AFTER @ LHC

Heavy ion physics with the Pb beam

Andry Rakotozafindrabe
CEA (Saclay) IRFU

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Institut de recherche
sur les lois fondamentales
de l'Univers

Joint meeting IPN-LAL LUA9-AFTER
Orsay, France, Nov. 2013

A Fixed Target ExpeRiment at LHC

Use LHC beams on fixed target :

- LHC 7 TeV proton beam
  - $\sqrt{s} \sim 115$ GeV : p–p, p–d, p–A
- LHC 2.76 TeV lead beam
  - $\sqrt{s} \sim 72$ GeV : Pb–p, Pb–A

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  - high luminosity, high boost (y_{CMS}=4.8 @ 115 GeV), target versatility

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spin physics

PDF and nPDF at large x_B

heavy quarkonium prod. and Cold Nuclear Matter effects

W, Z prod. near threshold

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UPC

QGP studies, high precision heavy quarkonium observatory, high p_T jets

diffractive physics

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  - high luminosity, high boost (y_{CMS}=4.8 @ 115 GeV), target versatility
- multipurpose experiment, modern detection techniques

More details

- on the website : after.in2p3.fr

AFTER @ LHC

- in Phys. Rept. :

[S. Brodsky, F. Fleuret, C. Hadjidakis, J.P. Lansberg, Phys. Rep. 522 (2013) 239]

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Physics Reports

journal homepage: www.elsevier.com/locate/physrep

ELSEVIER

Physics opportunities of a fixed-target experiment using LHC beams

S.J. Brodsky [a], F. Fleuret [b], C. Hadjidakis [c], J.P. Lansberg [c,*]

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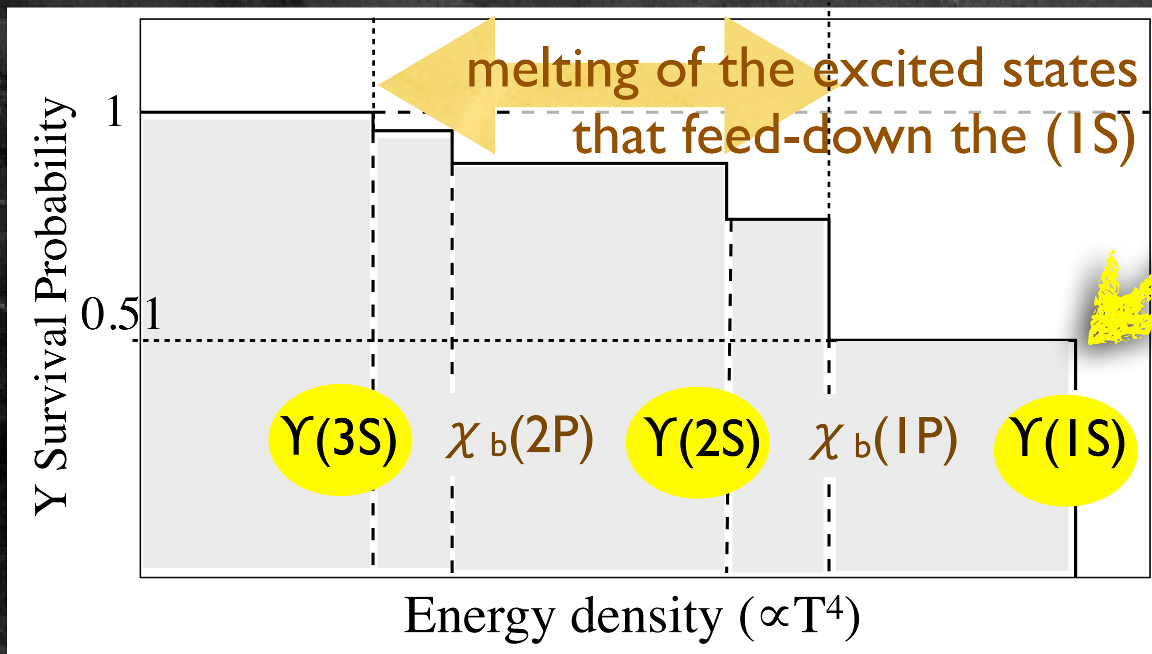
[b] *Laboratoire Leprince Ringuet, Ecole polytechnique, CNRS/IN2P3, 91128 Palaiseau, France*

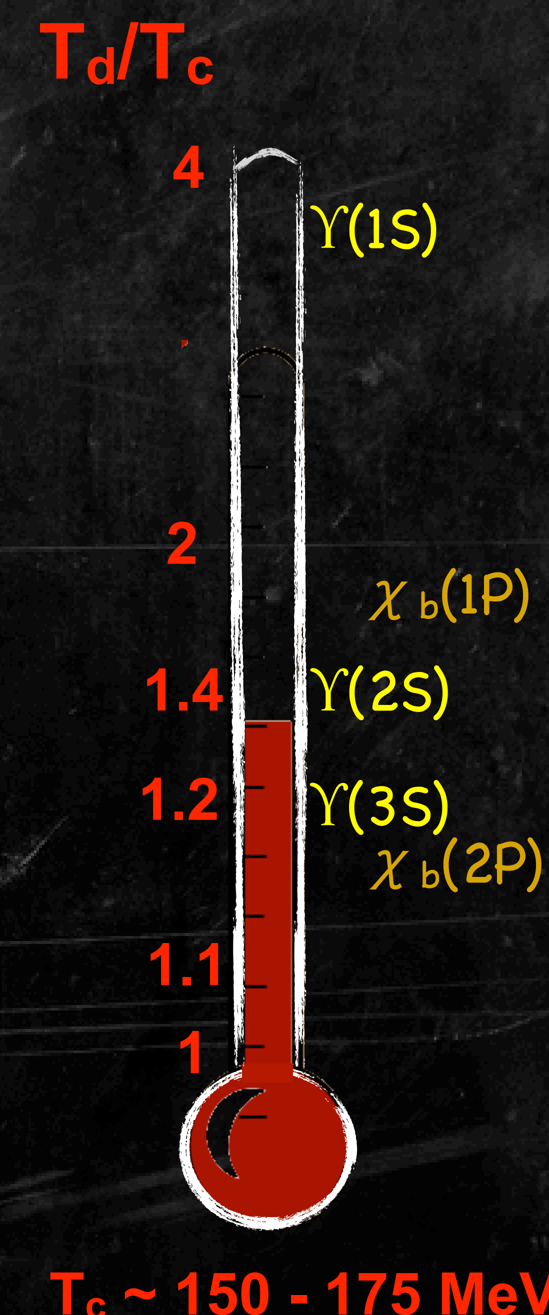
[c] *IPNO, Université Paris-Sud, CNRS/IN2P3, 91406 Orsay, France*

Sequential melting in QGP



melting of the direct Υ(1S)

Dissociation temperatures from lattice QCD (+hydro)



[Mocsy et al., Int.J.Mod.Phys. A28 (2013) 1340012]

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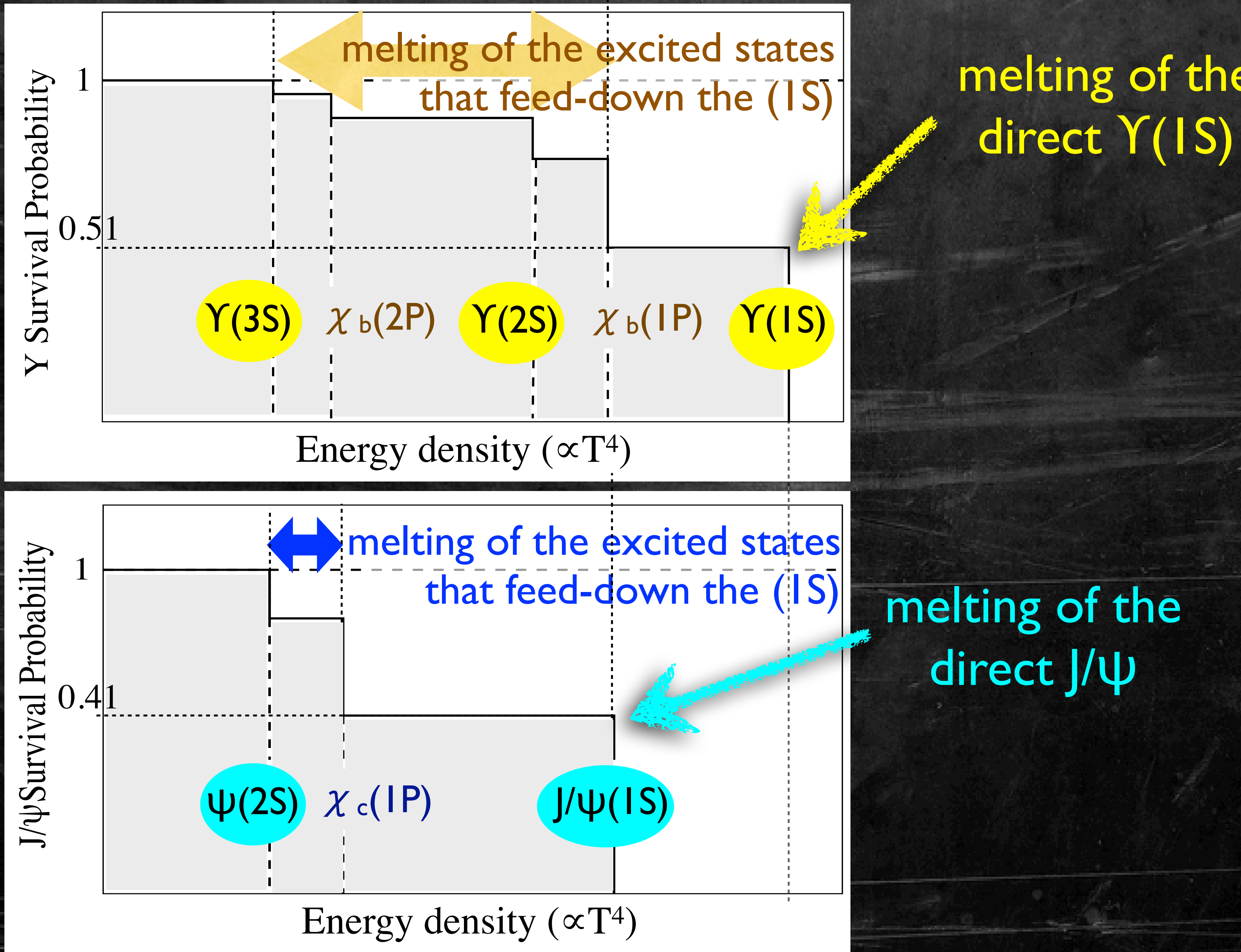

[Satz, Int.J.Mod.Phys. A28 (2013) 1330043]

Dissociation temperatures from lattice QCD (+hydro)

$T_c \sim$ 150 - 175 MeV

[Mocsy et al., Int.J.Mod.Phys. A28 (2013) 1340012]

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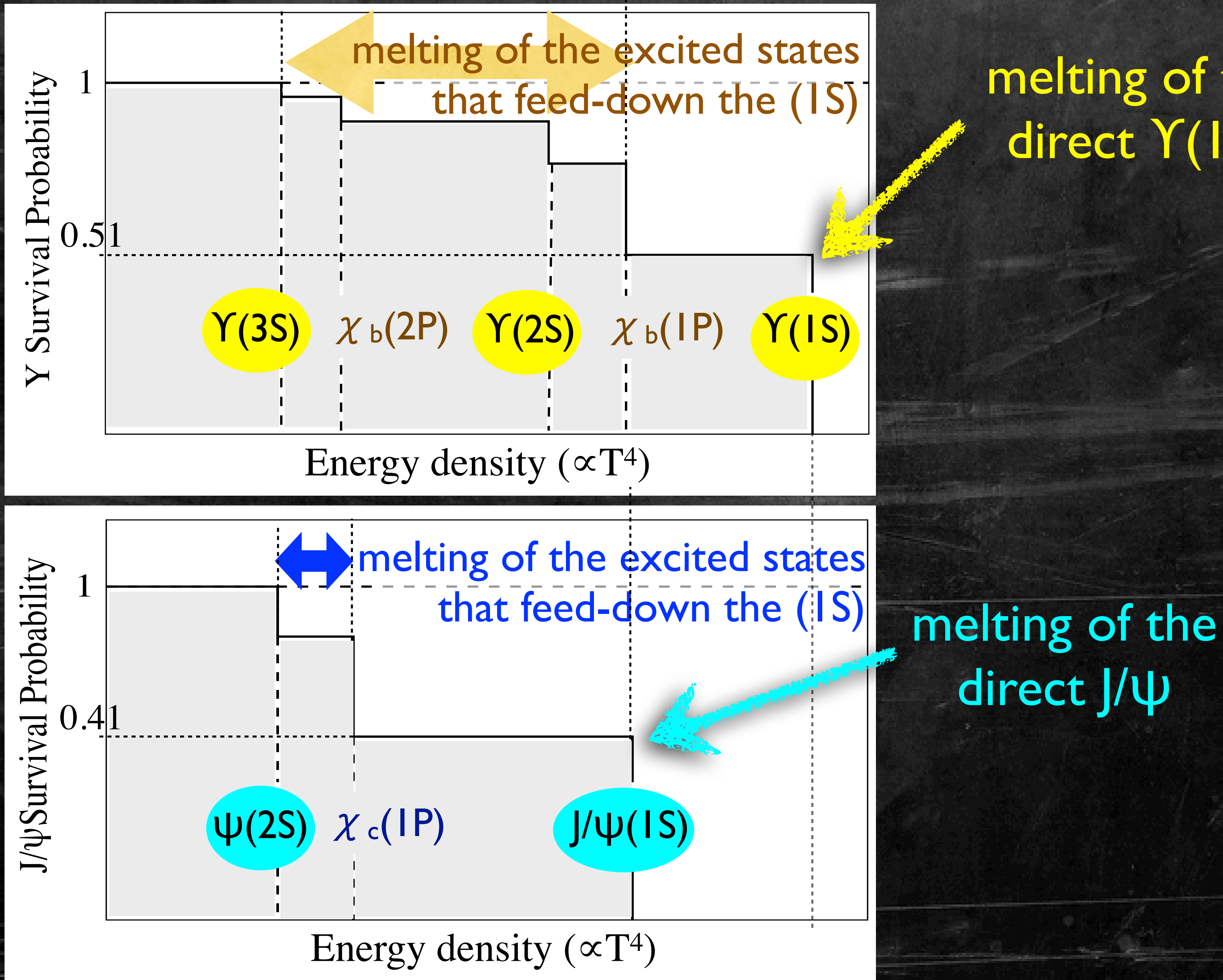

