eRHICの物理

後藤

個人的意見

- 新しい核子描像を作る
  - 統合された核子、原子核描像？
  - 新しい核物質（状態）？
- Collinearな描像
  - 高エネルギー実験では十分？
    - High-x、Low-xでは不確定
  - LHC/CMSのridgeのような研究も可能（アイデア次第）
    - High multiplicityのようなextreme condition
    - 核子と原子核の境界はあるか？
  - 他の問題？
- 新しい描像
  - 統合された核子、原子核描像
    - 原子核は単なる核子の集まりではない、Cold Nuclear Matter (CNM)
  - 新しい核物質
    - CGC、グラズマ
  - 多次元描像
    - GPD、TMD

RHICからRHIC+eRHICへ

- 新しい（統合された）核子、原子核描像を作る実験（施設）
- Strong、EM、Weakすべてのプローブを用いた研究
- eRHIC以前、eRHIC建設期、今後５年間？
  - W、transverse-spin、VTXを用いた物理（heavy-flavor、jet）
- eRHIC建設期、５年後？
  - Drell-Yan、detector upgradeによる物理（full jet?）
  - sPHENIX
- eRHIC初期、１０年後？
  - $\sqrt{s}$ ~ 70 GeV (e: 5 GeV + p: 250 GeV)
  - ePHENIX
- eRHIC完成期
  - $\sqrt{s}$ ~ 200 GeV (e: 30 GeV + p: 325 GeV)
    - HERAは$\sqrt{s}$ ~ 300 GeV (e: 27.5 GeV + p: 920 GeV)
  - 新検出器、新実験
  - 同時にRHIC実験（ePHENIX）

（拡張した）研究の対象

- Confined parton
  - 核子
  - 原子核
    - 単なる核子の集合ではない
    - Cold nuclear matter (CNM)
- Unconfined parton
  - QGP
    - 新しい核物質
    - Hot nuclear matter
  - RHICにおけるQGPの物性研究
    - 新しい核物質の理解
- RHIC+eRHICのプログラムを作る

*eA collider*による*CNM*の理解

- Saturation – CGC, glasma, …
  - Inclusive
    - F_2, F_L, F_2^c, F_L^c (at small-x)
    - Cross section
  - Semi-inclusive
    - Ridge
  - Diffraction
    - Initial condition
  - DVCS
- Fragmentation function in nuclear medium
  - Diffraction?
  - DVCS?

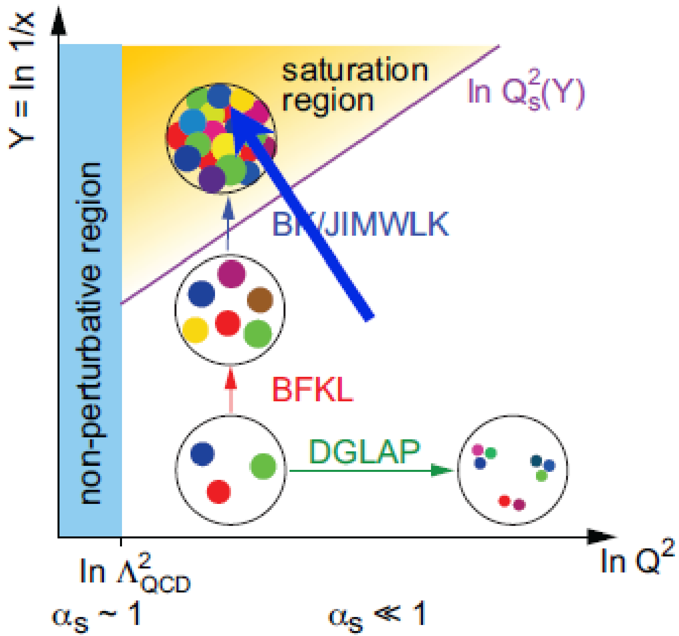
偏極ep colliderによる偏極核子構造の理解

- $\Delta\Sigma$、Δgの高精度決定
  - Inclusive
  - Semi-inclusive
    - Flavor separation
  - Charged & neutral current
- 軌道角運動量とGPD
  - DVCS
- TMD
  - Semi-inclusive

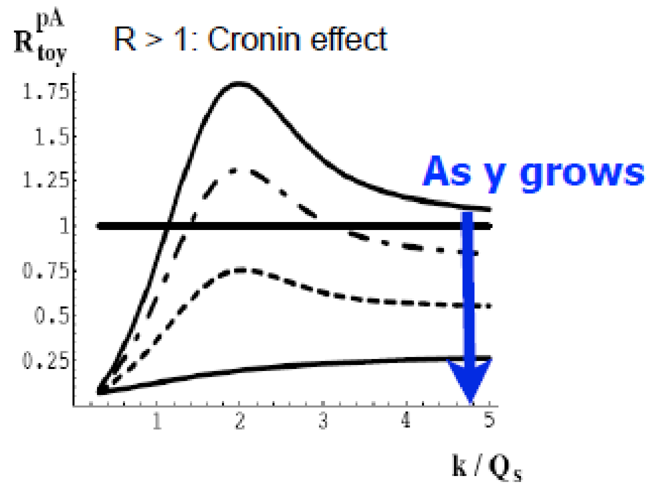
Saturation

Looking for Saturation in dA Collisions

Recall earlier plot:



$$R_{dAu} = \frac{N_{dAu}}{\frac{\langle N_{bin} \rangle}{\sigma_{pp}^{inel}} \sigma_{pp}}$$



Kharzeev, Kovchegov, Tuchin hep-ph/0307037

CGC expects suppression of forward hadron production

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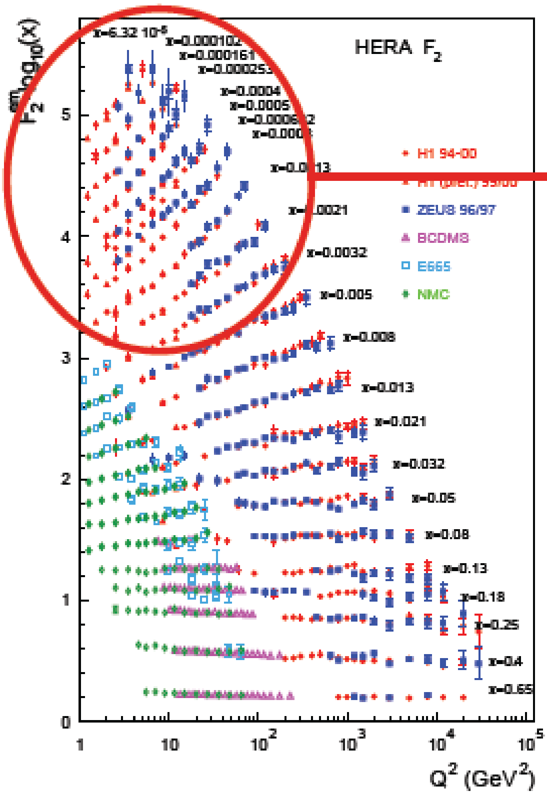
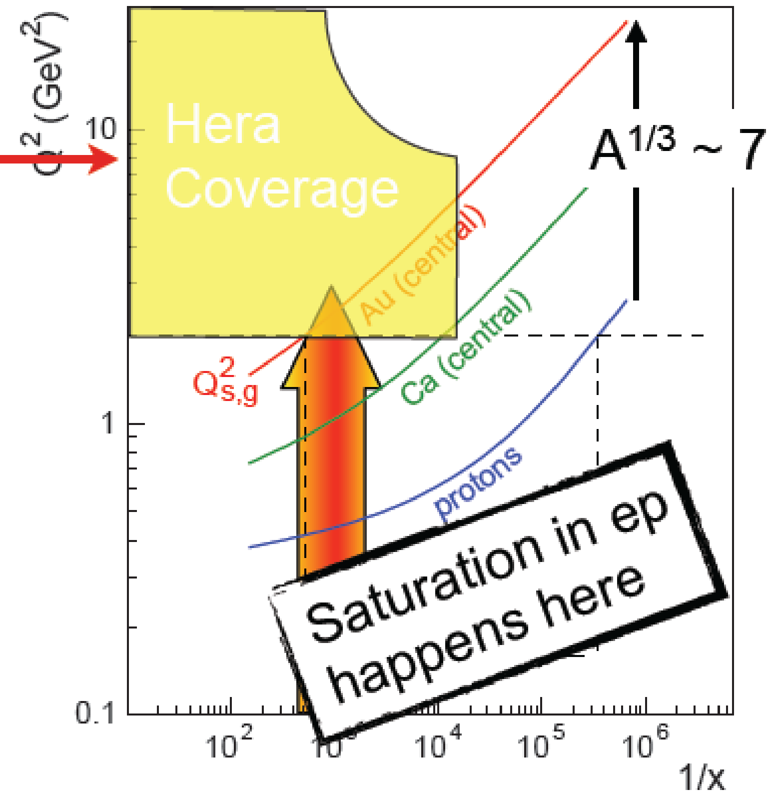
Saturation

Are RHIC & HERA Results consistent?





