Strong Interactions briefing

Jorgen D'Hondt and Krzysztof Redlich

Open Symposium towards updating the European Strategy for Particle Physics
May 13-16, 2019, Granada, Spain

European Strategy Update

Strong interactions

QCD theory: $\mathcal{L}_{\mathrm{QCD}} = -\frac{1}{4} F^a_{\mu\nu} F^{\mu\nu}_a + \bar{\psi}(i\not{D} - m)\psi$

colour confinement

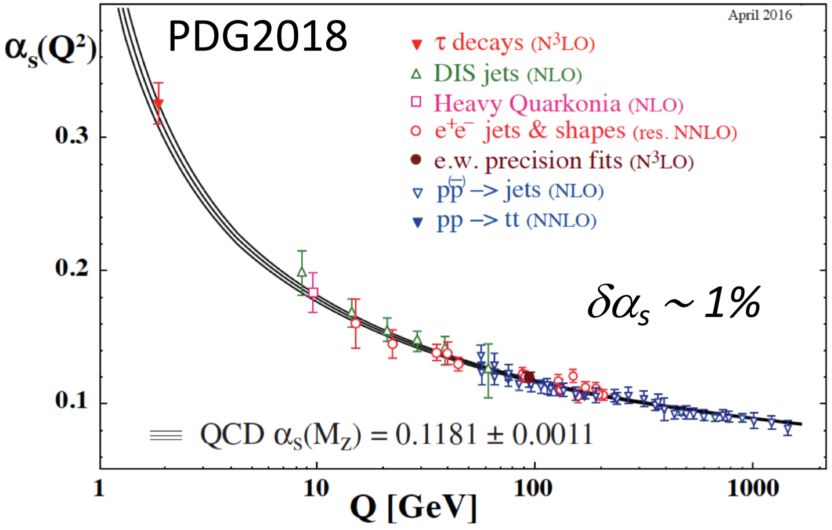
α_s (Q^2 low) ~ 1

key phenomena

(non-Abelian gauge group)

asymptotic freedom

α_s (Q^2 high) << 1



$\alpha_{EW} << \alpha_s$

"hot and dense QCD"

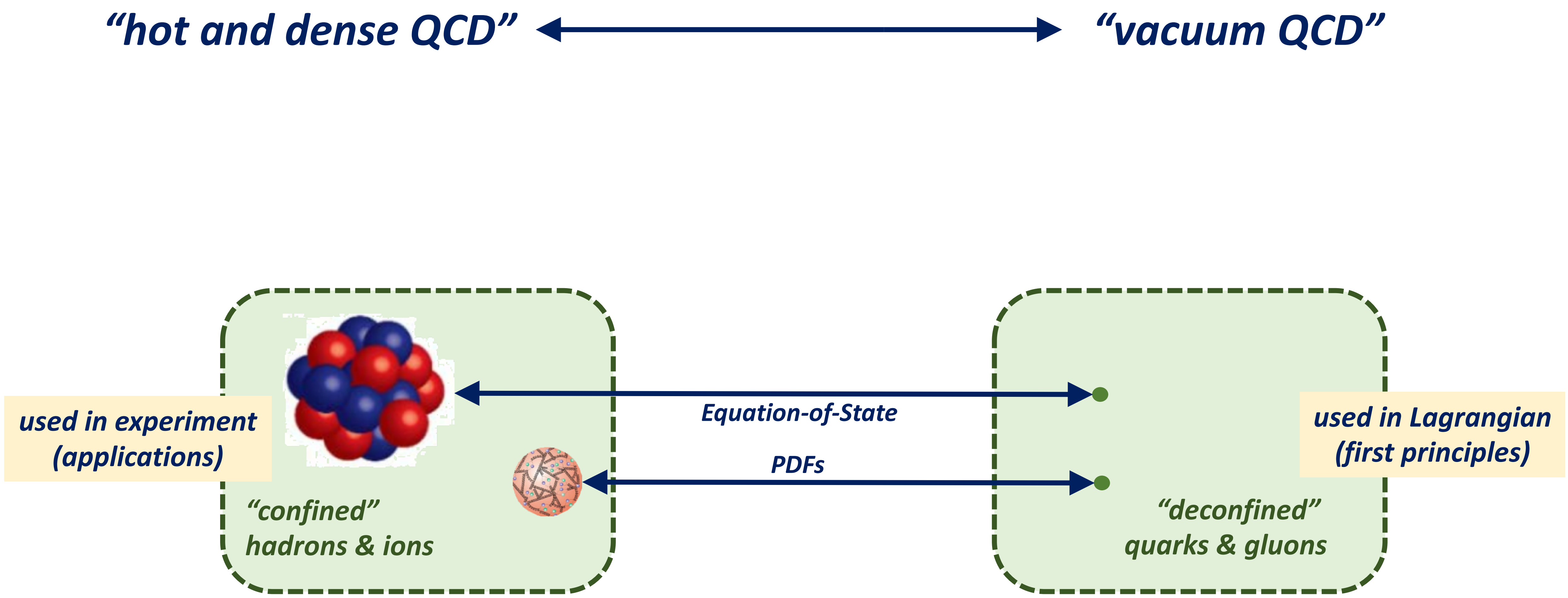
(low energy domain)

(lattice calculations)

"vacuum QCD"

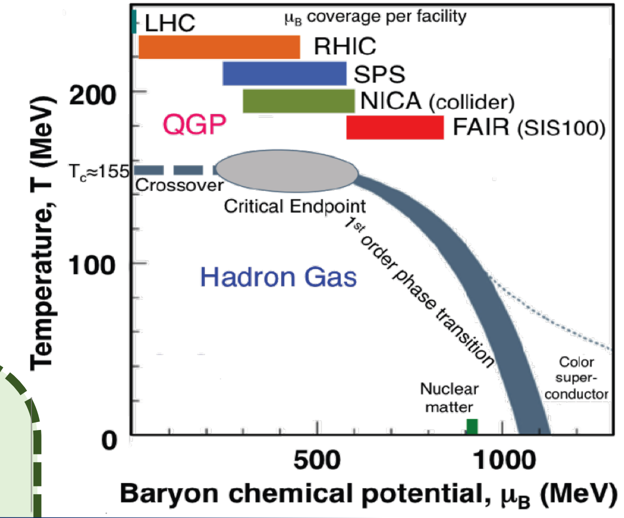
(high energy domain)

(perturbative calculations)


"hot and dense QCD"
"vacuum QCD"
used in experiment
(applications)
Equation-of-State
PDFs
"confined"
hadrons & ions
used in Lagrangian
(first principles)
"deconfined"
quarks & gluons

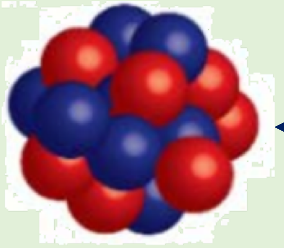
“hot and dense QCD” ⟷ *“vacuum QCD”*

How to probe the QGP equation-of-state and to establish whether there is a 1st order phase transition at high baryon density?

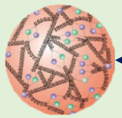


From LQCD: T_c = 156.5 ± 1.5 MeV

From Experiment: determination of chemical freeze-out temperature



used in experiment (applications)



“confined” hadrons & ions

Equation-of-State

PDFs

used in Lagrangian (first principles)

“deconfined” quarks & gluons

"hot and dense QCD" ⟷ *"vacuum QCD"*

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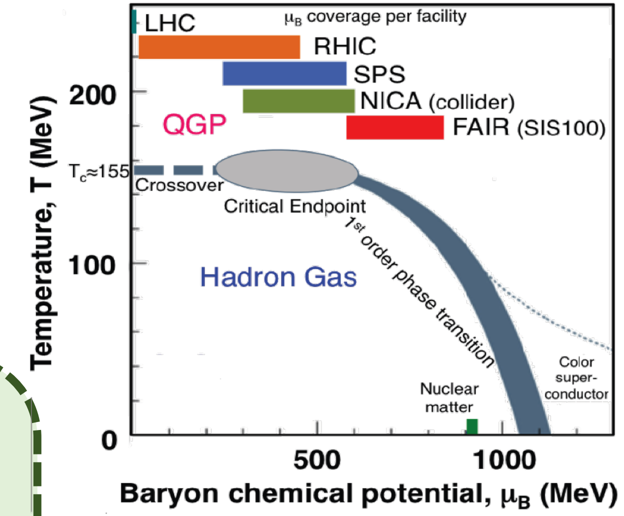

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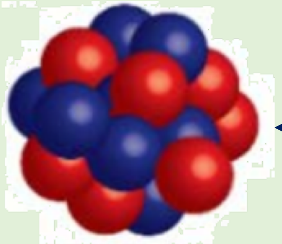

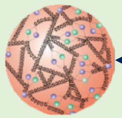

used in experiment (applications)

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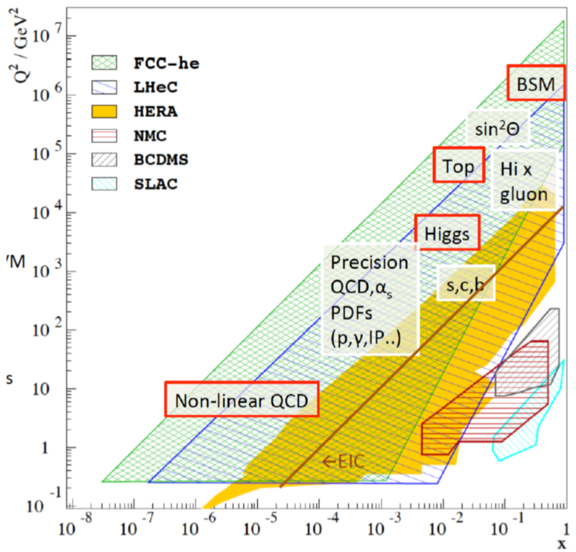
"deconfined" quarks & gluons

What are the experimental and theoretical pre-requisites to reach an adequate precision of perturbative and non-perturbative QCD predictions at the highest energies?



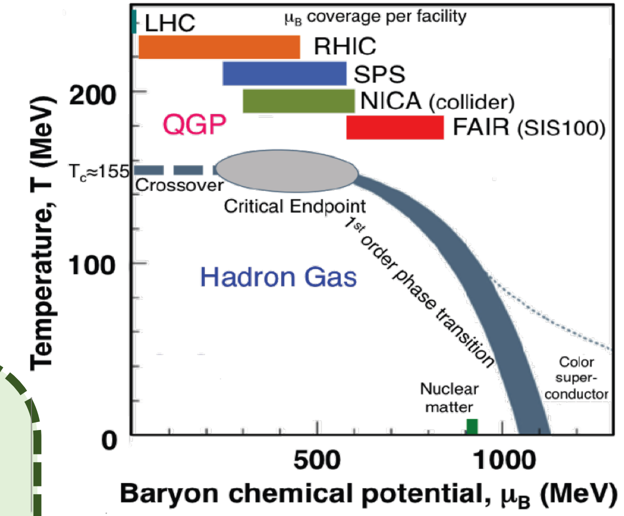
From QCD: functional DGLAP evolution of PDFs(Q^2,α_s)

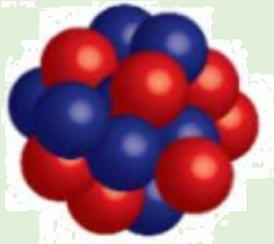
From Experiment: PDF parameters values themselves

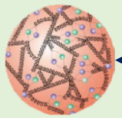
“hot and dense QCD” ⟷ “vacuum QCD”

How to probe the QGP equation-of-state and to establish whether there is a 1st order phase transition at high baryon density?

Key facilities involve collisions with heavy ions







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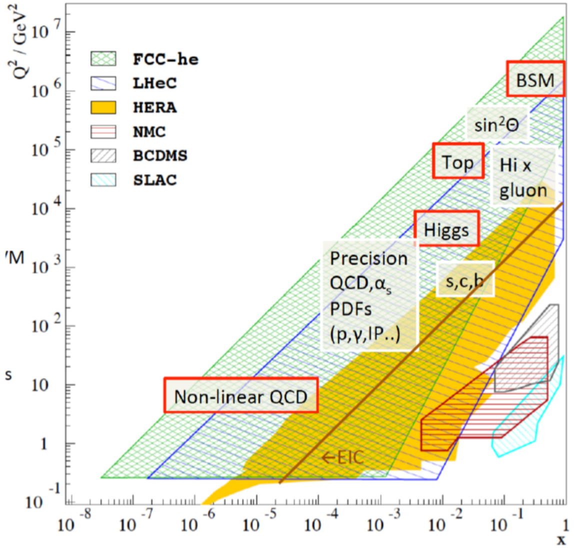

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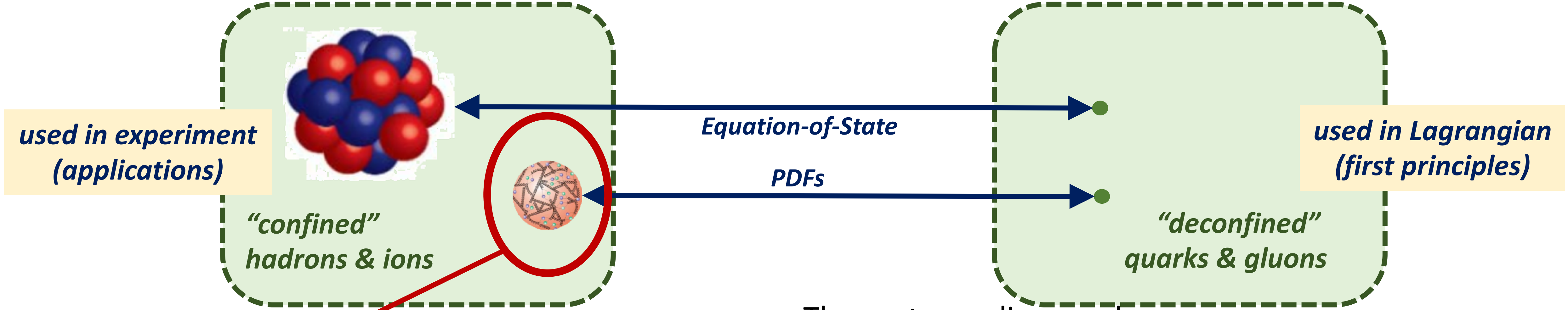
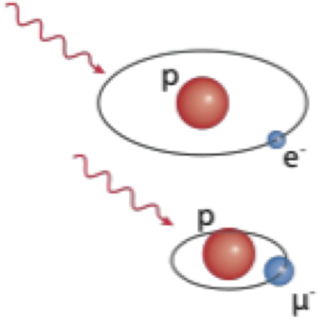
Key facilities involve collisions with protons



What is known about the make-up of the proton (mass, radius, spin, etc.) and how to extract it?



The proton radius puzzle

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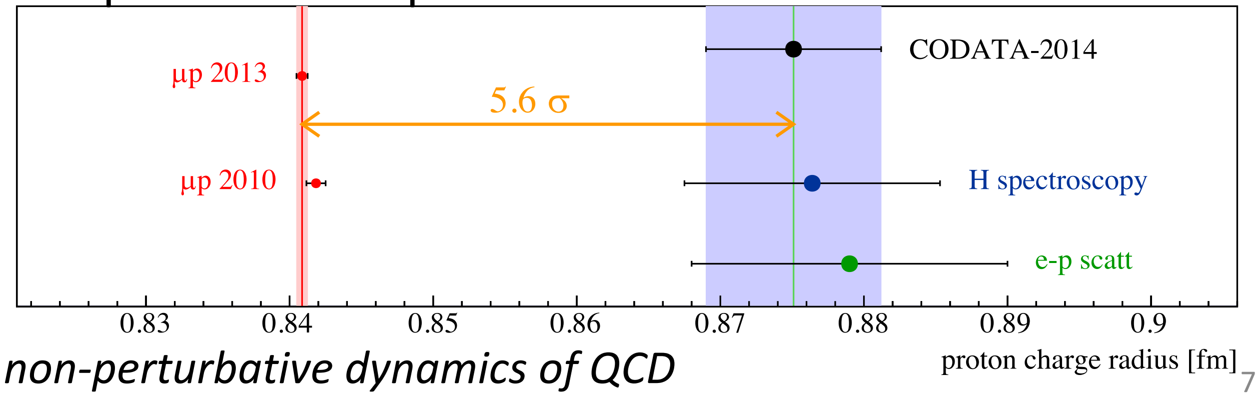


Need to understand non-perturbative dynamics of QCD

Inputs considered

Category: Facilities and experiments with strong interactions as key topic
(Id13) NA61++ (SPS)
(Id42) PBC@CERN, COMPASS++, MUSE@PSI, MUonE, DIRAC++, NA61++
(Id46) Heavy flavour in HI
(Id47 and Id67 and Id110) LHC-FT: ALICE and LHCb (LHCSpin)
(Id90) NA60+ (SPS)
(Id110) ALICE upgrade for HL-LHC
(Id135) QCD/HI at FCC-hh and FCC-eh
(Id143) COMPASS++/AMBER (SPS)
(Id152) QCD/HI at HL-LHC
(Id159) LHeC/PERLE
(Id160) QCD/HI at HE-LHC

Category: Synergies on a global scale
(Id76) J-PARC
(Id93) NICA
(Id99) US-based EIC

Category: Facilities & experiments with strong interactions as a topic
(Id13 and Id50) AWAKE
(Id49) Super Charm-Tau Factory

Category: QCD results in support for other programs
(Id117) Auger experiment
(Id131) LBNF/DUNE
(Id151) New physics with HI collisions

Category: QCD theory in support
(Id100 and Id101) Precise calculations @ colliders
(Id114) MC generators
(Id163) QCD theory

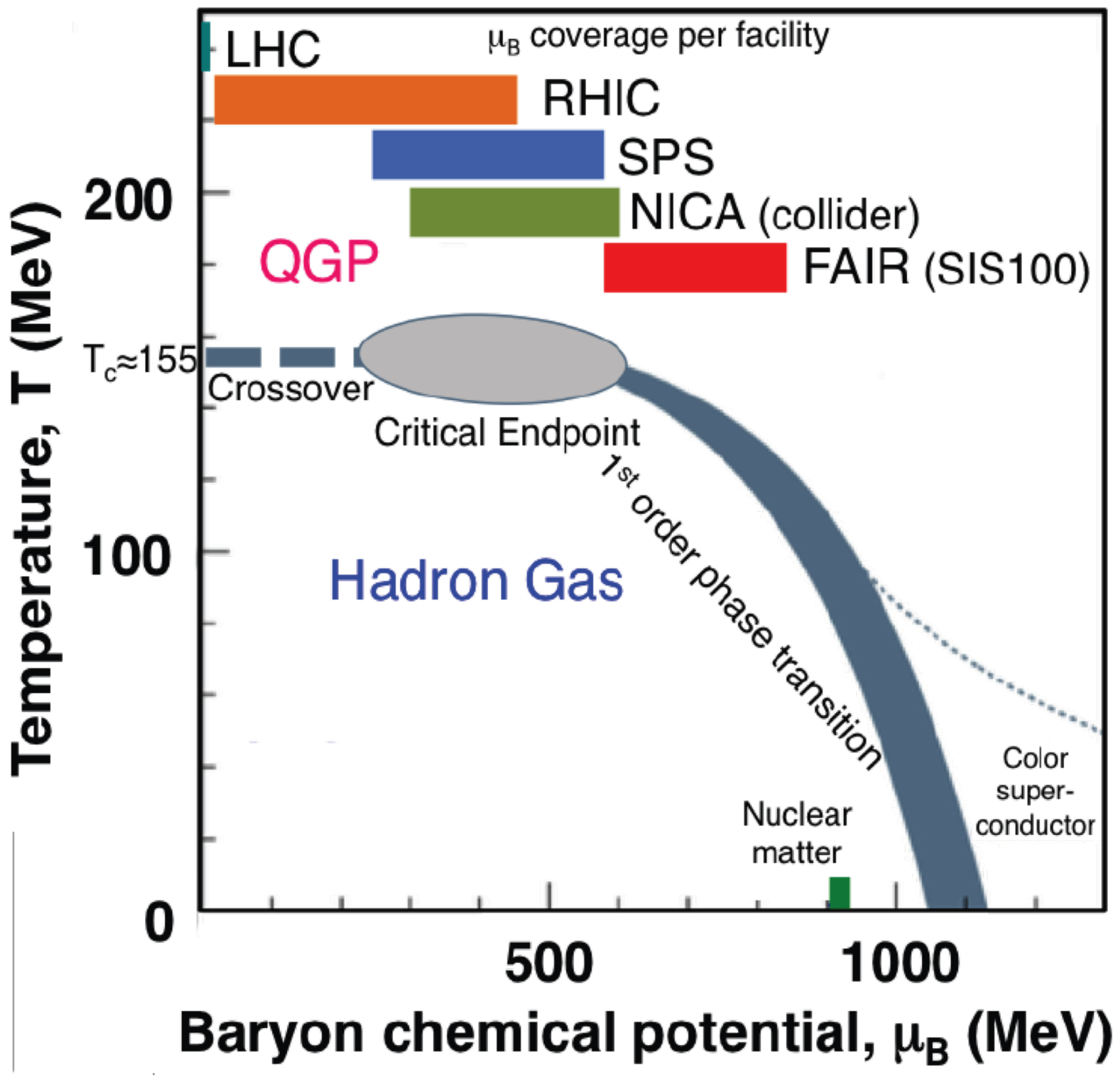
Category: QCD and nuclear physics
(Id39) ISOLDE/EPIC

Category: National roadmaps
(Id21) INFN Hadron
(Id37) Germany ALICE
(Id56) INFN HI
(Id115) Germany Hadron

Category: Individual and community thoughts
(Id48) Town meeting on Heavy Ions
(Id103) DIS
(Id140) personal input
(Id148) NuPECC

