FUTURE FACILITIES AND EXPERIMENTS

Andrea Dainese

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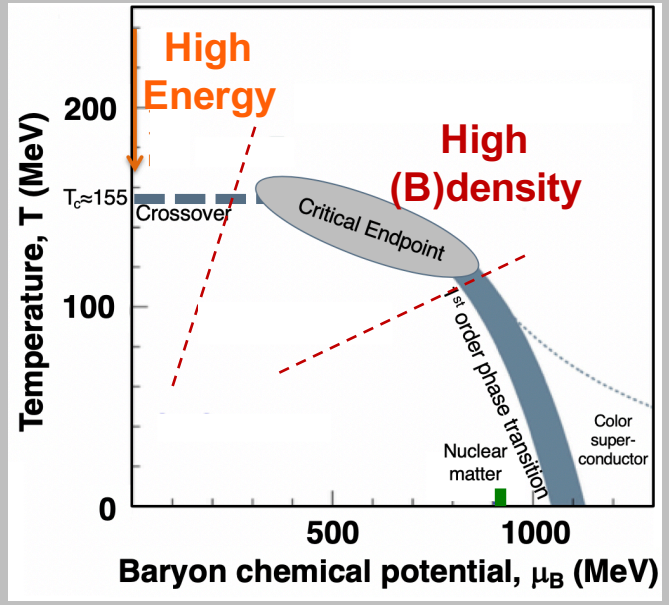
Outline

- Future AA/QGP research directions: high energy or high (B-)density
- eA colliders as precision cold-QCD machines
- Overview of low energy / high-μ_B facilities & experiments
  - HIAF, J-PARC, NICA, FAIR, SPS, RHIC-BES2
- Overview of high energy facilities & experiments
  - RHIC, LHC, FCC/SppC
- Selected physics objectives
  - Critical fluctuations and endpoint
  - QGP constituents and d.o.f.
  - Transport properties
  - Hadronisation
  - Thermal radiation

Sources:
QM18-19, SQM19
CERN HI Town Meeting
ESPPU

Future research directions with AA collisions



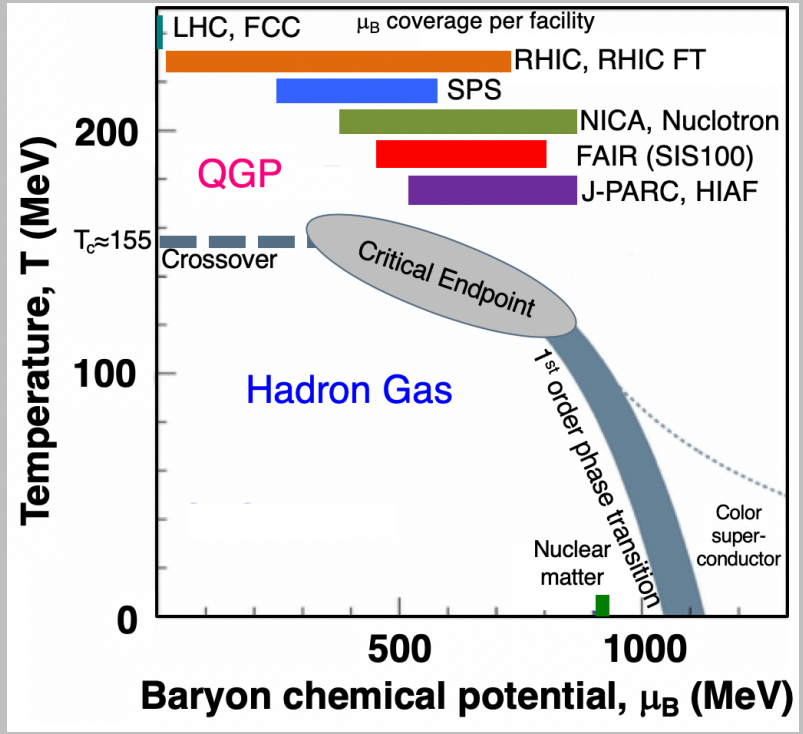
High energy collisions:

- Quantify properties of QGP fluid and relate them to its constituents
- How is collectivity developed? can it be developed also in small systems (pp, pA)?

High (B)density collisions:

- Onset of deconfinement via energy scans
- Direct observation of 1st order phase transition in QCD
- Search for the Critical Endpoint (lQCD: $\mu_B > 300$, $T < 140$)
- QGP constituents at high μ_B → Neutron Star EoS

