Deuteron and antideuteron production in DIS at HERA

S.Chekanov
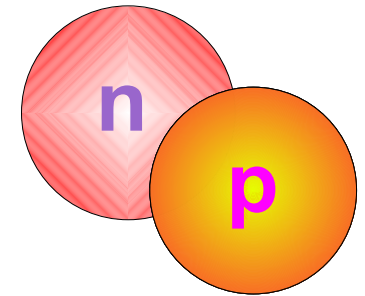**(DESY/ANL)**

on behalf of the ZEUS Collaboration

DIS07, Munich, Germany
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.. Deuterons? What do we know about them?

- **Deuteron (d):**

  - nucleus of deuterium
  - multiquark particle with one proton and one neutron

(anti)Deuterons in elementary particle collisions

- **p + n → d due to overlap of wave functions in the final state ~ $<\varphi_{pn}|\varphi_d>$**

  - p and n should be close in space and momentum

- **Cannot be produced by the standard hadronisation of quarks and gluons**

  - not even implemented in the current Monte Carlo models

- **$\bar{d}$ yield in e$^+$ e$^-$ → q$\bar{q}$ is factor ~5-10 smaller than in Upsilon production**
  (studies by ARGUS, OPAL, ALEPH, CLEO)

- **Observation of $\bar{d}$ in ep photoproduction (H1)**

- **No measurements of d:**

  - beam-gas, beam-wall & secondary interactions have to be understood

The coalescence model

- **Active topic for pp, pA, AA collisions and cosmic-ray studies:**
  - **pp, pA, AA: both d and $\overline{d}$ were measured**
  - **Explore nuclei production in the early universe**
  - **Created during "freeze-out" stage of fireball via coalescence:**

$$\frac{E_d}{\sigma_{tot}} \frac{\mathrm{d}^3 \sigma_d}{\mathrm{d}p_d^3} = B_2 \left(\frac{E_p}{\sigma_{tot}} \frac{\mathrm{d}^3 \sigma_p}{\mathrm{d}p_p^3} \right)^2$$

Coalescence parameter: **$B_2 \sim p_0^3 \, \gamma \sim r(n/p) / R^3$**

R   – source radius
r(n/p) – ratio of neutrons to protons yields (depends on the beam and target nuclei)

- if B_2 is the same for particles and antiparticles: $\overline{d}/d = (\overline{p}/p)^2$

- test the coalescence model by reconstructing $\overline{d}/d$

Recent measurement: Au+Au   **$\overline{d}/d = 0.47 \pm 0.03$**
PHENIX Coll. PRL (2005) 122302   **$\overline{p}/p = 0.73 \pm 0.01$**

Also by ISR (1973-1978), British-Scandin.(1978), E858 (1992), E864(2000), NA44 (1995), BRAHMS (2006) Collab...

Motivation

Possible connection with pentaquarks (PQ)?

- as PQ, d is multiquark state
- PQ may be explained using the coalescence model as well? (Karliner&Webber, 2004)
- PQ candidates where not found in e^+e^- where d production is suppressed compared to proton-initiated processes

Deuterons in DIS?

- $\bar{d}$ and d have not been observed so far
- Both d and $\bar{d}$ could be reconstructed under <u>clean experimental conditions</u>
  - detection of scattered electron reduces beam-gas contributions
- huge event sample with unbiased hadronic-final state selection

Look at baryon-antibaryon asymmetry in production yields:

- Asymmetry in ep is expected for final-state protons due to several effects
  - valence quark contribution (<2-4%)
  - baryon-number transfer by gluons (< 8%) (Kopeliovich&Povh, 1997)
- Asymmetry strength affected by baryons from quark and gluon fragmentation
- What about "compound" particles which are not contaminated by the standard fragmentation?

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Data selection and reconstruction

Event selection and kinematic range

- 120 pb^{-1}. HERAI data

- E_e>8.5 GeV

- $|Z_{vtx}|$<50 cm $X_{vtx}^2 + Y_{vtx}^2 < 1$ cm

- Q^2>1 GeV^2 (<Q^2> ~10 GeV^2)

- number of primary track >3

- P_T(tracks)>150 MeV

- all good quality tracks (>3 CTD super-layers)

- dE/dx for particle identification

- events with at least one track for dE/dx>2.5

- 0.3 < p_T/M<0.7 and central rapidity |Δy|<0.4

Primary tracks are selected using statistical background subtraction in 2 variables:

- **ΔZ**   - distance from track helix to Z_{vtx} in Z

- **DCA** - distance of closest approach of the track to the beam spot in the transverse plane
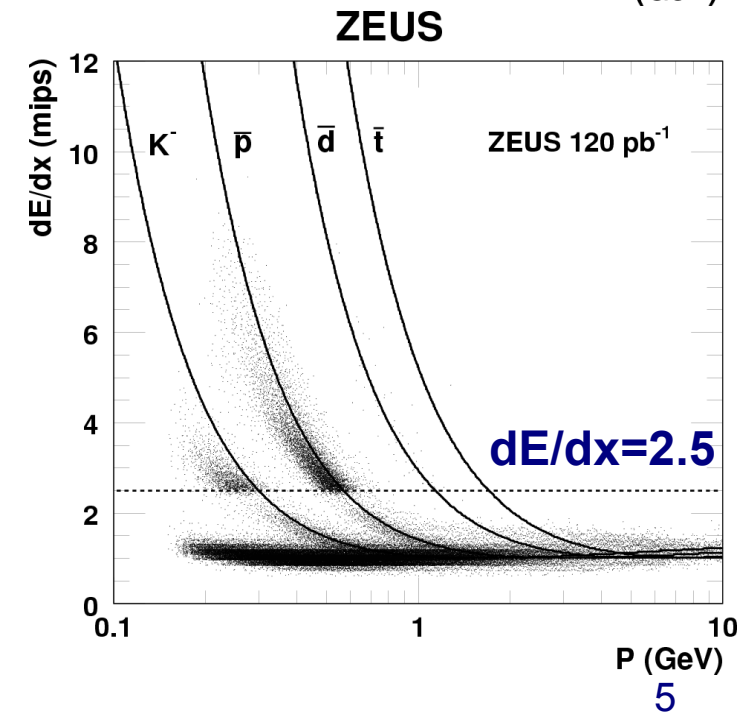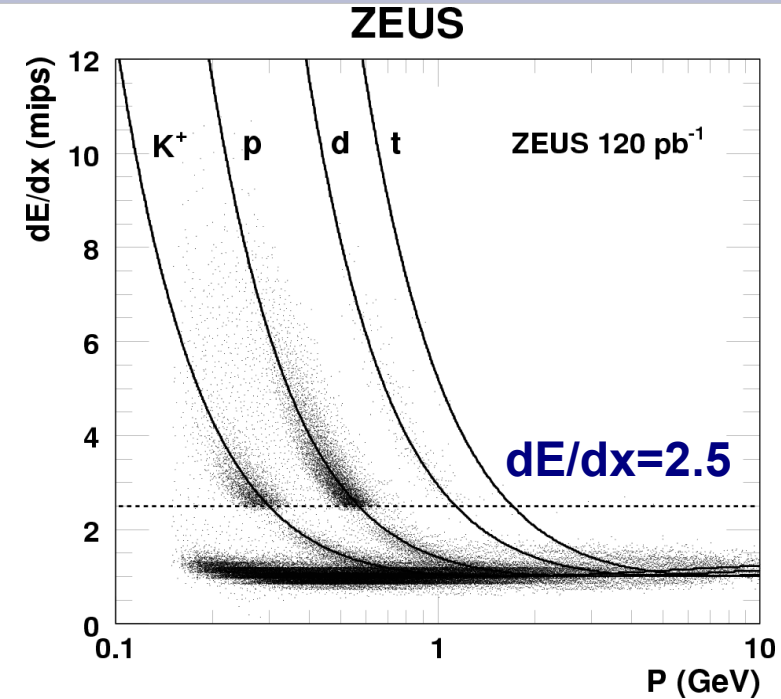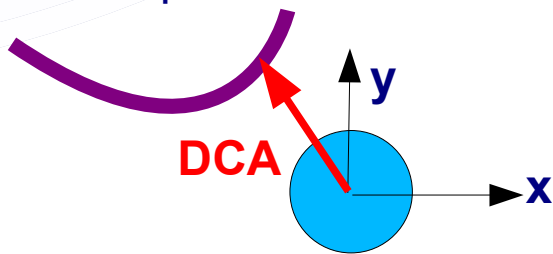
Data selection and reconstruction

- **Mass reconstruction:**
  - Use dE/dx Bethe-Bloch formula
  - scan mass where differences from the Bethe-Bloch expectations are minimal
- **Small shift for positive and negative tracks**
  (expected due to CTD structure)
- **Mass resolution:$\Delta M/M$ = +7-11 %**
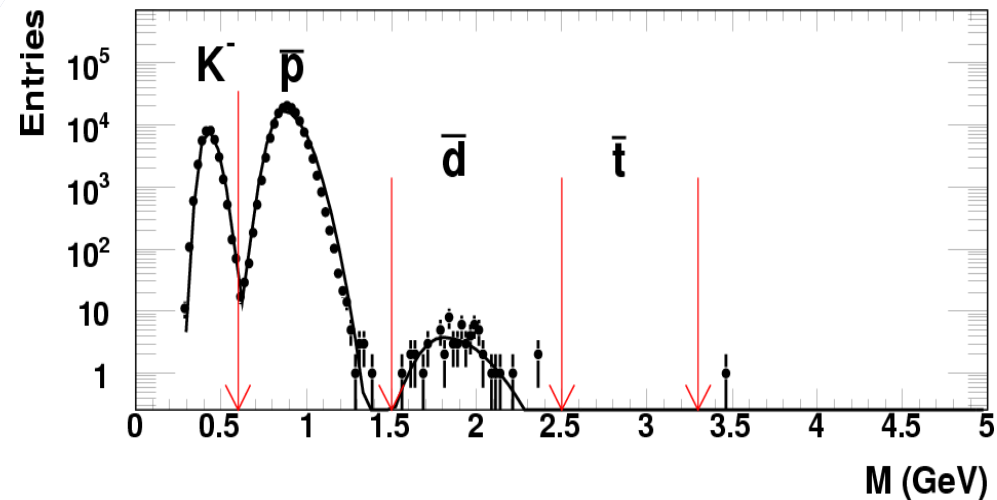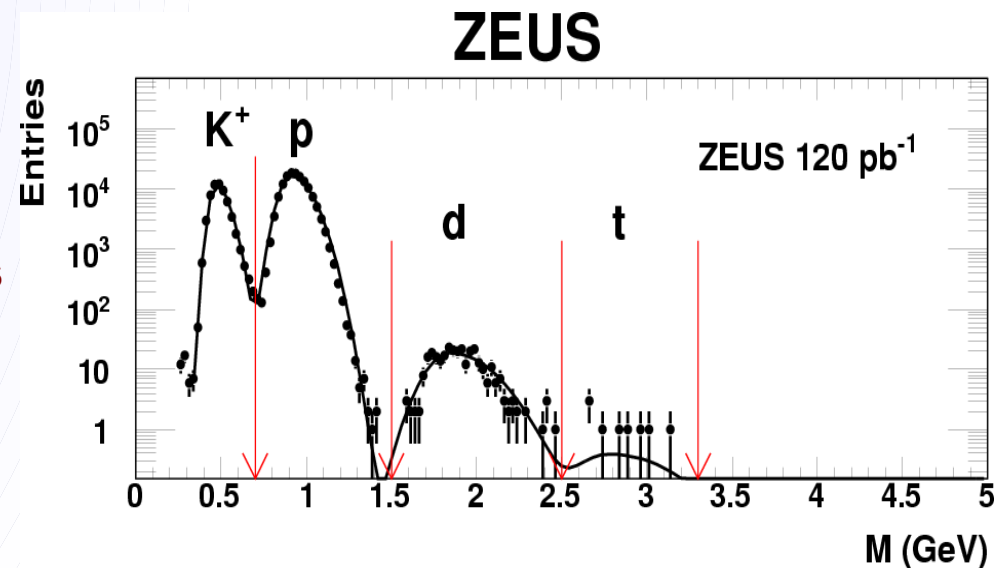
Mass requirements for candidates:

- p : 0.7 (0.6) < M < 1.5 GeV
- d : 1.5   < M < 2.5 GeV
- t : 2.5   < M < 3.3 GeV