Hot & Dense QCD

Colliders and fixed-target experiments in operation or being prepared



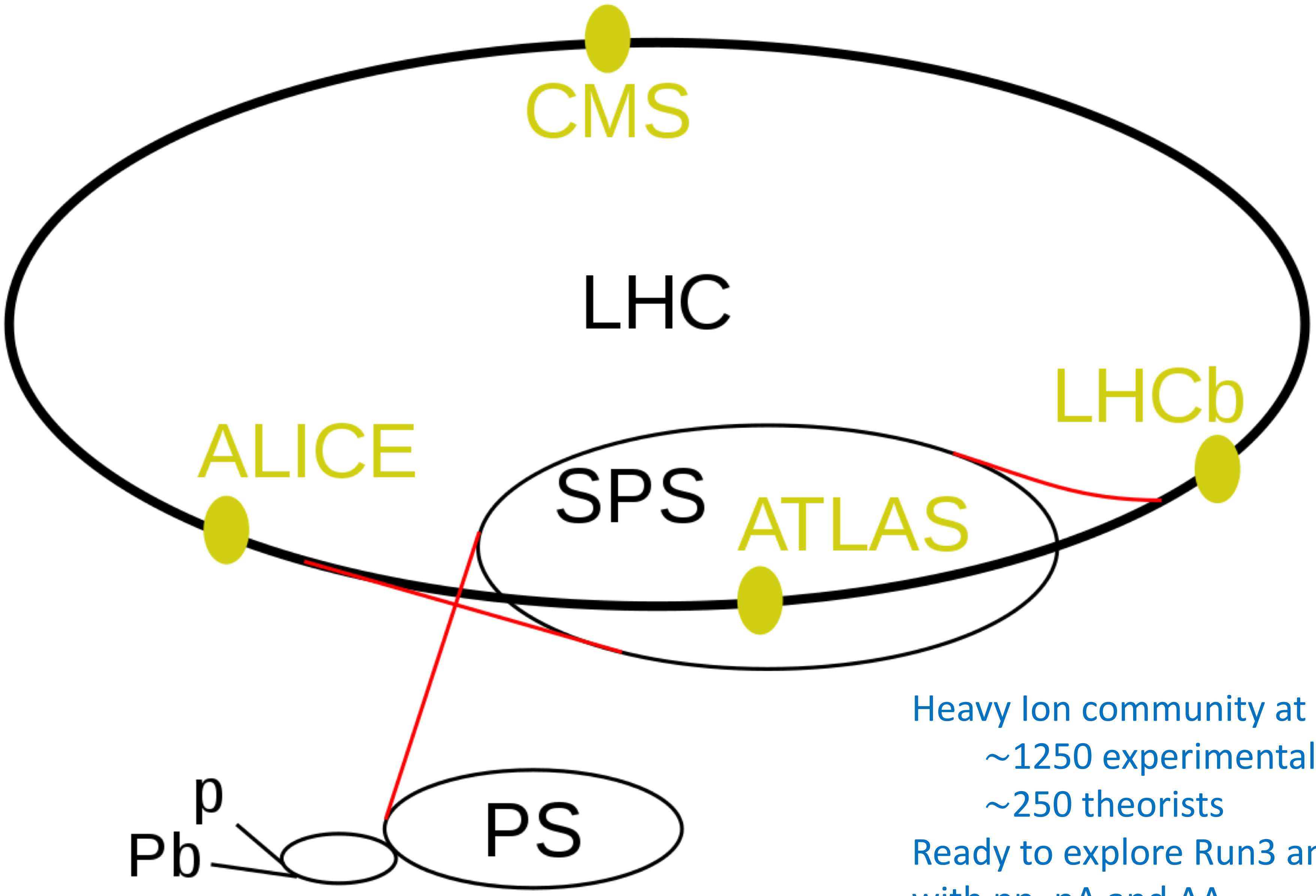
Collider experiments

- **HL-LHC**: heavy ion collisions at substantially increased luminosity open an excellent window to study strongly interacting matter at high temperature
- **HE-LHC/FCC**: prospects for a highly attractive heavy ion program are recognized with nuclear collisions at significantly higher energies to study the QGP at correspondingly higher energy density and temperature, while at FCC energies new probes will become accessible

Fixed-target experiments

- **SPS**: unique coverage in the QGP phase transition region and the critical point region
- **HL-LHC**: at ALICE and/or LHCb the most energetic fixed-target experiment ever can be performed to reach quark/gluon high-x PDFs

The CERN accelerator complex

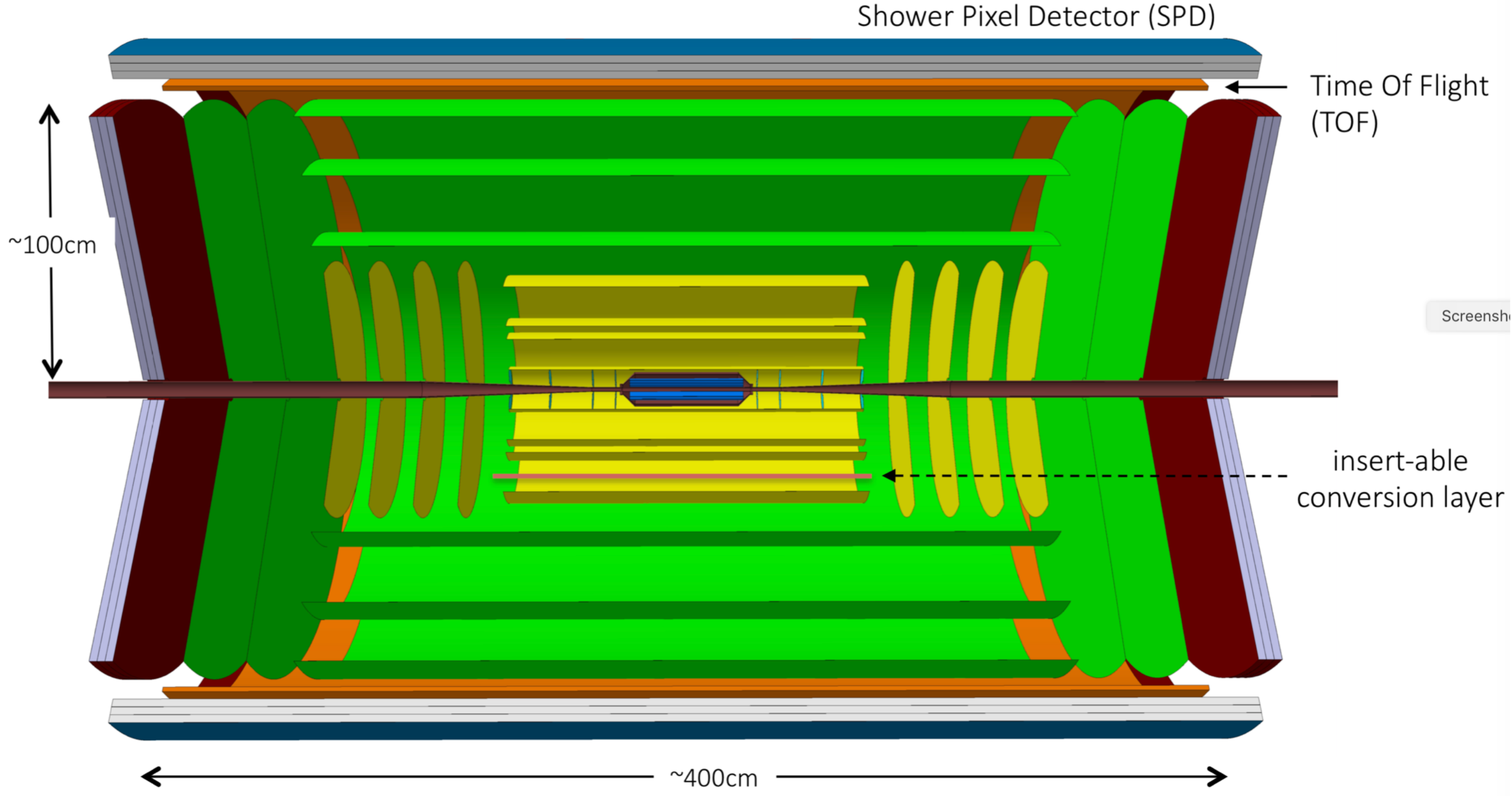


Heavy Ion community at the LHC:

- ~1250 experimental authors
- ~250 theorists

Ready to explore Run3 and Run4 with pp, pA and AA

The next generation of ALICE for AA/pA for installation beyond Run4 @ HL-LHC



Ultra-thin chip (<50 um): flexible with good stability

Detector upgrade (all Silicon detector):

- Pixel upgrade with fast and light CMOS MAPS
- High-rate capabilities of MAPS will allow the experiment to run at significantly higher luminosities (a factor 20 to 50), e.g. with lighter ions

Physics potential:

- QGP properties accessible via quenching of hard probes (heavy flavor and quarkonia)
- Access to new low-p_T phenomena (γ & hadrons)
- Low mass di-leptons

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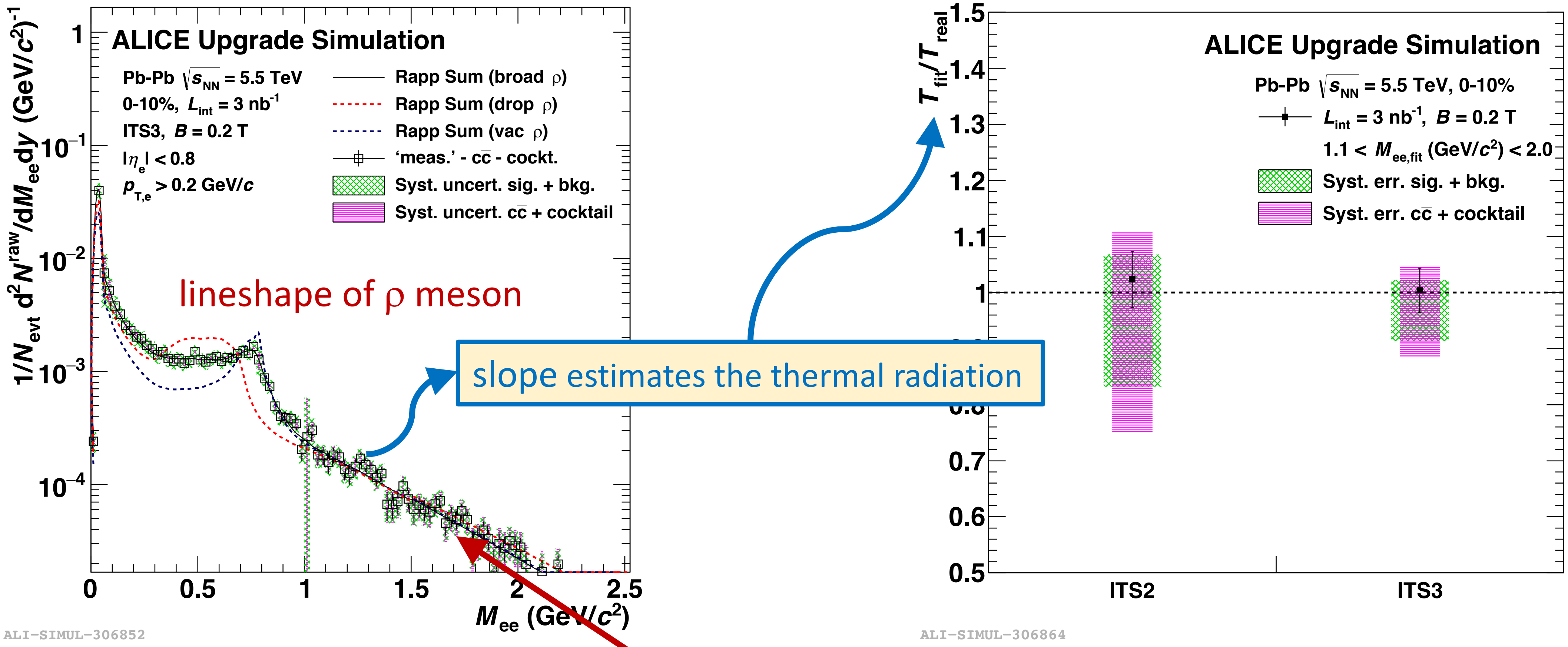

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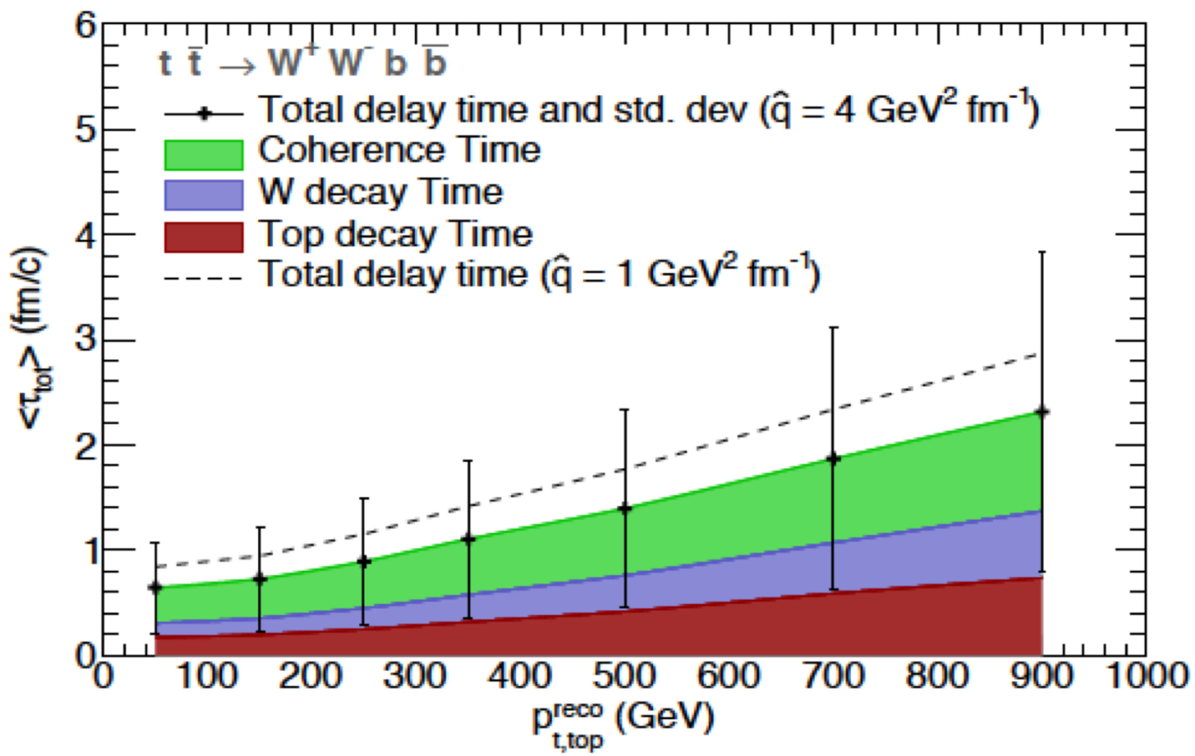
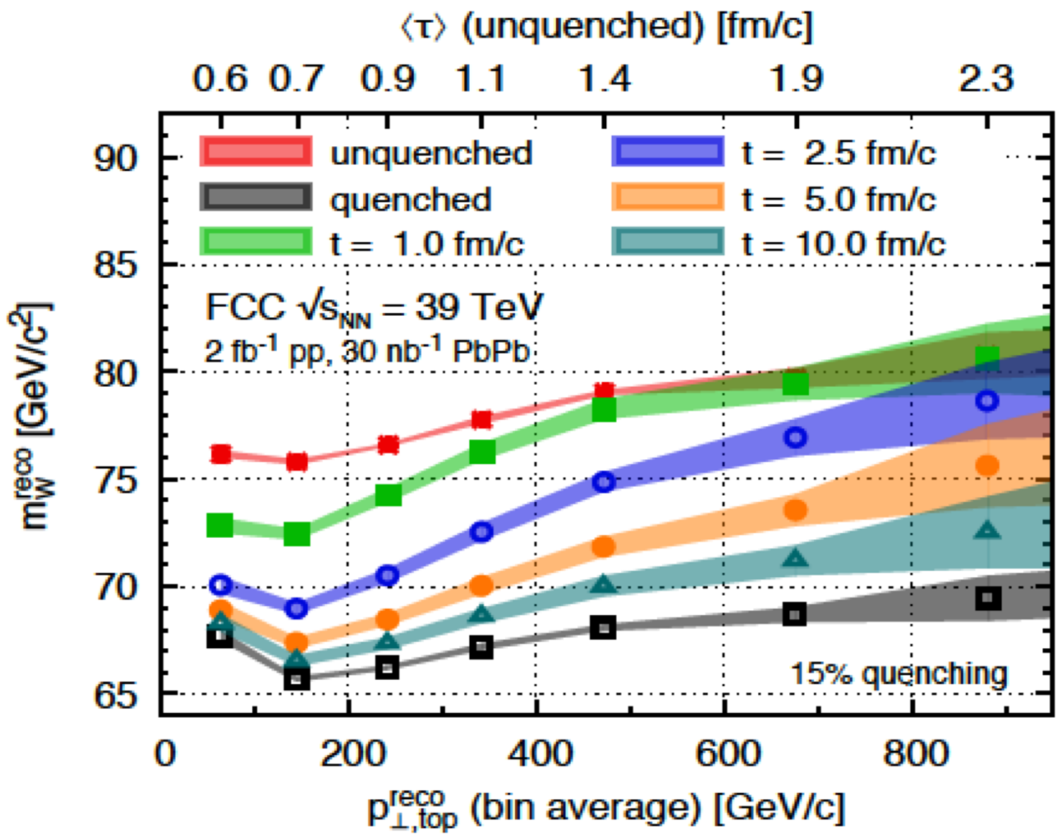
The case for AA/Ap collisions at higher energies (HE-LHC & FCC)

Part of the FCC design is to operate PbPb collisions at 39.4 TeV and pPb at 62.8 TeV, and with lighter ions
New probes become available, e.g. top quark production from LHC to FCC increase with a factor ~80

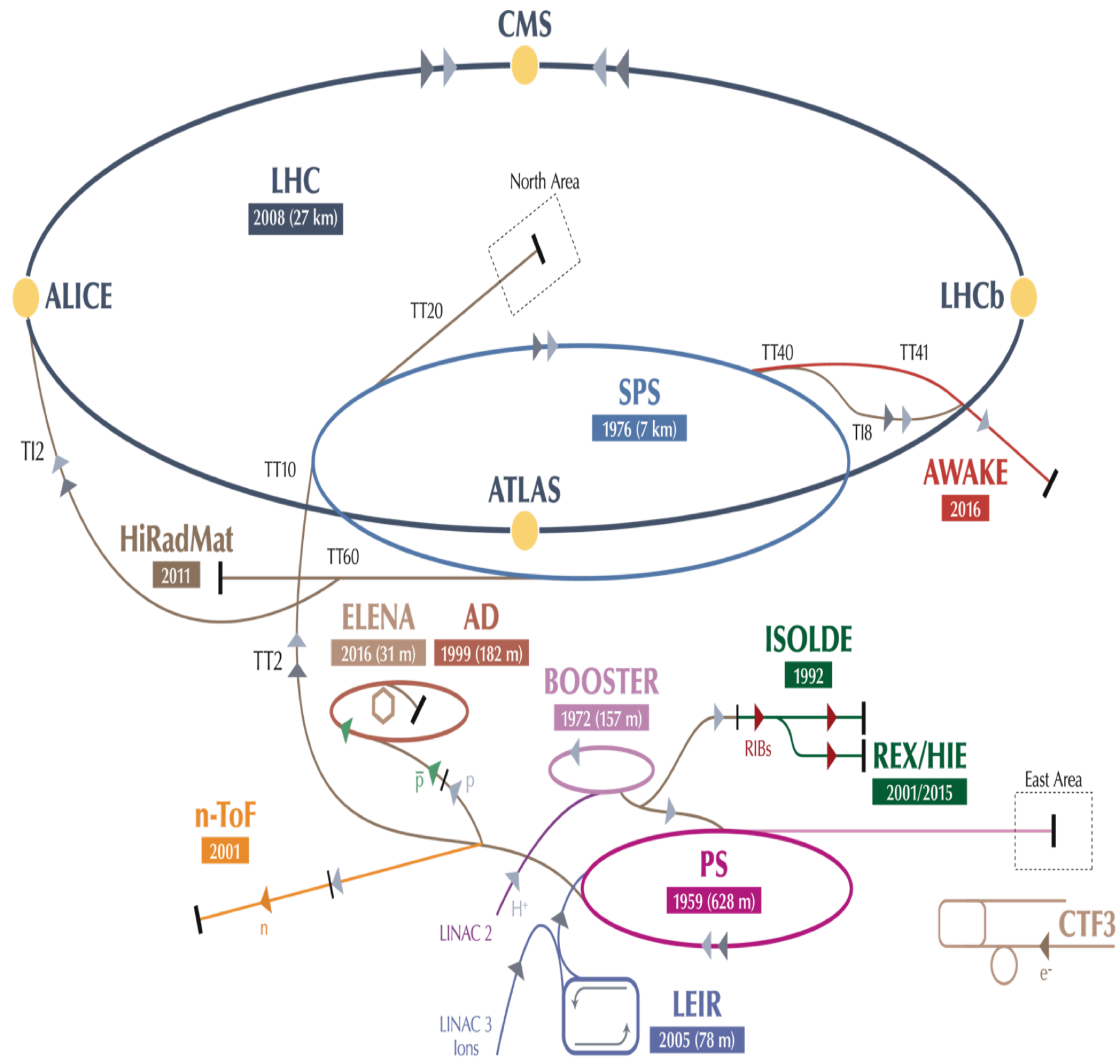


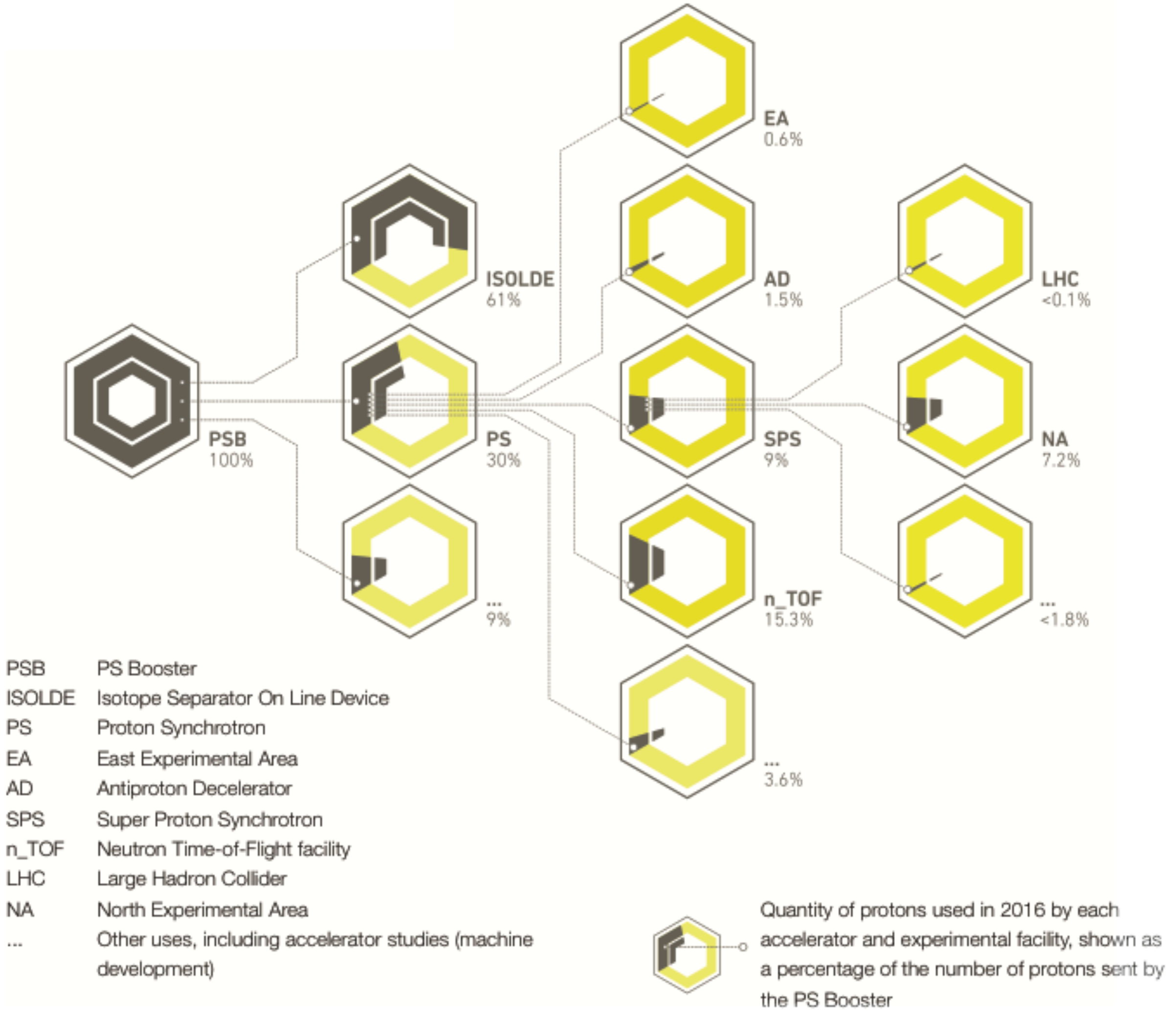


Top quark observables are sensitive to the energy-loss of heavy quarks in QGP
Boosted top quarks probe the QGP medium at later times as the decays of boosted top quarks become Lorentz time dilated (up to $p_T \approx 1.8$ TeV within reach)

