Theory status of quarkonium production in proton-nucleus collisions

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thanks to F. Arléo, E.G. Ferreiro

Part I

Introduction and motivations

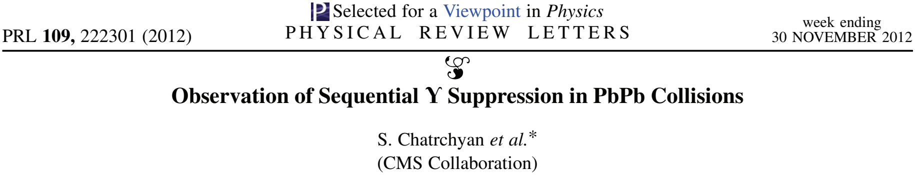
Quarkonium production in proton-nucleus collisions: Motivations I

Such reactions involve many physics effects of specific interest such as

- Parton distributions in nuclei
- Saturation & low x physics
- Time-evolution of a $Q\overline{Q}$ pair, dynamics of hadronisation
- Parton propagation in a dense medium, energy loss processes, Cronin effect
- Test of the quarkonium production mechanisms: octet vs. singlet
- Intrinsic charm in the proton
- Test of QCD factorisation in media
- Quarkonium-hadron interaction
- Mechanisms underlying single-spin asymmetries
- …

Most are also obviously relevant if one wishes to use quarkonia as probes of the QGP.

Motivations II



Selected for a Viewpoint in *Physics*

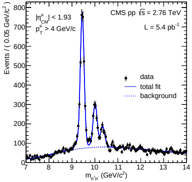
PRL **109,** 222301 (2012) PHYSICAL REVIEW LETTERS week ending 30 NOVEMBER 2012

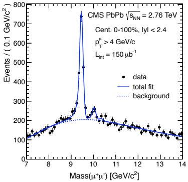
Observation of Sequential Υ Suppression in PbPb Collisions

S. Chatrchyan *et al.**
(CMS Collaboration)

Motivations II

CMS PRL 109 222301 (2012), JHEP04(2014)103





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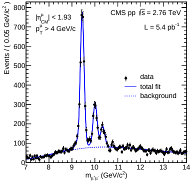

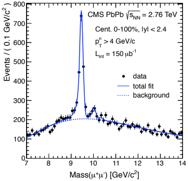

In addition to QGP formation, differences between quarkonium production yields in PbPb and pp collisions can also arise from cold-nuclear-matter effects [21]. However, such effects should have a small impact on the double ratios reported here. Initial-state nuclear effects are expected to affect similarly each of the three Υ *states, thereby canceling out in the ratio. Final-state "nuclear absorption" becomes weaker with increasing energy [22] and is expected to be negligible at the LHC [23].*

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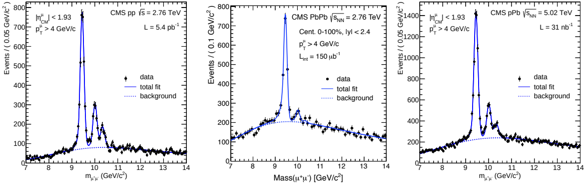

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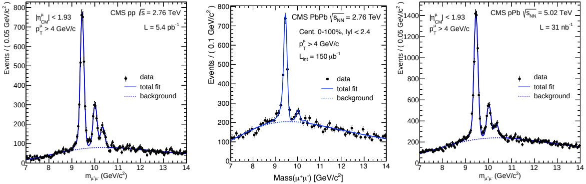

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If the effects responsible for the relative $nS/1S$ suppression in pPb collisions factorise, they could be responsible for half of the PbPb relative suppression !!!

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Disclaimer: I will not speak about any QGP-like effect

Part II

A baseline to understand the basics

Baseline: absorption and nPDFs in a collinear pQCD framework

See e.g. **E.G. Ferreiro, F. Fleuret, J.P.L., A. Rakotozafindrabe, PLB 680 (2009) 50**

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- If the meson is formed, this should be described by $\sigma_{\mathrm{break-up}} \propto r^2_{\mathrm{meson}}$
- Any differential cross section can then be obtained from the partonic one:

$$\frac{d\sigma_{pA\to\mathcal{Q}X}}{dy\, dP_T\, d\vec{b}} = \int dx_1 dx_2 g(x_1, \mu_f) \int dz_A \mathcal{F}_g^A(x_2, \vec{b}, z_B, \mu_f) \mathcal{J} \frac{d\sigma_{gg\to\mathcal{Q}+g}}{d\hat{t}} S_A(\vec{b}, z_A)$$

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$$S_A(\vec{r}_A,\, z_A) = \exp\left(-A\,\sigma_{\mathrm{break-up}} \int_{z_A}^{\infty} d\tilde{z}\, \rho_A(\vec{r}_A, \tilde{z})\right)$$

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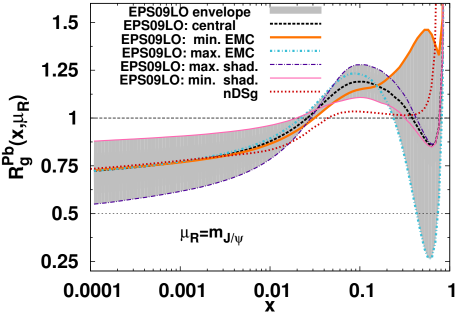
- the nuclear PDF (+ b dependence), $\mathcal{F}_g^A(x_1\,,\vec{r}_A,z_A,\mu_f)$, assumed to be factorisable in terms of the nucleon PDFs : **S.R. Klein, R. Vogt, PRL 91 (2003) 142301.**

$$\mathcal{F}_g^A(x_1\,,\vec{r}_A,z_A;\mu_f) = \rho_A(\vec{r}_A,z_A)\times g(x_1\,;\mu_f)\times(1+[R_g^A(x,\mu_f)-1]N_{\rho_A}\frac{\int dz\,\rho_A(\vec{r}_A,z)}{\int dz\,\rho_A(0,z)})$$

Typical gluon nuclear PDFs



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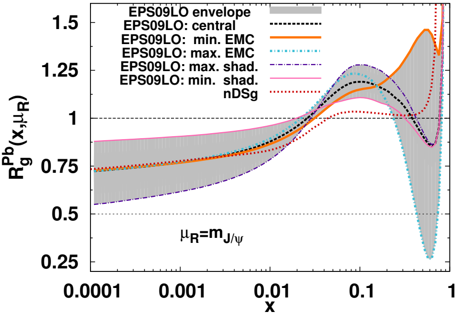