Numbers of candidates:

d:	309
$\overline{d}$	62
p:	1.61×10^5
$\overline{p}$:	1.66×10^5

more $\overline{p}$ than p
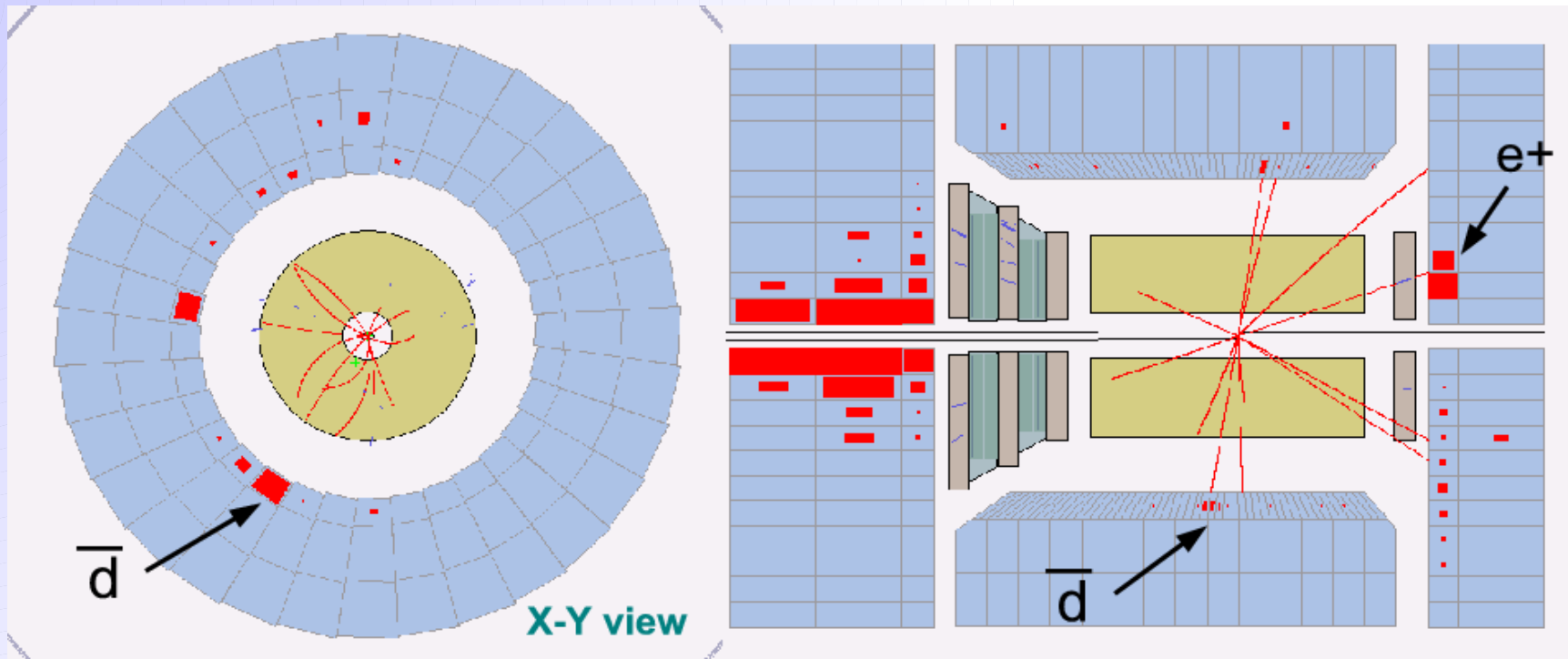due to CTD efficiency

No (anti)deuteron candidates are found
in the current region of the Breit frame
(analogous to a single hemisphere of e+e-)
No contradiction with low rate of $\overline{d}$ in e+e-

Final identification of primary particles
is based on ΔZ and DCA distributions

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DIS event with antideuteron

X-Y view

First observation of $\bar{d}$ in DIS
$\bar{d}$ annihilates on the surface of CAL

Q^2 = 45.5 GeV^2
E_e = 14.1 GeV
12 primary tracks
p =1.1 GeV
dE/dx=2.7 mips
E_{CAL} = 3.2 GeV
DCA=-0.09 cm

ZEUS interaction region:
- Beam-pipe: Al
        D=324 mm.
        thickness=1.5 mm
- CTD inner wall:
        2 Al skins with thickness 0.7 mm

**Small amount of inactive material
compared to other experiments (~0.03X0)**

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Identification of particles from ep

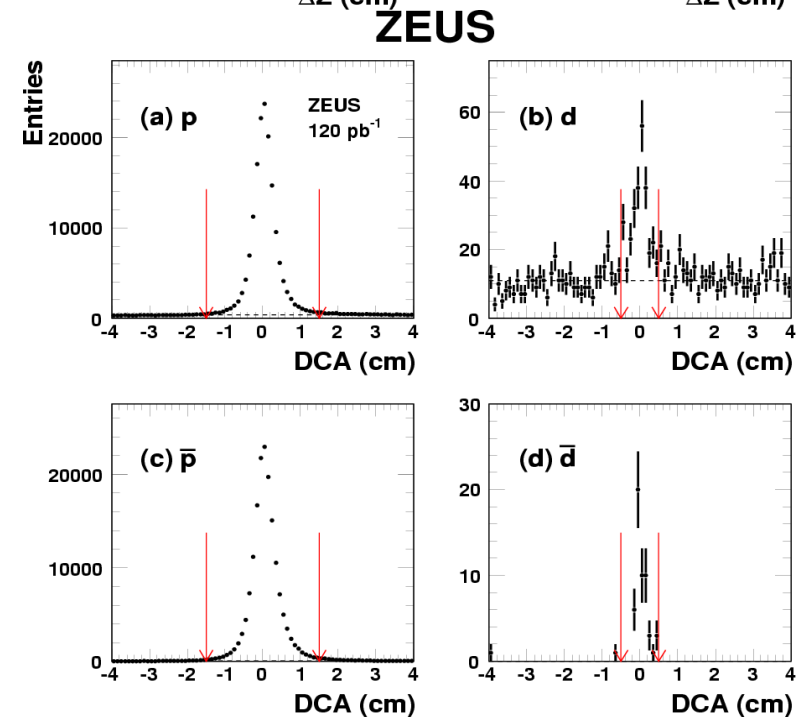**Clear peaks for ΔZ & DCA distributions due to primary ep particles**

