Return to ...

... the future

Andry Rakotozafindrabe
CEA (Saclay) IRFU

FAIR

SPS

LHC

Irfu - CEA Saclay
Institut de recherche
sur les lois fondamentales
de l'Univers

SaporeGravis Workshop (SWG 2013)– Nantes, France, Dec. 2013

Return to ...

... Fixed Target Experiments

Andry Rakotozafindrabe
CEA (Saclay) IRFU

CBM
FAIR

CHIC
SPS

AFTER @ LHC
LHC

Irfu - CEA Saclay
Institut de recherche
sur les lois fondamentales
de l'Univers

SaporeGravis Workshop (SWG 2013)– Nantes, France, Dec. 2013

CBM

The CBM Collaboration: 58 institutions, 500 members

Croatia:
RBI, Zagreb
Split Univ.

China:
CCNU Wuhan
Tsinghua Univ.
USTC Hefei

Czech Republic:
CAS, Rez
Techn. Univ.Prague

France:
IPHC Strasbourg

Hungaria:
KFKI Budapest
Budapest Univ.

Germany:
FAIR
Frankfurt Univ. IKF
Frankfurt Univ. FIAS
GSI Darmstadt
Giessen Univ.
Heidelberg Univ. P.I.
Heidelberg Univ. ZITI
HZ Dresden-Rossendorf
Münster Univ.
Tübingen Univ.
Wuppertal Univ.

Korea:
Korea Univ. Seoul
Pusan Nat. Univ.

Romania:
NIPNE Bucharest
Univ. Bucharest

India:
Aligarh Muslim Univ.
Bose Inst. Kolkata
Panjab Univ.
Rajasthan Univ.
Univ. of Jammu
Univ. of Kashmir
Univ. of Calcutta
B.H. Univ. Varanasi
VECC Kolkata
SAHA Kolkata
IOP Bhubaneswar
IIT Kharagpur
Gauhati Univ.

Poland:
AGH Krakow
Jag. Univ. Krakow
Silesia Univ. Katowice
Warsaw Univ.

Russia:
IHEP Protvino
INR Troitzk
ITEP Moscow
KRI, St. Petersburg
Kurchatov Inst., Moscow
LHEP, JINR Dubna
LIT, JINR Dubna
MEPHI Moscow
Obninsk State Univ.
PNPI Gatchina
SINP MSU, Moscow
St. Petersburg P. Univ.

Ukraine:
T. Shevchenko Univ. Kiev
Kiev Inst. Nucl. Research

19th CBM Collaboration Meeting, March 26-30, 2012, GSI Darmstadt

Compressed Baryonic Matter

‣ Physics program

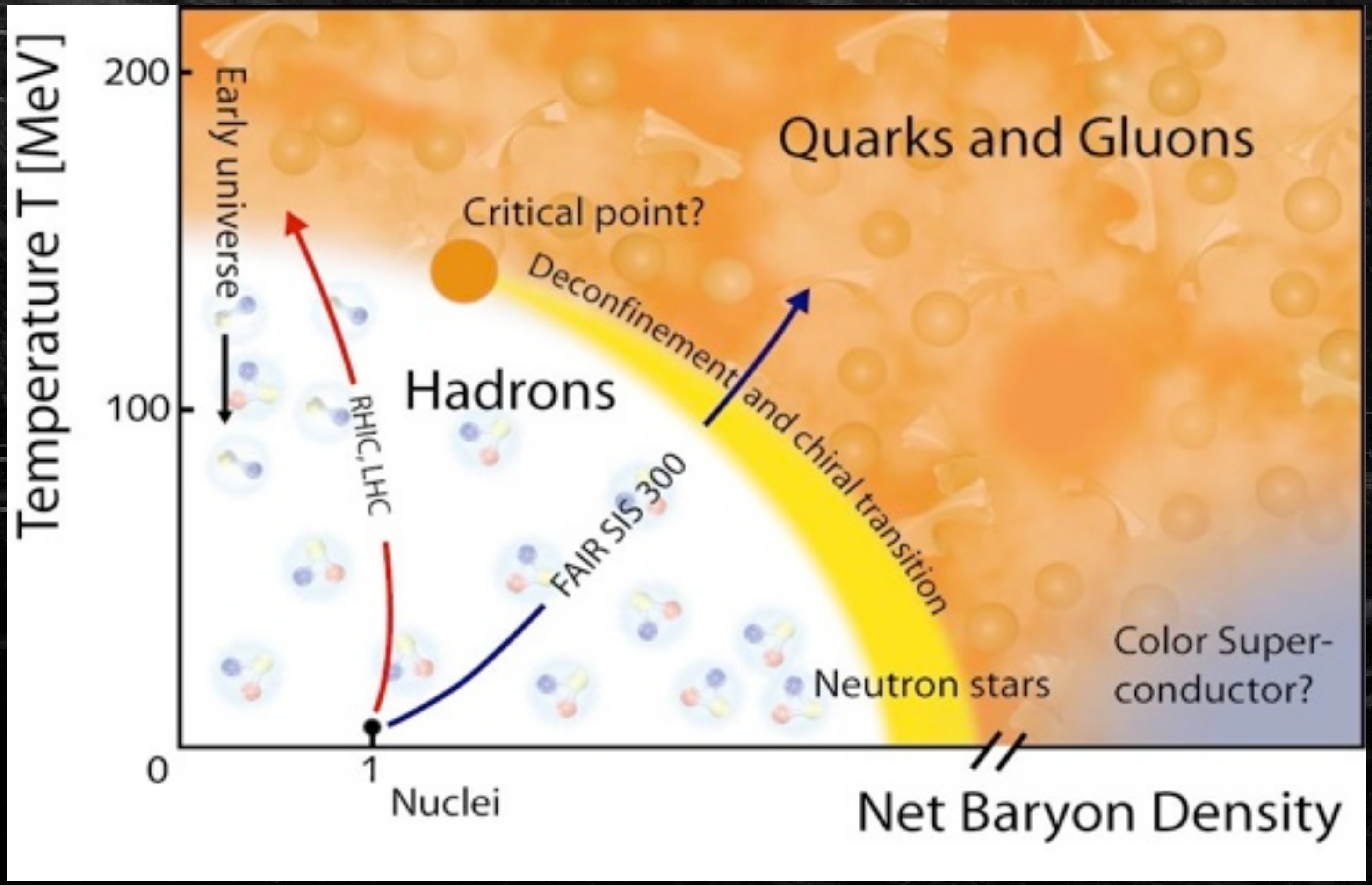
[J. M. Heuser, QM 2012]

Explore the QCD phase diagram

- equation of state at high net baryon density
- deconfinement phase transition
- QCD critical endpoint
- chiral symmetry restoration

Probes of the high-density phase

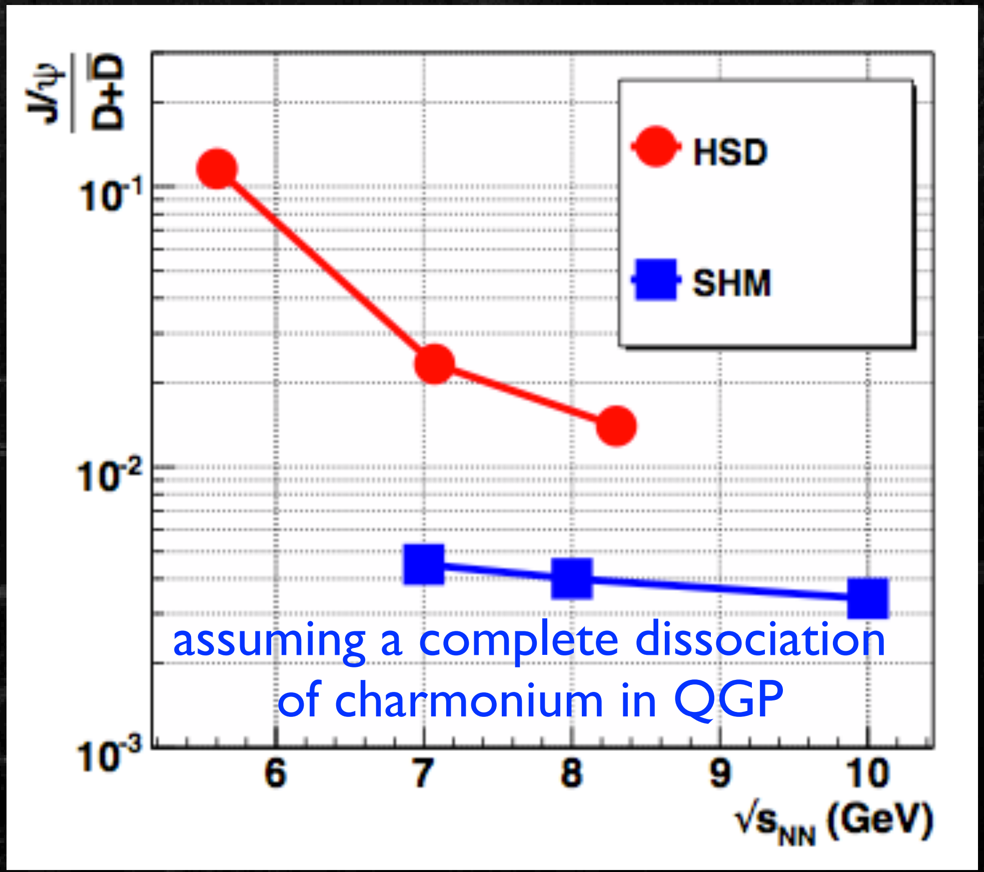
- open charm, charmonia
- low-mass vector mesons
- multistrange hyperons
- flow, fluctuations, correlations



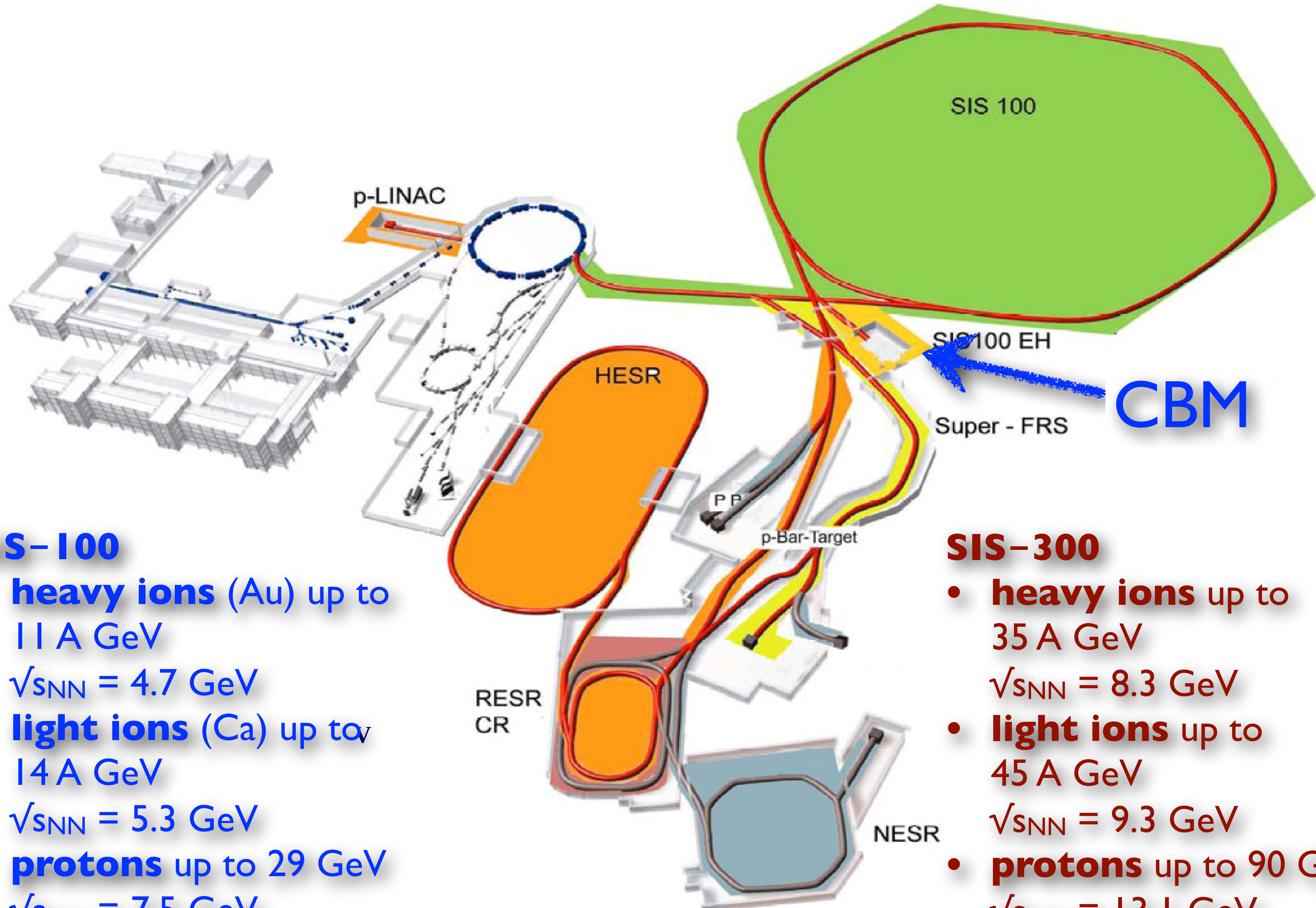
Open charm and charmonia @ CBM

- they are produced close to (nucleon-nucleon) threshold energies @ FAIR HI collisions
- hence, total and relative yields of hadrons with charm are very sensitive to the degrees of freedom in the early fireball
- predictions from hadronic transport model (HSD) vs statistical hadronization model (SHM) :

[CBM Physics Book]



CBM @ FAIR



SIS−100

- **heavy ions** (Au) up to 11 A GeV
  $\sqrt{s_{NN}}$ = 4.7 GeV
- **light ions** (Ca) up to 14 A GeV
  $\sqrt{s_{NN}}$ = 5.3 GeV
- **protons** up to 29 GeV
  $\sqrt{s_{NN}}$ = 7.5 GeV

SIS−300

- **heavy ions** up to 35 A GeV
  $\sqrt{s_{NN}}$ = 8.3 GeV
- **light ions** up to 45 A GeV
  $\sqrt{s_{NN}}$ = 9.3 GeV
- **protons** up to 90 GeV
  $\sqrt{s_{NN}}$ = 13.1 GeV

[M. Petrovici, EuNPC 2012]

FAIR today

The **F**acility for **A**ntiproton and **I**on **R**esearch

[F. Rami, Rencontres QGP-France 2013]

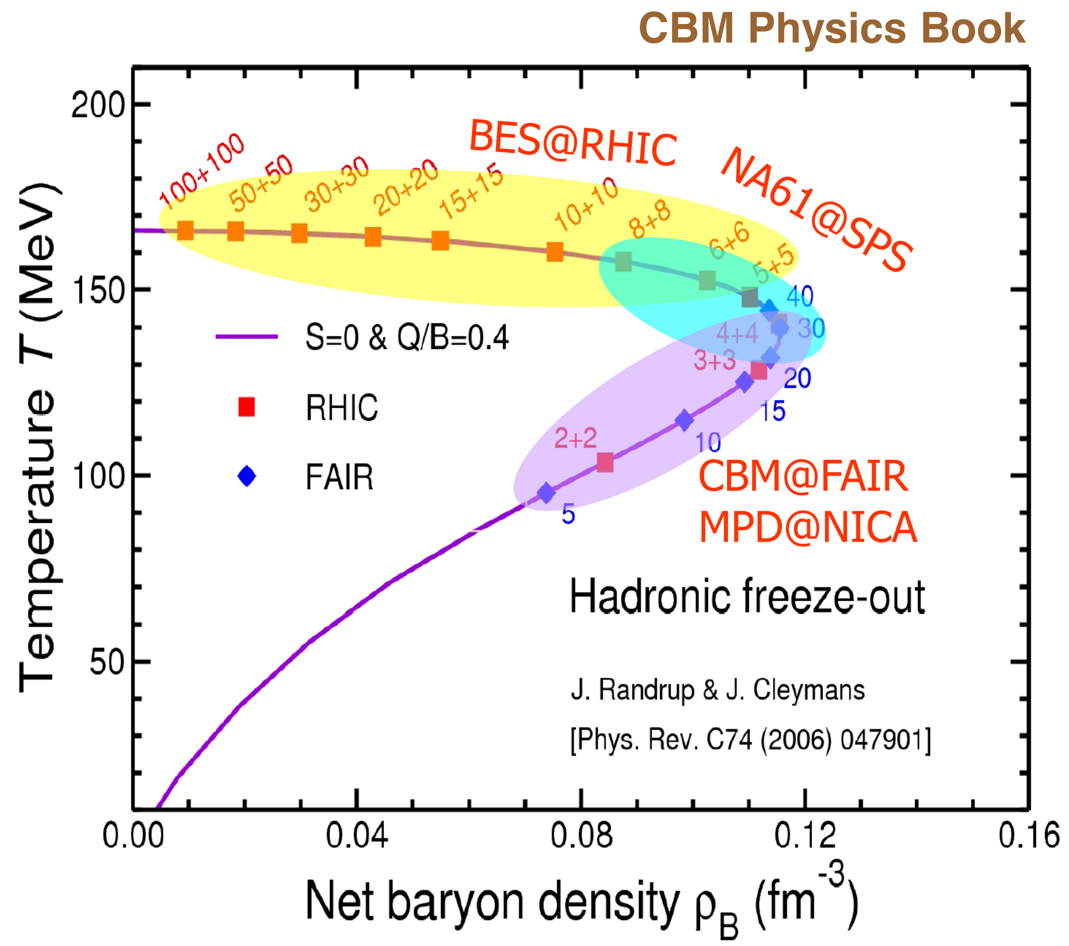
FAIR in 2018

[J. Heuser, Advanced Studies Institute - Symmetries and Spin, 2013]

First beam expected in 2018 with SIS-100

CBM challengers

Density and **Temperature at freezeout**
for different beam conditions
(from hadron gas model)



- **Maximum net-baryon density reached at ~30 AGeV ($\sqrt{s_{NN}} \approx 8$ GeV)**
- **well within SIS300 range**

[F. Rami, Rencontres QGP-France 2013]

CBM challengers

- Comparison @ $\sqrt{s_{NN}}$ = 8 GeV (⇒ case where SIS-300 is delivering heavy ions to CBM)

heavy flavour

Timeline	Experiment	Energy range (Au/Pb beams)	Reaction rates Hz	Observables, $\sqrt{s_{NN}}$= 8 GeV			
				hadrons	flow, fluct., correl.	dileptons	charm
BES-I : on-going BES-II : 2018-2021	STAR@RHIC BNL	$\sqrt{s_{NN}}$ = 7 – 200 GeV	1 – 800 (limit luminosity)	yes	no	no	no
2009-2015	NA61@SPS CERN	E_{kin}= 20 – 160 AGeV $\sqrt{s_{NN}}$= 6.4 – 17.4 GeV	80 (limit detector)	yes	no	no	no
Not yet funded > 2018 ?	MPD@NICA Dubna	$\sqrt{s_{NN}}$= 4.0 – 11.0 GeV	~1000 (at design luminosity)	yes	yes	no	no
Start (SIS-100) : 2018	**CBM@FAIR Darmstadt**	**E_{kin}= 2.0 – 35 AGeV $\sqrt{s_{NN}}$= 2.7 – 8.3 GeV**	**10^5 – 10^7 (limit detector)**	**yes**	**yes**	**yes**	**yes**

[F. Rami, Rencontres QGP-France 2013]

[J. M. Heuser, QM 2012]

Expected yields

multiplicity in min. bias collisions

reaction rate

trigger needed

acc x eff for central collisions

yield / s

yield / 10 weeks

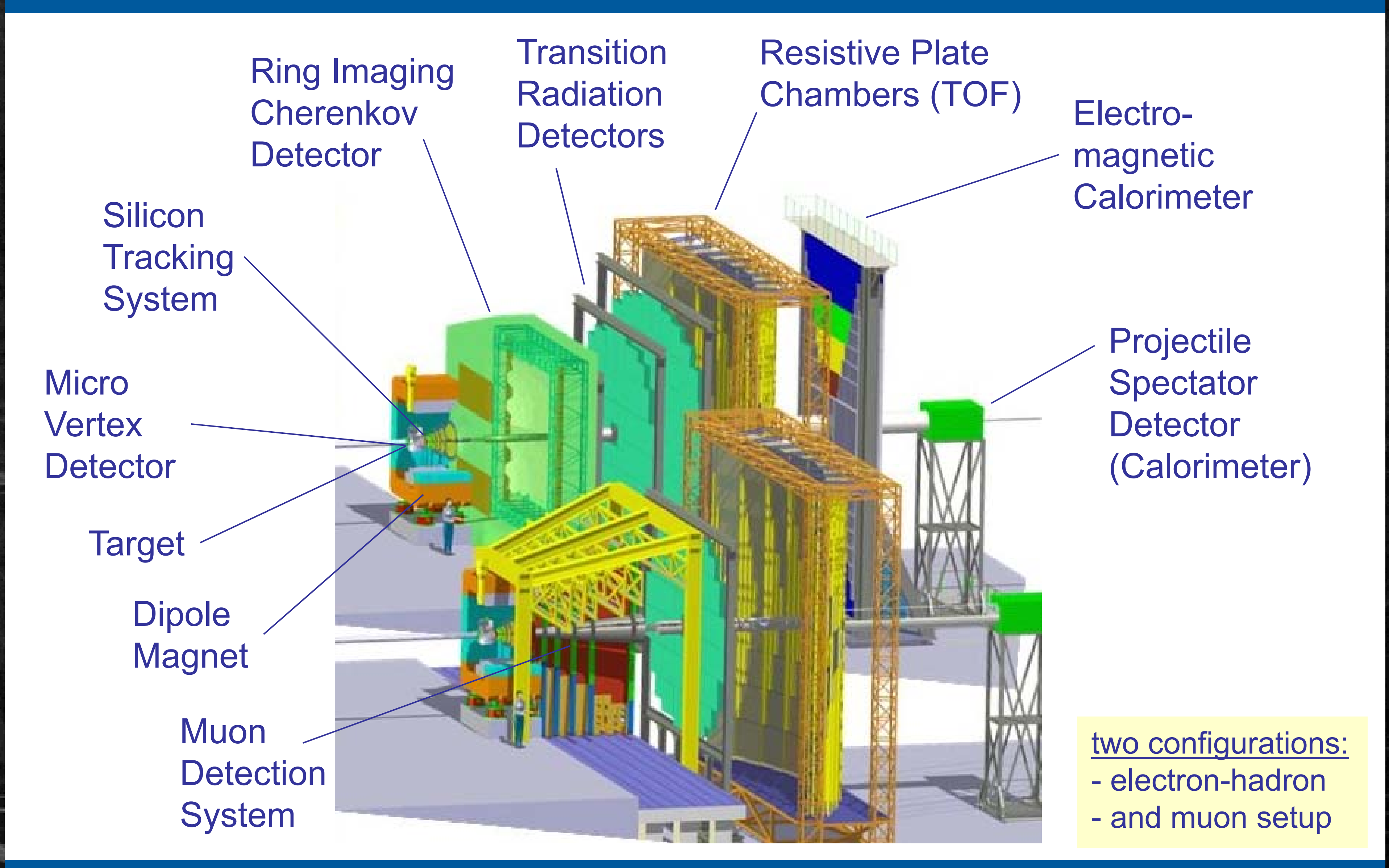
particle	N	decay mode	BR	R/s (MHz)	T	ϵ (%)	Y/s	Y/10 w
D^0	$7.5 \cdot 10^{-6}$	$K^-\pi^+$	0.038	0.1	y	3.25	$8.5 \cdot 10^{-4}$	$5.1 \cdot 10^3$
D^0	$7.5 \cdot 10^{-6}$	$K^-\pi^+\pi^+\pi^-$	0.075	0.1	y	0.37	$2.1 \cdot 10^{-4}$	$1.3 \cdot 10^3$
$\bar{D}^0$	$2.3 \cdot 10^{-5}$	$K^+\pi^-$	0.038	0.1	y	3.25	$2.6 \cdot 10^{-3}$	$1.6 \cdot 10^4$
D^+	$8 \cdot 10^{-6}$	$K^-\pi^+\pi^+$	0.092	0.1	y	4.2	$3.1 \cdot 10^{-3}$	$1.9 \cdot 10^4$
D^-	$1.8 \cdot 10^{-5}$	$K^+\pi^-\pi^-$	0.092	0.1	y	4.2	$7 \cdot 10^{-3}$	$4.2 \cdot 10^4$
D_s^+	$1.08 \cdot 10^{-6}$	$K^+K^-\pi^+$	0.053	0.1	y	1	$5.7 \cdot 10^{-5}$	$3.5 \cdot 10^2$
Λ_c	$4.9 \cdot 10^{-4}$	$pK^-\pi^+$	0.05	0.1	y	0.5	$1.2 \cdot 10^{-2}$	$7.4 \cdot 10^4$
J/ψ	$3.8 \cdot 10^{-6}$	e^+e^-	0.06	10	y	13	0.32	$1.9 \cdot 10^6$
ψ'	$5.1 \cdot 10^{-8}$	e^+e^-	$7.3 \cdot 10^{-3}$	10	y	14	$5.2 \cdot 10^{-4}$	$3.2 \cdot 10^3$
J/ψ	$3.8 \cdot 10^{-6}$	$\mu^+\mu^-$	0.06	10	y	16	0.36	$2.2 \cdot 10^6$
ψ'	$5.1 \cdot 10^{-8}$	$\mu^+\mu^-$	$7.3 \cdot 10^{-3}$	10	y	19	$7.1 \cdot 10^{-4}$	$4.3 \cdot 10^3$

[CBM Physics Book]

Au+Au collisions @ 25 A GeV,
based on HSD calculations

CBM modular design

full version



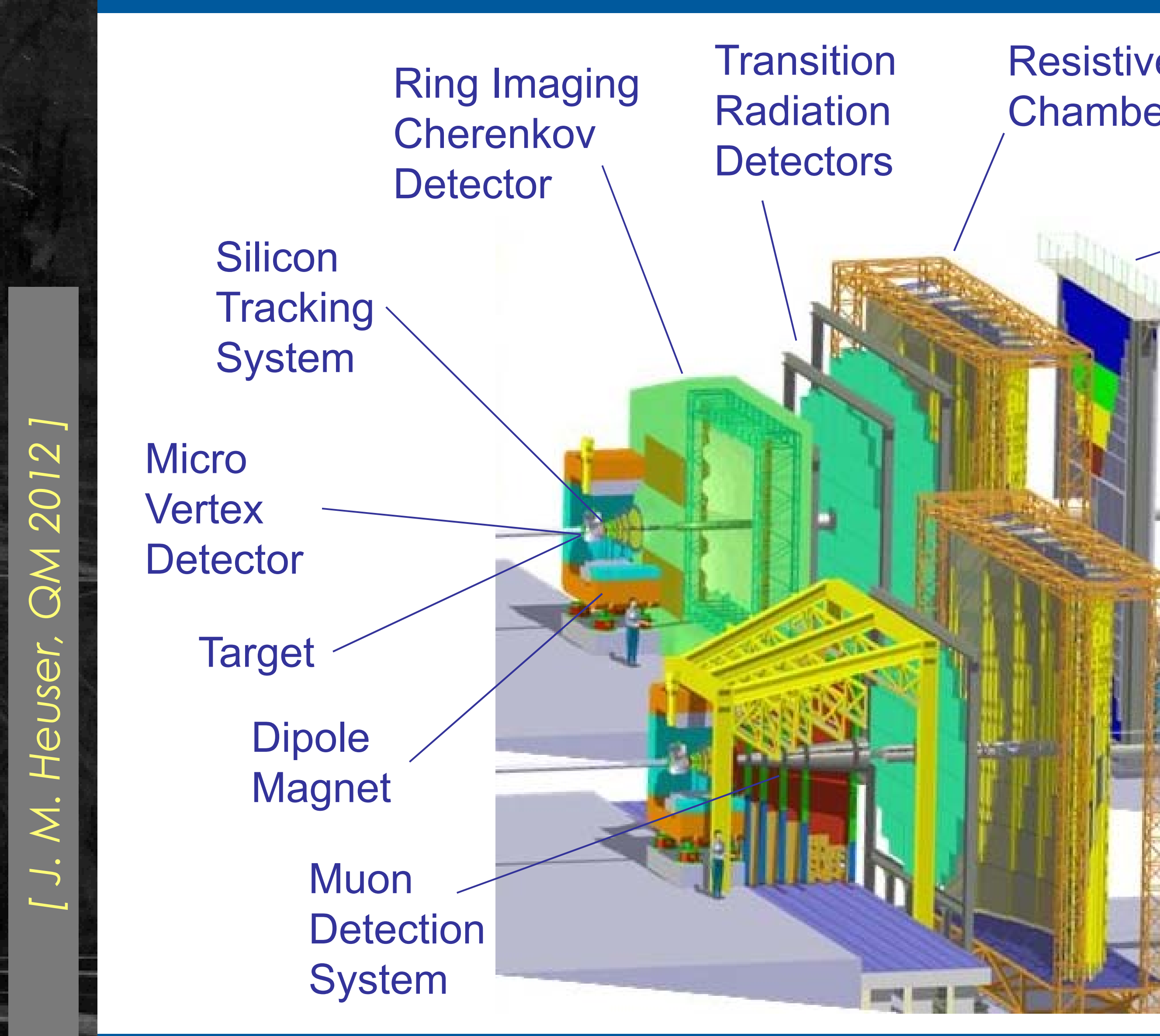
[J. M. Heuser, QM 2012]

Technically challenging !

- filter out rare probes at reaction rates of up to 10 MHz
- up to 1k charged particles / event

CBM modular design

full version



CBM Costs

Project	Costs full version	Costs start version
MVD	2.1	2.1
STS	11.5	11.5
TRD*	9.6	4.0
RICH	5.6	5.6
TOF	6.8	6.8
DAQ*	3.9	3.0
FLES*	6.0	3.0
Magnet	4.3	4.3
MuCh*	10.6	4.0
PSD	1.0	1.0
Infrastr.	4.2	4.2
ECAL*	10.6	3.0
Sum in 2009 €	**76.4**	**52.5**

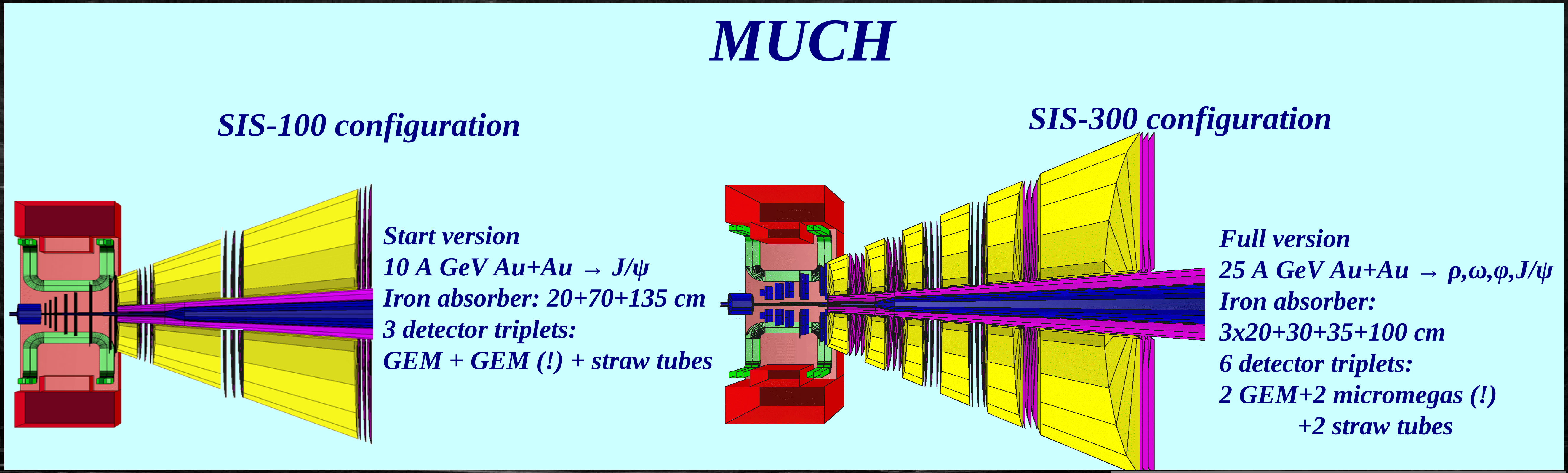
two versions

Technically challenging !

- filter out rare probes at reaction rates of up to 10 MHz
- up to 1k charged particles / event

Several scenarios : the example of the MuCh

Fe (absorbers) Detector triplets



[M. Petrovici, EuNPC 2012]

- impact on performances ?

