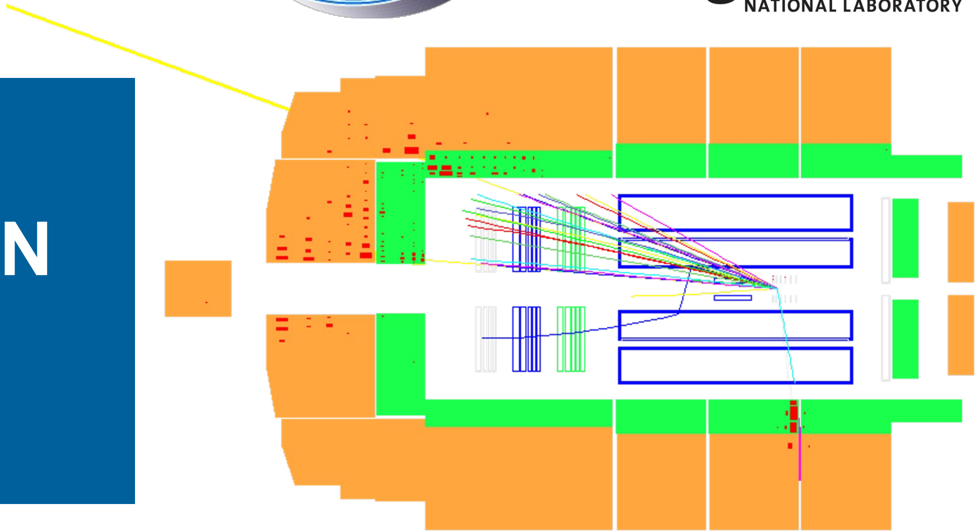
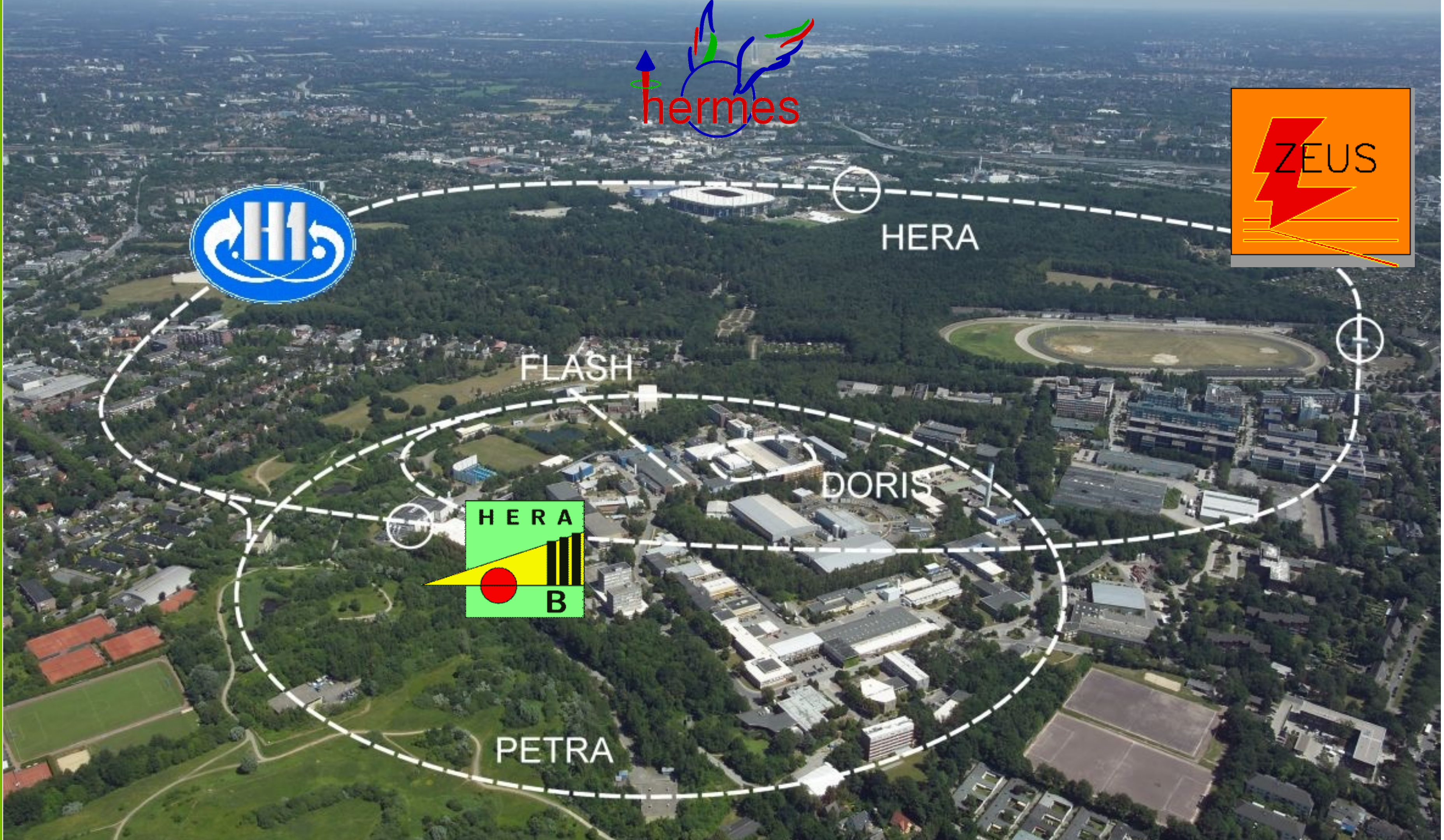
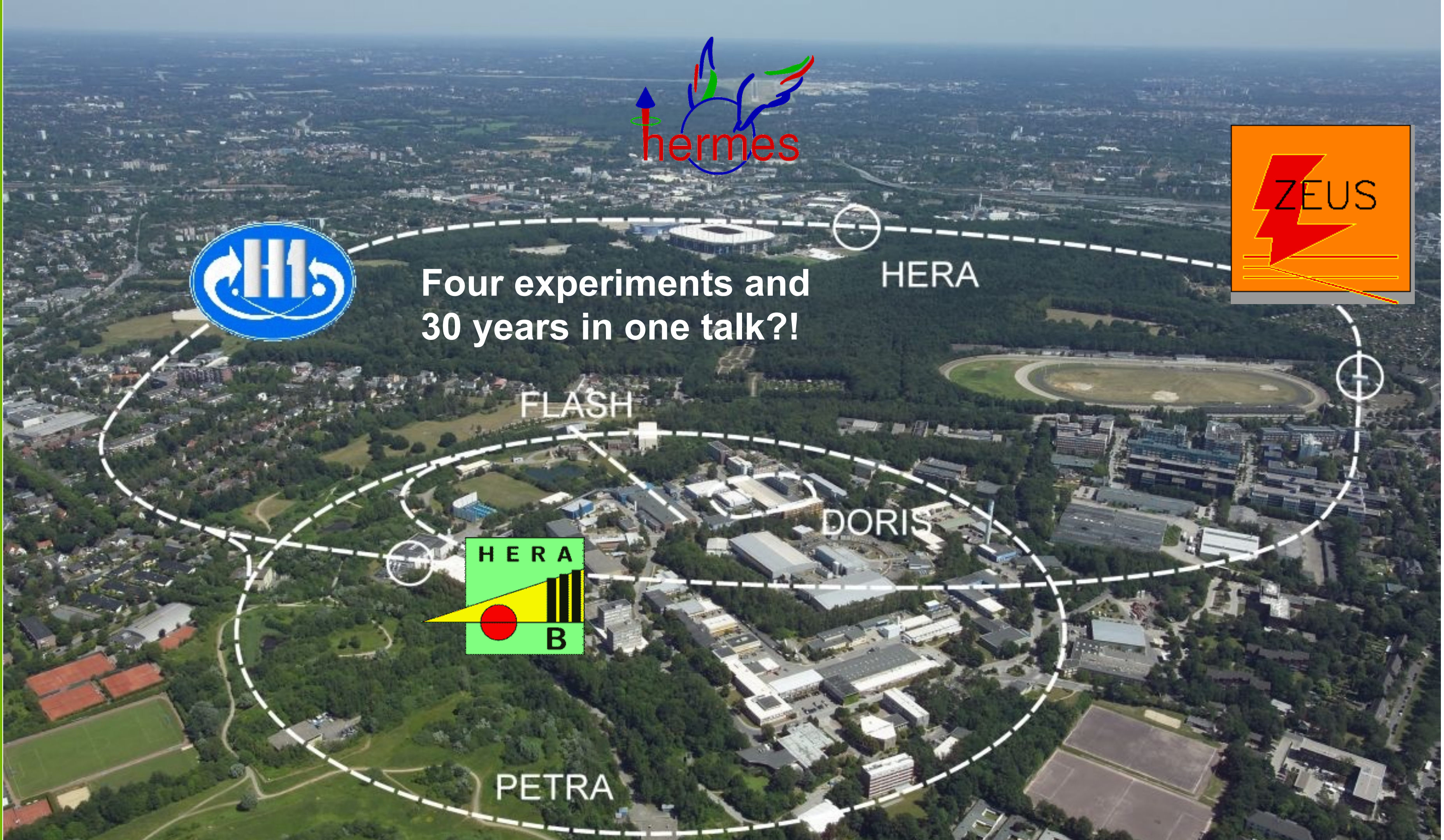
BARYON PRODUCTION AT HERA



HENRY KLEST

1st CFNS Workshop on Baryon Dynamics, SBU Jan 23, 2024


hermes
ZEUS
HERA
FLASH
DORIS
HERA
B
PETRA


Four experiments and
30 years in one talk?!
hermes
ZEUS
HERA
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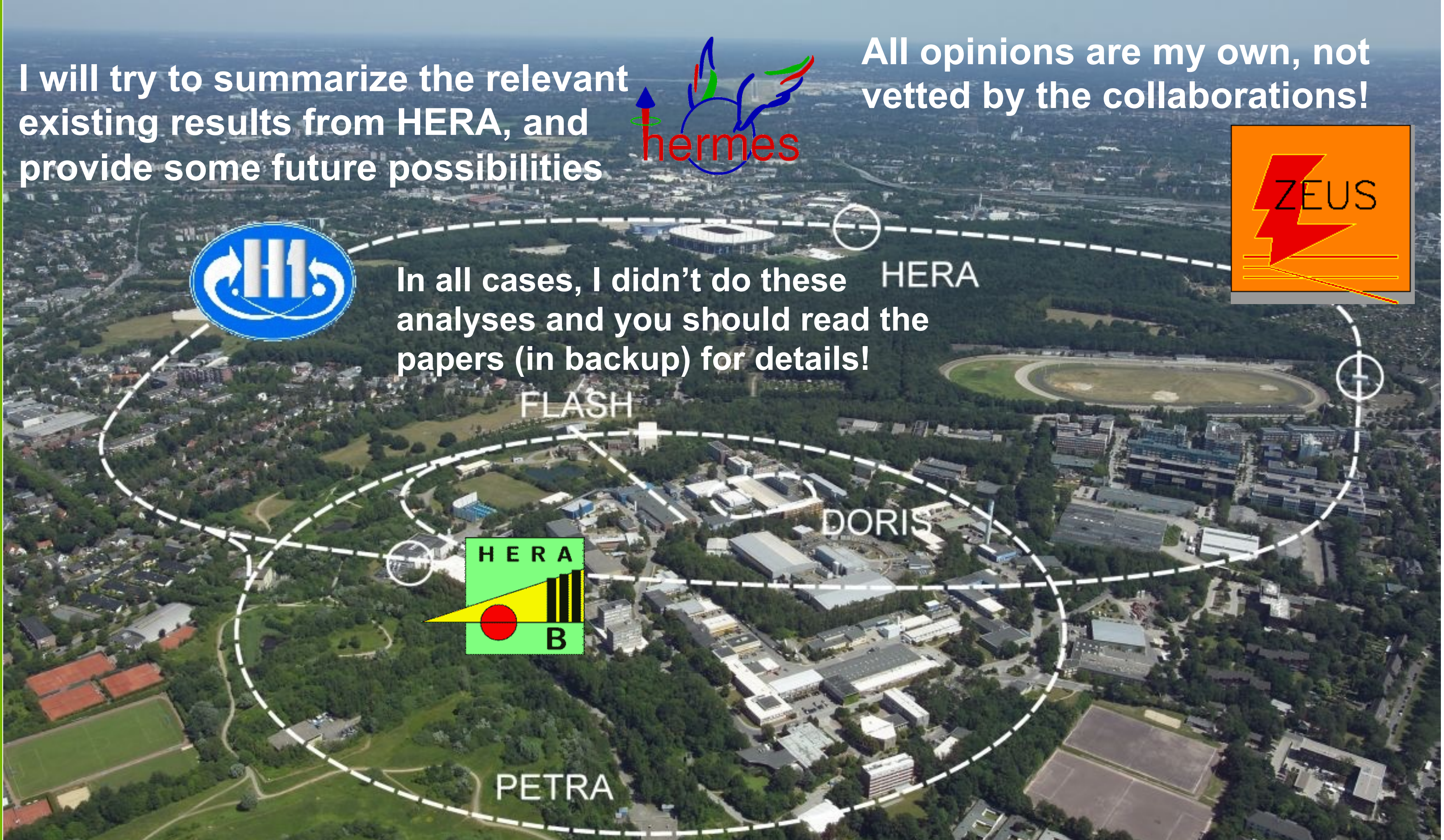
I will try to summarize the relevant existing results from HERA, and provide some future possibilities

All opinions are my own, not vetted by the collaborations!

