# QCD
# Experimental and theoretical context

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PBC Working Group Meeting
CERN, 1-2 March 2017

# Scope of this talk

- starting from slides of PBC Kickoff Meeting (Sept. 2016)
  we have tried to situate the different proposals within a global QCD context

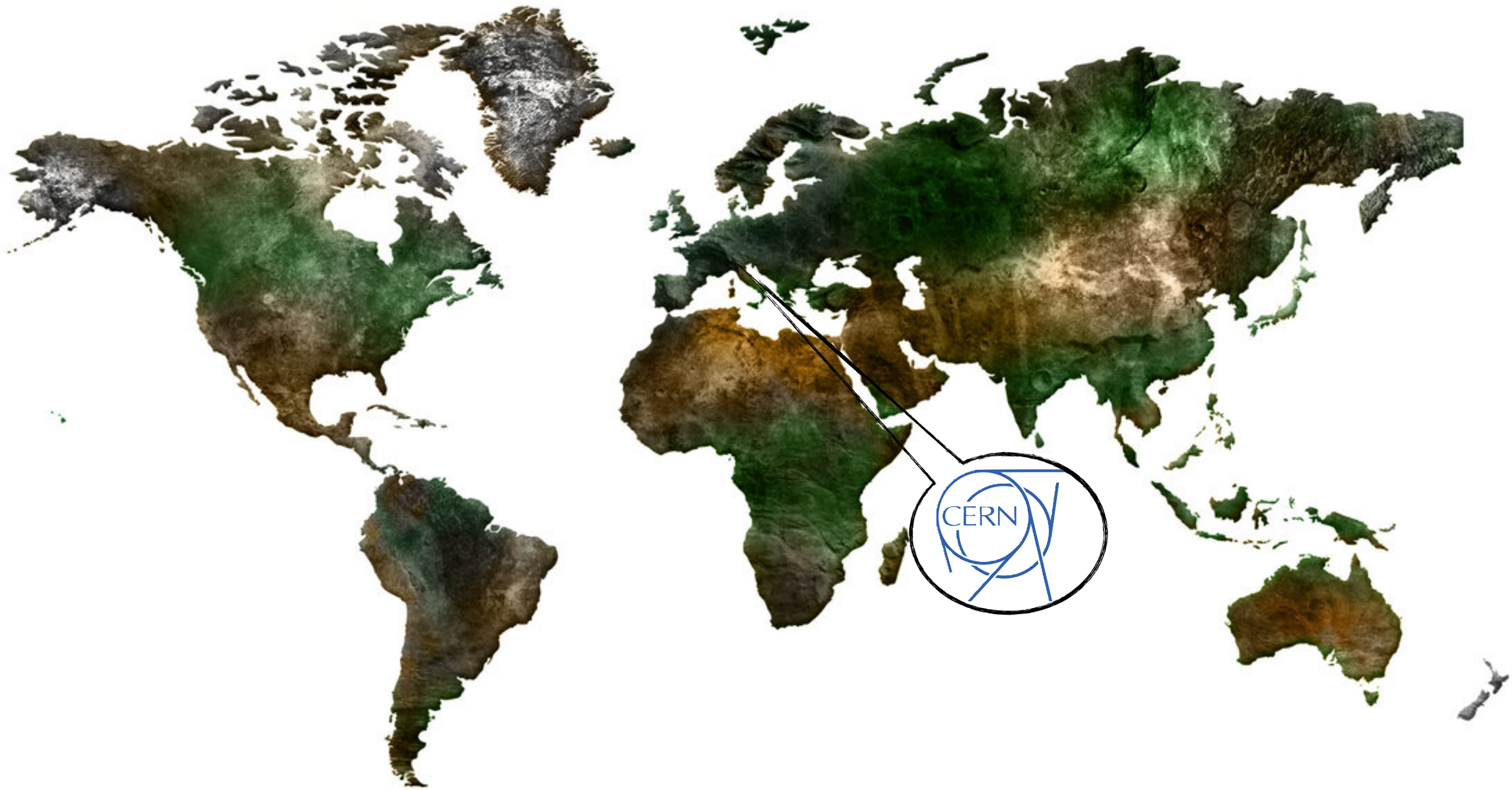
- we will ask critical questions, make suggestions
  please consider us as friendly critics/critical friends

  ★ others will ask tough questions later (review panels, management, the broader community), so better be prepared for those

- this is the beginning of a process we are not making final assessments now

- will now go through the various proposals one by one

# QCD experiment landscape (selection)



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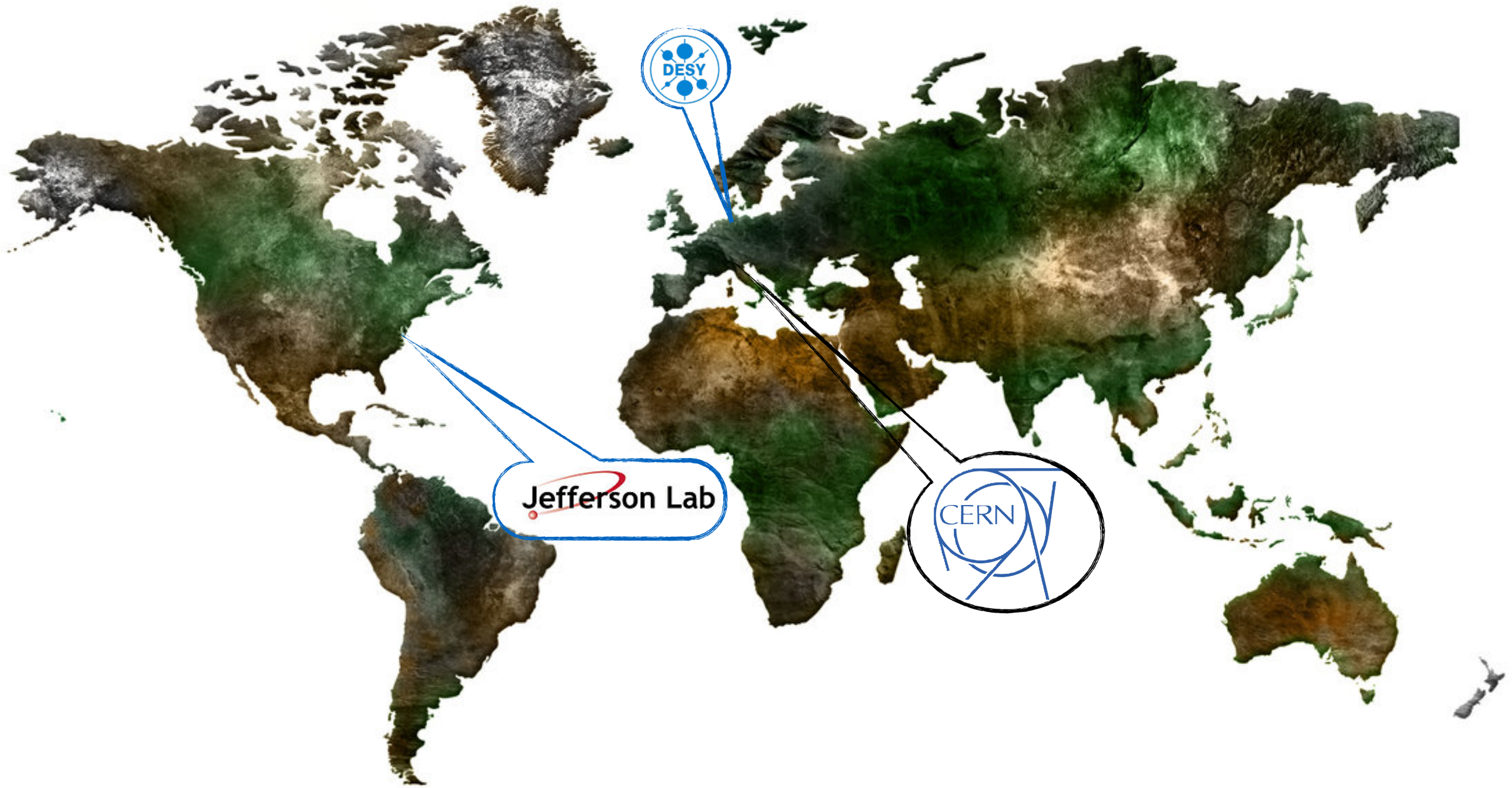

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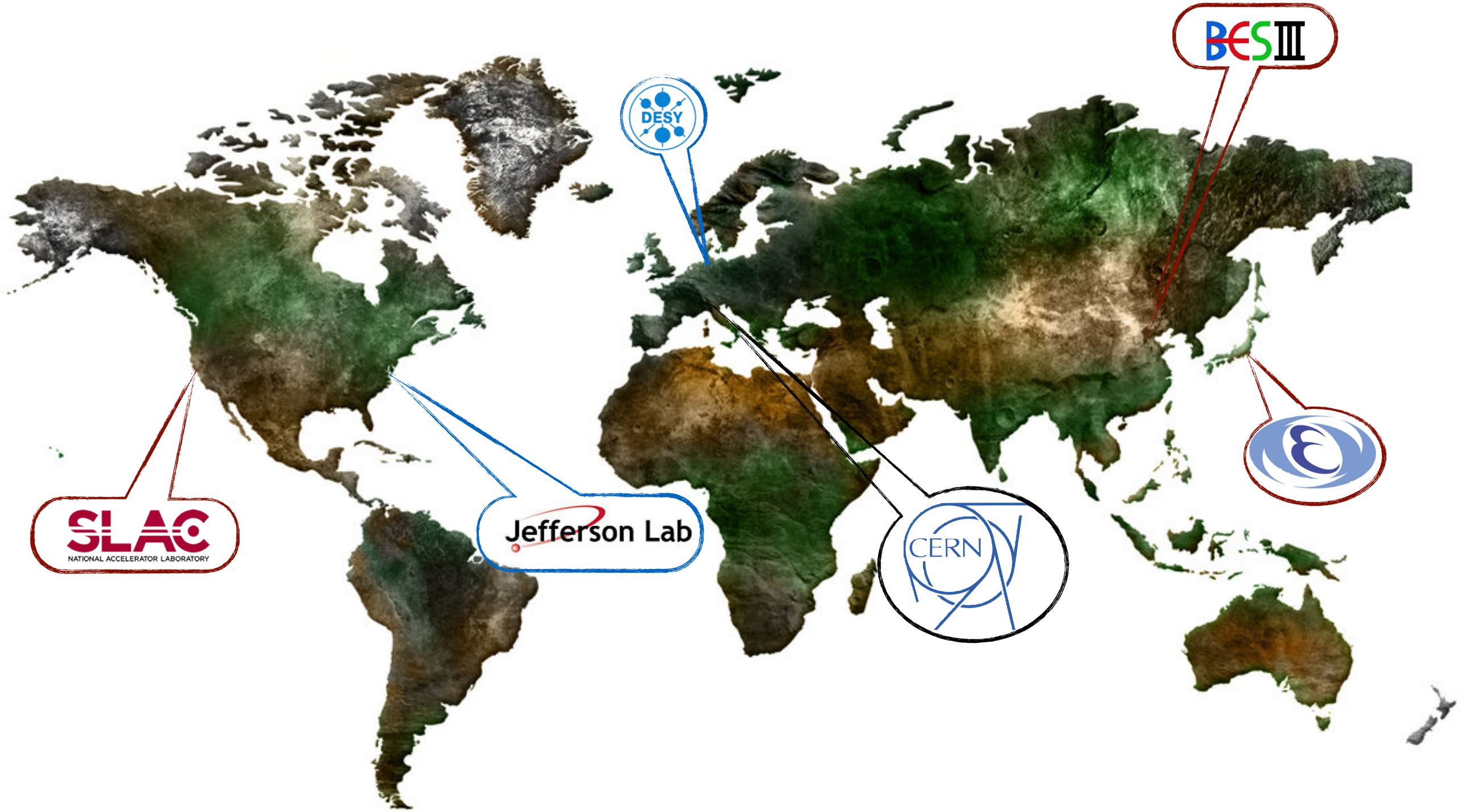

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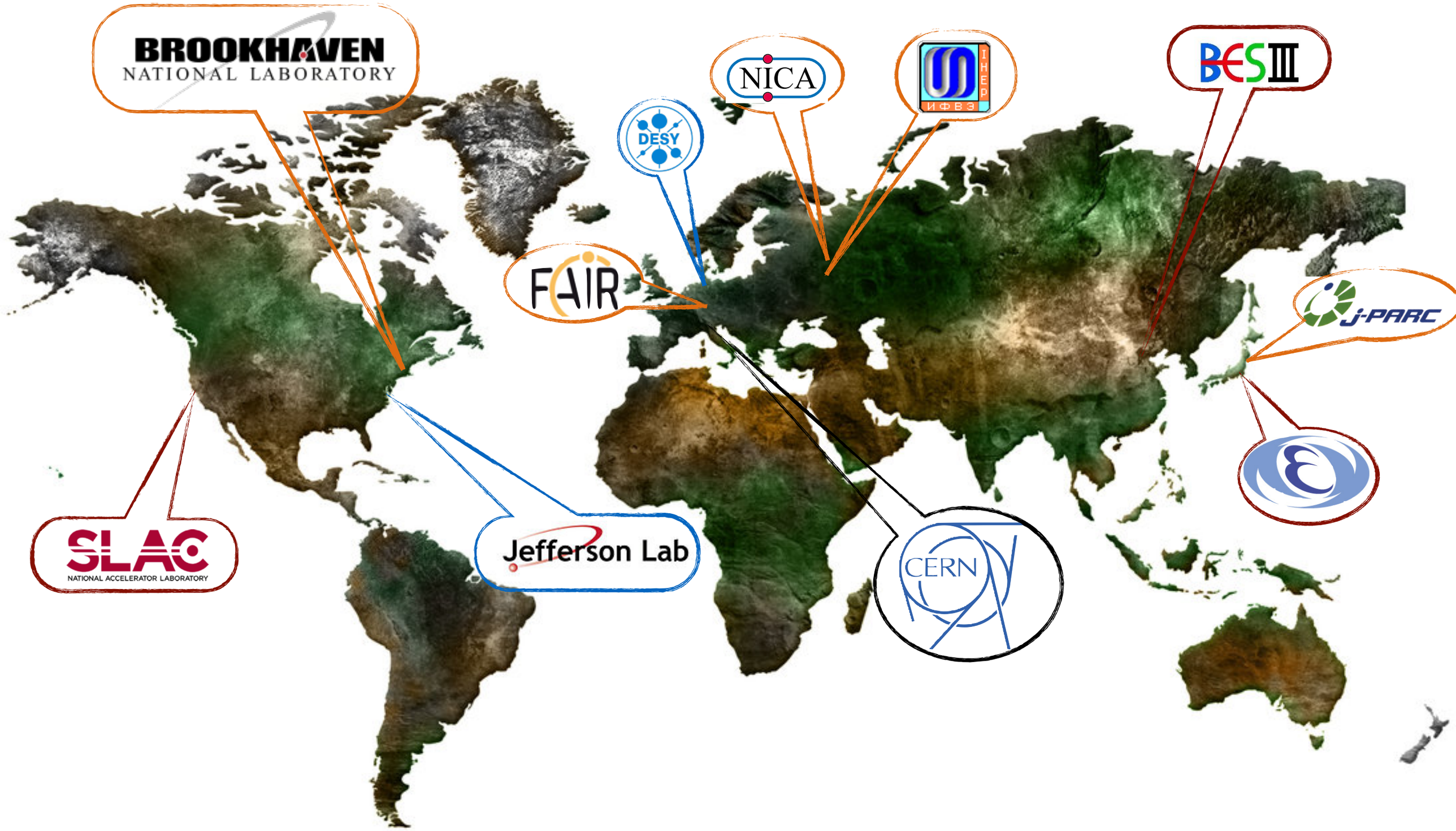

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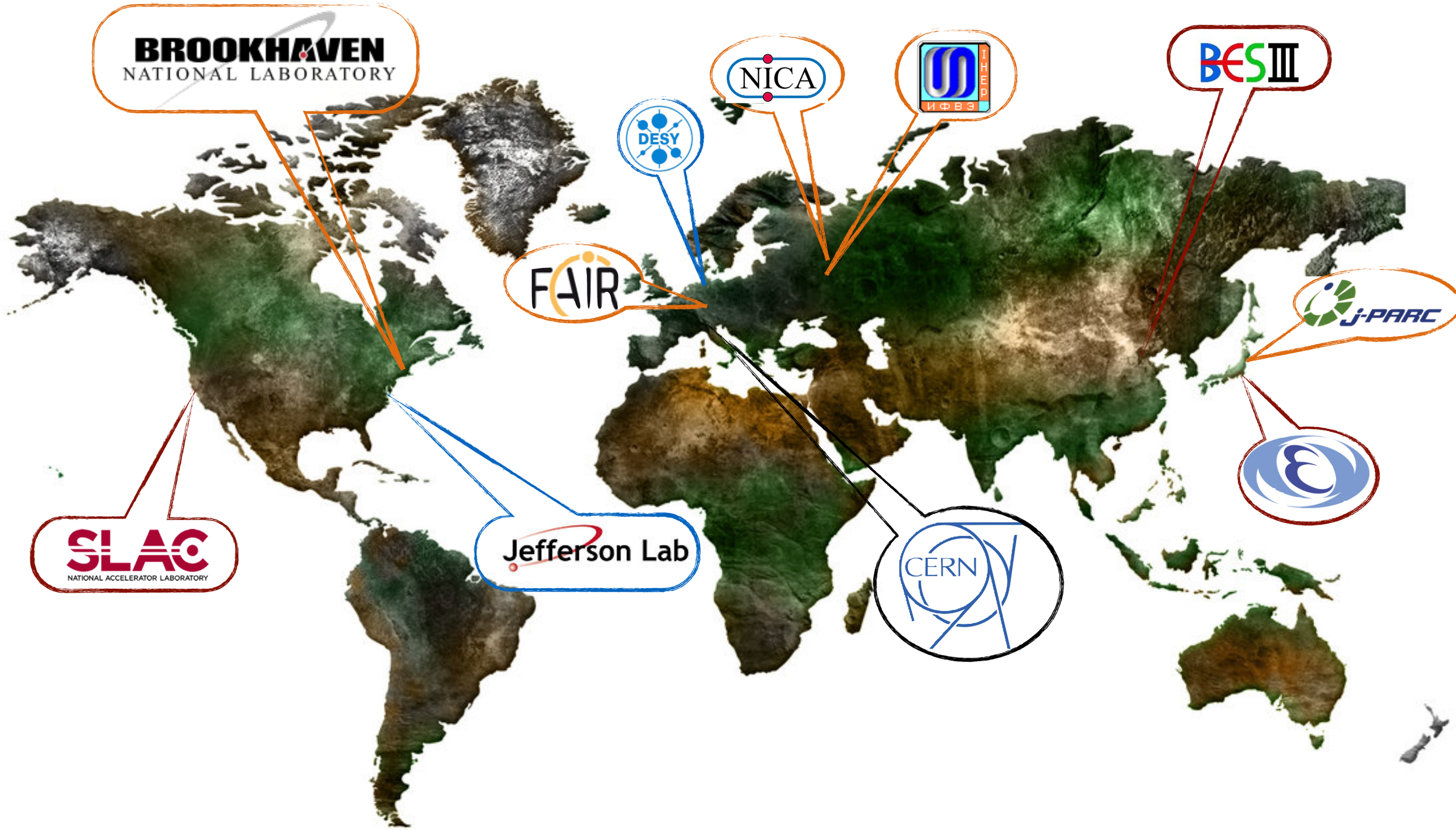



future EIC: either BNL or JLab

# Electron-positron annihilation

- mainly charm and B factories, but also useful for QCD studies, e.g.
  - ★ fragmentation functions
  - ★ spectroscopy

