Status of the understanding of quarkonium production

J.P. Lansberg
IPN Orsay – Paris-Sud 11

High-pT Probes of High-Density QCD at the LHC
May 30- June 1, 2011
Ecole Polytechnique, Palaiseau, France

Outline

Introduction

1. Basic pQCD approach: Colour Singlet Model $\rightarrow$ Puzzle
2. pQCD prediction for ψ from b's

Solution to the puzzle ... which puzzle ?

3. The CSM predictions and the total yield

Recent progresses: QCD corrections

4. Describing the mid- and high-P_T's: QCD corrections
5. Colour Octet Dominance is challenged at low/mid P_T in pp
6. QCD corrections and feed-down do matter for the polarisation

Cold Nuclear Matter Effects

7. Shadowing, absorption and kinematics
8. Υ and EMC effect
9. CNM for J/ψ production in PbPb at $\sqrt{s_{NN}} = 2.76$ TeV

Part I

Introduction

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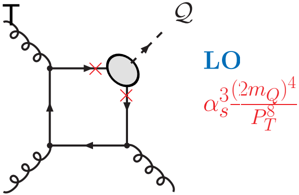

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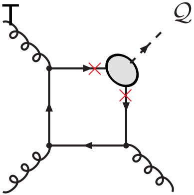

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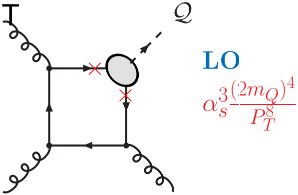

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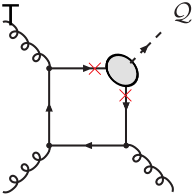

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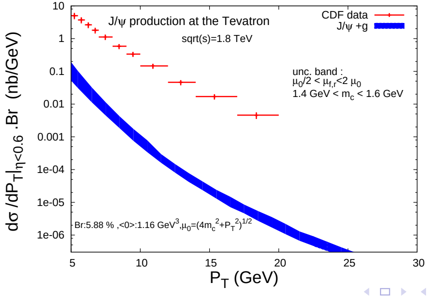

CDF, PRL 79:572 & 578,1997

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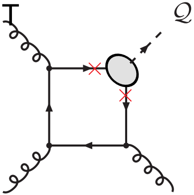

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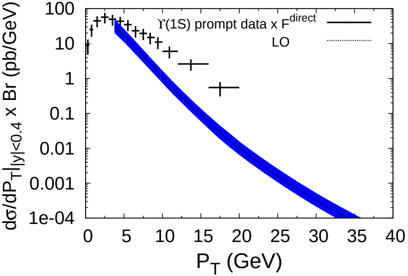

CDF, PRL 88:161802,2002

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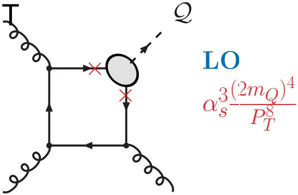

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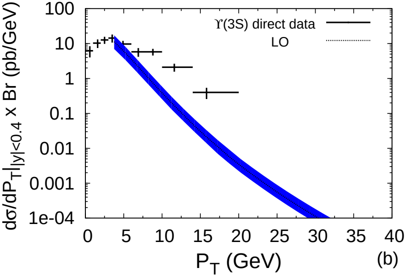

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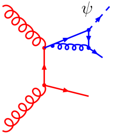

Cacciari, Greco, Phys.Rev.Lett.73:1586,1994

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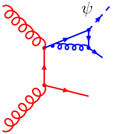

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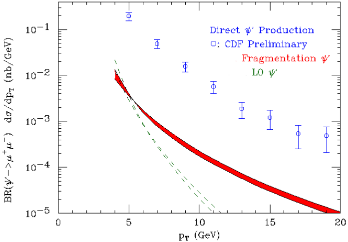
→ Illustration for the ψ'

× Off by factor 30-100 for J/ψ and ψ'

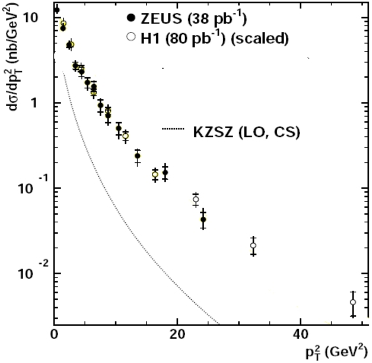
× Off by factor 10 for Υ's



J/ψ photoproduction at HERA

M.Kramer Nucl.Phys.B459:3 1996
H1,EPJC 25, 2,2002; ZEUS, EPJC 27, 173, 2003

LO CSM also fails in photoproduction at HERA...



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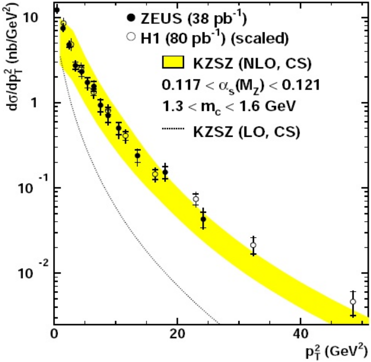
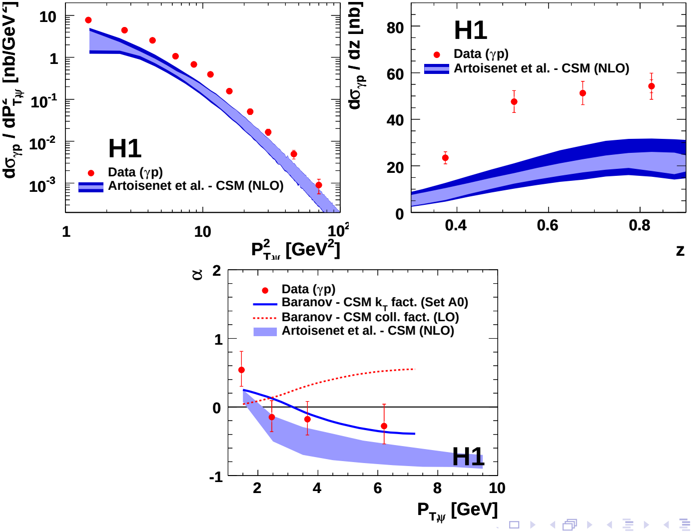


BUT NLO CSM is in better agreement with the data !

