Strong-interaction physics at the existing CERN pre-accelerator complex

Gunar Schnell

ESPP Update — Open Symposium Granada May 2019

- ID 039 - EPIC: Exploiting the Potential of ISOLDE at CERN
- ID 042 - The Physics Beyond Colliders Study at CERN (DIRAC++)
- ID 118 - MUonE
- ID 143 - COMPASS++/AMBER

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Universidad del País Vasco
Euskal Herriko Unibertsitatea

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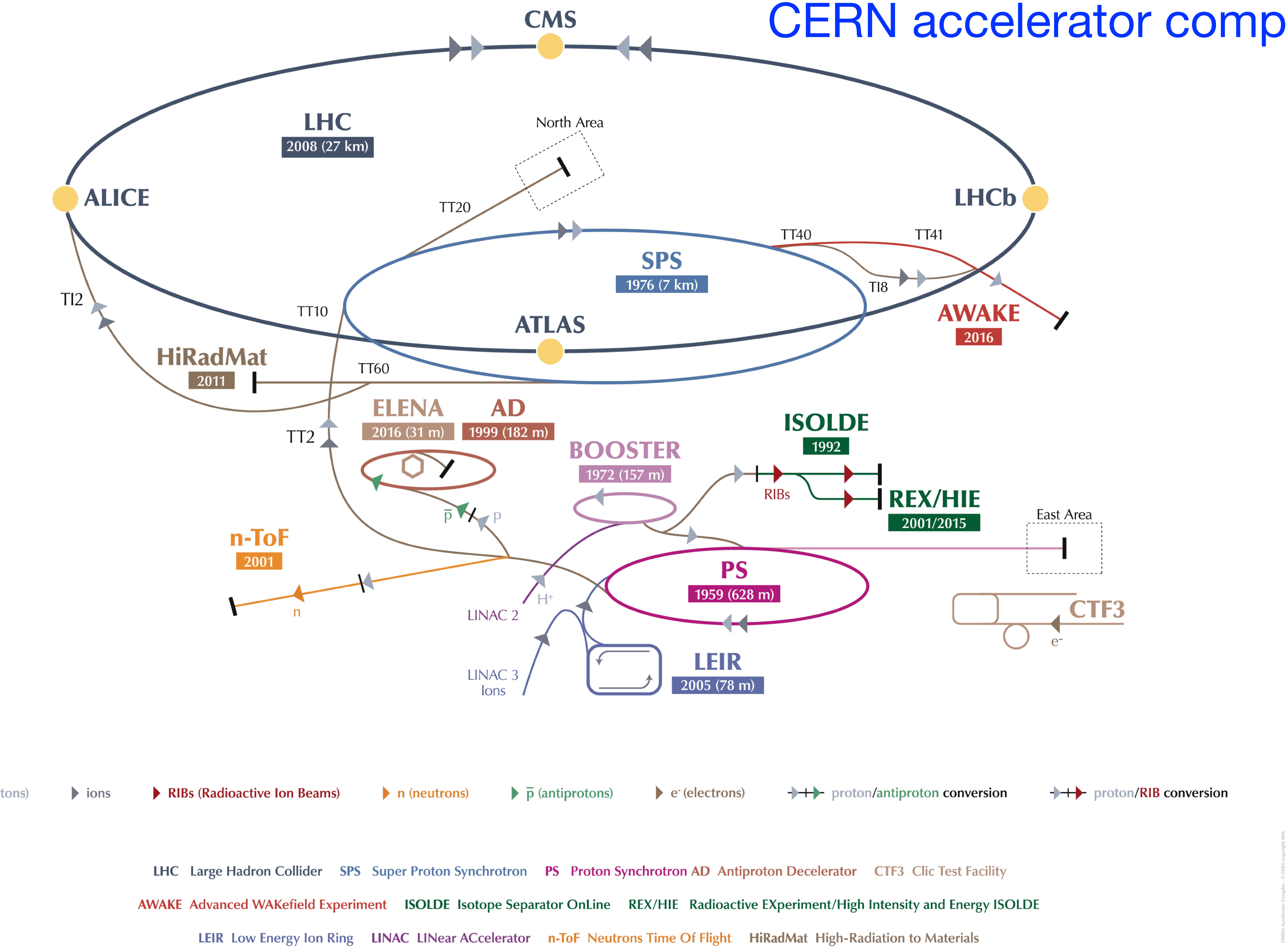
ESPP Update — Open Symposium Granada May 2019

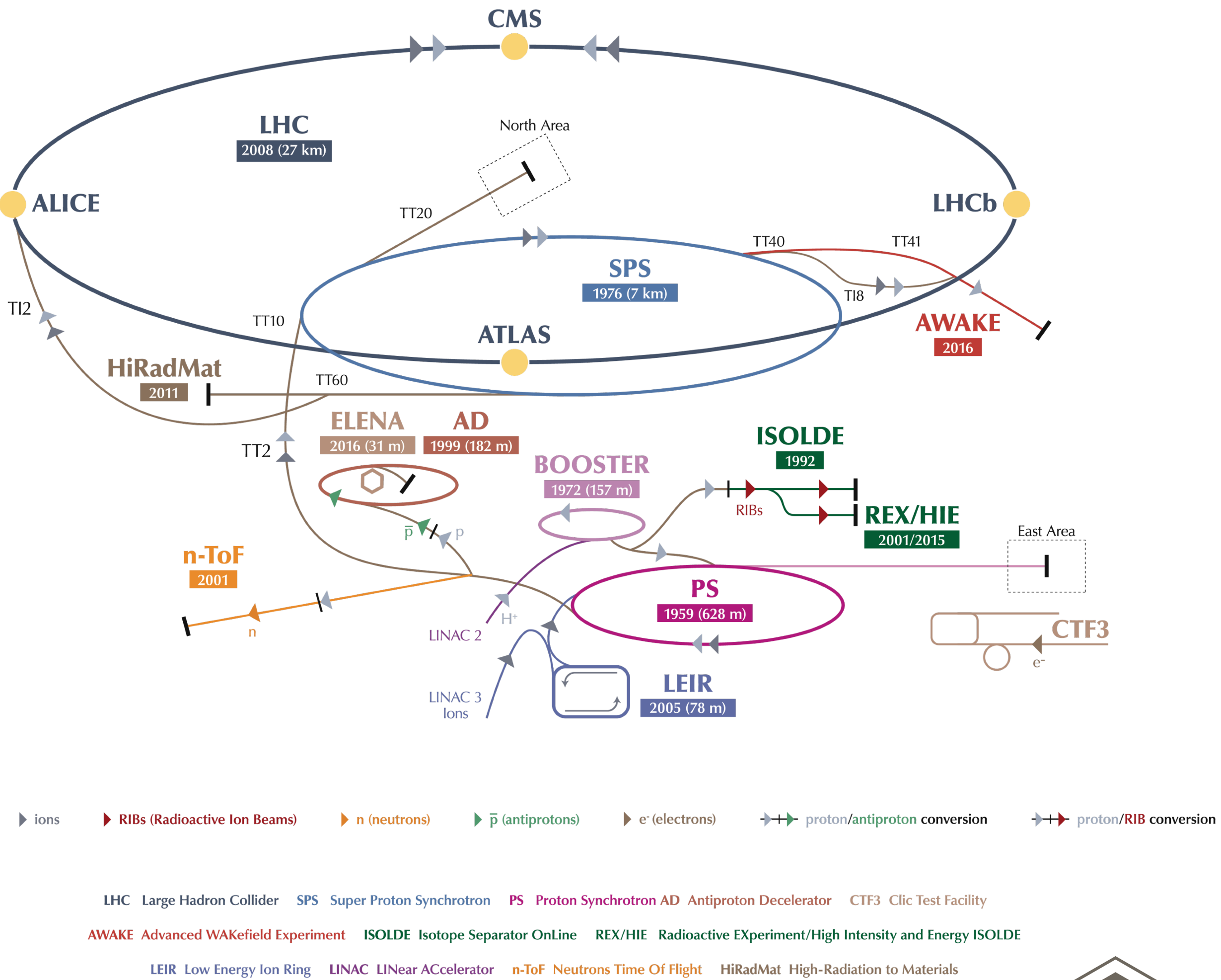
gratefully acknowledging input from

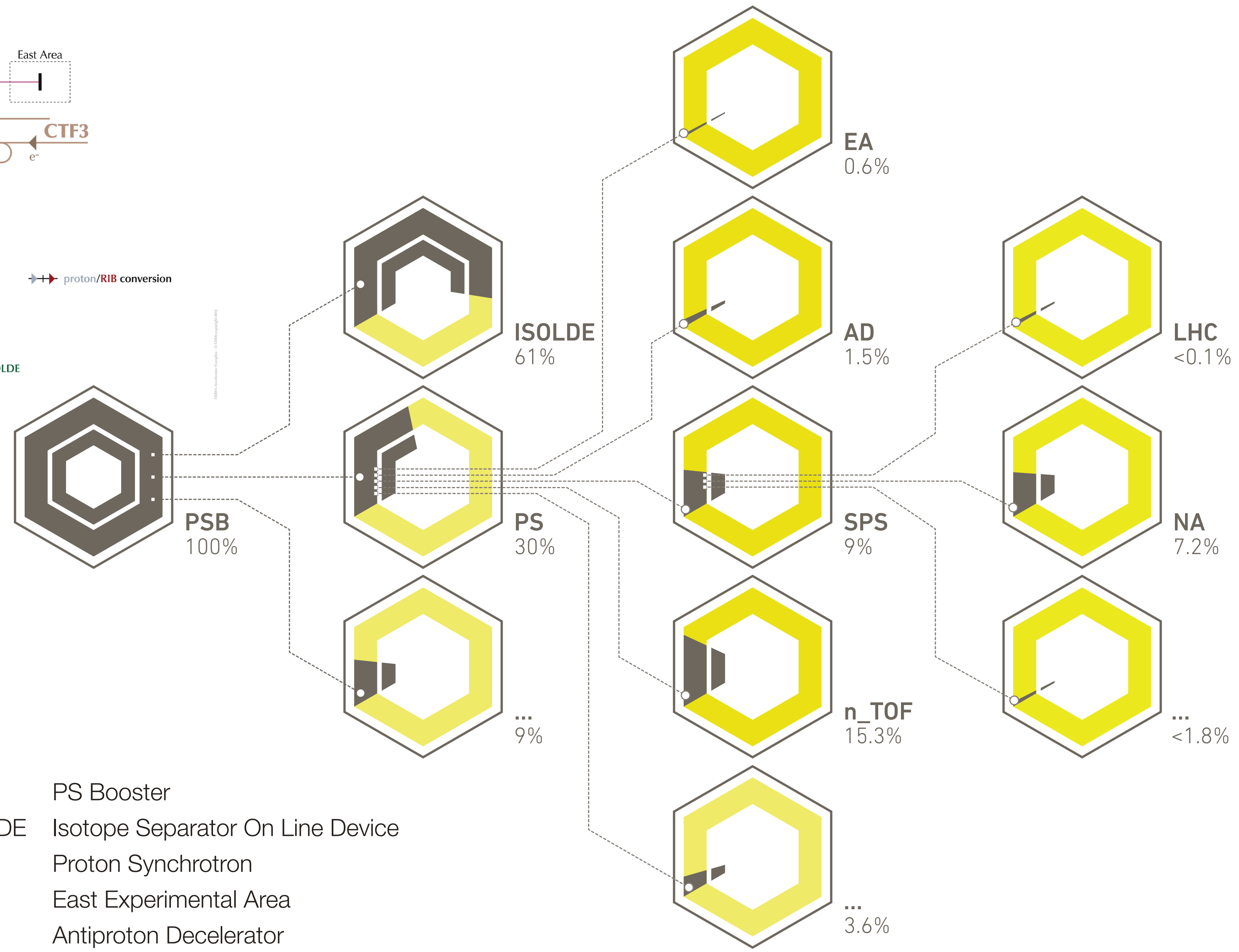
- Gerda Neyens
- Markus Diehl
- the CERN Physics Beyond Collider study group as well as the various proponents

CERN accelerator complex

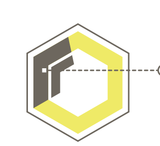


CERN accelerator complex





PSB	PS Booster
ISOLDE	Isotope Separator On Line Device
PS	Proton Synchrotron
EA	East Experimental Area
AD	Antiproton Decelerator
SPS	Super Proton Synchrotron
n_TOF	Neutron Time-of-Flight facility
LHC	Large Hadron Collider
NA	North Experimental Area
...	Other uses, including accelerator studies (machine development)



Quantity of protons used in 2016 by each accelerator and experimental facility, shown as a percentage of the number of protons sent by the PS Booster

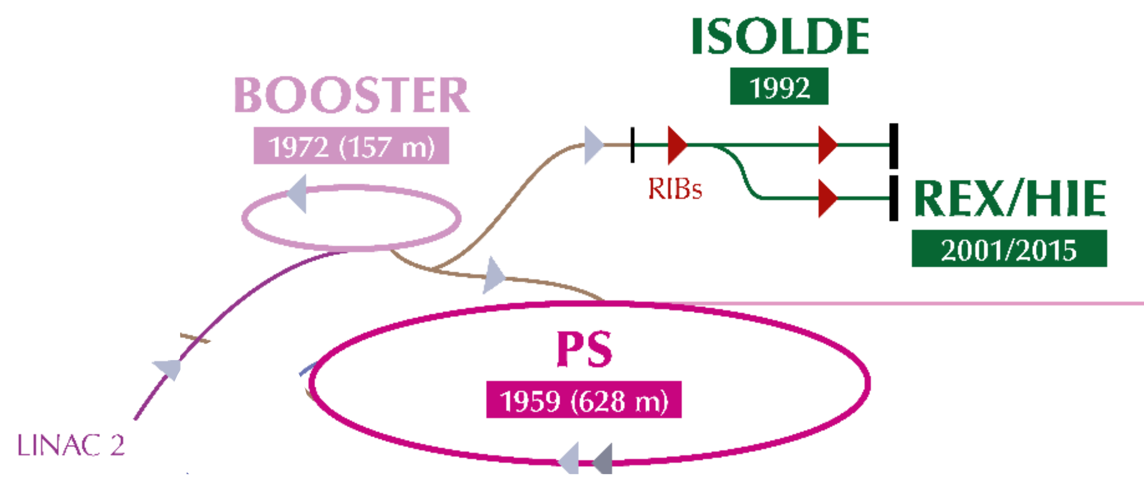
a Radioactive Ion Beam (RIB) facility at

ISOLDE: approved by CERN council in 1964

Started operation in 1967

Initially used 600 MeV protons from SC

Later 1.0 GeV (and 1.4 GeV) protons from PSB



UNIQUE worldwide thanks to 1.4 GeV protons on thick targets (20 cm)

More than 50 years of experience in production of <u>pure radioactive isotopes</u> <u>and beams</u>

- >1000 isotopes available already (of 3000 known)
- >70 different elements
- >10 different permanent experimental set-ups (and new ones coming!)

