QCD at FAIR workshop 2024
GSI, Darmstadt

Nucleon Structure at SIS100: Internal Charm, Trace Anomaly and GPDs

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Introduction and Overview

- The decomposition of global properties of the proton is a key issue in hadron physics

➔ How can the mass and the spin be described in terms of individual contributions from quarks and gluons?

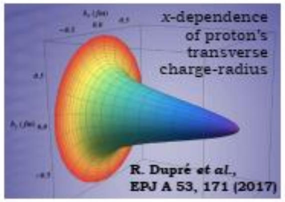
➔ Which components are really contributing to the protons wave function?

➔ How can we access the mechanical properties of the proton, like the distribution of the pressure and shear forces?

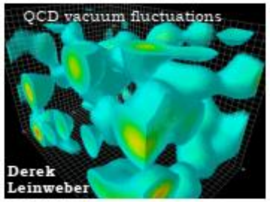
Hadron beams at SIS100 can make important contributions to these questions:

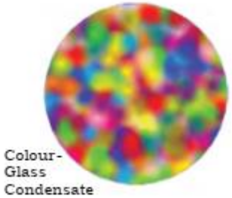
- Contribution of intrinsic charm to the protons wave function
- Trace anomaly and its contribution to the proton mass
- Gravitational form factors and GPDs

  ➔ 3D imaging of the nucleon and its resonances



R. Dupré et al., EPJ A 53, 171 (2017)

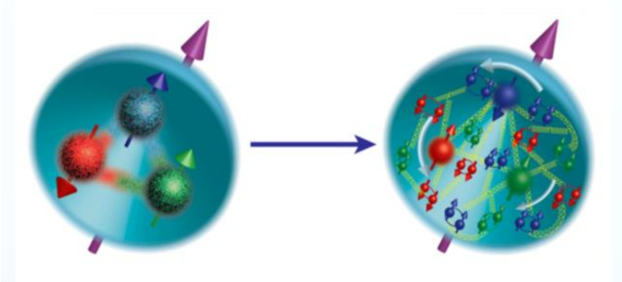




Intrinsic Charm

- QCD describes the proton in terms of quarks and gluons:

  2 up and 1 down quark + infinite number of quark-antiquark pairs (sea quarks)



m_c = 1.27 GeV/c²

- Quark sea: High energy collissions revealed both light and heavy quarks

  ➔ The mass of heavy quarks can be bigger than the proton mass!

- It is unclear, weather heavy quarks are part of the proton wave function

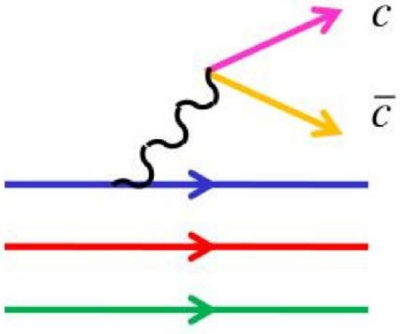
  ➔ Intrinsic heavy quarks

- Theories predict, that the proton could have a sizable intrinsic component of the lightest heavy quark, the charm quark

  BUT: Previous efforts in proving these arguements experimentally have not been fully conclusive

Intrinsic Charm

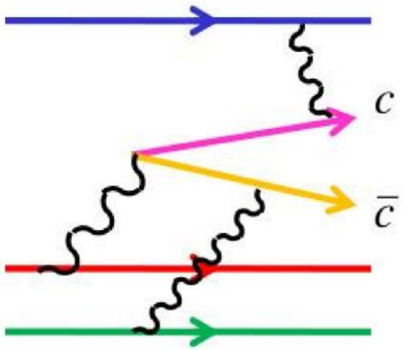
What is intrinsic charm?



„extrinsic charm“

Charm pair originates
from the QCD DGLAP evolution

➔ Description by perturbative QCD



„intrinsic charm“

Charm pair was there
before the evolution

➔ Strong non-perturbative effects

Intrinsic Charm

Model description:

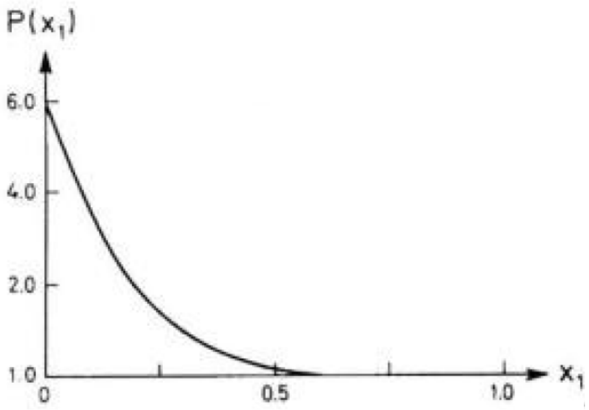
- Proton described as a „bag“ with five quarks: $|uud c\bar{c}>$

Brodsky, Hoyer, Peterson, Sakai (80)

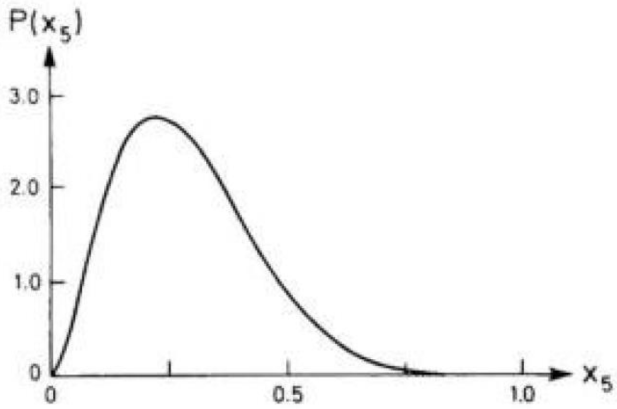
- Probability to find a charm-anticharm pair in the proton:

$$P = \frac{P_0}{[m_p^2 - M^2]^2} \qquad M^2 = \sum_{i=1}^{5} \frac{m_i^2}{x_i} \qquad x_i = \text{momentum of the parton i}$$