see however Phys. Rev. Lett. 102, 142001 (2009) and Phys.Rev.D80:034020,2009

J/ψ photoproduction at HERA

P. Artoisenet *et al.***Phys. Rev. Lett. 102, 142001 (2009)**
e.g. **H1,arXiv:1002.0234**



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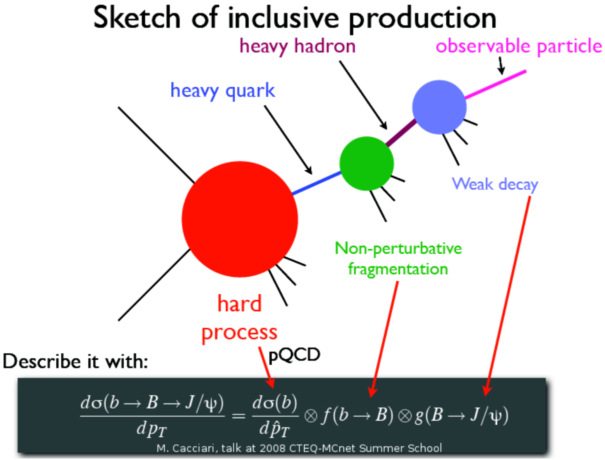

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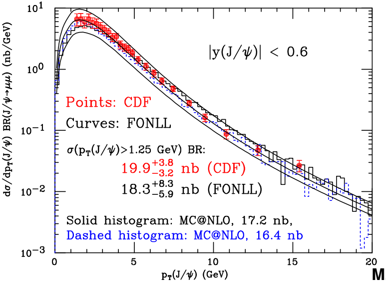

M.Cacciari ***et al.*****JHEP 0407:033,2004**

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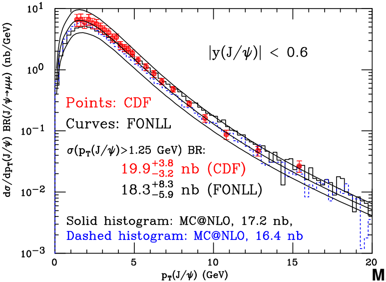

M.Cacciari *et al.***JHEP 0407:033,2004**

- The discrepancies of the late 90's disappeared

Part II

Back to the prompt yield: solution to the puzzle ... which puzzle ?

The CSM predictions for the total yield & $\frac{d\sigma}{dy}$?

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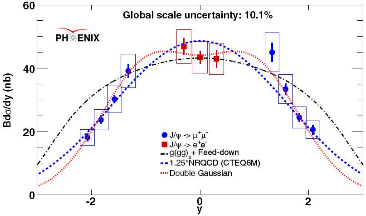

No CSM curve, why ?

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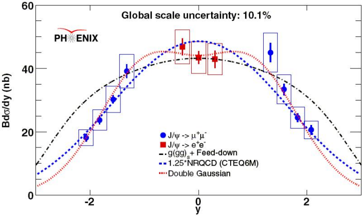

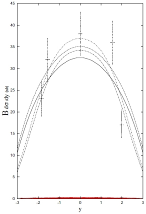

PHENIX, PRL98 232002,2007/ CSM: Cooper *et al.*, PRL 93:171801,2004

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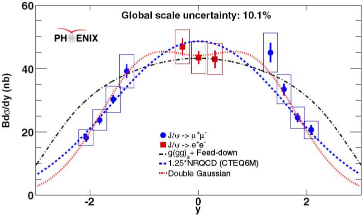
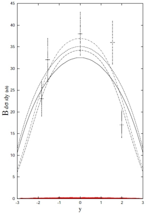




PHENIX, PRL98 232002,2007/ CSM: Cooper *et al.*, PRL 93:171801,2004

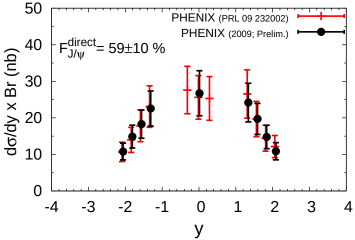
section in the singlet and octet channel. In the color singlet channel, the J/ψ production cross section at α_s^2 order is given by:

$$\sigma_1^{pp\to J/\psi}(s) = \sigma_1^{pp\to \chi_0}(s) BR_{\chi_0}, \quad + \sigma_1^{pp\to \chi_2}(s) BR_{\chi_2}. \quad (9)$$

The CSM predictions for the total yield & $\frac{d\sigma}{dy}$?

→ RHIC ($\sqrt{s} = 200$ GeV)

S. J. Brodsky and JPL, PRD 81 051502 (R), 2010.



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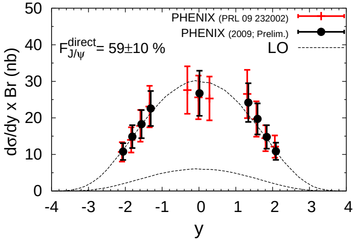

LO: $gg \to J/\psi g$ (see slide 5, nothing new !)

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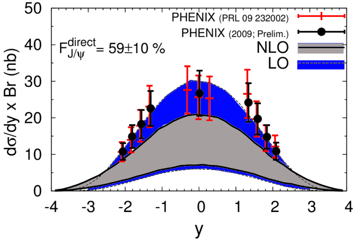

NLO: $gg \to J/\psi$, $gg\ gq \to J/\psi gq$, ...

using the matrix elements from J.Campbell, F. Maltoni, F. Tramontano, PRL 98:252002,2007

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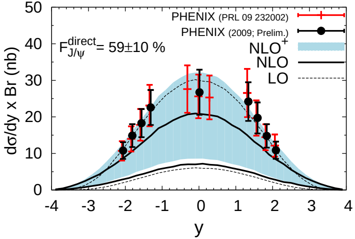

NLO$^+$: adding one new contribution at LO $cg \to J/\psi c$

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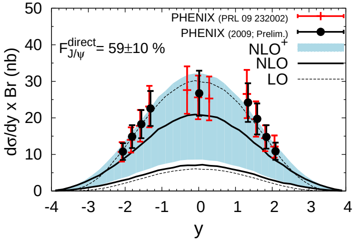
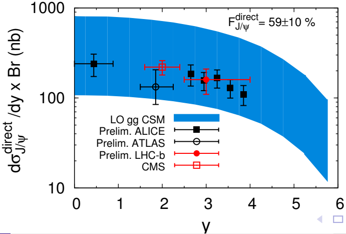


NLO$^+$: adding one new contribution at LO $cg \to J/\psi c$

→ LHC ($\sqrt{s} = 7$ TeV)

JPL, PoS(ICHEP 2010), 206 (2010)



the CSM predictions account for the yield

JPL, PoS(ICHEP 2010), 206 (2010)

→ The yield vs. $\sqrt{s}$ (here only LO curves)