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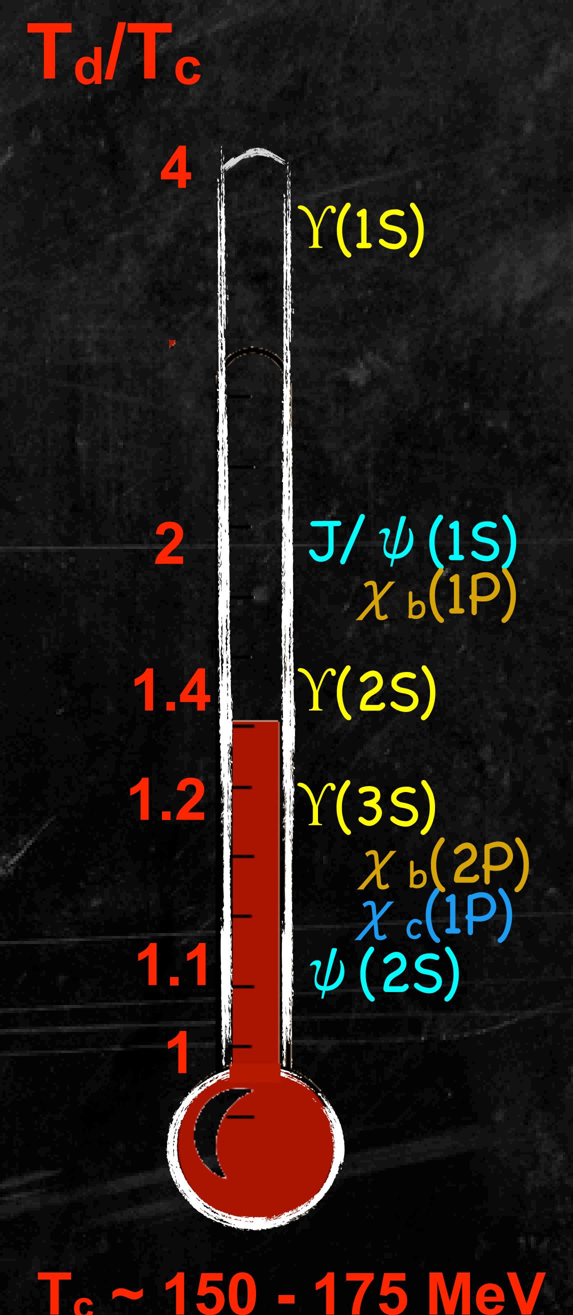
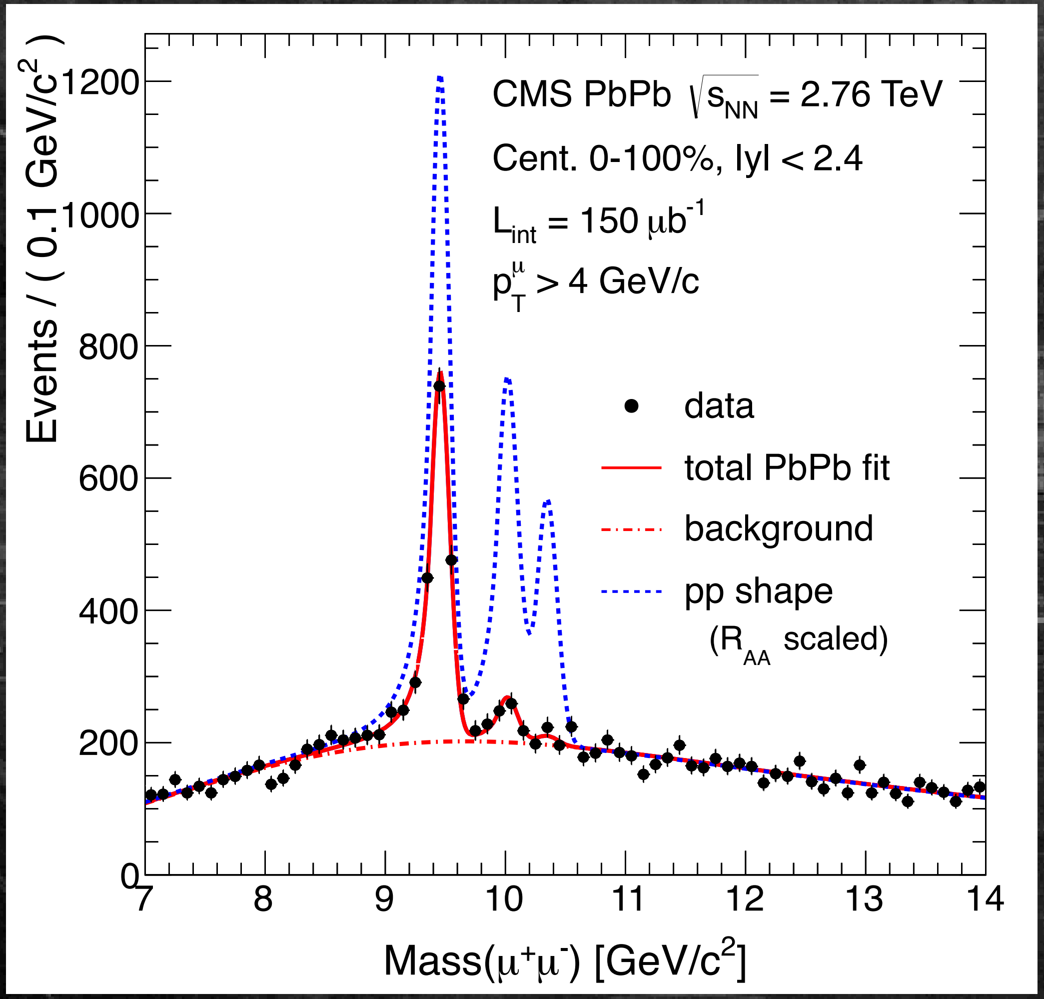


[Mocsy et al., Int.J.Mod.Phys. A28 (2013) 1340012]

- Bottomonium family : richer, broader range in T (compared to charmonium)
- Less necessary to measure χ_b(1P) state

Bottomonium sequential melting @ LHC

Serious candidate for a « textbook-like » plot
at the recent Hard Probes 2013 conference



[CMS, PRL 109 (2012) 222301]

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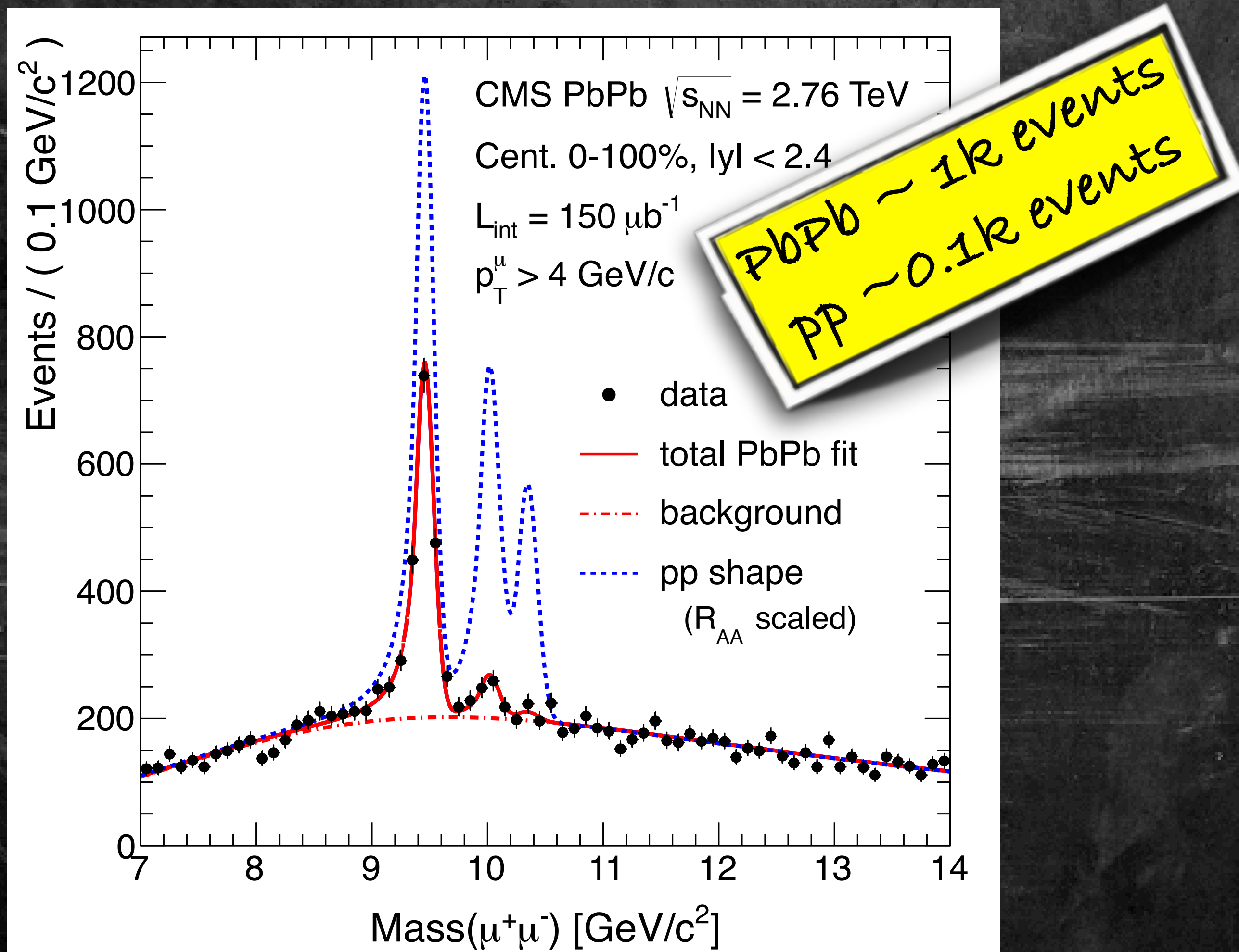

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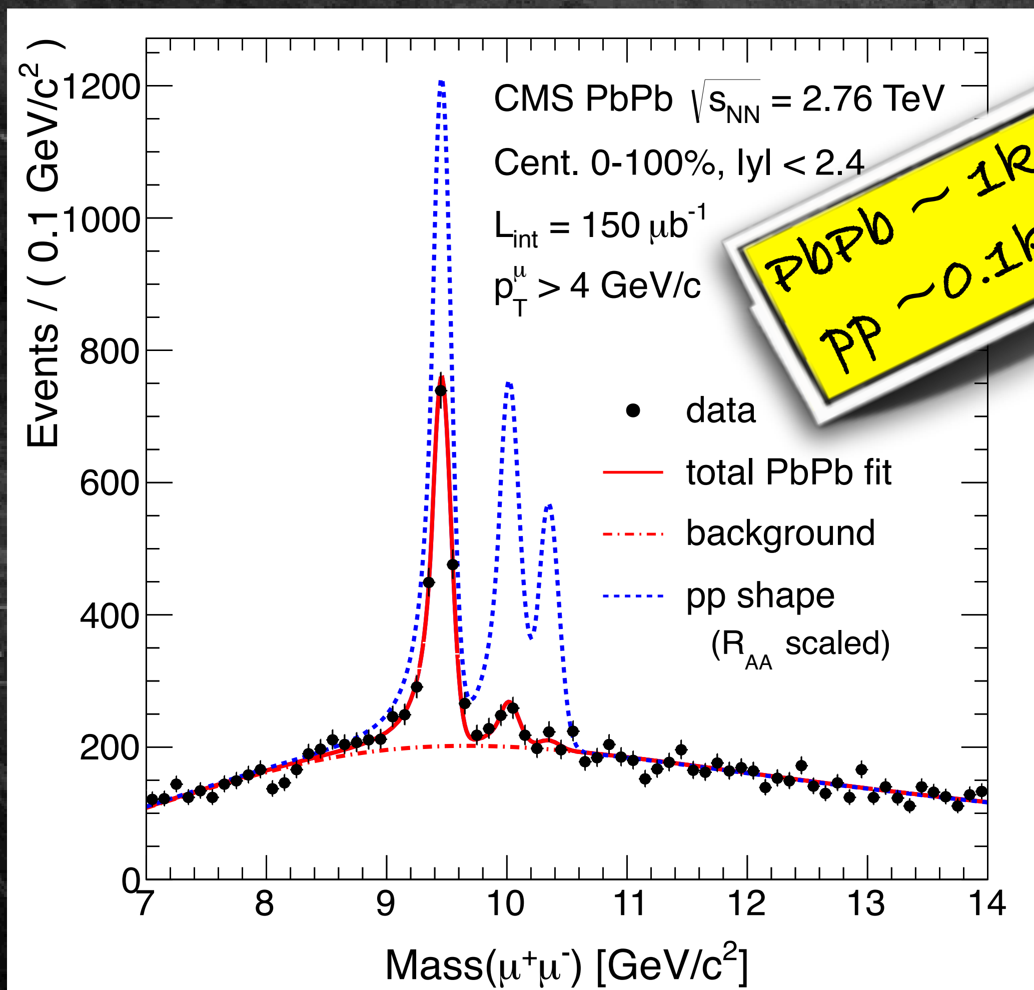

[CMS, PRL 109 (2012) 222301]

- necessary ingredients :

  high inv. mass resolution in pp and PbPb + background under control

- Sequential suppression seen :
  - (3S) completely melted ?
  - (2S) very suppressed
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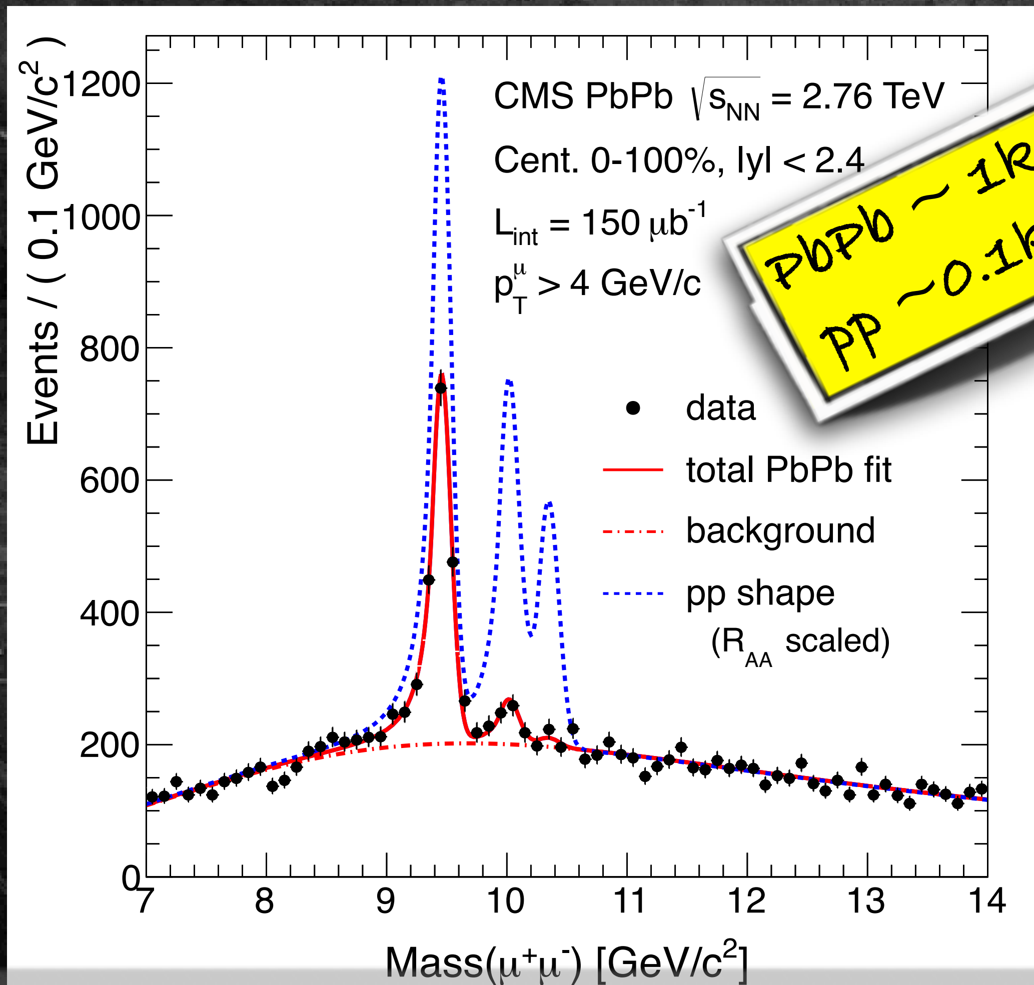

