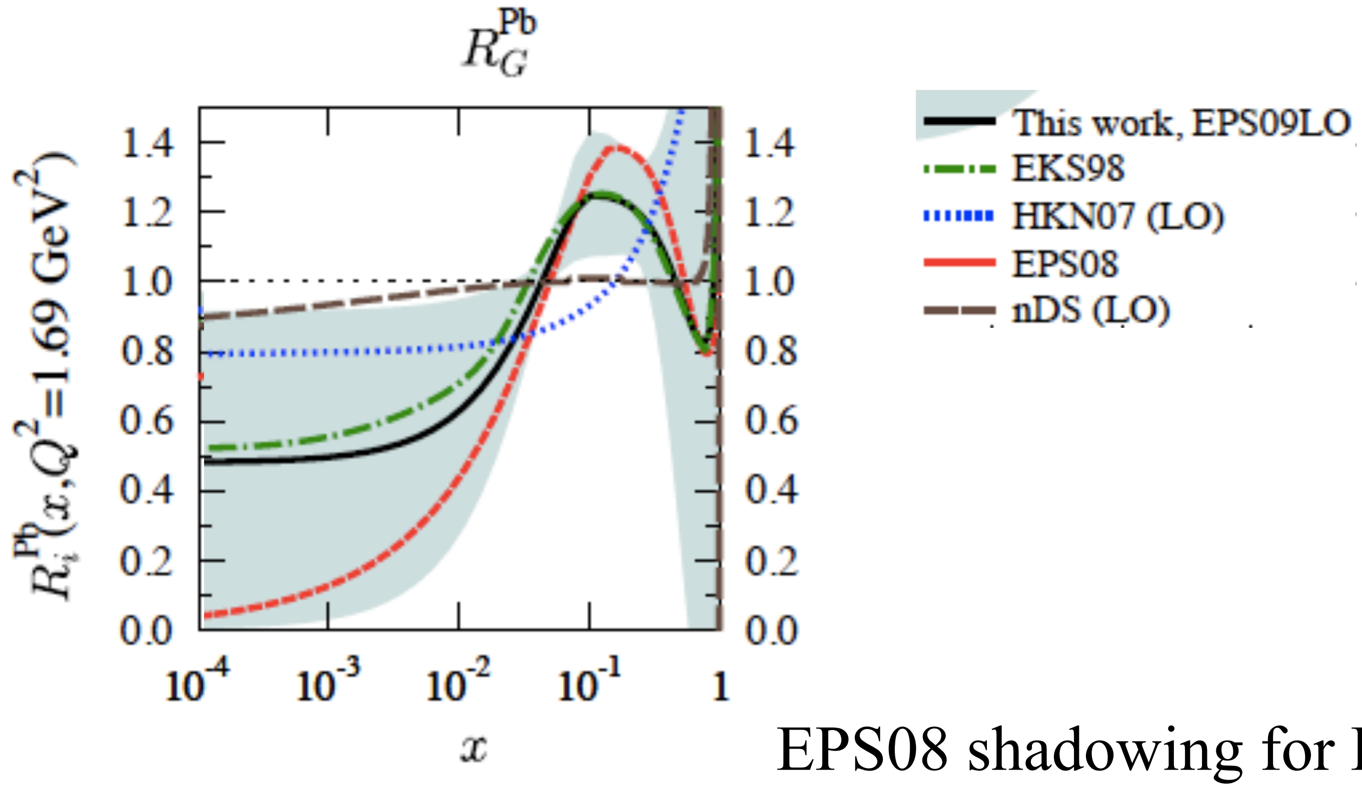
Estimation of $Q^2_{s,Au}$ @ $\sqrt{s}$ = 200 GeV

- hadron mutliplicity $dN^{hadron}/dy|_{\eta=0} \simeq 1100$
- hadronic transverse energy $E_T \simeq 500$ GeV