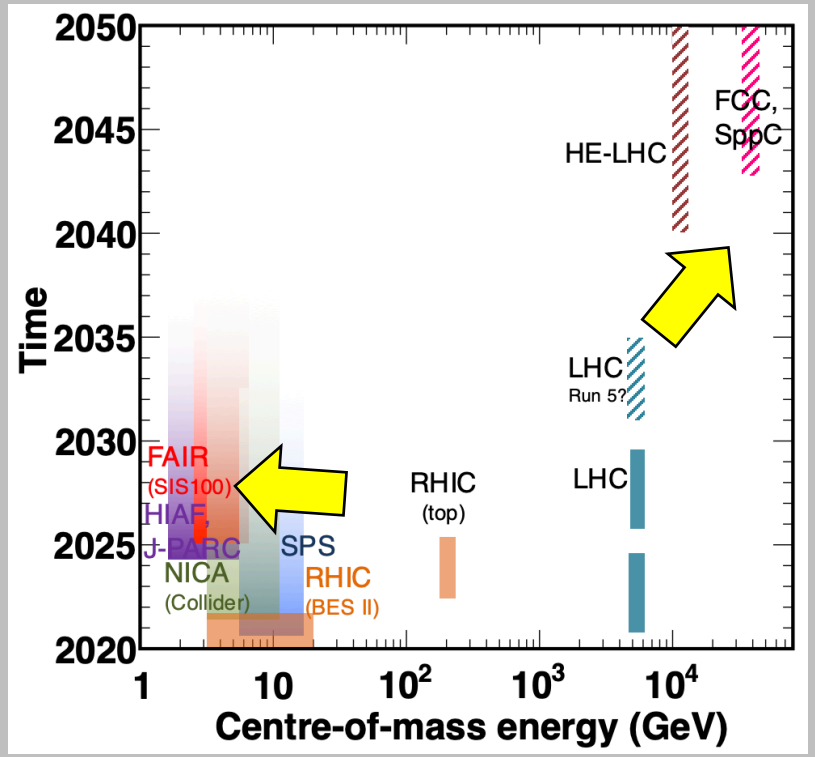
Future landscape of HI facilities



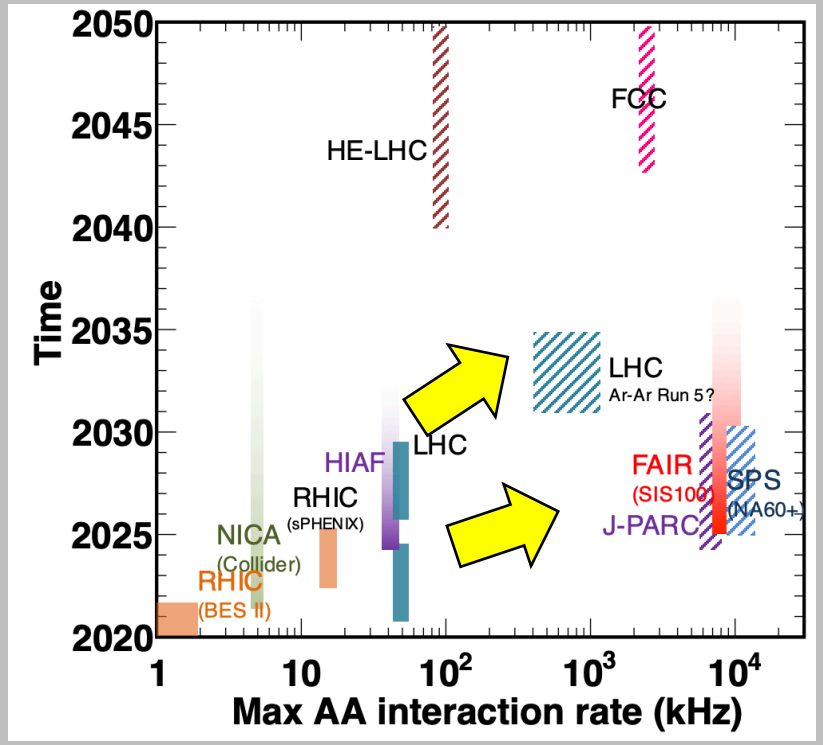
adapted from A. Dainese et al., arXiv:1602.04120

Push the frontiers

at low/high energy



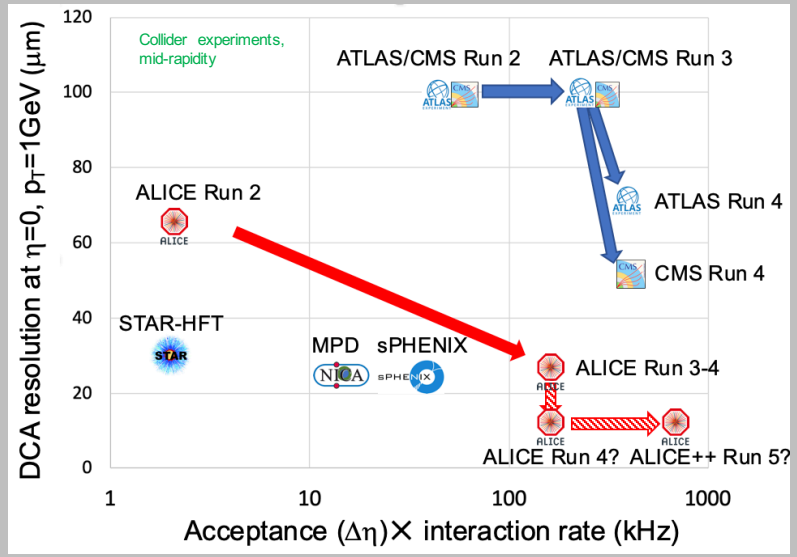
and high rate



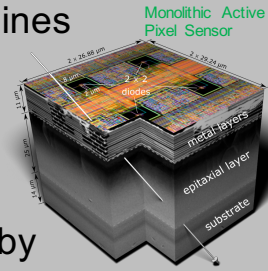
Detector technology frontier

- Main frontiers to enhance physics reach:
  - **rate capabilities & acceptance**
  - **tracking precision**

→ high precision, reduce backgrounds, access to rarer probes (e.g. Z-jet, higher harmonics or moments, (multi-)HF baryons, X states, tops, hypernuclei …)



- x10-100 in "statistics" at RHIC and LHC
  - Increased interaction rate at both machines
  - Faster readout and larger acceptance
- Monolithic pixel trackers bring DCA resolution to 20-30 μm at p_T=1 GeV/c
  - Pioneered by STAR; key development by ALICE, will be adopted also by sPHENIX, CBM, MPD, NA61, NA60+



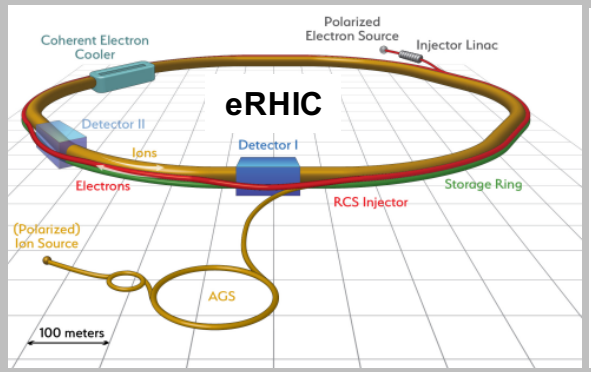
Precision cold-QCD at future eA colliders