PbPb ~ 1k events
pp ~0.1k events

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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.**
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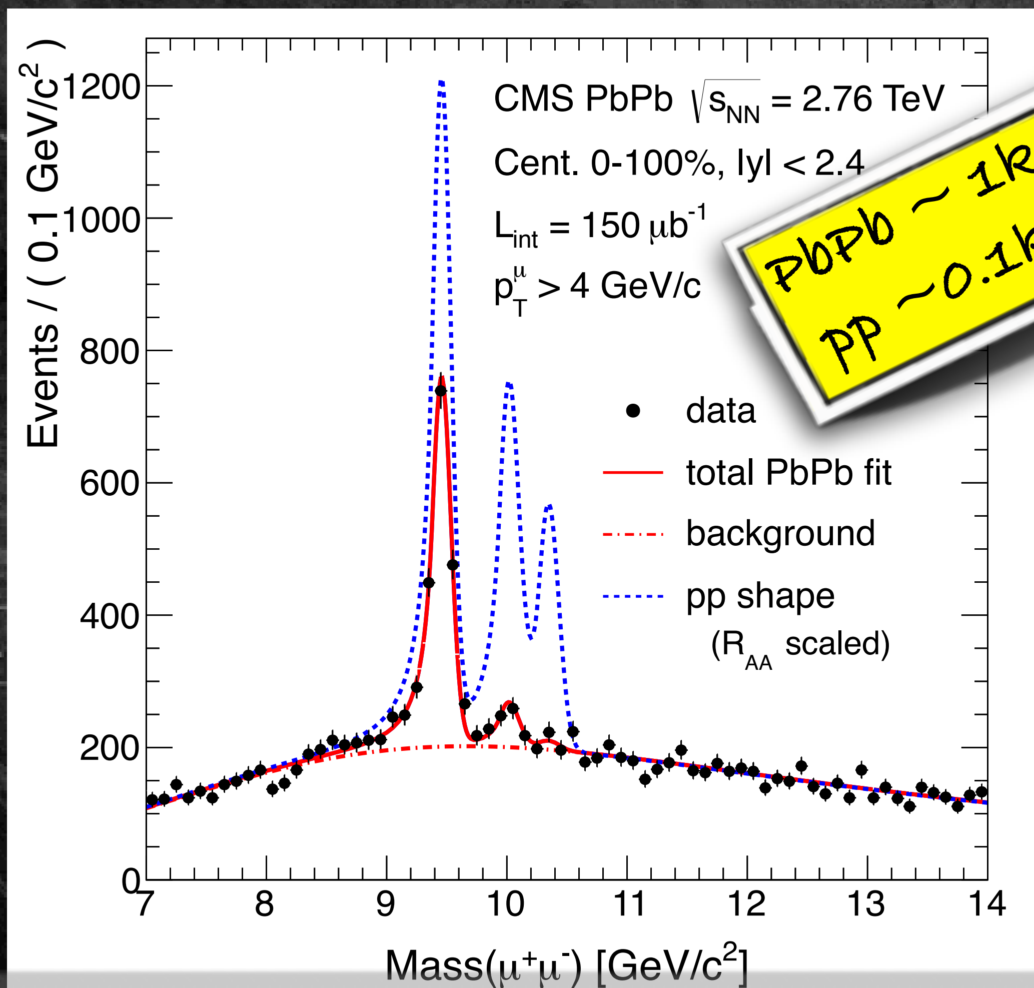

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Physics **5,** 132 (2012)

Physics

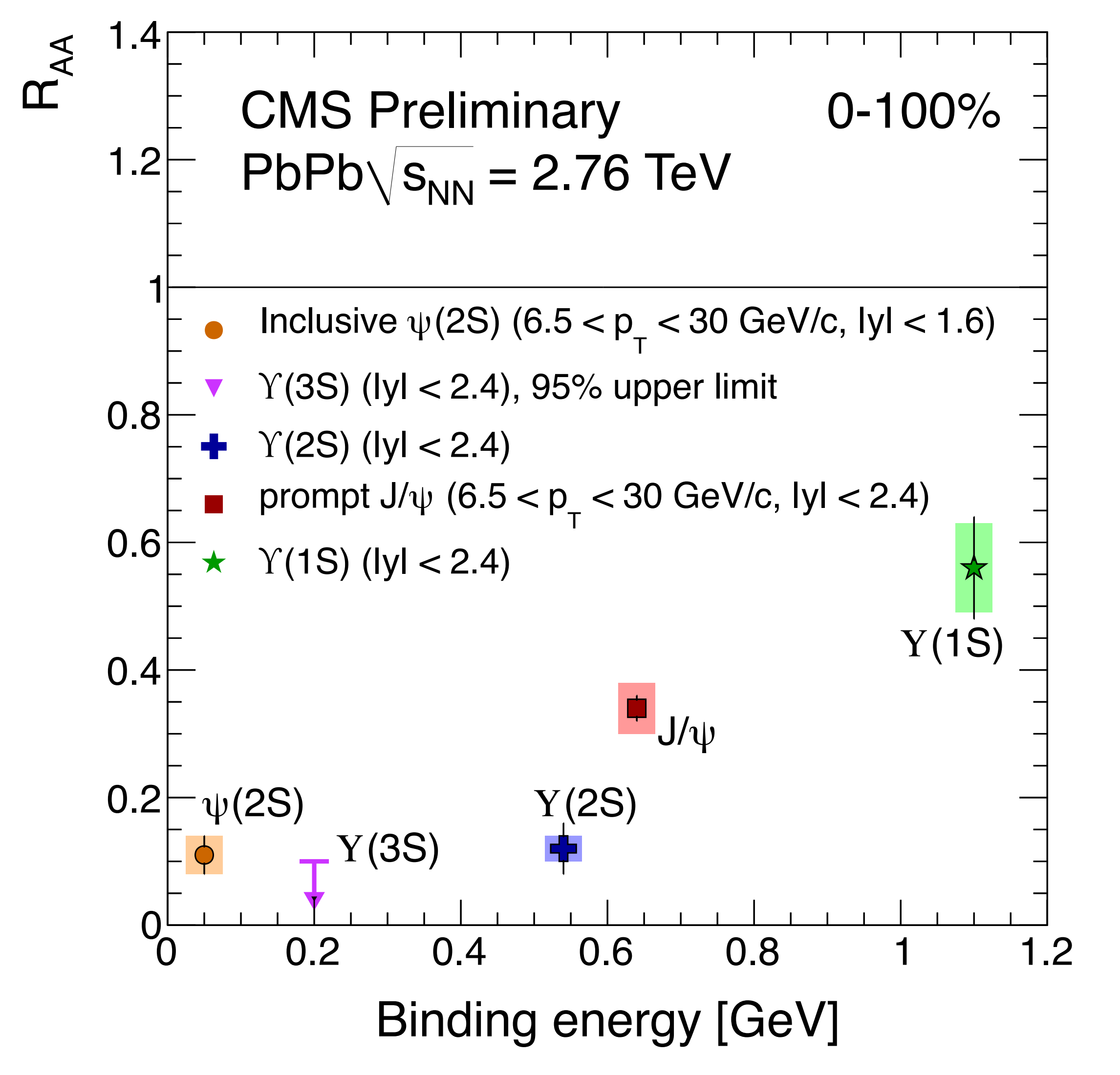
Viewpoint

New Temperature Probe for Quark-Gluon Plasma

Ramona Vogt
Lawrence Livermore National Laboratory, Livermore, CA 94551, USA and Physics Department, University of California at Davis, Davis, CA 95616, USA
Published November 26, 2012

The population of Upsilon mesons in quark-gluon plasma can be used to measure the plasma's temperature.

Sequential melting @ LHC



[Velkovska for CMS, HP2013]

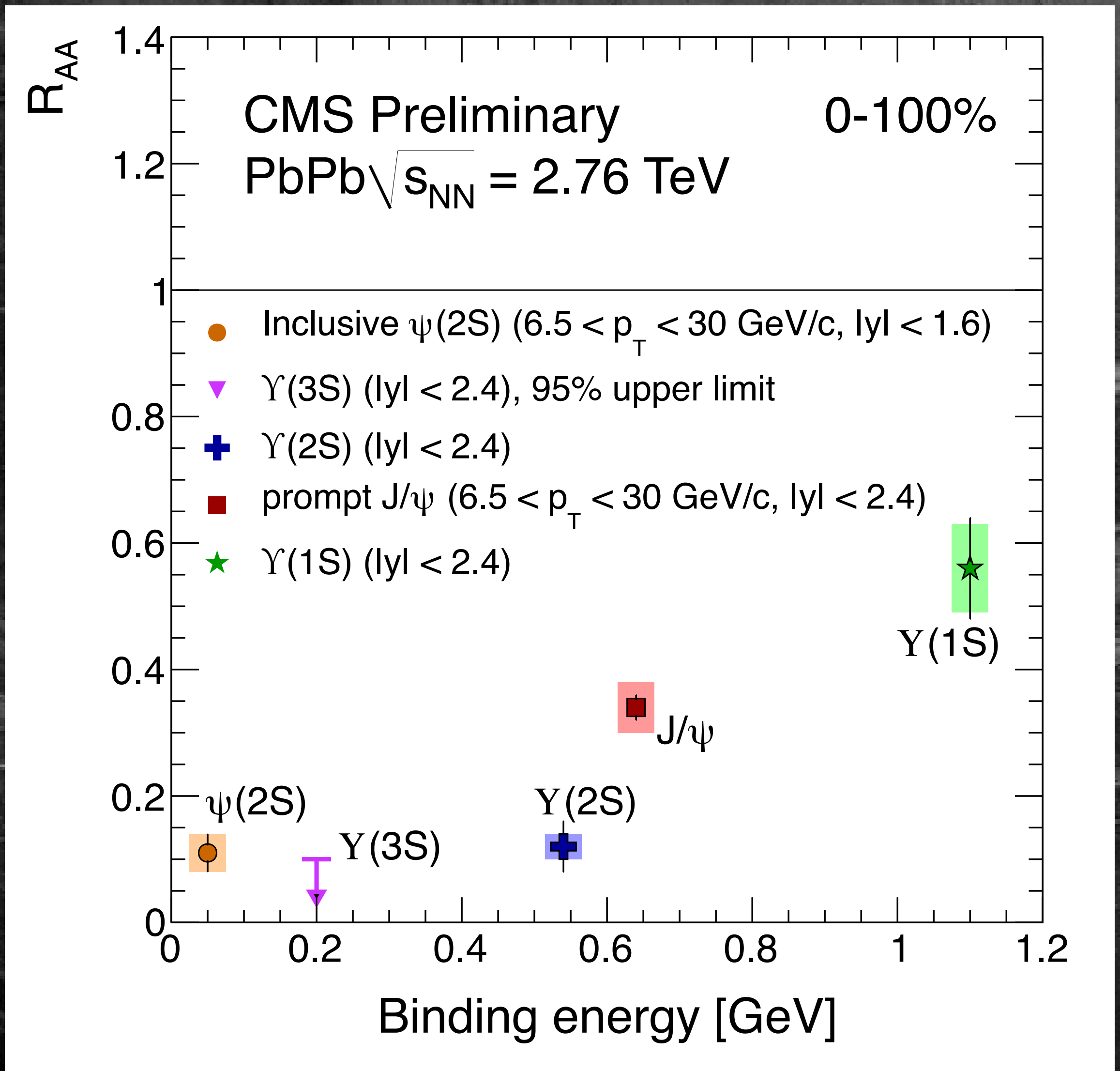
$$R_{AA} \equiv \frac{\sigma_{AA}}{\langle N_{coll}\rangle \, \sigma_{pp}}$$

- ϒ(3S) completely melted ?
- ϒ(2S) very suppressed
- direct ϒ(1S) not affected

state	R_{AA} ± stat ± syst
ϒ(1S)	0.56 ± 0.08 ± 0.07
ϒ(2S)	0.12 ± 0.04 ± 0.02
ϒ(3S)	<0.10 at 95% CL

[CMS, PRL 109 (2012) 222301]

Sequential melting @ LHC



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[CMS, PRL 109 (2012) 222301]

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If the sequential suppression is due to QGP effects *only*, what is the temperature reached @ LHC ?