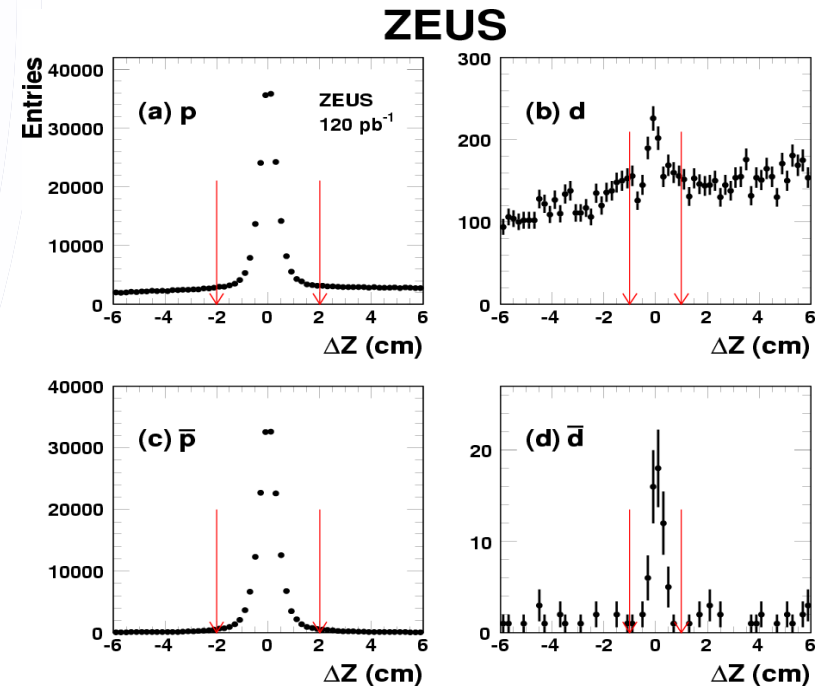- dE/dx mass cuts to identify particles
- |ΔZ|<2(1) cm for p (d) to reduce background
- DCA (best resolution!) background subtraction to reconstruct primary particles

Tracking efficiency:

- d implemented in MC
- For p and d using MC: ε~0.95; For $\bar{p}$: ε~0.90
- For $\bar{d}$: $\varepsilon(\bar{d})$~ $\varepsilon(d)\varepsilon(\bar{p})$ / $\varepsilon(p)$~0.9
  - GEANT/GHEISHA does not treat $\bar{d}$!
- Validate using few models for inelastic nuclear cross section
- Annihilation of $\bar{d}$ was found to be small (<5%):
  - beam-pipe + CTD inner wall: ~3%X0

dE/dx efficiency:

- ~ 70% in average
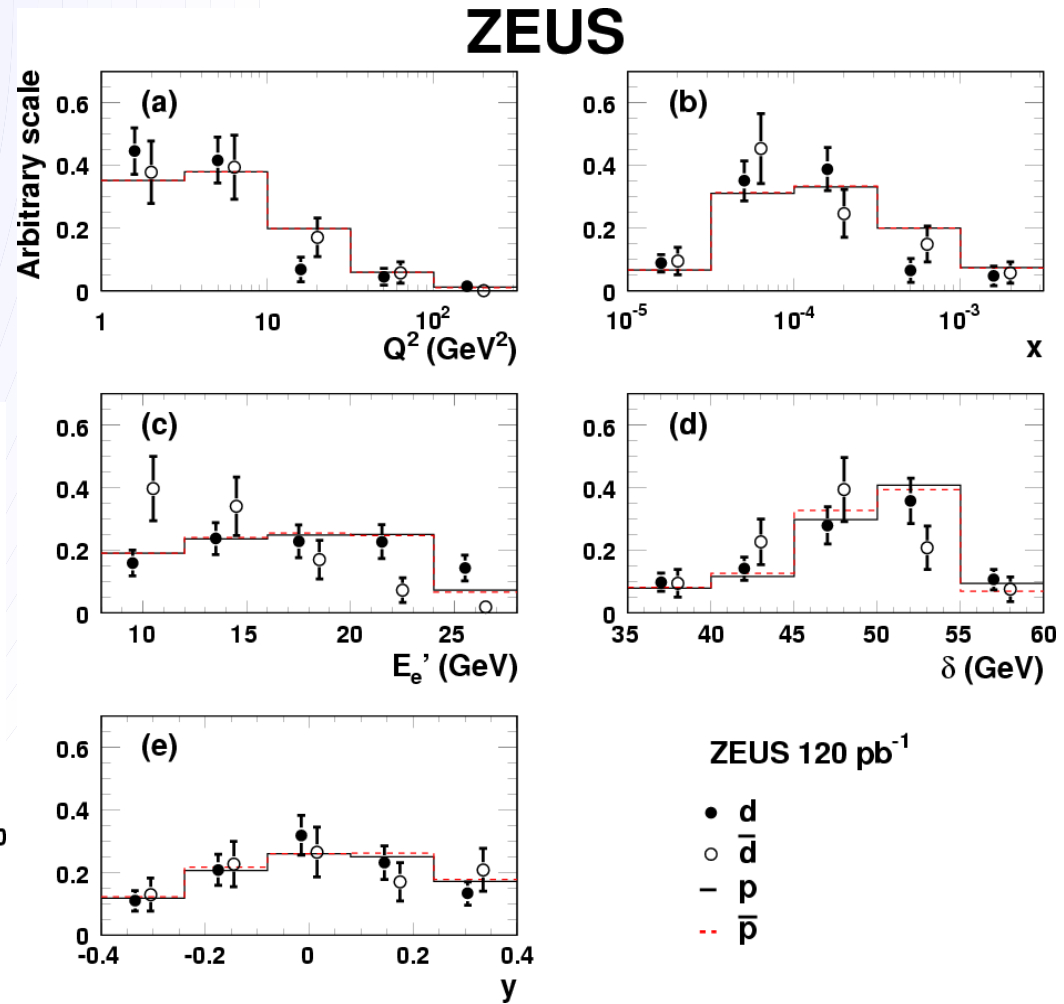- estimated using Λ→pπ and MC (as a cross check)
- MC was used to confirm
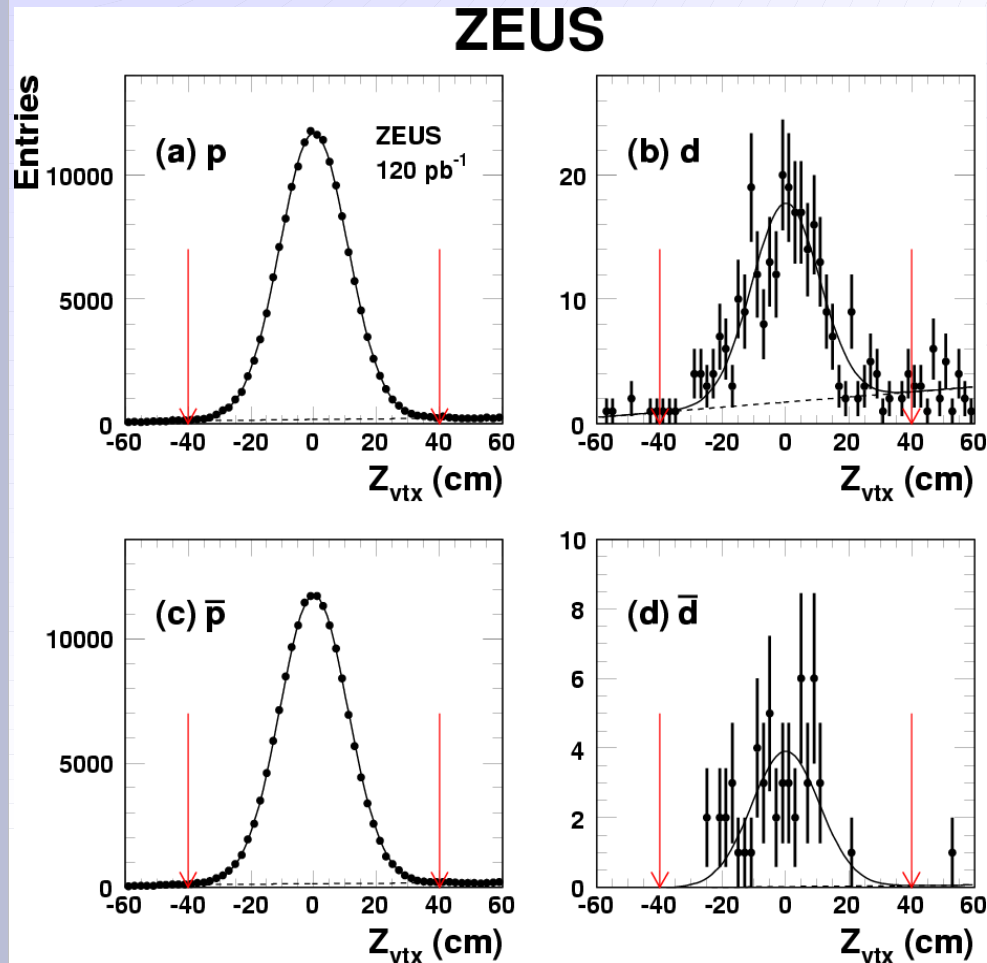
Clear peaks for Z_{vtx} distribution

