Summary and Conclusions of Yellow Report on Complementarity

IR2@EIC:
Workshop on Science and Instrumentation of the 2^{nd} IR for the EIC

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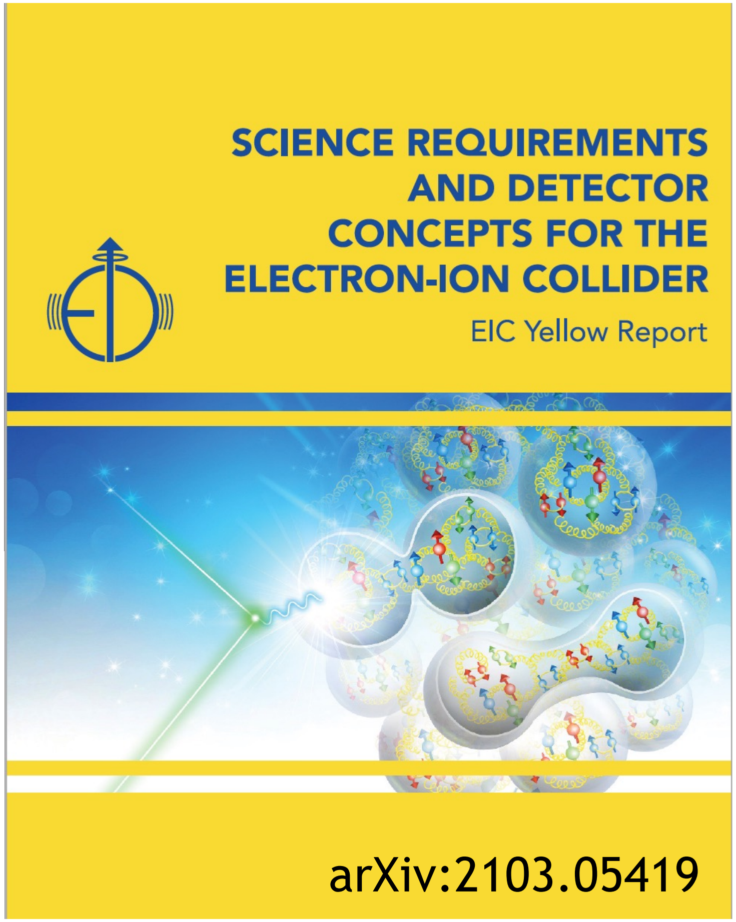
Background

- Funding Questions aside, colliders usually have (at least) two detectors

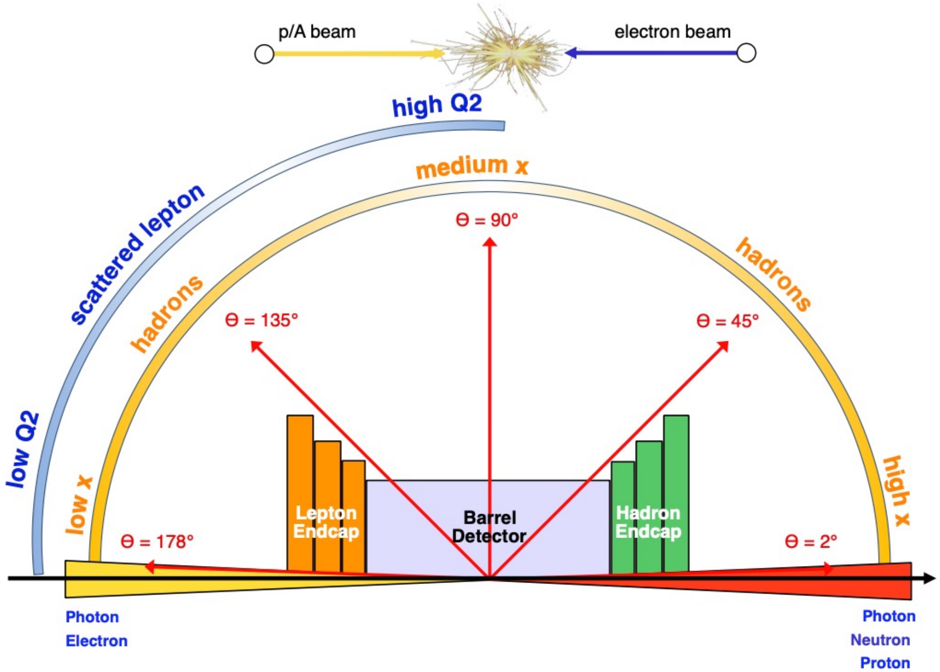
- Much of the work done up to now has focused on a ‘reference detector’

- Second detector more of a blank page → opportunity to refine and enhance EIC physics program by thinking in terms of Complementarity from the outset.

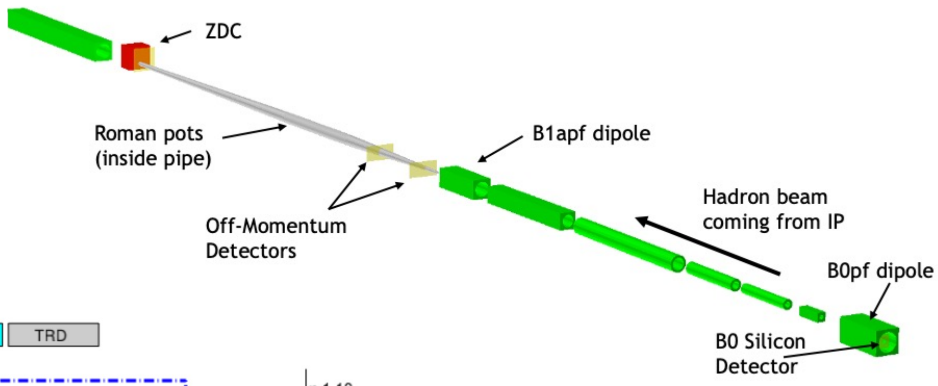
- Yellow Report Complementarity group charged with collecting arguments why two detectors will enhance scientific output