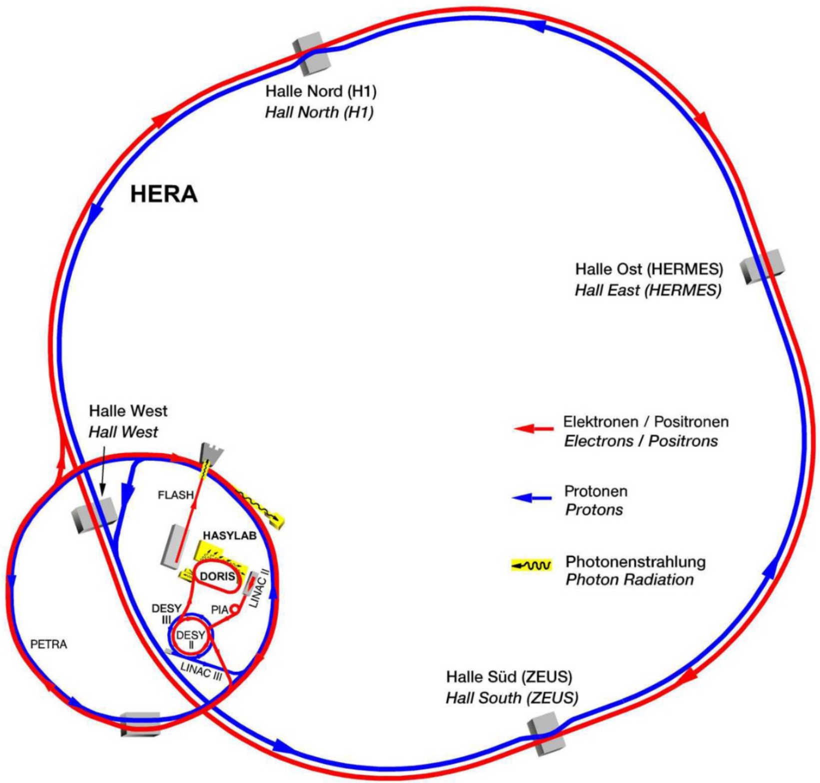
In all cases, I didn't do these analyses and you should read the papers (in backup) for details!



HERA

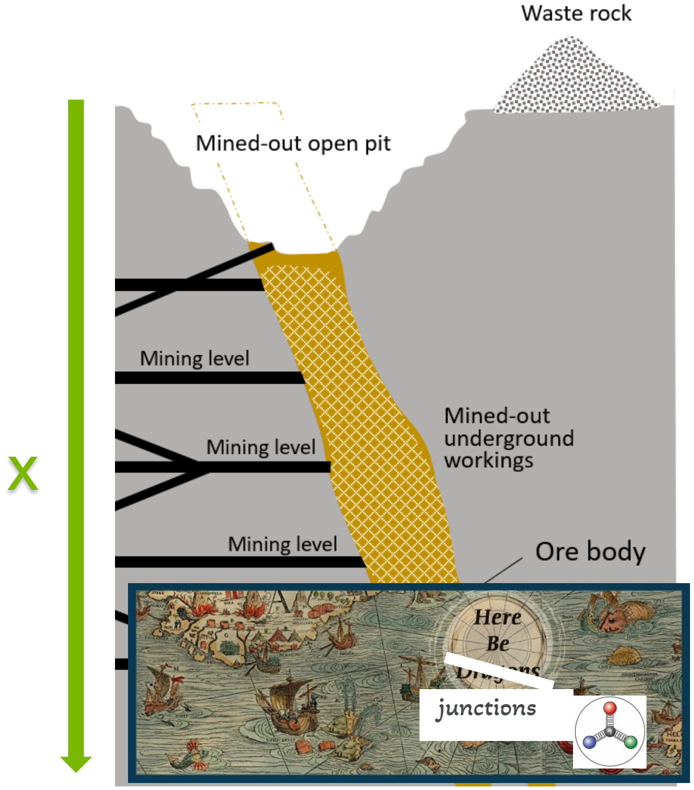
*HERA: **H**adron-**E**lektron-**R**ing**a**nlage*
*Hadron-**E**lectron **R**ing **A**ccelerator*

- World's only electron + proton collider
- Located at DESY in Hamburg, Germany
  - Nominal energies of 27.6 GeV $e^{-,+}$ on 920 GeV protons
  - $\sqrt{s} = 319$ GeV
- Ran from 1992-2007
  - Delivered ~1 fb^{-1} of e+p collisions to the two general purpose experiments, H1 and ZEUS
- Two fixed-target experiments
  - Hermes, utilizing electron beam
  - HERA-B, utilizing proton beam



WHY HERA?

- Several aspects make the HERA experiments an interesting place to mine for junctions
- Can reach low-x (and know you were there!)
  - Valence quark contribution can be controlled with kinematics
  - Current & target fragmentation can be easily separated
  - Knowing event-by-event kinematics enables studying observables as functions of x, Q^2, p_T, y, η,etc…
- Photoproduction & DIS both available
  - Photoproduction provides a “hadronic” probe that carries no baryon number itself

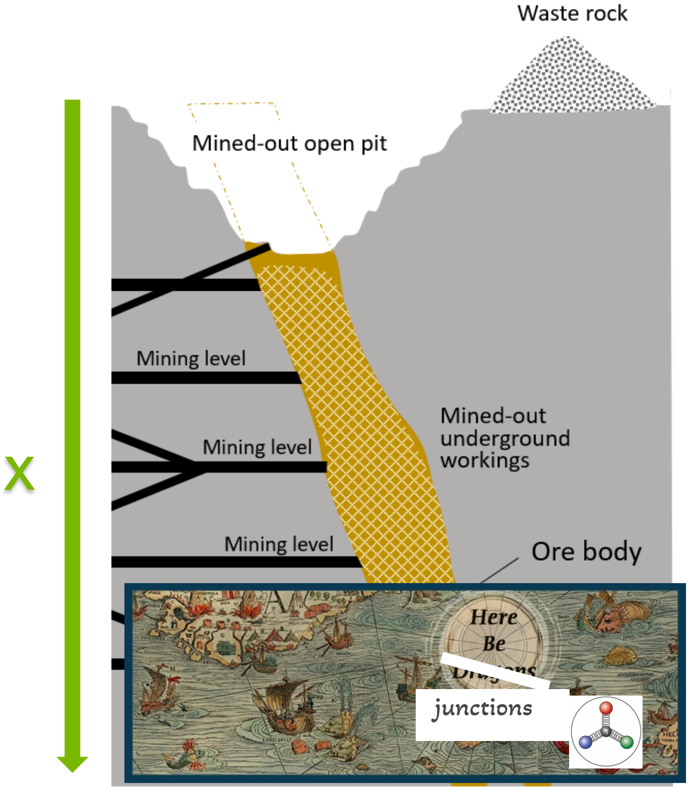


WHY HERA?

- Beam species asymmetry
  - Baryon number enters from one side only*
  - No forward-backward ambiguity as in p+p

- Diffraction
  - Know that baryon number was not transported in diffractive collisions
  - Can be used as a baseline

- Large detector acceptances
  - Good reach in rapidity
    - Especially in rapidity loss δy
  - Variable proton beam energy
    - 920, 820, 575, 460 GeV data exist



*This feature exists also in the $\pi + p/A$ collision system, begs revisiting fixed-target data

HERA STRATEGY

- An e+p collision has total baryon number of 1
  - Reduces complexity and ambiguity of observables
- Likelihood of striking a valence quark (or di-quark) and transporting it to midrapidity is small in DIS at HERA
  - Very high-x events, cross section tiny
  - HERA cross section dominated by low-x
- An observation of a non-zero baryon-antibaryon asymmetry at low-x would be a strong indication in favor of the junction model
  - Non-zero asymmetry in current region of Breit frame would indicate the same

Baryon Stopping at HERA: Evidence for Gluonic Mechanism

Boris Kopeliovich[1,2] and Bogdan Povh[1]

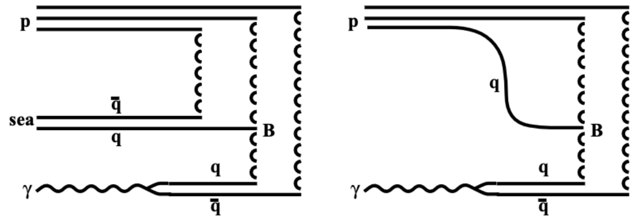
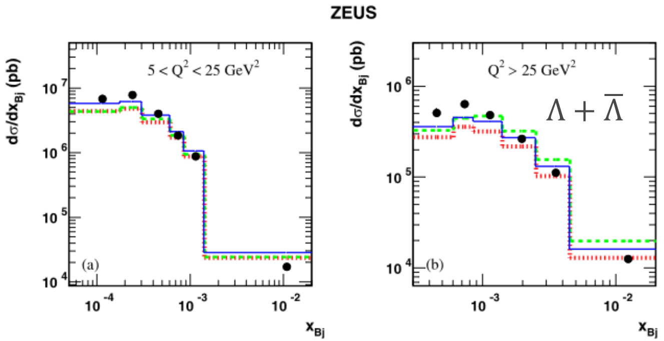


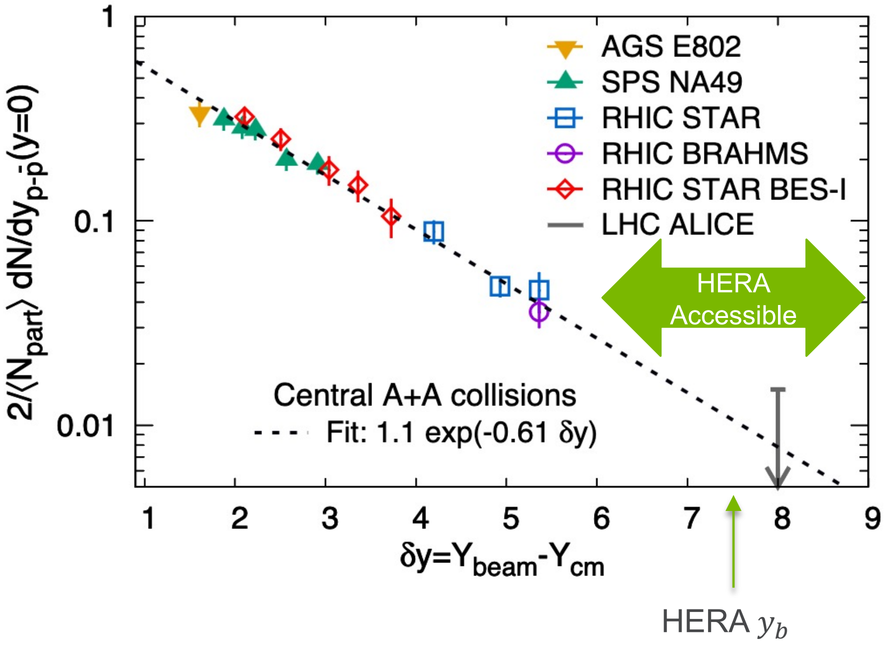
Figure 1: *Multiparticle production corresponding to the gluonic mechanism of BN transfer in $\gamma - p$ interaction. The BN is produced with the rapidity of the sea quark (left)*

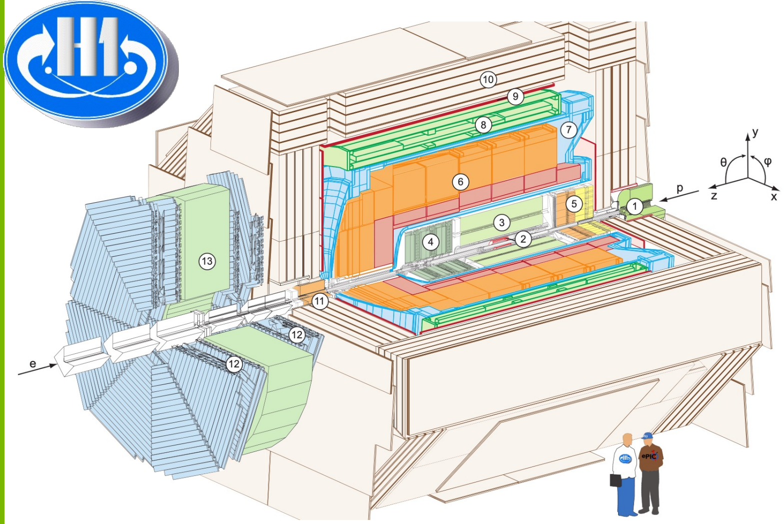
The same as on the left, but for the valence quark mechanism. BN has the rapidity of the valence quark (right).