$\rightarrow Q^2_{s,Au} = 2\ GeV^2$

Krasnitz, Nara, Venugopalan Nucl.Phys.A727:427-436,2003.
Karzeev, Levin , Nardi

EKS98 (EPS09) vs EPS08

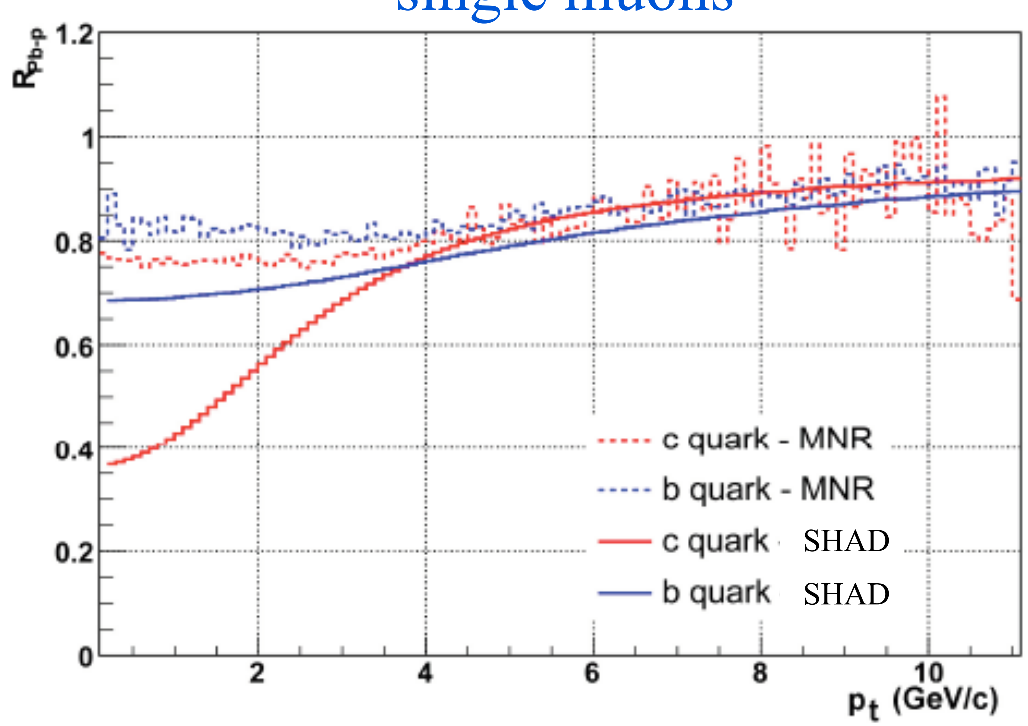


Eskola et al. ,2009

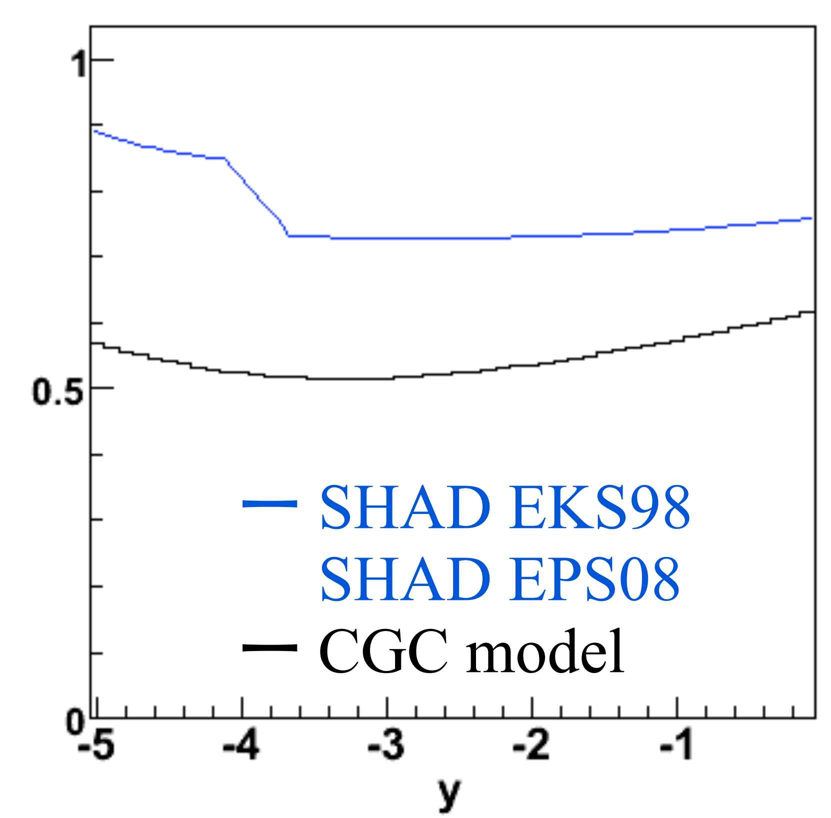
EPS09 close to EKS98 at low x
EPS09 uncertainties estimated! EPS08 (forward RHIC data included) ≃ lower bound of EPS09