Several scenarios : the example of the MuCh

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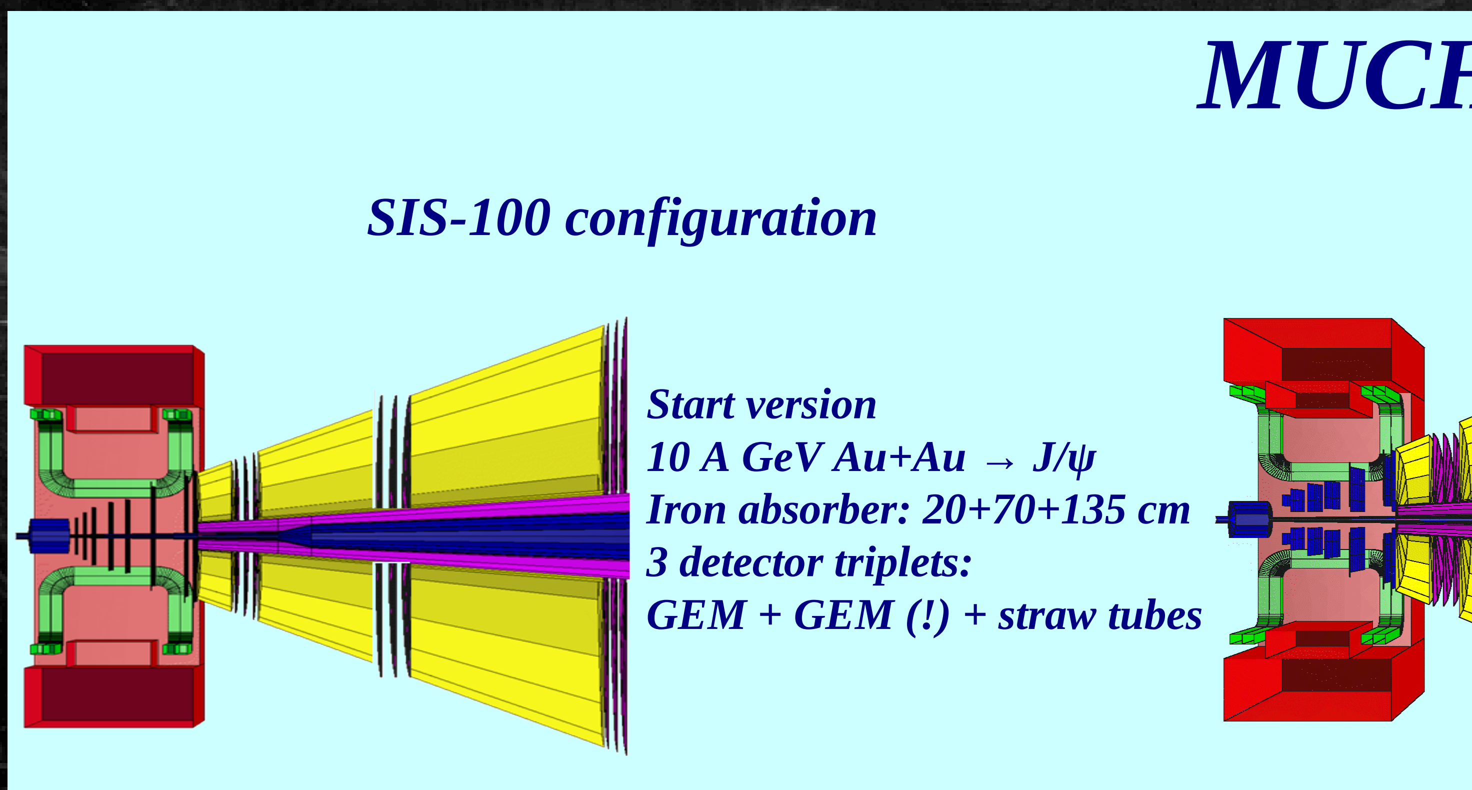
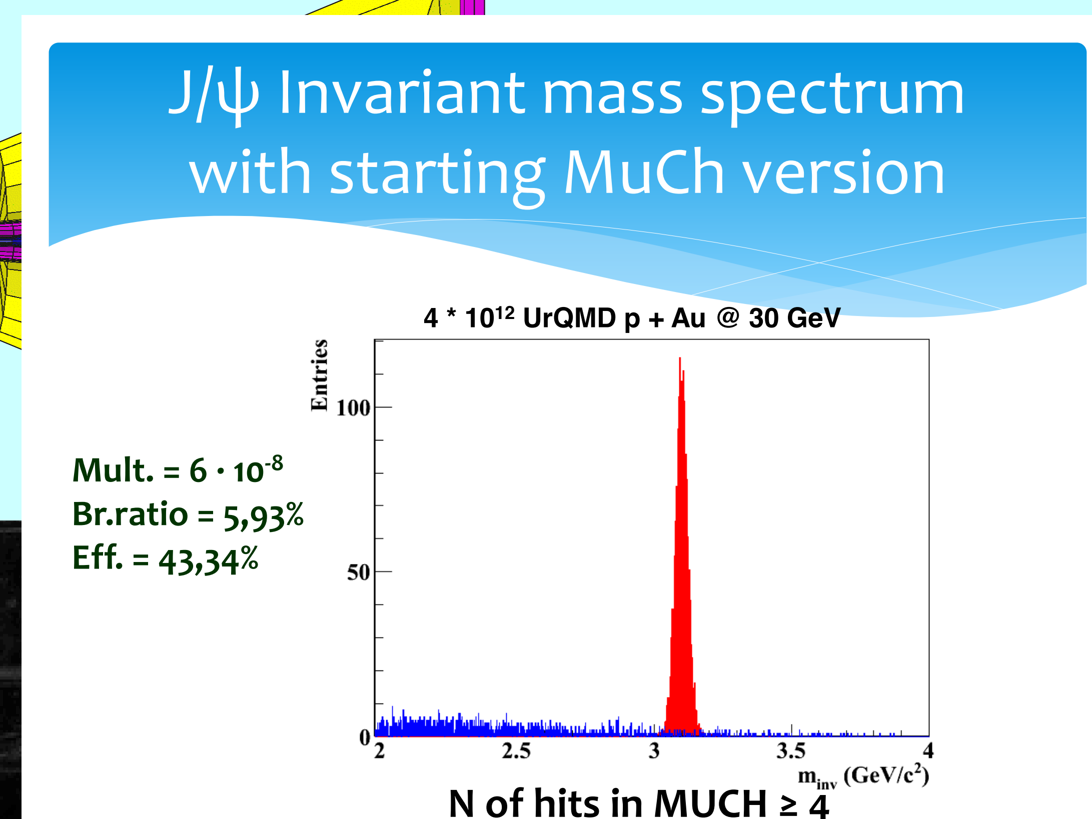




- impact on performances ?

[V. Akishina, FAIRNESS 2012]

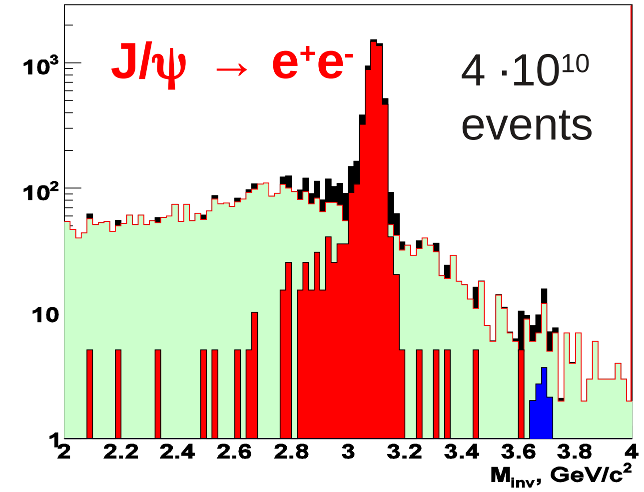
BERGISCHE UNIVERSITÄT WUPPERTAL

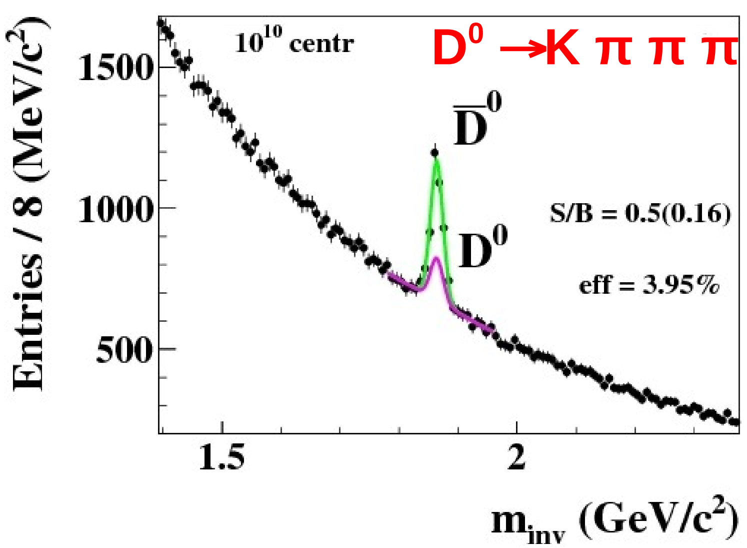
CBM performance (i): Charm / charmonium

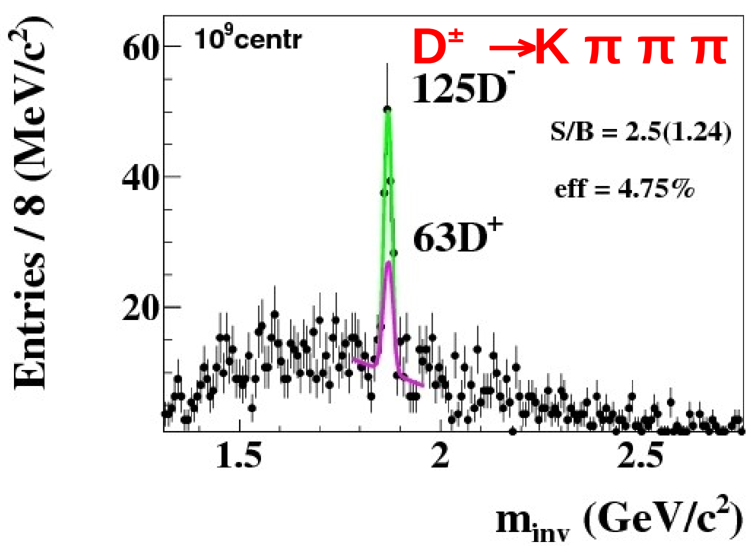
CBM

- All performance simulations:
  - → realistic detector geometry
  - → event generator: UrQMD (+PLUTO)
  - → GEANT3
- J/Ψ will be running at maximum event rate:
  - → 10 MHz minimum bias event rate
- Open charm at reduced rate:
  - → 100 kHz – 1MHz
  - → limited by Micro Vertex Detector MVD
  - → reconstruction of displaced vertices

Au+Au 25 A GeV (SIS300)







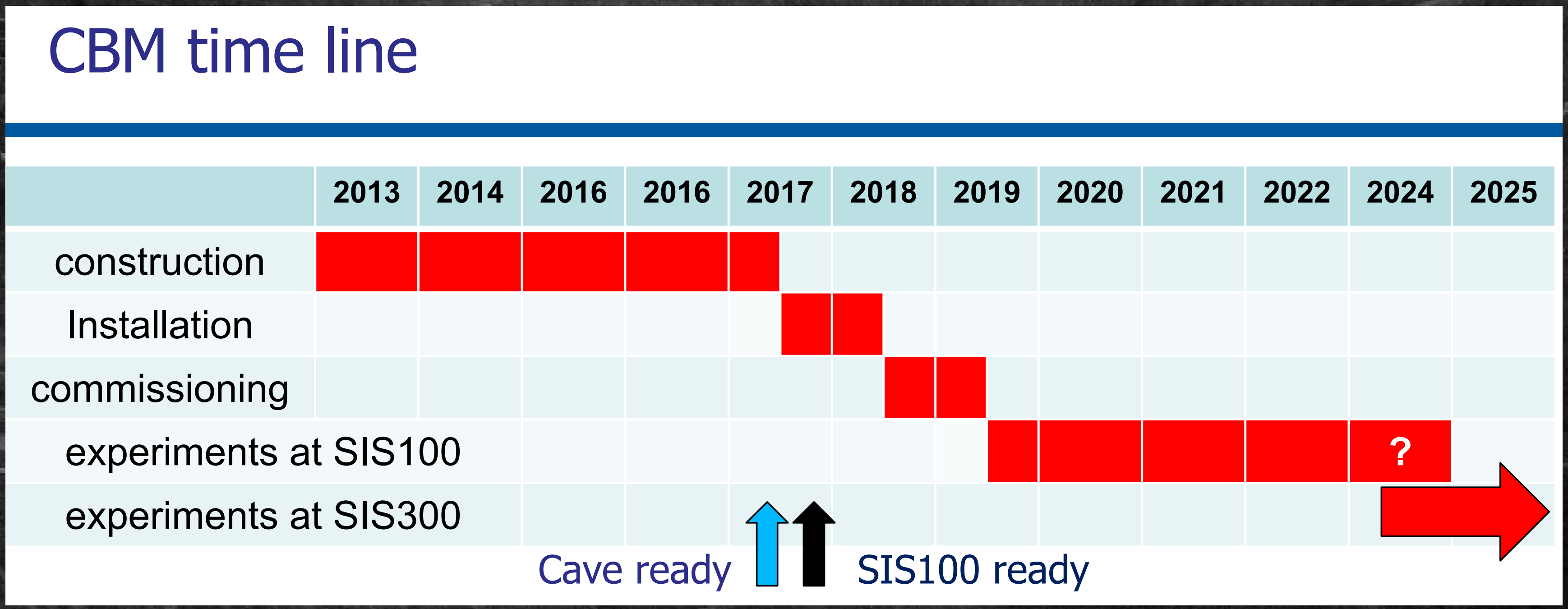
DPG Frühjahrstagung, Dresden, 07.03.2013

Slide 15

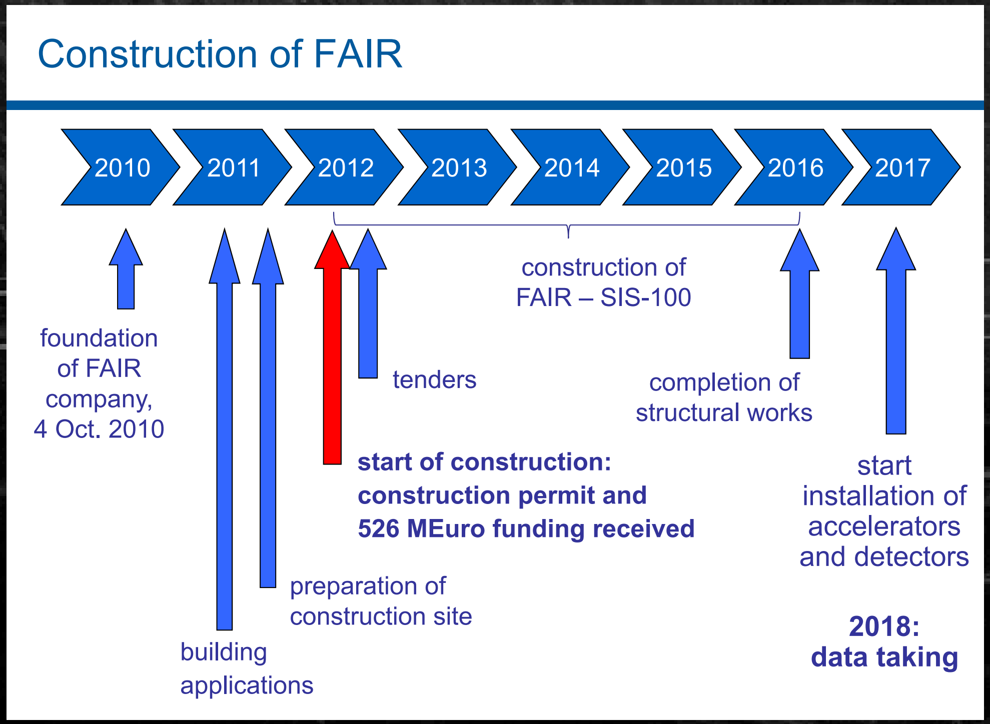
[C. Pauly, 2013]

Outlooks

[J. Heuser, Advanced Studies Institute - Symmetries and Spin, 2013]



[J. Heuser, QM 2012]



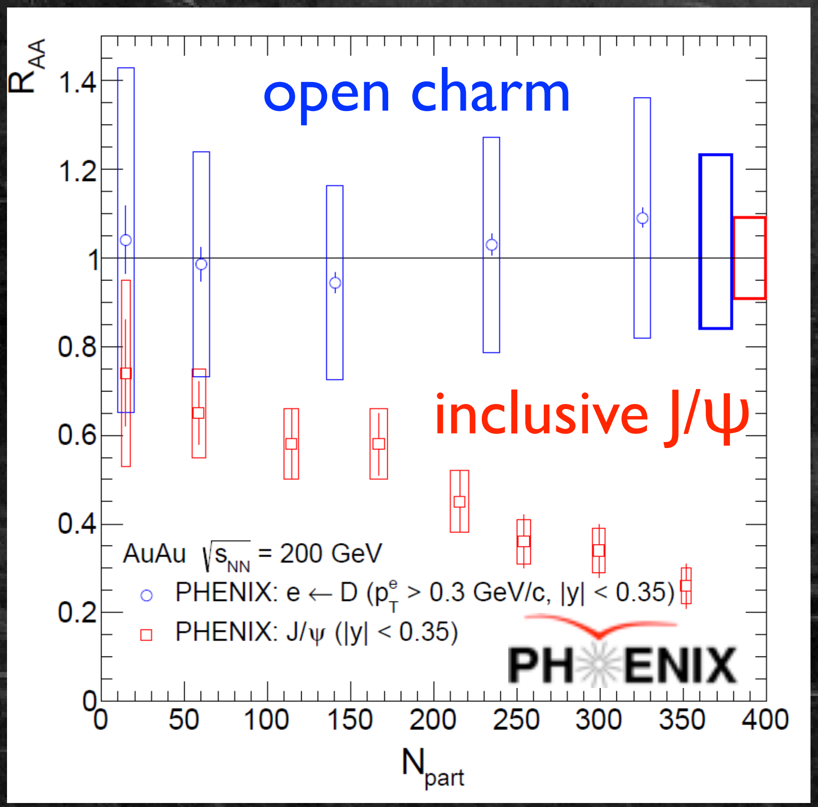
- SIS-100 financed
- Substantial part of CBM start version financed
- SIS-300 ?

CHIC: Charm in Heavy Ion Collisions

F. Fleuret [1], F. Arleo [2], E. G. Ferreiro [3], P.-B. Gossiaux [4], S. Peigné [4]

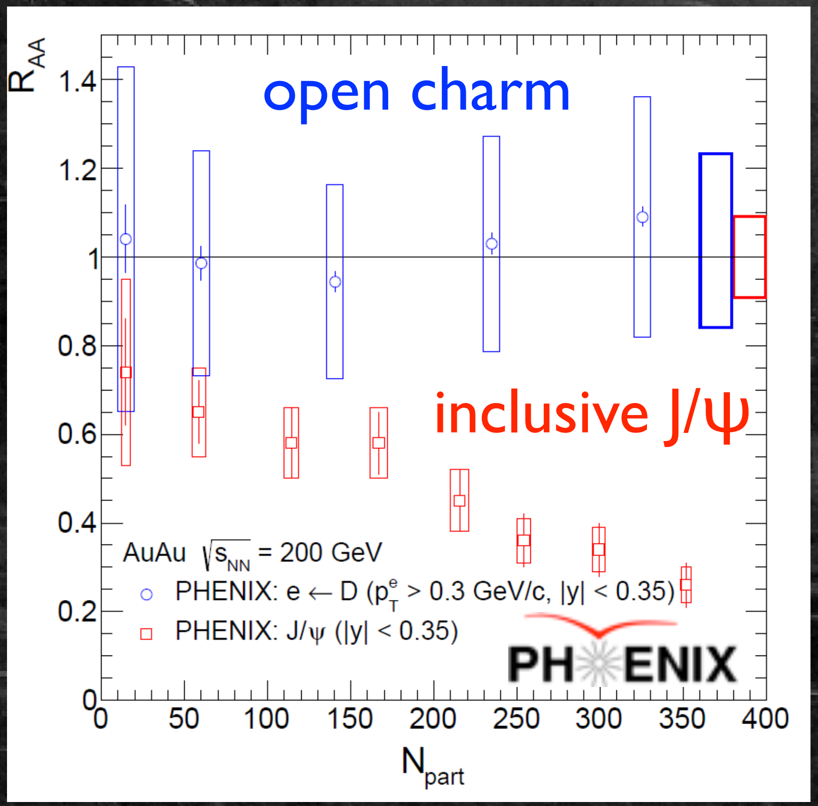
[1] LLR, École polytechnique – IN2P3/CNRS, Palaiseau, France
[2] LAPTh, Université de Savoie – CNRS, Annecy-le-Vieux, France
[3] Universidad de Santiago de Compostela, Santiago de Compostela, Spain
[4] SUBATECH, université de Nantes – IN2P3/CNRS, Nantes, France

Why the charm/charmonium at SPS ?



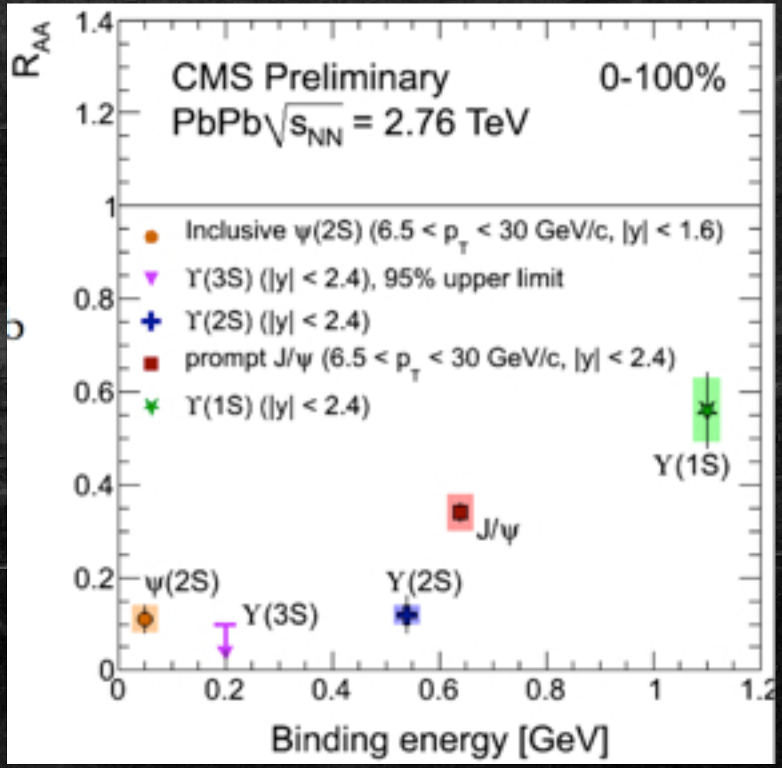
overall open charm production : (the?) reference, unmodified by the QGP

Why the charm/charmonium at SPS ?

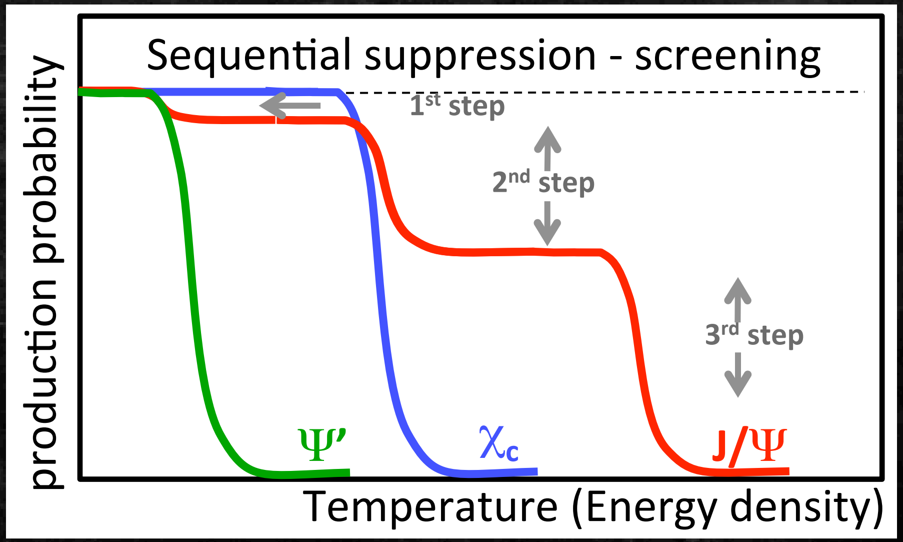


overall open charm production : (the?) reference, unmodified by the QGP

high p_T prompt J/ψ, inclusive ψ(2S)
ϒ(1S), (2S), (3S)



Sequential melting ?
χ_c is the missing piece for the charmonium family (30% of the prompt J/ψ yield)



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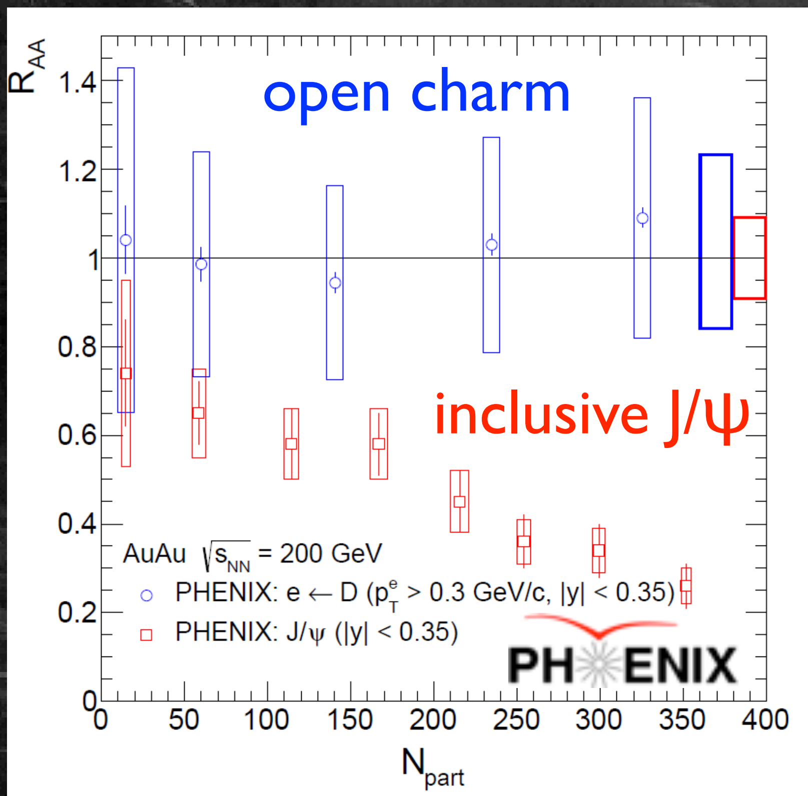

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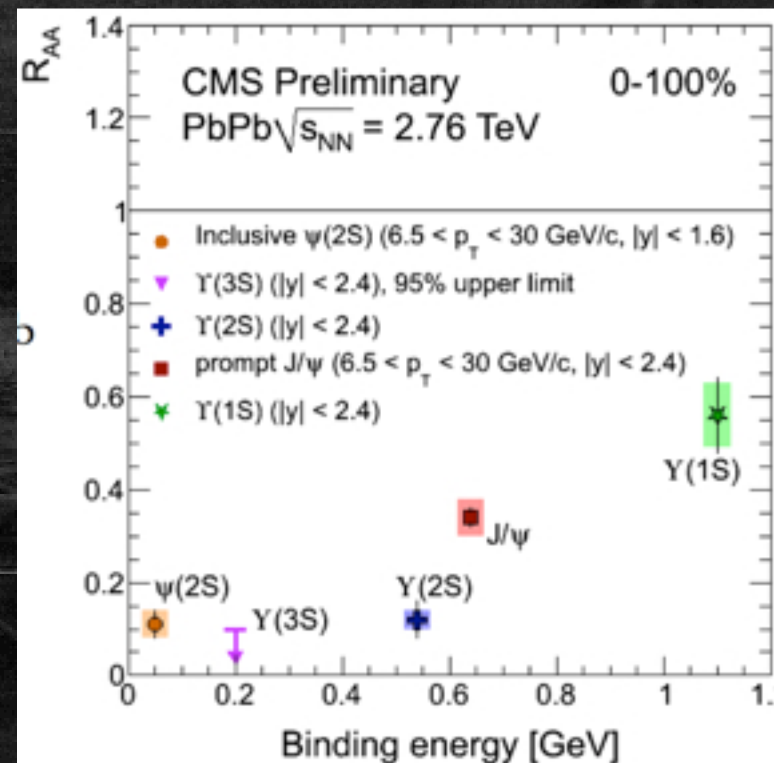

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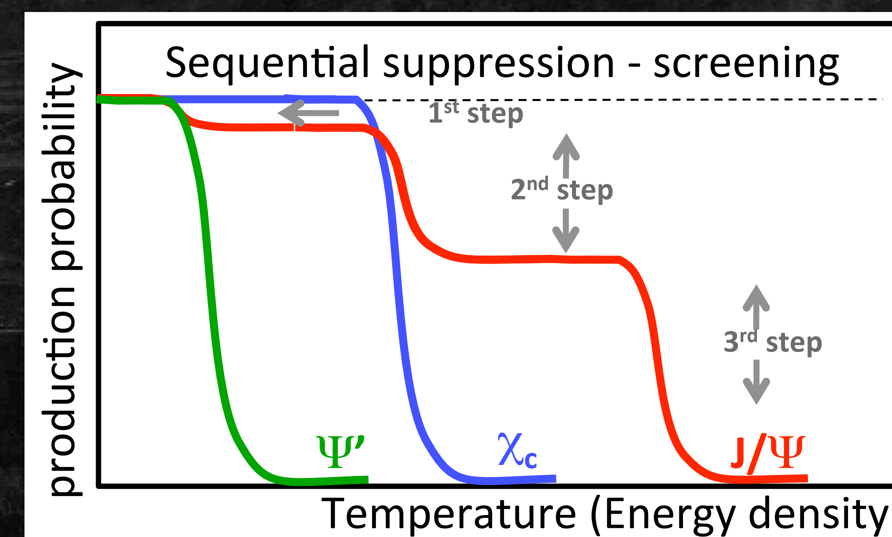
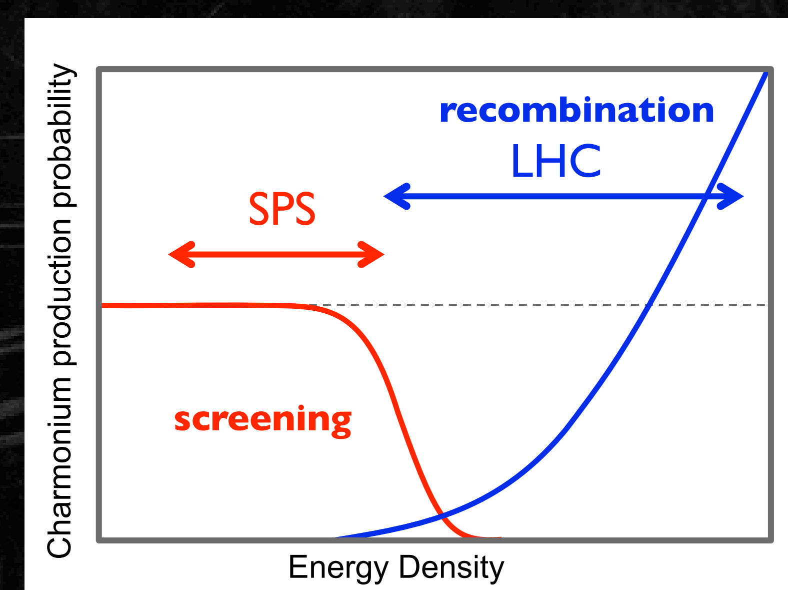
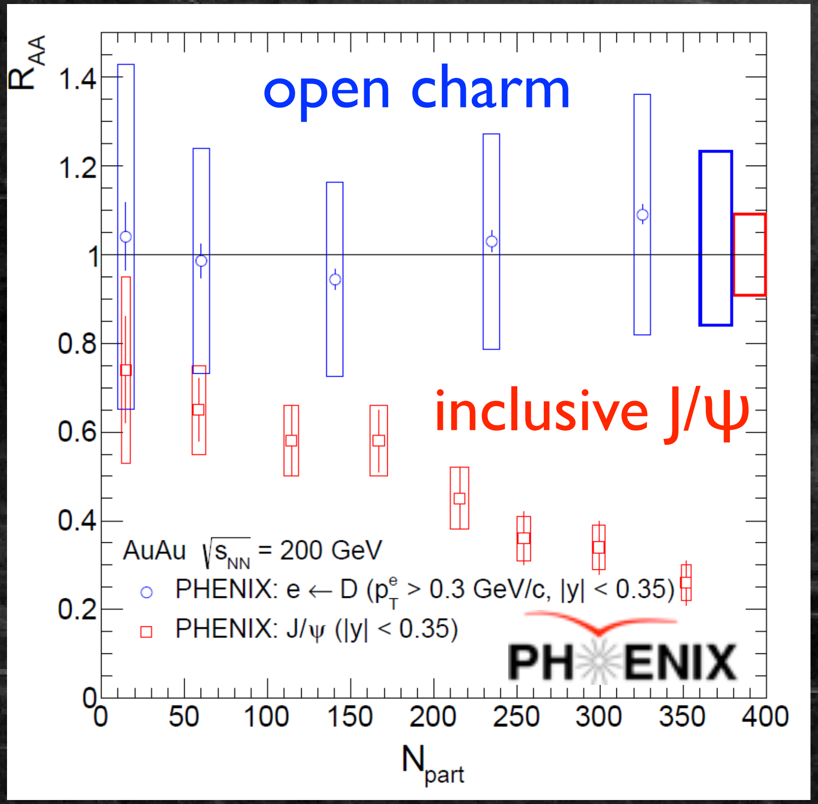




At SPS energies (Pb+Pb) :

- J/ψ suppression occurs in the middle of the accessible energy density range
- negligible recombination

Why the charm/charmonium at SPS ?



