

(theoretical) Wishes

François Arleo

LLR Palaiseau

New Observables in Quarkonium Production

ECT* Trento, Italy – 29 February - 4 March 2016

Preamble

A **poisoned** gift (thanks anyway to the organizers), because

- Many topics addressed during the workshop. . .
- On a notoriously difficult topic!

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- NRQCD or CSM?
- Spin, those who average or the others
- Single or Double Parton Scattering?
- Energy loss or nuclear parton densities?
- Debye screening or recombination ?

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Wish(es)

Different types of wishes

- **Theory wish**
 - ▶ Improved quantitative treatment or better understanding of QCD processes
- **Measurement wish**
 - ▶ Best measurement which could help solving the current mysteries
- **Data wish**
 - ▶ Best experimental results I'd like to see (highly subjective!)

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In this talk: I will try to address **a few of the puzzles and points raised** during the week (which hopefully can be solved in the future \equiv wish)

- Not a summary talk
- Unavoidably partial (but trying best to avoid any personal bias)

Quarkonium production

A longstanding issue

... and still ongoing!

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In Jianwei's words: "How to produce a bound state is a **debate**"

- Heavy quark mass is a hard scale^a $m_Q \gg \Lambda_{\text{QCD}}$ but...
- Binding energy is softish : $\alpha_s^2 m_Q \sim \Lambda_{\text{QCD}}$
 - ▶ TMD good framework to tackle this 2-scale problem $Q_2 \gg Q_1 \sim \Lambda_{\text{QCD}}$
Qiu
- No proof of factorization for the production of bound states

^awell, even this is a matter of debate!

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Qiu
- No proof of factorization for the production of bound states

Several frameworks discussed this week yet none of them fully satisfactory

- Color Singlet Model (CSM)
 - ▶ problem of perturbative expansion (p_\perp , polarization)
- Non-Relativistic QCD (NRQCD)
 - ▶ shape of p_\perp spectra, predictivity of polarization, LDME poorly known
- QCD factorization ($1/p_\perp$ expansion)
 - ▶ only leading powers p_\perp^{-4} and p_\perp^{-6} computed so far

To match (or not to match)

A **theory wish**: get a 'unified' picture in which the leading contributions in each framework are well identified and **properly matched**, e.g. like NLO–NLL or NLO-Parton Shower matching in another context

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Taking quarkonium hadronic p_{\perp} -spectra as an example:

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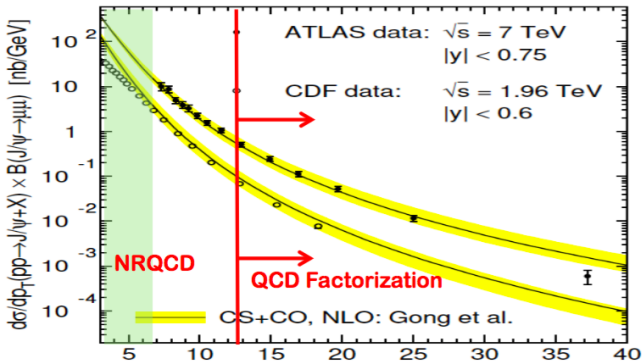
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- $p_{\perp} \lesssim m_Q$ in CSM (relax J-Phi, relax)

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Taking quark

- $p_{\perp} \gg \Lambda$
- $p_{\perp} \sim \Lambda$
- $p_{\perp} \lesssim \Lambda$



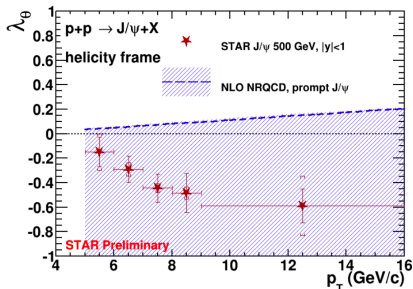
Qiu

Improving calculations

Always room for improvement! (theory wish)

NRQCD

- Could it be possible to agree on a common framework among NRQCD fitters?
- Better estimates of NRQCD matrix elements on the lattice?
- Better precision on polarization?