EPS08 shadowing for $R_{Pb\text{-}p}$ at the numerical level

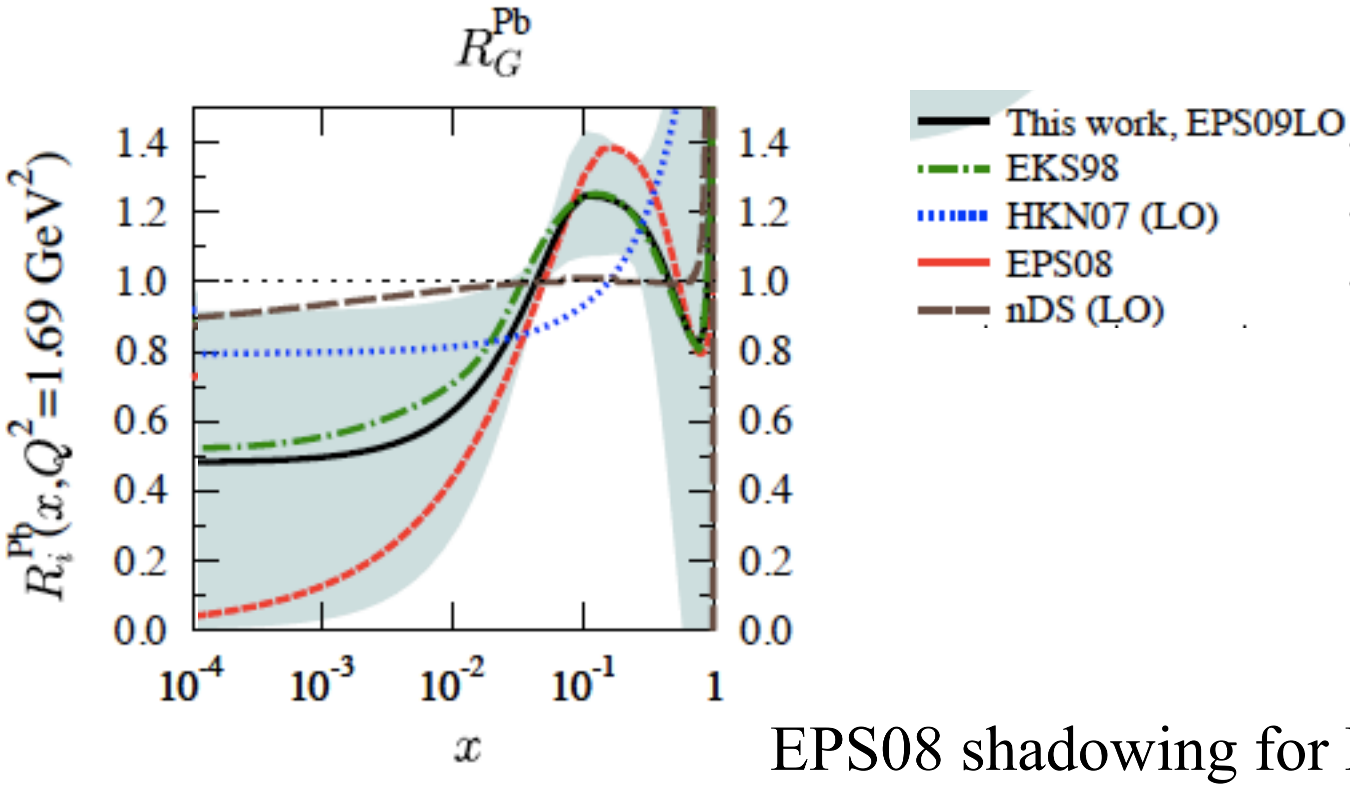
single muons



J/ψ



EKS98 (EPS09) vs EPS08



Eskola et al. ,2009