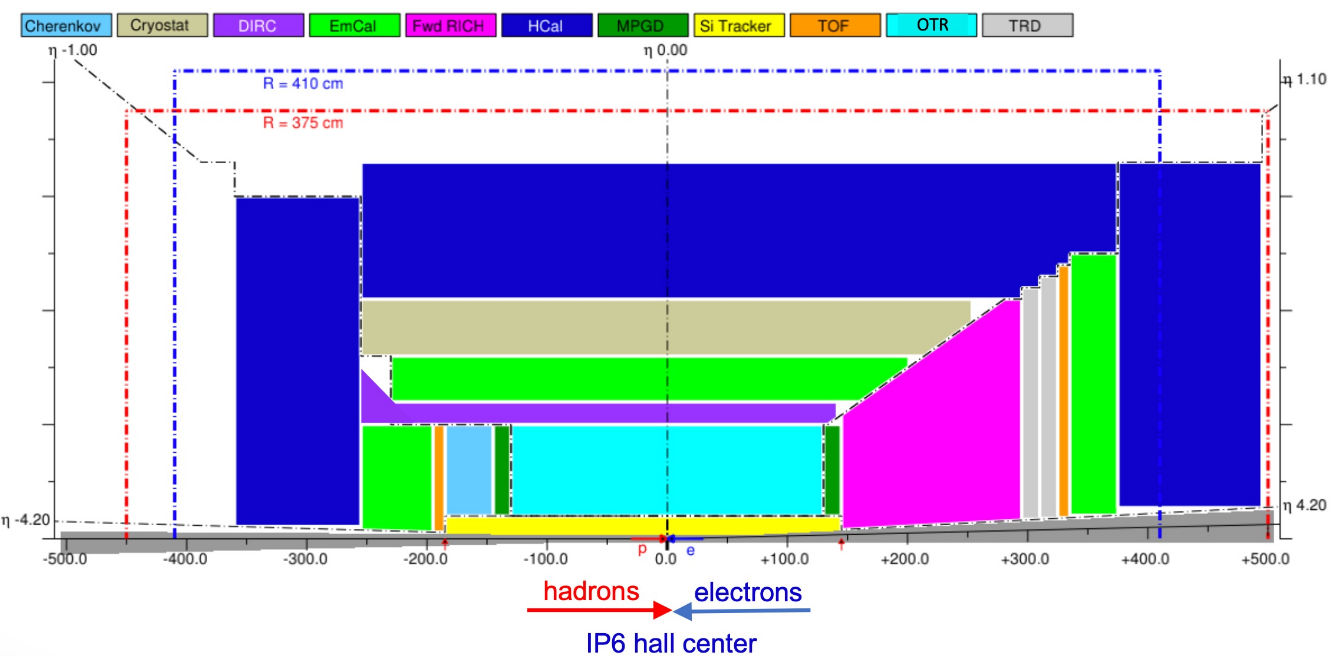


First Detector



Well developed reference concept for first detector and interaction region





- 3T Solenoid
- Technologies still under discussion

[See Yulia Furletova's talk]

What do we want from ‘Complementary’

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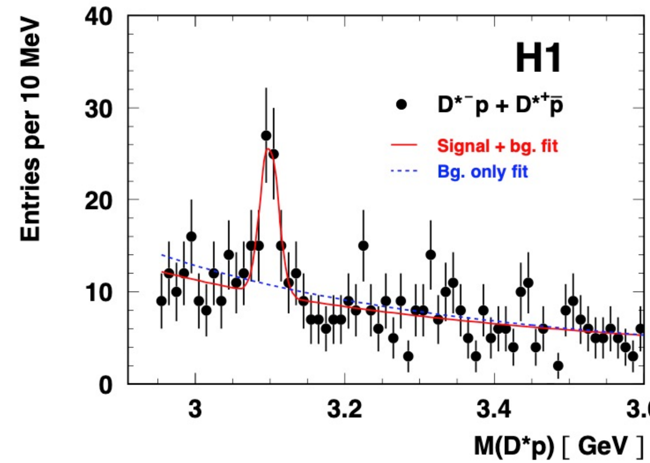
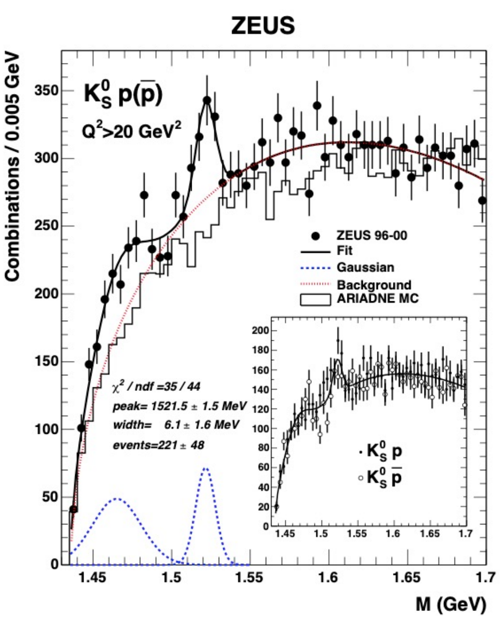
1) Cross-checking important results (obvious!)

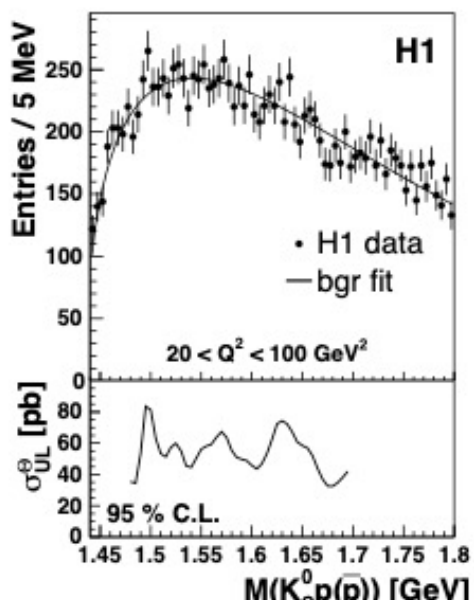
- Many examples of wrong turns in history of nuclear and particle physics.