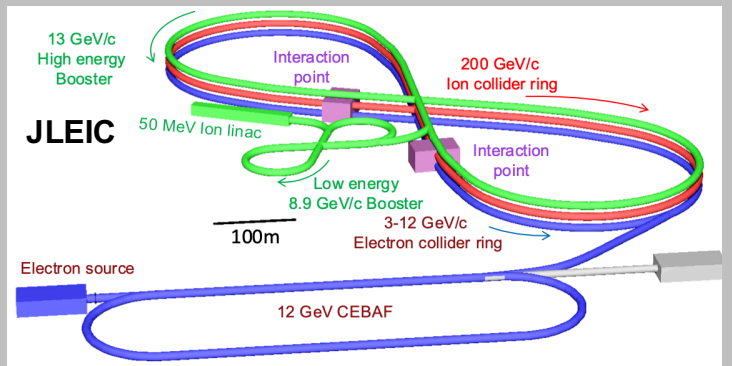
- Several eA collider facilities proposed in US, China, CERN

arXiv:1812.08110

Facility	Years	E_{cm} (GeV)	Luminosity ($10^{33} cm^{-2} s^{-1}$)	Ions	Polarization
EIC in US	> 2028	20 - 100 $\rightarrow$ 140	2 - 30	p $\rightarrow$ U	e, p, d, ^{3}He, Li
EIC in China	> 2028	16 - 34	1 $\rightarrow$ 100	p $\rightarrow$ Pb	e, p, light nuclei
LHeC (HE-LHeC)	> 2030	200 - 1300 (1800)	10	depends on LHC	e possible
PEPIC	> 2025	530 $\rightarrow$ 1400	$< 10^{-3}$	depends on LHC	e possible
VHEeP	> 2030	1000 - 9000	$10^{-5} - 10^{-4}$	depends on LHC	e possible
FCC-eh	> 2044	3500	15	depends on FCC-hh	e possible

- US EIC the most advanced proposal: already set as highest priority for a new US facility, CD-0 expected soon
- Two options: BNL, JLab





Physics goals → Y. Hatta

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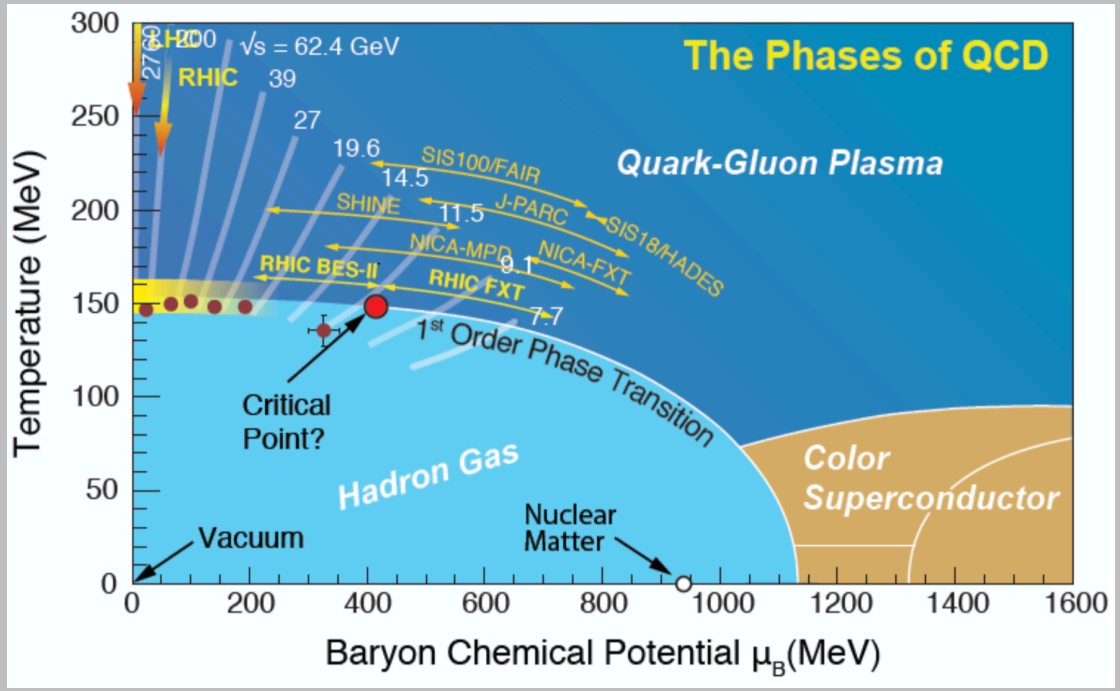
Future high (B)density experiments



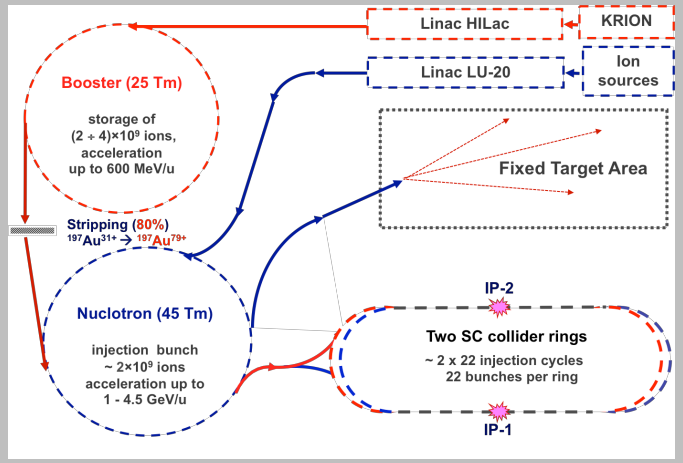
- Systematic exploration of high μ_B region in the coming decade
- Facilities:
  - BNL-RHIC
  - CERN-SPS
  - FAIR-SIS
  - JINR-NICA
  - J-PARC
  - HIAF