Since 2001: re-acceleration of RIB's with REX and HIE-ISOLDE (NC and SC Linac)

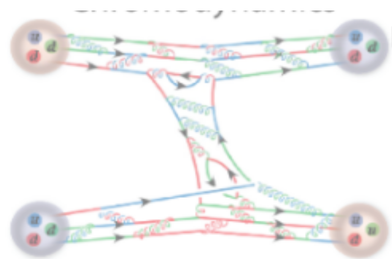
- Beams up to 9.5 MeV/nucleon
- Doubled the users community (reactions with RIB's)
- <u>More than 45 experiments</u> for more than <u>500 users/year</u> (from 43 countries)

(>**1300 registered ISOLDE users**)

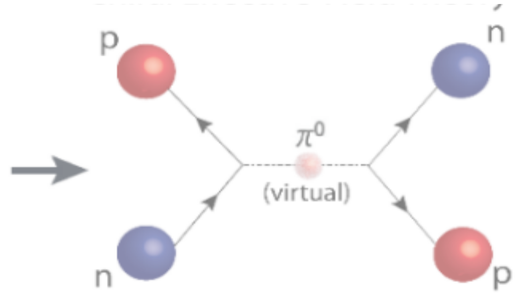
Example: Emergence of Nuclear Phenomena from QCD

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

Quantum Chromodynamics



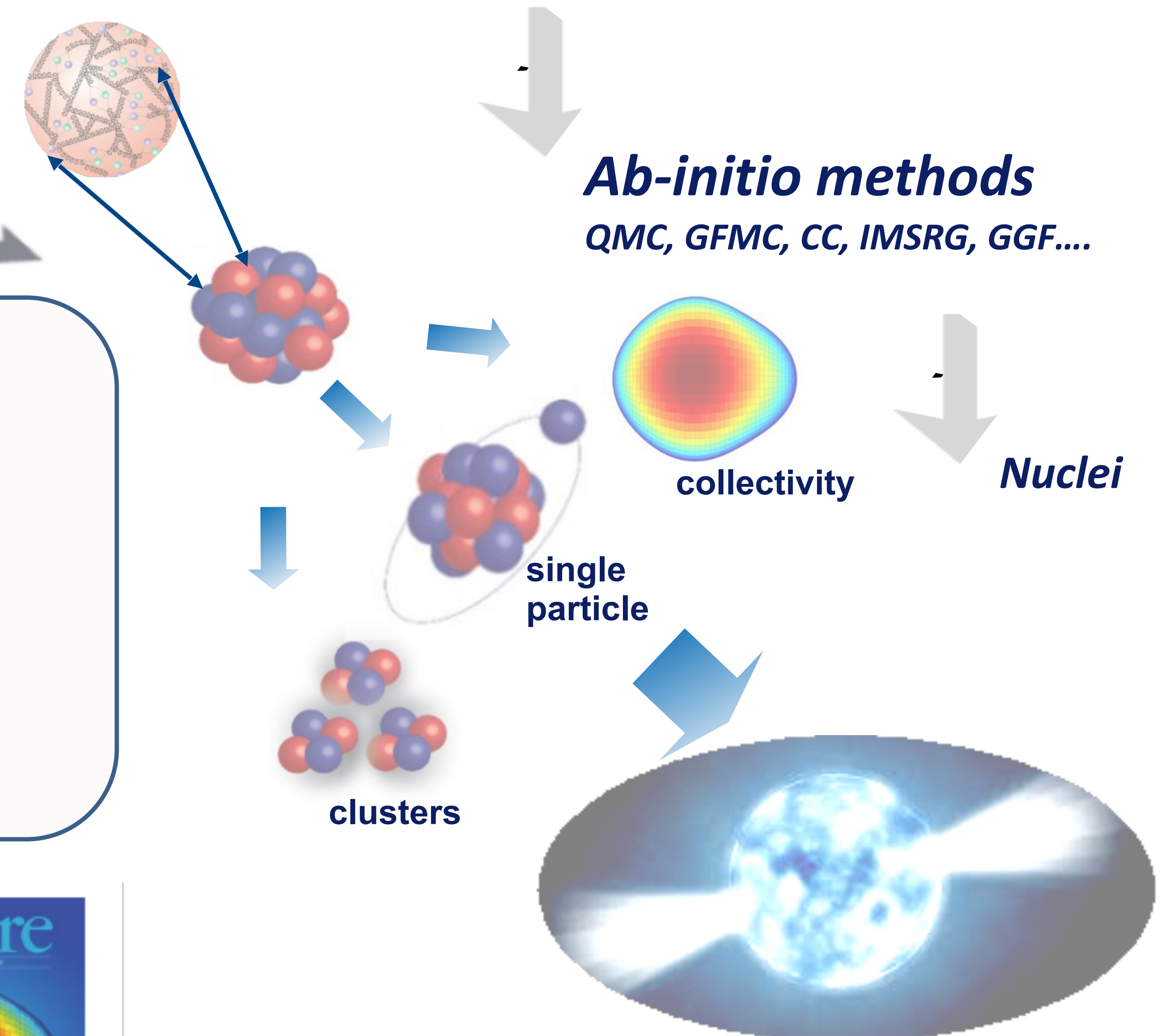
Chiral Effective-Field Theory



Lattice QCD

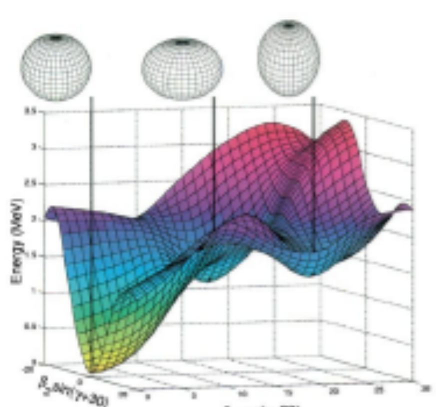
Ab-initio methods

QMC, GFMC, CC, IMSRG, GGF….



Recent highlights from exotic nuclei @ ISOLDE-CERN:

- **Shape Staggering**
  - [Marsh et al. Nature Phys. 14, 1163 (2018)]
- **New "magic" nuclei**
  - [Garcia Ruiz et al. Nature Phys. 12, 594 (2016)]
  - [Wienholtz et al. Nature 498, 346 (2013)]
- **Discovery of "pear" shaped nuclei**
  - [Gaffney et al. Nature 497, 199 (2013)]



Neutron-rich nuclei:
"Quantum simulators" of neutron stars

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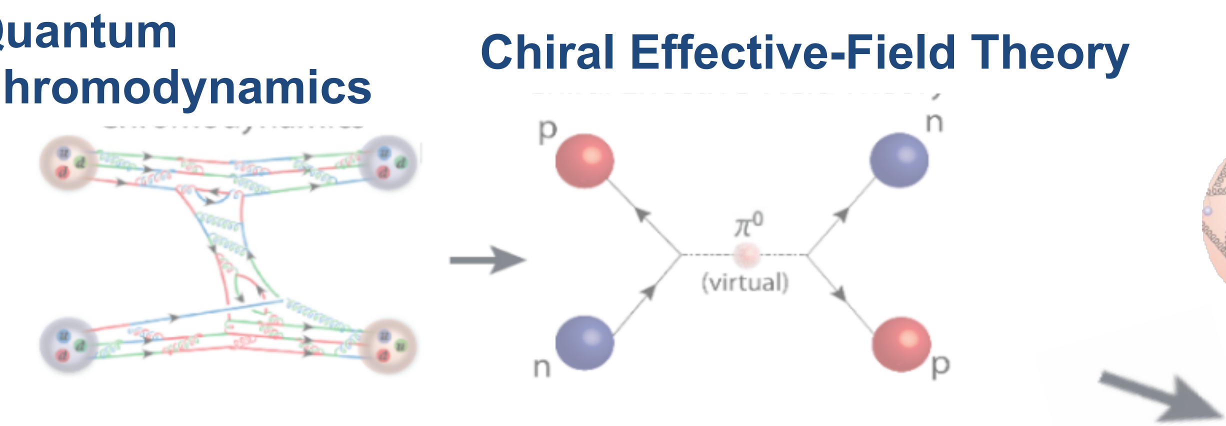

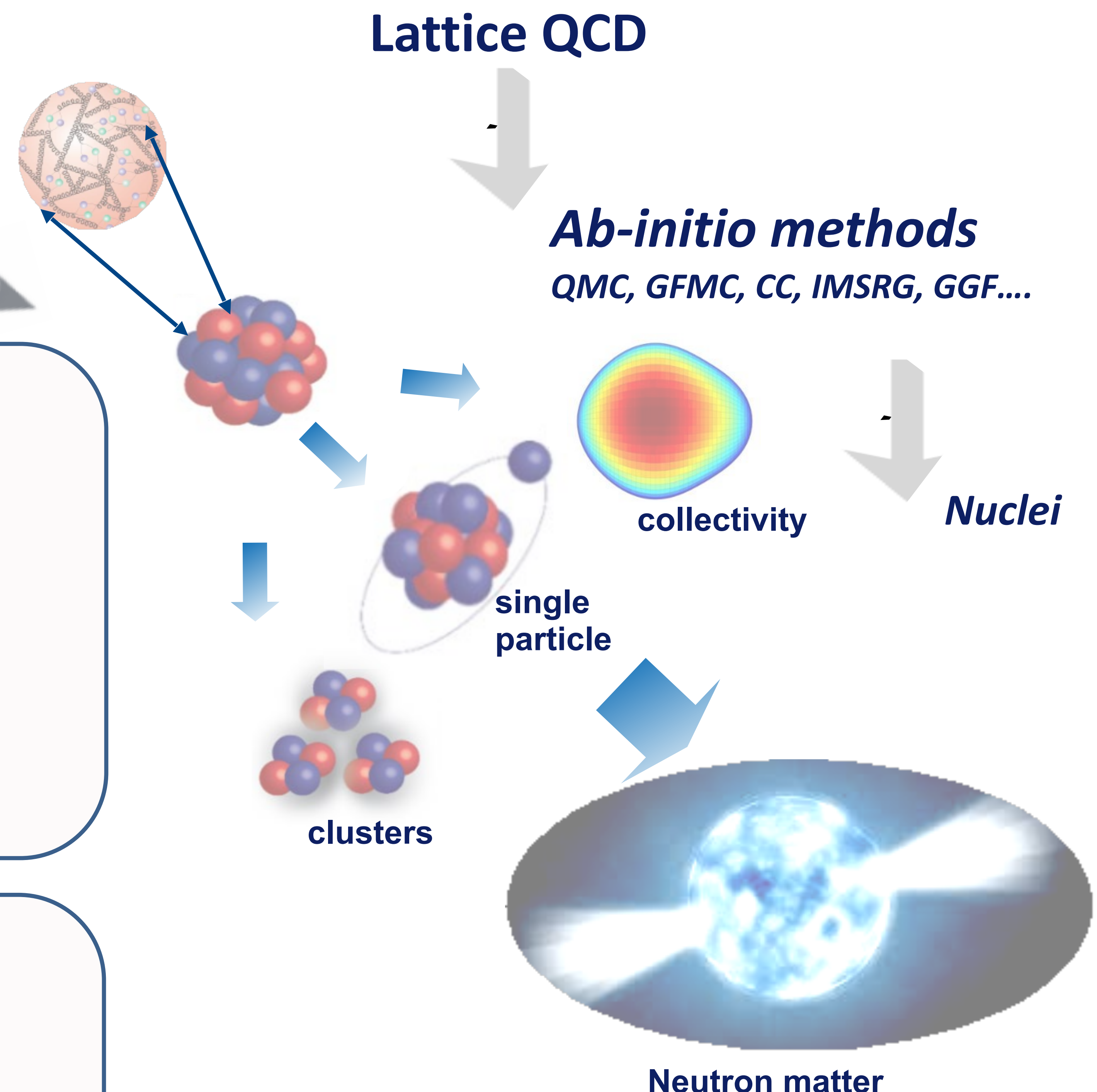

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Broad physics scope beyond SM complementary to HEP searches

☛ S. Paul

☛ S. Mertens

Neutron-rich nuclei:
"Quantum simulators" of neutron stars

The EPIC project @ ISOLDE

Exploiting the Potential of ISOLDE at CERN

1. **Take advantage of LHC Injector Upgrades: proton BOOSTER energy and intensity increase**
   → gain a factor of 2-10 in radioactive beam intensity

2. **Install additional target station(s): allow parallel beams**
   → double the beam time for increasing amount of users
   (more than 80 accepted experiments, typically 30 new per year coming)

3. **Install a 'Storage Ring' for short-lived (low-energy) isotopes – unique worldwide**
   → new opportunities in atomic, nuclear and fundamental (new) physics

4. **A new experimental hall** (new experiments coming – mostly low-energy for searching new symmetries/interactions)
   - **MIRACLS** (ultrapure beams)
   - **PUMA** (interactions between exotic matter/anti-matter)
   - **Set-up/Trap for RaF molecules** (eEDM and other symmetry violations)
   - **Large superconducting magnet** for materials studies

QCD @ Physics Beyond Collider

CERN-PBC-REPORT-2018-008

Physics Beyond Colliders
QCD Working Group Report

A. Dainese[1], M. Diehl[2,*], P. Di Nezza[3], J. Friedrich[4], M. Gaździcki[5,6] G. Graziani[7], C. Hadjidakis[8], J. Jäckel[9], M. Lamont[10] J. P. Lansberg[8], A. Magnon[10], G. Mallot[10], F. Martinez Vidal[11], L. M. Massacrier[8], L. Nemenov[12], N. Neri[13], J. M. Pawlowski[9,*], S. M. Puławski[14], J. Schacher[15], G. Schnell[16,*], A. Stocchi[17], G. L. Usai[18], C. Vallée[19], G. Venanzoni[20]

Abstract: This report summarises the main findings of the QCD Working Group in the CERN Physics Beyond Colliders Study.

- summary report of QCD studies within the “Physics Beyond Colliders” initiative
- selected results relevant for pre-accelerator complex:
    - COMPASS++ / AMBER
    - DIRAC++
    - MUonE

Proposals and studies within PBC-QCD

- experiments at SPS and fixed-target installations at LHC
- cover a broad range of topics in QCD
  - ★ parton densities, proton and nuclear structure
  - ★ heavy-ion physics
  - ★ low-energy dynamics
  - ★ measurements for other fields of HEP: $(g\text{-}2)_\mu$, cosmic rays, neutrinos

	LHC FT gas				LHC FT crystals	COMPASS++	MUonE	NA61++	NA60++	DIRAC++
	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	×	×		×		×		×		

Table 1. Schematic overview of the physics topics addressed by the studies presented in the QCD working group.