- **Strong hints** of saturation from RHIC: $x \sim 10^{-3}$ in Au
- ep: **No (weak) hints** in DIS at Hera up to $x=6.32\cdot10^{-5}$, Q^2=1-5 GeV^2

- Finding RHIC and Hera & Q_s scalings consistent
- At pA in RHIC we see the Nuclear "Oomph" $Q_s^2 \sim Q_0^2\,(A/x)^{1/3}$

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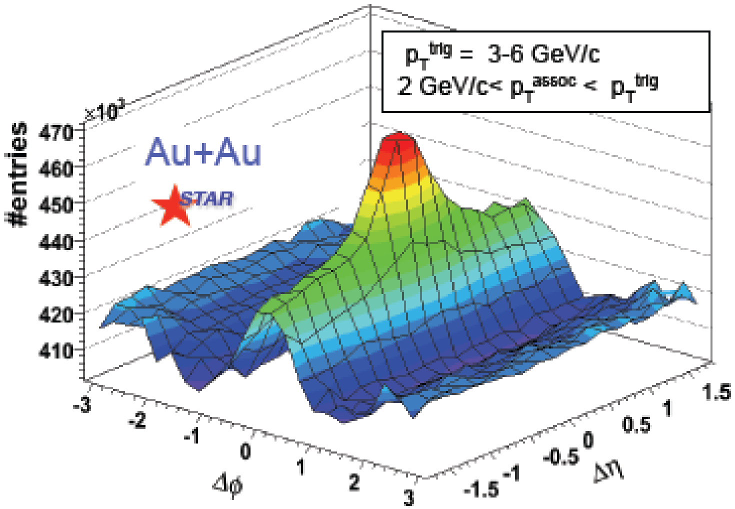
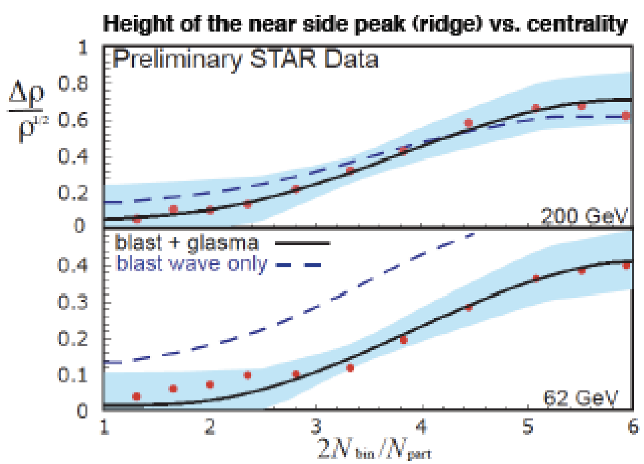
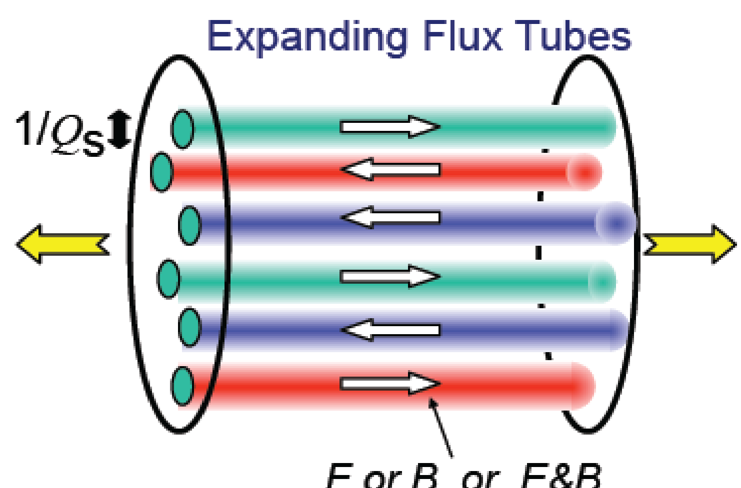
Ridge

The Ridge in AuAu at RHIC



- Long range $\Delta\eta$ correlations on the near-side - The "Ridge"
- CGC: ridge due to flux tubes formed from CGC in the early Glasma phase
- Important: radial flow





Dumitru, Gelis, McLerran, Venugopalan; Gavin, Moschelli '09

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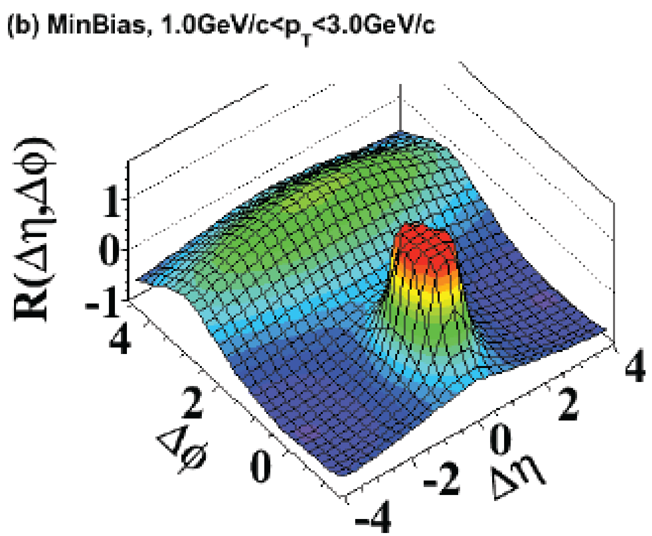
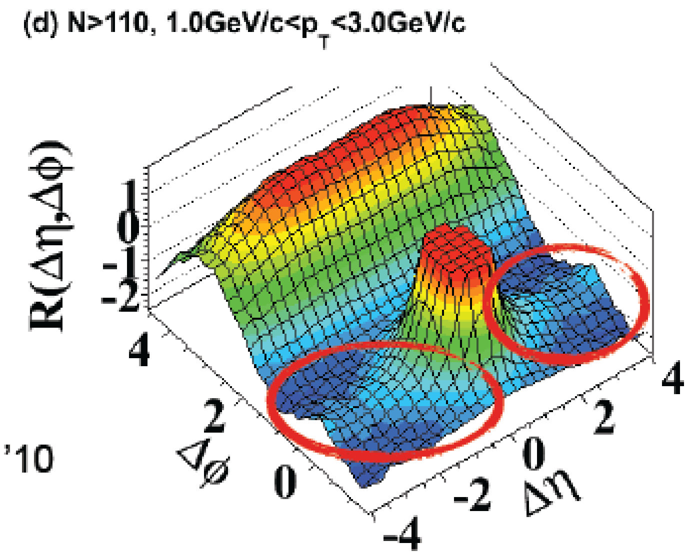
The Ridge in p+p at LHC

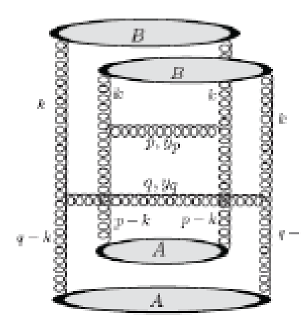
- CMS @ 7 TeV, charged hadron correlation |η| < 2.4
- Intermediate p_T = 1-3 GeV/c





CMS '10

- pp ridge predicted by CGC (Dumitru et al. RBRC Vol 95 p. 129)
  - Long-range rapidity correlations from classical gluon fields
  - Ridge is due to "something" like 4 (mini) jet diagrams

