Physics and detector requirements at zero degree of EIC

Workshop on Forward Physics and QCD at the LHC, the future Electron Ion Collider and Cosmic Ray Physics

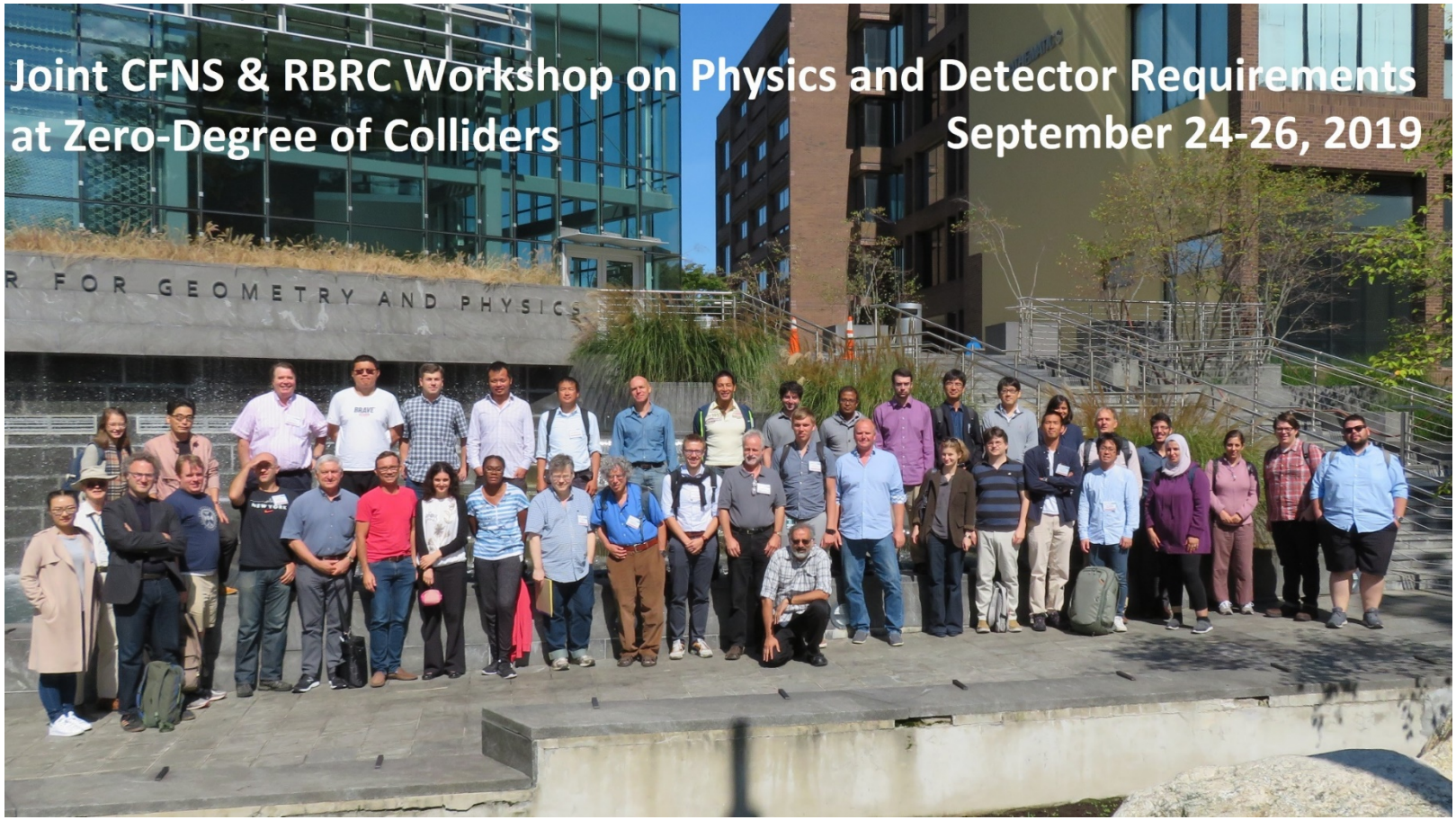
Guanajuato, Mexico

November 19th, 2019

Yuji Goto (RIKEN)

Joint CFNS & RBRC workshop

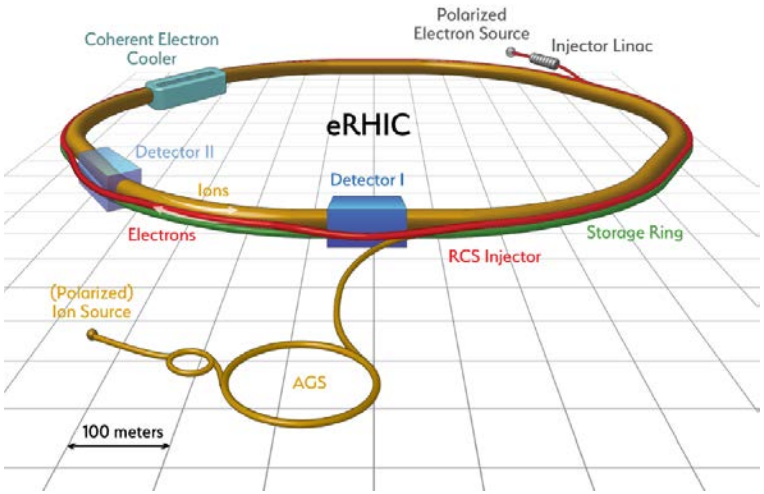
- Physics and detector requirements at zero-degree of colliders
  - 24-26 September 2019
  - Stony Brook University



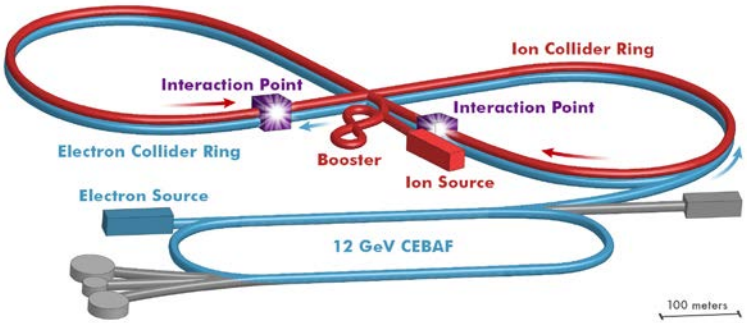
EIC - Electron Ion Collider

- High-energy QCD frontier to study nucleon (hadron) and nucleus (cold nuclear matter) from quarks and gluons
- World's first polarized electron + proton / light-ion / heavy-ion collider
  - Wide (Q^2, x) region
- Electron + proton / light-ion collision
  - Polarized beam
    - e, p, d/^{3}He
  - High luminosity
    - $L_{ep} \sim 10^{33\text{-}34}$ cm^{-2}s^{-1}
    - 100-1000 times HERA
  - Collision energy
    - $\sqrt{s}$ = 20 – 100 (140) GeV
- Electron + heavy-ion collision
  - Wide range in nuclei

eRHIC at BNL

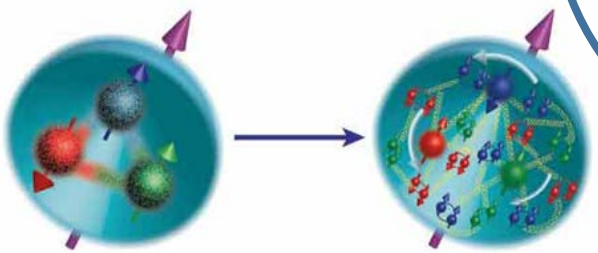


JLEIC at Jefferson Lab



Physics at EIC

Understanding how the nucleon structure and properties emerge from quarks and gluons and their interactions from QCD

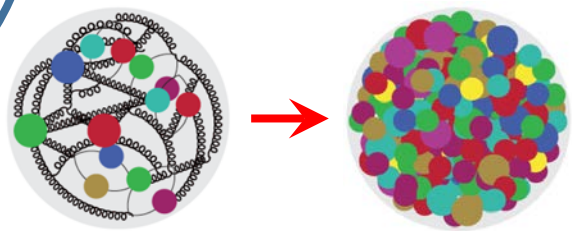


How does the mass of the nucleon arise?

3D Picture of the Nucleons and Nuclei

- *Transverse -Momentum Distribution and Spatial Imaging*
- *Orbital Motion of Quarks and Gluons Inside*

Systematic understanding of the structure of nucleons and nuclei covering the wide kinematic range



New Picture

Precision Measurement

Discovery

Luminosity

Collision Energy

How does the spin of the nucleon arise?

Spin and Flavor Structure of the Nucleons and Nuclei

- *Gluon Polarization*
- *Quarks and Gluons Inside the Nuclei*
- *Hadronization*

What are the emergent properties of dense systems of gluons?