The CERN accelerator complex

Plan for an optimal use of the SPS beams in order to verify how experiments can coexist





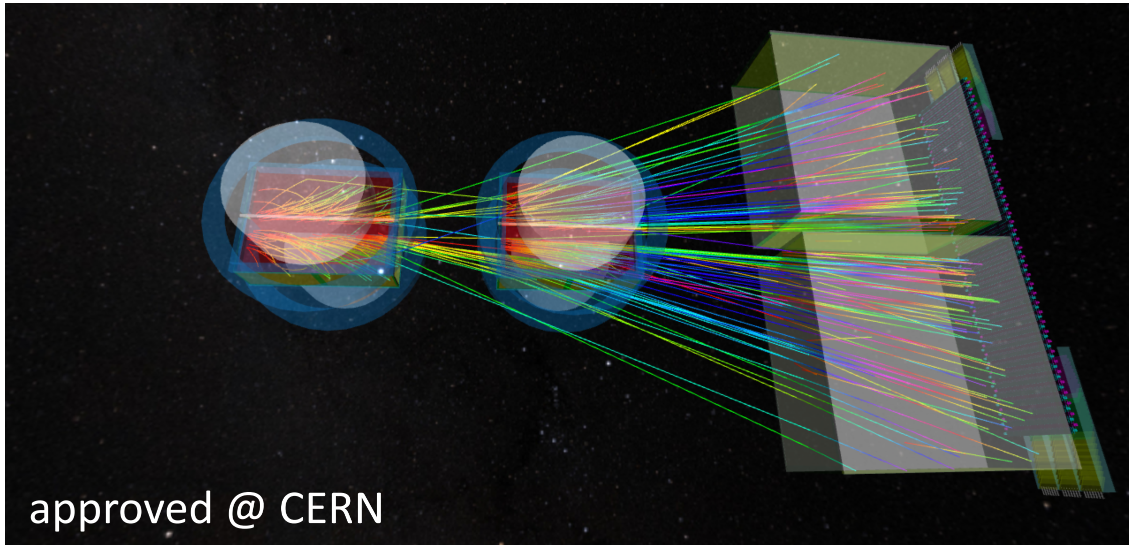
Large community using the protons not going to the LHC

The SPS beam for QCD at high-μ_B

NA61/SHINE (2020+)

upgraded detector
executed during the LS2 and the measurements are scheduled in the period 2021-2024

~150 physicists from 30 institutions and 14 countries

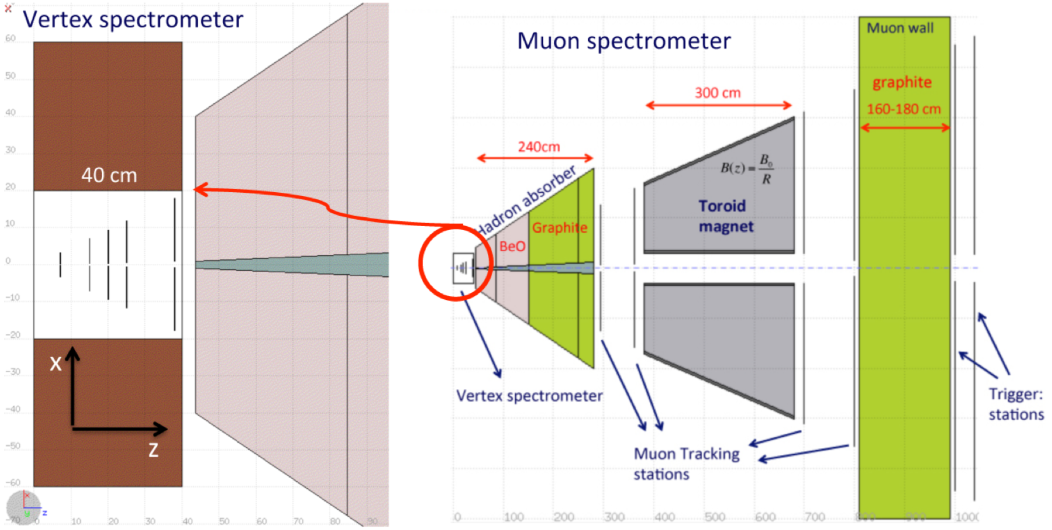


focus on charm hadron production
also nuclear fragmentation cross section & hadron production

NA60+

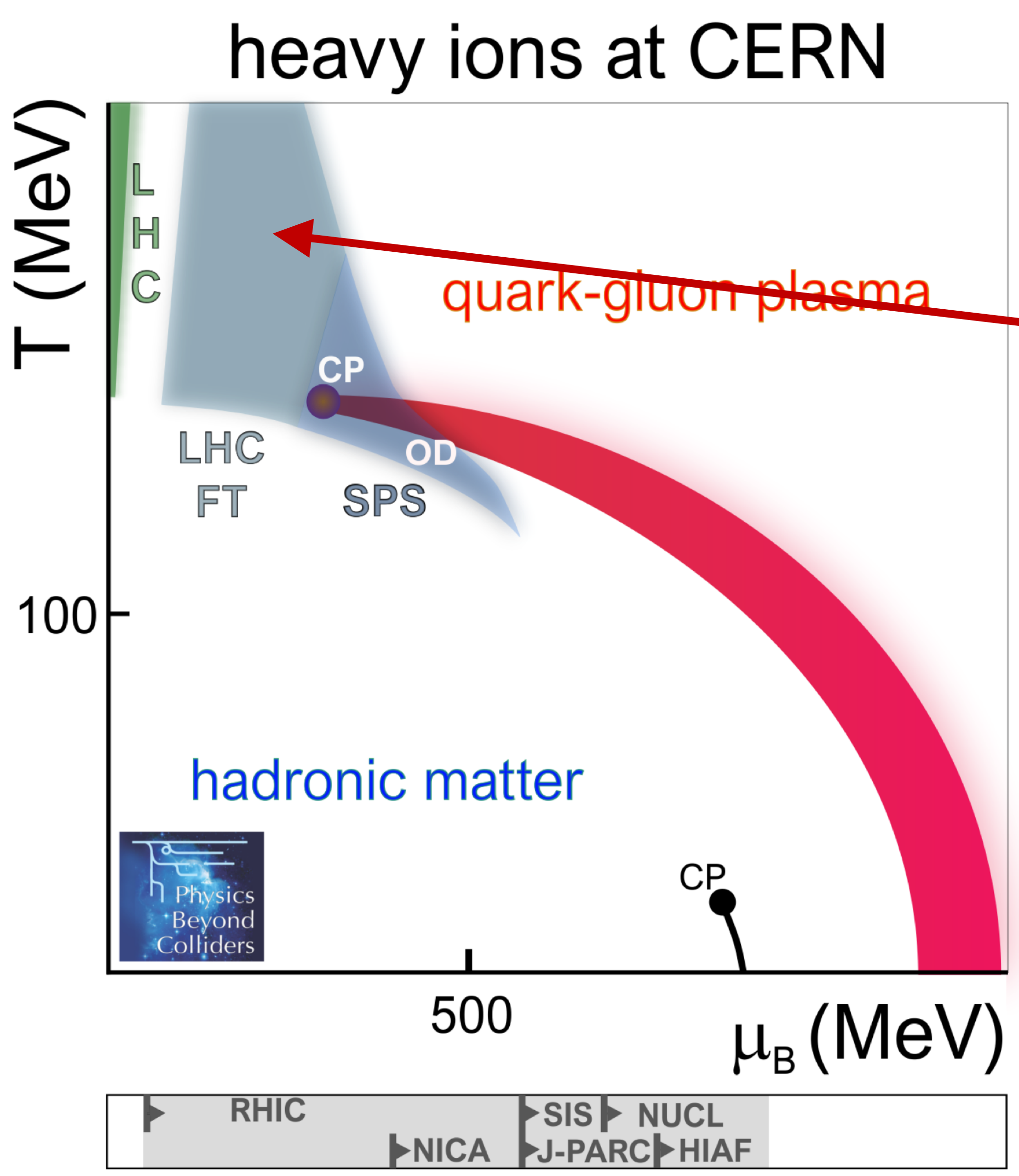
new experiment
very high intensities (underground)
proposal in the period >2025

~70 physicists from 23 institutions and 7 countries



focus on production of thermal dimuons
sensitive to the order of the phase transition

Fixed-target experiments: proton and ion beams from the LHC for high-μ_B



	LHC FT gas				LHC FT crystals
	ALICE	LHCb	LHCSpin	AFTER@LHC	
proton PDFs	×	×		×	
nuclear PDFs	×	×		×	
spin physics	×		×	×	
meson PDFs					
heavy ion physics	×			×	
elast. μ scattering					
chiral dynamics magnet. moments spectroscopy					×
measurements for cosmic rays and neutrino physics	×	×		×	

- High-x frontier for gluon, antiquark and heavy-quark content in the nucleon and nucleus
- Transverse dynamics and spin of gluons and quarks inside (un)polarised nucleons

QCD community support for a fixed-target program to coexist with the collider program at the (HL-)LHC

Emerging facilities worldwide at high-μ_B (~800 scientists community)

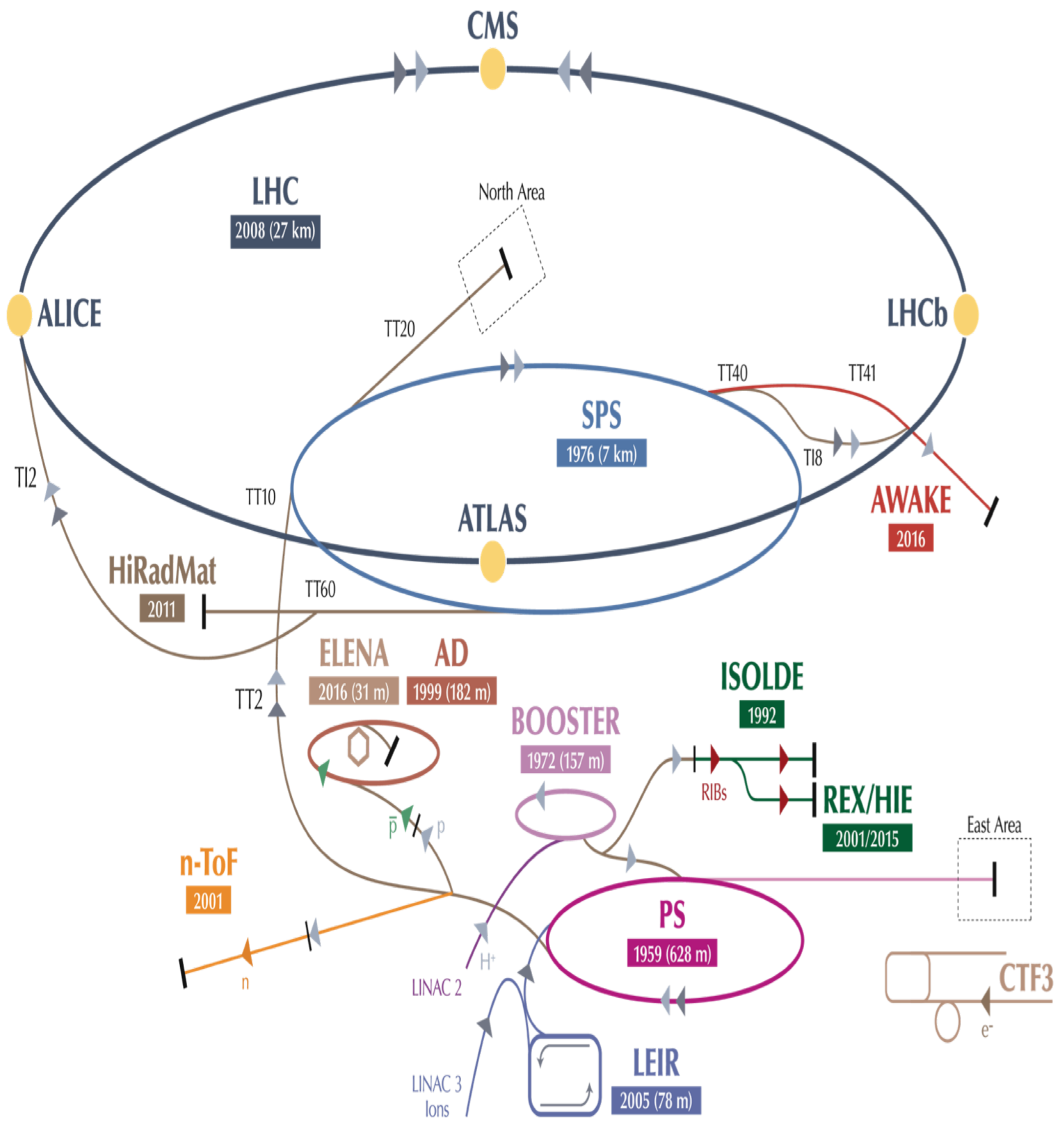
Complementarity of the operational and emerging facilities is essential to cover the QCD phase-diagram

compilation Tetyana Galatyuk, Nucl. Phys. A982 (2019)

Facility	SIS18	HIAF	Nuclotron	J-PARC-HI	SIS100	NICA	RHIC	SPS	SPS
Experiment	HADES /miniCBM	CEE	BM@N	DHS, D2S	CBM / HADES	MPD	STAR	NA61++	NA60+
Start	2012, 2018	2023	2022 (Au)	>2025(?)	2025	2023	2010,2019	2009, 2022	>2025(?)
$\sqrt{s_{NN}}$, GeV	2.4 – 2.6	2 – 2.7	2 – 3.5	2 – 6.2	2.7 – 5	2.7 - 11	3 – 19.6	4.9 – 17.3	4.9 – 17.3
μ_B, MeV	880 – 670	880 – 750	850 – 670	850 – 490	780 – 400	750 – 330	720 – 210	560 – 230	560 – 230
Hadrons	+	+	+	+	+	+	+	+	(+)
Dileptons	+		(+)	+	+	+	+		+
Charm				(+)	(+)	+	+	+	+

The future CERN accelerator complex… when the LHC will retire

Beyond the HL-LHC there are options to use the LHC machine for novel QCD research



What strong interaction physics can one do with the LHC after the HL-LHC?

(e.g. when the LHC becomes an injector for a future collider)

slide from Daniel Boer

Summary of opportunities and challenges

Opportunities and challenges for the strong interaction physics case for continued use of the LHC after the HL-LHC:

- **Unambiguous signals of small-x gluon saturation [opportunities]**
  Should one go for the smallest x (i.e. highest energy), even when the luminosity is modest?

e.g. plasma accelerated electrons (PEPIC, VHEeP)

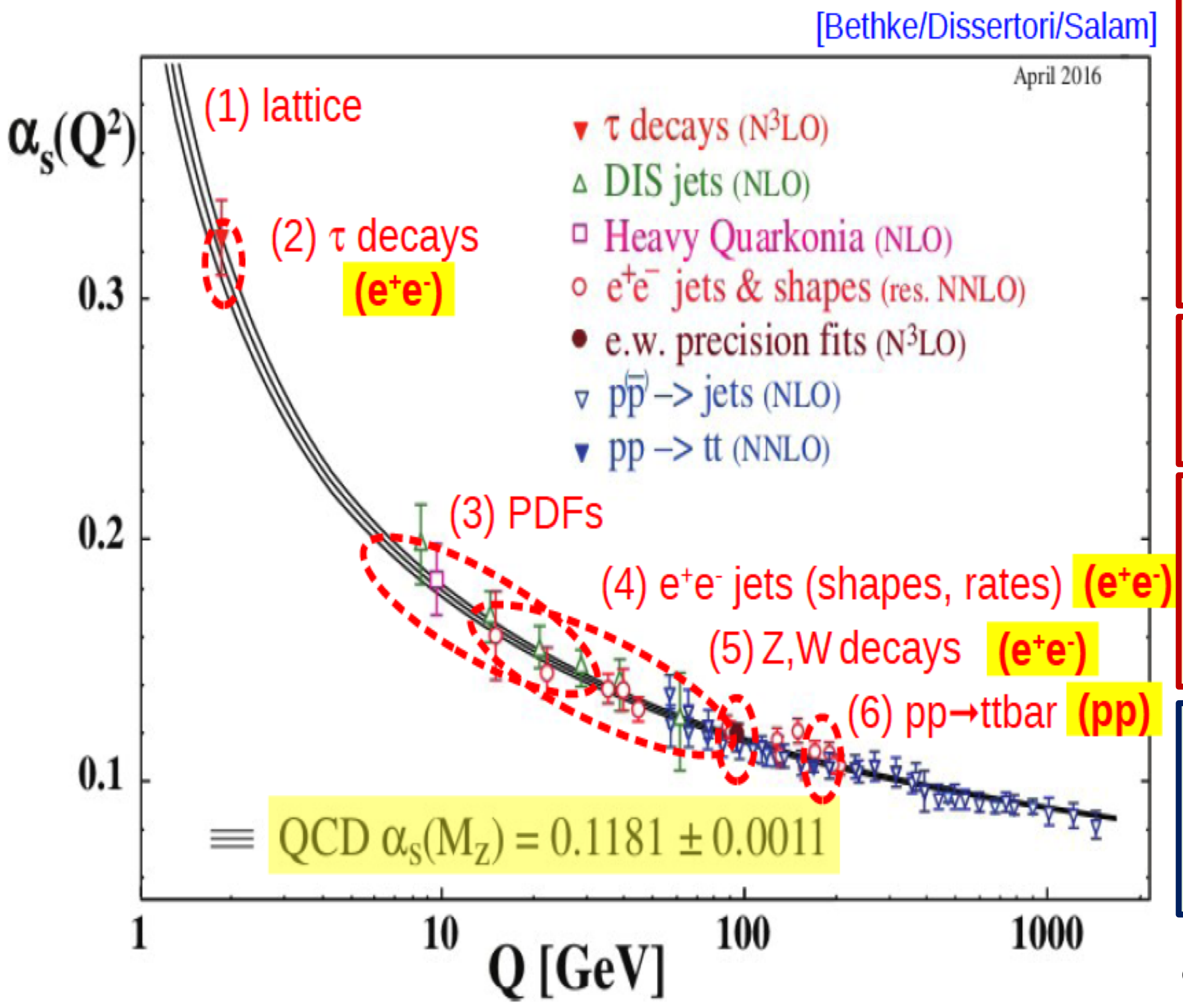
- **Control over less-inclusive and diffractive processes in pp [challenges]**
  Required for global analyses of multi-dimensional PDFs
- **Observation of new strongly interacting particles [opportunities]**
  Elucidation of the role or the embedding of QCD in BSM theory

Other opportunities/challenges for QCD@LHC after 2040?

Precision QCD

The strong coupling constant α_s

Determined by comparing experimental observables to pQCD (NNLO or N^{3}LO) predictions.
Need for a high-luminosity e^+e^- collider at EW scales.