HERA STRATEGY

- Expectation from A+A results is that at HERA rapidities, asymmetry should be very small
  - $y_{beam} = 7.5$ for H1 & ZEUS
  - δy between beam and central detectors ~ 6-9
  - A+A fit gives $1.1 * e^{-0.61*\delta y}$
  - Expected asymmetry of 2% - 0.4%
- However, A+A results generally integrate over x
  - e+p offers much better control
  - A 1% asymmetry could be built out of e.g. 0% at mid/high-x and 3% at low-x




H1
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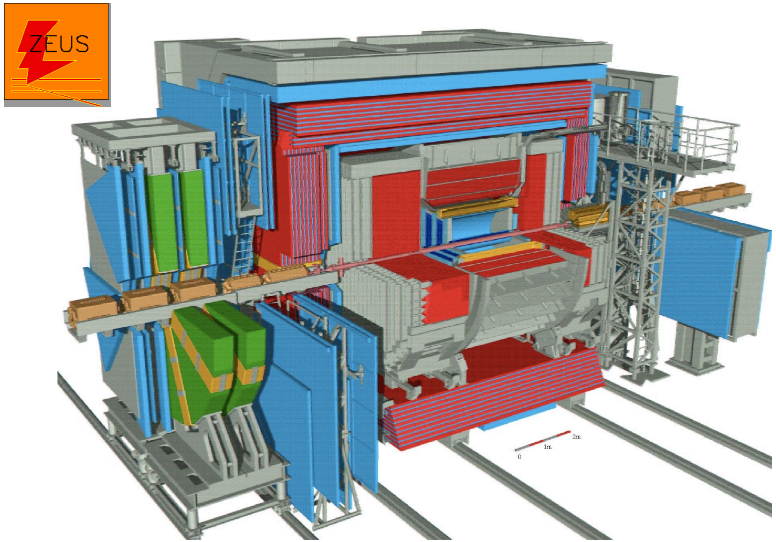
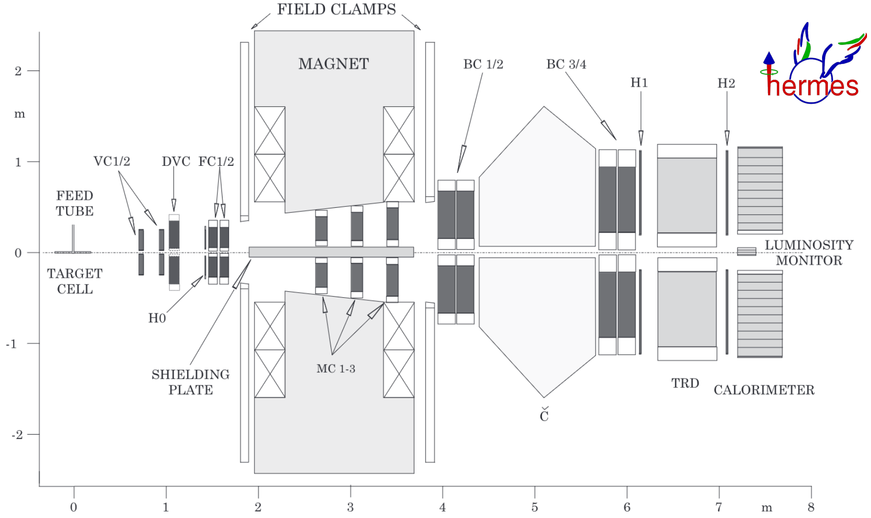

ZEUS


hermes
FIELD CLAMPS
MAGNET
BC 1/2
BC 3/4
H1
H2
FEED TUBE
TARGET CELL
VC1/2
DVC
FC1/2
H0
SHIELDING PLATE
MC 1-3
Č
TRD
CALORIMETER
LUMINOSITY MONITOR
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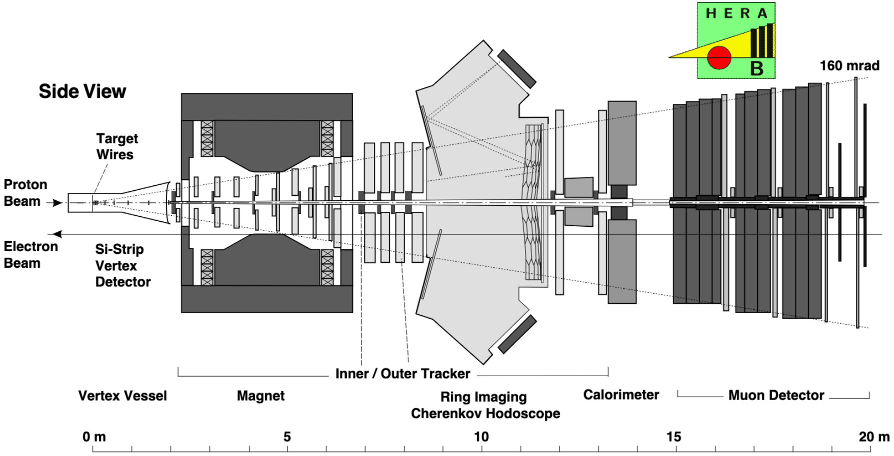
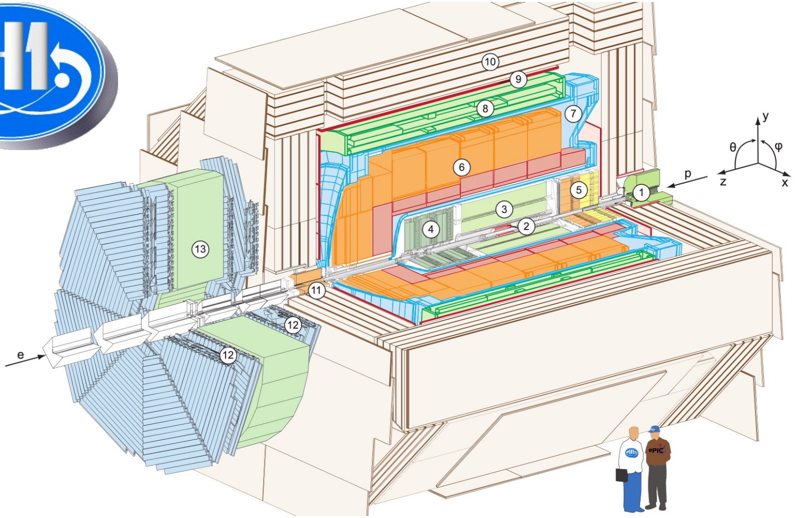
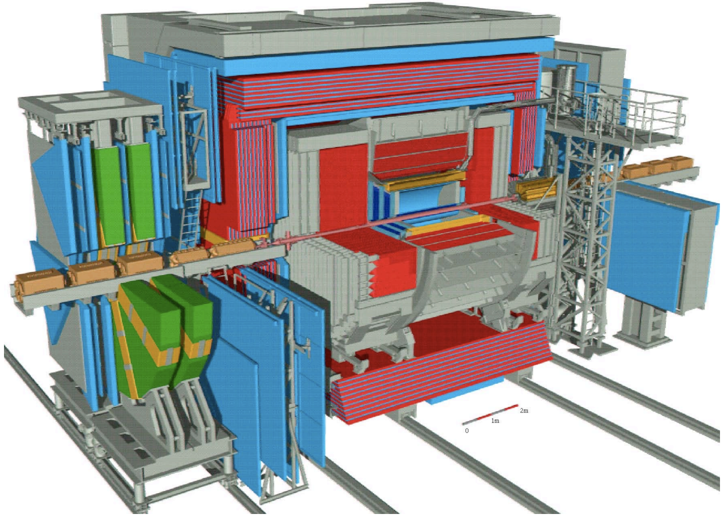

HERA
B
Side View
160 mrad
Target Wires
Proton Beam
Electron Beam
Si-Strip Vertex Detector
Inner / Outer Tracker
Vertex Vessel
Magnet
Ring Imaging Cherenkov Hodoscope
Calorimeter
Muon Detector
0 m
5
10
15
20 m

H1 & ZEUS

- General-purpose hermetic detectors
  - Focus on calorimetry & tracking
  - PID only from dE/dx in tracking detectors
- Large acceptance
  - Unfortunately, tracking only well understood in central regions ($|\eta| \leq \sim 1.5$)
  - Still gives good control over δy
- H1 & ZEUS never published studies of identified light hadrons
  - Some pitfalls, need precise description of backgrounds, detector material
- Workhorse for baryon physics was PID via displaced vertices
  - Λ, K^0





HERA DATA PRESERVATION

- Preservation effort started in 2009
  – Miniscule investment (<1%) compared to running experiments, resulting in ~10% of the total physics results

- H1 members have been a leading force in the DPHEP collaboration
  – ”Level-4” preservation, retaining full potential to do analyses
  – Keep as much low-level information and documentation as possible, enabling “outsiders” to do analyses such as $dN_{ch.}/d\eta$
  – Full analysis software updated in 2020 to ROOT6, C++17
  – ~1B events available

Table 1. Data preservation levels defined by the DPHEP study group [2].

Level	Preservation Model	Use Case
1	Provide additional documentation	Publication related info search
2	Preserve the data in a simplified format	Outreach, simple training analyses
3	Preserve the analysis level software and data format	Full scientific analyses, based on the existing reconstruction
4	Preserve the simulation and reconstruction software as well as basic level data	Retain the full potential of the experimental data

- ZEUS falls between level 3 and 4
  – Data & Simulation NTuples
  – Pre-calibrated low level basic objects (e.g. calorimeters deposits, tracks)
  – Higher level composite objects (e.g. jets, lepton candidates)
  – 360M events

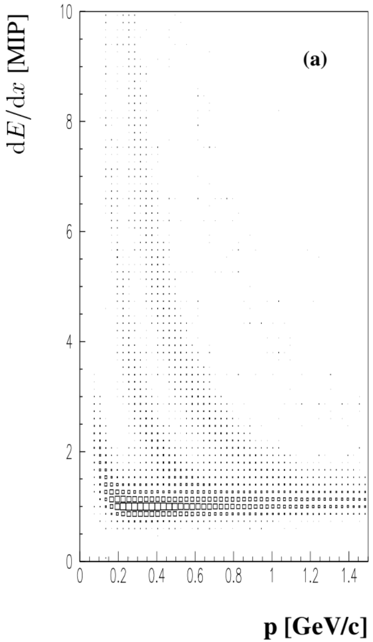
- HERMES less advanced than H1, ZEUS but still in principle analyzable

