# Heavy quarks and QGP with LHCb / SMOG

Physics case

LHCb / SMOG



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# • Heavy quarks and Quark Gluon Plasma (QGP)

***Heavy quarks are "special" QGP probes*** : $m_Q$ >> QGP critical temperature $T_C$ (~170 MeV),

➔ Heavy quarks should be produced in ***initial*** nucleon-nucleon collisions only,
the **QGP phase shouldn't modify the overall heavy quark yields**,

➔ ***QGP phase should modify relative heavy quark (hidden/open) bound state yields***

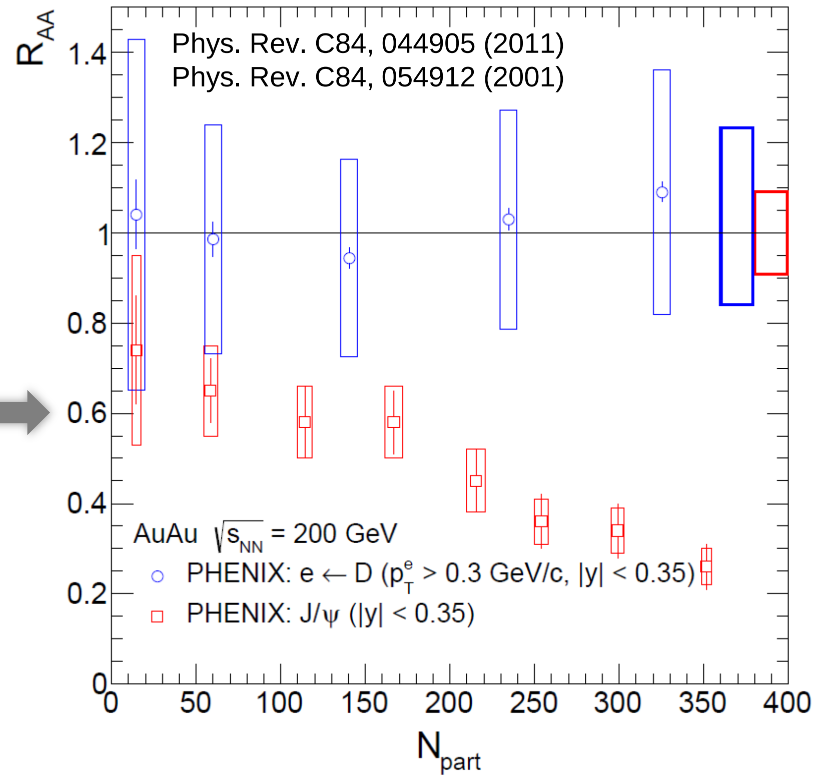
Heavy quark hadronization ($c\bar{c}$ example):

- ~90% of $c\bar{c}$ pairs → open charm
- ~10% of $c\bar{c}$ pairs → hidden charm (charmonia)

Since most of the produced $c\bar{c}$ pairs hadronize into open charm (~90%), **open charm production reflects the *original* charm quark yield.**

PHENIX Au+Au collisions @ $\sqrt{s_{NN}}$ = 200 GeV
Blue = open charm
Red = hidden charm

- no (little) modification of open charm yield
- modification of $J/\Psi$ (*$c\bar{c}$ bound state*) yield



# Heavy quarks and Quark Gluon Plasma (QGP)

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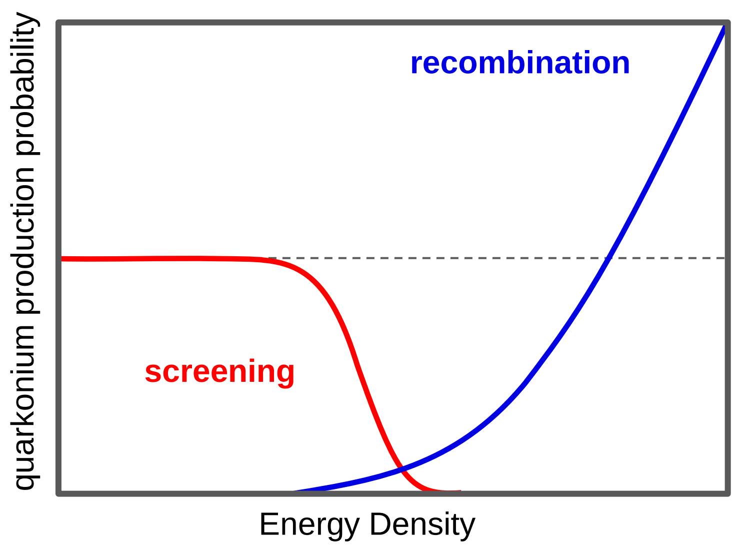
## – Modifying hidden bound state yields

## *Possible QGP effects on quarkonium:*

- **Color screening:** ***$Q\overline{Q}$ bound states suppression***
  - Color screening in a QGP decreases quarkonium binding
  - Color screening should lead to a suppression of quarkonium production yields
- **Recombination:** ***$Q\overline{Q}$ bound states enhancement***
  - at sufficiently high $\sqrt{s_{NN}}$, heavy quarks are abundantly produced.
  - After thermalisation, statistical combination can lead to an enhancement of quarkonium production yields

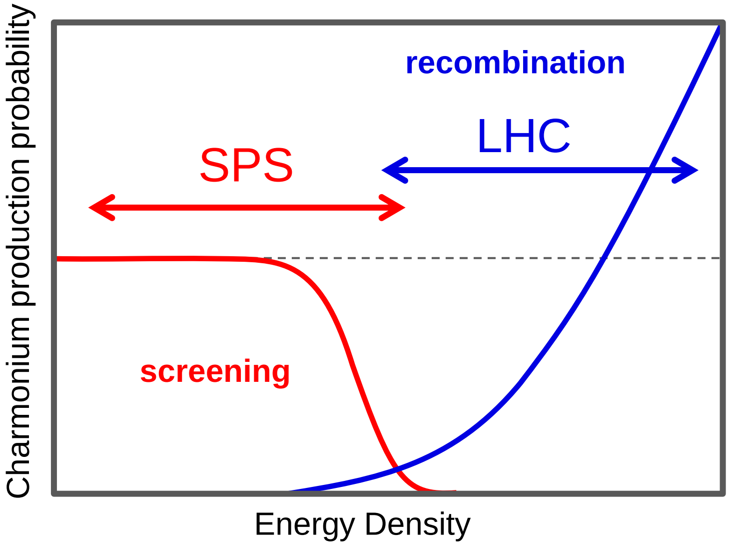


# The Physics case

- **Experimentally, charmonium is a priviledged probe**
  - Charmonium production in A+A collisions studied at:
    - CERN-SPS (√s=17 GeV) NA38, NA50, NA60 experiments
    - BNL-RHIC (√s=200 GeV) PHENIX, STAR experiments
    - CERN-LHC (√s=2.76 TeV) ALICE, CMS experiments
  - Short summary for J/Ψ:
    - NA50 (PbPb@SPS) observed an *anomalous* J/Ψ suppression
    - PHENIX (AuAu@RHIC) observed a *similar* suppression (than NA50)
    - ALICE (PbPb@LHC) observed a *smaller* suppression (than PHENIX)

**➔Possible Color screening starting at SPS**
**➔Possible recombination occuring at LHC**

- **Within the SPS+RHIC+LHC energy range, charm seems to be the adequate probe to investigate both screening and recombination.**



# The Physics case

- **What next to be done with charmonium**

  To confirm (and study) charmonium color screening and recombination, one must compare charmonium and open charm production in A+A collisions

  - Since most of the produced $c\bar{c}$ pairs hadronize into open charm (~90%), open charm production reflects the original $c\bar{c}$ pair production
  - Open charm is therefore an (the?) appropriate reference to calibrate charmonium screening/recombination studies.