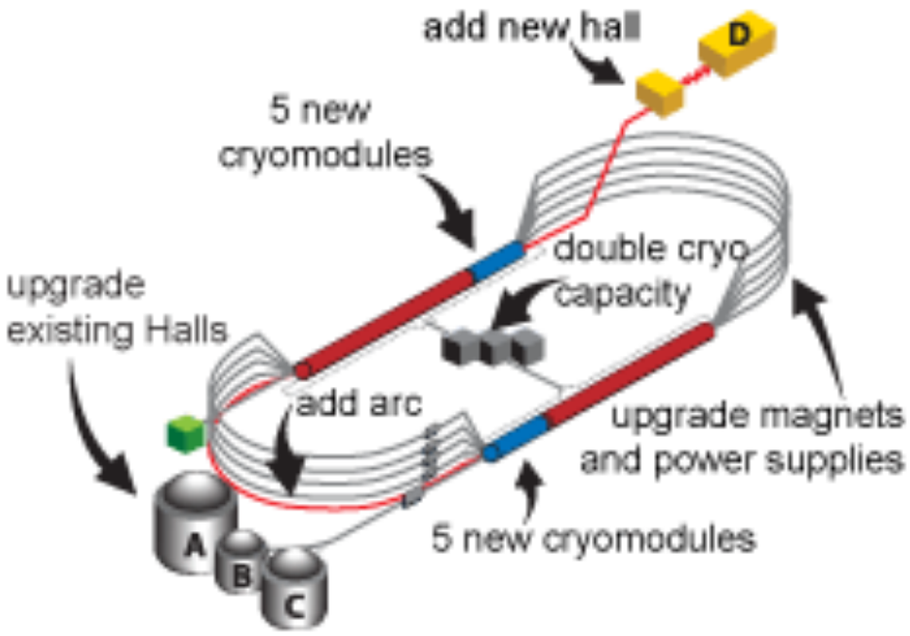
- BaBar@PEP-II (SLAC): $\sqrt{s}$ =10.58 GeV; until 2008

- Belle(2)@KEKB: $\sqrt{s}$ =10.58 GeV;
  Belle until 2010 accumulated ~1 $ab^{-1}$
  Belle2 2017++ to accumulate ~50 $ab^{-1}$

- BESIII@BEPC II: up to $\sqrt{s}$ =4.6 GeV with a design luminosity of $10^{33}$ $cm^{-2} \cdot s^{-1}$ (ongoing); acceptance $|\cos\theta|<0.8$

# Lepton-nucleon/nucleus scattering

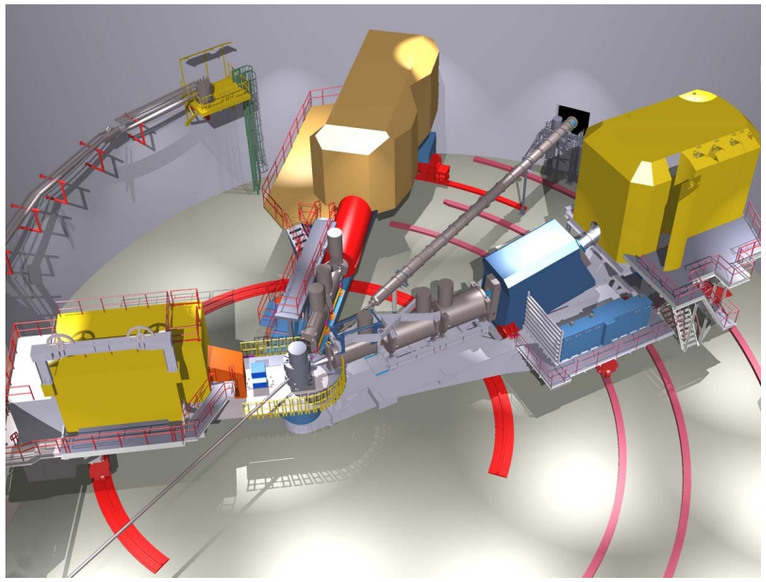
- HERA (until 2007): longitudinally pol. $e^{\pm}$ (27.6 GeV)
  unpolarized protons (460/575/820/920 GeV)
  - ★ H1, ZEUS: $e^{\pm}p$ ($\sqrt{s}$ = 225/251/300/320 GeV)
  - ★ HERMES: HERA $e^{\pm}$ on long. pol. H, D, $^3$He; transv. pol. H; unpolarized nuclei (H, D, He, … Kr, Xe)
- Jefferson Lab: longitudinally pol. $e^-$ (6 GeV; upgraded to 12 GeV)
  - ★ various experimental halls w/ diff. focus
  - ★ unpol. and polarized nuclear targets
  - ★ hadron structure via exclusive and (semi-)inclusive reactions
  - ★ dedicated hall for spectroscopy



# lepton-nucleon scattering @ JLab12

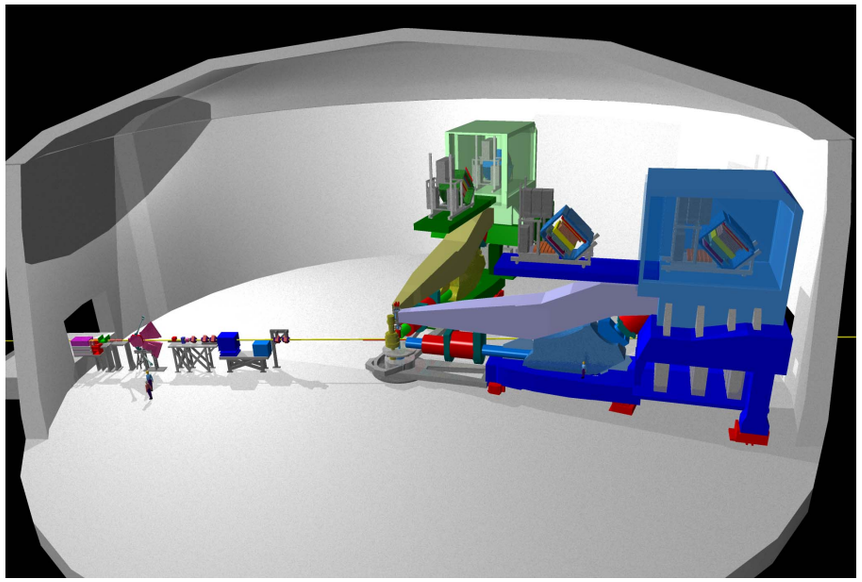
from: M. Contalbrigo @ QCD-N'16

**Hall-C**



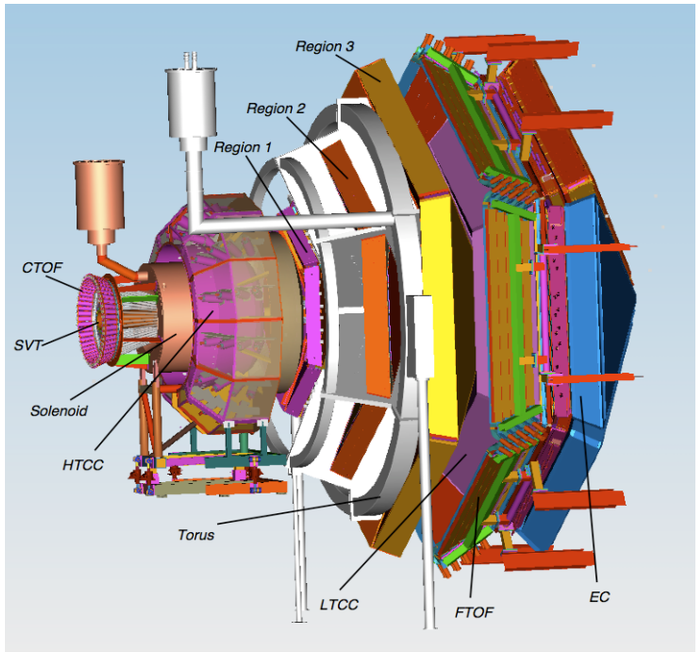
Super High Momentum Spectrometer (SHMS)
unpolarized SIDIS, hadron ID

**Hall-A**

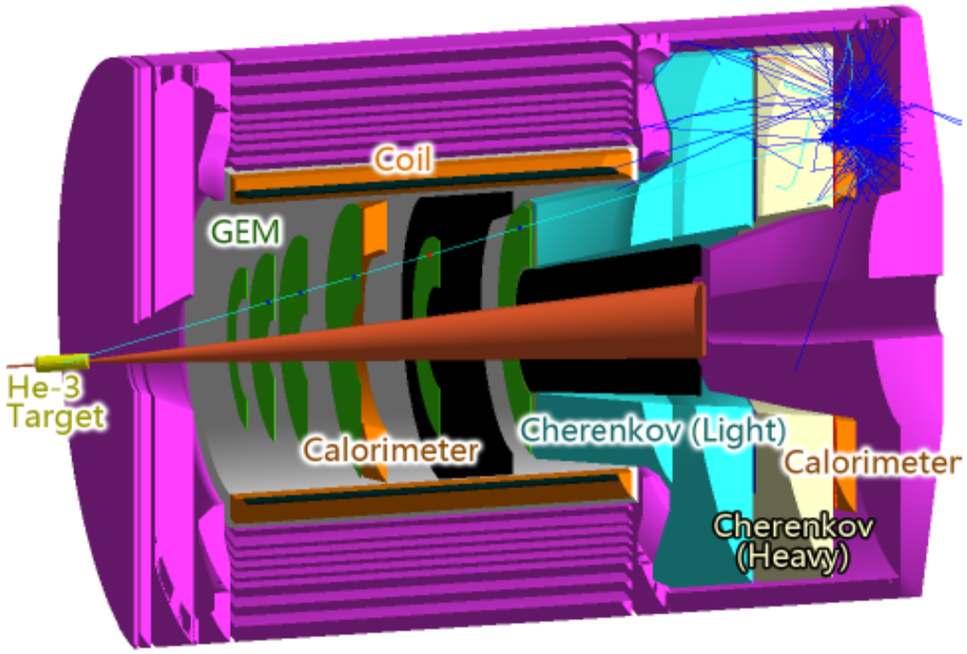


Spectrometer Pair, polarized $^3$He target
up to to $\mathbf{10^{38}\ cm^{-2}\ s^{-1}}$ hadron ID

**Hall-B**

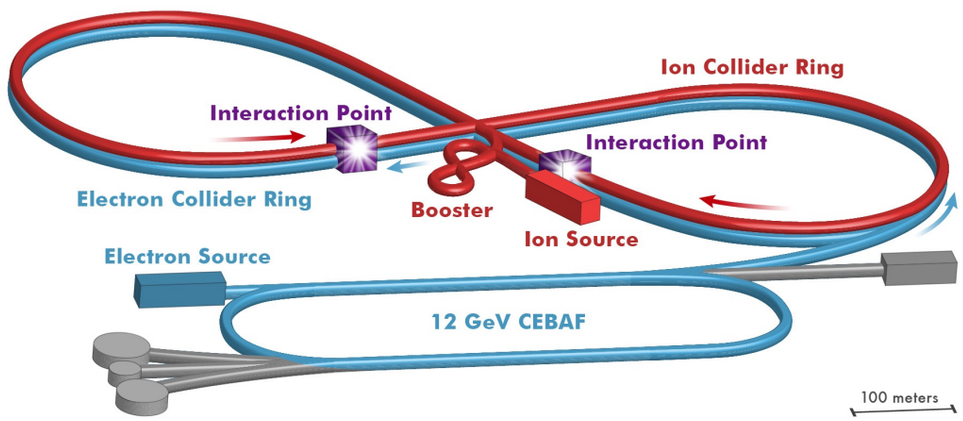



CLAS12 H,D polarized targets up to $\mathbf{10^{35}\ cm^{-2}\ s^{-1}}$
"complete" acceptance, hadron ID

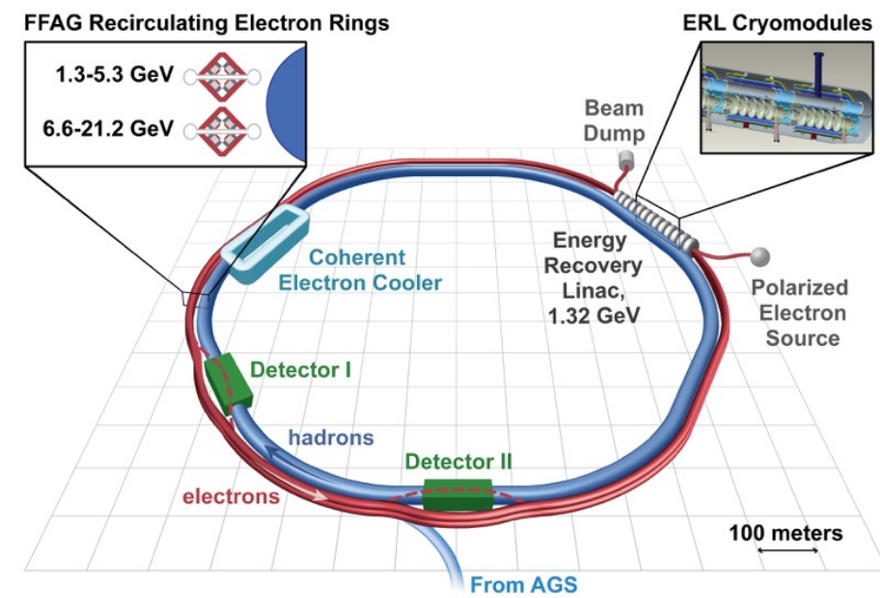



SOLID $^3$He, $NH_3$ polarized targets
up to $\mathbf{10^{36}\ cm^{-2}\ s^{-1}}$ large acceptance, pion ID

# A future Electron-Ion Collider (EIC) - 2025++




Jefferson Lab




Brookhaven

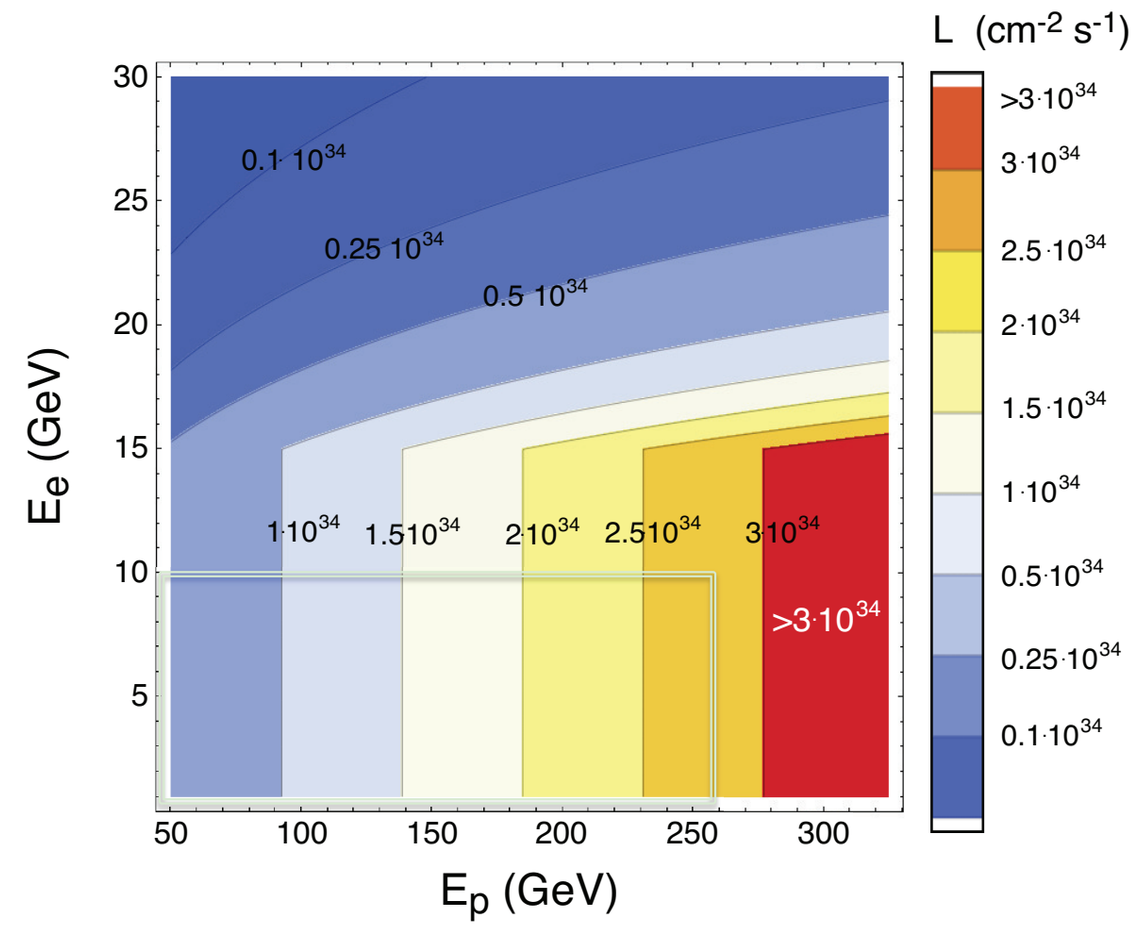
- high-luminosity, versatile, **polarized** ($e^-$ and p,d,$^3$He)
  - ★ Peak luminosity **$2\times10^{34}$ cm$^{-2}$s$^{-1}$** for $\sqrt{s}$ ~70-105 GeV (250 GeV p↑)
  - ★ "Low-risk" luminosity ~5-9$\times10^{32}$ cm$^{-2}$s$^{-1}$ (BNL)
    5-10$\times10^{33}$ cm$^{-2}$s$^{-1}$ (JLab)

**100-1000x HERA**

- 20-~100 (140) GeV **variable** CoM energy
- large and complementary kinematic coverage
- unpol. nuclei from $^2$H to Pb / U