- **Momentum distribution of the charm**: Integrate P over $x_1 - x_4$ ➔ $P(x_5) = c(x)$



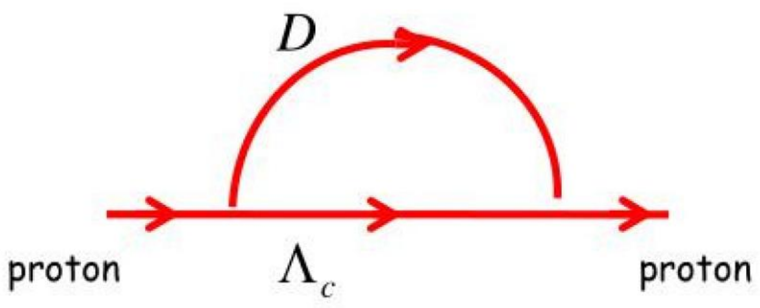
light quark



heavy quark

Intrinsic Charm

Charm component of the meson cloud:



Navarra, Nielsen, Nunes, Teixeira (96)
Paiva, Nielsen, Navarra, Duraes, Barz (98)
Carvalho, Duraes, Navarra, Nielsen (01)

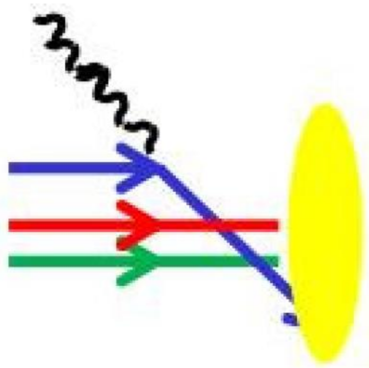
$$m_D = 1870 MeV$$
$$m_\Lambda = 2280 MeV$$

➔ **Both have a similar momentum fraction: x ~ 0.5**

➔ These intrinsic charm fluctuations can be freed by a soft interaction

Intrinsic Charm

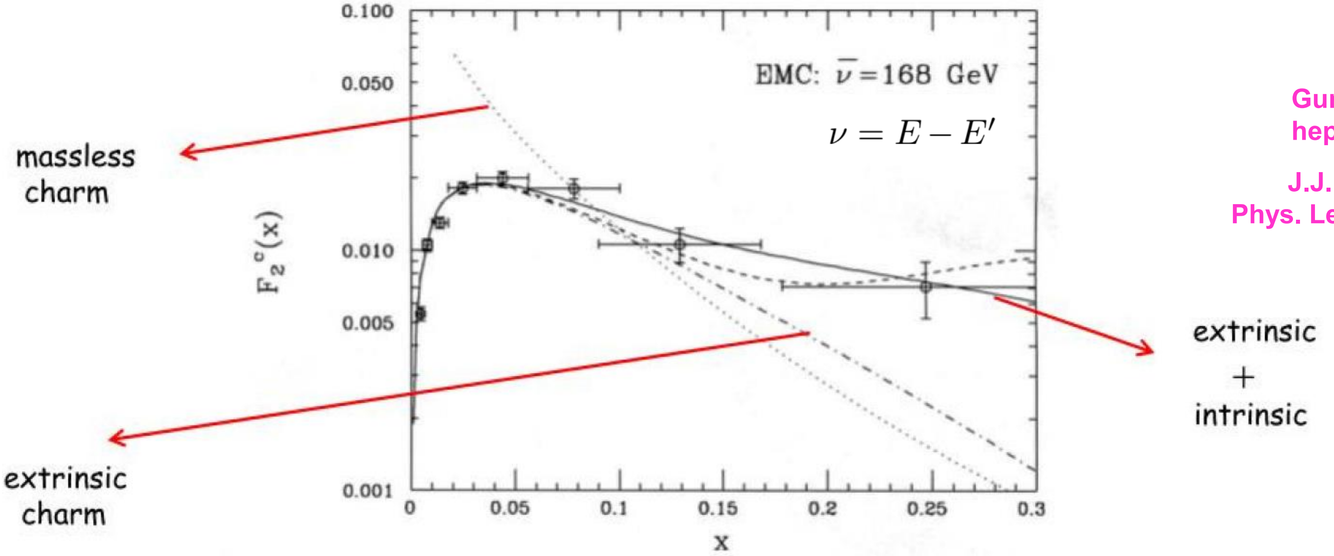
How can we measure the intrinsic charm?



1. Deep-inelastic scattering: Parton distributions

$$\sigma \propto F_2^c(x) \propto c(x)$$

EMC data for the deep-inelastic electromagnetic structure function F^c_2 based on μ scattering:



Gunion, Vogt, hep-ph/9706252

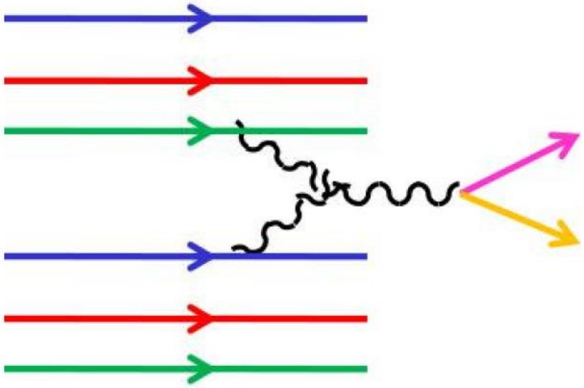
J.J. Aubert et al., Phys. Lett. B110 (1982), 72

➔ Fits of DIS data favour 1-2 % intrinsic charm

Pumplin, Lai, Tung, hep-ph/0701220

Intrinsic Charm

How does it look like in hadronic collissions?



➔ Intrinsic charm is hard and will produce charm at high momentum

$g\,g \to c\,\bar{c}$ $\qquad$ $q\,\bar{q} \to c\,\bar{c}$

➔ Intrinsic charm can be accessed in **inclusive reactions**

$p\,p \to \Lambda_c\,X$ $\qquad$ $p\,p \to J/\psi\,X$ $\qquad$ $p\,p \to D\,X$ $\qquad$ + other charm mesons

➔ Also p A and p $\bar{p}$ colissions are of interest!