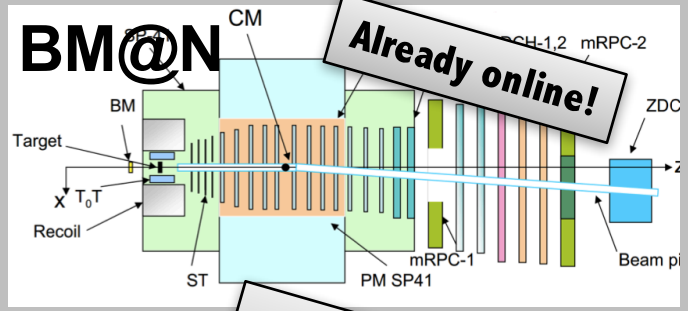
Future high (B)density experiments

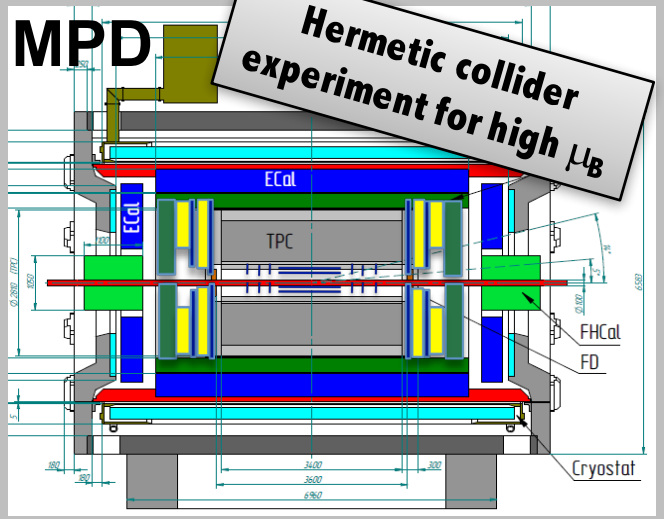
Facility	SIS18	HIAF	Nuclotron	J-PARC-HI	SIS100	NICA	RHIC	SPS	SPS
Experiment	HADES / miniCBM	CEE	BM@N	DHS, D2S	CBM / HADES	MPD	STAR	NA61	NA60+
Start	2012, 2018	2023	2019 (Au)	>2025(?)	2025	2021	2010,2019	2009, 2022	>2025(?)
$\sqrt{s_{NN}}$, GeV	2.4 – 2.6	1.8 – 2.7	2 – 3.5	2 – 6.2	2.7 – 5	2.7 - 11	3 – 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
Int. rate (kHz)	20	50	50	10,000	10,000	6	0.01 – 2	1	10,000
Hadrons	+	+	+	+	+	+	+	+	(+)
Dileptons	+		(+)	+	+	+	+		+
Charm				(+)	(+)	+	+	+	+

T. Galatyuk, QM2018

JINR BM @ Nuclotron (2019), MPD @ NICA (2021)





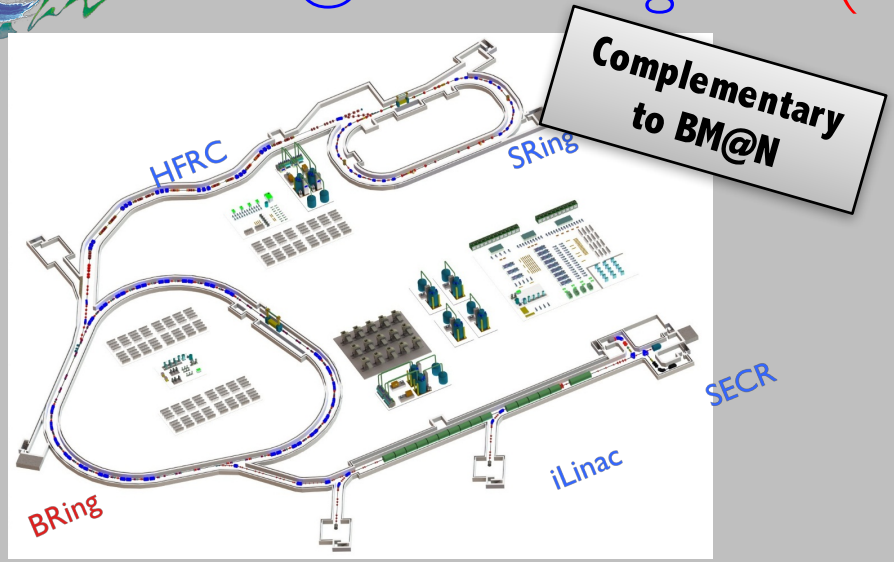


- Fixed-target $\sqrt{s_{NN}}$ = 2-3.5 GeV
- Up to 50 kHz
- Au-Au from 2020

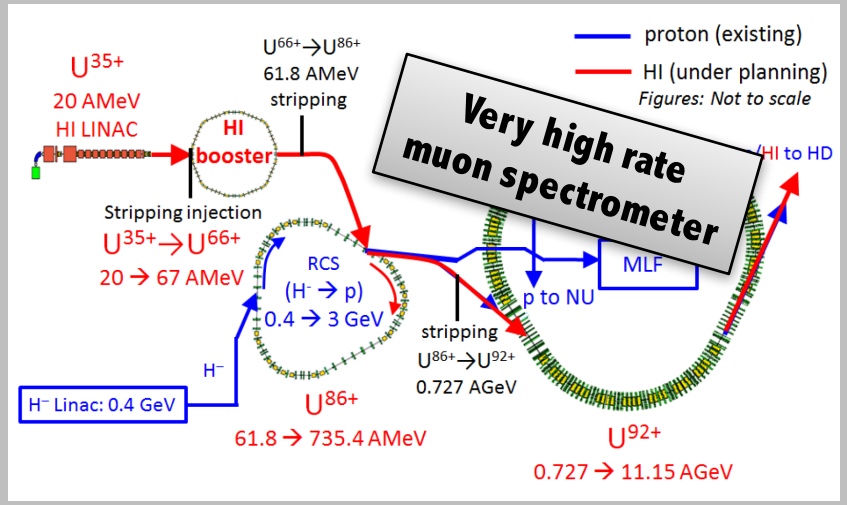
- $\sqrt{s_{NN}}$ = 4-11 GeV
- Up to 6 kHz
- Stage-1 (2020): barrel TPC, Ecal, PID
- Stage-2 (2023): silicon tracker, endcaps

A. Kisiel (MPD)

CEE @ HIAF-Langzhou (2023), J-PARC-HI (>2025?)