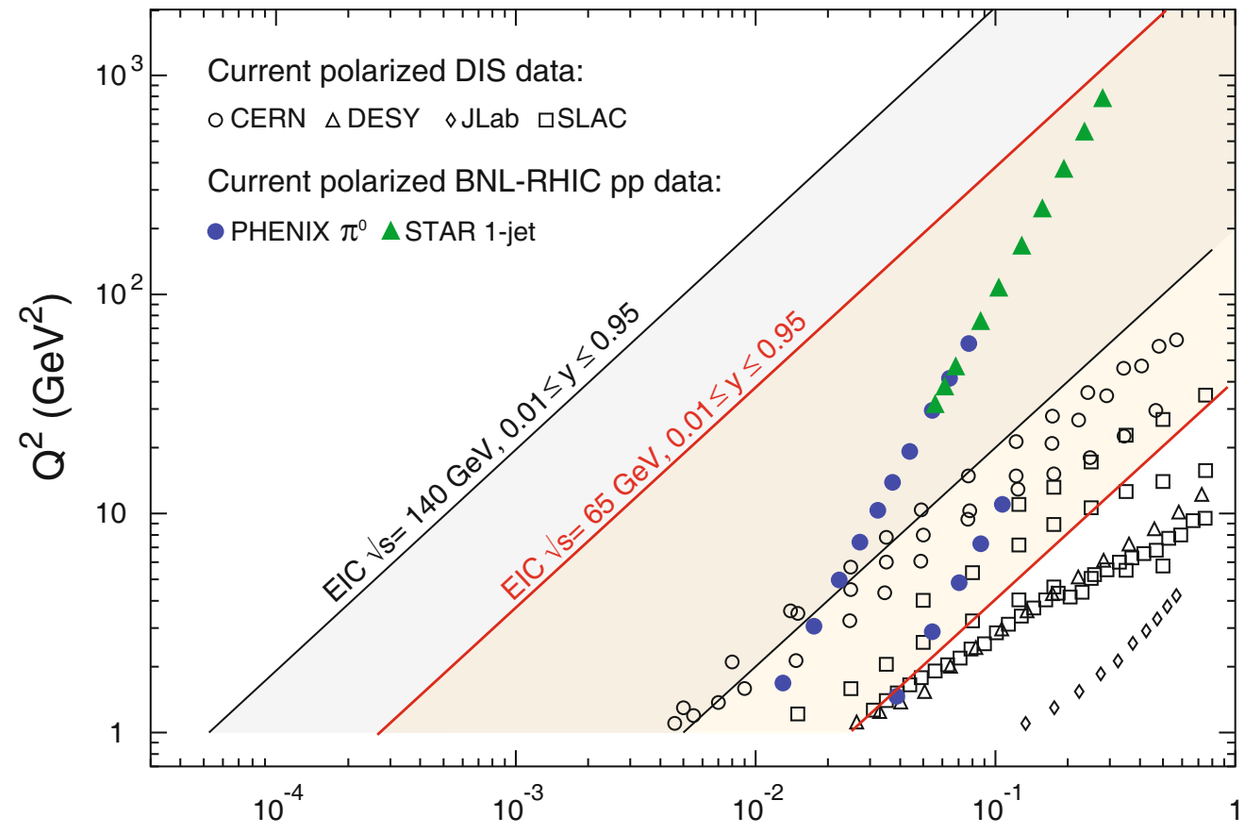
# A future Electron-Ion Collider (EIC) - 2025++

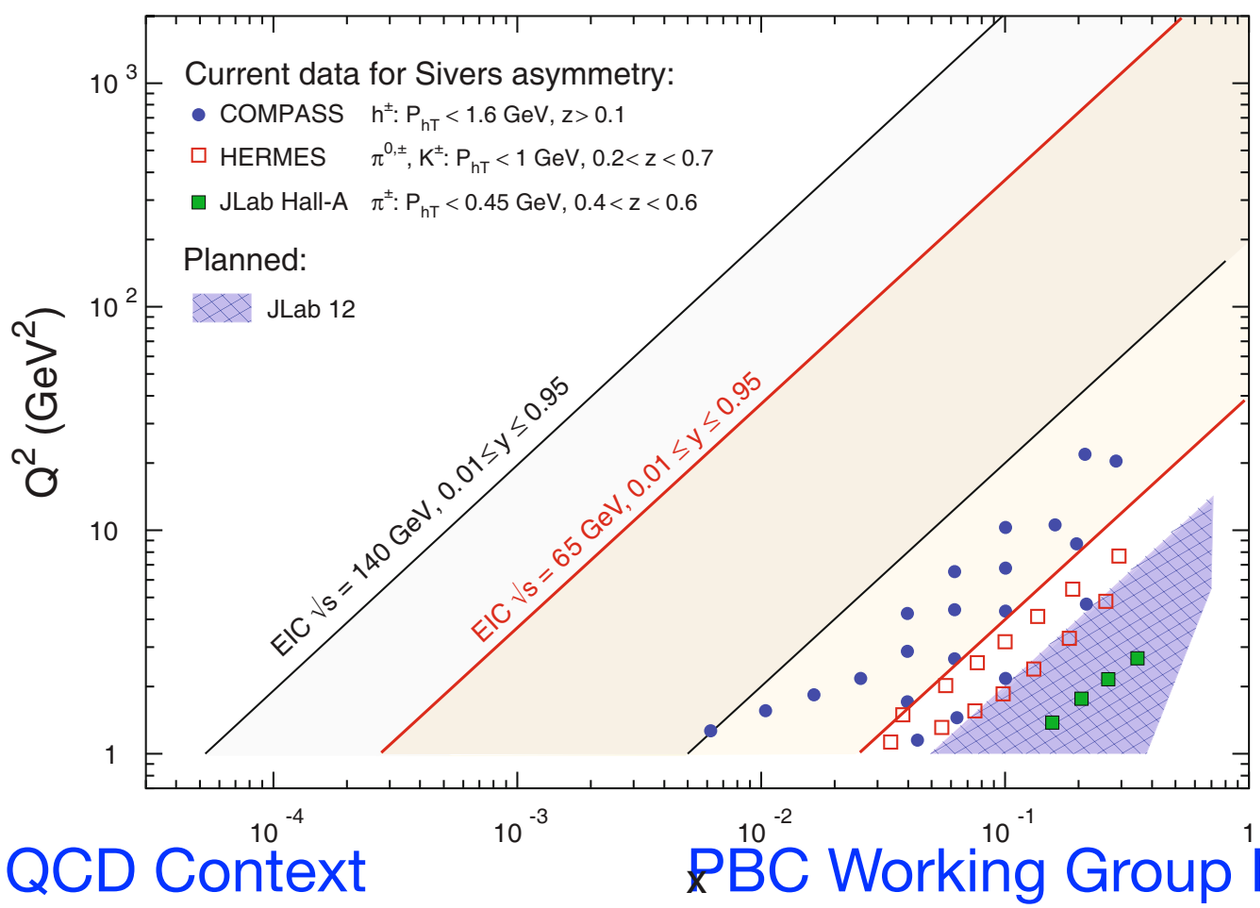
- lumi strongly increases with beam energy

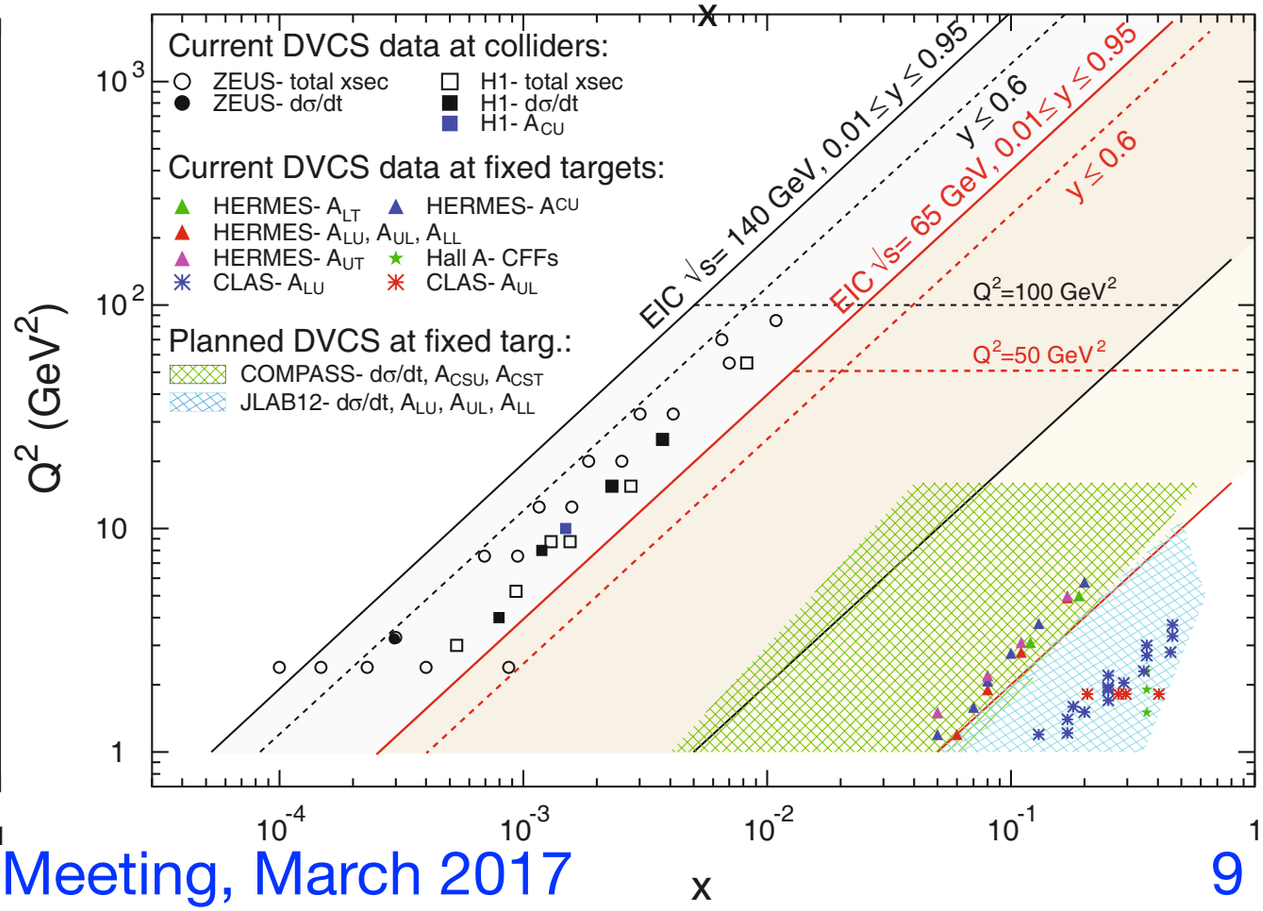


# A future Electron-Ion Collider (EIC) - 2025++

- lumi strongly increases with beam energy
- large kinematic coverage for a wide range of observables



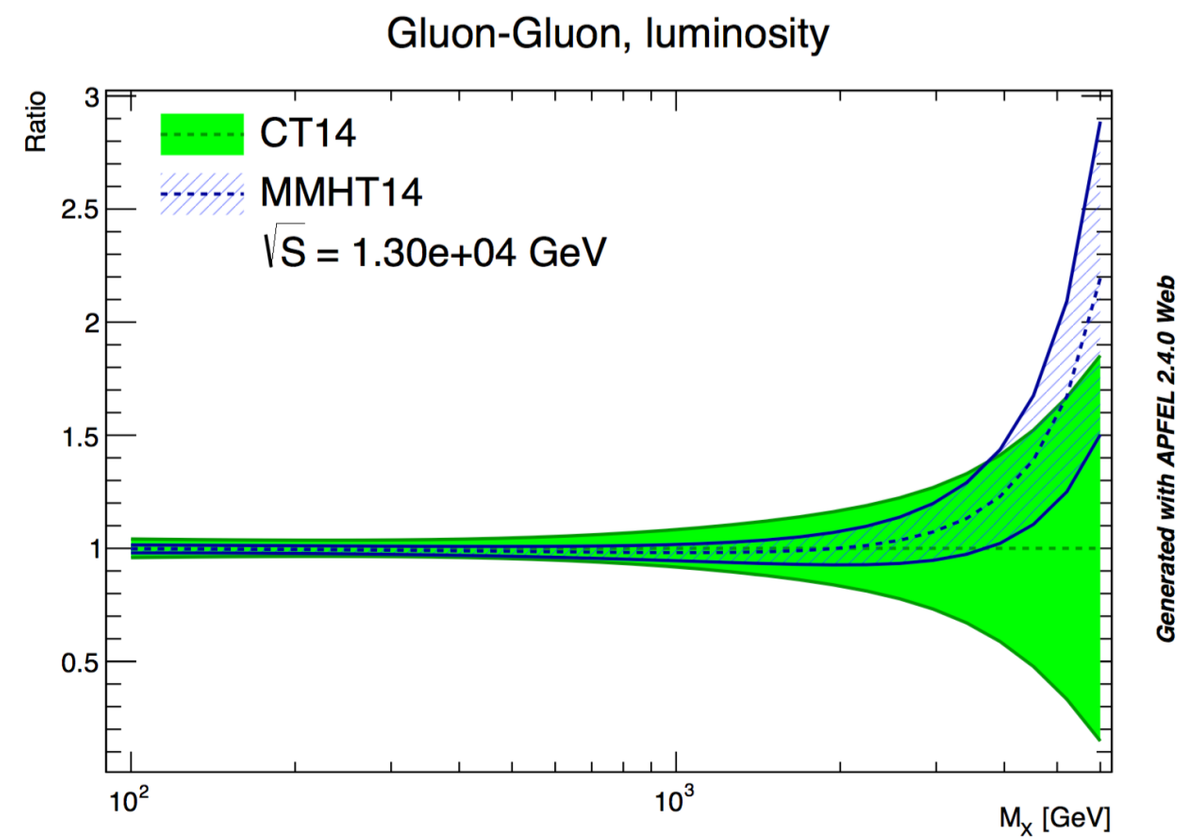



# Hadron structure: AFTER and COMPASS++

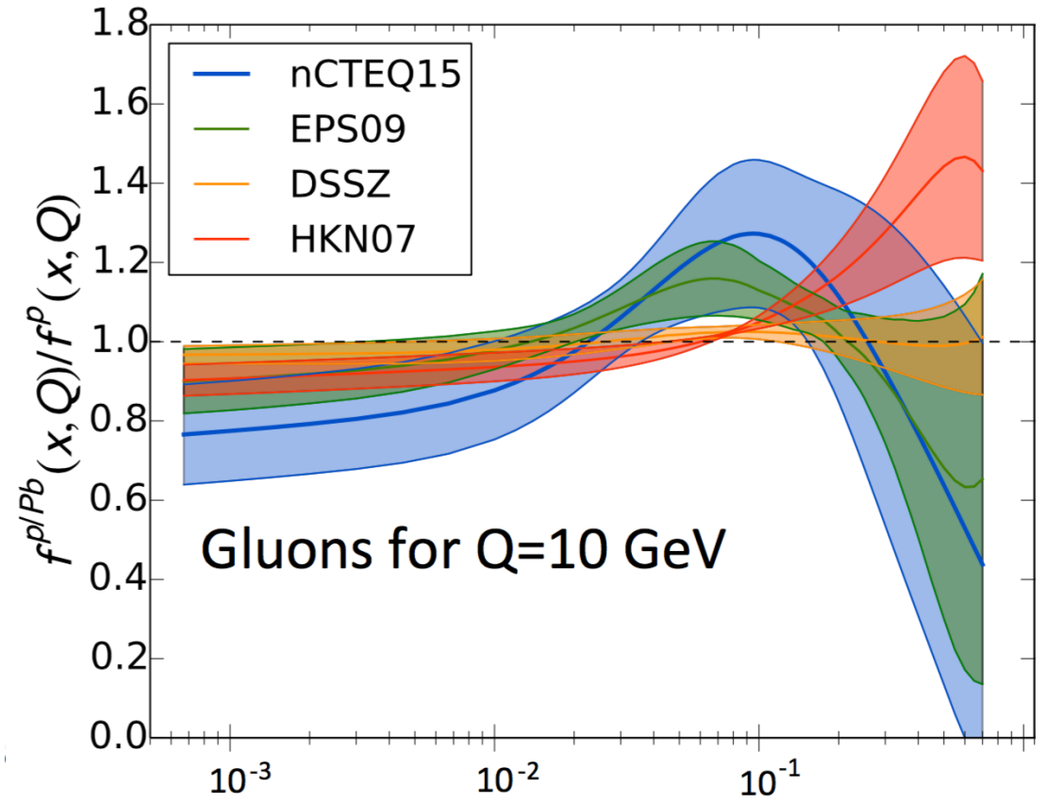
- understanding structure and dynamics of hadrons at level of quarks and gluons
  - ★ fundamental Lagrangian → physical states
  - ★ remains very active field, many open questions
- many possibilities sketched in presentations at kickoff workshop. Suggestion:
  - ★ identify a few measurements that can support a strong physics case and that may drive the experimental setup
  - ★ for these, make detailed feasibility/performance studies
  - ★ this requires some choices, but will provide focus and considerably ease the task of any review panel
  - ★ further possibilities can always be pointed out (but beware of "laundry lists")

# AFTER: possible highlights (1)




- Parton densities at high x
  - ★ current uncertainties very large
  - ★ important input for LHC!
    (heavy particle production)
  - ★ very little competition:
    JLAB: lower scale $Q^2$;
    higher $Q^2$ accessible at EIC, but potential not yet quantified,
    even then AFTER might have edge for gluons
  - ★ possible measurements: Drell-Yan for quarks?
    for gluons? open charm?
  - ★ intrinsic charm in proton (expected to reside at large x)
    measurement again open charm?
  - ★ for simulations beware: at high x expect soft-gluon resummation to be essential (should **increase** rates)

# AFTER: possible highlights (2)




from: J-P Lansberg @ PBC Kickoff

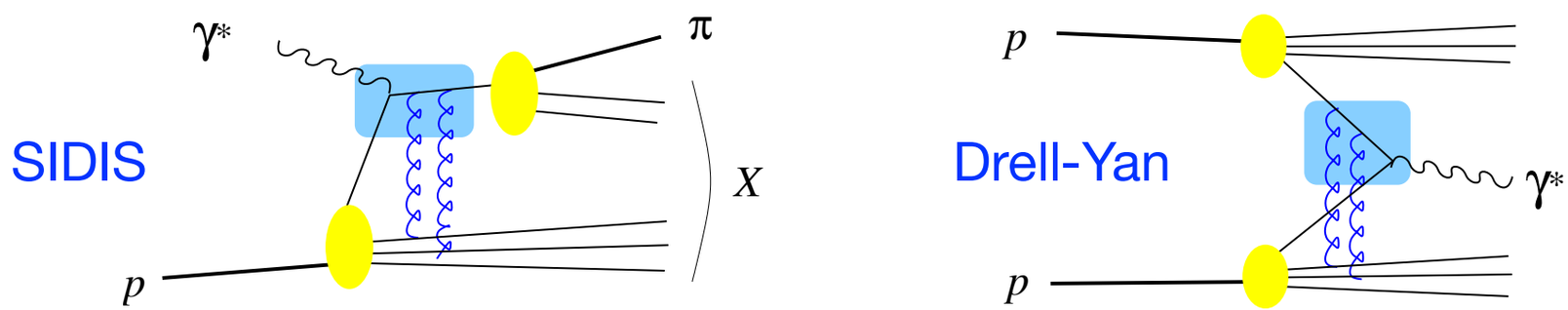
- nuclear parton densities?
  - ★ intrinsic interest: how does nucleus modify partonic structure of nucleon? collective effects?
  - ★ important input for heavy-ion collisions
  - ★ nuclear targets: reach large x in nucleus; with Pb beam would get low x in nucleus
  - ★ measurements? quantitative impact? possible competition from LHC? from EIC?

# Drell-Yan: target spin asymmetry

- transverse momentum distribution of partons is shifted in transversely polarised proton (Sivers effect)

  ★ spin-orbit coupling, sensitive to orbital angular mom.

