The "Muon Shot:" Muons as a pathway to the frontier

Fred Olness
SMU

nCTEQ
nuclear parton distribution functions

nuclear CTEQ

xFitter

C T E Q

Coordinated Theoretical-Experimental Project on QCD

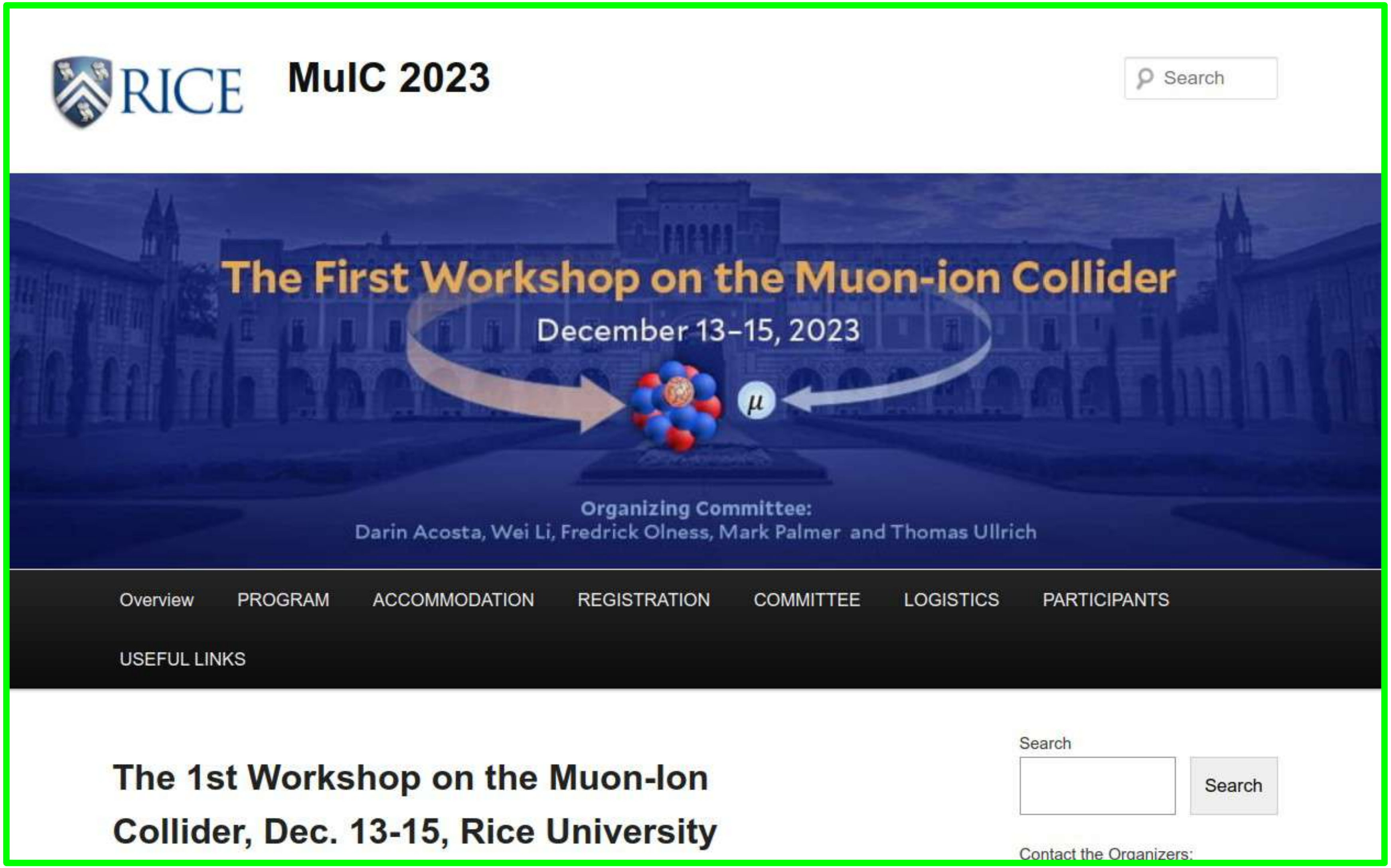
Thanks for substantial input from my friends & colleagues

CFNS Workshop
26 March 2024

… past year

… lost of activity

https://indico.cern.ch/event/1199314



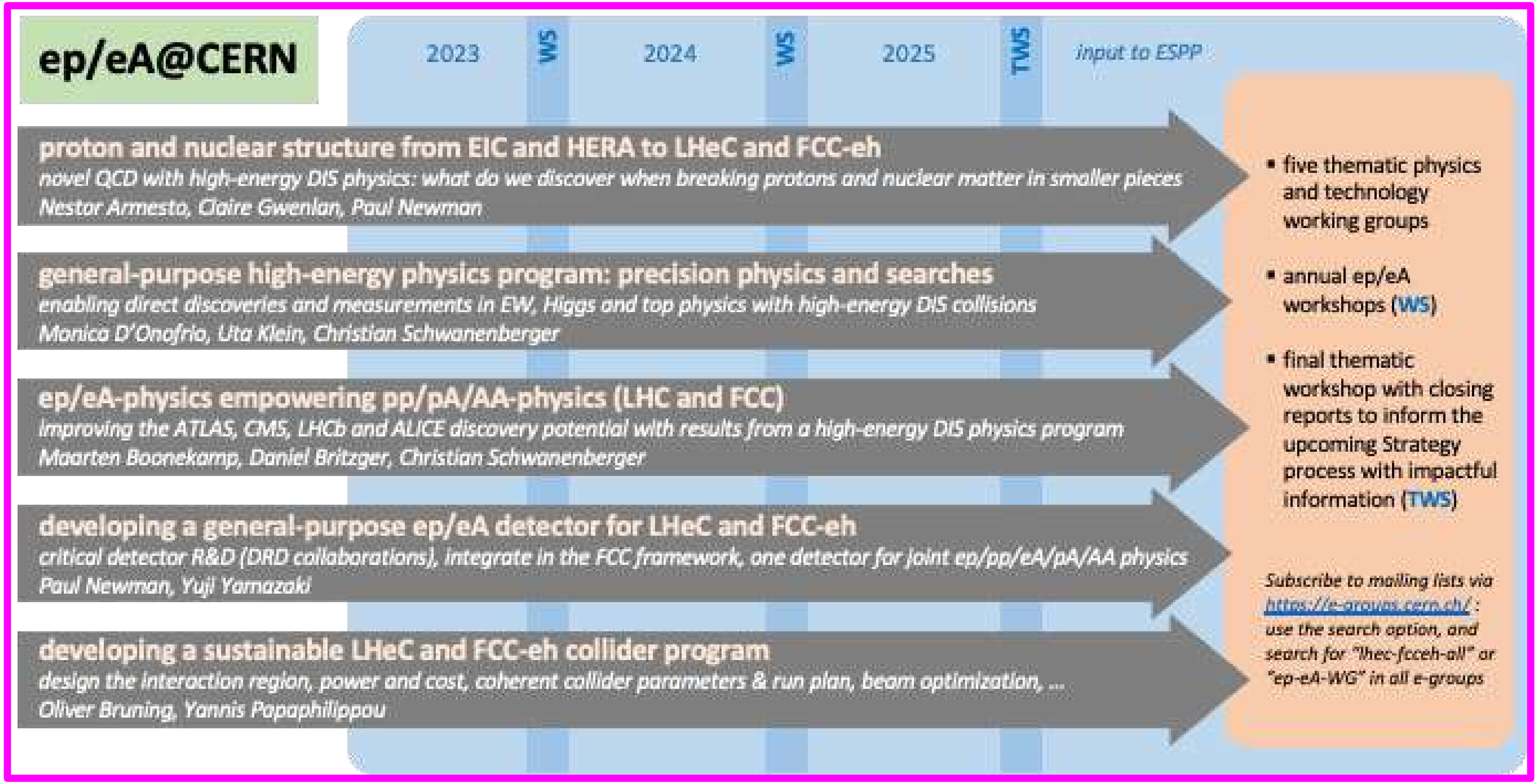
https://muic2023.rice.edu/

Synergy workshop between ep/eA and pp/pA/AA physics experiments

29 February 2024 to 1 March 2024
CERN
Europe/Zurich timezone

https://indico.cern.ch/event/1367865

Enter your search term

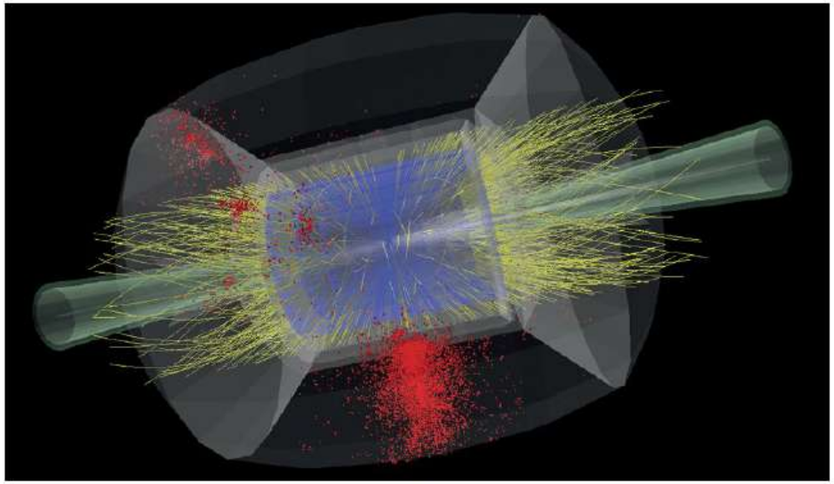


Big news ...

P5 Report

SCIENTIFIC AMERICAN

August 2023



A simulation indicates that Higgs-boson decays to a b-quark pair can be reconstructed at a muon collider despite the harsh environment: the two b-jets are identifiable (red dots) among the beam-induced background. (Image: D Lucchesi et al.) Banner image shows a model of the machine-detector interface of a muon collider (Image: N V Mokhov) Find out more in the CERN Courier.