  – **TeV scale**: Charmonium recombination

  - Both J/Ψ and open charm will be measured in PbPb at large energy densities at LHC

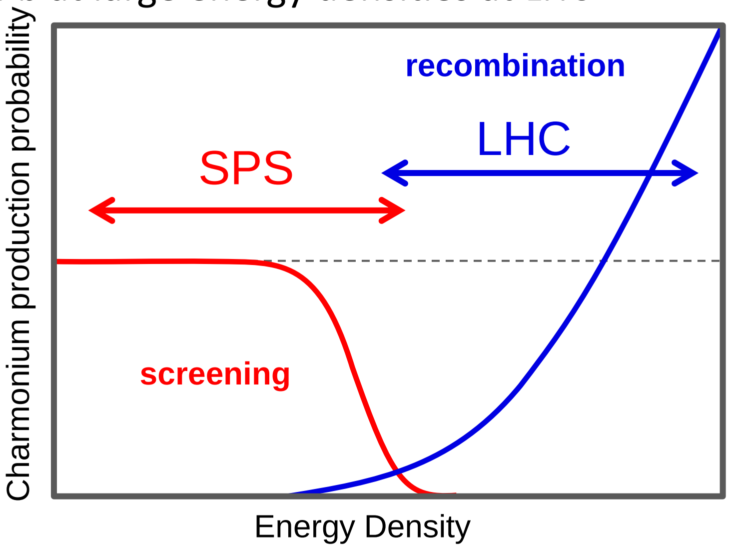
  ➔ **Best place to study charmonium recombination**

  – **20-GeV Scale**: Charmonium color screening

  - At SPS energies, in Pb+Pb collisions, J/Ψ suppression occurs in the middle of the accessible energy density range

  ➔ **Best place to study color screening**

  - ***Needs measurement of open charm yields***
  - ***Needs precise measurements of several $c\bar{c}$ states*** *to test if color screening leads indeed to a sequential suppression*



# Color screening

- **Quarkonium sequential suppression**
  - **Quarkonium sequential suppression** in a Quark Gluon Plasma is a prediction of **lattice QCD** :

H. Satz, J. Phys. G 32 (2006)

quarkonium dissociation temperature / critical QGP temperature →

| state | $J/\psi(1S)$ | $\chi_c(1P)$ | $\psi'(2S)$ | $\Upsilon(1S)$ | $\chi_b(1P)$ | $\Upsilon(2S)$ | $\chi_b(2P)$ | $\Upsilon(3S)$ |
|---|---|---|---|---|---|---|---|---|
| $T_d/T_c$ | 2.10 | 1.16 | 1.12 | $>4.0$ | 1.76 | 1.60 | 1.19 | 1.17 |

  - Because of feed-downs and different $T_d$, **sequential suppression** should show up.

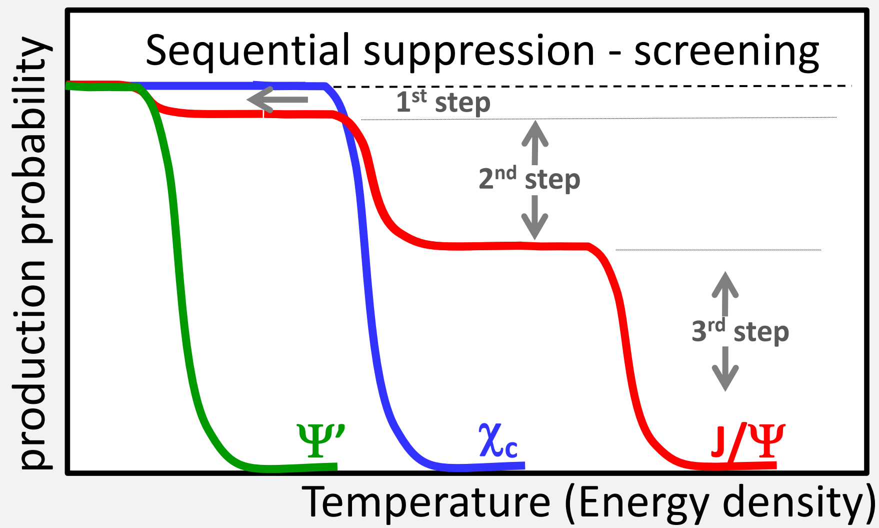
*Feed-downs contributing to J/Ψ inclusive yield*

**60%** direct J/Ψ
**+ 30%** $\chi_c \rightarrow J/\Psi + \gamma$
**+ 10%** Ψ' → J/Ψ + X

**Inclusive J/Ψ yield**

According to lattice calculations,
$T_d(\Psi') < T_d(\chi_c) < T_d(J/\Psi)$

➔ **One should observe a step-like suppression pattern**



# Charmonia in A+A

# NA50 results

- **Anomalous suppression at SPS**

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

**L** = length of nuclear matter seen by quarkonium state

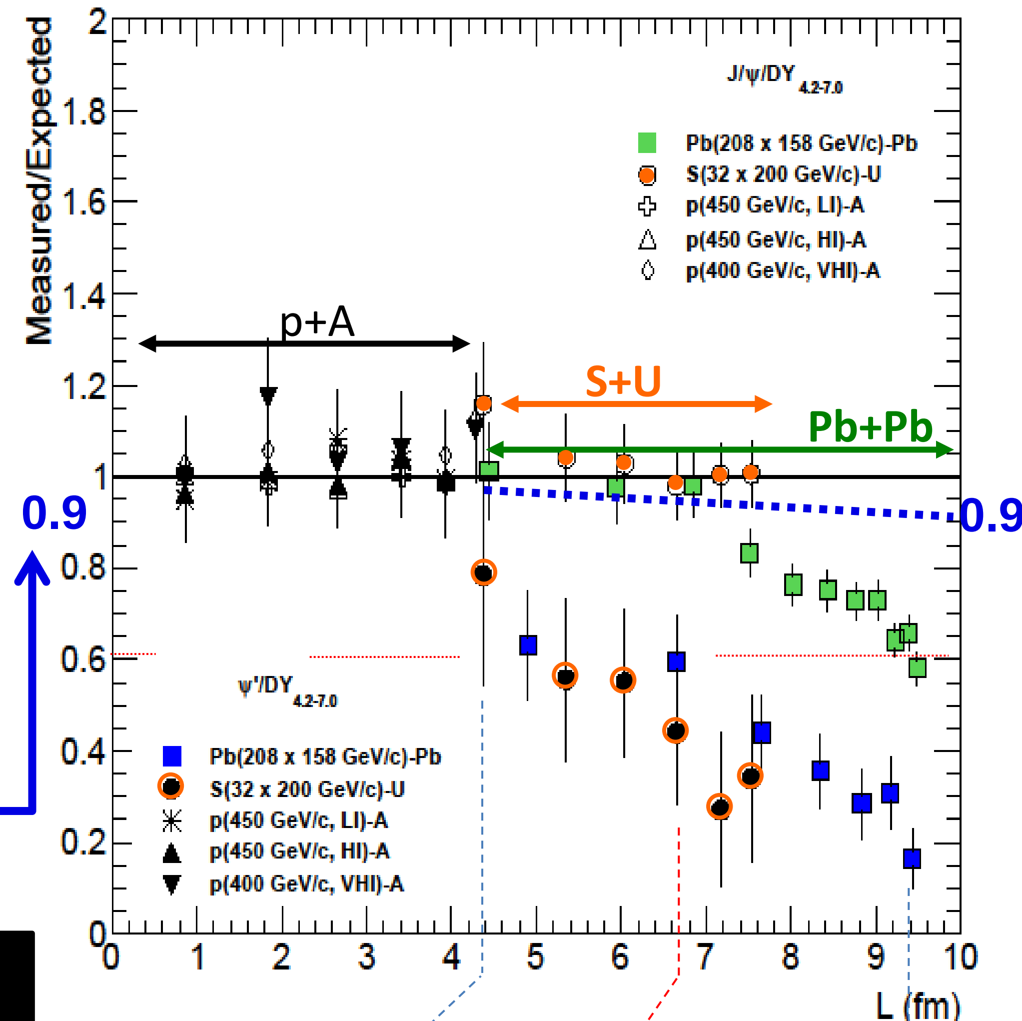
**Expected** = measured yields in p+A extrapolated to large L