Proposals and studies within PBC-QCD

- experiments at SPS and fixed-target installations at LHC
- cover a broad range of topics in QCD
  - ★ parton densities, proton and nuclear structure
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  - ★ low-energy dynamics
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☛ J.-P. Lansberg ☛ T. Galatyuk

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proton PDFs	×	×		×						
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elast. μ scattering						×	×			
chiral dynamics						×				×
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spectroscopy						×				
measurements for cosmic rays and neutrino physics	×	×		×		×		×		

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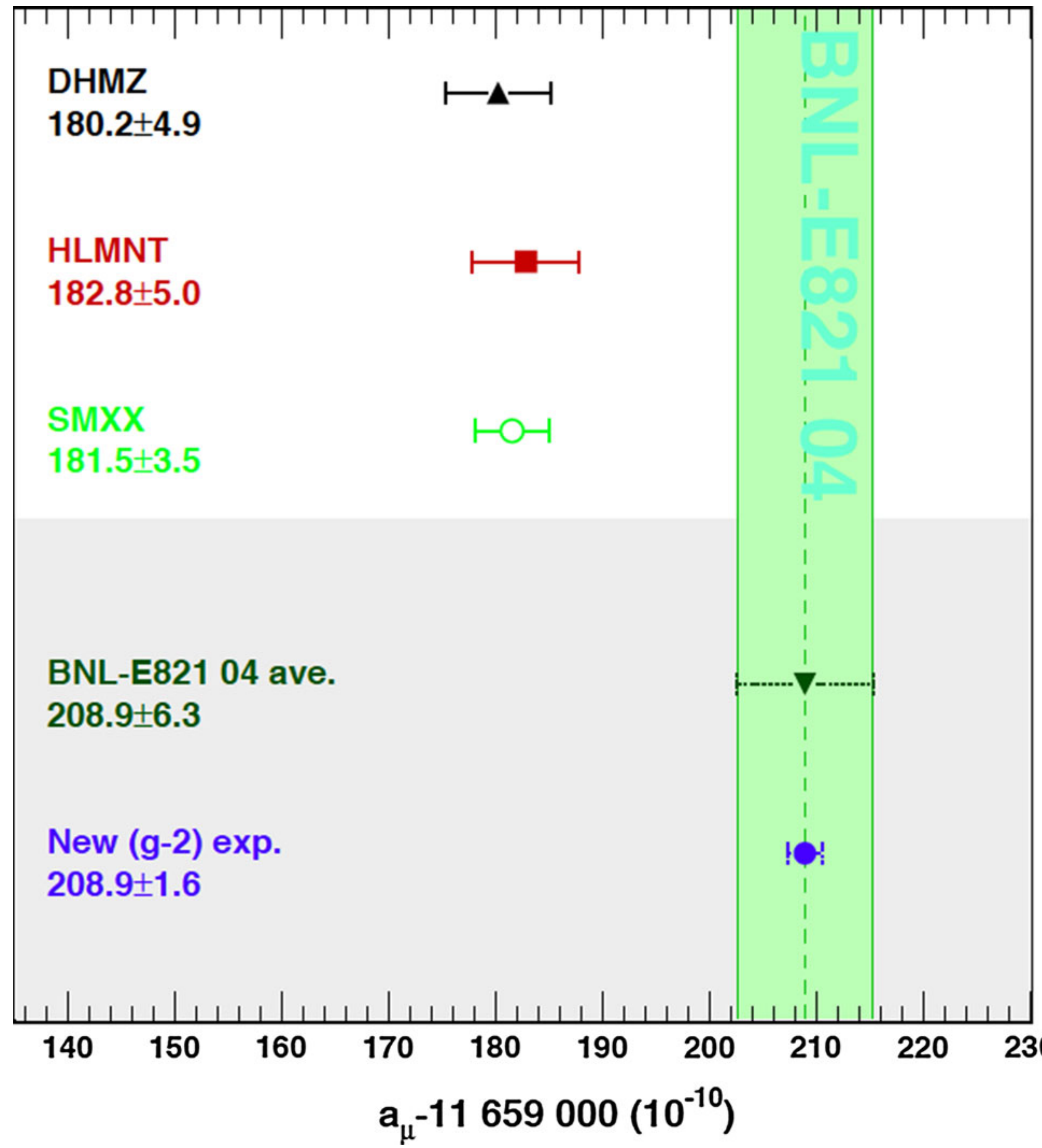
MUonE

anomalous magnetic moment
$a_\mu = (g-2)_\mu / 2$

- motivation:
  - ★ persistent discrepancy between measured $(g-2)_\mu$ and SM theory
  - ★ upcoming measurements at FNAL and J-PARC will improve $(g-2)_\mu$ precision

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



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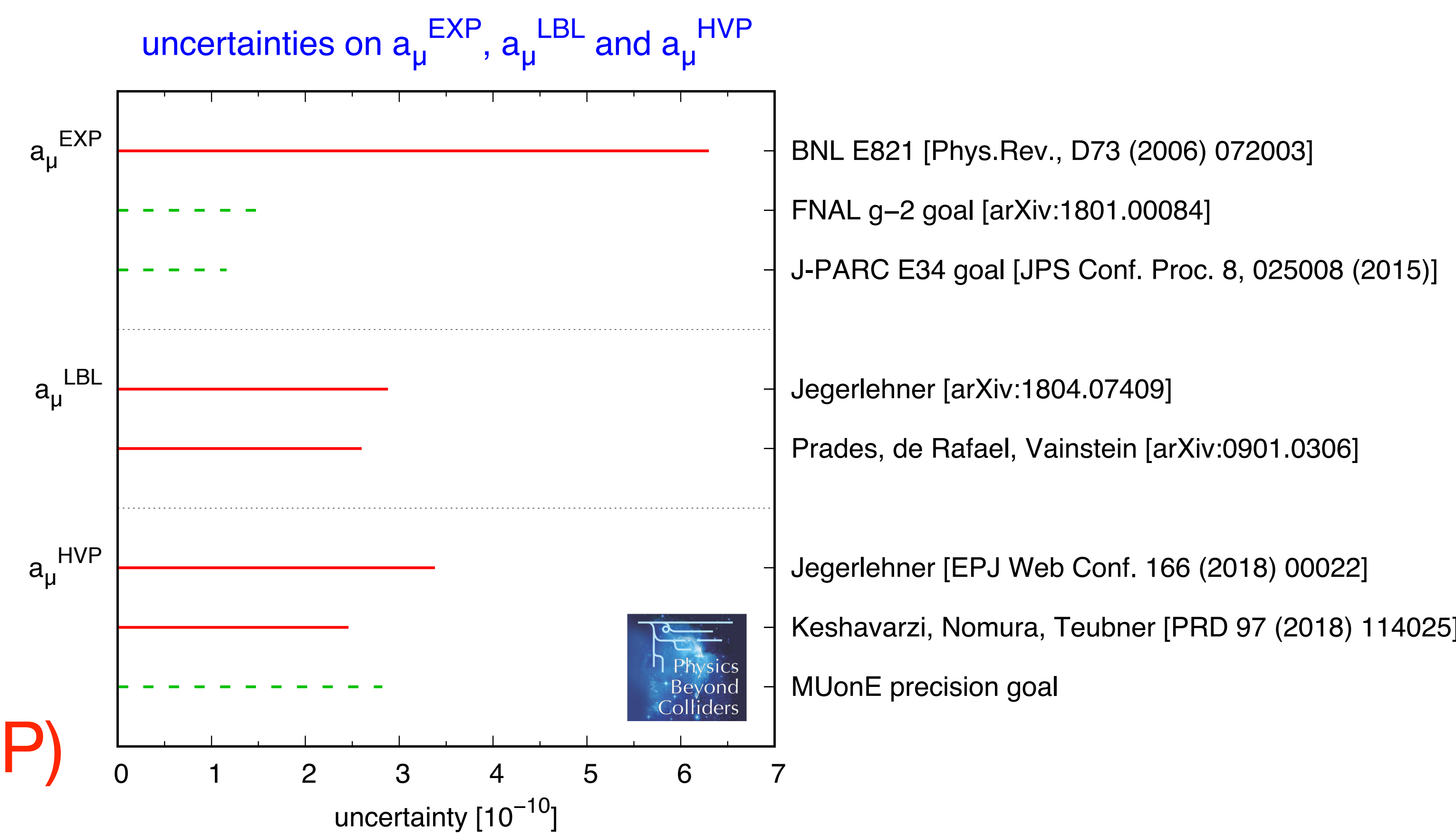
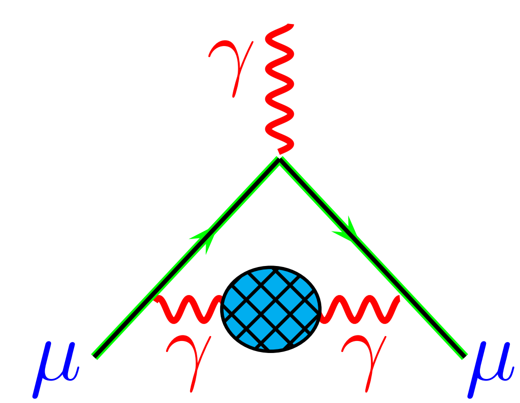
- motivation:
  - ★ persistent discrepancy between measured $(g-2)_\mu$ and SM theory
  - ★ upcoming measurements at FNAL and J-PARC will improve $(g-2)_\mu$ precision
  - ★ two main theory uncertainties: light-by-light (LBL) scattering, and hadronic vacuum pol. (HVP) (aka hadronic leading-order correction - HLO)

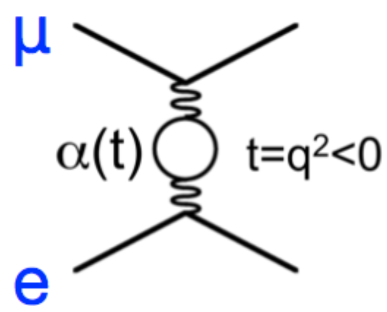


- ★ aim of MUonE: independent determination of HVP with comparable precision to extraction from $e^+ e^-$ annihilation and τ decays

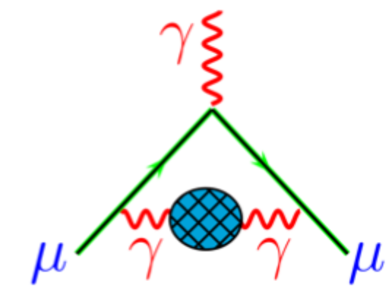


MUonE

- μe elastic scattering:



sum rule →



- requires relative accuracy of 10^{-5} on cross section for experiment and theory (QED radiative corrections)

[MUonE, id118]

$$\frac{\mathrm{d}\sigma}{\mathrm{d}t} \propto \frac{1}{[1-\Delta\alpha(t)]^2}$$

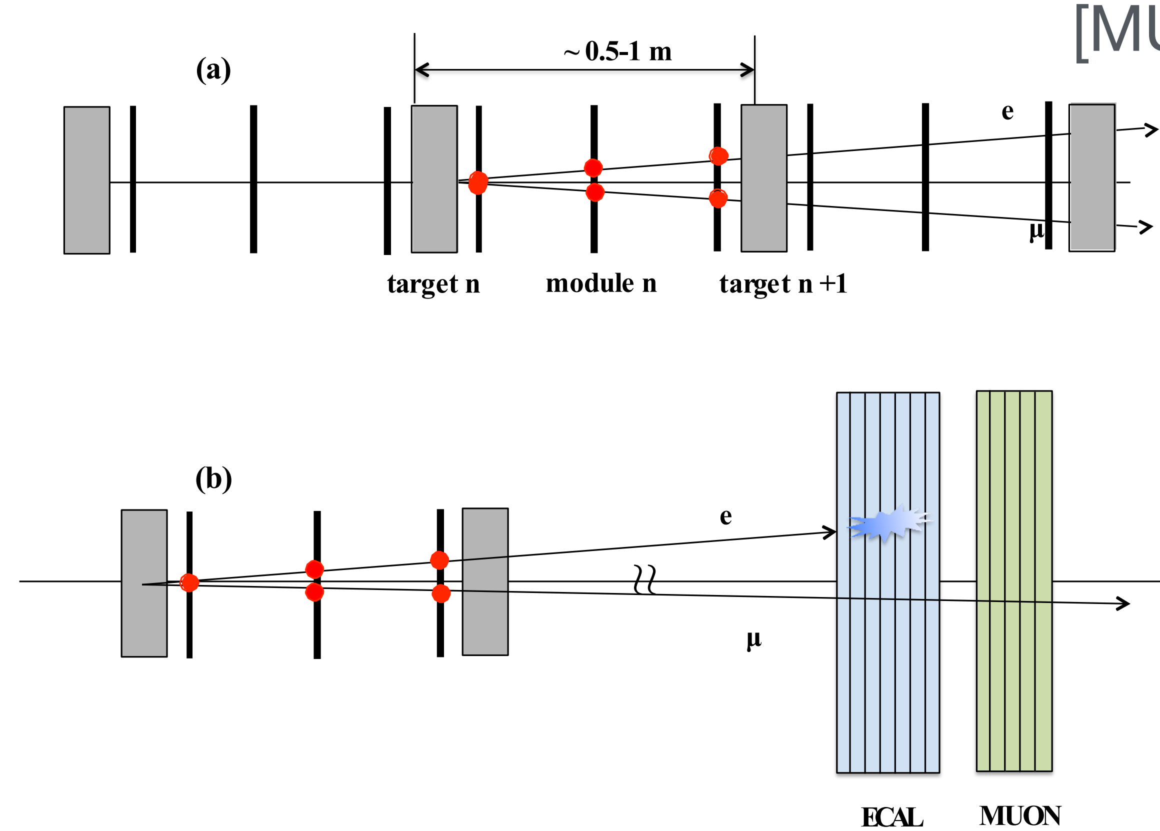
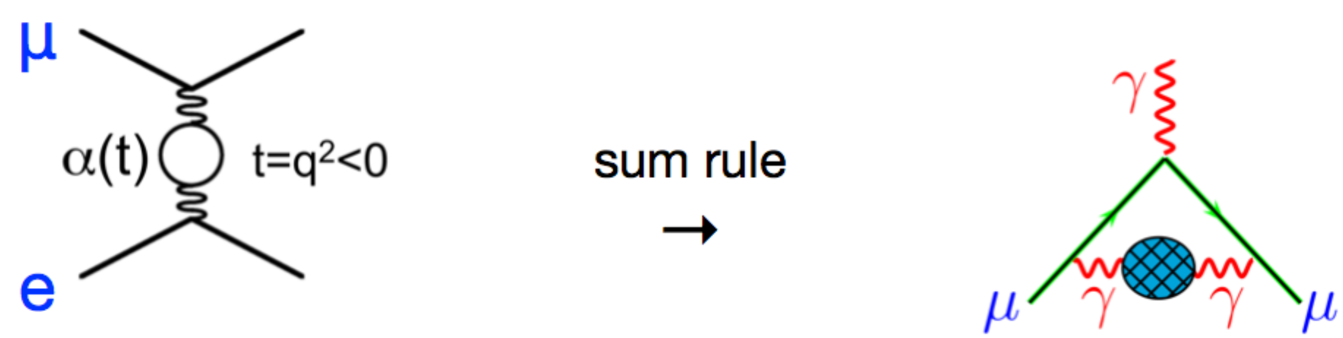


Figure 3: Scheme of a basic detector layout: a) modules sequence and b) last module. (*Not on scale*).