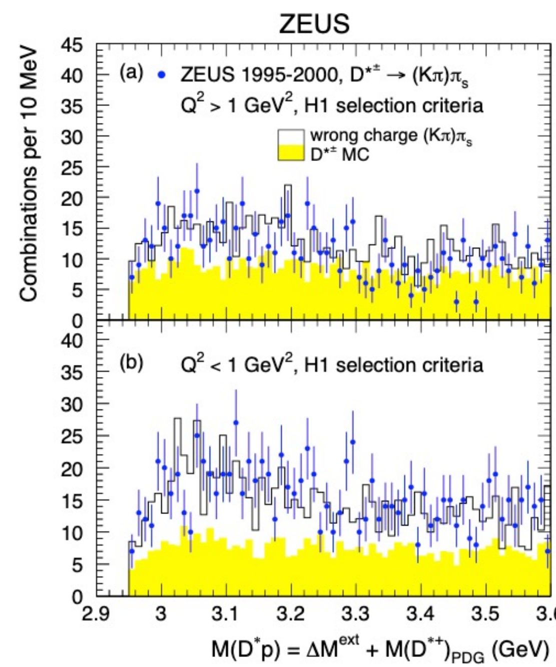
- Independent cross checks (detector, community, analysis tools) are essential for timely verifications and corrections



e.g: Pentaquarks in 2004 (K_sp & D*p at HERA)

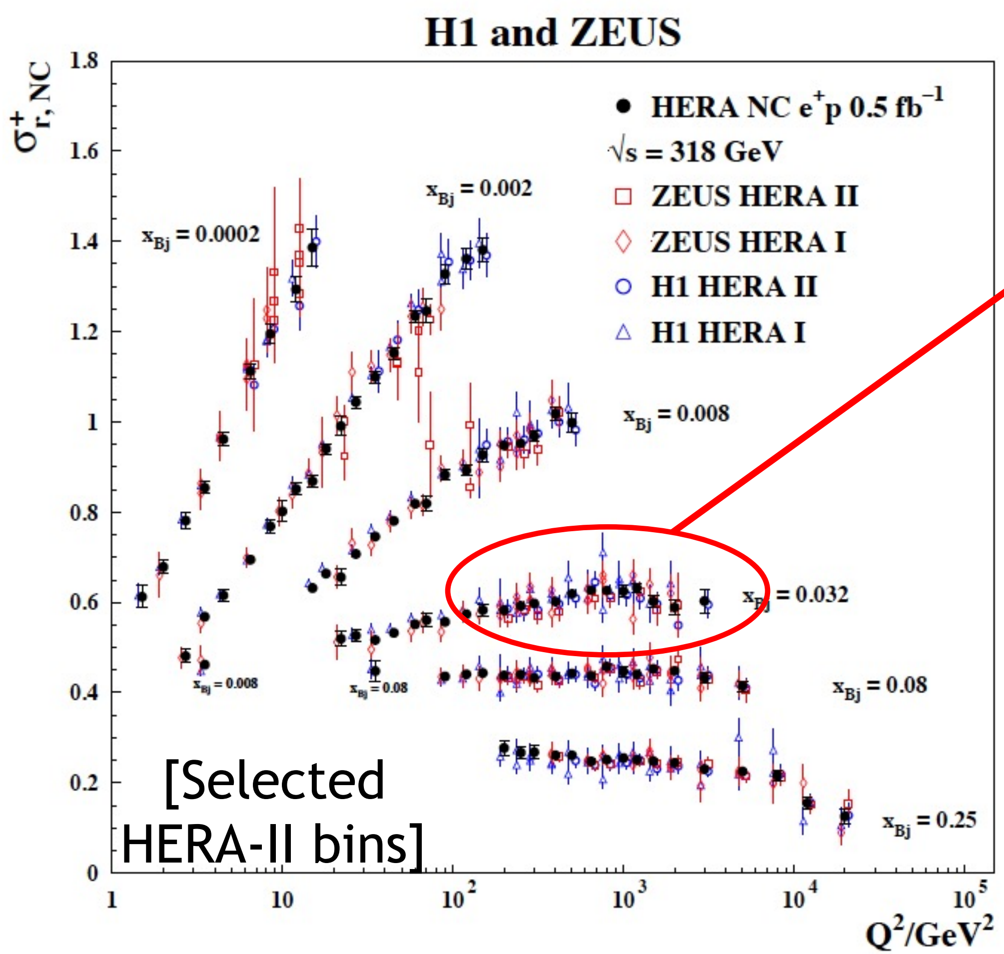


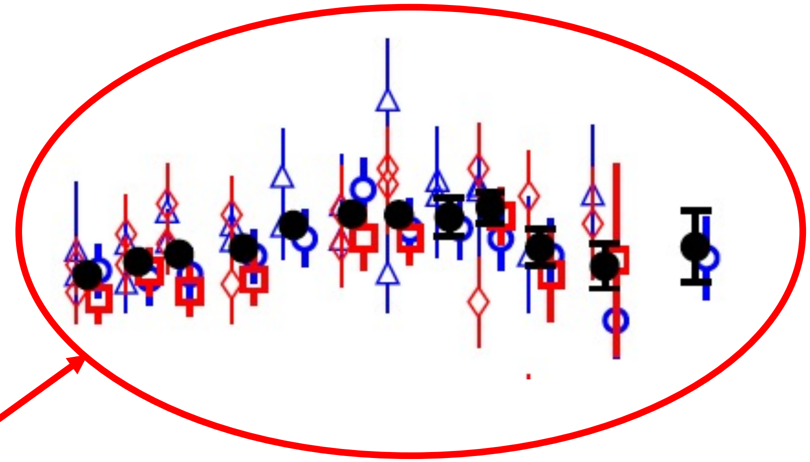




What do we want from ‘Complementary’

