Open charm production asymmetries

with LHCb in its fixed-target configuration

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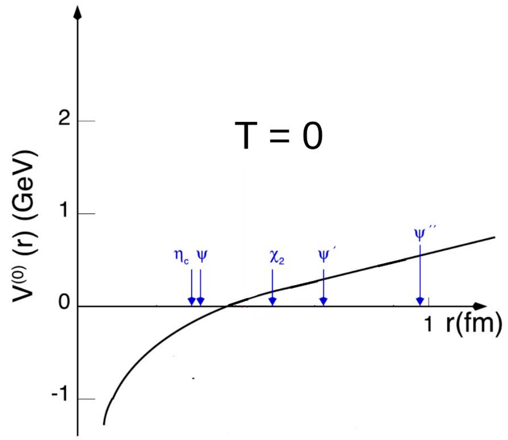
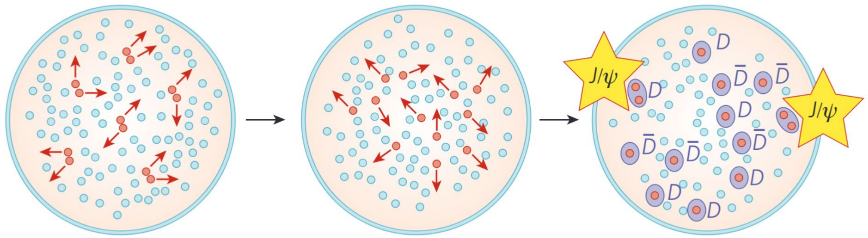
Charmonium as probe of deconfinement

- Search for signatures of deconfinement forms a key research area in heavy-ion physics.
- Heavy charmonia are model systems to study color charge interaction at T=0 (vacuum) and finite temperature (in medium).
- Charmonium suppression historically proposed as a probe of deconfinement in heavy-ion collisions.



EPJC 71:1534 (2011)



Nature 448, 302–309 (2007)

- Formation of charmonium from unbound heavy-quarks (recombination) is another sign of deconfinement.

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

- Charm is conserved in QGP.
- Total $c\bar{c}$ cross section emerges as a natural normalisation for charmonia modification.
- Large contributions from several mesons and baryons.
- Extensive measurements needed to deduce the sum, leading to the measurement of charm fragmentation fractions.

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

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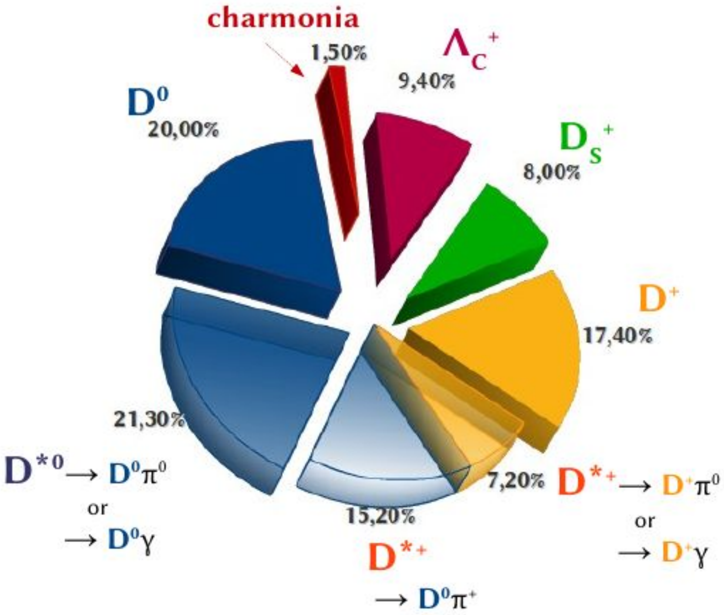
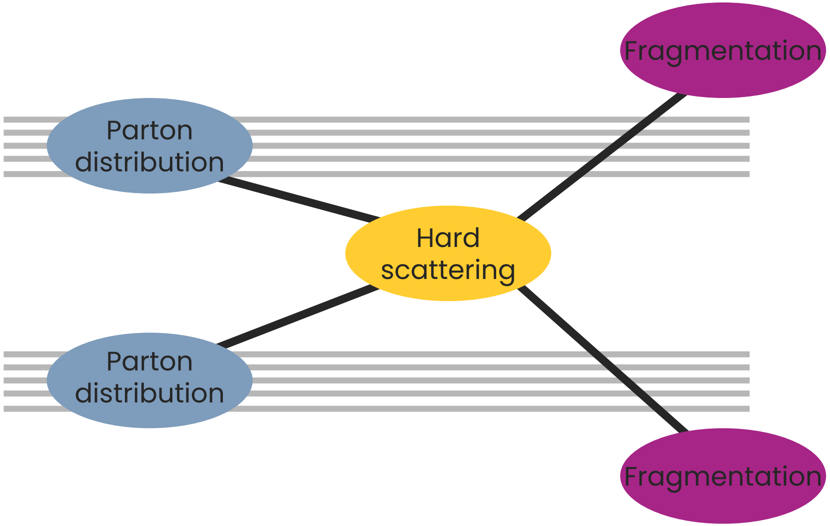