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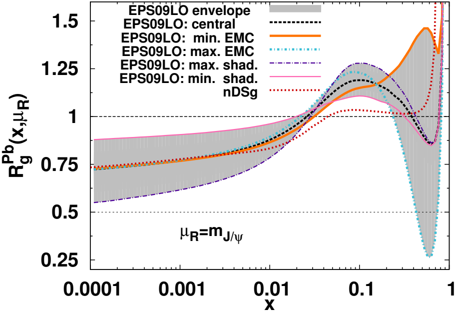

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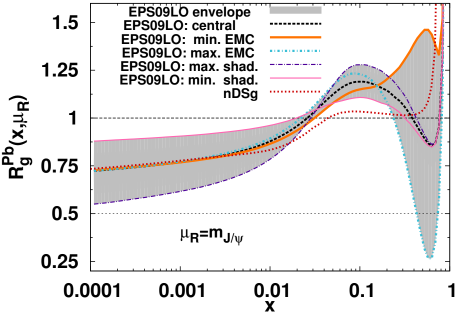

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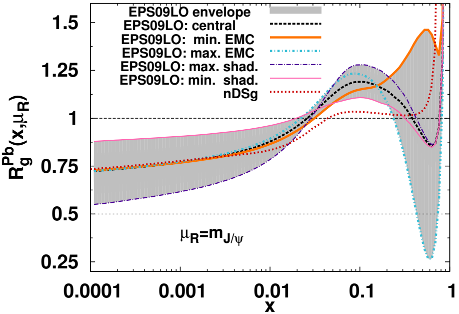

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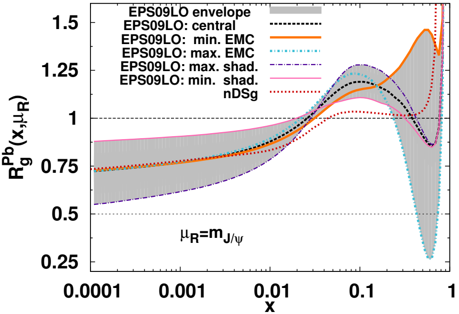

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- See R. Vogt's talk at HP2015 for more details

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- Naive high energy limit: $\sigma_{\rm break-up} \simeq \pi/m_Q^2$? $\simeq 0.5$ mb for charmonia ?

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- Nearly no data on Υ and on $\psi(2S)$

Fitting $\sigma_{\psi-N/\mathrm{break-up}}$ with fixed-target and early PHENIX data

- Global fit

F. Arleo, V.N. Tram, Eur.Phys.J. C55 (2008); 449, 61 (2009) 847

	Proton	nDS	nDSg	EKS98	EPS08	HKM
$\sigma^{\mathrm{nPDF}}_{J/\psi\mathrm{N}}$ (mb)	3.4 ± 0.2	3.5 ± 0.2	4.0 ± 0.2	5.2 ± 0.2	6.0 ± 0.2	3.6 ± 0.2
χ^2/ndf	1.4	1.4	1.5	1.5	1.7	1.4

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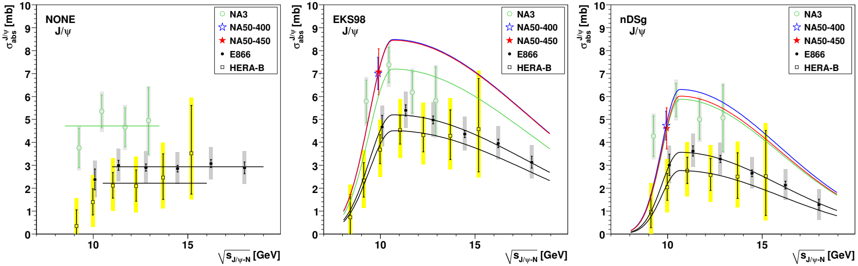
- Energy-dependence study at $y \simeq 0$ as an attempt to avoid other effects:

C. Lourenço, R. Vogt, H.K. Whoeri, JHEP 0902 (2009) 014



Fitting $\sigma_{\psi-N/\mathrm{break-up}}$ with fixed-target and early PHENIX data

- Global fit

F. Arleo, V.N. Tram, Eur.Phys.J. C55 (2008); 449, 61 (2009) 847

	Proton	nDS	nDSg	EKS98	EPS08	HKM
$\sigma_{J/\psi N}^{\mathrm{nPDF}}$ (mb)	3.4 ± 0.2	3.5 ± 0.2	4.0 ± 0.2	5.2 ± 0.2	6.0 ± 0.2	3.6 ± 0.2
χ^2/ndf	1.4	1.4	1.5	1.5	1.7	1.4

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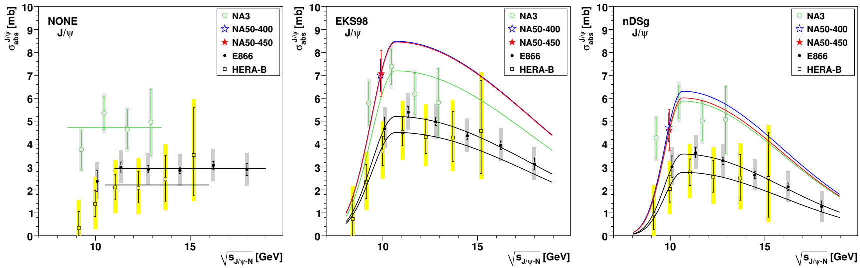

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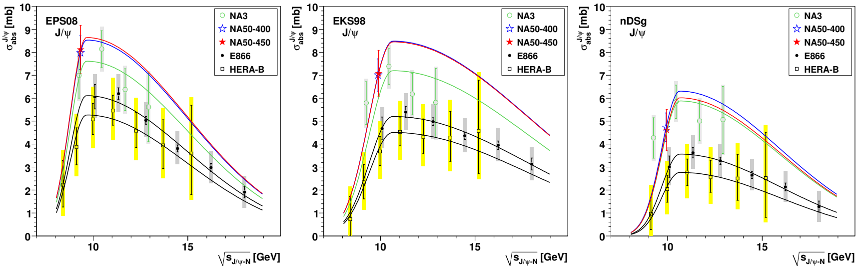

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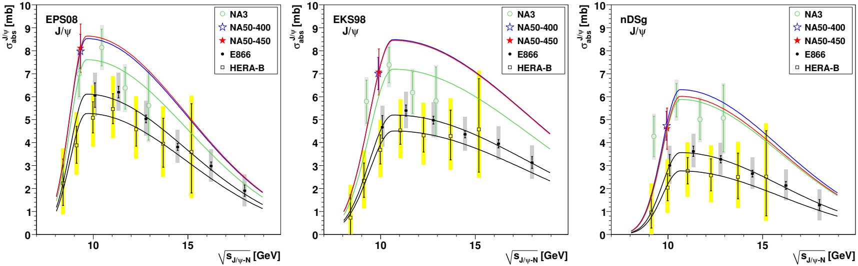