- Unfortunately, very large th. uncertainties: masses, scales (μ_R, μ_F), gluon PDFs at low x and Q^2, ...
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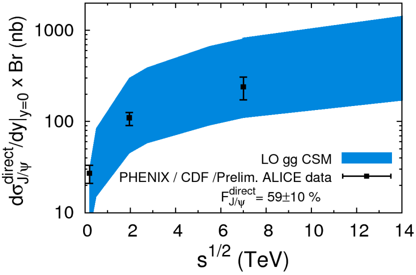

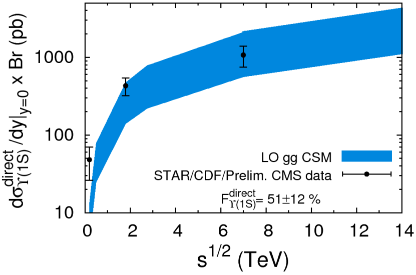

Part III

Recent progresses: QCD corrections

Describing the mid- and high-P_T's: QCD corrections

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J.Campbell, F. Maltoni, F. Tramontano, Phys.Rev.Lett. 98:252002,2007
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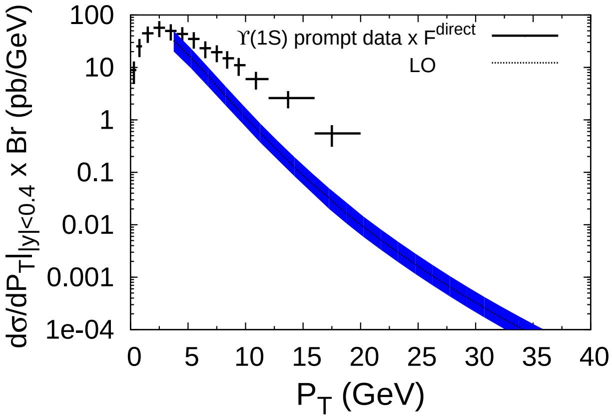

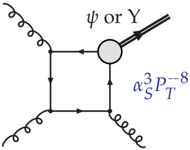

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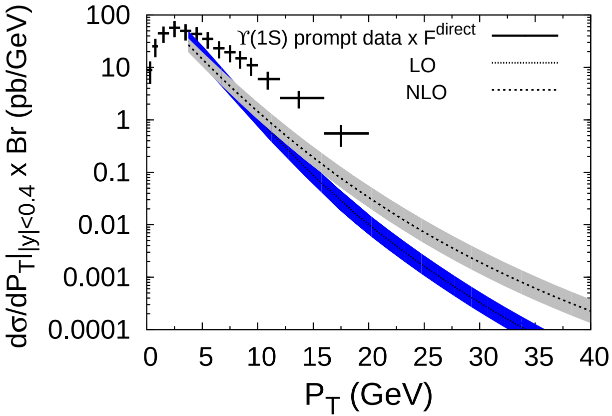

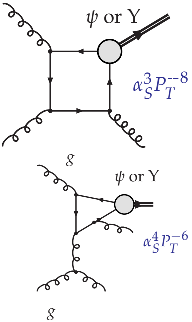

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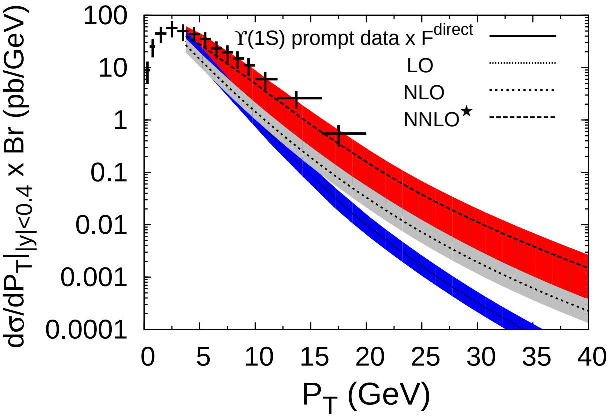

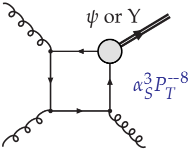

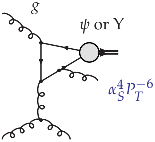

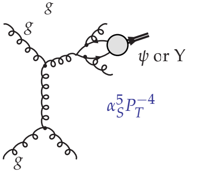

Yet, the impact of double *t*-channel gluon exchange at α_S^5 is unsure
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Describing the mid- and high-P_T's: QCD corrections

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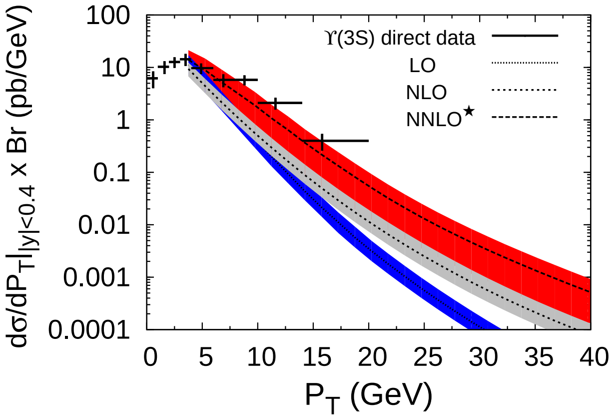

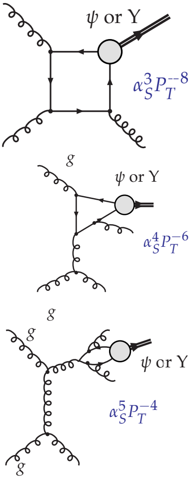

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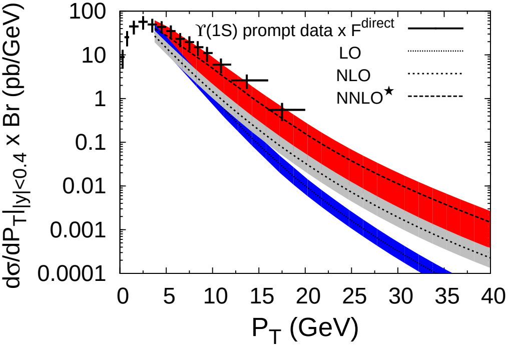
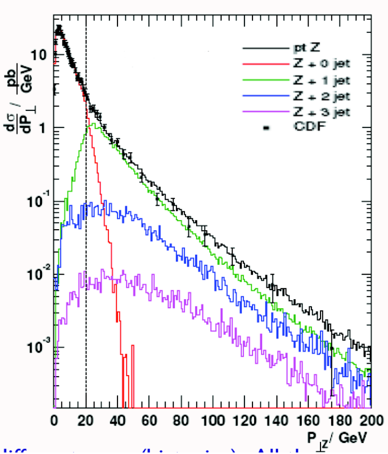
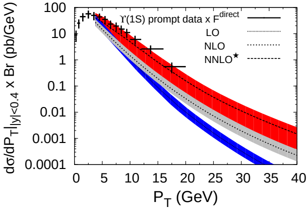
Analogy with the P_T spectrum for the Z^0 boson