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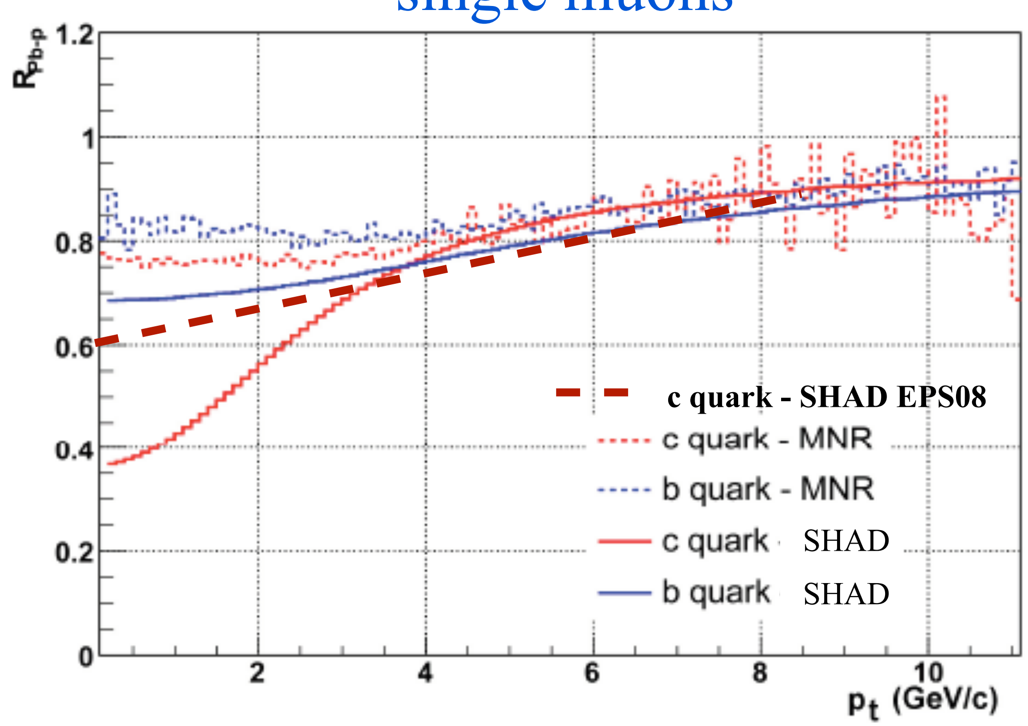
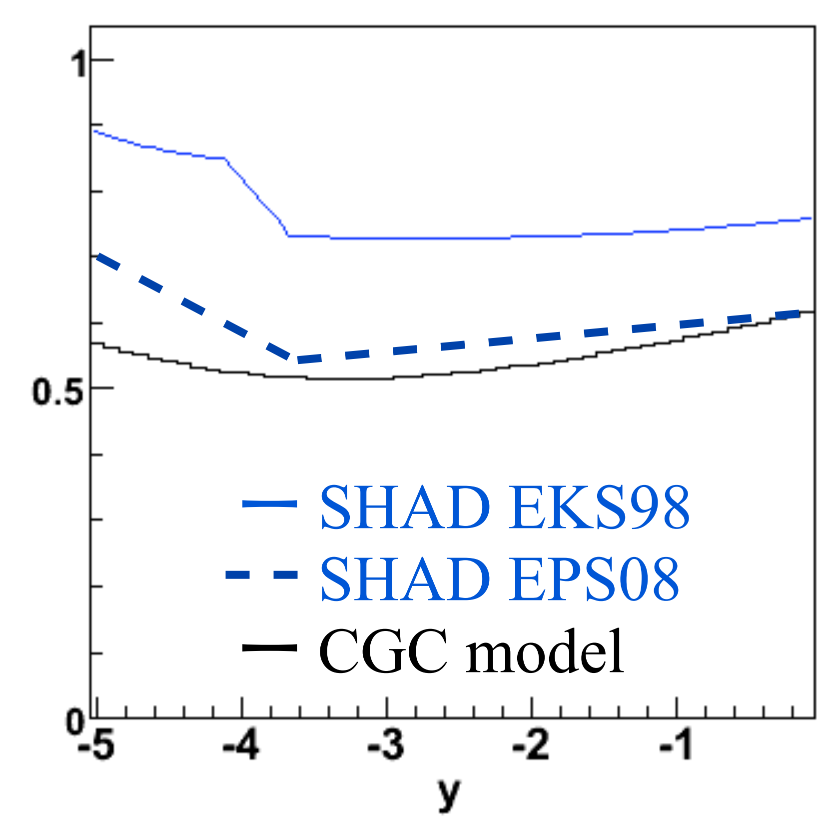
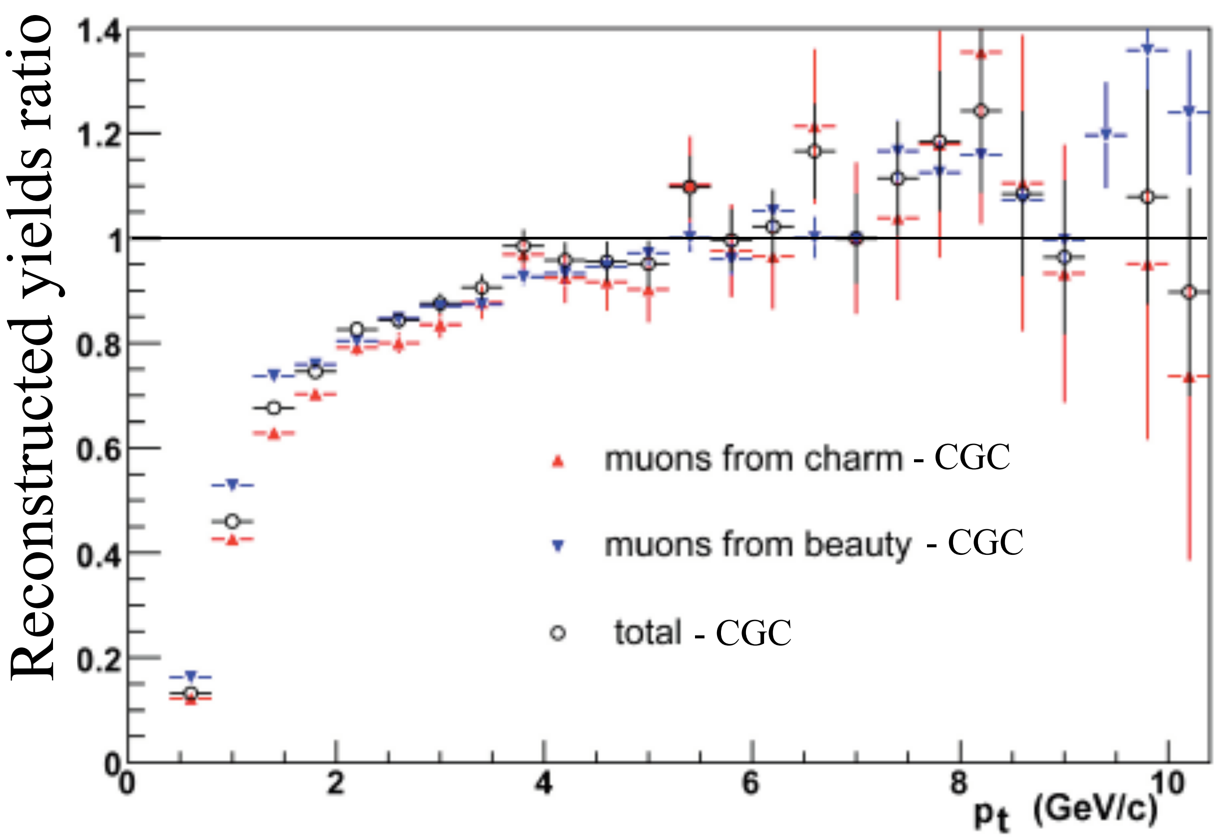