2) Cross calibration



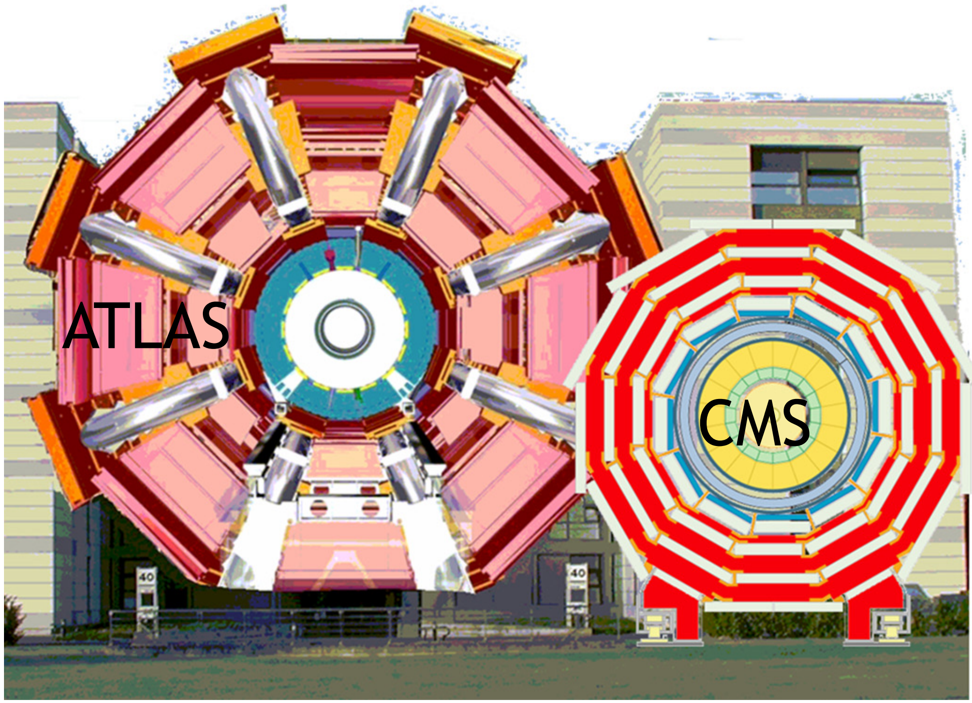


- Combining data gave well beyond the √2 statistical improvement …
- Different dominating H1, ZEUS systematics…
- Effectively use H1 electrons with ZEUS hadrons

… not all optimal solutions have to be in one detector…

What do we want from ‘Complementary’

3) <u>Technology Redundancy</u>
... applying different detector technologies and philosophies to similar physics aims
- mitigates technology risk v unforeseen backgrounds and
- differently optimises precision and systematics



What do we want from 'Complementary'

3) Technology Redundancy

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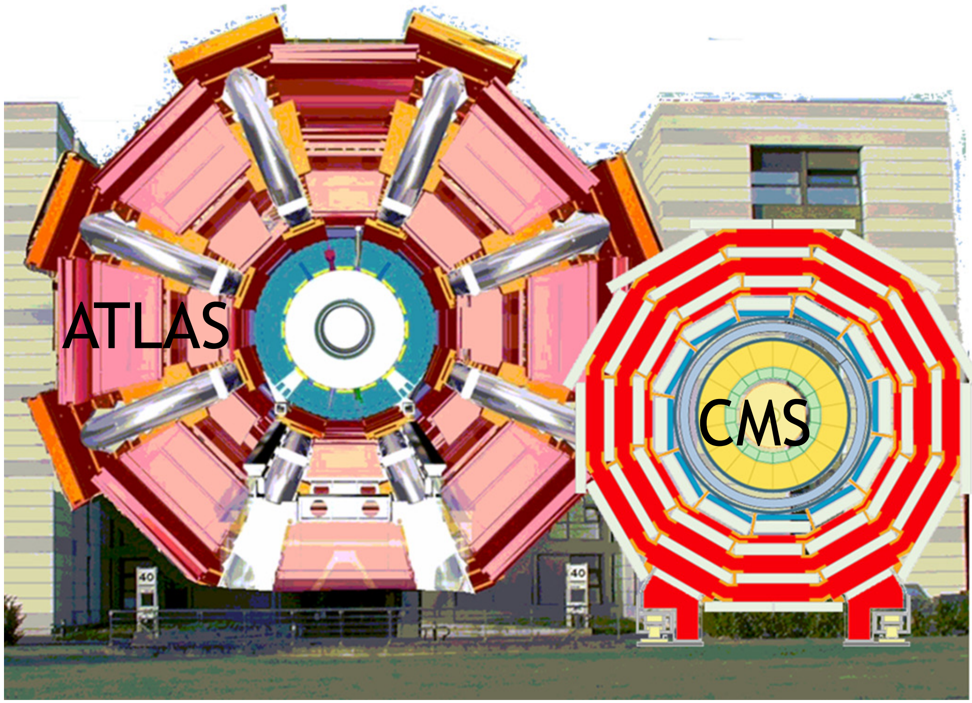


4) Different primary physics focuses ...

... EIC has unusually broad physics programme (from exclusive single particle production to high multiplicity eA or γA with complex nuclear fragmentation)

→ Impossible to optimise for the full programme in a single detector.

Complementarity Working Group Activities

1) Discussed detailed aims and needs with Physics Working Group conveners

"Have you identified key physics aims that conflict with the current baseline / schematic detector and IR design?"

