Total $c\bar{c}$ cross section measurements

and prospects for LHC in the fixed-target mode with LHCb

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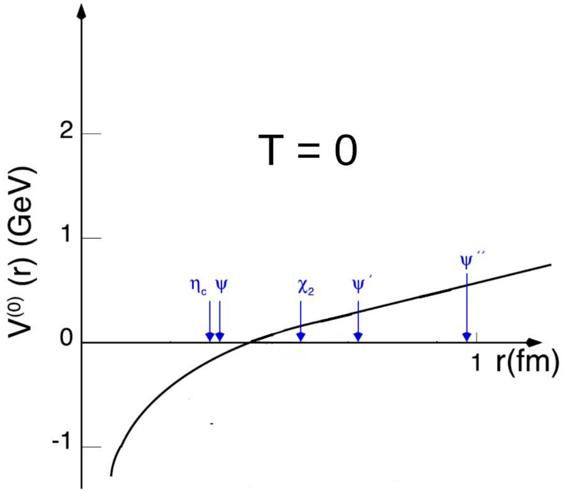
Quarkonia as Tools 2024

Charmonium as probe of deconfinement

- Search for signatures of deconfinement form a key research area in heavy-ion physics.
- Heavy quarkonia are model systems to study color charge interaction at T=0 (vacuum) and finite temperature (in medium).
- Quarkonium suppression via color screening historically used as a probe of deconfinement in heavy-ion collisions.
- Additional non-primordial production is another sign of deconfinement.

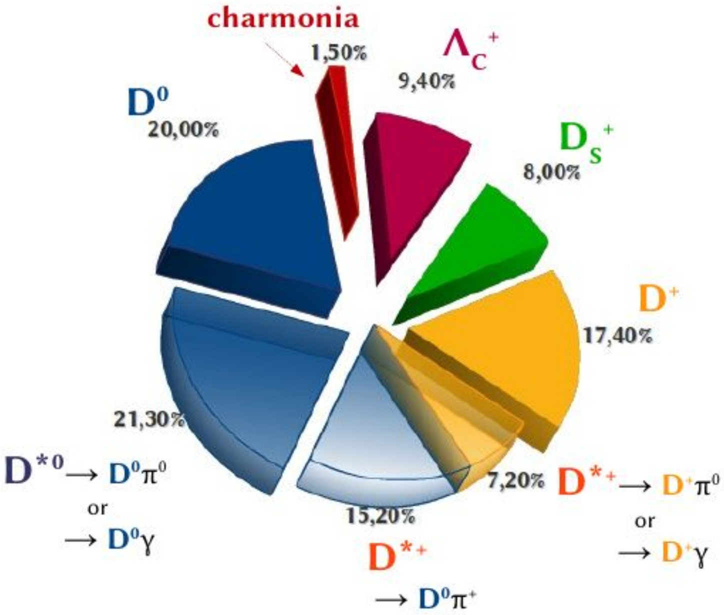


EPJC 71:1534 (2011)

Total $c\bar{c}$ cross section as baseline for charmonia modification

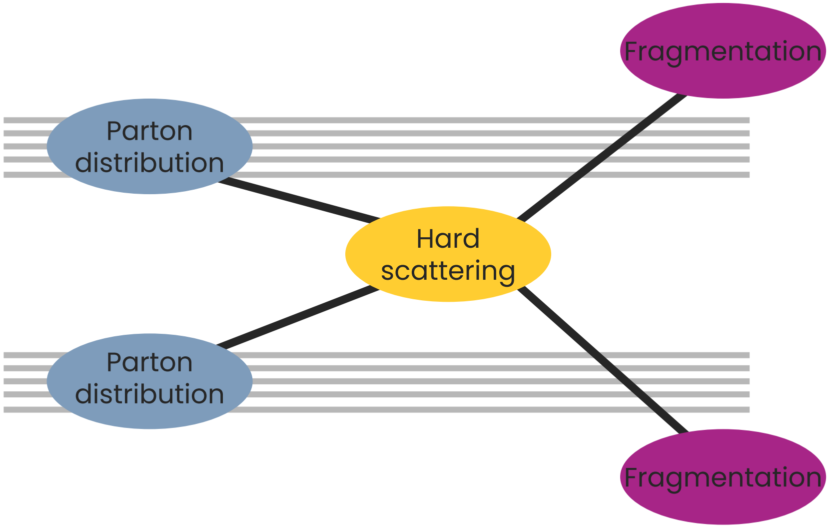
ALICE-PHO-SKE-2015-004

- Charm is conserved in QGP, which acts as a charm reservoir.
- Total $c\bar{c}$ cross section emerges as a natural normalisation for charmonia modification.
- Large contributions from several mesons and baryons.
- Extensive study needed to get a result.



Charm fragmentation fractions from e+e- annihilation and lepton-nucleon DIS.

Charm fragmentation universality



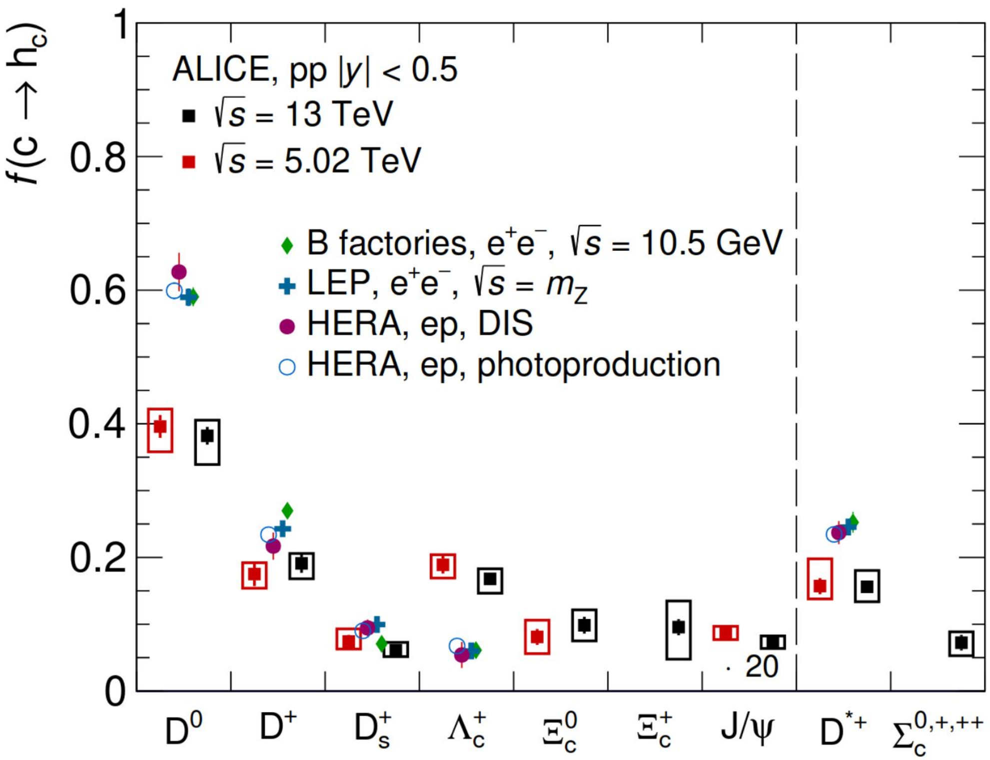
$$f\,(c \rightarrow H) = \sigma(H)/\sigma(c)$$