- rough guess 1.4 T_c (~230 MeV) < T< 4 T_c (~600 MeV)
- lattice QCD + hydro evolution : $T_{initial}$ ~ 550 MeV > T

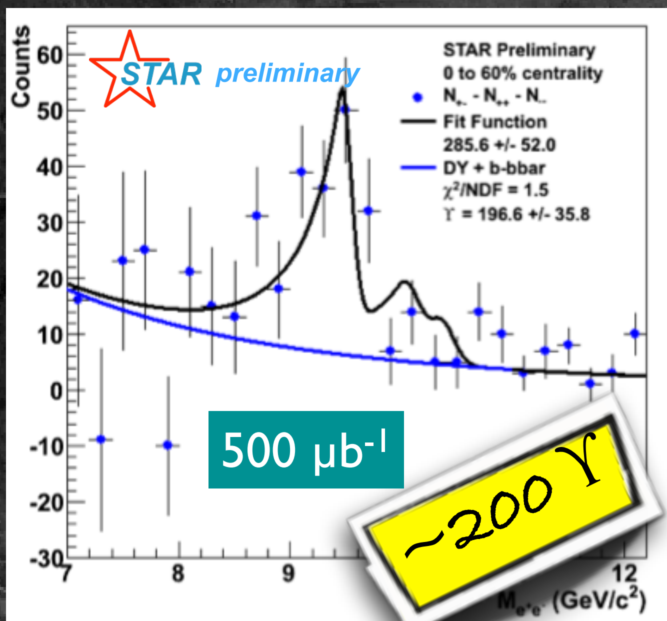
[Strickland et al., NPA 879 (2012) 25-58]

Measurement (thermal photons, dominant at low p_T) : T_{avg} ~ 304 ± 51 MeV (0-40% PbPb)

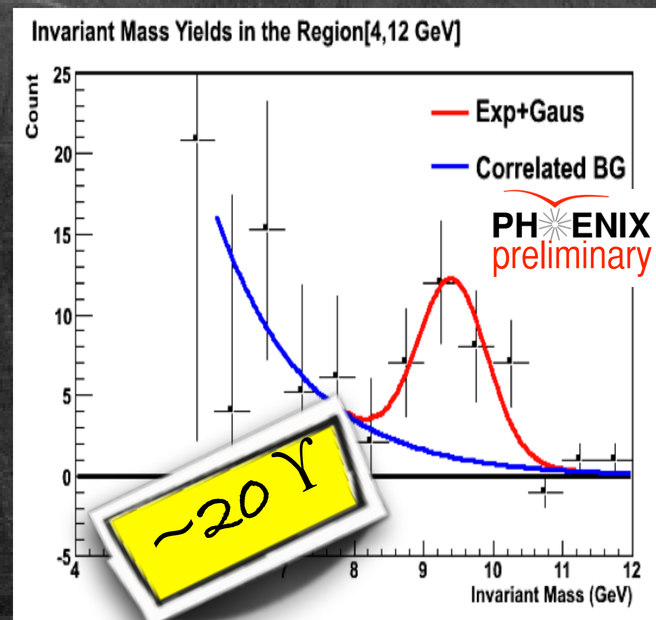
[Alice, NPA 904 (2013) 573c]

Υ(1S + 2S + 3S) melting @ RHIC

AuAu@200GeV (STAR run 2007, PHENIX run 2010)

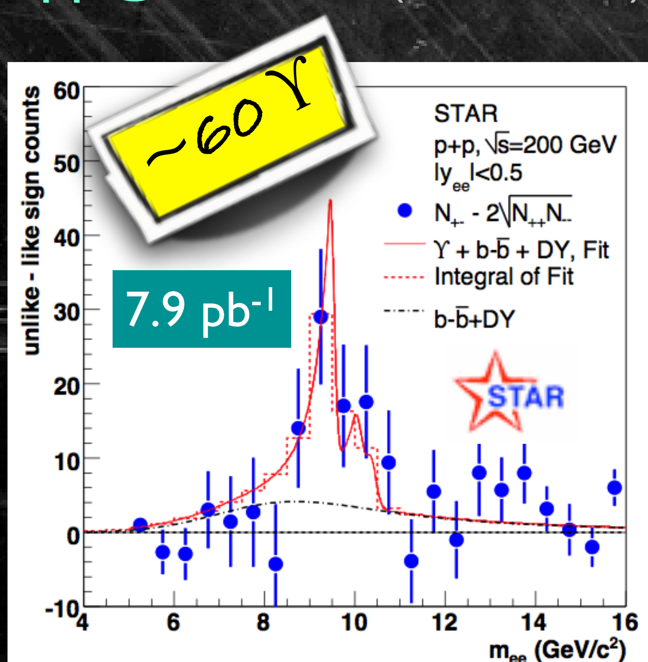


[Reed for STAR, JPG 38 (2011) 124185]

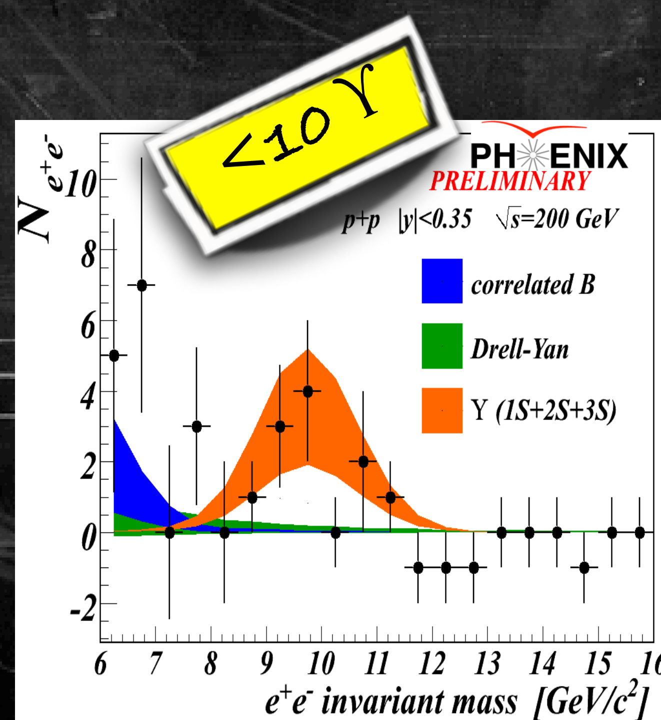


[Whitaker for PHENIX, poster at QM2012]

pp@200GeV (run 2006)



[STAR, PRD 82 (2010) 012004]



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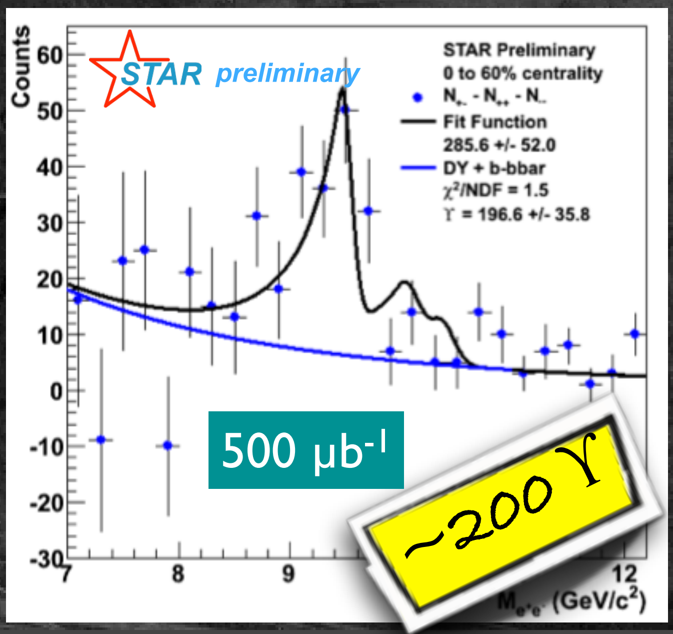

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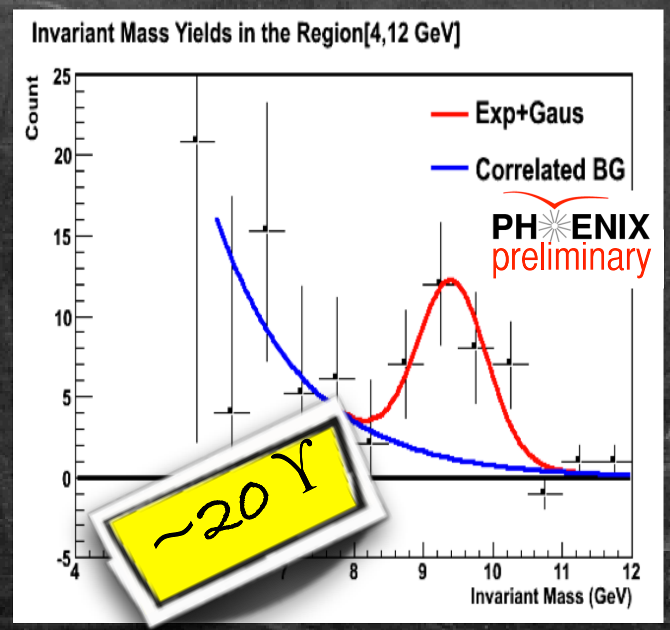

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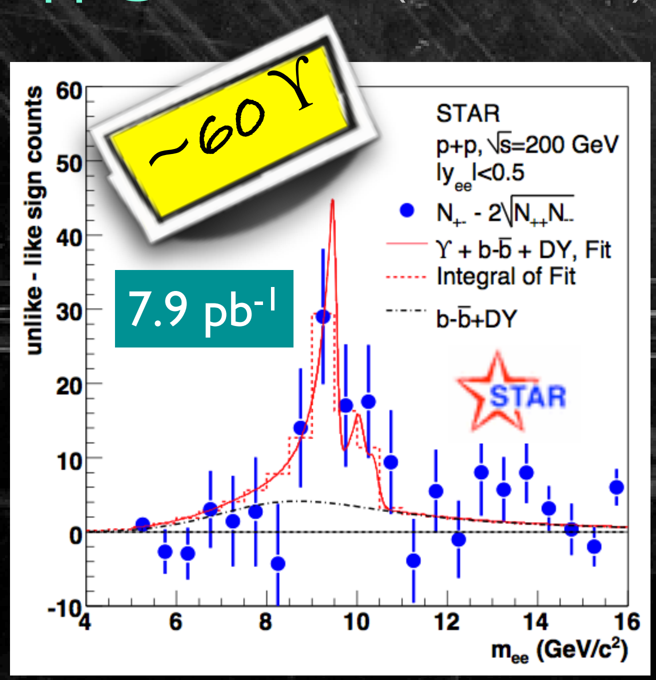

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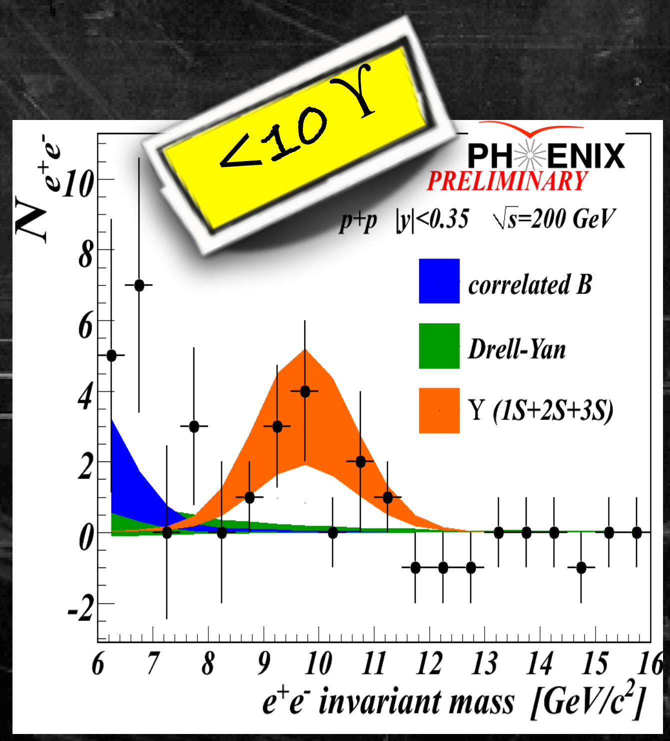

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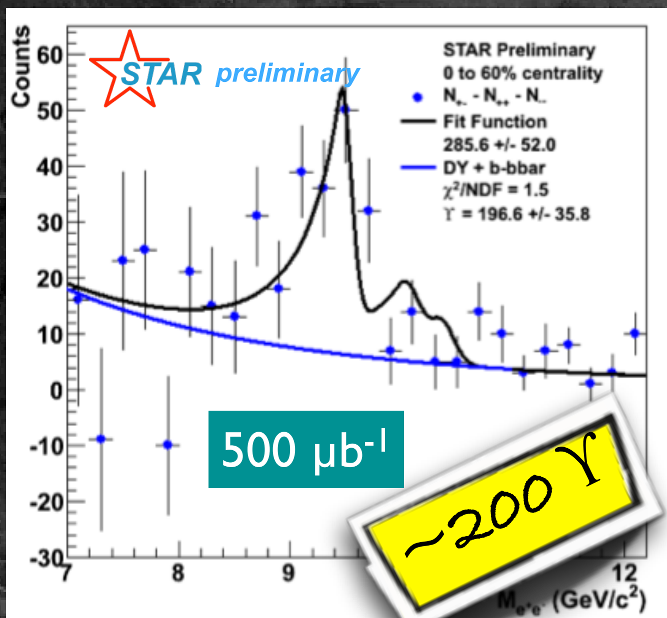

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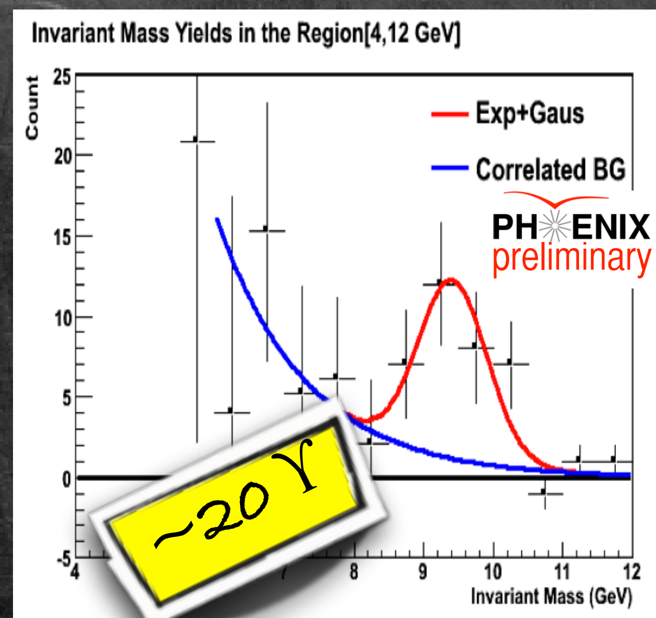

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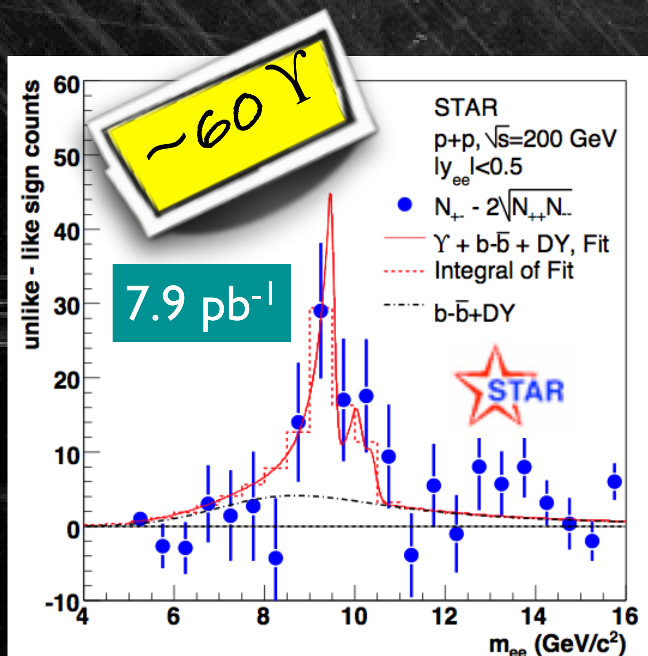
specific R_{AA} computation for PHENIX :
pp J/ψ, Υ run 2006
AuAu Υ run 2010

$$R_{AA}(\Upsilon) = \frac{[N(\Upsilon)/N(J/\psi)]_{AA}}{[N(\Upsilon)/N(J/\psi)]_{pp}} \times R_{AA}(J/\psi)$$

pp@200GeV (run 2006)