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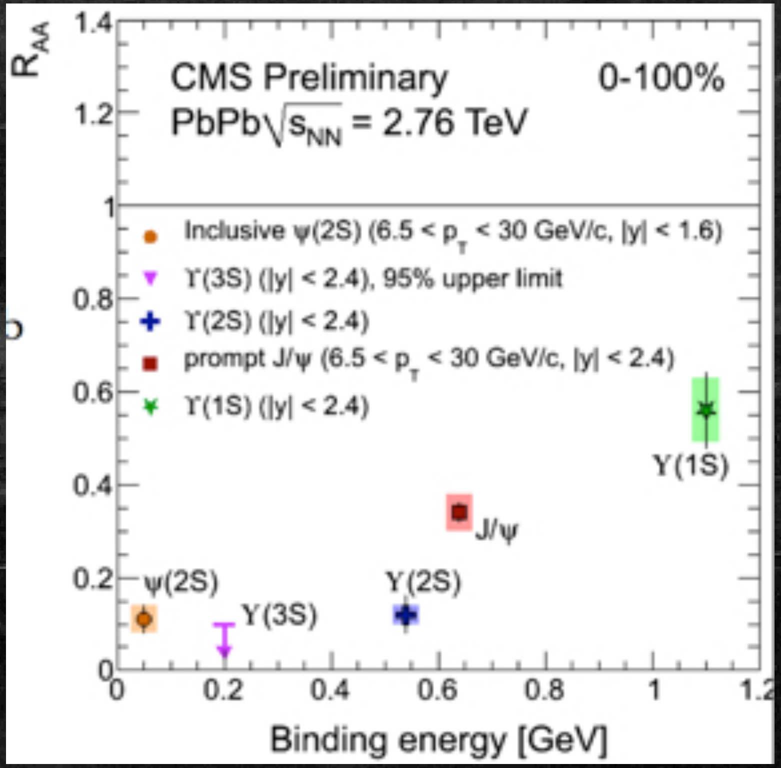

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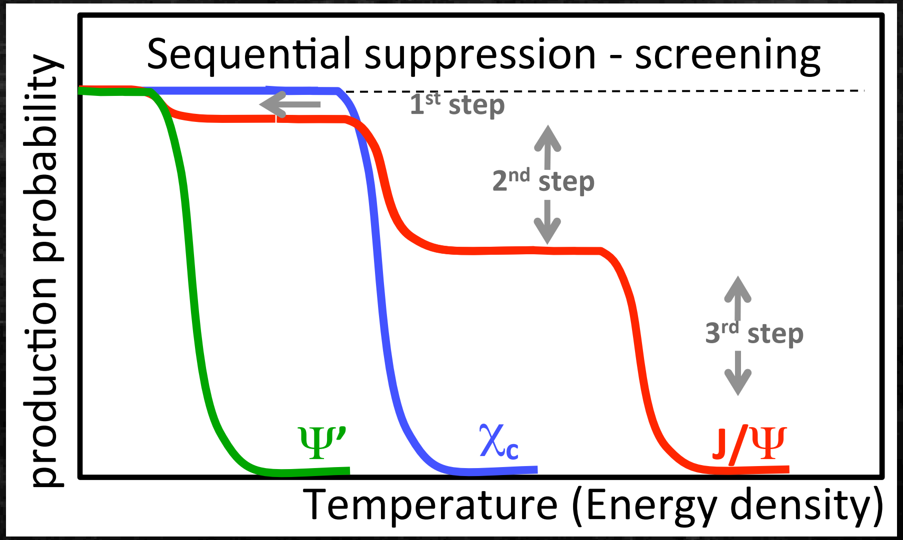
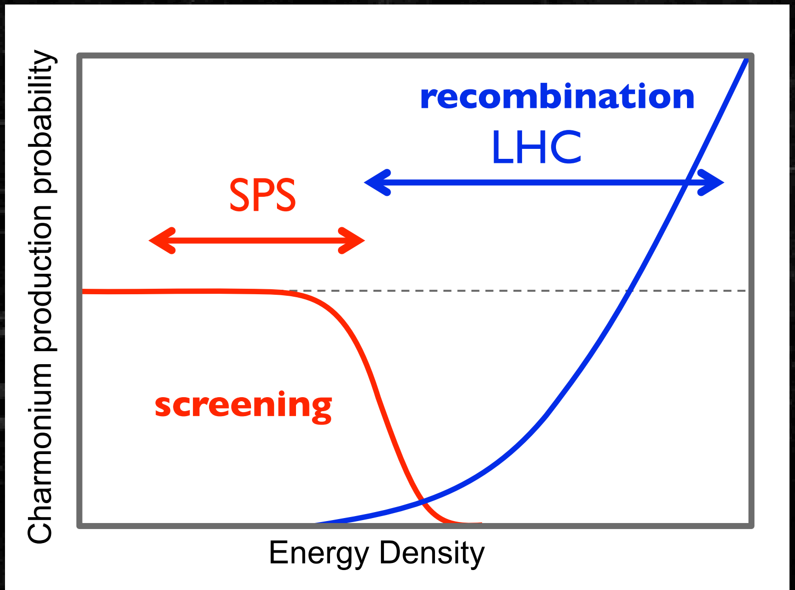


- SPS is the best place to study the color screening
- need open charm + χ_c measurements

At SPS energies (Pb+Pb) :

- J/ψ suppression occurs in the middle of the accessible energy density range
- negligible recombination



What is the expected suppression pattern for χ_c ?

60% direct J/ψ
+ 30% $\chi_c \rightarrow$ J/ψ+γ
+ 10% ψ' → J/ψ + X

Inclusive J/ψ yield

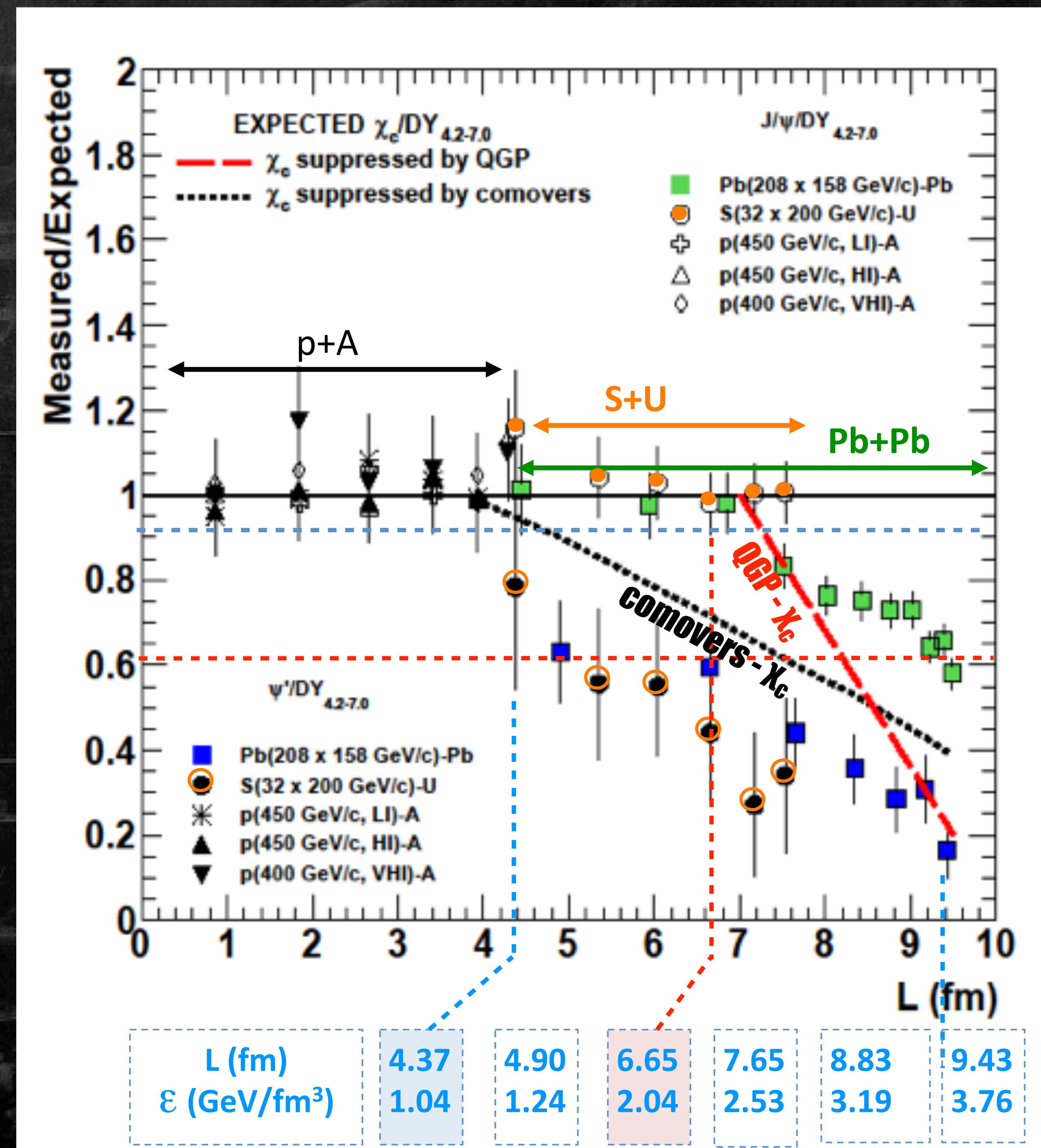
Two scenarios :

QGP :

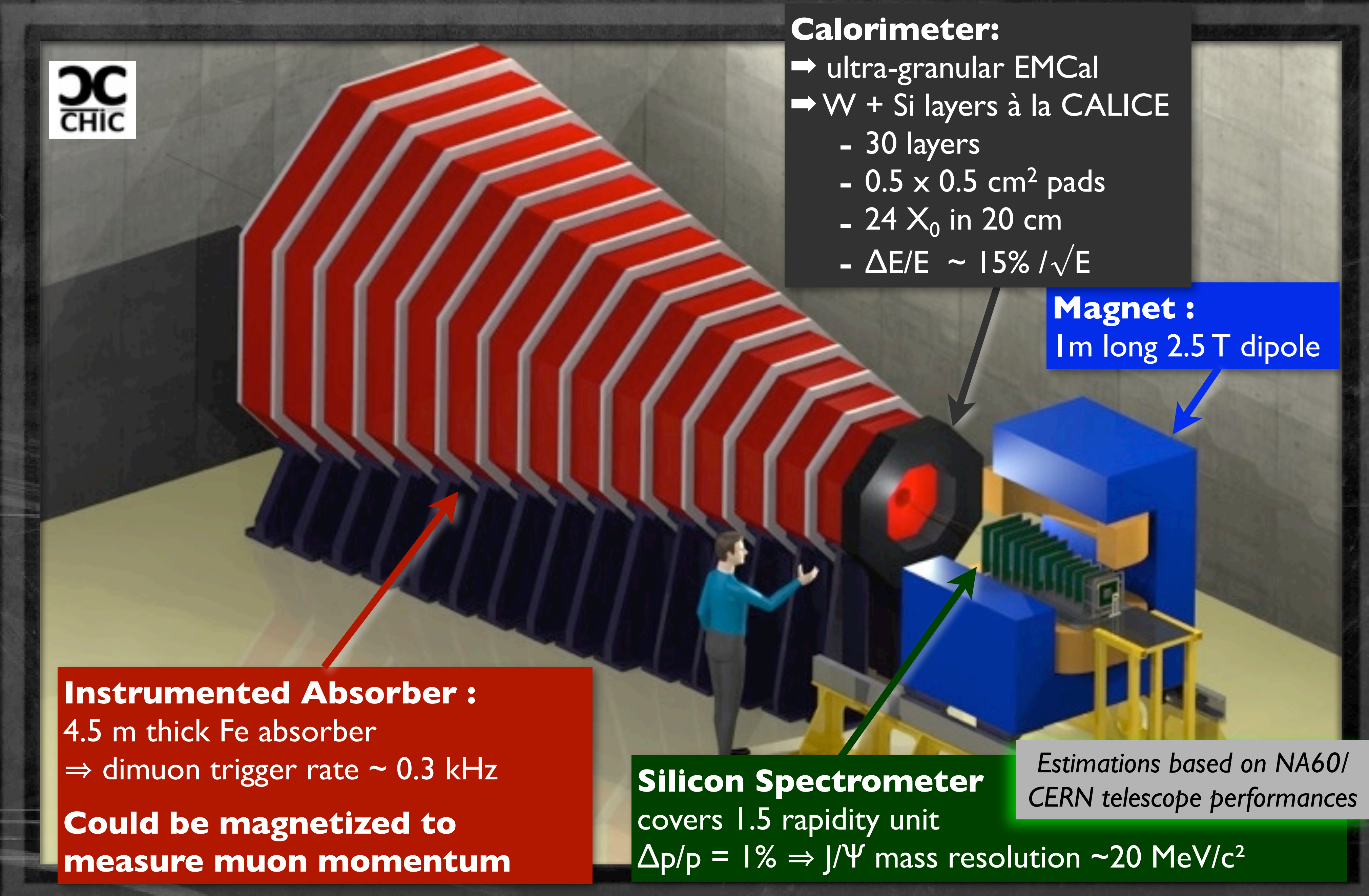
- current ψ' data shows a nearly complete melting of ψ' in central Pb+Pb
- χ_c melting should start after ψ' melting
- current inclusive J/ψ data suggests almost no χ_c remains in central Pb+Pb

Alternative (no QGP) scenario :

- suppression by comoving hadrons
- smooth suppression
- same suppression-starting point
- slopes related to binding energy : $S_{\psi'} > S_{\chi} > S_{J/\psi}$

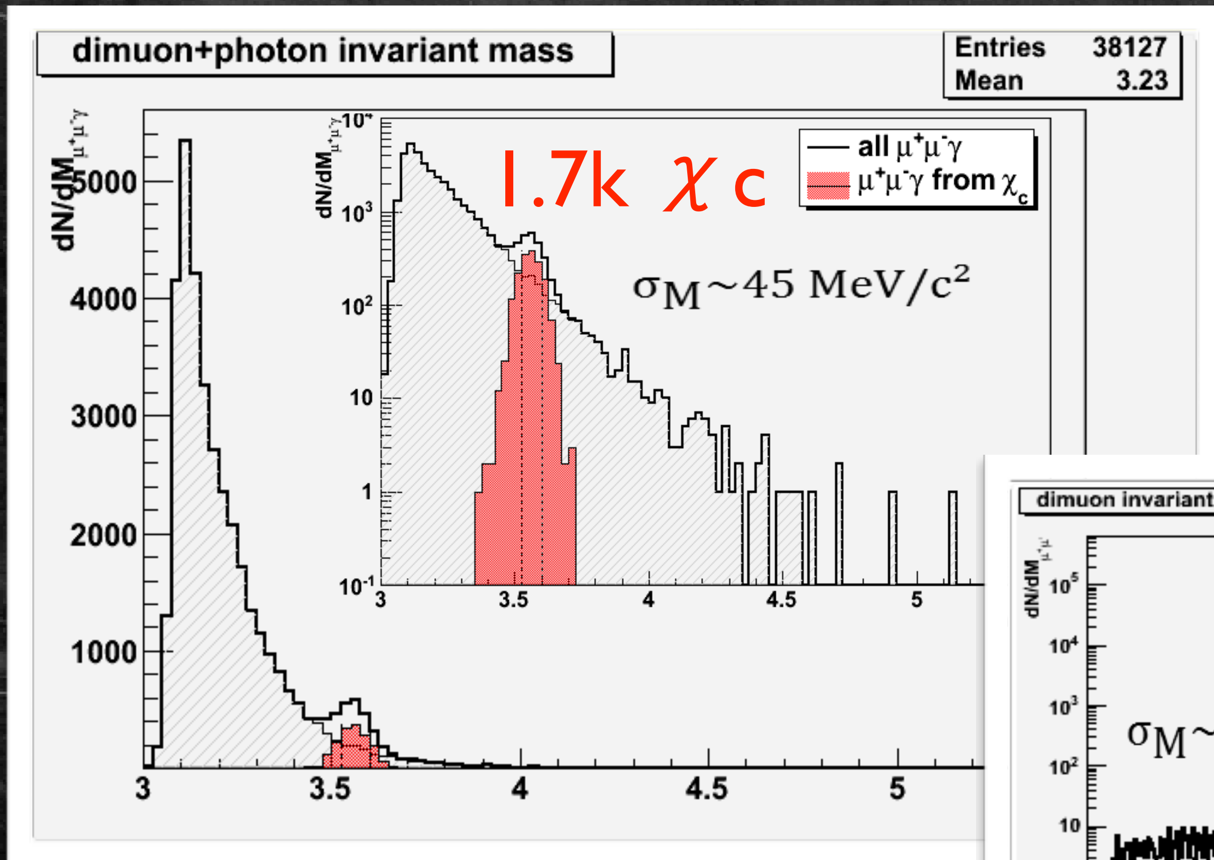


CHIC design



- Measure charmonia in di-muon channel with very good mass resolution
- Measure photon from χ_c decay in high π^0 multiplicity environment
- Muon absorber/trigger : minimize fake triggers from π/K decays

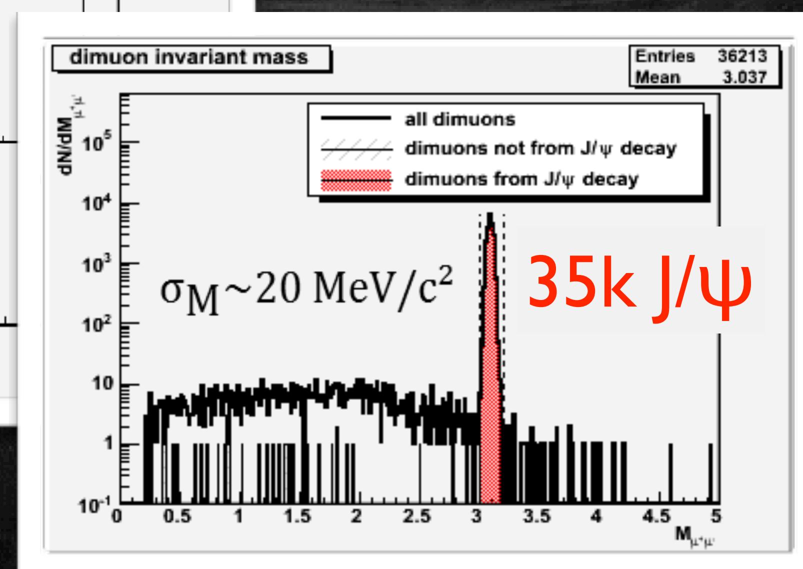
Performances in Pb+Pb



acc x eff ~ 2.8%

200k J/ψ embeded in Pb+Pb min. bias events from EPOS + decays in

- di-muon (70%)
- χ_c + photon (30%)



acc x eff ~ 17.4%

after acceptance/selection cuts within $y_{CMS} \in [-0.5 , 0.5]$

- Corresponds to ~1 week of data taking w/a 10% λ_I Pb target

Expected number of events

Statistics

- **Typical 40-day Pb+Pb run** **($10^7.s^{-1}$ Pb beam → 10% λ_I Pb target)**
  - ~ 180 000 $J/\Psi \rightarrow \mu^+\mu^-$ recorded
  - 2 extreme *numerical* scenarios:
    - If χ_c suppressed as J/Ψ $\frac{\chi_c \text{ yield}}{J/\Psi \text{ yield}} \sim 4\%$

$$\rightarrow \begin{pmatrix}\text{most periph.} \\ \chi_c \text{ yield}\end{pmatrix} = 16942 \times 4\% = 677$$

    - If χ_c suppressed as Ψ' $\frac{\chi_c \text{ yield}}{\Psi' \text{ yield}} = 2.18$

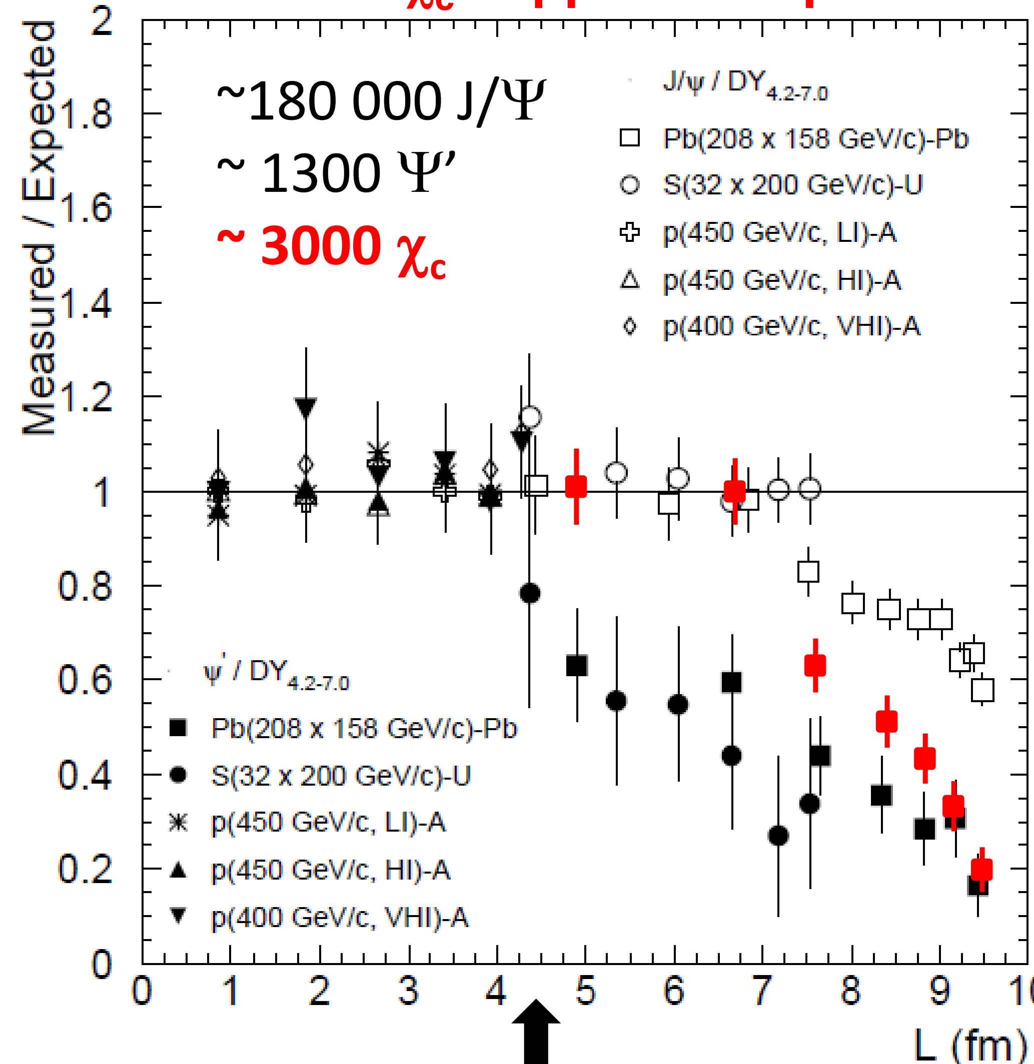
$$\begin{pmatrix}\text{most periph.} \\ \chi_c \text{ yield}\end{pmatrix} = 16942 \times 4\% \times 0.6 = 406$$

E_T range (GeV)	ψ'	J/ψ	χ_c as Ψ'	χ_c as J/Ψ
3–20	186 ± 25	16942 ± 146	406	677
20–35	243 ± 31	25229 ± 181	530	1010
35–50	227 ± 35	27276 ± 192	495	1091
50–65	193 ± 36	27681 ± 196	421	1107
65–80	154 ± 36	27315 ± 200	336	1093
80–95	159 ± 37	25111 ± 193	647	1004
95–150	110 ± 40	28570 ± 209	240	1143
			3075	**7125**

NA50 data

Eur.Phys.J.C49:559-567,2007

Possible χ_c suppression pattern



Expect 3000 < N_{χ_c} < 7000

[F. Fleuret, GDR PH-QCD 2013]

CHIC

p+A program

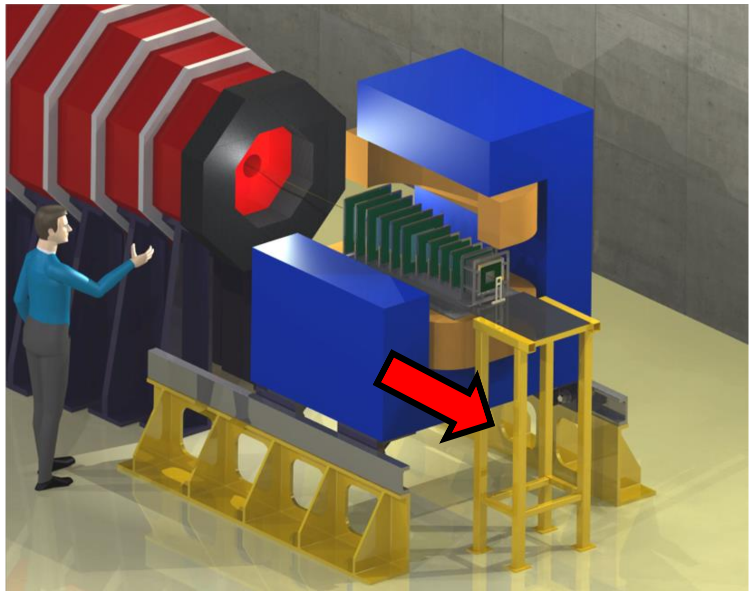
Cold Nuclear Matter

A thorough p+A program is mandatory to study Cold Nuclear Matter effects as a reference to study Hot Nuclear Matter effects

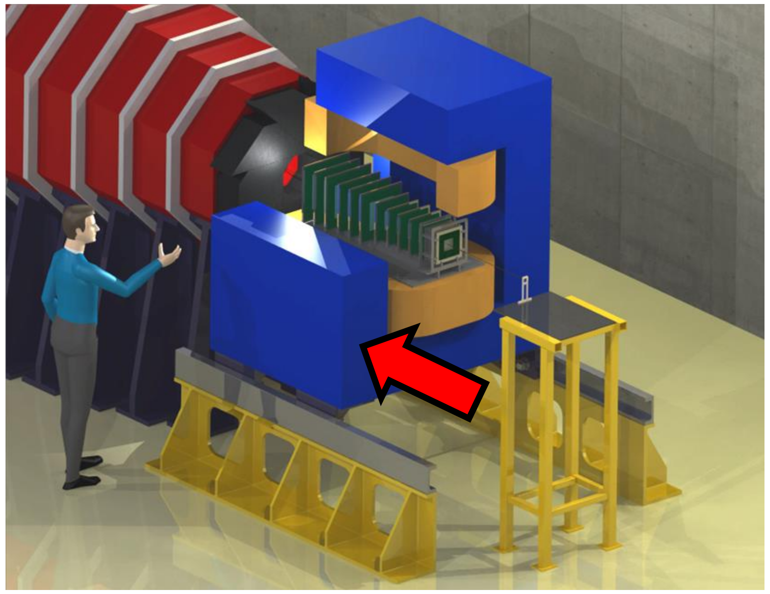
- **Must control (understand) :**
  - charmonium absorption by cold nuclear matter → A dependence
  - Shadowing/anti-shadowing (x_2 scaling)
  - Energy loss, formation time (x_F scaling)

→ **Need large y_{CMS} range**

Mid-rapidity : $y_{CMS} \in [-0.5 ; 1]$



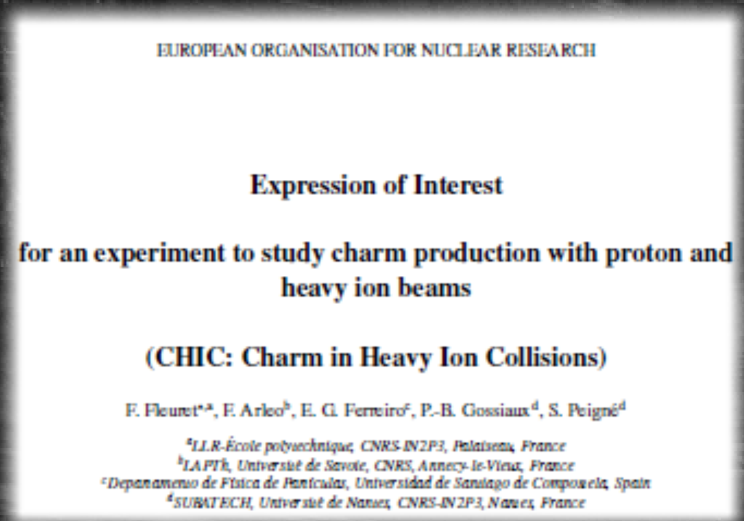
Forward-rapidity : $y_{CMS} \in [0.5 ; 2]$



[F. Fleuret, GDR PH-QCD 2013]

Status and outlook

EoI submitted to the SPS Committe (Oct. 2012)
CERN-SPSC-2012-031


EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH

Expression of Interest

for an experiment to study charm production with proton and heavy ion beams

(CHIC: Charm in Heavy Ion Collisions)

F. Fleuret*[a], F. Arleo[b], E. G. Ferreiro[c], P.-B. Gossiaux[d], S. Peigné[d]

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Status and outlook

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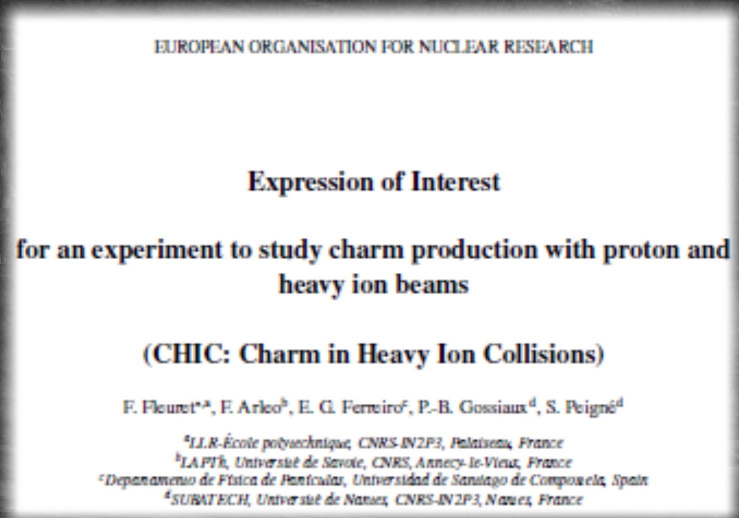
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MINUTES of the 108th Meeting of the SPSC (Jan. 2013)
CERN-SPSC-2013-008

The SPSC has received an expression of interest to study charm production with proton and heavy ion beams. The SPSC recognizes the strong physics motivation of a study that addresses central open questions about the color screening of charmonium in heavy ion collisions and about cold nuclear matter effects. For a comprehensive investigation, an extension including open charm production would be desirable.

For further review, the SPSC would require a letter of intent with information about the experimental implementation and the collaboration pursuing it.

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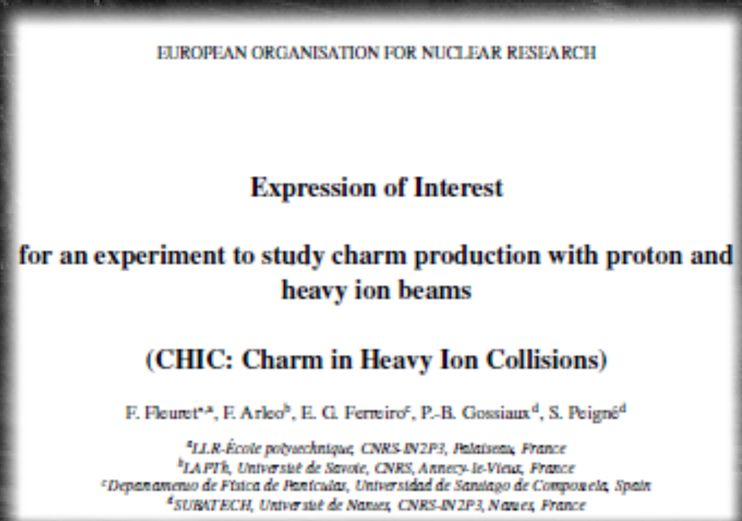
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Apparatus :

Tracking

- Needs low detector occupancy ⇒ silicon technology
- Welcomes group with expertise !

