Charm production in PbNe collisions at LHCb

investigating charmonium color screening in a QGP

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Fixed-target experiments at LHC – Strong2020 workshop

June 23, 2022

- Charm quarks, QGP and J/ψ sequential suppression
- Experimental results: NA50@17 GeV (SPS)
- LHCb-FT: PbNe @ 70 GeV and outlook

Charm quarks and QGP

- **Heavy quarks and Quark Gluon Plasma (QGP)**

  Heavy quarks are "special " QGP probes : m_Q >> QGP critical temperature T_C (~160 MeV),

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

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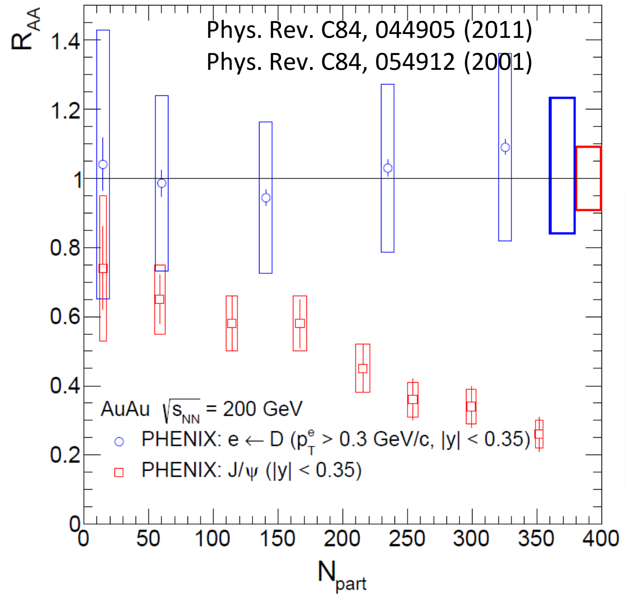
- **Heavy quark hadronization ($c\bar{c}$ example):**
  - ~90% of $c\bar{c}$ pairs → open charm
  - ~10% of $c\bar{c}$ pairs → hidden charm (charmonia)

  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 @ $\sqrt{s_{NN}}$ = 200 GeV

Blue = open charm, no (little) modification of open charm yield

Red = hidden charm, modification of J/Ψ (*$c\bar{c}$ bound state*) yield

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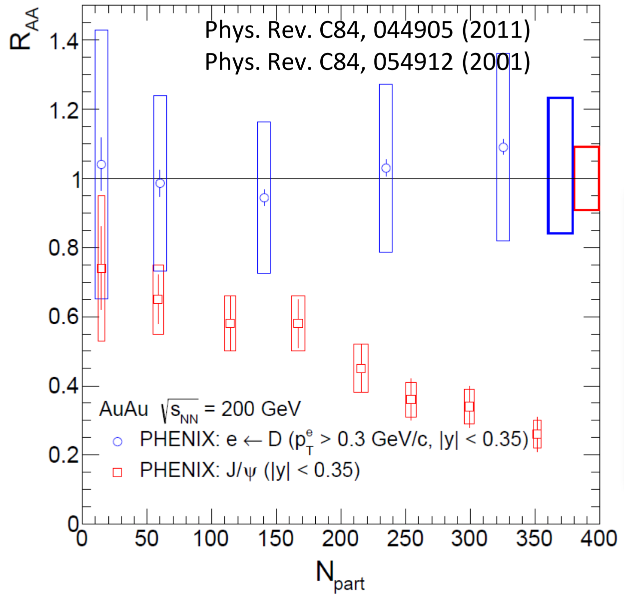
    - Color screening in a QGP decreases quarkonium binding
    - Color screening should lead to a suppression of quarkonium production yields



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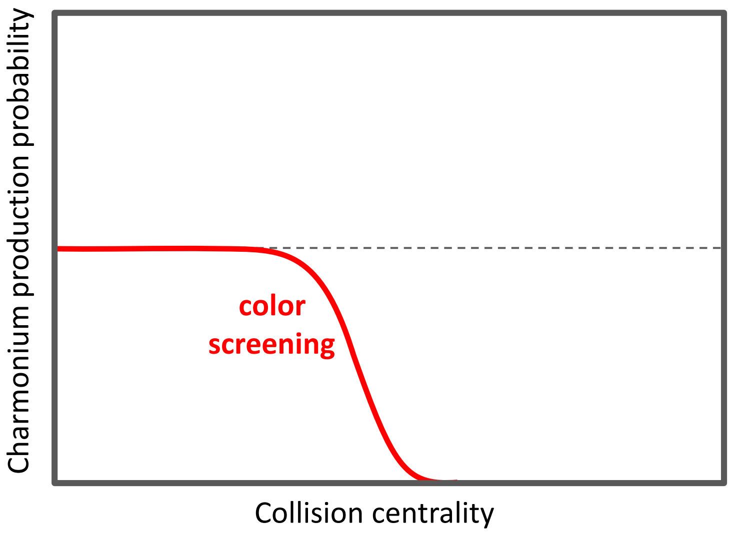

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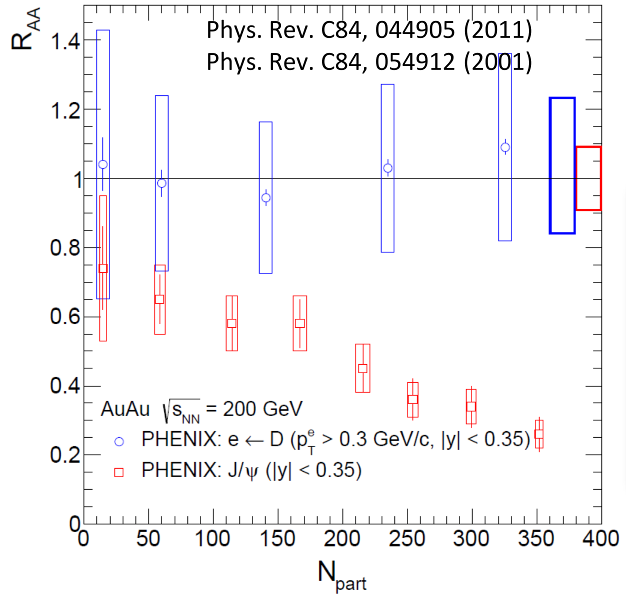
  - **Recombination: *$Q\bar{Q}$ bound states enhancement***
    - At sufficiently high $\sqrt{s_{NN}}$, heavy quarks are abundantly produced.
    - After thermalisation, statistical combination can lead to an enhancement of quarkonium production yields
    - *Occurs at **high energies only** (many $c\bar{c}$ pairs needed)*
  - At high energies: interplay *colour screening/recombination*



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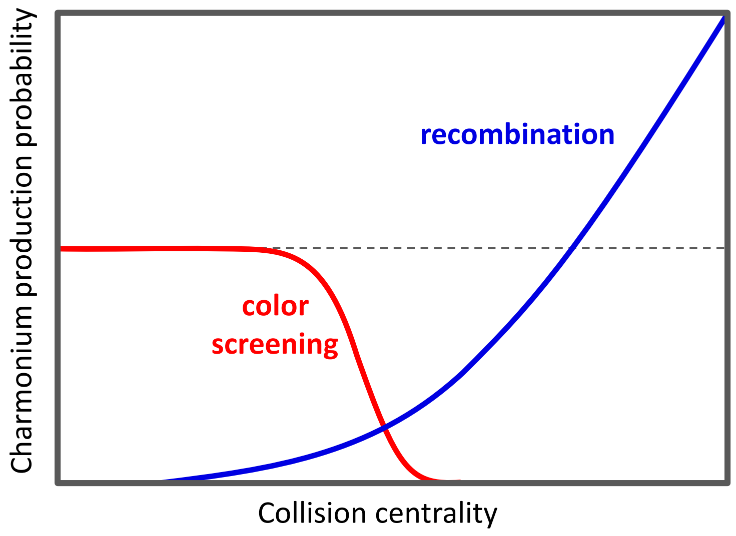


Charm quarks and QGP

- **Experimentally**

  – Charmonium production in A+A collisions studied at:
    - **CERN-SPS** (√s=17 GeV) NA38, NA50, NA60 experiments (~0.1 $c\bar{c}$ pair per central PbPb)
    - **BNL-RHIC** (√s=200 GeV) PHENIX, STAR experiments (~10 $c\bar{c}$ pair per central AuAu)
    - **CERN-LHC** (√s=2.76, 5 TeV) ALICE, CMS experiments (~100 $c\bar{c}$ pair per central PbPb)

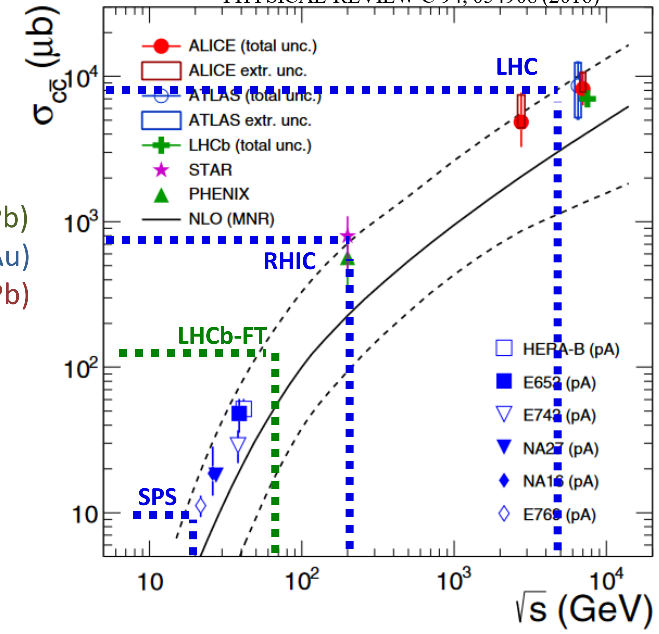
  – Short summary for J/ψ:
    - **NA50** (PbPb@SPS) observed an *anomalous* J/ψ suppression
    - **PHENIX** (AuAu@RHIC) observed a *similar* suppression (than NA50)
    - **ALICE** (PbPb@LHC) observed a *smaller* suppression (than PHENIX)