- **Description based on collinear factorisation:**

$$\frac{d\sigma^{pp\to c\bar{c}X}}{d x_D\, d x_{\bar{D}}\, d^2 p_T} = \int_0^1 d x_1 \int_0^1 d x_2\, f_g(x_1, Q^2)\, f_g(x_2, Q^2)\, \hat{\sigma}_{gg\to c\bar{c}}(x_1, x_2)\, D_c(x_D, p_T^2)\, D_c(x_{\bar{D}}, p_T^2)$$

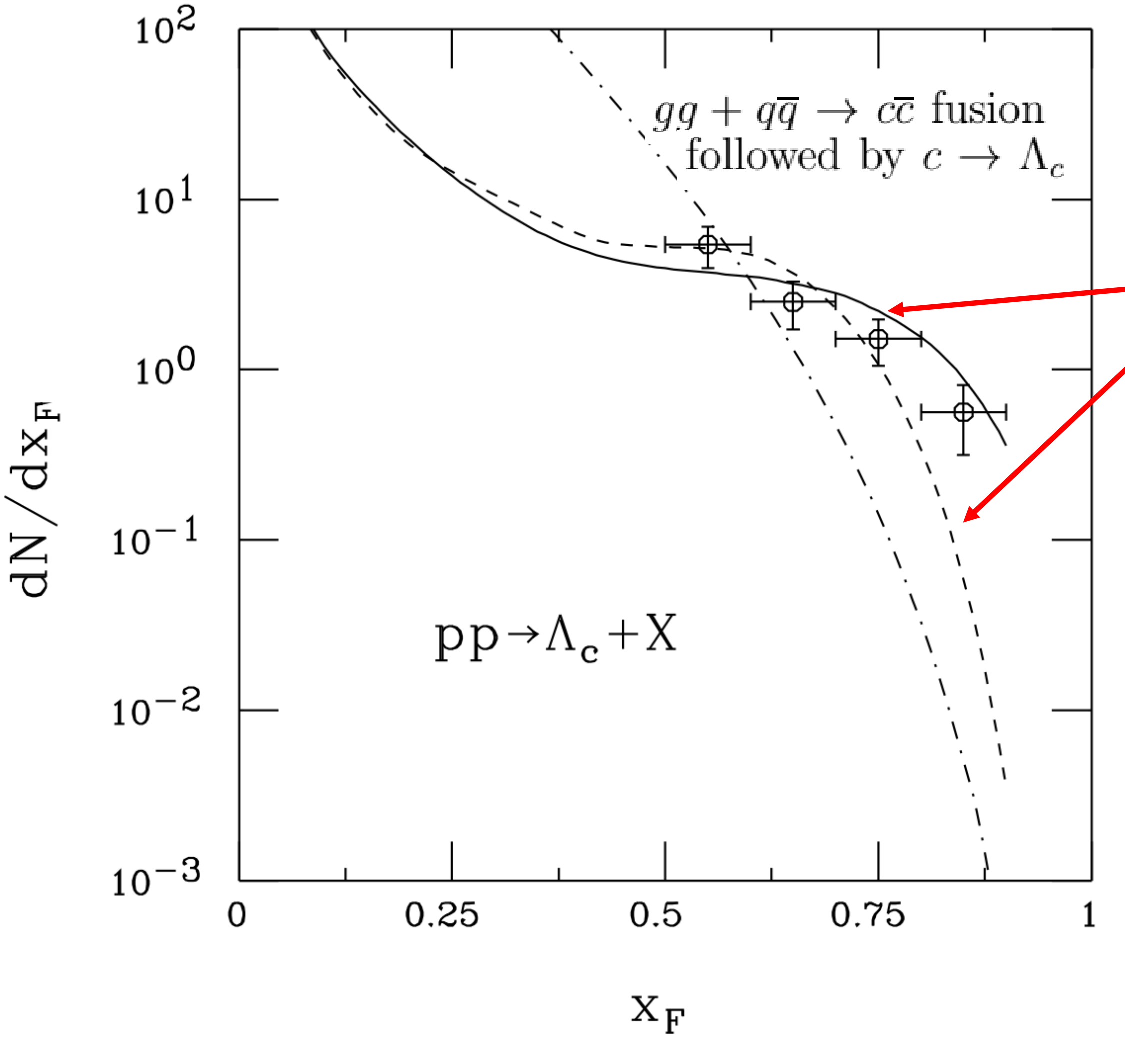
PDFs $\qquad\qquad$ **PDFs**

Intrinsic Charm

Data from the CERN Intersecting Storage Rings (ISR)

$$pp \rightarrow \Lambda_c + X$$

$$\sqrt{s} = 63 \text{ GeV}$$



fusion + intrinsic charm

➔ **IC component is needed to describe the data!**

P. Chauvat et al.,
Phys. Lett. B199, 304 (1987).

Intrinsic Charm

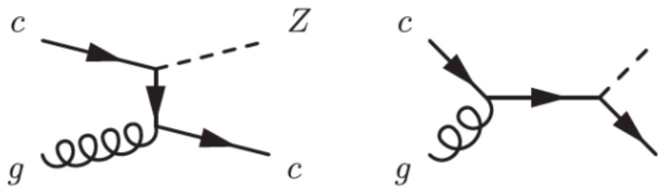
LHCb: Evidence of intrinsic charm
in Z+c-jet events

- Ratio of Z+c-jet to Z+all-jet events
  (PRL 128, 082001 (2022))