- based mainly on CMS Si tracker technology done by corresponding CMS experts

MUonE

- μe elastic scattering:



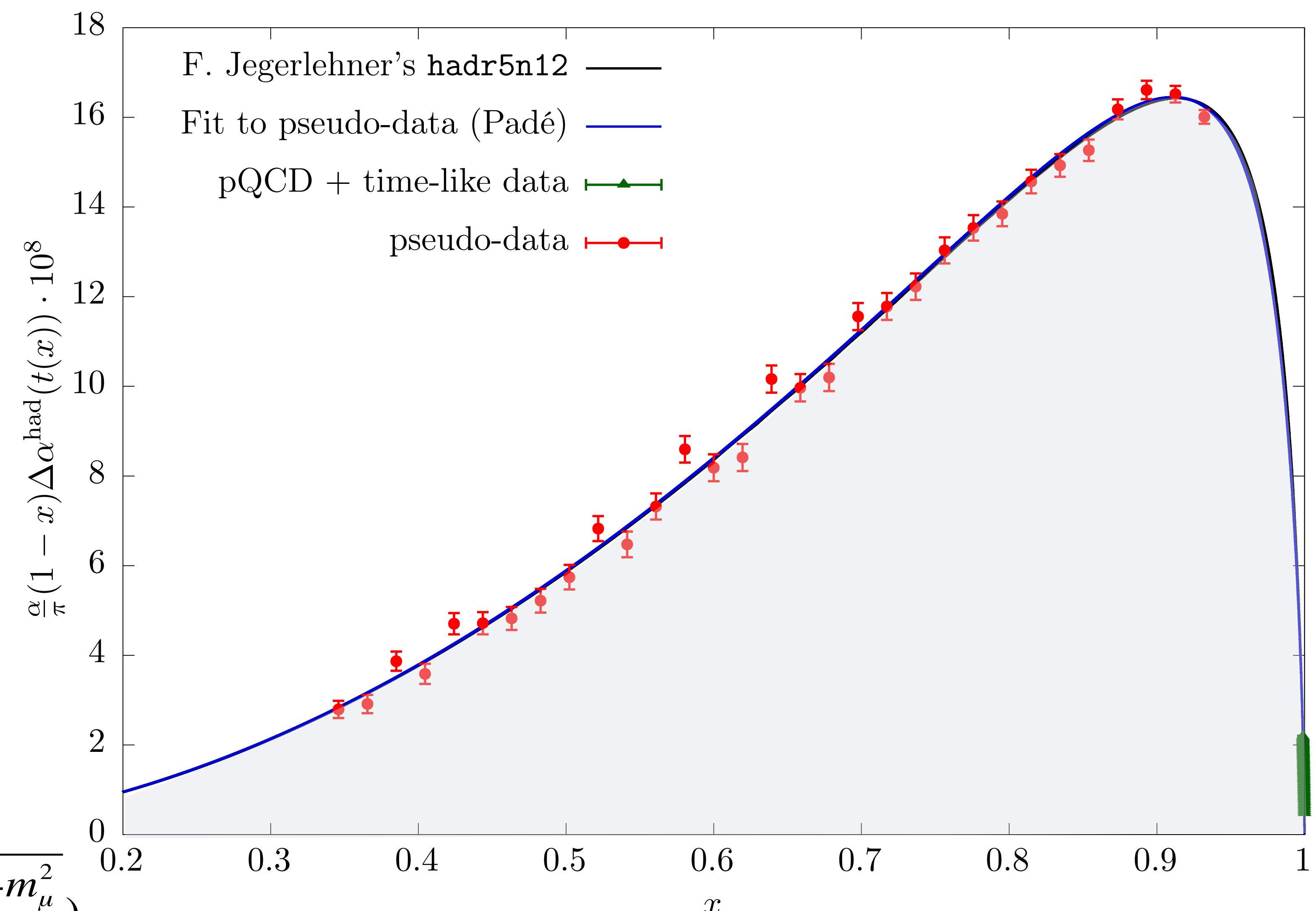
- requires relative accuracy of 10^{-5} on cross section for experiment and theory (QED radiative corrections)

physics target:
0.3% statistical precision on area under curve = a_μ^{HVP}

2 years of data taking (4×10^7 s)

from pseudo data:
$a_\mu^{HVP} = (686.9 \pm 2.3) \times 10^{-10}$

$a_\mu = g_\mu/2 - 1$



$$x = \frac{t}{2m_\mu^2}\left(1 - \sqrt{1 - \frac{4m_\mu^2}{t}}\right)$$

AMBER (aka COMPASS++)

- a comprehensive physics program suggested to run at the M2 beam line
- includes measurements with
  - conventional muon and hadron beams
  - upgraded RF-separated hadron beams
- spanning several LHC runs
- RF-separated beams would basically eliminate the high-E/high-I muon beam (unique in the world!)
- not all topics to be covered here!

Table 1: Requirements for future programmes at the M2 beam line after 2021. Muon beams are in blue, conventional hadron beams in green, and RF-separated hadron beams in red.

Program	Physics Goals	Beam Energy [GeV]	Beam Intensity [s^{-1}]	Trigger Rate [kHz]	Beam Type	Target	Earliest start time, duration	Hardware additions
muon-proton elastic scattering	Precision proton-radius measurement	100	$4 \cdot 10^6$	100	$\mu^\pm$	high-pressure H2	2022 1 year	active TPC, SciFi trigger, silicon veto,
Hard exclusive reactions	GPD E	160	$2 \cdot 10^7$	10	$\mu^\pm$	$NH_3^\uparrow$	2022 2 years	recoil silicon, modified polarised target magnet
Input for Dark Matter Search	$\bar{p}$ production cross section	20-280	$5 \cdot 10^5$	25	p	LH2, LHe	2022 1 month	liquid helium target
$\bar{p}$-induced spectroscopy	Heavy quark exotics	12, 20	$5 \cdot 10^7$	25	$\bar{p}$	LH2	2022 2 years	target spectrometer: tracking, calorimetry
Drell-Yan	Pion PDFs	190	$7 \cdot 10^7$	25	$\pi^\pm$	C/W	2022 1-2 years	
Drell-Yan (RF)	Kaon PDFs & Nucleon TMDs	~100	10^8	25-50	$K^\pm, \bar{p}$	$NH_3^\uparrow$, C/W	2026 2-3 years	"active absorber", vertex detector
Primakoff (RF)	Kaon polarisa-bility & pion life time	~100	$5 \cdot 10^6$	> 10	K^-	Ni	non-exclusive 2026 1 year	
Prompt Photons (RF)	Meson gluon PDFs	≥ 100	$5 \cdot 10^6$	10-100	$K^\pm$ $\pi^\pm$	LH2, Ni	non-exclusive 2026 1-2 years	hodoscope
K-induced Spectroscopy (RF)	High-precision strange-meson spectrum	50-100	$5 \cdot 10^6$	25	K^-	LH2	2026 1 year	recoil TOF, forward PID
Vector mesons (RF)	Spin Density Matrix Elements	50-100	$5 \cdot 10^6$	10-100	$K^\pm, \pi^\pm$	from H to Pb	2026 1 year	

[AMBER, arXiv:1808.00848]

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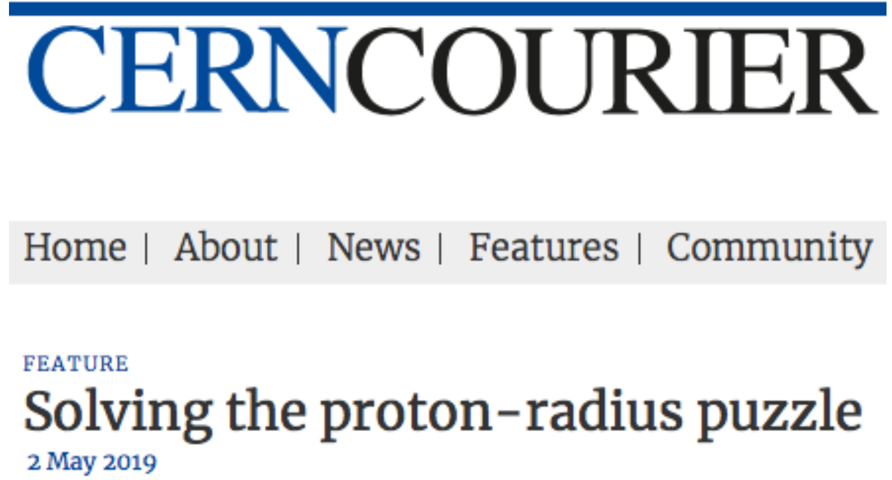
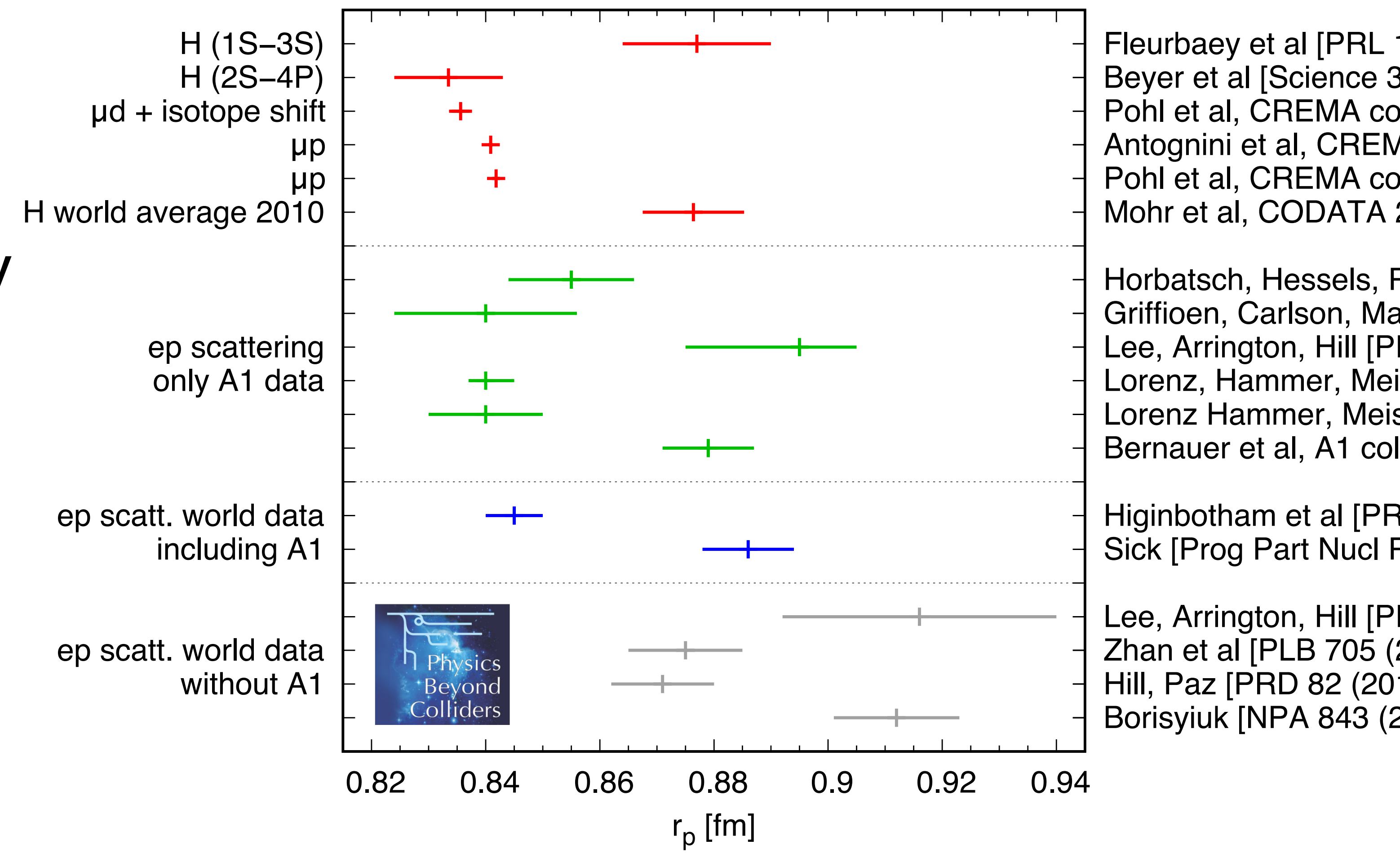


AMBER: proton radius

proton charge radius from spectroscopy or ep scattering

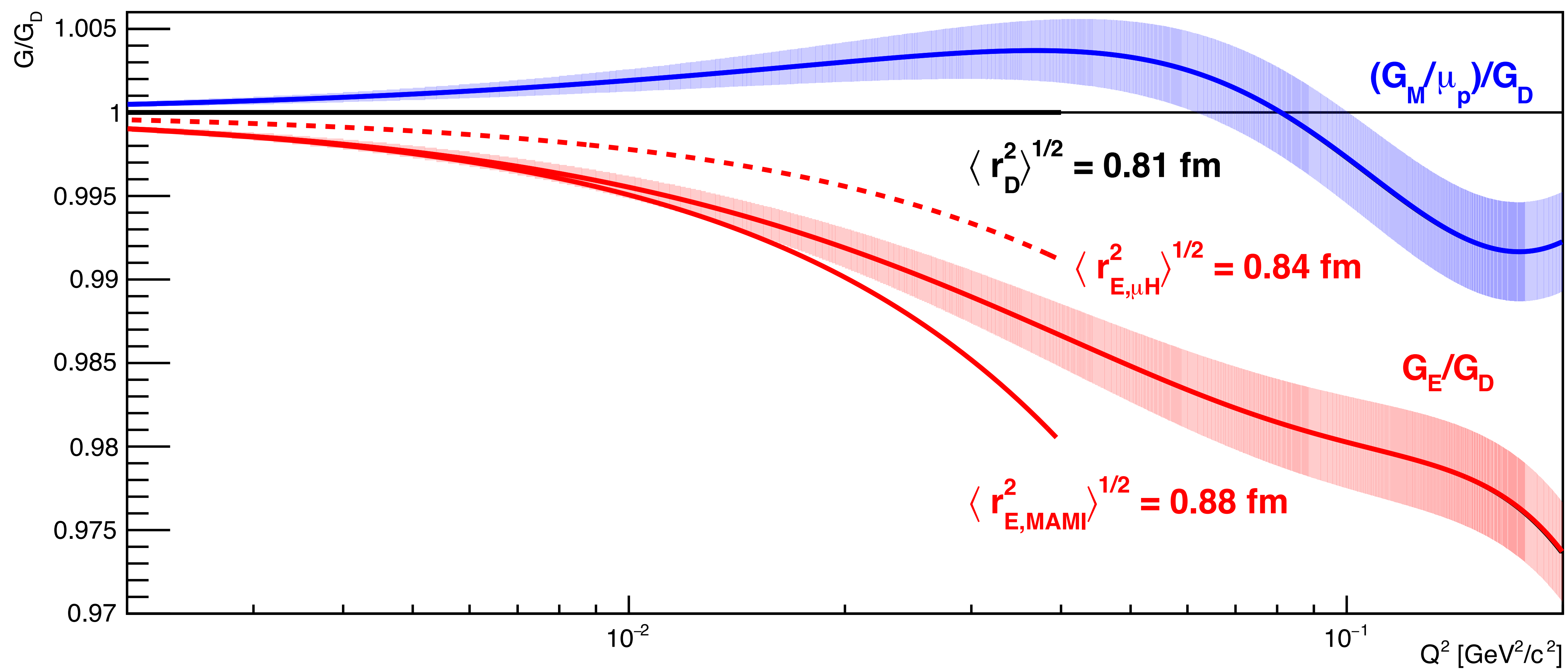


- persistent discrepancies on proton charge radius r_p determined from spectroscopy (H, muonic H) and ep elastic scattering
- different fits to ep data yield widely different r_p

$$\frac{1}{6} r_p^2 = - \left. \frac{\mathrm{d}}{\mathrm{d}Q^2} \right|_{Q^2=0} G_E(Q^2)$$