2) Discussed with Detector Working Group conveners

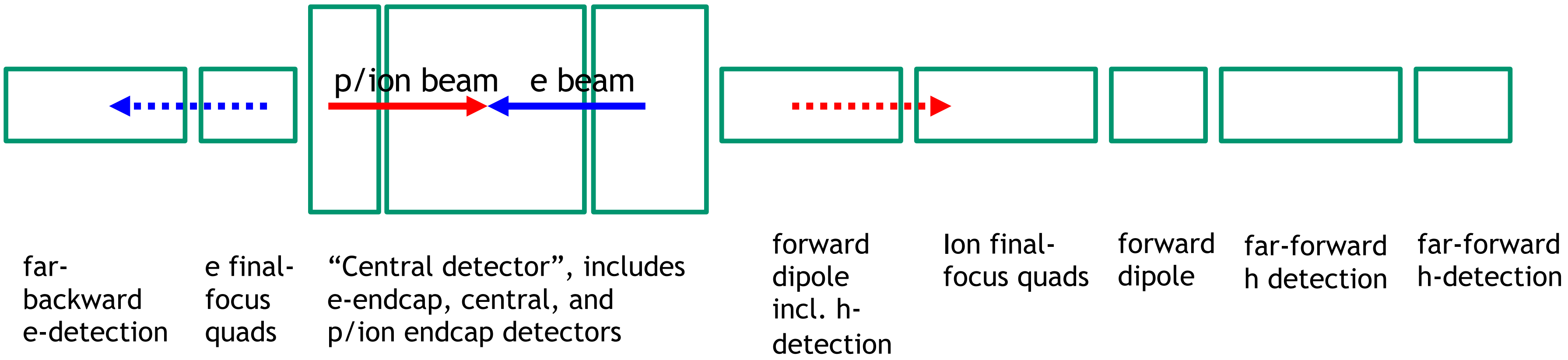
"Assuming we have two detectors, how you could build in complementarity within the overall constraints imposed by the accelerator and associated considerations?"

[Many subsidiary questions and iterations]

… no compelling argument for a second detector with specialised / limited physics focus.

→ **Working assumption is two complementary GPDs**

General Requirements for any EIC GPD:
1) Boundary Conditions from Machine



- IR2 detector design has to be compatible with (modified?) machine and IR design
- Solenoid aligned with electron beam (to limit synchrotron load)

… and at least for the nominal design:

- Rapidity coverage in main detector limited to $-4 < \eta < 4$ by crossing angle / synchrotron
- Main detector limited in length to ± 4.5m by first focusing quadrupole (to maintain high luminosity)
- Forward / backward detectors angular range limited to ~ 1.5^{o} by synchrotron
- Longitudinal space for far forward/backward detectors limited to $\pm$ 35m by crab cavities

Summary of Detector Requirements based on Physics Studies from Yellow Report

η	Nomenclature	Tracking: Resolution	Tracking: Relative Momentun	Tracking: Allowed X/X_0	Tracking: Minimum-p_T (MeV/c)	Tracking: Transverse Pointing Res.	Tracking: Longitudinal Pointing Res.	Electrons and Photons: Resolution σ_E/E	Electrons and Photons: PID	Electrons and Photons: Min E Photon	π/K/p: p-Range	π/K/p: Separation	HCAL: Resolution σ_E/E	HCAL: Energy	Muons
< -4.6	Low-Q2 tagger														
-4.6 to -4.0		Not Accessible													
-4.0 to -3.5			Reduced Performance												Muons useful for background suppression and improved resolution
-3.5 to -3.0	Backward Detector		σ_p/p ~ 0.1%×p⊕2%	~5% or less	150-300			1%/E ⊕ 2.5%/√E ⊕ 1%	π suppression up to $1:10^{-4}$	20 MeV	≤ 10 GeV/c	≥ 3σ	50%/√E ⊕ 10%	~500MeV	
-3.0 to -2.5															
-2.5 to -2.0			σ_p/p ~ 0.02% × p ⊕ 1%												
-2.0 to -1.5						dca(xy) ~ $40/p_T$ μm ⊕ 10 μm	dca(z) ~ $100/p_T$ μm ⊕ 20 μm	2%/E ⊕ (4-8)%/√E ⊕ 2%	π suppression up to $1:(10^{-3}-10^{-2})$	50 MeV					
-1.5 to -1.0															
-1.0 to -0.5	Barrel		σ_p/p ~ 0.02% × p ⊕ 5%		400	dca(xy) ~ $30/p_T$ μm ⊕ 5 μm	dca(z) ~ $30/p_T$ μm ⊕ 5 μm	2%/E ⊕ (12-14)%/√E ⊕ (2-3)%	π suppression up to $1:10^{-2}$	100 MeV	≤ 6 GeV/c		100%/√E ⊕ 10%		
-0.5 to 0.0															
0.0 to 0.5															
0.5 to 1.0															
1.0 to 1.5	Forward Detectors		σ_p/p ~ 0.02% × p ⊕ 1%		150-300	dca(xy) ~ $40/p_T$ μm ⊕ 10 μm	dca(z) ~ $100/p_T$ μm ⊕ 20 μm	2%/E ⊕ (4*-12)%/√E ⊕ 2%	3σ e/π up to 15 GeV/c	50 MeV	≤ 50 GeV/c		50%/√E ⊕ 10%		
1.5 to 2.0															
2.0 to 2.5															
2.5 to 3.0			σ_p/p ~ 0.1%×p⊕2%												
3.0 to 3.5															
3.5 to 4.0	Instrumentation to separate charged particles from photons		Reduced Performance												
4.0 to 4.5		Not Accessible													
> 4.6	Proton Spectrometer Zero Degree Neutral Detection														

→ Some of this is specific to 3T solenoid

→ Much of it is not …

General Requirements for any EIC GPD
2) Physics Considerations

- Able to perform well over entire EIC $\sqrt{s}$ and luminosity range

- Efficient scattered electron ID down to low energies / high y (10^{-4} e/π separation)
- Electromagnetic Calorimetry resolution (for scattered electron) pivotal (~ $2\%/\sqrt{E}$)

- Precision tracking (momentum resolution better than 2%), whilst keeping material budget low (<~5% X_0)
- High performance PID to separate π, K, p on track-by-track level (nominally 3σ π/K separation) up to high p_T ~50GeV
- Fine vertex resolution (~ 20 μm for all three coordinates)

- Hadronic calorimetry matching tracking and ECAL acceptance (~ 50% / $\sqrt{E}$).