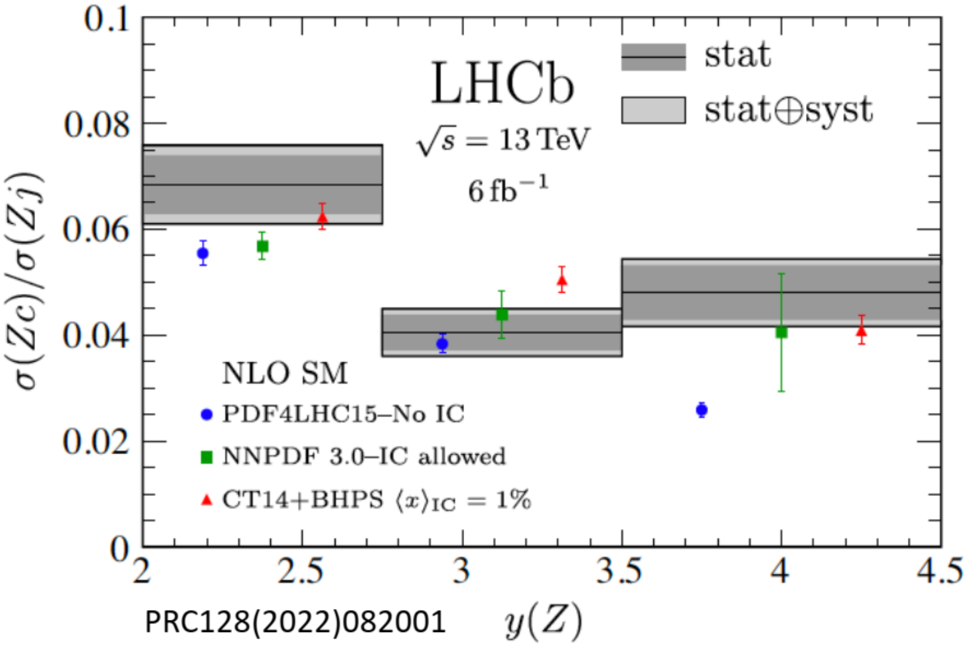
- Ratio at √s = 13 TeV is more consistent with calculations including intrinsic charm

- Differences between calculations with and without intrinsic charm get larger for the highest rapidity bin (in the most forward region)

➔ Up to 1% intrinsic charm content



Leading order diagrams producing Z + c-jet events



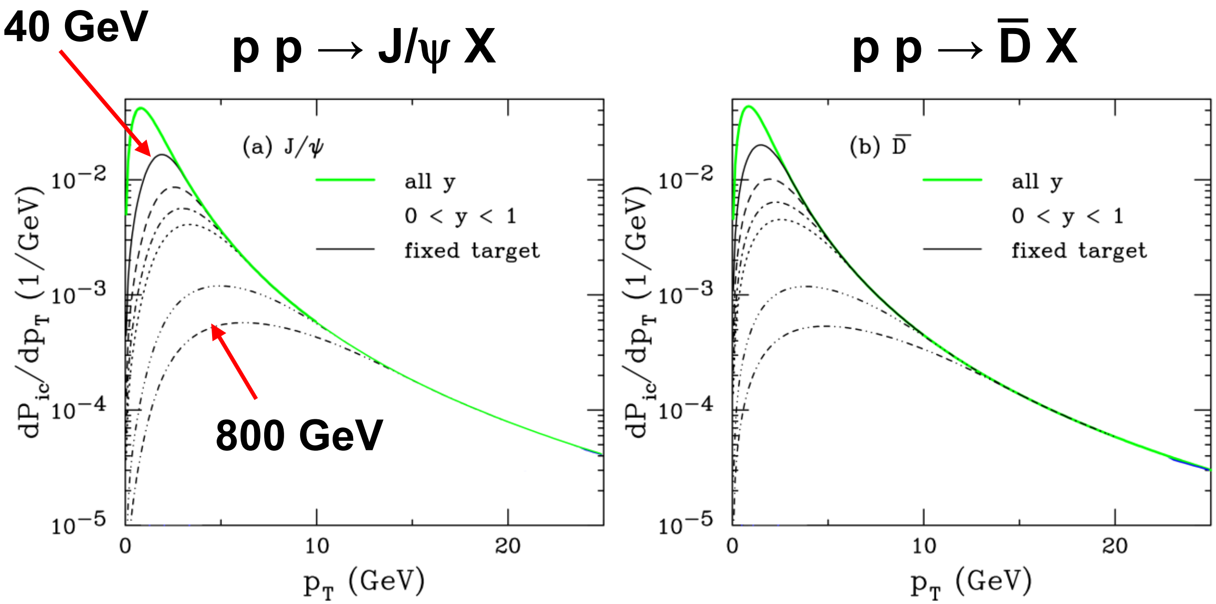
PRC128(2022)082001

➔ LHCb results need to be included in global PDF fits for a final conclusion

Intrinsic Charm

Predictions for intrinsic charm in inclusive charmonium production

R. Vogt, Energy dependence of intrinsic charm production: Determining the best energy for observation, Phys. Rev. C, 106(2):025201 (2022)



➔ Strongest IC contribution for pp colissions at lower beam energies and small p_T!

At SIS100 energies: IC contribution is in the range of 0.1 - 1.% compared to ”standard” gluon-gluon and quark-gluon charm production processes

➔ p_T and y distributions are needed ➔ IC casuses a flattening of the p_T distribution

Intrinsic Charm

FAIR: Production of charm in proton-proton and proton-nucleus collisions

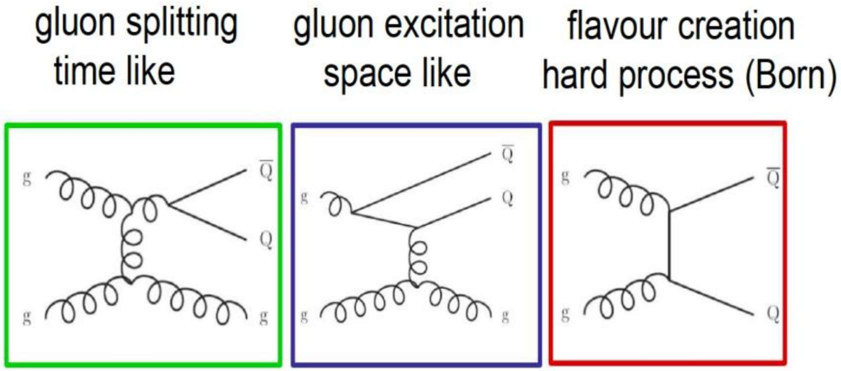
➔ From threshold up to p_{beam} = 30 GeV → $\sqrt{s}$ = 7.6 GeV

- According to model predictions low energy domain is well suited for such studies

LHC energies: IC effects only at forward rapidities

BUT: Factorization unclear at lower energies

- Potential production via multiple gluon exchange?