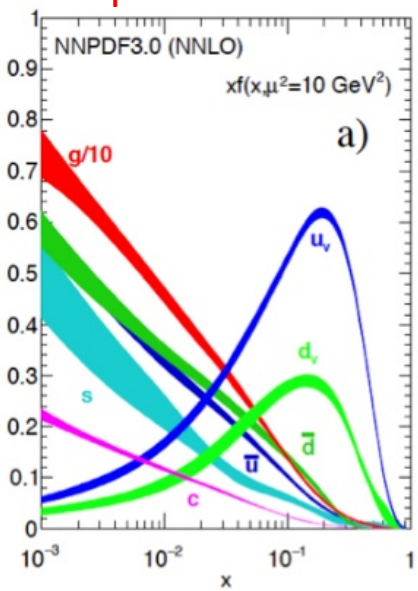
Gluon Saturation at Extreme Density

- *Initial State of the QGP (Quark-Gluon Plasma)*

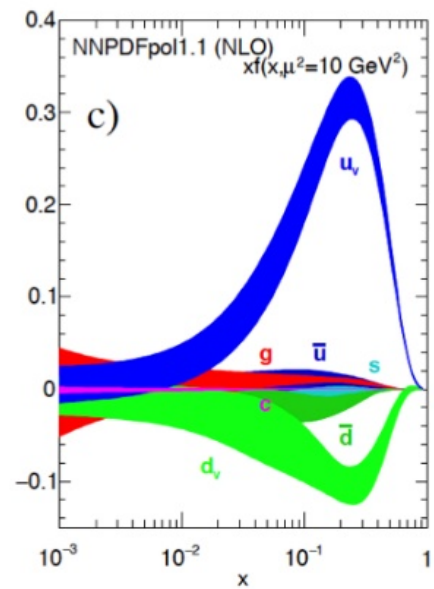
Quark-gluon structure

- 1-D picture
  - Parton distribution function (PDF) of quarks and gluons
  - *x*: momentum fraction of quarks and gluons
  - Significant improvement of precision of the polarized PDF at EIC
    - especially gluon polarization
- 3-D picture
  - Generalized parton distribution (GPD) function
    - charge distribution
    - magnetic-moment distribution
    - mass distribution
  - Comparison of radii (R)
  - New picture to be established at EIC

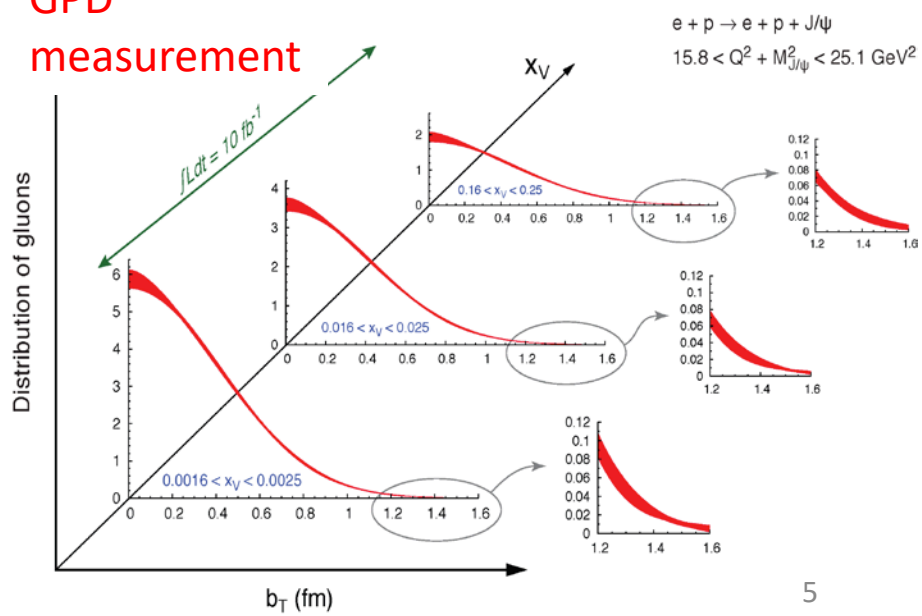
Unpolarized PDF



Polarized PDF

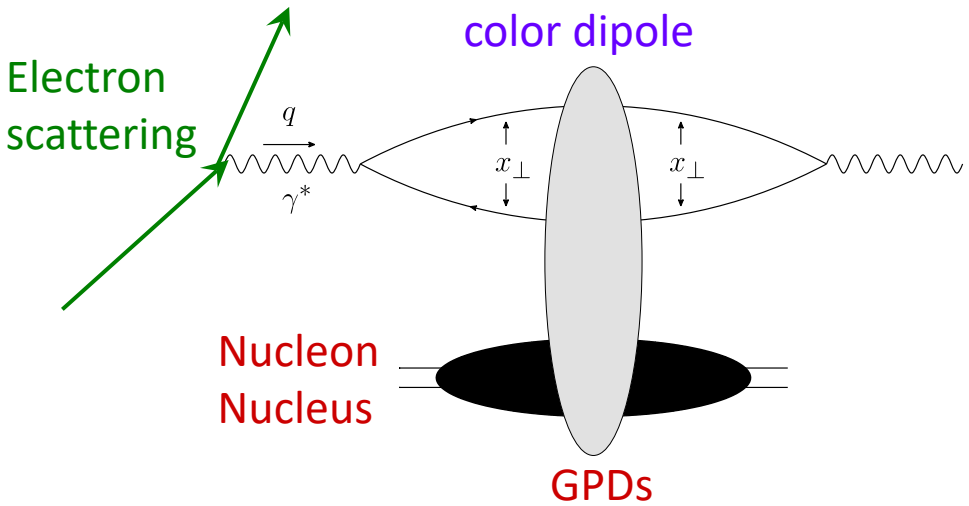


GPD measurement

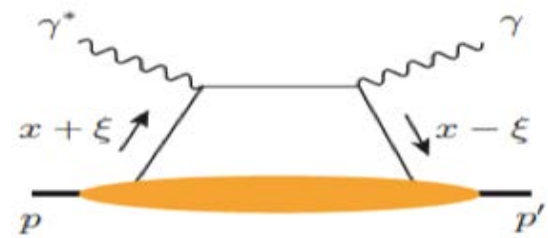


Tomography of the nucleon / nucleus

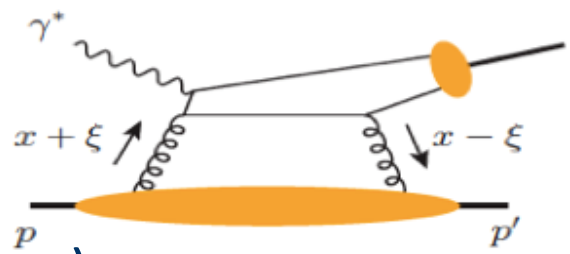
- EIC = color dipole microscope
  - Exclusive process and diffractive process
  - 3D distribution: transverse spatial distribution



DVCS (Deeply Virtual Compton Scattering)



Meson Production



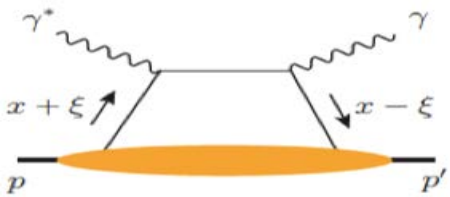
J/ψ, ϕ, ρ, etc.

- GPD (Generalized Parton Distribution)
  - Spatial imaging of gluons and quarks = tomography
    - HERA: 1st generation
    - EIC: 2nd generation (high luminosity, heavy ion, polarization)
  - Orbital angular momentum
    - Ji's sum rule
    - Origin of the nucleon spin

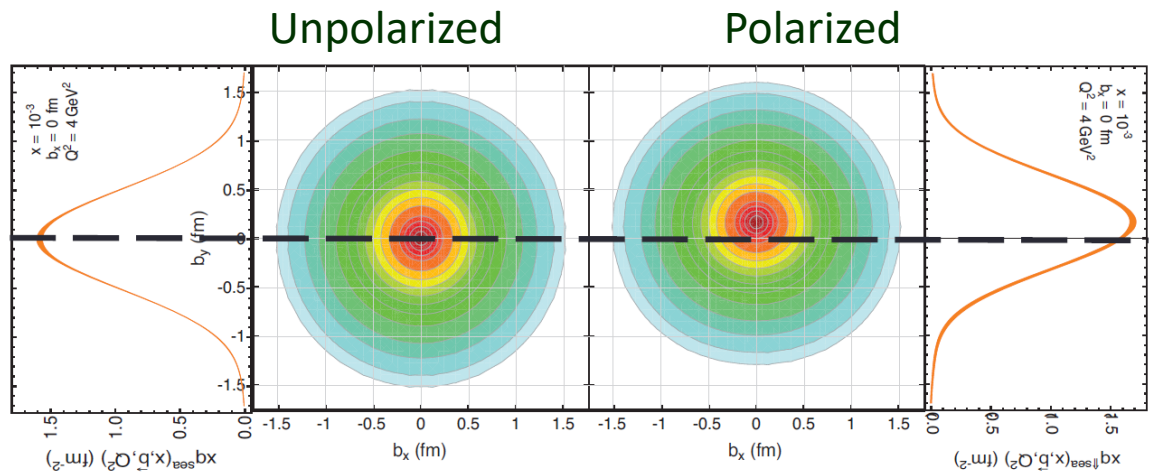
$$J_q^z = \frac{1}{2}\sum_q \Delta q + \sum_q L_q = \frac{1}{2}\left(\int_{-1}^{1} x dx (H^q + E^q)\right)_{t\to 0}$$

Tomography of the nucleon / nucleus

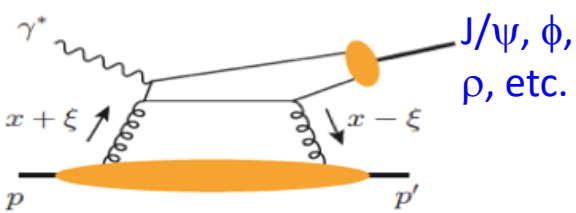
- DVCS
  - Deeply virtual Compton scattering