Almost background free

Small background for Z_{vtx} consistent with being contribution from:
- secondary interactions (from MC studies)
- electron-gas events?

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Events with d are consistent with being DIS events (with p and $\bar{p}$)

**Some small difference for $\bar{d}$ compared to proton sample**

Difference between the production yields of $\bar{d}$ and d after the DCA background subtraction is difficult to explain by the tracking efficiency

Possible background sources:
- beam-gas interactions
- secondary interactions of particles from ep

Beam-gas interactions (eA, pA)

- Expected to be negligible for DIS

- All DIS distributions for d looks as expected

  - clean peak at $Z_{vtx}=0$

- Beam-wall events are removed using tight cut on transverse component of the primary vertex

- Events were visually analysed using an event display

- Beam-gas events were studied for non-colliding bunches

  - No peak at $Z_{vtx}=0$

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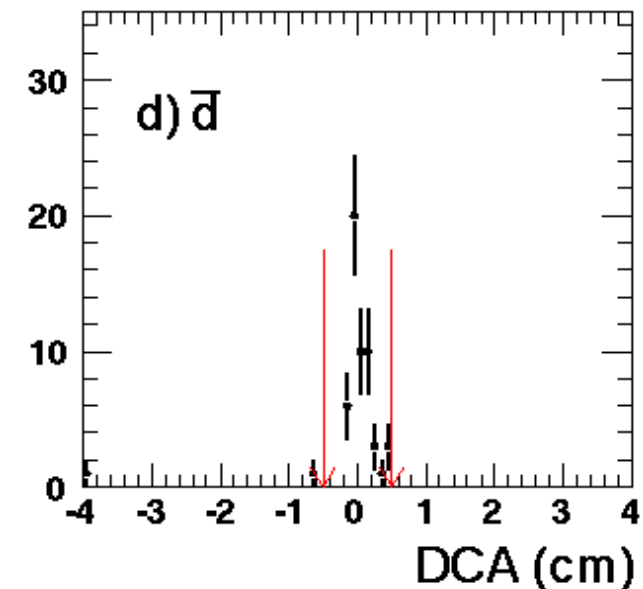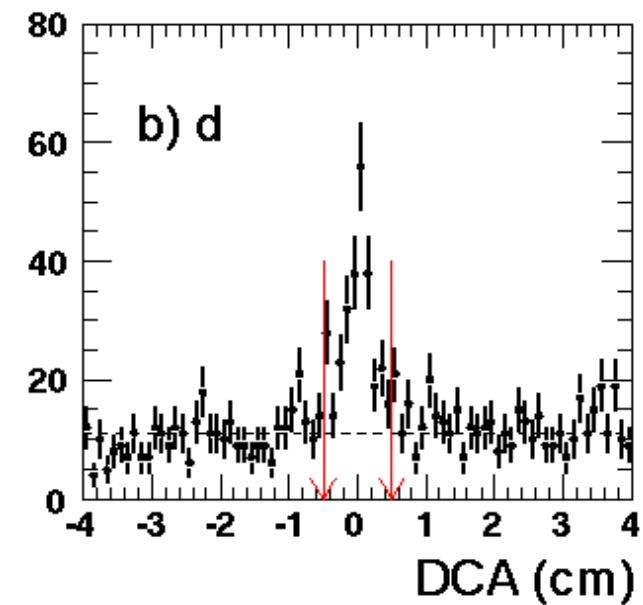
Secondary interactions on material

- MC (GEANT) does not show any peak at ΔZ=0 and DCA=0 for secondary d and p

- DCA widths for d and d̄ are statistically consistent.