- Far forward: Large acceptance and precise measurement of protons, neutrons, (nuclear fragment, photon) tagging
- Far backward: Coverage for electrons (and photons) at low Q^2

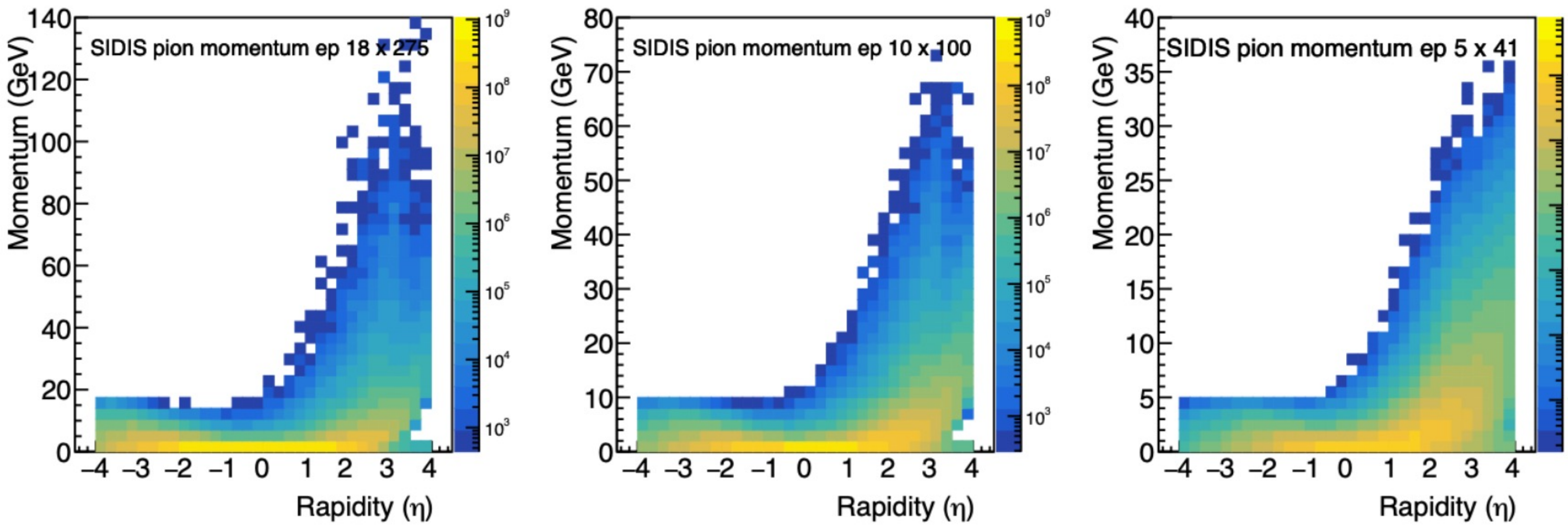
- Excellent control of systematics, matching statistical precision (redundancy in measurements, luminosity and polarimetry)

Complementarity from Solenoid Field Choice

Magnetic Field Strength compromises for charged particles in central region

- **High field → high p_T precision : Many good physics aims associated with scattered electron, heavy flavours, precision spectroscopy …**

- **Low field → low p_T acceptance:** eg 0.5T field - acceptance to p_T~50 MeV



- **SIDIS spectra dominated by low p_T (<~ 1 GeV).**
  → TMDs, FFs, samples for spectroscopy (HF etc)

Field Choice and Particle ID

- Field choice is also coupled with particle ID acceptance:

e.g. Suppose the innermost PID-capable detector is at r=1m
… acceptance cut-offs for pion ID versus only track p_T and charge with the silicon/microvertex tracker.

lowest p_T	0.5 Tesla	1 Tesla	3 Tesla
with PID @1m	75 MeV	225 MeV	450 MeV
no PID	25 MeV	50 MeV	100 MeV

- Other solenoid considerations:
→ Bore radius and length
→ Space used by cryostat

(assuming coil is inside HCAL)

IR1 Plans

Parameter	New Magnet	BABAR/sPHENIX Magnet
Maximum Central Field (T)	3	1.5
Coil length (mm)	3600	3512
Warm bore diameter (m)	3.2	2.8
Uniformity in tracking region ($z = 0, r < 80$ cm) (%)	3	3
Conductor	NbTi in Cu Matrix	Al stabilized NbTi
Operating Temperature (K)	4.5	4.5

Table 11.1: Summary of some of the main requirements of the EIC detector solenoid magnet.