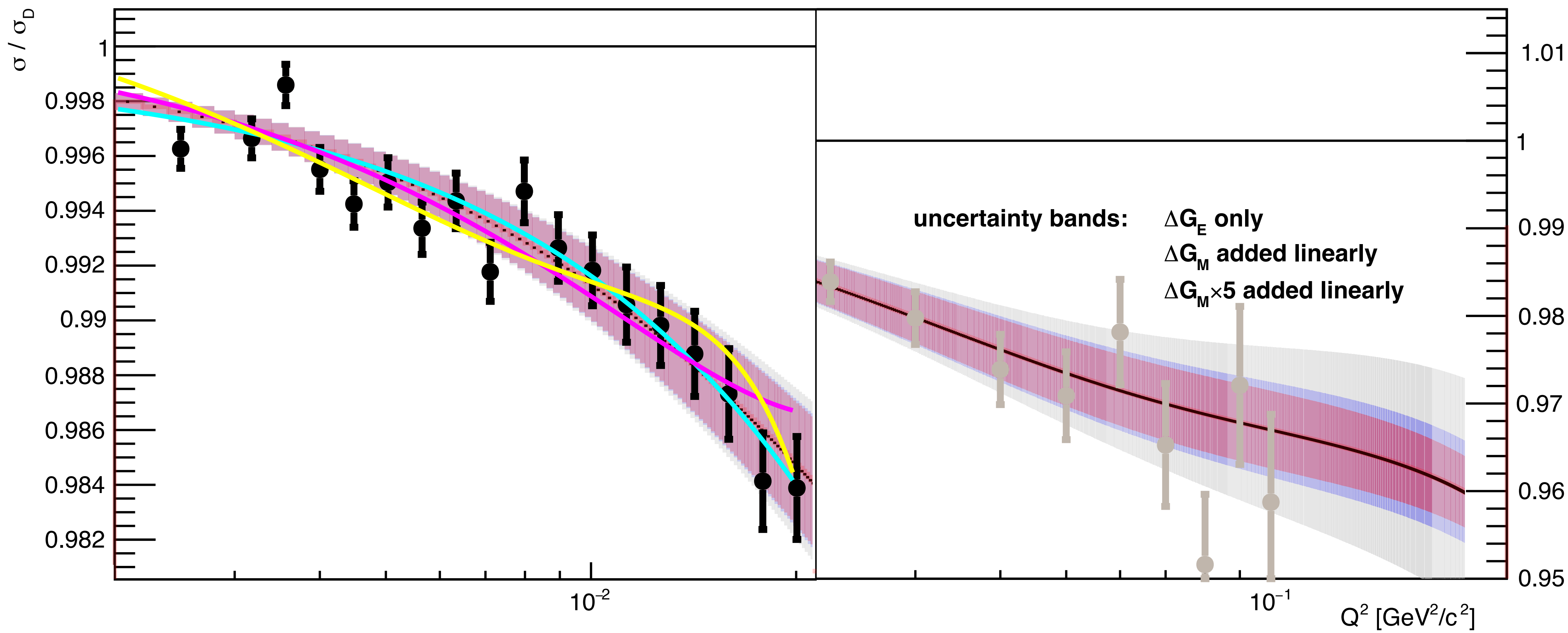
- goal: r_p from high-energy (100 GeV) μp elastic scattering
  - ★ advantages over ep scattering:
    - ✦ smaller QED radiative corrections as compared to e^- beam
    - ✦ very small contamination from magnetic form factor

- demanding measurement: small scattering angle
- form-factor measurement of elastic scattering in $10^{-3}...10^{-2}$ GeV^2 Q^2 range



(MAMI-A1 parametrization normalized to dipole form factor)

- demanding measurement: small scattering angle
- employ high-pressure hydrogen TPC as active target
  ☛ use recoil proton for kinematics



- pseudo-data [based on MAMI-A1 parametrization] and various fits
  - ★ preferred fit of pseudodata gives $\Delta_{stat}\, r_p = 0.013$ fm
  - ★ experimental and fitting uncertainties to be quantified

proton radius (world-wide efforts)

☛ K. Kirch

- MUSE: low-E $\mu^\pm$ and $e^\pm$ scattering to reduce systematics and to compare directly for hints of lepton-flavor violation. Data-taking in 2018-20; goal: sub-% relative precision over a Q^2 range of 0.002—0.07 GeV^2 to extract the proton radius to a precision of 0.007 fm.

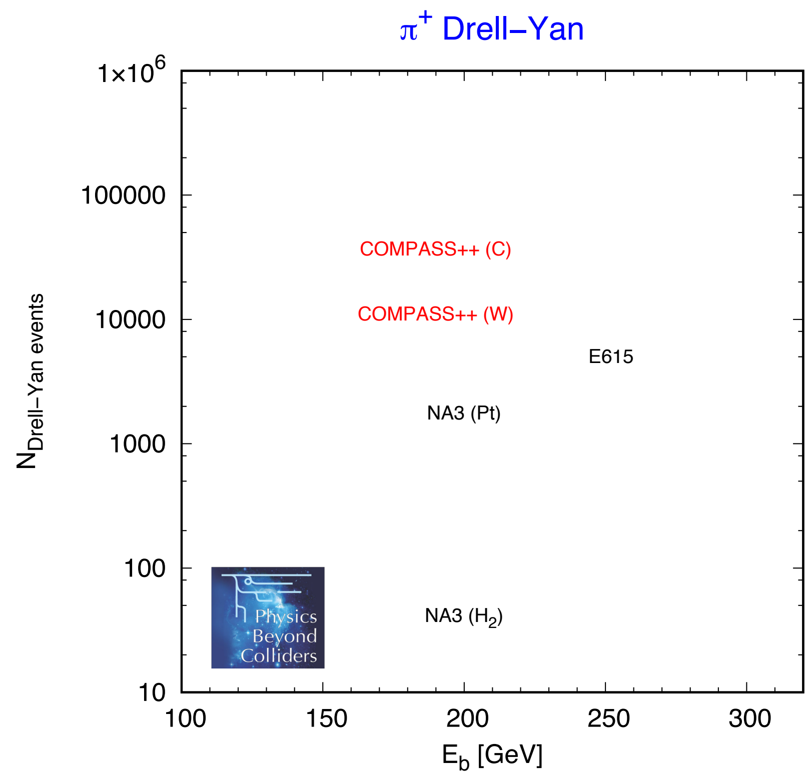
- PRad at JLab already took the presently lowest Q^2 data in ep elastic scattering. Preliminary results favor a generally lower proton radius of $0.830 \pm 0.008_{stat} \pm 0.018_{syst}$ fm.
  Exploits simultaneous measurement of well-known Møller scattering as reference to reduce systematics.

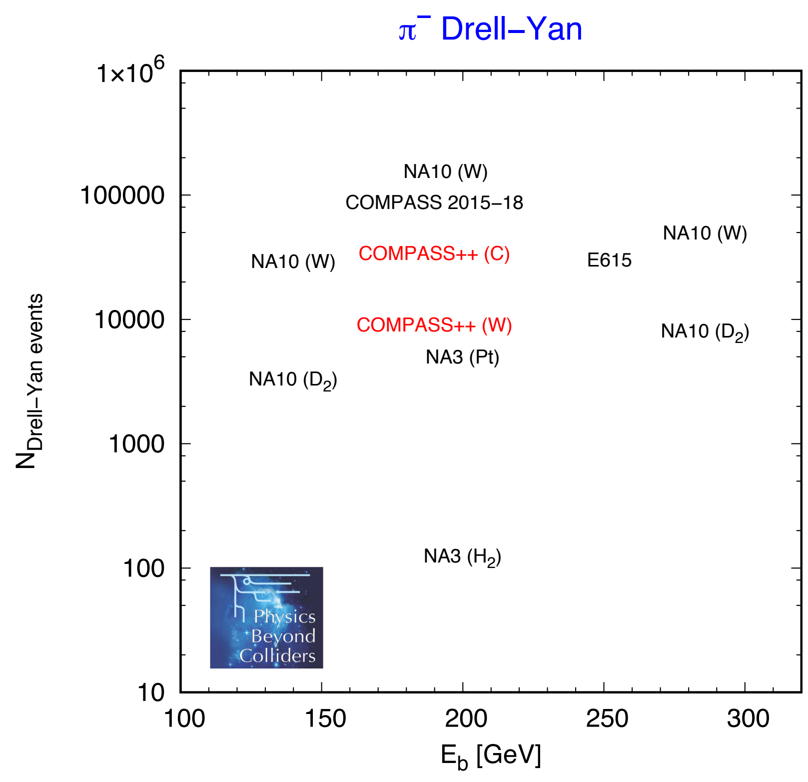
- @MAMI: use similar approach as AMBER (TPC as an active target), likely in 2020. Ongoing are runs with low beam-E and via ISR. Furthermore, MAGIX/MESA9 plans to run from 2021/22 on.

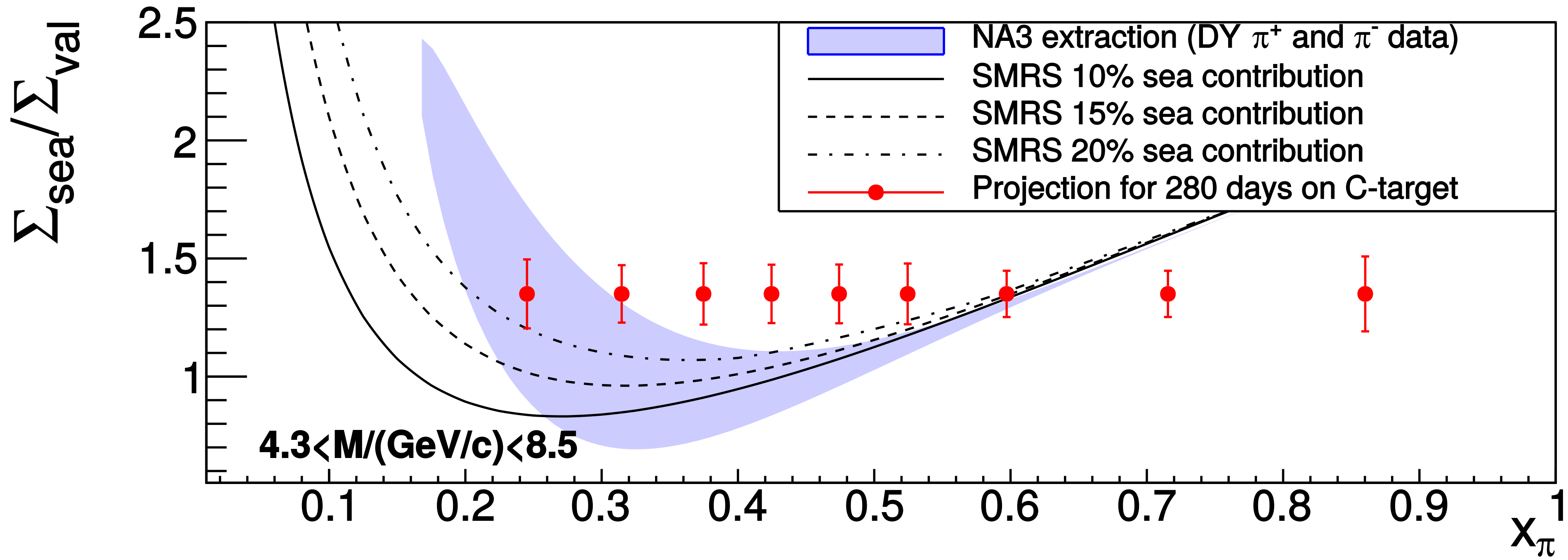
- Very-low Q^2 data to come from ULQ2 and ProRad experiments at Tohoku Low-Energy Electron Linac (Japan) and the PRAE facility in Orsay (France), respectively. ULQ2 (start in 2019?) aims at absolute cross-section measurement with 10^{-3} precision to obtain Rosenbluth separated G_E(Q2) and $G_M(Q^2)$ within $0.0003 \leq Q^2[GeV^2] \leq 0.008$, using a 10–60 MeV e^- beam. ProRad will utilize a 30–70 MeV e^- beam and aims at a 0.1% precision on the elastic cross section.

AMBER: Drell-Yan with π beams

- pion plays special role in QCD (Goldstone boson)
- π PDFs very poorly known
- unique opportunity: Drell-Yan with π^- and π^+ beams:
  - ★ separation of sea and valence quarks
  - ★ highly complementary to plans in ep scattering (JLab, EIC)





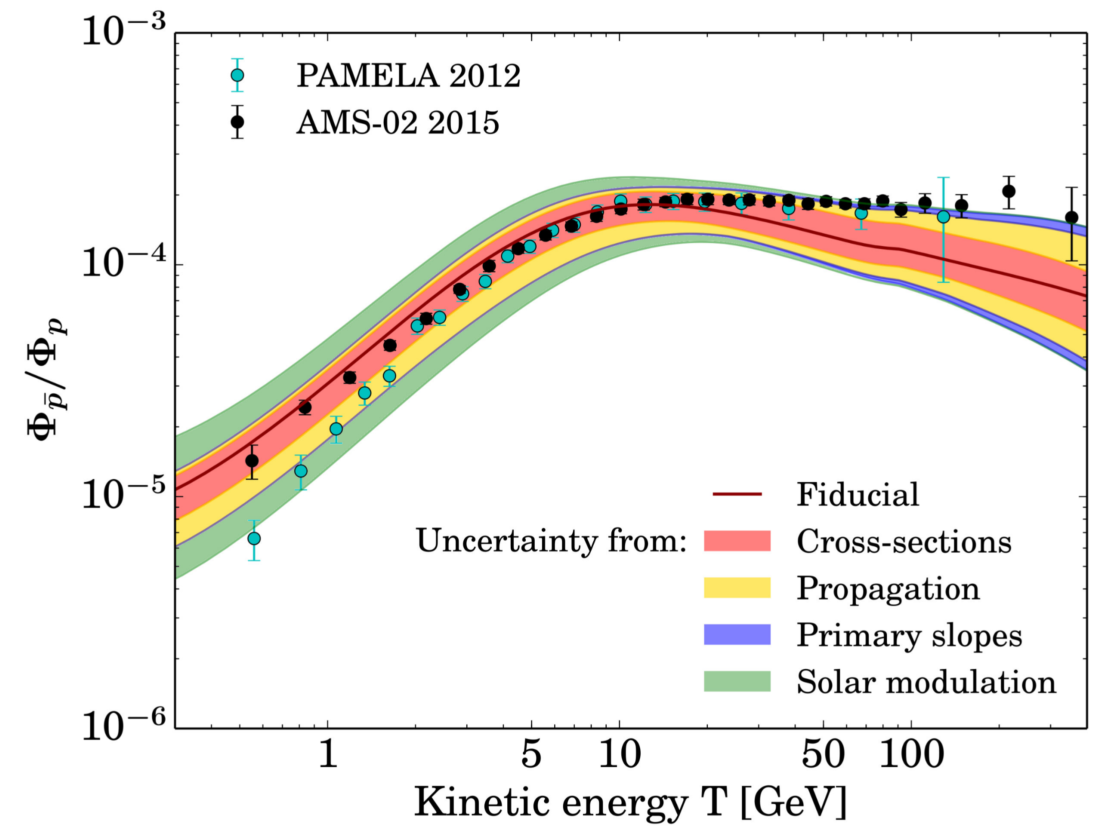


Synergy with cosmic-ray physics

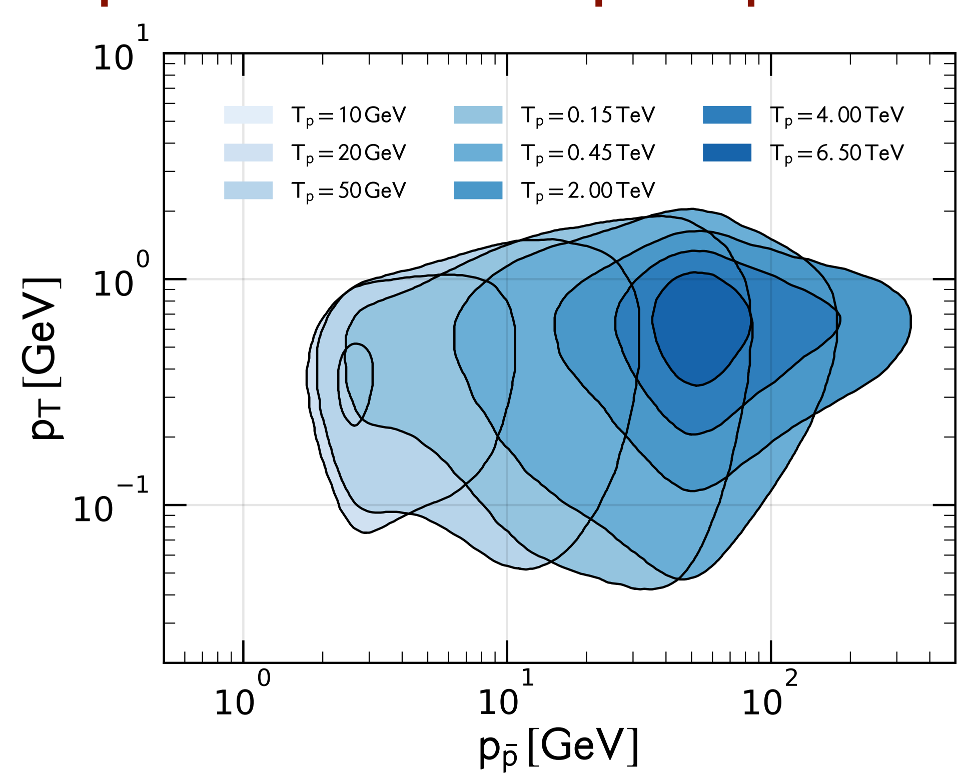
☛ T. Pierog

- Anti-proton production and nuclear fragmentation @PBC-QCD
  - ★ LHCb-FT
  - ★ ALICE-FT
  - ★ NA61++
  - ★ AMBER:
    - M2 p beam [20-280 GeV]
    - anti-proton production in p+p and p+^{4}He
    - O(5%) precision for 20x20 bins in, e.g., momentum and pseudo-rapidity