Impact of QCD corrections to CSM at mid and high P_T



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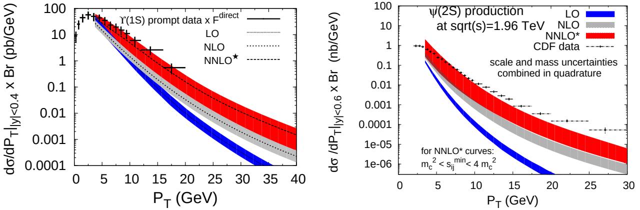

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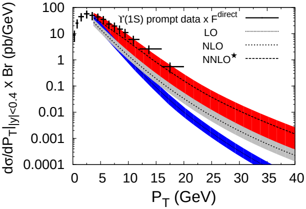

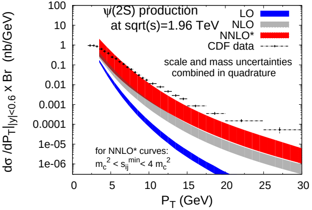

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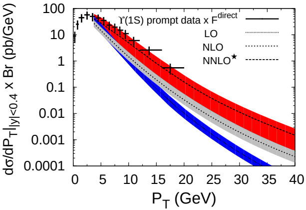

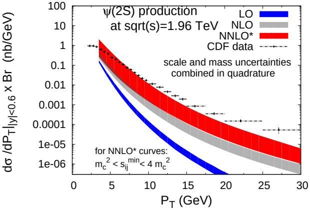

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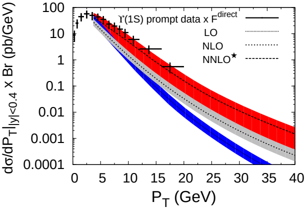

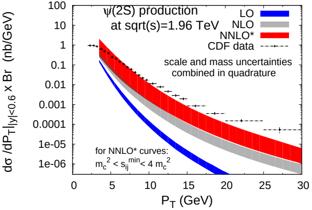

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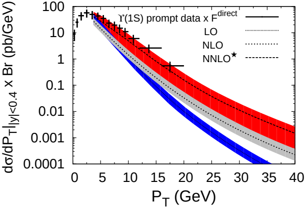

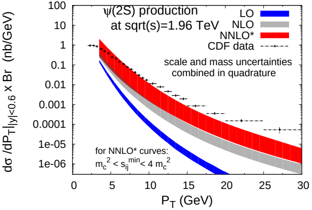

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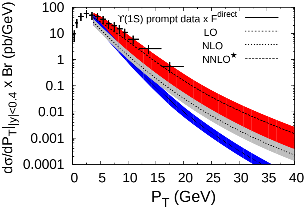

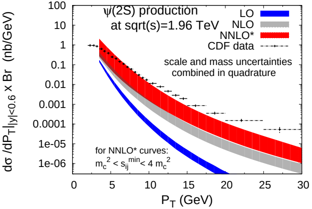

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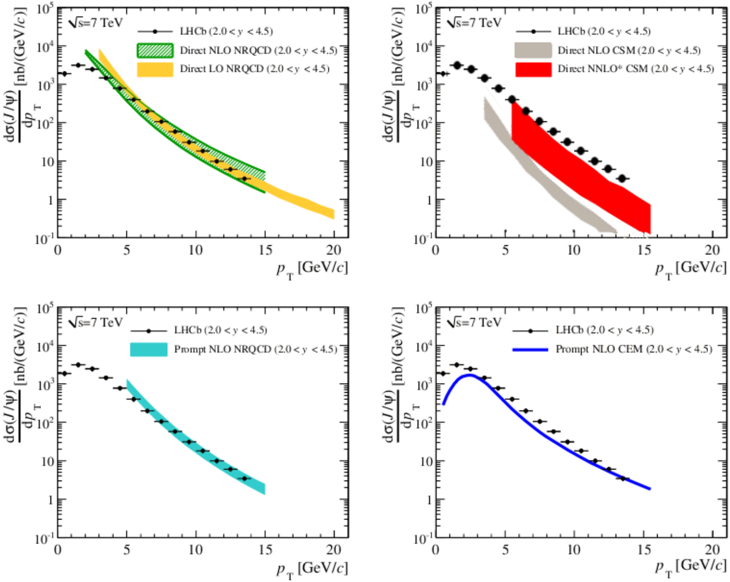
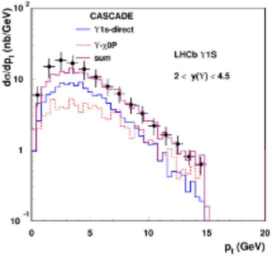
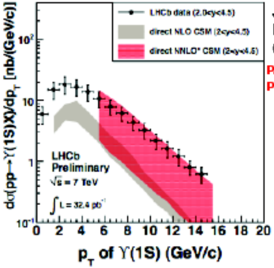
k_T fact. $\leftrightarrow$ NNLO Collinear fact. ?

Models vs. LHCb data for the J/ψ (Courtesy of J.He & P. Robbe)



Models vs. LHCb data for the Υ (borrowed from G. Manca, April'11)