Complementarity through Technology Choices

system	system components	reference detectors	detectors, alternative options considered by the community		
tracking	vertex	MAPS, 20 um pitch	MAPS, 10 um pitch		
	barrel	TPC	TPC[a]	MAPS, 20 um pitch	MICROMEGAS[b]
	forward & backward	MAPS, 20 um pitch & sTGCs[c]	GEMs	GEMs with Cr electrodes	
	very far-forward & far-backward	MAPS, 20 um pitch & AC-LGAD[d]	TimePix (very far-backward)		
ECal	barrel	W powder/ScFi or Pb/Sc Shashlyk	SciGlass	W/Sc Shashlyk	
	forward	W powder/ScFi	SciGlass	PbGl	Pb/Sc Shashlyk or W/Sc Shashlyk
	backward, inner	$PbWO_4$	SciGlass		
	backward, outer	SciGlass	$PbWO_4$	PbGl	W powder/ScFi or W/Sc Shashlyk[e]
	very far-forward	Si/W	W powder/ScFi	crystals[f]	SciGlass
h-PID	barrel	High performance DIRC & dE/dx (TPC)	reuse of BABAR DIRC bars	fine resolution TOF	
	forward, high p	double radiator RICH (fluorocarbon gas, aerogel)	fluorocarbon gaseous RICH	high pressure Ar RICH	
	forward, medium p		aerogel		
	forward, low p	TOF	dE/dx		
	backward	modular RICH (aerogel)	proximity focusing aerogel		
e/h separation at low p	barrel	hpDIRC & dE/dx (TPC)	very fine resolution TOF		
	forward	TOF & areogel			
	backward	modular RICH	adding TRD	Hadron Blind Detector	
HCal	barrel	Fe/Sc	RPC/DHCAL	Pb/Sc	
	forward	Fe/Sc	RPC/DHCAL	Pb/Sc	
	backward	Fe/Sc	RPC/DHCAL	Pb/Sc	
	very far-forward	quartz fibers/ scintillators			

Multiple proposals / alternatives in YR for each subdetector …

→ Different space requirements

(e.g. trade-offs between tracking and dedicated PID)

→ Different material budgets / systematics

→ Some combine multiple functions

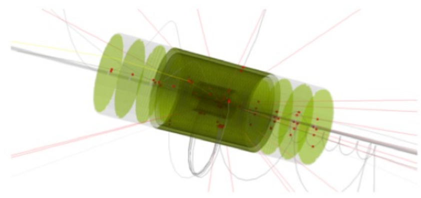
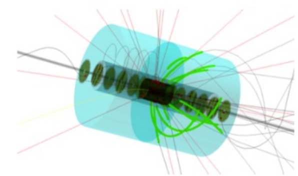
(eg e-h separation + tracking with TRDs

(eg PID by ToF + tracking with AC-LGADs)

→ Different risks / technology-readiness

- Making different choices in IR1 and IR2 detectors provides natural technology redundancy, plus ‘independent’ cross checking and cross-calibration

Example Complementarity through Detector Technology Choices: Tracking Region

	Radial space needs			
Function	Minimum	Maximum	Minimum	Maximum
Tracking	All Silicon 		Silicon + TPC 	
(includes 5 cm support)	50 cm	60 cm	85 cm	
Hadron PID	RICH 50 cm		DIRC 10 cm	
EM Calorimetry	30 cm	50 cm	High-Resolution to achieve P < 2 GeV 50 cm	
PID & EMCal Support Structure	10 cm	15 cm	10 cm	15 cm
Total	140 cm	175 cm	155 cm	160 cm

- Si + gas version provides PID from dE/dx & keeps low material budget

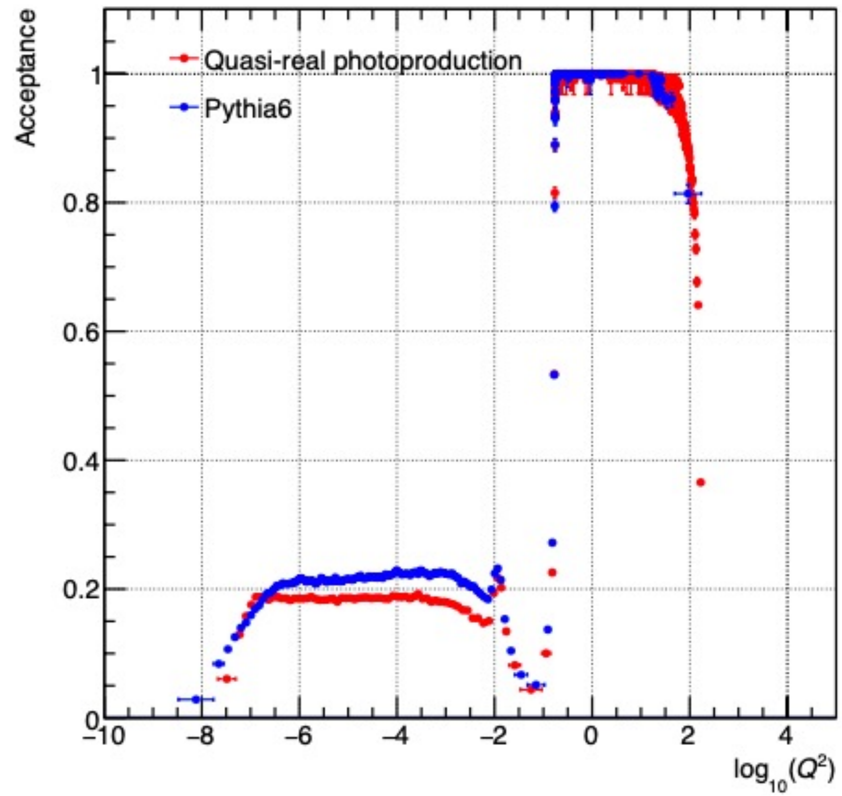
- All Si version slightly improves momentum, vertexing performance and is more compact (e.g. allowing implementation of PID beyond tracker for high p_T particles or reducing magnet bore / overall detector size)

- Here (and in many other places), detailed multi-detector simulation tools are needed to optimise combinations