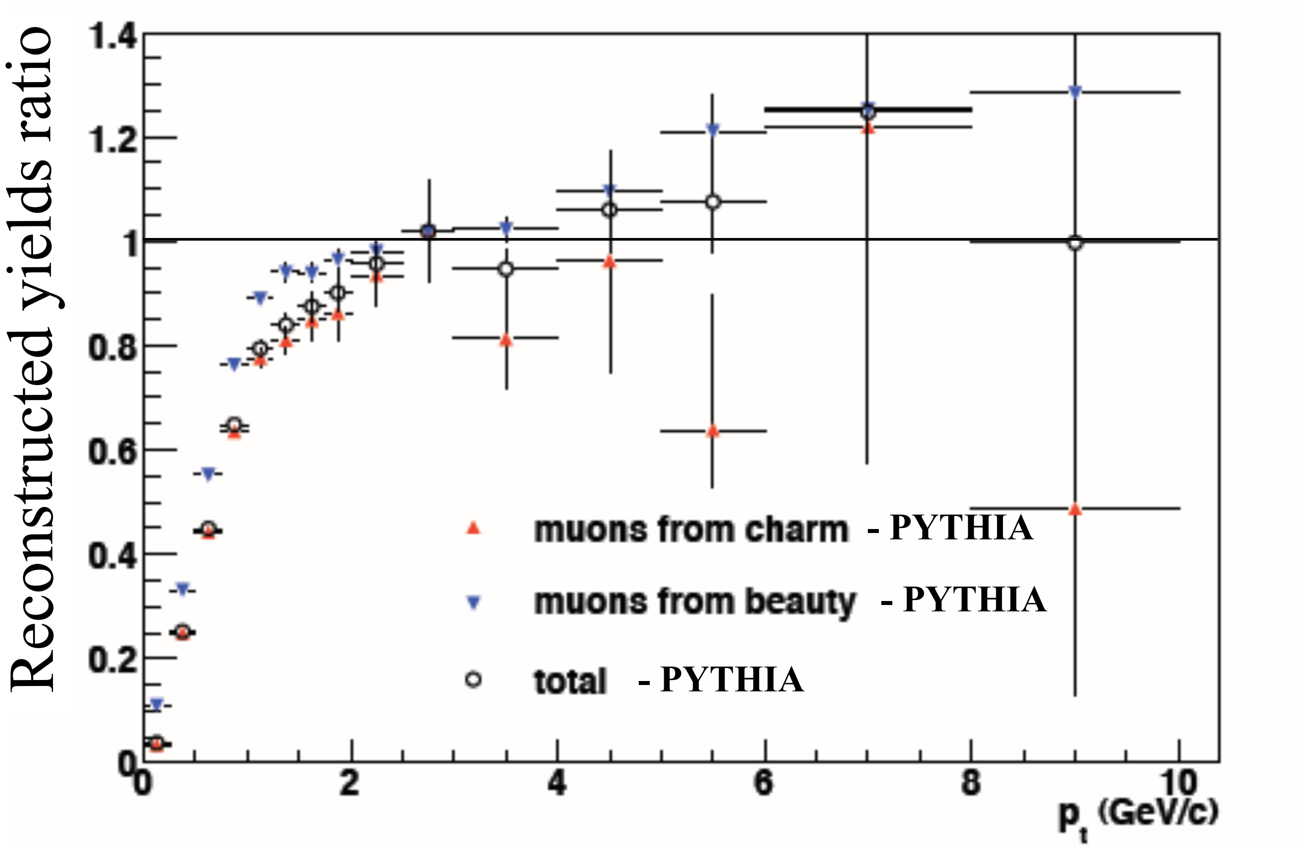
J/ψ



Single muon detection in the Muon spectrometer

Forward muon spectrometer $-4 < \eta < -2.5$
$p > 4$ GeV/c (muon absorber and filter)
muon trigger efficiency decreases at low p_T





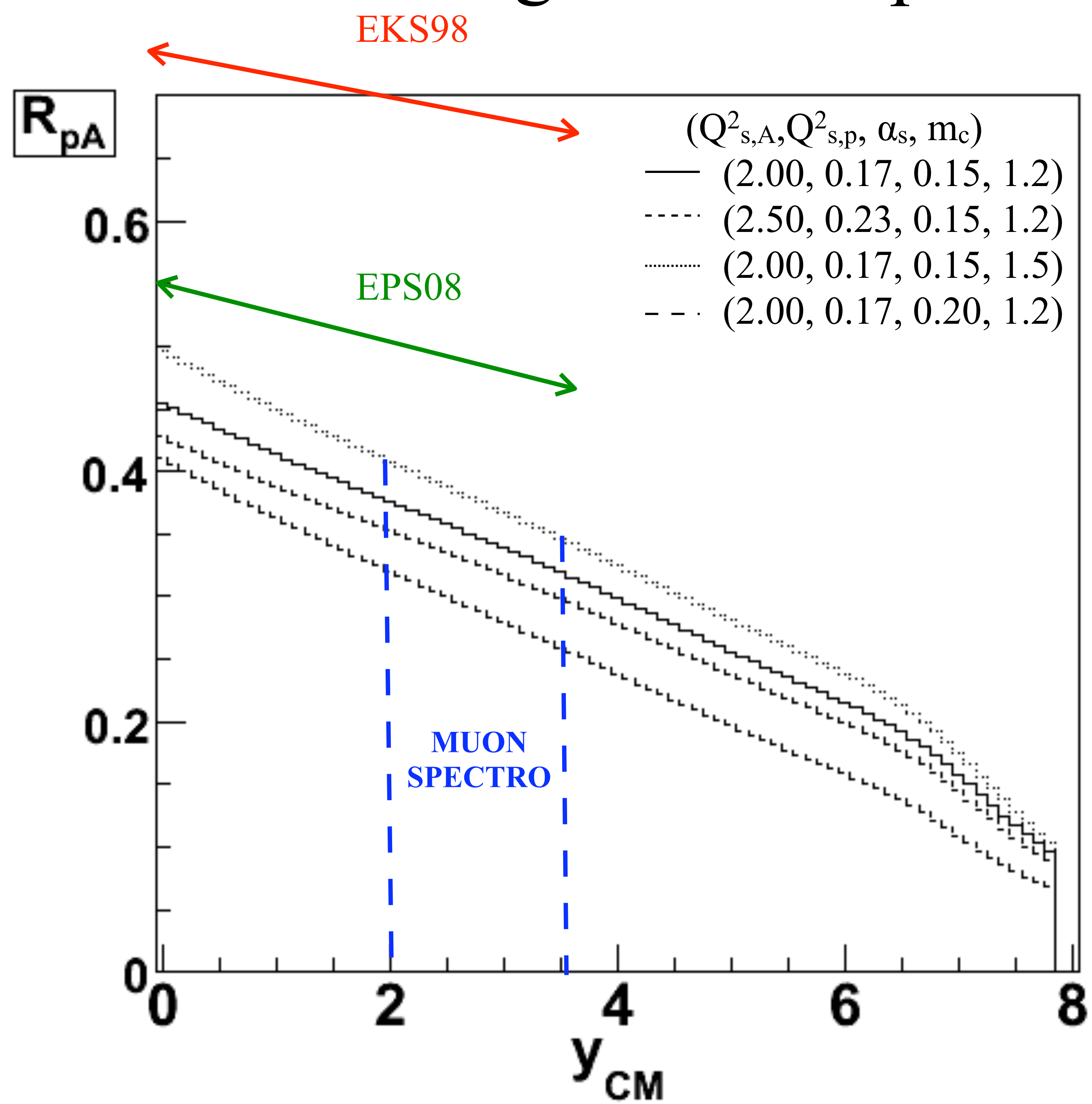
- Detector effects (y-shift in Pb-p leads to different momentum cut for a given p_T and y)
→ effects from gluon saturation less visible at low p_T
- Also, not simulated here, large background contribution from π and K at $p_T < 1.5$ GeV/c

Open heavy flavour in the muon spectrometer → challenging channel to study saturation effect