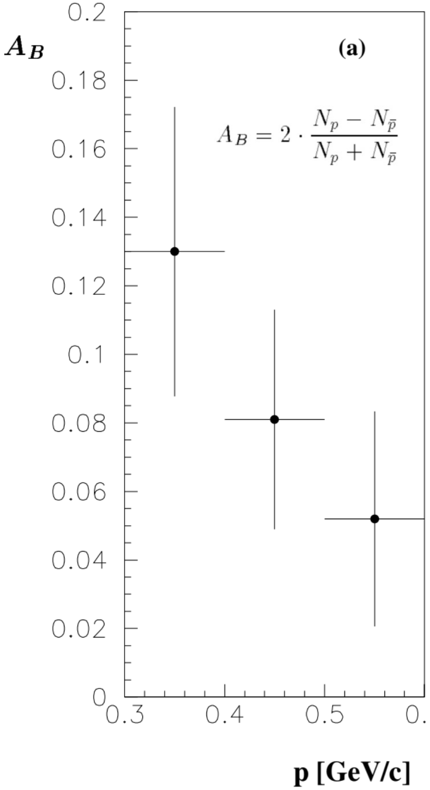
- HERA-B data essentially inaccessible

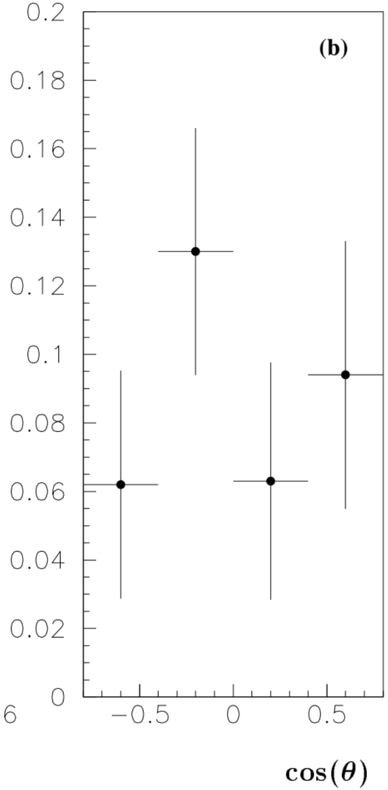
H1 PRELIMINARY

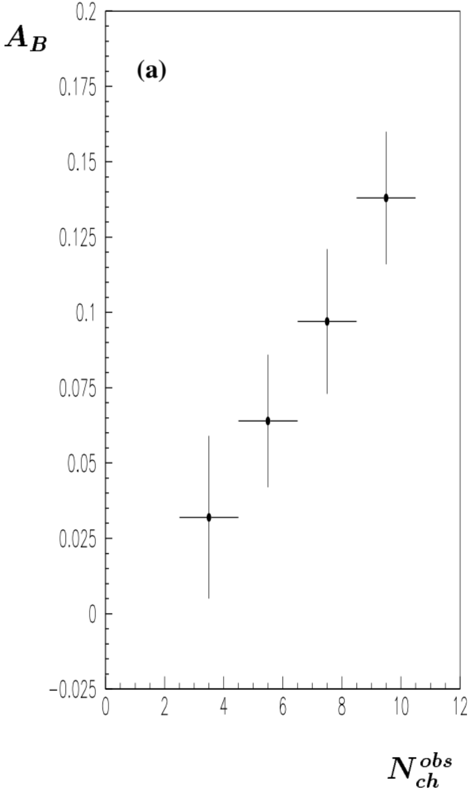
There is a much-discussed preliminary H1 result from 1999 of the proton-antiproton asymmetry

Current understanding is that this analysis suffered from large hadron beam-gas backgrounds (p+A collisions at $\sqrt{s}$ = 40 GeV) that induced the asymmetry









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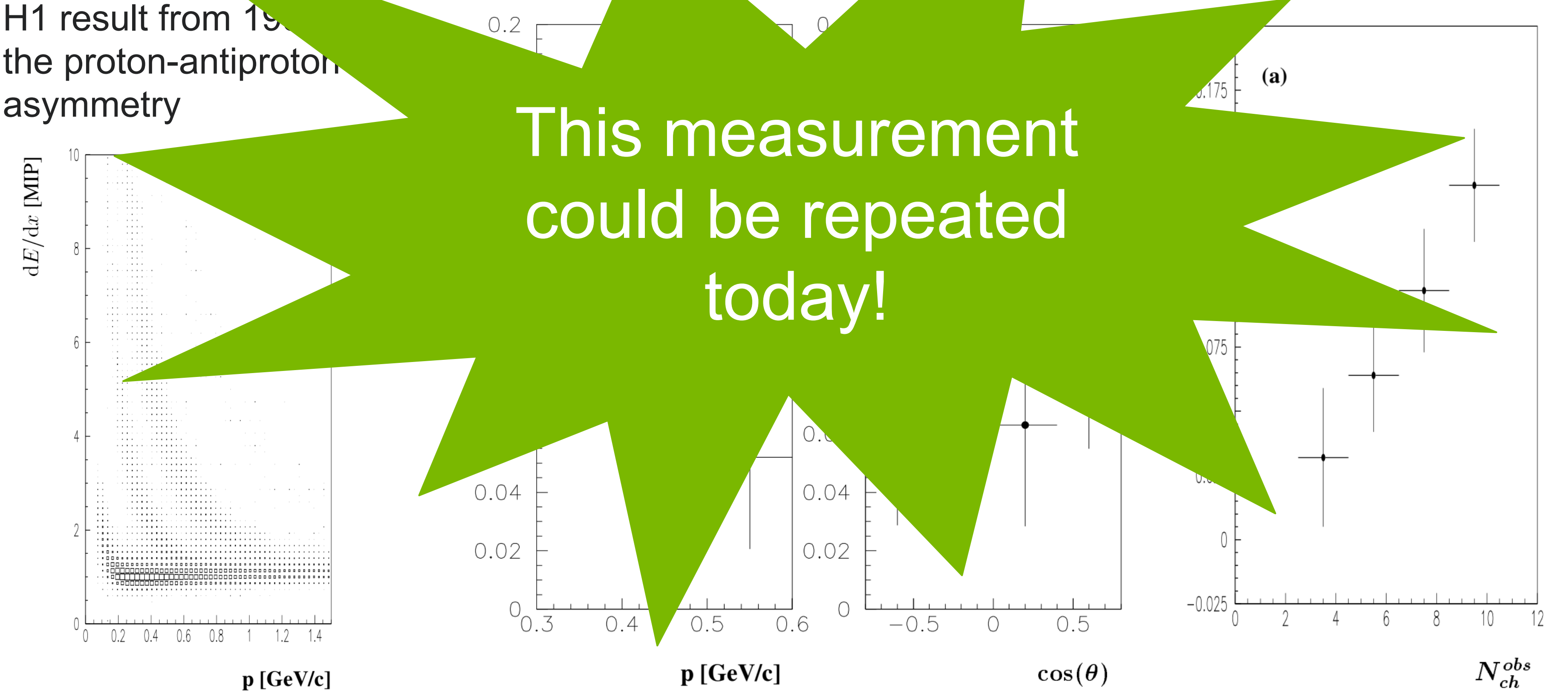
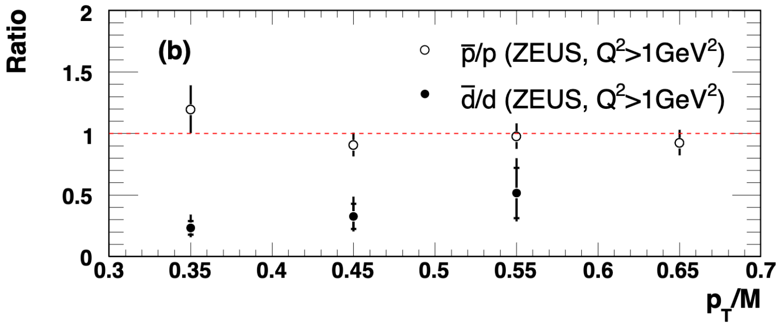


ZEUS P&D IN DIS

Measurement of (anti)deuteron and (anti)proton production in DIS at HERA

- ZEUS measured antiproton/proton and antideuteron/deuteron ratios in 2007
- Challenging measurement due to interactions with detector material
  - $p + n \to d$ and $N + N \to d + \pi$ reactions
    - Had to rely on extrapolations of cross sections from other materials using phenomenological models
- $\bar{p}/p$ ratio consistent with 1
  - Large error bars O(10%), don't have the precision to reach expected asymmetry of 7% from junction model
- $\bar{d}/d$ ratio very low, around 0.3
  - Disagrees strongly with coalescence prediction that $\frac{\bar{d}}{d} = \left(\frac{\bar{p}}{p}\right)^2$

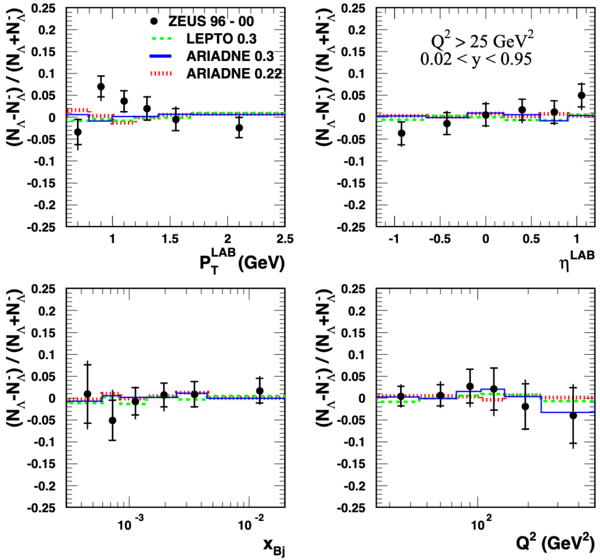


p_T/M	$R(\bar{p}/p)$	$R(\bar{d}/d)$
$0.3 - 0.4$	$1.19 \pm 0.01^{+0.20}_{-0.19}$	$0.23 \pm 0.05^{+0.09}_{-0.05}$
$0.4 - 0.5$	$0.90 \pm 0.01^{+0.10}_{-0.09}$	$0.33 \pm 0.10^{+0.12}_{-0.07}$
$0.5 - 0.6$	$0.97 \pm 0.01^{+0.11}_{-0.10}$	$0.52 \pm 0.21^{+0.19}_{-0.10}$
$0.6 - 0.7$	$0.92 \pm 0.03^{+0.10}_{-0.09}$	—
$0.3 - 0.7$	$1.05 \pm 0.01^{+0.15}_{-0.14}$	$0.31 \pm 0.05^{+0.11}_{-0.06}$

Table 5: *The measured $\bar{p}$-to-p and $\bar{d}$-to-d production ratios as a function of p_T/M. The last row of the table shows the data in the full measured phase space. The statistical and systematic uncertainties are also listed.*

STRANGE BARYONS

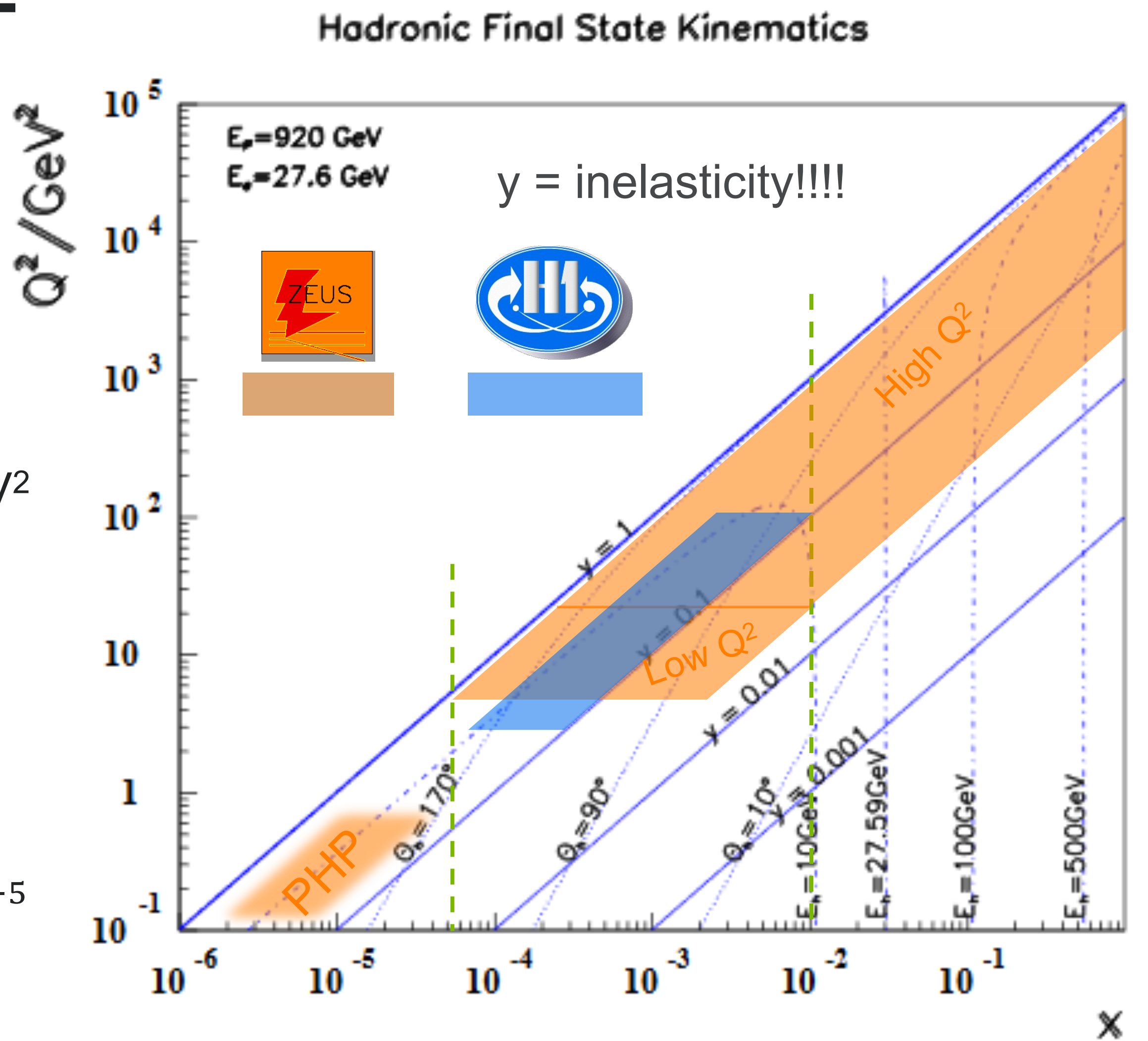
- Extensive studies of Λ & $\overline{\Lambda}$ carried out by H1 & ZEUS
  - Minimal PID necessary due to displaced vertex
  - Initially targeted toward tuning strangeness suppression in MCs
- Λ an equal probe of baryon number
  - Junction model flavor agnostic
- Hadronic interactions with detector material effect $p/\bar{p}$ ratio
  - Less the case for Λ, higher precision possible
  - HERA detectors were fairly thick