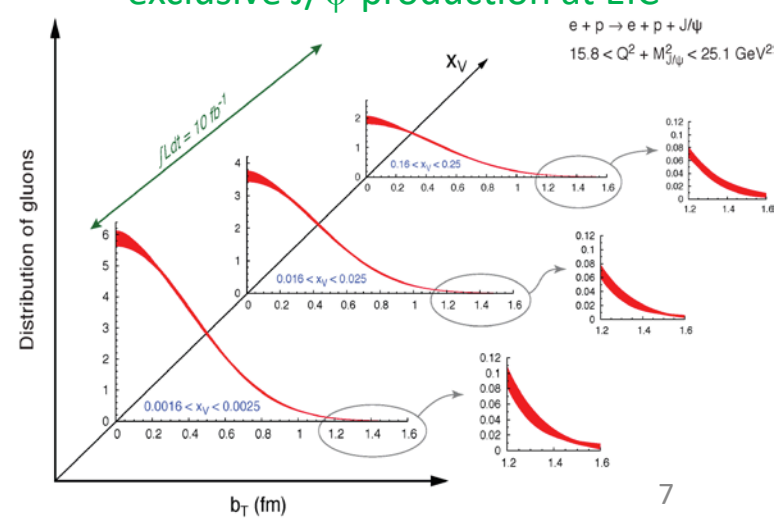
Spatial distribution of sea quarks at EIC 100 fb^{-1} and corresponding density of partons in the transverse plane



- Meson production
  - Gluon tomography by measuring J/ψ, ϕ, ρ, etc.
  - Precision measurement at large radius with high luminosity



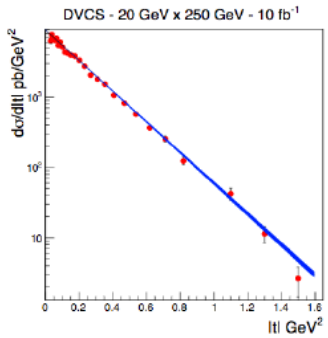
x-dependence of spatial distribution of gluons to be obtained by the exclusive J/ψ production at EIC



Physics at zero degree of EIC

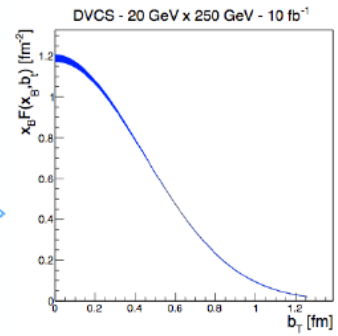
- Very forward proton acceptance for DVCS exclusive measurement

Measurement | **Physics observable** (cross-section vs impact parameter)

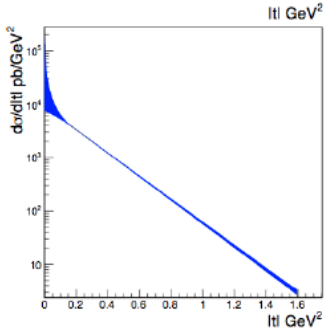


Plots from EIC White Paper:

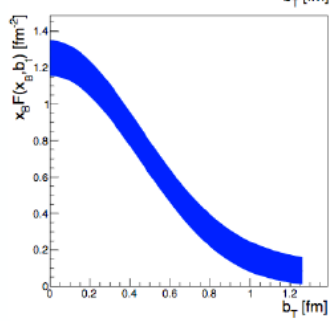
Fourier transform



Requirement:
$\int L_{int} = 10 fb^{-1}$
$0.18 < p_t$ (GeV) < 1.3
$0.03 < |t|$ (GeV^2) < 1.6

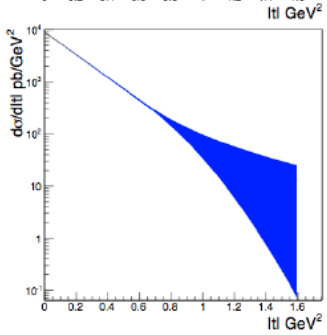


limited lower p_T-acceptance

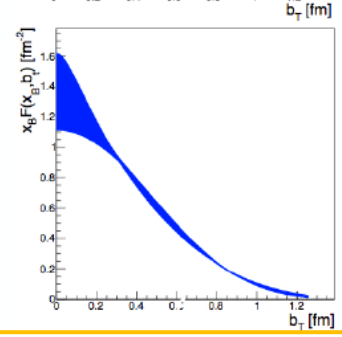


Uncertainty in normalization

$\int L_{int} = 10 fb^{-1}$
$0.44 < p_T$(GeV) < 1.3



limited higher p_T-acceptance



Uncertainty in slope and shape

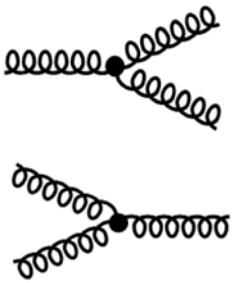
$\int L_{int} = 10 fb^{-1}$
$0.18 < p_T$ (GeV) < 0.8

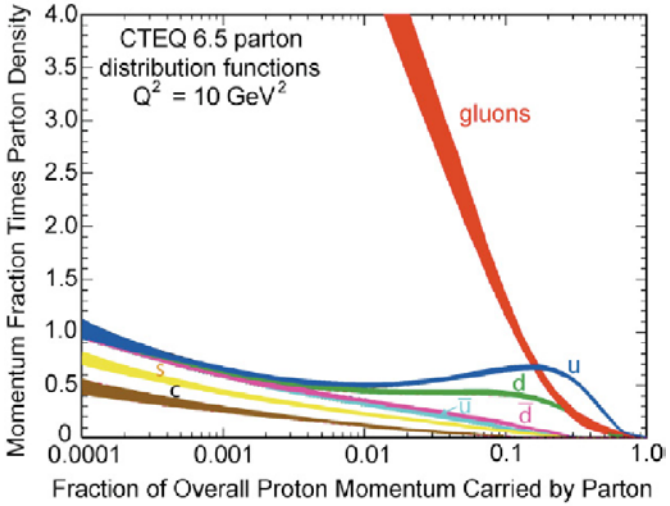
We need a proton spectrometer with large acceptance!

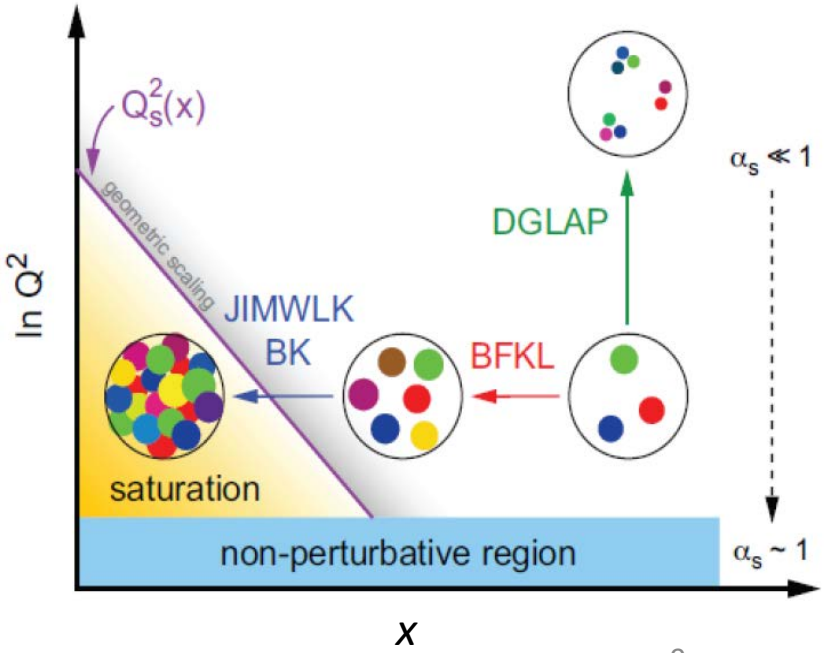
shown by Fazio & Jentsch

Gluon saturation in e+A collisions

- Gluon emission
  - Divergence at small x
- Gluon recombination
  - Restriction of divergence
- Gluon saturation in balanced
  - Based on classical idea of the saturation
- First observation of a quantum collective gluonic system
  - Precision comparison of experiment and Chiral Glass Condensate (CGC) as a theoretical model of the gluon saturation
- Precision understanding of nucleus with the quark-gluon picture necessary as the initial state of the QGP for understanding its production mechanism