***Color screening ?***

**NA50 measured J/Ψ and Ψ', but,**
- **too small Ψ'→ J/Ψ *feed-down***
- **too fragile Ψ'**

**to answer the question**

**→ need of a larger feed-down fraction**
**→ Need of a stronger bound state**
**→ Need to measure $\chi_c$ yield !**




| L (fm) ε (GeV/fm³) | 4.37 1.04 | 4.90 1.24 | 6.65 2.04 | 7.65 2.53 | 8.83 3.19 | 9.43 3.76 |
|---|---|---|---|---|---|---|

# Charmonia in A+A **Suppression patterns**

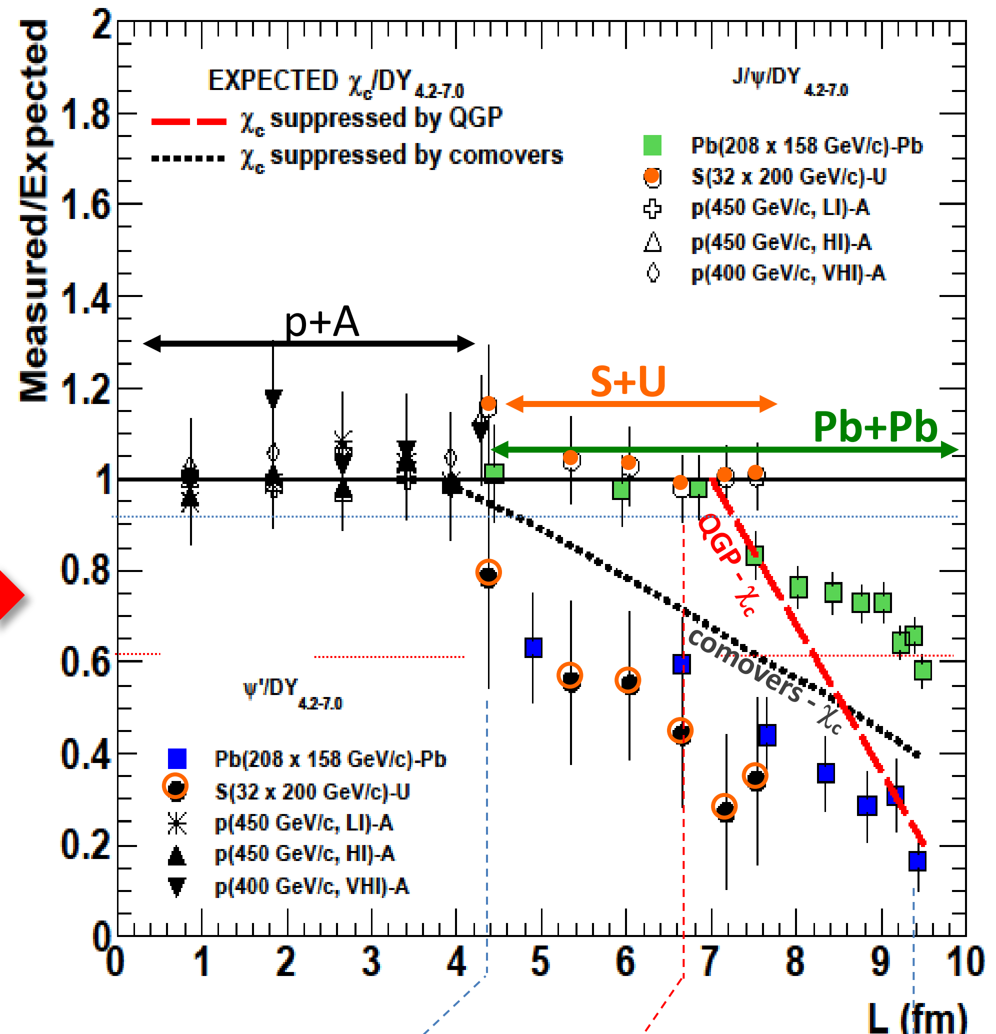
- **Anomalous suppression at SPS** Eur.Phys.J.C49:559-567,2007

***Color screening ?***

Take advantage of large $\chi_c \rightarrow J/\Psi$ feed-down fraction

$$\frac{\textbf{60\% direct } J/\Psi + \textbf{30\% } \chi_c \rightarrow J/\Psi + \gamma + \textbf{10\% } \Psi' \rightarrow J/\Psi + X}{\textbf{Inclusive } J/\Psi \textbf{ yield}}$$

**Measuring $J/\Psi$, $\Psi'$ and $\chi_c$ suppression patterns will give the answer**




| | | | | | | |
|---|---|---|---|---|---|---|
| L (fm) | 4.37 | 4.90 | 6.65 | 7.65 | 8.83 | 9.43 |
| ε (GeV/fm³) | 1.04 | 1.24 | 2.04 | 2.53 | 3.19 | 3.76 |

- ***Alternative (no QGP) scenario: suppression by comoving hadrons***
  - *Smooth suppression*
  - *Same suppression-starting point*
  - *Slopes related to binding energy :* $S_{\Psi'} > S_{\chi} > S_{J/\Psi}$

# Measuring $\chi_c$ in A+A

- **Hint of color screening at SPS**
  - Anomalous suppression of J/ψ
  - Anomalous suppression of ψ'
- **But, need to be confirmed**
  - by measuring together J/ψ, ψ', $\chi_c$ and open charm
- **Measuring $\chi_c$ may also permit to**
  - Contrain J/ψ $T_C$
  - test the phase transition