- Existing measurements of asymmetries and cross sections vs. basically every kinematic quantity you could want
  - In the lab frame and in the Breit frame (separated current & target region)

Λ MEASUREMENT PHASE SPACE

- H1: 49.9 pb^{-1}
  - $2 < Q^2 < 100$ GeV^2
  - $0.1 < y < 0.6$
- ZEUS: 121 pb^{-1}
  - Low Q^2: $5 < Q^2 < 25$ GeV^2
    - $0.02 < y < 0.95$
  - High Q^2: $Q^2 > 25$
    - $0.02 < y < 0.95$
  - Photoproduction: $Q^2 < 1$
    - $0.2 < y_{JB} < 0.85$
- Coverage in DIS: $x > 5\times10^{-5}$



Λ MEASUREMENT RESULTS

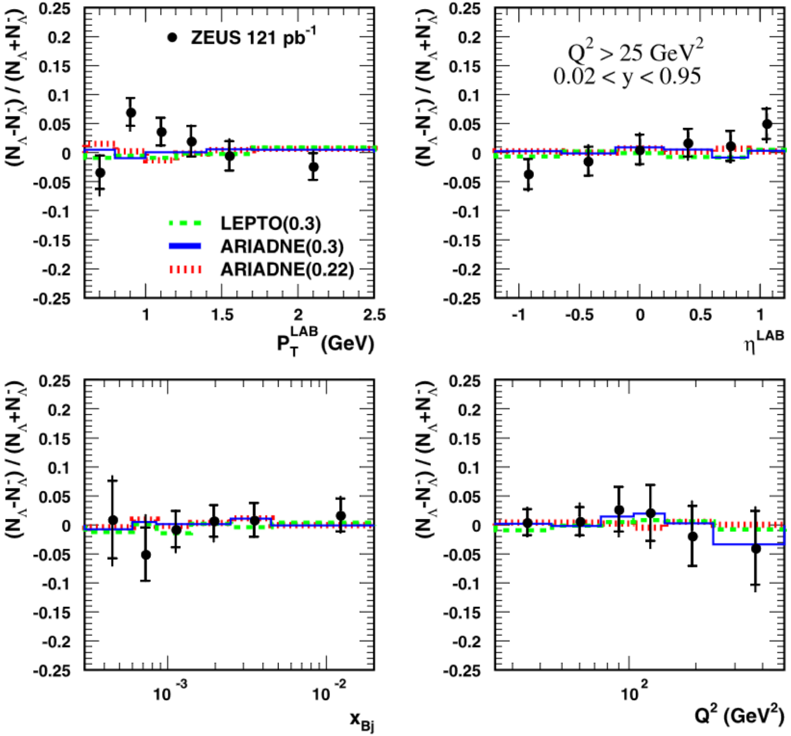
Baryon Asymmetry of the Proton Sea at Low x

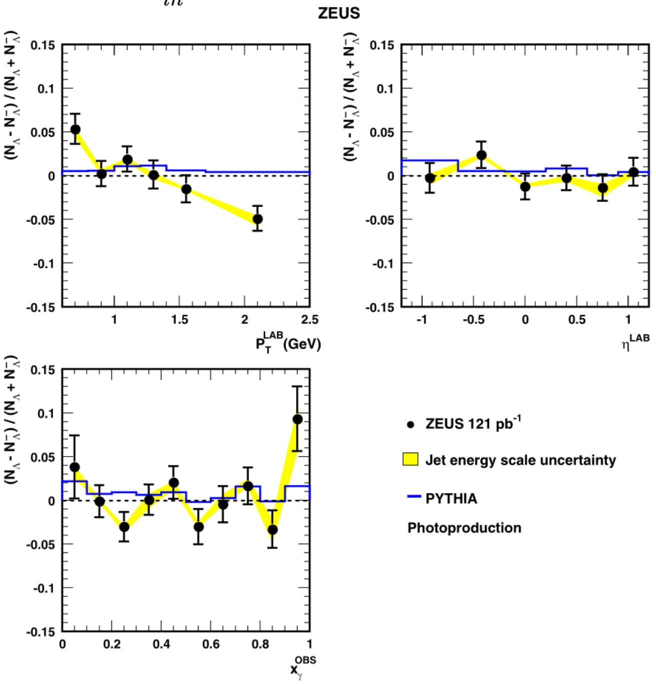
Boris Kopeliovich* and Bogdan Povh†

- Kopeliovich & Povh predict 3.5% asymmetry for DIS from baryon junction model

$$A_B(x) = \frac{\sigma_{ann}^{B\bar{B}}(s = m_N^2/x)}{\sigma_{in}^{hp}}$$

- ZEUS results consistent with 0% in all three systems
  - All asymmetry measurements statistics dominated





- at high Q^2: $\mathcal{A} = 0.3 \pm 1.3^{+0.5}_{-0.8}\%$, compared to the ARIADNE ($\lambda_s = 0.3$) prediction of $0.4 \pm 0.2\%$;
- at low Q^2: $\mathcal{A} = 1.2 \pm 1.6^{+0.7}_{-2.1}\%$, compared to the ARIADNE ($\lambda_s = 0.3$) prediction of $1.0 \pm 0.2\%$;
- in photoproduction: $\mathcal{A} = -0.07 \pm 0.6^{+1.0}_{-1.0}\%$, compared to the PYTHIA prediction of $0.6 \pm 0.1\%$.

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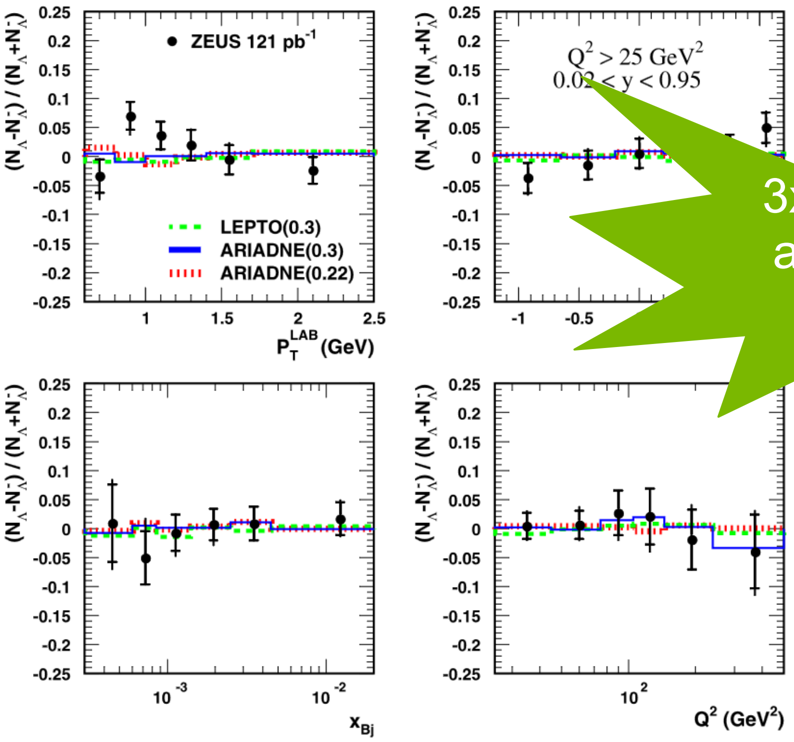

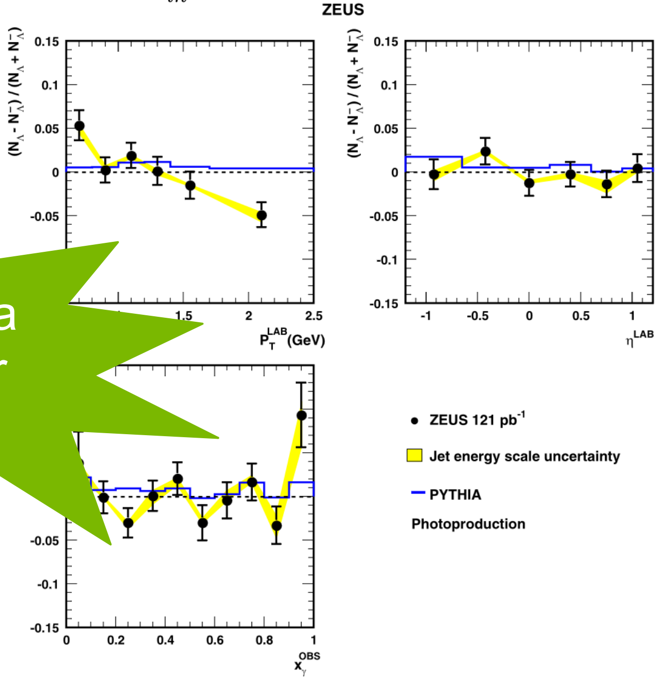

3x more data available for analysis!

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Λ MEASUREMENT RESULTS

- Kopeliovich & Povh predict 3.5% asymmetry for DIS from baryon junction model
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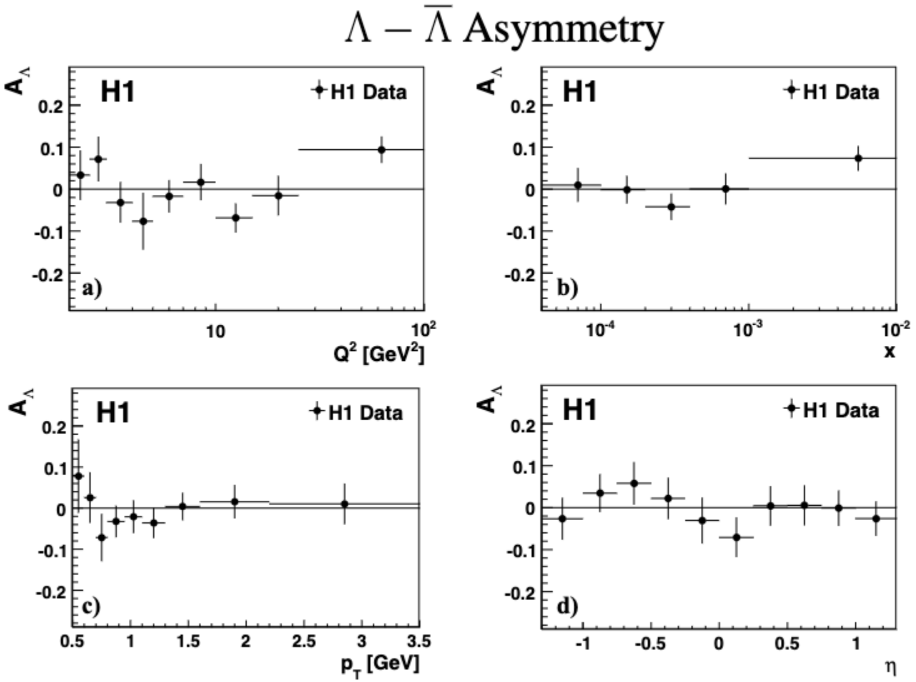
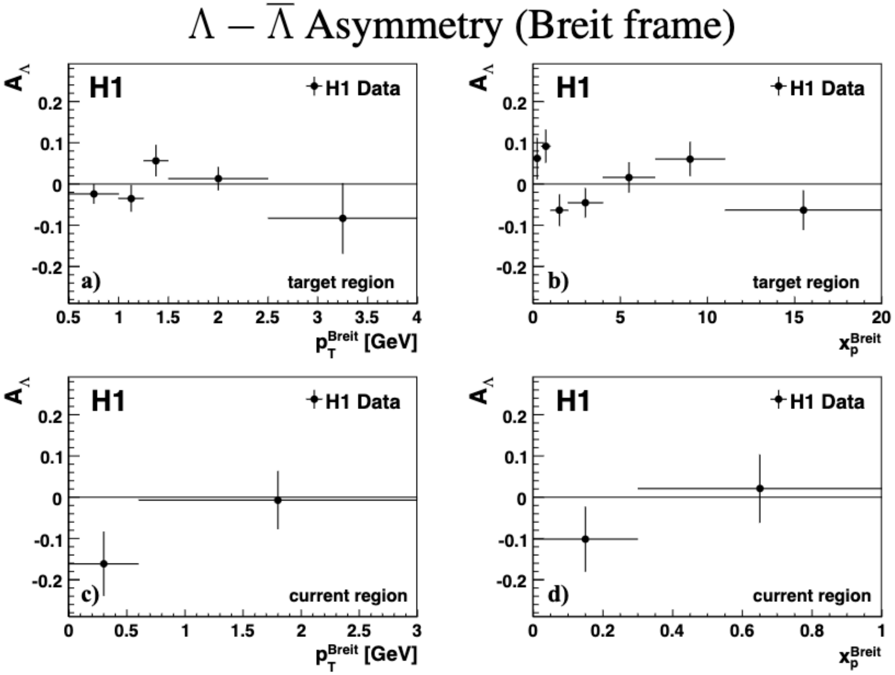
  - Studied both in the lab and the Breit frame