Example for QCD-related limitations in flux calculations



Parameter space needed to be covered for p+^{4}He channel for anti-proton production



Synergy with cosmic-ray physics

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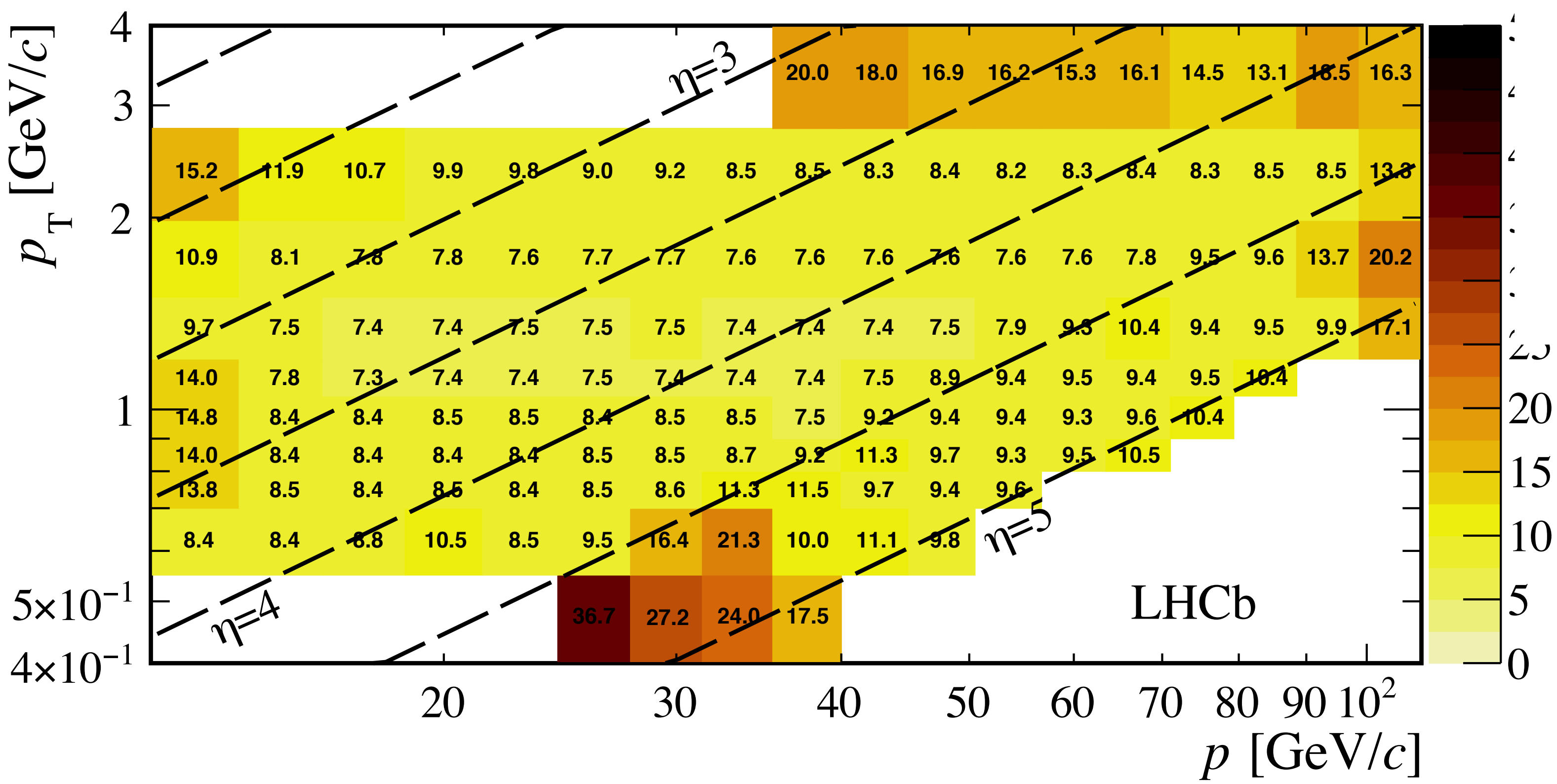
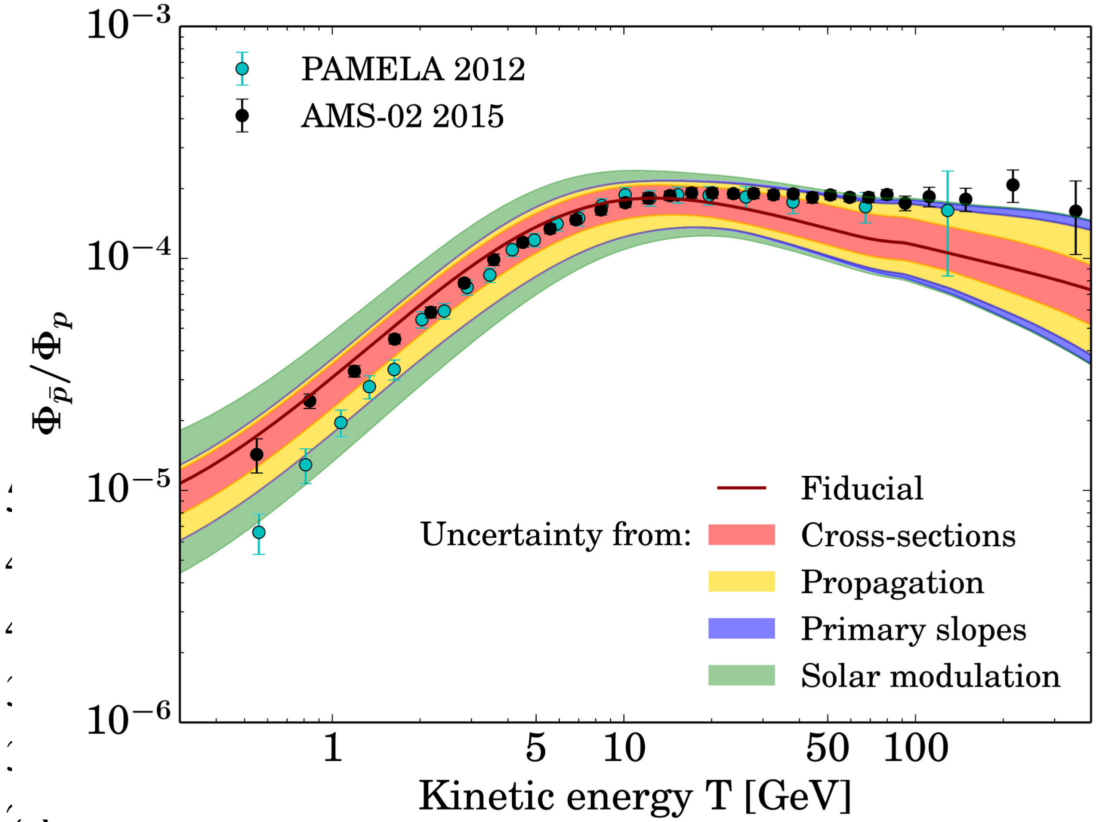
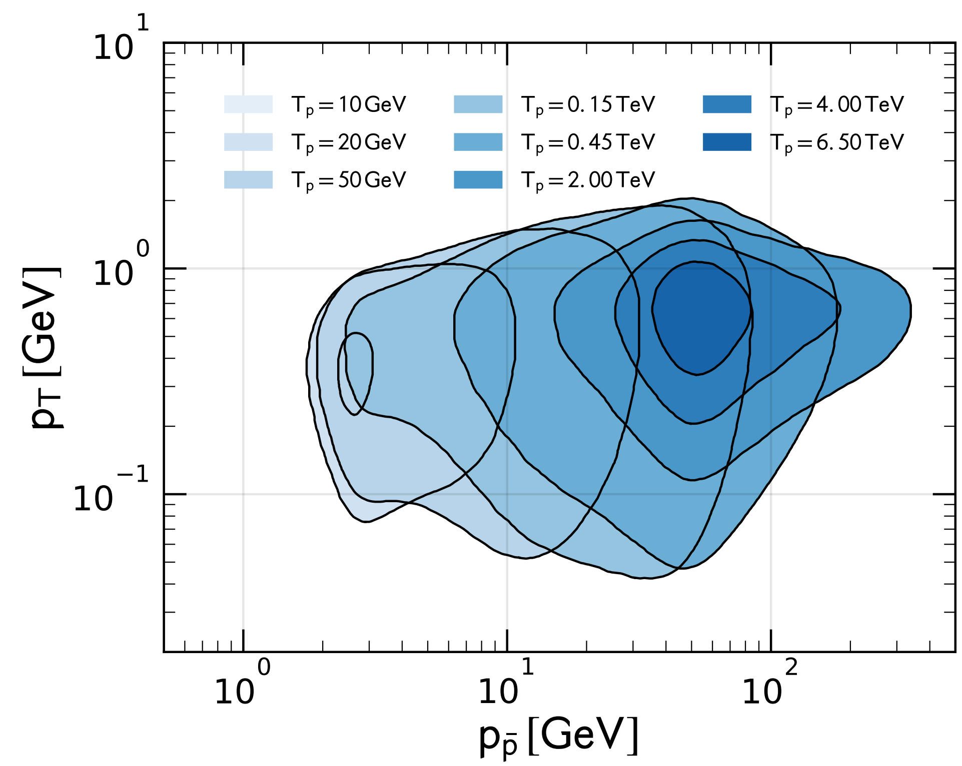


- complementary to, e.g., LHCb-FT

Example for QCD-related limitations in flux calculations



Parameter space needed to be covered for $p+{}^4He$ channel for anti-proton production



Long-term prospect: RF-separated beams @ M2 line

- RF-separated kaon beams would allow wide range of unique QCD studies with AMBER
  - ★ kaon spectroscopy
  - ★ kaon polarizabilities (Primakov reaction, chiral symmetry breaking)
  - ★ PDFs (Drell-Yan, prompt photons)

- feasibility study for RF-separated beams started in PBC conventional beams working group
  - ★ to be followed up: achievable beam parameters (energy, intensity)
  - ★ what are minimum beam requirements for the different physics?

[AMBER, arXiv:1808.00848]

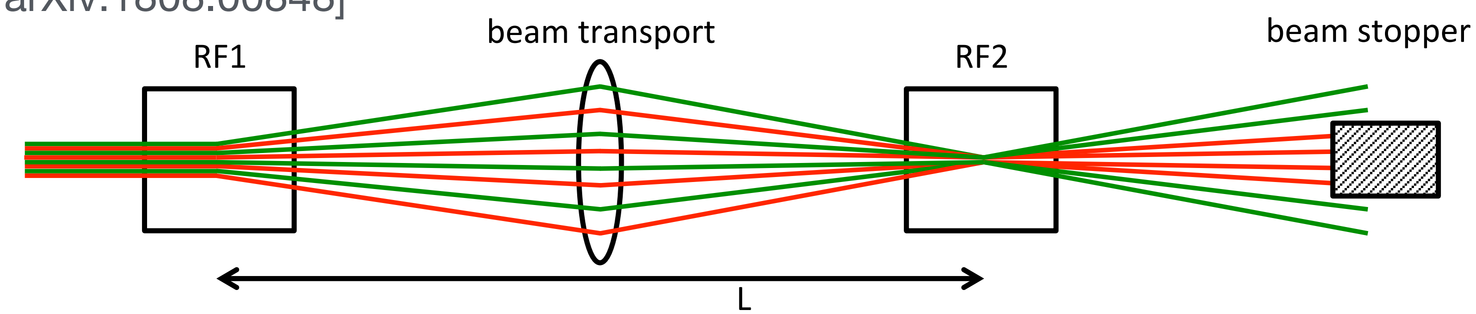
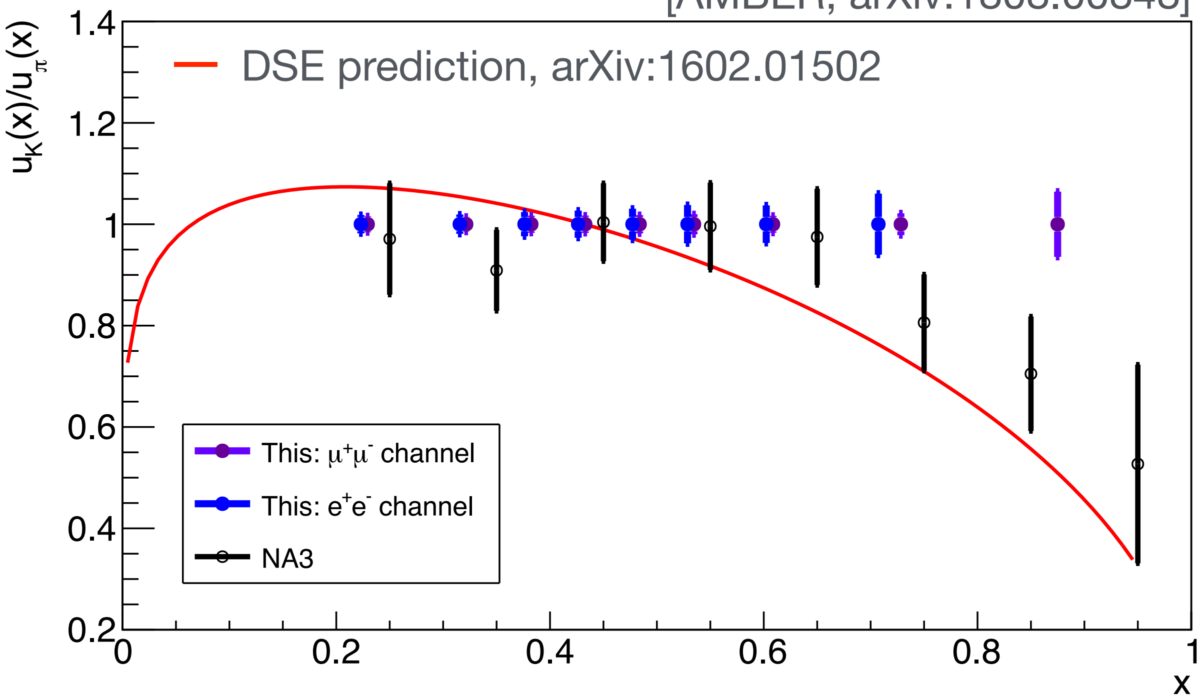


Figure 26: Panofsky-Schnell method for RF-separated beams. The unwanted particles (red) are stopped by a beam stopper while the wanted particles (green) receive a net deflection by the combination of the RF1 and RF2 dipole RF cavities out of the central axis, which is sufficient to go around the stopper.