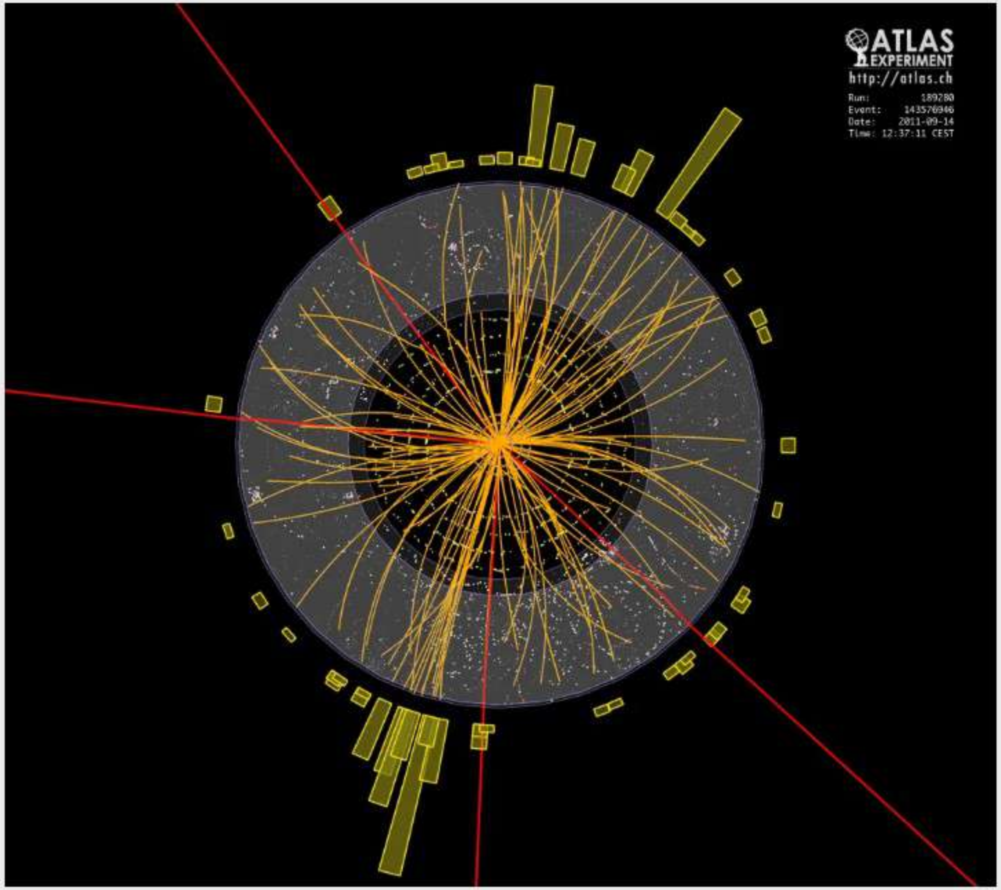
https://www.scientificamerican.com/article/particle-physicists-dream-of-a-muon-collider/

AUGUST 28, 2023 | 10 MIN READ

Particle Physicists Dream of a Muon Collider

After years spent languishing in obscurity, proposals for a muon collider are regaining momentum among particle physicists

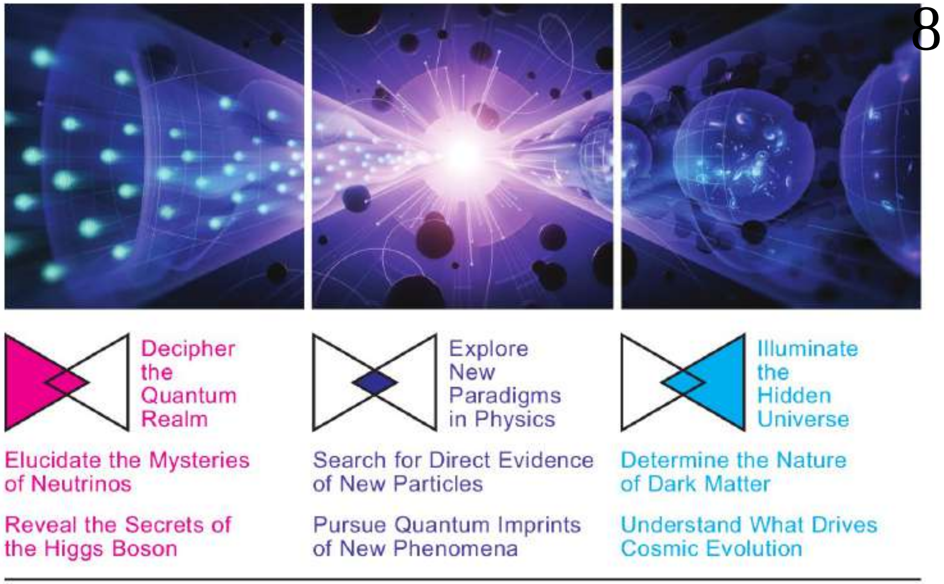
BY DANIEL GARISTO



Muons—heavier cousins of electrons—appear as red tracks in this data visualization of a muon-producing collision in the Large Hadron Collider's ATLAS detector. Credit: ATLAS/CERN

P5

Report Released



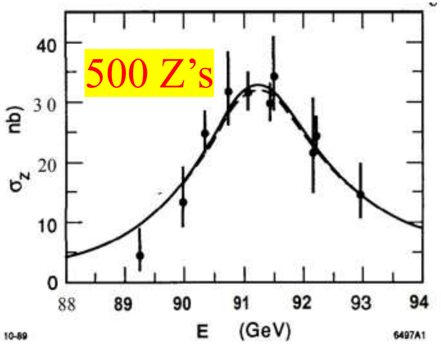
As part of this initiative, we recommend **targeted collider R&D** to establish the feasibility of a **10 TeV pCM muon collider**. A key milestone on this path is to design a muon collider demonstrator facility. If favorably reviewed by the collider panel, such a facility would open the door to building facilities at Fermilab that test muon collider design elements while producing exceptionally bright muon and neutrino beams. By taking up this challenge, the US blazes a trail toward a new future by advancing critical R&D that can benefit multiple science drivers and ultimately bring an unparalleled global facility to US soil.

https://www.usparticlephysics.org/2023-p5-report/

some perspective

1989 … SLC & LEP

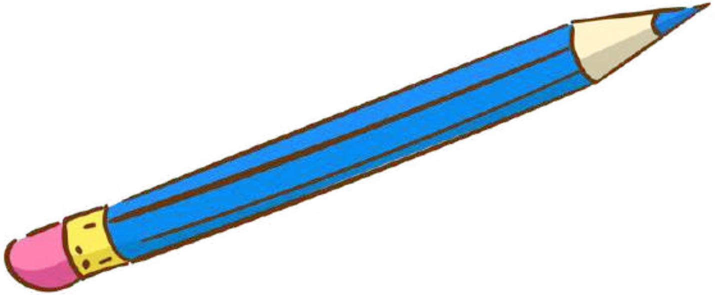
a step at a time



Mark II discovered the first
Z event on 12 April 1989

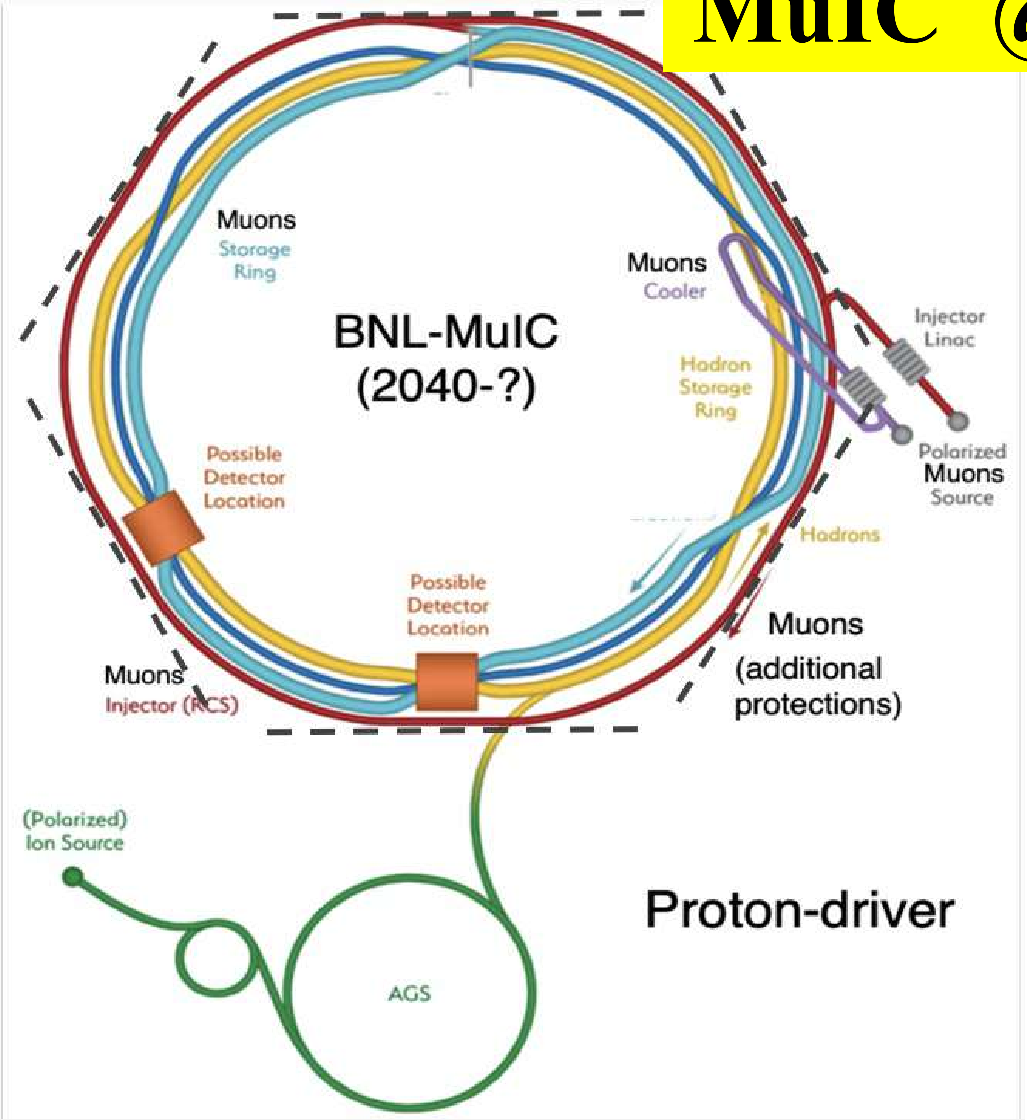
the LEP collider
started operation in
August 1989