- effect comes from soft gluon exchange in physical process




  ★ definite change of distribution between SIDIS and DY:

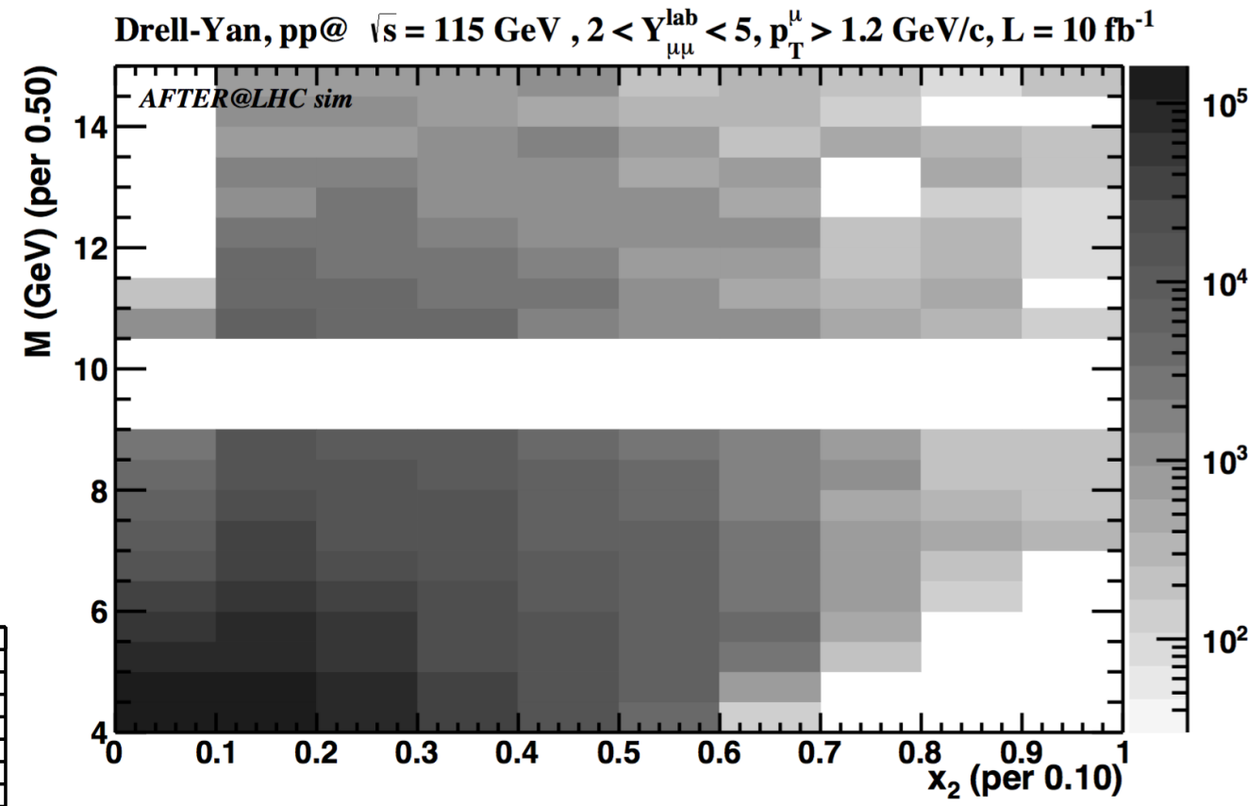
$$f_{\text{Sivers, SIDIS}}(x,k_T) = - f_{\text{Sivers, DY}}(x,k_T)$$

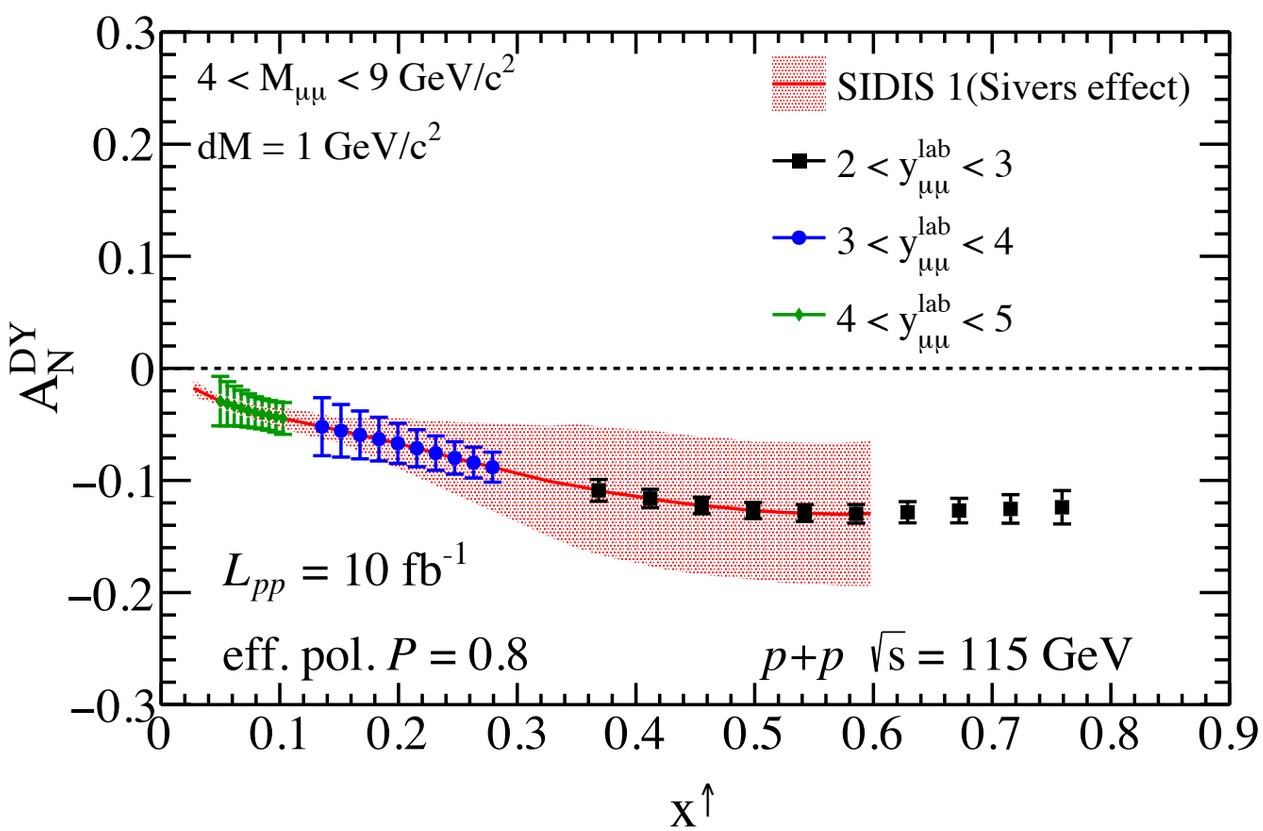
  ★ fundamentally tests our understanding of soft gluon effects on hadron structure

- related: Boer-Mulders shift for transv. quark pol. in unpol. p

# AFTER: possible highlights (3)

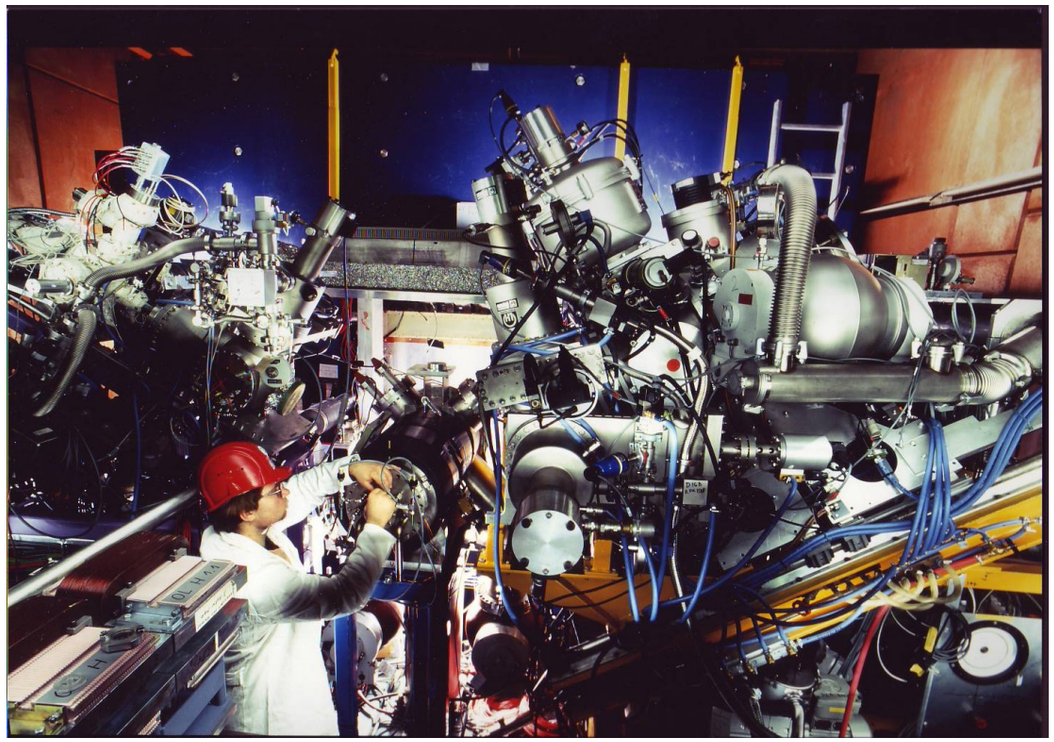
- ★ measurement: Drell-Yan on transversely polarised target
- ★ detailed recent study arXiv:1702.01546
  - ★ for LHCb setup find wide coverage in x comfortable rates, e.g., with HERMES-like target

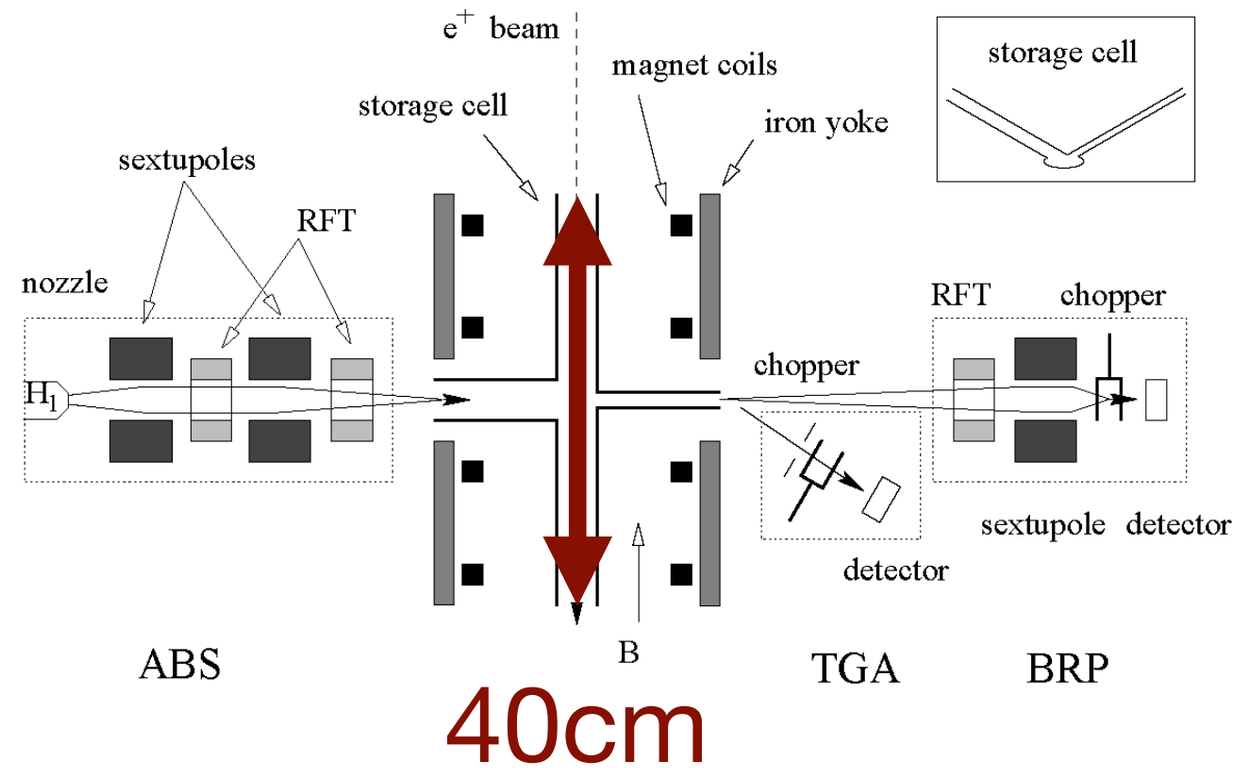


# HERMES polarized target

- storage cell with atomic-beam source internal to (HERA-e) ring





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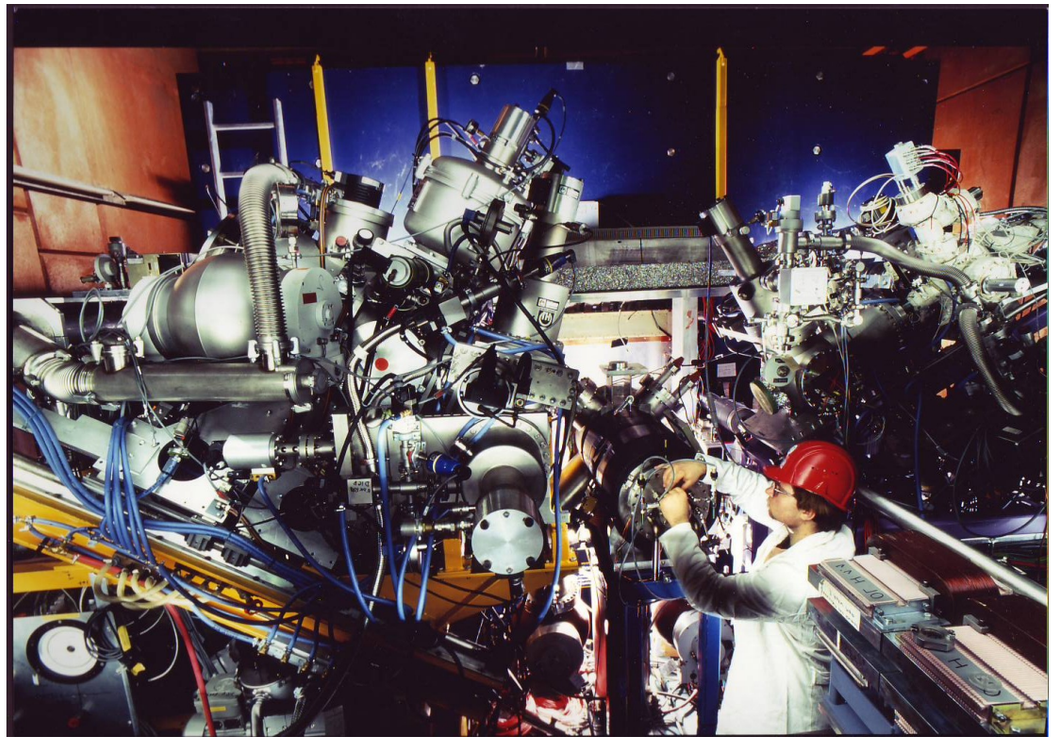