J. Aichelin

Another challenge: Low production cross sections

➔ A few tens of nanobarns (for open charm)

➔ Currently, at 30 GeV colission energy only poor data on pp and very little data on pA

Intrinsic Charm

CBM: Designed to handle high interaction rates (1-10 MHz)

➔ Detection becomes possible

➔ Excellent coverage for p-p and p-A reactions to measure inclusive processes, covering the forward and mid rapidity, where the effects are predicted to be largest

- The absorption of *J/ψ* and D mesons in nuclear matter can be studied in pA colissions

➔ IC is expected to show a dependence of the production cross section on A

➔ Nucleon PDFs can be accessed at large x (anti-shadowing and EMC effects)

Additional topic: Strangness production e.g. $p\,p \to \phi\,X$

➔ Already well explored, but a combined high statistics study could reduce the systematics!

Intrinsic Charm

Complementarity to J-PARC:

Detector setup will measure mid-rapidity to backward production (complementary to CBM)

- Especially for pA reactions: Key interactions change between forward and backward region

Forward production:

- Interaction between the pre-resonance state of the charm pair and the nucleon is important because the state of a charm pair before forming J/ψ passes through the nucleus

Backward production:

- J/ψ passes through the nucleus, so the J/ψ-N interaction becomes important

➔ Effects lead to a difference between the forward and backward A dependence of the production cross section

Goal: Combine results from FAIR and J-PARC to obtain a complete understanding!

Trace anomaly and origin of the nucleon mass

- **QCD** shows an approximate conformal symmetry at the classical level

Energy momentum tensor (EMT): $T^{\mu\nu} = -F^{\mu\lambda}F^{\nu}{}_{\lambda} + \frac{\eta^{\mu\nu}}{4}F^2 + i\bar{q}\gamma^{(\mu}D^{\nu)}q$

➔ Trace vanishes in the chiral limit: $T^{\mu}_{\mu} = m\bar{q}q$

➔ Classical massles QCD is invariant under scale transformations

$$\boldsymbol{x \to \lambda x\ ,\ q(x) \to \lambda^{3/2}q(\lambda x)\ ,\ A_\mu(x) \to \lambda A_\mu(\lambda x)}$$

➔ Quantization / renormalization generates a scale **Λ$_{\mathbf{QCD}}$** that breaks scale invariance

➔ **Trace anomaly**

$$\boldsymbol{\theta^{\mu}_{\mu} = \frac{\beta_{\mathrm{QCD}}}{2g}G^{a}_{\mu\nu}G^{\mu\nu}_{a} + m_u\bar{u}u + m_d\bar{d}d + m_s\bar{s}s + \ldots}$$

- Trace anomaly = Signal for the generation of hadron masses
- The mass of any hadron made of light quarks is essentially field (“binding”) energy

Trace anomaly and origin of the nucleon mass

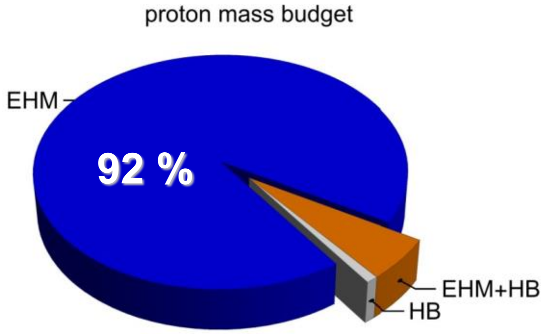
- Separation of the various contributions leads to the sigma - terms:

$$\langle N(p)|m_u\bar{u}u + m_d\bar{d}d|N(p)\rangle = 40\ldots70\ \mathrm{MeV} \doteq \sigma_{\pi N}$$

$$\langle N(p)|m_s\bar{s}s|N(p)\rangle = 20\ldots60\ \mathrm{MeV}$$

➔ Bulk of the nucleon mass is generated by the gluon fields / field energy

➔ Central result of QCD



- Recent calculations confirm that the trace anomaly of the QCD energy momentum tensor contributes around 92% of the proton mass

Yi-Bo Yang, Jian Liang, Yu-Jiang Bi, Ying Chen, Terrence Draper, Keh-Fei Liu, and Zhaofeng Liu, Proton Mass Decomposition from the QCD Energy Momentum Tensor. Phys. Rev. Lett., 121(21):212001 (2018)

Fangcheng He, Peng Sun, and Yi-Bo Yang. Demonstration of the hadron mass origin from the QCD trace anomaly. *Phys. Rev. D*, 104(7):074507 (2021)

- QCD dynamics are therefore the major source of the proton mass

➔ More experimental input is needed to obtain better constraints

Trace anomaly and origin of the nucleon mass

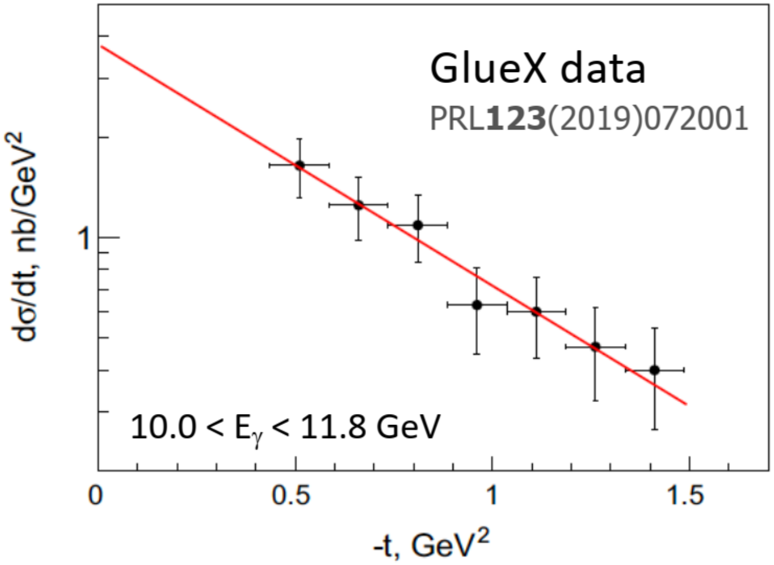
- Recent experiments mainly focus on the access to the trace anomaly based on near-threshold photo-production of vector mesons like ϕ and *J/ψ*