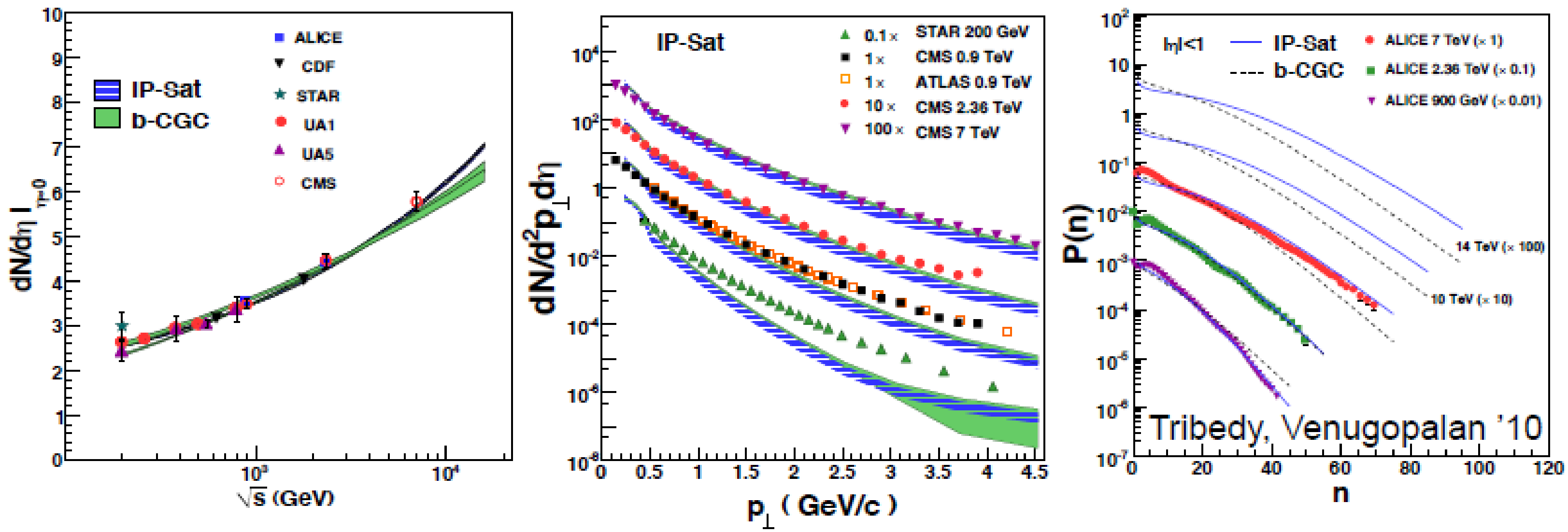


Dumitru,Dusling, Gelis, Jalilian-Marian, Lappi, Venugopalan '10

19

Saturation

Inclusive h Spectra in pp at LHC



Applying saturation at LHC:

- Unintegrated gluon distributions extracted from HERA in the dipole approach
- Compute inclusive hadron production in p+p collisions at the LHC
- IP-Sat, b-CGC and NLO-BK models give reasonable description
- Issues: $k_\perp$ factorization formalism for inclusive multiplicity distributions is rather fragile for $k_\perp \leq Q_S$ (no multi-parton rescatterings)

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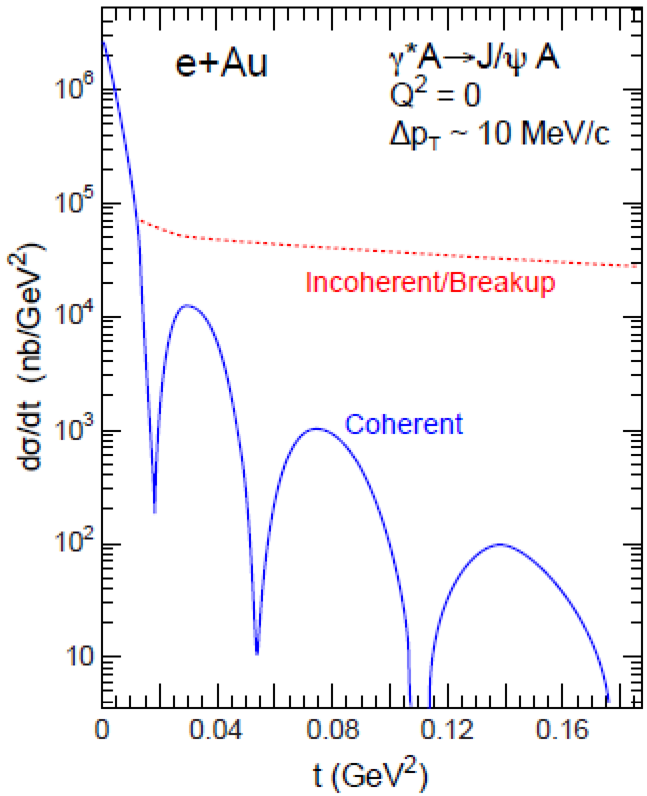
Initial condition of CNM

Probing Gluonic Structure of Nuclear Forces

Exclusive diffractive VM production:

- e A → e' A' V
- $d\sigma_A/dt \Rightarrow F_g(b)$
- Promising method to measure gluon form factor in nuclei



Kowalski, Caldwell '09

Experimental Aspects:

- Photo-production cross section large & $|t| \approx p_{T,V}^2$
- J/ψ easy detection at |η|<2 well separated from background
- Crucial: detecting breakup of nuclei
- Need e' to measure *t* for $Q^2 > 10^{-3}$ GeV²

Critique: Will measure $F_{p/n} \otimes$ Wood-Saxon (B. Kopeliovich/INT)?

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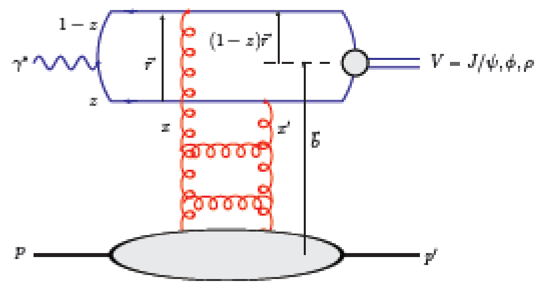
Initial condition of CNM

Recent Development Wood-Saxon vs. KLN

Dipole Model
(b-Sat):

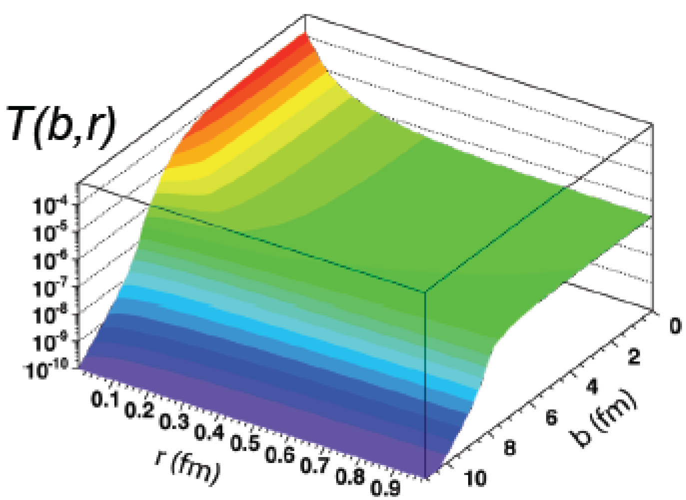


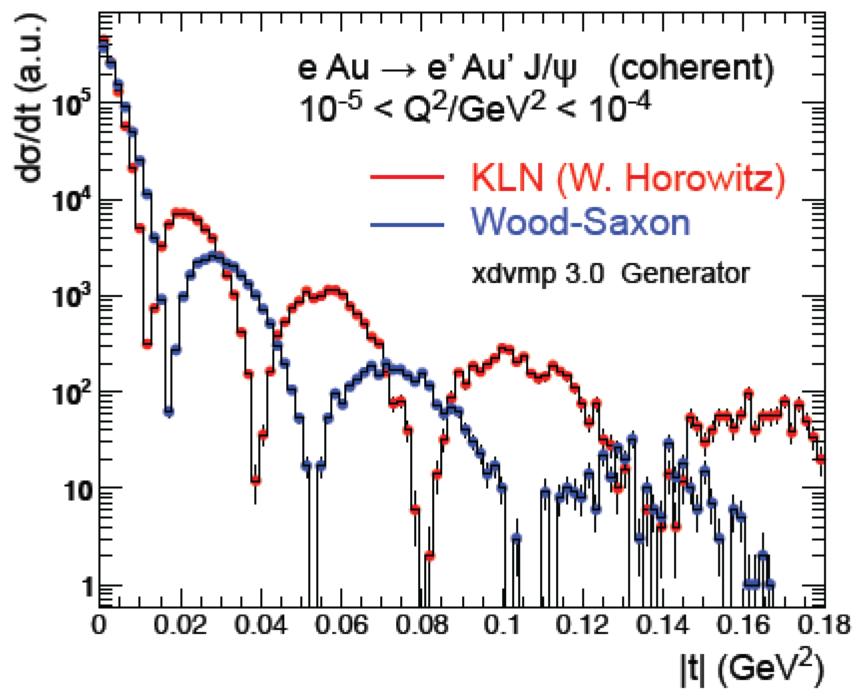
$$\frac{d\sigma^{\gamma^* p \to pV}}{dt} \sim \left| \int \Psi_V^* \frac{d\sigma_{q\bar{q}}}{d^2 b} \Psi e^{-ib\Delta} \right|^2$$

$$\left\langle \frac{\mathrm{d}\sigma^A_{\mathrm{dip}}}{\mathrm{d}^2 \mathrm{b}_\perp} \right\rangle_{\mathrm{N}} \approx 2 \left[1 - \left(1 - \frac{T_A(\mathrm{b}_\perp)}{2} \sigma^{\mathrm{P}}_{\mathrm{dip}} \right)^A \right]$$

W. Horowitz (work in progress):

High energies: KLN/CGC like ρ(r) is what matters not Wood-Saxon





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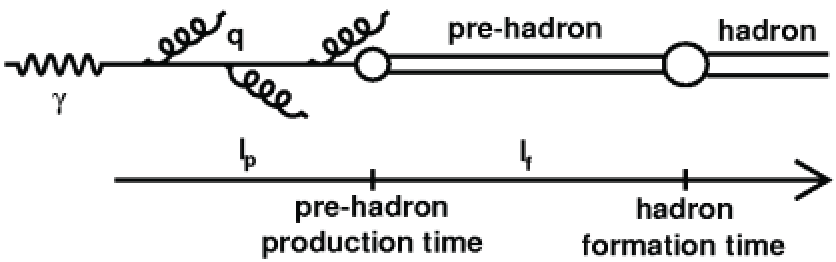
Fragmentation function in nuclear medium

Parton Interactions in Cold Nuclear Matter

nDIS:

- Suppression of high-p_T hadrons analogous but weaker than at RHIC
- Clean measurement in 'cold' nuclear matter
- Important control measurements for RHIC & LHC ?