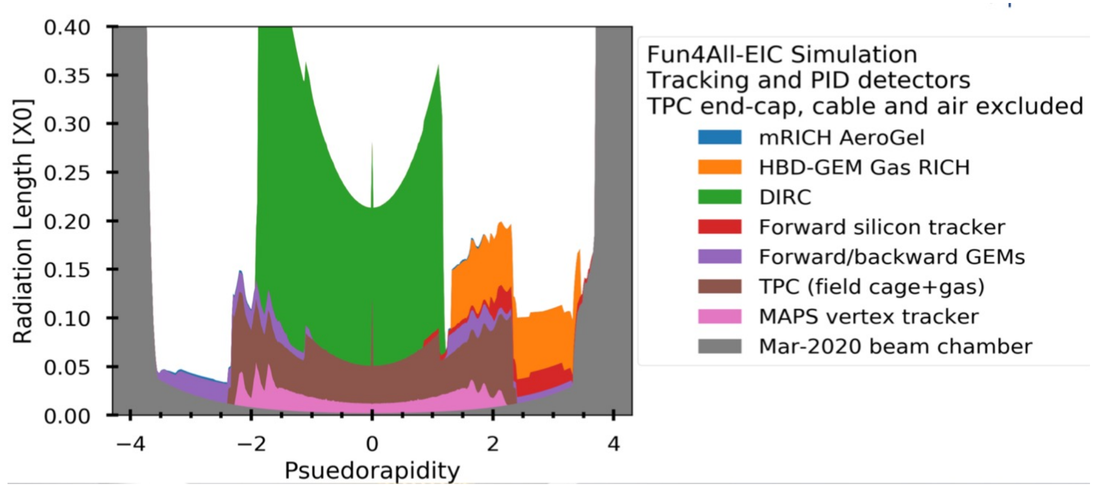
Complementarity by Mitigating Acceptance Gaps

- **All detectors have gaps and cracks**

… e.g. place gap in scattered electron acceptance between main detector and dipole/tagger in different places?

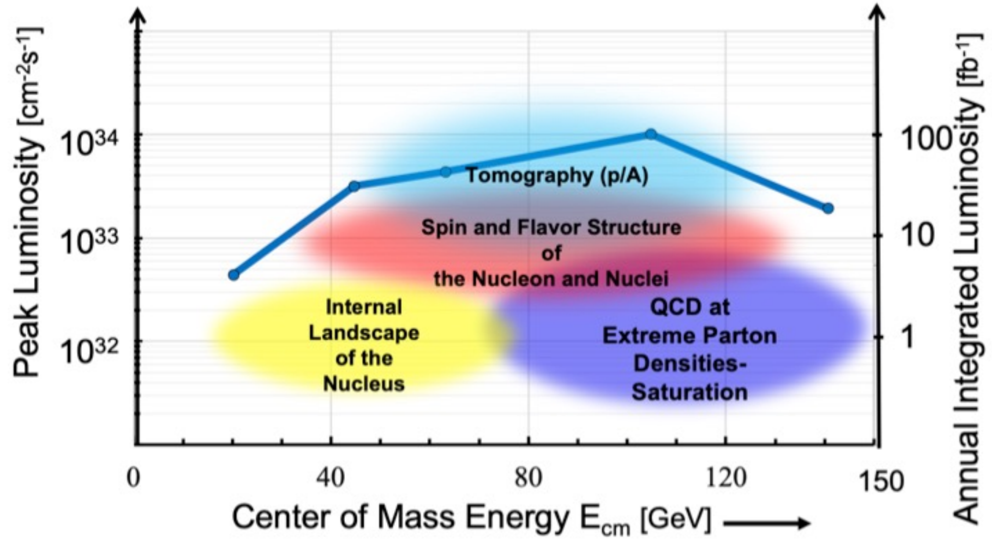


- **Similar arguments may apply to directional peaks in dead material**



Optimisation to Different CMS Energies

- EIC science needs points to (staged) programme with multiple CMS energies



→ Automatic complementary of kinematic regions corresponding to central acceptance

→ Scope to design second IR that optimises luminosity / performance at reduced $\sqrt{s}$ (see talk of Vasily Mororov)

- Lower β^* with quads closer to the IP, even inside detector acceptance?
- Larger crossing angle, reducing parasitic interactions?
- Reduced proton bunch length
- Increased number of bunches
- Different secondary focus

→ Influence detector design, eg radically different beamline instrumentation

→ Not discussed in detail in YR exercise

→ Physics opportunities and different detector solutions to be evaluated as part of this workshop.

Some sort of Summary from the YR

Table 12.2: Summary of 2nd IR design opportunities and their comparison to the 1st IR.

#	Parameter	EIC IR #1	EIC IR #2	Impact
1	Energy range electrons [GeV] protons [GeV]	 $5-18$ $41, 100-275$	 $5-18$ $41, 100-275$	Facility operation
2	CM energy range of optimum luminosity [GeV]	 $80-120$	 $45-80$	Physics priorities
3	Crossing angle [mrad]	≤ 25	≤ 50	p_T resolution, acceptance, geometry
4	Detector space symmetry [m]	$-4.5/+5.0$	$-(3.5-4.5)/+(5.5-4.5)$	Forward/rear acceptance balance
5	Forward angular acceptance [mrad]	20	$20-30$	Spectrometer dipole aperture
6	Far-forward angular acceptance [mrad]	4.5	$5-10$	Neutron cone, p_T^{max}
7	Minimum $\Delta(B\rho)/(B\rho)$ allowing for detection of $p_T = 0$ fragments	0.1	$0.003-0.01$	Beam focus with dispersion, reach in x_L and p_T resolution, reach in x_B for exclusive processes
8	Angular beam divergence at IP, h/v, rms [mrad]	 0.1/0.2	 < 0.2	p_T^{min}, p_T resolution
9	Low Q^2 electron acceptance	< 0.1	< 0.1	Not a hard requirement

Note: much of the IR2 details came very late in the exercise → scope for re-evaluation, refinement, new ideas

Summary

- Essential to robustness of science programme to have two detectors

- Yellow report exercise recommended two GPDs with complementarity in details such as solenoid field, technology choices.

- Novel IR design optimised to reduced $\sqrt{s}$ emerged as key consideration

- For cross-checks and cross-calibration, IR2 time-line should not be (very) different from IR1

- Further progress will ultimately require detailed simulations

- Things have moved fast!
  → Some of complementarity discussion already superseded by collaboration formation discussions
  → still plenty of scope to sharpen up physics arguments