Calorimetry

- Need ultragranular calorimetry à la CALICE
- Expertise at LLR - Ecole polytechnique (France)

Trigger

- Instrumented (magnetized) Fe Absorber
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Many opportunities to join

Expected timeline
T0 (3 labs involved) + approx. 5 Years
- full simulation and final design (2 years)
- construction and installation (2 years)
- commisionning (1 year)

[F. Fleuret, GDR PH-QCD 2013]

A Fixed Target ExpeRiment using LHC beams

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)

AFTER @ LHC

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- $\sqrt{s}$ ~ 115 GeV : p−p, p−d, p−A (using LHC 7 TeV p beam)
- $\sqrt{s}$ ~ 72 GeV : Pb−p, Pb−A (using LHC 2.76 TeV Pb beam)

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comparable to RHIC energies

- $\sqrt{s} \sim 115$ GeV : p−p, p−d, p−A (using LHC 7 TeV p beam)

between SPS and top RHIC energies

- $\sqrt{s} \sim 72$ GeV : Pb−p, Pb−A (using LHC 2.76 TeV Pb beam)

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]

Contents

Aller à la page 242

Physics Reports 522 (2013) 239–255

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

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Physics opportunities of a fixed-target experiment using LHC beams

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

[a] *SLAC National Accelerator Laboratory, Stanford University, Menlo Park, CA 94025, USA*

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

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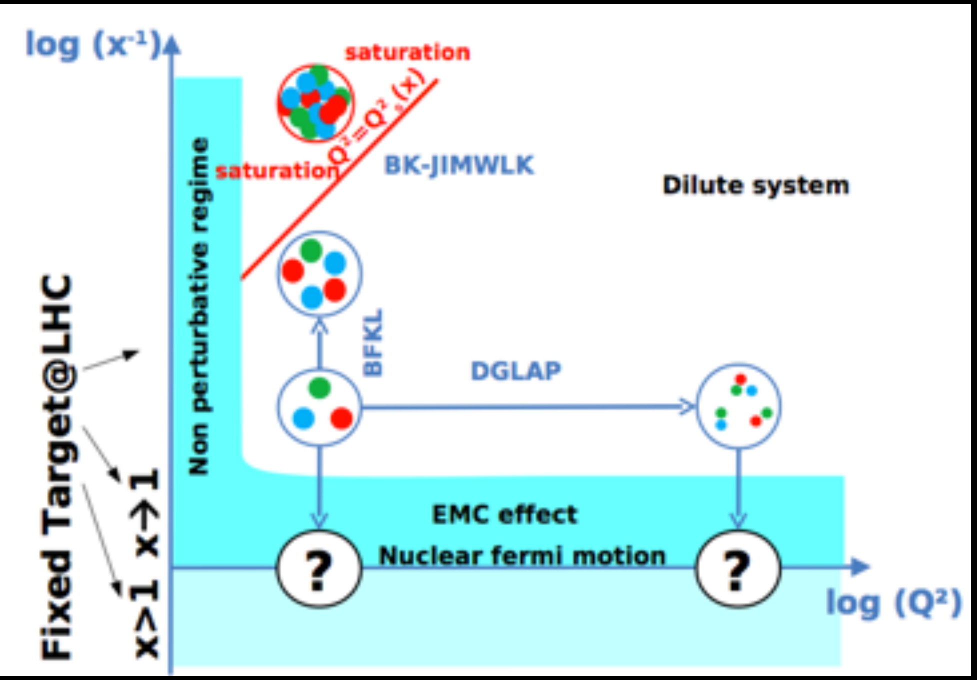
QCD near the high x frontier

AFTER @ LHC



Test the high x frontier of QCD
x = 0.3 – 1

- Nucleon partonic structure (PDF)
  ➠ gluon at high x, intrinsic charm/beauty at high x, proton vs neutron PDF
- Correlations between partons (spatial position, momentum, spin ...)
  ➠ nucleon 3D structure

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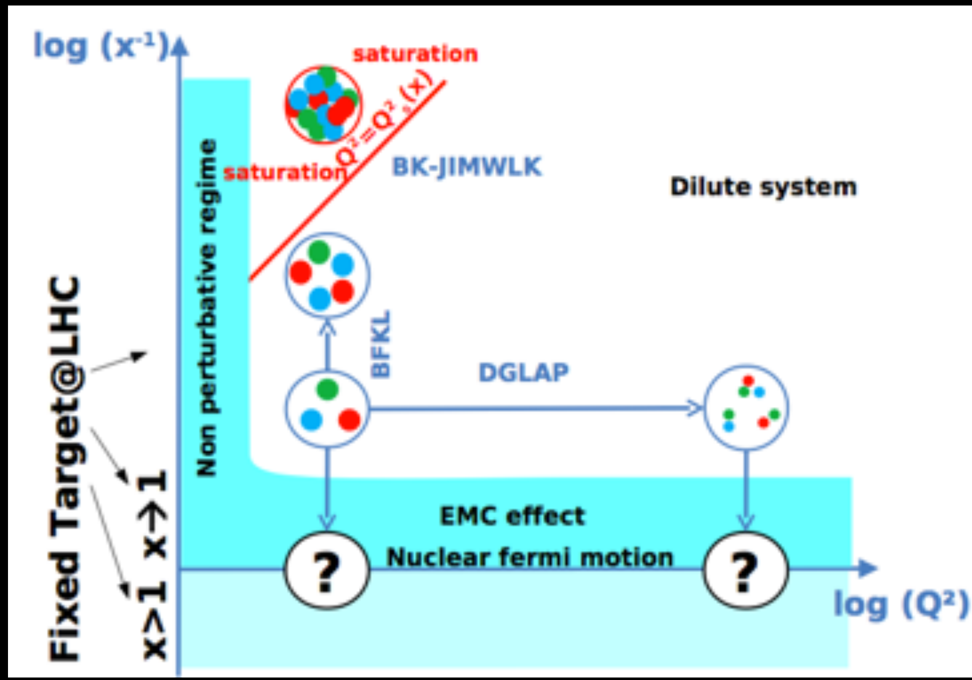

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- Correlations between partons (spatial position, momentum, spin ...)
  ➠ nucleon 3D structure

A Fixed Target ExpeRiment @ LHC :

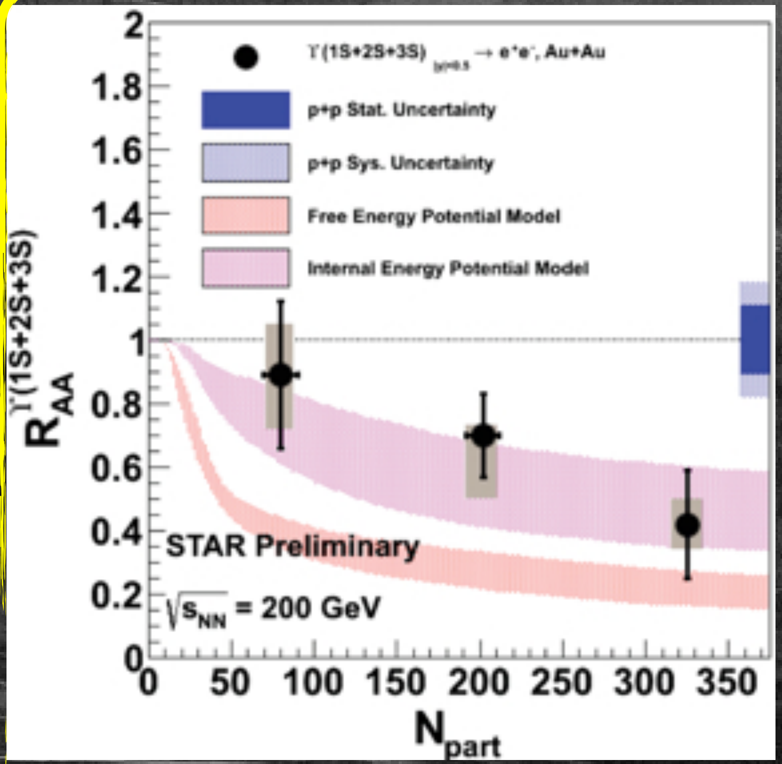
- very energetic unpolarised p beam
- polarised or unpolarised nuclear target, where $(x^{\uparrow} = x_2)$
- full backward access, up to $(x_F \to -1) \Leftrightarrow (x^{\uparrow} \to 1)$
  - the target rapidity region corresponds to high $x^{\uparrow}$

high luminosity & scan in x_F

- complementarity with JLAB (intermediate to large x) and LHeC (very low x)

Bottomonium studies: from RHIC to AFTER

Pb–A



[Bielcik for STAR, HP2013]

Today :

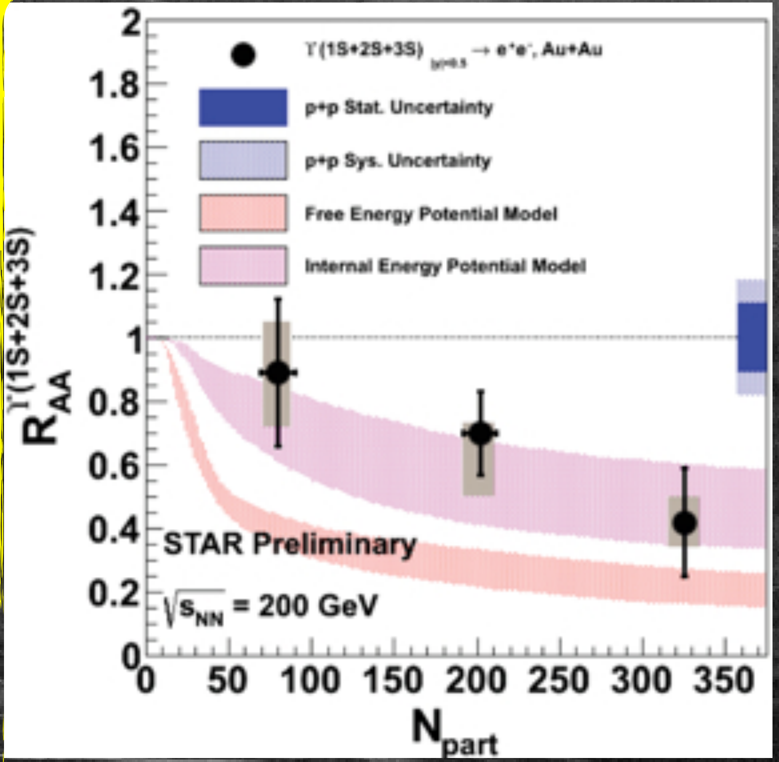
- inclusive Υ(1S + 2S + 3S) R_{AA} vs centrality
- the most central point is compatible with a complete melting of (3S) and a very strong suppression of (2S), with $T_{initial}$ ~ 430 MeV in this model

From thermal photon p_T spectra :

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

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

Bottomonium studies: from RHIC to AFTER (Pb–A)



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decompose this model into each state

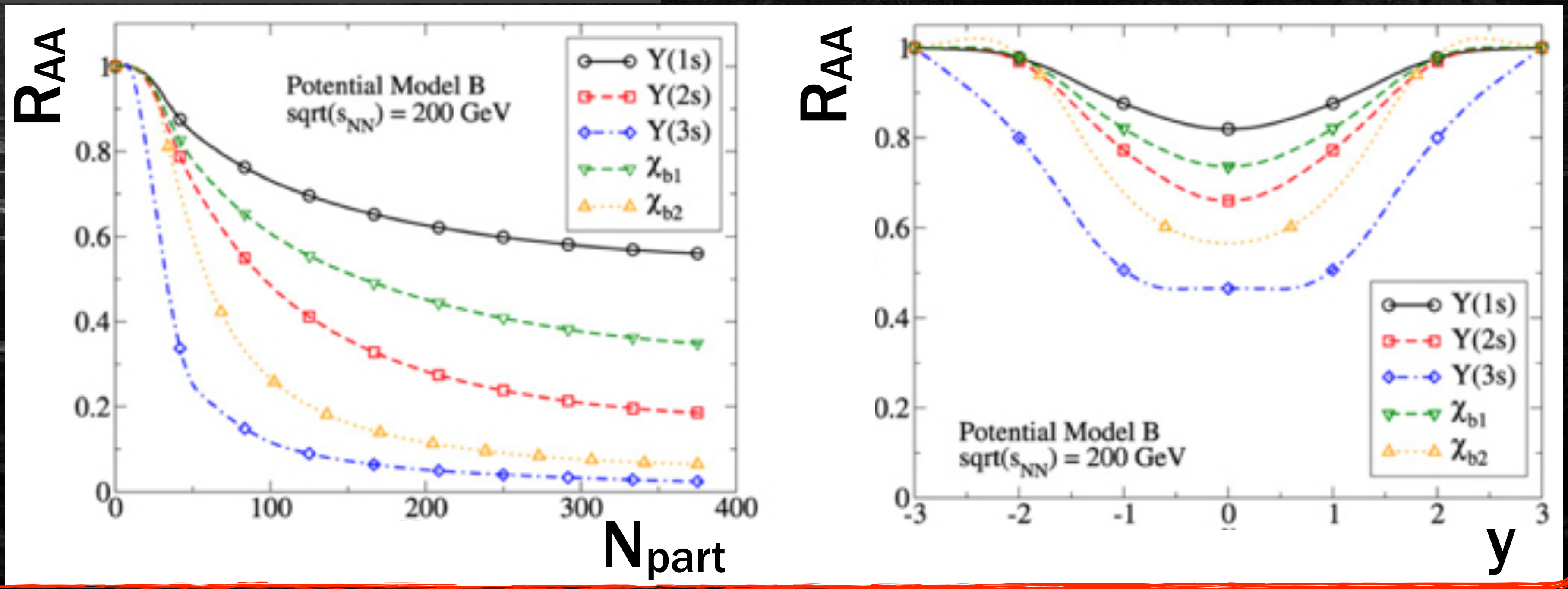
↓

need more stat in AA + very good resolution

reminder
STAR : ~200 Υ
CMS : ~1k Υ

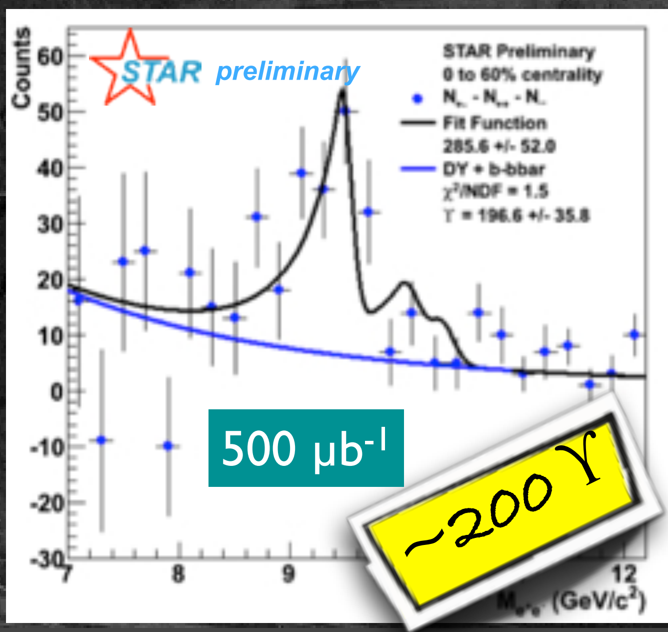
[Strickland et al., NPA 879 (2012) 25-58]

The dreamed measurements :

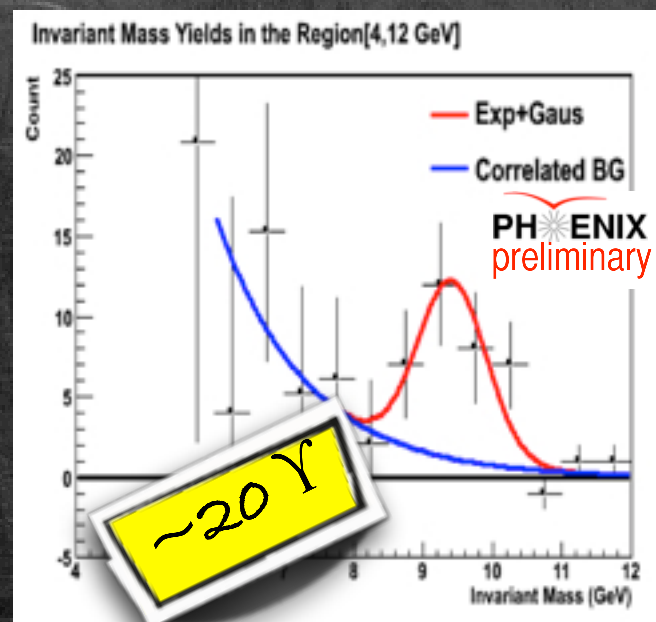


Υ(1S + 2S + 3S) @ RHIC

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

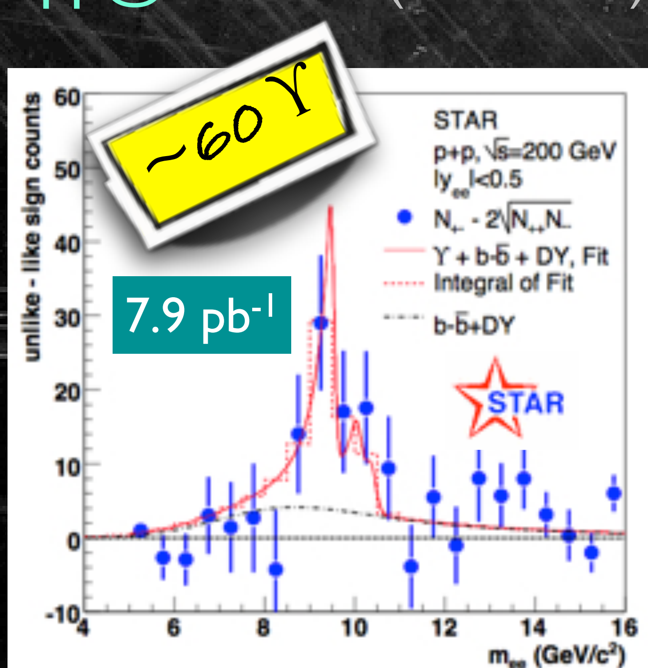


[Reed for STAR, JPG 38 (2011) 124185]

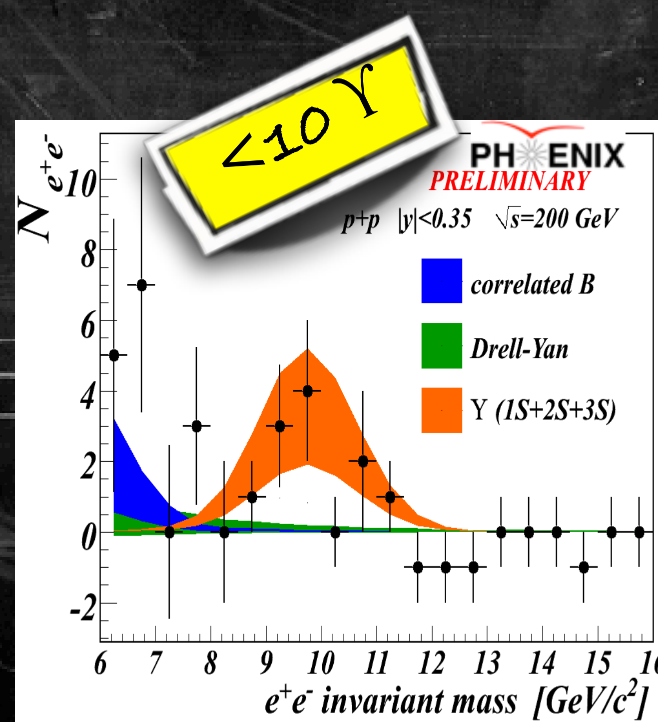


[Whitaker for PHENIX, poster at QM2012]

pp@200GeV (run 2006)



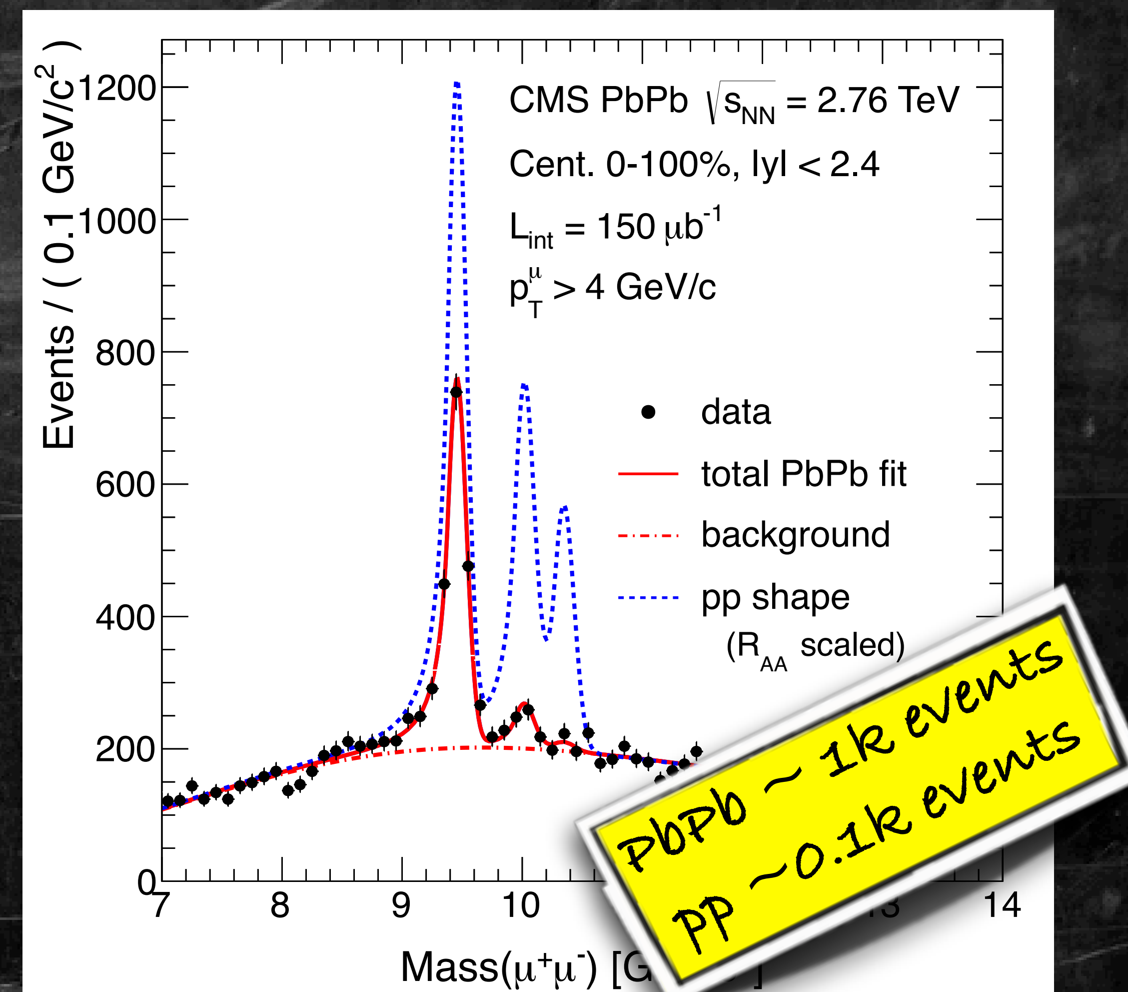
[STAR, PRD 82 (2010) 012004]



[Leitch for PHENIX, QM2009]

sequential melting @ LHC

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



[CMS, PRL 109 (2012) 222301]

From thermal photons p_T spectra :

T_{avg} ~ 304 ± 51 MeV (0-40% PbPb)

[Alice, NPA 904 (2013) 573c]

AFTER : inclusive Υ yield in PbA @ $\sqrt{s}$ = 72 GeV

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

yield / unit of y @ y = 0

	Target	$\int dt\mathcal{L}$	$\mathcal{B}_{\ell\ell} \frac{dN_\Upsilon}{dy}\Big\vert_{y=0}$
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	$1.9\ 10^3$
	1 cm Cu	17	$0.9\ 10^3$
	1 cm W	13	$1.9\ 10^4$
	1 cm Pb	7	$1.1\ 10^4$
RHIC	*d*Au RHIC (200 GeV)	150	$5.9\ 10^3$
	*d*Au RHIC (62 GeV)	3.8	$1.8\ 10^1$
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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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[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

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

10^2 x RHIC @ 62 GeV

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

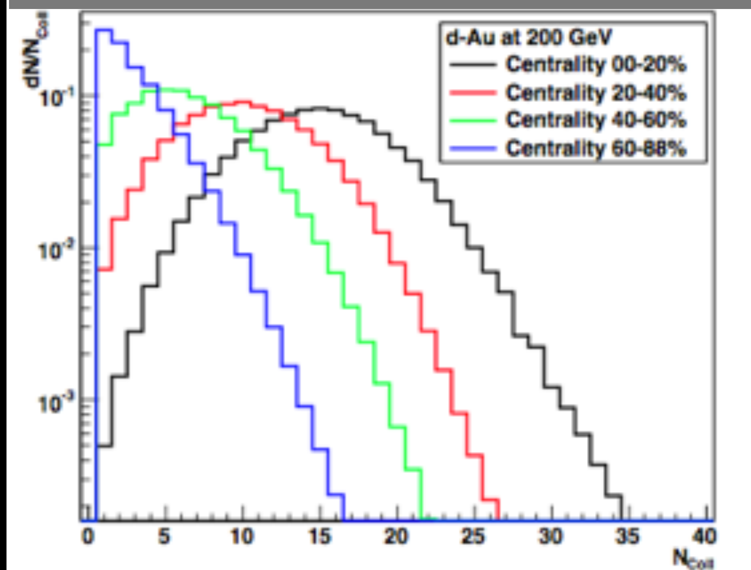
Towards a Cold Effect reference : gluon nPDF

p−A

Pb−p

- A dependence thanks to target versatility

[PHENIX, arXiv:1204.0777]



$\langle N_{coll} \rangle$ dependence ⇛ A dependence (à la NA50, NA60)

Towards a Cold Effect reference : gluon nPDF

p−A

Pb−p

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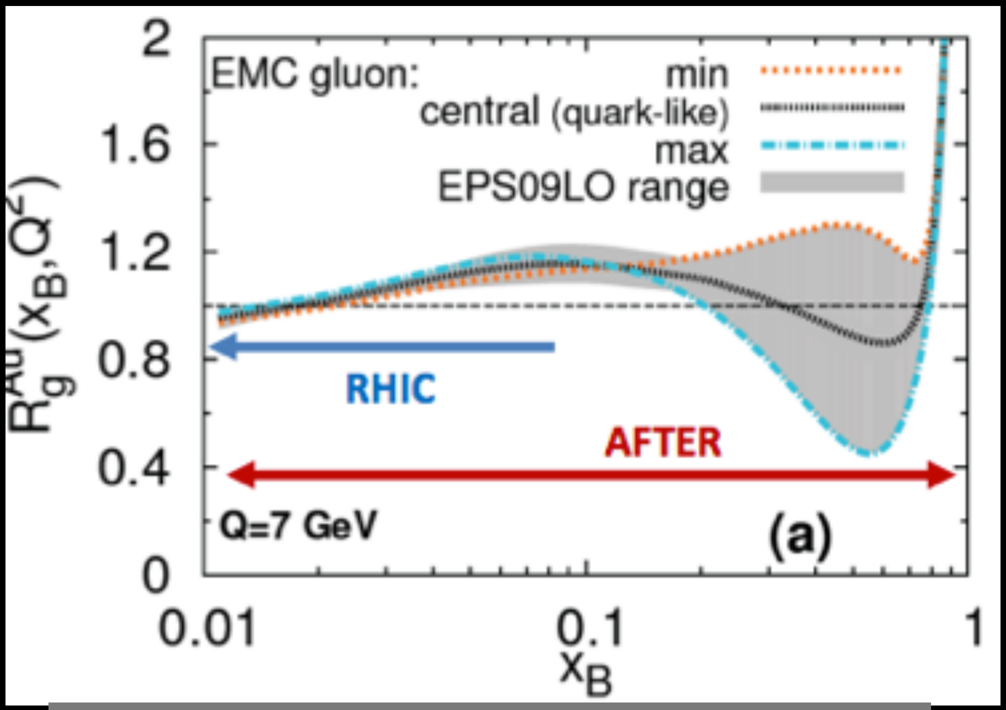
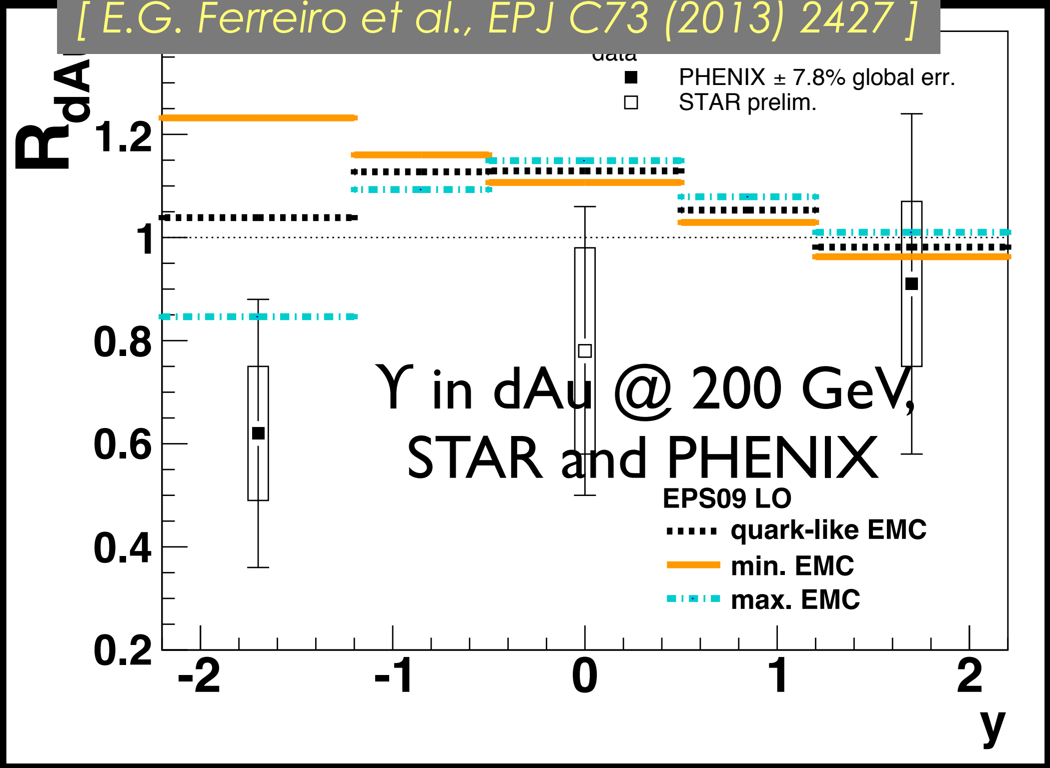
- nuclear PDF from intermediate to high x : antishadowing , EMC region , Fermi motion
- extraction using quarkonia, isolated photons, photon-jet correlation

nuclear modification of g PDF in Au



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



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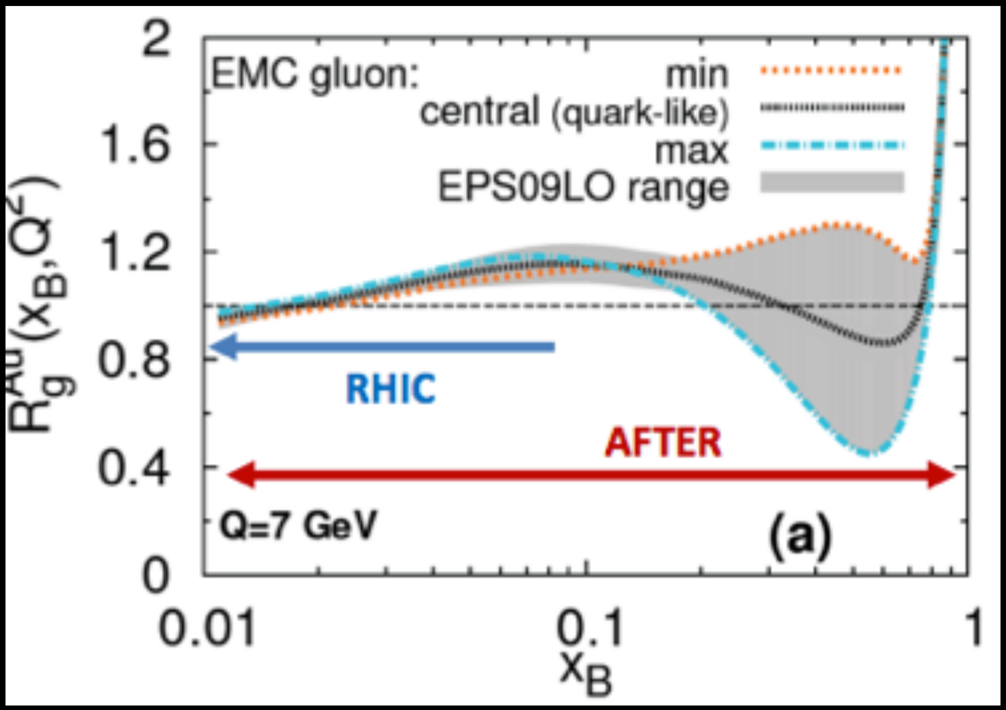

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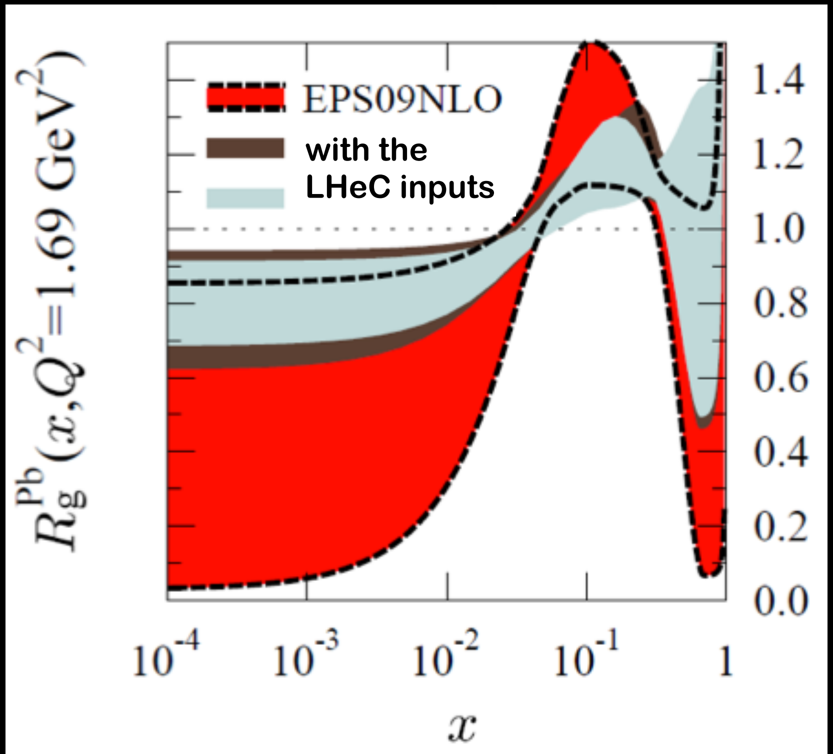

[LHeC CDR, J. Phys. G 39 (2012) 075001]

complementary with LHeC (focus at low x)

Bottomonium : a cleaner QGP probe ?