➢ Possible color screening starting at SPS

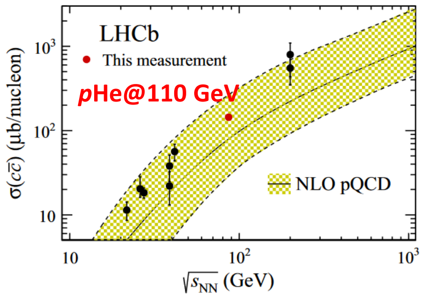
➢ Possible recombination occuring at LHC

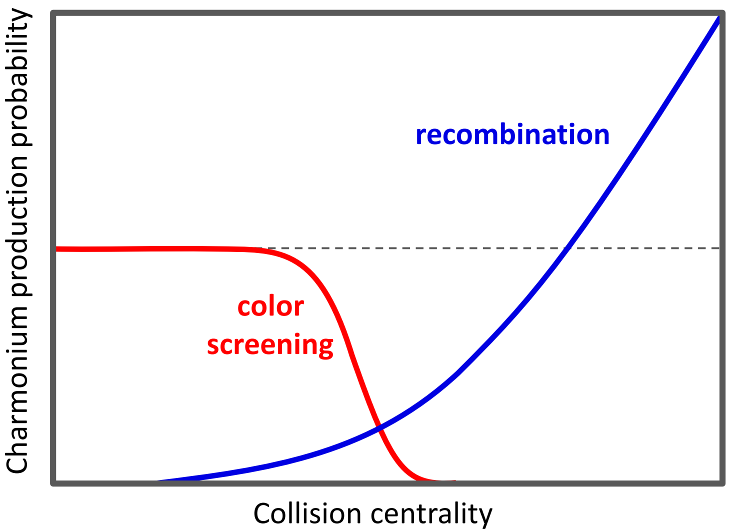
  – With the ***LHCb Fixed-Target*** program
    - **No recombination:** at 70 GeV, expect ~1 $c\bar{c}$ pair per central PbA (w/ big A)
    - Goal: investigate **color screening**

PHYSICAL REVIEW C 94, 054908 (2016)



PRL 122 (2019) 132002

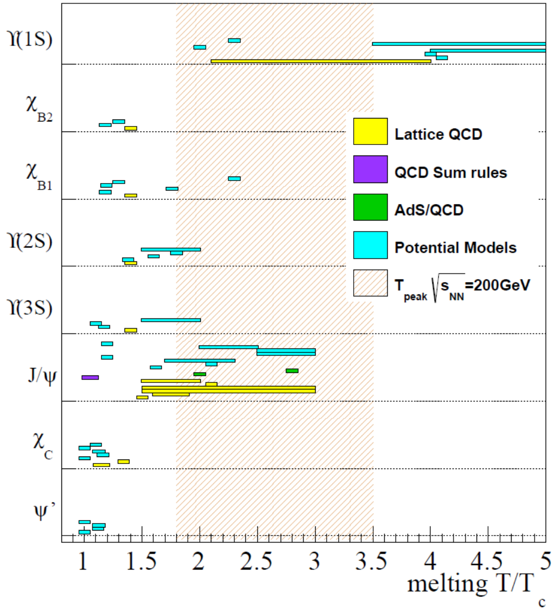




Color screening and Sequential suppression

- **Quarkonium dissociation in a QGP**
  - In QGP quarkonium states are expected to « melt » at dissociation temperature $T_d > T_c$
  - Different T_d for different quarkonium states: $T_d (J/\psi) > T_d (\chi_c) > T_d (\psi') > T_c$

PRC91, 024913 (2015)

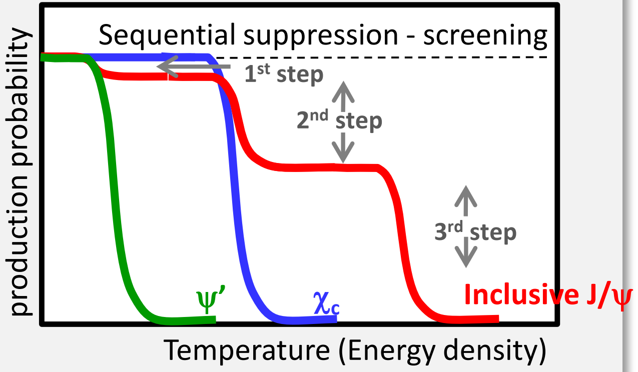


- **Sequential suppression**
  - Because of different T_d and because of J/ψ feed-downs, **J/ψ sequential suppression** should show up.

Feed-downs contributing to J/ψ inclusive yield

60% direct J/ψ
+ 30% $\chi_c \rightarrow J/\psi+\gamma$
+ 10% $\psi' \rightarrow J/\psi + X$
J/ψ inclusive yield

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



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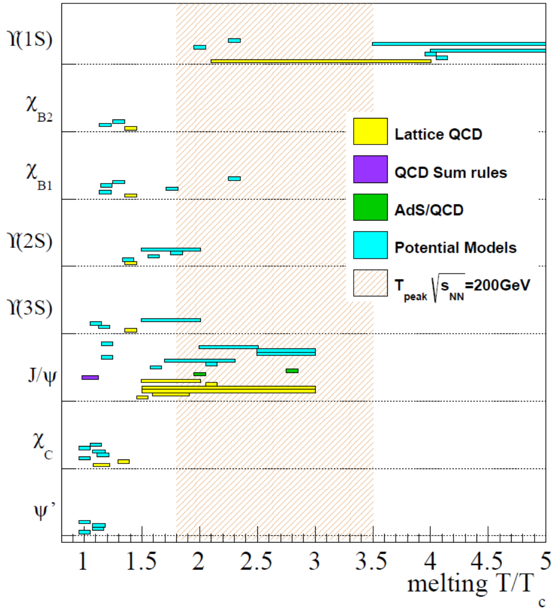

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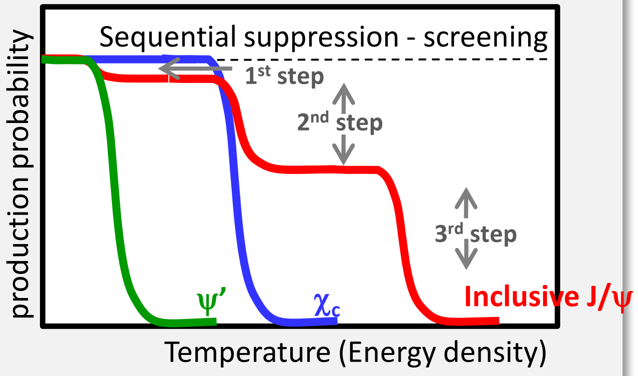
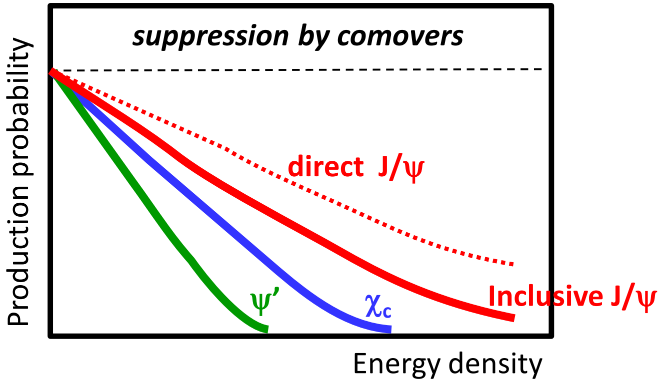
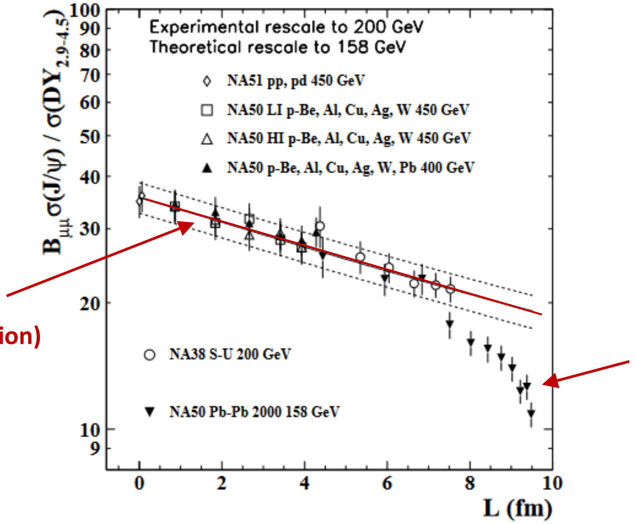


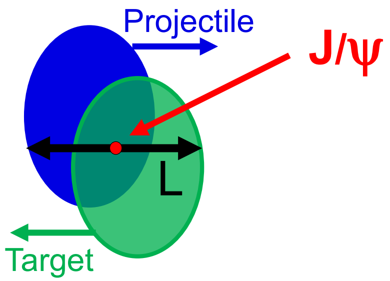
- **Alternative (no QGP) scenario: suppression by comoving hadrons**
  - Charmonia are suppressed by their interaction with comoving hadrons
  - Smooth suppression
  - Same suppression-starting point
  - Slopes related to binding energy : $S_{\psi'} > S_{\chi} > S_{J/\psi}$



- **Anomalous suppression at SPS**
  - NA50 measured J/ψ/DY ratio for **several *pA* and PbPb**
  - Drell-Yan ($q\bar{q} \rightarrow \mu^{+}\mu^{-}$) = proxy for N_{coll}
  - *L = length of nuclear matter seen by quarkonium state*
  - Measured yields in ***pA* to evaluate quarkonium nuclear absorption** (breakup) when traversing nuclear matter

Eur. Phys. J. C 39, 335–345 (2005)