$$A_\Lambda = \frac{\sigma_{vis}(ep \to e\Lambda X) - \sigma_{vis}(ep \to e\bar{\Lambda} X)}{\sigma_{vis}(ep \to e\Lambda X) + \sigma_{vis}(ep \to e\bar{\Lambda} X)}$$





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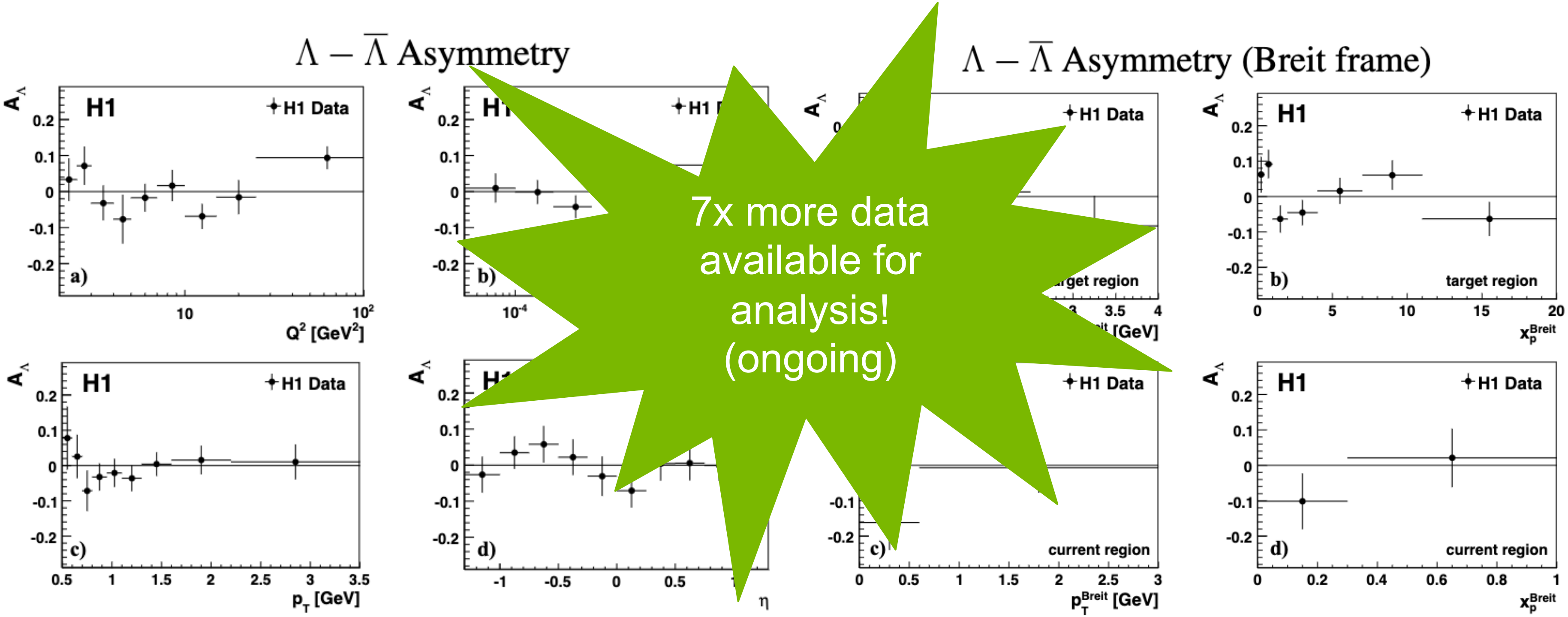
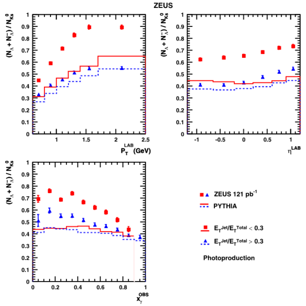
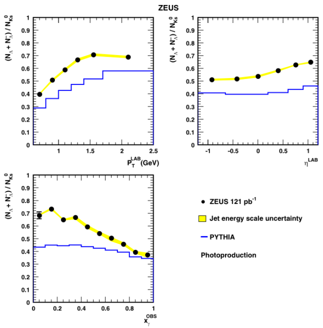
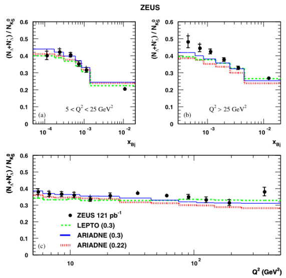


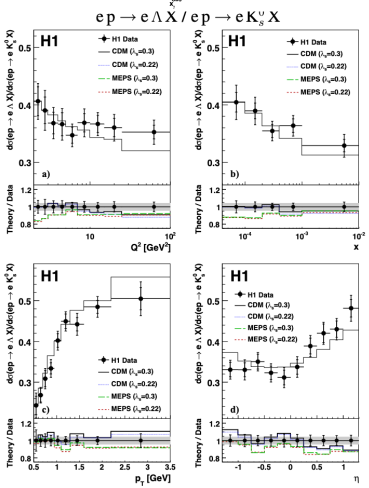
Λ MEASUREMENT RESULTS

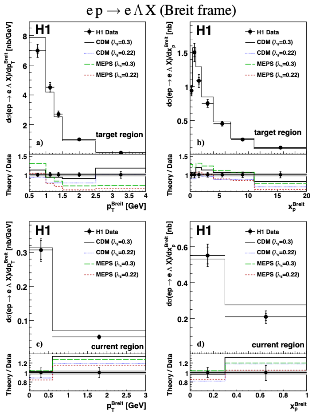
- Many more results contained in these papers
  - Notably baryon-to-meson ratios
  - Encourage you to check them out!

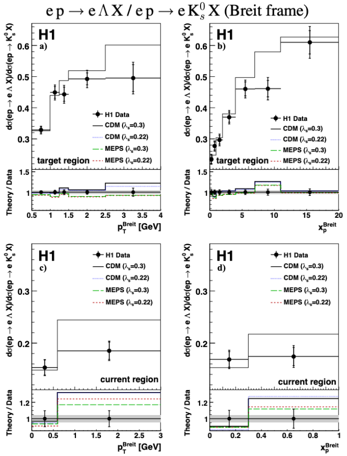












Measurement of K^0_S, Λ and $\bar{\Lambda}$ production at HERA

ZEUS Collaboration

Strangeness Production at low Q^2 in Deep-Inelastic *ep* Scattering at HERA

H1 Collaboration

ArXiv links in backup slides

Broadly speaking, the MCs accurately capture the features of the data, i.e. no "unique" phenomena observed

BONUS: TEVATRON

- Not within the purview of my talk, but some very important data exist from the Tevatron
- Similarly asymmetric collision system, with baryon number of +1 and -1 in the beams
  - Measured directional asymmetries of single, double, and triple strange baryons

- Asymmetry observed in production of $\Lambda, \bar{\Lambda}$
  - Interpreted as being consistent with strange quark coalescing with di-quark remnant

arxiv.org/pdf/1511.05113.pdf

Fermilab-Pub-15-496-E

Measurement of the forward-backward asymmetry of Λ and $\bar{\Lambda}$ production in $p\bar{p}$ collisions

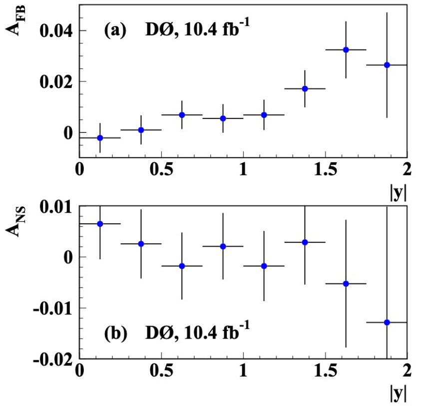


FIG. 8: Asymmetries (a) $A_{FB} = A'_{FB}$ and (b) $A_{NS} = A'_{NS} - A'_{NS}(K_S)$ of Λ and $\bar{\Lambda}$ with $p_T > 2.0$ GeV, as functions of $|y|$, for the data sample $p\bar{p} \to J/\psi\Lambda(\bar{\Lambda})X$. Uncertainties are statistical.

arxiv.org/pdf/1605.03513.pdf

FERMILAB-PUB-16-168-E

Measurement of the forward-backward asymmetries in the production of Ξ and Ω baryons in $p\bar{p}$ collisions

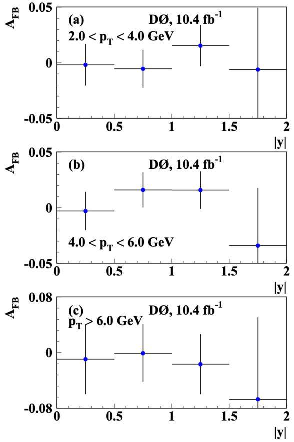


FIG. 7: Asymmetry $A'_{FB} = A_{FB}$ as a function of $|y|$ for $p\bar{p} \to \mu\Xi^{\mp}X$ events with (a) $2.0 < p_T < 4.0$ GeV, (b) $4.0 < p_T < 6.0$ GeV, and (c) $p_T > 6.0$ GeV. The uncertainties are statistical.

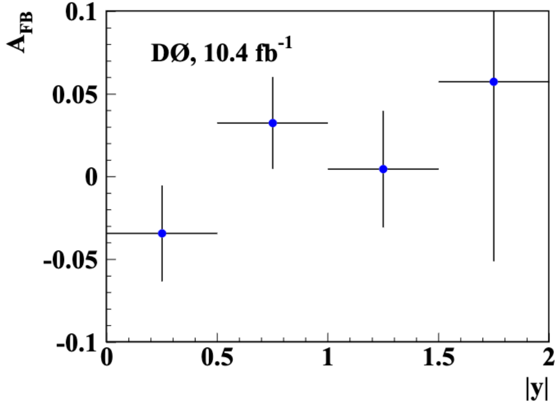
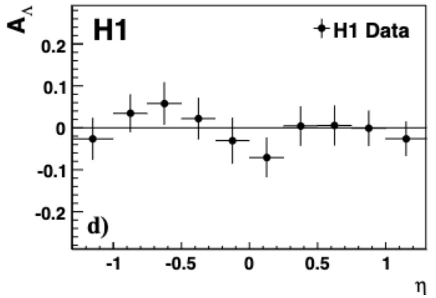


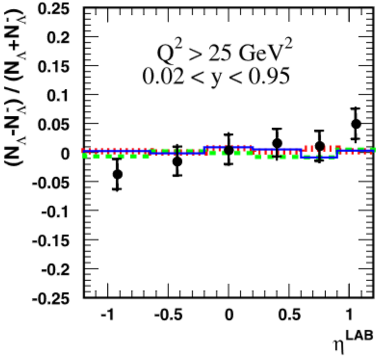
FIG. 9: Asymmetry A_{FB} as a function of $|y|$ for events $p\bar{p} \to \mu\Omega^{\mp}X$ for $p_T > 2$ GeV. The uncertainties are statistical.