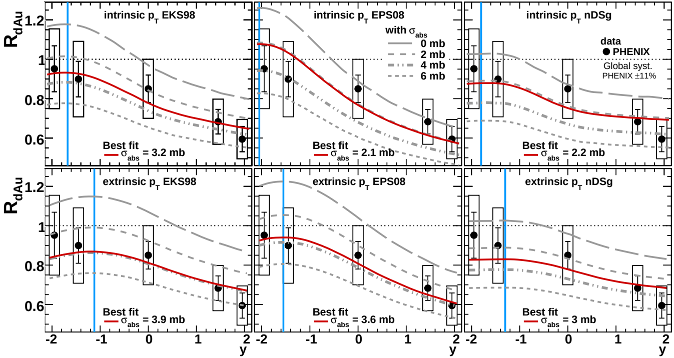
- no scaling in $\sqrt{s_{\psi-N}}$ w/o (anti)shadowing, not so clear with strong (anti)shadowing (as in EPS08)
- Consensus: $\sigma_{\mathrm{break-up}}$ is getting small at high energies (via s_{NN} or $s_{\psi-N}$)

Part III

RHIC & LHC

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; PHENIX PRC 77: 024912, 2008



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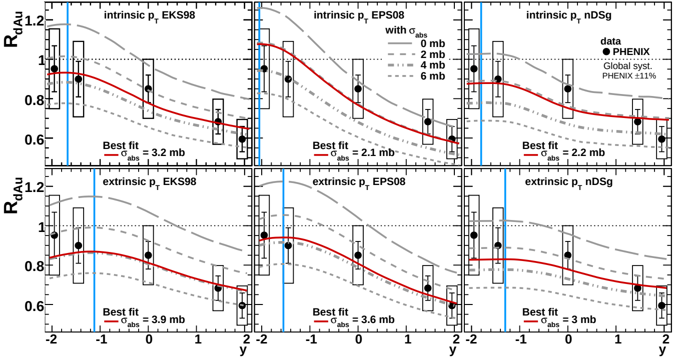

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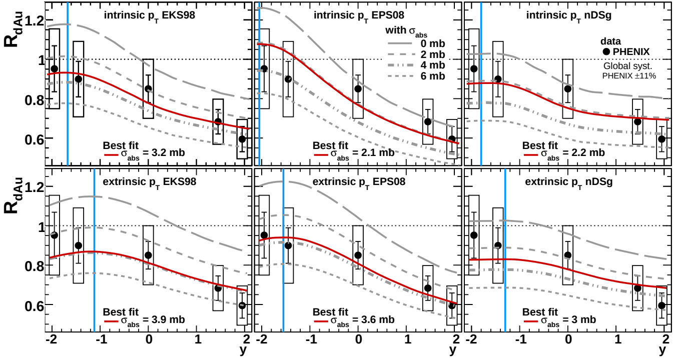

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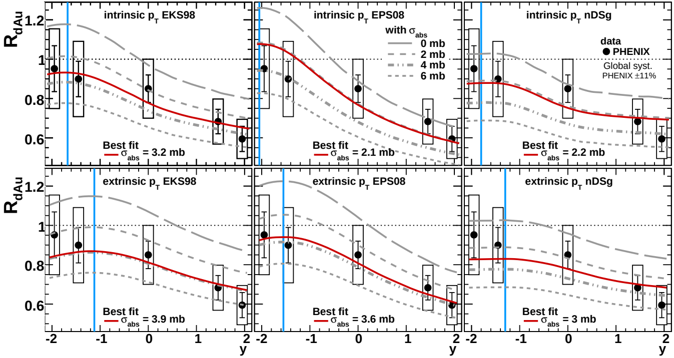


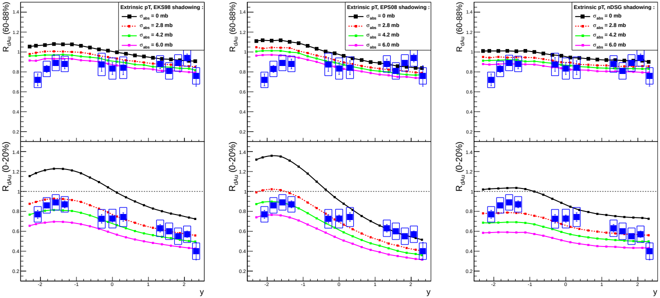
TABLE I. $\sigma_{\rm abs}$ extracted from fit of $R_{d\rm Au}$ (all cross section in unit of mb).

	$\sigma_{\rm abs}$	$\chi^2_{\rm min}$
EKS98 Int.	3.2 ± 2.4	0.9
EPS08 Int.	$2.1^{+2.6}_{-2.2}$	1.1
nDSg Int.	$2.2^{+2.3}_{-2.1}$	1.3
EKS98 Ext.	$3.9^{+2.7}_{-2.3}$	1.1
EPS08 Ext.	$3.6^{+2.4}_{-2.5}$	0.5
nDSg Ext.	$3.0^{+2.2}_{-2.4}$	1.2

- The shadowing impact also depend on the kinematics: $\underbrace{2 \to 1}_{\text{intrinsic}}$ vs $\underbrace{2 \to 2}_{\text{extrinsic}}$
- Shift of the rapidity distribution (see the vertical blue line)
- Different resulting $\sigma_{\rm break-up}$ fitted as a constant with a good $\chi^2_{\rm min}$

Comparison with more recent PHENIX data

E.G. Ferreiro, F. Fleuret, J.P.L., N. Matagne A. Rakotozafindrabe, FBS 53: 27, 2012; PHENIX PRL 107: 142301, 2011



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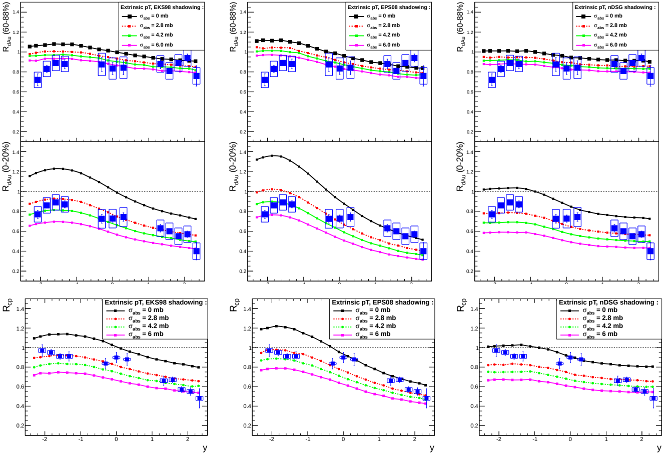