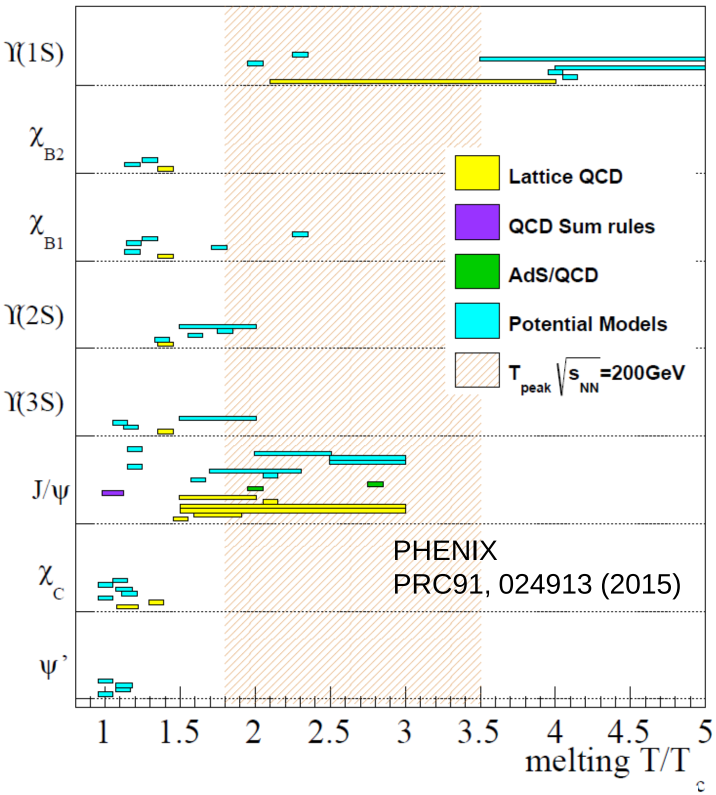
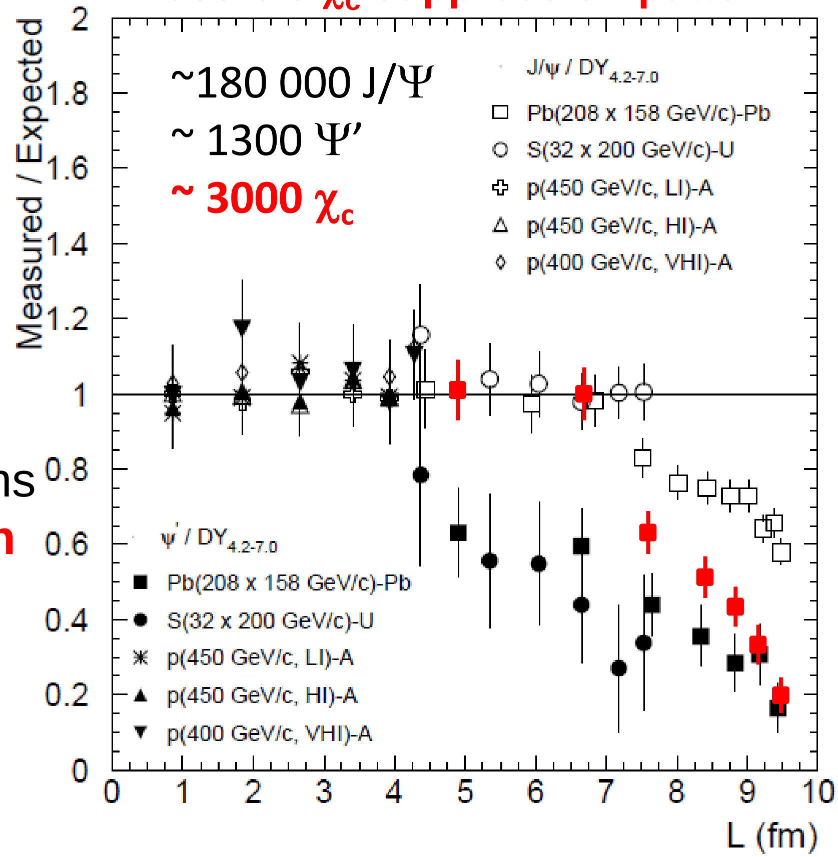



FIG. 1. (Color online) Compilation of medium temperatures relative to the critical temperature ($T_c$) where quarkonium states are dissociated in the quark-gluon plasma. Note that these estimations were performed assuming different $T_c$ values. Each horizontal bar corresponds to one estimation and its temperature extension (when applied) represents the range where the quarkonia state undergoes a mass/size modification until it completely melts. Techniques used in calculations: Lattice QCD [5–15], QCD sum rules [4, 16–20], AdS/QCD [21–24], effective field theories [27, 28] and potential models [15, 29–35]. The shaded band from 1.8 to 3.5 $T/T_c$ represents the hydrodynamic estimation for the peak temperature reached in Au+Au collisions at 200 GeV [36].

- **Typical 40-day Pb+Pb run @SPS** **($10^7.s^{-1}$ Pb beam → 10% $\lambda_I$ Pb target)**

  – ~ 180 000 $J/\Psi \rightarrow \mu^+\mu^-$ recorded by NA50
  – ~ 1300 $\Psi' \rightarrow \mu^+\mu^-$ recorded by NA50
  – If capable of measuring $\chi_c \rightarrow J/\Psi\gamma$, in NA50 acceptance : **$3000 < \chi_c < 7000$**

**Possible $\chi_c$ suppression pattern**




**But**

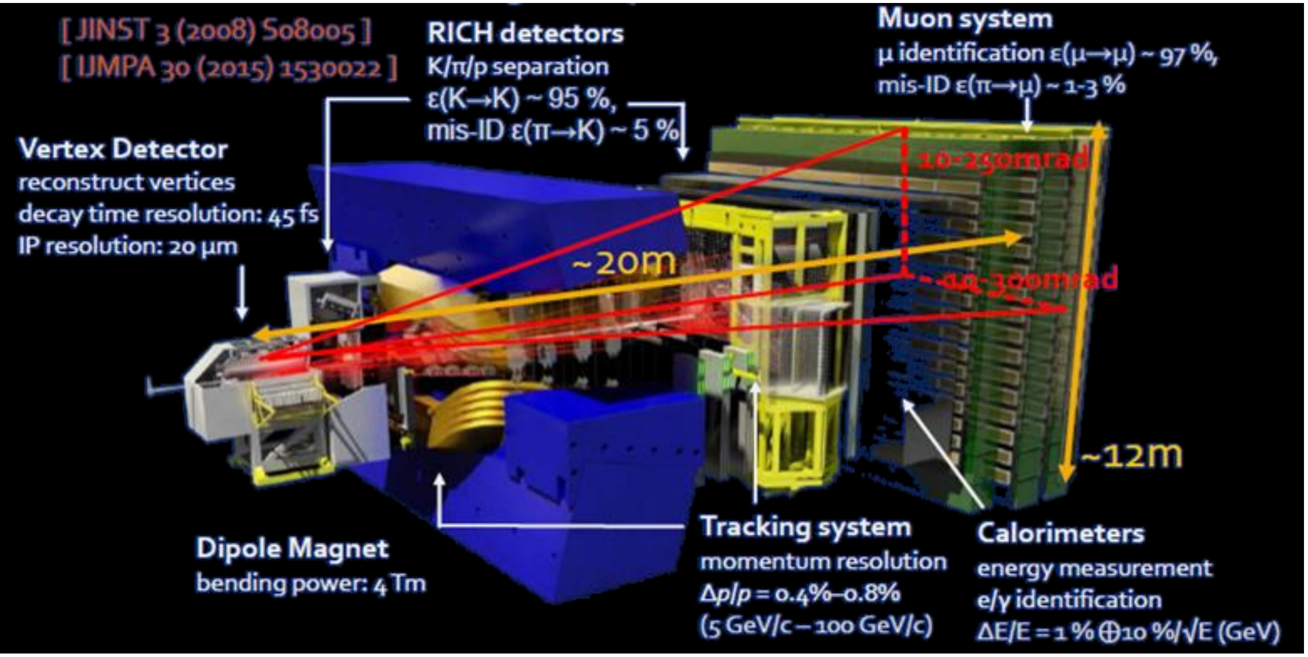
- NA50 was not instrumented to measure photons
  → **not able to measure $\chi_c$ production**