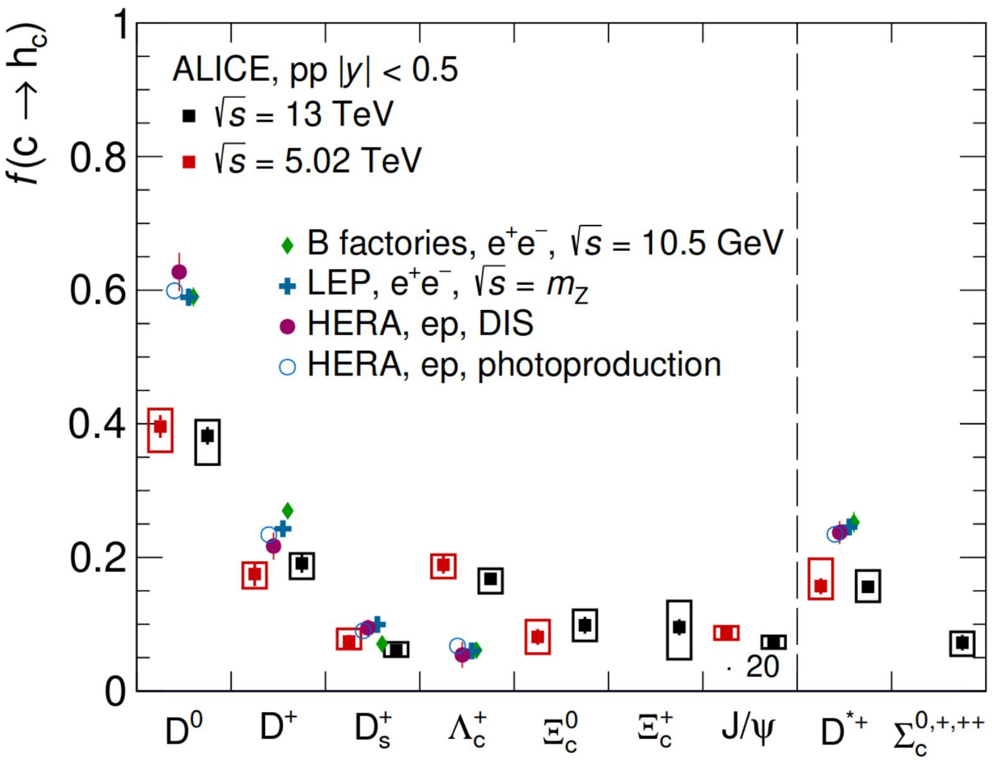
Charm fragmentation fractions from e+e- annihilation and lepton-nucleon DIS.

Charm fragmentation universality



- 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.

Charm fragmentation non-universality



JHEP 12 (2023) 086

- Significant enhancement of charm baryon contribution to the $c\bar{c}$ cross-section compared to e^+e^- and ep data.
- Additional contribution from charm baryons not measured until now.
- To be confirmed by other experiments.
- Need measurement of all ground state open charm hadrons.

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

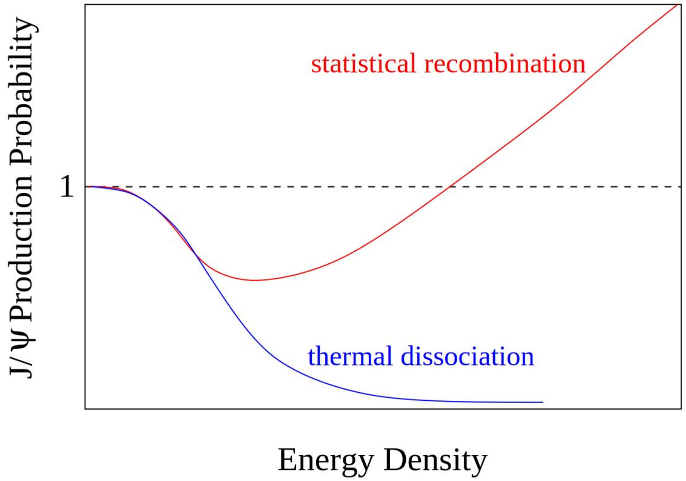
Baryons

- 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 fixed-target LHC.

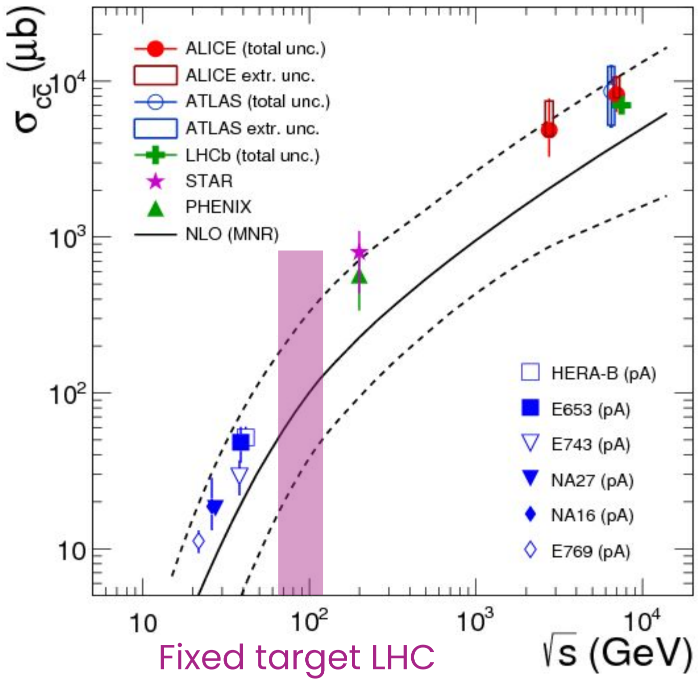
Recombination at fixed-target LHC energies