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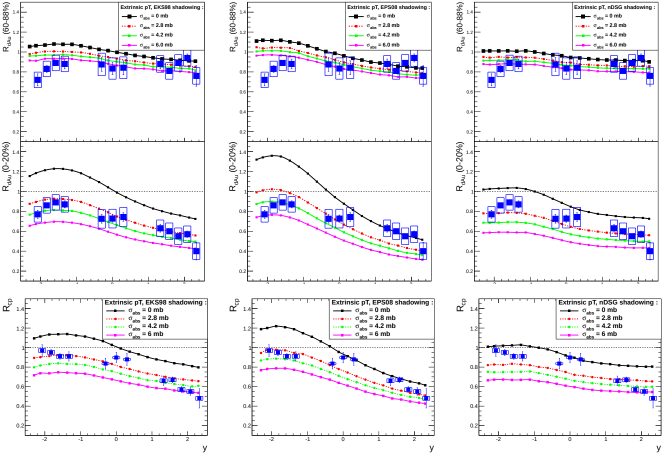

- EKS98 with $\sigma_{abs} \simeq$ 3mb (red curve) seems to do a good job
- Less true when one looks at R_{CP} (EPS08 (i.e. strong shadowing) better)
- R_{CP} can be quite instructive, even when one has R_{pA}

Beyond nPDF and break-up in the nuclear matter

E.G. Ferreiro, F. Fleuret, J.P.L., A. Rakotozafindrabe, PRC 81, 064911 (2010)+ A. D. Frawley (2009)

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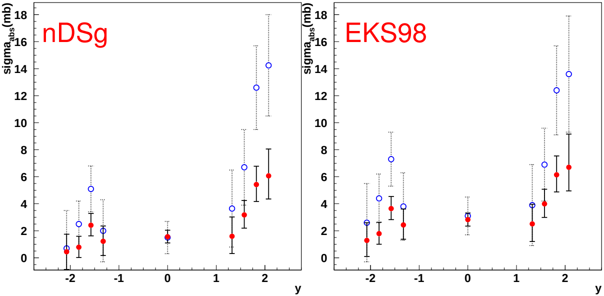

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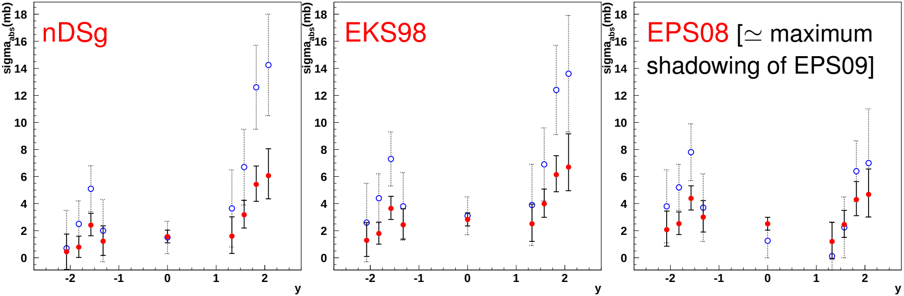

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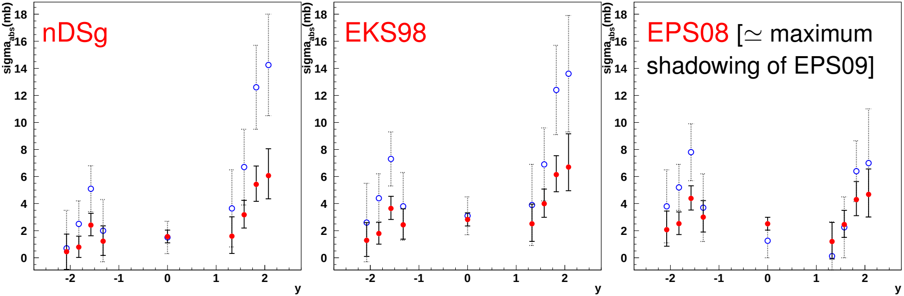

- This counter-intuitive behaviour is less marked with a strong gluon depletion at small x (shadowing, saturation,. . .) under a 2 → 2 kinematics
- This may hint at some overlooked mechanisms in the forward region: Energy loss, coherent/CGC multiple scattering

Rapidity dependence in pPb collisions at $\sqrt{s_{NN}} = 5$ TeV

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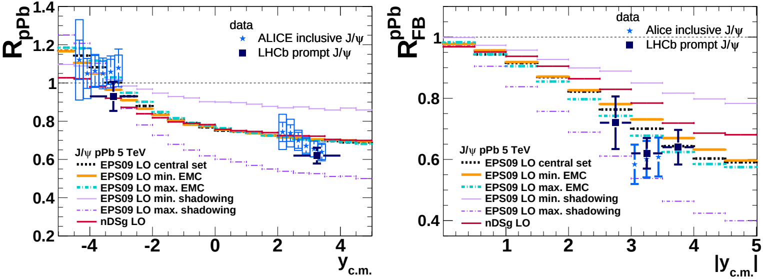

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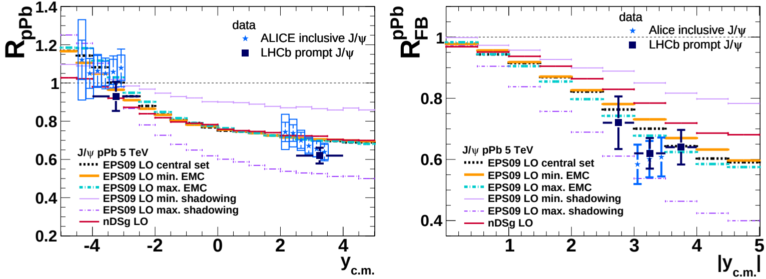

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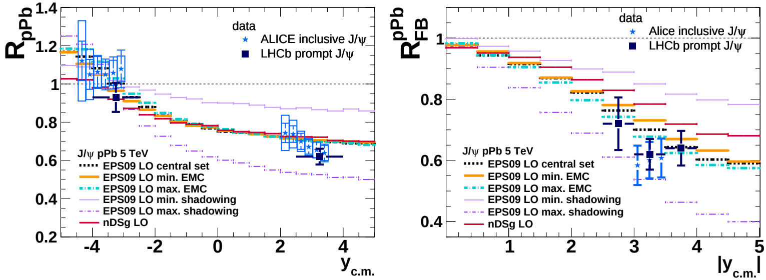

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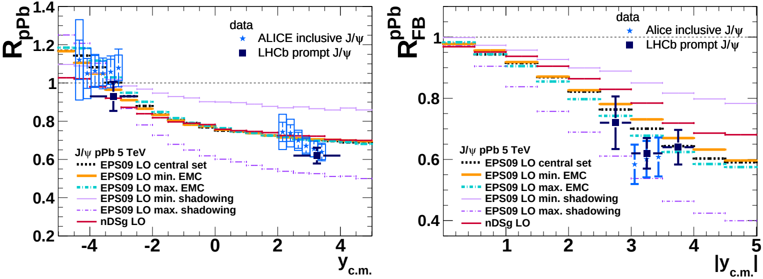