FCC-ee

from hadronic Z decays	$\delta\alpha_s$ <0.15%	*(today 2.5%)*
from hadronic W decays	$\delta\alpha_s$ < 0.2%	*(today 35%)*
from hadronic τ decays	$\delta\alpha_s$ < 1%	*(today 1.5%)*
event shapes	$\delta\alpha_s$ < 1%	*(today 2.9%)*

FCC-eh or LHeC

would be able to reach $\delta\alpha_s \sim 0.2\%$

FCC-hh

from top quark pair production
test the running of α_s up to 25 TeV (jet cross sections)

Lattice QCD

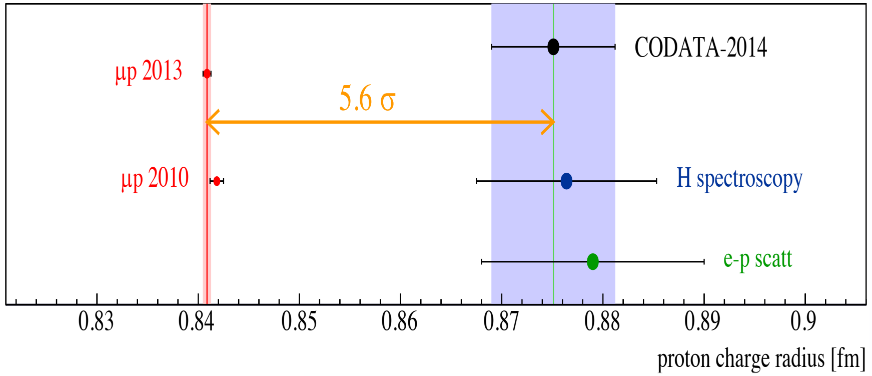
with adequate R&D on computing a robust calculation up to 0.3% precision might be within reach

$\delta\alpha_s$ at 0.1% precision is essential for H, t, EWPO at colliders

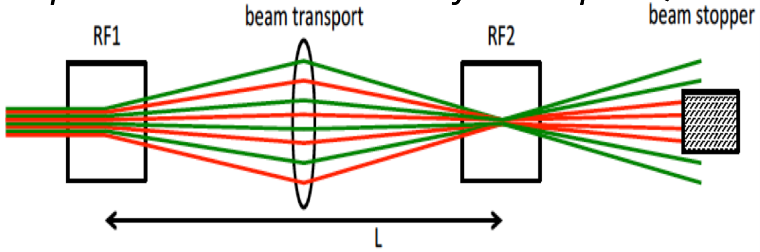
The low-energy precision puzzle…

From the report of the Physics Beyond Colliders working group: COMPASS++/AMBER, DIRAC++, MUonE

persistent discrepancies on proton charge radius determined from spectroscopy (H, muonic H) and ep elastic scattering

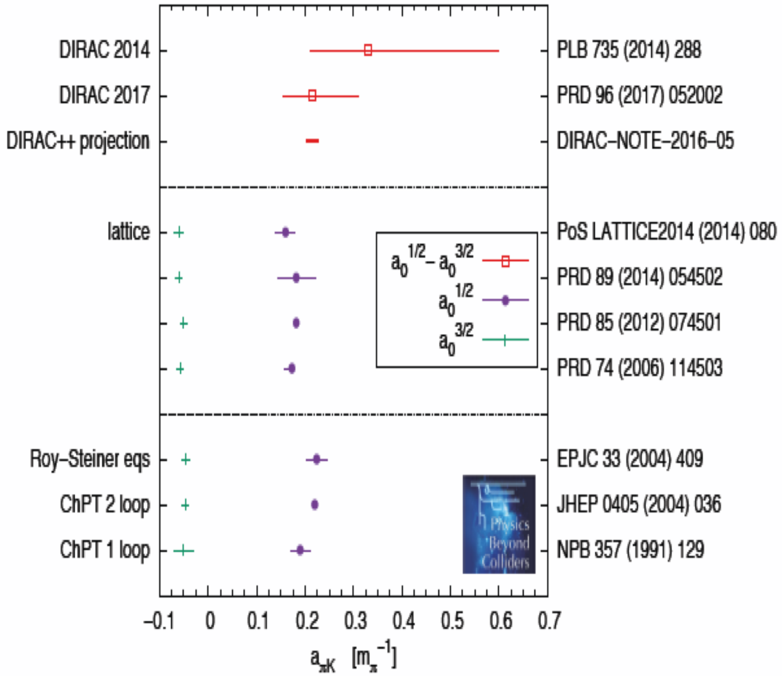


RF-separated hadron beams for unique QCD



A long-term multipurpose hadron structure facility **COMPASS++/AMBER** at the M2 beam line beyond 2021 (muon and hadron beams)

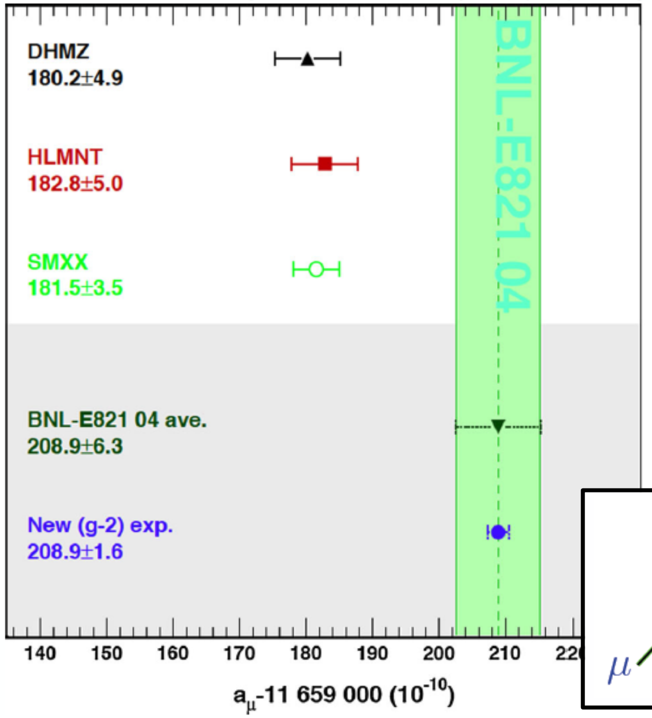
πK scattering lengths are benchmark quantities for chiral symmetry breaking in the strange-quark sector

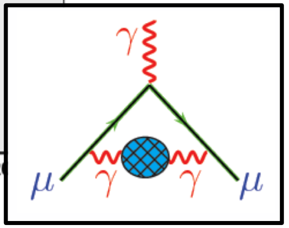


Study of πK atoms with **DIRAC++** would yield an experimental uncertainty comparable with the theoretical one

persistent discrepancy between measured anomalous magnetic moment $a_\mu = (g-2)_\mu/2$ and SM theory

[G. Abbiendi et al., Eur. Phys. J. C (2017) 77:139]





With 2-years of elastic muon scattering **MUonE** aims for an independent measurement of the hadronic vacuum polarization

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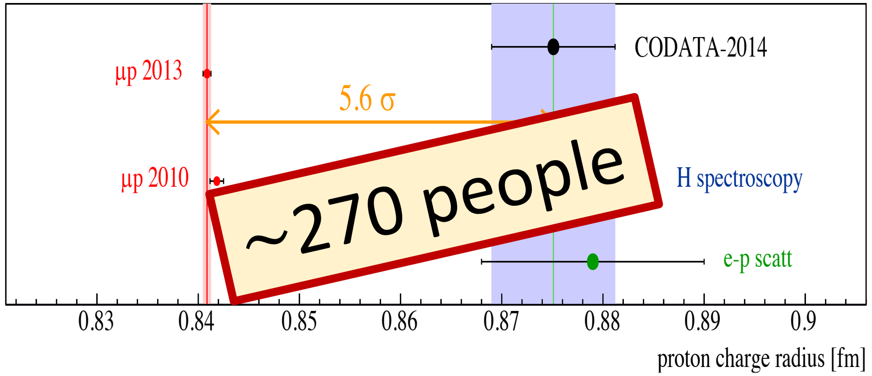

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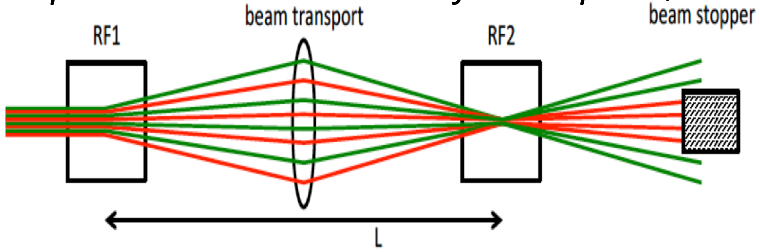

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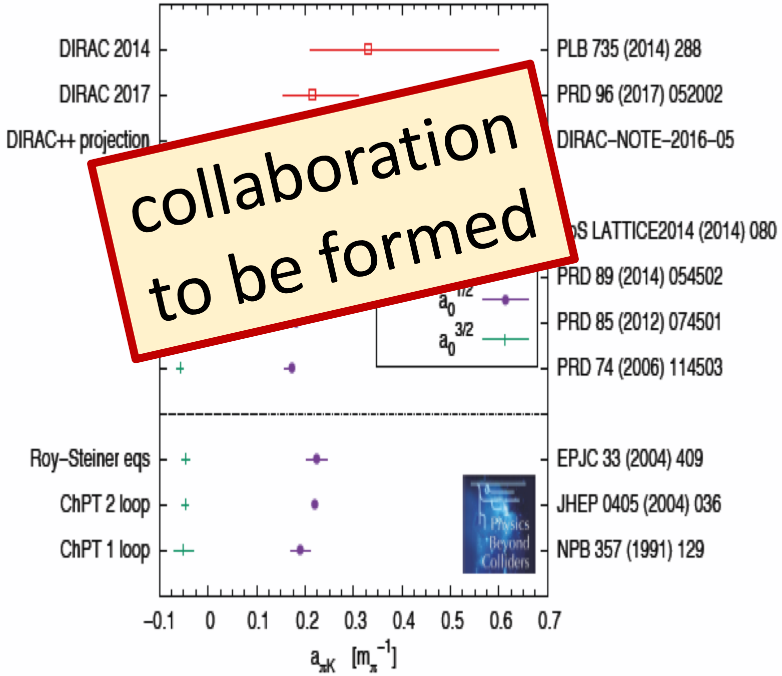

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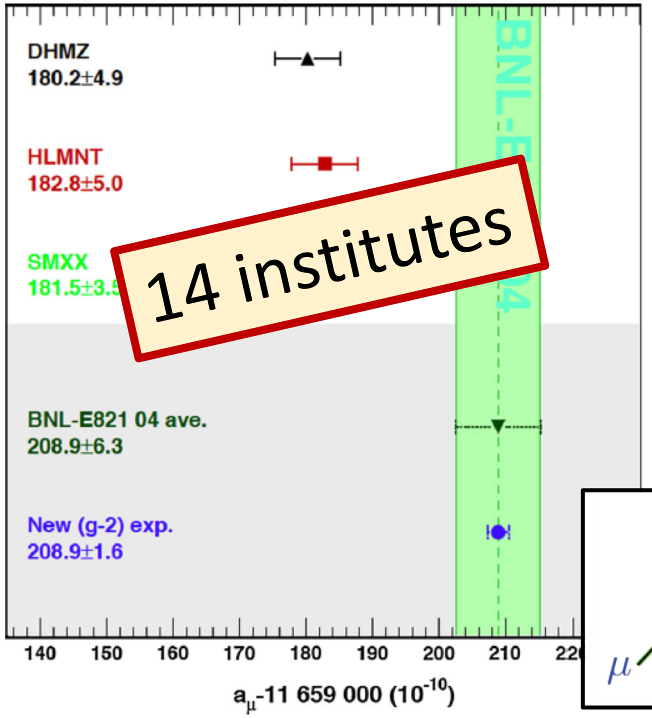

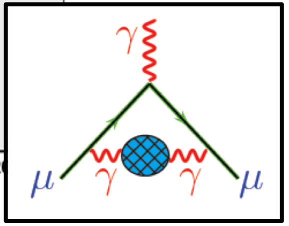

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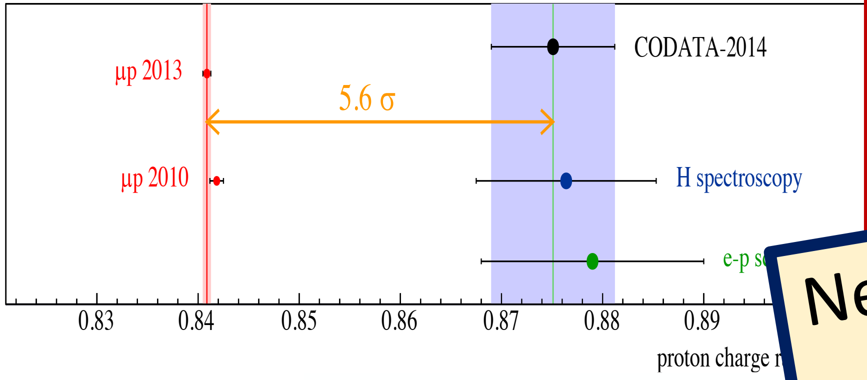

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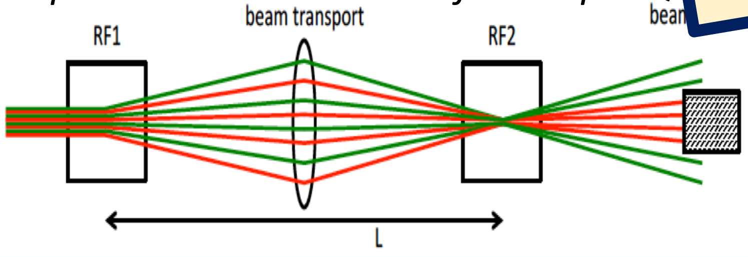
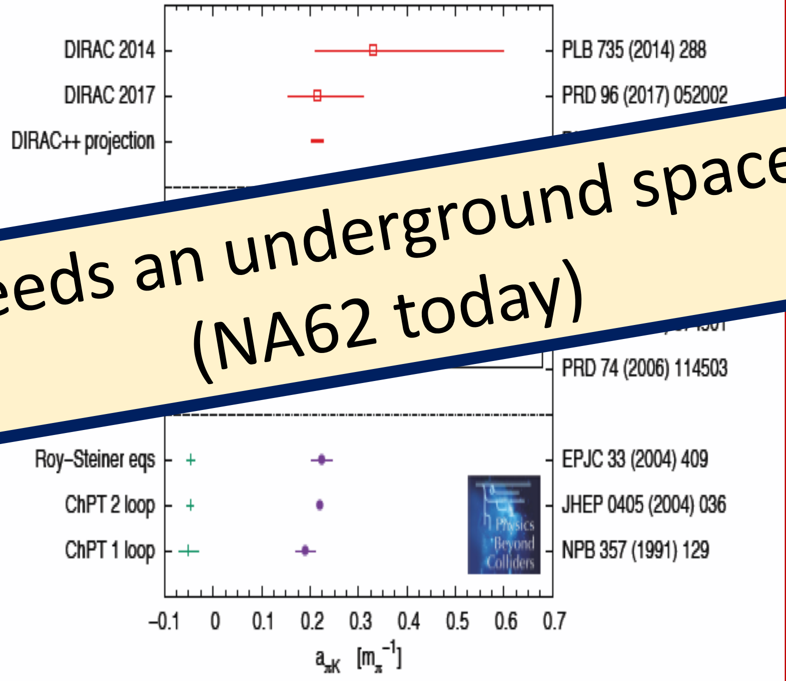
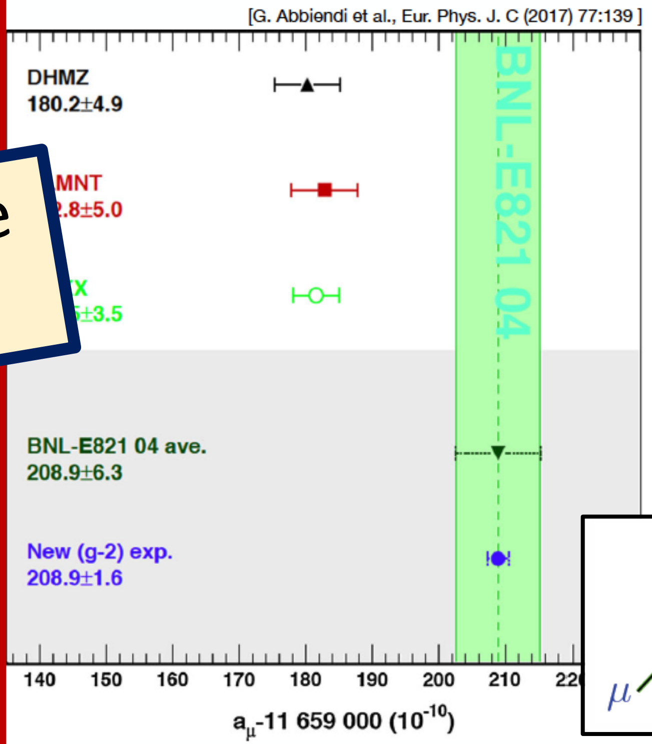
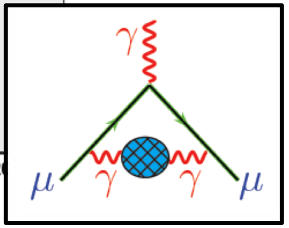








Needs an underground space (NA62 today)

A long-term multipurpose hadron structure facility **COMPASS++/AMBER** at the M2 beam line beyond 2021 (muon and hadron beams)

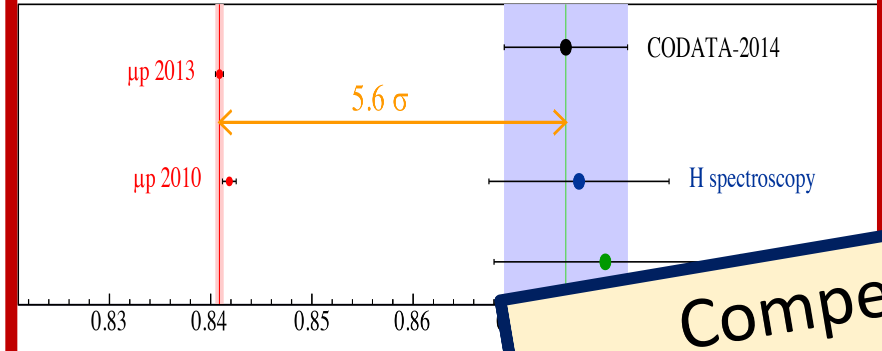
Study of πK atoms with **DIRAC++** would yield an experimental uncertainty comparable with the theoretical one

With 2-years of elastic muon scattering **MUonE** aims for an independent measurement of the hadronic vacuum polarization

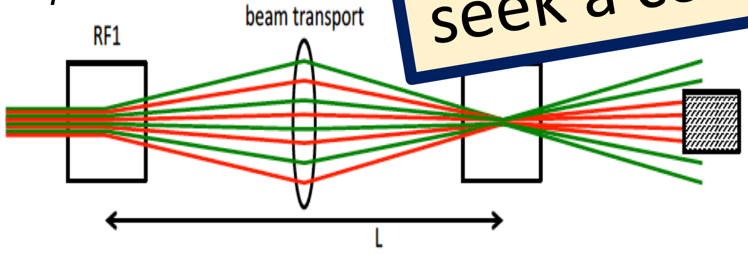
The low-energy precision puzzle…

From the report of the Physics Beyond Colliders working group: COMPASS++/AMBER, DIRAC++, MUonE

persistent discrepancies on proton charge radius determined from spectroscopy (H, muonic H) and ep elastic scattering

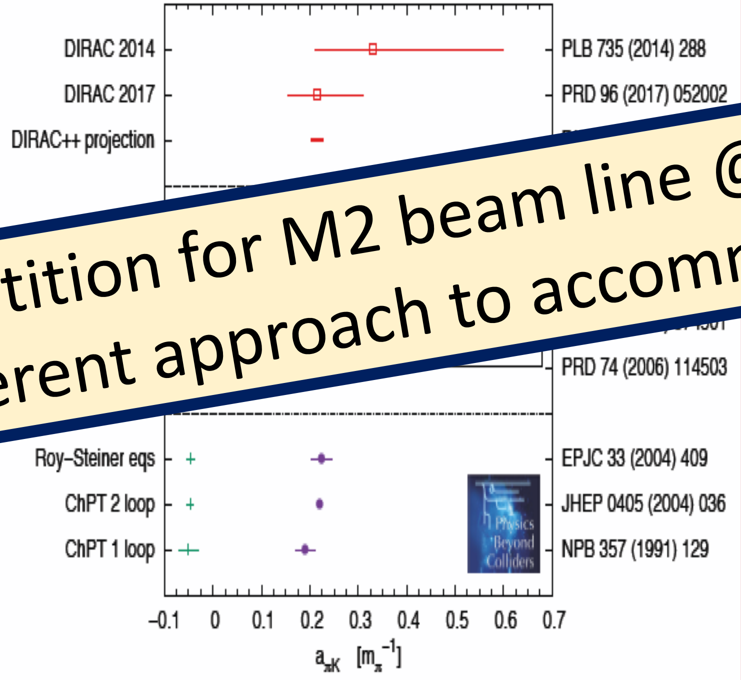


RF-separated hadron bea



A long-term multipurpose hadron structure facility **COMPASS++/AMBER** at the M2 beam line beyond 2021 (muon and hadron beams)

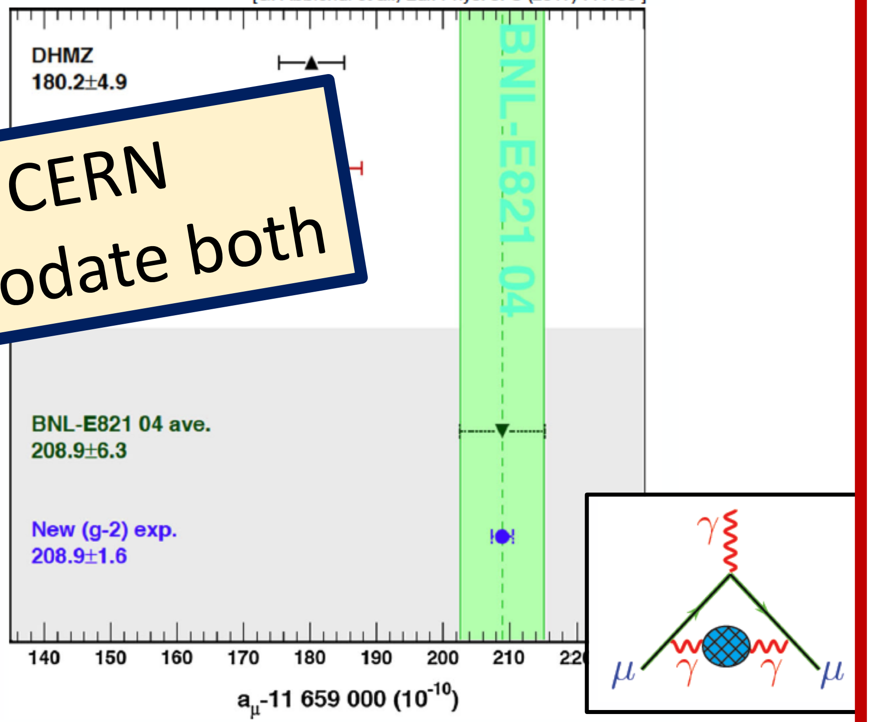
πK scattering lengths are benchmark quantities for chiral symmetry breaking in the strange-quark sector