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

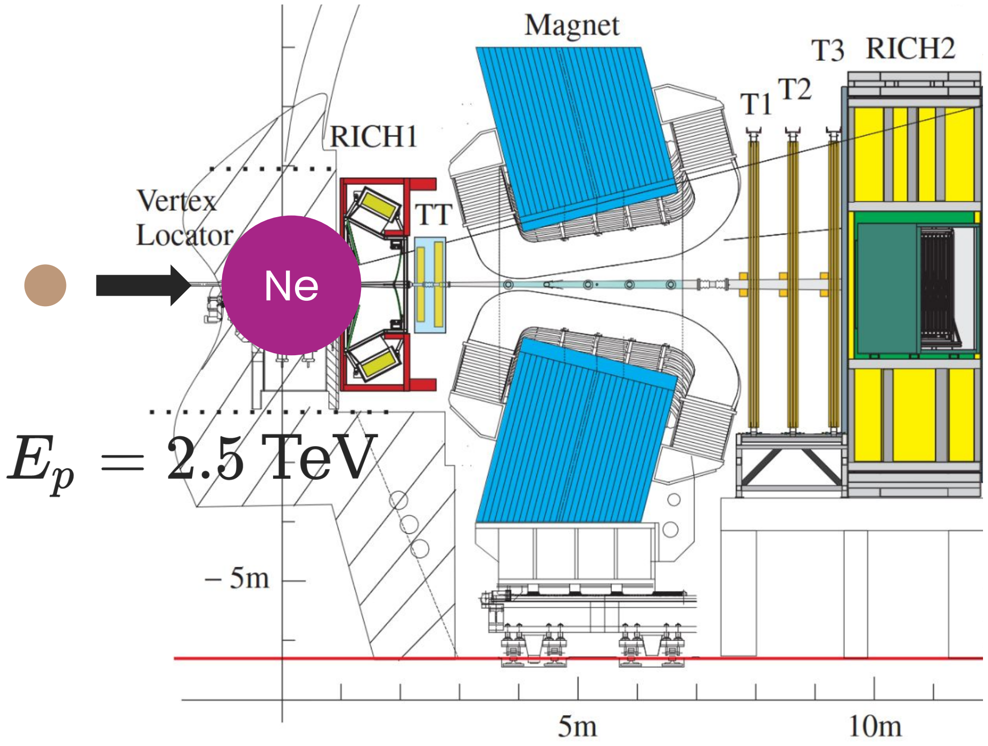


Kluberg-Satz review, 2009

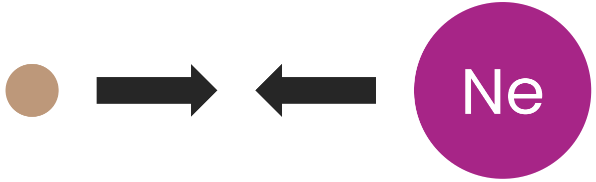
Phys. Rev. C 94, 054908 (2016)



Fixed target LHCb

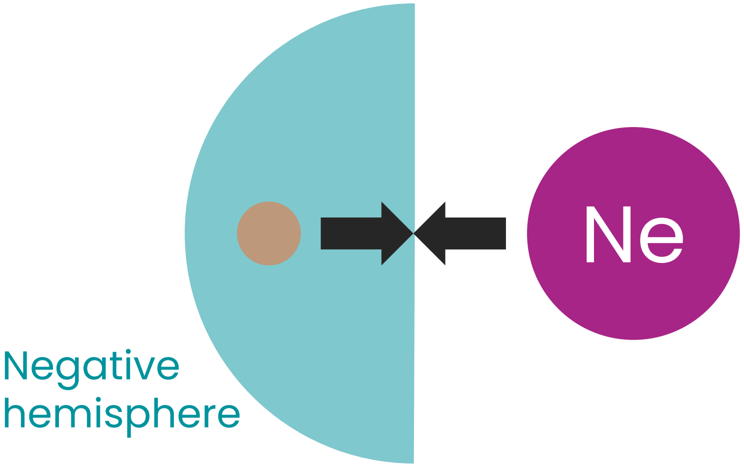


$$\sqrt{s_{NN}} = 69 \text{ GeV}$$

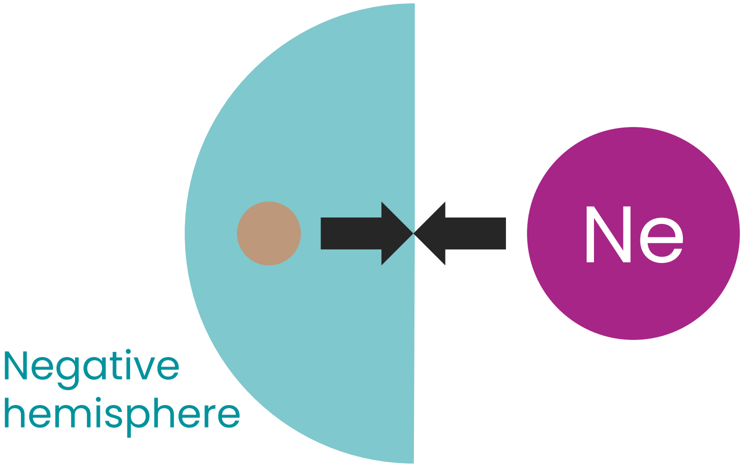


- Nucleon-nucleon center of mass boost of 4.29:
  - $y^* = y_{lab} - 4.29$
- LHCb forward acceptance becomes backward ($-2.29 < y^* < 0$) with fixed-target configuration.
- Allows to probe the valence region of the target nucleon using charm.