$$f\,(c \rightarrow H) = \sigma(H)/\sum_{w.d.} \sigma(H)$$

- Simplest assumption, fragmentation universal:
  - No energy dependence
  - No colliding system dependence (e^+e^-, pp, ep, …)
  - No production process dependence (photoproduction, DIS, …)
- Then, total $c\bar{c}$ cross section at the LHC can be extrapolated from a single charm hadron measurement, typically D^0.

Are charm fragmentation fractions really universal?

ALICE results in pp 5 and 13 TeV



JHEP 12 (2023) 086

- Significant enhancement of charm baryon contribution to the $c\bar{c}$ cross-section compared to e^+e^- and ep data.
- To be confirmed by other experiments.
- Need measurement of all ground state open charm hadrons.
- Needs to be measured in pPb in PbPb.

List of open charm ground states

Mesons

- D^0 ($c\bar{u}$)
  - Straightforward hadronic 2 body decay (~4%).
  - cτ ~ 120 μm
- D^+ ($c\bar{d}$)
  - Hadronic 3 body decay (~9%).
  - cτ ~ 310 μm
- D_s^+ ($c\bar{s}$)
  - Hadronic 3 body decay (~5%).
  - cτ ~ 150 μm

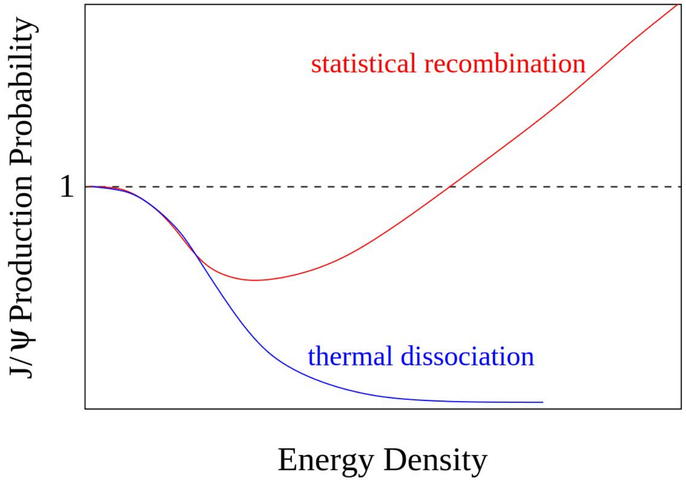
Baryons

- Λ_c^+ (udc)
  - Hadronic 3 body decay in pKπ (~6%).
  - cτ ~ 60 μm
- Ξ_c^+ (usc)
  - Decay via long lived strange baryons, Cabibbo-favored.
  - Hadronic 3 body decay in pKπ, Cabibbo-suppressed (~.5% with 50% uncertainty).
  - cτ ~ 130 μm
- Ξ_c^0 (dsc)
  - Decay via long lived strange baryons.
  - Hadronic 4 body decay (~.5%)
  - cτ ~ 50 μm
- Ω_c^0 (ssc)
  - No absolute branching fraction has been measured yet.
  - cτ ~ 100 μm

Exploring charm production with LHC fixed-target.

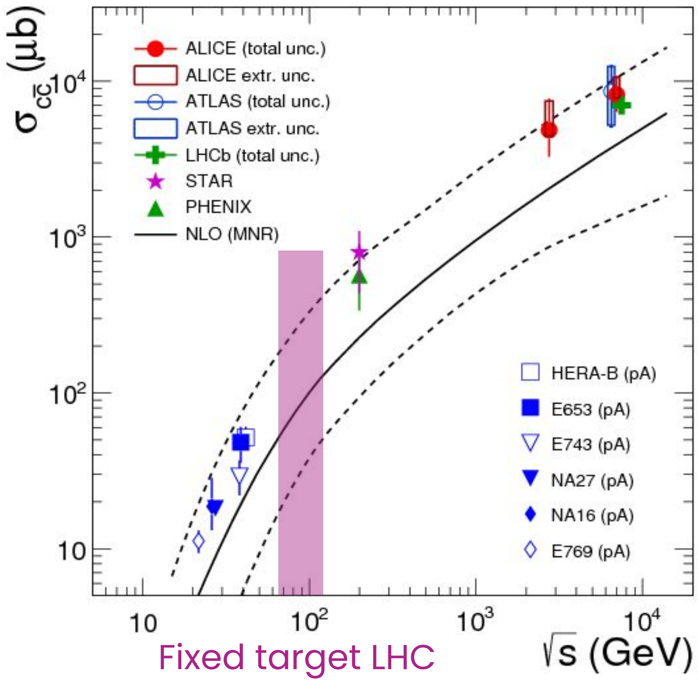
Recombination at fixed-target LHC energies

- Opportunity to test deconfinement at:
  - Expected lower energy density
  - Expected lower charm quark density
- Recombination of $c\bar{c}$ into charmonia expected to be lower than at LHC energies.