$\gamma + p \rightarrow \phi + p$ $\gamma + p \rightarrow J/\psi + p$

Wei Kou, Rong Wang, and Xurong Chen. Extraction of proton trace anomaly energy from near-threshold ϕ and J/ψ photo-productions. Eur. Phys. J. A, 58(8):155, 2022

Example: GlueX @ JLab

- Forward (small t) differential dσ/dt cross section of J/ψ can be related to the J/ψ–N scattering amplitude, and the nucleon mass via trace anomaly



$$\left.\frac{d\sigma_{VN\rightarrow VN}}{dt}\right|_{t=t_{min}} = \frac{1}{64\pi}\frac{1}{m_V^2\left(\lambda^2 - m_N^2\right)}\left|F_{VN}\right|^2$$

Elastic scattering amplitude:

$$F_{VN} = r_0^3 d_2 \frac{2\pi^2}{27} 2M_N^2 \underbrace{(1-b)}_{4\frac{M_a}{M_N}}$$

➔ Extraction of trace anomaly and mass radius

Trace anomaly and origin of the nucleon mass

Hadronic reactions:

- The interpretation of the traditionally used photo-production cross-section measurements strongly relies on the vector-meson dominance assumption (model dependent)

- A more model independent access to the trace anomaly and the mass radius may be provided by alternative approaches like p p scattering.

➔ Exclusive vector-meson production: $p\,p \to p\,p\,V$ with $V = J/\psi,\ \phi,\ \omega$

➔ Exclusive open charm production: $p\,p \to D\,\Lambda_c\,p$ like $D^0/\bar{D}^0\Lambda_c^+ p$

➔ Asymmetry of $D^0/\bar{D}^0$

➔ Measure the energy excess above the threshold for both reactions

Trace anomaly and origin of the nucleon mass

- **SIS100 and CBM will provide …**

➔ Unique kinematics + a relatively clean signal

➔ A uniform acceptance of the Dalitz plot for exclusive final states with hadronic decays and also for p p J/ψ

➔ Extractions via partial wave analyses --- Search for potential pentaquark candidates

- Also charmonium-nucleon final state interactions (FSI) could be accessed in p+A collissions

➔ Test of the color transparency based on energy and target (A) scans

BUT: Reaction dynamics at SIS100 energies need to be better understood

➔ Hadronic vs partonic picture

Gravitational form factors and GPDs

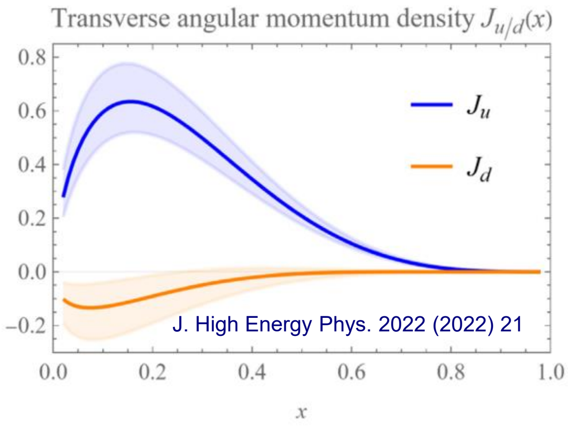
- The QCD energy momentum tensor contains rich information about the structure of the nucleon
- Even richer structure if we discuss quark and gluon parts separately

➔ Partonic decomposition of the nucleon mass and spin

$$\langle P'|T^{\mu\nu}_{q,g}|P\rangle = \bar{u}(P')\Big[\underset{\uparrow}{A_{q,g}}\gamma^{(\mu}\bar{P}^{\nu)} + \underset{\uparrow}{B_{q,g}}\frac{\bar{P}^{(\mu}i\sigma^{\nu)\alpha}\Delta_\alpha}{2M} + \underset{\uparrow}{D_{q,g}}\frac{\Delta^\mu\Delta^\nu - g^{\mu\nu}\Delta^2}{4M} + \underset{\uparrow}{\bar{C}_{q,g}}M\eta^{\mu\nu}\Big]u(P)$$

- Ji sum rule for the nucleon spin $\frac{1}{2} = J_q + J_g$

$$J_{q,g} = \frac{1}{2}(A_{q,g} + B_{q,g})|_{\Delta\to 0}$$



J. High Energy Phys. 2022 (2022) 21

Relation to the second moments of the generalized parton distributions (GPDs):

$$J^q = \frac{1}{2}\int dx\, x(H_q(x) + E_q(x)) \qquad J^g = \frac{1}{2}\int dx\, x(H_g(x) + E_g(x))$$

- *H, E* measurable in Deeply Virtual Compton Scattering (DVCS) at JLab, COMPASS, EIC,…