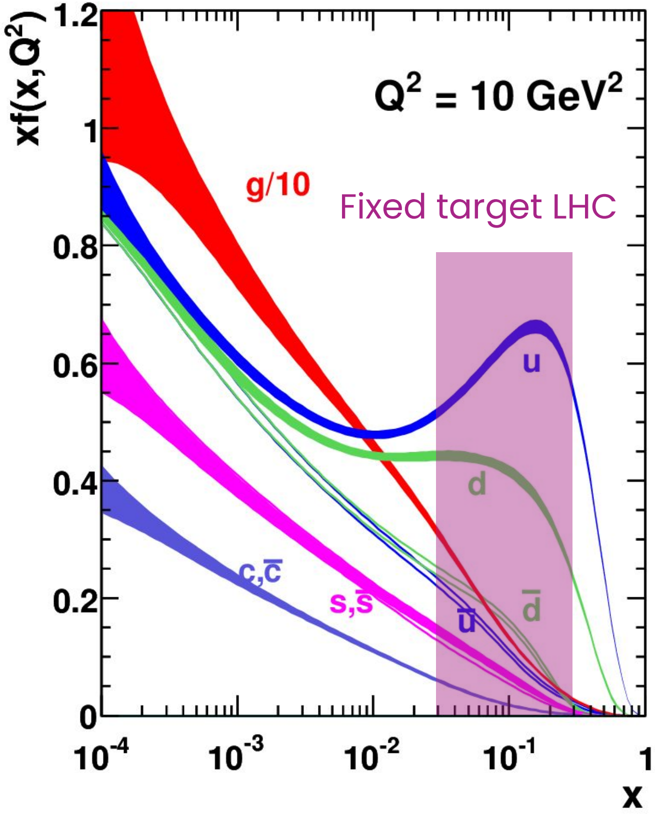
Fixed-target kinematics



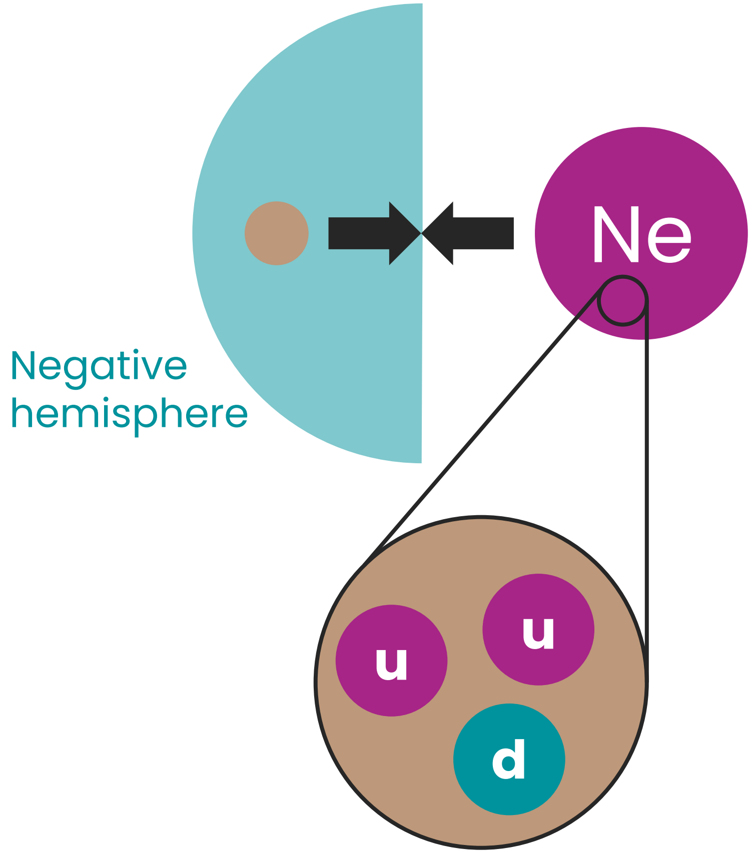
Fixed-target kinematics



Eur.Phys.J.C69:379-397,2010



Fixed-target kinematics



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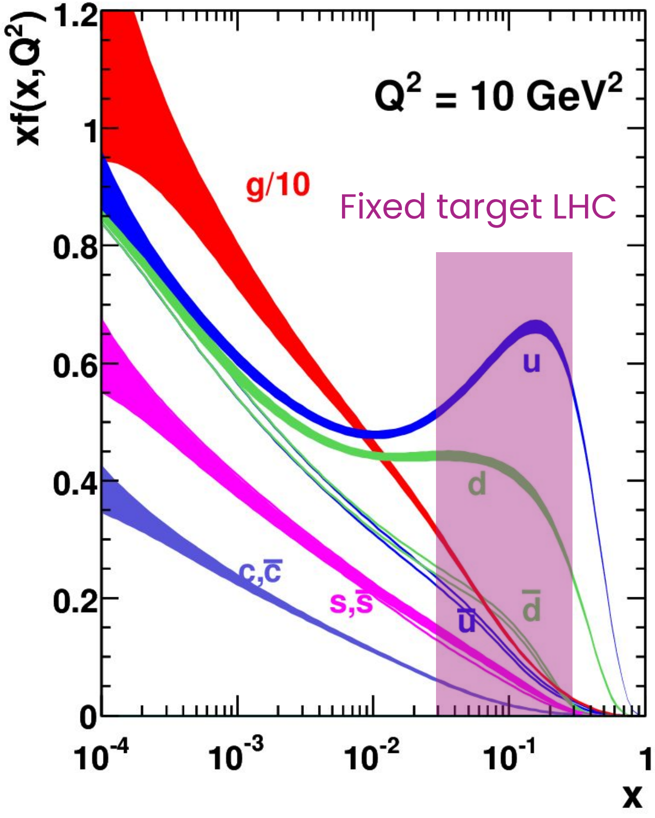
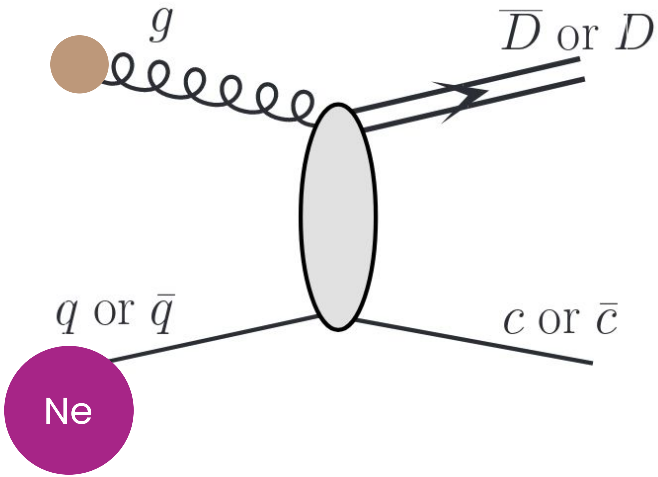