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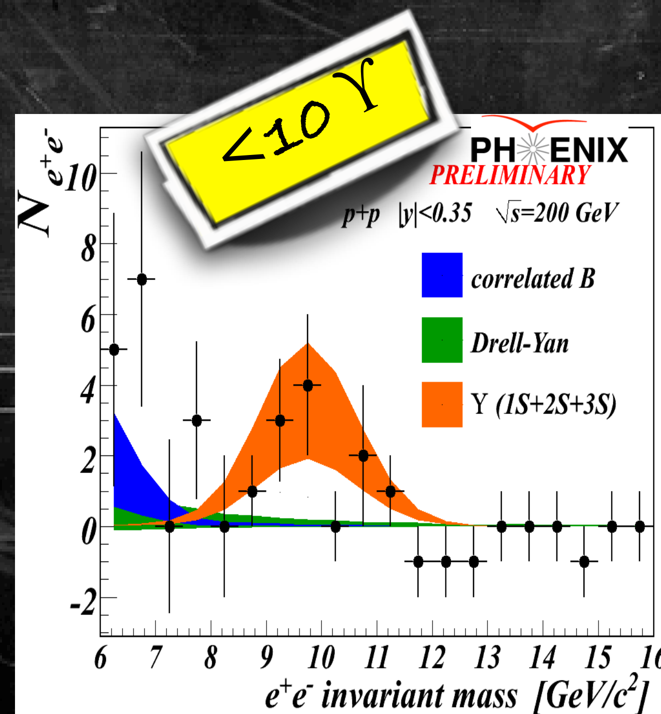

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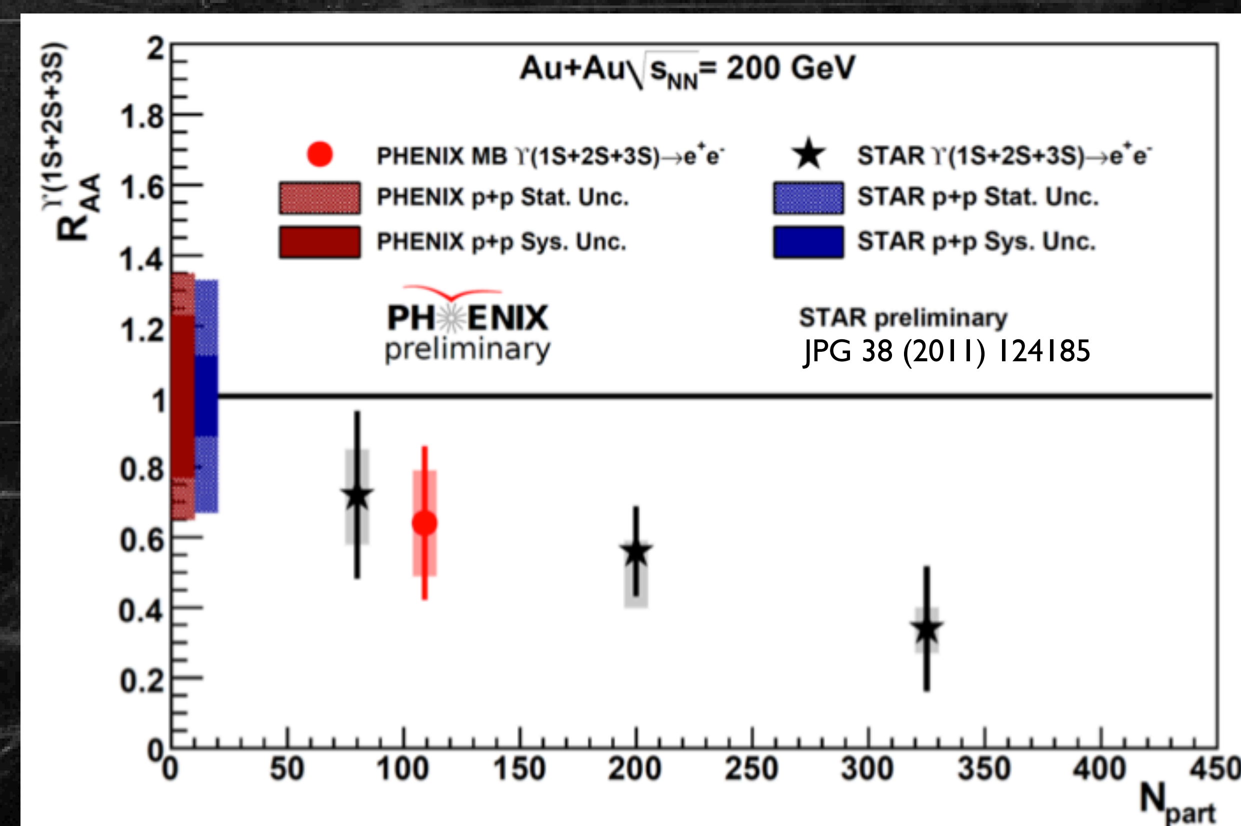

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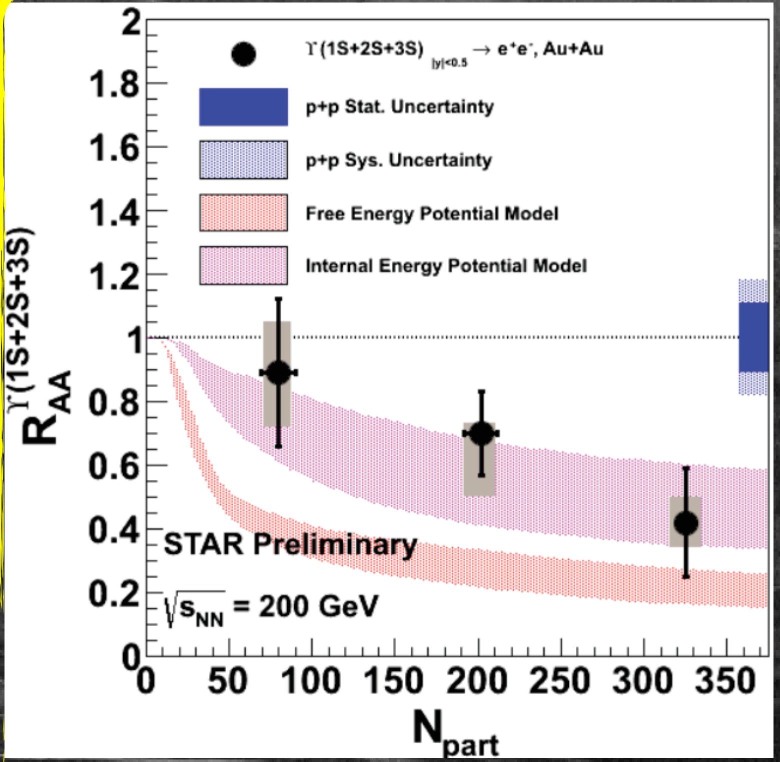
Bottomonium studies: from RHIC to AFTER



[Bielcik for STAR, HP2013]

Today :

- inclusive ϒ R_{AA} vs centrality
- the most central point is compatible with a complete melting of (3S) and a very strong suppression of (2S), with $T_{initial}$ ~ 430 MeV in this model

From thermal photon p_T spectra :

T_{avg} = 221 ± 19 (stat) ± 19 (syst) MeV

(0-20% AuAu)

[PHENIX, PRL. 104 (2010) 132301]

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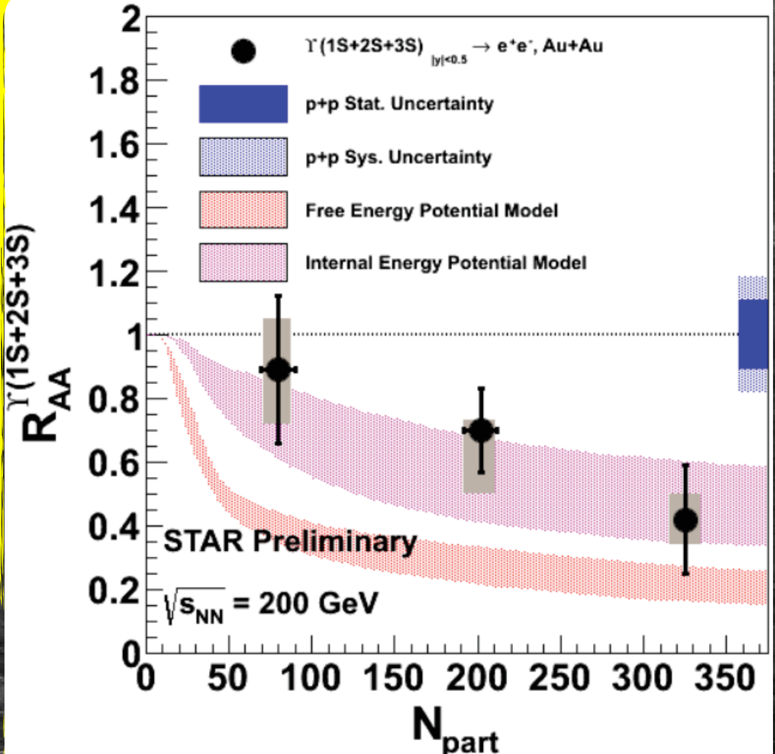

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(0-20% AuAu) *[PHENIX, PRL. 104 (2010) 132301]*

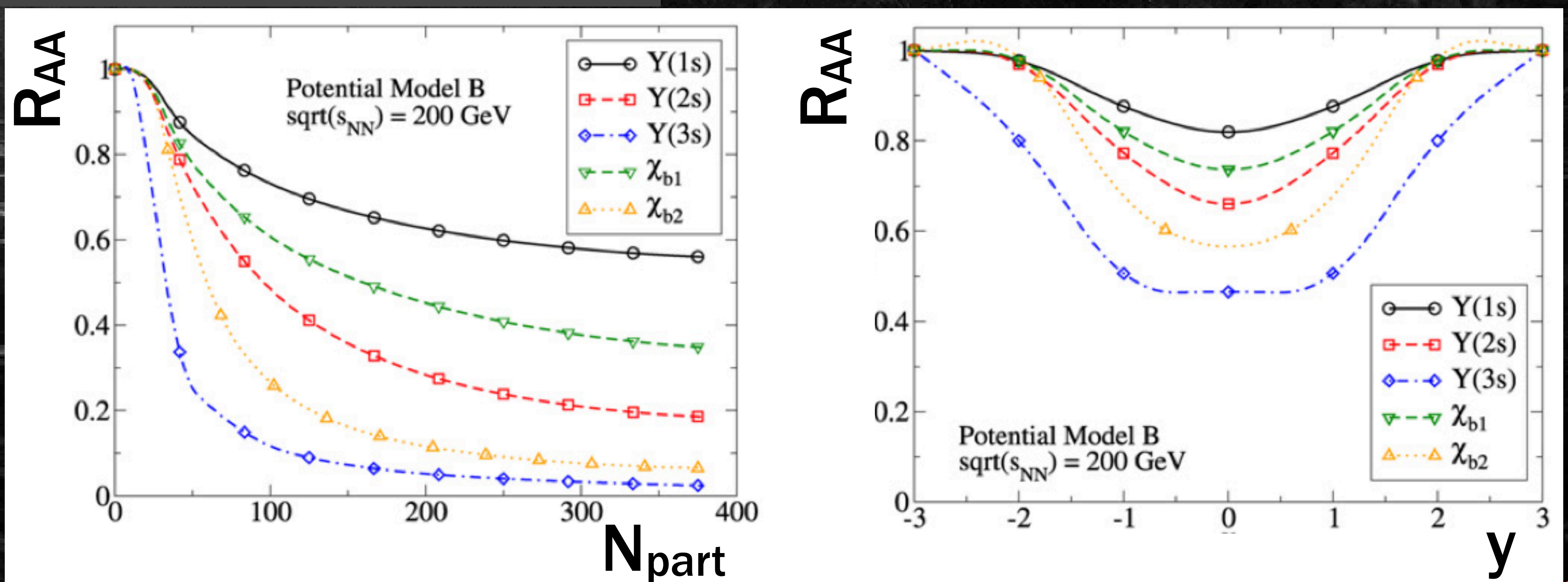
decompose this model into each state

need more stat in AA + very good resolution

reminder
STAR : ~200 Υ
CMS : ~1k Υ

[Strickland et al., NPA 879 (2012) 25-58]

The dreamed measurements :



AFTER : inclusive Υ yield in PbA @ √s = 72 GeV

integrated luminosity (nb^{-1} $year^{-1}$)

yield / unit of y @ y = 0

	Target	$\int dt \mathcal{L}$	$\mathcal{B}_{\ell\ell} \frac{dN_{\Upsilon}}{dy}\Big\|_{y=0}$
AFTER	10 cm solid H	110	$8.9\ 10^2$
	10 cm liquid H	83	$6.9\ 10^2$
	10 cm liquid D	100	$1.6\ 10^3$
	1 cm Be	25	$1.9\ 10^3$
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RHIC lumi. from PHENIX decadal plan (run plan 2011-2015)

[S. Brodsky, F. Fleuret, C. Hadjidakis, J.P. Lansberg, Phys. Rep. 522 (2013) 239]

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PbA : at y = 0 within one unit of y

same stat. w.r.t. RHIC @ 200 GeV and LHC

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10^2 x RHIC @ 62 GeV

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[S. Brodsky, F. Fleuret, C. Hadjidakis, J.P. Lansberg, Phys. Rep. 522 (2013) 239]

PbA : at y = 0 within one unit of y

same stat. w.r.t. RHIC @ 200 GeV and LHC

10^2 x RHIC @ 62 GeV

RHIC lumi. from PHENIX decadal plan (run plan 2011-2015)

could be enhanced by the total number of rapidity units to be covered by AFTER

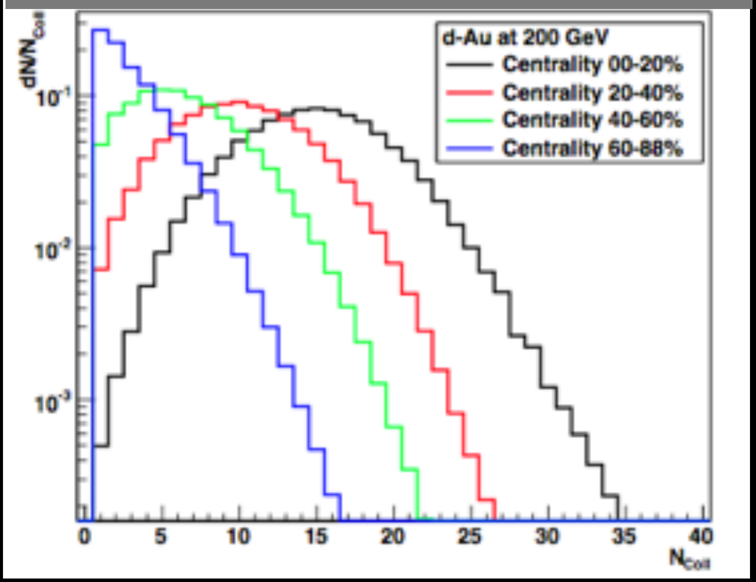
Towards a Cold Effect reference : gluon nPDF

p–A

Pb–p

- A dependence thanks to target versatility

[PHENIX, arXiv:1204.0777]