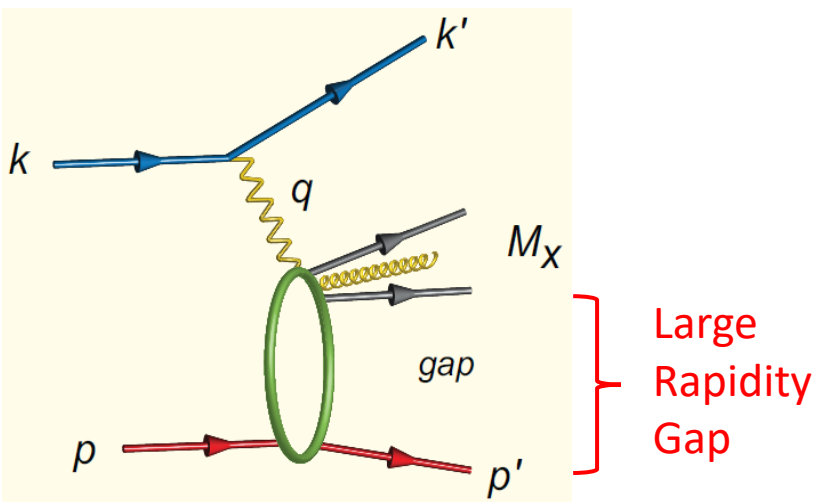


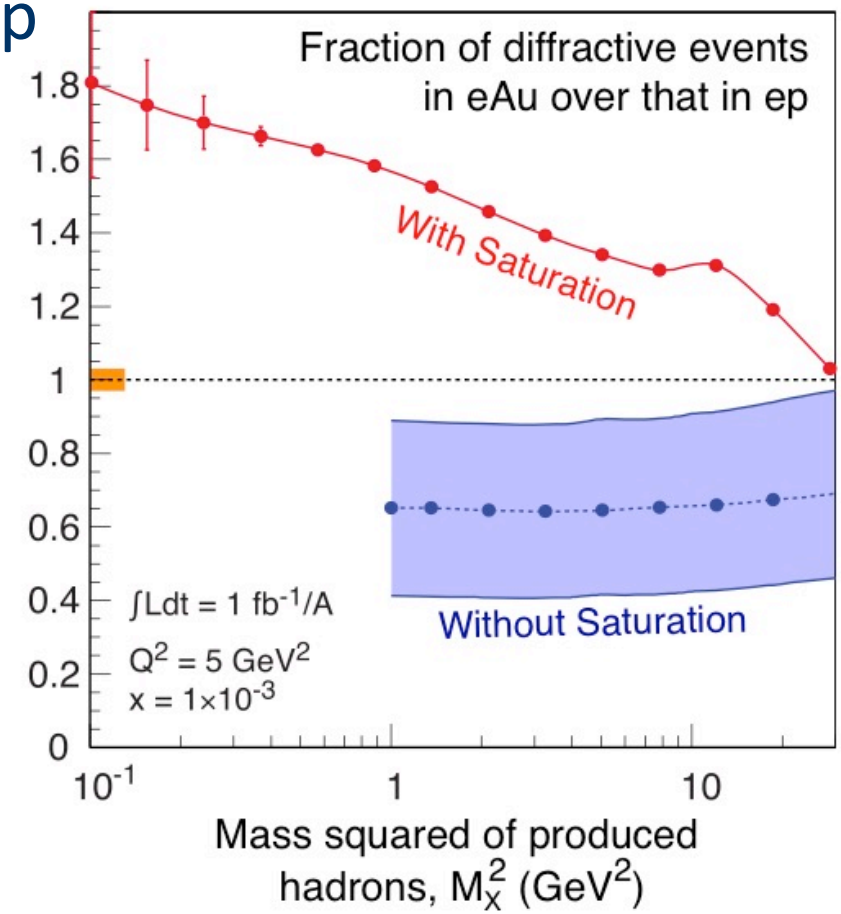
Gluon saturation in e+A collisions

- Diffractive cross section
  - Most sensitive way to study the gluon saturation

$$\sigma_{\text{diff}} \propto [g(x, Q^2)]^2$$

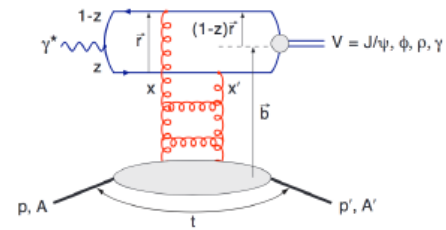
- 10-15% diffractive at HERA e+p
- 25-30% diffractive predicted by CGC at EIC e+A





GPD studies with exclusive processes

Imaging the gluons in nuclei



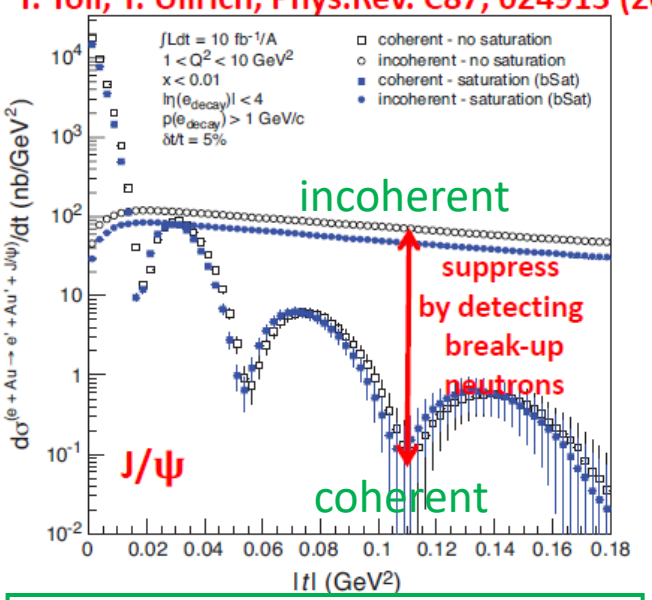
Diffractive physics in eA

→ Measure spatial gluon distribution in nuclei

→ Reaction: e + Au → e′ + Au′ + J/ψ, φ, ρ

→ Momentum transfer $t = |p_{Au} - p_{Au'}|^2$

T. Toll, T. Ullrich, Phys.Rev. C87, 024913 (2013)



Coherent requires forward scattered nucleus needs to stay intact

→ Veto breakup through neutron detection

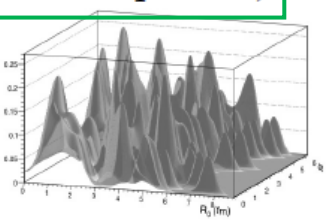
Hot topic:

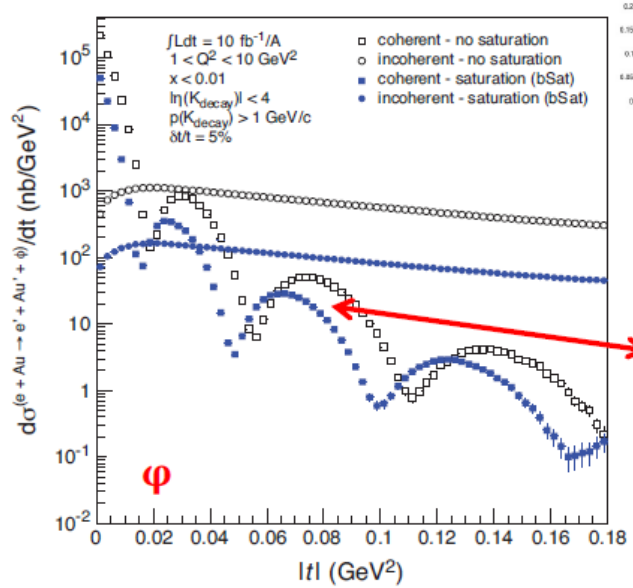
- Lumpiness of source?
- Just Wood-Saxon+nucleon $g(b_T)$

❑ coherent part probes "shape of black disc"

❑ incoherent part (large t) sensitive to "lumpiness" of the source [= proton] (fluctuations, hot spots, ...)

possible Source distribution with $b_T^g = 2$ GeV^{-2}





Sensitive to saturation effects!

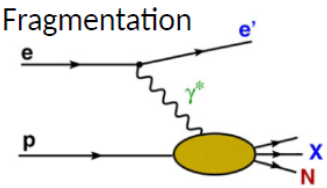
24 September 2019 S. Fazio (BNL) 20

slide by Fazio

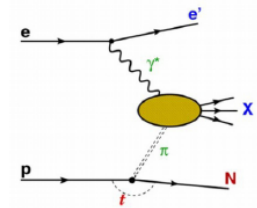
Physics at zero degree of EIC

- Leading baryons
  - Fragmentation
  - One pion exchange (OPE)

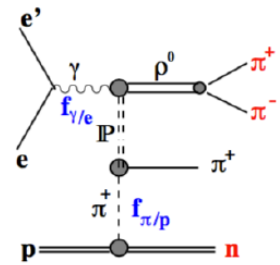
Fragmentation



One Pion Exchange (OPE)



LN in DIS

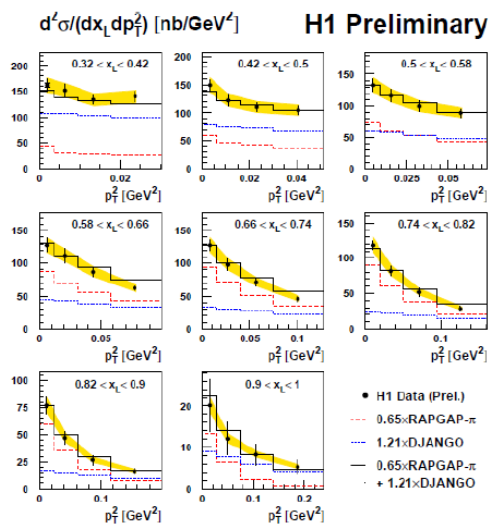


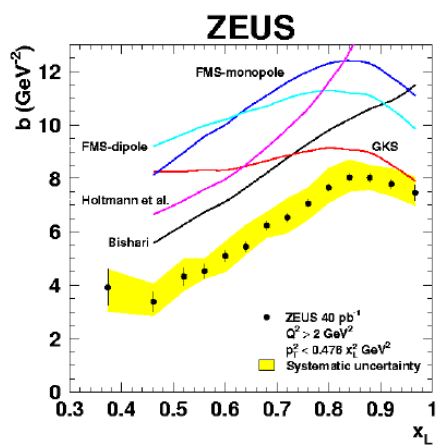
$$d\sigma_{\gamma^* p \to nx} = f_{\pi/p}(x_L, t) \times d\sigma_{\gamma^* \pi \to X}$$