Qualitative explanation

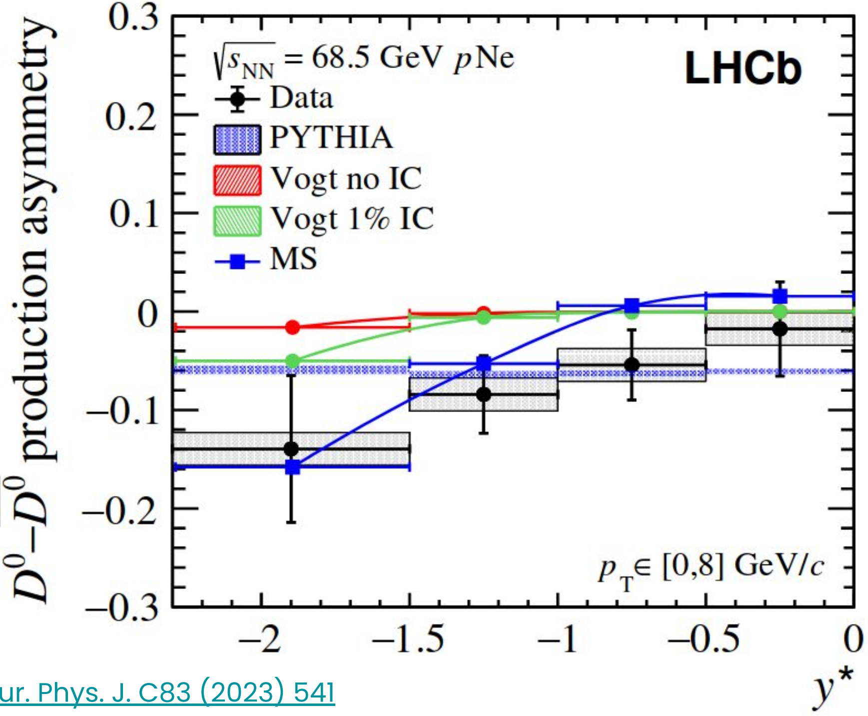


Physics Letters B 835 (2022)

- Charge production asymmetry expected when a charm quark hadronizes 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.
- Additional fragmentation fraction non universality.
- Need to measure rapidity dependance of all mesons and baryons.

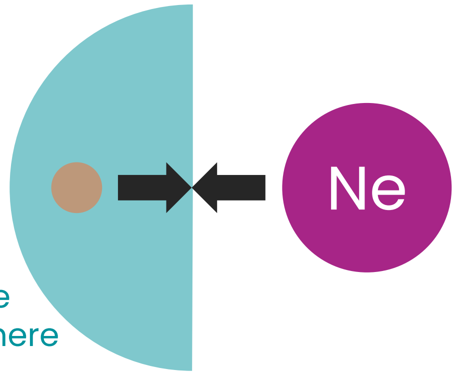
D^0 production asymmetry

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



Eur. Phys. J. C83 (2023) 541

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



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Decay chains currently studied in pNe collisions

$$D^+ \to K^-\pi^+\pi^+$$

$$D_s^+ \to K^+K^-\pi^+$$

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

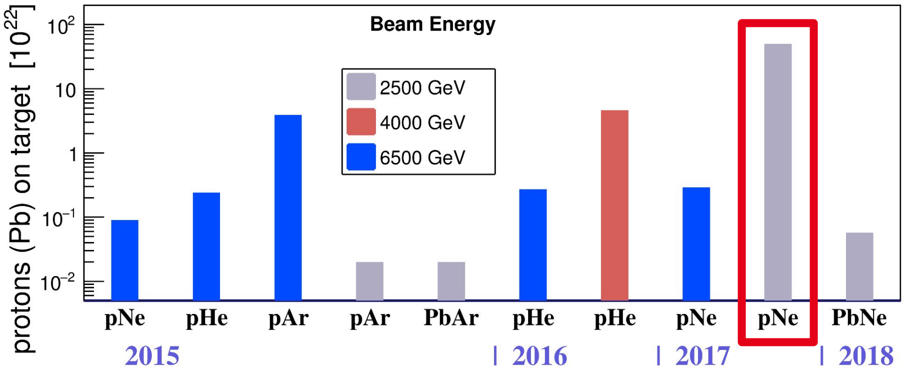
$$\Lambda_c^+ \to pK^-\pi^+$$

and charge conjugates

Dataset

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

SMOG2 TDR

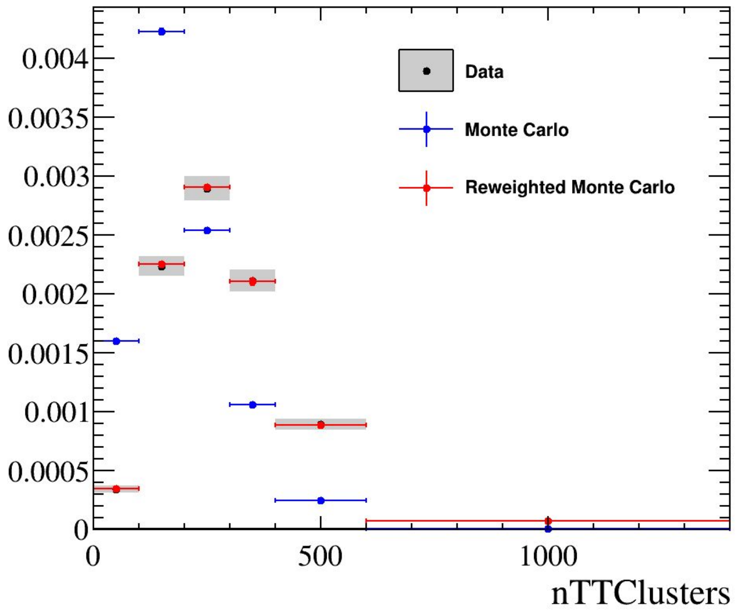


	y* range	p_T range
$D^{\pm}$	[-2.29, 0]	[0.6, 8] GeV
$D_s^{\pm}$		[1.1, 8] GeV
$D^{*\pm}$		[0, 8] GeV
$\Lambda_c^{\pm}$		

- Ongoing analysis for cross-section and asymmetry measurements.
- Limited low p_T reach for D^+ and D_s^+ due to cuts in software trigger.
- Lesson learned for the future, with high statistics coming this year!