<N_{coll}> dependence ⇛ A dependence (à la NA50, NA60)

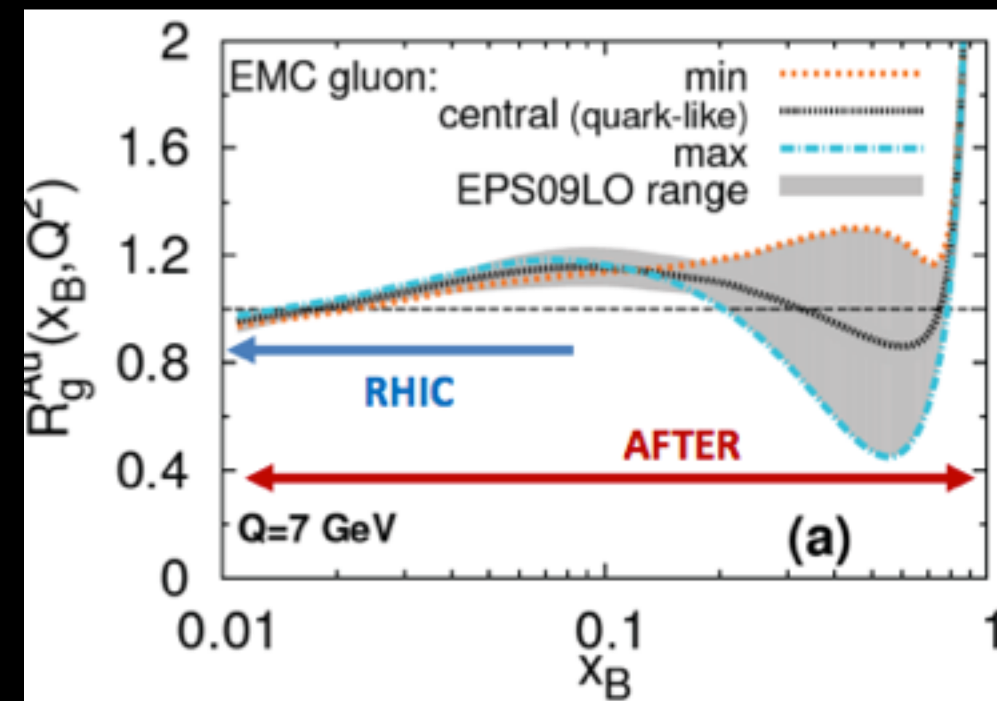
Towards a Cold Effect reference : gluon nPDF

p−A

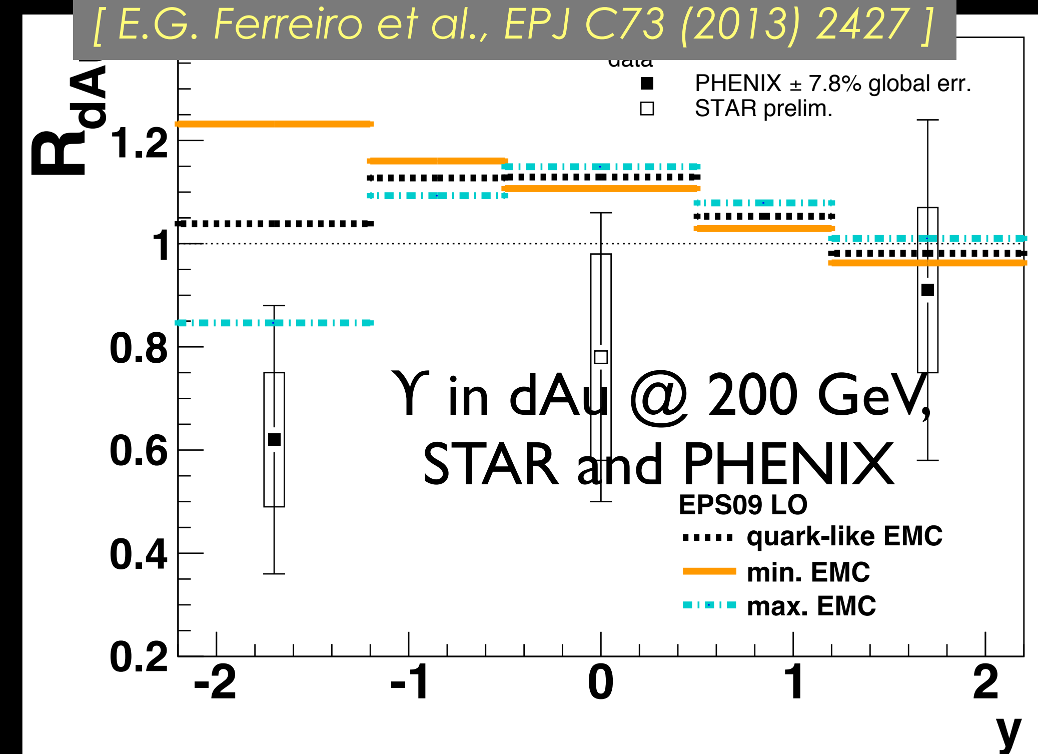
Pb−p

- A dependence thanks to target versatility
- nuclear PDF from intermediate to high x : antishadowing , EMC region , Fermi motion
- extraction using quarkonia, isolated photons, photon-jet correlation

nuclear modification of g PDF in Au



[E.G. Ferreiro et al., EPJ C73 (2013) 2427]



Towards a Cold Effect reference : gluon nPDF

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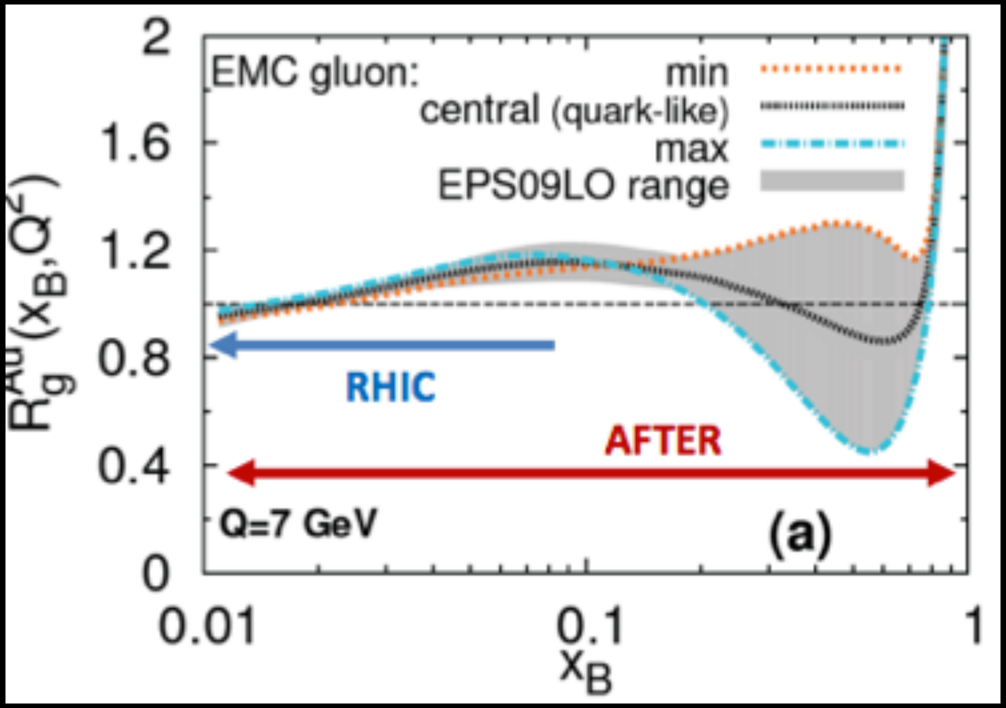
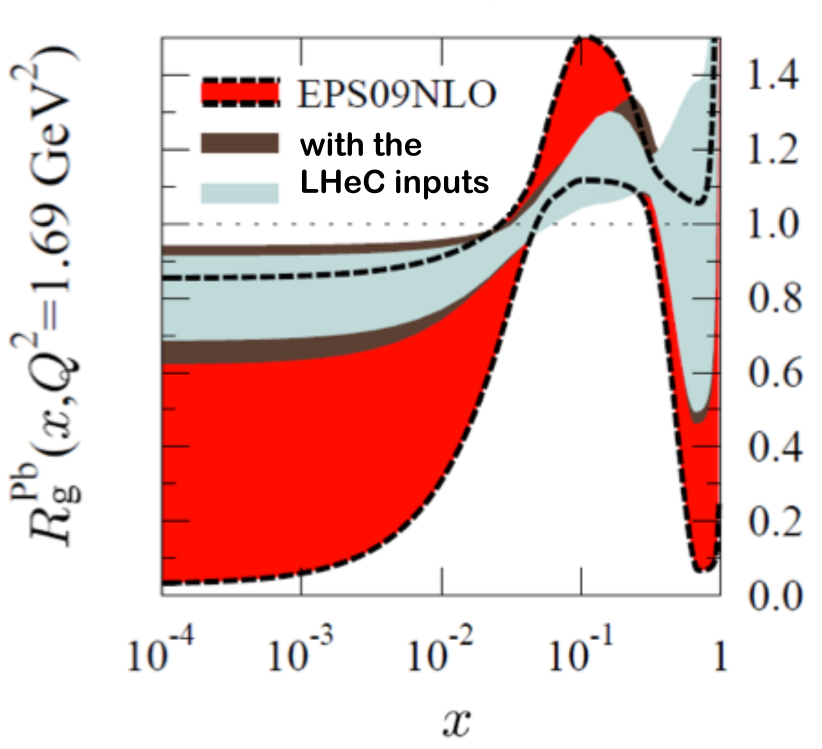


nuclear modification of g PDF in Pb



[LHeC CDR, J. Phys. G 39 (2012) 075001]

complementary with LHeC (focus at low x)

Heavy Quarkonium yields in pH, pA

yield / dy (fb^{-1} $year^{-1}$) @ $\sqrt{s}$ = 115 GeV

J/ψ ↓ ϒ ↓

	Target	$\int dt \mathcal{L}$		$\mathcal{B}_{\ell\ell} \frac{dN_{J/\psi}}{dy}\Big\|_{y=0}$	$\mathcal{B}_{\ell\ell} \frac{dN_{\Upsilon}}{dy}\Big\|_{y=0}$
AFTER	10 cm solid H	2.6		$5.2\ 10^{7}$	$1.0\ 10^{5}$
	10 cm liquid H	2		$4.0\ 10^{7}$	$8.0\ 10^{4}$
	10 cm liquid D	2.4		$9.6\ 10^{7}$	$1.9\ 10^{5}$
	1 cm Be	0.62		$1.1\ 10^{8}$	$2.2\ 10^{5}$
	1 cm Cu	0.42		$5.3\ 10^{8}$	$1.1\ 10^{6}$
	1 cm W	0.31		$1.1\ 10^{9}$	$2.3\ 10^{6}$
	1 cm Pb	0.16		$6.7\ 10^{8}$	$1.3\ 10^{6}$
LHC	pp low P_T LHC (14 TeV)	0.05	ALICE	$3.6\ 10^{7}$	$1.8\ 10^{5}$
		2	LHCb	$1.4\ 10^{9}$	$7.2\ 10^{6}$
	pPb LHC (8.8 TeV)	10^{-4}		$1.0\ 10^{7}$	$7.5\ 10^{4}$
RHIC	pp RHIC (200 GeV)	$1.2\ 10^{-2}$		$4.8\ 10^{5}$	$1.2\ 10^{3}$
	dAu RHIC (200 GeV)	$1.5\ 10^{-4}$		$2.4\ 10^{6}$	$5.9\ 10^{3}$
	dAu RHIC (62 GeV)	$3.8\ 10^{-6}$		$1.2\ 10^{4}$	$1.8\ 10^{1}$

RHIC lumi. from PHENIX decadal plan (run plan 2011-2015)

[S. Brodsky, F. Fleuret, C. Hadjidakis, J.P. Lansberg, Phys. Rep. 522 (2013) 239]

Heavy Quarkonium yields in pH, pA

yield / dy (fb^{-1} $year^{-1}$) @ $\sqrt{s}$ = 115 GeV

	Target	$\int dt\mathcal{L}$	$\mathcal{B}_{\ell\ell}\frac{dN_{J/\psi}}{dy}\Big\vert_{y=0}$ (J/ψ)	$\mathcal{B}_{\ell\ell}\frac{dN_{\Upsilon}}{dy}\Big\vert_{y=0}$ (ϒ)
AFTER	10 cm solid H	2.6	$5.2\ 10^7$	$1.0\ 10^5$
AFTER	10 cm liquid H	2	$4.0\ 10^7$	$8.0\ 10^4$
AFTER	10 cm liquid D	2.4	$9.6\ 10^7$	$1.9\ 10^5$
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pp : 100 x RHIC, comparable to LHCb

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Heavy Quarkonium yields in pH, pA

yield / dy (fb^{-1} $year^{-1}$) @ $\sqrt{s}$ = 115 GeV

	Target	$\int dt \mathcal{L}$		J/ψ: $\mathcal{B}_{\ell\ell} \frac{dN_{J/\psi}}{dy}\Big\vert_{y=0}$	Υ: $\mathcal{B}_{\ell\ell} \frac{dN_{\Upsilon}}{dy}\Big\vert_{y=0}$
AFTER	10 cm solid H	2.6		5.2 10^7	1.0 10^5
AFTER	10 cm liquid H	2		4.0 10^7	8.0 10^4
AFTER	10 cm liquid D	2.4		9.6 10^7	1.9 10^5
AFTER	1 cm Be	0.62		1.1 10^8	2.2 10^5
AFTER	1 cm Cu	0.42		5.3 10^8	1.1 10^6
AFTER	1 cm W	0.31		1.1 10^9	2.3 10^6
AFTER	1 cm Pb	0.16		6.7 10^8	1.3 10^6
LHC	*pp* low P_T LHC (14 TeV)	0.05	ALICE	3.6 10^7	1.8 10^5
LHC	*pp* low P_T LHC (14 TeV)	2	LHCb	1.4 10^9	7.2 10^6
LHC	*p*Pb LHC (8.8 TeV)	10^{-4}		1.0 10^7	7.5 10^4
RHIC	*pp* RHIC (200 GeV)	1.2 10^{-2}		4.8 10^5	1.2 10^3
RHIC	*d*Au RHIC (200 GeV)	1.5 10^{-4}		2.4 10^6	5.9 10^3
RHIC	*d*Au RHIC (62 GeV)	3.8 10^{-6}		1.2 10^4	1.8 10^1

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RHIC lumi. from PHENIX decadal plan (run plan 2011-2015)

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pA : 10^{2}-10^{3} x RHIC

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J/ψ ↓ Υ ↓

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[S. Brodsky, F. Fleuret, C. Hadjidakis, J.P. Lansberg, Phys. Rep. 522 (2013) 239]

pp : 100 x RHIC, comparable to LHCb

pA : 10^2-10^3 x RHIC

RHIC lumi. from PHENIX decadal plan (run plan 2011-2015)

Recycle the LHC beam loss → a luminosity comparable to the LHC itself !