- DCA width for d is also consistent with that for p (p̄)

- Pickup processes p+n→d (one nucleon from material) were studied from previous experiments:

  - DCA is expected to be significantly wider

  - absolute rate is difficult to verify

- N+N→d +π (one nucleon from material)
  - No enhancements for:
    – track multiplicity compared to d̄ events
    – tracks close to d

- HERAII data analysed with a larger amount of inactive material in from of the CTD
  - consistent d̄/d ratio with HERAI was found

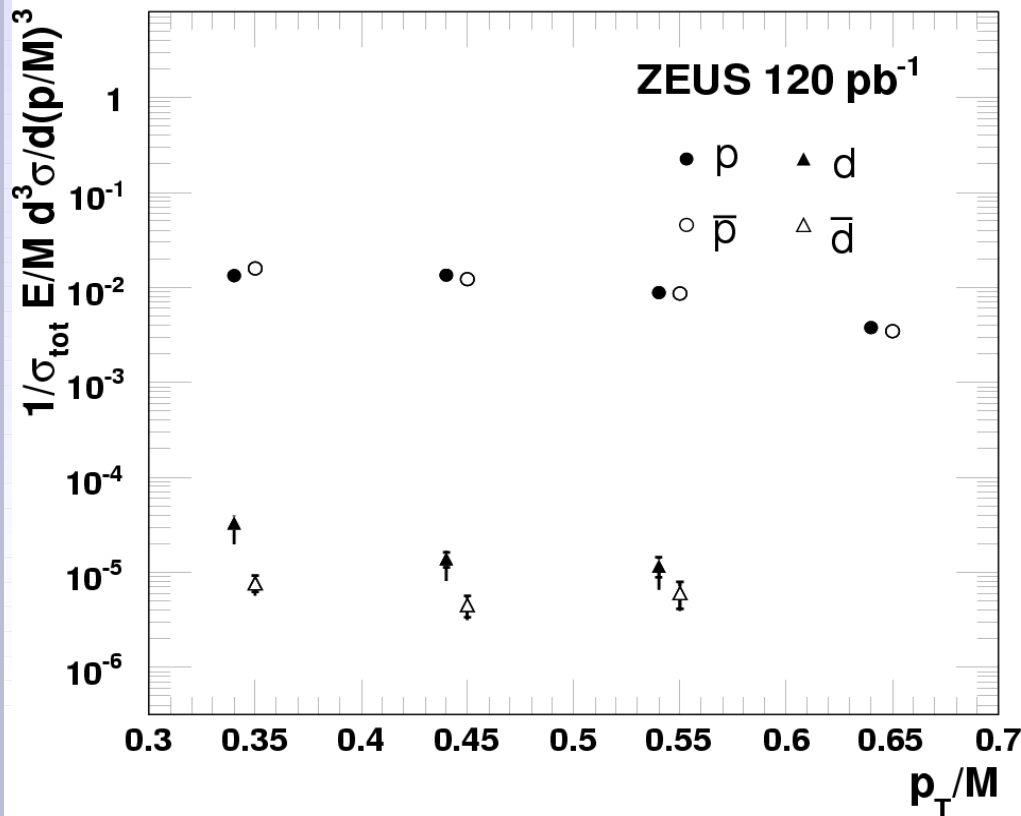**No experimental evidence for d originating from secondary/beam-gas interactions found**
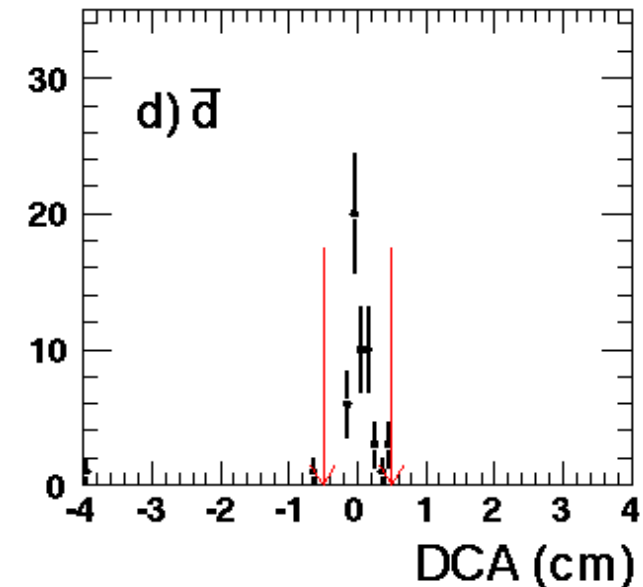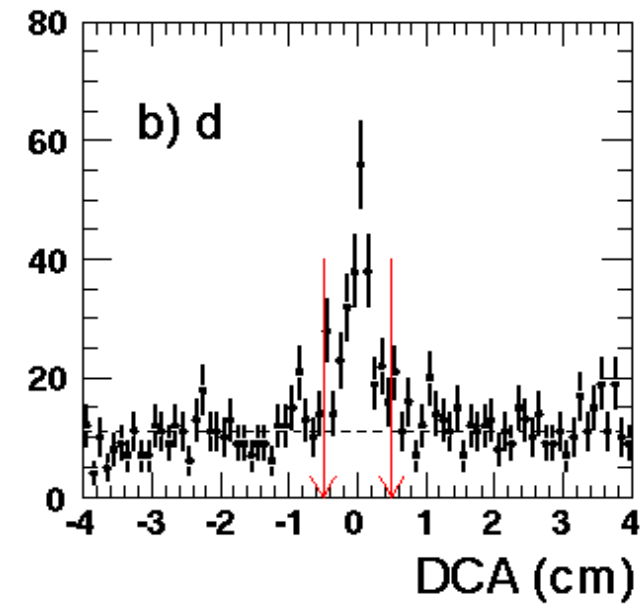
- **Deuteron yield suppressed by a factor of about 1000 (relative to protons)**
- **Good agreement for B_2 between DIS and photoproduction (H1)**
- **Some systematic difference in the production rate of d and $\overline{d}$**

$$\frac{E_d}{\sigma}\frac{\mathrm{d}^3\sigma_d}{\mathrm{d}p_d^3} = B_2 \left(\frac{E_p}{\sigma}\frac{\mathrm{d}^3\sigma_p}{\mathrm{d}(p_d/2)^3} \right)^2$$

$$B_2 = M_p^4\, M_d^{-2}\, R^2(d/p) \left(\frac{\gamma_d}{\sigma}\frac{\mathrm{d}^3\sigma_d}{\mathrm{d}(p_d/M_d)^3} \right)^{-1}$$