- better applicability of pQCD
- in QGP : at RHIC energies, negligible regeneration effects
  - ➡ no dilution of the « thermometer-like » behaviour of the bottomonium family

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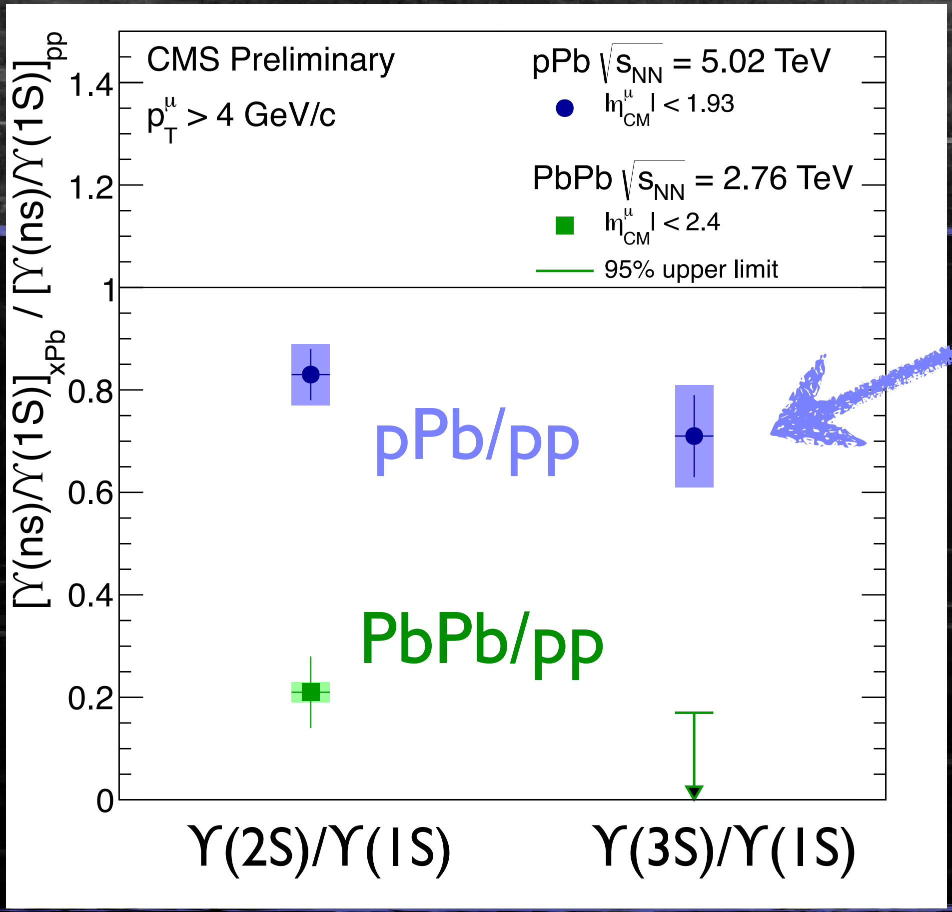
pPb vs. pp: excited states suppressed more than the ground state in pPb compared to pp collisions (significance < 3σ)



[Benhabib for CMS, HP2013]

But : Cold effects (i.e. not QGP)

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

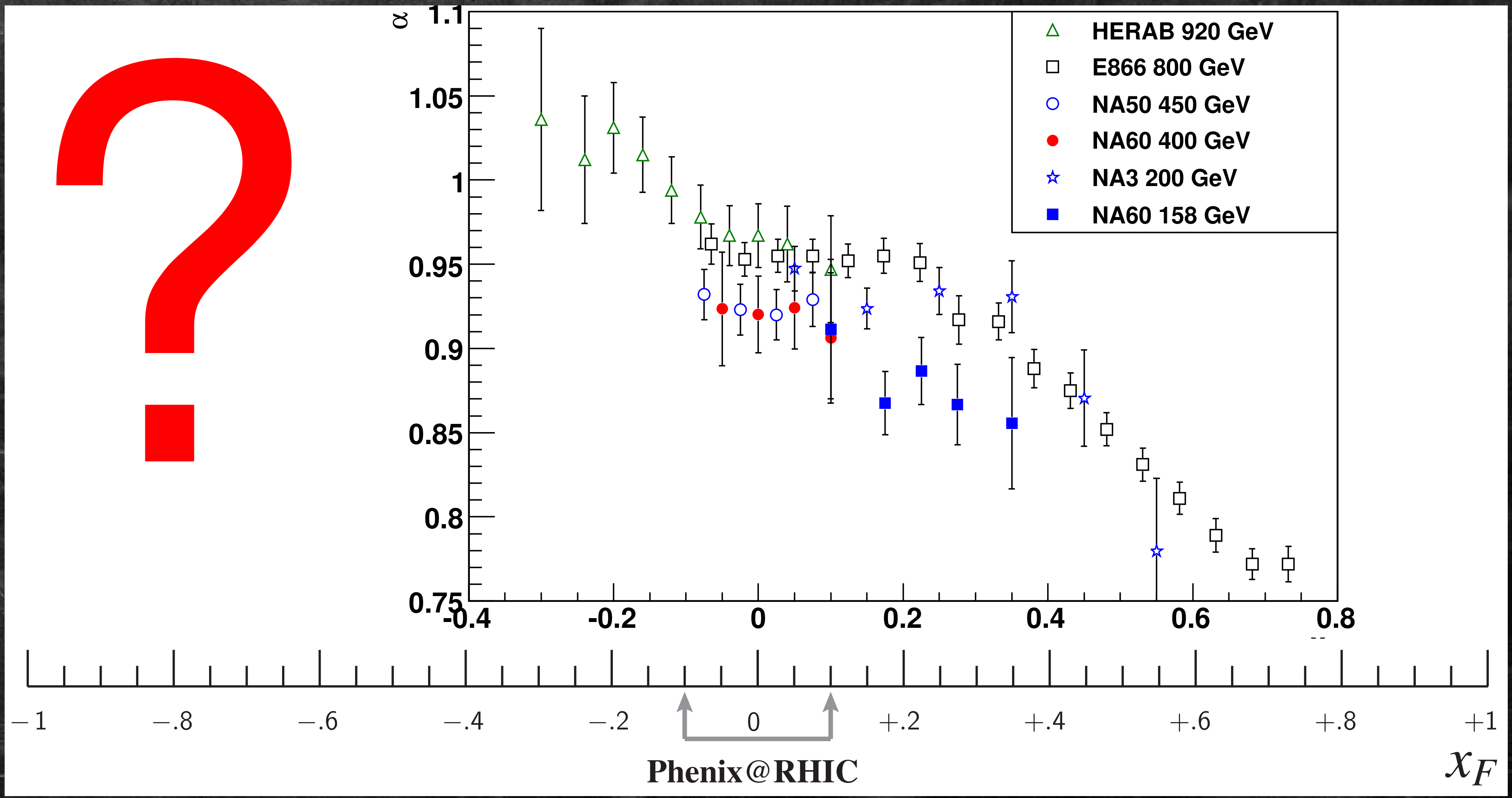
The uncharted negative x_F region

p-A

J/ψ suppression in pA

- HeraB down to $x_F = -0.3$
- PHENIX @ RHIC :
  $|x_F| < 0.1$
  (could be wider with Υ, but low stat.)
- CMS/ATLAS : $|x_F| < 5.10^{-3}$
- LHCb : $5.10^{-3} < x_F < 4.10^{-2}$

?



Precision studies of the nuclear matter :

First systematic access to the target-rapidity region, down to $x_F \to -1$

Heavy Quarkonium yields in pH, pA

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

J/ψ ↓ ϒ ↓

	Target	$\int dt\mathcal{L}$		$\mathcal{B}_{\ell\ell} \frac{dN_{J/\psi}}{dy}\Big\vert_{y=0}$	$\mathcal{B}_{\ell\ell} \frac{dN_{\Upsilon}}{dy}\Big\vert_{y=0}$
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	pPb LHC (8.8 TeV)	10^{-4}		$1.0\ 10^7$	$7.5\ 10^4$
RHIC	pp RHIC (200 GeV)	$1.2\ 10^{-2}$		$4.8\ 10^5$	$1.2\ 10^3$
RHIC	dAu RHIC (200 GeV)	$1.5\ 10^{-4}$		$2.4\ 10^6$	$5.9\ 10^3$
RHIC	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

J/ψ ↓ ϒ ↓

	Target	$\int dt \mathcal{L}$		$\mathcal{B}_{\ell\ell} \frac{dN_{J/\psi}}{dy}\Big\vert_{y=0}$	$\mathcal{B}_{\ell\ell} \frac{dN_{\Upsilon}}{dy}\Big\vert_{y=0}$
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pp : 100 x RHIC,
comparable to LHCb

RHIC lumi. from
PHENIX decadal plan
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[S. Brodsky, F. Fleuret, C. Hadjidakis, J.P. Lansberg, Phys. Rep. 522 (2013) 239]

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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

J/ψ ↓ Υ ↓

	Target	$\int dt \mathcal{L}$	$\mathcal{B}_{\ell\ell} \frac{dN_{J/\psi}}{dy}\Big\vert_{y=0}$	$\mathcal{B}_{\ell\ell} \frac{dN_{\Upsilon}}{dy}\Big\vert_{y=0}$
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pA : 10^{2}-10^{3} x RHIC

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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AFTER / LHC / RHIC

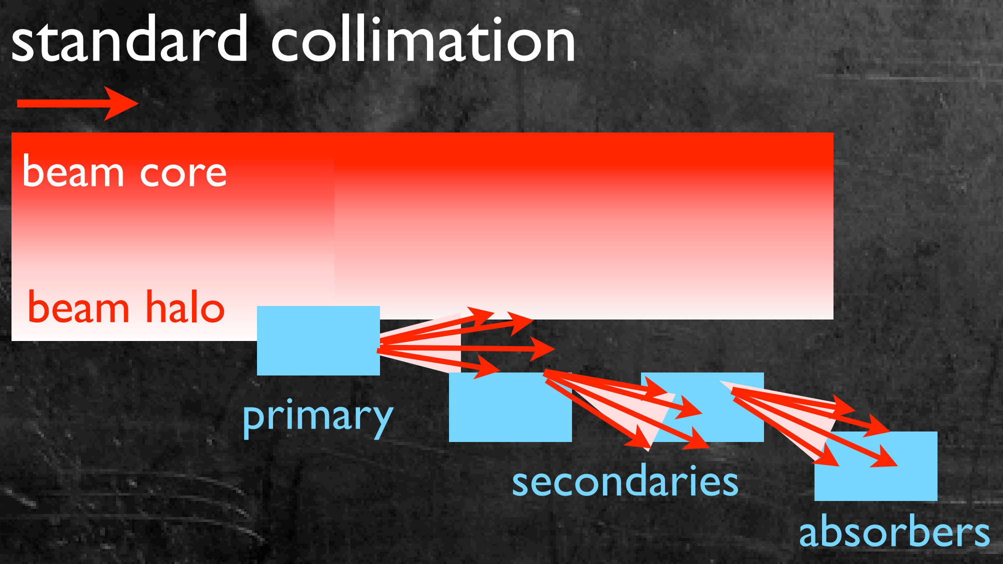
[S. Brodsky, F. Fleuret, C. Hadjidakis, J.P. Lansberg, Phys. Rep. 522 (2013) 239]

pp : 100 x RHIC, comparable to LHCb

pA : 10^2-10^3 x RHIC

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

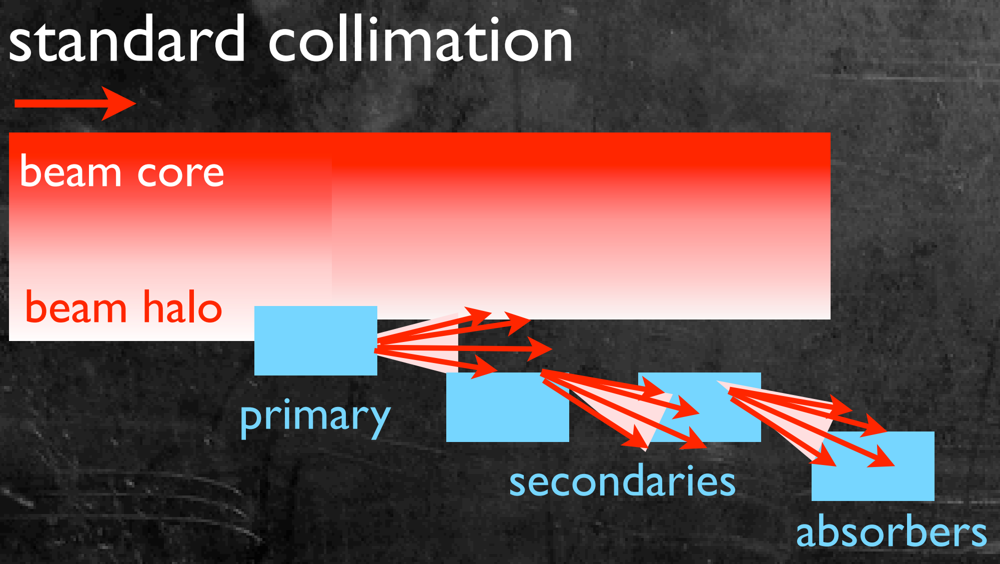
Recycle 50% of the LHC beam loss → a luminosity comparable to the LHC itself !

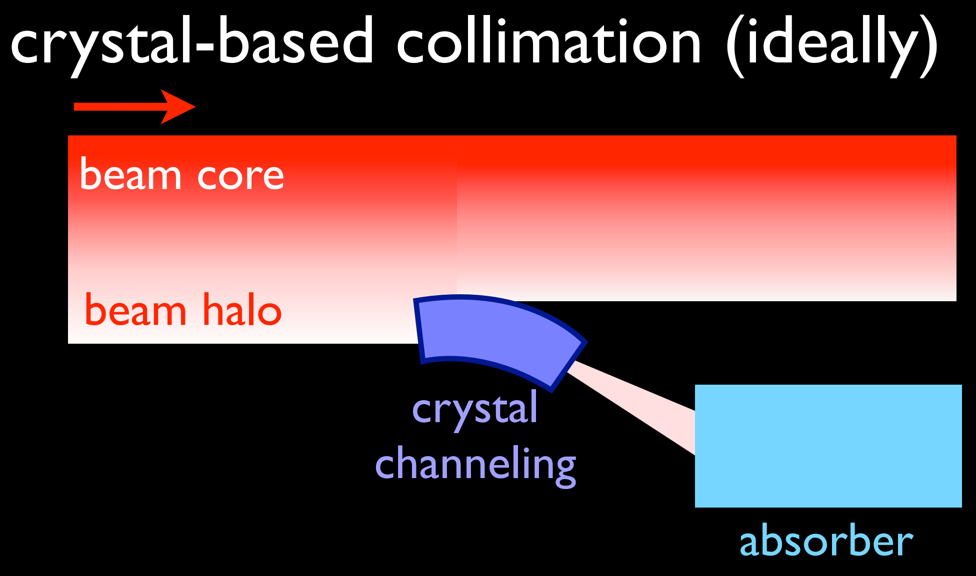


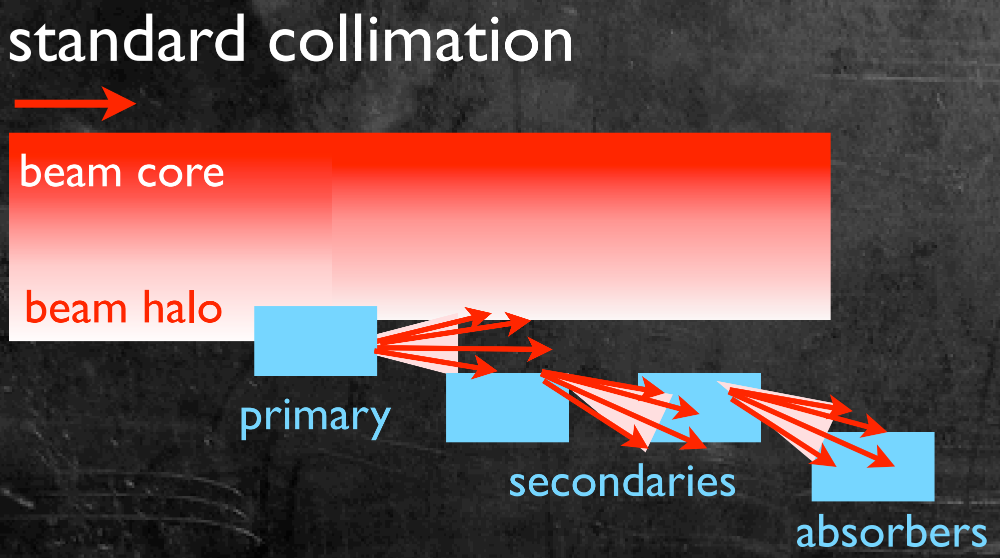
From beam collimation ...

Bent crystal channeling

From beam collimation ...





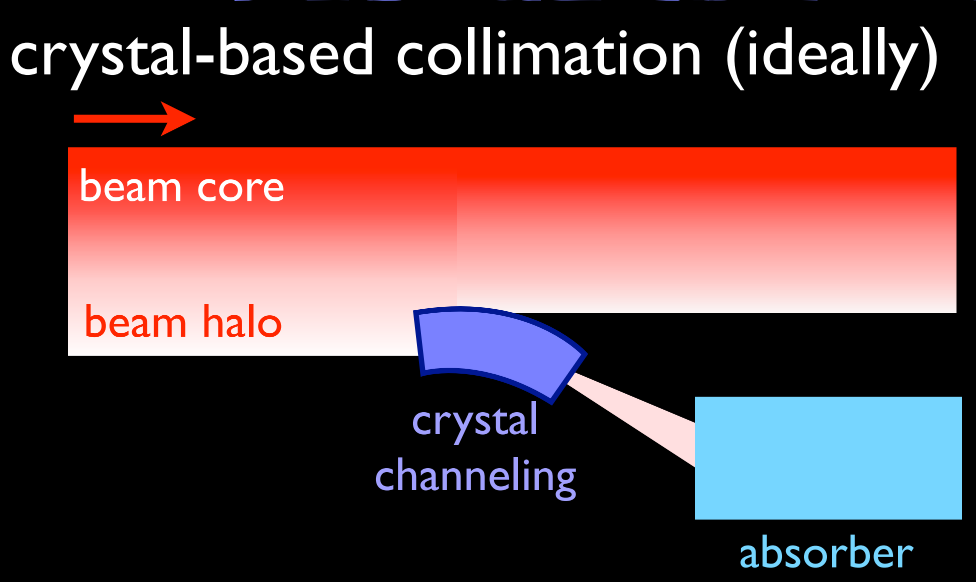


Bent crystal channeling

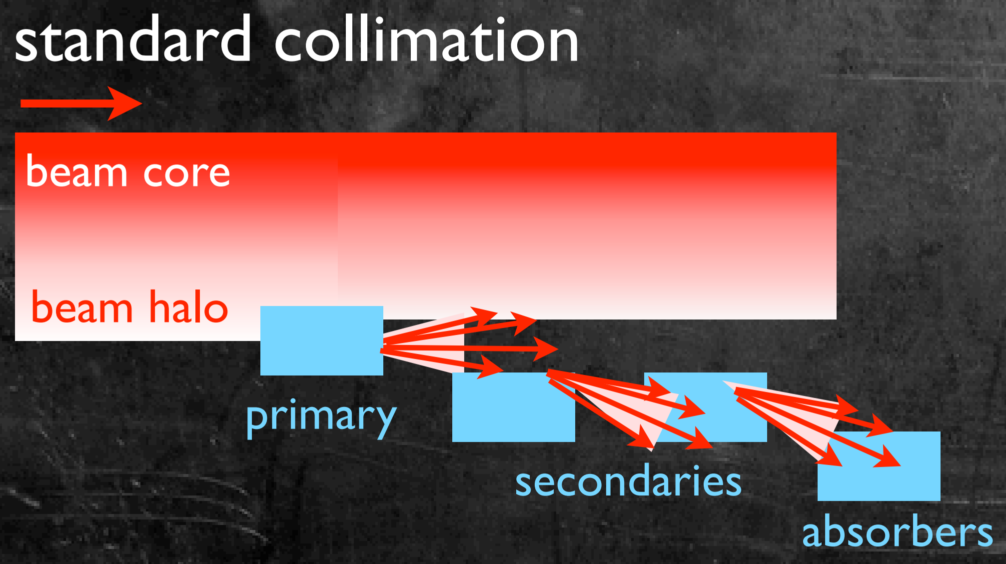
From beam collimation ...

RD22 @ SPS (1990 - 95)
E853 @ Tevatron (1993 - 98)
@ RHIC (2001 - 2005)
@ Tevatron (2005 - 2011)

UA9 @ SPS (2008 - ...)
LUA9 @ LHC (approved by the LHCC in end 2011)



[W. Scandale, Joint LUA9-AFTER meeting, Nov. 2013]



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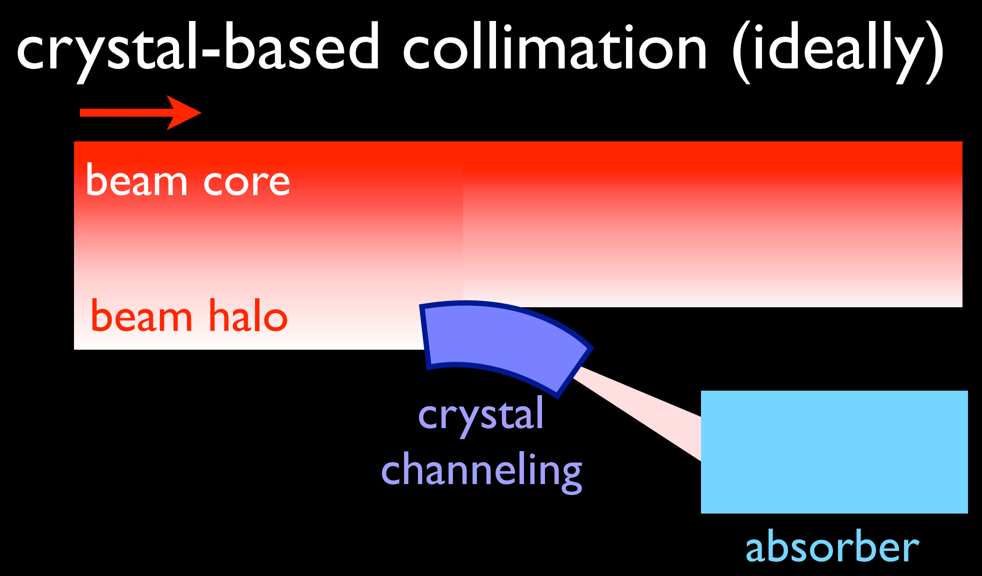


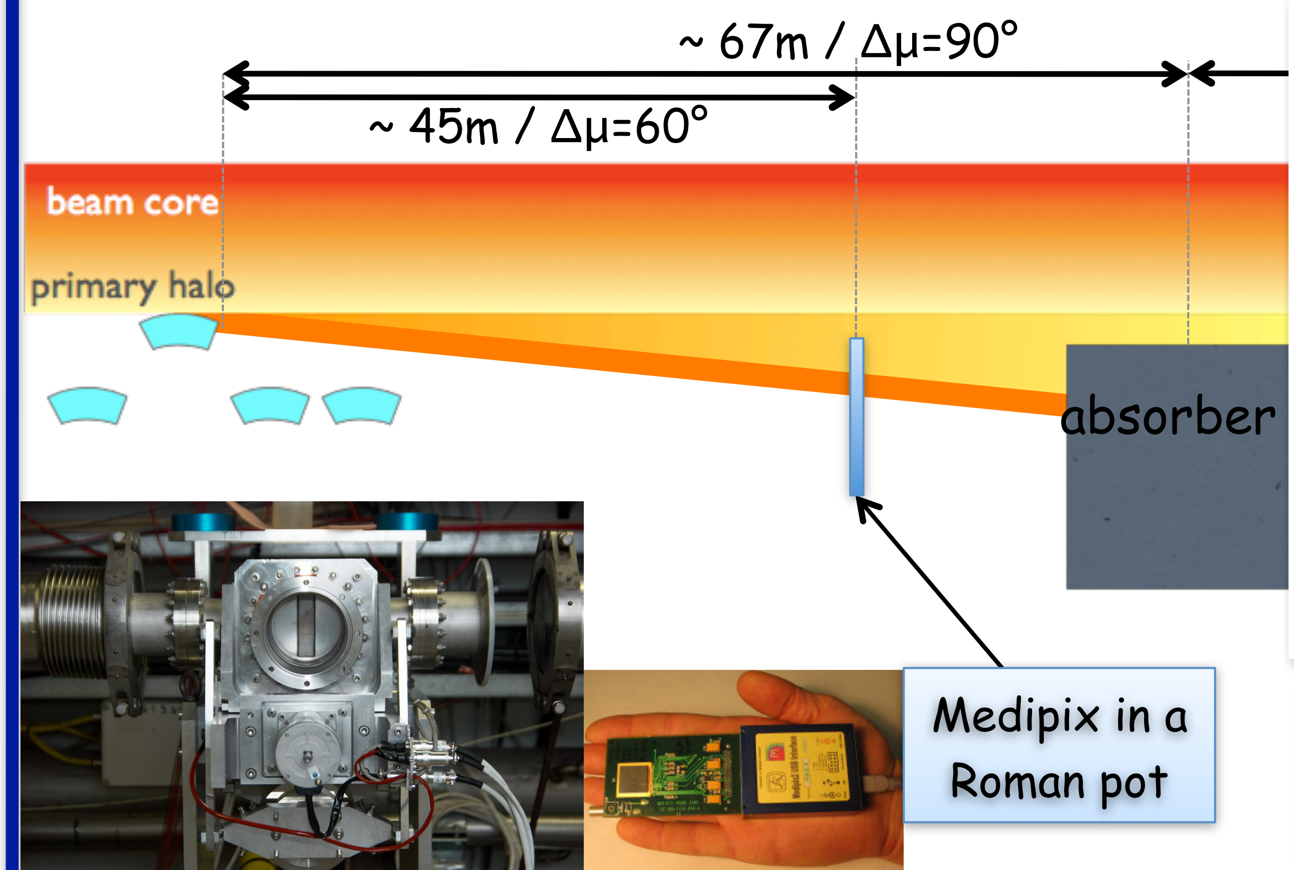
[W. Scandale, Joint LUA9-AFTER meeting, Nov. 2013]

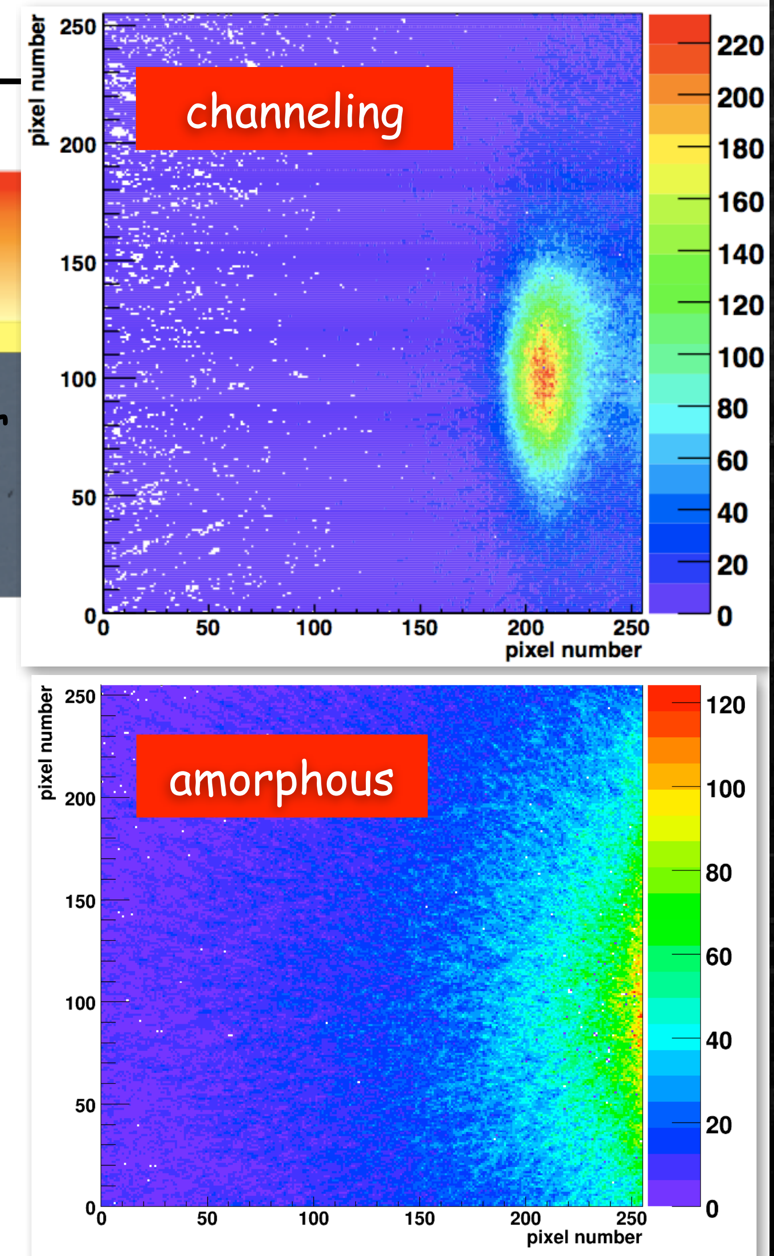
... to beam extraction

- CRYSBEAM
- AFTER @ LHC

UA9 @ SPS

Direct view of channeled beam





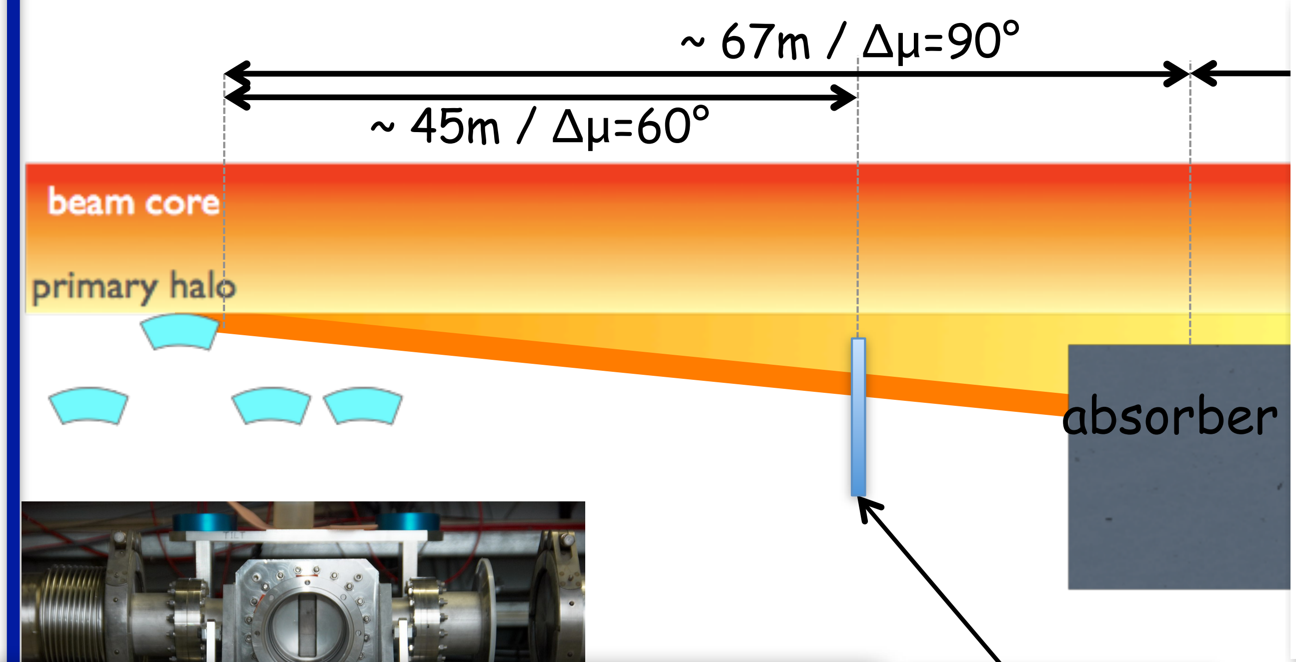
Medipix pixel detector in a Roman pot:

- Intensity, profile and angle of the deflected beam
- Efficiency of channeling (with multi-turn effect) (needs information on circulating beam current)

[W. Scandale, Joint LUA9-AFTER meeting, Nov. 2013]