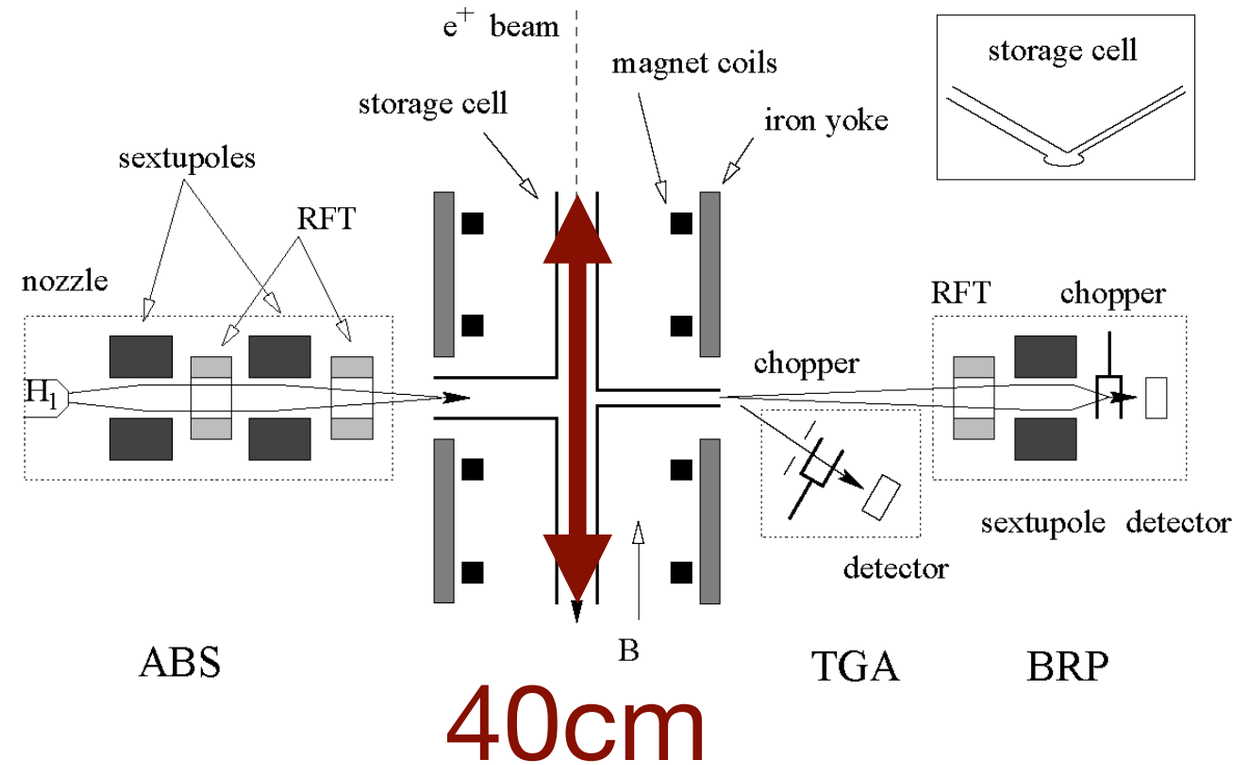

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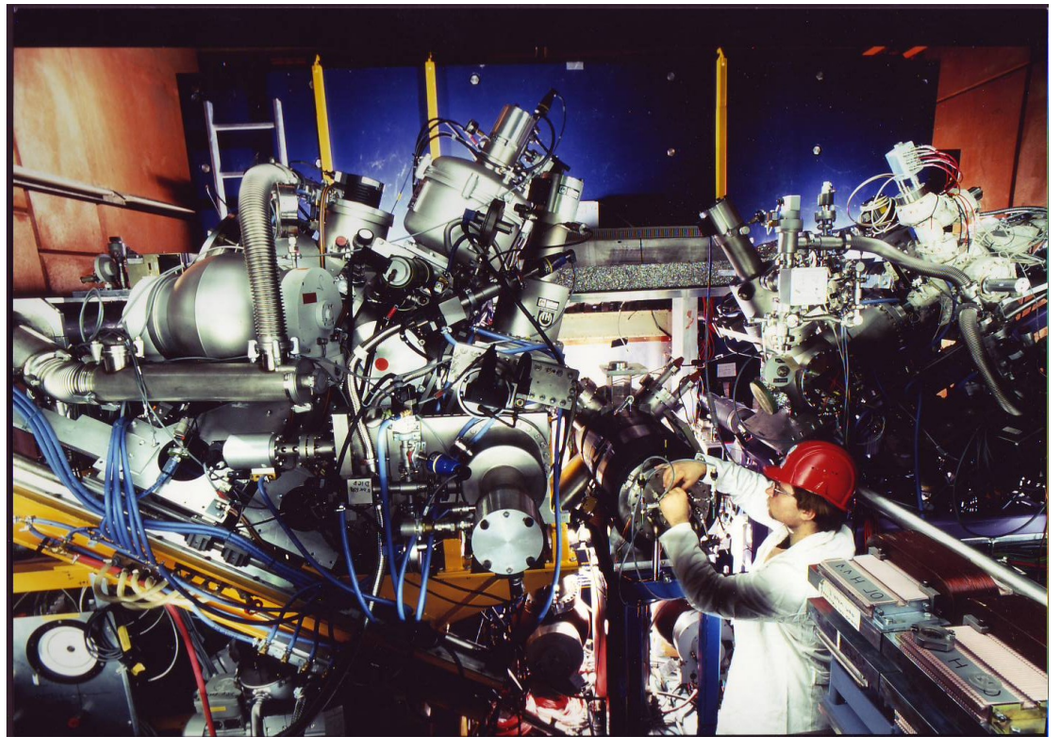
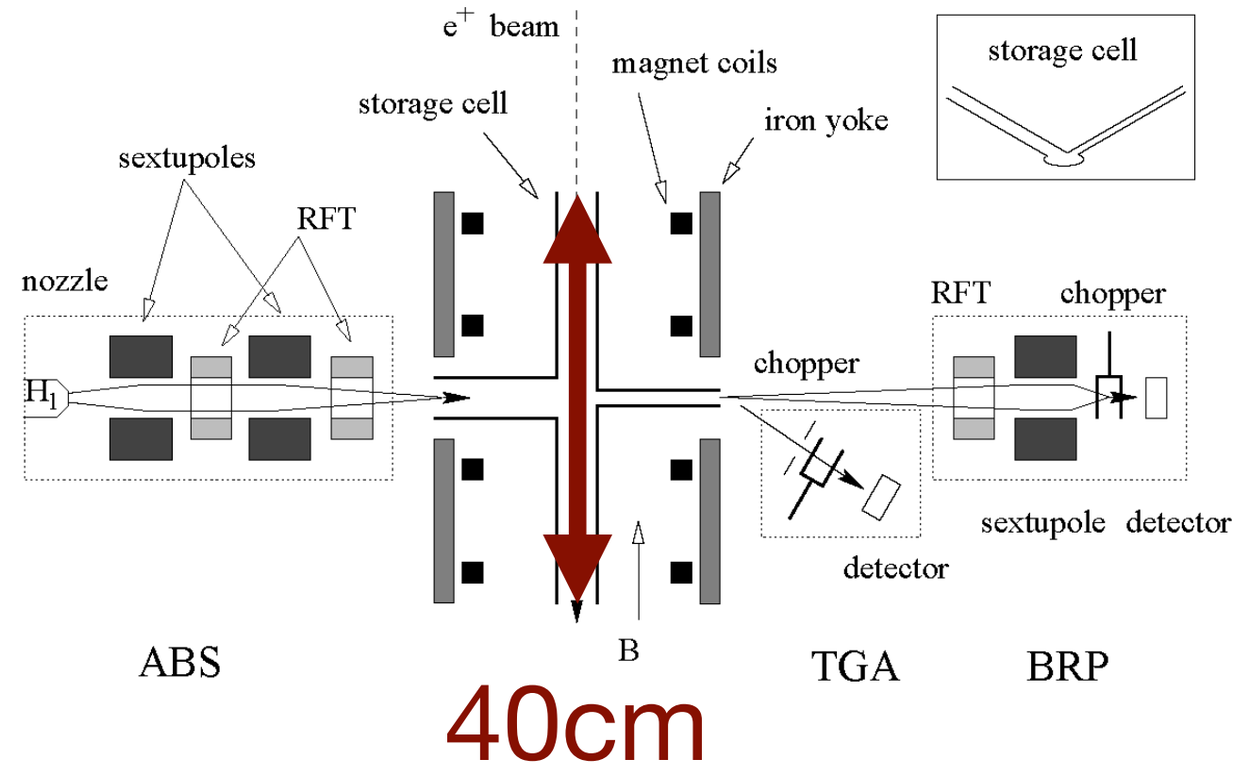


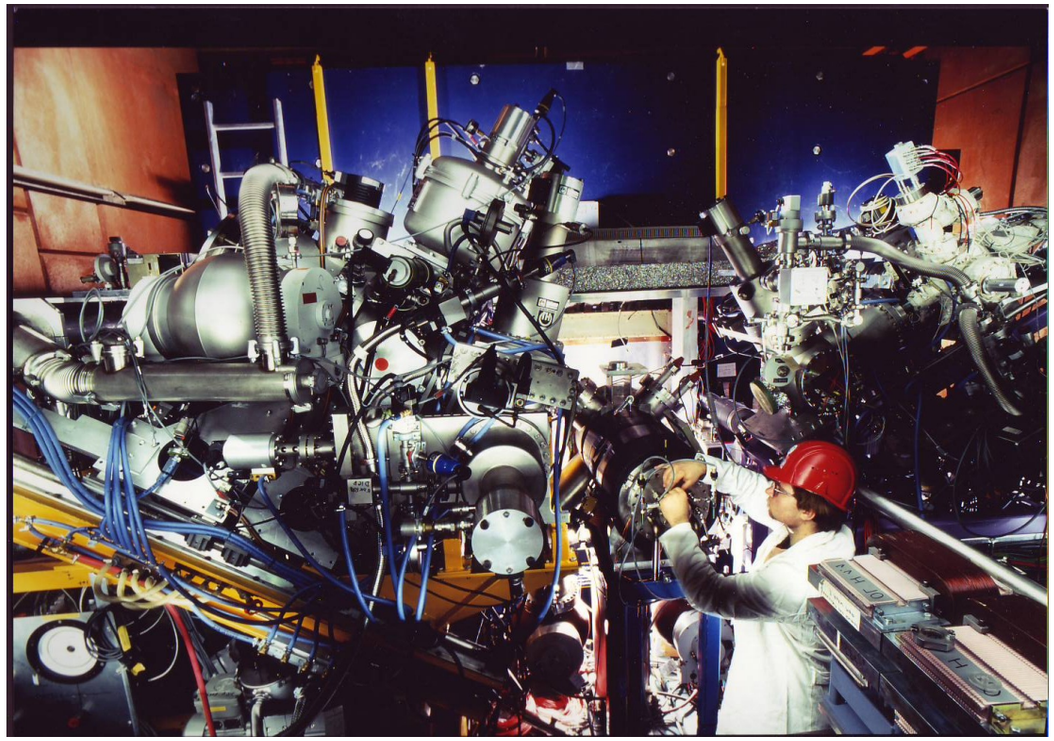


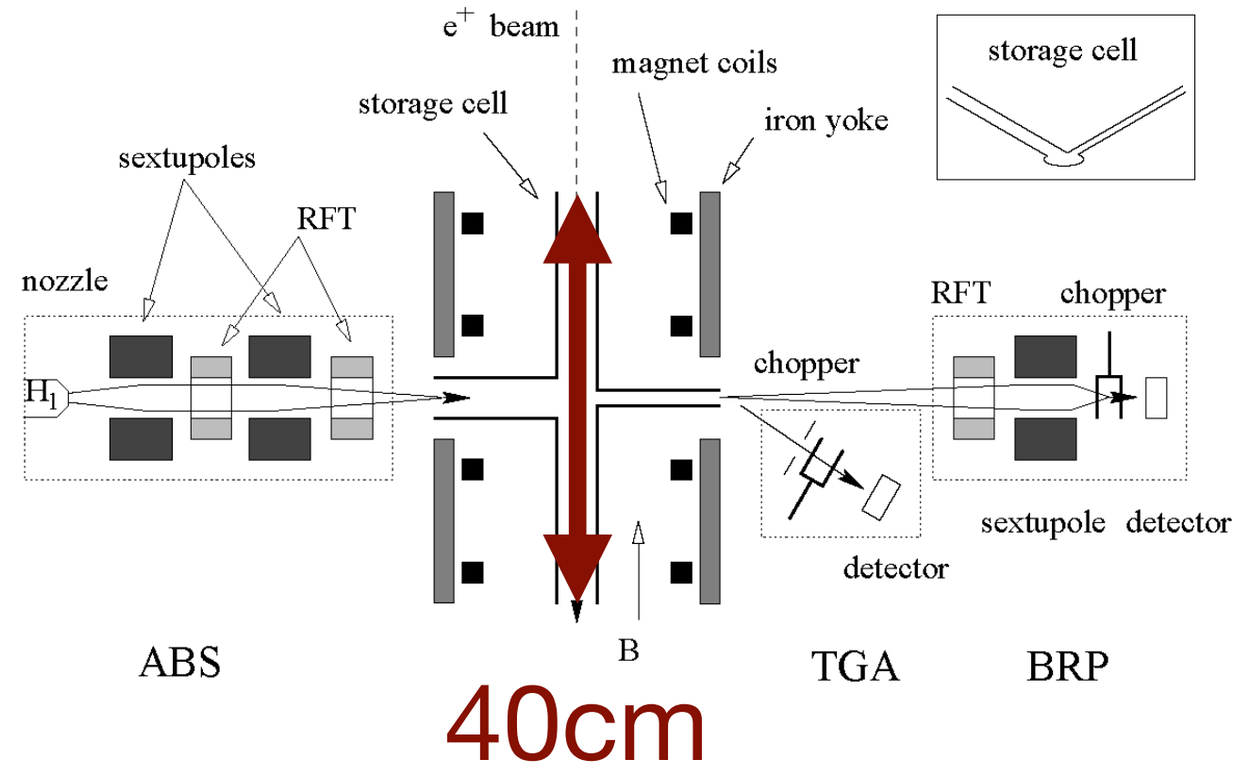

- both long./transv. polarization, as well as diff. target gases

| Target/year | $H_{\parallel}$ (1997) | $D_{\parallel}$ (2000) | $H_{\perp}$ (2003) |
|---|---|---|---|
| $P_T$ | 0.851±0.033 | 0.845±0.028 | 0.795±0.033 |
| t ($10^{14}$ nucl./cm$^2$) | 0.7 | 2.1 | 1.1 |
| FOM ($P_T^2 \cdot t$) | 0.5 | 1.5 | 0.7 |

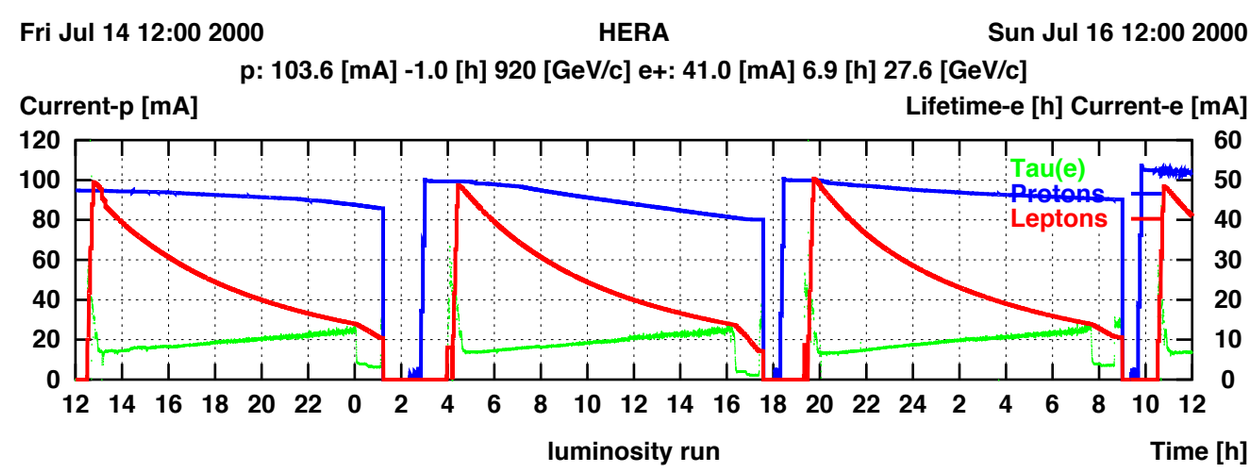
# HERMES polarized target

- storage cell with atomic-beam source internal to (HERA-e) ring






- both long./transv. polarization, as well as diff. target gases
- various unpolarized gases, e.g. high-density end-of-fill runs



# Present/future polarized Drell-Yan experiments

arXiv:1702.01546

| Experiment | particles | beam energy (GeV) | $\sqrt{s}$ (GeV) | $x^{\uparrow}$ | $\mathcal{L}$ (cm$^{-2}$s$^{-1}$) | $\mathcal{P}_{\text{eff}}$ | $\mathcal{F}$ (cm$^{-2}$s$^{-1}$) |
|---|---|---|---|---|---|---|---|
| AFTER@LHCb | $p + p^{\uparrow}$ | 7000 | 115 | $0.05 \div 0.95$ | $1 \cdot 10^{33}$ | 80% | $6.4 \cdot 10^{32}$ |
| AFTER@LHCb | $p$+$^3$He$^{\uparrow}$ | 7000 | 115 | $0.05 \div 0.95$ | $2.5 \cdot 10^{32}$ | 23% | $1.4 \cdot 10^{31}$ |
| AFTER@ALICE$_{\mu}$ | $p + p^{\uparrow}$ | 7000 | 115 | $0.1 \div 0.3$ | $2.5 \cdot 10^{31}$ | 80% | $1.6 \cdot 10^{31}$ |
| COMPASS (CERN) | $\pi^{\pm} + p^{\uparrow}$ | 190 | 19 | 0.1 ~~0.2~~ $\div 0.3$ | $2 \cdot 10^{33}$ | 18% | $6.5 \cdot 10^{31}$ |
| PHENIX/STAR (RHIC) | $p^{\uparrow} + p^{\uparrow}$ | collider | 510 | $0.05 \div 0.1$ | $2 \cdot 10^{32}$ | 50% | $5.0 \cdot 10^{31}$ |
| E1039 (FNAL) | $p + p^{\uparrow}$ | 120 | 15 | $0.1 \div 0.45$ | $4 \cdot 10^{35}$ | 15% | $9.0 \cdot 10^{33}$ |
| E1027 (FNAL) | $p^{\uparrow} + p$ | 120 | 15 | $0.35 \div 0.9$ | $2 \cdot 10^{35}$ | 60% | $7.2 \cdot 10^{34}$ |
| NICA (JINR) | $p^{\uparrow} + p$ | collider | 26 | $0.1 \div 0.8$ | $1 \cdot 10^{32}$ | 70% | $4.9 \cdot 10^{31}$ |
| fsPHENIX (RHIC) | $p^{\uparrow} + p^{\uparrow}$ | collider | 200 | $0.1 \div 0.5$ | $8 \cdot 10^{31}$ | 60% | $2.9 \cdot 10^{31}$ |
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| PANDA (GSI) | $\bar{p} + p^{\uparrow}$ | 15 | 5.5 | $0.2 \div 0.4$ | $2 \cdot 10^{32}$ | 20% | $8.0 \cdot 10^{30}$ |

Table 3: Compilation inspired from [17, 56] of the relevant parameters for the future or planned polarised DY experiments. The effective polarisation ($\mathcal{P}_{\text{eff}}$ ) is a beam polarisation (where relevant) or an average polarisation times a (possible) dilution factor (for a gas target, similar to the one developed for HERMES [52, 112, 113]) or a target polarisation times a dilution factor (for the $NH_3$ target used by COMPASS and E1039). For AFTER@LHC the numbers correspond to a gas target. $\mathcal{F}$ is the (instantaneous) spin figure of merit of the target defined as $\mathcal{F} = \mathcal{P}_{\text{eff}}^2 \times \mathcal{L}$, with $\mathcal{L}$ being the instantaneous luminosity.

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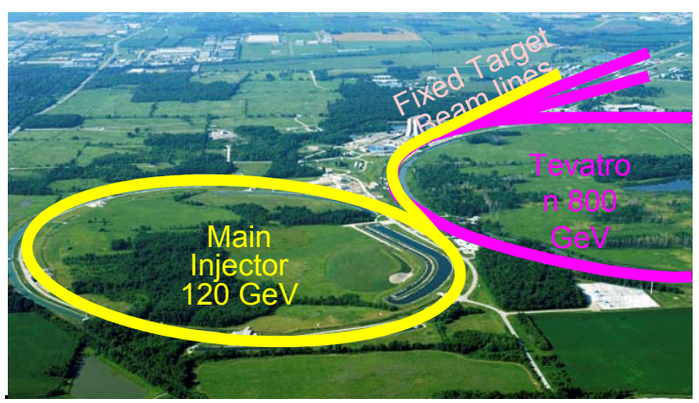
| AFTER@ALICE$_{\mu}$ | $p + p^{\uparrow}$ | 7000 | 115 | $0.1 \div 0.3$ | $2.5 \cdot 10^{31}$ | 80% | $1.6 \cdot 10^{31}$ |
| COMPASS (CERN) | $\pi^{\pm} + p^{\uparrow}$ | 190 | 19 | 0.1 ~~0.2~~ $\div 0.3$ | $2 \cdot 10^{33}$ | 18% | $6.5 \cdot 10^{31}$ |
| PHENIX/STAR (RHIC) | $p^{\uparrow} + p^{\uparrow}$ | collider | 510 | $0.05 \div 0.1$ | $2 \cdot 10^{32}$ | 50% | $5.0 \cdot 10^{31}$ |
| E1039 (FNAL) | $p + p^{\uparrow}$ | 120 | 15 | $0.1 \div 0.45$ | $4 \cdot 10^{35}$ | 15% | $9.0 \cdot 10^{33}$ |
| E1027 (FNAL) | $p^{\uparrow} + p$ | 120 | 15 | $0.35 \div 0.9$ | $2 \cdot 10^{35}$ | 60% | $7.2 \cdot 10^{34}$ |
| NICA (JINR) | $p^{\uparrow} + p$ | collider | 26 | $0.1 \div 0.8$ | $1 \cdot 10^{32}$ | 70% | $4.9 \cdot 10^{31}$ |
| fsPHENIX (RHIC) | $p^{\uparrow} + p^{\uparrow}$ | collider | 200 | $0.1 \div 0.5$ | $8 \cdot 10^{31}$ | 60% | $2.9 \cdot 10^{31}$ |
| fsPHENIX (RHIC) | $p^{\uparrow} + p^{\uparrow}$ | collider | 510 | $0.05 \div 0.6$ | $6 \cdot 10^{32}$ | 50% | $1.5 \cdot 10^{32}$ |
| PANDA (GSI) | $\bar{p} + p^{\uparrow}$ | 15 | 5.5 | $0.2 \div 0.4$ | $2 \cdot 10^{32}$ | 20% | $8.0 \cdot 10^{30}$ |

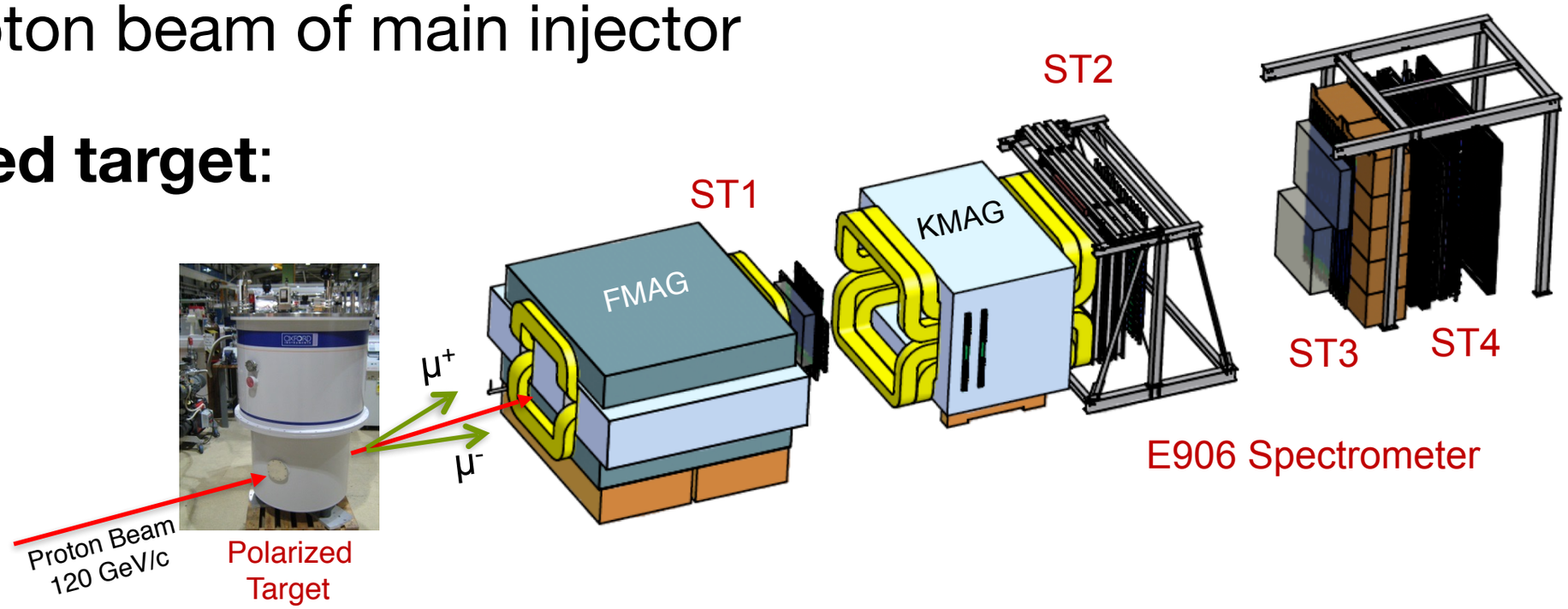
Table 3: Compilation inspired from [17, 56] of the relevant parameters for the future or planned polarised DY experiments. The effective polarisation ($\mathcal{P}_{\rm eff}$ ) is a beam polarisation (where relevant) or an average polarisation times a (possible) dilution factor (for a gas target, similar to the one developed for HERMES [52, 112, 113]) or a target polarisation times a dilution factor (for the $NH_3$ target used by COMPASS and E1039). For AFTER@LHC the numbers correspond to a gas target. $\mathcal{F}$ is the (instantaneous) spin figure of merit of the target defined as $\mathcal{F} = \mathcal{P}_{\rm eff}^2 \times \mathcal{L}$, with $\mathcal{L}$ being the instantaneous luminosity.