Experimental results : NA50 @ SPS

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  - Measured yields in ***pA* to evaluate quarkonium nuclear absorption** (breakup) when traversing nuclear matter
  - **Expected** = measured yields in p+A extrapolated to large L
    - No anomalous suppression: Measured/expected = 1
    - **Anomalous suppression: Measured/expected < 1**
    - Anomalous suppression ***observed in Pb+Pb collisions***
  - Is anomalous suppression due to **color screening ?**

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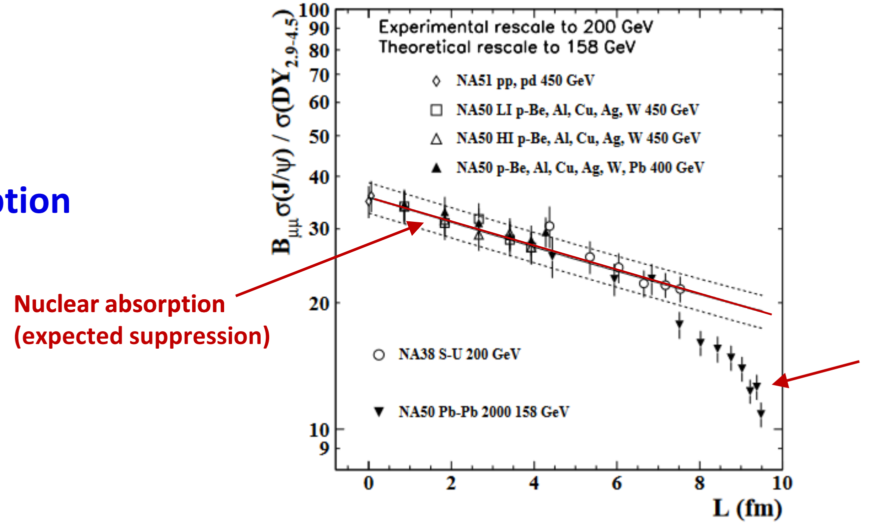

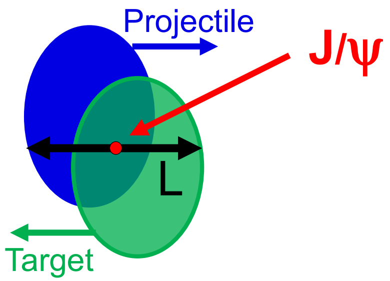

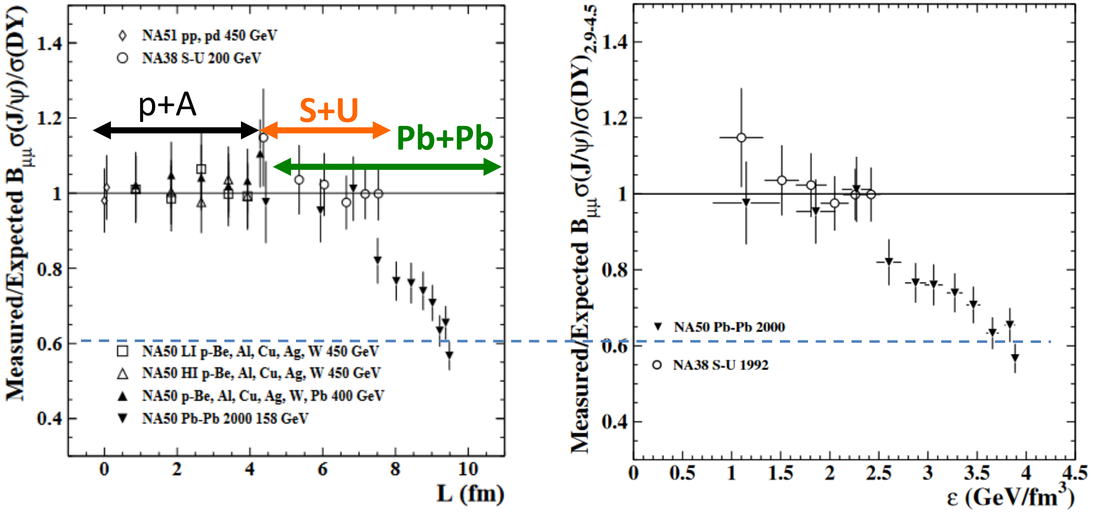

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  - Is anomalous suppression due to **color screening ?**
    - Not clear yet
    - **χ_c measurement missing**
      - χ_c -> J/ψ feed-down ~30%
    - **Energy density range not large enough**
    - **LHCb is very well placed to address this question**
      - χ_c measurement capability
      - Larger energy → larger energy density
        - $\sqrt{s_{NN}}$ =70 GeV@LHC .vs. 17 GeV @ SPS

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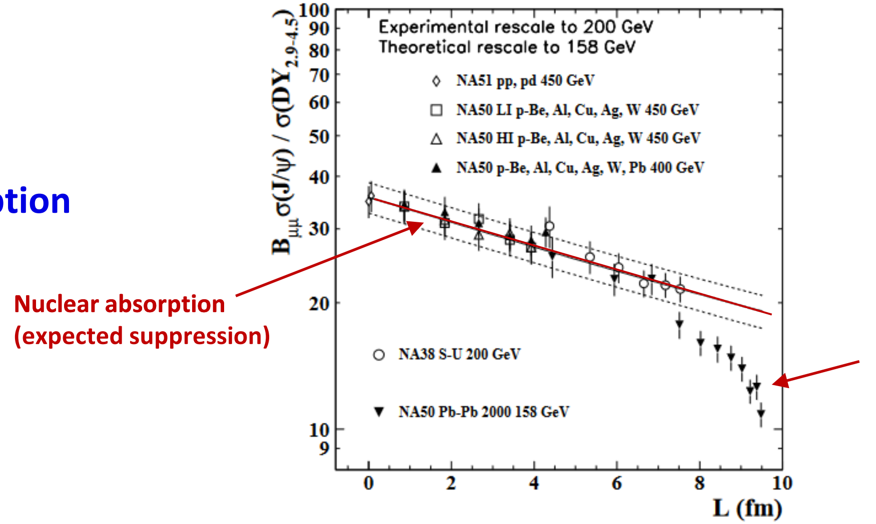

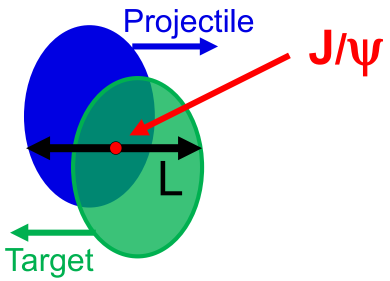

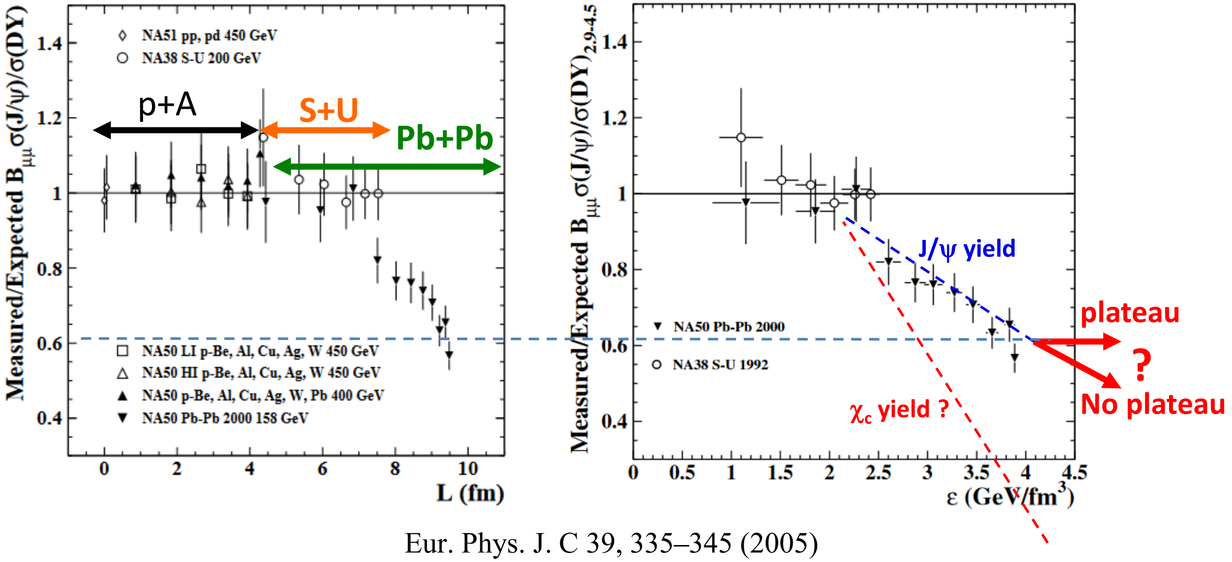

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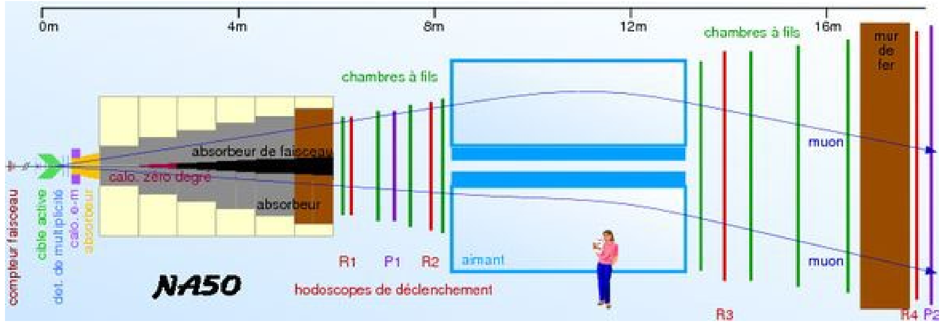
Detector performances : NA50@SPS .vs. LHCb@LHC