Kluberg-Satz review, 2009

Phys. Rev. C 94, 054908 (2016)

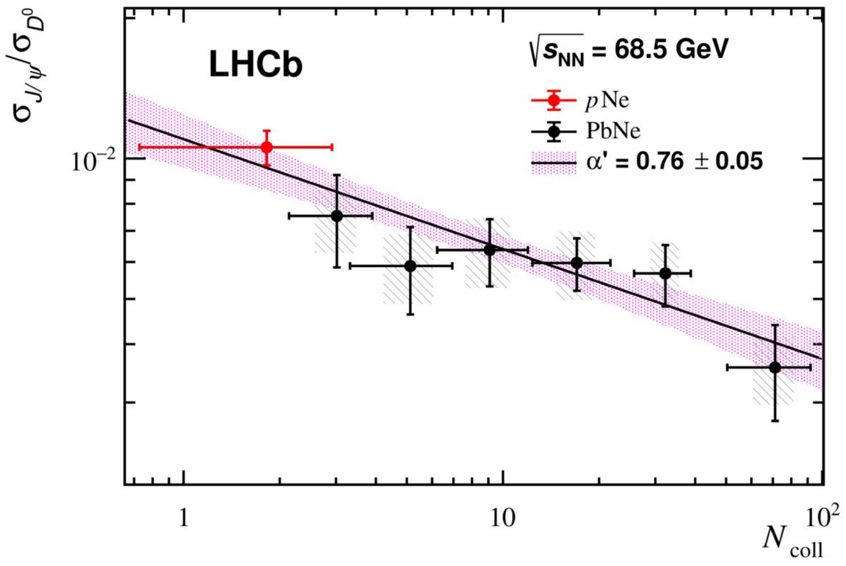


D^0 as proxy for total $c\bar{c}$ cross section

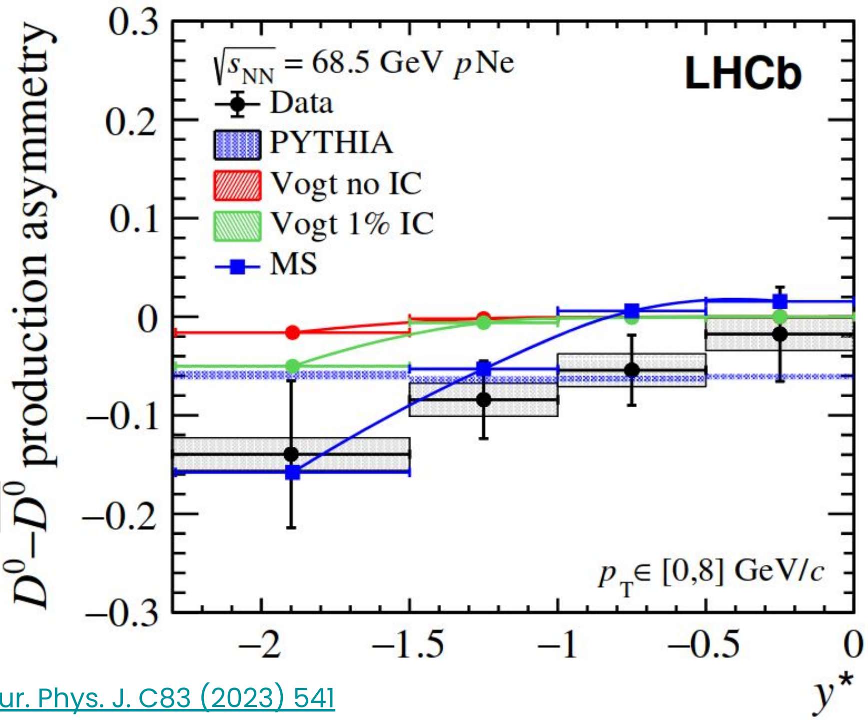
cea irfu

- J/Ψ over D^0 ratio measured in both fixed-target *p*Ne and PbNe.
- PbNe data splitted in several centrality bins and matched to the number of binary nucleon-nucleon collisions (N_{coll}).
- Assume $\sigma_{J/\Psi}$ scaling in $<N_{coll}>^{\alpha'}$.
- D^0 used as proxy for total $c\bar{c}$ cross-section: σ_{D^0} scaling in $<N_{coll}>$.
- However, additional effects can affect D^0 production via charm hadronization with the target valence quarks.

Eur. Phys. J. C83 (2023) 658



D^0 production asymmetry

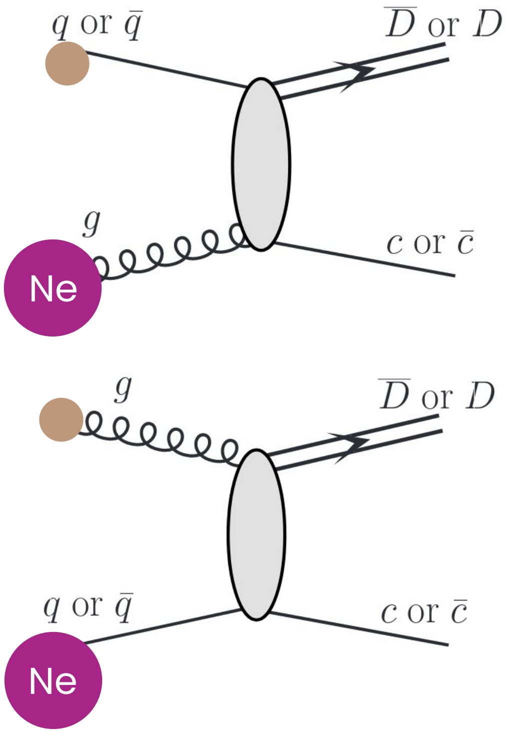


Eur. Phys. J. C83 (2023) 541

- Open charm charge asymmetry tendency observed in fixed-target *p*Ne at LHCb.
- Additional fragmentation fraction non universality.
- Needs confirmation with other open charm hadrons and colliding systems.