# polarized Drell-Yan @FNAL

- two main fixed-target polarized-DY programs with 120 GeV proton beam of main injector

★ **E-1039 polarized target**:



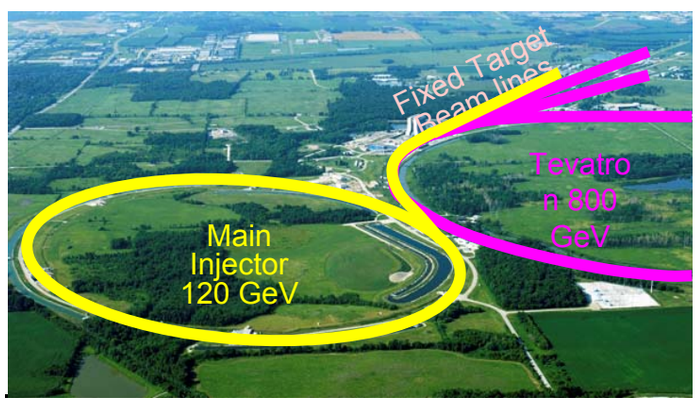



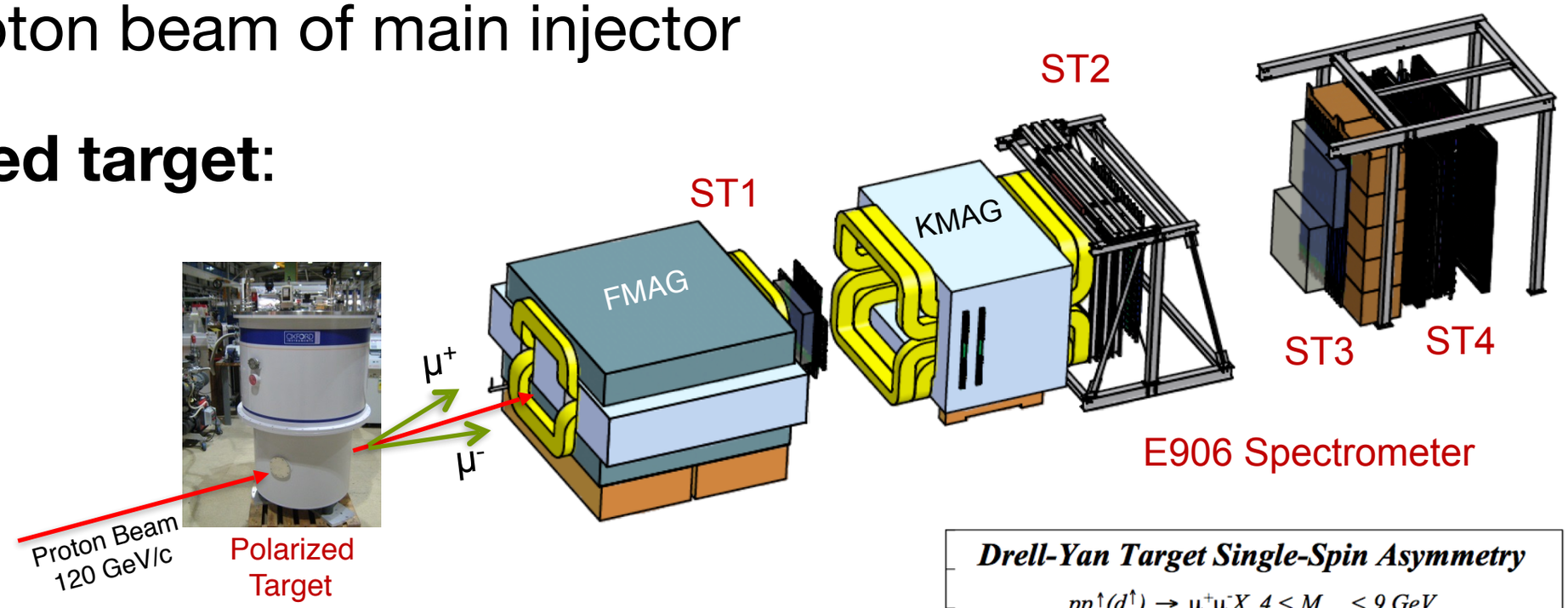

★ kinematic range 4 < M <9 GeV @ $\sqrt{s}$ = 15 GeV
luminosity: $3 \cdot 10^{35}$ /cm$^2$/s ($NH_3$)
dilution factor : 0.176 ($NH_3$) , 0.3 ($ND_3$)
Polarization <80%>, <32%>
$L_{int}$ **= 1.82 *$10^{42}$/cm$^2$ $NH_3$** and
**2.11 *$10^{42}$/cm$^2$ $ND_3$** for 2 years
mainly sensitive to sea quark Sivers function

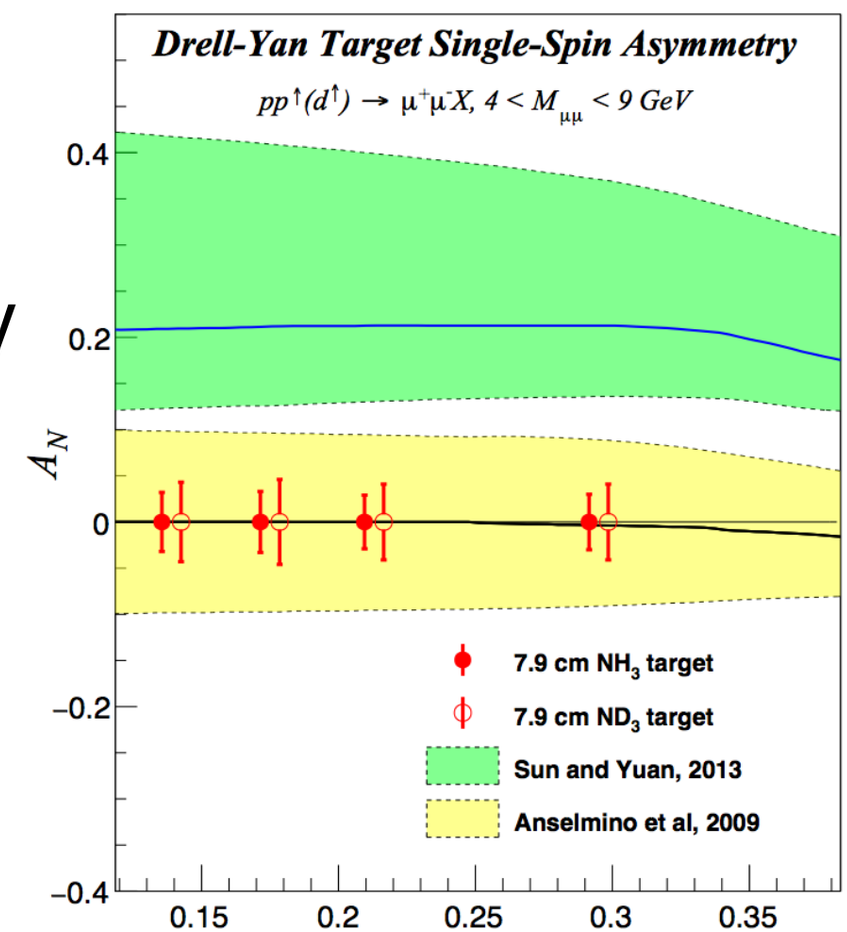
# polarized Drell-Yan @FNAL

- two main fixed-target polarized-DY programs with 120 GeV proton beam of main injector

★ **E-1039 polarized target**:

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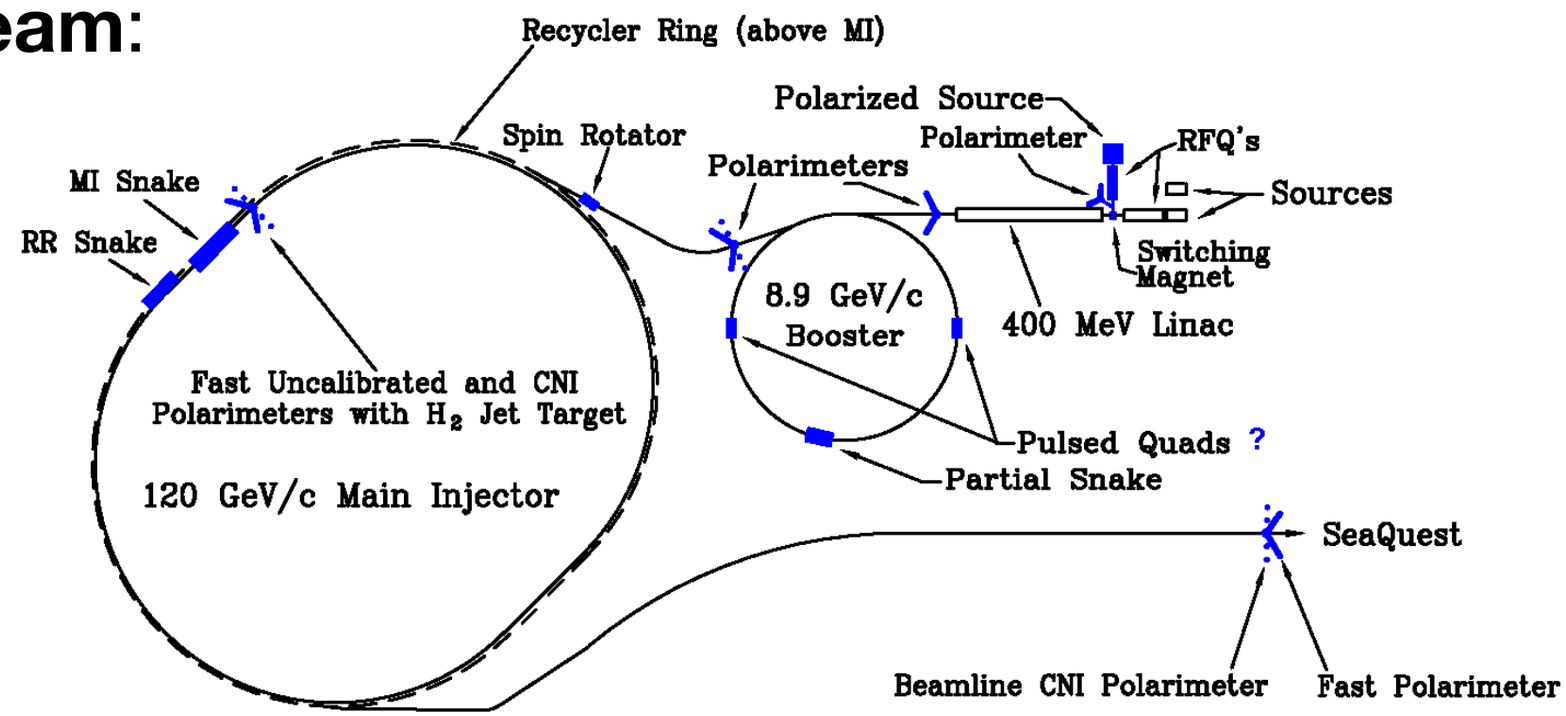
# polarized Drell-Yan @FNAL

- two main fixed-target polarized-DY programs with 120 GeV proton beam of main injector

★ **E-1027 polarized beam**:




★ kinematic range 4 < M <9 GeV @ $\sqrt{s}$ = 15 GeV
luminosity: $2 \cdot 10^{35}$ /cm$^2$/s ($NH_3$)
polarization <60%> no dilution!

probes valence-quark Sivers function in DY at high precision

# polarized Drell-Yan @FNAL

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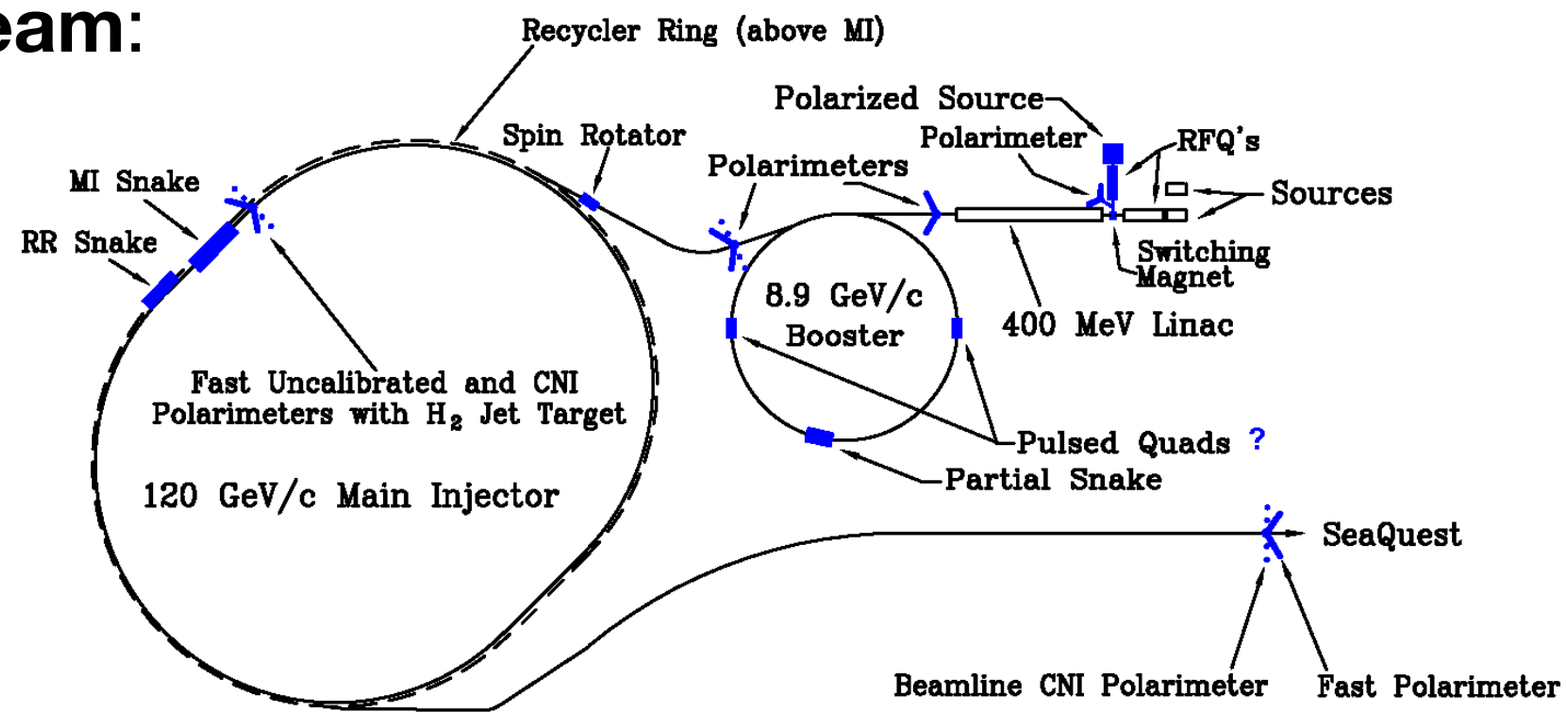
★ **E-1027 polarized beam**:

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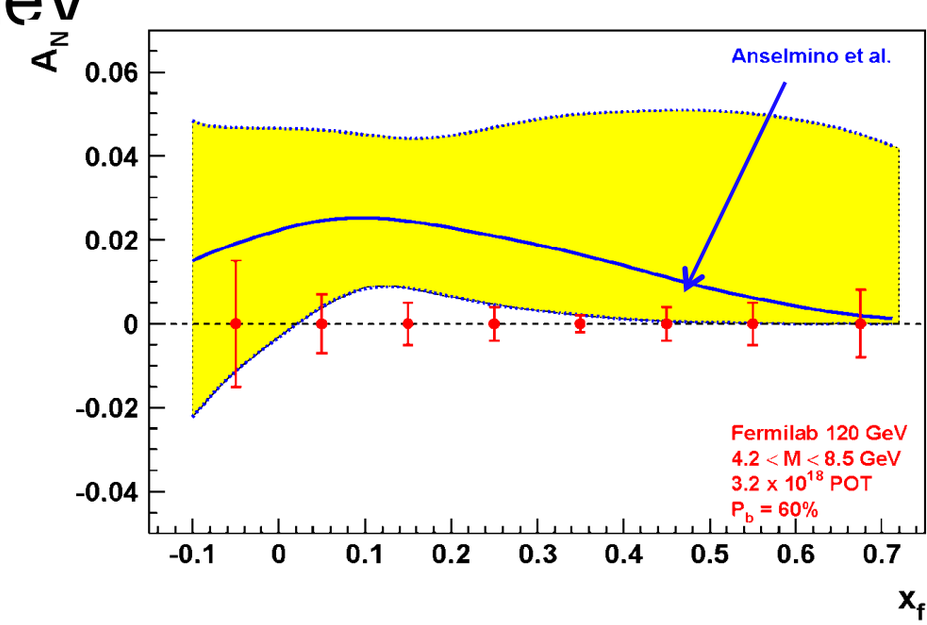
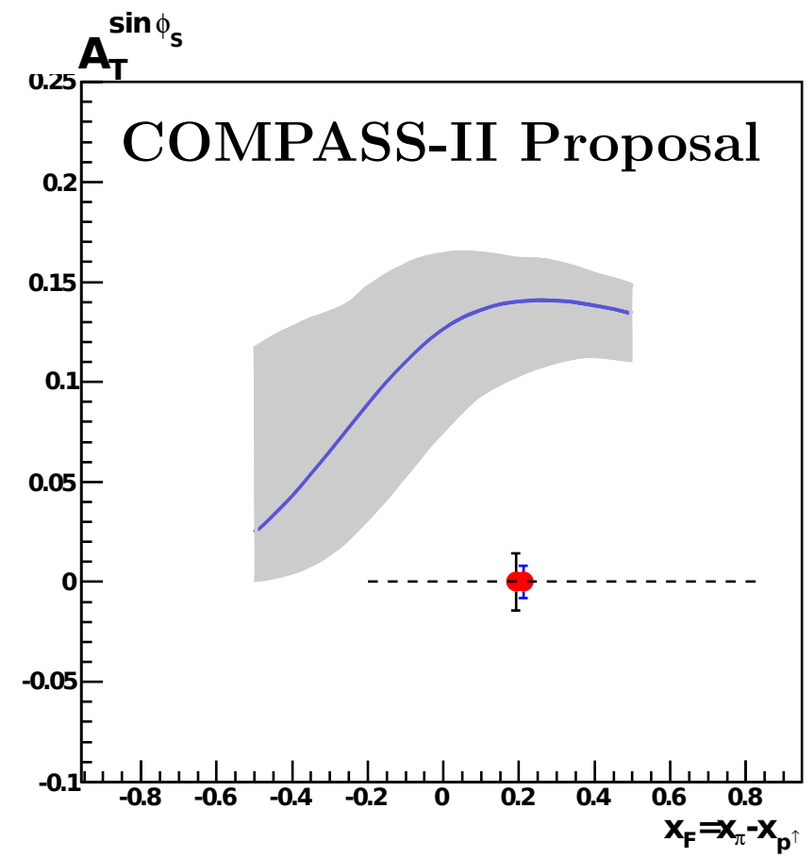