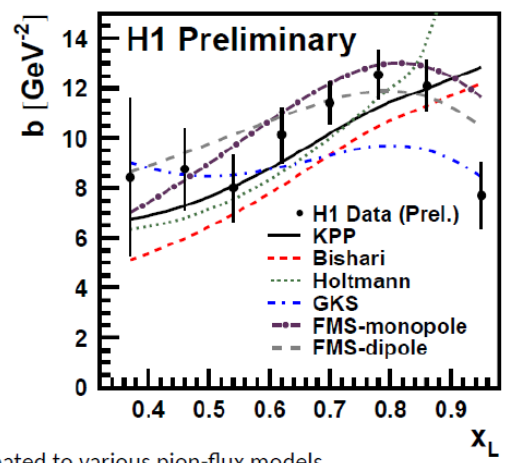
The distribution of p_T^2 (=t) is defined solely by the pion flux

Sensitivity to the pion flux

p_T^2 dependence in bins of x_L







Slope of exponential p_T^2 dependence compated to various pion-flux models

18

slide by Ciesielski

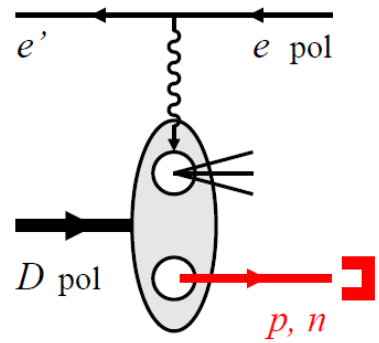
Inconsistency @ HERA

→ Need more data to understand production mechanism

Physics at zero degree of EIC

- Spectator tagging
  - Neutron structure
    - Neutron spin structure, S & D waves
  - Nucleon interactions
    - SRC/EMC at large *x*
    - Diffraction and shadowing at small *x*
- Geometry tagging in e+A collisions
  - *b*: impact parameter & *d*: path length
  - "Centrality" (high *d*) & "Skin" (low *d*)
  - Breakup determination & veto with ZDC
    - + forward photons requiring wide aperture
- Event generator
  - GCF: https://www.mit.edu/~src_emc/fri/schmidt_20190322.pdf
  - BeAGLE: https://wiki.bnl.gov/eic/index.php/BeAGLE

e+D



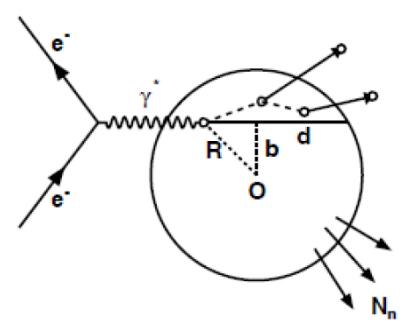
High−energy process

Forward spectator detected

Roman pot

ZDC

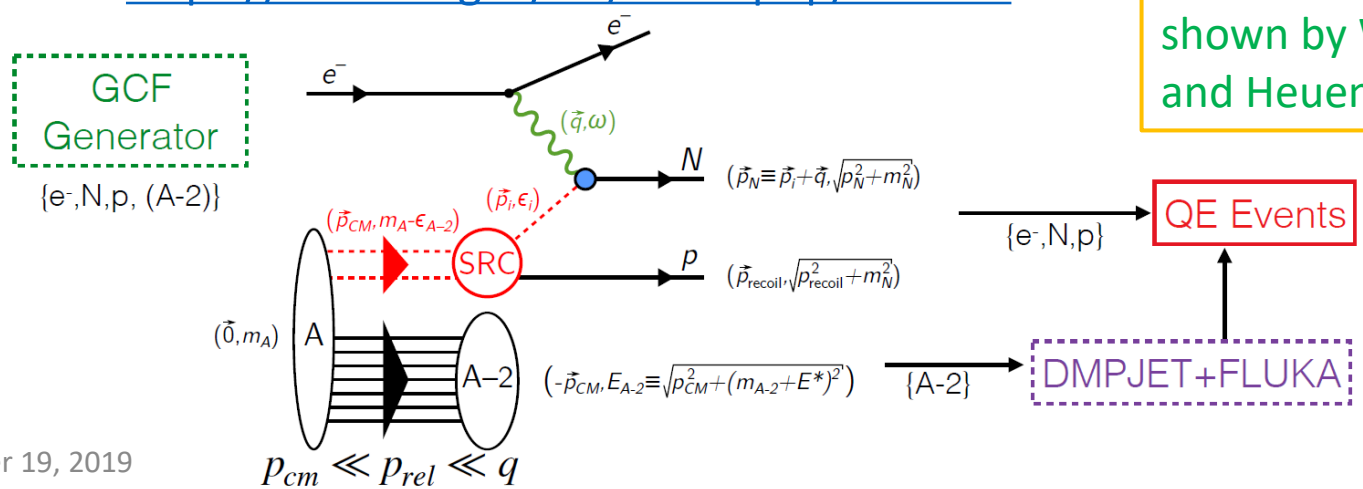
e+A



Intra-nuclear cascading increases with d (forward particle production)

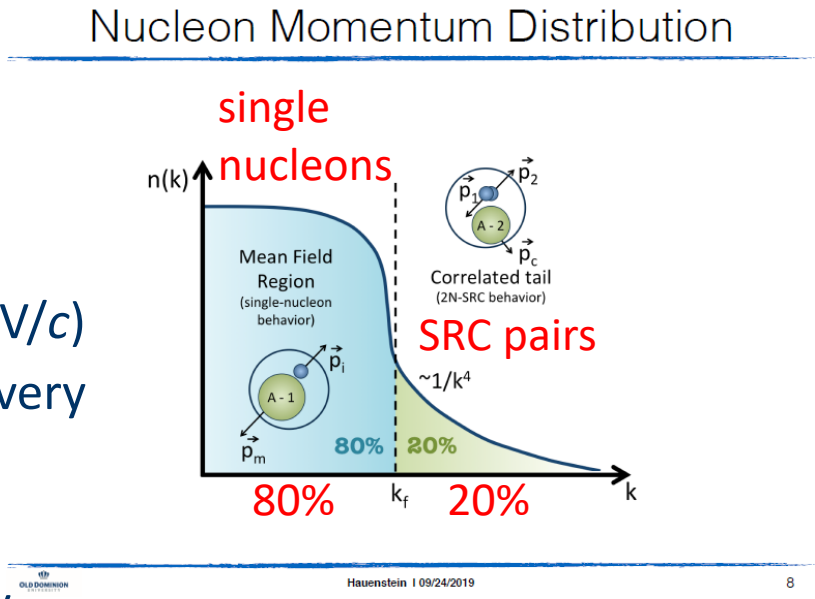
Leads to evaporation of nucleons from excited nucleus (very forward)

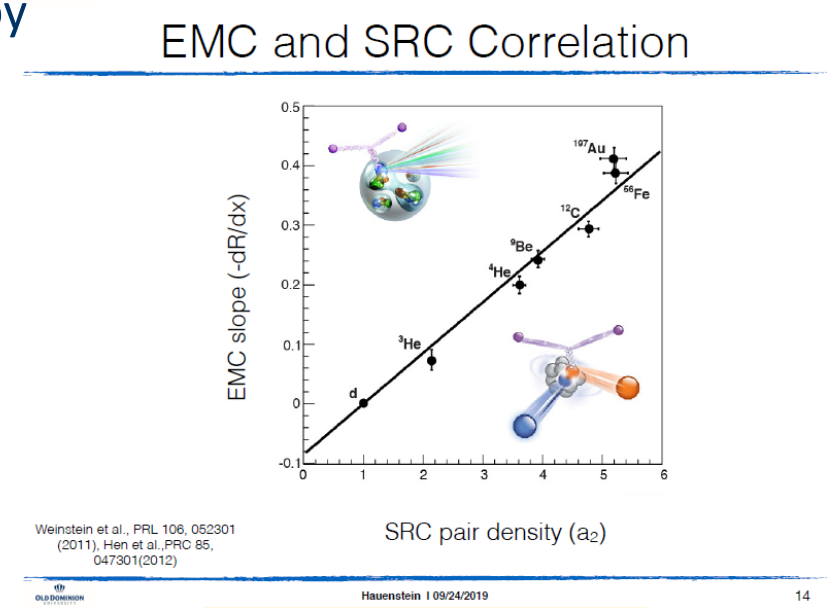
shown by Weiss, Baker and Heuenstein



Physics at zero degree of EIC

- Short range correlation (SRC)
  - ~20% of nucleons in SRC pairs
    - 18% p-n pairs
    - Large relative momentum (> 300 MeV/*c*)
    - Small c.m. momentum and spatially very close each other
  - EMC effect
    - Nuclear PDF significantly modified by SRC pairs
- Tagged DIS at JLab → EIC
  - e+D at JLab: Hall B & C
  - e+D & e+A at EIC
- Tagged SRC at EIC