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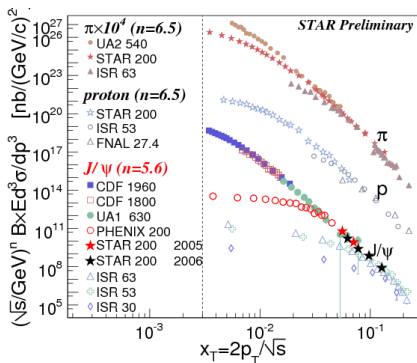
CSM

- Going virtual and removing the \star in NNLO \star calculations?
- Improving calculation of the total cross section?

Make data speak (?)

I like the x_{\perp} scaling analysis performed by STAR

see B. Trzeciak



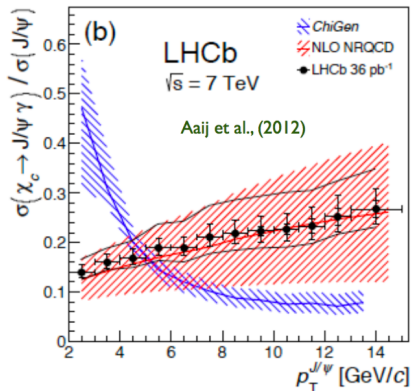
- Surprisingly $n^{J/\psi} \simeq n^h$
- Extract the scaling exponent from LHC data at various energies, to be compared to that predicted by the various quarkonium production models available (hopefully different \equiv wish)

... and look for other final states

Several observables other than J/ψ and Υ single production discussed during the workshop:

- Single inclusive particles
 - ▶ $\eta_{c,b}$, $h_{c,b}$, $\chi_{c,b}$, ...

Shao, Kratschmer



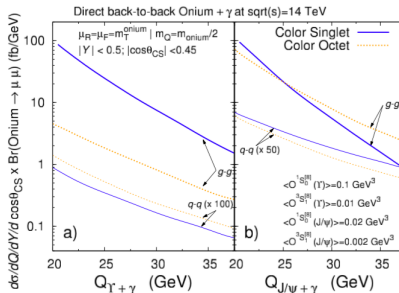
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Several observables other than J/ψ and Υ single production discussed during the workshop:

- Single inclusive particles
 - ▶ $\eta_{c,b}, h_{c,b}, \chi_{c,b}, \dots$
- Double inclusive particle production
 - ▶ J/ψ in association with a prompt photon
 - ▶ enhanced color singlet contributions

Shao, Kratschmer

Pisano



Isolated quarkonium production

... or more 'exclusive' final-state, like **isolated** quarkonium.

- Measuring quarkonia 'just like' prompt photons
- Could be used to disentangle color singlet or color octet dynamics (**theory wish**)
- Could be accessible experimentally (**measurement wish**)
- The ratio

$$r = \frac{\text{isolated } J/\psi}{\text{inclusive } J/\psi}$$

could be $r \simeq 1$ or $r \ll 1$ (**data wish**)

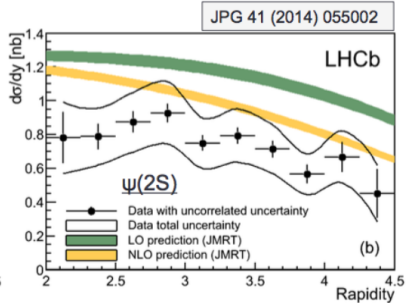
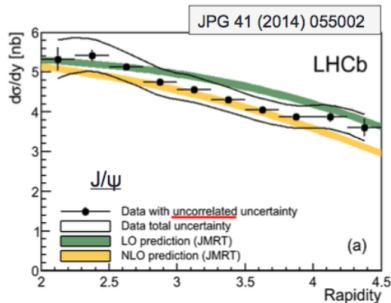
- Would need to be computed in CSM and NRQCD

More tests

Playing with the partonic process to learn on the production mechanism (a big **theory wish**)

- comparing hadroproduction (gg) to photoproduction (γg) and central exclusive production $\gamma[gg]_1$