Complementary to BM@N

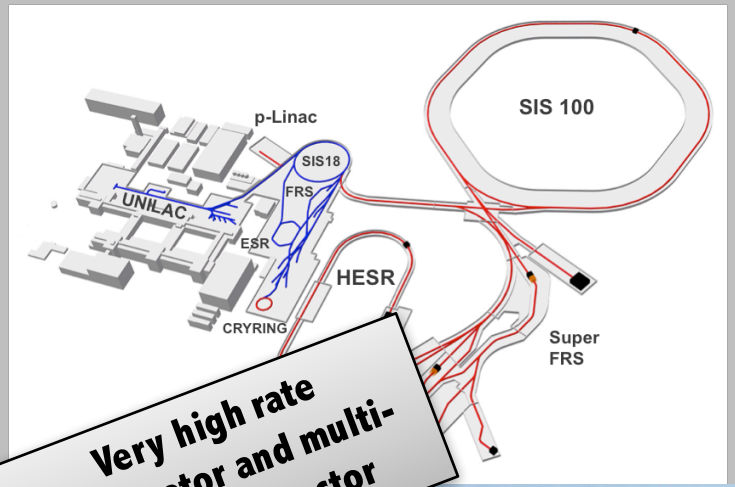


Very high rate muon spectrometer

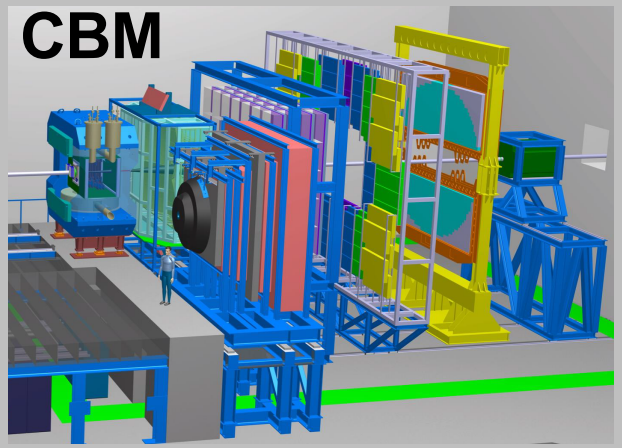
- Fixed-target $\sqrt{s_{NN}}$ = 1.8-2.7 GeV
- Up to 50 kHz
- Hadron spectrometer

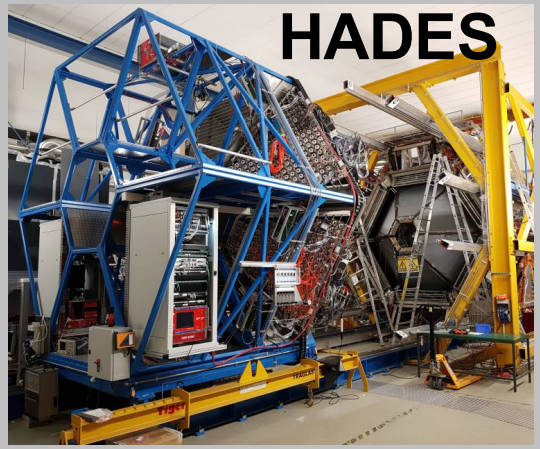
- HI operation in proposal / design phase
- New booster and linac needed
- Fixed-target $\sqrt{s_{NN}}$ = 2-6.2 GeV
- Hadron spectrometer ~10 kHz
- Muon spectrometer ~ 10 MHz

FAIR – CBM, HADES @ SIS100 (2025)



Very high rate accelerator and multi-purpose detector

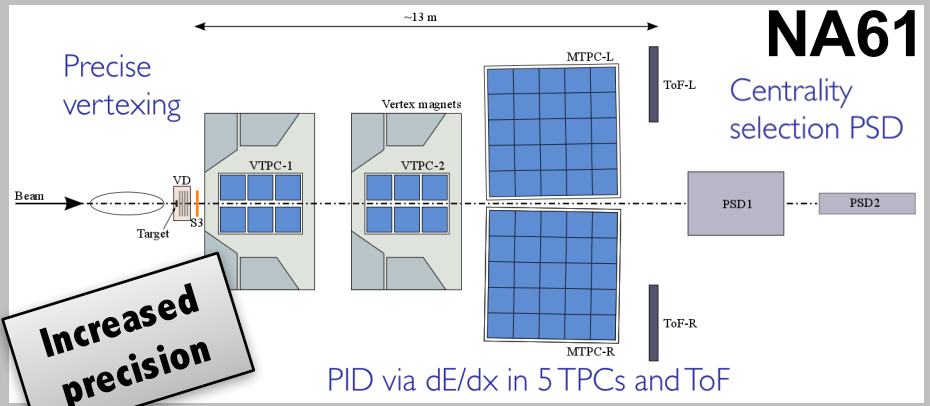


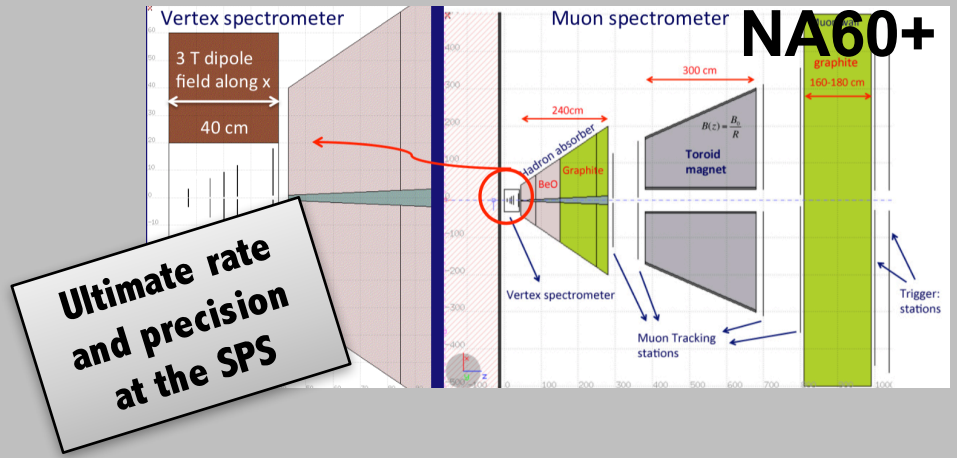


- Fixed target ion and proton beams, $\sqrt{s_{NN}}$ = 2.7-5 GeV
- CBM: high-precision tracking, hadron and electron ID, very high rate capability (10 MHz) with real-time processing
- HADES: focus on low mult. AA, dileptons