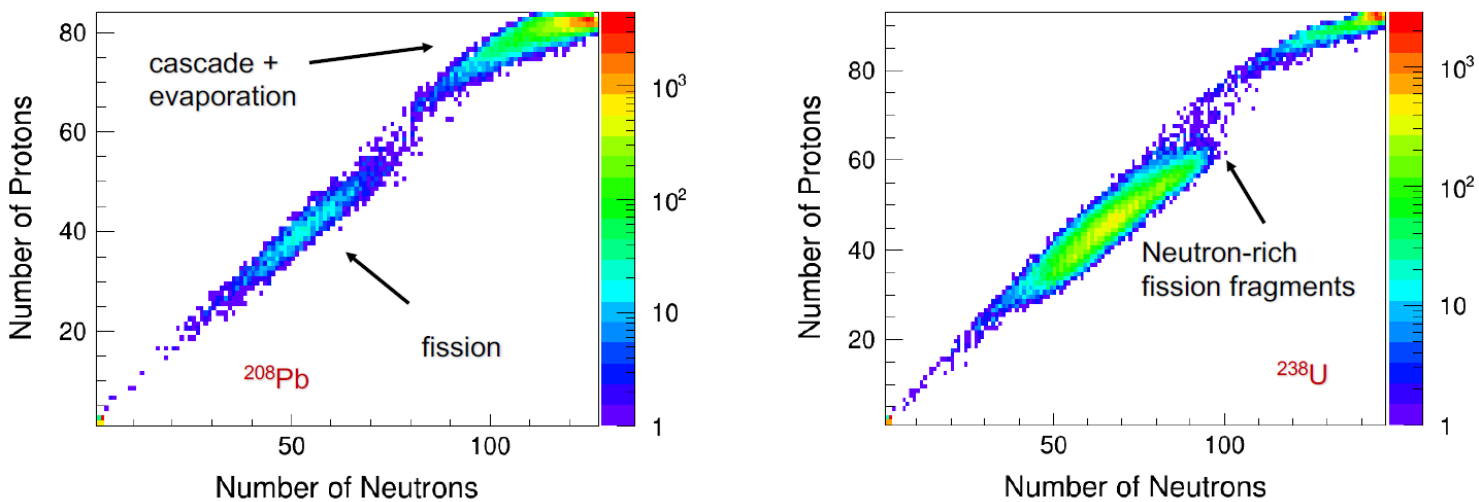


slides by Heuenstein

Physics at zero degree of EIC

- Isotope tagging
  - Nuclear fragments need to be tagged to reconstruct the Fermi momentum of the struck nucleon
- Rates at the EIC?
  - Needs further studies

Nuclei from ^{208}Pb and ^{238}U (1s of simulated beam time at the EIC)

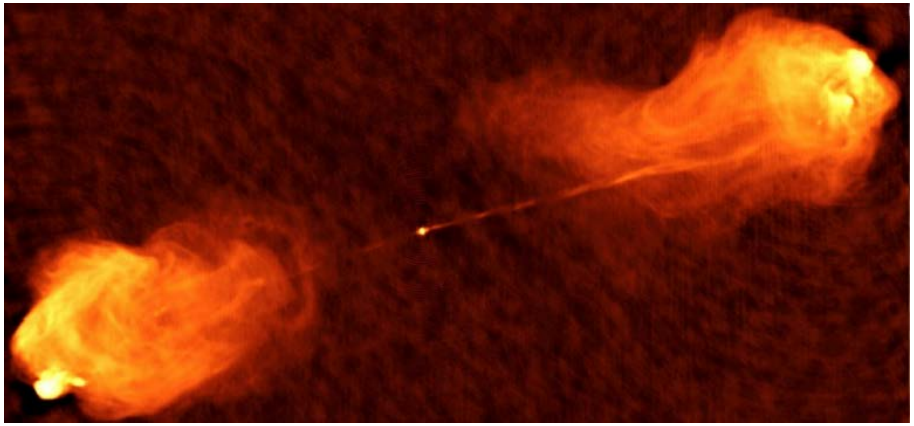


- ^{208}Pb (left) produces mainly heavy isotopes from evaporation
- ^{238}U (right) produces fewer, but heavier isotopes from evaporation. It also produces very neutron-rich fission fragments (medium-mass nuclei have fewer neutrons).

slide by Nadal-Turonski

Relation to cosmic-ray physics

- e+p, e+A at EIC
  - Limited relation to cosmic-ray physics
    - Understanding hadronization
  - Cosmic ray acceleration in blazars?
    - Source of high-energy cosmic ray & neutrino?

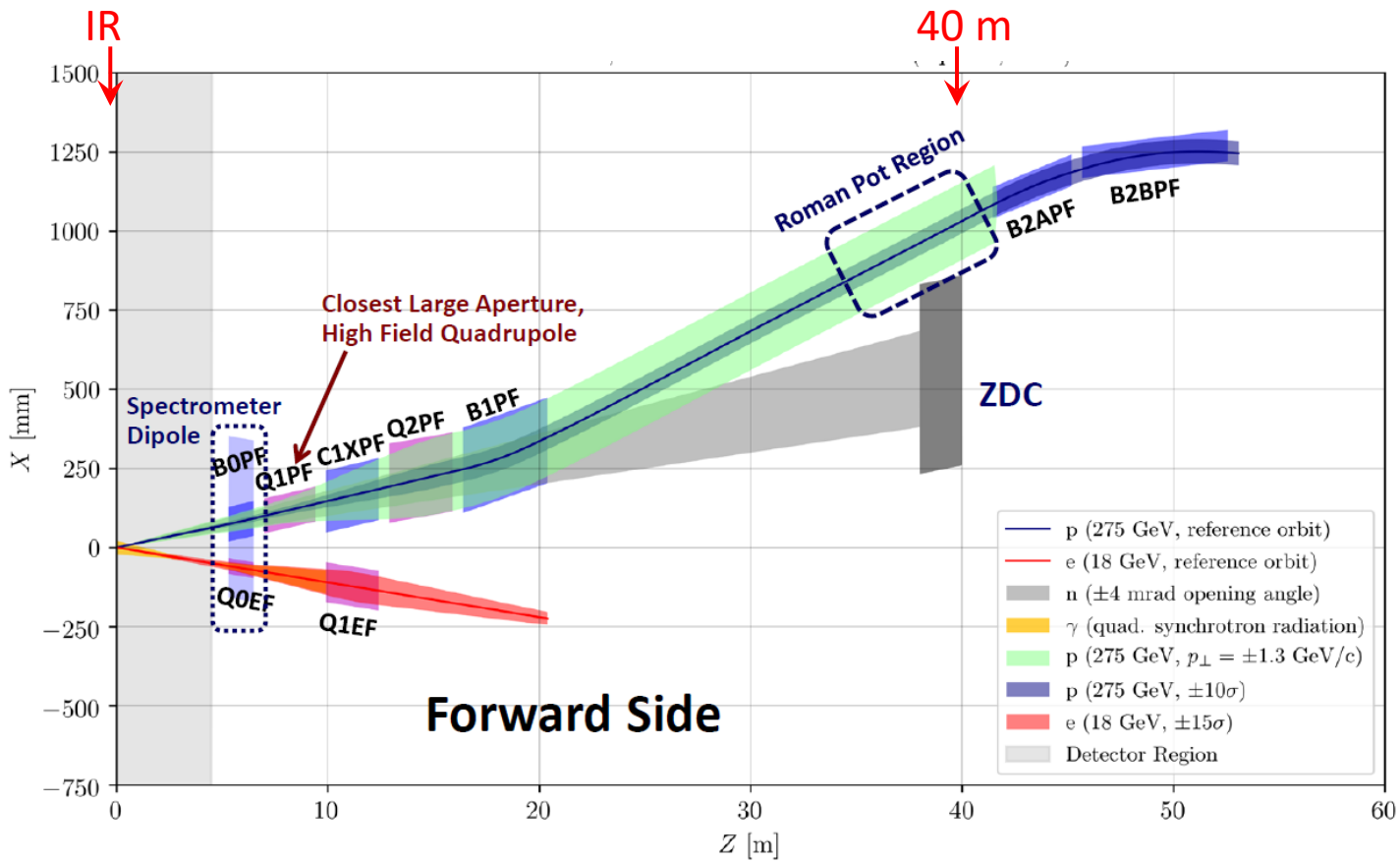


shown by Liodakis

- p+p, p+A, A+A (at RHIC & LHC)
  - More relevance to the cosmic-ray physics
    - Understanding air-shower evolution
    - Event generator development

eRHIC IR design

- 25 mrad crossing angle
- Forward magnet aperture
  - ±4 mrad opening angle for neutron (ZDC)