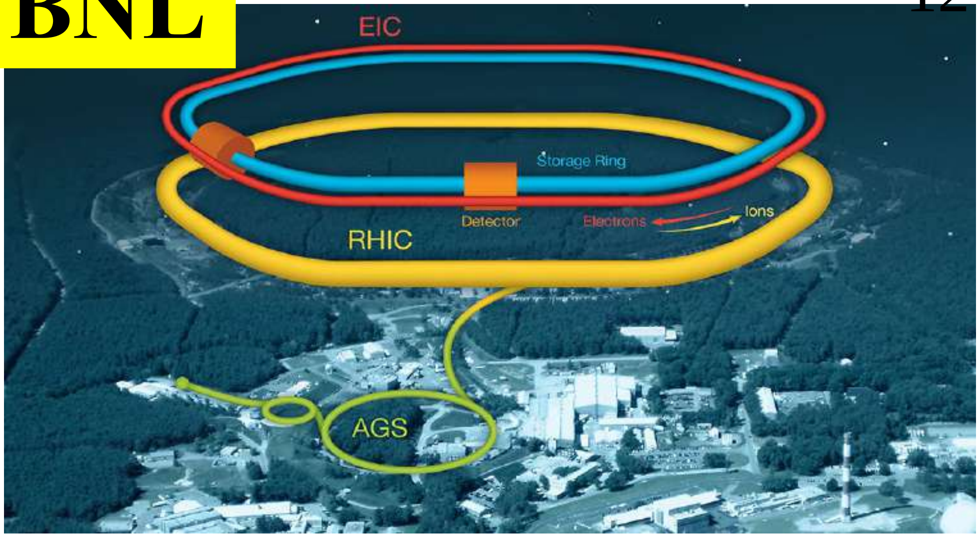
14th International Symposium on Lepton and Photon Interactions at High Energies. 7-12 August 1989. Stanford, CA

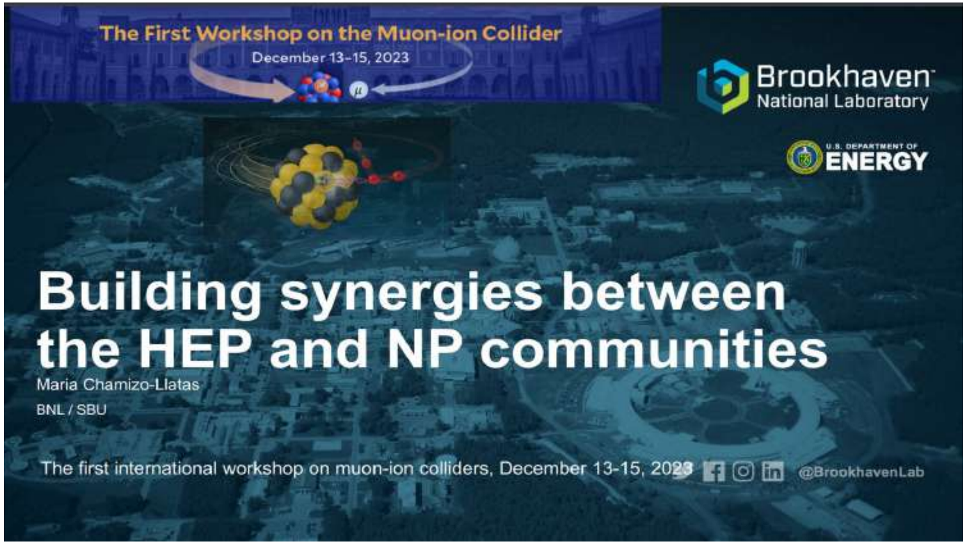


x 197

MuIC @ BNL


BNL-MuIC
(2040-?)
Muons
Storage
Ring
Muons
Cooler
Injector
Linac
Hadron
Storage
Ring
Polarized
Muons
Source
Possible
Detector
Location
Hadrons
Possible
Detector
Location
Muons
(additional
protections)
Muons
Injector (RCS)
(Polarized)
Ion Source
AGS
Proton-driver


EIC
Storage Ring
Detector
Electrons
Ions
RHIC
AGS


The First Workshop on the Muon-ion Collider
December 13-15, 2023
Brookhaven
National Laboratory
U.S. DEPARTMENT OF
ENERGY
Building synergies between
the HEP and NP communities
Maria Chamizo-Llatas
BNL / SBU
The first international workshop on muon-ion colliders, December 13-15, 2023
@BrookhavenLab

Energy Configurations and Luminosity

Parameter	BNL options: MuIC			MuIC2	LHmuC	
$\sqrt{s_{\mu p}}$ (TeV)	0.33	0.74	1.0	→ 2.0	6.5	
$L_{\mu p}$ (10^{33}cm^{-2}s^{-1})	0.07	2.1	4.7		2.8	
Int. Lumi. (fb^{-1}) per 10 yrs	6	178	400		237	
Staging options		Muon		Proton	Muon	Proton
Beam energy (TeV)	0.1	0.5	0.96	0.275 → 1.0	1.5	7
N_b (10^{11})	40	20	20	3	20	2.2
f^{μ}_{rep} (Hz)	15	15	15		12	
Cycles per μ bunch, N^{μ}_{cycle}	1134	1719	3300		3300	
$\varepsilon^*_{x,y}$ (μm)	200	25	25	0.3	25	2.5
$\beta^*_{x,y}$ @IP (cm)	1.7	1	0.75	5	0.5	15
Trans. beam size, $\sigma_{x,y}$ (μm)	48	7.6	4.7	7.1	3	7.1

LHC option

← √s

← Estimate of lumi

← Beam energies

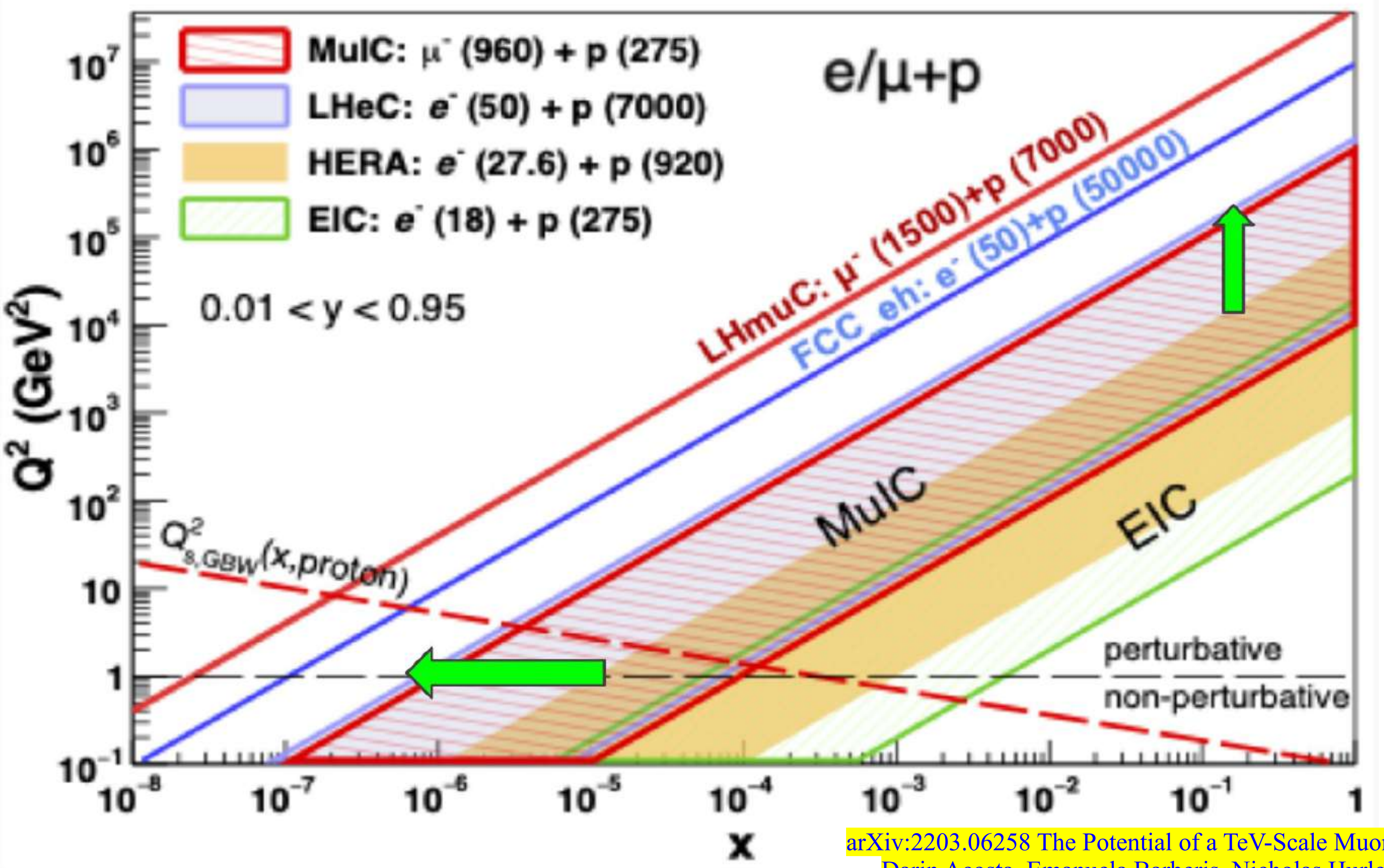
$$\mathcal{L}_{\mu p} = \frac{N^{\mu} N^{p}}{4\pi \max[\sigma^{\mu}_{x}, \sigma^{p}_{x}] \max[\sigma^{\mu}_{y}, \sigma^{p}_{y}]} \min[f^{\mu}_{c}, f^{p}_{c}] H_{hg},$$

$$\sigma^{\mu,p}_{x,y} = \sqrt{\varepsilon^{*}_{x,y} \beta^{*}_{x,y} m^{\mu,p} / E^{\mu,p}}$$