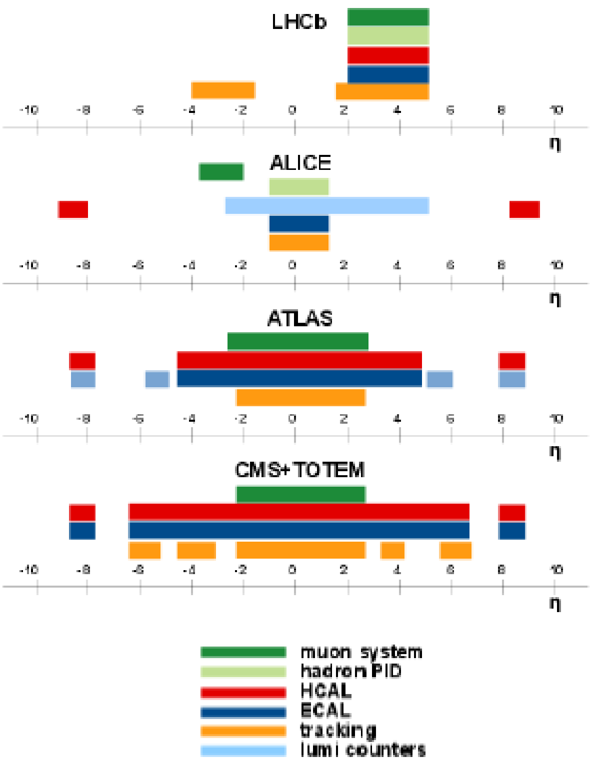
- NA50 was not instrumented to perform PID
  → **not able to measure $D^0$ production**