NA50 experiment



- Muon spectrometer → designed for high mass dimuons
- 400 GeV/proton → Pb beam@158 GeV/nucleon → **$\sqrt{s_{NN}}$ = 17 GeV**
- Absorber downstream of the target
  - **$\Delta M_{J/\psi}$ ~100 MeV/c²**
  - **No limitation in centrality reach** due to occupancy
- Acceptance = one rapidity unit : -0.5< y* < 0.5
- Open charm measurement via semi-leptonic decays
- Normalize J/ψ production with Drell-Yan ($q\bar{q} \rightarrow \mu^+\mu^-$)
- **Cannot measure $\chi_c \rightarrow J/\psi\, \gamma$**

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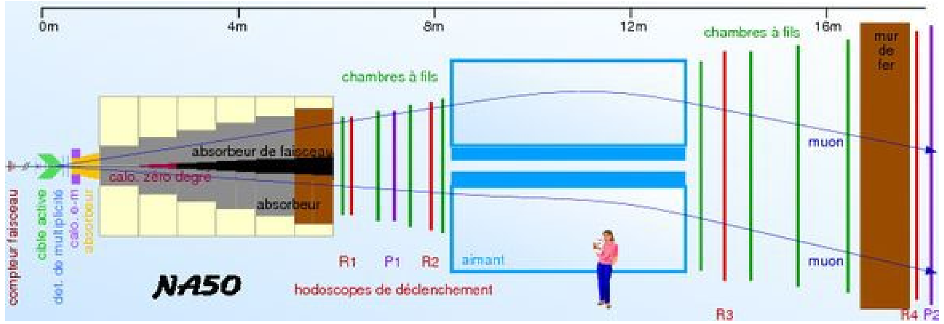

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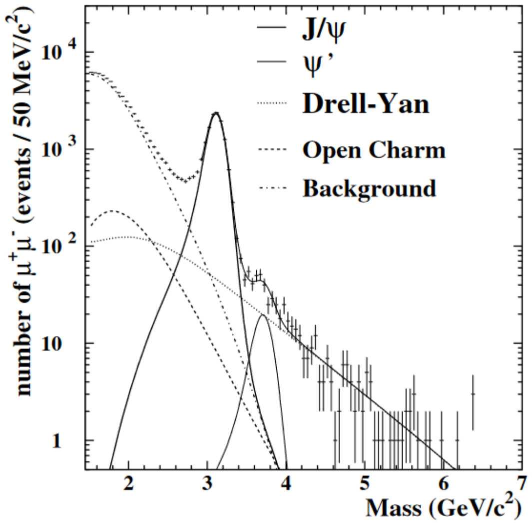

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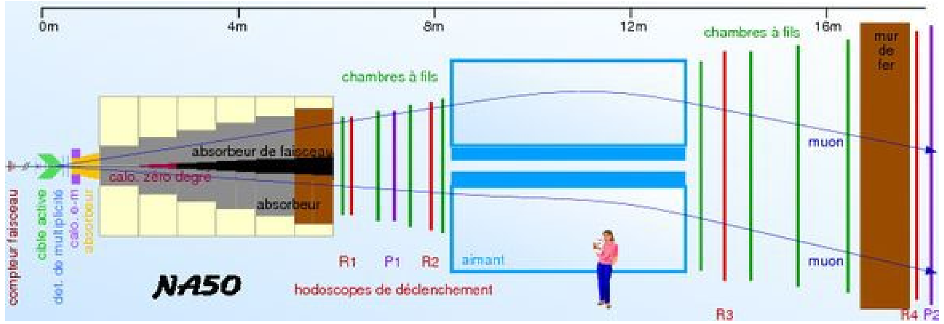

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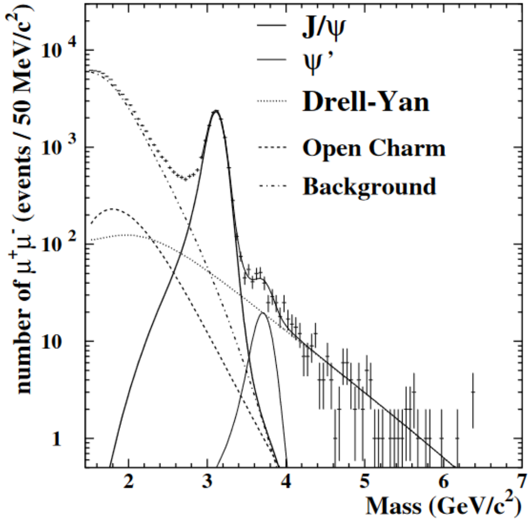
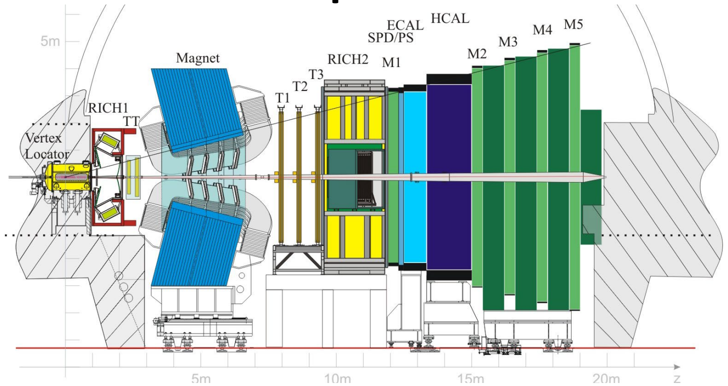


LHCb experiment



- Forward spectrometer: vertexing, tracking, Calo, PID, MuonID
- 7 TeV/proton → Pb beam@2.75 TeV/nucleon → $\sqrt{s_{NN}}$ ~ 70 GeV
- No absorber
  - $\Delta M_{J/\psi}$ ~15 MeV/c²
  - **limitation in centrality reach** due to occupancy
- Acceptance = three rapidity units: -2.5 < y* < 0.5
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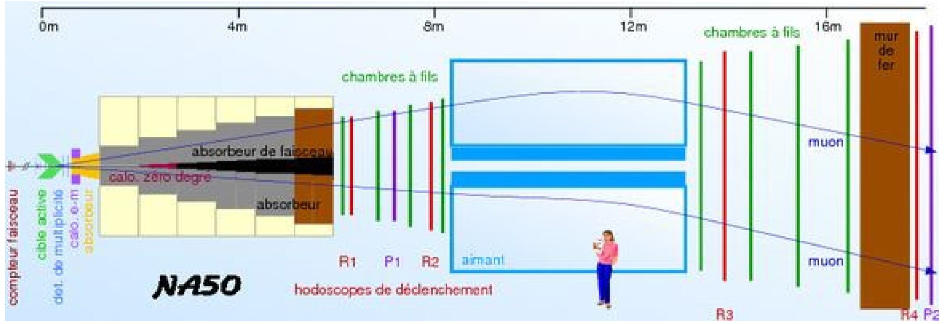

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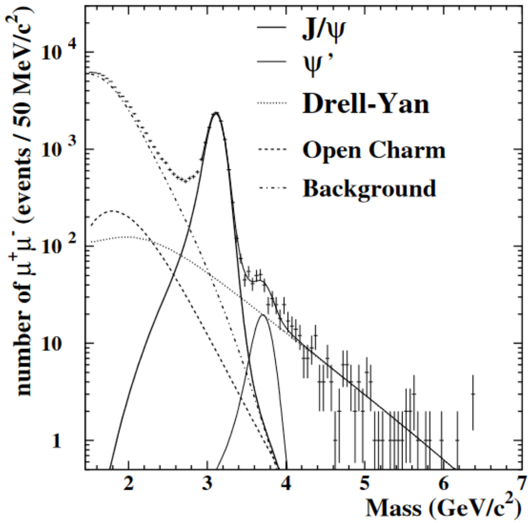

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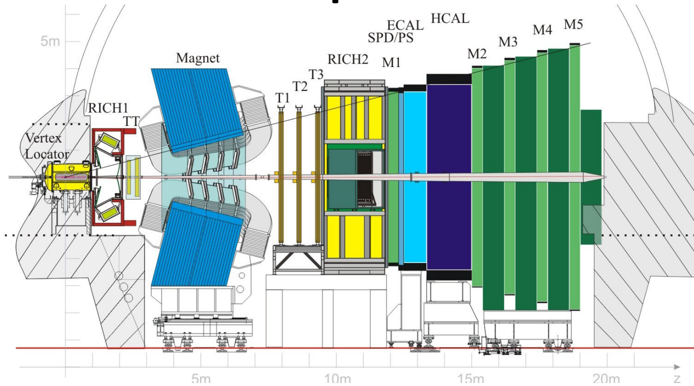

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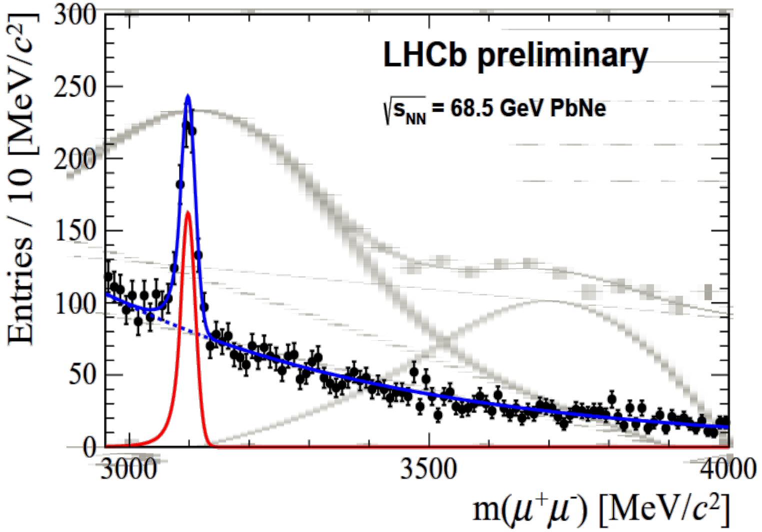


Operation: NA50@SPS .vs. LHCb-FT@LHC

- **Looking for anomalous J/ψ suppression with LHCb-FT**
  - **LHCb-FT ➔** $\sqrt{s_{NN}} \sim 70$ GeV .vs. **NA50 ➔** $\sqrt{s_{NN}} \sim 17$ GeV