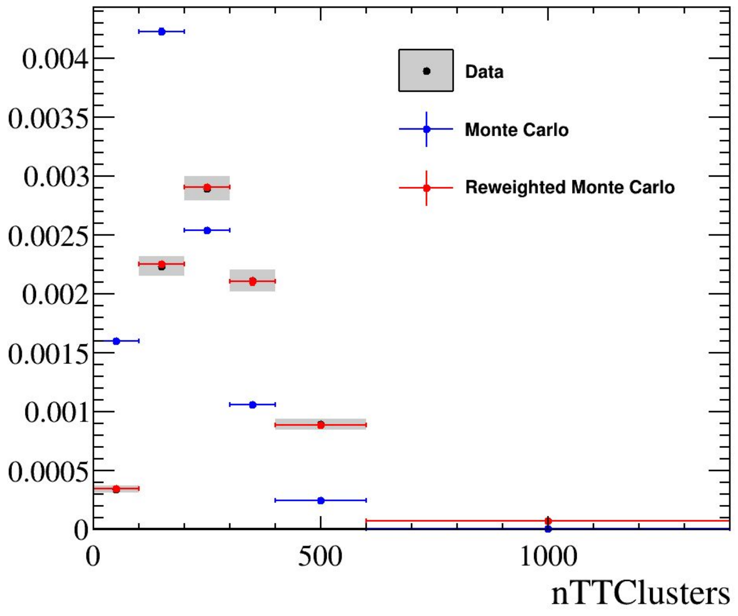
Monte Carlo reweighting

- Before efficiency computations, Monte-Carlo reweighting is needed.
- Binned 4 x 1D (transverse momentum, rapidity, longitudinal PV position, multiplicity) reweighting performed.



Monte Carlo reweighting

- Before efficiency computations, Monte-Carlo reweighting is needed.
- Binned 4 x 1D (transverse momentum, rapidity, longitudinal PV position, multiplicity) reweighting performed.
- High impact of reweighting on efficiency values.
- Independent reweighting and efficiency computing between charge conjugates.

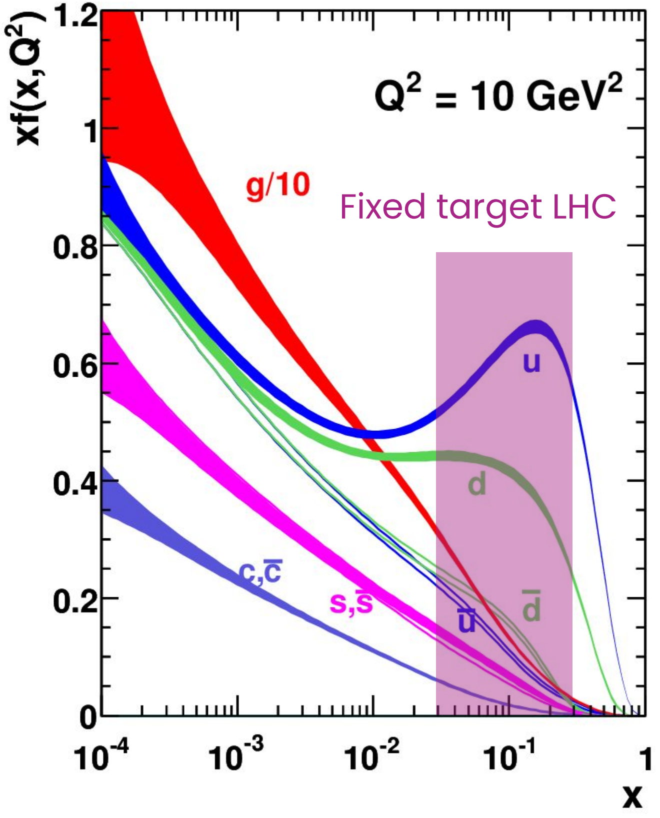


$D_s^{\pm}$ production asymmetry

- No strong hint of asymmetry, as expected.
- No strange valence quarks.
- More data needed to formally exclude asymmetry.
- Missing systematic uncertainty from reweighting.

$D_s^{\pm}$ production asymmetry

Eur.Phys.J.C69:379-397,2010



$D^{\pm}$ production asymmetry

- Negative asymmetry increasing at backward rapidity.
- Compatible trend with D^0 asymmetry and hadronization with a quark from the target valence region.
- However, more data is needed to confirm this trend.

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Conclusion

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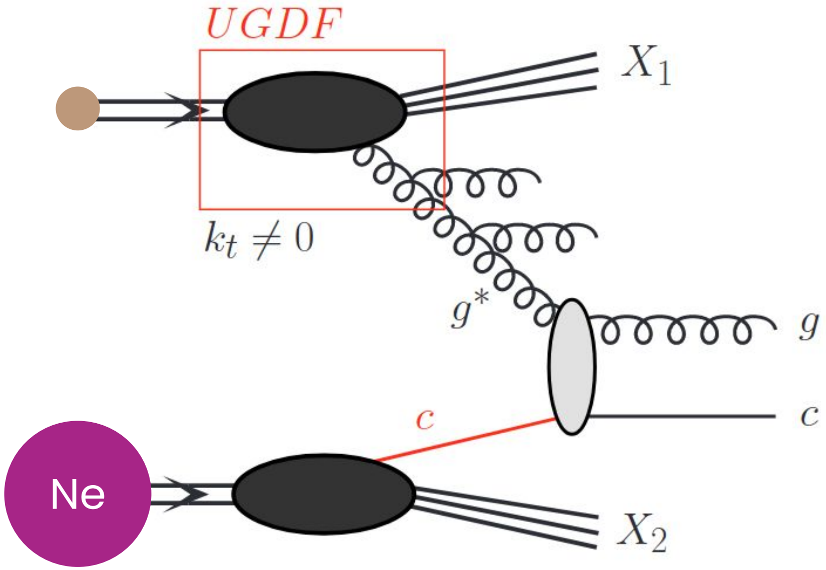
- Total charm production arises as the natural normalisation for charmonium modification in QGP studies.
- Charm fragmentation universality questioned.
- Need measurement of all ground state open charm hadrons.
- At fixed target energy, hint of further charm hadronization universality breaking by hadronization with target valence quarks.
- Ongoing analysis with charged open charm mesons and baryons, with promising preliminary results.
- Rich SMOG2 charm program will allow to explore hadronization in numerous colliding systems.