**Today, these measurements are possible with LHCb / SMOG**

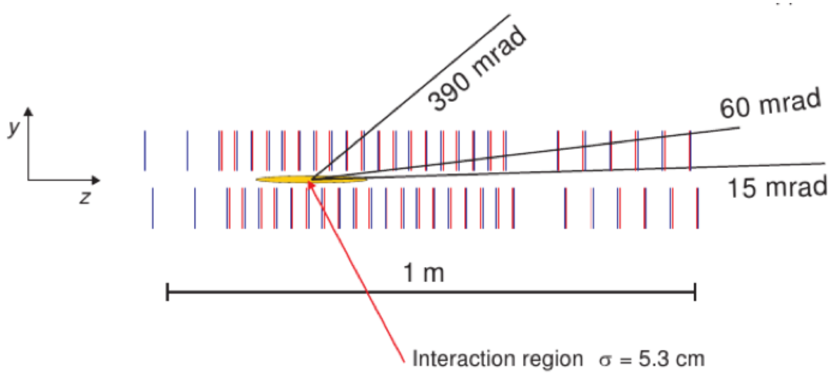
# The detector

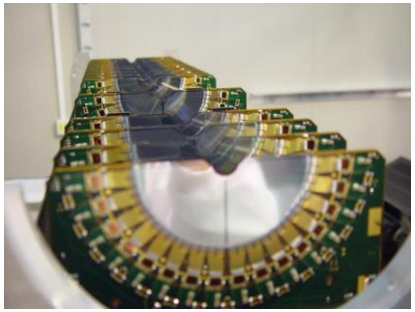


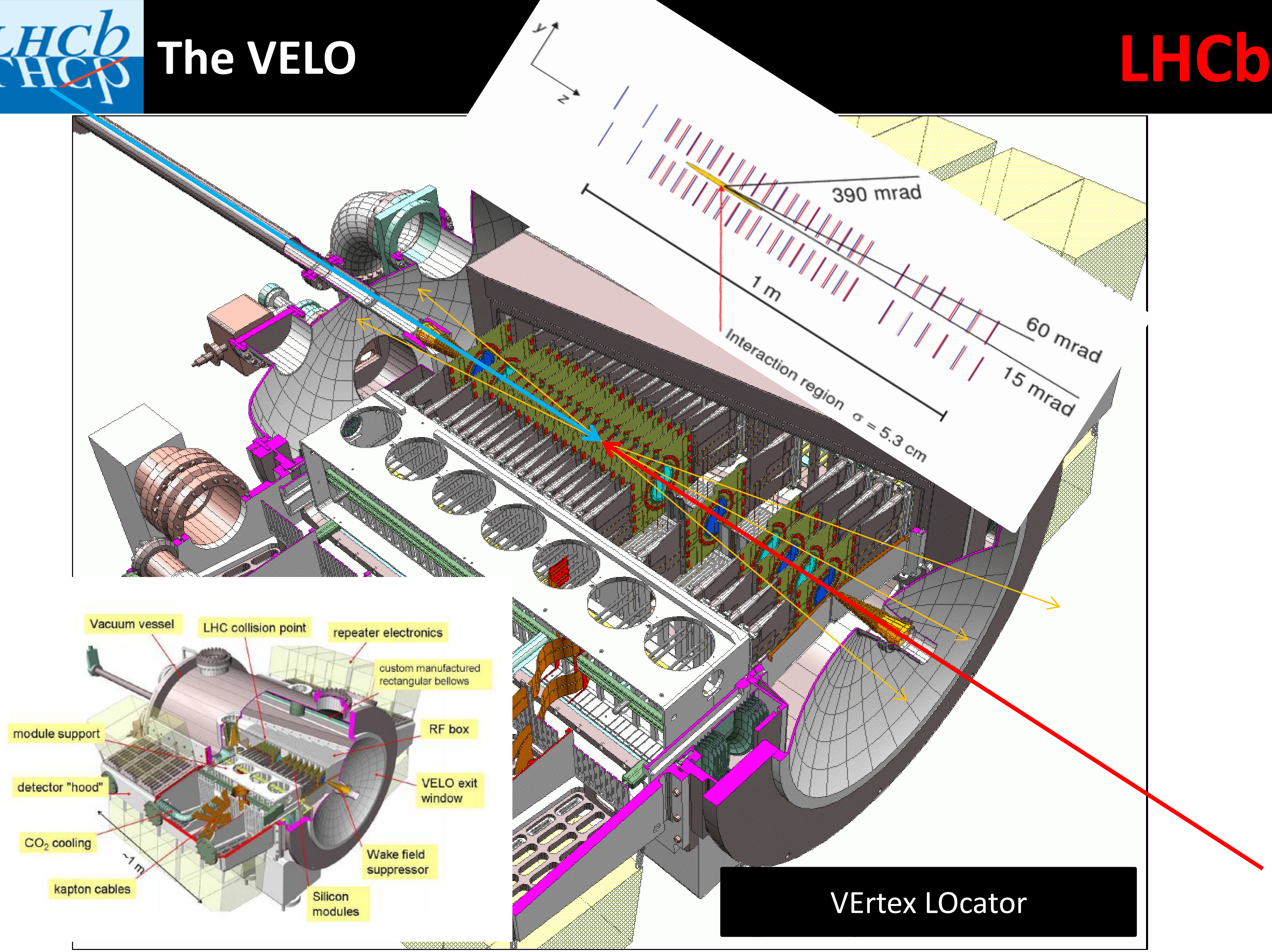



## Le VELO (Vertex LOcator)



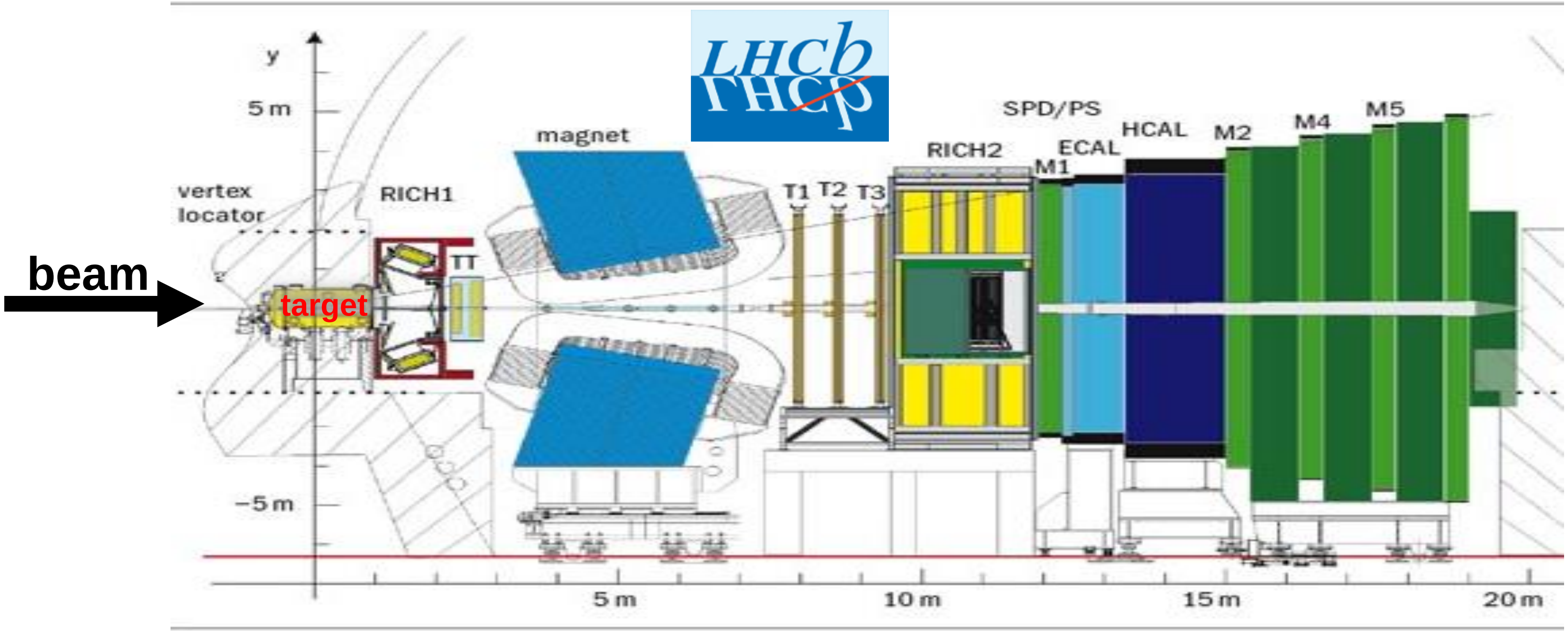





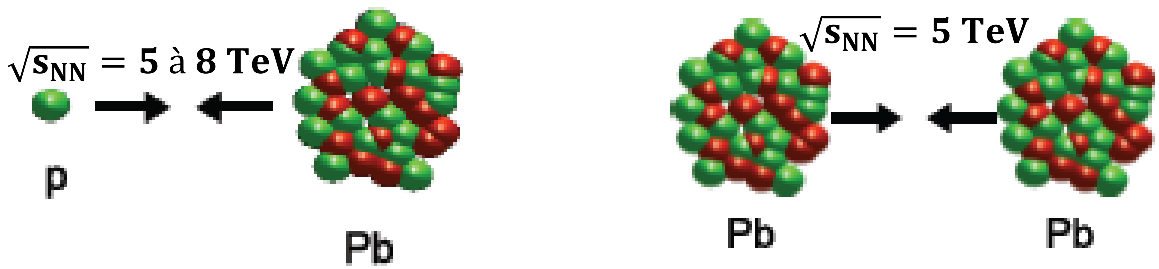
y
z
390 mrad
1 m
60 mrad
15 mrad
Interaction region σ = 5.3 cm
Vacuum vessel
LHC collision point
repeater electronics
custom manufactured rectangular bellows
module support
RF box
detector "hood"
VELO exit window
CO2 cooling
~1 m
Wake field suppressor
kapton cables
Silicon modules
VErtex LOcator

# SMOG (System for Measuring Overlap with Gas)

- **Injecting gas in LHCb Vertex Locator (VELO) region**
  - Primary role : luminosity measurement
  - Can be used as an internal gas target
  - Noble gas only : (very low chemical reactivity)
    - He (4), Ne (20), Ar (40), Kr (84), Xe (131)
    - Gaz pressure : $10^{-7}$ to $10^{-6}$ mbar



- **LHCb fonctionnera en deux modes**
  - Mode collisionneur

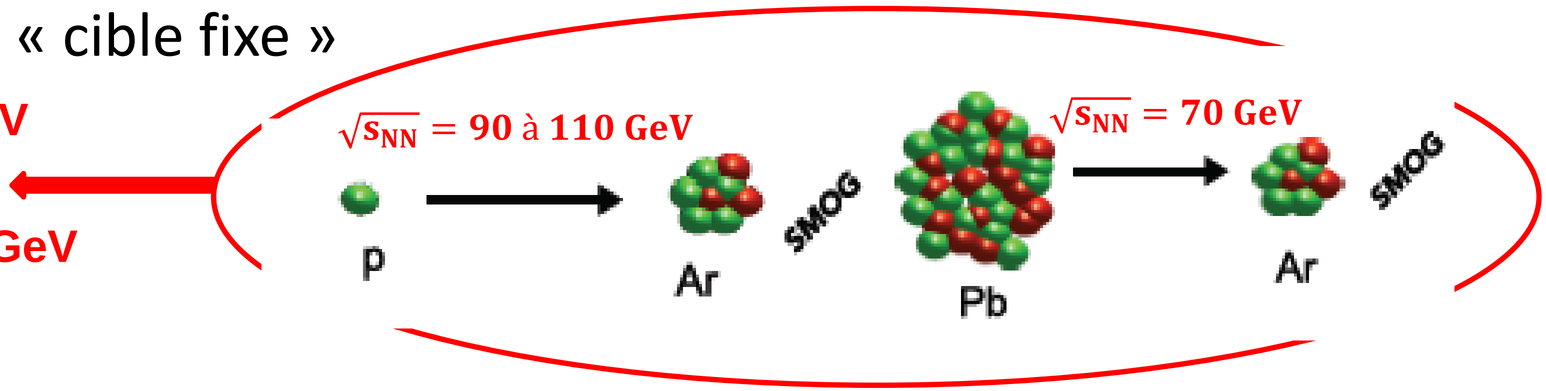



  - Mode « cible fixe »