- **Which target should we operate with LHCb ?** (to compare to NA50 PbPb collisions)
  - Multiplicity is related to event centrality and center-of-mass energy
  - Multiplicity can be used to compare different A+B collisions at different $\sqrt{s_{NN}}$

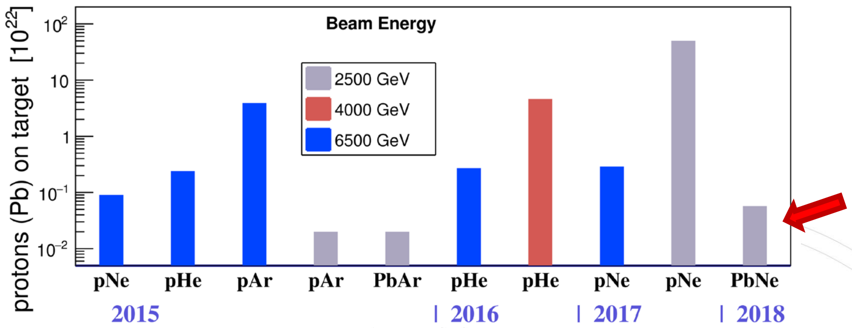
	Peripheral collisions						Central collisions
System \ centrality	**100 – 60%**	**60 – 50%**	**50 – 40%**	**40 – 30%**	**30 – 20%**	**20 – 10 %**	**10 – 0%**
PbNe – 71 GeV	108.6	254.4	392.5	588.0	814.5	1086.0	1494.9
PbAr – 71 GeV	**123,6**	**308,8**	**496,5**	**806,6**	**1228,3**	**1711,9**	**2372,7**
PbKr – 71 GeV	196,9	533,6	919,1	1451,2	2205,5	2986,6	4084,3
PbXe – 71 GeV	201,4	581,7	1031,0	1587,3	2400,2	3541,7	5065,7
PbPb – 17 GeV	**124,2**	**331,6**	**605,9**	**919,6**	**1338,7**	**2035,8**	**2980,5**

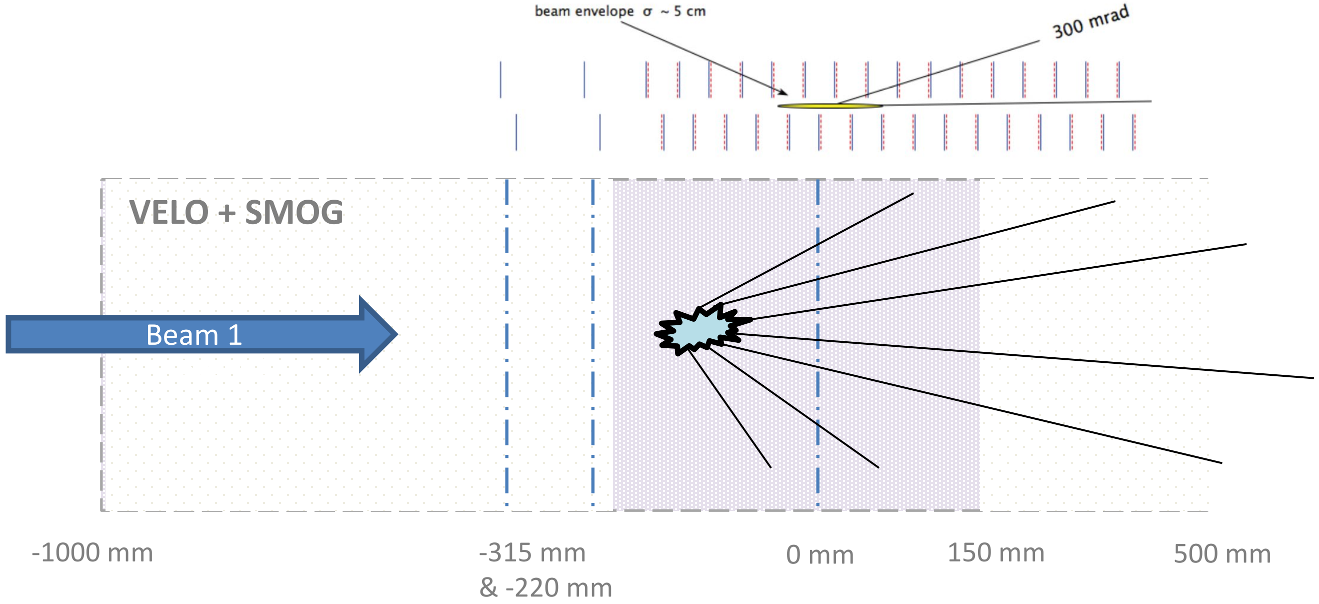
(based on EPOS-LHC-v3400)

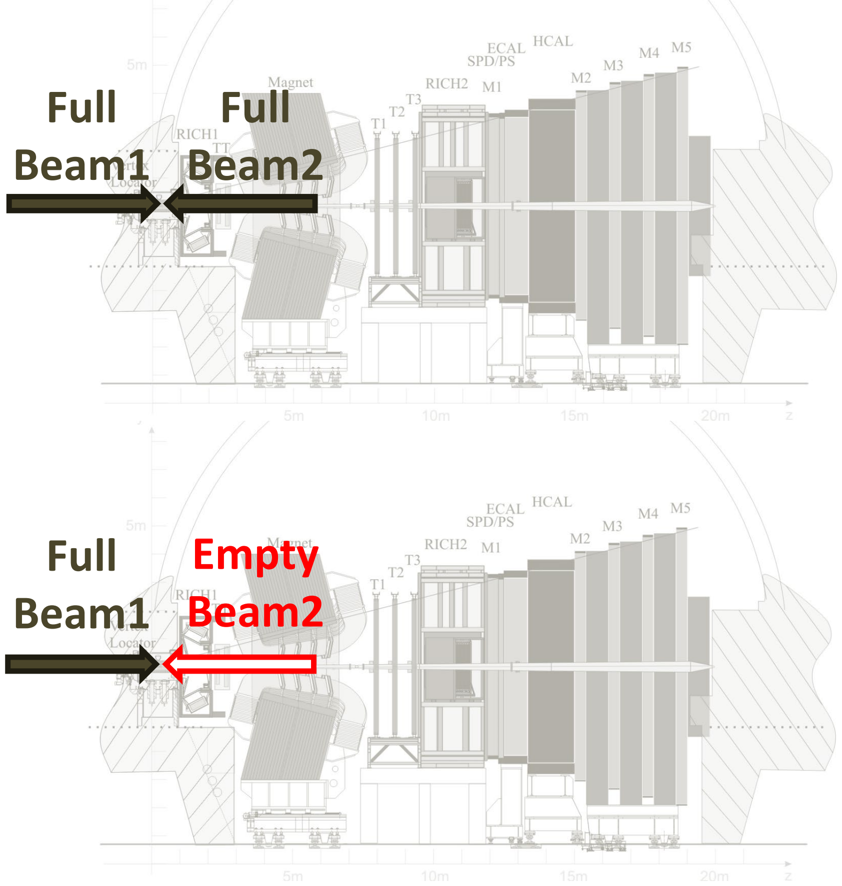
- PbAr @ 71 GeV multiplicity ≡ PbPb@17 GeV multiplicity ➔ **PbAr @ 71 GeV is a good starting point to compare with NA50**
- But **multiplicity in PbAr too large for Run1+Run2 LHCb setup** (saturation of the vertex Locator, drop of reconstruction efficiency)

- Study **PbNe as a starting point → demonstrate the faisibility** of the physics program (no saturation)

- **Data taken during 2018 PbPb run**
  - From nov. 9, 2018 to Dec. 2, 2018
  - 2500 GeV Pb beam
  - 33 fills: Two main filling schemes
    - 15 fills with 100 ns, 648 Pb, **52 Coll**, **596 non-Coll**
    - 18 fills with 75 ns, 733 Pb, **468 Coll**, **265 non-Coll**
  - **Use non-Coll bunches only**
  - Very small contamination due to debunched ions (<0.3%)