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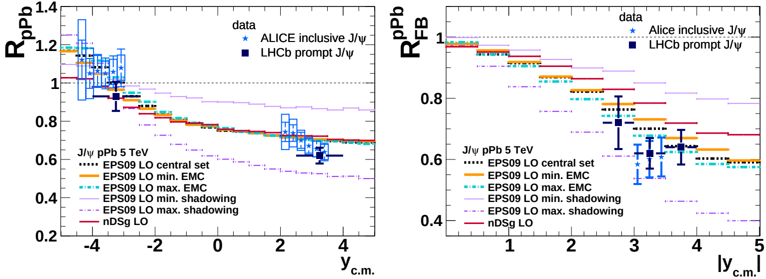

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- The uncertainty band of a given set may not encompass other nPDFs
- If this was the only effect, data would really constraint nPDFs

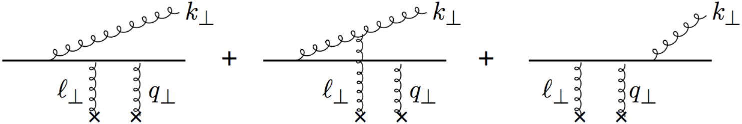
Part IV

Back to theory

Revisiting energy loss scaling properties

F. Arleo, S. Peigne PRL 109 (2012) 122301, JHEP 1410 (2014) 73; F. Arleo *et al.*JHEP 1305 (2013) 155

Coherent radiation (interference) in the initial/final state crucial for $t_f \gg L$



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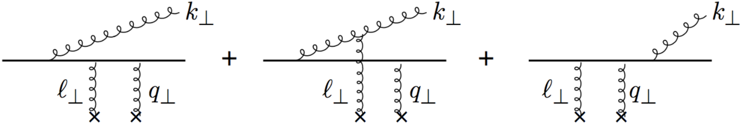

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$$\Delta E = \int d\omega\, \omega \left.\frac{dI}{d\omega}\right|_{\mathrm{ind}} = N_c \alpha_s \frac{\sqrt{\Delta q_\perp^2}}{m_T} E$$

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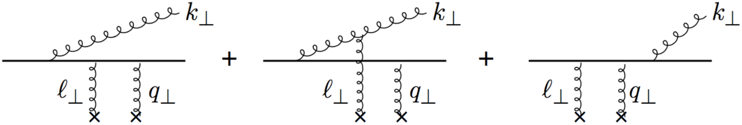

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- $\sqrt{\Delta q_\perp^2}$ related to $\hat{q}(x) = \hat{q}_0 (10^{-2}/x)^{0.3}$ where $\hat{q}_0$ is the only fitted parameter of this approach + the option to switch on/off the shadowing

Evaluation the impact of such a coherent energy loss

Energy shift computed according to :

$$\frac{1}{A}\frac{d\sigma^{\mathcal{Q}}_{\rm pA}}{dE}\left(E,\sqrt{s}\right) = \int_0^{\varepsilon_{\rm max}} d\varepsilon\,\mathcal{P}(\varepsilon, E)\,\frac{d\sigma^{\mathcal{Q}}_{\rm pp}}{dE}\left(E+\varepsilon,\sqrt{s}\right)$$

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Ingredients:

- pp cross section fitted from experimental data

$$E\,\frac{d\sigma_{\mathrm{pp}}^{\psi}}{dE} = \frac{d\sigma_{pp}^{\psi}}{dy} \propto \left(1-\frac{2m_T}{\sqrt{s}}\cosh y\right)^{n(\sqrt{s})}$$

- Length L given by a Glauber model for minimum bias and centrality dependence
- $\mathcal{P}(\epsilon)$: probability distribution (quenching weight)

CGC computations: not just gluon saturation

H. Fujii, K. Watanabe,NPA 915 (2013) 1

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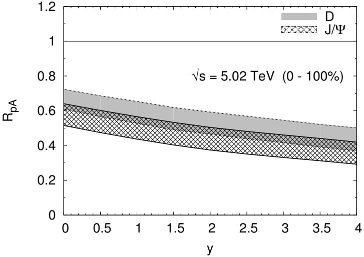
- $R_{\rm pPb}^{J/\psi}$ slightly lower, although at slightly higher scales and *x* than *D*'s



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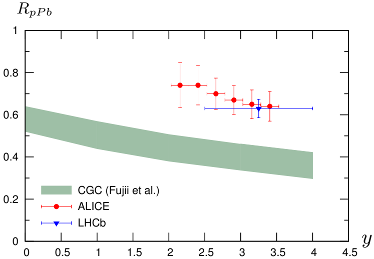

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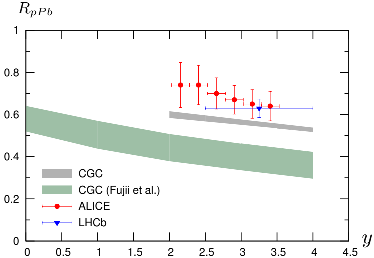

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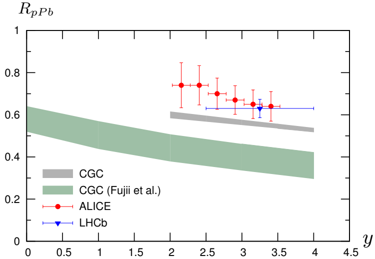

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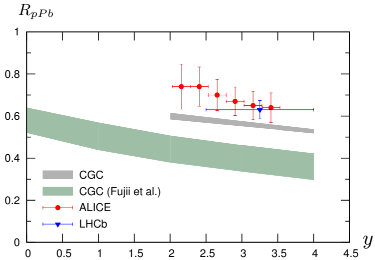

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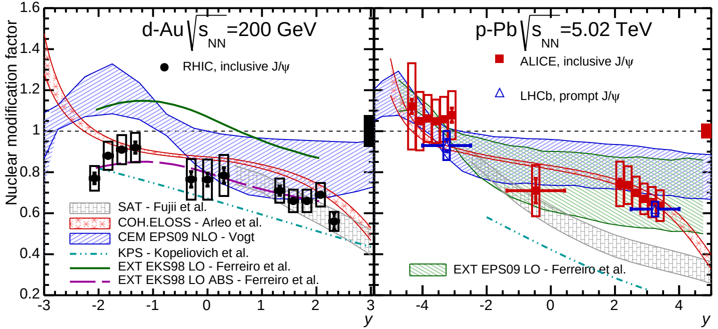
- Overall, CGC predictions very much widespread
- The J/ψ suppression at forward rapidities in pA collisions at the LHC is not quite the expected CGC smoking gun signal before the LHC start-up

Part V

Back to the data

J/ψ suppression

Plot from the Sapore Gravis Network review: arXiv:1506.03981



J/ψ suppression: energy independent ?