# Drell-Yan @ COMPASS

- 2 years of pion-induced polarized-target DY data by LS2
- substantial increase of precision possible with much more running time or substantial improve in target (can't really improve polarization, but dilution - currently factor 4-6), → how?
- new beam possibilities discussed:
  RF-separated hadron beam (1yr data taking)




| | $NH_3$ | Al (7cm) | W | NA3 | NA10 | E537 | E615 |
|---|---|---|---|---|---|---|---|
| $K^-$ beam | 14,000 | 2,800 | 29,600 | 700 | | | |
| $\bar{p}$ beam | 15,750 | 2,750 | 22,500 | | | 387 | |

[Oleg @ PBC Kick-Off]

→ 1%(?) precision on K/π induced DY (integrated over acceptance)

# COMPASS++: kaon beams

- Drell-Yan: $K + p \rightarrow \mu^+\mu^- + X$

★ compared with $\pi + p$ : parton densities in kaon

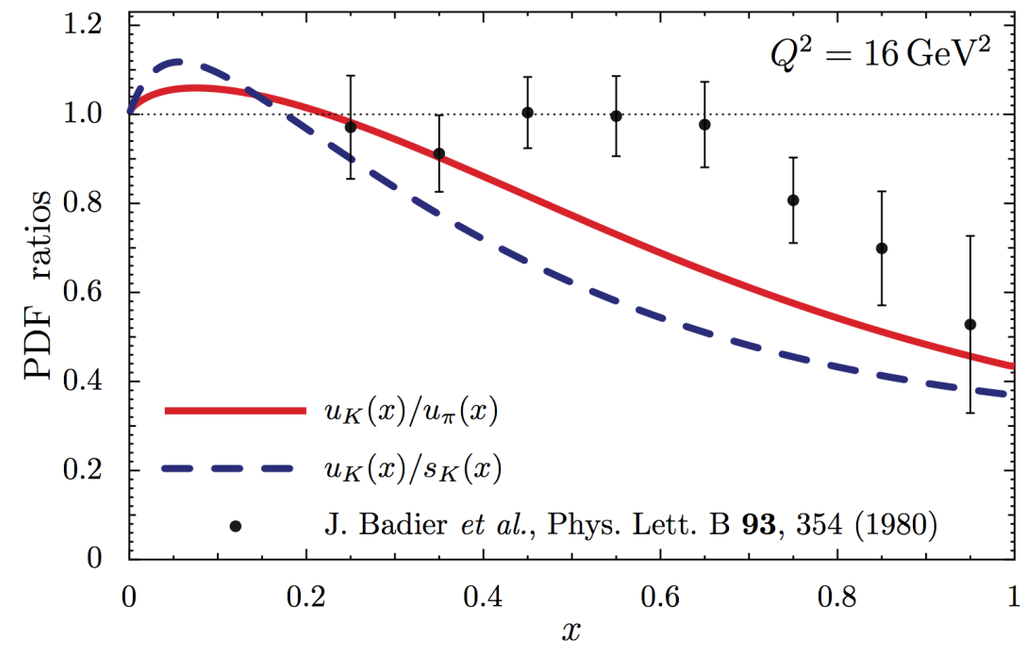
★ kaon and pion distributions related by SU(3) flavour symmetry → study SU(3) breaking (influence of strange mass)

Estimate in NJL model, arXiv:1604.02853

★ measurement without competition

★ expected size of effects vs. experimental accuracy?

★ strong enough as physics driver?



# COMPASS++: antiproton beams

- Drell-Yan with $\bar{p}$ + p(pol)

★ strong physics motivation: see earlier slide

★ possible advantage for rates compared with p+p:

$x_1\, x_2\, s = Q^2$ gives $x_1\, x_2 > 0.01$
→ (anti)quarks in valence region in beam and target

★ but: tough competition with p+p Drell-Yan proposals
→ to be worked out quantitatively

# selected further Drell-Yan activities

- J-Parc: polarized DY program “in stasis”
  (30 or even 50 GeV proton beam)
  “near-term” (2020~), 20 GeV pi- beam fixed-target program
  possibility for <10 GeV pion/kaon/(anti-)proton beam

- PANDA@FAIR (under construction); 2025++
  $\sqrt{s}$ = 5.5 GeV; valence quarks because of anti-proton beam

- SPASCHARM @ IHEP 20xx ?
  40-70 (100?) GeV proton beam on (pol.) fixed-target
  secondary hadron beams & tertiary polarized (anti)protons

- NICA (under construction); 2023++
  $\sqrt{s}$ = 26 GeV, but polarized beam uncertain

- fsPHENIX@RHIC (under consideration); 2021++
  $\sqrt{s}$ = 200/500 GeV doubly polarized DY possible

Reminder: DY cross section ~1/s ; BG processes increase with s

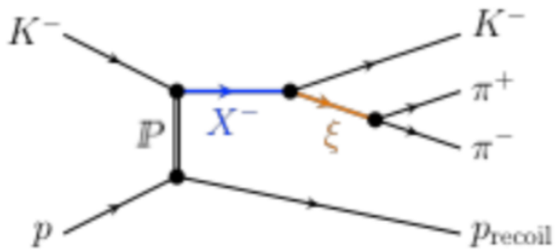
# COMPASS++

**RF separated kaon beam ~ 8 x $10^6$ /s, beam momentum ~100 GeV**

What can we contribute as COMPASS?

- State-of-the-art high-resolution spectrometer with full PID
- Advanced analysis techniques being developed in the light-quark sector

Method to be used: Kaon beam diffraction scattering on $LH_2$ and thin nuclear targets




- Goal: ~10 larger data sample than existing worldwide what would make possible to have similar to pion diffraction wave set: 88 waves in 11 t′ bins;
- COMPASS could rewrite PDG tables for strange mesons
- Extend studies of chiral dynamics to strange sector

No real competitors

JParc - ~$10^5$ /s, low momenta kaons

JLab - ~$10^4$ /s, $K^0$ long beam, lower momenta

from: O Denisov @ PBC Kickoff

- quantitative comparison with competition? is high energy essential?
- strange spectroscopy at PANDA?

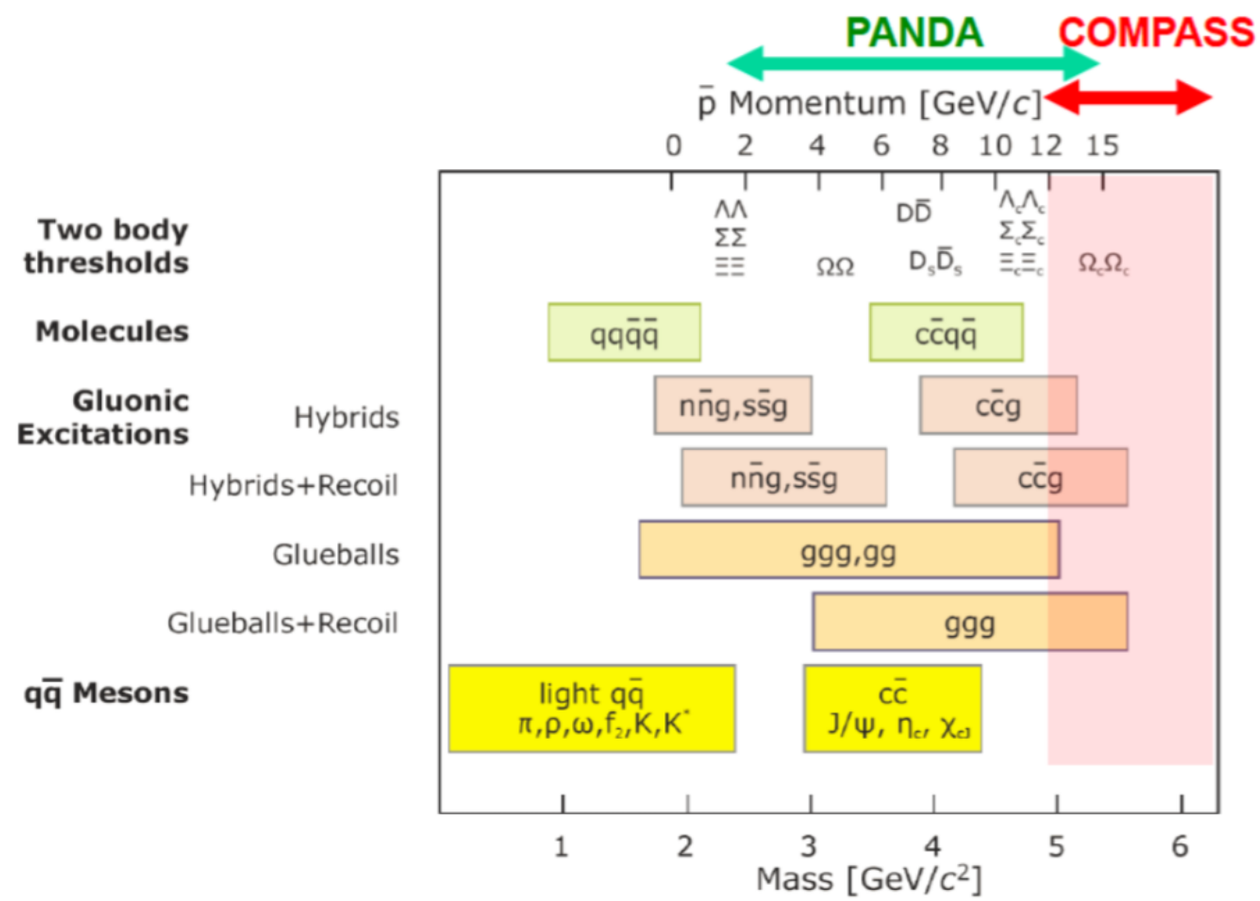
# COMPASS++

**RF separated antiproton beam, beam momentum ~ 20 GeV**

Method: antiproton-proton annihilation

Goal: charmed hybrids and exotics study in the mass range higher than reachable in PANDA

**Complementary to LHCb**
**(p-pbar annihilation – gluon rich environment and it allows high spin states)**
**Otherwise no competitors for the next at least 10 years**

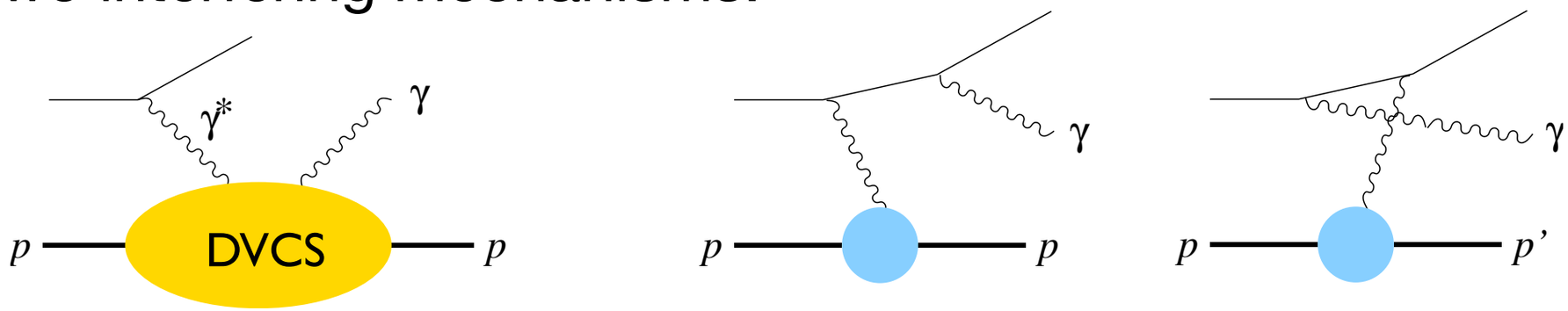



from: O Denisov @ PBC Kickoff

- gain compared with PANDA large enough?
- comparison with LHCb? what is advantage of p+pbar over p+p for producing these states?

# COMPASS++

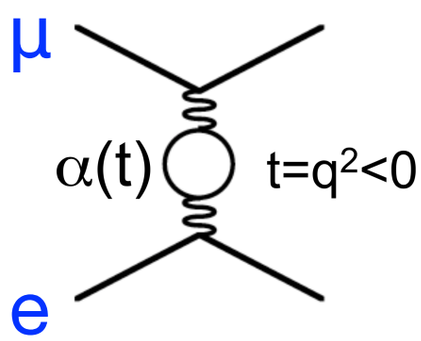
- possible extension of muon programme: DVCS
  Deeply Virtual Compton Scattering (μp → μpγ)
- two interfering mechanisms:



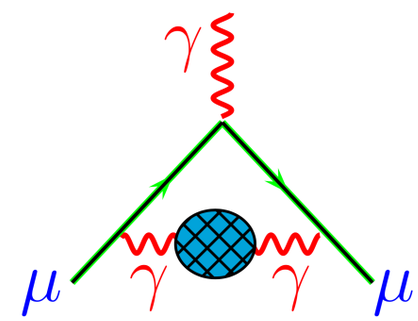

- $p_T$ of scattered proton → spatial distributions of quarks/ gluons inside proton  femtometer analogue of Bragg refraction
- under investigation: transverse target polarisation
  - ★ related with sum rule for orbital angular momentum
  - ★ technically demanding (pol. target with proton recoil det.)
  - ★ severe competition from EIC

# μ-e

- idea: measurement of μ-e elastic scattering
  → hadronic vacuum pol. contribution to $(g-2)_\mu$




sum rule
→




- physics motivation:

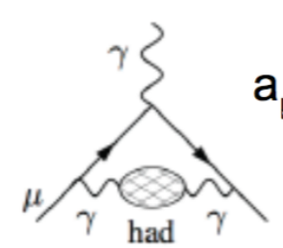
$$a_\mu^{E821} - a_\mu^{SM} \sim (28 \pm 8) \times 10^{-10}$$

Current discrepancy limited by:

- Experimental uncertainty→ New experiments at FNAL and J-PARC **x4** accuracy
- Theoretical uncertanty→ limited by hadronic effects

$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{HAD} + a_\mu^{Weak}$$

Hadronic Vacuum polarization (HLO)



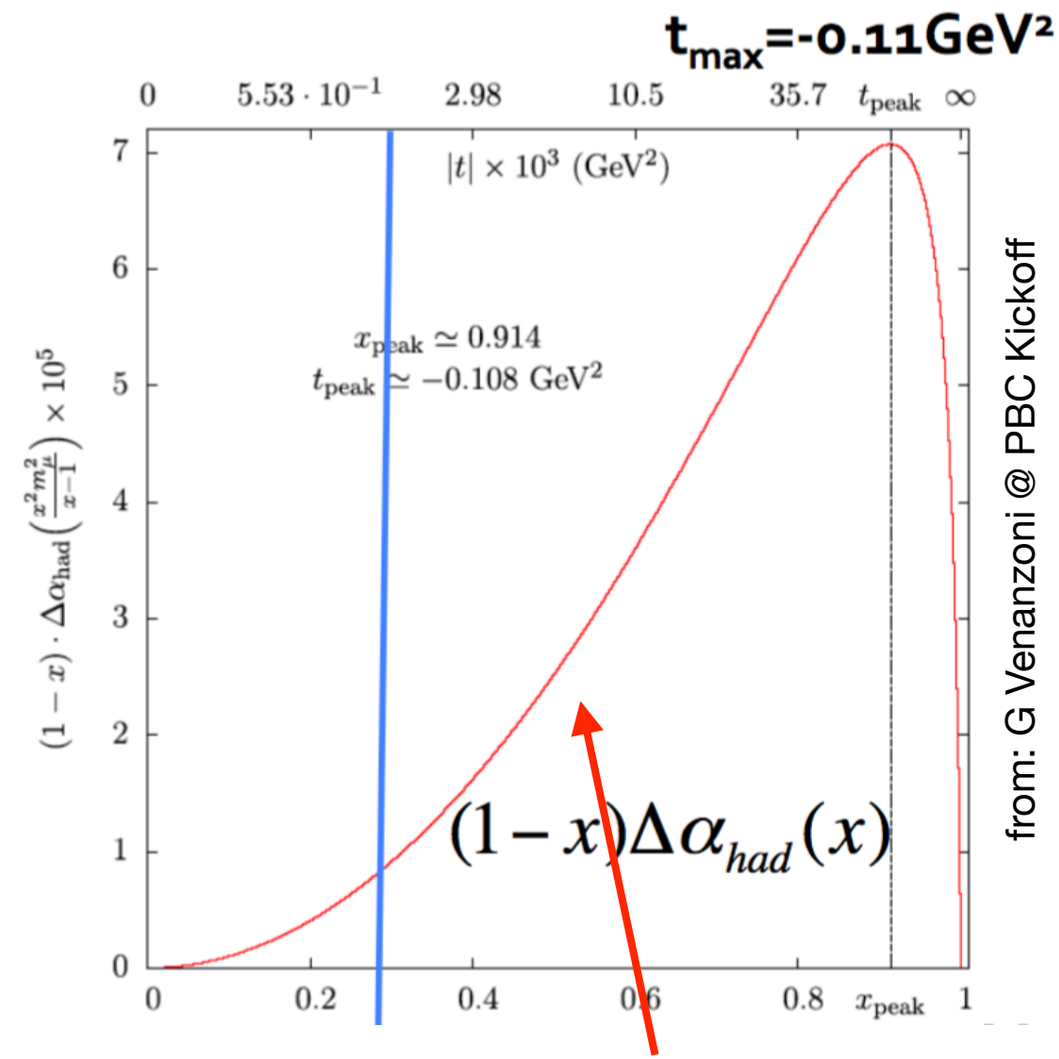

$a_\mu^{HLO} = (692.3 \pm 4.2)10^{-10}$

$\delta a_\mu / a_\mu \sim 0.6\%$

from: G Venanzoni @ PBC Kickoff

# μ-e

- determination would be "more direct" than via $e^+e^-$ annihilation data and dispersion relation and complementary to efforts to compute in lattice QCD
- need $O(10^{-5})$ accuracy on s for target precision of 0.3% on $a_\mu$
- uncertainty from unmeasured t region?
- competition?
  scattering at BES?
  other muon beams worldwide?
- could this be done with COMPASS?