V. Klochkov (CBM)

NA61/SHINE (2022), NA60+ (>2025?) @ SPS

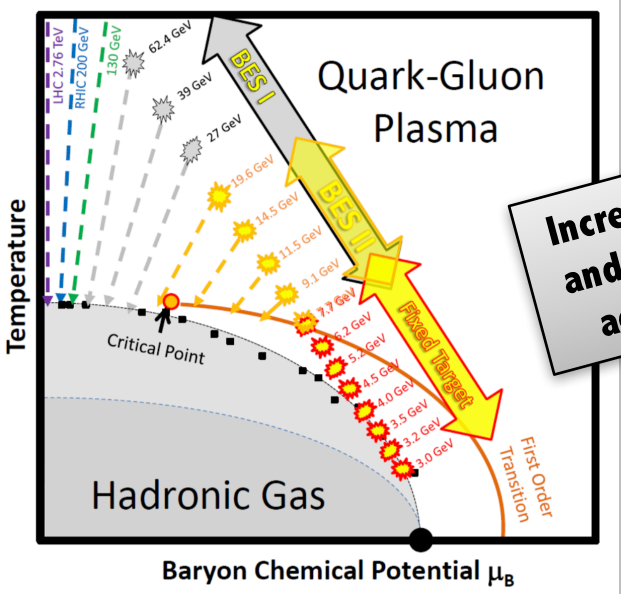




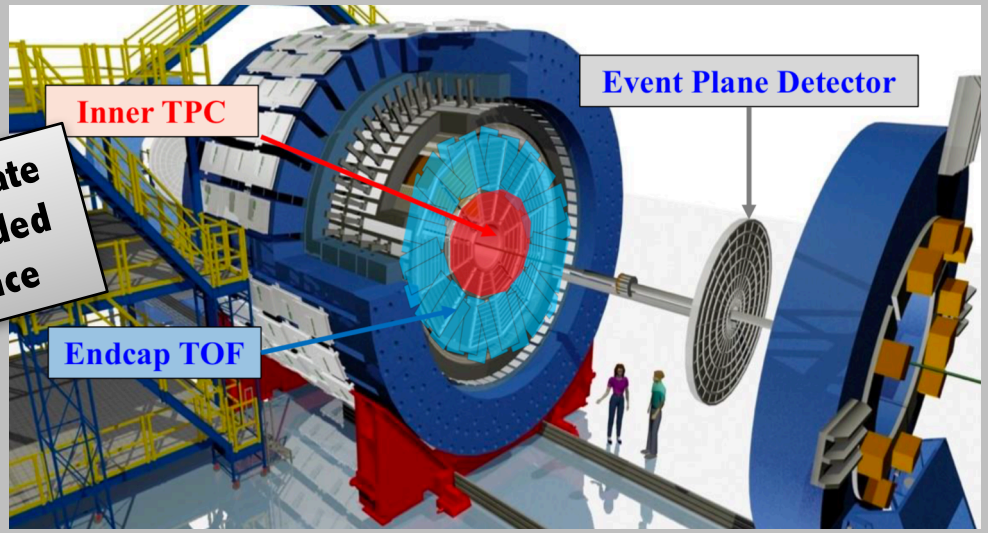
- Ongoing upgrade: pixel tracker, TPC readout at 1 kHz
- Pb-Pb at $\sqrt{s_{NN}}$ = 5 and 17 GeV in 2022-24
- Main goals: open charm cross section with ~10% precision, critical fluctuations with higher precision

- Proposal for a high-rate dimuon spectrometer with a silicon pixel tracker
  - EoI submitted to SPSC, LoI in prep.
- 10 MHz Pb-Pb at $\sqrt{s_{NN}}$ = 5-17 GeV
- Main goals: caloric curve with thermal dimuons, characterize χ-symmetry restoration, charmonia and open charm (~1% precision)

STAR @ RHIC-BES2 (2019)



Increased rate and extended acceptance



- BES2: beam energy scan with upgraded STAR detector (extended acceptance in η)
- Au-Au: collider at $\sqrt{s_{NN}}$ = 7.7-19.6 GeV + Fixed Target at $\sqrt{s_{NN}}$ = 3-7.7 GeV
- Higher luminosity with electron cooling: 1-2 order of magnitude wrt BES1

Y. Yang

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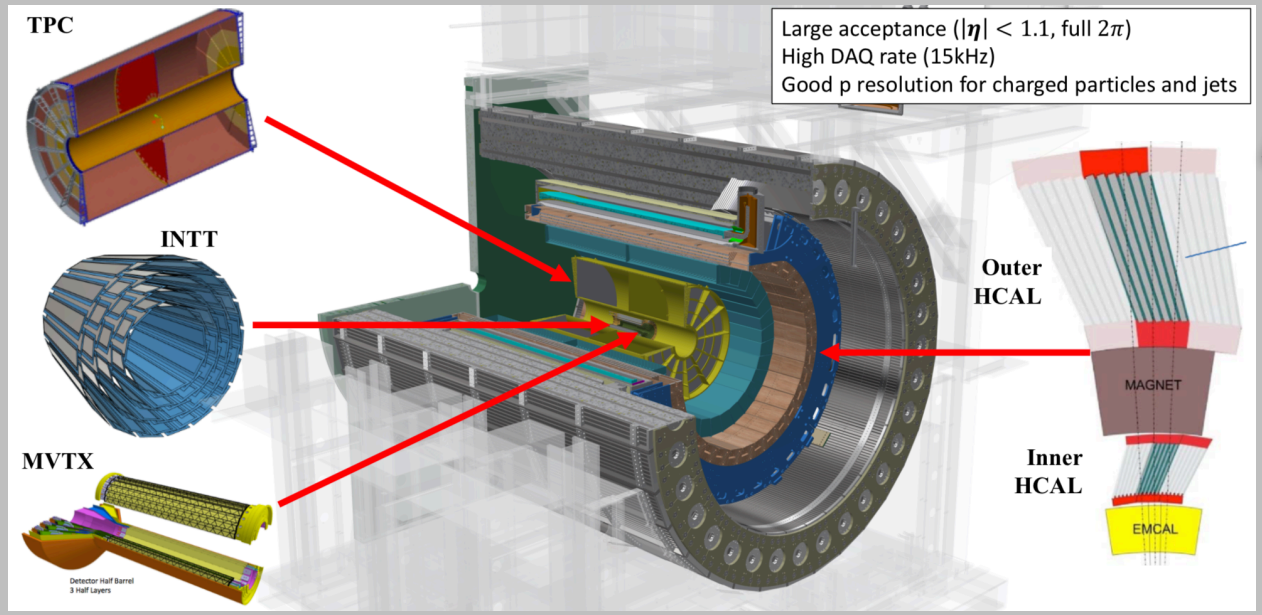
High-E colliders: RHIC, LHC, HE-LHC/FCC/SppC