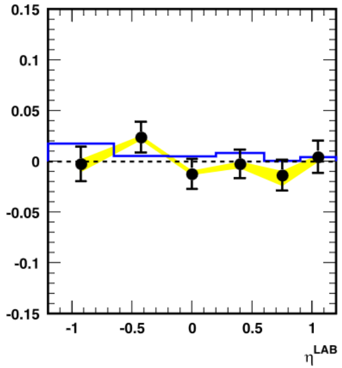
PUTTING IT ALL TOGETHER: Λ RESULTS

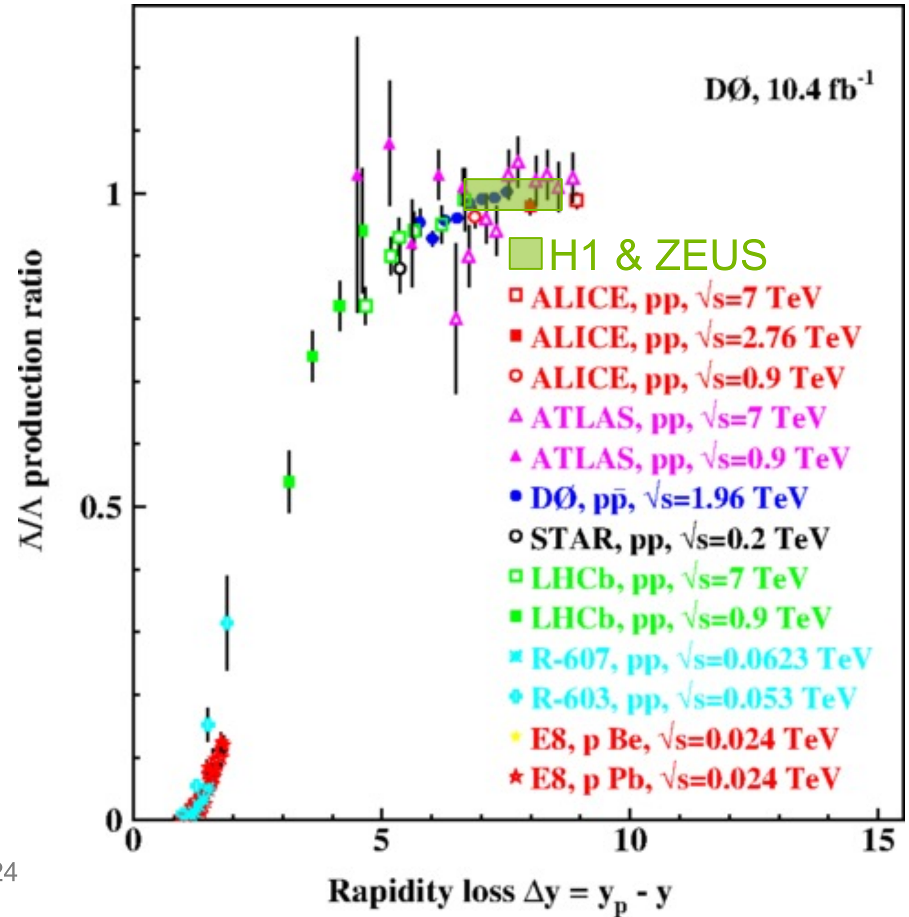
- H1 & ZEUS measure no statistically significant asymmetry in DIS or photoproduction with few % uncertainties



In agreement with MC predictions, but not precise enough to rule out a 3.5% asymmetry







HERA-B

V^0 production in p+A collisions at $\sqrt{s} = 41.6\,\mathrm{GeV}$

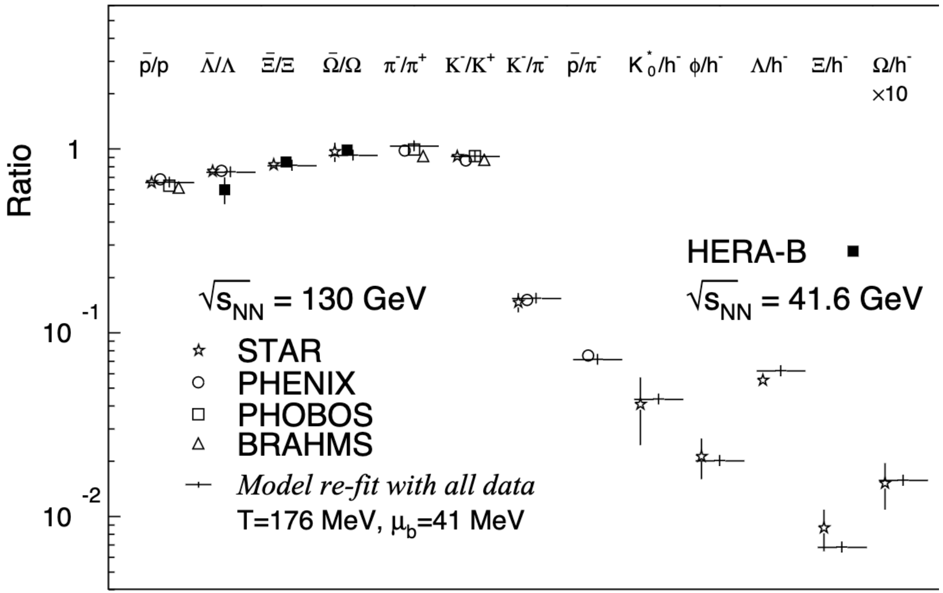
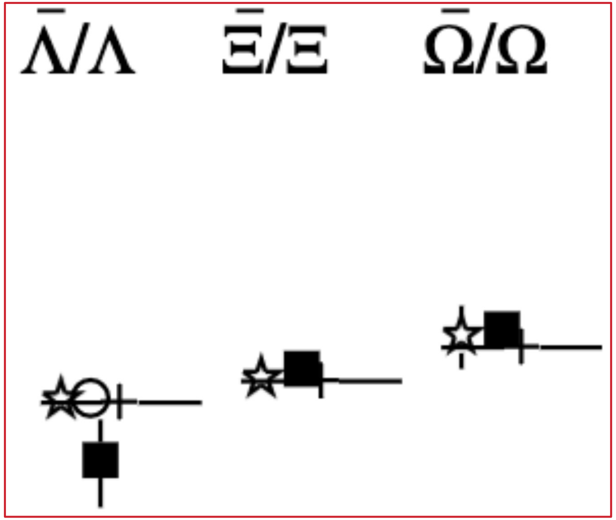


Figure 5: The anti-particle to particle ratio measured at HERA-B

Species	Carbon Target	Titanium Target	Tungsten Target
$\bar{\Lambda}/\Lambda$	0.51±0.05	0.52±0.05	0.47±0.05



HERA-B results agree with STAR

Only $\bar{\Lambda}/\Lambda$ shows energy dependence ($\sqrt{s}$ = 130 vs. 41.6 GeV)

No significant A-dependence

HERMES

- Fixed target with 27.6 GeV electron beam
  - Similar kinematics to JLab
  - $\sqrt{s}$ = 7.2 GeV
- Substantial raw yield of baryons to anti-baryons
  - Expected from phase space, but can't draw quantitative conclusions since yields are uncorrected

Hadron	Mean values of kinematic variables				
	$\langle Q^2 \rangle$	$\langle x \rangle$	$\langle y \rangle$	$\langle z \rangle$	$\langle P_{h\perp} \rangle$
π^+	2.445 GeV^2	0.095	0.544	0.362	0.394 GeV
π^0	2.506 GeV^2	0.089	0.588	0.357	0.396 GeV
π^-	2.366 GeV^2	0.092	0.548	0.354	0.393 GeV
K^+	2.524 GeV^2	0.097	0.548	0.391	0.417 GeV
K^-	2.381 GeV^2	0.089	0.569	0.356	0.412 GeV
p	2.595 GeV^2	0.095	0.574	0.421	0.452 GeV
$\bar{p}$	2.393 GeV^2	0.076	0.655	0.364	0.477 GeV

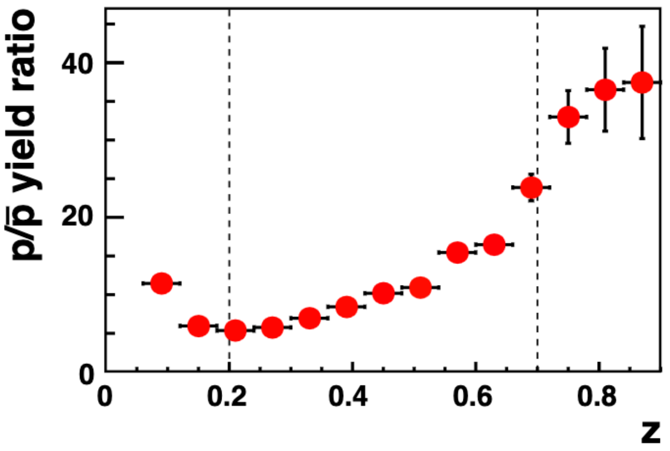
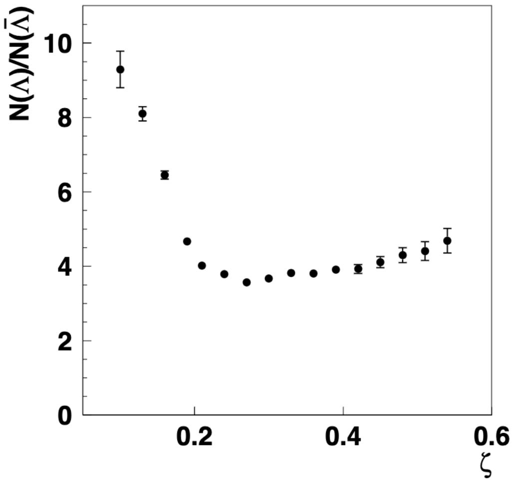


Figure 18. Ratio of raw proton to antiproton yields at HERMES as a function of z. The bin boundaries for the semi-inclusive DIS range are marked by dashed lines. The ratio exhibits a clear rise towards very low z, which might indicate the onset of significant target-fragmentation contributions, excluded in the data sample used by the minimum-z requirement of 0.2.



function of $\zeta \equiv (E_\Lambda + p_{z\Lambda})/(E_\mathrm{B} + p_\mathrm{B})$, which represents the light cone momentum fraction of the beam positron carried by the outgoing Λ or $\bar{\Lambda}$.

FUTURE PROSPECTS

- Data of H1, ZEUS, and HERMES is preserved and available for analysis thanks to significant investment from DESY
  - Anyone can join the collaborations and have access to the data!
- Promising directions for future analyses:
  - Repeat proton/antiproton asymmetry measurement with better understanding of detectors and backgrounds
  - Strange baryons in diffractive DIS
    - Use as a baseline for non-diffractive DIS measurements
  - Proton energy scan data
    - Reach smaller beam rapidities
  - Utilize the whole HERA dataset!
    - Current H1 & ZEUS baryon publications use only ~1/4 of the whole dataset
    - Higher statistics to access e.g Ξ^0, where diquark cannot be responsible
    - For asymmetry measurements where statistical uncertainty dominates, substantial improvements possible!