Massacrier, Souza



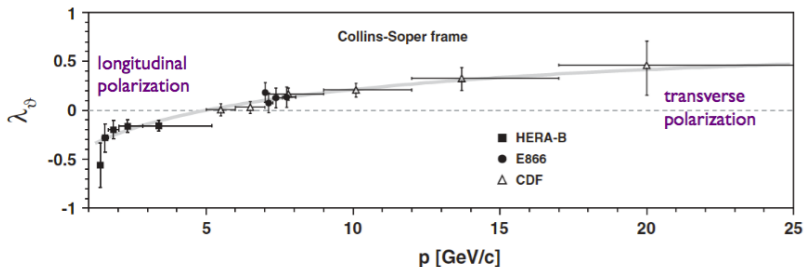
More tests

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- comparing hadroproduction (gg) to photoproduction (γg) and central exclusive production $\gamma[gg]_1$ Massacrier, Souza
- ... or use polarization and Lam-Tung violation to probe the initial channel

Faccioli, Lourenço, Seixas, Wöhri, PRL 102, 151802 (2009)

λ_{θ} for J/ψ as function of total momentum:

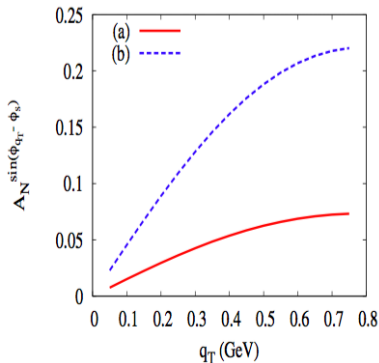
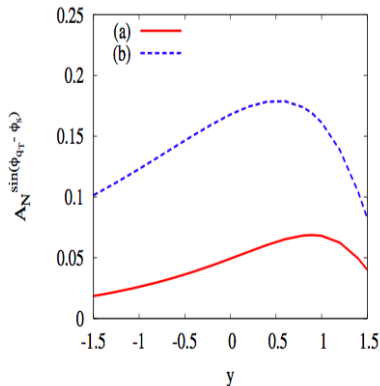


Single Spin Asymmetries

Sensitive tests of SSA's on various observables

- Comparing SIDIS and Drell-Yan
- Generalizing to several final states: light hadrons, jets... including quarkonia

Mukherjee



Single Spin Asymmetries

Sensitive tests of SSA's on various observables

- Comparing SIDIS and Drell-Yan
- Generalizing to several final states: light hadrons, jets. . . including quarkonia
- Could be fun to investigate (th. & exp.) how things get modified in nuclei (**theory wish**, **measurement wish**) – how rescattering would affect the observable

Mukherjee

Double Parton Scattering

Double J/ψ and other measurements

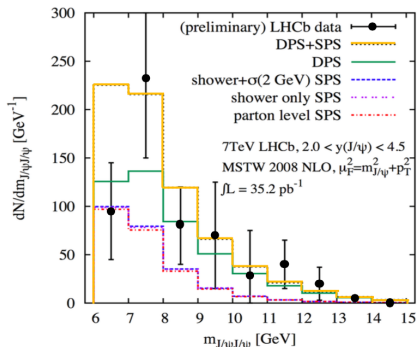
- Quarkonium as a **tool** to enhance (and reveal) double parton scattering
- Spectacular results from low energy to colliders
 - ▶ $J/\psi + \Upsilon$ production at the Tevatron
 - ▶ quarkonium + weak bosons

Price, Kamin

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$$\sigma_{\text{DPS}}^{a,b} = \mathcal{L}_{\text{eff}} \sigma_{\text{SPS}}^a \sigma_{\text{SPS}}^b$$

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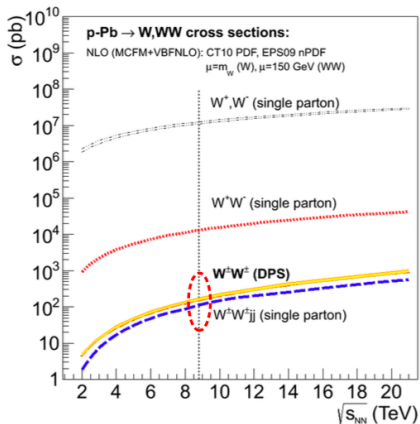
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DPS in nuclear collisions

A 'natural' place to look for DPS given the combinatorics in p-A and A-A collisions

- Case study on same-sign W production in p-Pb at LHC

d'Enterria



p-Pb @ 8.8 TeV:

$\sigma(WW, \text{DPS}) \approx 150 \text{ pb}$

$\sigma(WW_{jj}) \approx 100 \text{ pb}$

$\pm 18\%$ uncertainties:

$\pm 15\%$ for σ_{eff}

$\pm 10\%$ for scales&PDFs

DPS in nuclear collisions

A 'natural' place to look for DPS given the combinatorics in p-A and A-A collisions

- Case study on same-sign W production in p-Pb at LHC d'Enterria
- Case study on double J/ψ in Pb-Pb at LHC
- Possibly significant impact on the nuclear modification factor of (double) hard processes d'Enterria, Hadjidakis
- ... yet this needs some clarification

Cold nuclear matter effects

An interesting playground

Quarkonium production in p–A collisions as an interesting playground to test QCD in a controlled medium (\neq expanding QGP)

- **Formation time dynamics** at low \sqrt{s} and/or large negative rapidity
 - ▶ Hadronization inside the medium, use the nucleus as a femtometer detector
- **nPDF** and/or **saturation** effects
 - ▶ At small x saturation scale, $Q_s \simeq m_Q$, non-linear effects may come into play
- **Coherent energy loss** induced by the multiple scattering the parton in nuclei
 - ▶ Occurs at all \sqrt{s} and particularly at large positive rapidity

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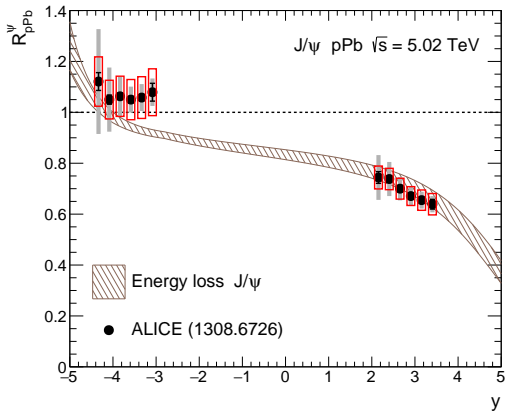
Issue: important uncertainty of nPDF and saturation effects on J/ψ suppression at LHC

Comparing to data

Measurement wish: ALICE & LHCb data at LHC on a large rapidity interval should be able to (dis)favor models

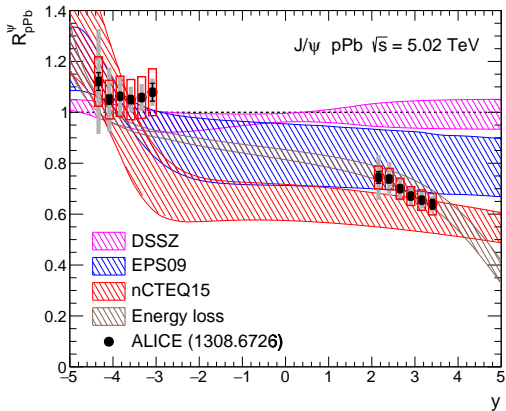
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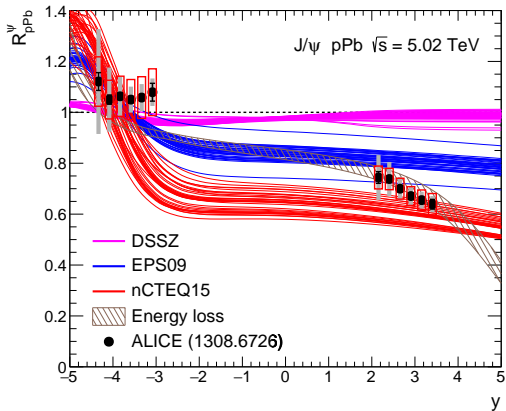
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- Some individual nPDF sets also compatible with data
 - ▶ Need independent constraints from data (**measurement wish**)
 - ▶ E.g. in e A collisions where coherent energy loss plays no role
- Saturation effects very much depend the formalism used
 - ▶ Smaller suppression in NRQCD than in CEM
 - ▶ Needs an improved understanding (**theory wish**)