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ZEUS 120 pb^{-1}

- p ▲ d
- ○ $\overline{p}$ △ $\overline{d}$

$\frac{1}{\sigma_{tot}}$ E/M d$^3\sigma$/d(p/M)^3

p$_T$/M

ZEUS

B_2 (GeV^2)

- ● d (ZEUS, $Q^2 > 1$ GeV^2)
- ○ $\overline{d}$ (ZEUS, $Q^2 > 1$ GeV^2)
- △ $\overline{d}$ (H1, γp)

p$_T$/M

$B_2 \sim r(n/p)/R^3$

B_2 world data
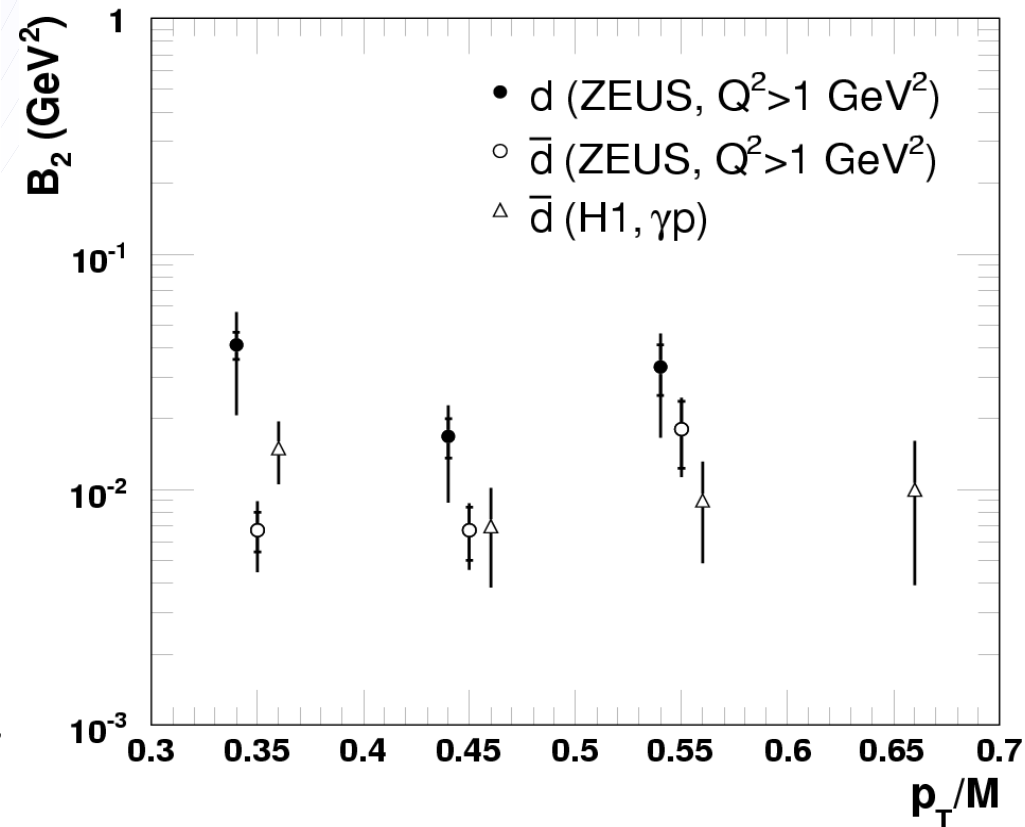
R   – source radius
r(n/p) – ratio of neutrons to protons

B_2 in DIS and photoproduction are consistent
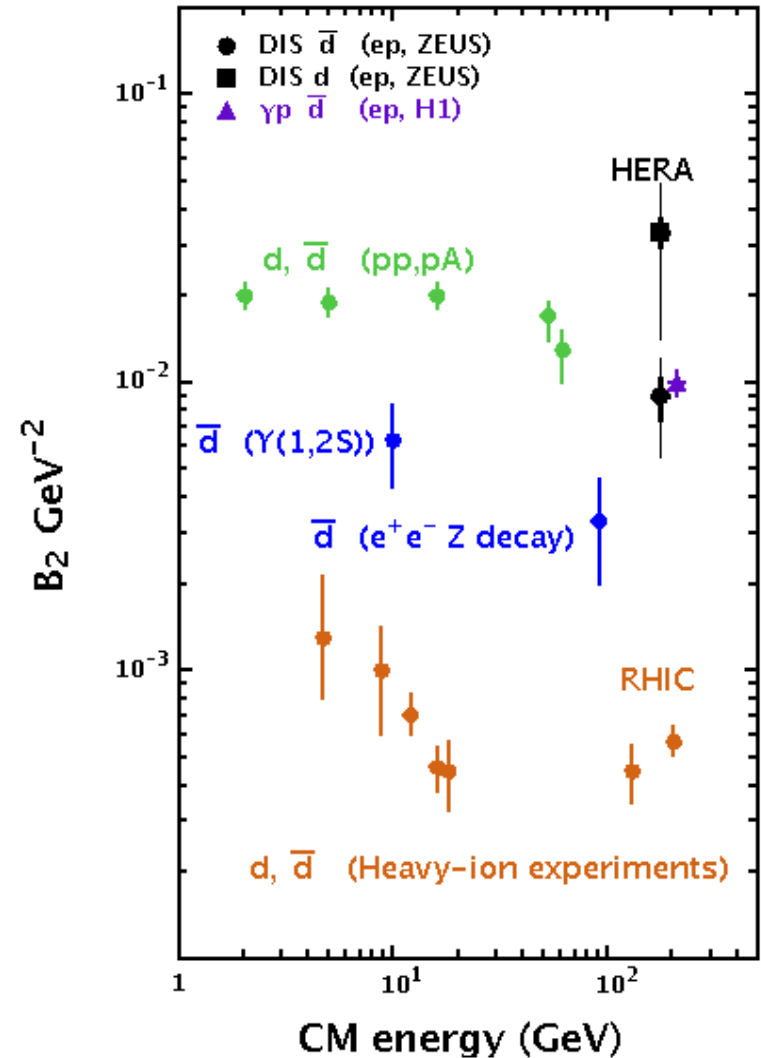
B_2 in ep is significantly larger than in heavy-ion collisions and $e^+ e^- \rightarrow q\bar{q}$

➡ **Smaller source radius**

Assuming the coalescence model:
- indication for a smaller source radius for d compared to $\bar{d}$?
- or.. r(n/p) is larger than $r(\bar{n}/\bar{p})$?