CGC model parameters uncertainty

uncertainty roughly estimated
$Q_s^2{}_{,Au} = [2.0\text{-}2.5]\ GeV^2$

Integrated over p_T

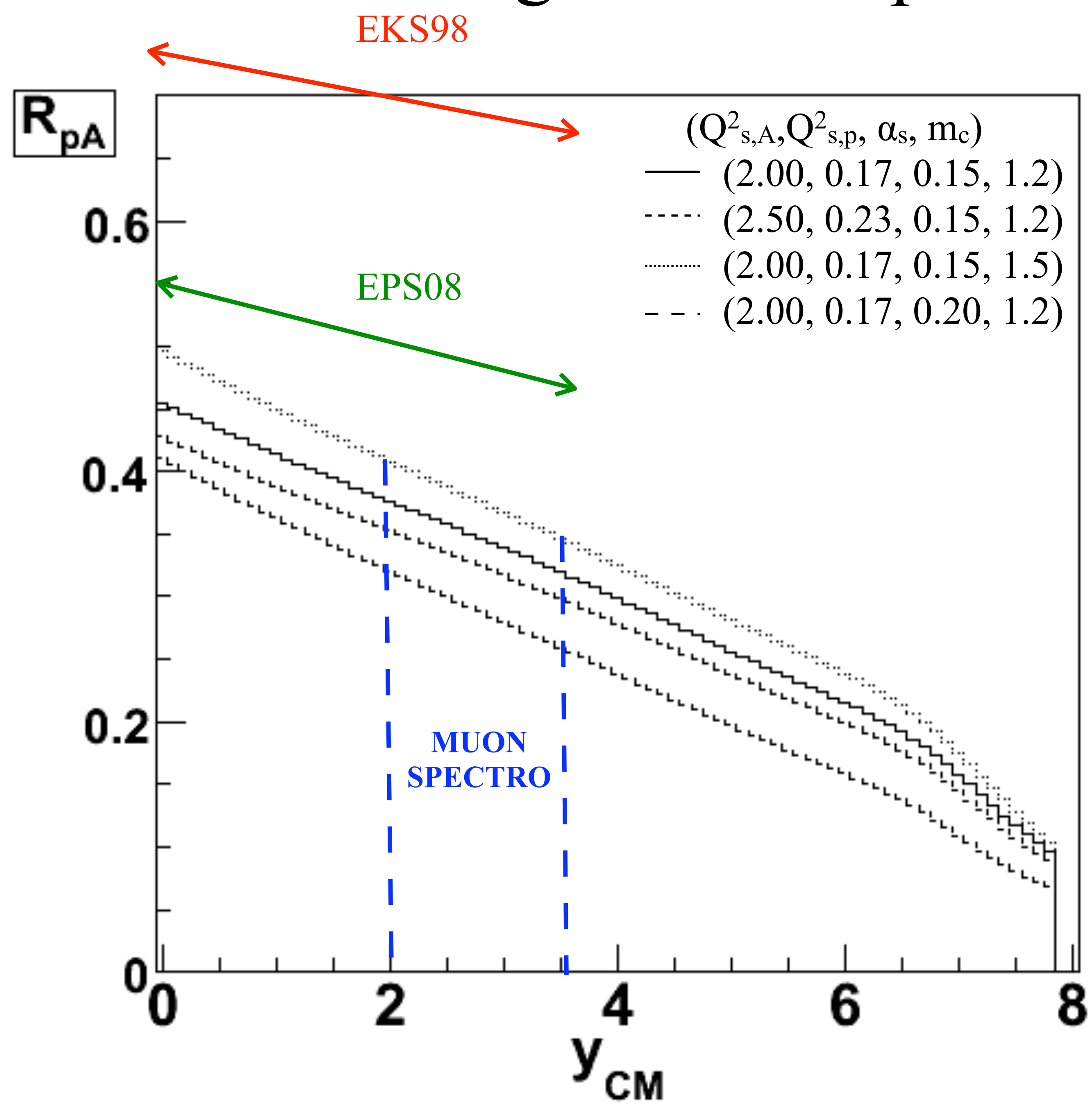


CGC model parameters uncertainty

- saturation scale Q^2_s : in MV model, defined at x_0=0.01.
  - evaluated from $dN^{h+/-}/dy|_{y=0}$ @ RHIC
    $Q_s{}^2{}_{,Au} = 2\ GeV^2$