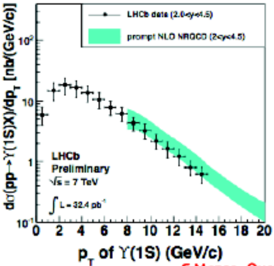


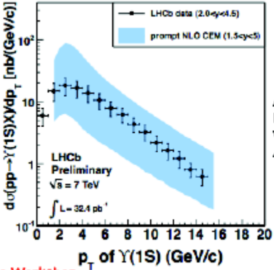


J.-P. Lansberg, Eur. Phys. J. C 61 (2009) 693

P. Artoisenet et al, PRL101,152001,2008

Y. Q. Ma, K. Wang and K. T. Chao, Phys. Rev. Lett. 106 (2011) 042002.

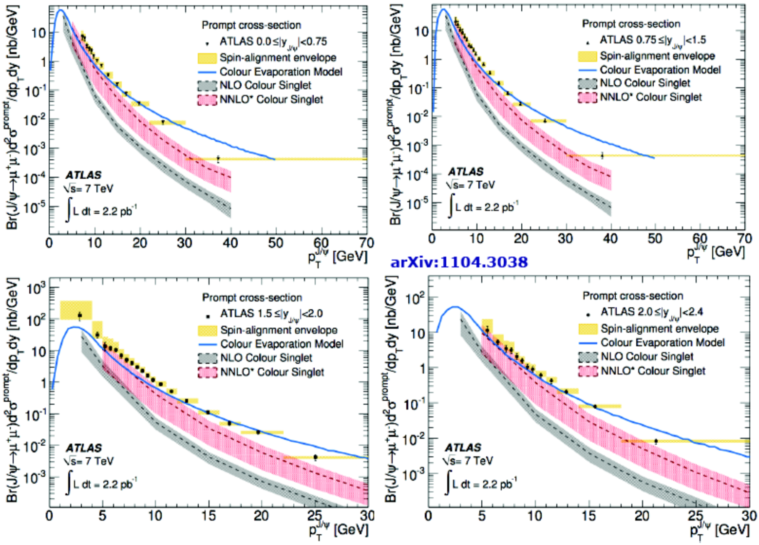




A. D. Frawley, T. Ullrich and R. Vogt, Phys. Rep. 462 (2008) 125.

19.4.2011 G.Manca, Quarkonia Workshop 28

Models vs. ATLAS data for the J/ψ (borrowed from D. Price, April'11)



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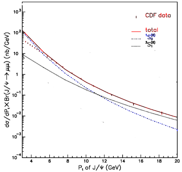

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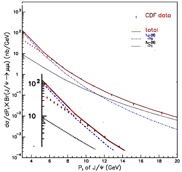

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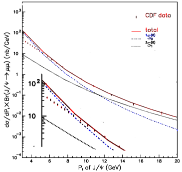

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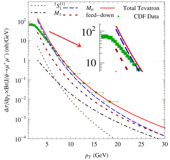

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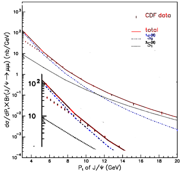

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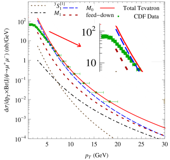

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  - ISR resummations would smear the divergence at $P_T \to 0$ out

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QCD corrections, feed-down and polarisation

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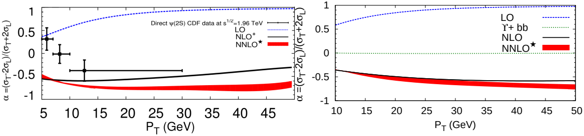
→ Complete modification of the CSM polarisation at NLO (also at NNLO*)



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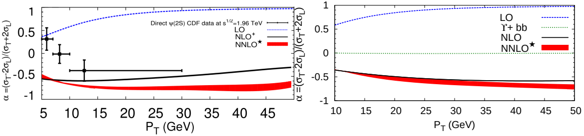

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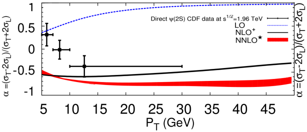

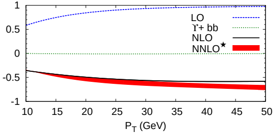

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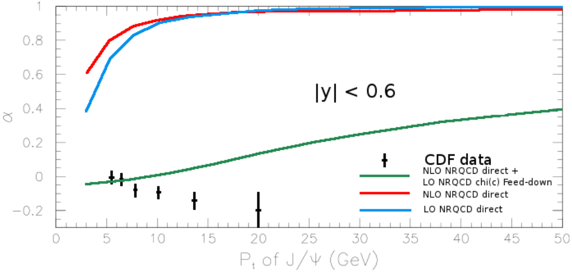

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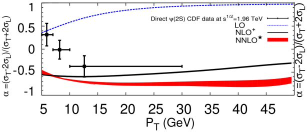

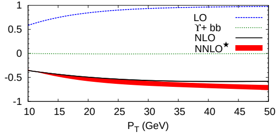

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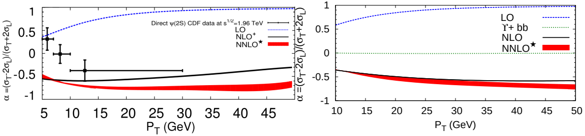

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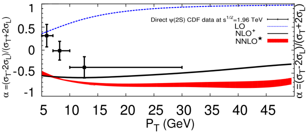

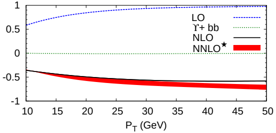

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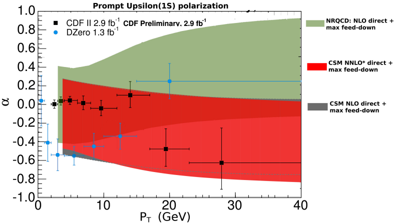
- For the $\Upsilon(1S)$ without assumptions



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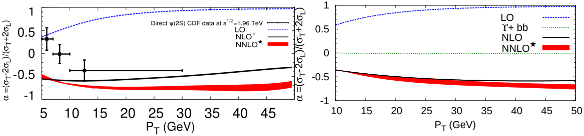

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- If $\chi_c \rightarrow^3 S_1\gamma$ is E1: $\alpha^{max}_{from\,\chi_c} = +1.00$ and $\alpha^{min}_{from\,\chi_c} = -0.45$

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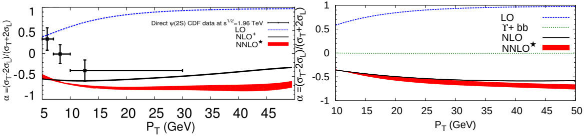

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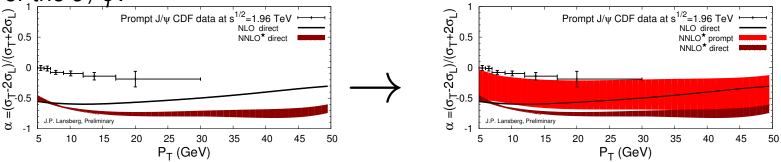

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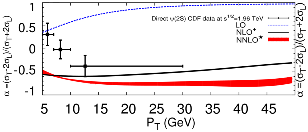

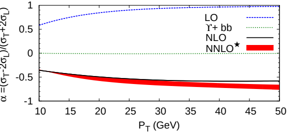

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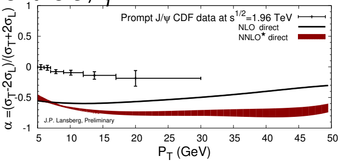
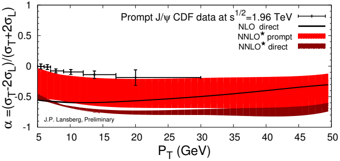