$$A = \frac{N(c\bar{q}) - N(\bar{c}q)}{N(c\bar{q}) + N(\bar{c}q)}$$

Qualitative explanation



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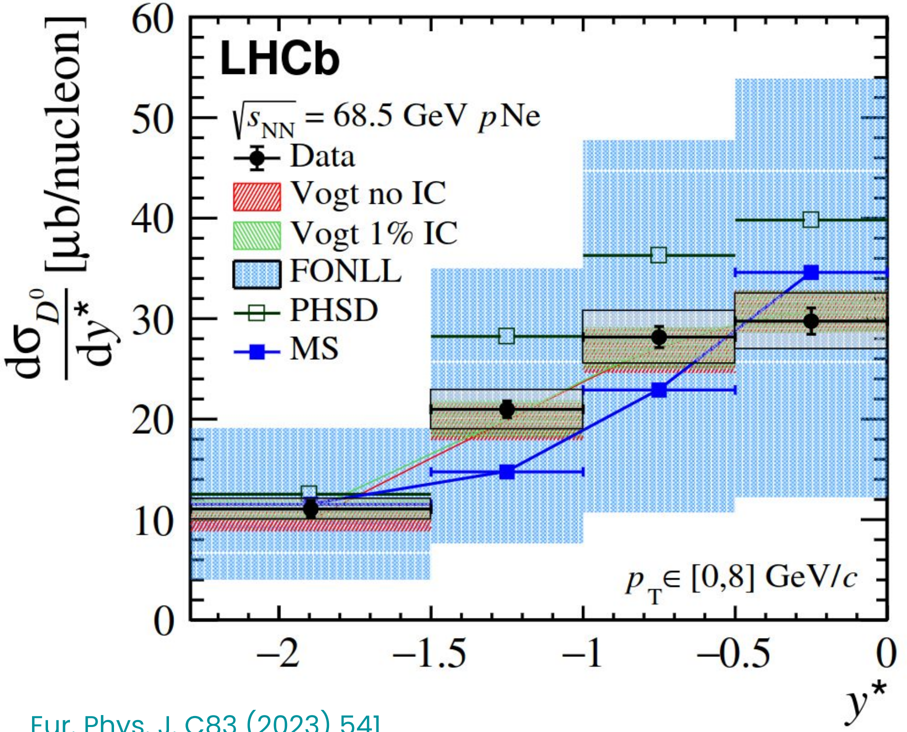
- Charge production asymmetry expected when a charm quark recombines with a valence quark of the target nucleon.
- As valence region of the target nucleon is dominated by u and d quarks, expect a negative asymmetry increasing at backward rapidity.
- Need to measure rapidity dependance of all mesons and baryons.

Feasibility at fixed-target LHCb



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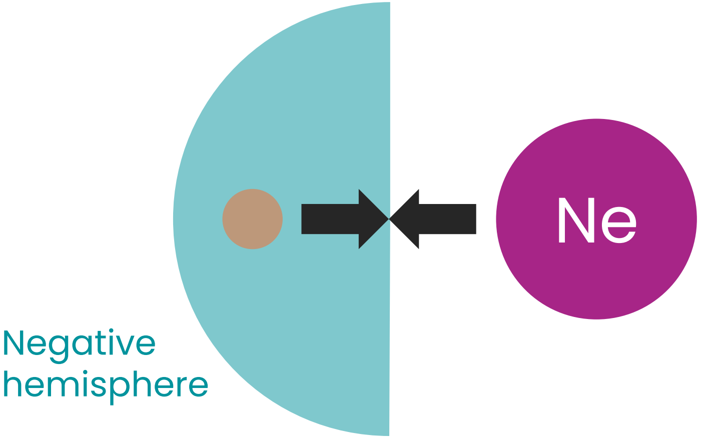
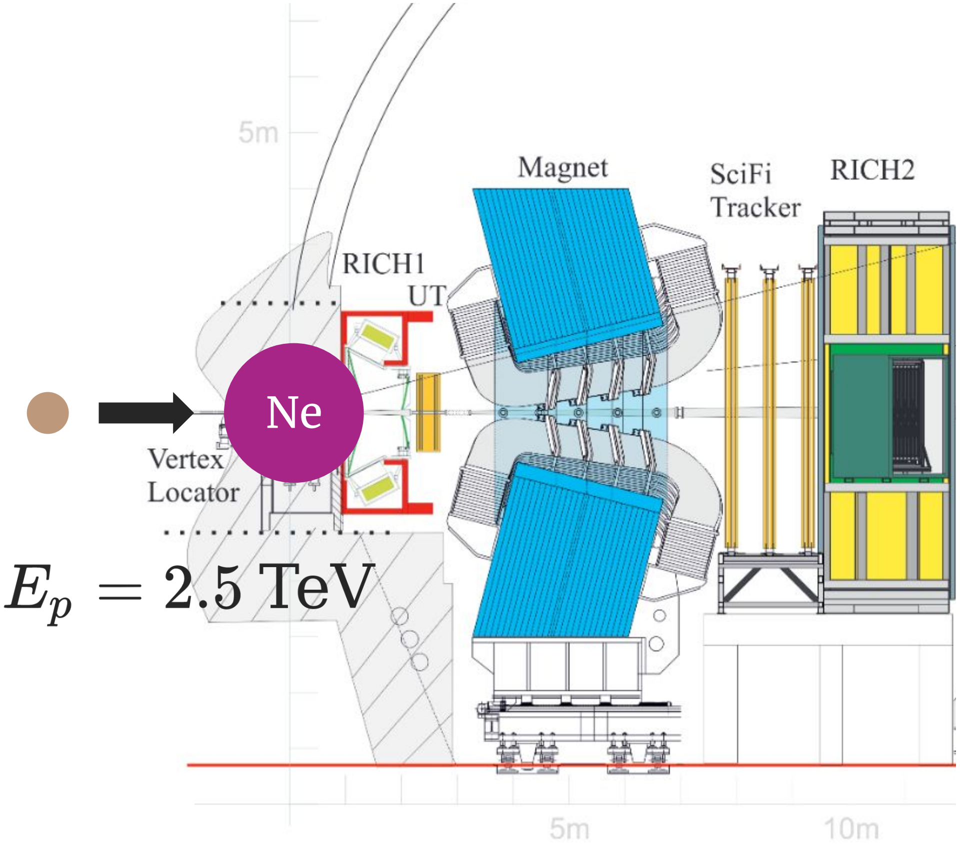
- Negative half hemisphere nearly fully covered.
- All charm hadrons accessible thanks to longitudinal boost and excellent vertexing.