$\sqrt{s_{NN}^{SPS}} \sim$ 20 GeV

$\sqrt{s_{NN}^{RHIC}}$ = 200 GeV

$\sqrt{s_{NN}^{LHC}}$ = 5 TeV




LHCb rapidity 2.5 < yLHCb < 4.5 $\Longrightarrow \begin{cases} \text{7 TeV beam:} & -2.3 < y^*_{LHCb} < -0.3 \\ \text{2.75 TeV beam:} & -1.8 < y^*_{LHCb} < 0.2 \end{cases}$

- **PbAr@70 GeV .vs. PbPb@17 GeV**
  - Multiplicity is related to event centrality and center-of-mass energy
  - Multiplicity can be used to compare different A+B collisions at different $\sqrt{s_{NN}}$

| System \ centrality | 60 – 100% | 50 – 60% | 40 – 50% | 30 – 40% | 20 – 30% | 10 – 20 % | 0 – 10% |
|---|---|---|---|---|---|---|---|
| PbNe – 71 GeV | 108.6 | 254.4 | 392.5 | 588.0 | 814.5 | 1086.0 | 1494.9 |
| **PbAr – 71 GeV** | **123,6** | **308,8** | **496,5** | **806,6** | **1228,3** | **1711,9** | **2372,7** |
| PbKr – 71 GeV | 196,9 | 533,6 | 919,1 | 1451,2 | 2205,5 | 2986,6 | 4084,3 |
| **PbPb – 17 GeV** | **124,2** | **331,6** | **605,9** | **919,6** | **1338,7** | **2035,8** | **2980,5** |

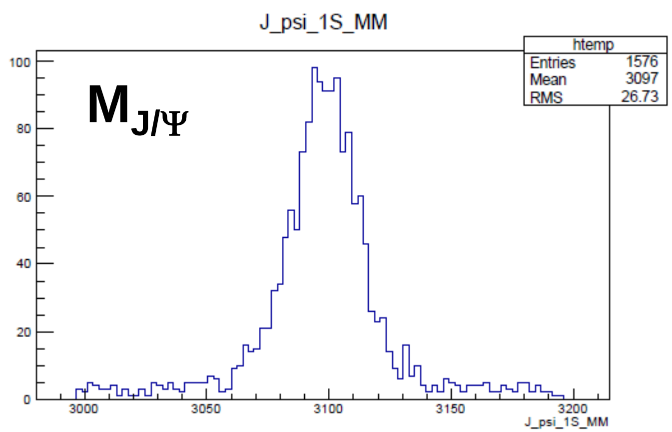
(based on EPOS-LHC-v3400)

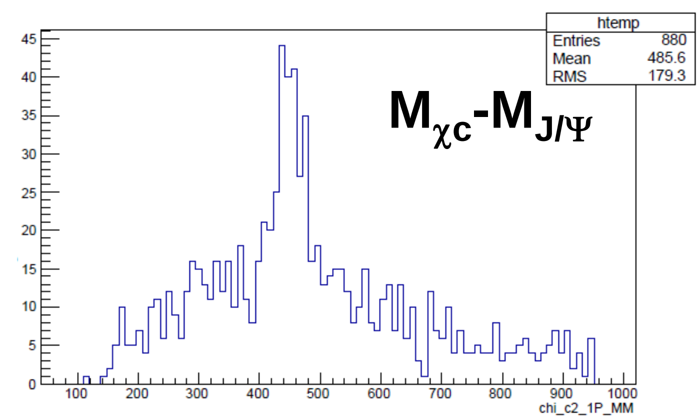
  - PbAr @ 71 GeV multiplicity ≡ PbPb@17 GeV multiplicity