Upgrade hadron ring

Muon Collider parameters + BNL/EIC and LHC proton beam parameters

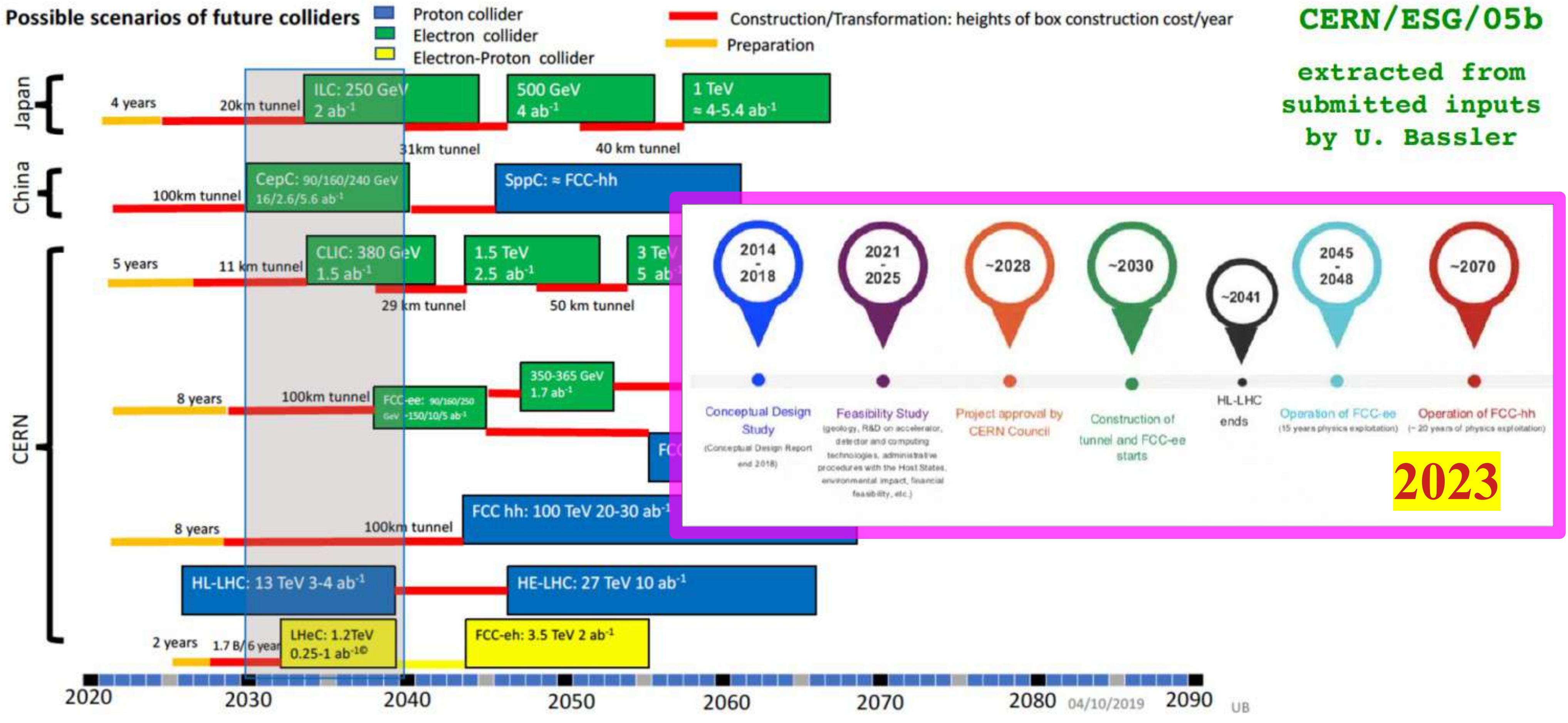
D. Acosta



arXiv:2203.06258 The Potential of a TeV-Scale Muon-Ion Collider
Darin Acosta, Emanuela Barberis, Nicholas Hurley, Wei Li,
Osvaldo Miguel Colin, Yijie Wang, Darien Wood, Xunwu Zuo

Contemporary Facilities

Timeline of Future Colliders in European Strategy 2020



Complementary Facilities

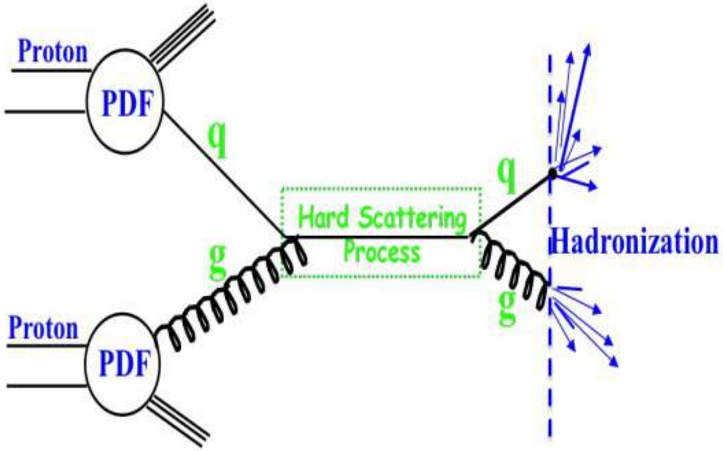
... why essential

Need for multiple colliders

We need multiple colliders (ee, eh, hh) to test

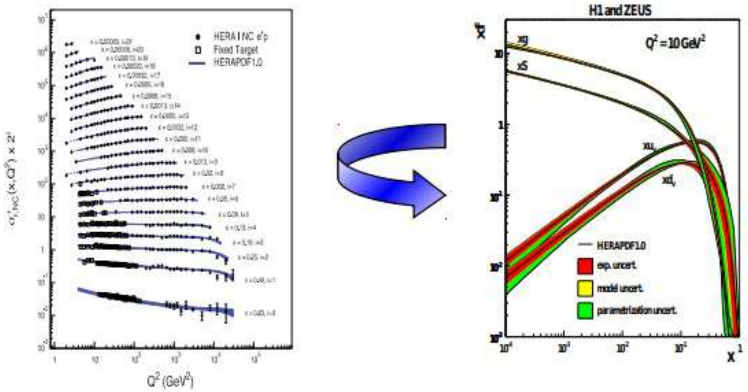
E. Aschenauer

Factorization



Universality

Example: Measure PDFs at HERA at √s=0.3 TeV:



Predict pp and compare to measurements at √s=0.2, 1.96 & 7 TeV

p-p

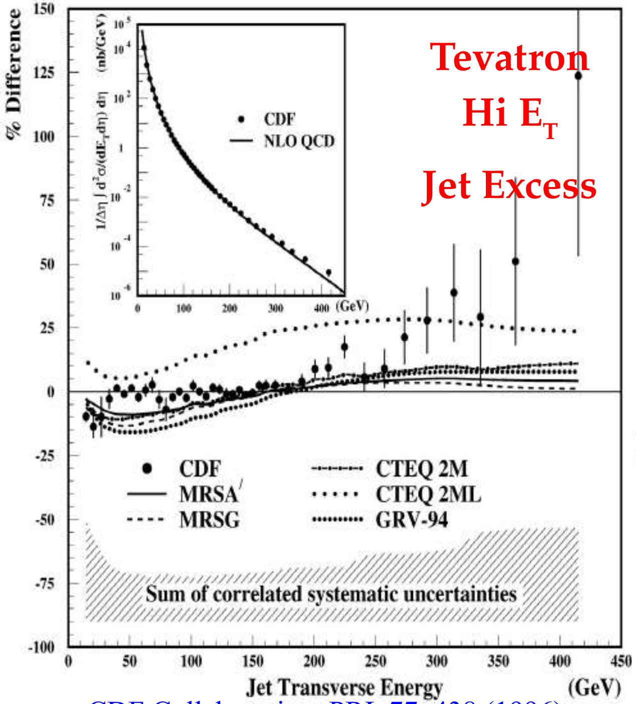
- ❑ probe has complex structure
- ❑ no simple access to parton kinematics
- ❑ Gluons can be accessed directly via qg &gg

e-h

- ❑ Point-like probe gives good resolution
- ❑ High precision & access to partonic kinematics through scattered lepton
  - ❑ initial and final state effects can be cleanly disentangled
    - ➢ inclusive measurements of structure functions only sensitive to initial state