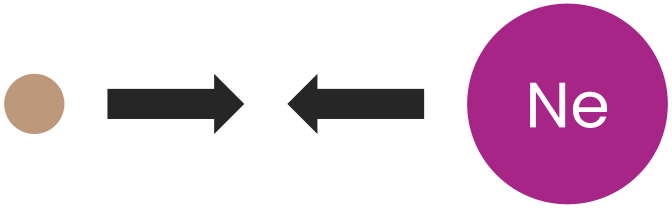
Open charm production in fixed-target proton-Neon collisions with LHCb

Fixed target LHCb



$E_p = 2.5\ \text{TeV}$

$\sqrt{s_{NN}} = 69\ \text{GeV}$



- LHCb forward acceptance becomes backward ($-2.3 < y^* < 0$) with fixed-target configuration.
- Allows to probe large Bjorken-x values of the target nucleon using charm.

LHCb Tracker Upgrade TDR

Decay chains currently studied in pNe collisions

$$D^{+} \rightarrow K^{-}\pi^{+}\pi^{+}$$

$$D_s^{+} \rightarrow K^{+}K^{-}\pi^{+}$$

$$D^{*+} \rightarrow \left(D^{0} \rightarrow K^{-}\pi^{+}\right)\pi^{+}$$

$$\Lambda_c^{+} \rightarrow pK^{-}\pi^{+}$$

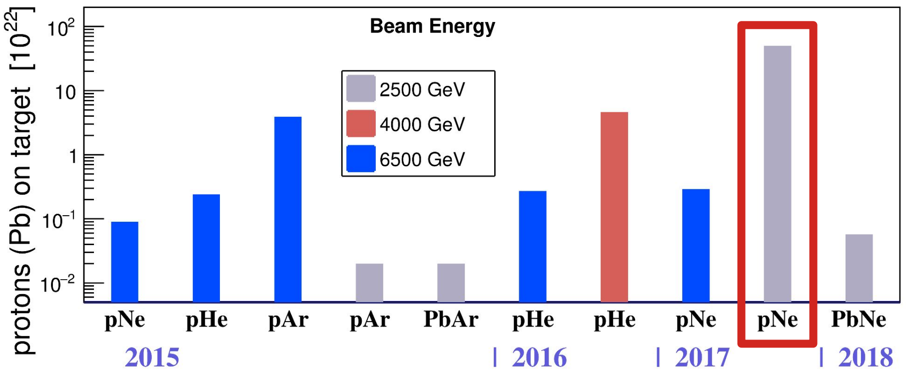
and charge conjugates

Dataset

- *p*Ne data taken with SMOG in 2017.
- 2.5 TeV proton beam.
- $\sqrt{s_{NN}}$ = 68.5 GeV
- Luminosity : L_{pNe} = 21.7 ± 1.4 nb^{-1}

	y* range	p_T range
$D^{\pm}$	[-2.3, 0]	[1.5, 8] GeV
$D_s^{\pm}$		
$D^{*\pm}$		[0, 8] GeV
$\Lambda_c^{\pm}$		

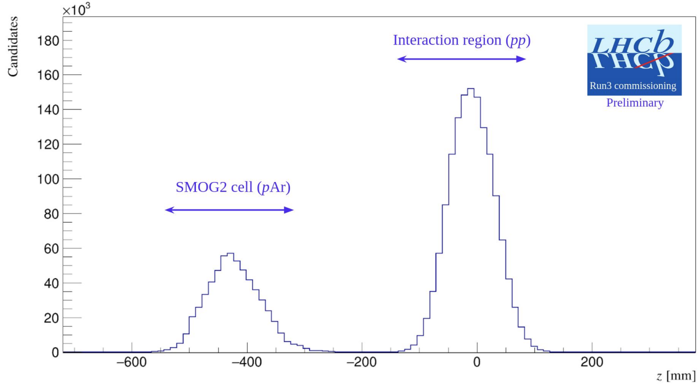
SMOG2 TDR



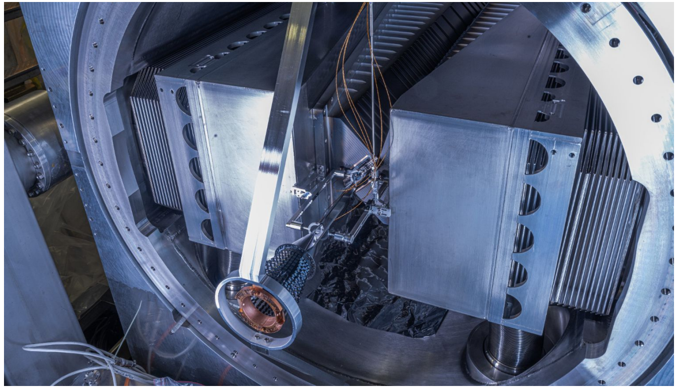
- Ongoing analysis for cross-section and asymmetry measurements.
- Limited low p_T reach for D^+ and D_s^+ due to tight cuts in high level trigger.
- Lesson learned for SMOG2!