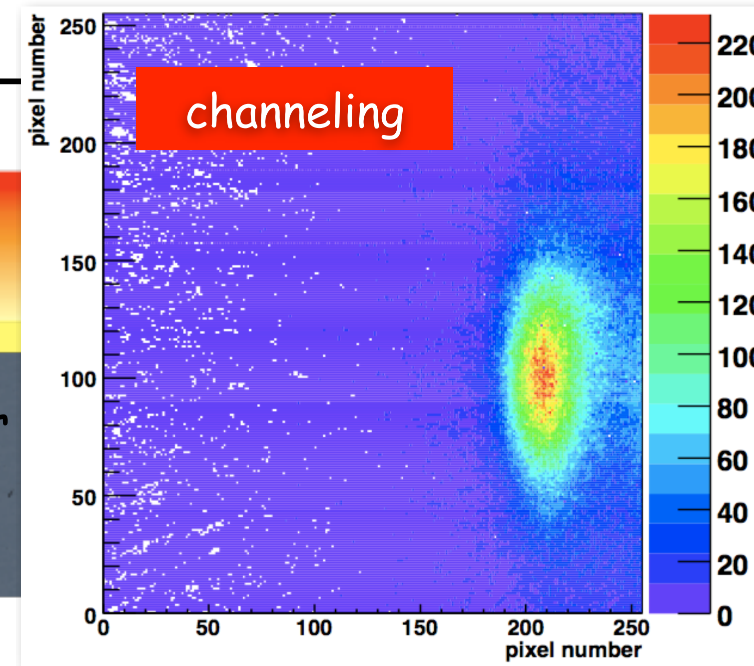
UA9 @ SPS

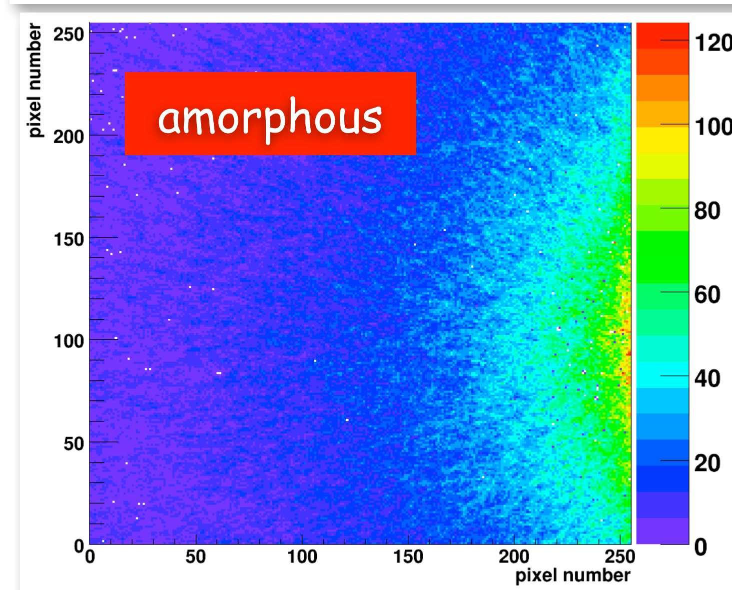
Direct view of channeled beam



Multi-turn channeling efficiency
70÷80% for protons
50÷70% for ions

Medipix in a Roman pot





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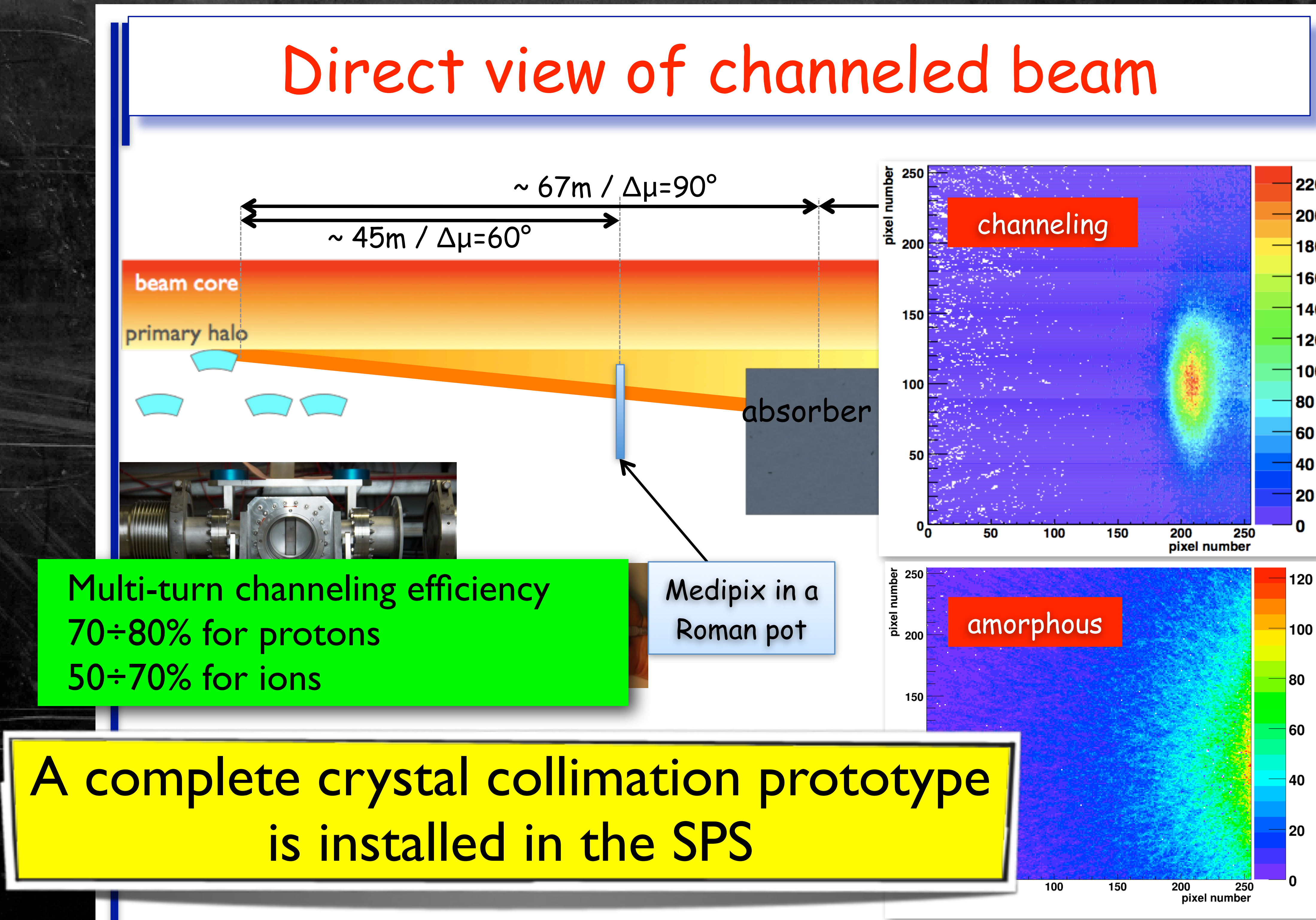
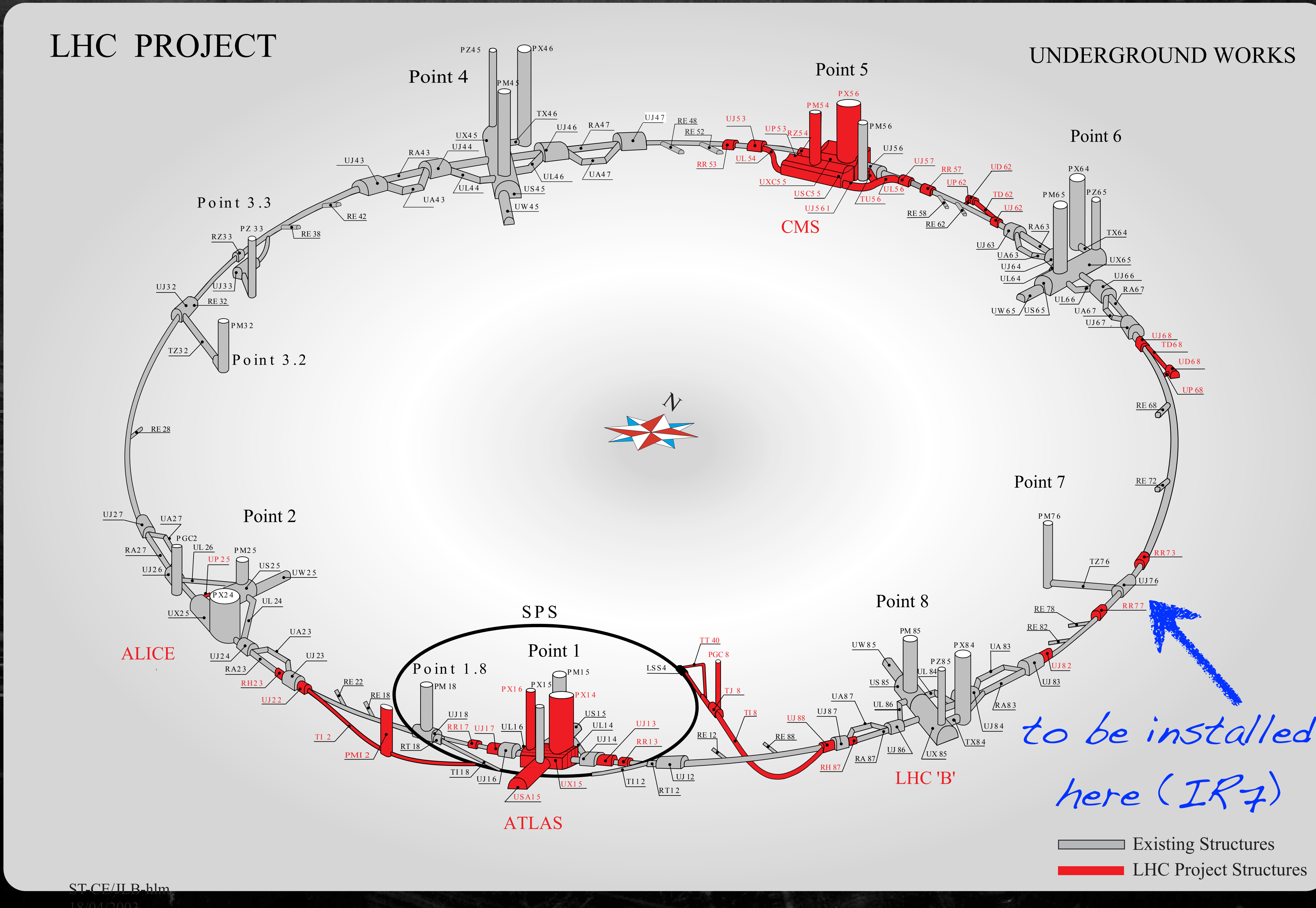
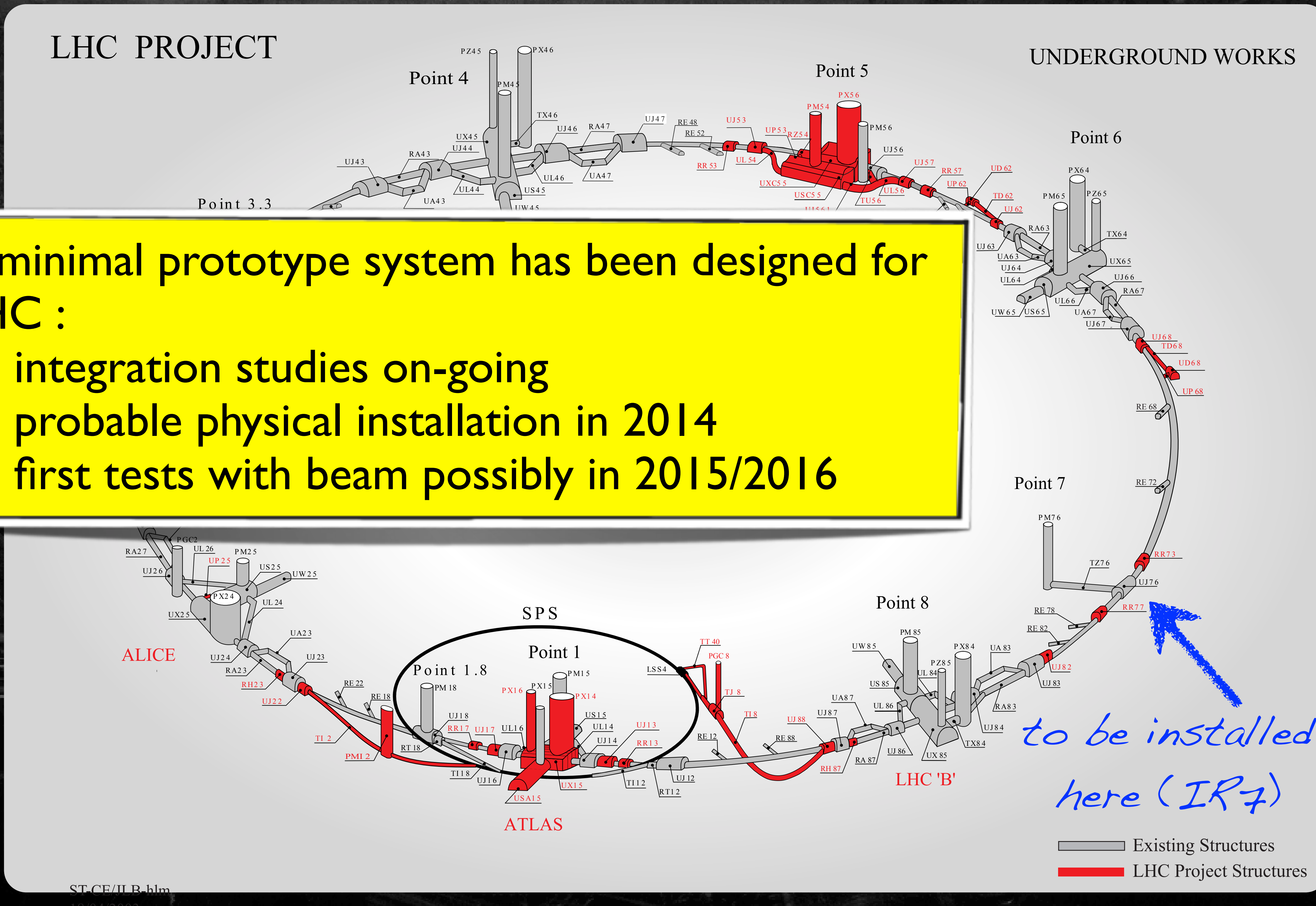


[W. Scandale, Joint LUA9-AFTER meeting, Nov. 2013]

LUA9 @ LHC


LHC PROJECT
UNDERGROUND WORKS
Point 4
Point 5
Point 6
Point 3.3
Point 3.2
Point 2
Point 1.8
Point 1
Point 8
Point 7
SPS
CMS
ALICE
ATLAS
LHC 'B'
N
to be installed here (IR7)
Existing Structures
LHC Project Structures
ST-CE/JLB-hlm
18/04/2003

LUA9 @ LHC



A minimal prototype system has been designed for LHC :

- integration studies on-going
- probable physical installation in 2014
- first tests with beam possibly in 2015/2016

Program & registration :

http://indico.in2p3.fr/event/AFTER@LesHouches

Program & registration :

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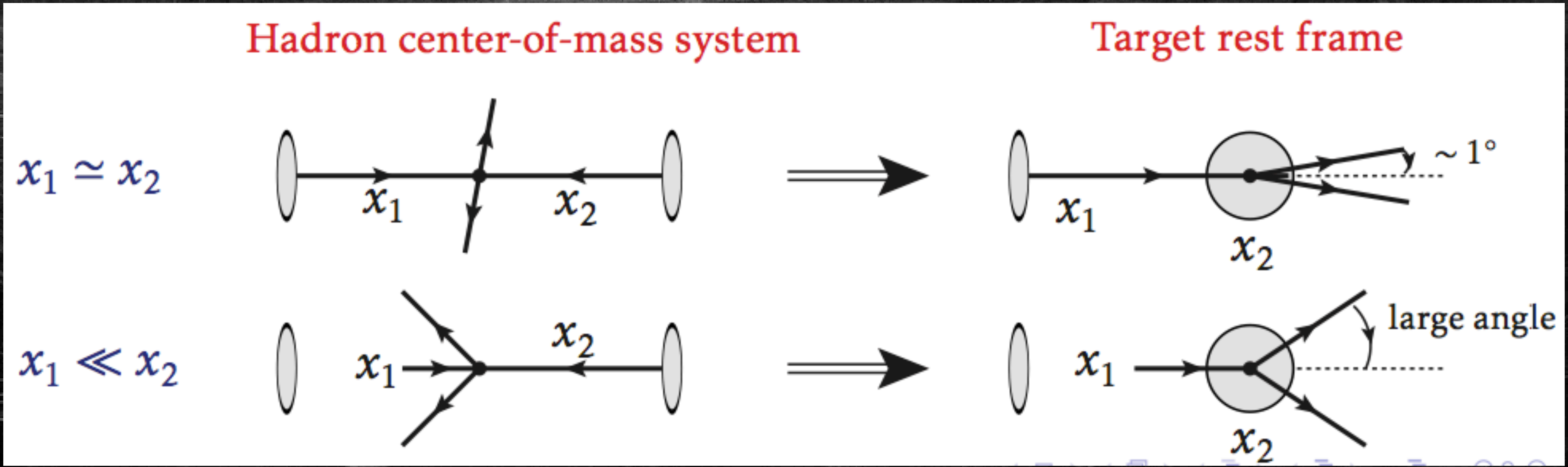
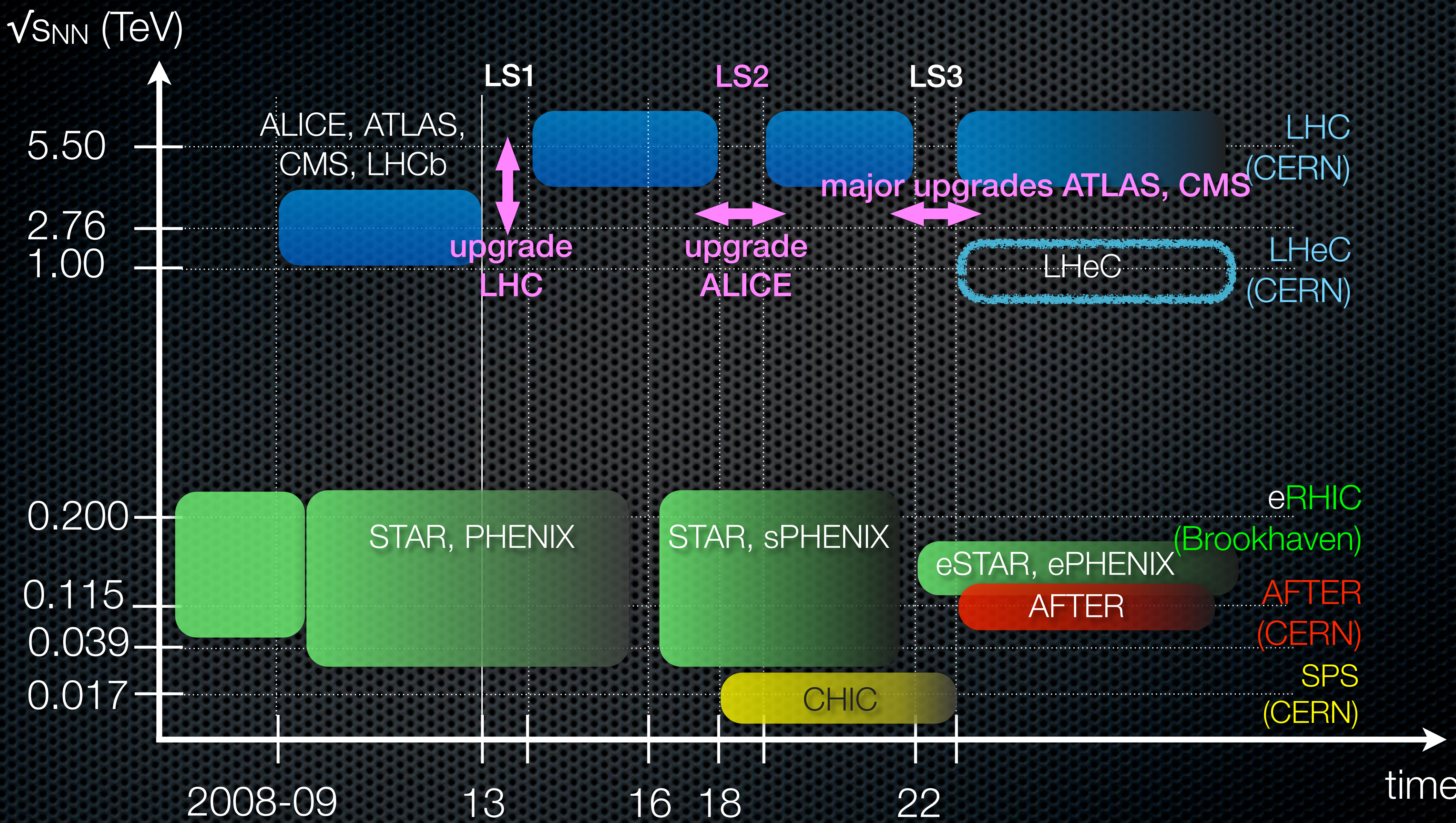
SPARE SLIDES

Backward physics



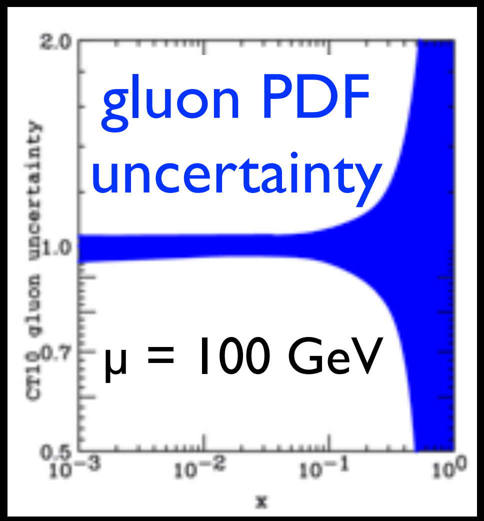
A rough timeline*

(*) focusing on AA, pA, eA, collisions only



Gluon PDF

p-p



gluon PDF at high x :
with large uncertainties for proton
need high luminosity to reach large x
exp. probes :
- heavy quarkonia (gg fusion at high energy)

for heavy quarkonia :

- many hopes in quarkonium studies to extract gluon PDF
- but ... production puzzles ⇒ quarkonium not used any more in global fits

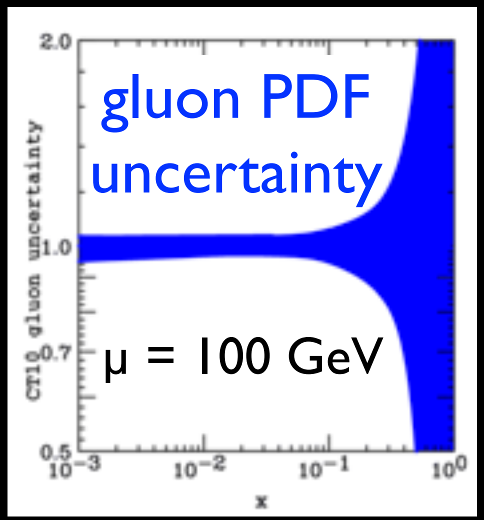
To restore its status :

✓ need systematic studies
✓ check factorization, especially at high x_F
✓ start with the use of C-even charmonia (χ_{c2}, η_c) and bottomonia (χ_{b2})

[D. Diakonov, M. G. Ryskin, A. G. Shuvaev, JHEP 1302 (2013) 069]

Gluon PDF

p-p



gluon PDF at high x :

with large uncertainties for proton

need high luminosity to reach large x

exp. probes :

- heavy quarkonia (gg fusion at high energy)
- isolated photons (gq fusion)
- high p_T jets (p_T >20 GeV, accessible up to 40 GeV)

for heavy quarkonia :

- many hopes in quarkonium studies to extract gluon PDF
- but ... production puzzles ⇒ quarkonium not used any more in global fits

To restore its status :

✓ need systematic studies

✓ check factorization, especially at high x_F

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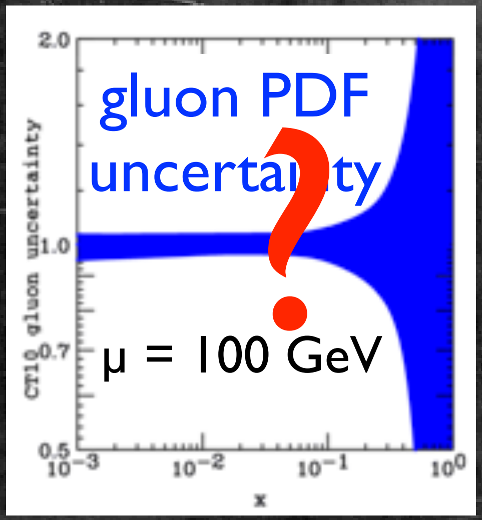
[D. Diakonov, M. G. Ryskin, A. G. Shuvaev, JHEP 1302 (2013) 069]

Gluon : proton vs neutron ?

p–p
p–d
p–n



gluon PDF experimentally unknown for neutron

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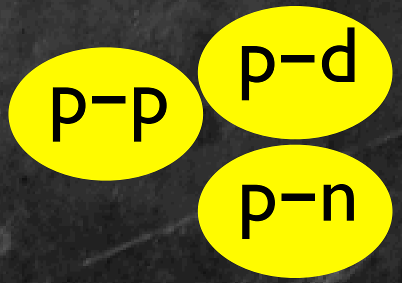
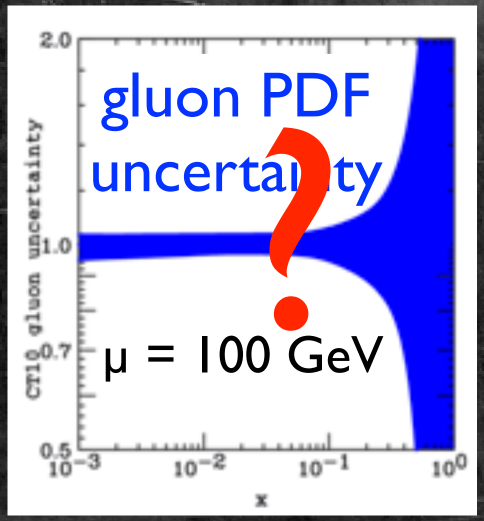
- high p_T jets

Gluon : proton vs neutron ?





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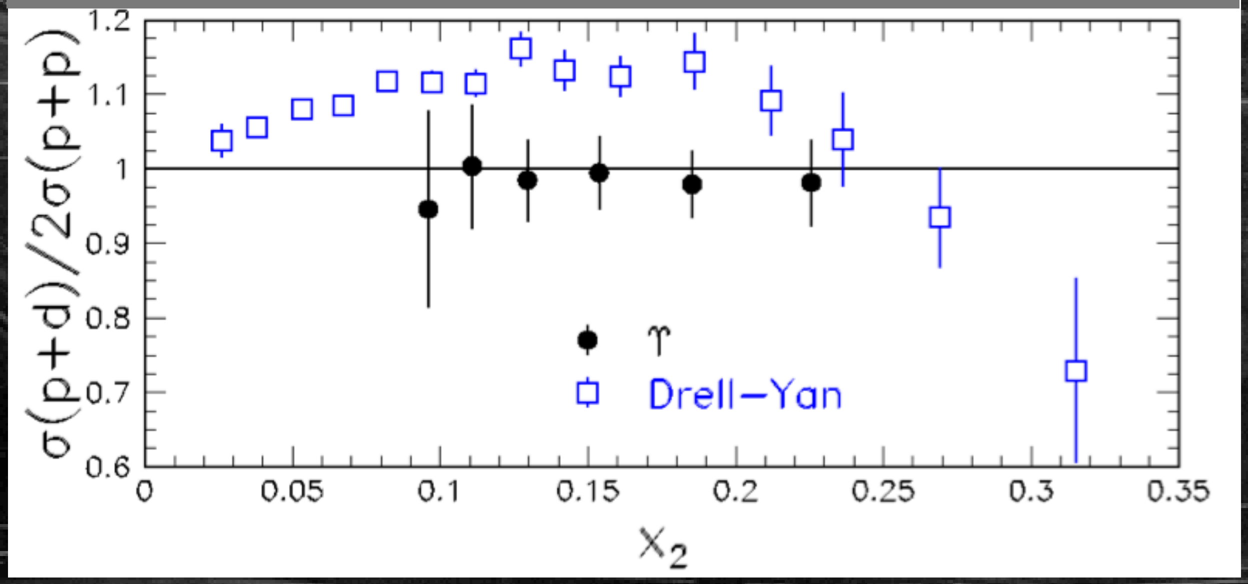
[E866, PRL 100 (2008) 062301]



Pioneering measurement by E866 @ Fermilab :

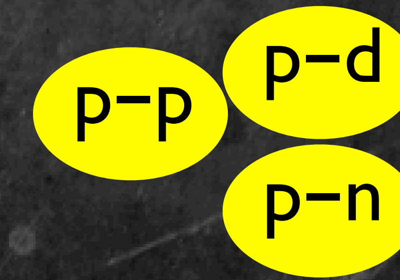
- using Υ
- at Q^2 ~ 100 GeV^2 similar gluon distribution in proton and neutron

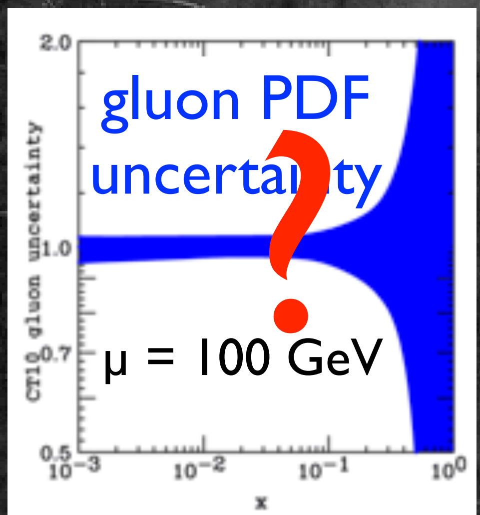
could be extended using J/ψ :

- to (~10x) lower x
- to lower Q^2

Need high luminosity.

Gluon : proton vs neutron ?





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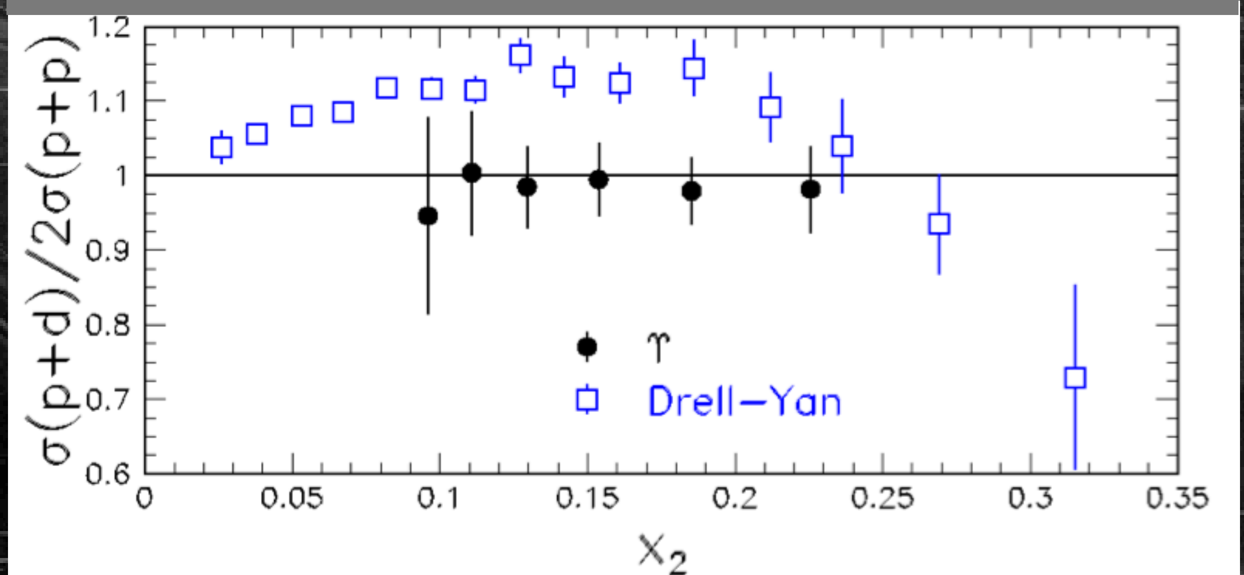
- high p_T jets

[E866, PRL 100 (2008) 062301]



Pioneering measurement by E866 @ Fermilab :

- using Υ
- at Q^2 ~ 100 GeV^2 similar gluon distribution in proton and neutron

could be extended using J/ψ :

- to (~10x) lower x
- to lower Q^2

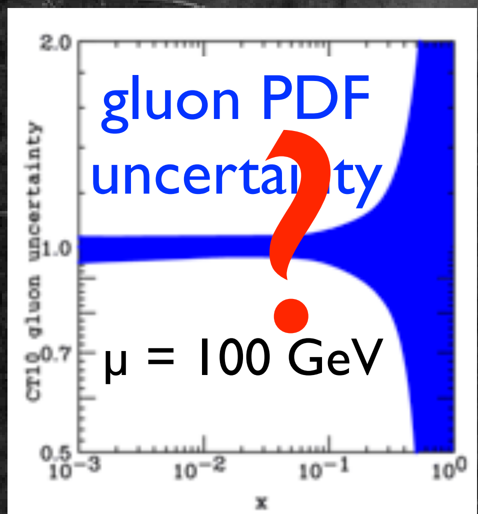
Need high luminosity.