→

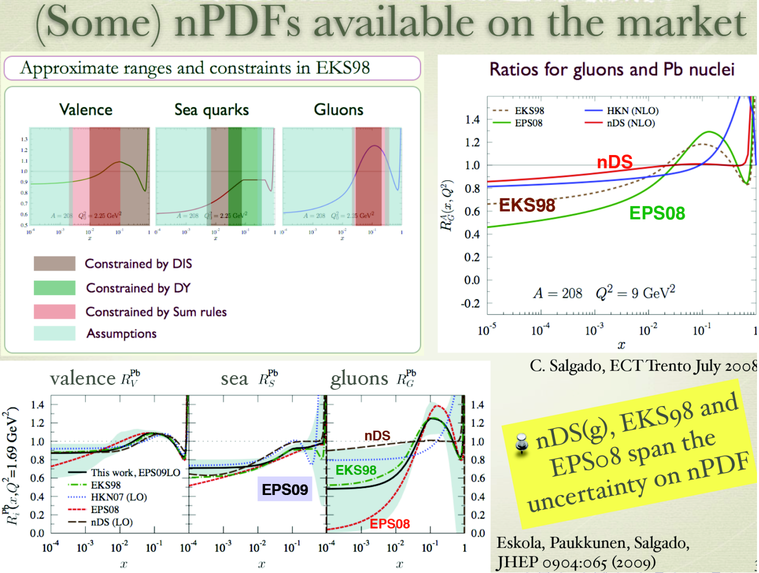


The CSM does describe the data

Part IV

Cold Nuclear Matter Effects

Shadowing, anti-shadowing and a bit of EMC effect



Absorption: an (effective) final-state cold nuclear matter effect

Particle spectrum altered by interactions with the nuclear matter they traverse
$\Rightarrow$ J/ψ **suppression** due to final state interactions with spectator nucleons
Usual parametrisation (Glauber model) :

$$S_{abs} = exp(-\rho\sigma_{abs}L)$$

- ρ the nuclear matter density
- σ_{abs} the break-up cross section
- L the path length

Energy dependence (see E. G. Ferreiro talk, Rencontres d'Etretat, 20-23/09)

- **At low energy**: the heavy system undergoes successive interactions with nucleons in its path and has to survive all of them $\Rightarrow$ **Strong nuclear absorption**
- **At high energy**: the coherence length is large and the projectile interacts with the nucleus as a whole $\Rightarrow$ **Smaller nuclear absorption**

On the kinematics of J/ψ production

E.G. Ferreiro, F. Fleuret, J.P.L., A. Rakotozafindrabe, PLB 680:50,2009

If $\mathcal{F}_g^A(x, \vec{r}, z, \mu_f)$ gives the distribution of a gluon of mom. fract. x at a position $\vec{r}$, z in a nucleus A, the differential cross-section reads:

$$\frac{d\sigma_{AB}}{dy\, dP_T\, d\vec{b}} =$$

2 $\rightarrow$ **1** kinematics with instrinsic p_T	**2** $\rightarrow$ **2** kinematics with extrinsic p_T

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$2 \to 1$ kinematics with instrinsic p_T	$2 \to 2$ kinematics with extrinsic p_T
$\int d\vec{r}_A\, dz_A\, dz_B$	$\int dx_1\, dx_2 \int d\vec{r}_A dz_A dz_B$
$\times\ \mathcal{F}_g^A(x_1^0, \vec{r}_A, z_A, \mu_f)\mathcal{F}_g^B(x_2^0, \vec{r}_B, z_B, \mu_f)$	$\times\ \mathcal{F}_g^A(x_1, \vec{r}_A, z_A, \mu_f)\mathcal{F}_g^B(x_2, \vec{r}_B, z_B, \mu_f)$
$\times\ \sigma_{gg}^{\mathrm{Intr.}}(x_1^0, x_2^0)$	$\times\ 2\hat{s} P_T \frac{d\sigma_{gg\to J/\psi+g}}{d\hat{t}} \delta(\hat{s} - \hat{t} - \hat{u} - M^2)$
$\times\ S_A(\vec{r}_A, z_A)\, S_B(\vec{r}_B, z_B)$	$\times\ S_A(\vec{r}, z_A) S_B(\vec{r}_B, z_B)$

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$$\frac{d\sigma_{AB}}{dy\, dP_T\, d\vec{b}} =$$

$2 \to 1$ kinematics with instrinsic p_T

$$\int d\vec{r}_A\, dz_A\, dz_B$$
$$\times\ \mathcal{F}_g^A(x_1^0, \vec{r}_A, z_A, \mu_f)\mathcal{F}_g^B(x_2^0, \vec{r}_B, z_B, \mu_f)$$
$$\times\ \sigma_{gg}^{\mathrm{Intr.}}(x_1^0, x_2^0)$$
$$\times\ S_A(\vec{r}_A, z_A)\, S_B(\vec{r}_B, z_B)$$

$$x_{1,2} = \frac{m_T}{\sqrt{s_{NN}}} \exp(\pm y) \equiv x_{1,2}^0(y, P_T)$$

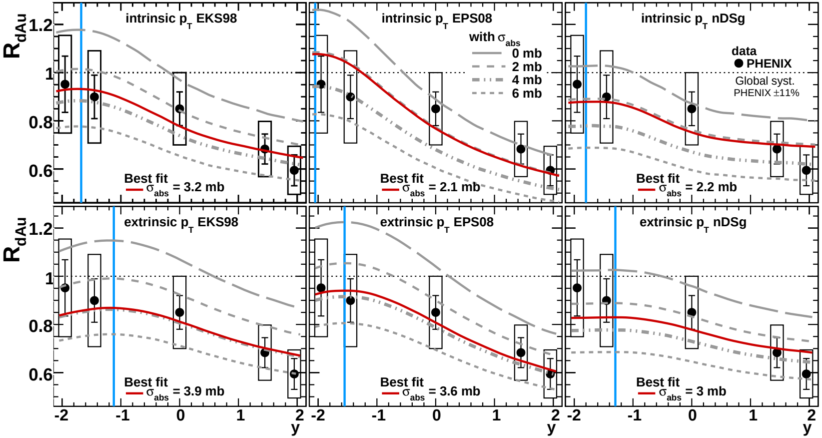
$2 \to 2$ kinematics with extrinsic p_T

$$\int dx_1\, dx_2 \int d\vec{r}_A dz_A dz_B$$
$$\times\ \mathcal{F}_g^A(x_1, \vec{r}_A, z_A, \mu_f)\mathcal{F}_g^B(x_2, \vec{r}_B, z_B, \mu_f)$$
$$\times\ 2\hat{s}P_T \frac{d\sigma_{gg\to J/\psi+g}}{d\hat{t}}\delta(\hat{s}-\hat{t}-\hat{u}-M^2)$$
$$\times\ S_A(\vec{r}, z_A)S_B(\vec{r}_B, z_B)$$

$$\delta(..) \to x_2 = \frac{x_1 m_T \sqrt{s_{NN}} e^{-y} - M^2}{\sqrt{s_{NN}}(\sqrt{s_{NN}} x_1 - m_T e^y)}$$