CONCLUSION

- e+p and ɣ+p collisions are promising avenues to search for baryon junctions

- There are a surprising number of relevant published results on baryon production mechanisms from HERA
  - With more on the way!
  - HERA data very easy to work with
    - Nice projects for students pre-EIC

- Existing & upcoming HERA measurements nicely set the stage for the EIC!
  - EIC detectors, statistics, beam flexibility will make it the ultimate tool for these studies

REFERENCES

H1:
https://arxiv.org/pdf/0810.4036.pdf

ZEUS:
https://arxiv.org/pdf/hep-ex/0612023.pdf
https://arxiv.org/pdf/0705.3770.pdf

HERMES:
https://arxiv.org/pdf/0704.3133.pdf

https://arxiv.org/pdf/1406.3236.pdf

HERA-B:
https://arxiv.org/pdf/0812.0471.pdf

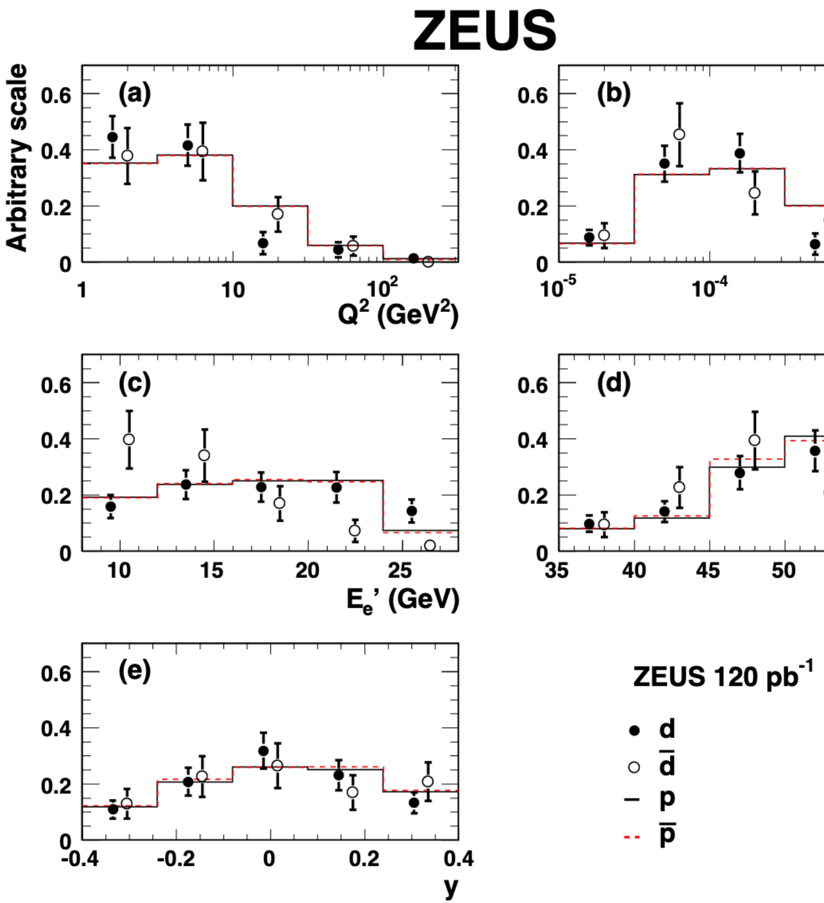


Figure 5: *The distributions of the number of events with at least one $d(\bar{d})$ and $p(\bar{p})$ candidate normalised to unity as a function of: (a)-(d) DIS kinematic variables and (e) rapidity y. The points for d and $\bar{d}$ are slightly shifted horizontally for clarity.*

The events containing at least one $p(\bar{p})$ or $d(\bar{d})$ were analysed in the Breit frame [39]. The number of events with $p(\bar{p})$ in the current region of the Breit frame was about 2.5% of the total number of observed events with $p(\bar{p})$. In this region, neither d nor $\bar{d}$ was found. Since the current region of the Breit frame is analogous to a single hemisphere of e^+e^-, the observation of $d(\bar{d})$ reported in this paper is not in contradiction with the low $\bar{d}$ rate observed in e^+e^- [2–4].

The amount of the sea $B\bar{B}$ pairs stored in the photon fluctuation cancels in the relative asymmetry (14), and we arrive at a very simple expression for the baryon asymmetry

$$A_B(x) = \frac{\sigma_{ann}^{B\bar{B}}(s = m_N^2/x)}{\sigma_{in}^{hp}} \ , \qquad (15)$$

which is very important for further applications. Here σ_{in}^{hp} is the inelastic cross section for the dominant hadronic fluctuation of the photon at $s = m_N^2/x$. It is the ρ-meson in the case of a real photon, so we will use $\sigma_{in}^{hp} \approx 20\ mb$. We do not expect any strong Q^2-dependence of the baryon asymmetry, despite the fact that the photoabsorption cross section for highly virtual photons decreases as $1/Q^2$. This may be interpreted as a suppression $\sim 1/Q^2$ of interaction of small-size, $\propto 1/Q^2$, fluctuations of the photon. At the same time the baryon-antibaryon component of these fluctuations has to have a small transverse separation as well. Thus the annihilation cross section acquires the same suppression factor $1/Q^2$.

In order to proceed further with the evaluation of the baryon asymmetry (15) one needs to know the baryon-antibaryon annihilation cross section $\sigma_{ann}^{B\bar{B}}$ at high energies. As mentioned in the introduction, the asymptotic behaviour of the annihilation cross section was studied in nonperturbative [17] and perturbative [14, 16] QCD approaches, and also analysing data on multiplicity distribution in pp and $p\bar{p}$ interactions [15, 16]. Using so different ideas all these approaches arrive at the same conclusion: the annihilation cross section at high energies is about $1 - 2\ mb$ and nearly energy-independent.

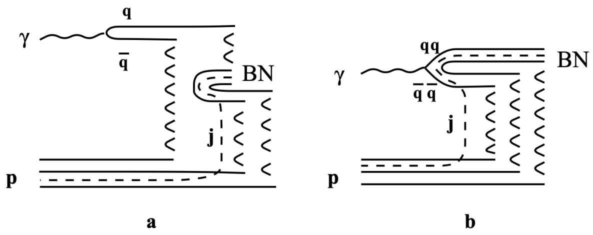
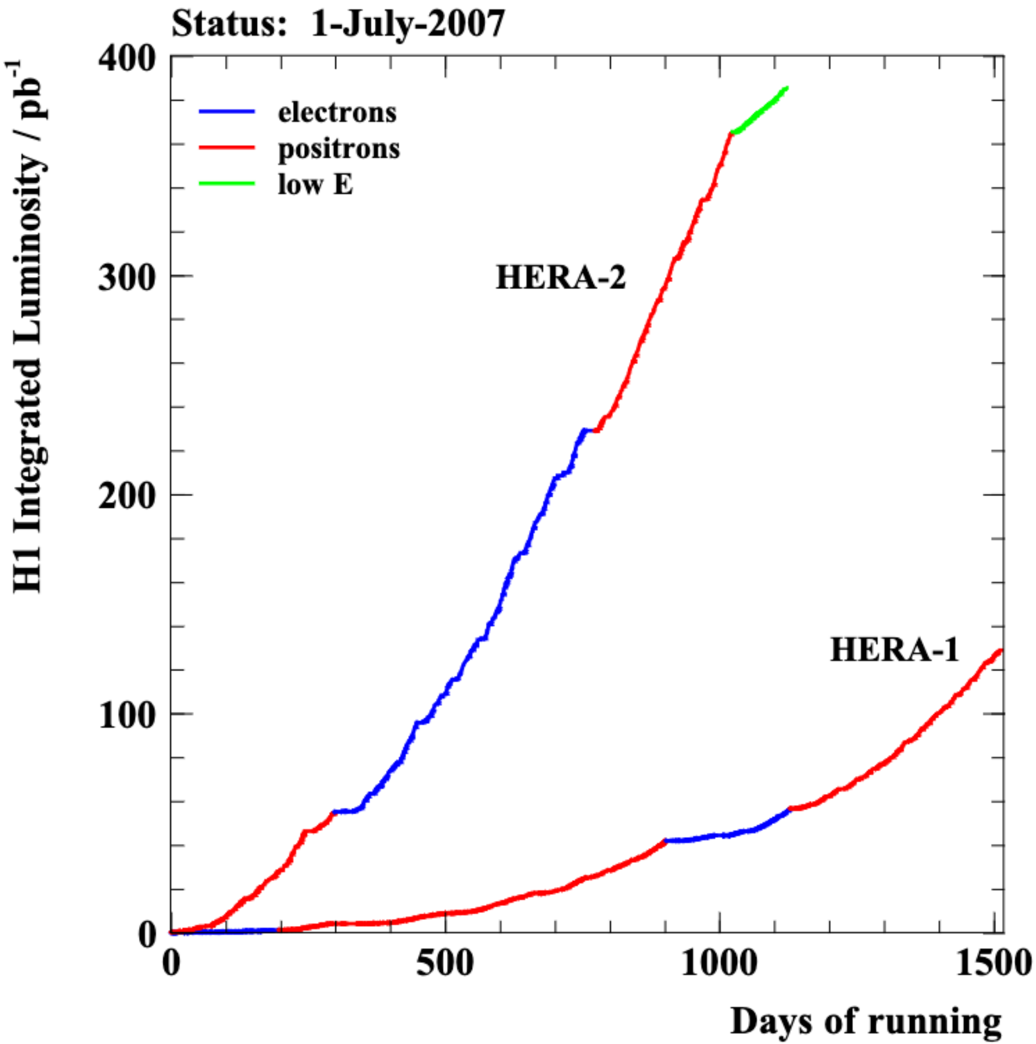


Figure 4: *Gluonic mechanism of the proton BN flow to the central rapidity region (***a***) and to the photon fragmentation region (***b***). The dashed lines show the trajectory of the string junction*


Status: 1-July-2007
H1 Integrated Luminosity / pb^{-1}
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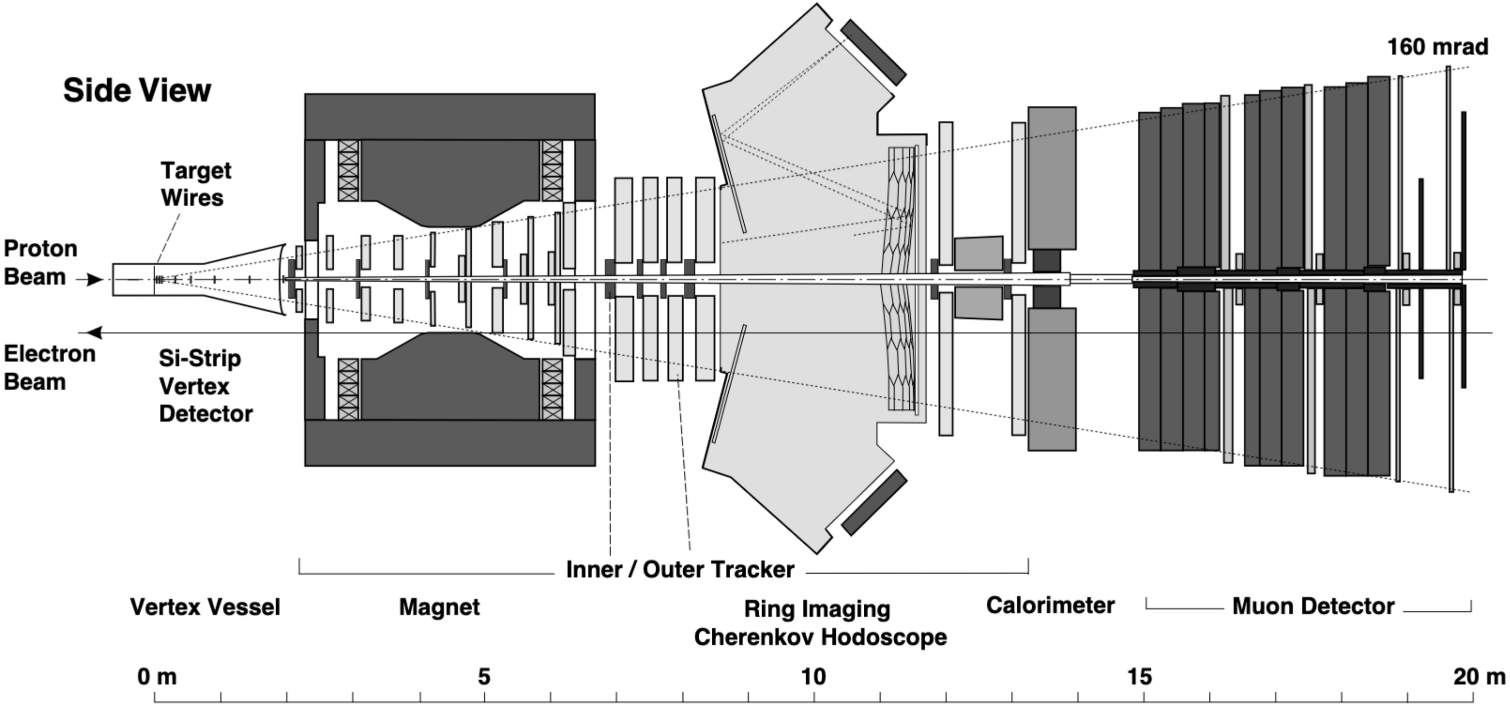
200
100
0
electrons
positrons
low E
HERA-2
HERA-1
0
500
1000
1500
Days of running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Proton
Beam
Electron
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Inner / Outer Tracker
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Cherenkov Hodoscope
Calorimeter
Muon Detector
0 m
5
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