AMBER: kaon structure

- Drell-Yan: $K^- + C \to \mu^+\mu^-$ (or e^+e^-) + X
  - ★ comparing with π^- + C Drell-Yan: u-quark density in kaon (relative to pion)
  - ★ kaon and pion distributions related by $SU(3)_f$ symmetry → study of $SU(3)_f$ breaking (influence of s-quark mass)
  - ★ measurement w/o competition

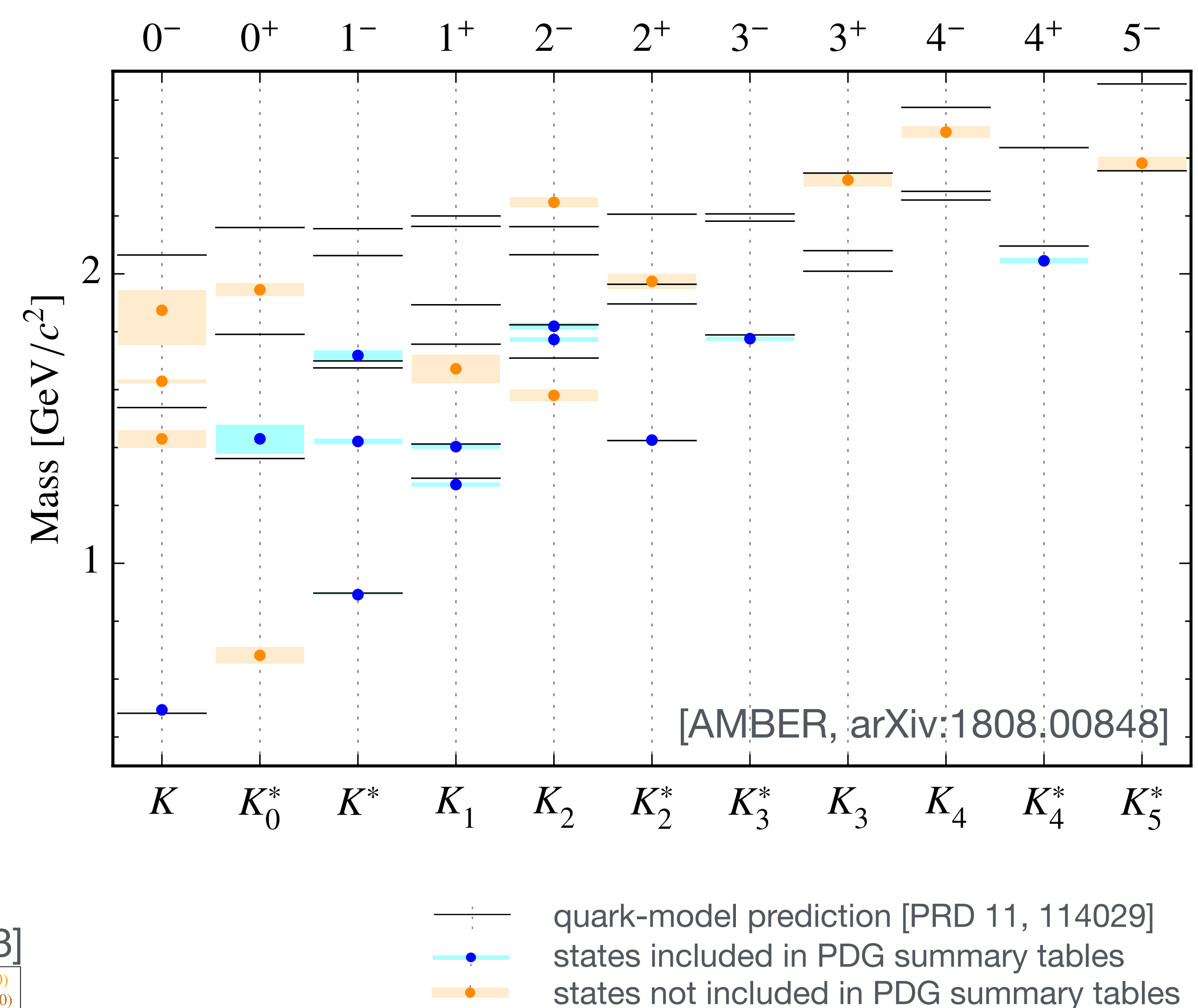
[AMBER, arXiv:1808.00848]



- Drell-Yan: $K^\pm$ + C
  - ★ kaon sea/valence distributions
- Drell-Yan: $K^+ + p \to \gamma + X$
  - ★ kaon gluon distribution through prompt-photon production

AMBER: kaon spectroscopy

- strange-meson spectrum remains poorly known
- measurement with high-energy RF-separated K beam
  - ★ clear separation of strange-meson and recoiling systems
  - ★ aim at similar-size data set (~20×10^6 events) as collected with π beam (example below)



[COMPASS, arXiv:1802.05913]

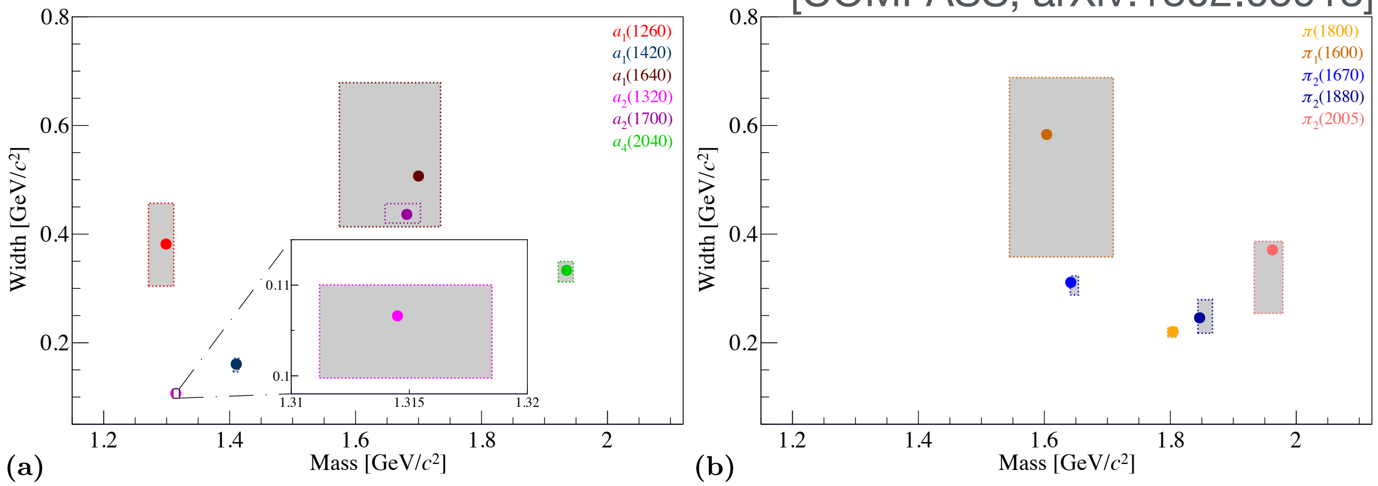
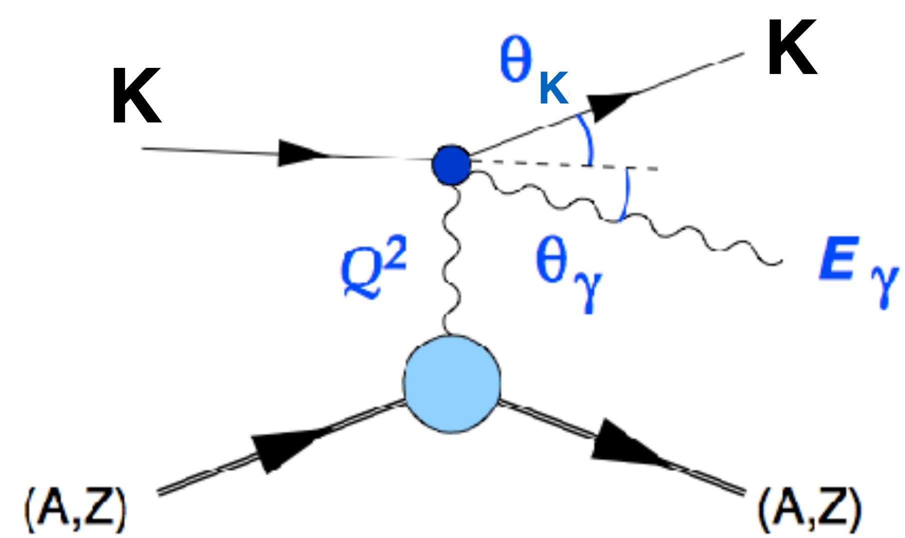


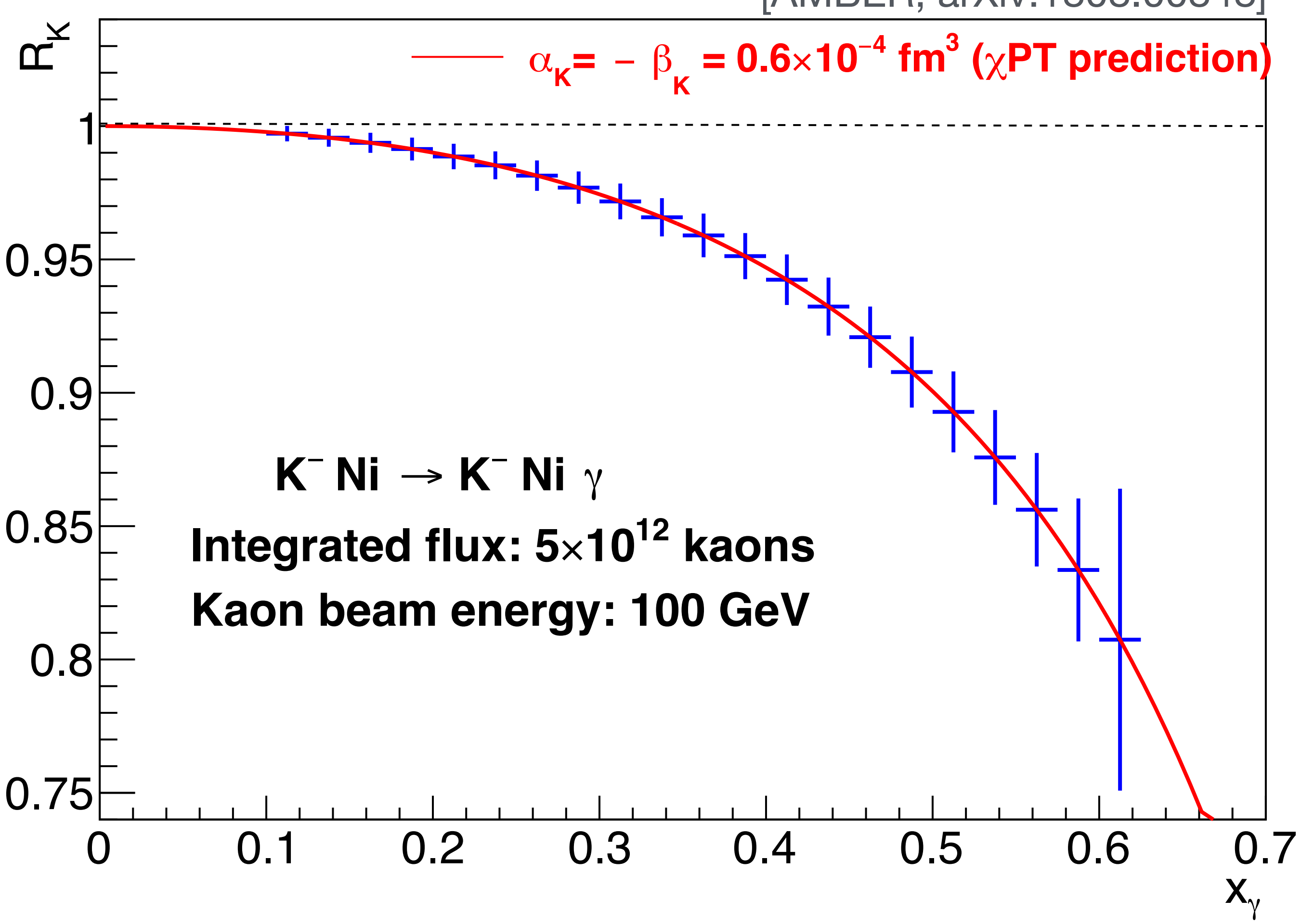
FIG. 56: Masses and widths of (a) a_J-like and (b) π_J-like resonances extracted in this analysis (points). The systematic uncertainties are represented by the boxes. The statistical uncertainties are at least an order of magnitude smaller than the systematic ones and are hence omitted. Different colors encode different resonances.