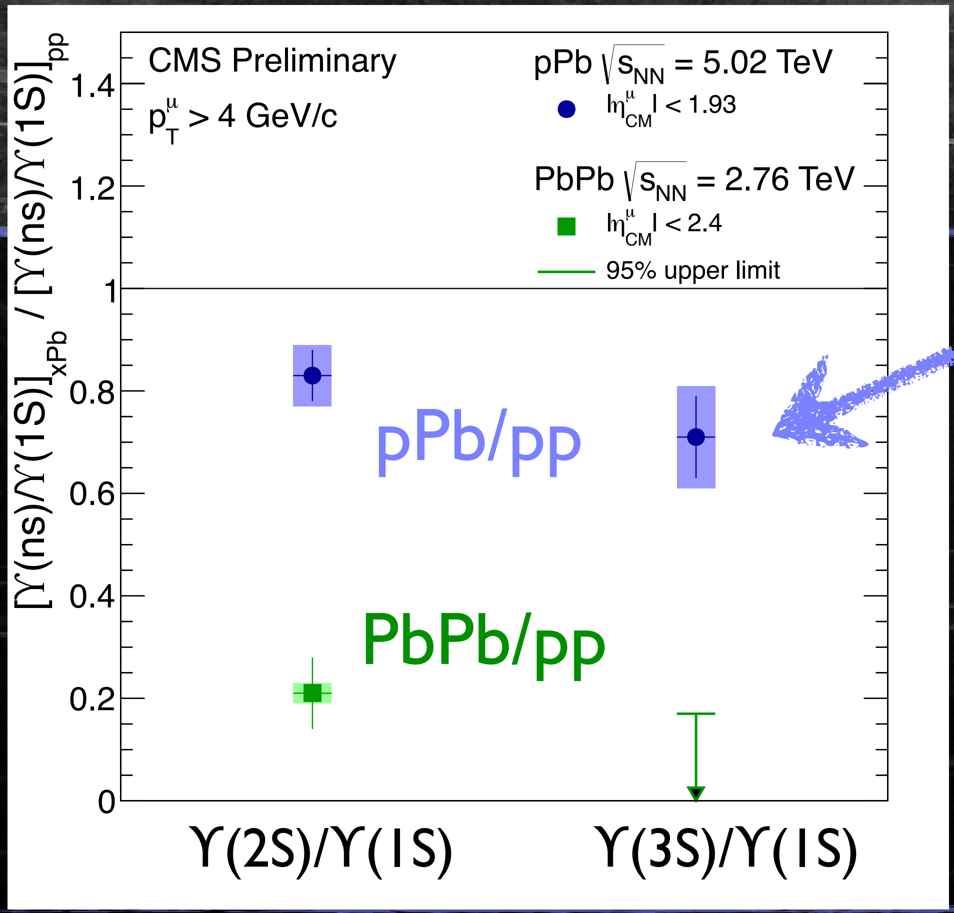
Bottomonium : a cleaner QGP probe ?

- better understanding of pp ?
- in QGP : negligible regeneration effects
  - ➡ no dilution of the « thermometer-like » behaviour of the bottomonium family

Bottomonium : a cleaner QGP probe ?

- better understanding of pp ?
- in QGP : negligible regeneration effects
  - ➡ no dilution of the « thermometer-like » behaviour of the bottomonium family

pPb vs. pp: excited states suppressed more than the ground state in pPb compared to pp collisions (significance < 3σ)



[Benhabib for CMS, HP2013]

Cold effects (i.e. not QGP) :

- non-trivial effects seen in pA
- need more studies and precise measurements
  - ➡ can be beautifully addressed by AFTER

Summary and outlooks

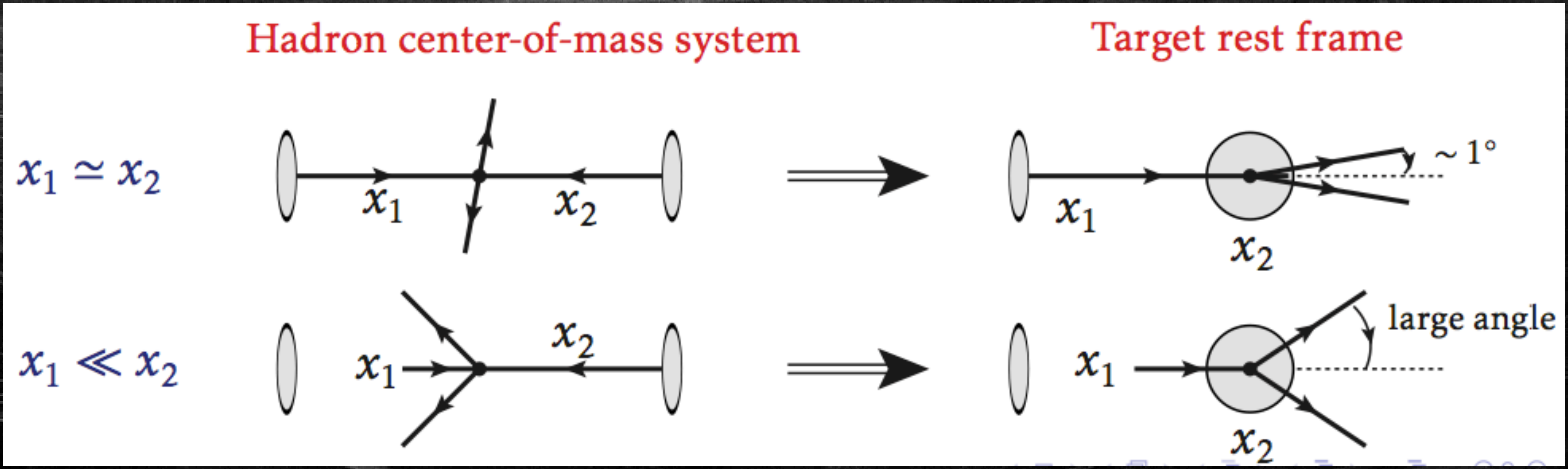
AFTER @ LHC

M. Anselmino (Torino), R. Arnarldi (Torino), S.J. Brodsky (SLAC), V. Chambert (IPN), J.P. Didelez (IPN), B. Genolini (IPN), E.G. Ferreiro (USC), F. Fleuret (LLR), C. Hadjidakis (IPN), J.P. Lansberg (IPN), C. Lorcé (IPN), A. Rakotozafindrabe (CEA), P. Rosier (IPN), I. Schienbein (LPSC), E. Scomparin (Torino), U.I. Uggerhøj (Aarhus)

- Using LHC Pb beam on A target : $\sqrt{s_{NN}}$ ~ 72 GeV, between SPS and top RHIC energies
- Enhancement of luminosities, typical of fixed-target experiments
- High luminosities allow QGP studies with rather small production cross-section probes at $\sqrt{s_{NN}}$ ~ 72 GeV, especially the bottomonium family.
- Sequential melting of the bottomonium family observed by CMS, could be observed at lower energy by AFTER, with comparable yields, and precise measurement of the cold nuclear matter effects.
- Measurement of χ_b states not mandatory (since we could use all three Υ(nS) states), but could add very interesting piece of information.

SPARE SLIDES

Backward physics

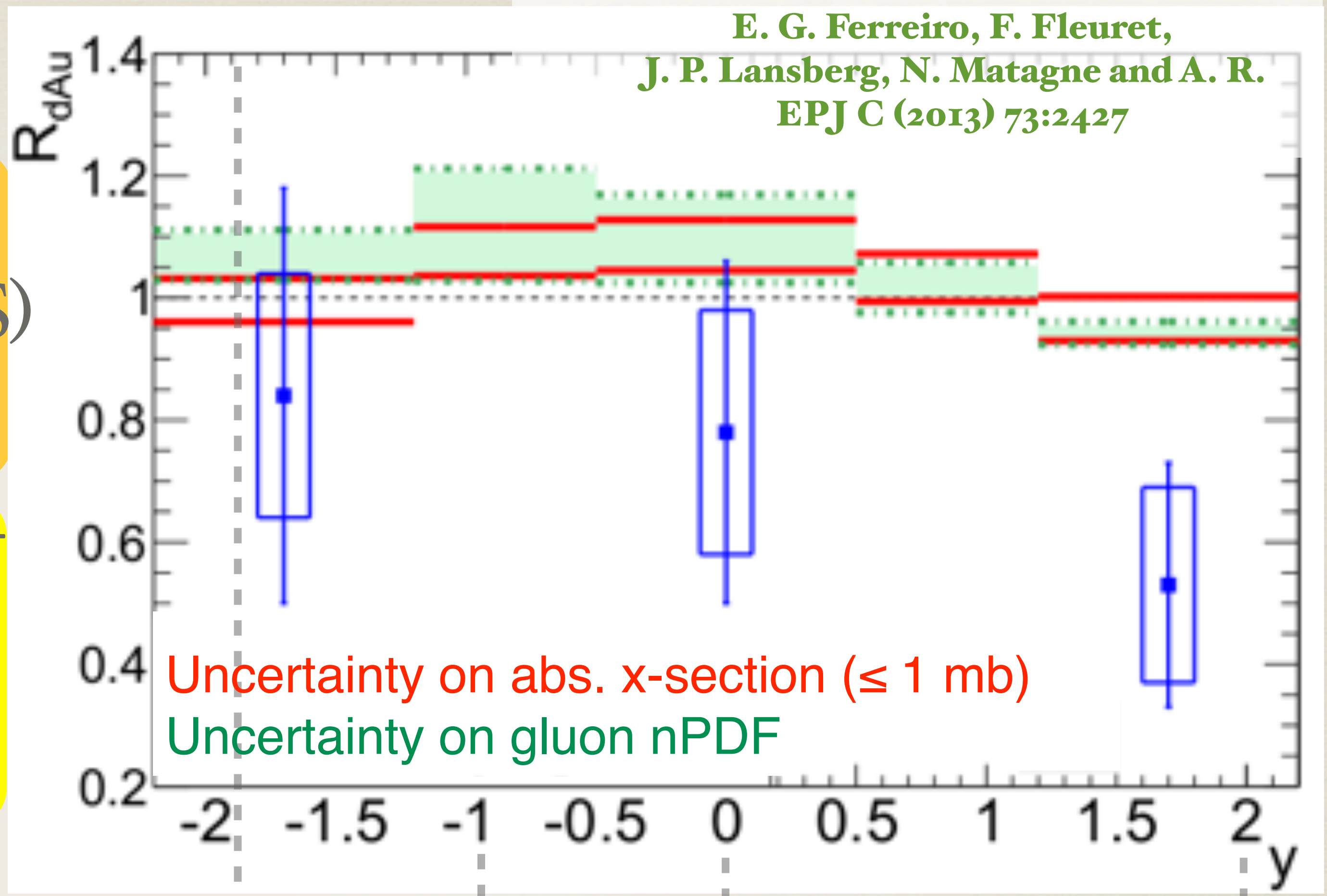


Υ in dAu @ RHIC : abs. **effective** x-section

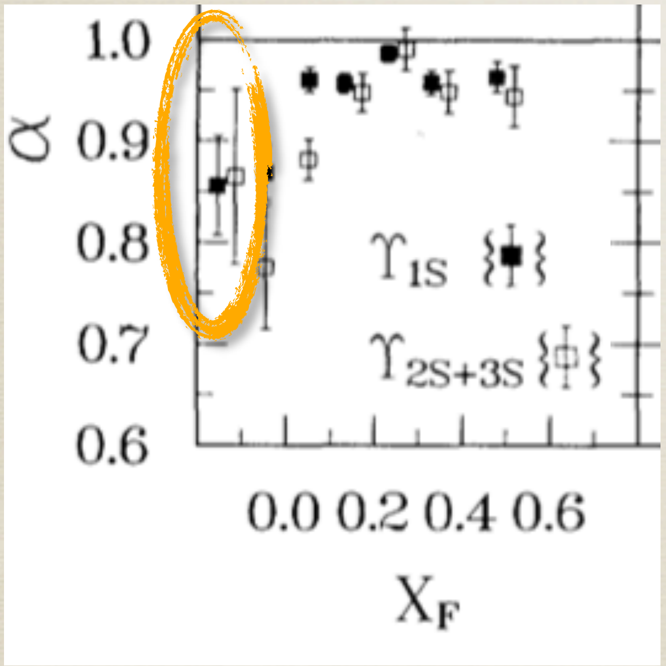
σ_{abs} **should be small :**

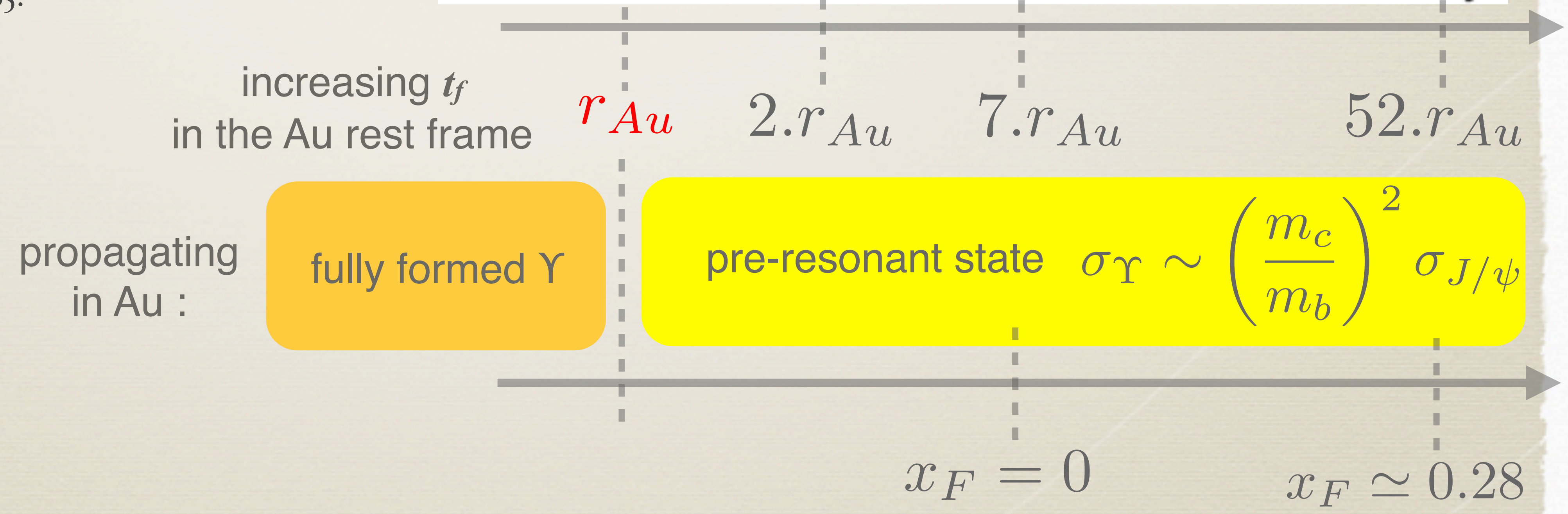
- at bkwd-y, $t_f < r_{Au}$, fully formed Υ. But no diff. exp. seen between Υ(1S) and Υ(2S+3S) σ_{abs}.
- at y>0, $t_f > r_{Au}$, same small-size pre-resonance for all Υ states

$$\sigma_\Upsilon \sim 0.1\, \sigma_{J/\psi}\ ?$$



E772 collaboration, PRL 66 (1991) 2285.