Watanabe, Ducloué

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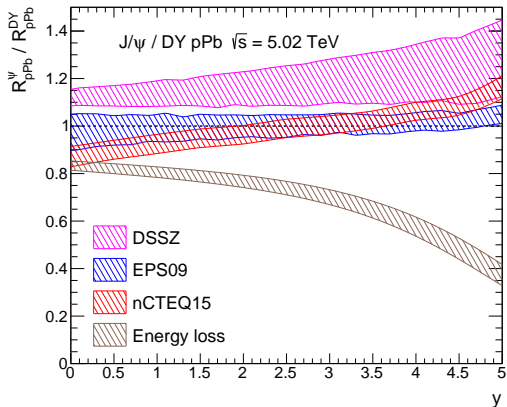
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Watanabe, Ducloué

Yet another **measurement wish**: Drell-Yan in pPb

- Affected by nPDF but not by coherent energy loss

Double ratio $\mathcal{R}^{\psi/DY}$



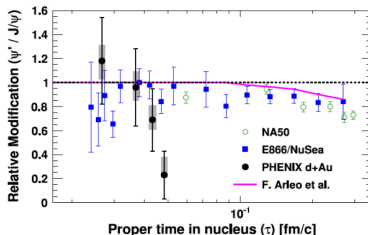
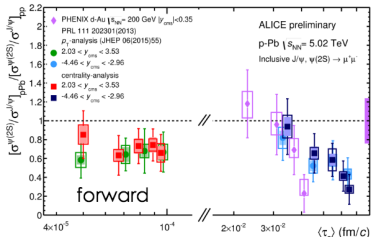
- Spectacular difference between shadowing and coherent energy loss
- Should be computed in the saturation framework too (theory wish)
- Could be measured by LHCb this year! (measurement wish) Winn
- Interesting prospects with COMPASS too (measurement wish)

Excited states in pA

- At low \sqrt{s} and/or large negative y , the stronger (2S) suppression looks nicely compatible with nuclear absorption (final-state inelastic interaction in the nucleus)
 - SPS, E866, PHENIX (?), LHC at $y \lesssim -3$ (??)
- More puzzling is the suppression at LHC at large **positive** rapidity
 - Comover effect
 - Rescattering and/or energy loss from a different color composition (**theory wish**)

Da Silva

Ferreiro



Quarkonium production and the QGP

Cooking quarkonia

In the good old days

- One hot matter effect: Debye screening (**theory wish**)
- Later 'spoiled' by comovers interaction

Ferreiro

Cooking quarkonia

In the good old days

- One hot matter effect: Debye screening (theory wish)
- Later 'spoiled' by comovers interaction

Ferreiro

30 years later

- Debye screening
- Comovers
- Gluon dissociation
- Landau damping
- Recombination

Zhou

Exciting phenomena to investigate (theory wish) but a real challenge for phenomenology

Cooking quarkonia

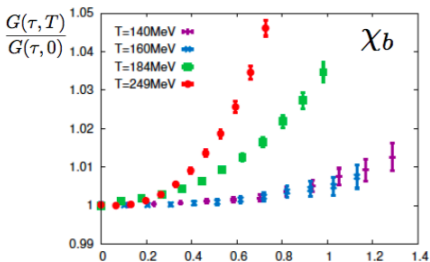
Progress on various aspects

- Hot medium effects on quarkonia Vairo
- Improved description of the produced medium and quantum evolution of quarkonia Gossiaux
- Progress on the lattice: charmonium correlators vs T Petreczky

Cooking quarkonia

Progress on various:

- Hot medium ϵ
- Improved description of quarkonia
- Progress on the



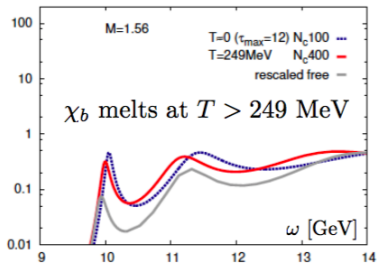
Vairo

quantum evolution

Gossiaux

T

Petreczky



Cooking quarkonia

Production process

- Timescales: $\tau_{Q\bar{Q}} \ll \tau_f \sim \tau_{QGP}$
 - ▶ Quarkonium production while inside (?) the medium
 - ▶ ... but not clear whether or not color neutralization happens before the medium is produced (CSM v. NRQCD) \rightarrow consequences at large p_{\perp}
- Need to connect with pp and pA collision data

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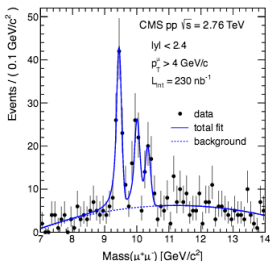
What about jet quenching?