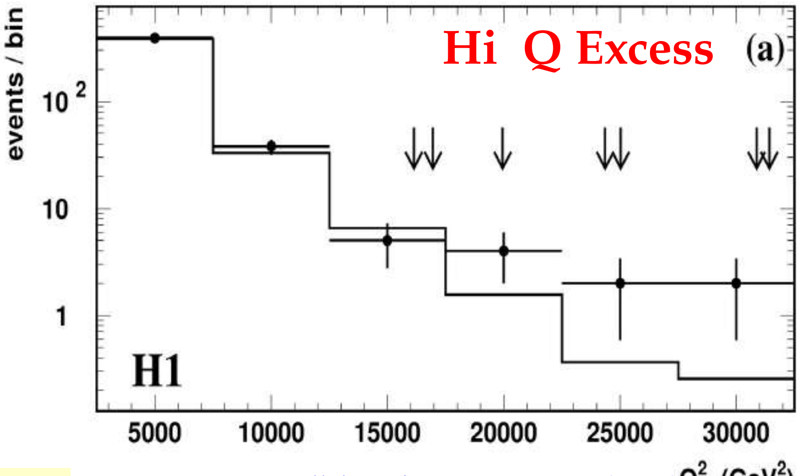
e.g. Tevatron + HERA

Can you find the Nobel Prize

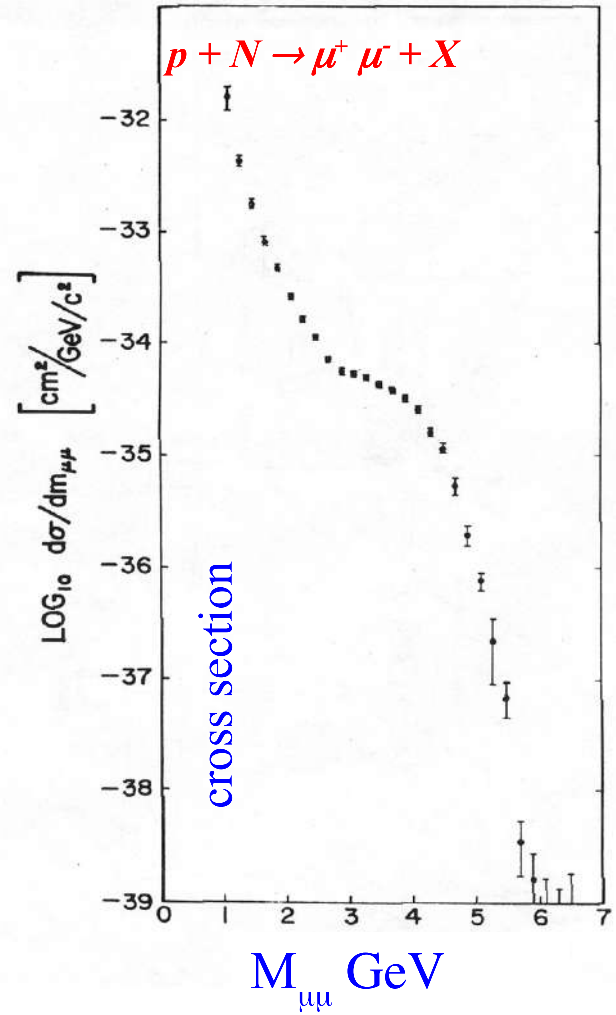


CDF Collaboration, PRL 77, 438 (1996)

... I can probably absorb these effects into the PDFs



H1 Collaboration, ZPC74, 191 (1997)
ZEUS Collaboration, ZPC74, 207 (1997)



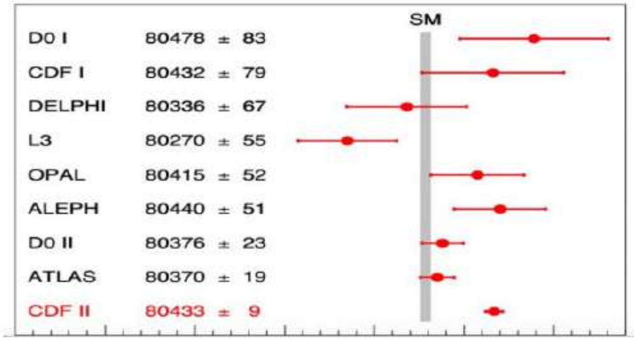
beware circular arguments

RESEARCH

PARTICLE PHYSICS

High-precision measurement of the *W* boson mass with the CDF II detector

CDF Collaboration†‡, T. Aaltonen[1,2], S. Amerio[3,4], D. Amidei[5], A. Anastassov[6]



1994

ICHEP'94

Table 1. Uncertainties in W mass measurements, in MeV.

	CDF (e)	CDF (μ)	DØ(e)
Energy Scale	130	60	260
Resolution	140	120	70
Background	50	50	30
Fitting	20	20	30
PDF	100	100	70
p_T^W and und. evt.	120	145	120
Width	-	-	20
Total Sys.	250	240	307
Statistical	150	200	160
Total (Stat + Sys)	290	300	346

2022

Table 2. Uncertainties on the combined M_W result.

Source	Uncertainty (MeV)
Lepton energy scale	3.0
Lepton energy resolution	1.2
Recoil energy scale	1.2
Recoil energy resolution	1.8
Lepton efficiency	0.4
Lepton removal	1.2
Backgrounds	3.3
p_T^Z model	1.8
p_T^W/p_T^Z model	1.3
Parton distributions	3.9
QED radiation	2.7
W boson statistics	6.4
Total	9.4

CSS Resummation

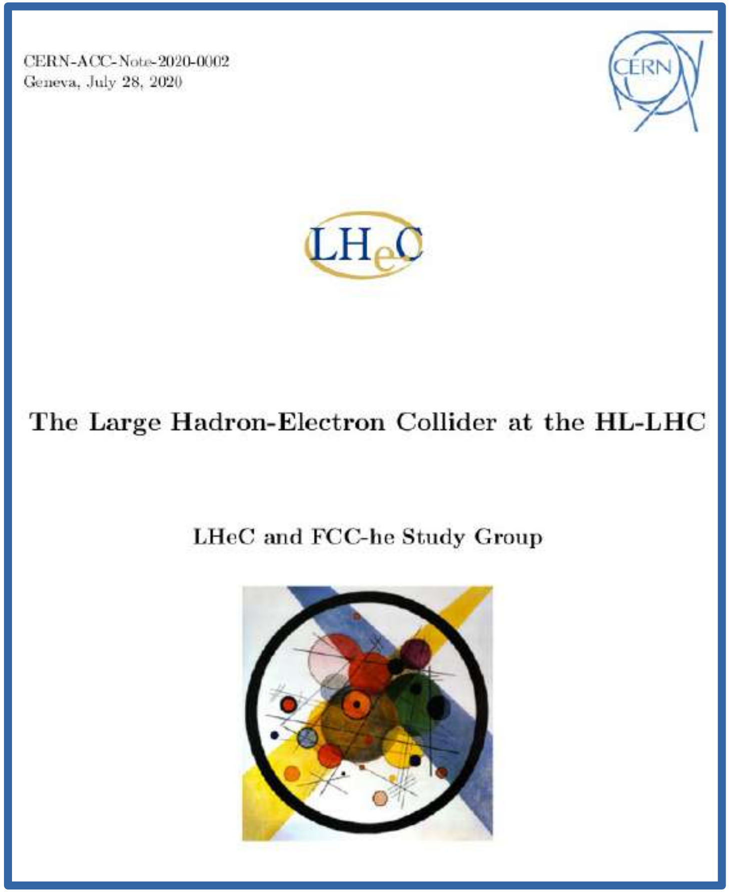
Strange PDF

PDF Precision

CDF Collaboration et al., Science 376, 170–176 (2022)

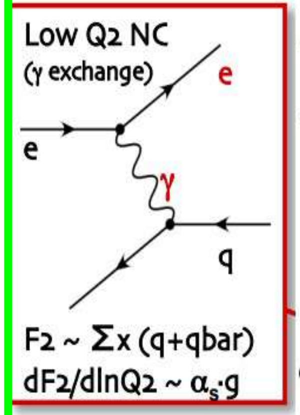
What can Mu do for You

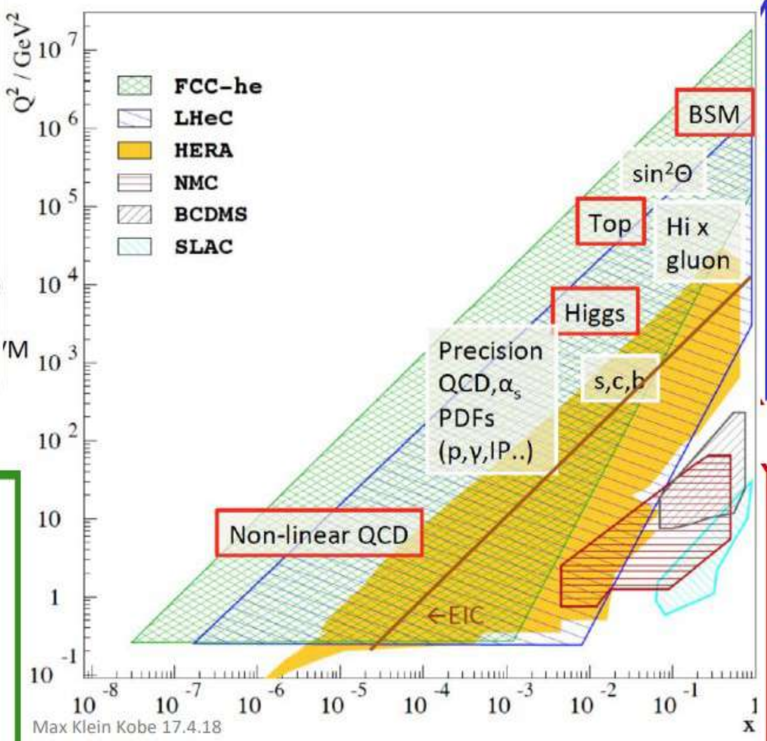
LHeC Whitepaper

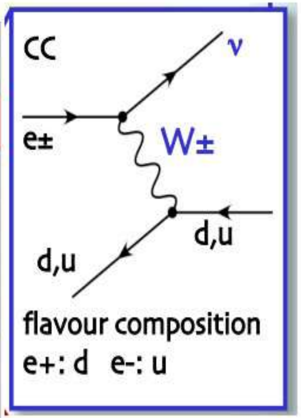


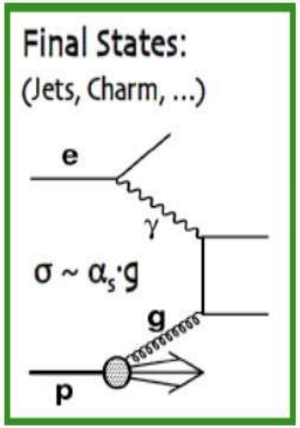
https://arxiv.org/abs/2007.14491

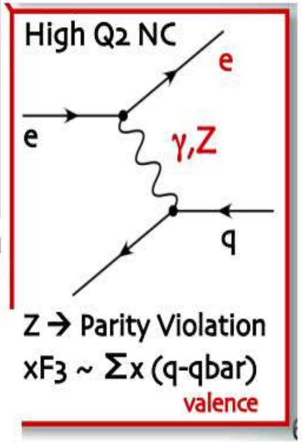
Where does the information come from?