    ➔ **PbAr @ 71 GeV is a good starting point to compare with NA50**

Acceptance × efficiency
*(PbAr full LHCb simulations)*

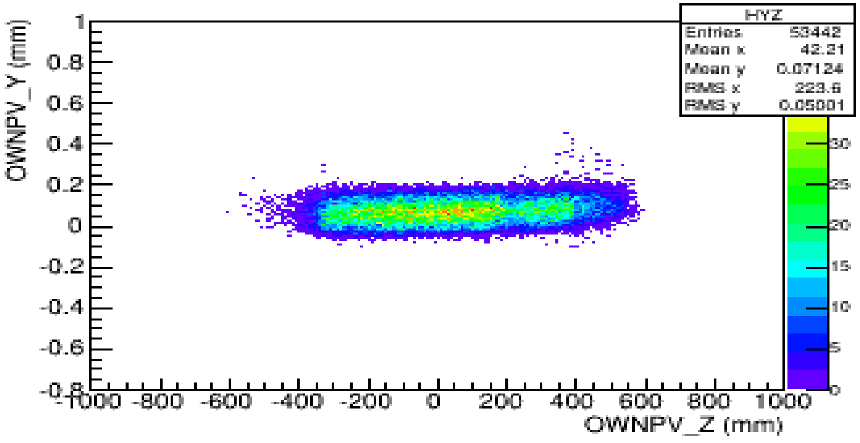
J/Ψ ~ 20%, $\chi_c$ (J/Ψ γ) ~ 5%

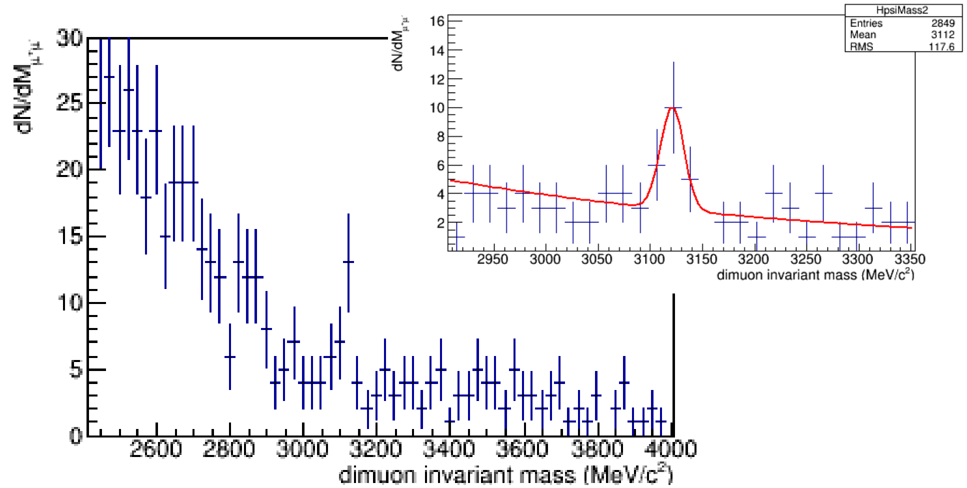


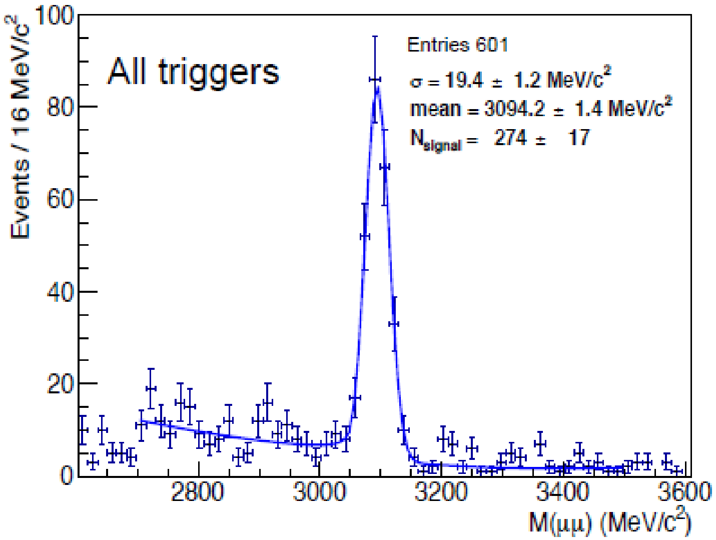
# LHCb SMOG **Real data**

- **Feb. 2013 : 27 minutes Pb+Ne @ 54 GeV**




- **August 2015 : 12h p-Ne @ ~110 GeV**
  - 36 protons bunches



- **Testing color screening**
  - Measuring together $\chi_c$, J/$\Psi$ and $\Psi'$ is crucial
  - Open charm is the appropriate reference

- **LHCb**
  - **Fantastic opportunity** to perform this program
  - SMOG acts as a fixed target (He, Ne, Ar, Xe, Kr)
  - First full data taking in 2015
    - **October 2015 : 3 days of pAr (~20000 J/$\psi$)**
    - **November-december 2015 : 21 days of PbAr (~15000 J/$\psi$)**
  - **Leading role of LAL/LLR** team for heavy flavor: Francesco Bossu, Frédéric Fleuret, Giulia Manca, Laure Massacrié, Patrick Robbe, Yanxi Zhanj

- **Not discussed in this talk : a thorough pA program**
  - Capable of reaching **large $x_2$** (up to 0.3 for J/$\psi$, 0.9 for $\Upsilon$)
  - First look at the program proposed by the **AFTER** team (after.in2p3.fr)

# backup

# Open charm production

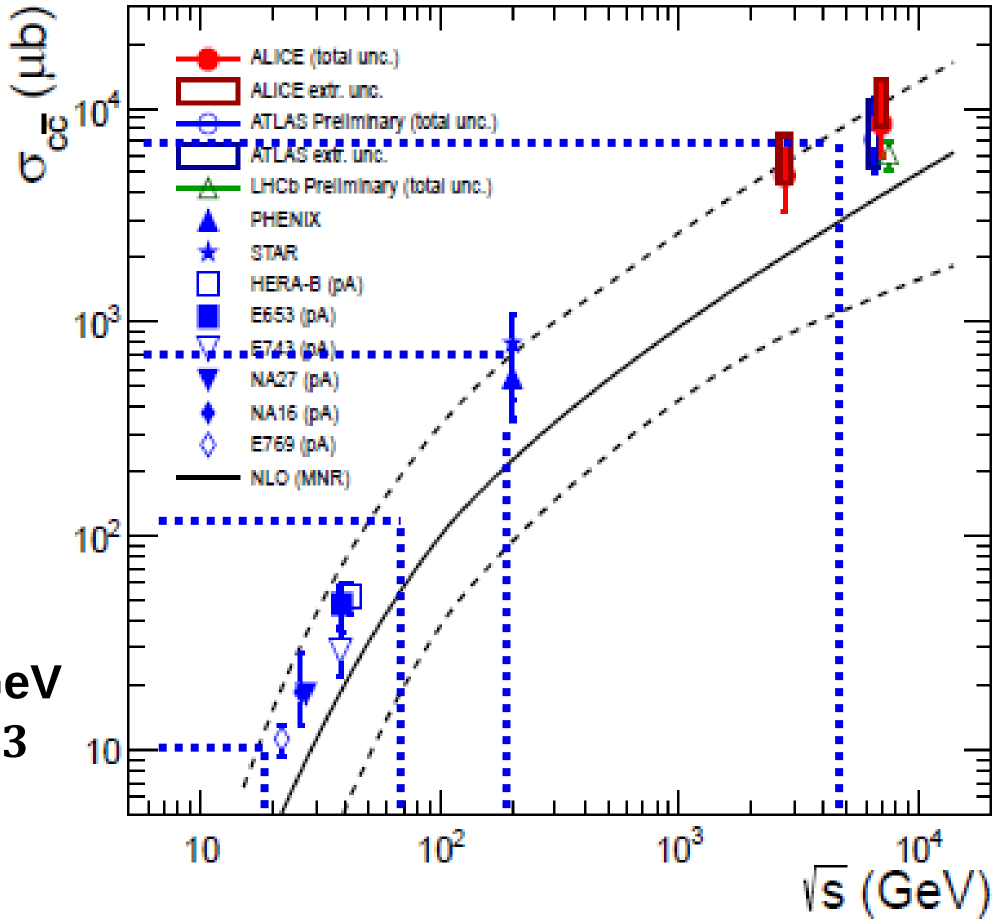
TABLE I: Centrality bin, number of $NN$ collisions, nuclear overlap function, charm cross section per $NN$ collision, and total charm multiplicity per $NN$ collision, in $\sqrt{s_{NN}}$ = 200 GeV Au+Au reactions.

| Centrality | $N_{coll}$ | $T_{AA}$ ($mb^{-1}$) | $\frac{1}{T_{AA}}\frac{dN_{c\bar{c}}}{dy}\|_{y=0}$ ($\mu b$) | $N_{c\bar{c}}/T_{AA}$ ($\mu b$) |
|---|---|---|---|---|
| min. bias | 258±25 | 6.14±0.45 | 143±13±36 | 622±57 ±160 |
| 0–10 % | 955±94 | 22.8±1.6 | 137±21±35 | 597±93 ±156 |
| 10–20 % | 603±59 | 14.4±1.0 | 137±26±35 | 596±115±158 |
| 20–40 % | 297±31 | 7.07±0.58 | 168±27±45 | 731±117±199 |
| 40–60 % | 91±12 | 2.16±0.26 | 193±47±52 | 841±205±232 |
| 60–92 % | 14.5±4.0 | 0.35±0.10 | 116±87±43 | 504±378±190 |

Phys. Rev. Lett. 94, 082301 (2005)

**In central Au+Au collisions @ 200 GeV**

$$N_{c\bar{c}} \sim 597 \cdot 10^{-3} mb \times 22.8\, mb^{-1} \sim 13$$




**~0.1 $c\bar{c}$ @ 20 GeV**
**~1 $c\bar{c}$ @ 70 GeV**
**~10 $c\bar{c}$ @ 200 GeV**
**~100 $c\bar{c}$ @ 5500 GeV**

$$\sigma_{c\bar{c}}^{5500\,GeV} \sim 10 \times \sigma_{c\bar{c}}^{200\,GeV} \sim 100 \times \sigma_{c\bar{c}}^{70\,GeV} \sim 1000 \times \sigma_{c\bar{c}}^{20\,GeV}$$