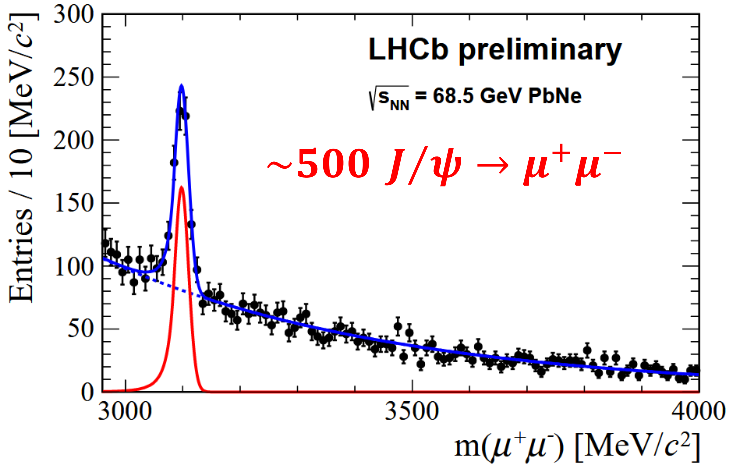


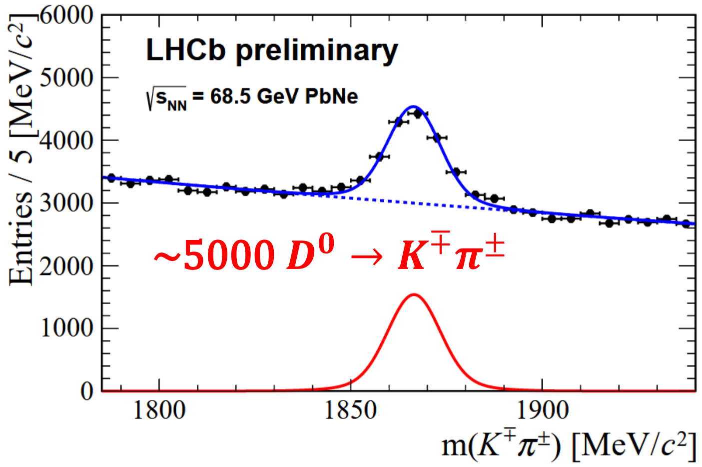




J/ψ and D^0 measurement in PbNe with LHCb

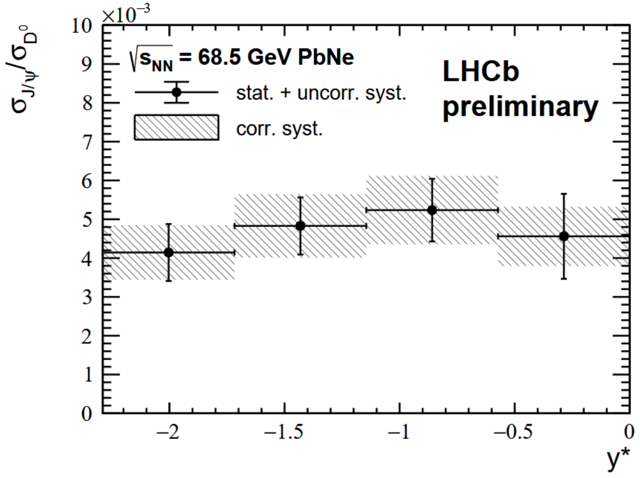
- **Signal**



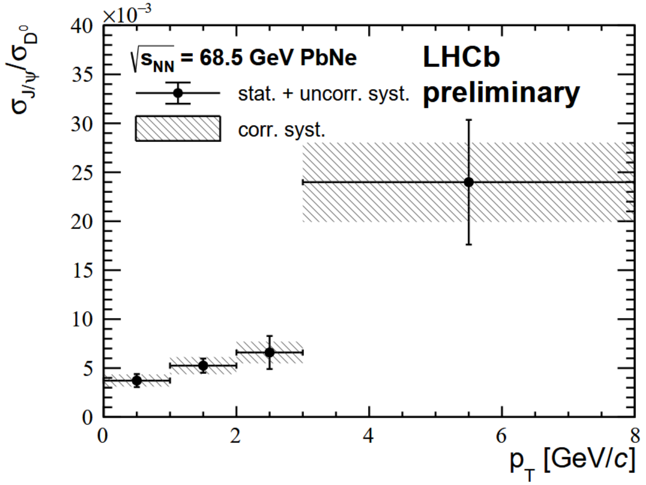


$$\frac{\sigma_{J/\psi}}{\sigma_{D^0}} = (5{,}1 \pm 0{,}4 \pm 0{,}9) \times 10^{-3}$$

- **J/ψ / D^0 ratios**



No dependence with rapidity (within uncertainties)



Strong dependence on p_T

To be compared with J/ψ / D^0 ratios in pNe (coming soon)

- **J/ψ/D^0 ratio as a function of the number of binary nucleon-nucleon collisions N_{coll}**
  - Centrality determined by energy deposit in the electromagnetic calorimeter
  - N_{coll} estimated from Glauber model to data

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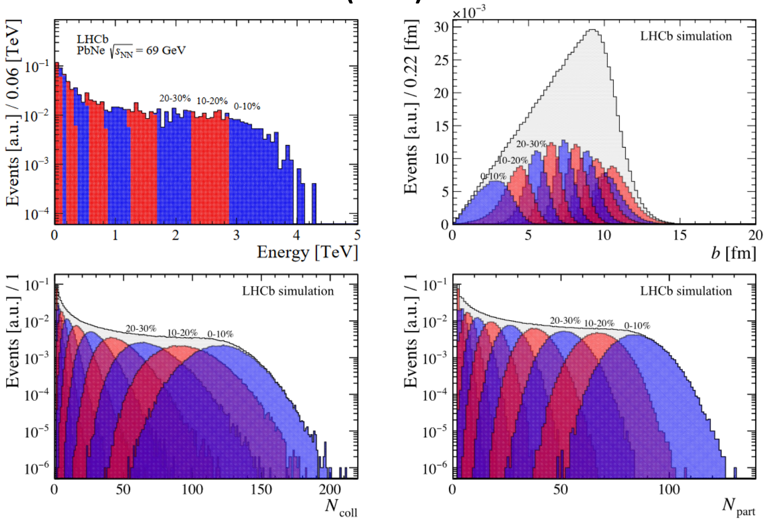
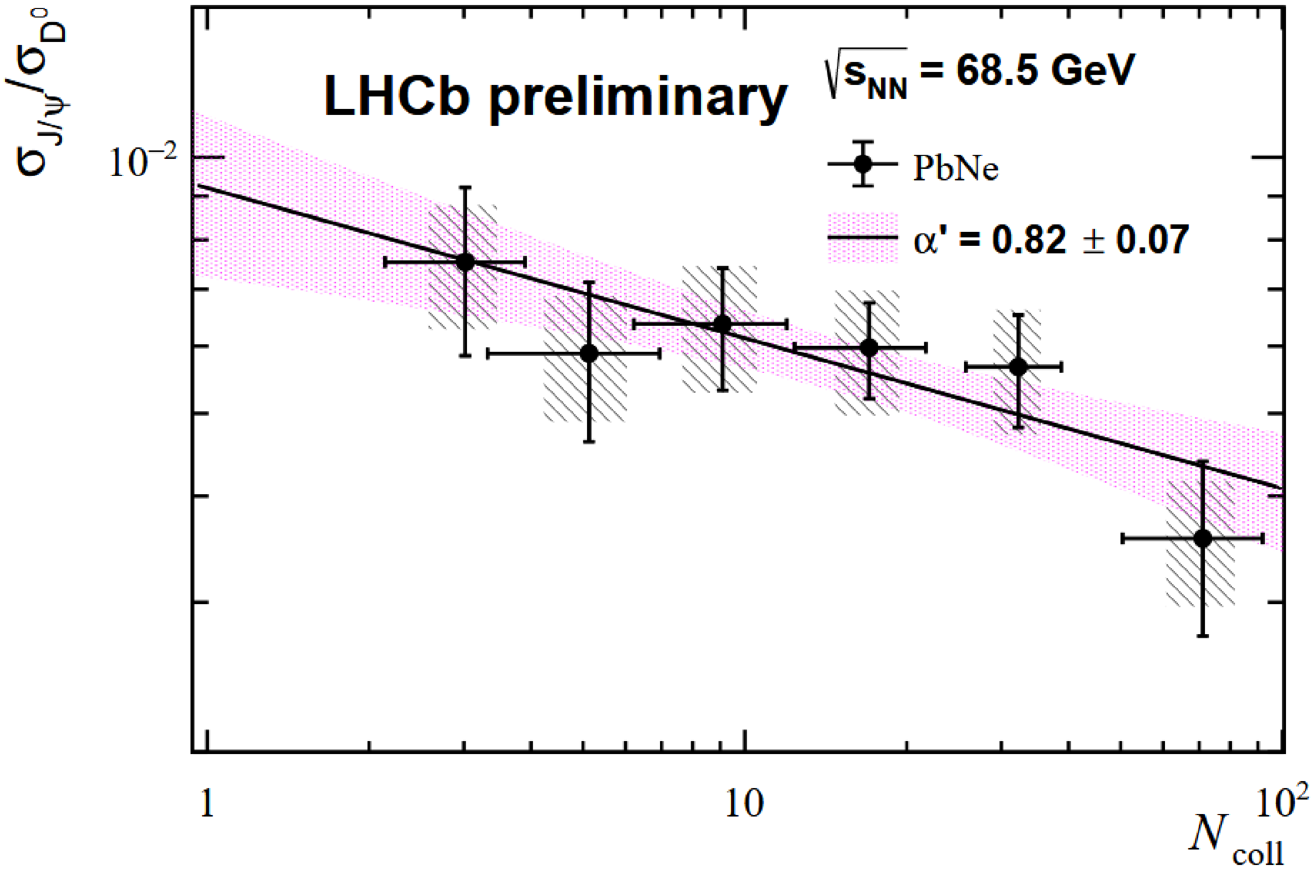




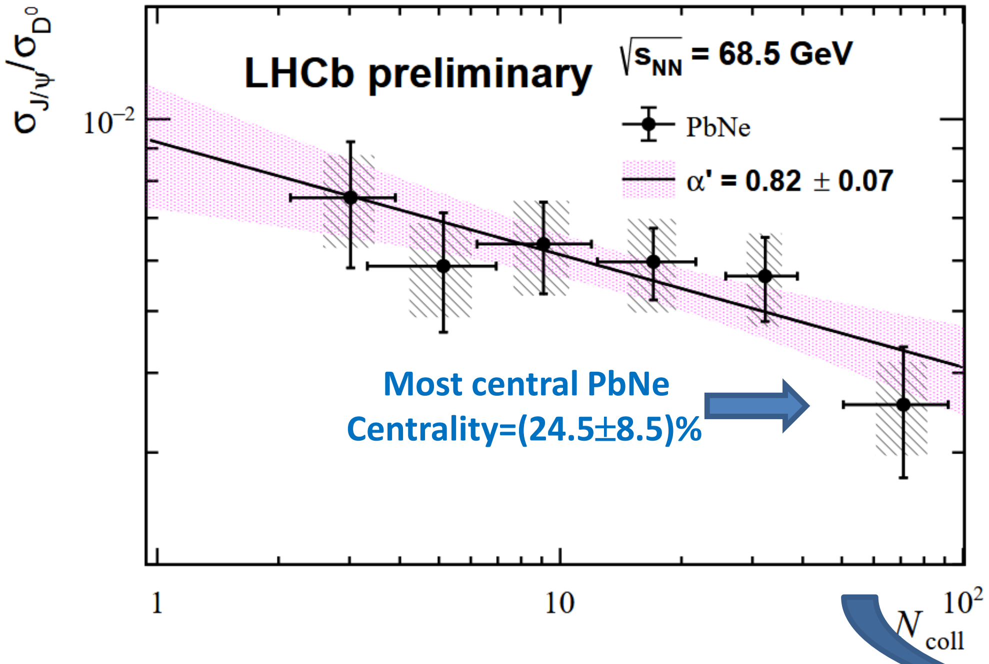
  - Ratio fitted with a power law function,