Gravitational form factors and GPDs

- The Fourier transform of the D-term can be interpreted as the radial pressure distribution inside a nucleon

$$\langle P'|T^{ij}|P\rangle \sim (\Delta^i\Delta^k - \delta^{ik}\Delta^2)D(t)$$

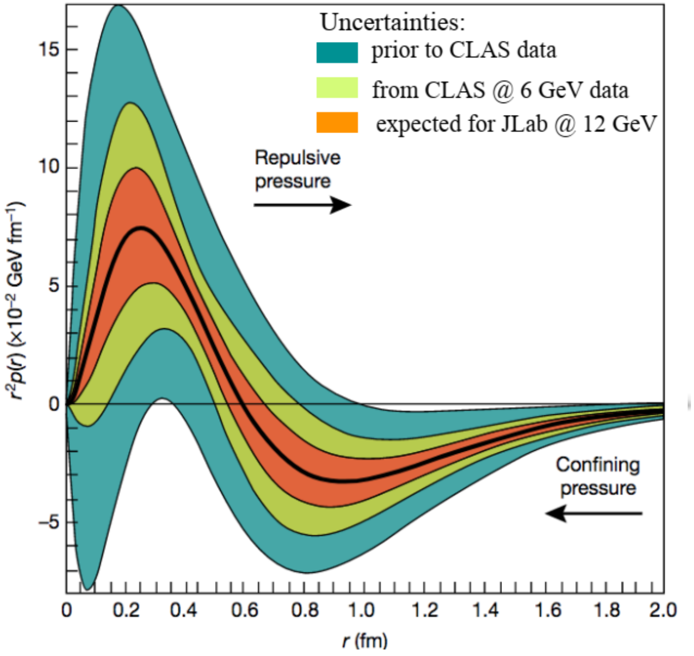
$$T^{ij}(r) = \left(\frac{r^i r^j}{r^2} - \frac{1}{3}\delta^{ij}\right) s(r) + \delta^{ij} p(r)$$

- GPDs provide indirect access to mechanical properties of the nucleon ➔ gravitational form factors

$$\int xH(x,\xi,t)\mathrm{d}x = M_2(t) + \frac{4}{5}\xi^2 d_1(t)$$

mass

pressure and shear forces

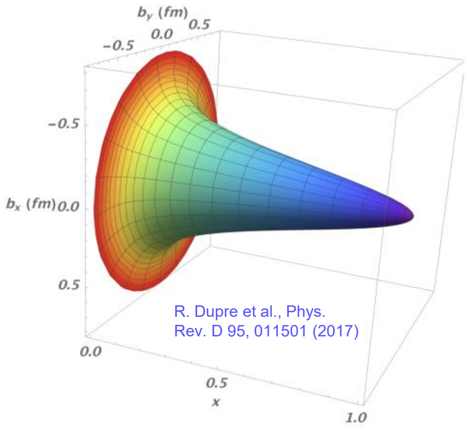


➔The pressure distribution in the proton can be accessed via Deeply Virtual Compton - Scattering

X. D. Ji, PRD **55**, 7114-7125 (1997)
M. Polyakov, PLB **555**, 57-62 (2016)
V. Burkert, L. Elouadrhiri, F.-X. Girod, Nature **557**, 396-399 (2018)
K. Kumerički, Nature **570**, E1-E2 (2019)

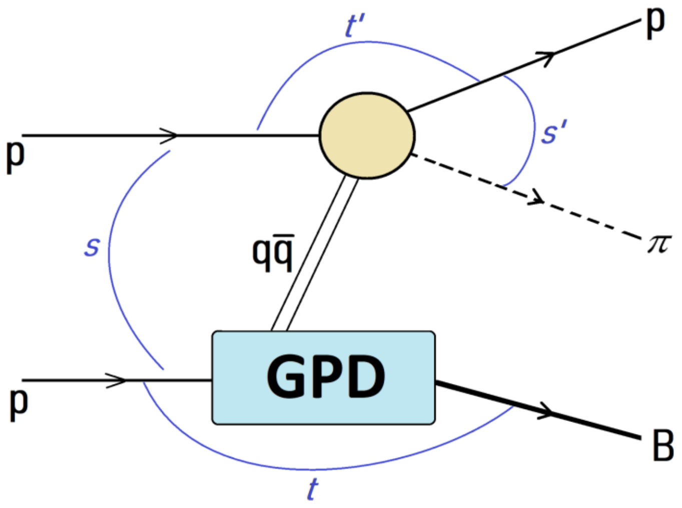
GPDs from p p → p π B Processes

- GPDs also provide a 3D picture of the nucleon in terms of the transverse position and the longitudinal momentum fraction of the partons



R. Dupre et al., Phys. Rev. D 95, 011501 (2017)

@ SIS100: GPDs potentially accessible via 2 → 3 reactions



S. Kumano, M. Strikman, K. Sudoh,
Phys. Rev. D 80, 074003 (2009) arXiv:0905.1453

Factorisation for: $|s'|, |t'|, |u'| \gg M_N^2$

$t'/s' = const. \quad |t| \ll M_N^2$

- Sensitive to classical twist-2 nucleon GPDs $H,\ E,\ \widetilde{H}$ and $\widetilde{E}$
- Probe GPDs in the ERBL kinematic regime (-ξ < x < ξ) not accessible in lepton scattering experiments
- Access to transition GPDs via Baryon resonances in the final state