Fundamental question:

- Fragmentation time scales (dynamic of hadronization)
- In-medium parton energy loss mechanism

Observables:

- Broadening: $\Delta p_T^2 = \langle p_T^2 \rangle_A - \langle p_T^2 \rangle_p$
- Attenuation: $R_A^h(Q^2, x, z, p_T)$

Link Δp_T^2 directly to saturation scale (Kopeliovich '10)

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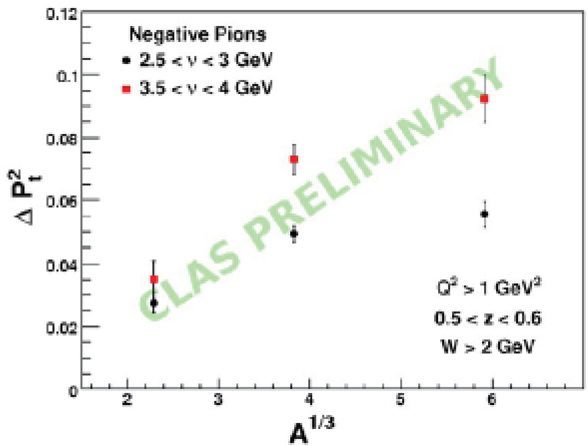
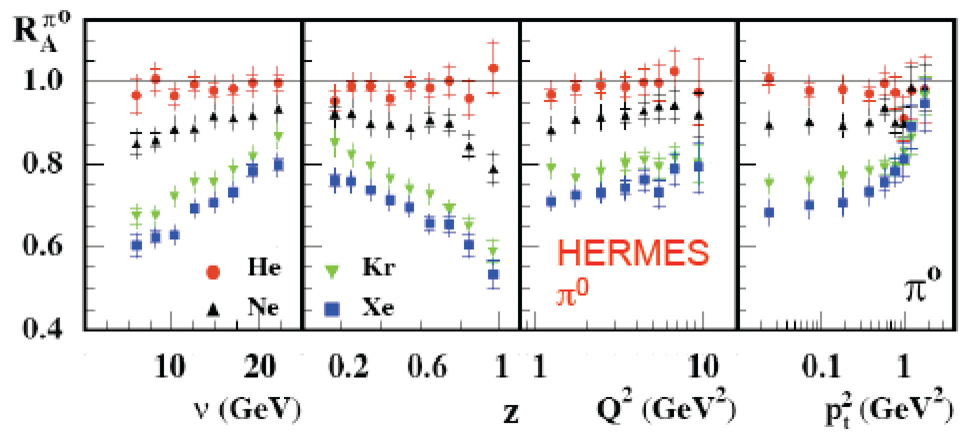
Fragmentation function in nuclear medium

Parton Interactions in Cold Nuclear Matter

p_T broadening (CLAS)

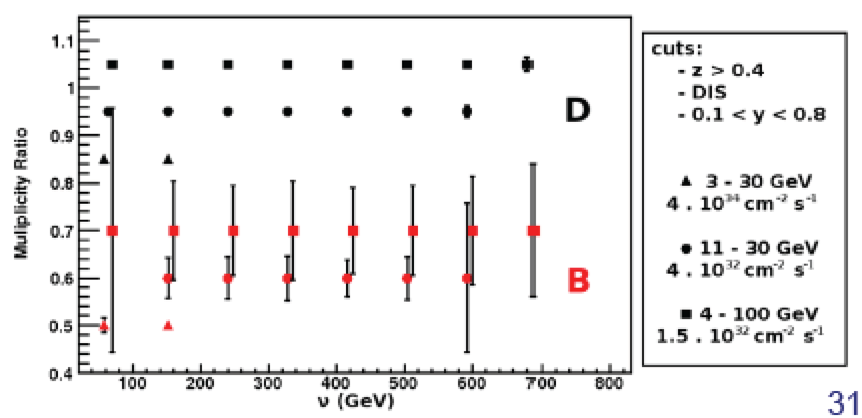


Attenuation (HERMES)



Energy transfer in lab rest frame
HERMES: 2-25 GeV
EIC: 10 < ν < 1600 GeV
(LHC range)
EIC: *heavy flavor*!

EIC Projections:



R. Dupre/INT '10

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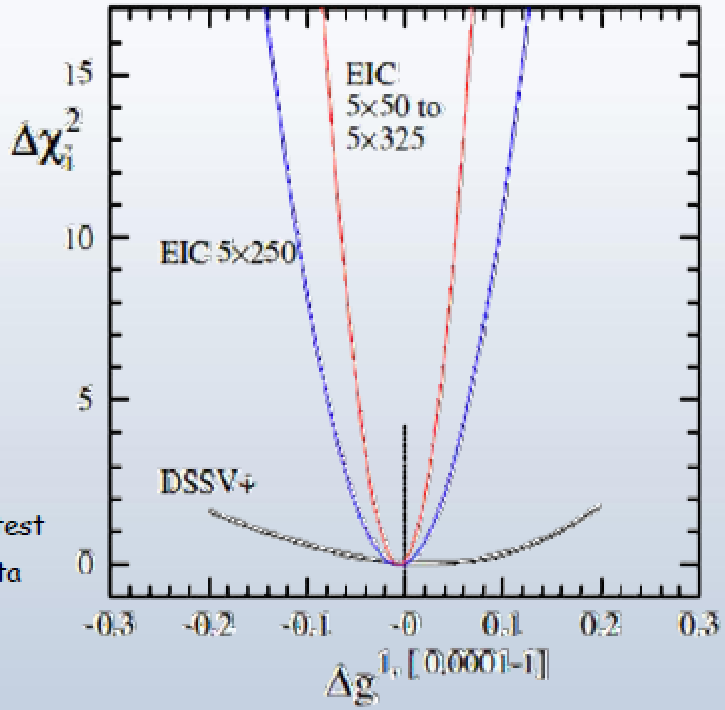
ΔΣ、Δgの高精度決定

what can be achieved for Δg? - cont'd

how effective are scaling violations at the EIC…

Sassot, MS



DSSV+ includes also latest COMPASS (SI)DIS data (no impact on DSSV Δg)

χ^2 profile slims down significantly already for EIC stage-1 (one month of running)

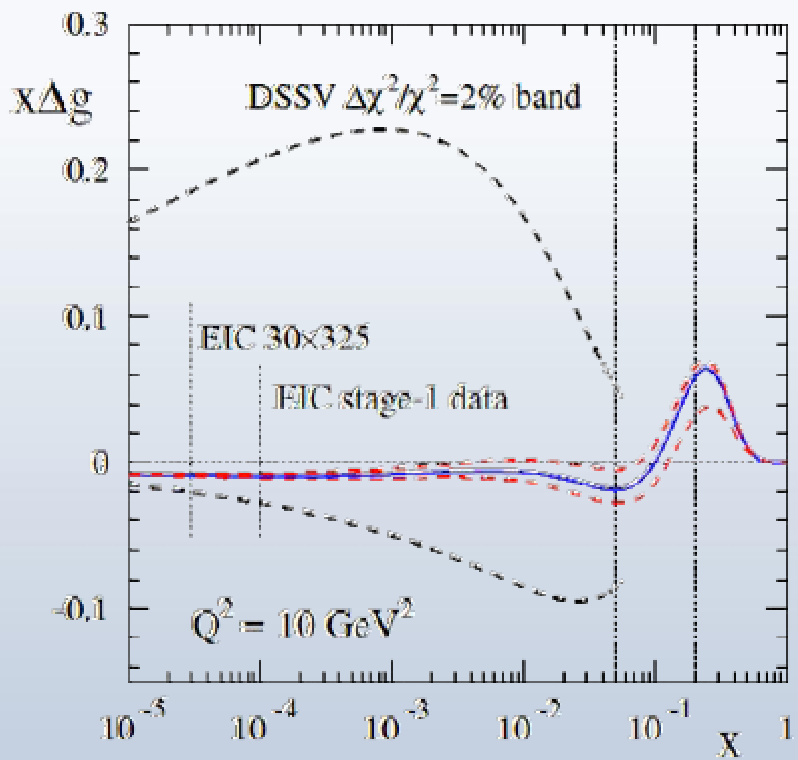
- with 30x325 one can reach down to $x \approx 3 \times 10^{-5}$ (impact needs to be studied)

ΔΣ、Δgの高精度決定

what can be achieved for Δg? - cont'd

what about the uncertainties on the x-shape …

Sassot, MS



… wow - cool!