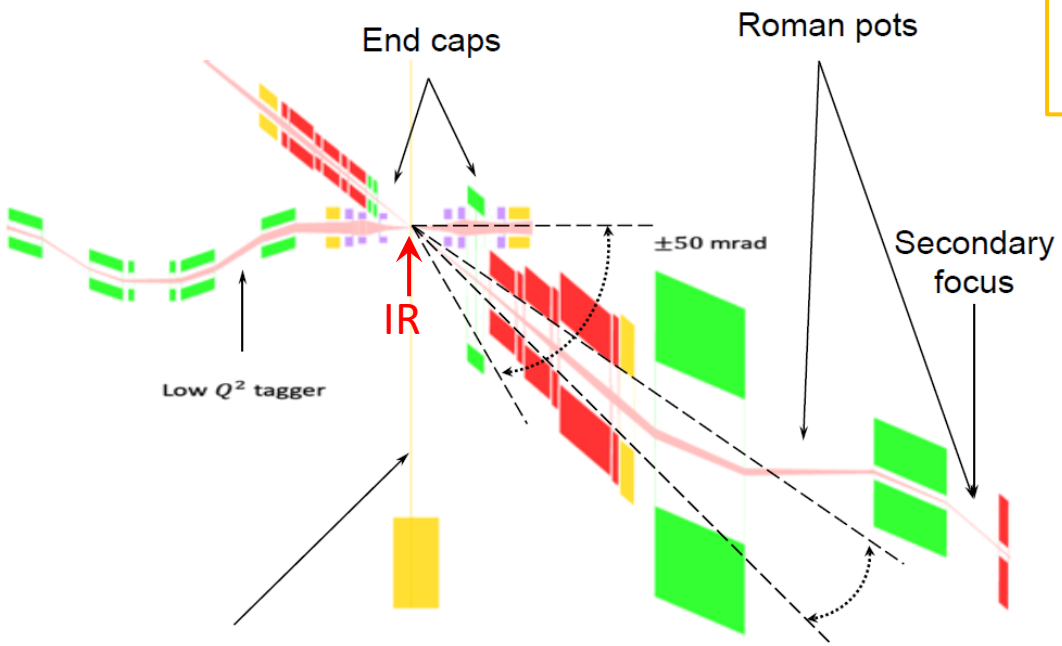


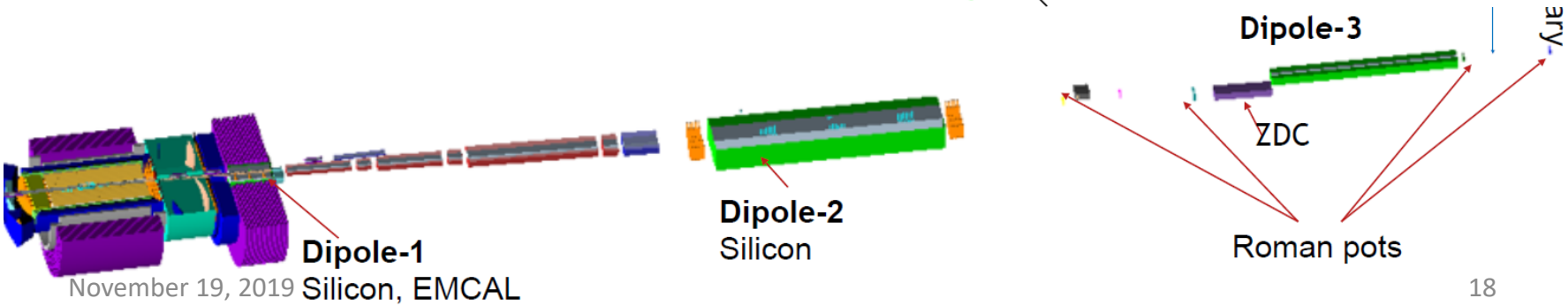
shown by Montag

JLEIC IR design

- 50 mrad crossing angle
- Forward magnet aperture
  - ±10 mrad opening angle for neutron

shown by Furletova & Weiss



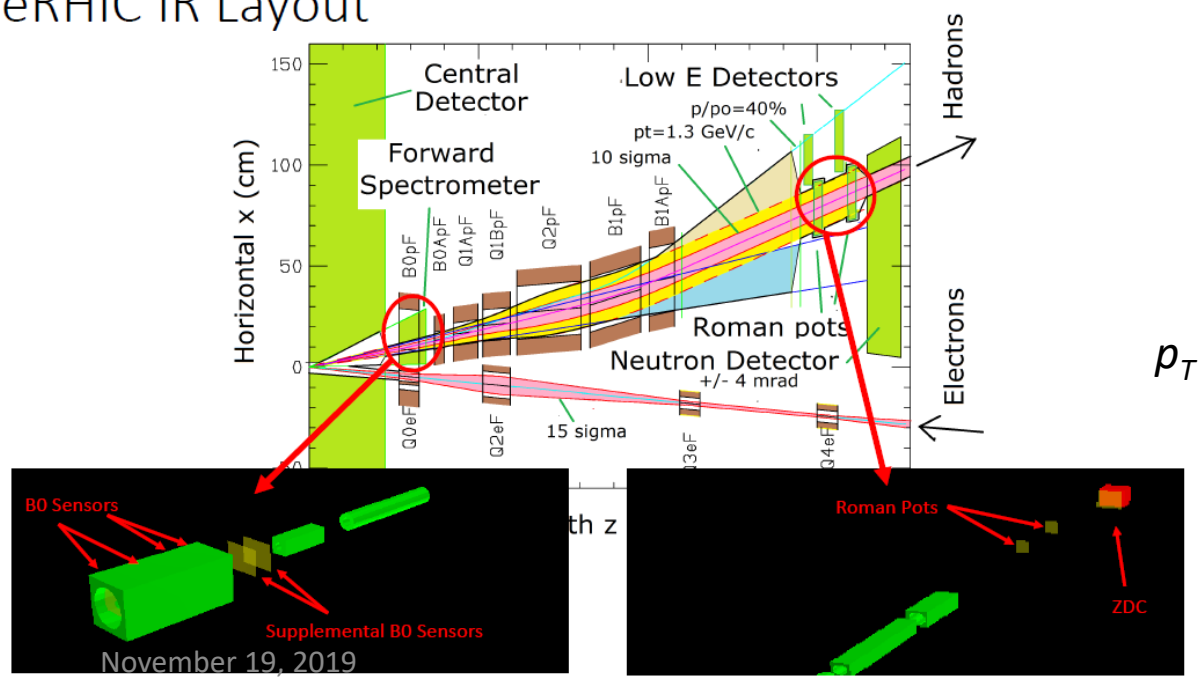


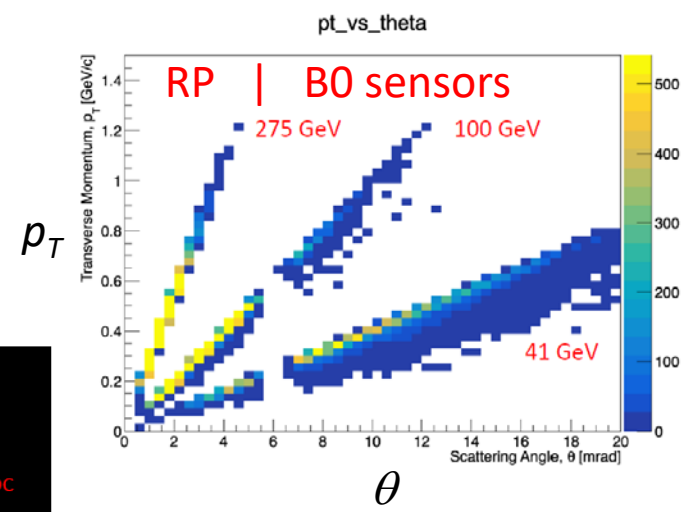
Proton spectrometer

- GPD measurement
  - Normalization (low p_T or $|t|$ coverage)
  - Slope and shape (high p_T or $|t|$ coverage)
- Veto of nuclear breakup events in e+A
  - for proton detection, with ZDC for neutron detection
- Isotope tagging
  - with particle ID
- B0 sensors and Roman pots at eRHIC
  - ± 1.3 GeV/c p_T for 275 GeV proton (Roman pot)

eRHIC IR Layout

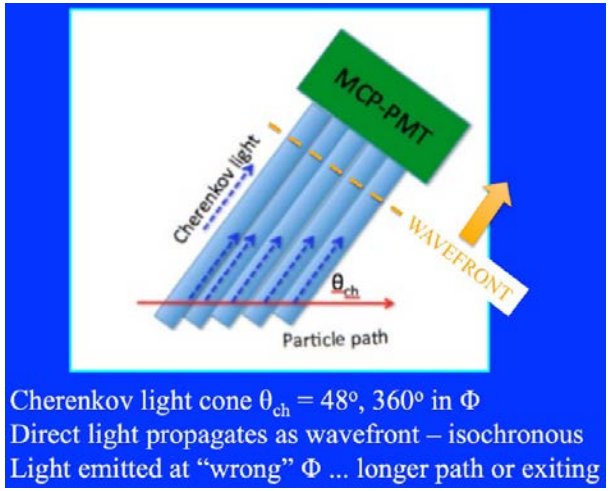
shown by Jentsch





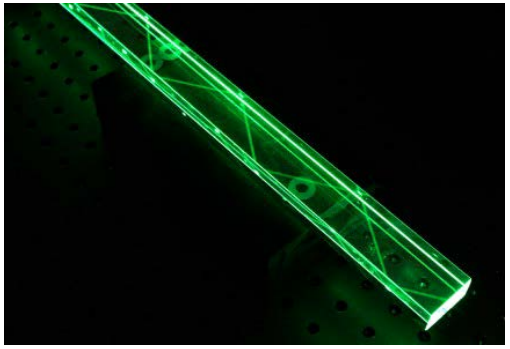
Particle ID

- psTOF in very forward region
  - MCP-PMT shows 5 ps capability
  - Mass (M) and charge (Z)
  - 0.1 ps required for 1% mass resolution



shown by Chiu

- Mini-DIRC inside a Roman pot
  - Identify ions to ~1% in Z^2



shown by Nadal-Turonski

- Isotope tagging
  - Mass, charge and rigidity
- Spectroscopy
  - Strangeness and heavy flavors

Zero Degree Calorimeter (ZDC)

- Position sensitive ZDC
  - Energy (E) resolution
    - Geometry tagging
  - Position (or θ) resolution
  - p_T (or $|t|$) resolution
    - Need both E and θ resolution
    - Intrinsic momentum spread from beam emittance
    - Spectator tagging
    - Isotope tagging
  - Uniformity (position dependence)
  - Aperture (IR & detector design)
    - $\pm$4 mrad @ eRHIC
    - $\pm$10 mrad @ JLEIC
  - Radiation dose & hardness