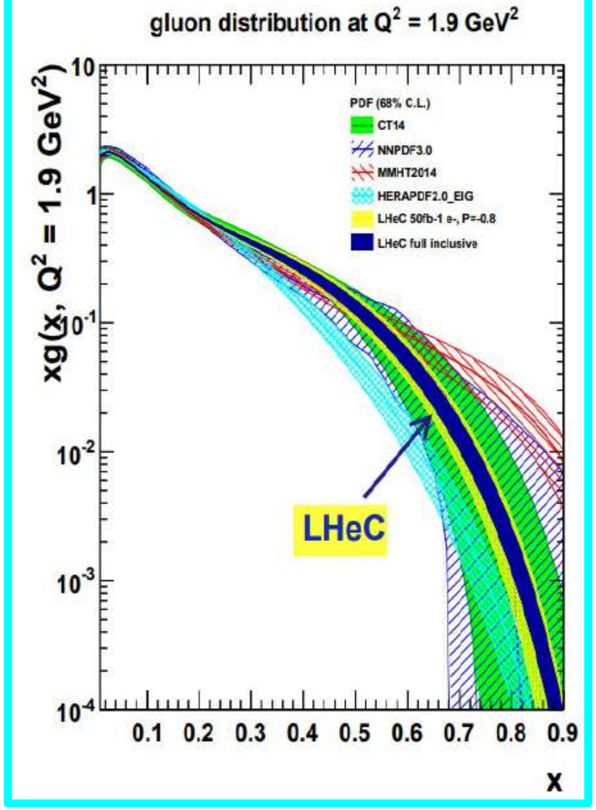


A future DIS machine would be a vast improvement on HERA in both luminosity and kinematic reach

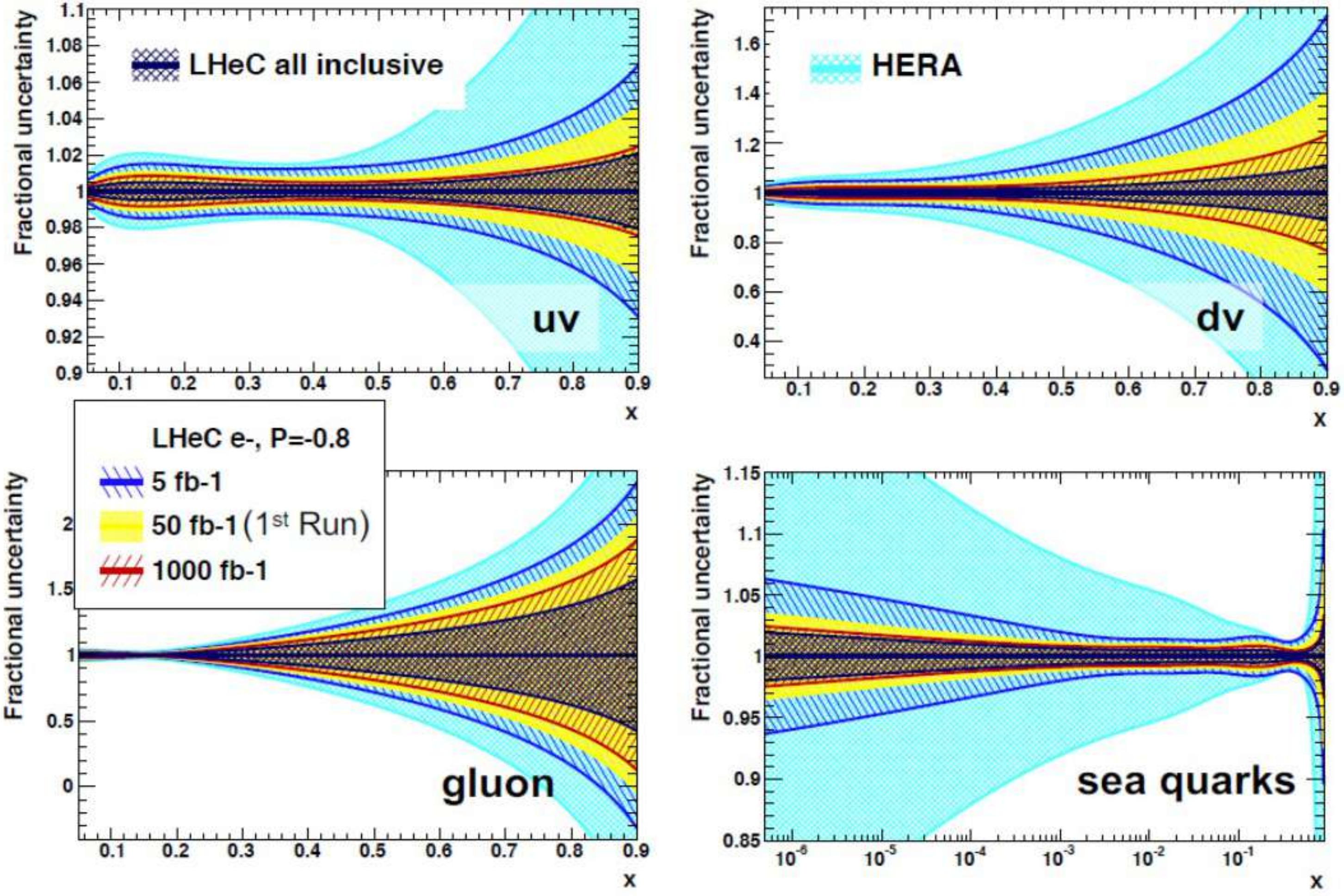
×**15**/**120** extension in Q^2,1/x reach vs **HERA**

12

PDF uncertainties are a limiting factor for many LHC measurements



Impact of luminosity on PDFs



small and medium x quickly constrained (5 fb-1 ≡ ×5 HERA ≡ 1 year LHeC)

HIGGS COUPLINGS

Mangano
ICEP 2023

T. Barklow et al.,

Coupling deviations for various BSM models, likely to remain unconstrained by direct searches at HL-LHC

HIGGS COUPLINGS

https://arxiv.org/pdf/1708.08912.pdf

	Model	$b\bar{b}$	$c\bar{c}$	gg	WW	$\tau\tau$	ZZ	$\gamma\gamma$	$\mu\mu$
1	MSSM [40]	+4.8	-0.8	- 0.8	-0.2	+0.4	-0.5	+0.1	+0.3
2	Type II 2HD [42]	+10.1	-0.2	-0.2	0.0	+9.8	0.0	+0.1	+9.8
3	Type X 2HD [42]	-0.2	-0.2	-0.2	0.0	+7.8	0.0	0.0	+7.8
4	Type Y 2HD [42]	+10.1	-0.2	-0.2	0.0	-0.2	0.0	0.1	-0.2
5	Composite Higgs [44]	-6.4	-6.4	-6.4	-2.1	-6.4	-2.1	-2.1	-6.4
6	Little Higgs w. T-parity [45]	0.0	0.0	-6.1	-2.5	0.0	-2.5	-1.5	0.0
7	Little Higgs w. T-parity [46]	-7.8	-4.6	-3.5	-1.5	-7.8	-1.5	-1.0	-7.8
8	Higgs-Radion [47]	-1.5	- 1.5	+10.	-1.5	-1.5	-1.5	-1.0	-1.5
9	Higgs Singlet [48]	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5

5 – 10 %

> 10%

NB: when the b coupling is modified, BR deviations are smaller than the square of the coupling deviation. Eg in model 5, the BR to b, c, tau, mu are practically SM-like

Table 5: Deviations from the Standard Model predictions for the Higgs boson couplings, in %, for the set of new physics models

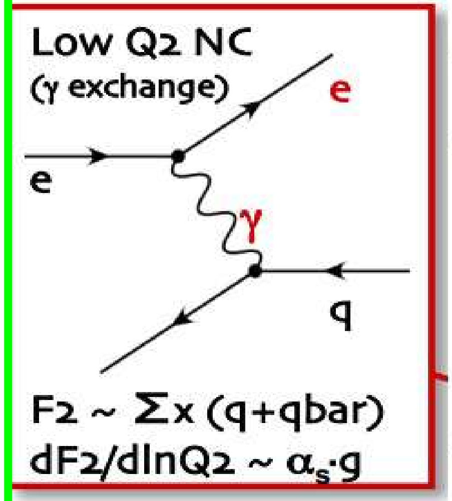
(sub)-% precision must be the goal to ensure 3-5σ evidence of deviations, and to cross-correlate coupling deviations across different channels