Study of πK atoms with **DIRAC++** would yield an experimental uncertainty comparable with the theoretical one

persistent discrepancy between measured anomalous magnetic moment $a_\mu = (g-2)_\mu/2$ and SM theory

[G. Abbiendi et al., Eur. Phys. J. C (2017) 77:139]

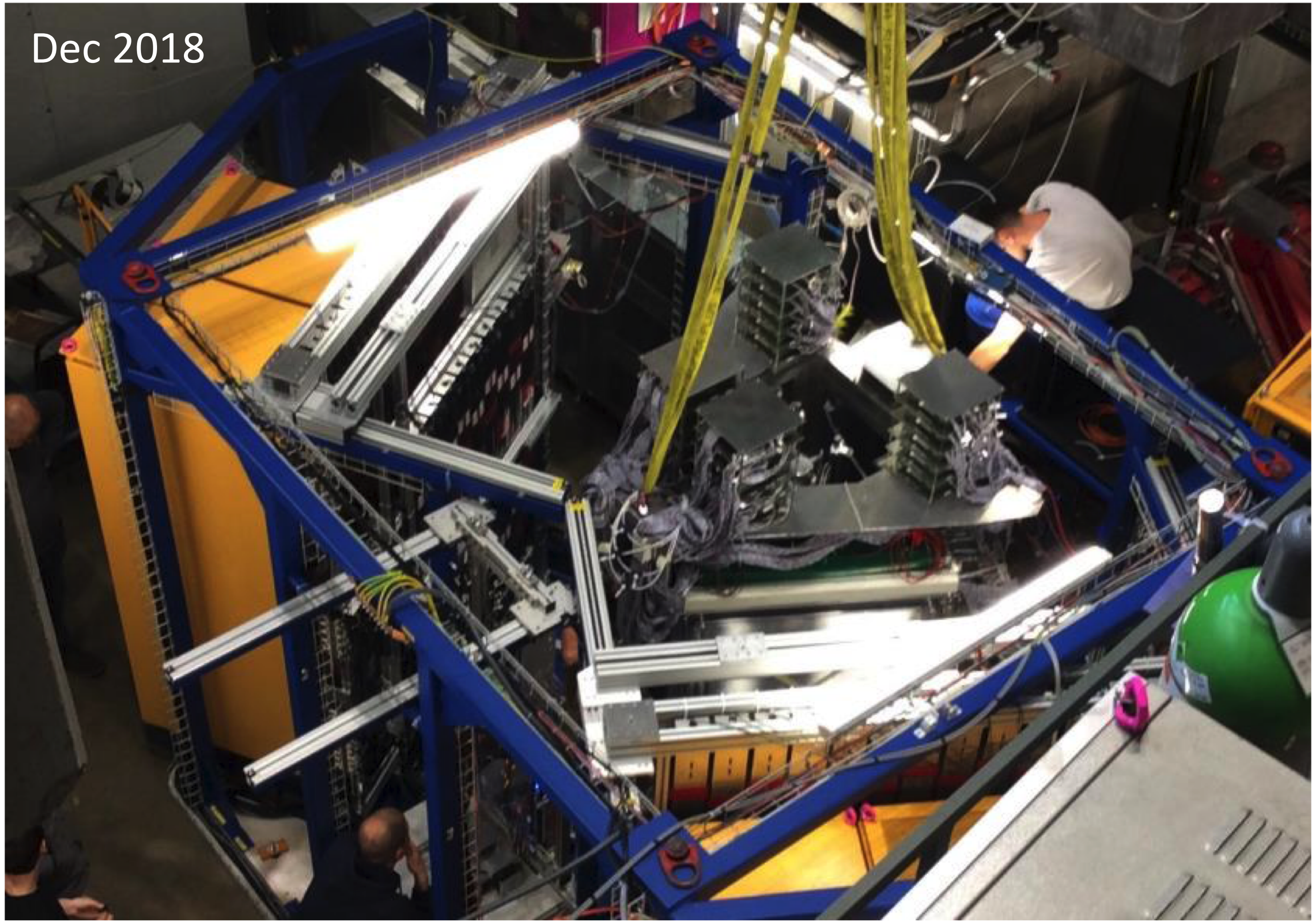


With 2-years of elastic muon scattering **MUonE** aims for an independent measurement of the hadronic vacuum polarization

Competition for M2 beam line @ CERN
seek a coherent approach to accommodate both

The proton radius puzzle… the QCD community is motivated to solve it

With the PSI beams and the MUon proton Scattering Experiment (MUSE) experiment… *ready to go*



Measure simultaneously low-energy $\mu^{\pm}$ and $e^{\pm}$ scattering to reduce systematics in the search for hints of lepton-flavor violation.

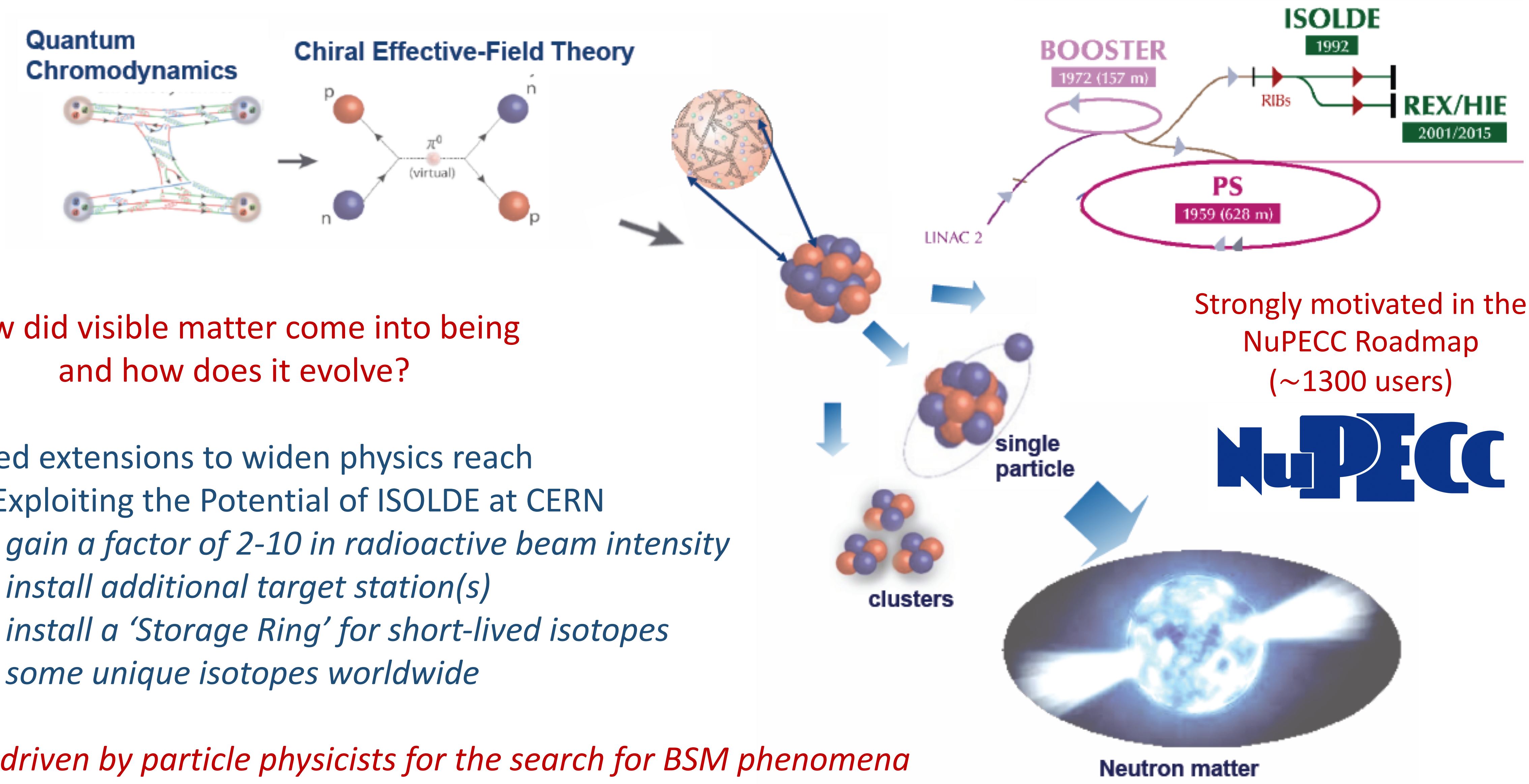
Data-taking from 2020 onwards with the goal to reach sub-percent relative precision (Q^2 = 0.002—0.07 GeV^2) to extract the proton radius difference e versus μ with a precision of 0.007 fm.

Solving the proton puzzle will require a concerted approach with complementary experiments worldwide.

Several more QCD precision efforts worldwide.

Nuclear precision with HIE-ISOLDE and the EPIC upgrade

Radioactive ion beam at CERN to study the emergence of nuclear phenomena from QCD



How did visible matter come into being and how does it evolve?

Strongly motivated in the NuPECC Roadmap (~1300 users)

Proposed extensions to widen physics reach

EPIC = Exploiting the Potential of ISOLDE at CERN

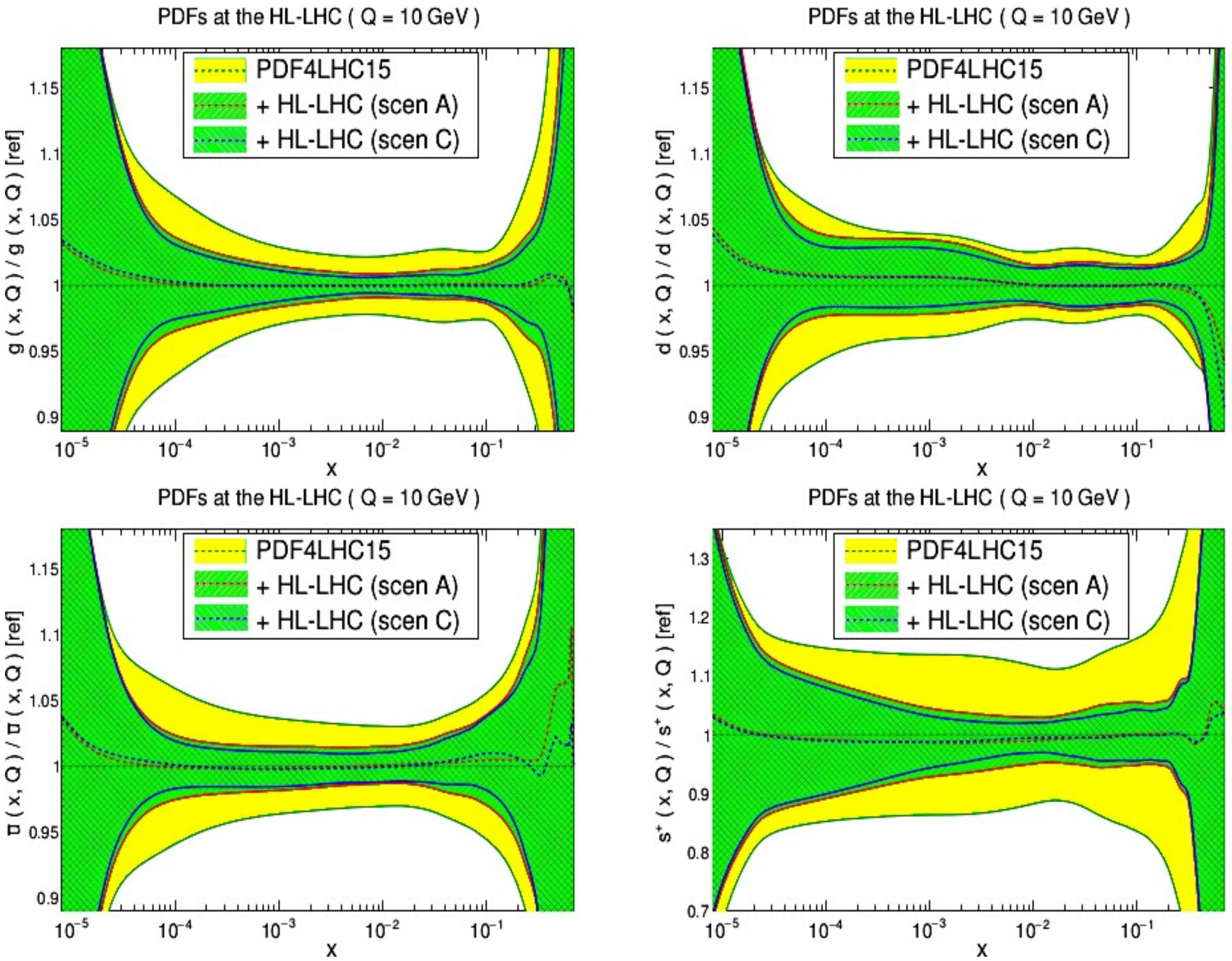
- *gain a factor of 2-10 in radioactive beam intensity*
- *install additional target station(s)*
- *install a 'Storage Ring' for short-lived isotopes*
- *some unique isotopes worldwide*

Mostly driven by particle physicists for the search for BSM phenomena

Partonic Structure

PDFs measured from W, Z, top processes from LHC to HL-LHC

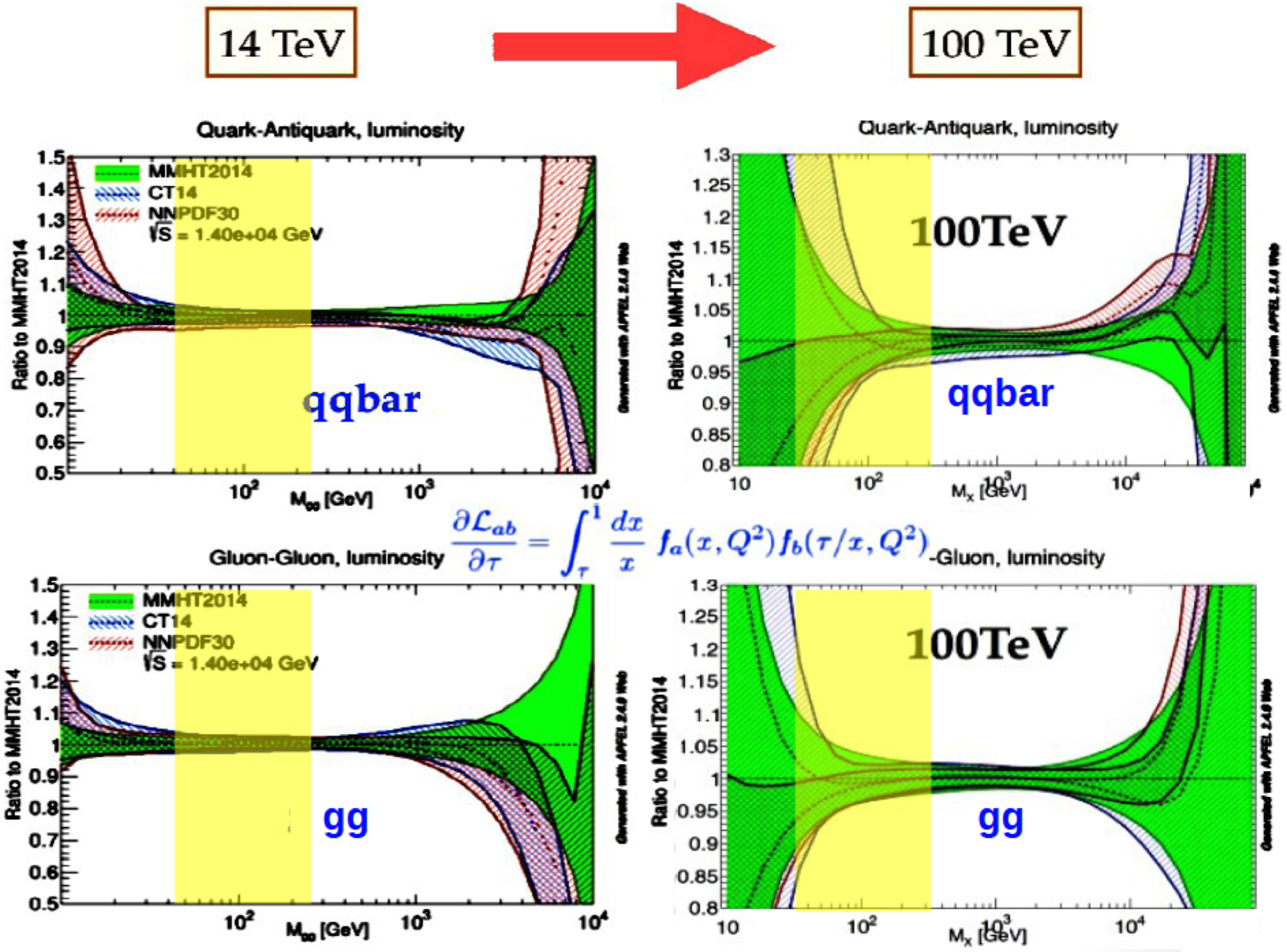
R.A. Khalek et al. arXiv:1810.03639



- factor ~2 improvement in the mid-x region
- no improvement in the low-x and high-x region
- requires to further develop methodologies to not fit away BSM effects when estimating PDFs from pp collision processes, e.g. fit the PDFs in-situ while doing measurements

The case for ep collisions at high energies (LHeC, FCC-ep)

"Precision" region at FCC-pp: **5–7%** PDF uncertainty for σ(W,Z,H)



$$\frac{\partial \mathcal{L}_{ab}}{\partial \tau} = \int_\tau^1 \frac{dx}{x} f_a(x,Q^2) f_b(\tau/x, Q^2)$$

→ ep collisions essential

- *a clean experimental environment with low multiplicity, no pileup, fully constrained kinematics (x,Q^2) reconstructing the outgoing lepton*
- *a more controlled theoretical setup with many 1st-principles calculations, factorisation tests*

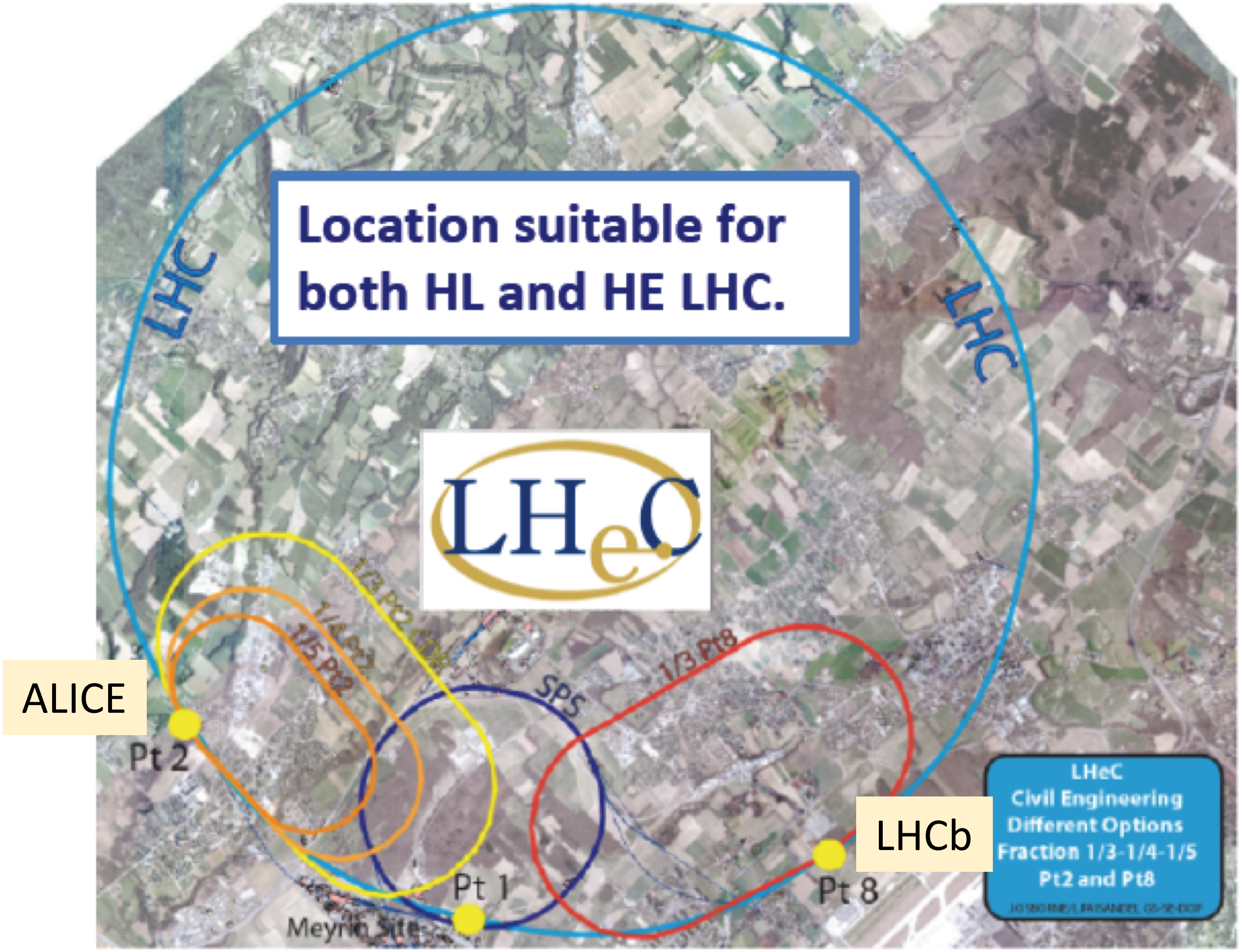
EIC (3-20 GeV e-)
E_{cms} = 0.02 – 0.13 TeV