Facility	RHIC	LHC	HE-LHC, FCC / SppC
Experiments	sPHENIX, STAR	ALICE, ATLAS, CMS, LHCb, ?	?
When	2023 – 2025	2021 – 2029, 2030?	>2040?, >2045?
$\sqrt{s_{NN}}$ (TeV)	0.2	5.5	10.5, 39
Int. rate (kHz)	~15	~50	~100 (HE-LHC), ~2500 (FCC)

- General goals – as phrased in HL-LHC Yellow Report (arXiv:1812.06772):
  1. Macroscopic long-wavelength **QGP properties** with unprecedented **precision**
  2. **Microscopic** parton **dynamics** underlying QGP properties
  3. **Parton densities** in broad kinematic range and search for saturation
  4. Collectivity **across colliding systems**, hot medium in small systems?
- Complementarity of RHIC and LHC is crucial
- FCC/SppC open completely new opportunities in all these scientific lines

sPHENIX @ RHIC (2023)



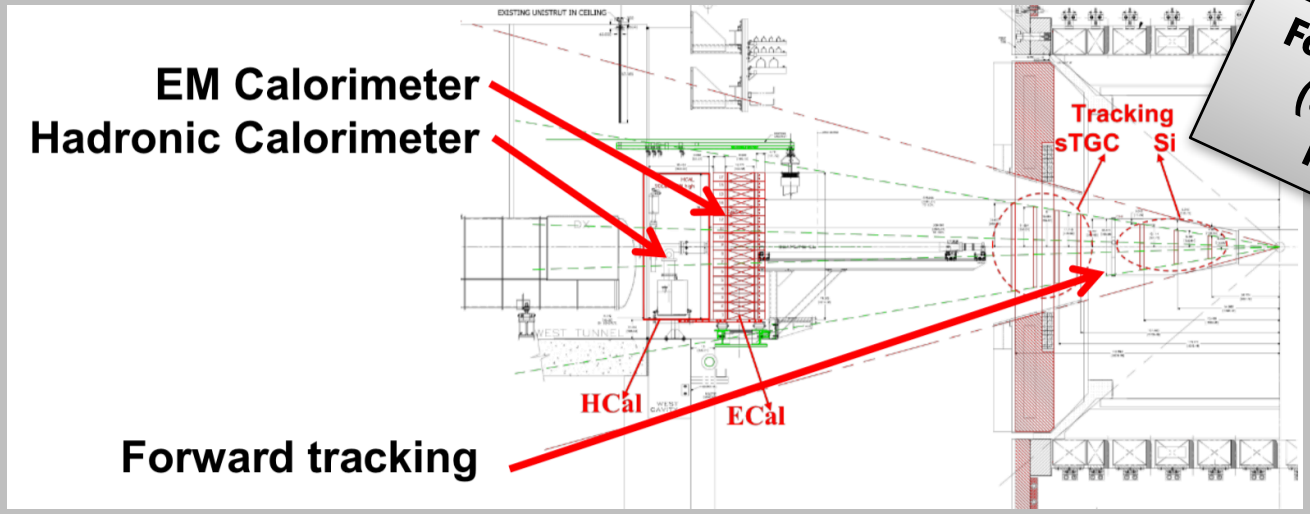
Ultimate performance for jets and HQs at RHIC

- Got CD2/3: construction can start
- Compact and hermetic design
- Continuous readout at 15 kHz
  - ~100B Au-Au events per year

- Focus on:
  - Fully reconstructed jets, with HCAL
  - Bottomonium states
  - HF mesons and baryons, with MAPS

Y. Ji

STAR @ RHIC (2023)

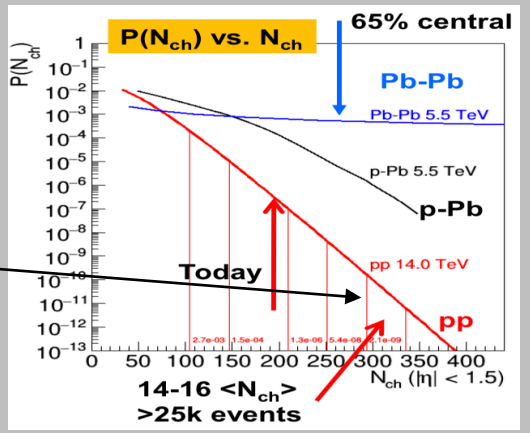


- Forward upgrade ready in 2021 – Au-Au and d-Au runs in 2023-2025
  - Tracking and calorimeters $2.8 < \eta < 4.2$: nPDFs, small-x with p-Au, longitudinal dynamics
- + exploit extended barrel acceptance in Au-Au at full RHIC energy
- Running at 1.4 kHz
  - 4B Au-Au events per year

Y. Yang

Future LHC programme

- Run 3 and Run 4 programme recently discussed (HL-LHC ws)
- **Main priority: large Pb-Pb sample, 13/nb**
  - **x10** L_{int} for "rare" triggers wrt Run 2
  - **x100** MB sample for upgraded ALICE
- Proposed extension of **"small system" programme**
  - **Extended p-Pb** run: nPDFs, collectivity, hot system signals?
  - **pp 14 TeV** low pile-up with focus on **high multiplicity**
  - Short **^{16}O-^{16}O** (and p-O) run in Run 3:
    - E-loss in central AA with p-Pb-like multiplicity?
    - Flow ←→ initial eccentricities