- even with flexible DSSV x-shape we can now determine $\int_0^1 dx\, \Delta g(x,Q^2)$ up to ± 0.07
- work in progress: try weird x-shapes below x = 10^{-4} to improve/check error estimate

Flavor separation

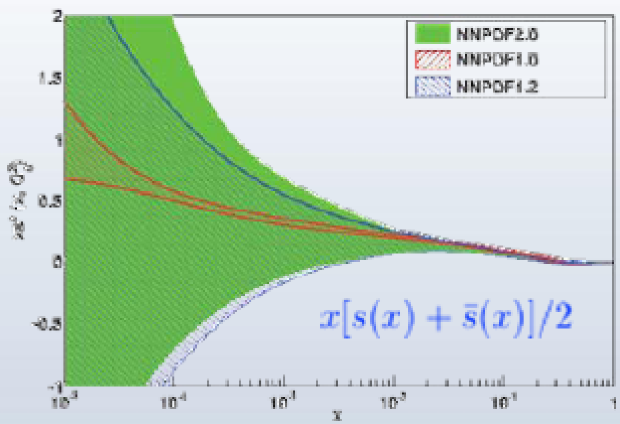
selected open issues in flavor structure

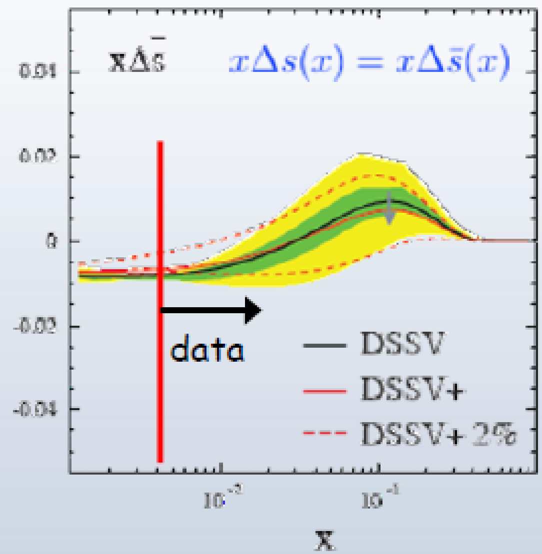
strangeness was identified to be one of the least known quantities

- both unpolarized and polarized - where significant progress is unlikely w/o the EIC

DSSV (incl. all latest COMPASS data)

NNPDF collaboration





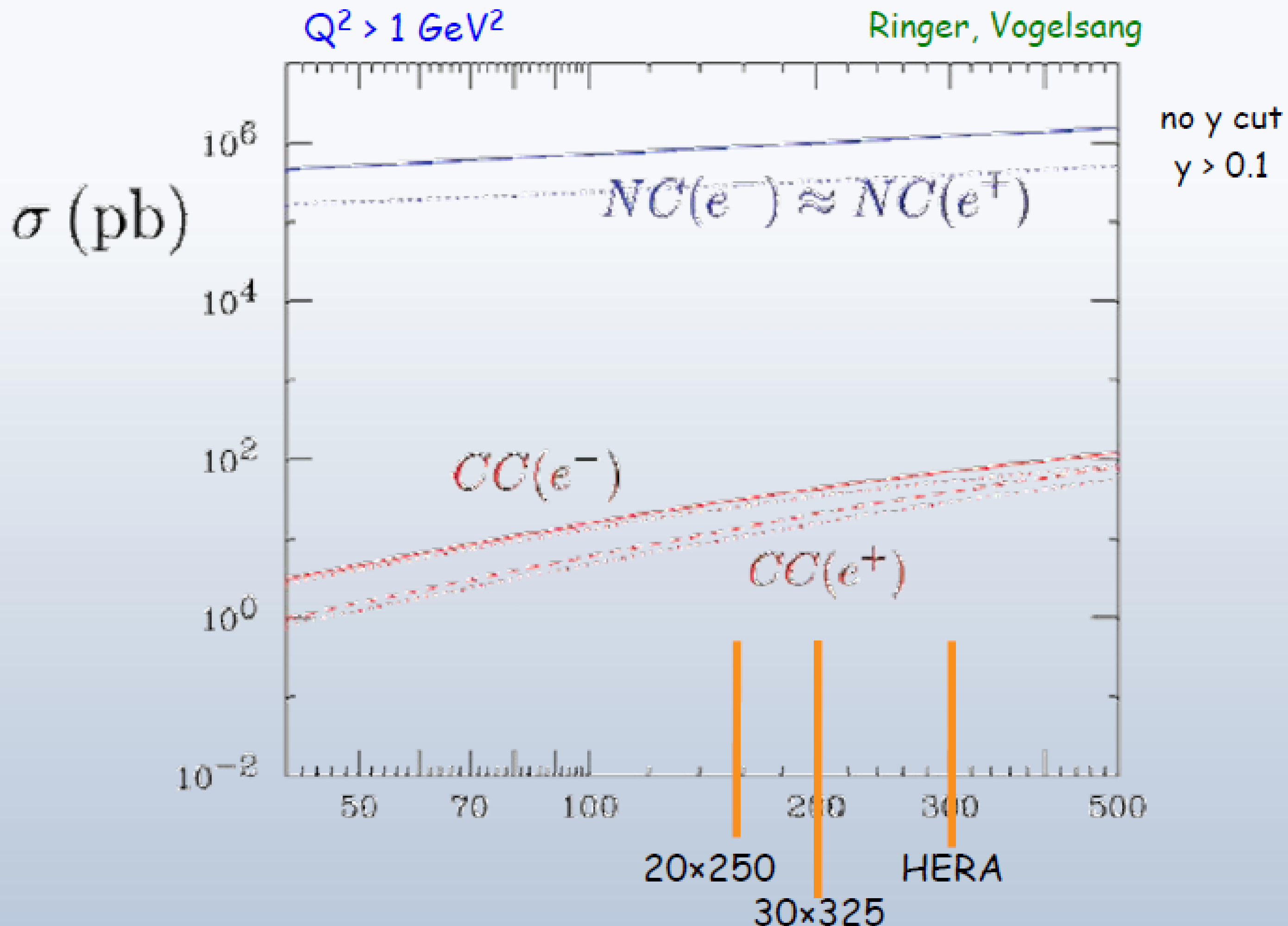
- substantial uncertainties
- known issues with HERMES data at large x
- **hot topic:** $s(x) - \bar{s}(x)$

- **surprise:** Δs small & positive from SIDIS dat
- but 1st moment is negative and sizable due to "constraint" from hyperon decays (F,D) (assumed SU(3) symmetry debatable M. Savage)
- drives uncertainties on $\Delta\Sigma$ (spin sum)

we really need to determine it ! (as well as their u,d quark colleagues)

Charged and neutral current

feasibility – 1st exploratory studies



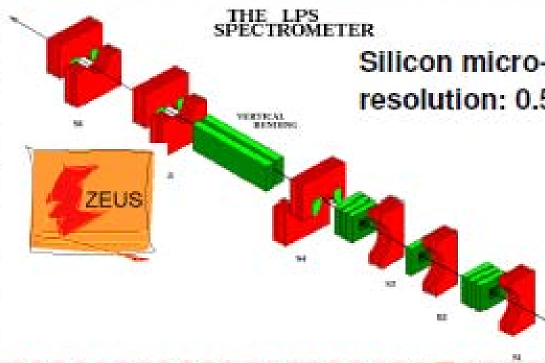
2nd indep. study: Kumar, Riordan, Deshpande, Taneja, Paschke

軌道角運動量とGPD

Direct t measurement at EIC

But… is an indirect measurement of t really an issue for EIC?

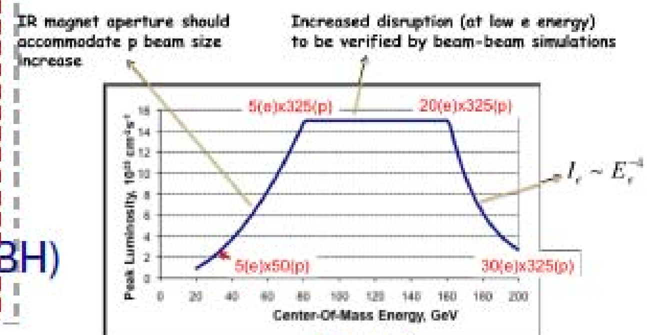
We'll get roman pots in the forward region at EIC!