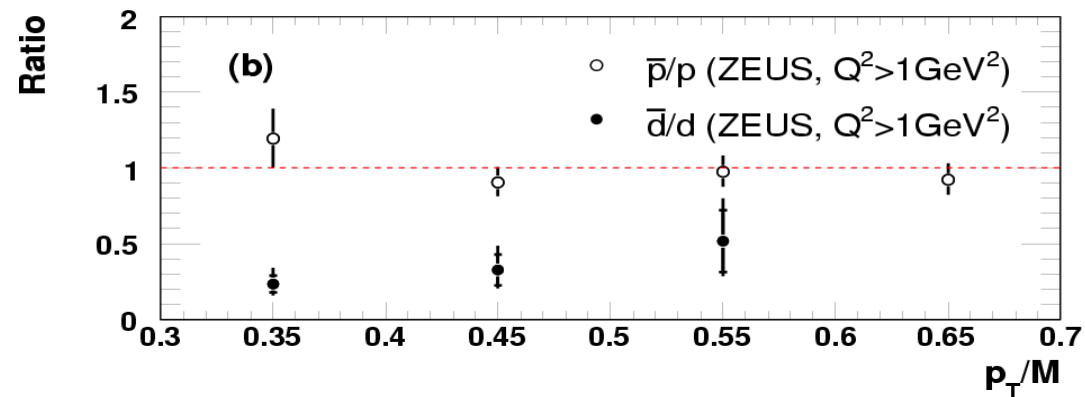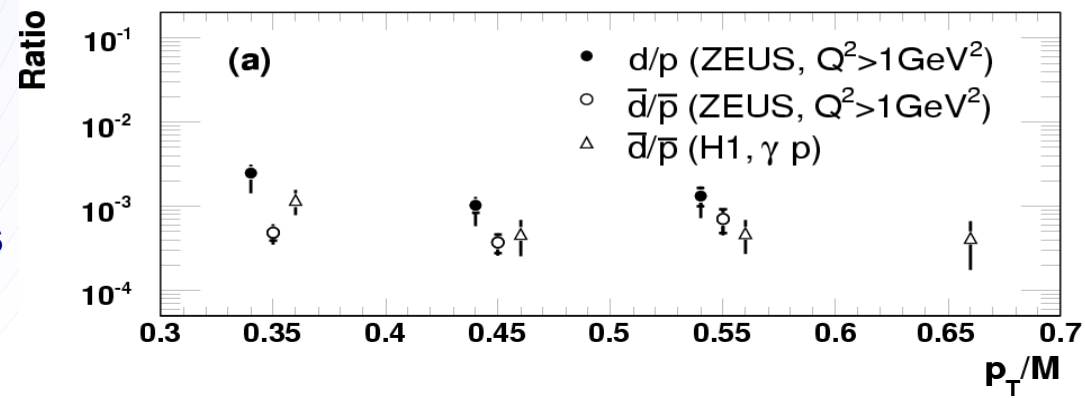*S.Chekanov: (anti)deuteron production at HERA*

Ratios

- **Look at particle/antiparticle yields directly**
  - Remember: for the coalescence model: $\bar{d}/d = (\bar{p}/p)^2$ **(*)**
- **Good agreement between $\bar{p}$ and p yields for 0.3<p_T/M<0.7**
- **Systematic difference in yields between d and $\bar{d}$**

- **For many heavy-ion and pp experiments, the rate of d is indeed higher than that for $\bar{d}$, but agrees with (*)**
- **Assuming that background processes do not produce a peak at DCA=0 →**
  $$\bar{d}/d < 1$$
  - **does not support (*)**
- **Open questions:**
  - Does this contradict other measurements?
  - Does this contradict theoretical expectations?

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(a)
- • d/p (ZEUS, Q^2>1GeV^2)
- ○ $\bar{d}/\bar{p}$ (ZEUS, Q^2>1GeV^2)
- △ $\bar{d}/\bar{p}$ (H1, γ p)

(b)
- ○ $\bar{p}$/p (ZEUS, Q^2>1GeV^2)
- • $\bar{d}$/d (ZEUS, Q^2>1GeV^2)

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$\bar{d}/d < 1$ contradicts to what we know?

Experimental situation:

- **No d measurement in collisions with elementary particles:**
  - ARGUS (e+e-). No DCA available, only $\bar{d}$ can be measured
    Phys.Lett. B236 (1990) 102
  - ALEPH (e+e-). DCA too complicated without a clear background level (spallations?)
    Phys.Lett. B639 (2006) 16
  - OPAL did not find antideuterons. Sets a limit.
  - H1 (γp). No deuteron measurement due "background" (beam-gas?)
    Eur. Phys. J C36 (2004) 413
  - CLEO (e+e-). No deuteron measurement, only checks for "consistency"
    hep-ex/0612019

- **All other measurements done in heavy-ion and pp, pA experiments:**
  - **all indicate $\bar{d}/d<1$, but usually consistent with $(\bar{p}/p)^2$**

Theoretical remarks:

- **No theory for deuteron production from "first principles"**
- **Open questions for the coalescence model:**
  - B_2 for e+e- is a factor ~5-10 suppressed compared to hadronic and photonic collisions (including the present result)
  - The only model for elementary collisions (G.Gustafson & J.Hakkinen) fails

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Conclusions

- **First observation of $d(\bar{d})$ in DIS**

- **First measurement of d in collisions with elementary particles**

- **Rates are three orders of magnitude suppressed relative to protons**

  - consistent with the world measurements

  - ~5-10 times higher compared to e+e-

- **Yield of p is consistent with that for $\bar{p}$ for $0.3 < p_T/M < 0.7$**

  - ~12% experimental uncertainty

  - difficult to verify models predicting 4-8% p-$\bar{p}$ asymmetry

- **Rate of d is ~3 times larger than that for $\bar{d}$**

  - no evidence for d originating from secondary/beam-gas interactions found

- **Production rates were studied in terms of the coalescence model:**

  - invariant cross sections and B_2 are consistent with results in photoproduction (H1)
  - significantly smaller production volume compare to AA