SMOG2

LHCB-FIGURE-2023-001

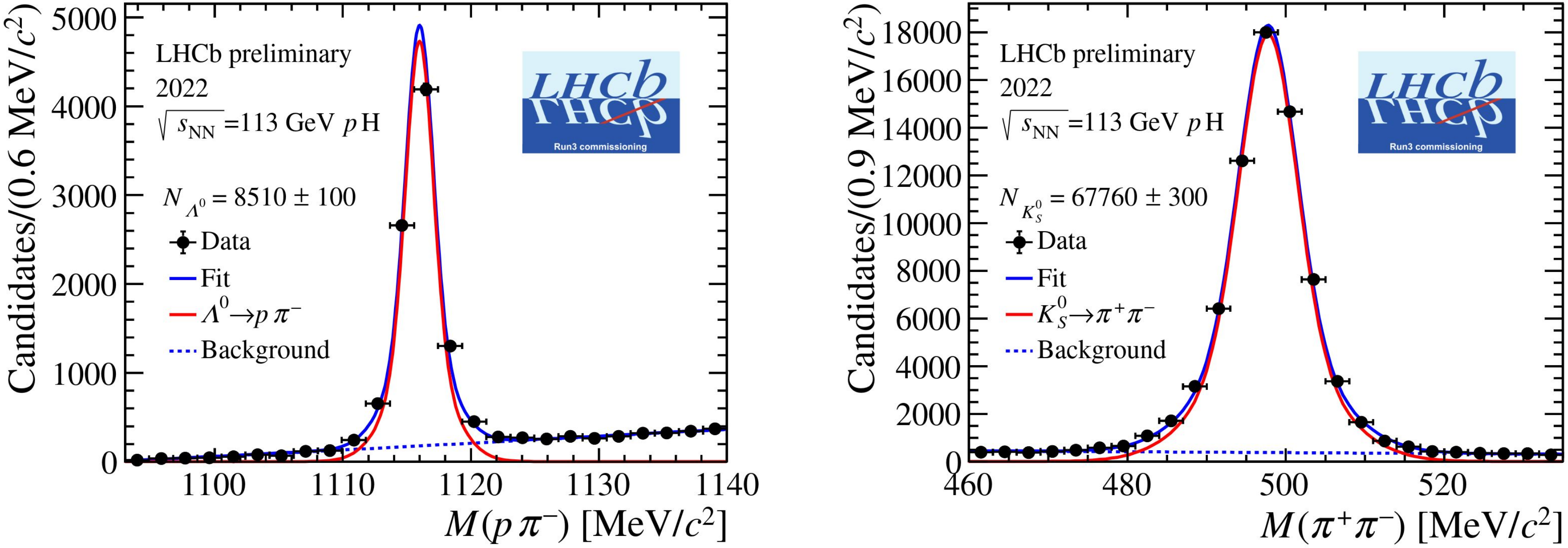


- Gas storage cell upstream of the VELO.
- Higher pressure than SMOG.
- Possible parallel running with proton-proton data taking.
- Dedicated open charm trigger lines for total cc cross section measurements.
- Numerous noble gas: ^{4}He, ^{20}Ne, ^{40}Ar, (^{84}Kr, ^{132}Xe)
- But also non-noble gas: H^2, D^2, N^2, O^2



SMOG2 *p*H commissioning data

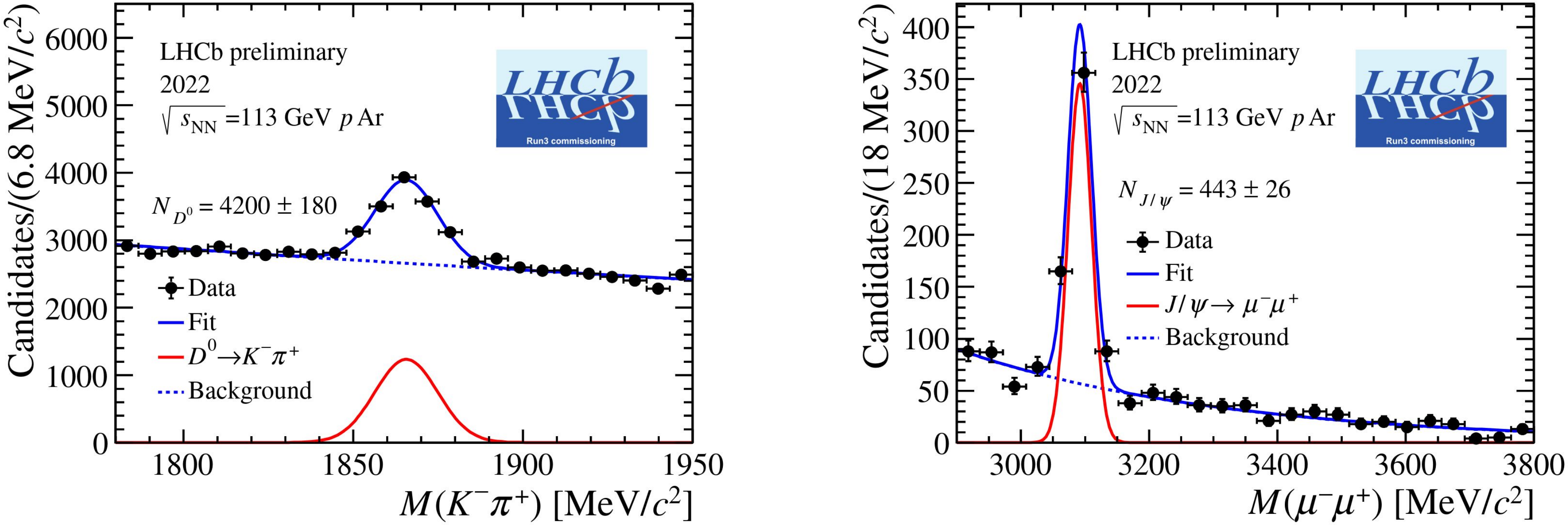
LHCB-FIGURE-2023-008



- Λ^0 and K_s^0 invariant mass peaks observed in fixed-target pH during SMOG2 commissioning from 18 minutes of data taking in 2022.