Silicon micro-strips
resolution: 0.5% for P_L ; 5 MeV for P_T

$\mathcal{L}$ = 27.77 pb^{-1}

55 events (DVCS + BH)



EIC lumi

for eRHIC: 1.4 10^{34}* E_p/325 $cm^{-2}s^{-1}$

assuming 50% operations efficiency one week corresponds to:

L(1 w)= 0.5 * 604800(s in a week) * (1.4x10^{34} $cm^{-2}s^{-1}$) = 4*10^{39} cm^{-2} = 4000pb^{-1}

+ Roman Pots → ~ 8000 events/week !!

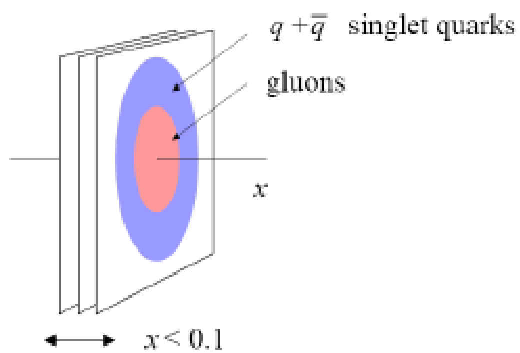
assuming the same acceptance ad LPS (~2%)

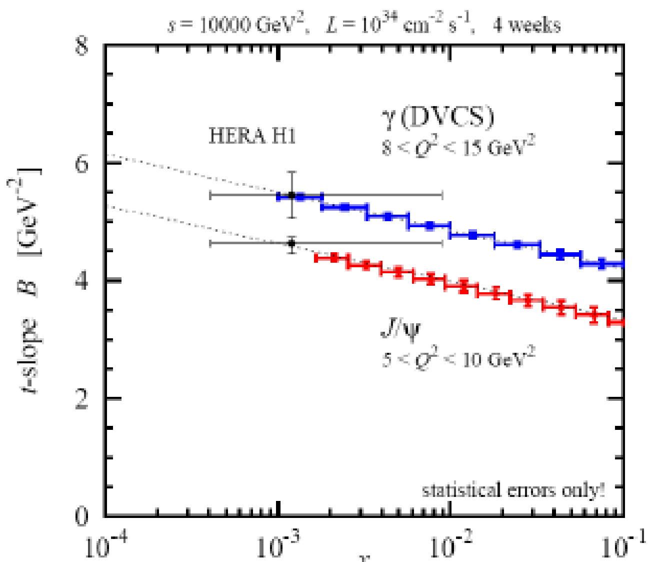
Calculations are absolutely not rigorous! But give an idea…

Nov. 9, 2010 S. Fazio: INT-workshop, Univ. of Washington, Seattle **talk by S. Fazio** 8

軌道角運動量とGPD

Gluon imaging: gluon vs. singlet quark size





Sandacz, Hyde, CW

- Do singlet quarks and gluons have the same transverse distribution?
  - Hints from HERA: $Area(q+\bar{q}) > Area(g)$
  - Dynamical models predict difference: pion cloud, constituent quark picture [Strikman, Weiss 09]
  - No difference assumed in present pp MC generators for LHC!

- EIC: gluon size from J/ ψ , singlet quark size from DVCS
  - x-dependence: quark vs. gluon diffusion in wave function
  - Detailed analysis: LO NLO [Mueller et al.]

Detailed differential image of nucleon's partonic structure

talk by T. Horn

TMD

sensitivity to sea-quark *Sivers*

[talk by **T. Burton**: week-9]

zoom:

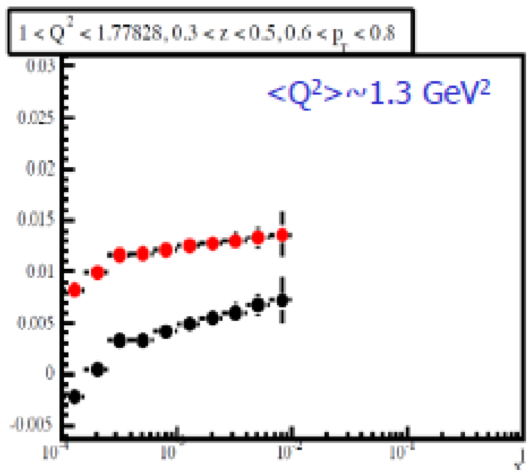
0.3<z<0.5

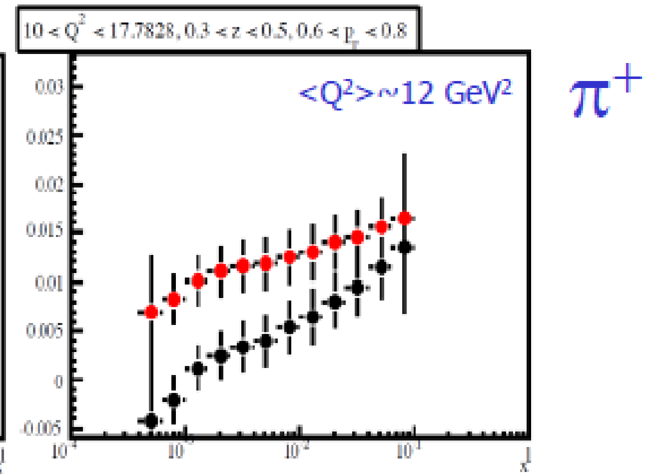
0.6<P_{hT}<0.8 GeV

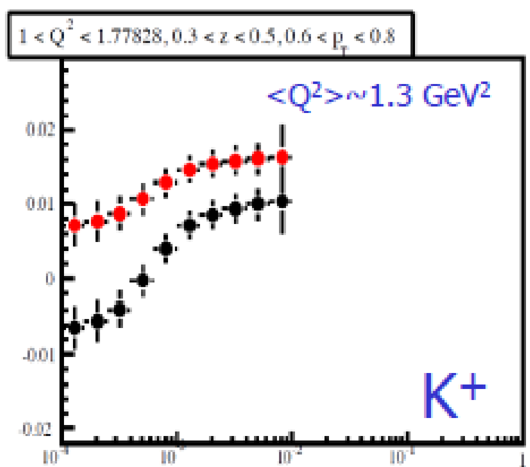
20x250 GeV

20 fb^{-1}

30 days
50% efficiency







- Desire wide kinematic coverage
  - delivered by EIC designs
- High luminosity means:
  - High Q^2 (x, z, $p_{h\perp}$)-binning plausible
  - Low Q^2 rapidly systematics-dominated