Backup

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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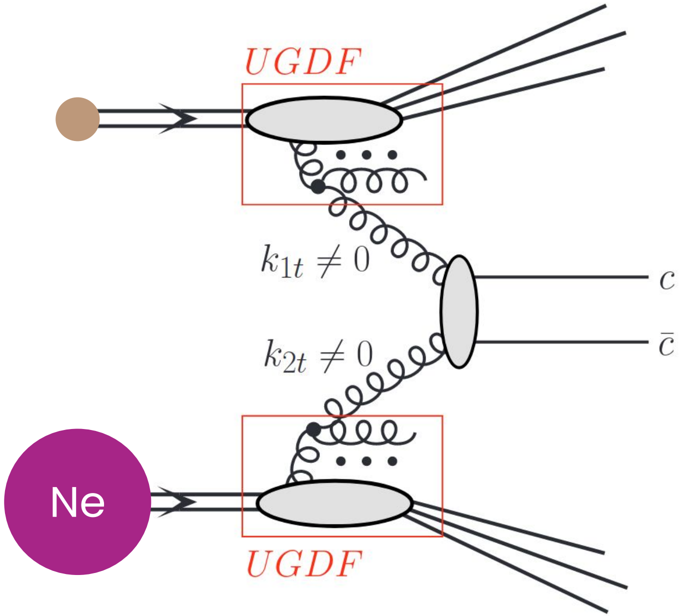
Charm production at fixed-target LHCb

- 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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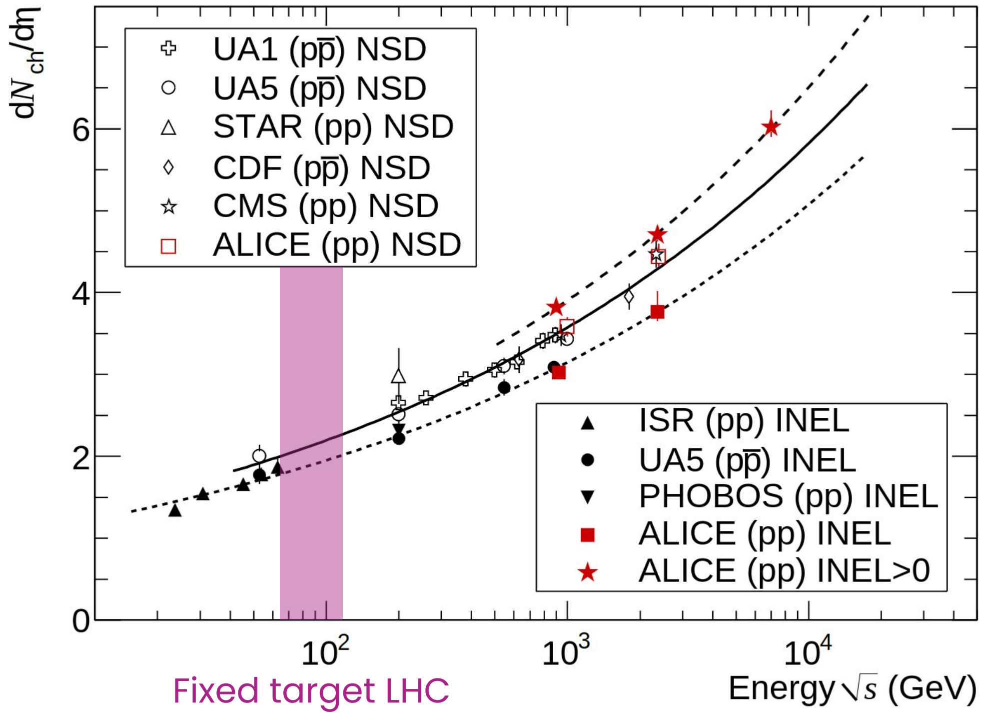
Multiplicity vs energy

Eur. Phys. J. C 68 (2010) 345-354

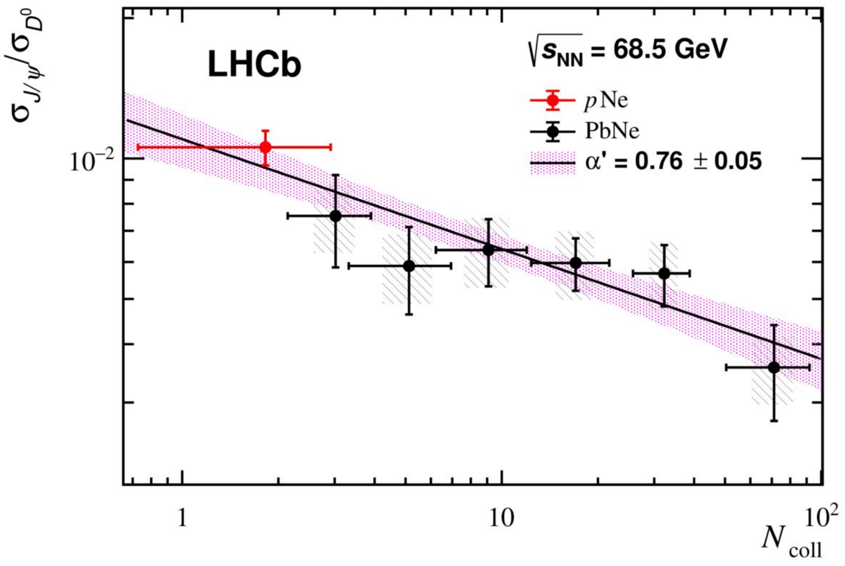


- Energy density can roughly be estimated from charged particle density.
- ~3 times lower energy density expected at LHC fixed-target compared to collider mode.

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

- 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 $<N_{coll}>^{\alpha'}$.
- D⁰ used as proxy for total $c\bar{c}$ cross-section: σ_{D^0} scaling in $<N_{coll}>$.
- However, universality breaking of charm fragmentation can affect the usage of D^0 as a proxy for total $c\bar{c}$ cross-section.

Eur. Phys. J. C83 (2023) 658



Triggers, stripping and data quality

- proton-proton collisions at $\sqrt{s}$ = 5 TeV in parallel to the *p*Ne data taking.
- Ghost contamination from debunched protons.
- Data quality cuts from LHCb-INT-2020-012.