[Lansberg et al., FBS 53 (2012) 11]

target	yearly lumi(fb^{-1})	$B_{ll}\frac{dN_{J/\psi}}{dy}\Big\|_{y=0}$	$B_{ll}\frac{dN_{\Upsilon}}{dy}\Big\|_{y=0}$
1 m Liq. H_2	20	4.0 10^8	8.0 10^5
1 m Lid. D_2	24	9.6 10^8	1.9 10^6

Gluon : proton vs neutron ?

p-p p-d p-n



gluon PDF experimentally unknown for neutron

exp. probes :

- heavy quarkonia
- isolated photons
- high p_T jets

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- at Q^2 ~ 100 GeV^2 similar gluon distribution in proton and neutron

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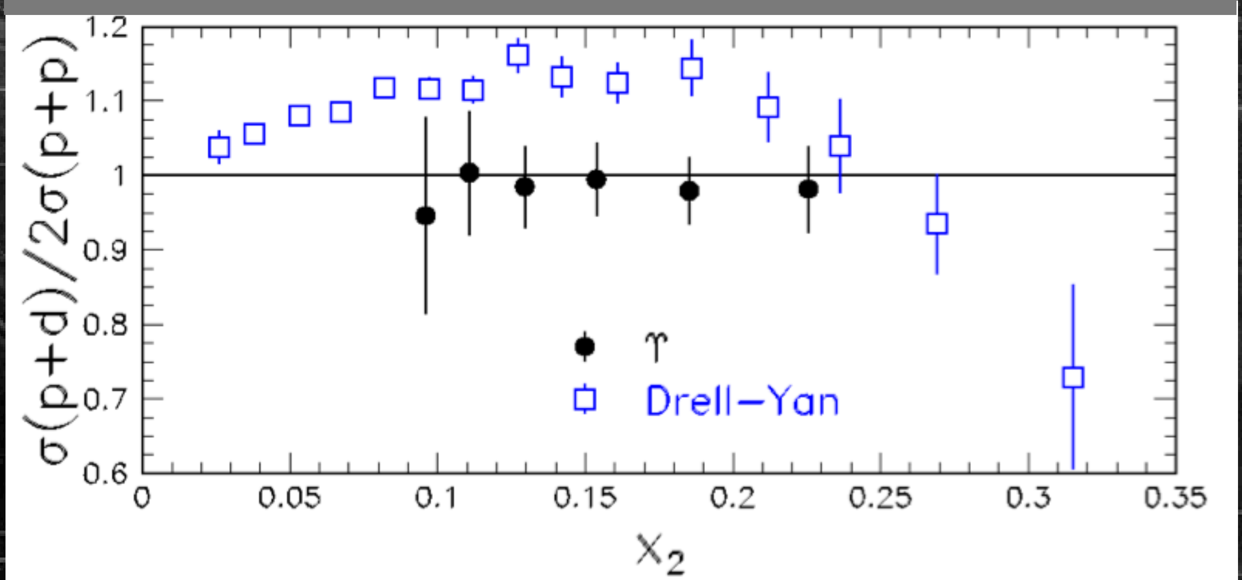

High energy + deuteron target :
rare opportunity, feasible in AFTER

[Lansberg et al., FBS 53 (2012) 11]

target	yearly lumi(fb^{-1})	$B_{ll} \frac{dN_{J/\psi}}{dy}\Big\vert_{y=0}$	$B_{ll} \frac{dN_{\Upsilon}}{dy}\Big\vert_{y=0}$
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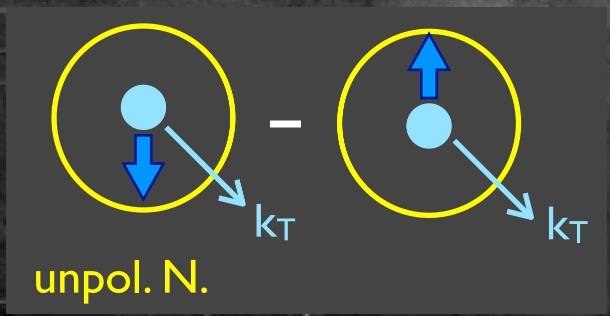
Gluon momentum tomography – Boer-Mulders

p–p

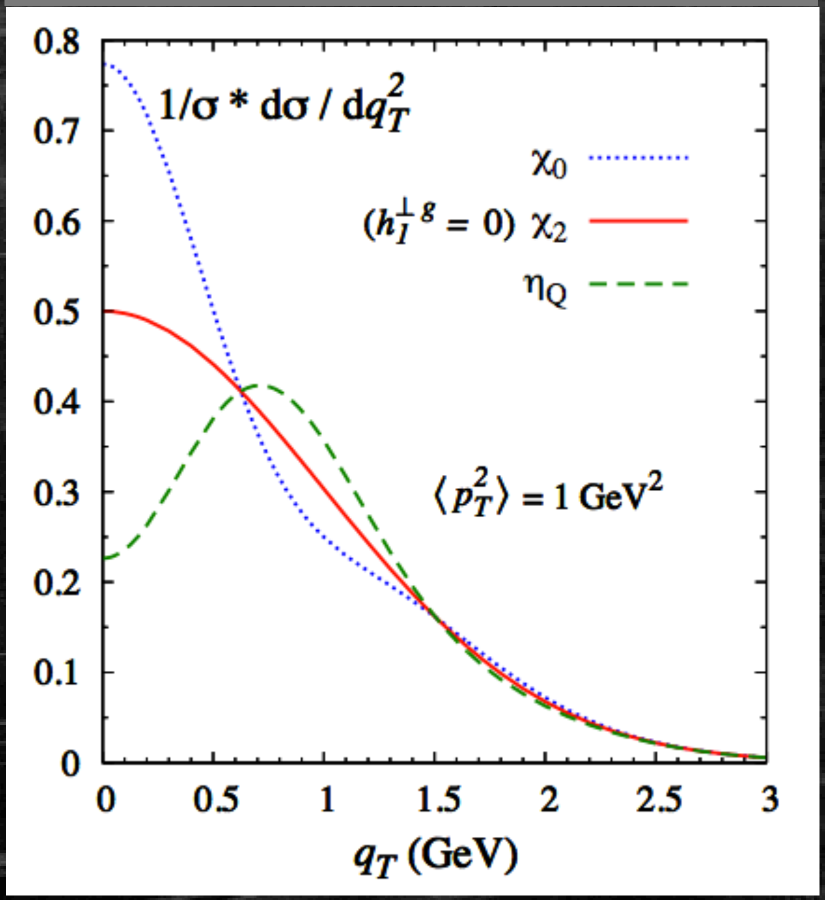


Boer-Mulders function :
Correlation between gluon k_T and gluon transverse spin

- unknown distribution of linearly polarised gluons in unpolarised N
- tool to determine if Higgs is a scalar or pseudo-scalar boson *[Boer et al, PRL 108 (2012) 032002]*
- can be accessed by modulations of the transverse-momentum distribution of $J^{PC} = 0^{\pm +}$ quarkonia (η_c, η_b, χ_{c0}, χ_{b0})

AFTER : large quarkonium yields + modern calorimetry (χ_Q detection)

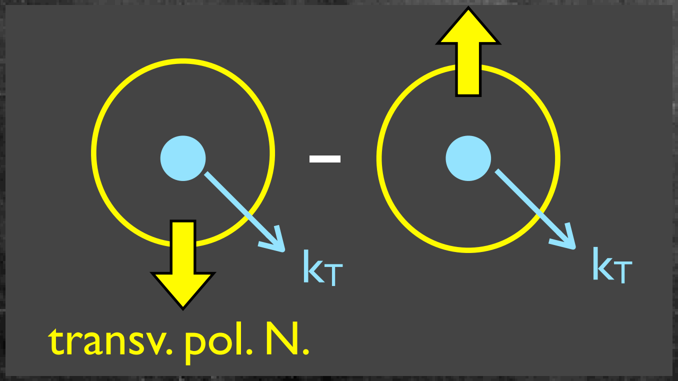
[Boer, Pisano, PRD 86 (2012) 094007]



double-node structure (unknown magnitude) and sign difference between scalar and pseudo-scalar

Gluon momentum tomography – Sivers effect

p–p↑



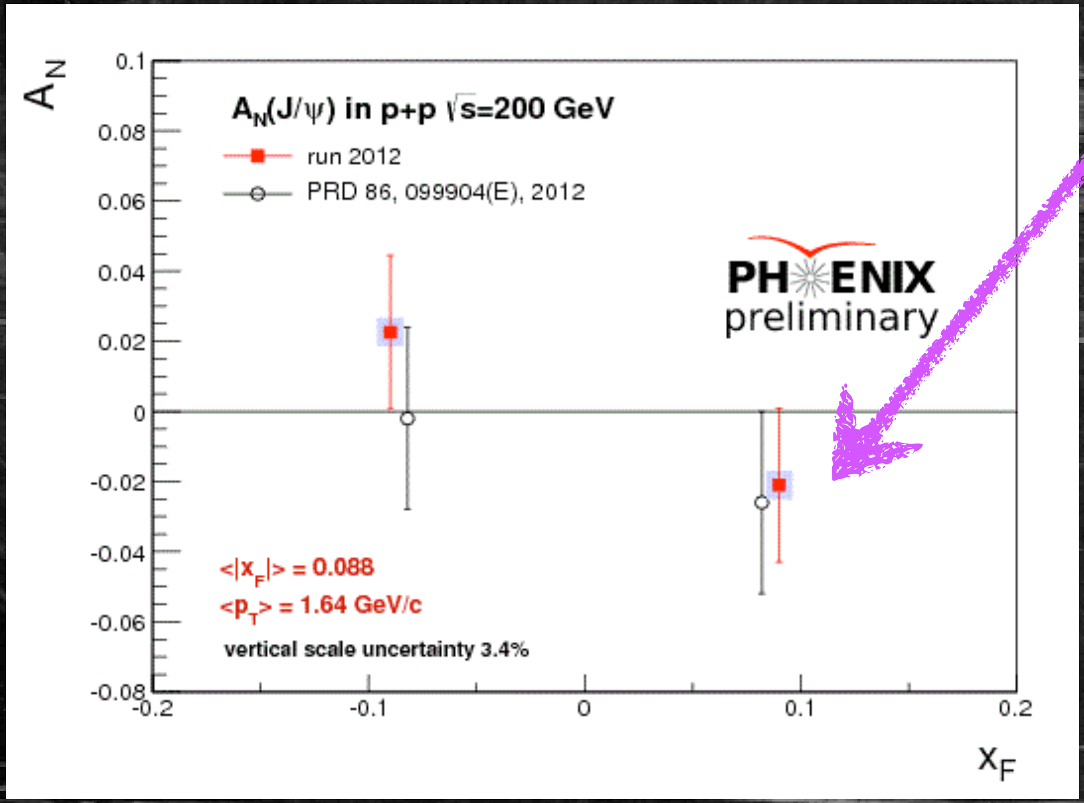
Sivers function :
Correlation between gluon k_T and nucleon spin

- Non zero gluon Sivers effect ? SSA in J/ψ production
- with AFTER, extension with more exp. probes sensitive to gluons
  - quarkonia (J/ψ , Υ , χ_c , ...)
  - B & D meson production
  - γ and γ-jet
  - γγ

[Anselmino et al., PRD 70 (2004) 074025]

[Bachetta et al., PRL 99 (2007) 212002]

[Qiu, Schegel, Vogelsang, PRL 107 (2011) 062001]

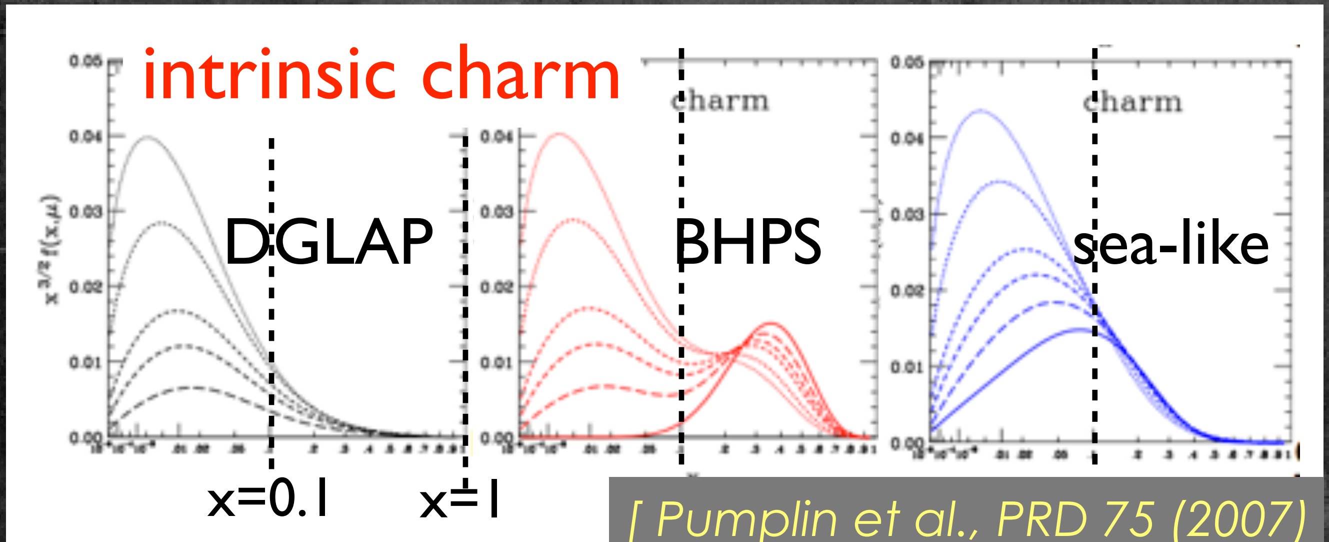


A non-zero gluon Sivers function will produce a finite SSA for color-singlet J/ψ production.

[Yuan, PRD 78 (2008) 014024]

Heavy quark PDF

p-p



[Pumplin et al., PRD 75 (2007) 054029]

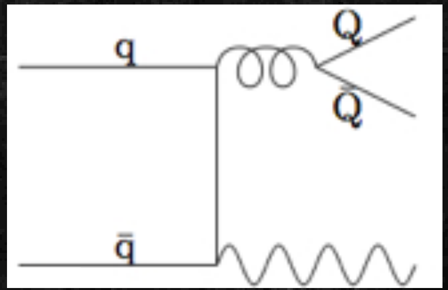
charm (and bottom) PDF at high x :
discriminate all charm PDFs currently in agreement with DIS data

exp. probes :

- open charm, open beauty
- new open c, b hadrons at high x_F ?

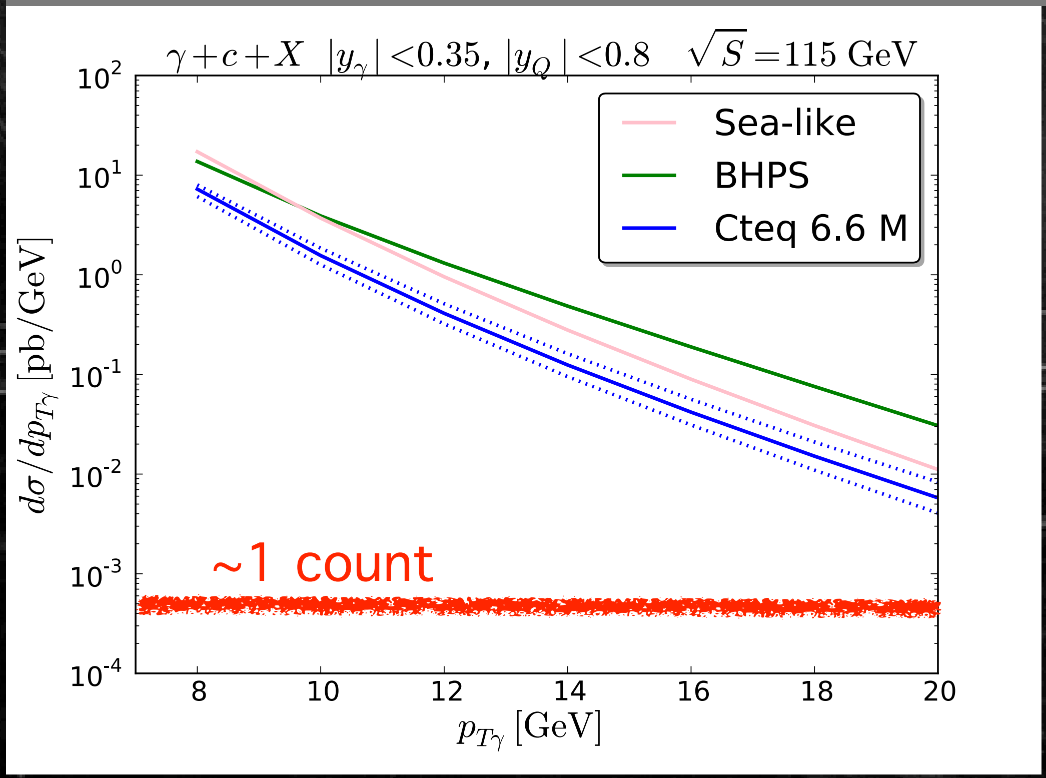
[Chang and Peng, PLB 704 (2011) 197]

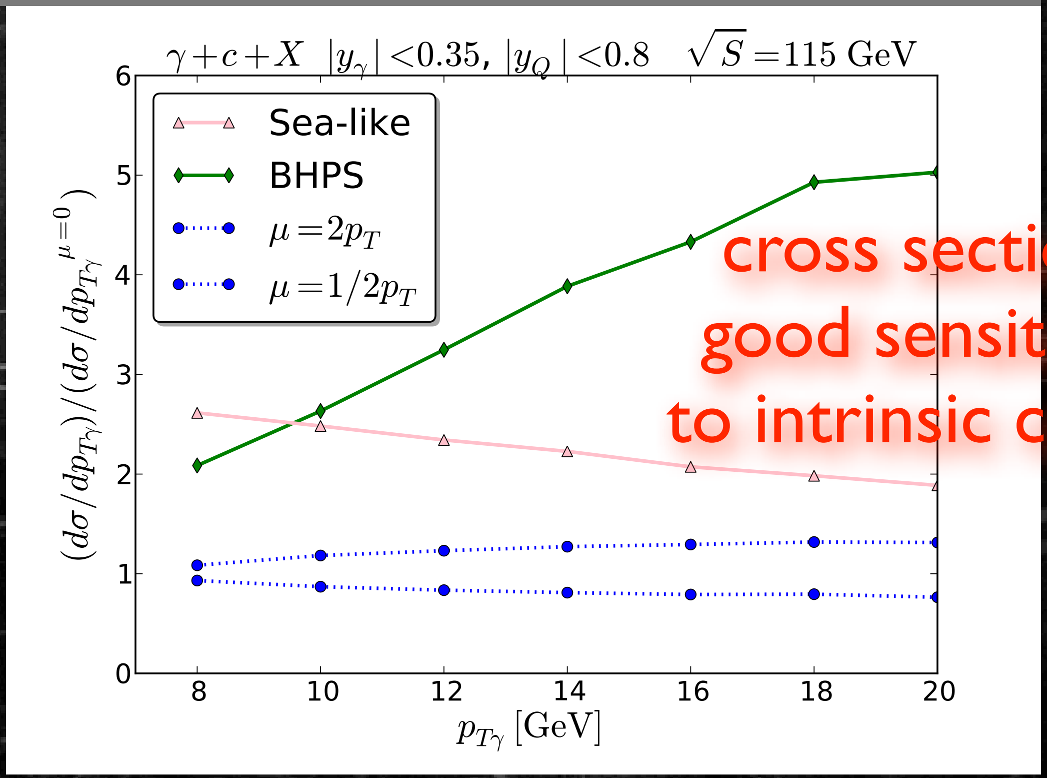
- γ + c , γ + b production



dominant diagram : photon couples to initial quarks

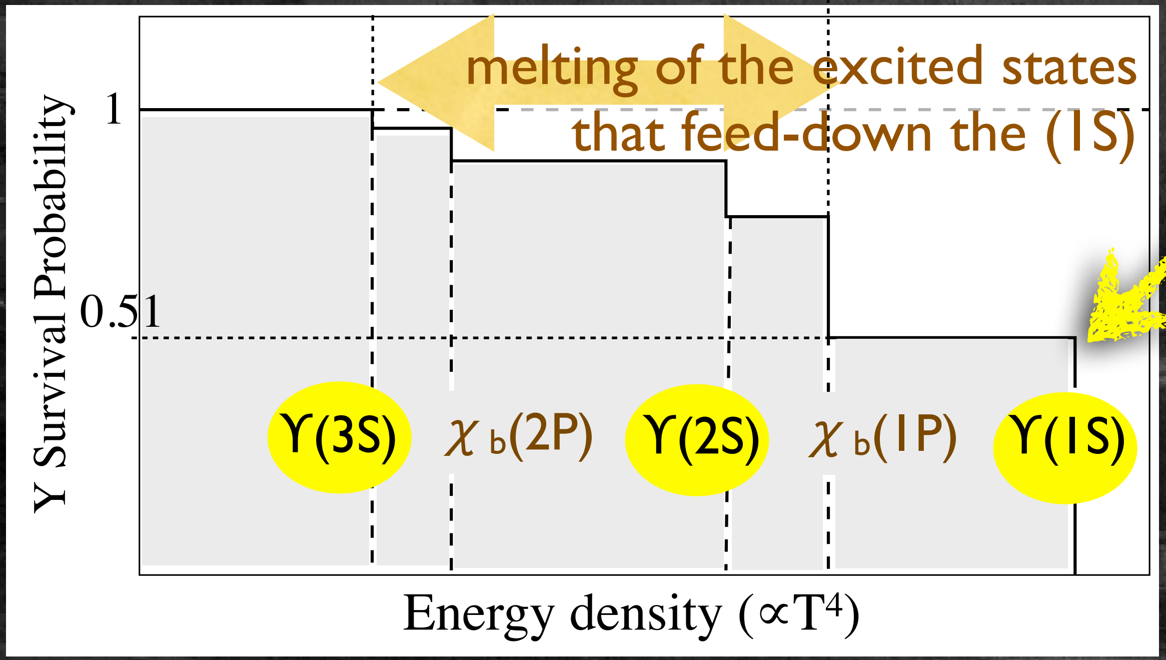
[T. Stavreva, Physics at AFTER using LHC beams, ECT* Trento, Feb. 2013]





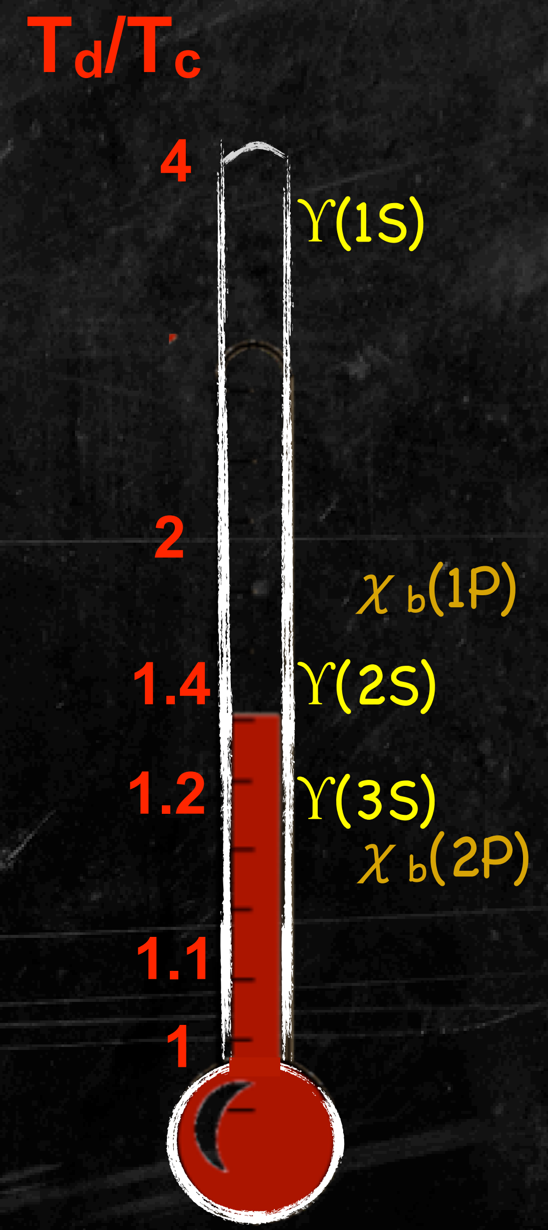
cross section :
good sensitivity
to intrinsic charm

Sequential melting in QGP



melting of the direct Υ(1S)

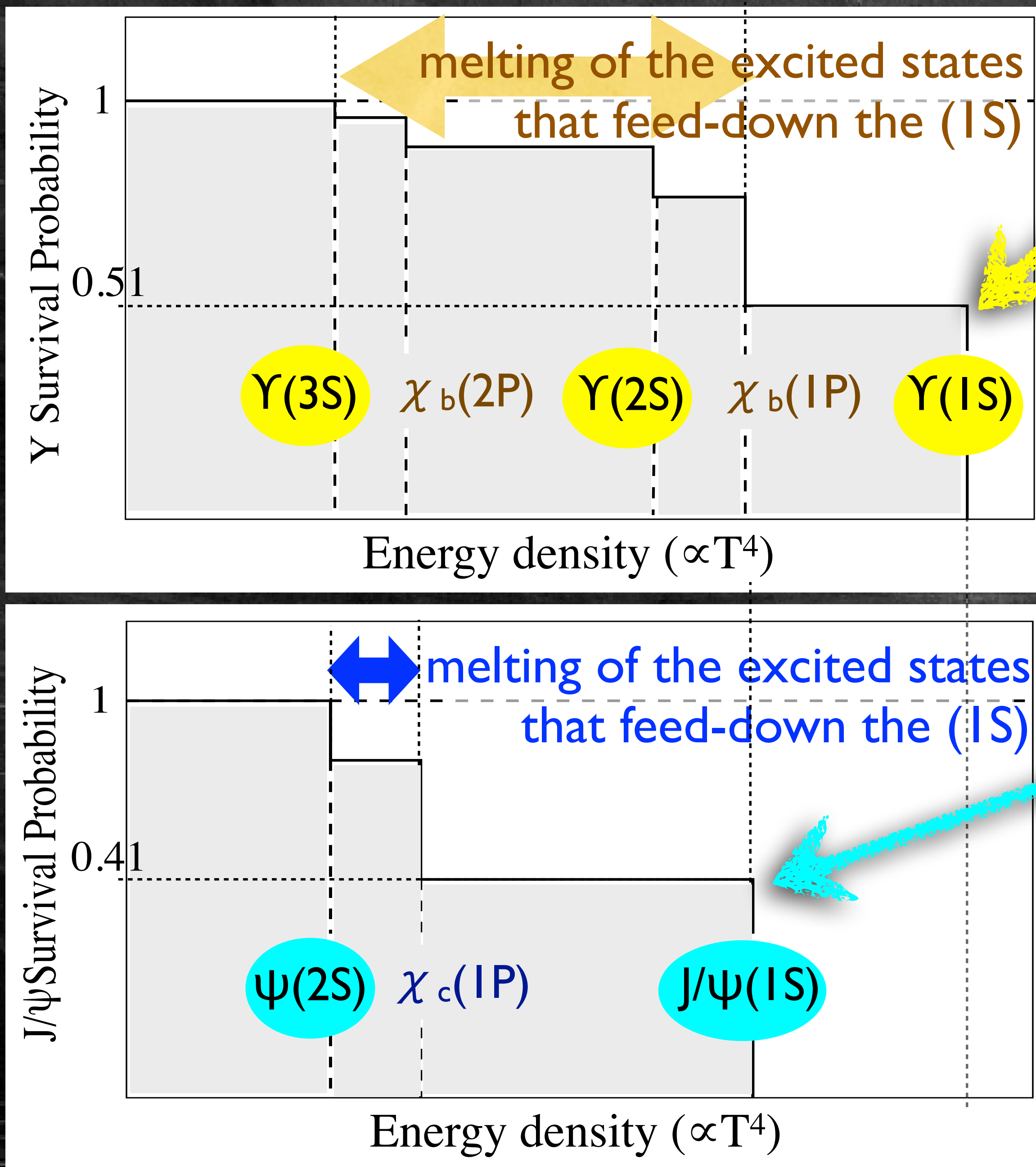
Dissociation temperatures from lattice QCD (+hydro)



$T_c \sim 150 - 175$ MeV

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

Sequential melting in QGP

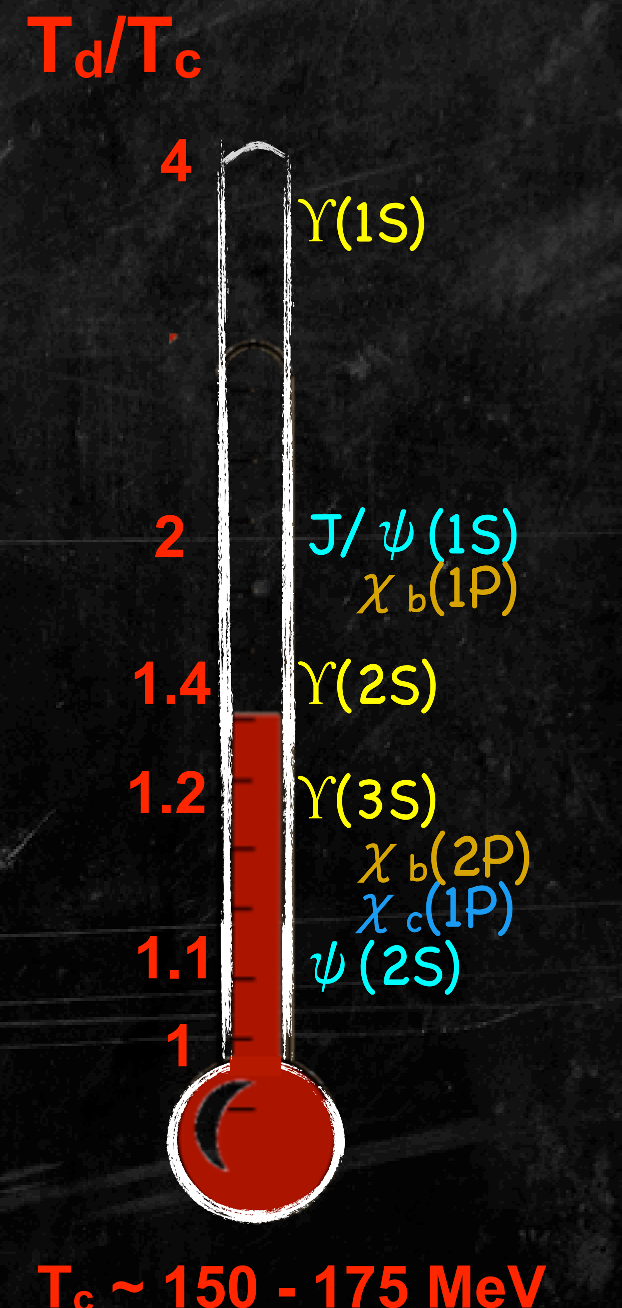


[Satz, Int.J.Mod.Phys. A28 (2013) 1330043]

melting of the direct Υ(1S)

melting of the direct J/ψ

Dissociation temperatures from lattice QCD (+hydro)



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

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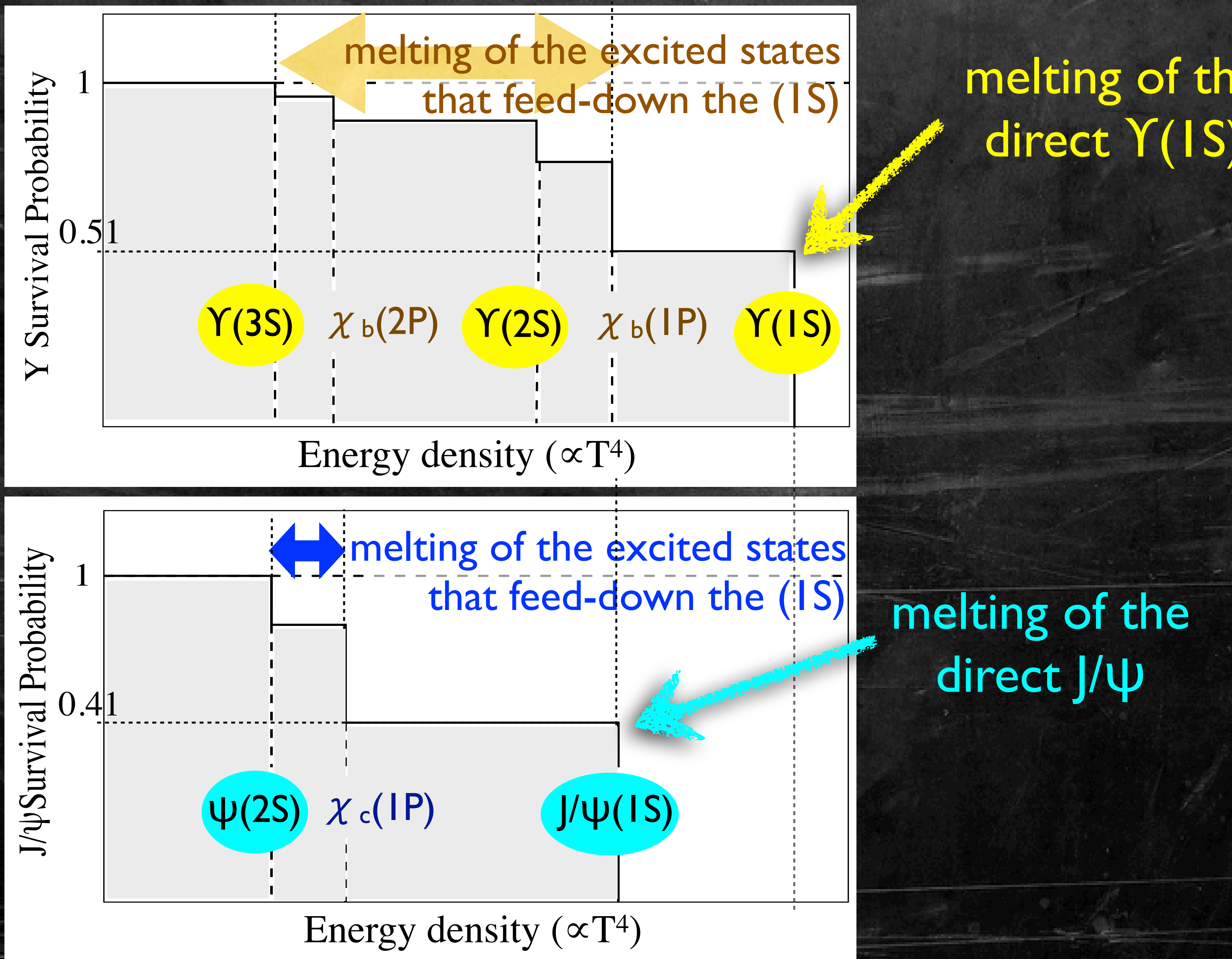
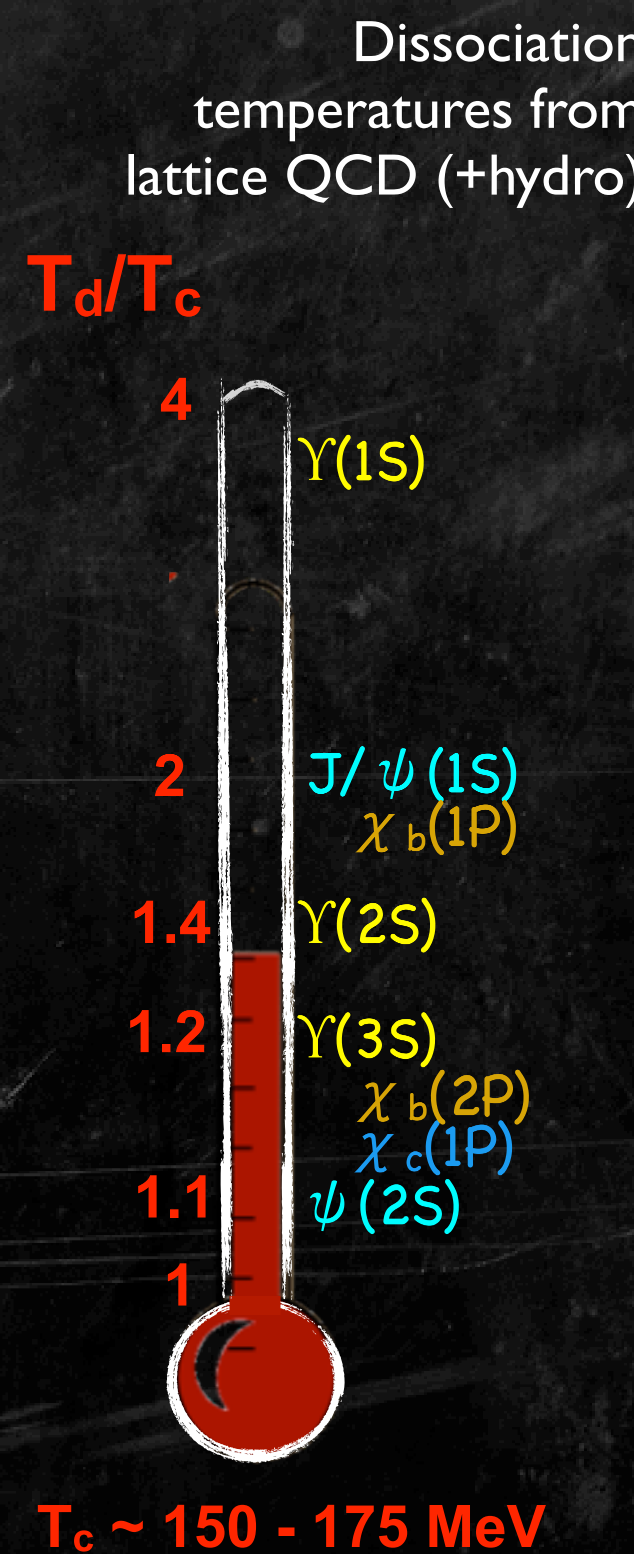