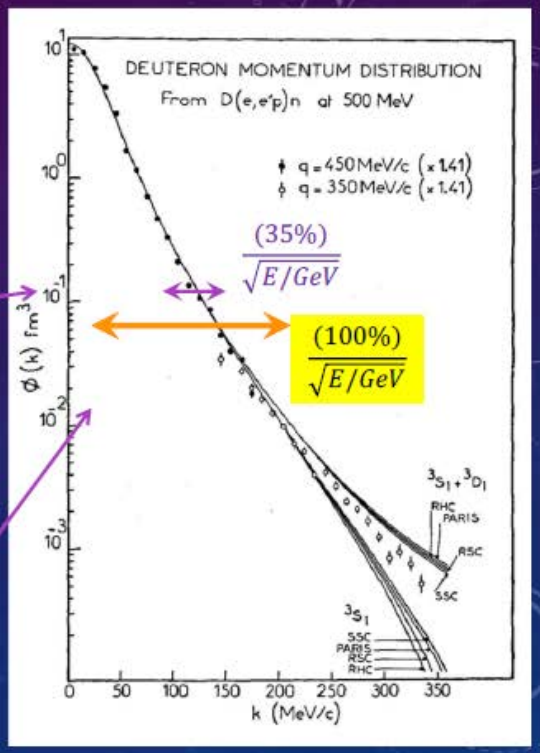
ZDC at EIC

- Detector requirements for spectator neutron tagging
  - p_T resolution

$D(e,e'n_S)X \approx p_{bound}(e,e')X$

200 GeV/c D ➔ 100 GeV/c spectator neutron

- Hadronic Calorimeter at 45 m (JLEIC)
- Impact point resolution 1.5 cm *rms*:
  - $\frac{\delta p_T}{p} = 0.33$ mrad ➔ $\delta p_T = 33$ MeV
  - Equivalent to *rms* beam spread
- If energy Resolution $\frac{\delta E}{E} = \frac{(35\%)}{\sqrt{E/GeV}}$
  - $\alpha = A\frac{p_n^+}{P_A^+} \approx \left[1 + \frac{p_n}{M_N}\right]_{Deuteron\ Rest-Frame}$
  - $\delta\alpha = \frac{\delta E}{E} = 3.5\%$ ➔ $\delta p_n^{D\text{-}rest} \approx 35$ MeV/c
  - If $\frac{(100\%)}{\sqrt{E/GeV}}$ ➔ $\delta p_n^{D\text{-}rest} \approx 100$ MeV/c



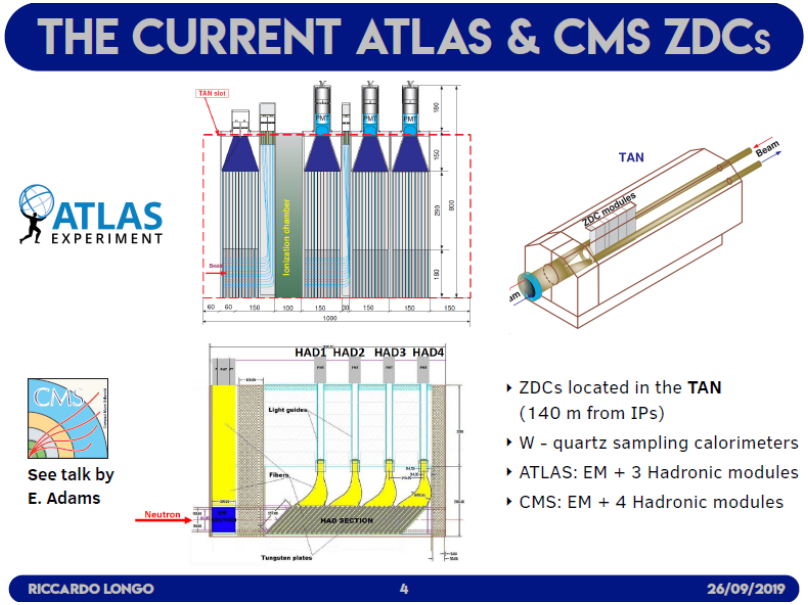
C.Hyde 9/25/19 4

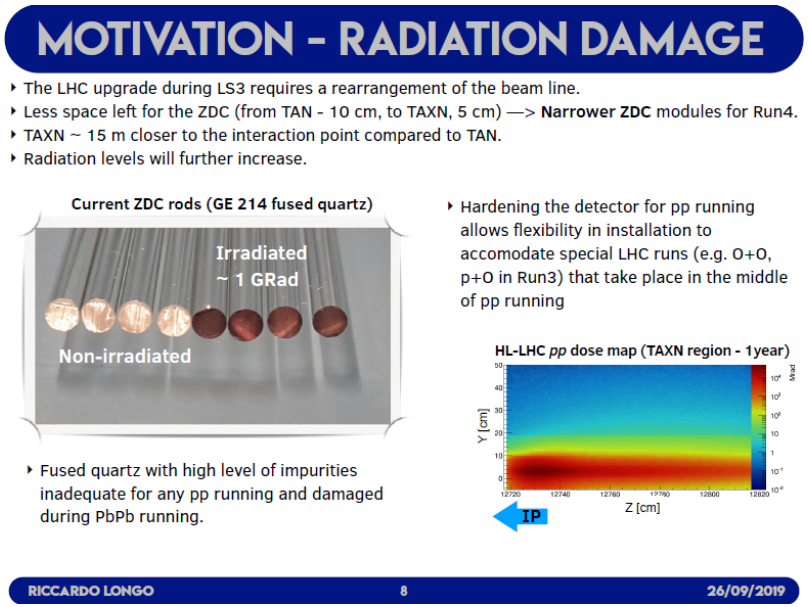
slide by Hyde

ZDC at LHC

- CMS ZDC (M. Murray's talk)
  - W-quartz sampling calorimeter

- JZCaP collaboration
  - ATLAS + CMS joint R&D effort
  - Radiation-hard fused silica rods
  - Increasing H_2 concentration

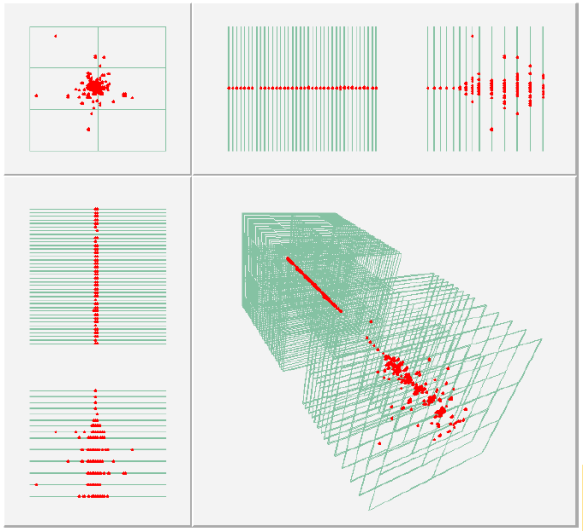




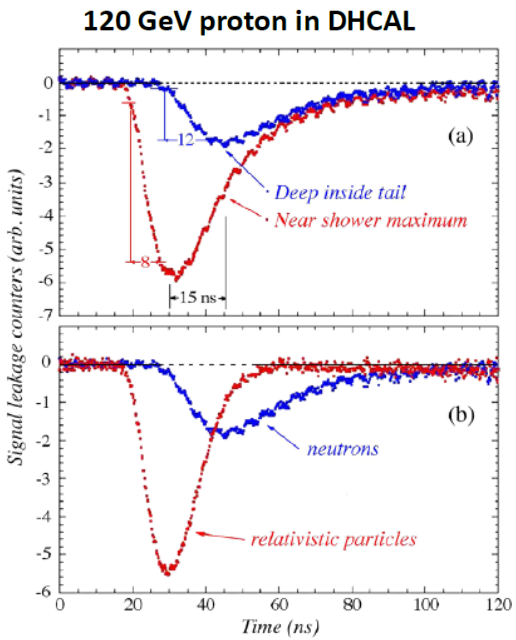
slides by Longo

Detector requirements

- TOPSiDE / CALICE
  - Imaging calorimeter
  - Improving e/h with software compensation
- EIC HCal R&D
  - Improving e/h with timing (dual-gate offline compensation)
  - Energy resolution better than ~40%/√E (GeV) + few% is challenging
- ALICE FoCal



shown by Repond



shown by Tsai

Detector requirements

- Position layers (or Shower Max Detector)
  - Scintillation fiber/bar
    - Plastic fiber
    - Crystal bar (~1mm)
  - Cherenkov
    - Quartz fiber
  - Silicon sensor

	Plastic fiber	Crystal bar	Quartz fiber	Silicon
Source	Scintillation		Cherenkov	
Signal	good	good	weak	good
Rad Hardness	poor	OK	excellent	OK
Cost	$	$$	$$	$$$
Position Resolution	good	good	poor	best
Large acceptance	OK	position dependent	OK	OK

Summary

- Physics at zero degree of EIC
  - GPD, gluon saturation in e+A, leading baryons, spectator tagging, geometry tagging, SRC/EMC, isospin tagging, spectroscopy, …
- IR & detector requirements
  - Proton spectrometer, partic ID, ZDC, …
- Next goals
  - Physics, detector and IR requirements at zero degree to be compiled in an EIC detector R&D letter of interest of the zero-degree apparatus (January, 2020)
  - Next meeting to be planned before making an EIC detector R&D proposal (July, 2020)
  - Please consider to join us