Nuclear modification factor for J/ψ in dAu collisions at RHIC

E.G. Ferreiro, F. Fleuret, J.P.L., A. Rakotozafindrabe, PLB 680:50,2009, PRC 81, 064911 (2010)



- The shadowing impact does depend on the kinematics

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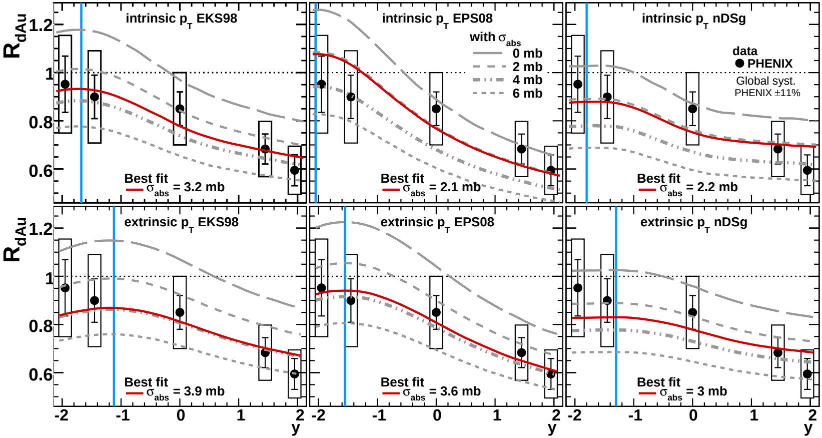
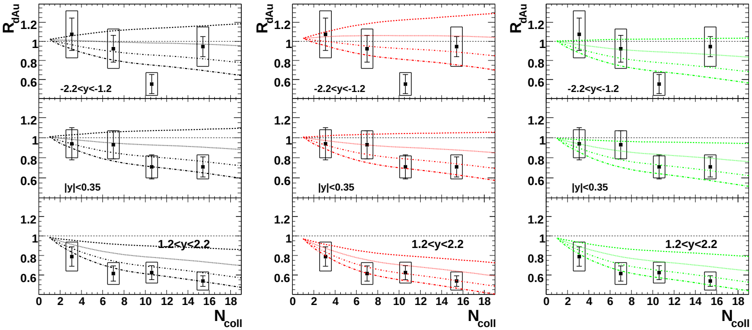


- The shadowing impact does depend on the kinematics
- The effective absorption (σ_{abs}) fit from the data is different

Centrality dependence in *d*Au

E.G. Ferreiro, F. Fleuret, J.P.L., A. Rakotozafindrabe, PLB 680:50,2009, PRC 81, 064911 (2010)

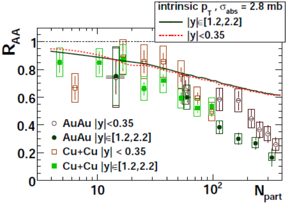


(a) EKS98 (b) EPS08 (c) nDSg

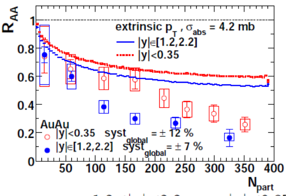
- Backward region $-2.2 < y < 1.2$: the gluon in the Au is very energetic (large x) $\rightarrow$ antishadowing
- Central region $-0.35 < y < 0.35$: the gluon in the Au is energetic (mid x) $\rightarrow$ slight shadowing
- Forward region $1.2 < y < 2.2$: the gluon in the Au is not energetic (small x) $\rightarrow$ stronger shadowing

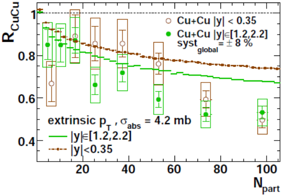
Centrality dependence in AuAu and CuCu

E.G. Ferreiro, F. Fleuret, J.P.L., A. Rakotozafindrabe, PLB 680:50,2009, PRC 81, 064911 (2010)



- Intrinsic scheme : no visible difference for $|y| < 0.35$ and $1.2 < |y| < 2.2$.

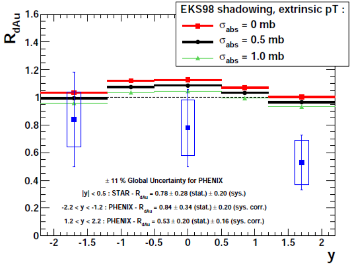


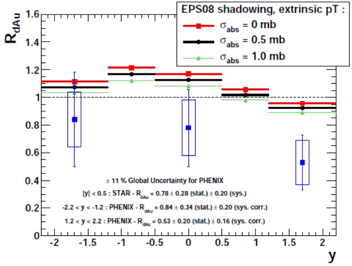


- Extrinsic scheme : $R_{AA}^{1.2<|y|<2.2} < R_{AA}^{|y|<0.35}$
- Meets the trend of the data
- Hot Nuclear Matter effect still needed in central collisions

Nuclear modification factor for Υ in *d*Au collisions at RHIC

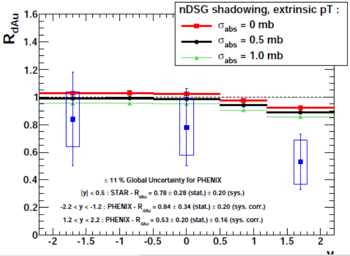
E.G. Ferreiro, F. Fleuret, J.P.L., N. Matagne, A. Rakotozafindrabe, to appear