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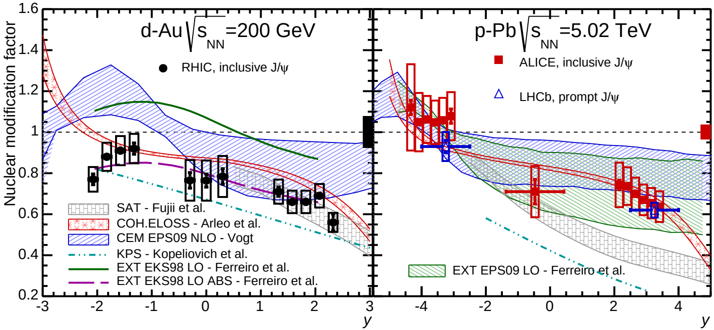
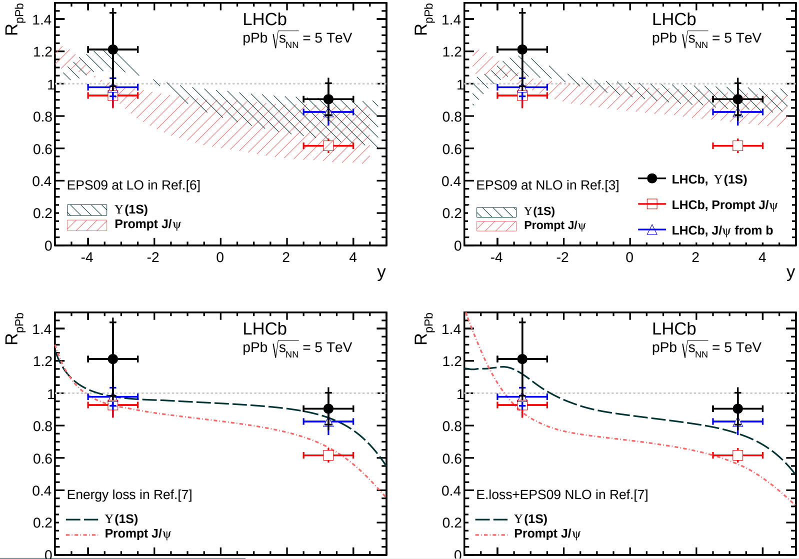


- Most models – except maybe the Eloss *without shadowing* predicted an increase of the suppression
- Now . . . –although they were done with care– the LHC results rely on a *pp* cross section interpolation
- KPS is an approach accounting for the suppression induced by coherent multiple scatterings

B. Kopeliovich, I. Potashnikova, I. Schmidt, NPA 864 (2011) 203
See also J.W. Qiu *et al.*PRD 89 (2014) 3, 034007

Comparison of different states by LHCb

LHCb JHEP 07 (2014) 094 + theory references given here



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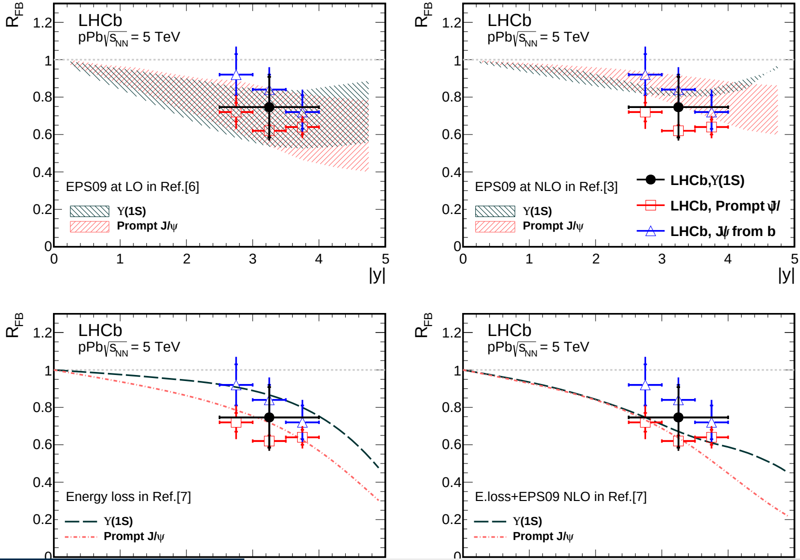
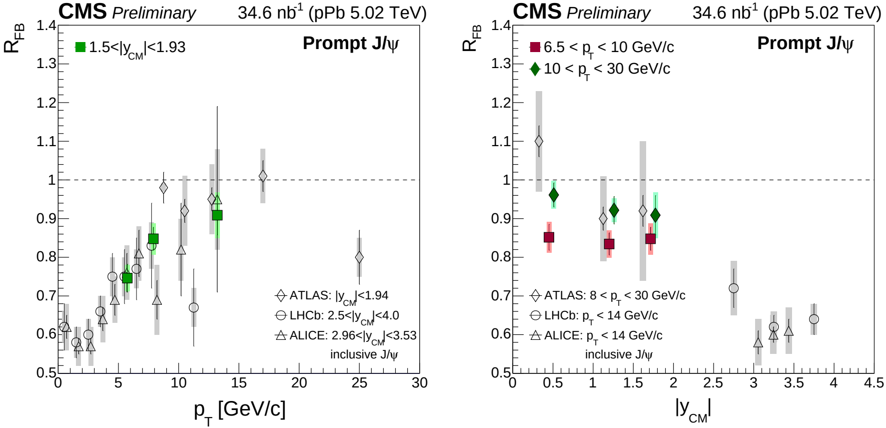


P_T dependence: nothing unexpected

ATLAS arXiv:1505.08141 [hep-ex]; CMS (N. Filipovic, HP 2015)



Suppression decreases with P_T

Part VI

Back to the excited states

An intriguing relative suppression

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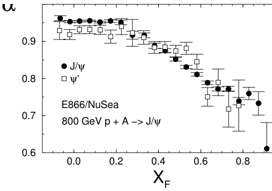
E866 PRL 84 (2000) 3256



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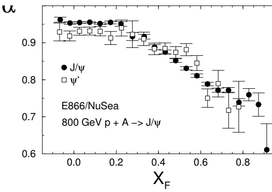

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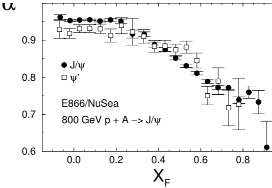

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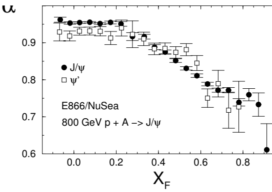

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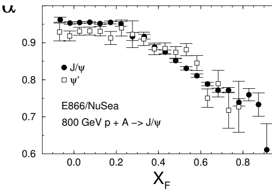

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- The most natural explanation would be a final-state effect acting over sufficiently long time in order to impact different states with a different magnitude → comover interaction model ?