Luminosities using :

7 TeV proton beam

pp, pd, pA $\sqrt{s}$ = 115 GeV

2.76 TeV lead beam

Pbp, Pbd, PbA $\sqrt{s}$ = 72 GeV

[S. Brodsky, F. Fleuret, C. Hadjidakis, J.P. Lansberg, Phys. Rep. 522 (2013) 239]

Target (1 cm thick)	ρ (g cm^{-3})	A	$\mathcal{L}$ (μb^{-1} s^{-1})	$\int\mathcal{L}$ (pb^{-1} yr^{-1})
solid H	0.088	1	26	260
liquid H	0.068	1	20	200
liquid D	0.16	2	24	240
Be	1.85	9	62	620
Cu	8.96	64	42	420
W	19.1	185	31	310
Pb	11.35	207	16	160

Table 1: Instantaneous and yearly luminosities obtained with an extracted beam of 5×10^8 p$^+$/s with a momentum of 7 TeV for various 1cm thick targets

Target (1 cm thick)	ρ (g cm^{-3})	A	$\mathcal{L}$ (mb^{-1} s^{-1})	$\int\mathcal{L}$ (nb^{-1} yr^{-1})
solid H	0.088	1	11	11
liquid H	0.068	1	8	8
liquid D	0.16	2	10	10
Be	1.85	9	25	25
Cu	8.96	64	17	17
W	19.1	185	13	13
Pb	11.35	207	7	7

Table 2: Instantaneous and yearly luminosities obtained with an extracted beam of 2×10^5 Pb/s with a momentum per nucleon of 2.76 TeV for various 1cm thick targets

extracted beam $N_{beam} = 5 .10^8$ p$^+$/s
9 months running / year $\Leftrightarrow 10^7$ s

extracted beam $N_{beam} = 2 .10^5$ Pb/s
1 month running / year $\Leftrightarrow 10^6$ s

Instantaneous luminosity :
$L = N_{beam} \times N_{target} = N_{beam} \times (\rho . e . N_A)$ with e = target thickness

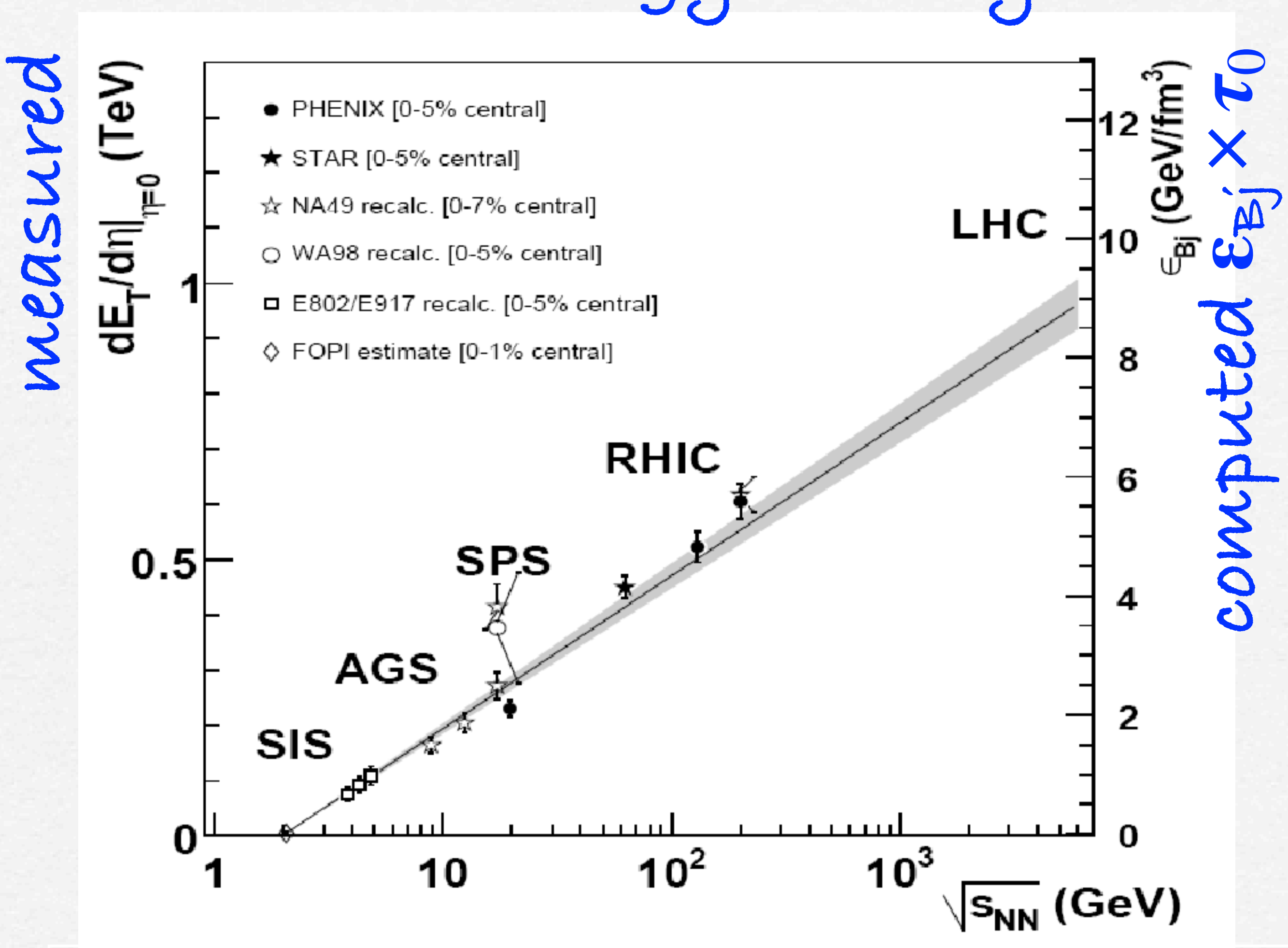
Planned luminosity for PHENIX :

- @ 200 GeV run14pp 12 pb^{-1}, run14dAu 0.15 pb^{-1}
- @ 200 GeV run15AuAu 2.8 pb^{-1} (0.13 nb^{-1} @ 62 GeV)

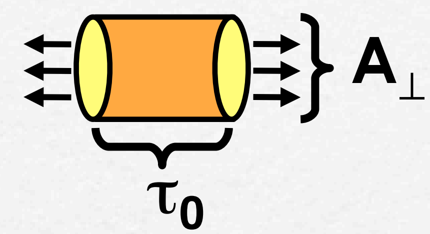
Nominal LHC luminosity PbPb 0.5 nb^{-1}

Heavy ion colliders

Initial energy density :



Longitudinal QGP expansion :



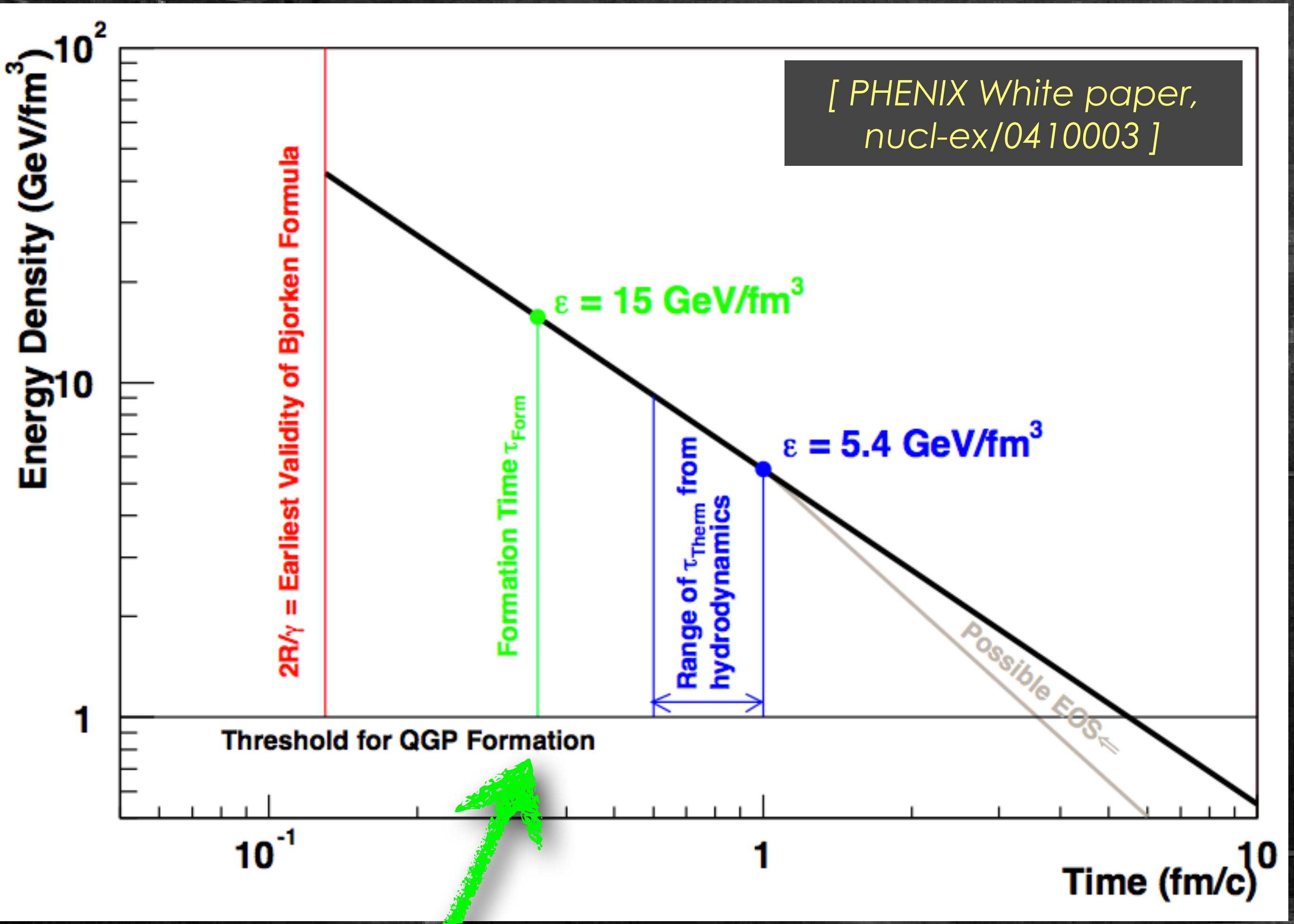
Bjorken formula :

$$\epsilon_{Bj} = \frac{dE_t}{dy} \frac{1}{A_\perp \tau_0}$$

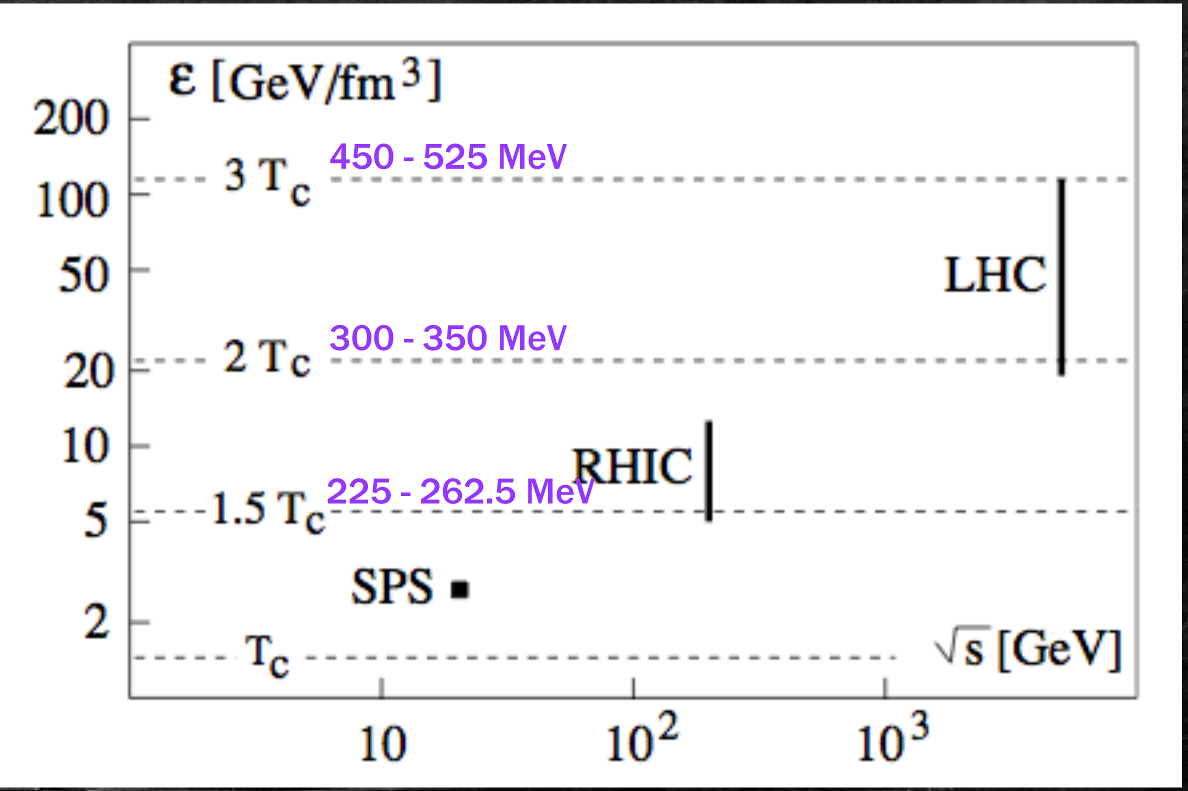
facility	collision species	$\sqrt{s_{NN}}$ (GeV)	$\varepsilon_{Bj} \times \tau_0$ (GeV/fm^{-3} . fm/c)
AGS (BNL)	Au+Au	5	1,5
SPS (CERN)	Pb+Pb	17	3,9
RHIC (BNL)	Au+Au	200	5,5
LHC (CERN)	Pb+Pb	5500	10

Energy density and temperature

Energy density vs time @ RHIC



Energy density, max. collision energy, and temperature



[Satz, J.Phys. G32 (2006) R25]

?

T_{avg} = 221 ± 19 (stat) ± 19 (syst) MeV (0-20% AuAu)

[PHENIX, PRL. 104 (2010) 132301]

T_c ~ 150 - 175 MeV

$T_{initial}$

370 - 450 MeV

[Strickland et al., NPA 879 (2012) 25-58]

[Turbide et al., PRC 69 (2004) 014903]