    uncertainty roughly estimated
    $Q_s{}^2{}_{,Au} = [2.0\text{-}2.5]\ GeV^2$

Integrated over p_T



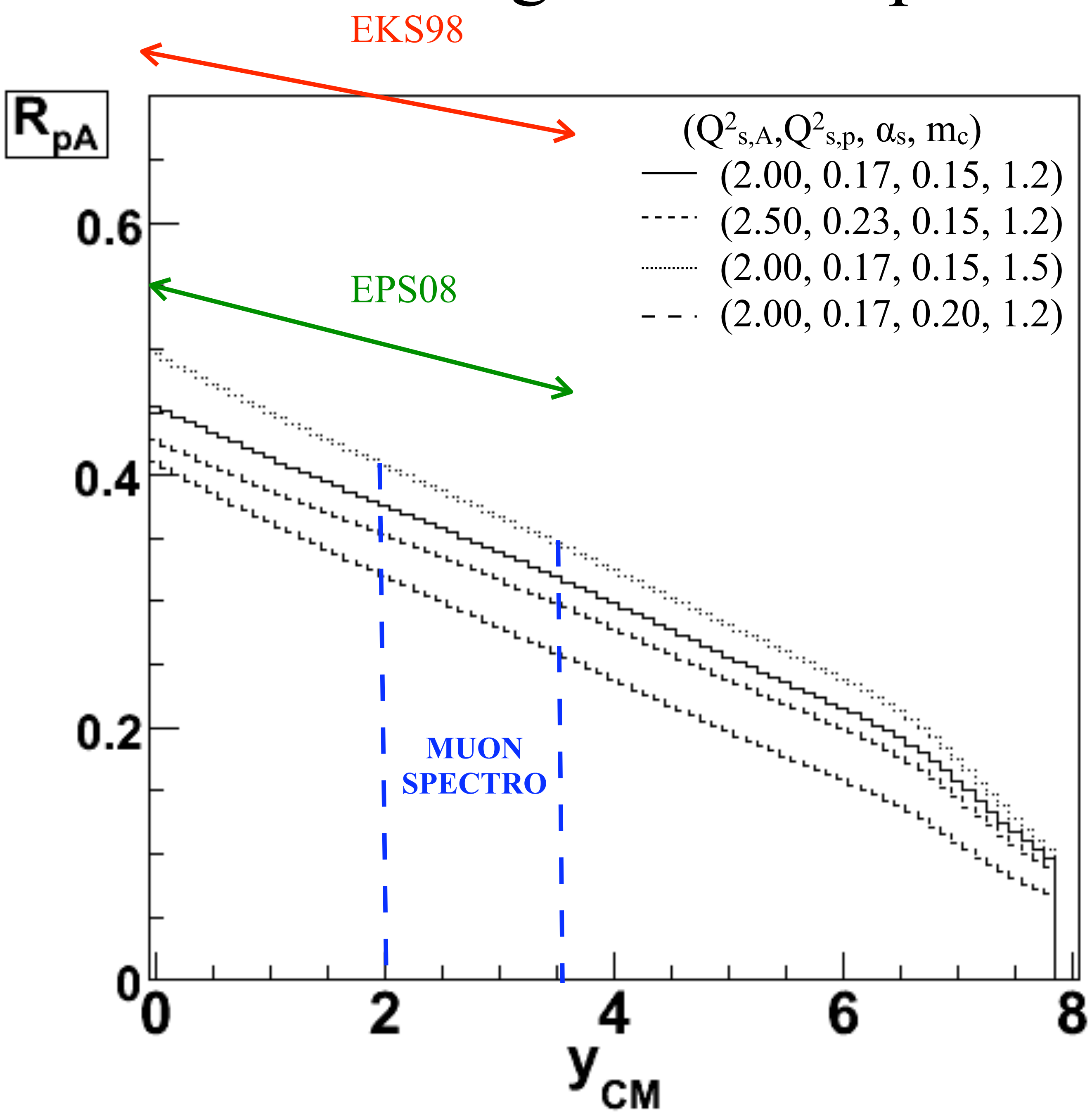
CGC model parameters uncertainty

- saturation scale Q^2_s : in MV model, defined at x_0=0.01.
  - evaluated from $dN^{h+/-}/dy|_{y=0}$ @ RHIC $Q_s^2{}_{,Au} = 2\ GeV^2$