AMBER: chiral dynamics

- Primakov process
- extract kaon polarizability
- requires RF separated beam
- similar to previous COMPASS measurement for pion



[AMBER, arXiv:1808.00848]



1 year with Ni target

$\sigma_{stat}=0.03\times10^{-4}$ fm^3

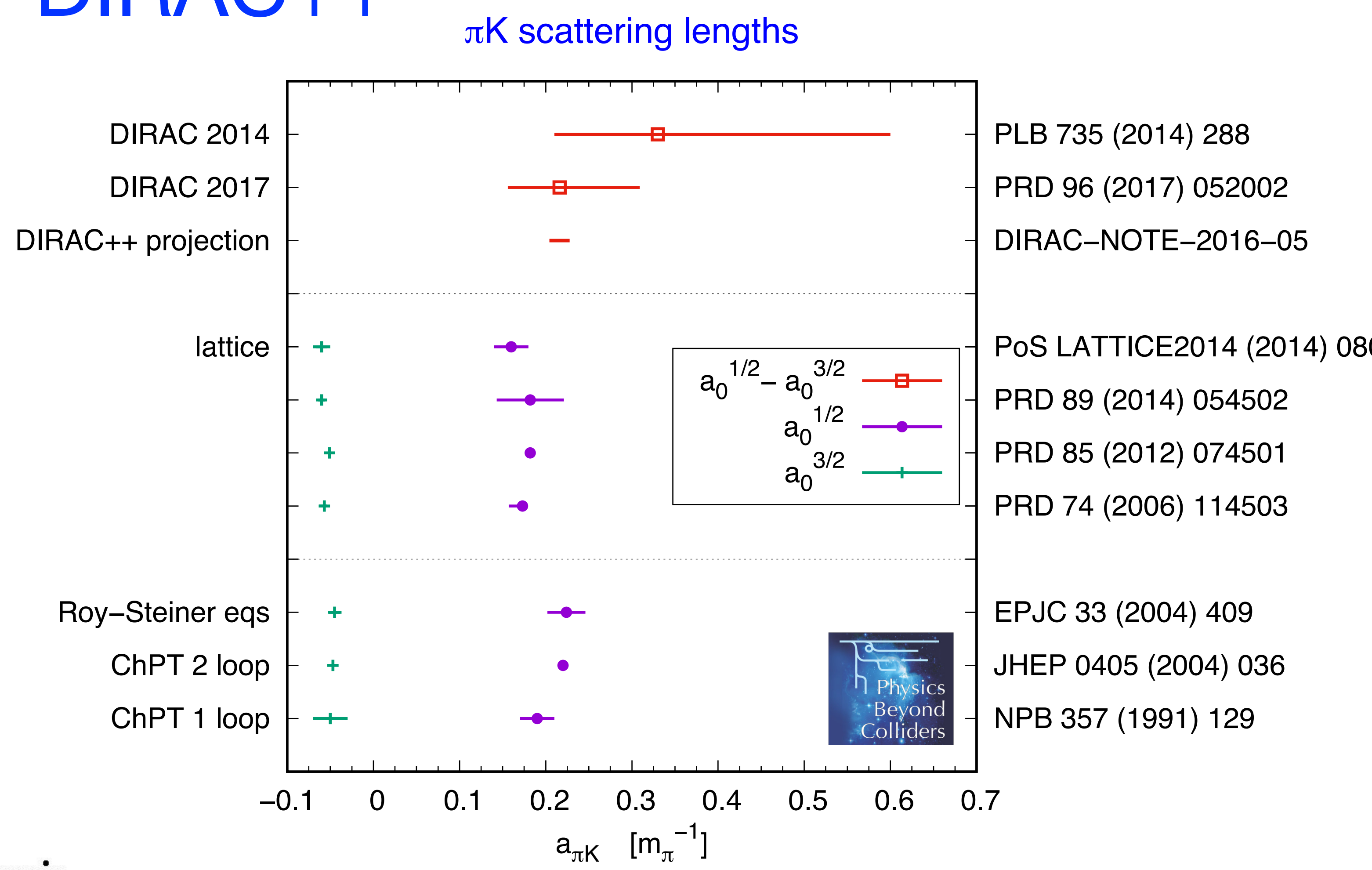
χPT prediction O(p⁴):

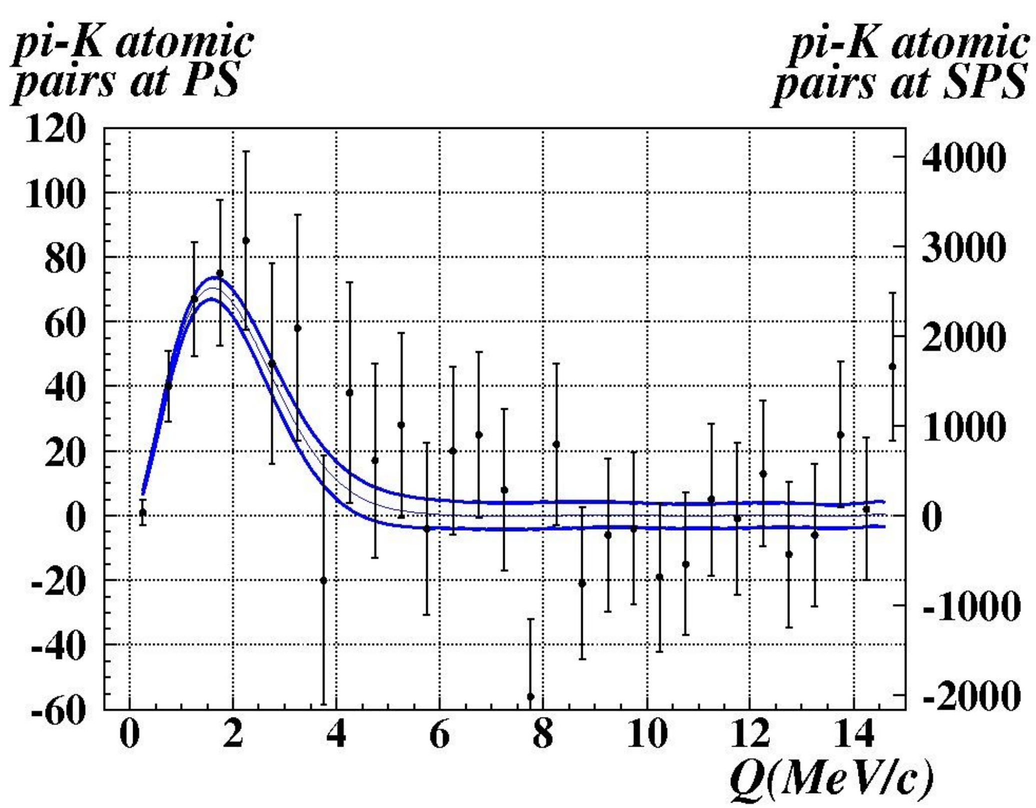
$$\alpha_K + \beta_K = 0$$

$$\alpha_K = \alpha_\pi \times \frac{m_\pi F_\pi^2}{m_K F_K^2} \approx \frac{\alpha_\pi}{5} \approx 0.6\times10^{-4} fm^3$$

DIRAC++

- πK scattering lengths: benchmark quantities for chiral symmetry breaking in the strange-quark sector
- study of πK atoms at SPS would yield experimental uncertainty comparable to theory uncertainties





- rates at SPS ≫ at PS (DIRAC 2014, 2017)
- beam intensity required needs an underground hall→ ECN 3
- challenge: collaboration / time line

summarizing slides

(timelines, costs, community challenges & opportunities)

time lines of EPIC projects

[EPIC addendum, id 039]

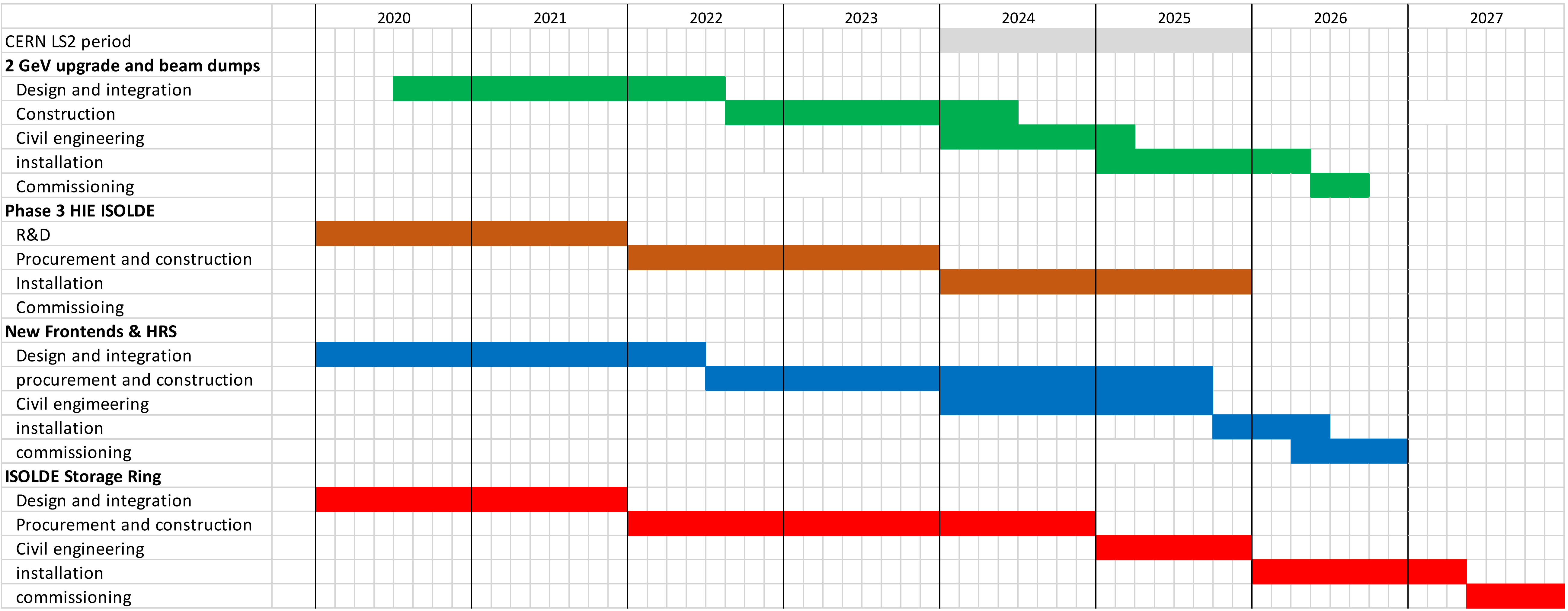
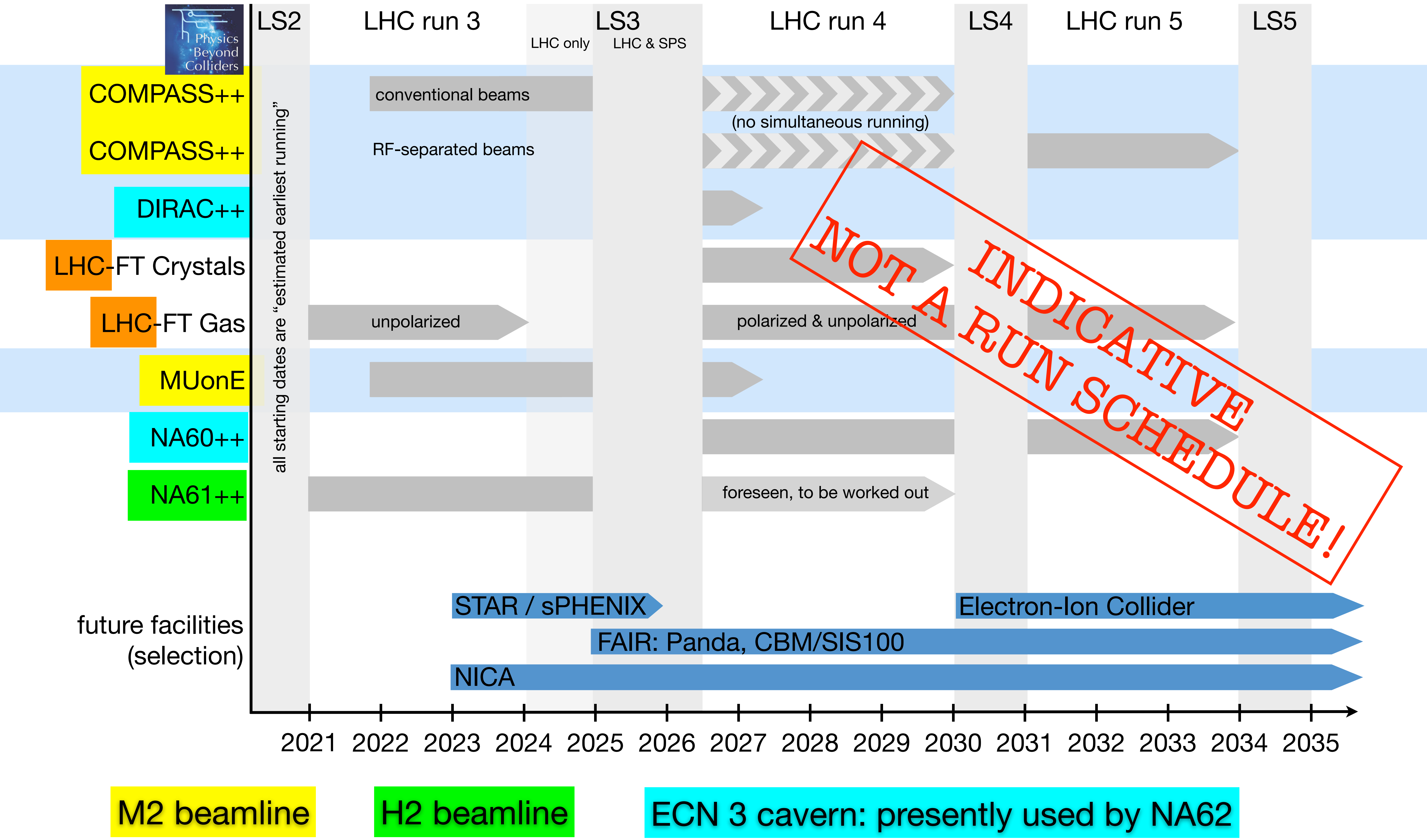


Figure 2. A proposed schedule for the EPIC project based on the CERN's long shutdown 3.

time lines and (possible!) locations of PBC-QCD projects



collaboration strength / project costs

- AMBER:
  - ★ >270 people (Ph.D. students and higher)
  - ★ ~20M CHF + RF-separated beam
- DIRAC++:
  - ★ an actual collaboration to be formed
  - ★ ~3M CHF for detector
- MUonE:
  - ★ 14 institutes - growing
  - ★ ~10M CHF
- EPIC / ISOLDE:
  - ★ >1300 users since 2015 from 43 countries (☛ backup slides)
  - ★ ~100M CHF total including new target stations & storage ring

Challenges: MUonE and AMBER r_{proton} measurement @M2

- both measurements
  - ★ are highly demanding, strict precision requirements
  - ★ should be done (soon) in view of worldwide activities

- ongoing discussions on running scenarios
  - ★ requirements on beam and detector setup
    parallel running possible? or interleaved running?

- in parallel: NA64μ with muon beams (BSM, not QCD)
  would also run at same beam line to search for dark matter
  - ★ only short running envisaged before LS3, longer running after LS3

- requires coordinated discussions between the projects (ongoing)
  and input from strategy discussion on urgency / physics impact

Challenges: other NA projects

- RF-separated beams (AMBER)
  - ★ what are minimum beam requirements for the different physics?
  - ★ larger-scale investment and loss of M2 muon beam
    - ➡ will clearly require strategy discussion on physics impact, e.g., long-term need of high-E/high-I muon beam

- DIRAC++
  - ★ due to requirements on beam and detector setup: ECN3 cavern
  - ★ no coexistence with current NA62
    (but possibly w/ potential NA60++ experiment)
  - ★ challenge of collaboration strength, especially if only after LS3

Conclusions

- AMBER offers wide & worthwhile physics program on hadron structure
  - ★ several unique measurements concerning light-meson structure, spectroscopy and low-energy QCD parameters
  - ★ valuable complementarity in world-wide efforts (r_{proton}, p-bar production)
  - ★ feasibility and physics reach of RF-separated beams to be shown
- DIRAC++: challenging (due to location requirement and collaboration strength) but unique project for low-energy QCD
- MUonE: highly complementary and timely measurement of hadronic vacuum polarization contribution to muon g-2
  - ★ precision challenge (e.g. mult. scatt.); coexistence w/ AMBER & NA64μ
- ISOLDE/EPIC: outstanding ion-beam facility with very large user base
  - ★ proposed extensions and unique light-ion (incl. short-lived) storage ring needed and clearly desirable to meet growing beam demands and to widen physics reach and diversify CERN's research scope

backup slides

cost breakdown and user base of ISOLDE/EPIC

Items	Cost kCHF	FTE	Comments
Beam dumps and 2 GeV	9,000	15	Includes civil engineering for the existing beam dumps, 4 beam dumps and bending magnets
Phase 3 HIE-ISOLDE	8,000		Includes beam chopper, 2 low Beta cryo-modules and refurbishing of cooling plant
Target stations and HRS	67,000	400	2 new target stations, pre separators , HRS, RFQ Cooler, beam lines, civil engineering, shielding and cooling and ventilation, additional laser laboratory
ISR	17,000	46	Procurement of all ISR equipment and hall extension
Total	**101,000**