- Above which p_{\perp} ($\gg M$?) shall we start considering energy loss and gluon radiation?
- Need to connect low $p_{\perp} \lesssim M$ and high $p_{\perp} \gg M$, especially if the (vacuum) production channels are very different

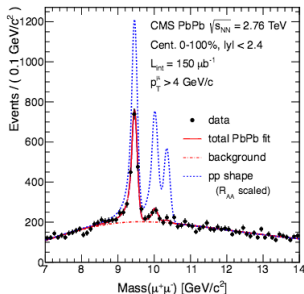
Cooking excited states

- ψ'/ψ measured by ALICE & CMS: strong constraints on the models
- Beautiful suppression hierarchy of the Υ family by CMS

Calderón de la Barca



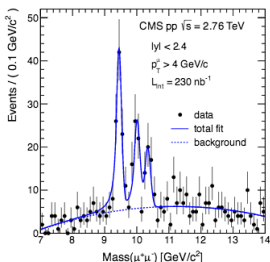
CMS: PRL 109 222301 (2012)



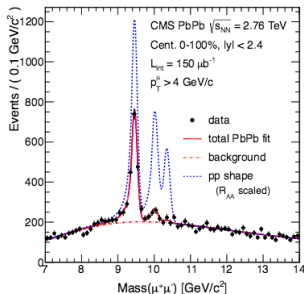
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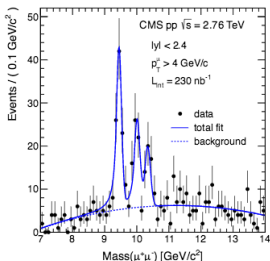


- ▶ Almost complete disappearance of $\Upsilon(3S)$ = one of the most spectacular results in heavy ions at LHC
- ▶ Same hierarchy qualitatively observed in pPb... but not in **magnitude**
- ▶ χ_c in heavy ion collisions? (**measurement wish**)

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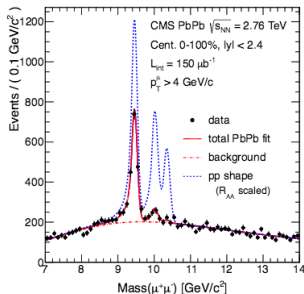
Calderón de la Barca



CMS: PRL 109 222301 (2012)

Data wish at 5 TeV

- ▶ More suppression of $\Upsilon(1S, 2S)$ states
- ▶ Less suppression of $\psi(1S, 2S)$ states
- ▶ Otherwise we would have to **rethink** (which is OK)



Summary

Quarkonium physics is rich and complicated (which makes it **more interesting**)

- Production puzzle not solved yet but...
 - ▶ Huge progress to look for new final states within well established frameworks
 - ▶ New developments on TMD and QCD factorization
- New developments on nuclear effects
 - ▶ Energy loss and saturation, on top of nPDF effects
 - ▶ Current situation slightly frustrating due to large uncertainties
 - ▶ Excited states puzzling
 - ▶ Future measurements in pA should help
- Quarkonia in QGP
 - ▶ Spectacular results at LHC: J/ψ 'enhancement' and $\Upsilon(3S)$ disappearance
 - ▶ Very complicated topic but strong interest of the theory/phenomenology community

More on QCD!

One last **wish**: learning many facets of QCD in a beautiful and relaxed environment !

QCD Masterclass

- Saturation
- Factorization
- Conformal Symmetry in QCD
- PDF's and GPD's
- Infrared structure of QCD
- QCD at Colliders

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QCD Masterclass

Date: 6–18 June 2016 (2 weeks)

Location: Saint-Jacut, in Brittany (France)

Application deadline: 15 March 2016

Website: <http://indico.cern.ch/e/QCDMasterClass>



La plage du Chatelet - Fanch Galvez

Thanks for your attention!