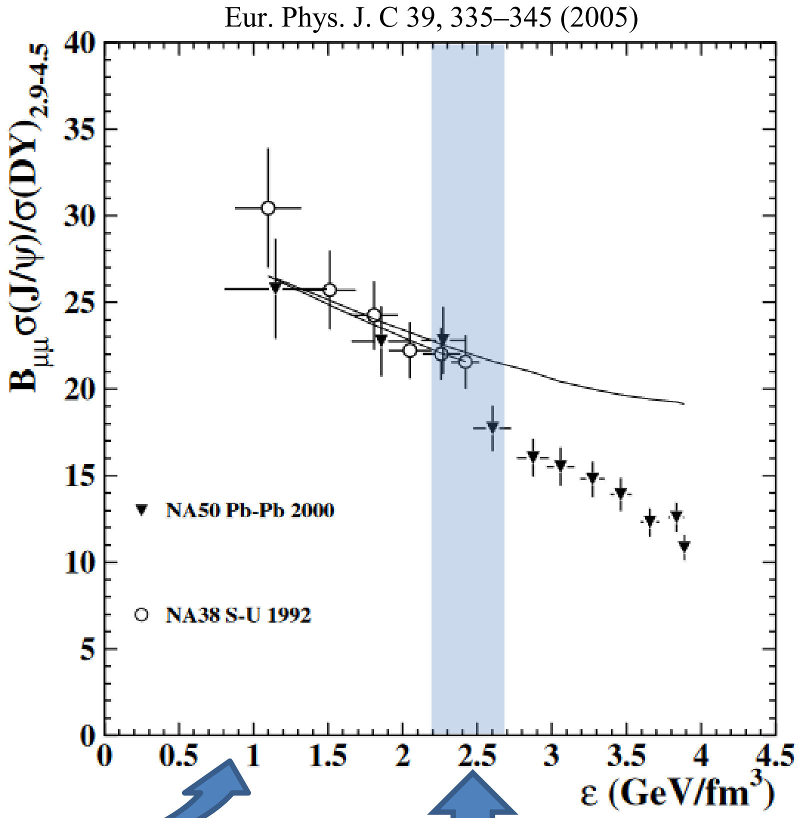
assuming $\sigma_{D^0} \propto N_{coll}$, $\sigma_{J/\psi} \propto N_{coll}^{\alpha'}$ $\Rightarrow$ $\frac{\sigma_{J/\psi}}{\sigma_{D^0}} \propto N_{coll}^{\alpha'-1}$

- *No evidence of anomalous J/ψ suppression*

PbNe@70 GeV .vs. PbPb@17 GeV

- **No evidence of anomalous J/ψ suppression : is it expected?**
  - Back-Of-The-Envelope calculation indicates that charge particle multiplicity for most **central PbNe@68.5 GeV** is **similar to mid-central PbPb@17 GeV**





B.O.T.E. calculation

Most central PbNe

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
PbXe – 71 GeV	201,4	581,7	1031,0	1587,3	2400,2	3541,7	5065,7
PbPb – 17 GeV	**124,2**	**331,6**	**605,9**	**919,6**	**1338,7**	**2035,8**	**2980,5**

(based on EPOS-LHC-v3400)

+

Class	$dN_{ch}/d\eta$		N_{part}		b (fm)		L (fm)	
	range	average	average	rms	average	rms	average	rms
1_N	1–41	22.4	39	21	11.7	1.0	4.58	0.97
2_N	41–81	62.0	70	25	10.4	0.9	5.83	0.78
3_N	81–120	101.2	101	29	9.3	0.9	6.70	0.66
4_N	120–173	147.2	138	34	8.3	0.9	7.44	0.57
5_N	173–226	200.0	179	38	7.2	1.0	8.06	0.48
6_N	226–279	253.0	220	41	6.2	1.0	8.53	0.40
7_N	279–332	305.7	260	43	5.1	1.1	8.88	0.32
8_N	332–385	358.1	297	41	4.1	1.2	9.13	0.25
9_N	385–438	410.1	327	36	3.2	1.2	9.30	0.18
10_N	438–835	487.9	352	27	2.3	1.1	9.42	0.13

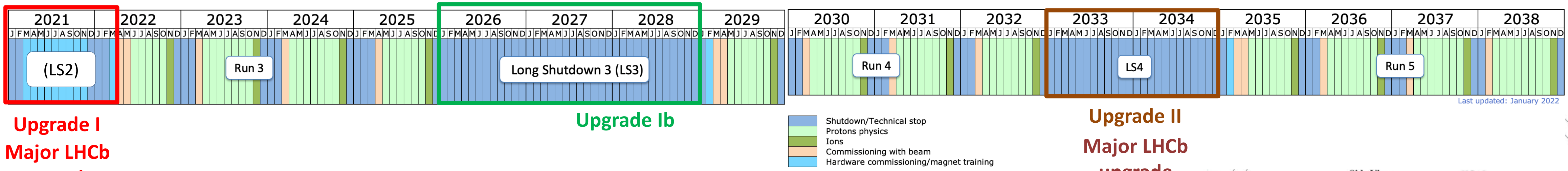
Next at LHC Run 3

(Run1 + Run2) 9 fb^{-1}

Goal: 50 fb^{-1} (Run3 + Run4)

Goal: 300 fb^{-1} (Run5 + Run6)

Lumi *pp*



Upgrade I
Major LHCb upgrade

Upgrade Ib

Upgrade II
Major LHCb upgrade

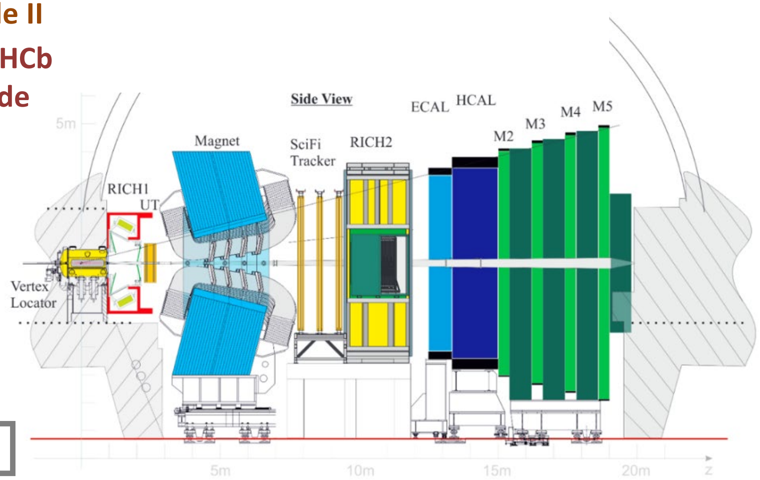
- **LHCb has been upgraded during LS2**
  - New tracking system
  - Strong improvement of detector performances for high multiplicity events
  - **With LHCb Upgrade I**
    - From 50% centrality to 30% centrality in PbPb@5 TeV
    - **Capability to reconstruct PbAr**

New pixel VELO

New Tracking system :
- Silicon upstream detector (UT)
- Scintillating Fiber Tracker (SciFi)

New RICH optics and photodetectors

New electronics for muon and calorimeter systems



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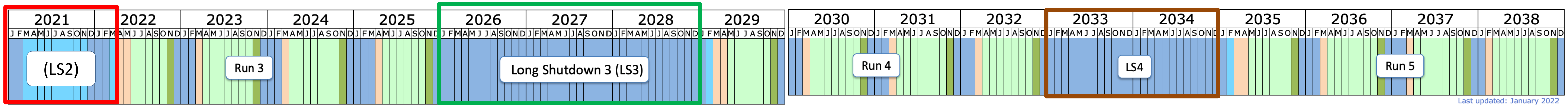

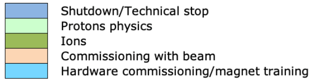

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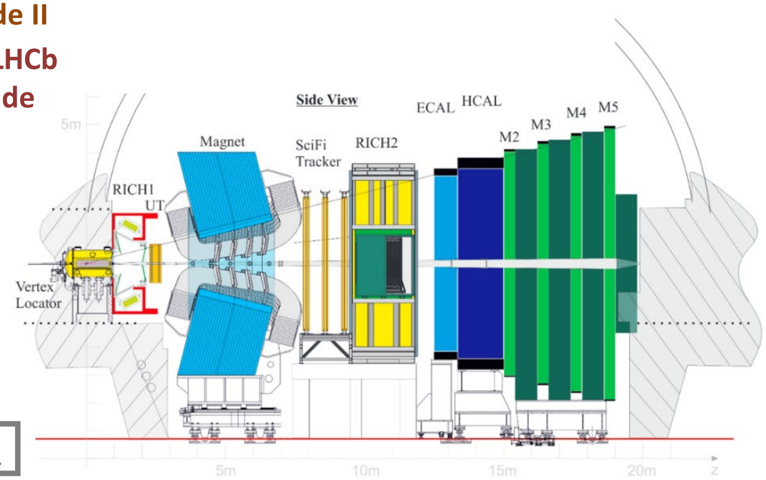
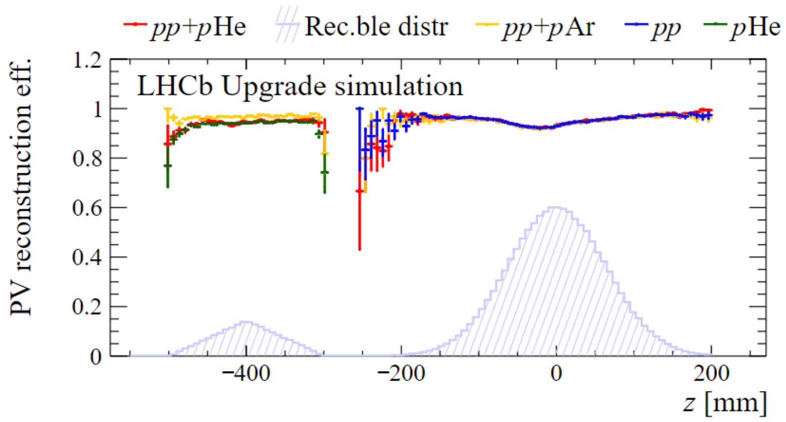