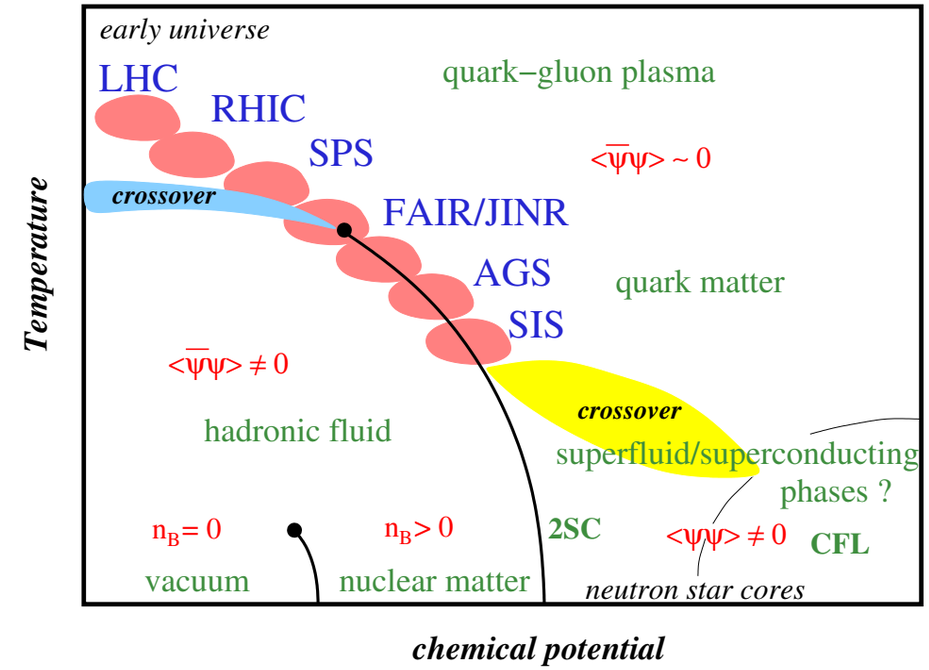

from: G Venanzoni @ PBC Kickoff

integral under curve → $a^{had}_\mu$

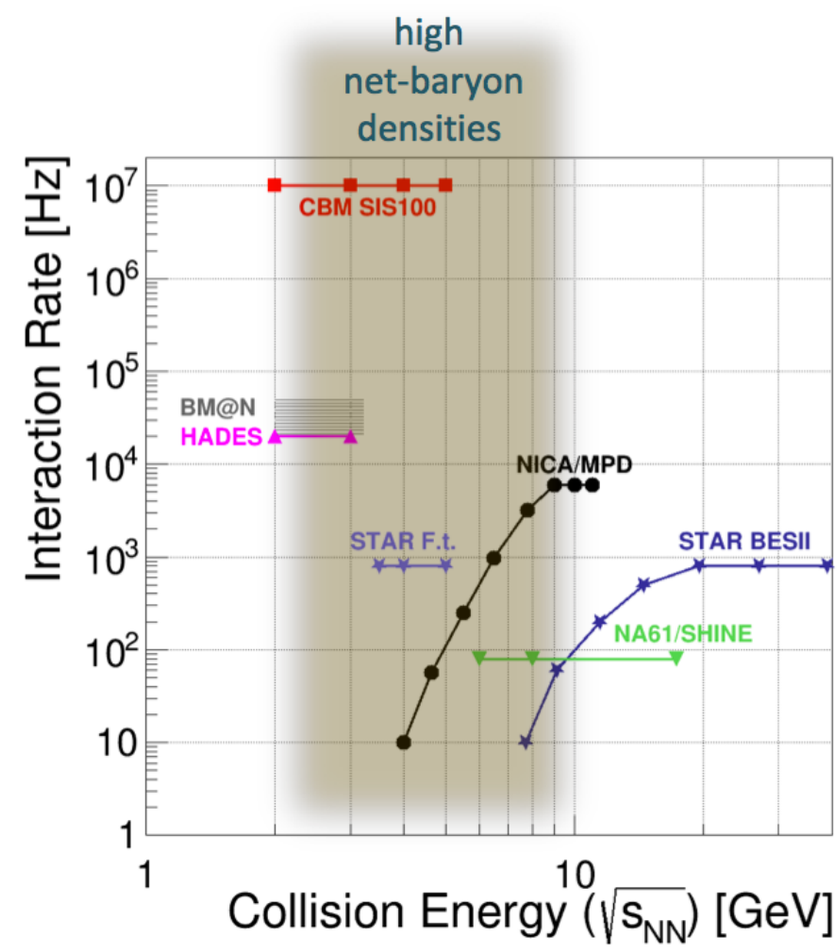
# NA60++

- CERN-SPS: wide range of $\mu_B$ coverage & interaction rate

  ★ complementary to existing/planned experiments:
  SIS & HADES, BES RHIC



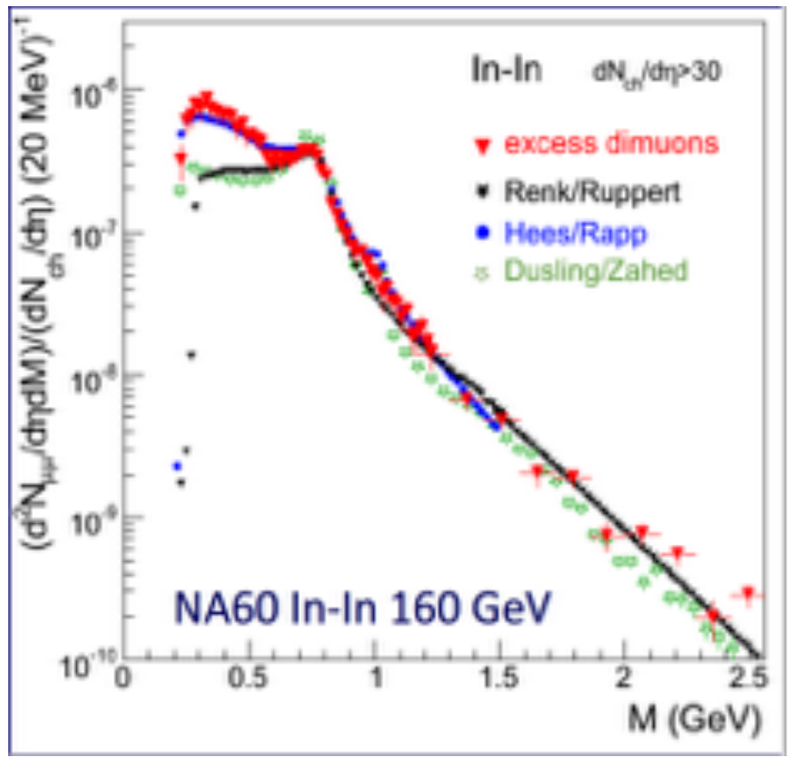

  ★ High interaction rate
  (higher than NICA; plot would have to be provided)




  ★ very interesting proposal:
  sharpen physics case!

# NA60++

- Dilepton thermometer as probe of confinement-deconfinement temperature




$$\propto M^{3/2} e^{-M/T}$$

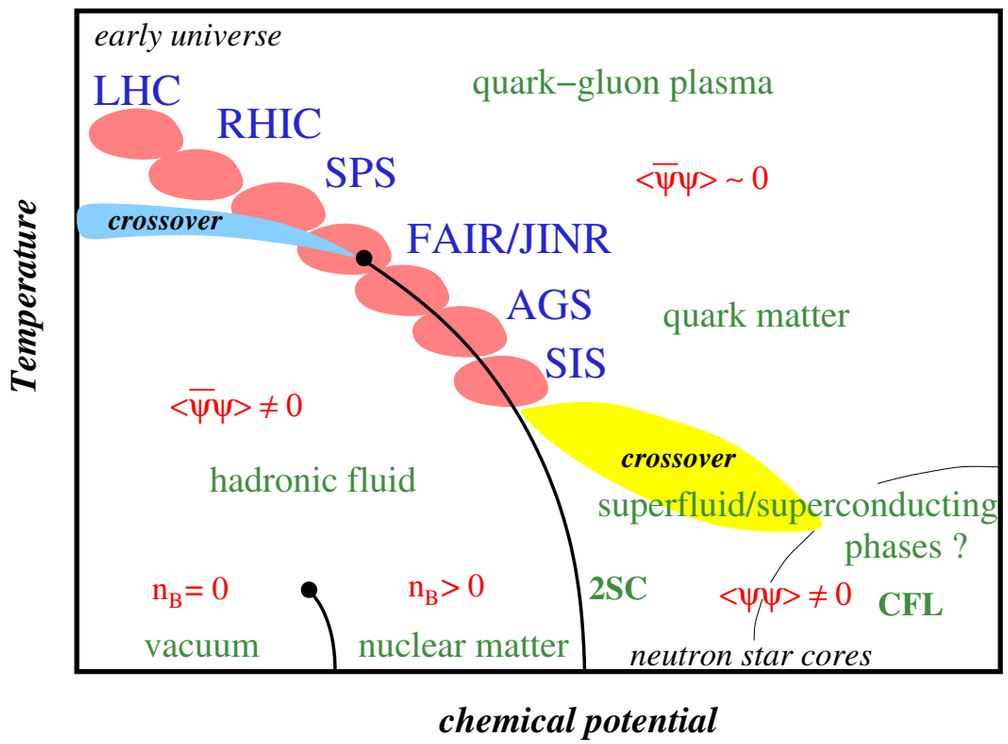
- Charmonium & open charm

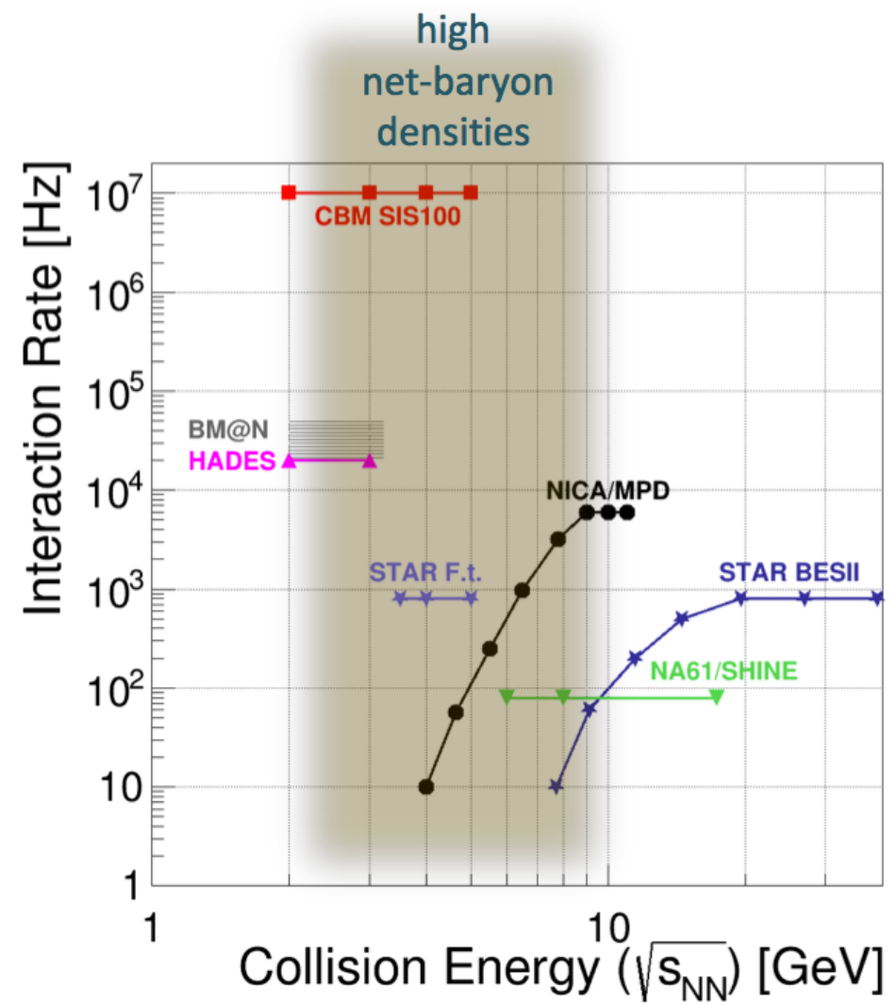
  ★ J/psi anomalous suppression, refined analysis

- Sharpen case for NA60++: (New) physics impact!

# NA61++

- Experimental competition?



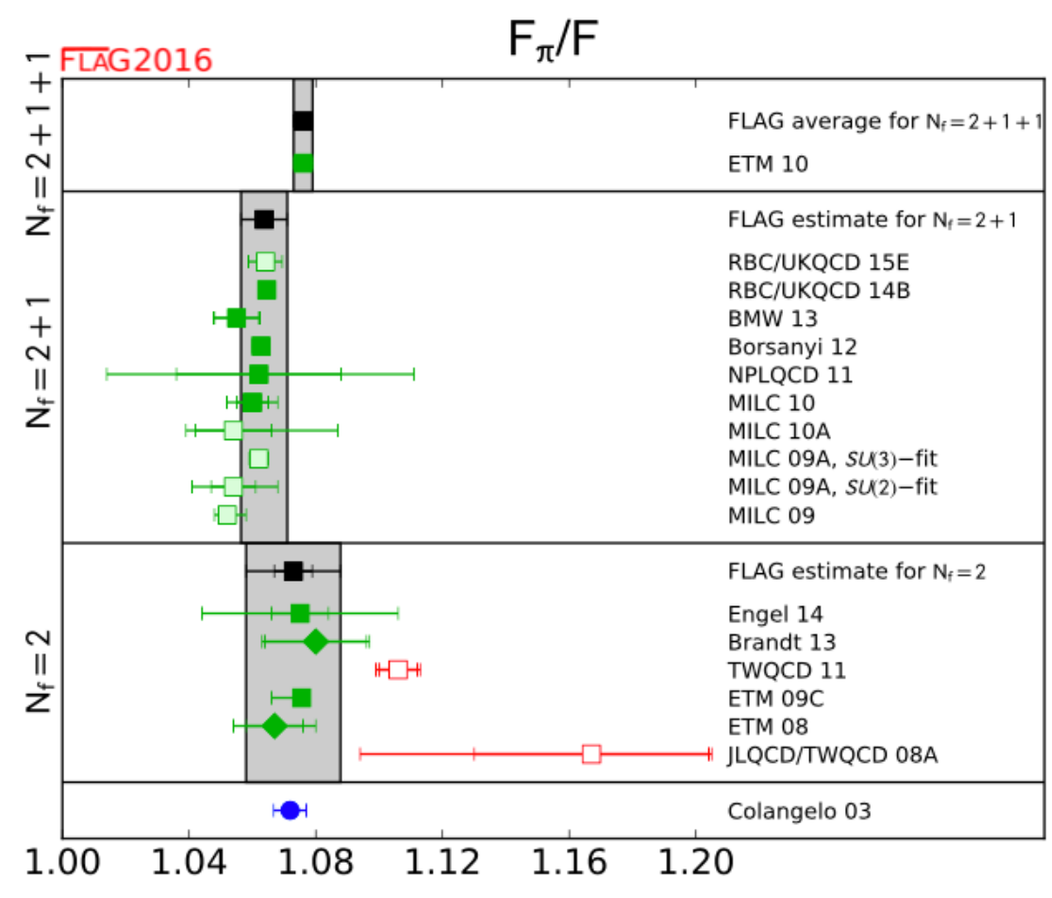

- Physics case:

  ★ Statistical Model vs. dynamical approaches (strong enough?)

# DIRAC++

- DIRAC: pioneering experiment at CERN PS producing ππ and πK atoms and measuring their lifetimes → compute ππ and πK scattering lengths
- physics: chiral symmetry breaking in QCD → low-energy interactions between π's and K's predicted → chiral perturbation theory (ChPT)
- lattice computation of low-energy constants: very active field, significant progress

compilation of results in arXiv:1607.00299



# DIRAC++

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- physics: chiral symmetry breaking in QCD
  → low-energy interactions between π's and K's predicted → chiral perturbation theory (ChPT)
- DIRAC++ at SPS: would have significantly higher yield for πK atoms
  → measure $|a_{1/2} - a_{3/2}|$ with accuracy below 5%

★ quantity computed using ChPT/lattice techniques

which impact would this measurement have on the field?

# DIRAC++

- in pp sector: could improve existing accuracy on $|a_0 - a_2|$ from ~4% to ~2%
- possibility to measure $|2\ a_0 + a_2|$ with long-lived pp atoms? (observed by DIRAC)
  - ★ quantitative estimates? would probably require different expt'l setup than πK programme
  - ★ expected physics impact?

# Baryon magnetic moments

- idea: measure magnetic moments of short-lived baryons $\Lambda_c$ (udc), possibly also $X_c$ (usc) or $X_{cb}$ (ubc) via spin precession using bent crystal at LHC
  - ★ possibly extend technique to $\tau$ lepton ?
- physics motivation (for baryons): probe anomalous magnetic moment of c (or b) quark
- physics questions (QCD):
  - ★ how reliably can connect magn. moments of baryon and heavy quark?

| Baryons | Bag | Nonrel | [15] | [16] | [17] | [20] | [24] | [25] |
|---|---|---|---|---|---|---|---|---|
| $\Lambda_c^+$ | 0.411 | 0.39 | 0.40 | 0.341 | 0.42 | 0.37 | 0.39 | 0.37 |
| $\Sigma_c^0$ | −1.043 | −1.37 | −1.38 | −1.391 | −1.04 | −1.17 | −1.60 | – |
| $\Sigma_c^+$ | 0.318 | 0.49 | 0.49 | 0.525 | 0.36 | 0.63 | 0.30 | – |
| $\Sigma_c^{++}$ | 1.679 | 2.35 | 2.36 | 2.44 | 1.76 | 2.18 | 2.20 | – |
| $\Xi_c^0$ | 0.421 | 0.41 | 0.41 | 0.341 | 0.39 | 0.36 | 0.28 | 0.32 |
| $\Xi_c'^0$ | −0.914 | −1.18 | −1.12 | −1.12 | −0.95 | −0.93 | −1.32 | – |
| $\Xi_c^+$ | 0.257 | 0.20 | 0.40 | 0.341 | 0.41 | 0.37 | 0.40 | 0.42 |
| $\Xi_c'^+$ | 0.591 | 0.89 | 0.75 | 0.796 | 0.47 | 0.76 | 0.76 | |

from: A Stocchi @ PBC Kickoff

# Baryon magnetic moments

- idea: measure magnetic moments of short-lived baryons $\Lambda_c$ (udc), possibly also $X_c$ (usc) or $X_{cb}$ (ubc) via spin precession using bent crystal at LHC
  - ★ possibly extend technique to $\tau$ lepton ?
- physics motivation (for baryons): probe anomalous magnetic moment of c (or b) quark
- physics questions (BSM):
  - ★ existing constraints on $(g\text{-}2)_c$ or $(g\text{-}2)_b$ or $(g\text{-}2)_\tau$ ? e.g. from $e^+e^-$ annihilation?
  - ★ estimates on their size from BSM models?
  - ➡ achievable experimental precision adequate?