Global Event Cuts
PVz ∈ [-200; -100] ∪ [+100; +150] mm
nPV ≥ 1, PUHits < 5, BCType = 1, PVntracks > 4

$D^{\pm}$	Hlt1	Hlt1SMOGSingleTrackDecision_TOS
	Hlt2	Hlt2SMOGDpm2KPiPiDecision_TOS
	Stripping	StrippingHeavyIonOpenCharmDp2KHHLineDecision
$D_s^{\pm}$	Hlt1	Hlt1SMOGSingleTrackDecision_TOS
	Hlt2	Hlt2SMOGDs2KKPiDecision_TOS
	Stripping	StrippingHeavyIonOpenCharmDs2KKHLineDecision

Signal extraction cuts

Stripping

Combination cuts
MAXCHILD(p_T) > 1 GeV MAXCHILD($IP_{\chi^2}^{PV}$) > 9 DOCA < 2 mm At least 2 children with $IP_{\chi^2}^{PV}$ > 4 At least 2 children with p_T > 400 MeV

Children cuts		
$K^{\pm}$	DLL_K > 5	track χ^2/ndof < 5 $IP_{\chi^2}^{PV}$ > 2 p_T > 200 MeV p > 3 GeV
$\pi^{\pm}$	DLL_K < 5	

Parent cuts
Vertex χ^2/ndof < 25

Additional cuts

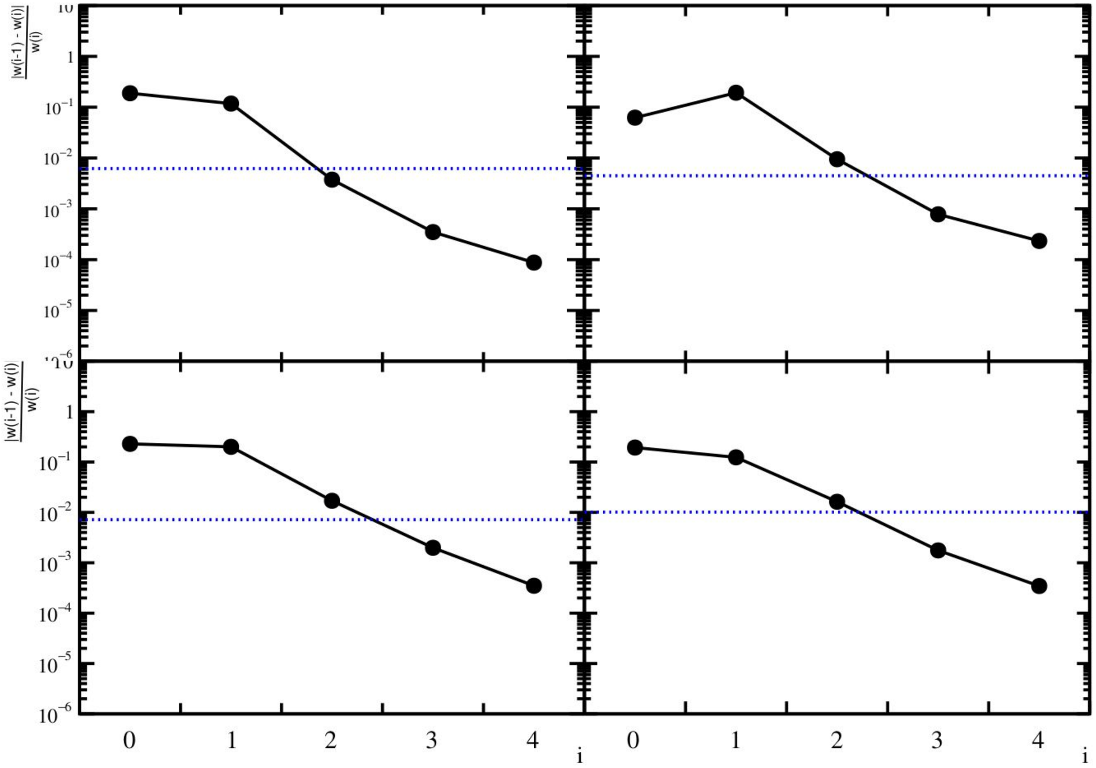
	Children cuts		
	Acceptance	Kinematics	PID
$K^{\pm}$	2 < η < 4.5 p > 3 GeV	p_T > 200 MeV	DLL_K > 5
$\pi^{\pm}$			DLL_K < 0

	Parent cuts
$D^{\pm}$	$IP_{\chi^2}^{PV}$ < 15 Vertex χ^2 < 22 DIRA > 0.999 τ > 0.5 ps
$D_s^{\pm}$	

Monte Carlo simulation reweighting

- Binned 4x1D (p_T, y, PVz, multiplicity) reweighting performed.
- Iterative process used:
  - Weights computed in each variable distribution by comparing data to reconstructed Monte Carlo.
  - Efficiency distributions computed with weighted Monte Carlo ($w_{tot} = w_{pT}.w_y.w_{PVz}.w_{mult}$). Reweighting is done at the candidate level.
  - New weights computed by comparing efficiency corrected data to non-weighted generated Monte Carlo.
  - New efficiencies computed the same way as before.

Convergence criteria



δ values in D^- p_T bins

- Convergence studied by comparing the weights values in each bins for two subsequent iterations :

$$\delta = \frac{|w(i) - w(i-1)|}{w(i)}$$

- Convergence criteria: δ negligible compared to statistical uncertainty.
- Blue dotted line: $\sigma_{stat}/10$
- Satisfactory convergence obtained after 5 iterations.

Uncertainties for asymmetries

- Uncertainties considered fully correlated between charges, thus cancelling out:
  - Tracking
  - PID
  - Truth matching
  - Luminosity
  - Neon purity
  - Branching ratio
- Leaving the following uncertainties as uncorrelated:
  - Statistical uncertainty
  - Signal extraction
  - Reweighting
  - MC statistics