SMOG2 charm commissioning data

LHCB-FIGURE-2023-008



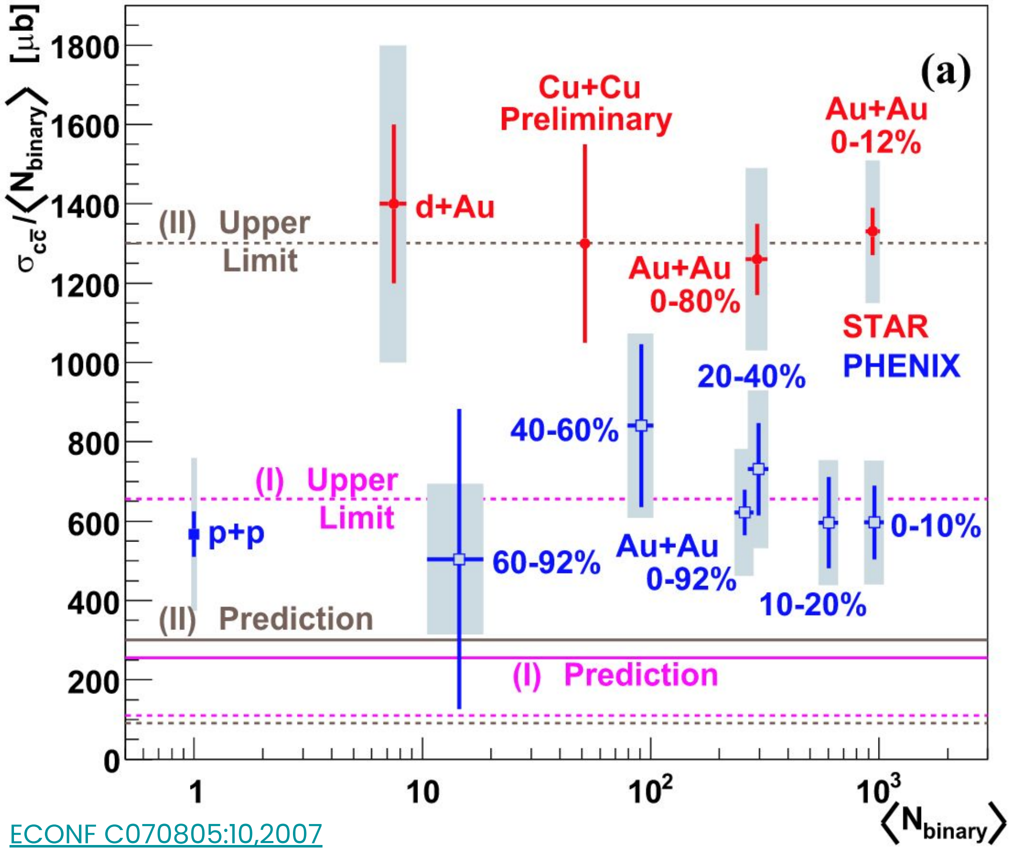
- Both open and hidden charm invariant mass peaks observed in fixed-target *p*Ar during SMOG2 commissioning from 18 minutes of data taking in 2022.

Conclusion

- Total charm production arises as the natural normalisation for charmonium modification in QGP studies.
- Charm fragmentation universality questioned.
- Need measurement of all ground state open charm hadrons.
- At fixed target energy, hint of further charm hadronization universality breaking by hadronization with target valence quarks.
- Total $c\bar{c}$ cross-section measurements are feasible with LHCb in its fixed-target configuration.
- Rich SMOG2 charm program will allow to explore hadronization in numerous colliding systems.

Back-up

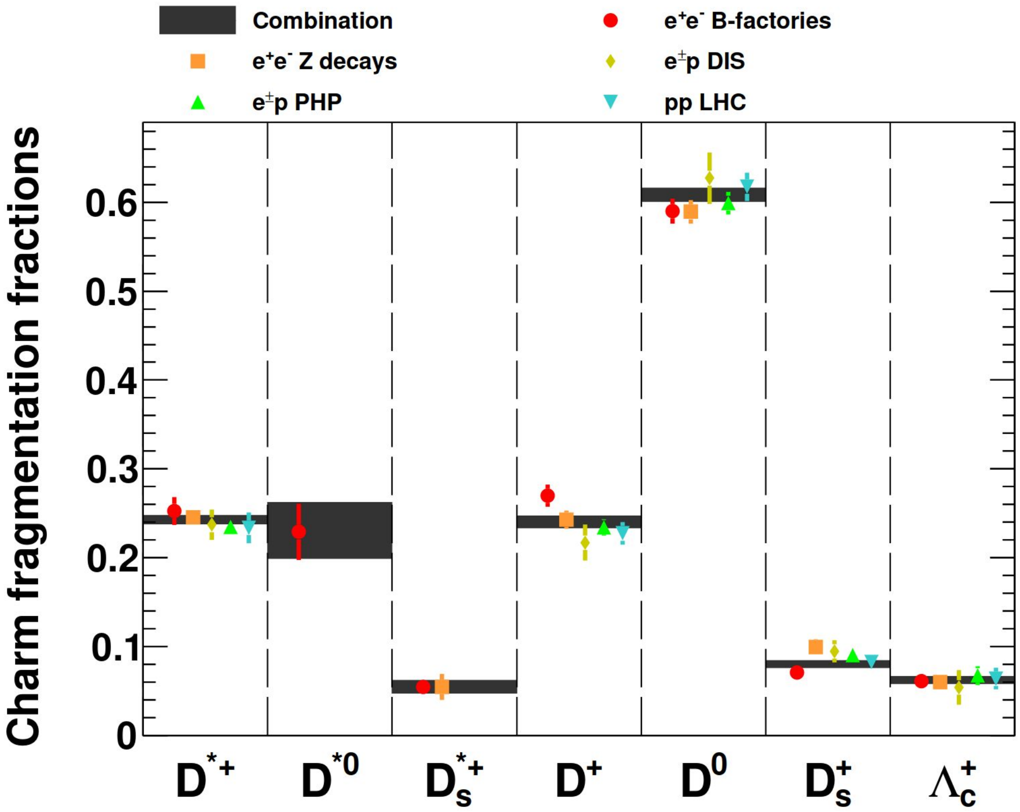
RHIC



- Total $c\bar{c}$ cross-section measured with a combination of reconstructed D^0, low p_T muons and single electrons.
- Linear scaling with N_{binary} expected for point-like production.
- Comparison with FONLL predictions (I) with updated uncertainties (II).
- PHENIX data compatible with FONLL while STAR data lays on the upper limit.