EICs

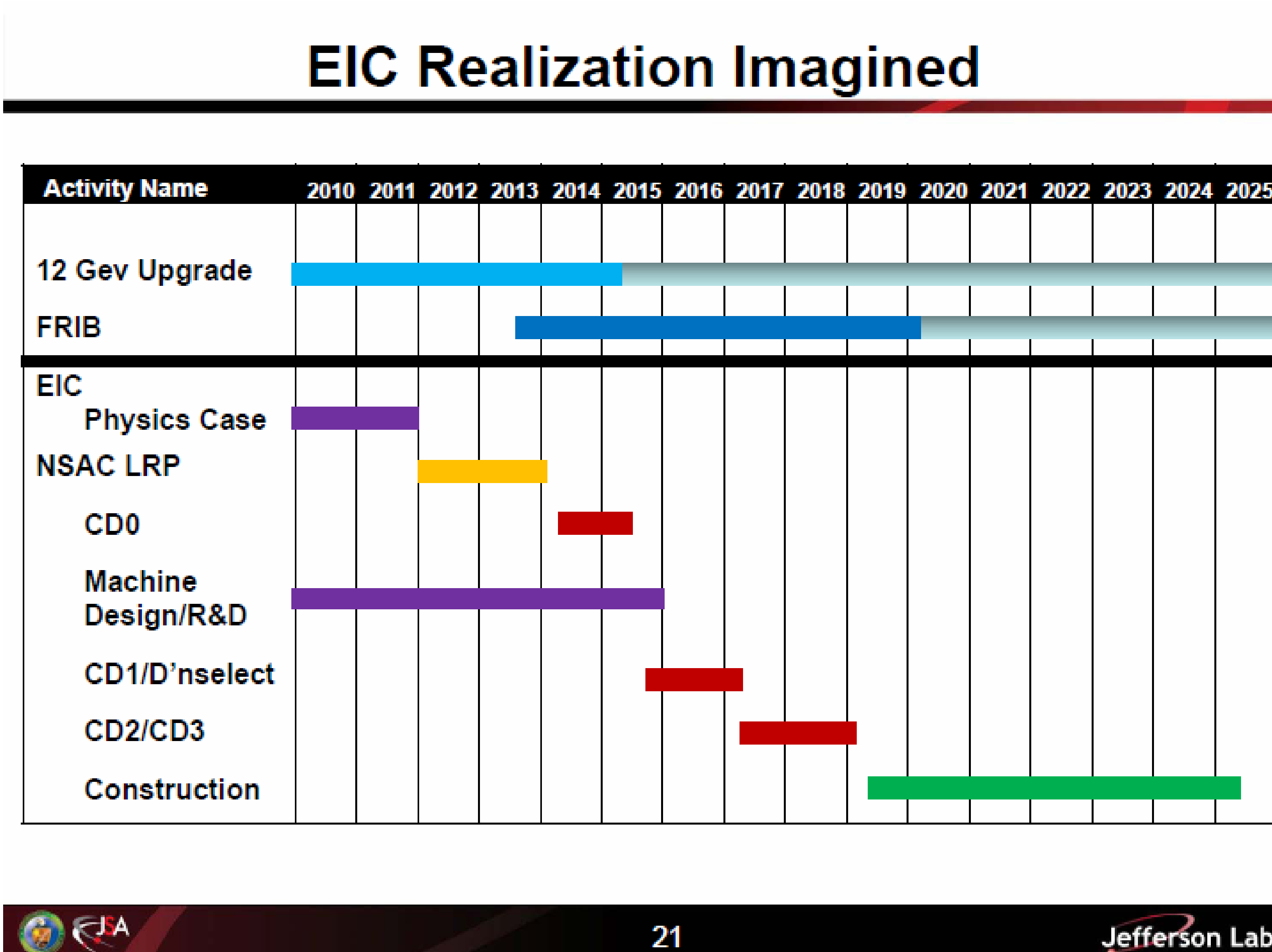
Electron Ion Colliders

Design Goals for Colliders Under Consideration World-wide

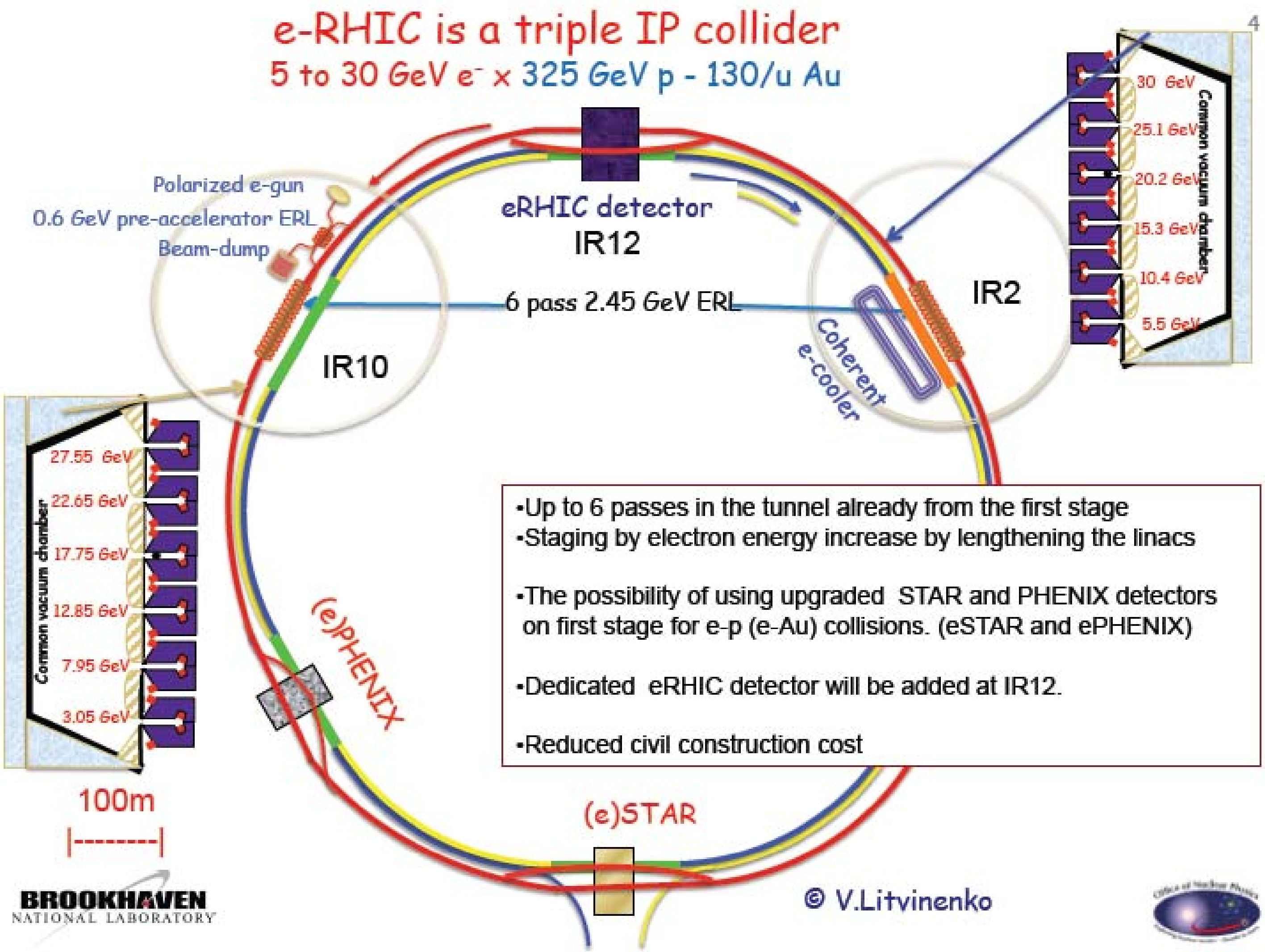
	Energies	s	Design Luminosity
(M)EIC@JLab	Up to 11 x 60+	240-3000	Close to 10^{34}
Future ELIC@JLab	Up to 11 x 250 (20? x 250)	11000 (20000?)	Close to 10^{35}
Staged MeRHIC@BNL	Up to 5 x 250	600-5000	Close to 10^{34}
eRHIC@BNL	Up to 20 x 325 (30 x 325)	26000 (39000)	Close to 10^{34}
ENC@GSI	Up to 3 x 15	180	Few x 10^{32}
LHeC@CERN	Up to 150 x 7000	4200000	Close to 10^{33}

Present focus of interest (in the US) are the (M)EIC and Staged MeRHIC versions, with s up to ~3000 and 5000, resp.

EIC timeline



eRHIC

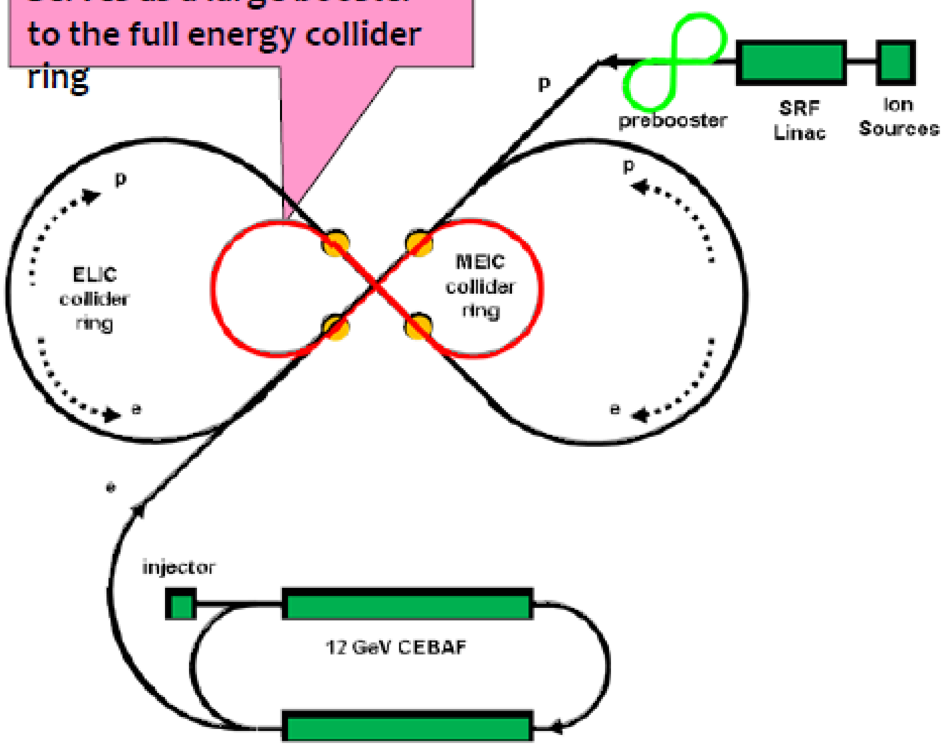


- Up to 6 passes in the tunnel already from the first stage
- Staging by electron energy increase by lengthening the linacs
- The possibility of using upgraded STAR and PHENIX detectors on first stage for e-p (e-Au) collisions. (eSTAR and ePHENIX)
- Dedicated eRHIC detector will be added at IR12.
- Reduced civil construction cost