    uncertainty roughly estimated $Q_s^2{}_{,Au} = [2.0\text{-}2.5]\ GeV^2$

- quark mass m_c = 1.2-1.5 GeV

Integrated over p_T

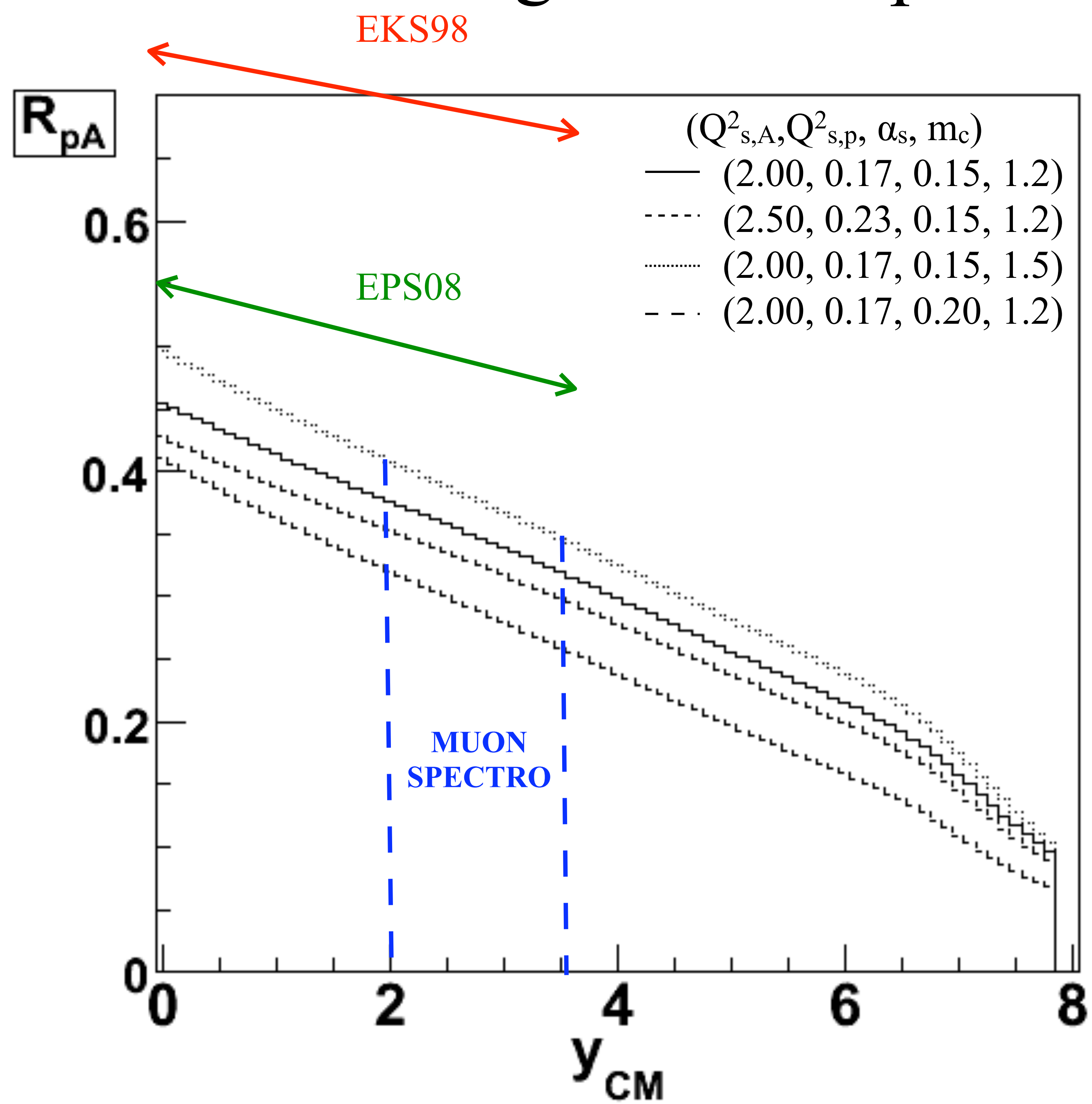


CGC model parameters uncertainty

- saturation scale Q^2_s : in MV model, defined at x_0=0.01.
  - evaluated from $dN^{h+/-}/dy|_{y=0}$ @ RHIC $Q_s^2{}_{,Au}$ = 2 GeV^2

    uncertainty roughly estimated $Q_s^2{}_{,Au}$ = [2.0-2.5] GeV^2
- quark mass m_c = 1.2-1.5 GeV
- coupling constant α_s ... not running but fixed in order to reproduce the y-dependence of F_2 HERA data (effective way to account for NLO correction in α_s)
  - from HERA data: α_s = [0.15-0.2]

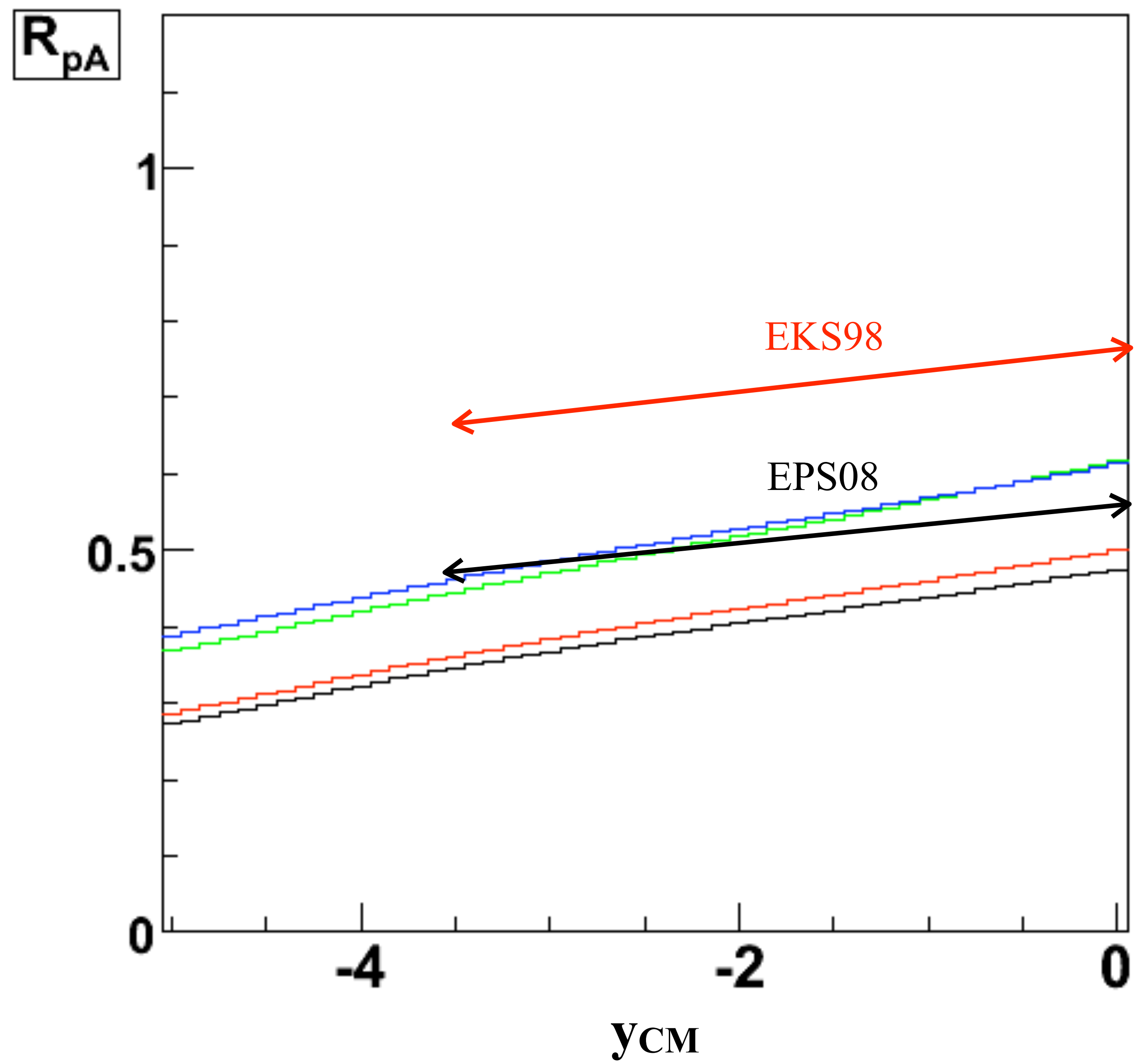
Integrated over p_T



$R_{p\text{-}Pb}$ sensitivity to k_t-distribution of the gluon

option 1
— k0 = 0
option 2 (Gaussian)
— k0 = 1.33 GeV
— **k0 = 5.0 GeV**
option 3 (Power)
— **k0 = 1.33 GeV**

integrated over p_T



• option 3 is chosen : $R_{p\text{-}Pb}$ similar to shadowing EPS08