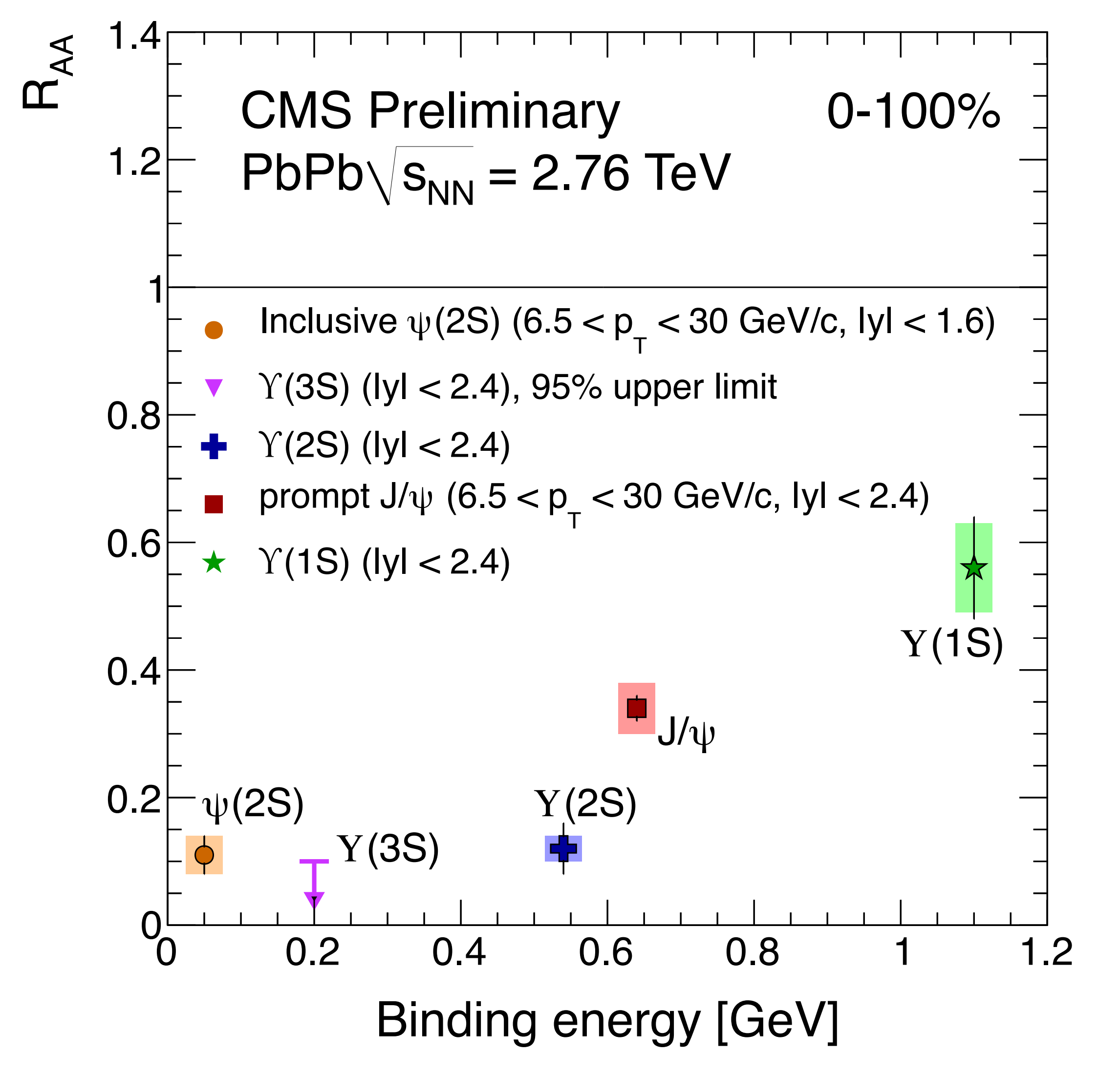
[Satz, Int.J.Mod.Phys. A28 (2013) 1330043]



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

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

Sequential melting @ LHC



[Velkovska for CMS, HP2013]

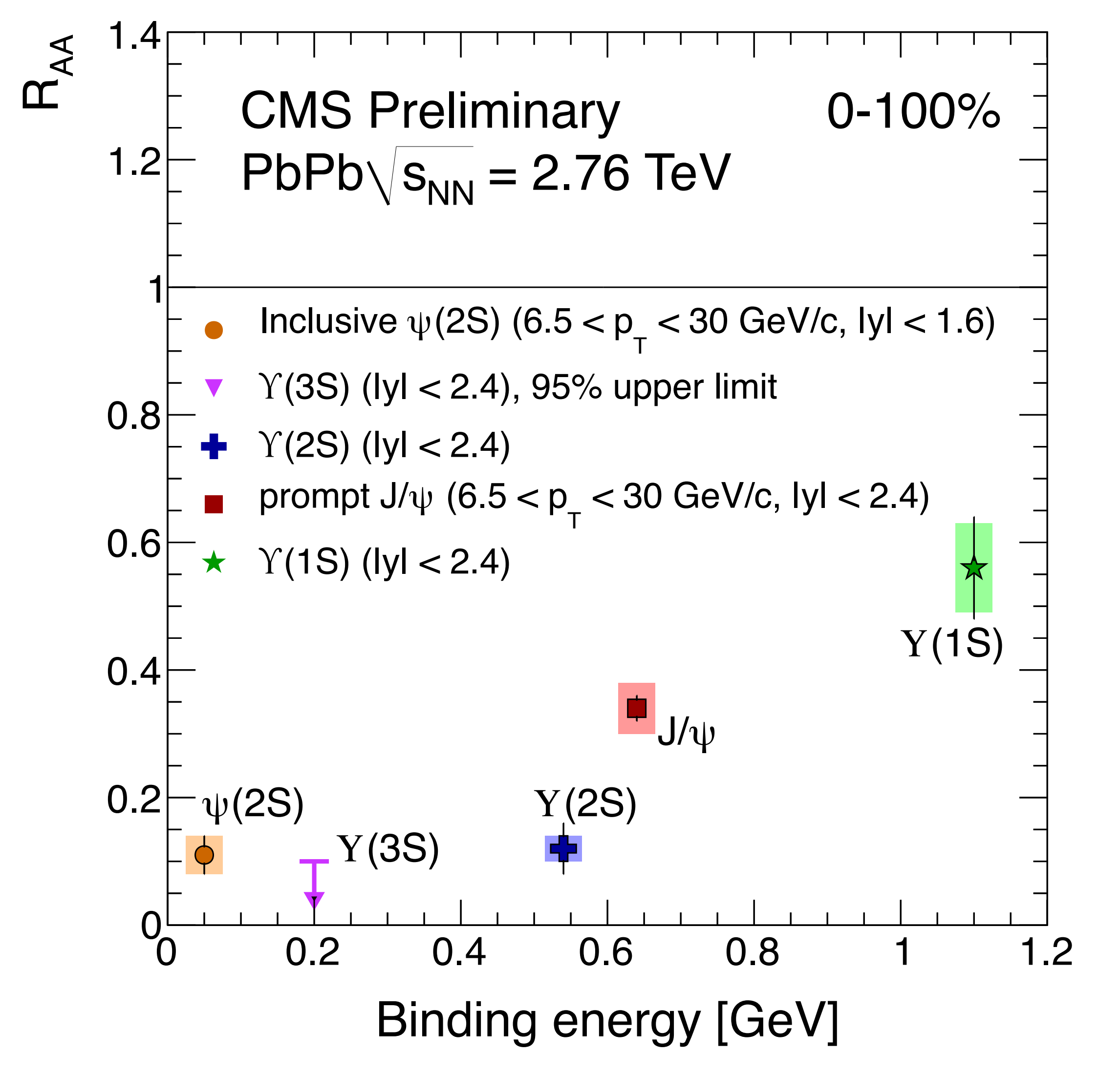
$$R_{AA} \equiv \frac{\sigma_{AA}}{\langle N_{coll}\rangle \sigma_{pp}}$$

- (3S) completely melted ?
- (2S) very suppressed
- direct (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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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]

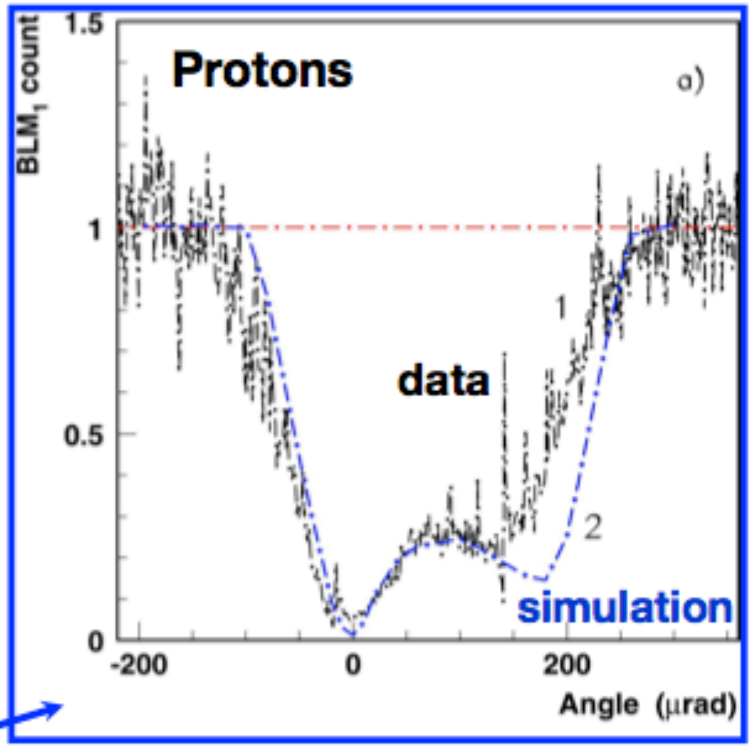
Measurement (thermal photons, dominant at low p_T) : T_{avg} ~ 304 ± 51 MeV (0-40% PbPb)

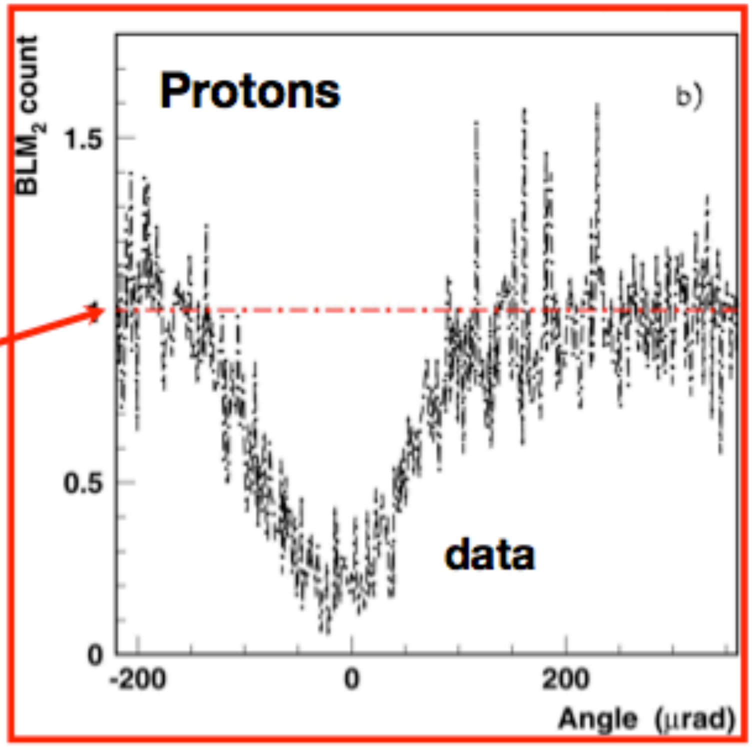
[Alice, NPA 904 (2013) 573c]

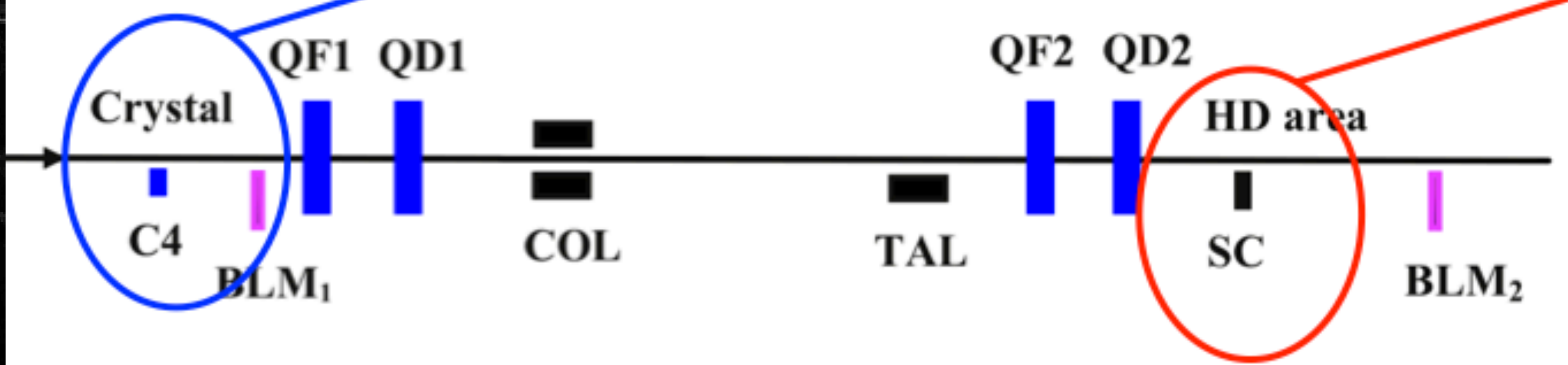
Main SPS achievements

UA 9

- **Alignment** (linear and angular) of the crystal is fast and well reproducible.
- **Multi-turn channeling efficiency**: 70÷80% for protons, 50÷70% for ions.
- **Channeled beam observed** with the Medipix.
- **Loss rate reduction at crystal**: 20x for protons, 7x for ions.
- **Off-momentum loss reduction**: 6x for protons, 7x for ions.
  - → *This is what matters for the LHC, limited by dispersion losses!*
- **Loss maps**: consistent reduction of the losses around the full ring when comparing crystal in channeling and crystal in amorphous.
- **Dependence of the off-momentum leakage on the clearance between crystal and absorber.**
- **Test multi-strip crystals in volume-reflection**







[S. Montesano, Joint LUA9-AFTER meeting, Nov. 2013]

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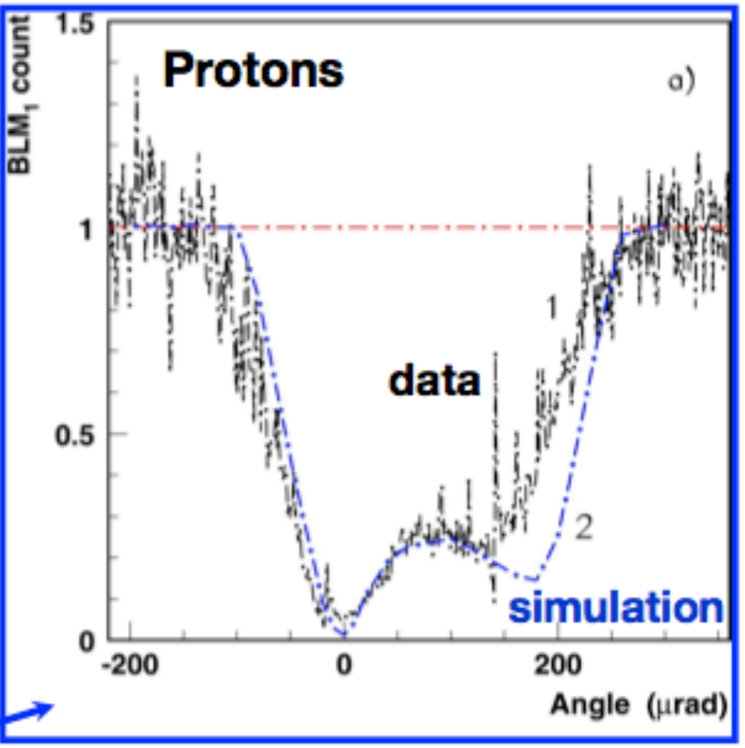
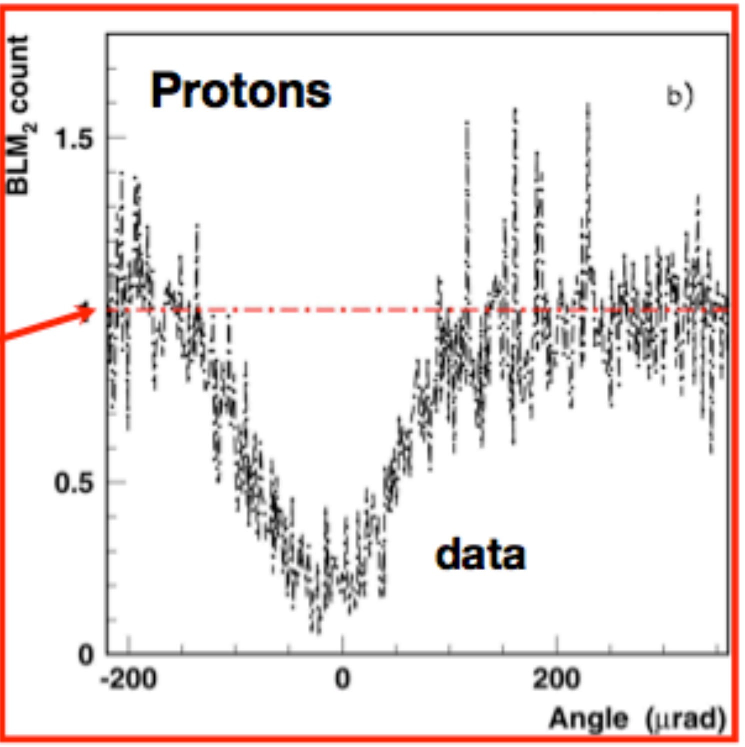
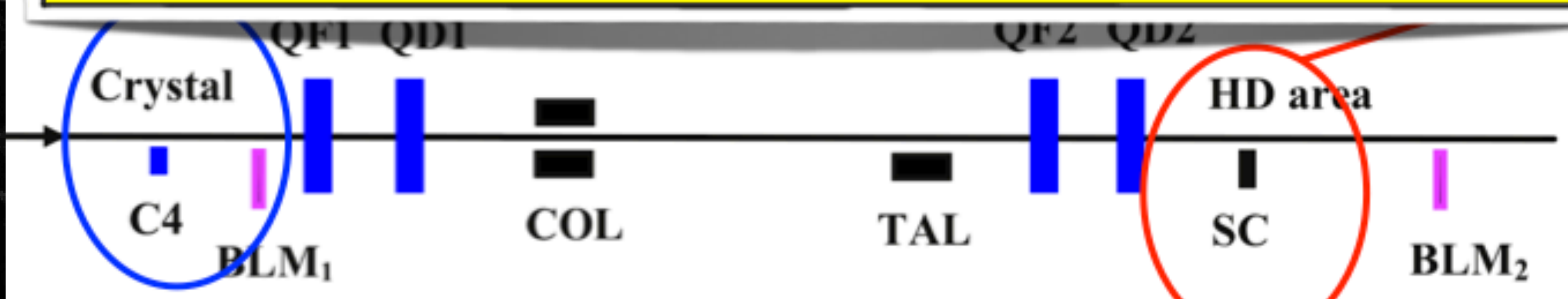
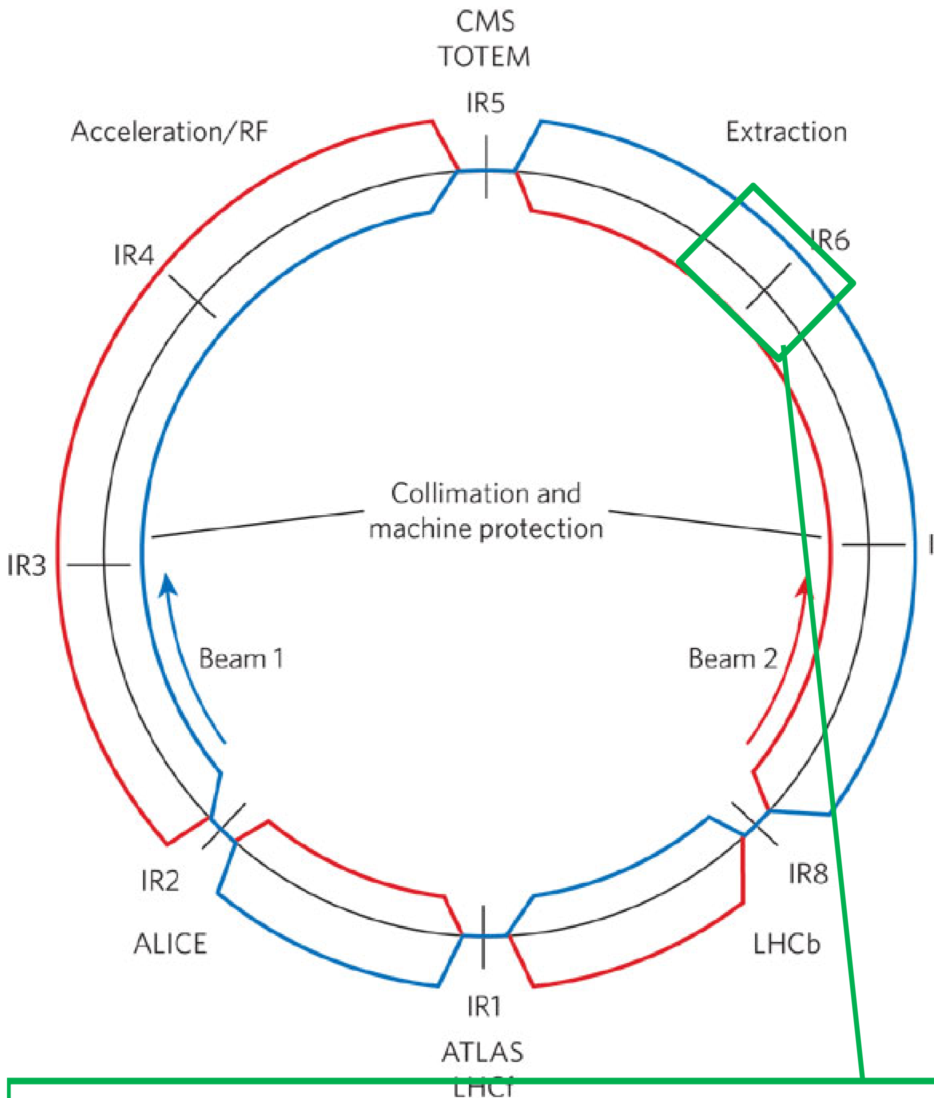




A complete crystal collimation prototype is installed in the SPS





One new possibility: LHC dump, IR6

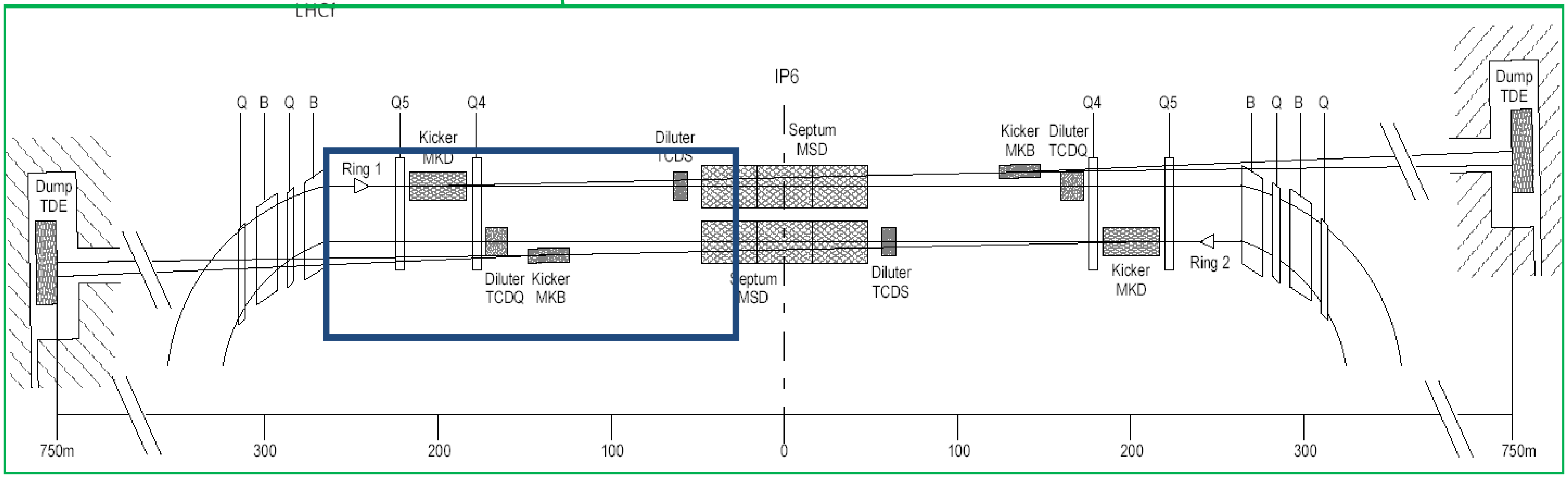
(IR7 and IR3 to be investigated)

Nuclear Instruments and Methods in Physics Research B 234 (2005) 31–39

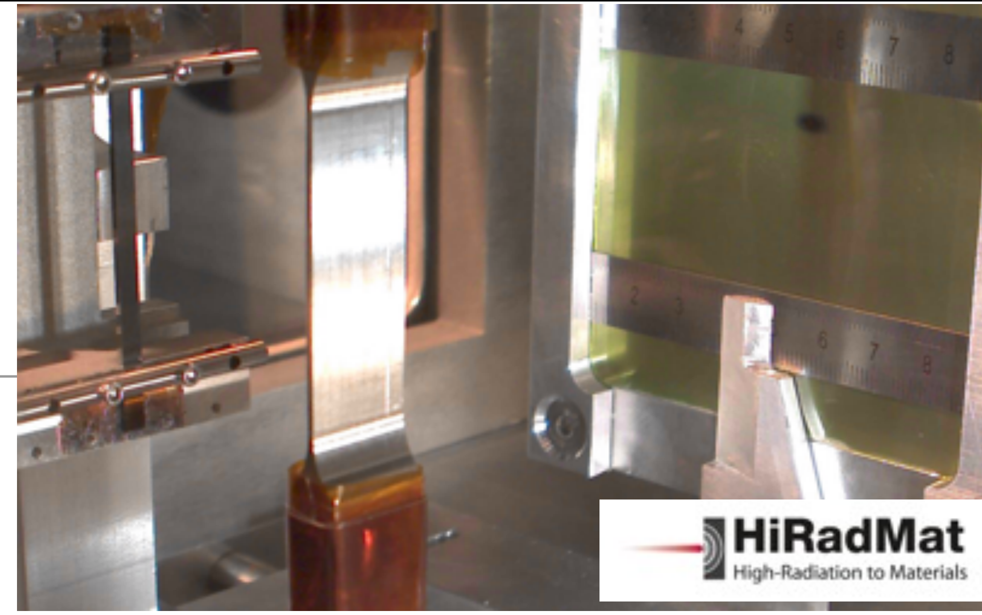
Strong crystalline fields – a possibility for extraction from the LHC

E. Uggerhøj, U.I. Uggerhøj *

Department of Physics and Astronomy, University of Aarhus,

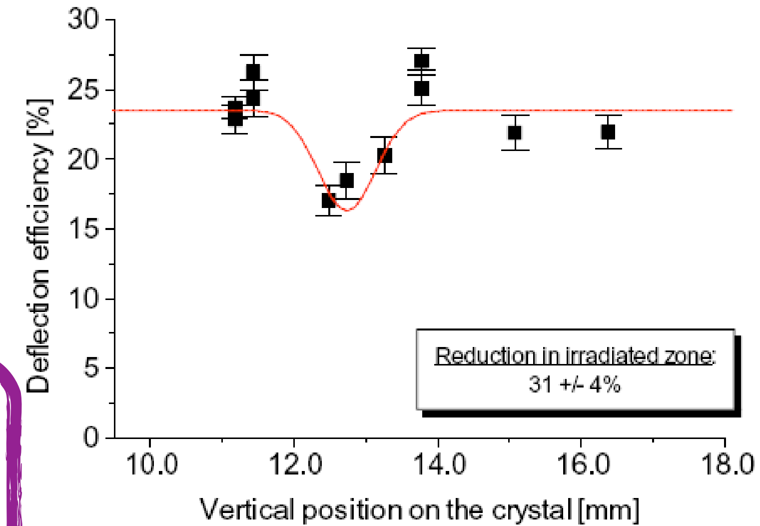


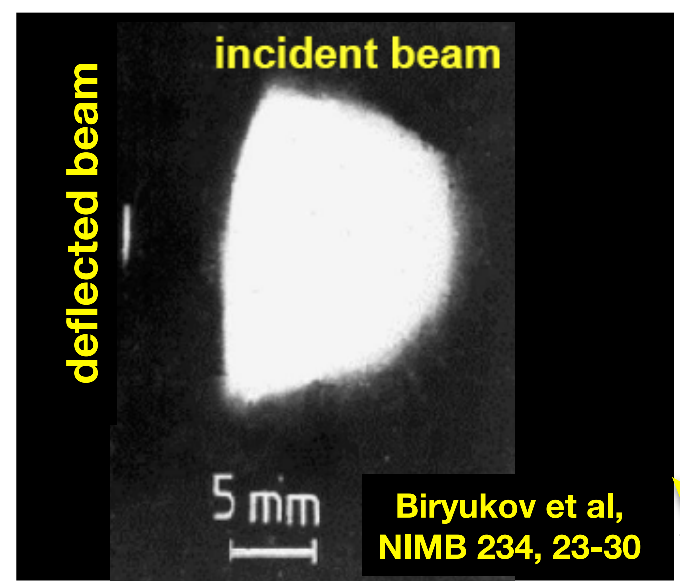
Crystal resistance to irradiation



- **IHEP U-70** (Biryukov et al, NIMB 234, 23-30):
  - 70 GeV protons, 50 ms spills of **10^{14} protons every 9.6 s**, several minutes irradiation
  - equivalent to 2 nominal LHC bunches for 500 turns every 10 s
  - 5 mm silicon crystal, **channeling efficiency unchanged**
- **SPS North Area - NA48** (Biino et al, CERN-SL-96-30-EA):
  - 450 GeV protons, 2.4 s spill of 5 x 10^{12} protons every 14.4 s, one year irradiation, **2.4 x 10^{20} protons/cm^2** in total,
  - equivalent to several year of operation for a primary collimator in LHC
  - 10 x 50 x 0.9 mm^3 silicon crystal, 0.8 x 0.3 mm^2 area irradiated, **channeling efficiency reduced by 30%**.
- **HRMT16-UA9CRY** (HiRadMat facility, November 2012):
  - 440 GeV protons, up to 288 bunches **in 7.2 μs**, 1.1 x 10^{11} protons per bunch (**3 x 10^{13} protons** in total)
  - energy deposition comparable to an asynchronous beam dump in LHC
  - 3 mm long silicon crystal, **no damage to the crystal after accurate visual inspection**, more tests planned to assess possible crystal lattice damage
    - **accurate FLUKA simulation of energy deposition** and residual dose

NA48 - Biino et al, CERN-SL-96-30-EA





ECT*
Trento

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})
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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 ⇔ 10^7 s

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