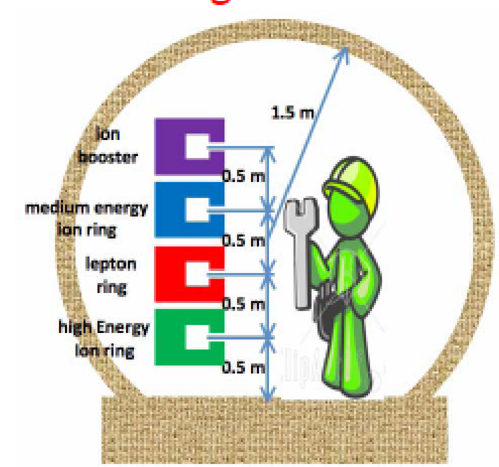
ELIC

ELIC: High Energy & Staging

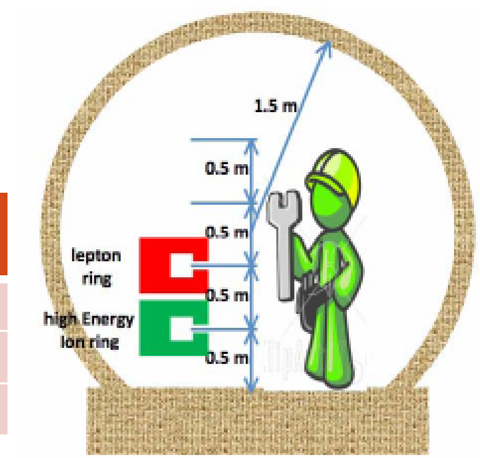
Serves as a large booster to the full energy collider ring



Straight section



Arc



Stage	Max. Energy (GeV/c)		Ring Size (m)	Ring Type		IP #
	p	e		p	e	
Medium	96	11	1000	Cold	Warm	3
High	250	20	2500	Cold	Warm	4

Jefferson Lab

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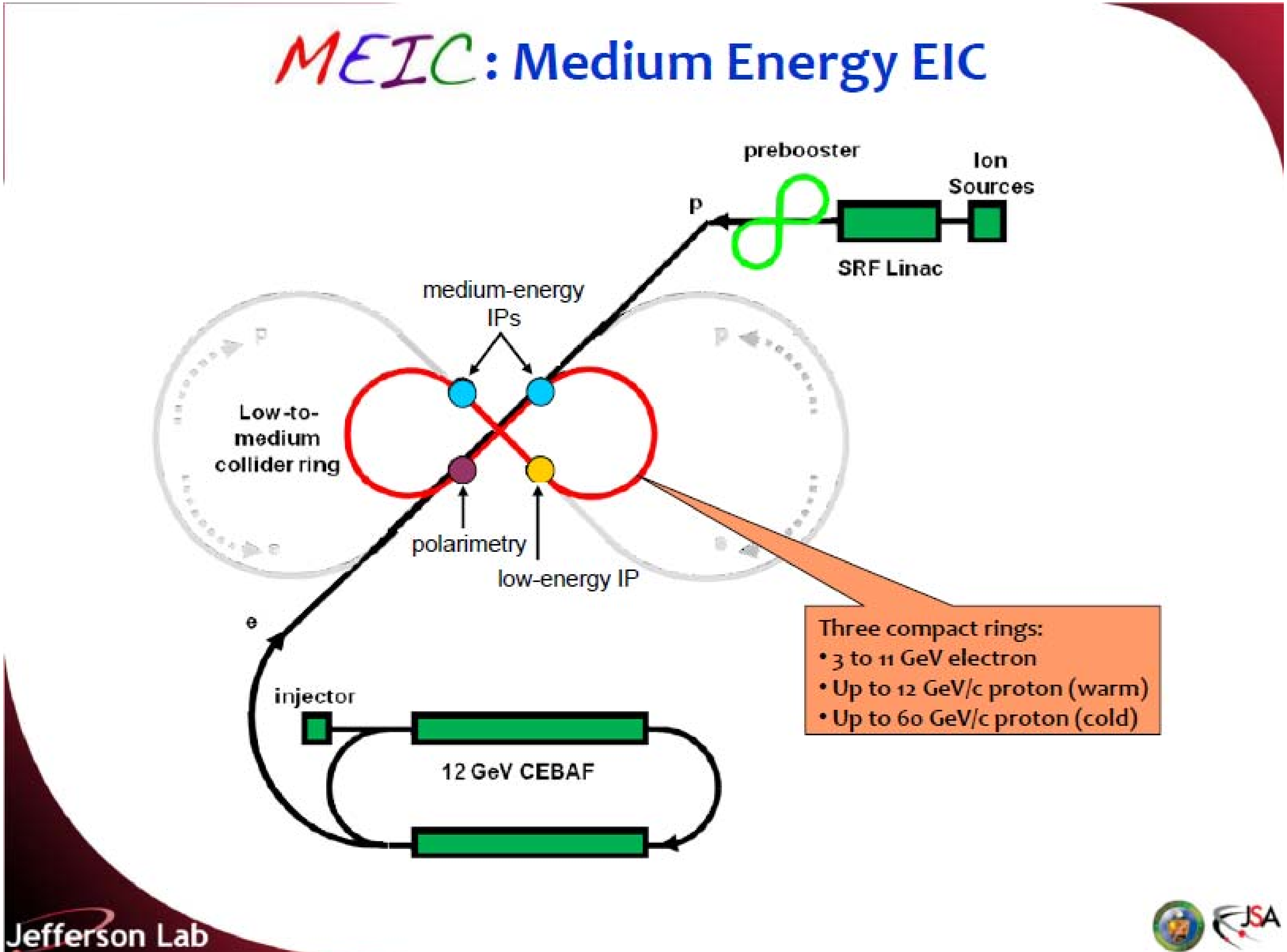
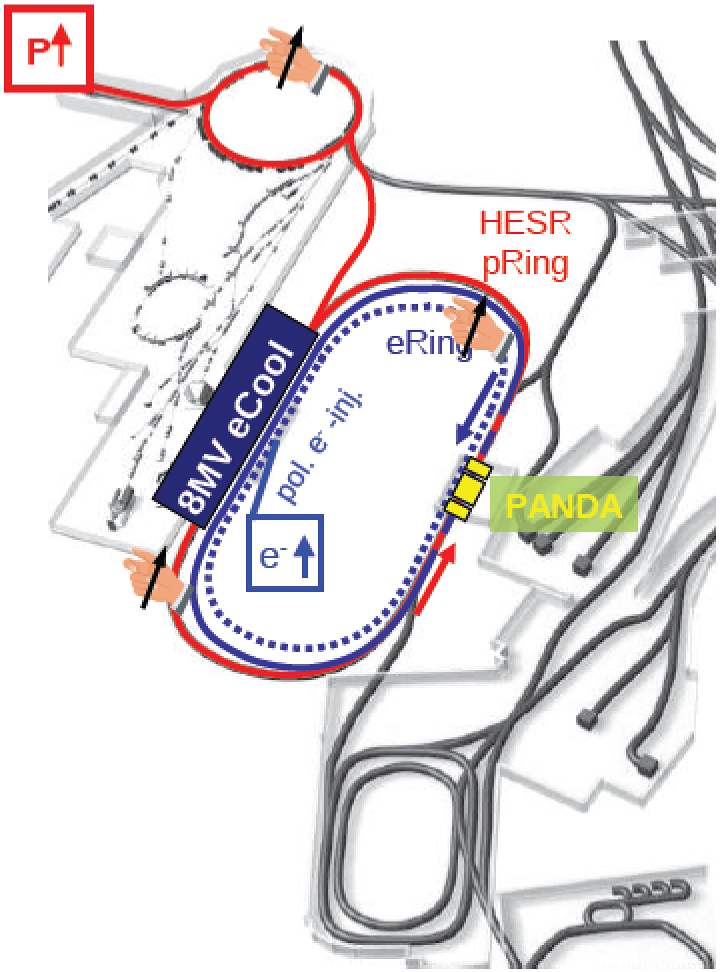
MEIC


MEIC: Medium Energy EIC
prebooster
Ion Sources
p
SRF Linac
medium-energy IPs
Low-to-medium collider ring
polarimetry
low-energy IP
e
injector
12 GeV CEBAF
Three compact rings:
• 3 to 11 GeV electron
• Up to 12 GeV/c proton (warm)
• Up to 60 GeV/c proton (cold)
Jefferson Lab
JSA

ENC

An 'easy' idea: ENC at HESR



- **Idea emerged Aug 2008**
- $\sqrt{s} > 10$ **GeV**
  $3.3\,\mathrm{GeV}/c\ e^-$ on $15\,\mathrm{GeV}/c\ p$
- **polarised** e^- ($> 80\%$)
- **polarised** p, d ($> 80\%$)
  (transversal & longitudinal)
- use as much of PANDA detector as possible
- Common effort of German universities (Bonn, Mainz, Dortmund) in collaboration with Research Centres Jülich, DESY, GSI, ...

LHeC