Comover-interaction model (CIM)

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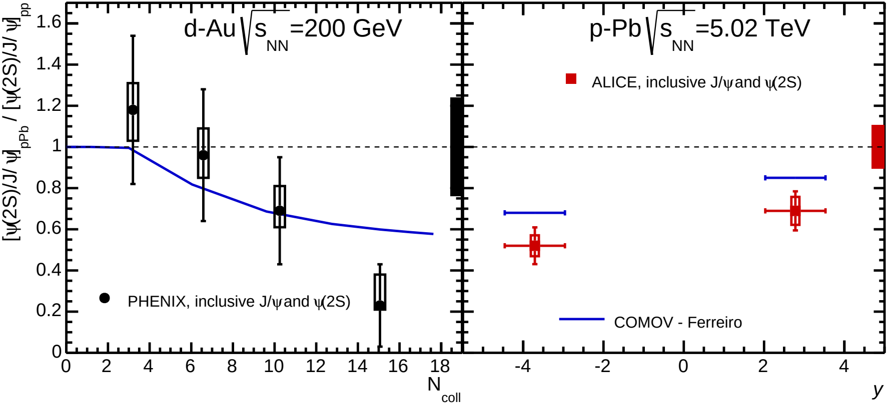
- $\sigma^{co-\psi}$ fixed from fits to low-energy *AA* data **N. Armesto, A. Capella, PLB 430 (1998) 23**

  [$\sigma^{co-J/\psi} = 0.65$ mb for the J/ψ and $\sigma^{co-\psi(2S)} = 6$ mb for the $\psi(2S)$]

CIM result vs. data

Theory: E.G. Ferreiro arXiv:1411.0549; Plot from the SGNR review: arXiv:1506.03981; PHENIX PRL 111, 202301 (2013); ALICE JHEP 02 (2014) 072



Given that all the other models discussed so far predict no difference and that the comover cross sections from *AA* data at SPS were re-used, this is encouraging…

Part VII

AFTER: before concluding

AFTER@LHC

S.J Brodsky. F. Fleuret, C. Hadjidakis, J.P.L., Phys.Rept. 522 (2013) 239; FBS (2012) 53:11

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  - cover half of the phase space
  - allow one to scan formation times from below 1 fm up to 30 fm
  - with unheard of statistical precision with such luminosities
  - with resolutions and γ detection to study $\psi(2S)$, $\chi_{c,b}$ and $\Upsilon(nS)$
- Example for the Υ **L. Massacrier** *et al.***arXiv:1504.05145; R. Vogt to appear in Adv. High. En. Phys.**

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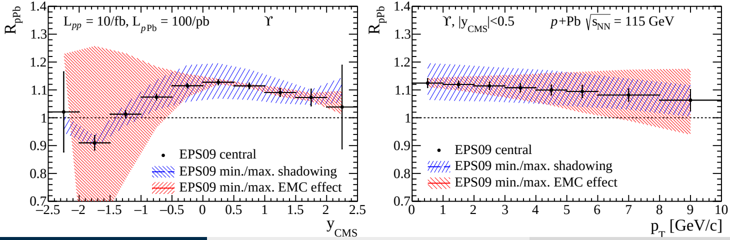

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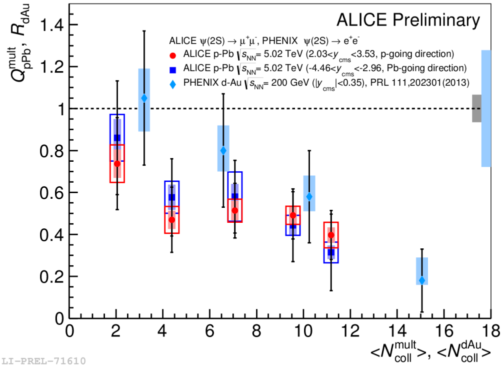
- A possible explanation is the rescattering by comovers, also used to explain the J/ψ anomalous suppression at the SPS
- As usual in such cases, more data are needed and will come from RHIC, the LHC Run-II & perhaps new projects like AFTER@LHC

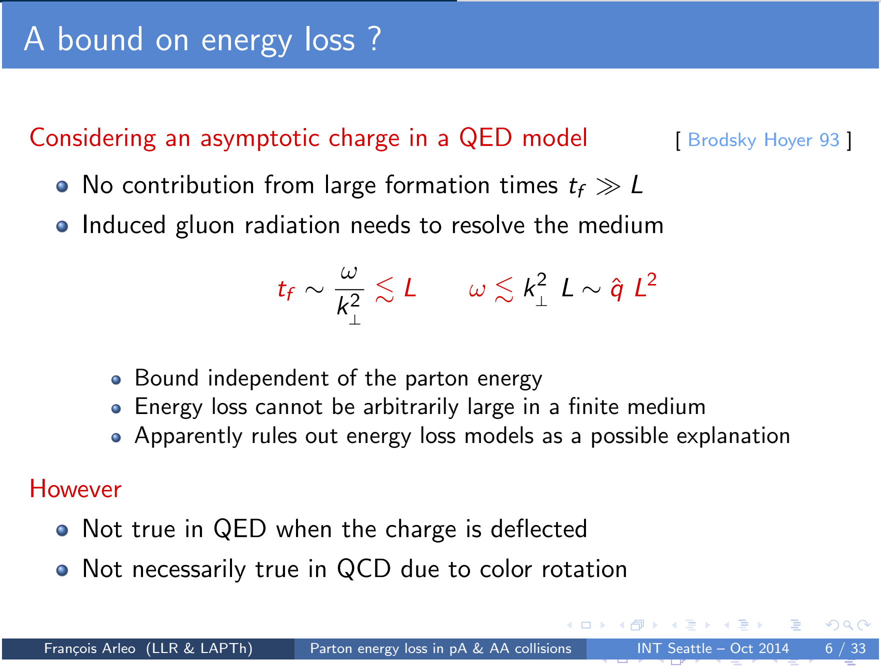
Part VIII

Backup

$\psi(2S)$ absolute suppression



I. Lakomov, HP 2015



A bound on energy loss ?