- backward: EMC effect
- central: antishadowing
- forward : shadowing ≈ 1

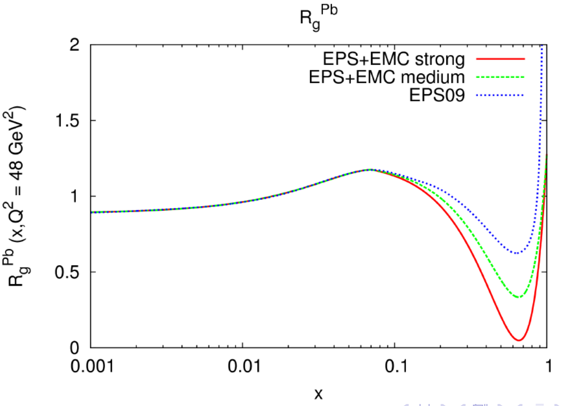
  fractional energy loss is needed



EMC effect for gluons

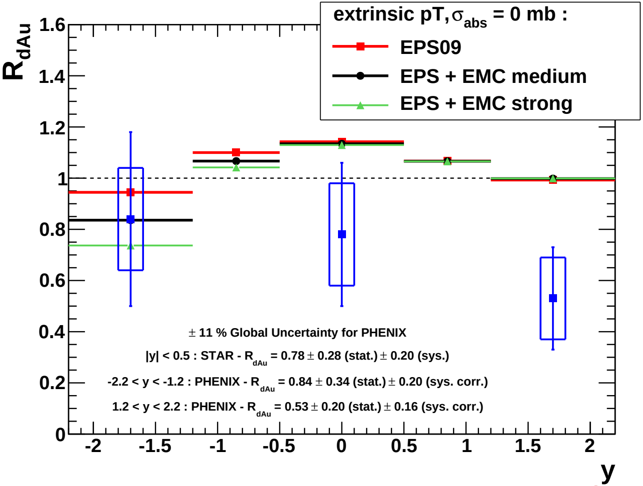
E.G. Ferreiro, F. Fleuret, J.P.L., N. Matagne, A. Rakotozafindrabe, to appear

- Let us try to increase the suppression of $g(x)$ in the EMC region
- Keeping momentum conservation : $\int xg(x)\, dx = Cst$



EMC effect and Υ in *d*Au collisions

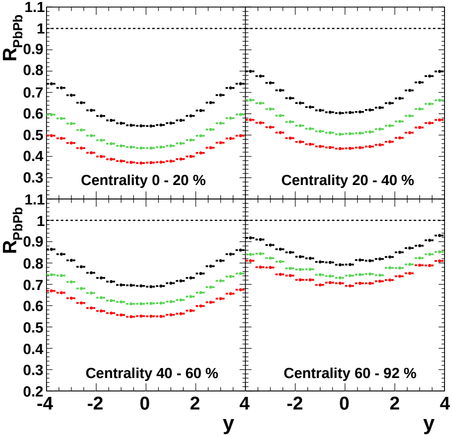
E.G. Ferreiro, F. Fleuret, J.P.L., N. Matagne, A. Rakotozafindrabe, to appear

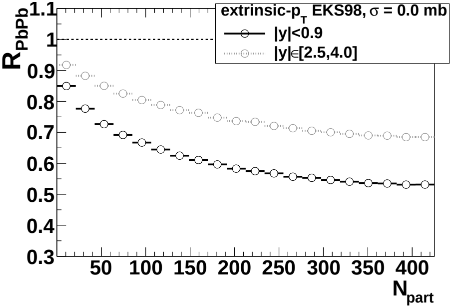


Improvement in the backward region: hint for gluon EMC effect ?

CNM for J/ψ production in PbPb at $\sqrt{s_{NN}} = 2.76$ TeV

E.G. Ferreiro, F. Fleuret, J.P.L., N. Matagne, A. Rakotozafindrabe, Nucl. Phys. A 855 (2011) 327-330

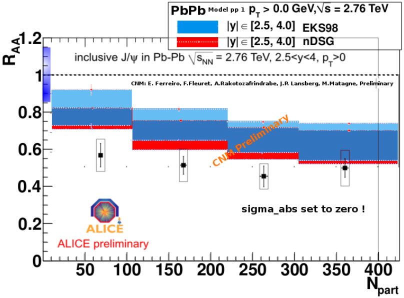


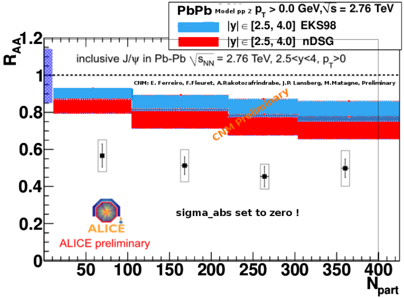


In black, $\sigma_{abs}^{eff} = 0.0$ mb, in green, $\sigma_{abs}^{eff} = 1.5$ mb, in red, $\sigma_{abs}^{eff} = 2.8$ mb

Strong rapidity dependence of R_{PbPb}!

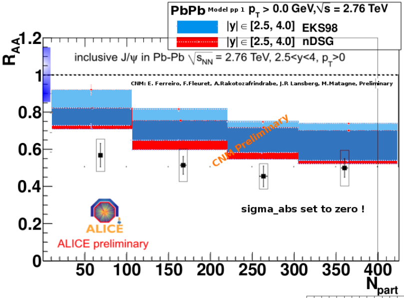
The P_T cut matters

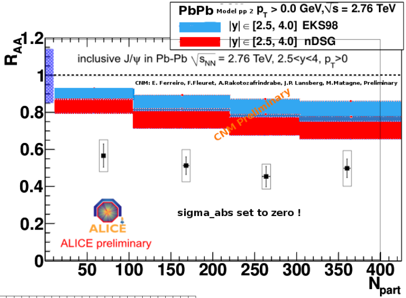




Without P_T cut and forward (ALICE acceptance)

The P_T cut matters





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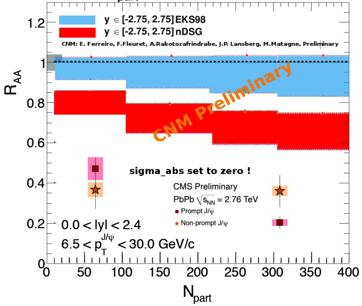

With $P_T > 6.5$ GeV cut and mostly central (CMS/ATLAS acceptance)

CNM vs data for PbPb at $\sqrt{s_{NN}} = 2.76$ TeV

- The data shows a weak centrality dependence
- That of shadowing is more pronounced

(should be even more if one believes PHENIX)

CNM vs data for PbPb at $\sqrt{s_{NN}} = 2.76$ TeV

- The data shows a weak centrality dependence
- That of shadowing is more pronounced
  (should be even more if one believes PHENIX)
- Data seems to show a decrease of R_{AA} for increasing P_T
- Opposite trend with EKS98 (as expected);
  nDSG is rather insensitive (surprising)

CNM vs data for PbPb at $\sqrt{s_{NN}} = 2.76$ TeV

- The data shows a weak centrality dependence
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- The CNM baseline is nearly the key point here ...

Part V

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Part VI

Backup

Gluon shadowing at different scales for Pb ions