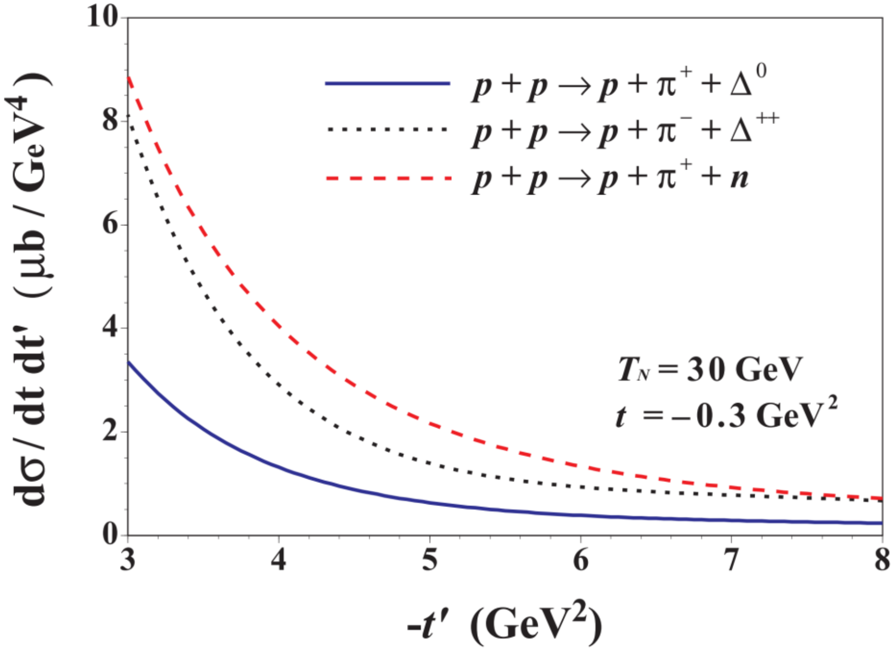
GPDs from p p → p π B Processes

Predictions for a 30 GeV proton beam:

The measurement of –t' dependence could be used to explore the x-dependence of GPDs.

Qiu & Yu, JHEP 08 (2022) 103, PRD 107 (2023) 014007, arXiv:2305.15397

Whitepaper: Exploring Baryon Resonances with Transition Generalized Parton Distributions: Status and Perspectives, arXiv:2405.15386 [hep-ph]



S. Kumano, M. Strikman, K. Sudoh, Phys. Rev. D 80, 074003 (2009)

p p → p π^0 p

p p → p π^+ n

p p → p π^- Δ^{++} → p π^- (p π^+)

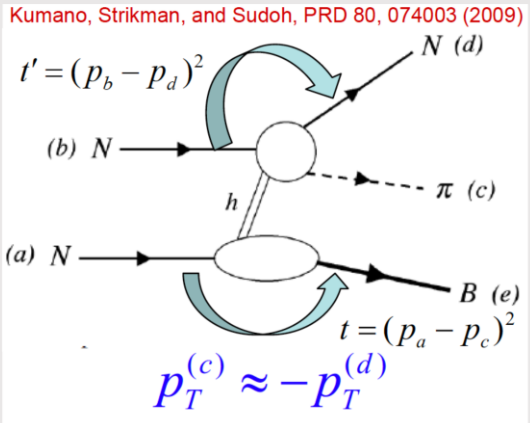
p p → p π^+ Δ^0 → p π^+ (p π^-)

p p → p K^+ Λ^0 → p K^+ (p π^-)

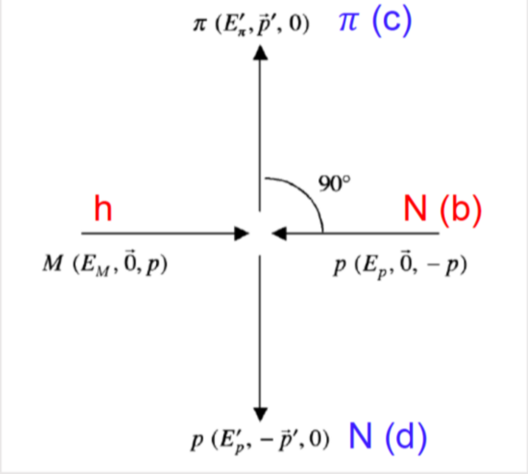
+ many options with neutrons and or π^0

But: Potential non-factorizing contributions!

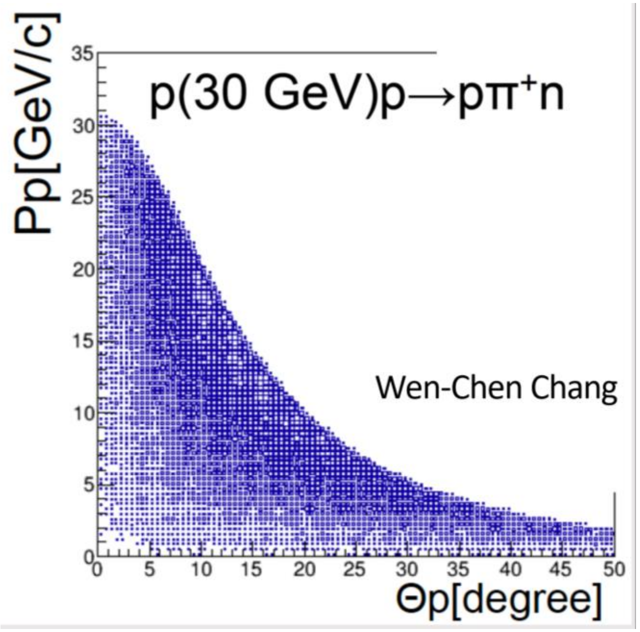
GPDs from p p → p π B Processes


Kumano, Strikman, and Sudoh, PRD 80, 074003 (2009)

$$p_T^{(c)} \approx -p_T^{(d)}$$



- Forward baryon B
- π N at ≈ 90° in CM



Wen-Chen Chang

- Limits to t' at JPARC E16 (30 GeV/c protons)
  $\Theta_{\pi,p} > 15°$, $\phi_{\pi\text{-}p} > 160°$
- CBM covers complimentary kinematics
  $\Theta_{\pi,p} < 25°$, all $\phi_{\pi\text{-}p}$ NCAL for forward neutron

➔ Simulations needed for the acceptance of the other particles

Summary and Outlook

- Experiments at SIS100 can potentially …

  - provide access to the intrinsic charm in the proton

    ➔ Inclusive charm production: p p → J/ψ X   p p → D X

  - access the trace anomaly of the QCD energy momentum tensor and contribute to the understanding of the origin of the nucleon mass

    ➔ Exclusive charm and strangeness production: p p → p p V   V = J/ψ, ϕ

  - access GPDs and transition GPDs in the ERBL kinematic regime, which is complementary to lepton scattering experiments

    ➔ 2 → 3 reactions: p p → p π B

- The kinematic coverage is forward focussed and therefore complementary to J-PARC

- Simulations are needed to check the acceptance and general feasibility for the individual reactions