Considering an asymptotic charge in a QED model [Brodsky Hoyer 93]

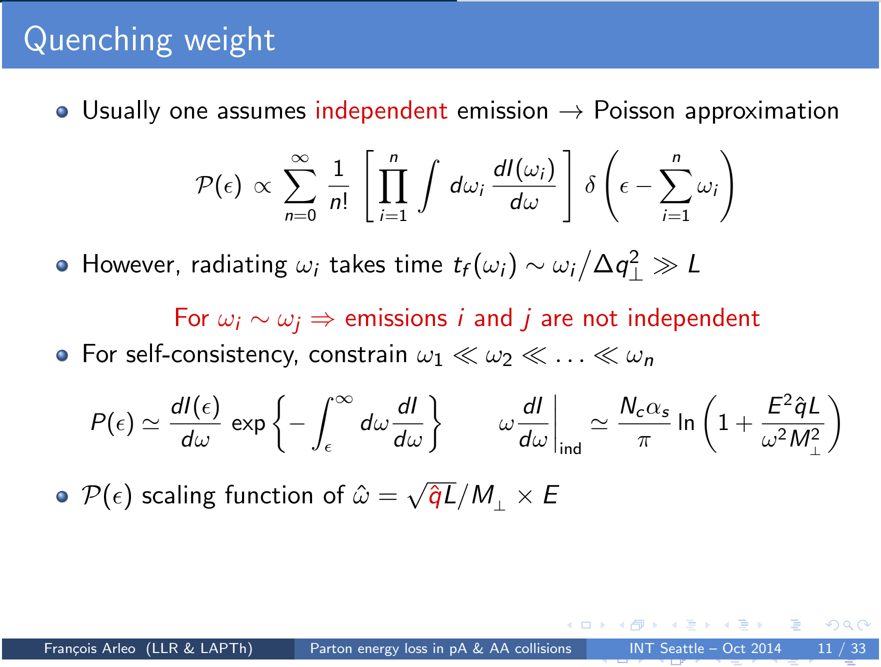
- No contribution from large formation times $t_f \gg L$
- Induced gluon radiation needs to resolve the medium

$$t_f \sim \frac{\omega}{k_\perp^2} \lesssim L \qquad \omega \lesssim k_\perp^2 \ L \sim \hat{q} \ L^2$$

  - Bound independent of the parton energy
  - Energy loss cannot be arbitrarily large in a finite medium
  - Apparently rules out energy loss models as a possible explanation

However

- Not true in QED when the charge is deflected
- Not necessarily true in QCD due to color rotation



Quenching weight

- Usually one assumes independent emission → Poisson approximation

$$\mathcal{P}(\epsilon) \propto \sum_{n=0}^{\infty} \frac{1}{n!} \left[\prod_{i=1}^{n} \int d\omega_i \, \frac{dI(\omega_i)}{d\omega} \right] \delta\left(\epsilon - \sum_{i=1}^{n} \omega_i \right)$$

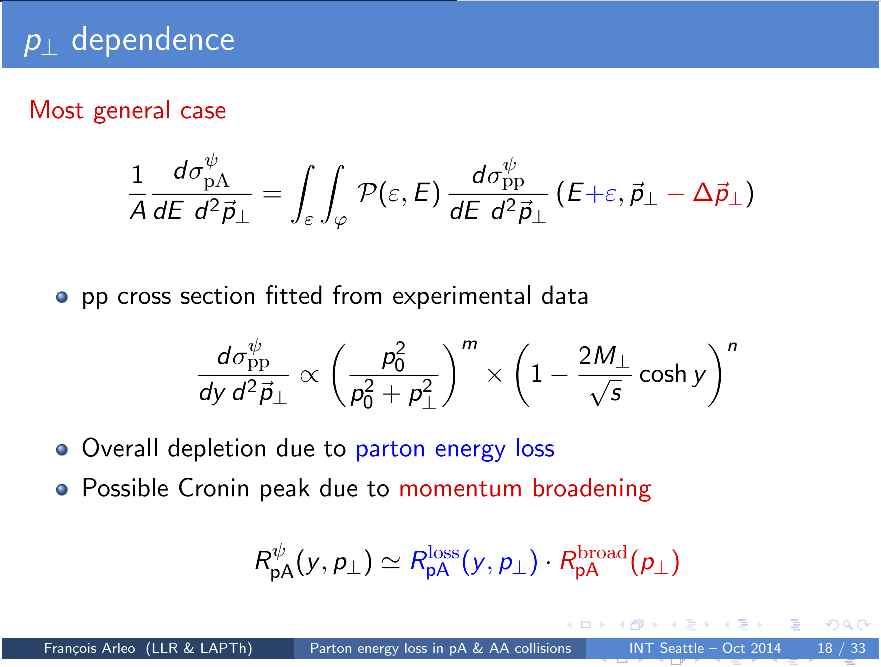
- However, radiating ω_i takes time $t_f(\omega_i) \sim \omega_i / \Delta q_\perp^2 \gg L$

For $\omega_i \sim \omega_j \Rightarrow$ emissions i and j are not independent

- For self-consistency, constrain $\omega_1 \ll \omega_2 \ll \ldots \ll \omega_n$

$$P(\epsilon) \simeq \frac{dI(\epsilon)}{d\omega} \exp\left\{ - \int_{\epsilon}^{\infty} d\omega \frac{dI}{d\omega} \right\} \qquad \omega \frac{dI}{d\omega}\bigg|_{\text{ind}} \simeq \frac{N_c \alpha_s}{\pi} \ln\left(1 + \frac{E^2 \hat{q} L}{\omega^2 M_\perp^2} \right)$$

- $\mathcal{P}(\epsilon)$ scaling function of $\hat{\omega} = \sqrt{\hat{q} L} / M_\perp \times E$



$p_\perp$ dependence

Most general case

$$\frac{1}{A}\,\frac{d\sigma^{\psi}_{\mathrm{pA}}}{dE\;d^2\vec{p}_\perp} = \int_\varepsilon\int_\varphi \mathcal{P}(\varepsilon, E)\,\frac{d\sigma^{\psi}_{\mathrm{pp}}}{dE\;d^2\vec{p}_\perp}\left(E{\color{blue}+\varepsilon}, \vec{p}_\perp {\color{red}-\Delta\vec{p}_\perp}\right)$$

- pp cross section fitted from experimental data

$$\frac{d\sigma^{\psi}_{\mathrm{pp}}}{dy\,d^2\vec{p}_\perp} \propto \left(\frac{p_0^2}{p_0^2+p_\perp^2}\right)^m \times \left(1-\frac{2M_\perp}{\sqrt{s}}\cosh y\right)^n$$

- Overall depletion due to parton energy loss
- Possible Cronin peak due to momentum broadening

$$R^{\psi}_{\mathrm{pA}}(y, p_\perp) \simeq {\color{blue}R^{\mathrm{loss}}_{\mathrm{pA}}(y, p_\perp)} \cdot {\color{red}R^{\mathrm{broad}}_{\mathrm{pA}}(p_\perp)}$$