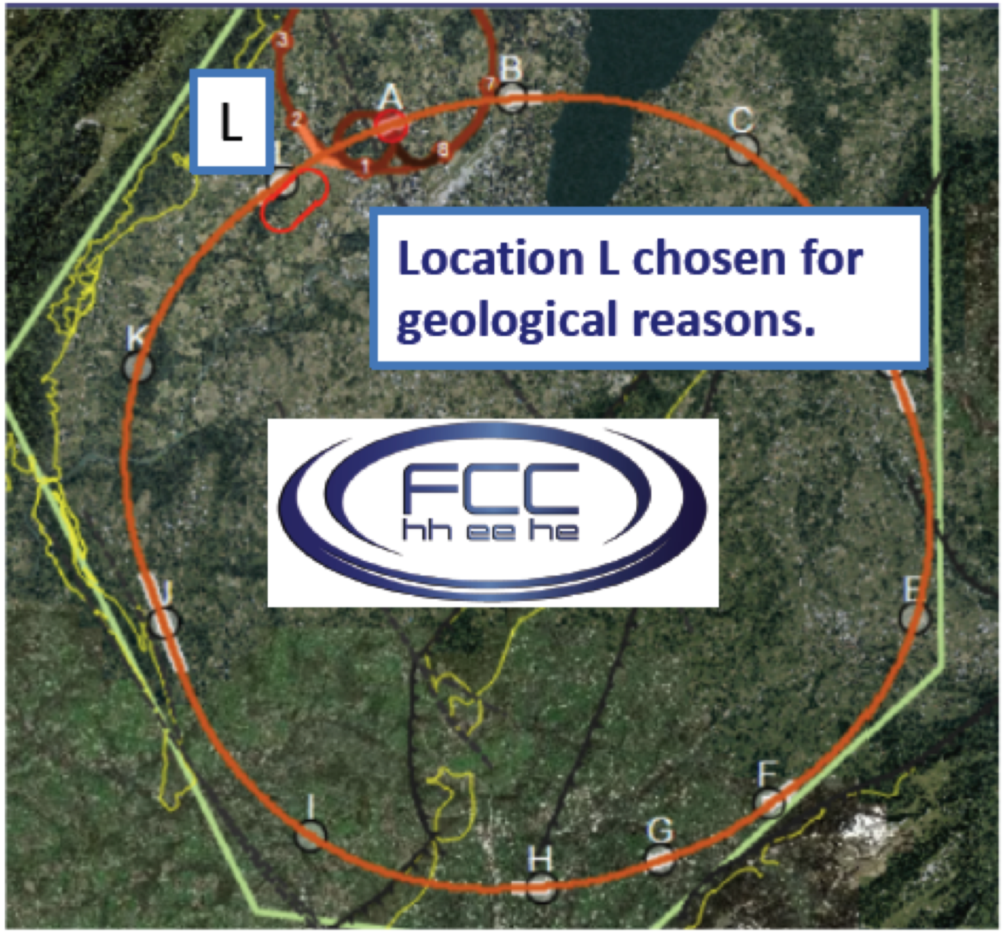
LHeC (60 GeV e- from ERL)
E_{cms} = 0.2 – 1.3 TeV
run with the HL-LHC (≳ Run5)

FCC-ep (60 GeV e- from ERL)
E_{cms} *up to 3.5 TeV*
is required to reach O(1%) uncertainty for σ(W,Z,H) at FCC-pp

The case for ep collisions at high energies (LHeC, FCC-ep) – novel ERL systems

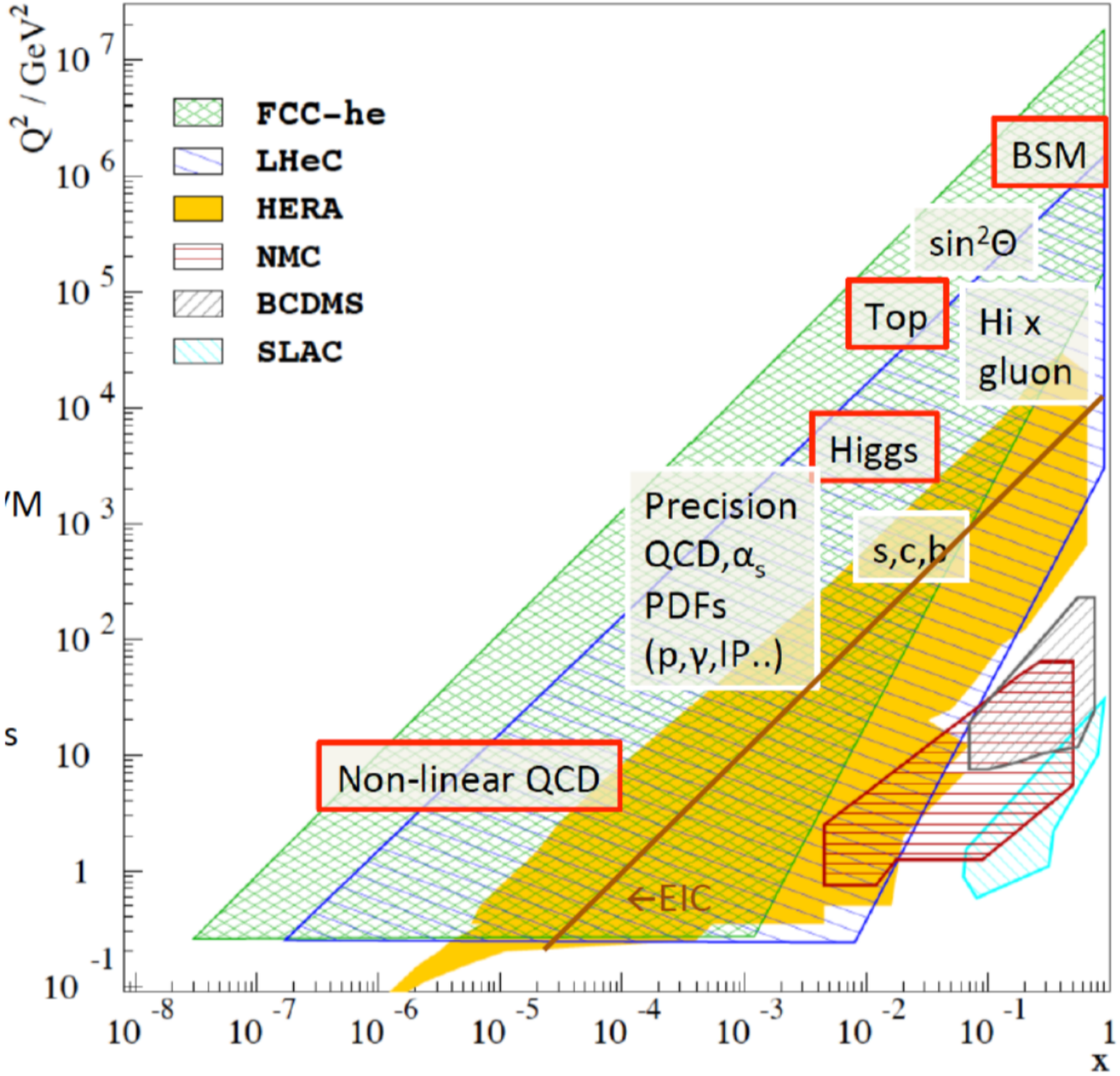
Energy Recovery Linac (ERL) provides the electron beams at 60 GeV and high polarization of 80-90%.



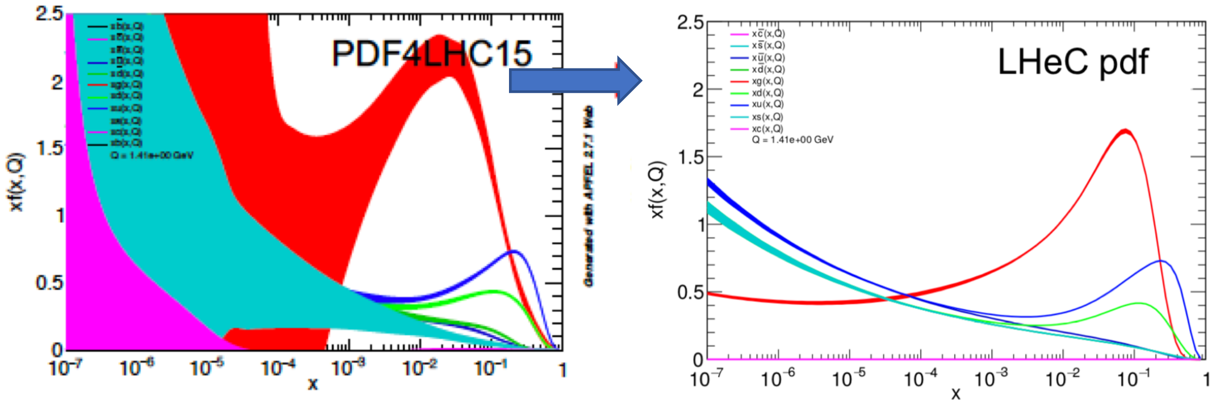


Smaller PERLE demonstrator at Orsay with maximal beam energy of 0.5 GeV.
No showstoppers, but need more resources to bring it forward.

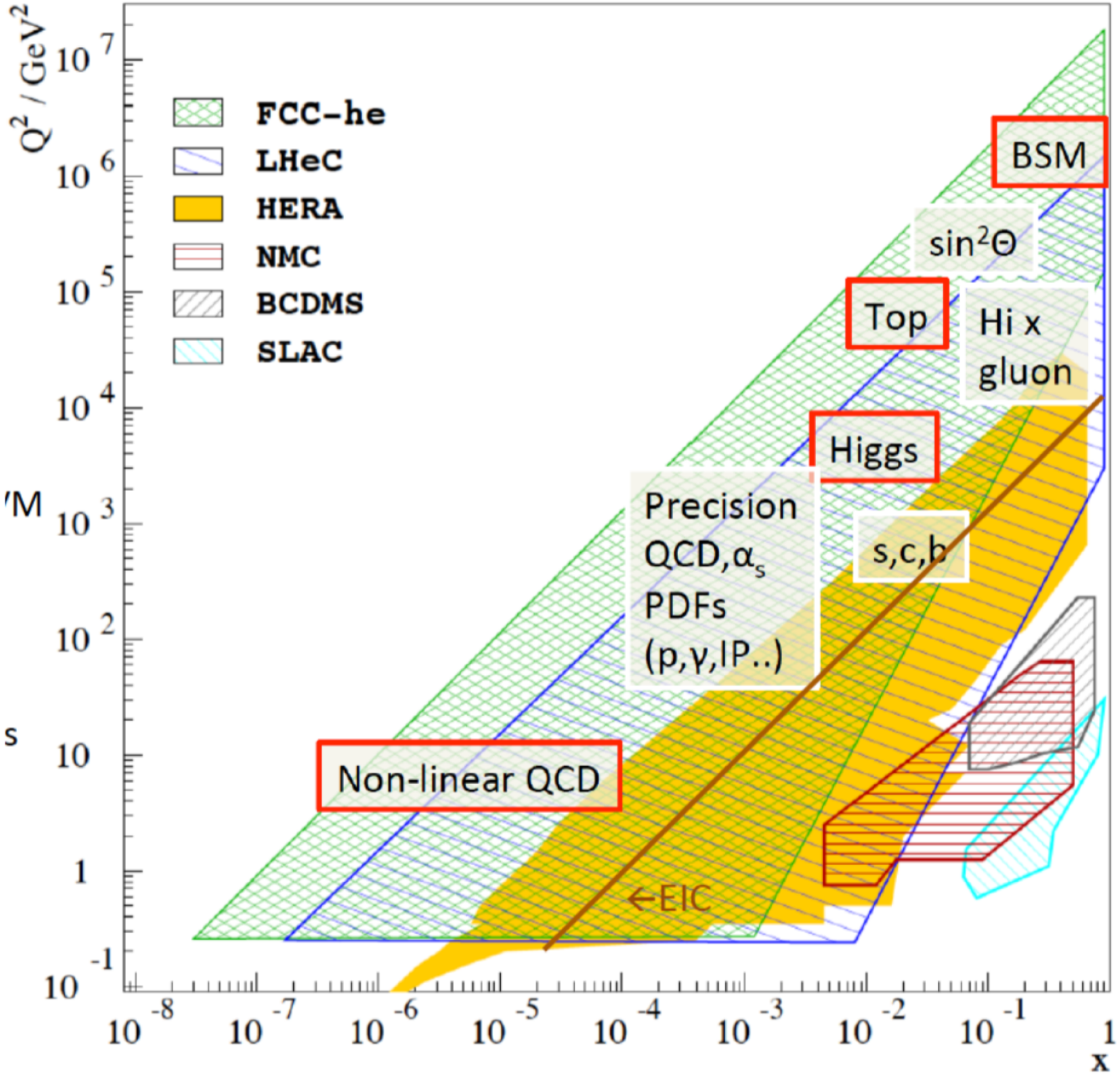
DIS at the highest collision energies: test QCD and vital for particle physics



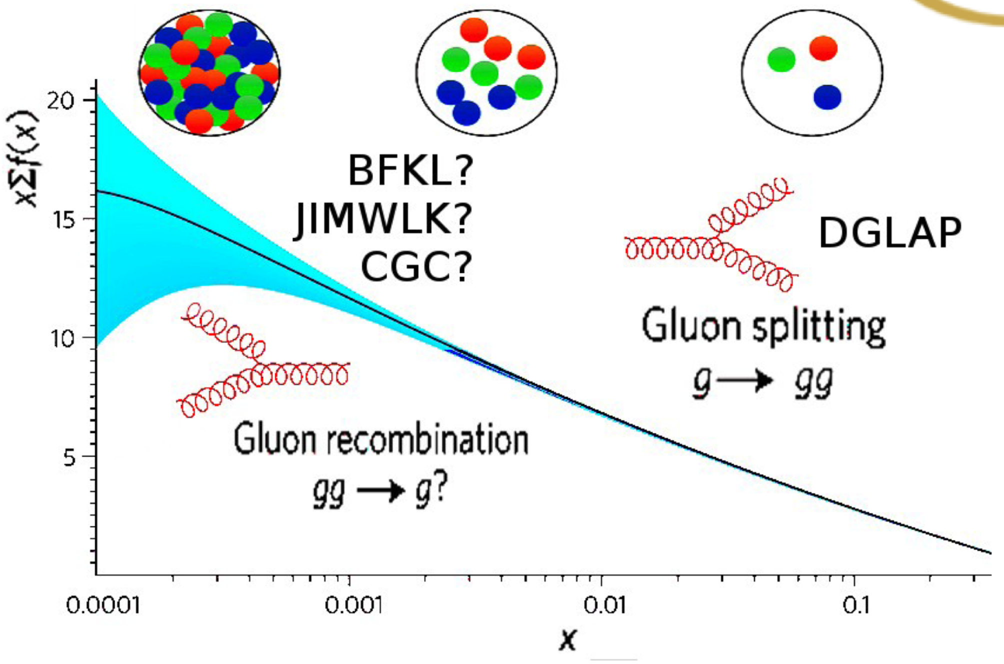
- Precision on large-x, highest-Q^2, flavor decomposition
- Reliable quantification of uncertainties (theory and experiment)
- Beyond the collinear parton model: establish three-dimensional nucleon structure (spin-dependent, transverse momentum, …)



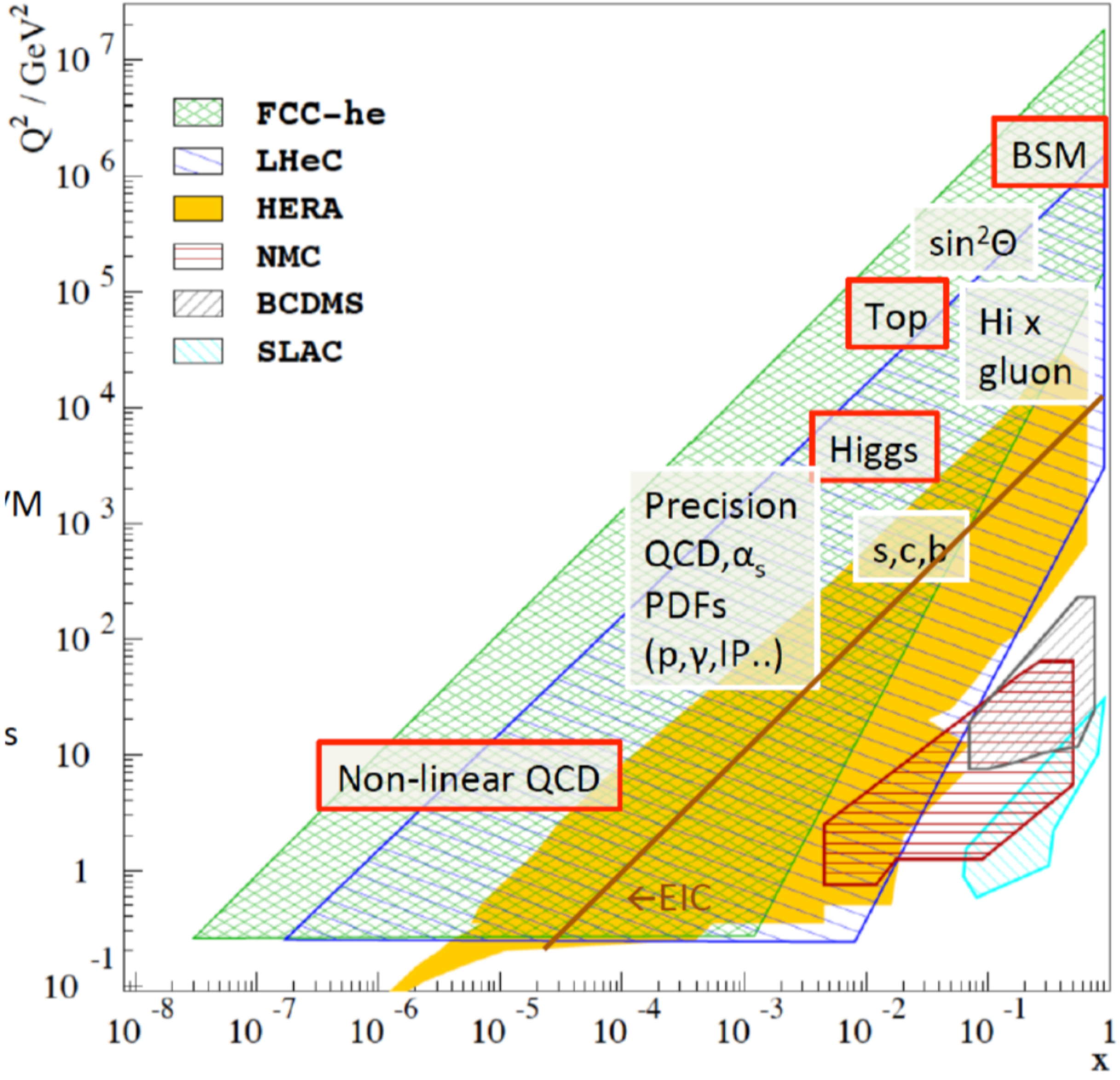
DIS at the highest collision energies: test QCD and vital for particle physics



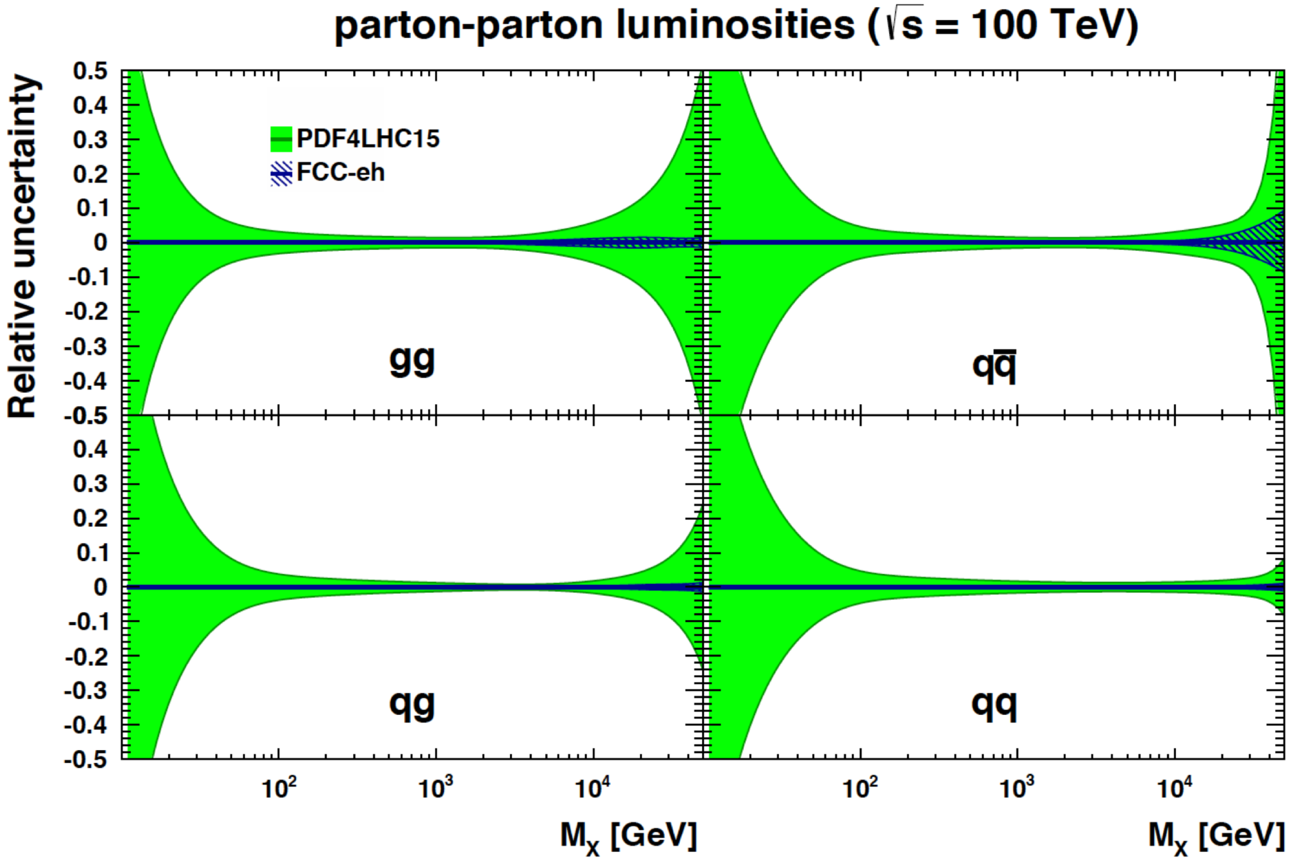
- Precision on large-x, highest-Q^2, flavor decomposition
- Reliable quantification of uncertainties (theory and experiment)
- Beyond the collinear parton model: establish three-dimensional nucleon structure (spin-dependent, transverse momentum, …)
- Test parton dynamics at low-x



DIS at the highest collision energies: test QCD and vital for particle physics



- The set of PDFs from the FCC-ep program will reduce the PDF uncertainties in searches for heavy objects

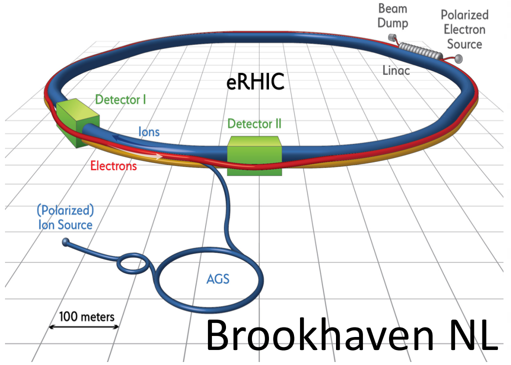


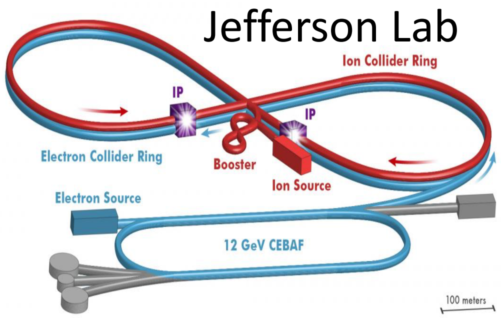
The QCD case for eA collisions at high energies (EIC@US, FCC-eA)

The US-based Electron-Ion Collider (EIC) can address three key questions.