ECONF C070805:10,2007

Combined charm FF analysis

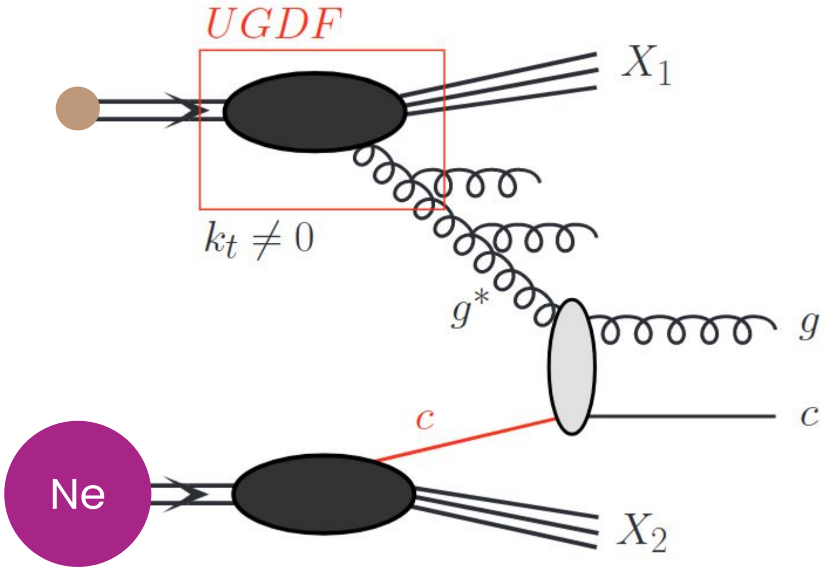


EPJ C 76 (2016) no.7, 397

- Combined analysis with results from several experiments:
  - **B-factories**: ARGUS, BABAR, BELLE, CLEO
  - **HERA**: ZEUS, H1
  - **LEP**: ALEPH, DELPHI, OPAL
  - **LHC**: ALICE, ATLAS, LHCb
- Only Λ_c measurement in pp collisions from LHCb at 7 TeV.
- Universality seems to hold.

Charm production at fixed-target LHCb

- Knock-off of a charm quark from the target nucleon.
- Expected to enhance the D-meson cross-section at backward rapidity.
- However effect remains small, at the percent level.



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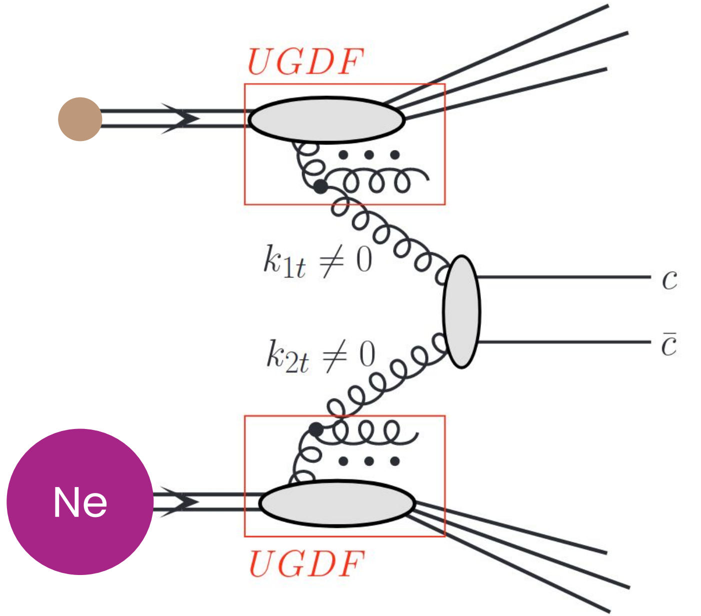
Charm production at fixed-target LHCb

- Backward D-meson production models are still not completely understood.
- Fixed-target LHCb allows to directly probe this kinematic region.
- Leading contribution from "standard" QCD gluon-gluon fusion process.



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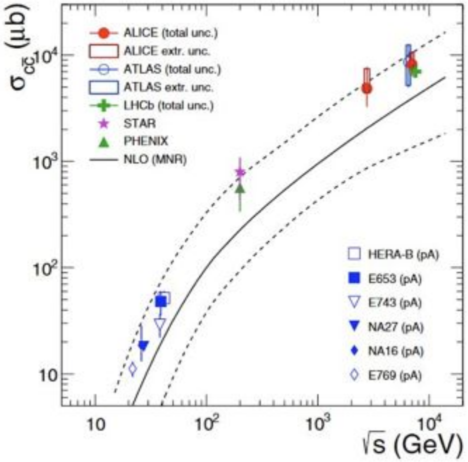
Projected SMOG2 performances

SMOG2 projected performances							
Reaction	DAQ time	Non coll. bunches	Lumi (nb^{-1})	Decays	SMOG yields	Scale factor	SMOG2 proj. yields
pAr	18 h	684	~ 2	$D^0 \rightarrow K^-\pi^+$	6450	62	400 k
				$D^+ \rightarrow K^-\pi^+\pi^+$	975		60 k
				$D_s^+ \rightarrow K^-K^+\pi^+$	131		8 k
				$D^{*+} \rightarrow D^0\pi^+$	2300		140 k
				$\Lambda_c^+ \rightarrow pK^-\pi^+$	50		3 k
				$J/\psi^+ \rightarrow \mu^+\mu^-$	500		30 k
				$\psi' \rightarrow \mu^+\mu^-$	20		1.2 k
pHe	84 h	648	7.6	$J/\psi^+ \rightarrow \mu^+\mu^-$	500	19.6	10 k
				$\psi' \rightarrow \mu^+\mu^-$	20		0.4 k

SMOG2 TDR

How many $c\bar{c}$ pairs are produced in PbA SMOG2 conditions?

- Charm cross-section across $\sqrt{s_{\rm NN}}$:
  - $\sigma_{c\bar{c}}^{5.5\ TeV} \sim 10 \times \sigma_{c\bar{c}}^{200\ GeV} \sim 100 \times \sigma_{c\bar{c}}^{70\ GeV} \sim 1000 \times \sigma_{c\bar{c}}^{20\ GeV}$
- Then, for $0 - 10\,\%$ centrality at RHIC:
  - $N_{c\bar{c}} = 597.10^{-3}\,\text{mb} \times 22.8\,\text{mb}^{-1} = 13$
- Therefore, we expect, on average:
  - $\sim 100\ c\bar{c}$ pairs produced at 5.5 TeV
  - $\sim 10\ c\bar{c}$ pairs produced at 200 GeV
  - $\sim 1\ c\bar{c}$ pairs produced at 70 GeV
  - $\sim 0.1\ c\bar{c}$ pairs produced at 20 GeV



PRC 94, 054908 (2016)

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})	$\frac{1}{T_{AA}}\frac{dN_{c\bar{c}}}{dy}\vert_{y=0}$ (μb)	$N_{c\bar{c}}/T_{AA}$ (μb)
Minimum 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

PRL 94, 082301 (2005)