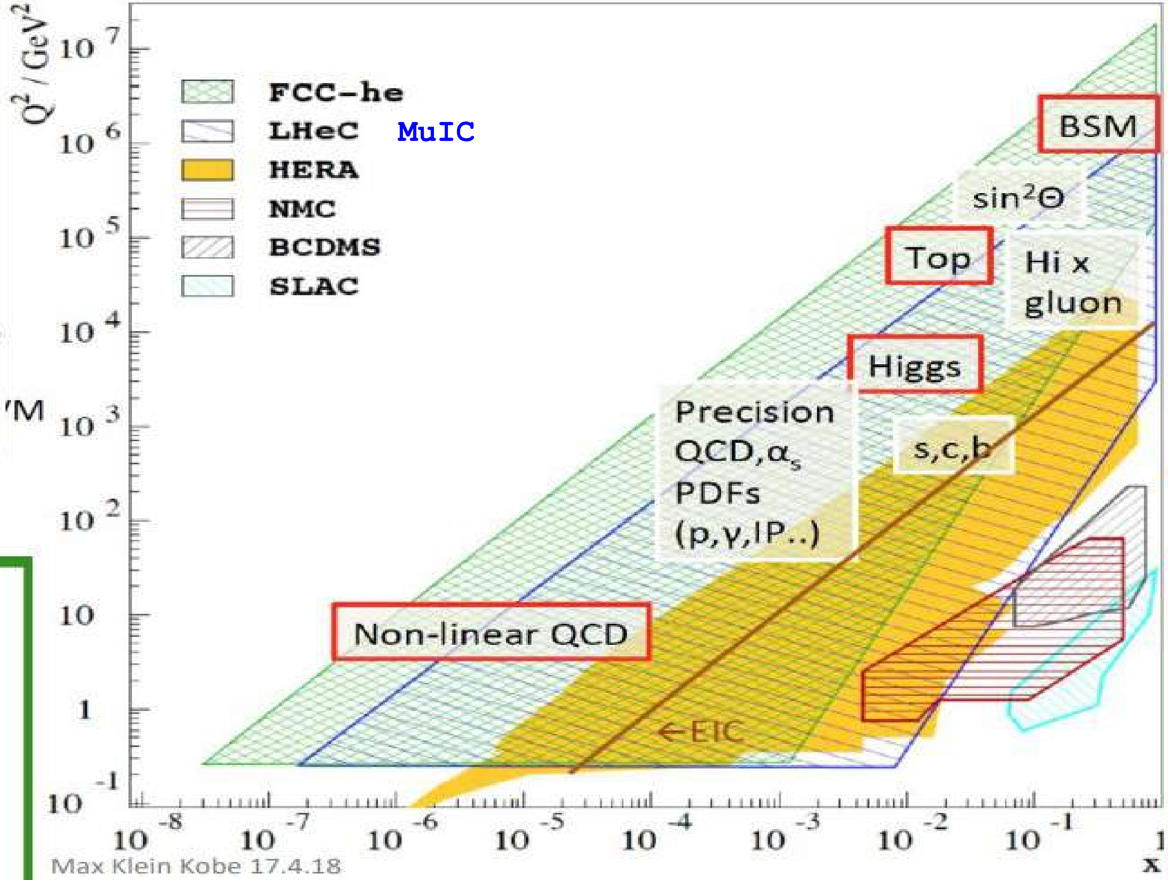
Signposts for the future

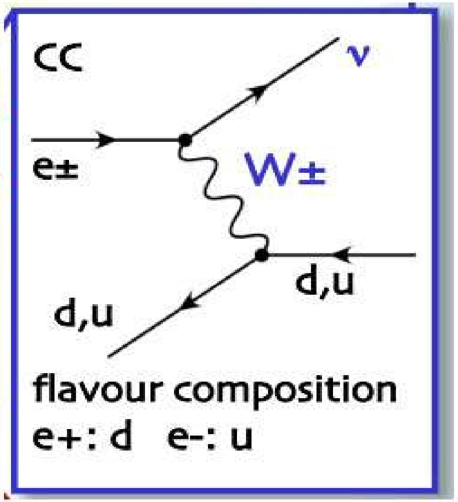
PRE-LHC

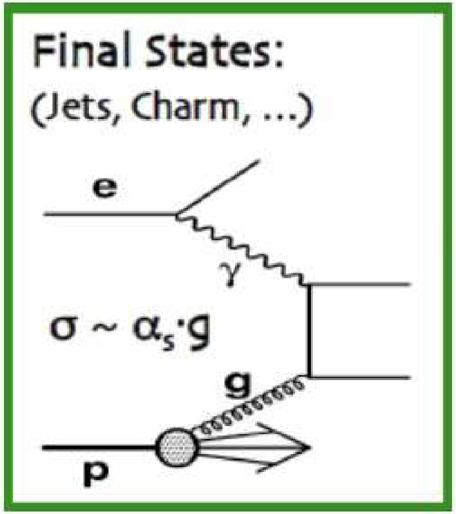
POST-LHC

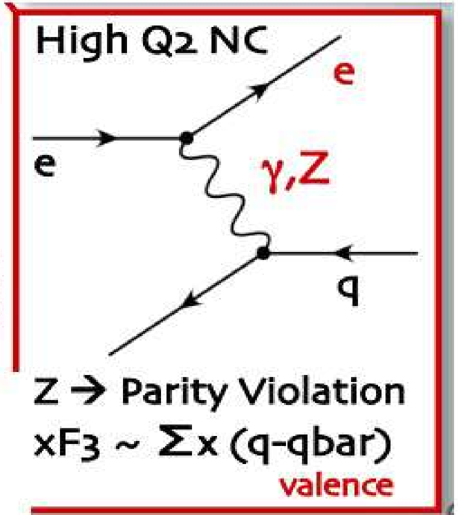
… high precision … infer high scales









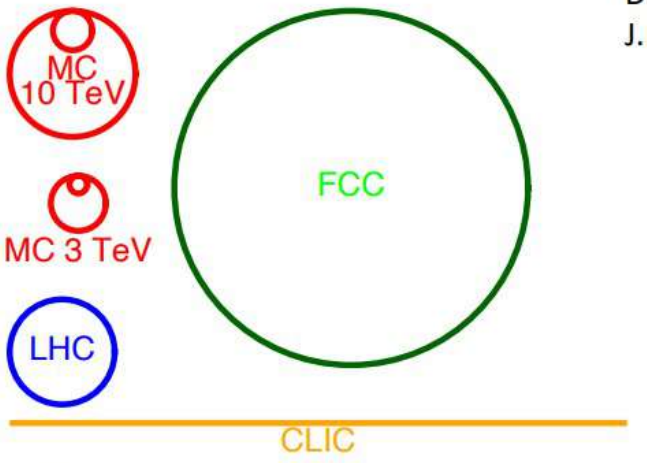


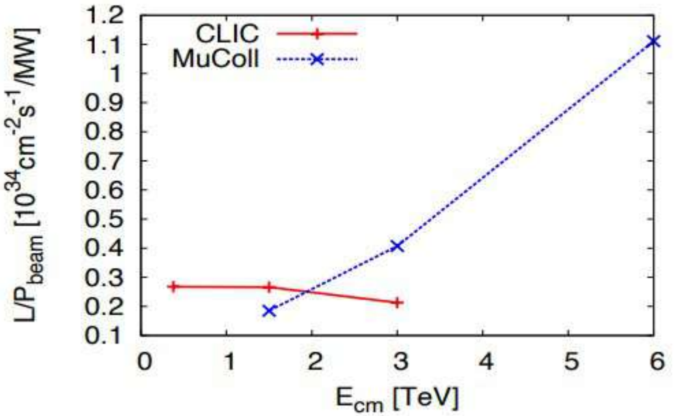
A future DIS machine would be a vast improvement on HERA in both luminosity and kinematic reach

EXTRA

Muon Collider Promises

US Snowmass Implementation Task Force: Th. Roser, R. Brinkmann, S. Cousineau, D. Denisov, S. Gessner, S. Gourlay, Ph. Lebrun, M. Narain, K. Oide, T. Raubenheimer, J. Seeman, V. Shiltsev, J. Straight, M. Turner, L. Wang et al.





	CME [TeV]	Lumi per IP [$10^{34}cm^{-2}s^{-1}$]	Years to physics	Cost range [B$]	Power [MW]
FCC-ee	0.24	8.5	13-18	12-18	290
ILC	0.25	2.7	<12	7-12	140
CLIC	0.38	2.3	13-18	7-12	110
ILC	3	6.1	19-24	18-30	400
CLIC	3	5.9	19-24	18-30	550
MC	3	1.8	19-24	7-12	230
MC	10	20	>25	12-18	300
FCC-hh	100	30	>25	30-50	560