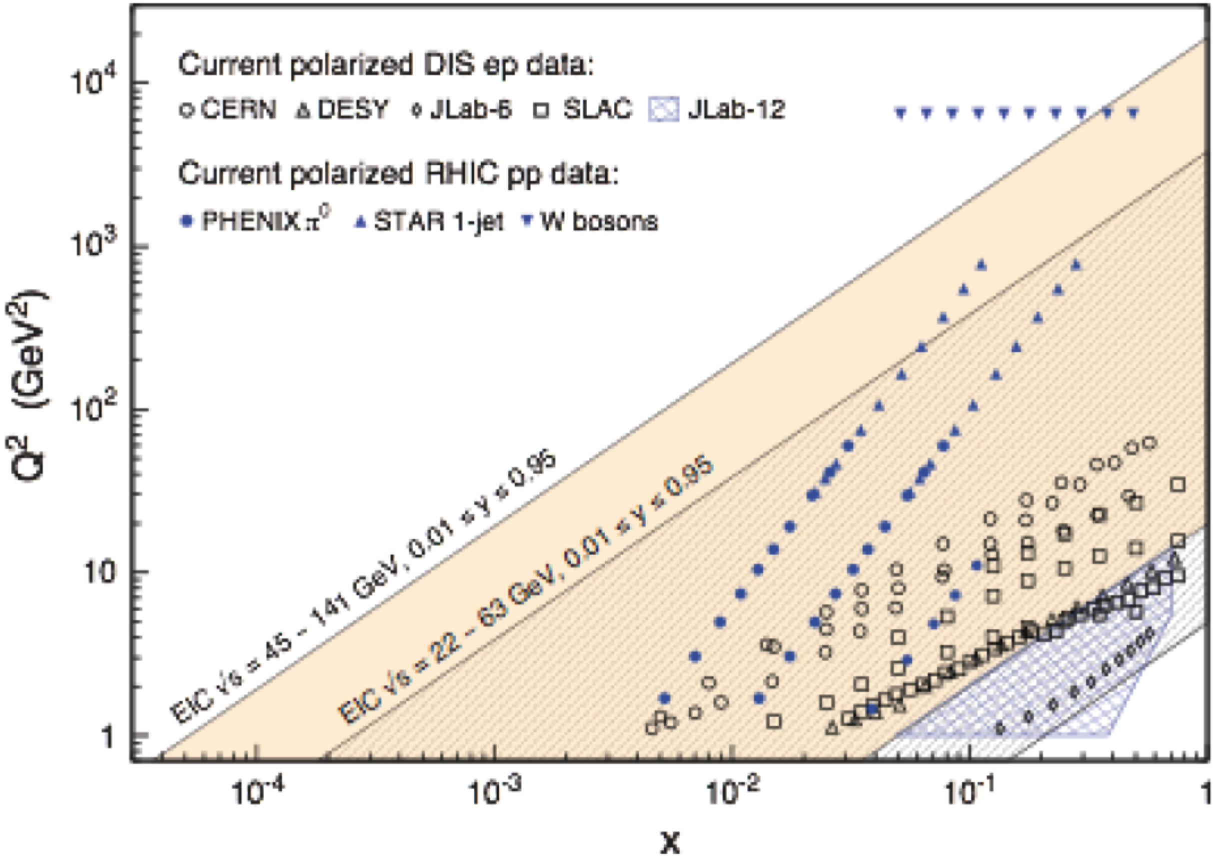
- *How does the mass of the nucleon arise?*
- *How does the spin of the nucleon arise?*
- *What are the emergent properties of a dense system of gluons?*

Two realization concepts being developed.
First collisions from 2029-2030 onwards.



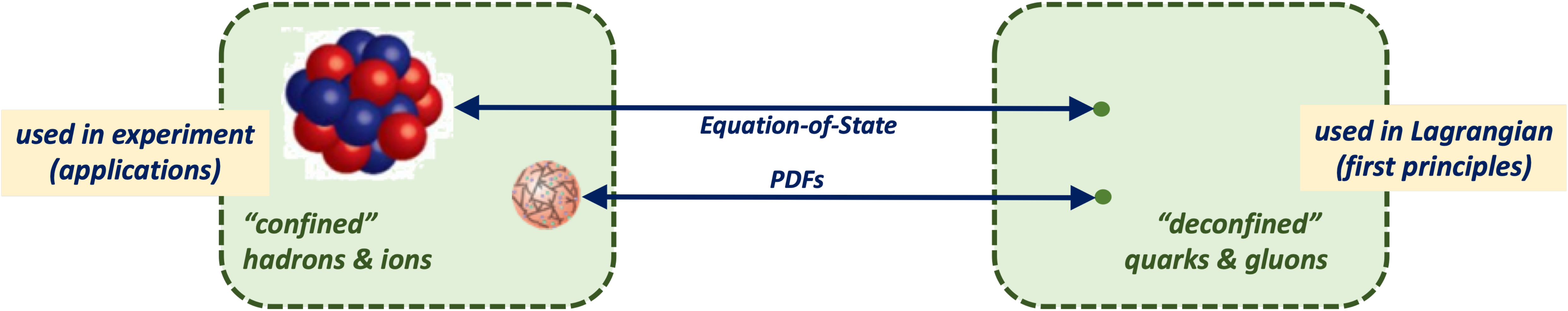


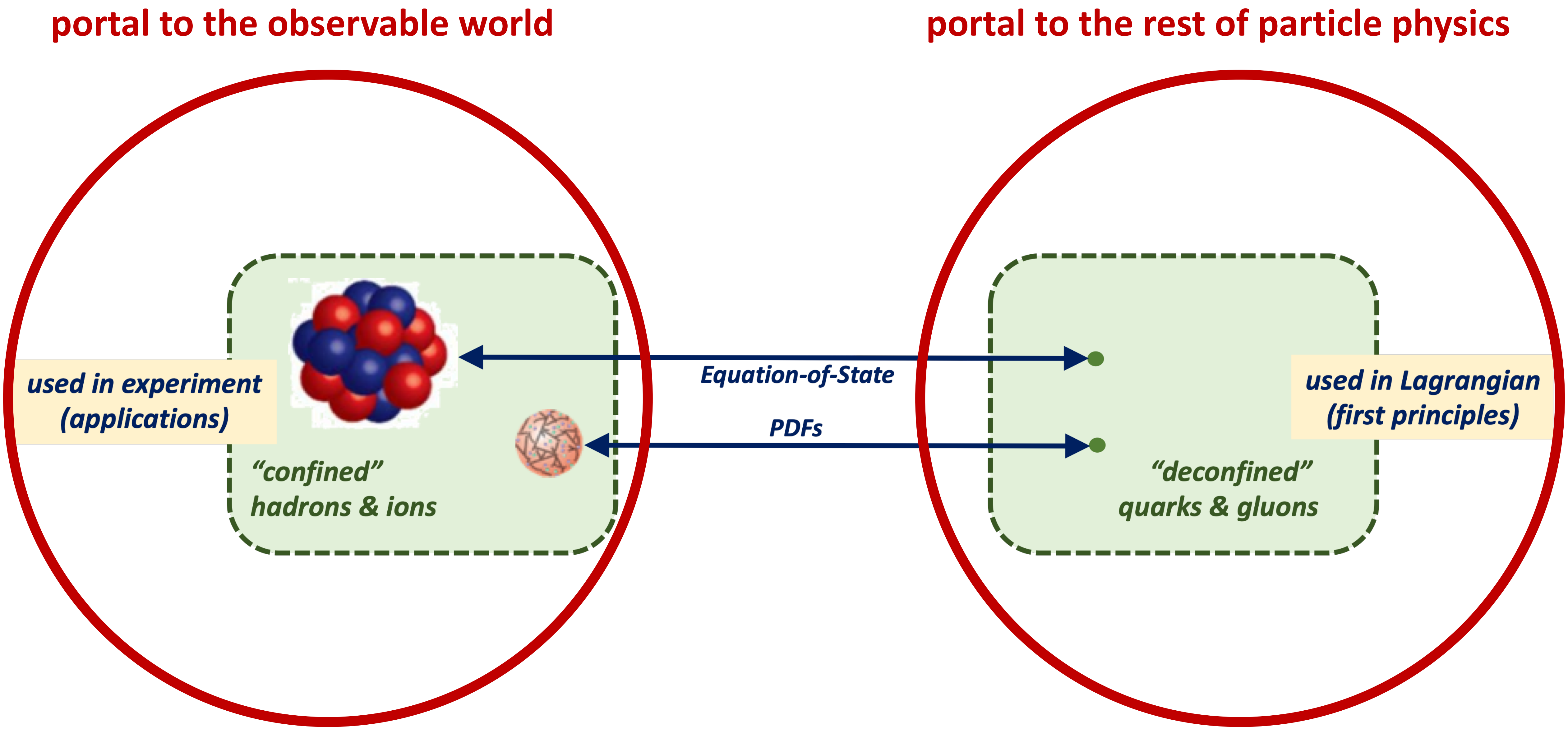
electron-proton DIS at EIC for high-x PDFs
(towards 3D nucleon structures)



Research community at EIC is 1/3 European
Synergies with COMPASS, LHC-FT, LHeC, FCC-eh at CERN

QCD
&
Particle Physics


used in experiment
(applications)
Equation-of-State
PDFs
"confined"
hadrons & ions
used in Lagrangian
(first principles)
"deconfined"
quarks & gluons


portal to the observable world
portal to the rest of particle physics
used in experiment
(applications)
"confined"
hadrons & ions
Equation-of-State
PDFs
used in Lagrangian
(first principles)
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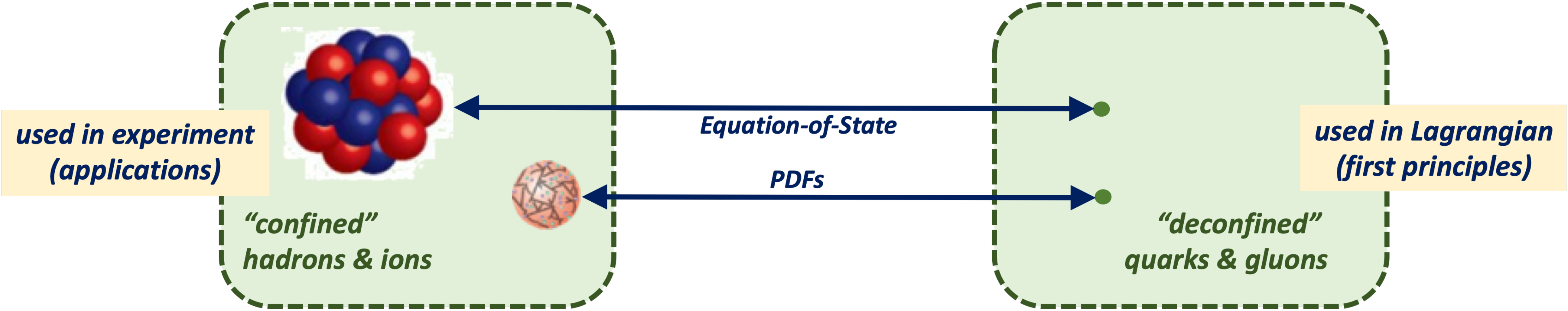
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used in experiment
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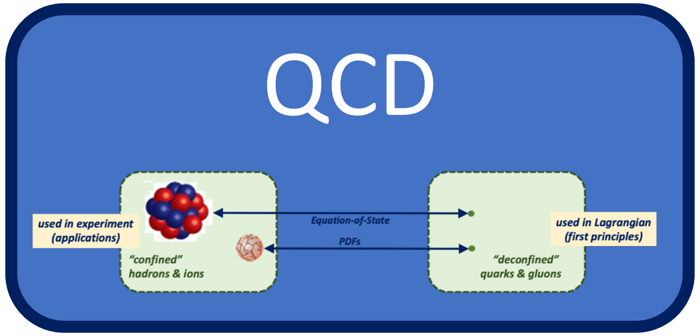
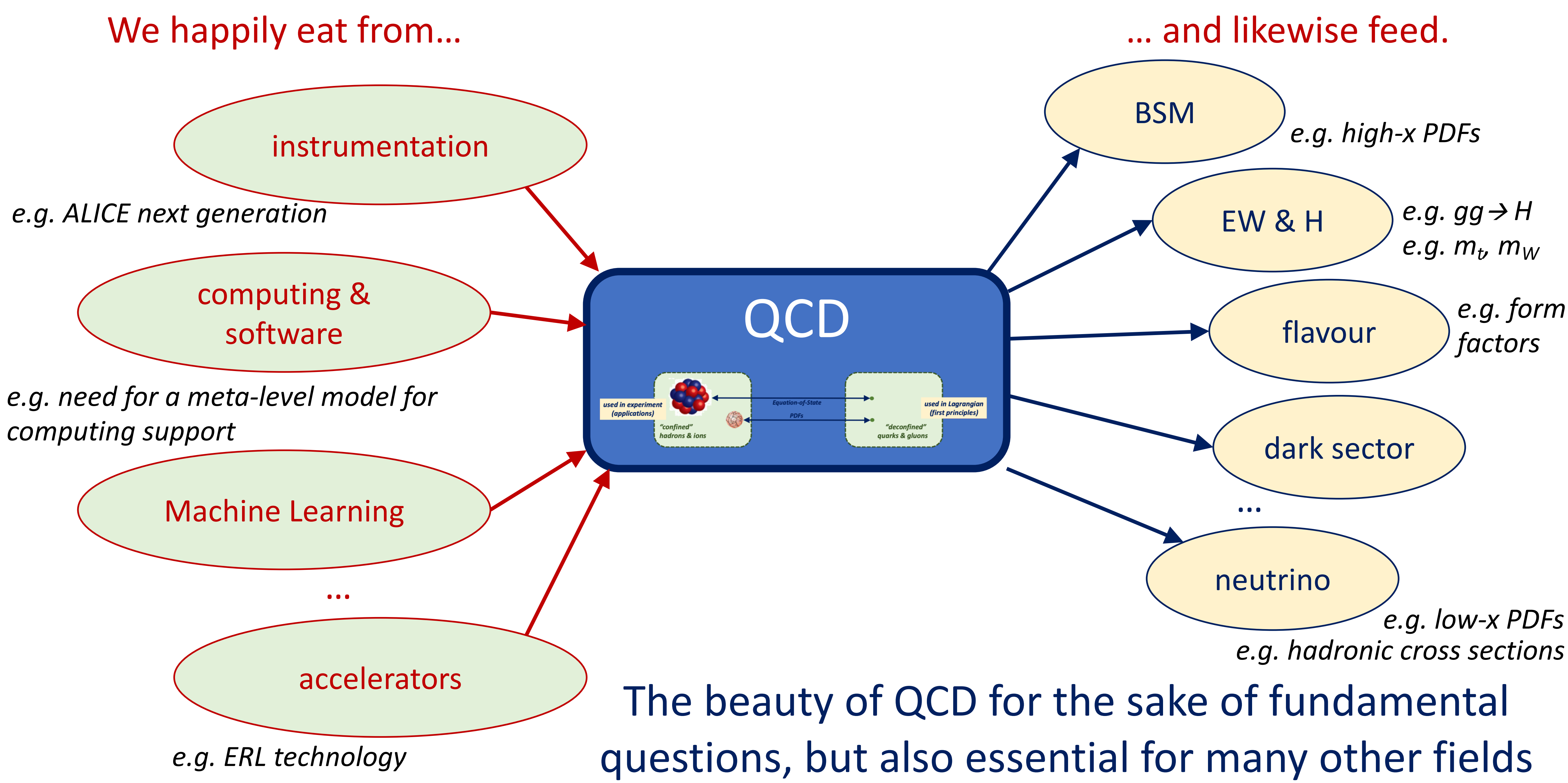

QCD
used in experiment (applications)
Equation-of-State
PDFs
used in Lagrangian (first principles)
"confined" hadrons & ions
"deconfined" quarks & gluons

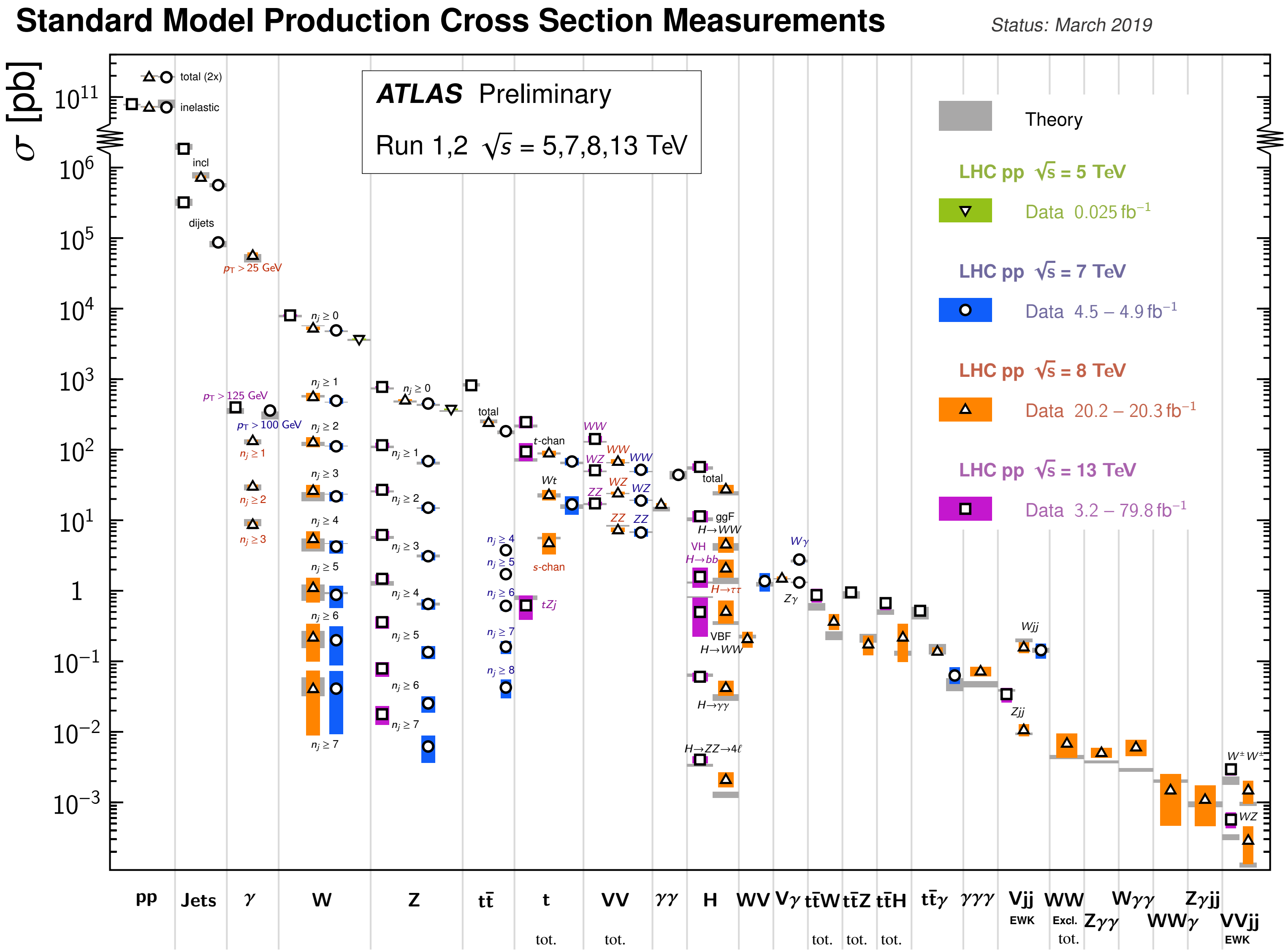

We happily eat from…
… and likewise feed.
instrumentation
e.g. ALICE next generation
computing & software
e.g. need for a meta-level model for computing support
Machine Learning
…
accelerators
e.g. ERL technology
QCD
used in experiment (applications)
“confined” hadrons & ions
Equation-of-State
PDFs
used in Lagrangian (first principles)
“deconfined” quarks & gluons
BSM
e.g. high-x PDFs
EW & H
e.g. gg→H
e.g. m_t, m_W
flavour
e.g. form factors
dark sector
…
neutrino
e.g. low-x PDFs
e.g. hadronic cross sections
The beauty of QCD for the sake of fundamental questions, but also essential for many other fields

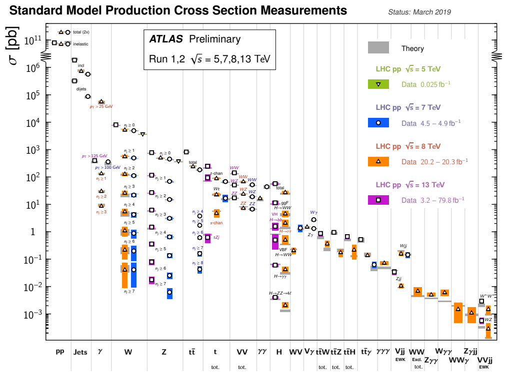
QCD
Methods & Tools

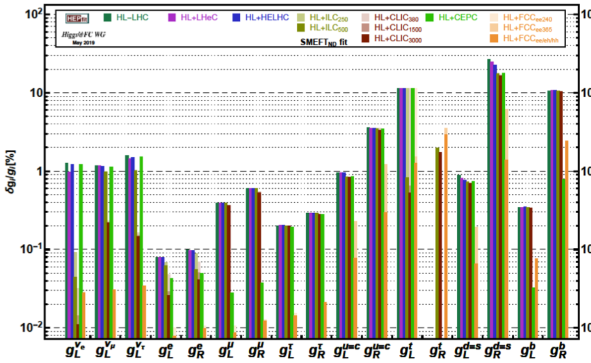
“Experimental measurements are key to guide us into the unknown in the search for new physics”