- **Storage cell (SMOG2) installed upstream of the nominal IP**
  - (PVz in [-500, -300] mm)
  - Two retractable halves coping with Velo opening
  - Gas density **increase by up to two orders** of magnitude for the same gas flow
  - H_2, D_2, He, N_2, O_2, Ne, Ar, Kr, Xe gases (potentially) injectable
  - Don't interfere with regular collider events



Summary

- The LHCb-Fixed Target program offers the opportunity to **test sequential suppression** as an effect of quarkonium color screening in a QGP
  - Measure all quarkonium states (including χ_c)
  - Measure open charm

- LHCb has successfully operated and analyse **PbNe** collisions at 68.5 GeV
  - **No evidence of anomalous J/ψ suppression observed**
  - Small statistical sample (~500 J/ψ)

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  - **SMOG2:** Strong increase of statistical samples
  - **Improvement of detector performances** for high-mult events
    - **Full performances** expected **for PbAr**

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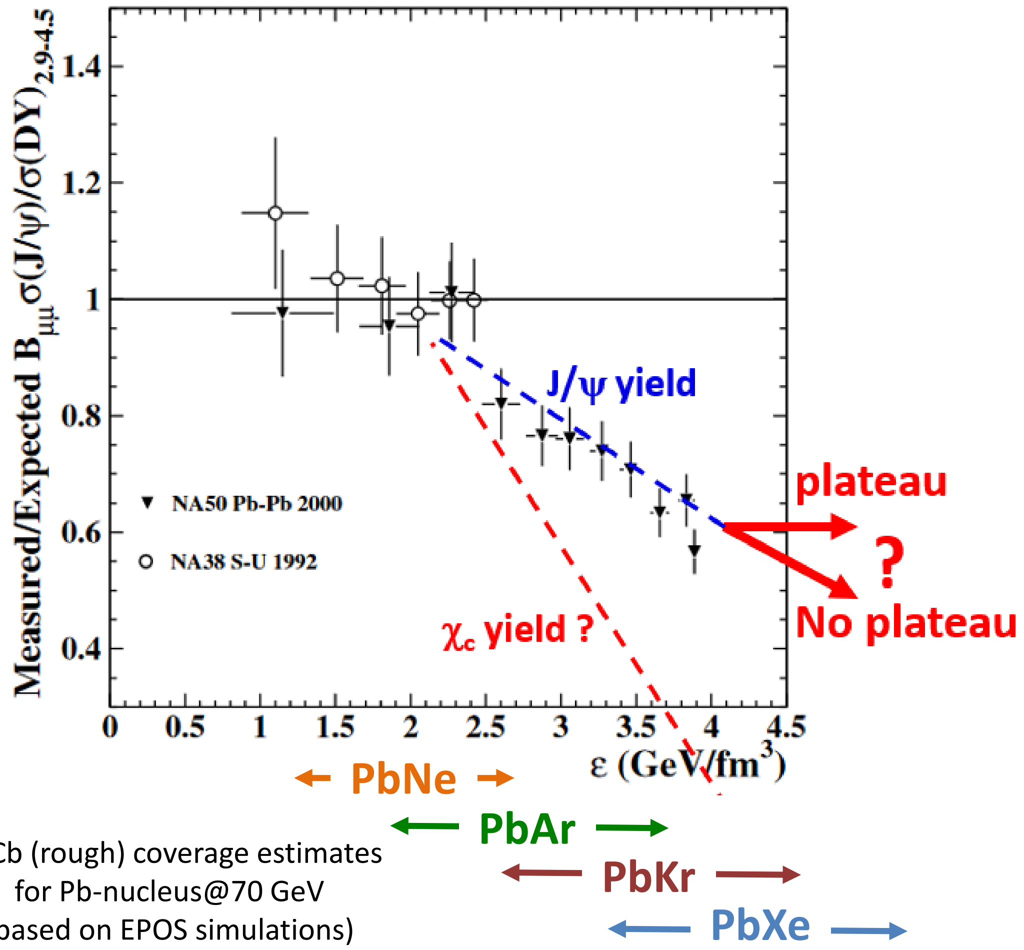

LHCb (rough) coverage estimates for Pb-nucleus@70 GeV (based on EPOS simulations)

Looking for anomalous J/ψ suppression in PbNe@68.5 GeV

- **J/ψ/D^0 ratio as a function of the number of binary nucleon-nucleon collisions N_{coll}**
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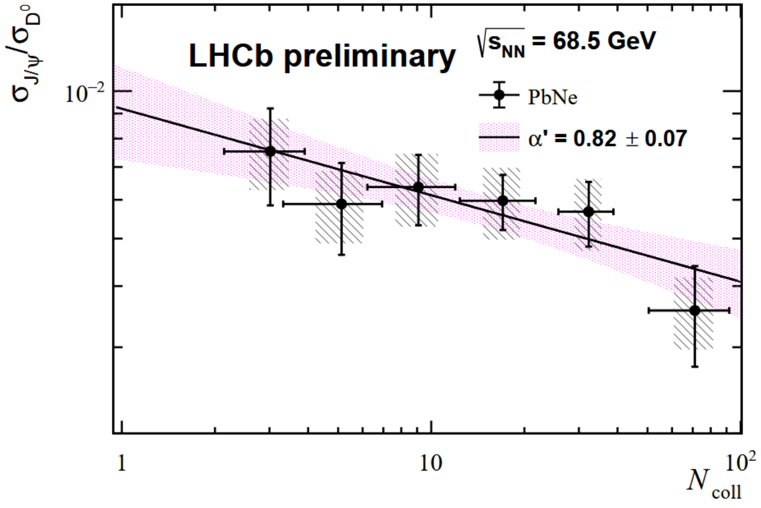
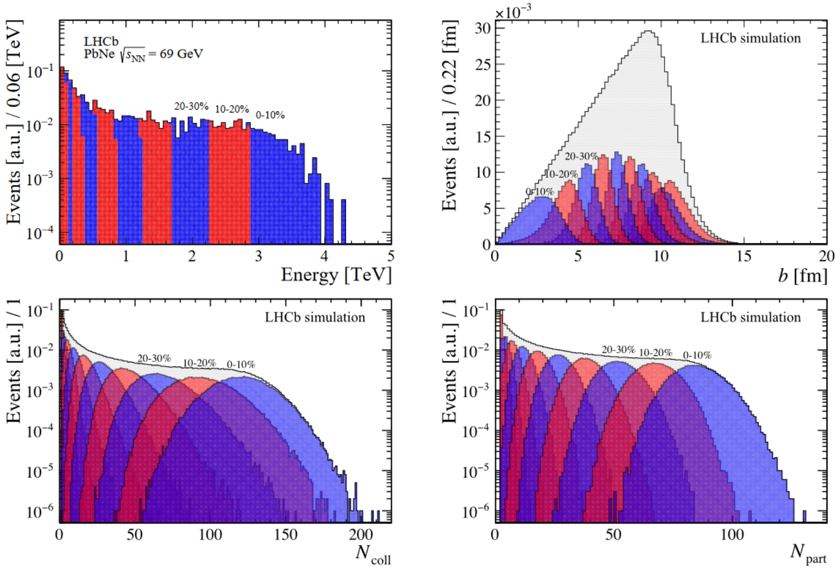


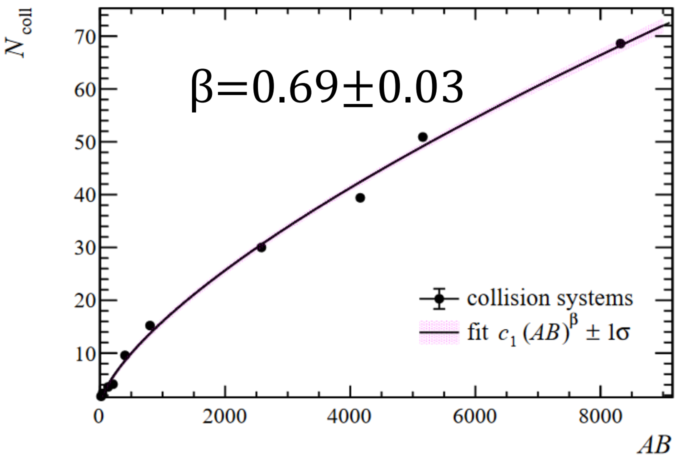


  - Ratio fitted with a power law function,

$$\text{assuming} \quad \begin{matrix} \sigma_{D^0} \propto N_{coll} \\ \sigma_{J/\psi} \propto N_{coll}^{\alpha'} \end{matrix} \Rightarrow \frac{\sigma_{J/\psi}}{\sigma_{D^0}} \propto N_{coll}^{\alpha'-1}$$

- *No evidence of anomalous J/ψ suppression*

- $\sigma_{J/\psi} \propto N_{coll}^{\alpha'}$ can be related to the (old fashion) $\sigma_{J/\psi} \propto AB^{\alpha}$ (see Felipe Garcia's thesis)
  - α' = 0.82±0.07 → α = 0.88 ±0.05



Felipe Garcia's thesis
https://tel.archives-ouvertes.fr/tel-03543117

$$\begin{cases} \frac{\sigma_{J/\psi}}{\sigma_{D^0}} \propto N_{coll}^{\alpha'-1} \\ \frac{\sigma_{J/\psi}}{\sigma_{D^0}} \propto AB^{\alpha} \\ N_{coll} = c_1 AB^{\beta} \end{cases} \rightarrow \alpha - 1 = \beta \times (\alpha' - 1)$$