Judgement by ITF, take it *cum grano salis*

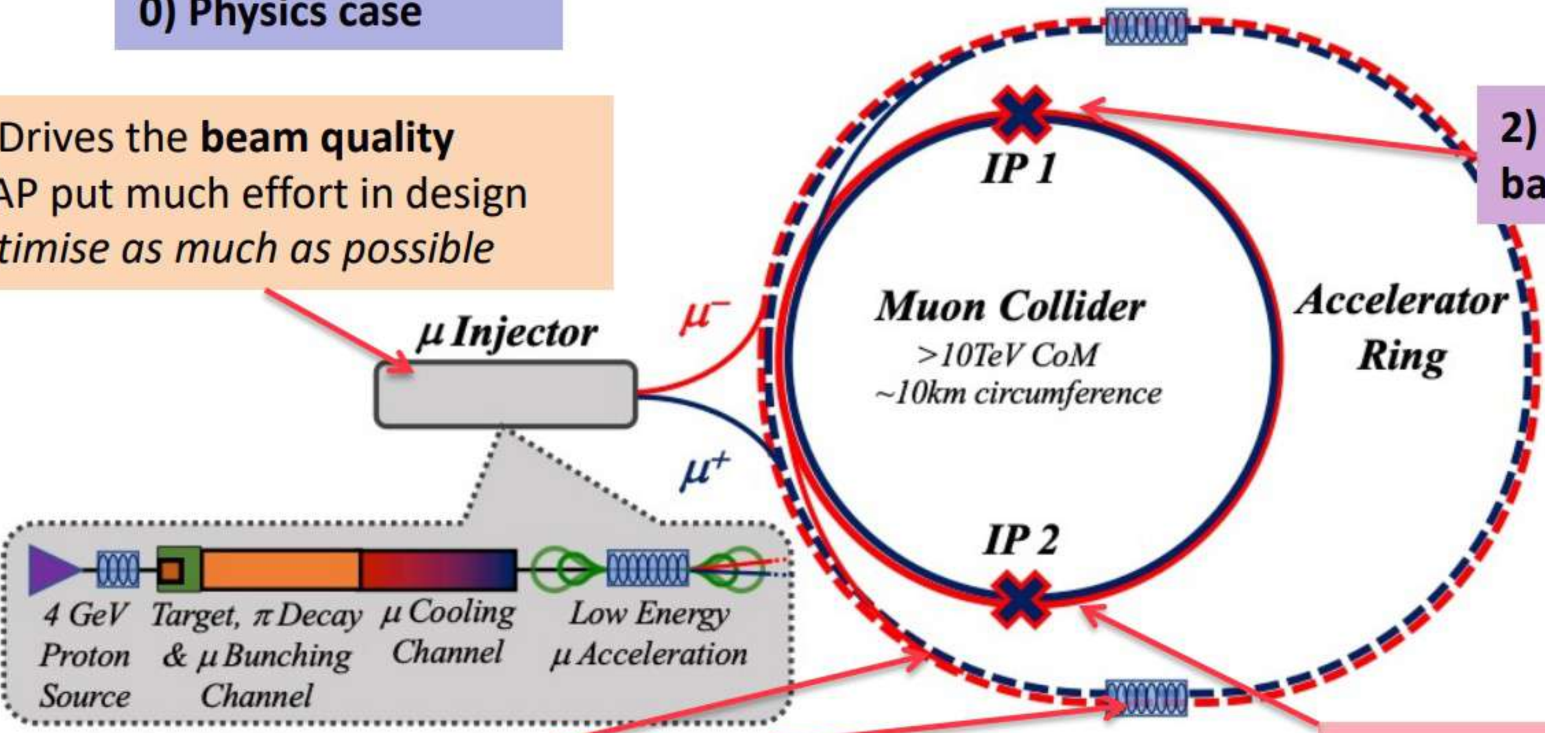
Key Challenges

MuCo

International MUON Collider Collaboration

0) Physics case

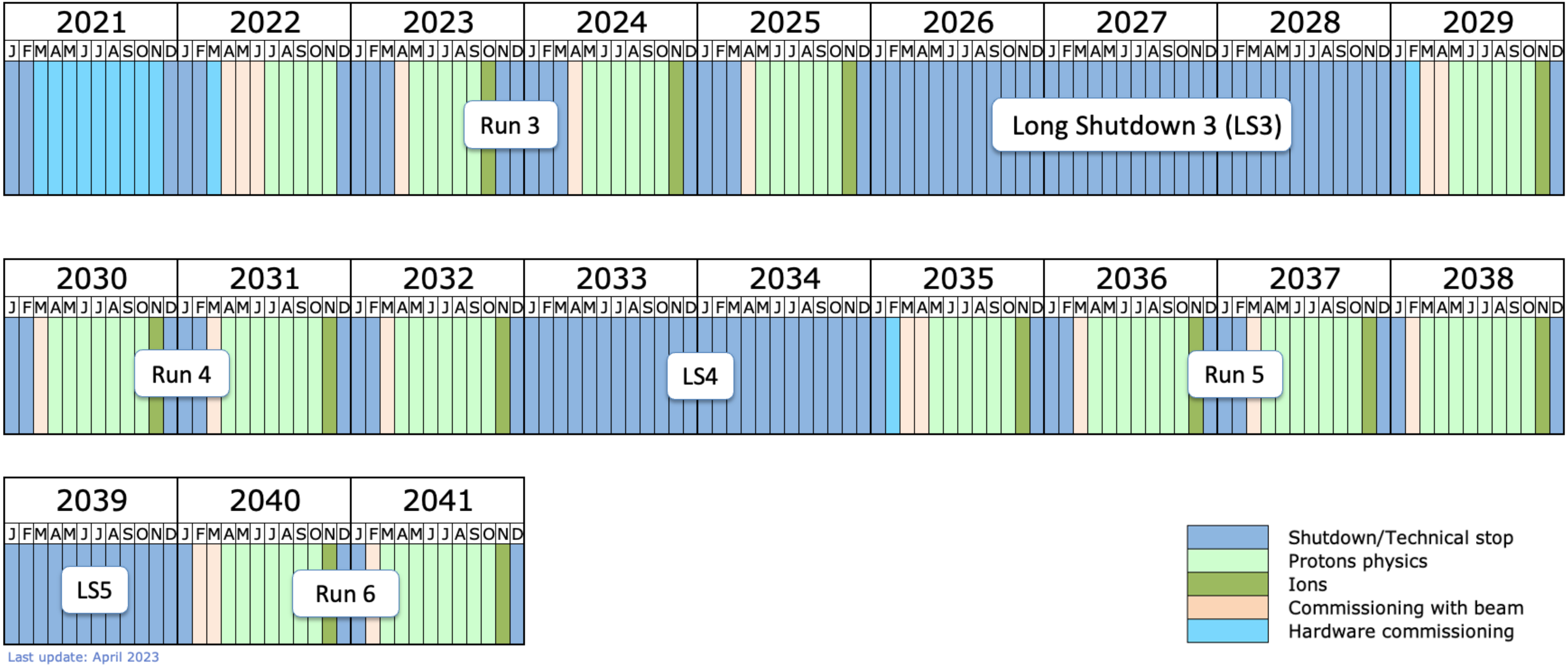
4) Drives the **beam quality**
MAP put much effort in design
optimise as much as possible



2) Beam-induced background

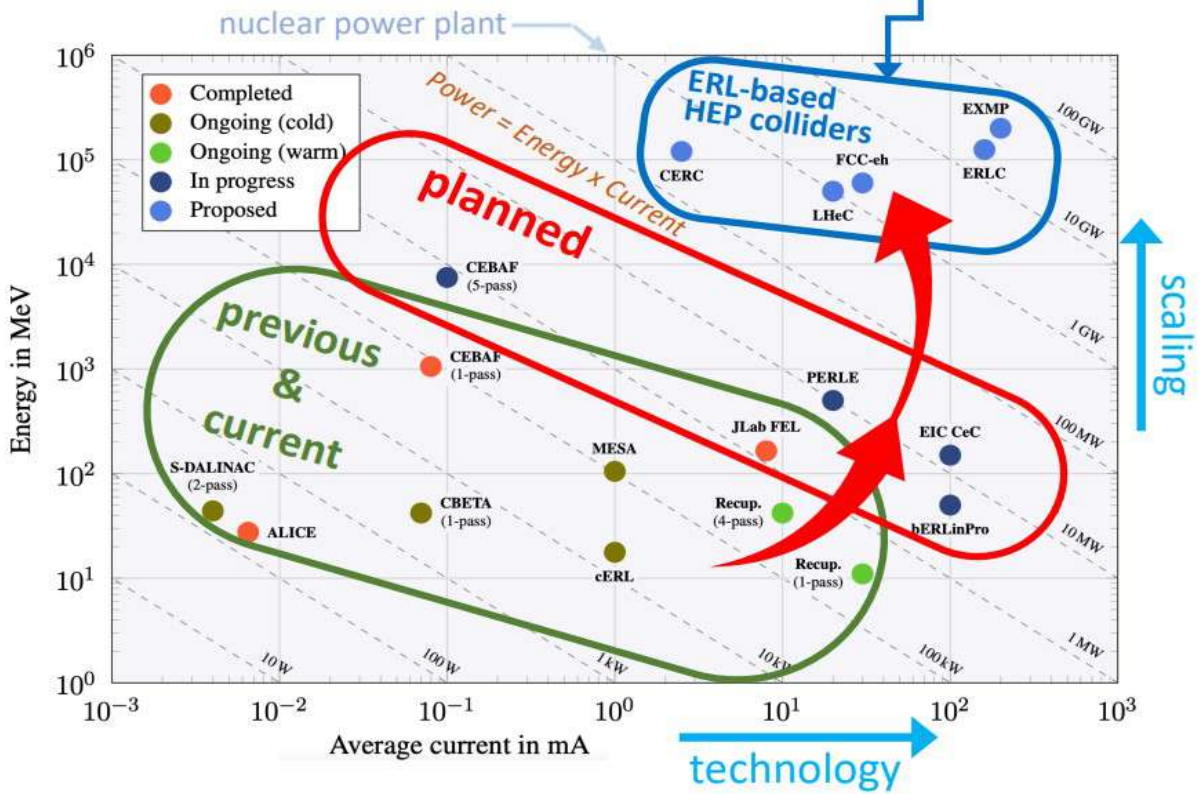
1) Dense neutrino flux
mitigated by mover system
and site selection

3) Cost and **power** consumption limit energy reach
e.g. 35 km accelerator for 10 TeV, 10 km collider ring
Also impacts **beam quality**



https://lhc-commissioning.web.cern.ch/schedule/LHC-long-term.htm

ERL to enable high-power beams that would otherwise require one or more nuclear power plants



R&D Roadmap

Future ERL-based Colliders

H, HH, ep/eA, muons, …

bERLinPro & PERLE

essential accelerator R&D labs with ambitions overlapping with those of the particle physics community

towards high power

Energy Recovery demonstrated

great achievements on all aspects and large research infrastructures based on Energy Recovery systems have been operated successfully

Energy Recovery Linacs (ERL): reaching higher luminosities with less power requirements