(HL-)LHC experiments at the frontline the next 15-20 years

key to discovery potential is precision





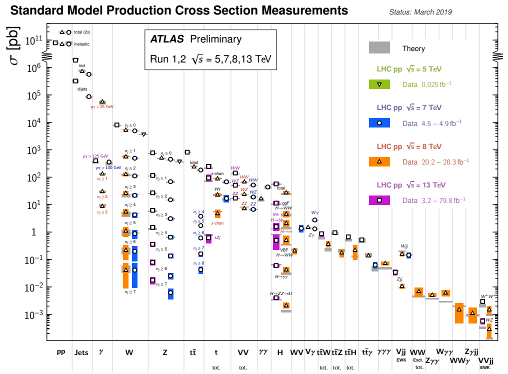


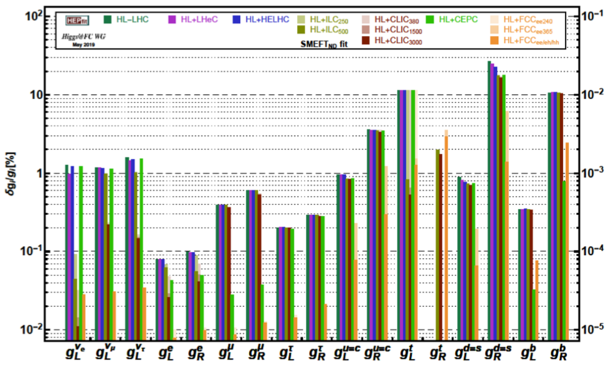
precise measurements

precise exploration

Methods & Tools

e.g. EFT, PDFs, generators, N^{X}O calculations, Lattice, …





precise measurements

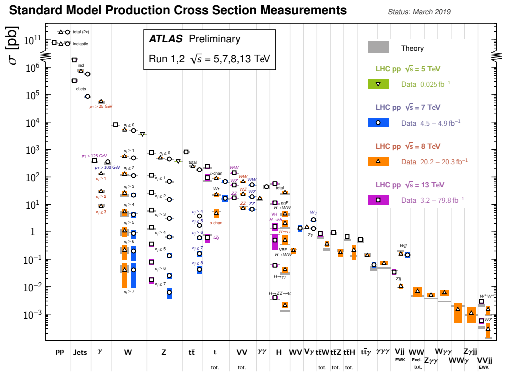
precise exploration

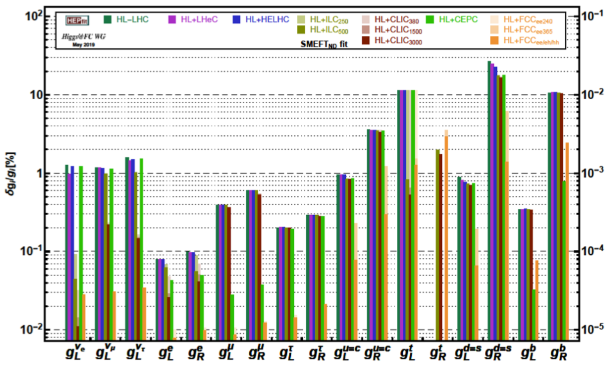
Methods & Tools

e.g. EFT, PDFs, generators, N^XO calculations, Lattice, …

Profound experimental knowledge and theoretical understanding of QCD will be vital to succeed in our exploration with the LHC and HL-LHC, and all future colliders

(for both Direct & Indirect searches)





precise measurements

precise exploration

Methods & Tools

e.g. EFT, PDFs, generators, N^{X}O calculations, Lattice, …

Lattice QCD comes into the precision era

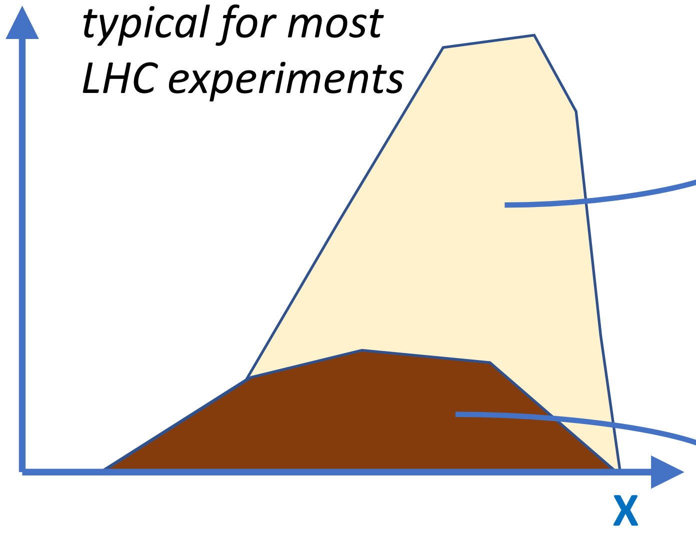
Made possible an essential link between theory and experiment

e.g. α_s, proton radius, (g-2), …

e.g. form factors, PDFs, …

e.g. phase-diagram T vs μ_B, …

QCD theory for particle physics, i.e. for all other physics themes this week



the QCD impact is typically the limiting factor for many LHC analysis

acceptance of the signal (SM and BSM)

examples
- *need N^{3}LO precision for many 2→1 and 2→2 processes (including top quark processes)*
- *coherent approach for higher-order calculations and parton shower*
- *interpretations like the top quark mass*

modelling of the background

Substantial further theory progress is needed to allow a precise interpretation for a wide range of HL-LHC data

- sustain the strong and concerted support for QCD theory work (e.g. *MCnet* Horizon 2020 network)
- foster a community-wide and long-term close collaboration between the experimental and theoretical communities (e.g. inter-experiment workshops with theoreticians)
- explore the complementarity of pp and ep colliders to model collision phenomena

European institutions observe a leading and successful role to face these challenges, and hence have a leading responsibility

QCD
&
Other Disciplines

the visible universe

humans

biological cell

ion

hadron

quarks

~100·000·000·000·000·000·000·000·000

0.00000000000000000001 meter

Synergy with nuclear physics

the visible universe ↓

~100·000·000·000·000·000·000·000·000

humans ↓

biological cell ↓ | ion ↓ | hadron ↓ | quarks ↓

0.0000000000000000001 meter

synergy nuclear & particle physics

- *understand the properties of hadrons and nuclei from first principles*
- *novel detector technologies*

Synergy with nuclear physics

the visible universe — humans — biological cell — ion — hadron — quarks

~100·000·000·000·000·000·000·000·000

0.0000000000000000001 meter

synergy nuclear & particle physics

- *understand the properties of hadrons and nuclei from first principles*
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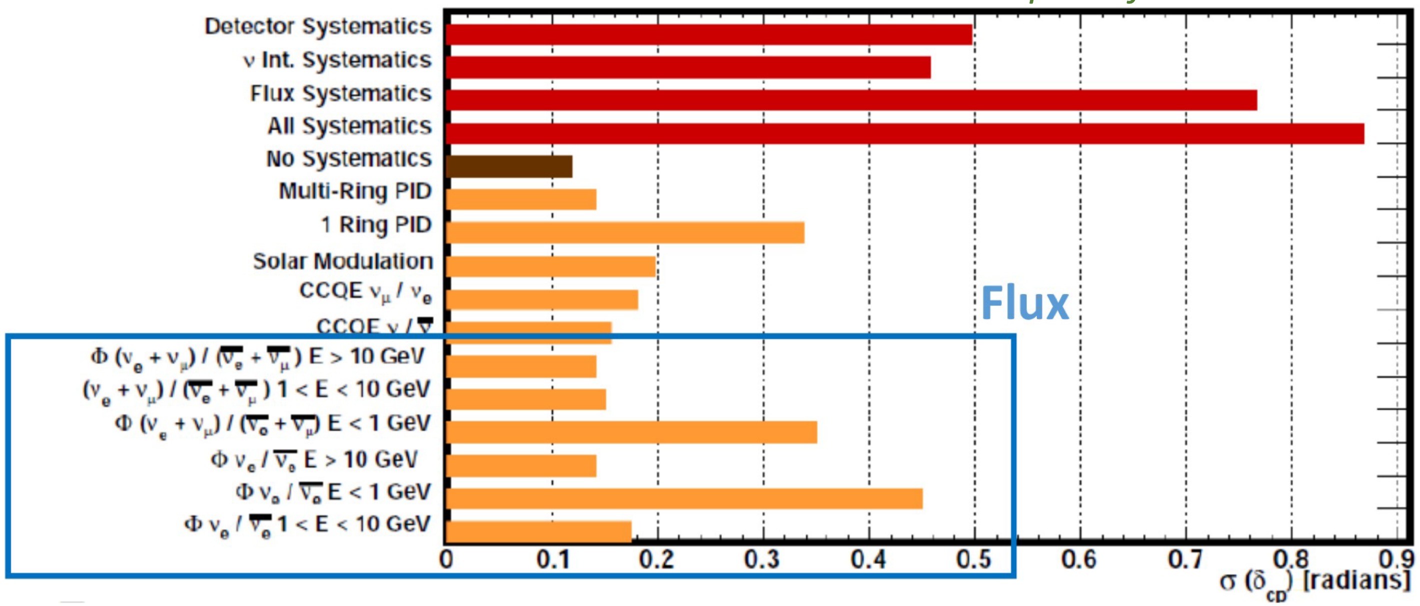
Systematics on δ_{CP} Sensitivity

in Super-K from R. Wendell



Low-energy pA measurements at SPS needed to get precise neutrino fluxes from accelerator & atmospheric (Dune, Super/HyperK, IceCube...)

Synergy with astro and astroparticle physics

the visible universe ↓ humans ↓ biological cell ↓ ion ↓ hadron ↓ quarks ↓

~100·000·000·000·000·000·000·000·000

0.00000000000000000001 meter

synergy astro(particle) & particle physics

- *cosmic rays*
- *star formation*
- *detector technologies*
- *hadronic cross sections*

APPEC

Synergy with astro and astroparticle physics

the visible universe ↓ humans ↓ biological cell ↓ ion ↓ hadron ↓ quarks ↓

~100·000·000·000·000·000·000·000·000

0.0000000000000000001 meter

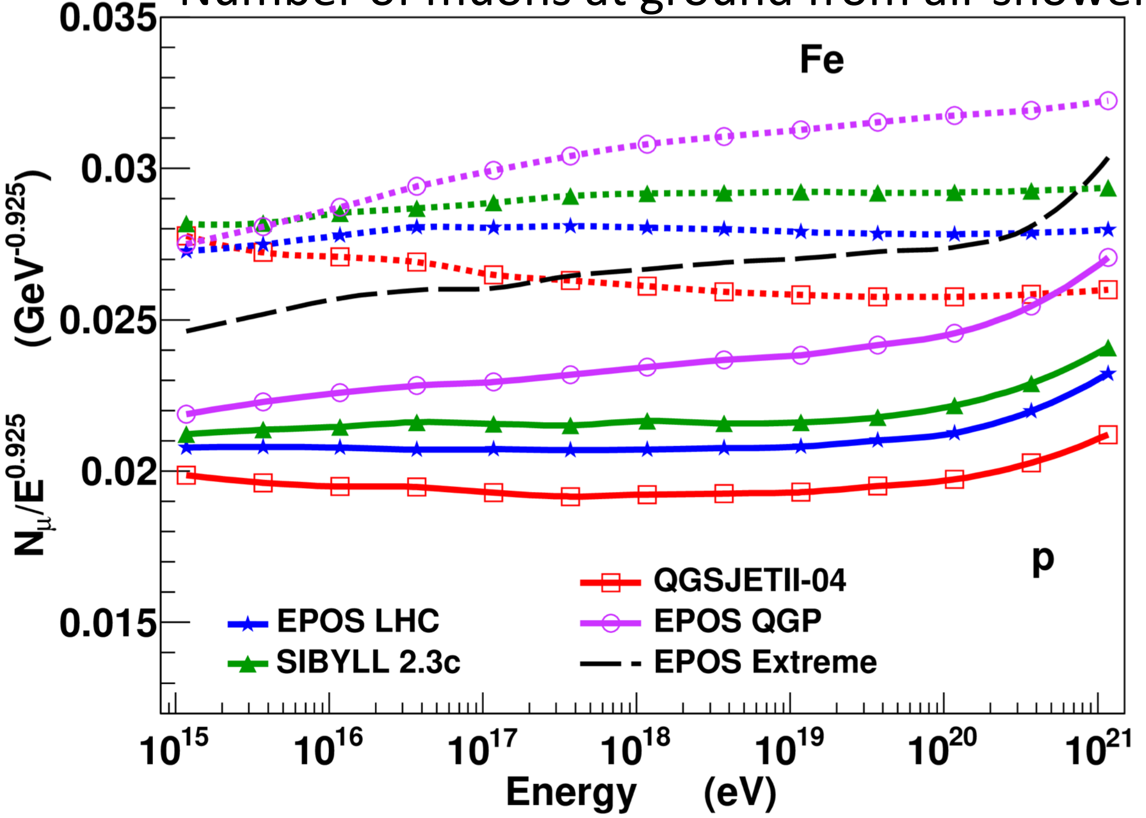
synergy astro(particle) & particle physics

- *cosmic rays (e.g. Pierre Auger observatory)*
- *star formation*
- *detector technologies*
- *hadronic cross sections*

Precise measurements needed in pA and AA (A<20) at highest energies:

- inelastic cross-section
- multiplicity
- diffraction
- forward rapidities

Number of muons at ground from air showers



the visible universe | humans | biological cell | ion | hadron | quarks

~100·000·000·000·000·000·000·000·000 0.0000000000000000001 meter

synergy astro(particle) & particle physics

- *cosmic rays*
- *star formation*
- *detector technologies*
- *hadronic cross sections*

synergy nuclear & particle physics

- *understand the properties of hadrons and nuclei from first principles*
- *novel detector technologies*

"to make the invisible visible"

applications for health, safety, energy, …

QCD is an essential aspect

APPEC

ECFA
European Committee for Future Accelerators

NuPECC

Strong Interactions

Principle Components

Scientific Secretaries:
Anton Adronic (Munster) and Ferenc Sikler (Wigner)

Schedule

Tuesday morning

Session 1 (1 ¾ hours) – QCD oriented

- Talk 1: Scientific aspirations (20+10) T. Gehrmann (Zurich)
- Talk 2: Experimental QCD at high-energy colliders (20+10) D. d'Enterria (CERN)
- Talk 3: Theory challenges (20+10) G. Salam (Oxford)
- *Reserve 15 min*

Session 2 (2 ¼ hours) – Target oriented

- Talk 4: QCD with pre-accelerators @(HL-)LHC (30+15) G. Schnell (Bilbao)
- Talk 5: Precision at low energies (20+10) K. Kirch (PSI)
- Talk 6: Lattice QCD (20+10) H. Wittig (Universität Mainz)
- Talk 7: Fixed Target @(HL-)LHC (20+10) J-P. Lansberg (IPN-Orsay)

Wednesday morning

Session 3 (1 ¾ hours) – HI oriented

- Talk 8: Heavy Ion theory (20+10) U. Wiedemann (CERN)
- Talk 9: Heavy Ion physics at high-energy colliders (20+10) J. Stachel (Heidelberg)
- Talk 10: QCD at eA colliders (20+10) N. Armesto (Santiago de Compostella)
- *Reserve 15 min*

Session 4 (2 ¼ hours) – Topical

- Talk 11: Around the world (20+10) T. Galatyuk (Darmstadt)
- Talk 12: Synergies ApPEC/NuPECC/Neutrino (20+10) T. Pierog (KIT)
- Talk 13: QCD at ep colliders (20+10) U. Klein (Liverpool)
- Talk 14: Use the LHC facility post HL-LHC for QCD (10+20) D. Boer (Groningen)
- *Reserve 15 min*

European Strategy Update

Scientific Secretaries:
Anton Adronic (Munster) and Ferenc Sikler (Wigner)

Schedule

Thank you very much!

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- Talk 10: QCD at eA colliders (20+10) N. Armesto (Santiago de Compostella)
- *Reserve 15 min*

Session 4 (2 ¼ hours) – Topical
- Talk 11: Around the world (20+10) T. Galatyuk (Darmstadt)
- Talk 12: Synergies ApPEC/NuPECC/Neutrino (20+10) T. Pierog (KIT)
- Talk 13: QCD at ep colliders (20+10) U. Klein (Liverpool)
- Talk 14: Use the LHC facility post HL-LHC for QCD (10+20) D. Boer (Groningen)
- *Reserve 15 min*

Principle Components for QCD

Hot & Dense QCD

A coherent and complementary “hot & dense QCD program” at the SPS brings valuable and unique contributions in the exploration of the QCD phase diagram.

An (HL-HE-)LHC/FCC based AA/pA/fixed-target program is unique and provides essential science at the frontline towards a profound understanding of particle physics.

Precision QCD

A globally concerted “precision QCD program” provides a unique avenue to find new physics that breaks the Standard Model.

An EW scale and high-luminosity e^+e^- collider provides a unique test for pQCD, essential for most of our aspirations in particle physics.

Partonic Structure

A “nuclear structure program” exploring the complementarity of ep/pp/eA colliders provides vital ingredients to high-precision exploration (QCD to serve particle physics) and steps into unique unknown territories of new physics (QCD to test particle physics).

Theory

It is vital to support coherently the QCD theory community to succeed in all these programs and to link QCD to the rest of the particle physics research program, especially for our HL-LHC exploration.

Organization

Strengthening the synergies in research and technology with adjacent fields will reinforce our efforts.

Global platforms, networks and institutes have the potential to enhance the research exchange among experts worldwide and to provide essential training opportunities.

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Thank you for your attention

Back-up

From the previous Physics Briefing Book

5.6 Strategy Issues

The following points could be considered in the discussion on the strategy update:

- For the upgrade of the LHC Pb beam programme after LS2, luminosities of order $6 \times 10^{27}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ are essential to reach the proposed physics goals.
- Some of the possible LHC measurements, which are crucial for understanding of strong interactions, require dedicated low-pileup running. The resulting loss in the total luminosity is expected to be small.
- Dedicated analysis, taking into account all relevant experimental and theoretical aspects, should be performed to give quantitative estimates of the PDF accuracy which can be ultimately reached with the LHC data. This is required for comparison with LHeC capabilities, against the background of the exact requirements of HL-LHC for PDF uncertainties, which should be established as well.
- The LHeC project offers, in addition to the PDF studies motivated by LHC needs, a very rich and diverse physics programme by itself. If the project is to be considered as one of the future collider options, dedicated effort towards the preparation of a Technical Design Report is needed.
- The fixed-target programme at CERN gives a very valuable contribution to research in strong interaction physics. It offers unique measurement possibilities which can not be covered at other facilities.

“Big Questions” on Open Symposium website

- What are the experimental and theoretical pre-requisites to reach an adequate precision of perturbative and non-perturbative QCD predictions at the highest energies?
- What can be learned from beams-on-target experiments at current and potential future (pre-)accelerators to test strong interactions?
- How to probe the QGP equation of state and to establish whether there is a 1st order phase transition at high baryon density?
- What is known about the make-up of the proton (mass, radius, spin, etc.) and how to extract it?
- What is the role of strong interactions at very low and very high (up to astrophysical) energies?

Strong Interactions

Copied from the input submission page:

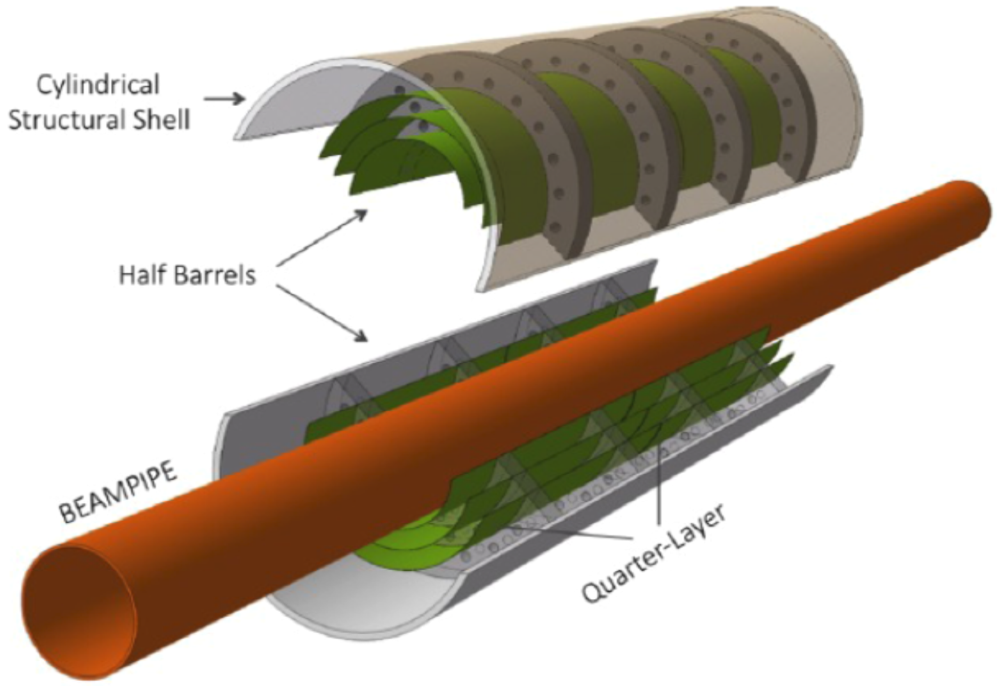
- perturbative and non-perturbative QCD
- DIS
- Heavy Ions

The upgrade of ALICE for Run4 @ HL-LHC: AA/pA

slide from Johanna Stachel

Proposed ITS3 in ALICE

3 layers of stitched CMOS MAPS sensors of up to 508 cm^2
with 56 M pixels (30 x 30 μm^2)



near-term realization of this technology in a running experiment will revolutionize vertexing

Ultra-thin chip (<50 um): flexible with good stability

expression of interest for an ALICE ITS upgrade in LS3 – ALICE-PUBLIC-2018-013

Johanna Stachel   RUPRECHT-KARLS-UNIVERSITÄT HEIDELBERG

QCD
Organization

QCD in the organization