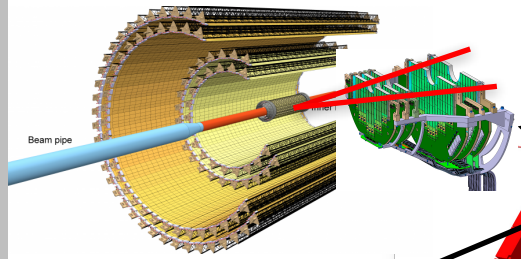


pp 14 TeV: e.g. with 200/pb sample same $dN_{ch}/d\eta$ as 60% central Pb-Pb

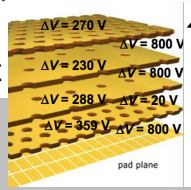
arXiv:1812.06772

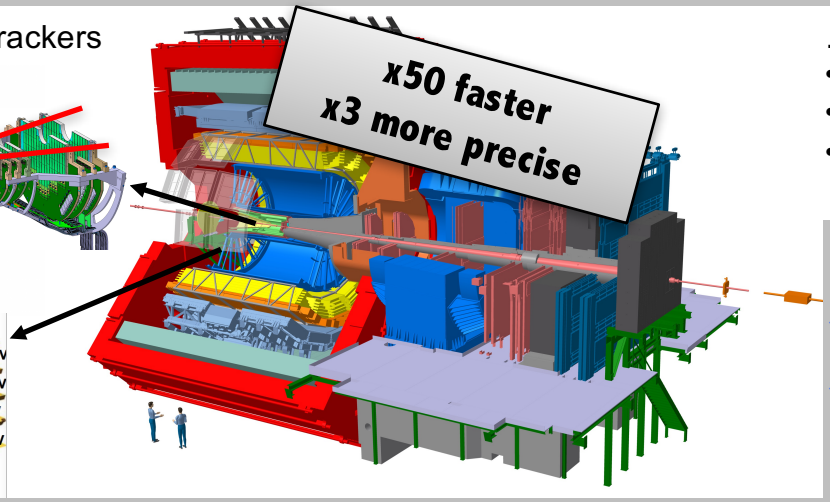
ALICE LS2 Upgrade (2021) and LS3 ideas

All-pixel central and fwd trackers



GEM-based TPC readout



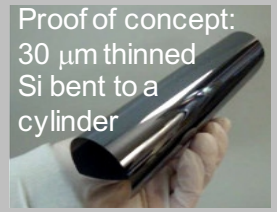


… and more:
- Fast Interaction Trigger
- New Online-Offline system
- Readout upgrade of several detectors

- x3 better tracking precision
- Continuous readout at 50 kHz

→ ~100B Pb-Pb in Runs 3+4

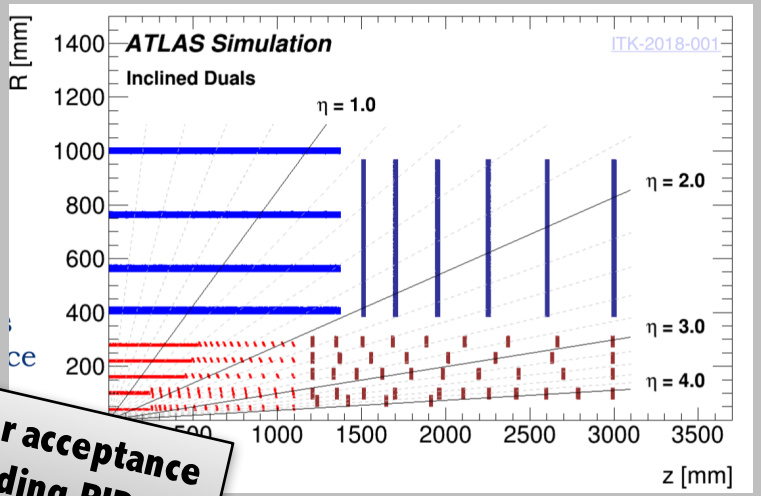
- Upgrade proposals for LS3 (2026):
  - Replace **inner barrel** with a **truly-cylindrical ultralight** one: x3 less material
  - FoCal with high-granularity readout for **direct photons at 3.2 < η < 5.8**: probe gluon density down to **x ~ 5x10^{-6}**
  - Exploring fixed-target programme with crystal collimated beam halo



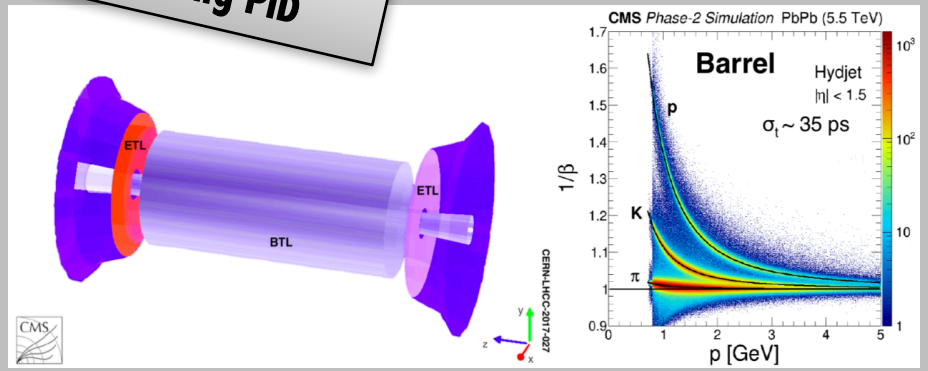
F. Reidt

ATLAS and CMS LS3 Upgrades (2026)

- Run 3+4: goal 13/nb Pb-Pb, focus on rare triggers
- CMS, also large bandwidth for MB events: 6 kHz in Run 3, goal to increase for Run 4
- Major Phase-2 upgrades for HL-LHC
  - Extension of tracker acceptance from $|\eta|<2.5$ to $|\eta|<4$
  - Endcap calorimeters with higher granularity
  - Precise timing detectors for pile-up rejection → t.o.f. PID
    - ATLAS $2.5 < |\eta| < 5$
    - CMS $|\eta| < 4$



Larger acceptance Adding PID



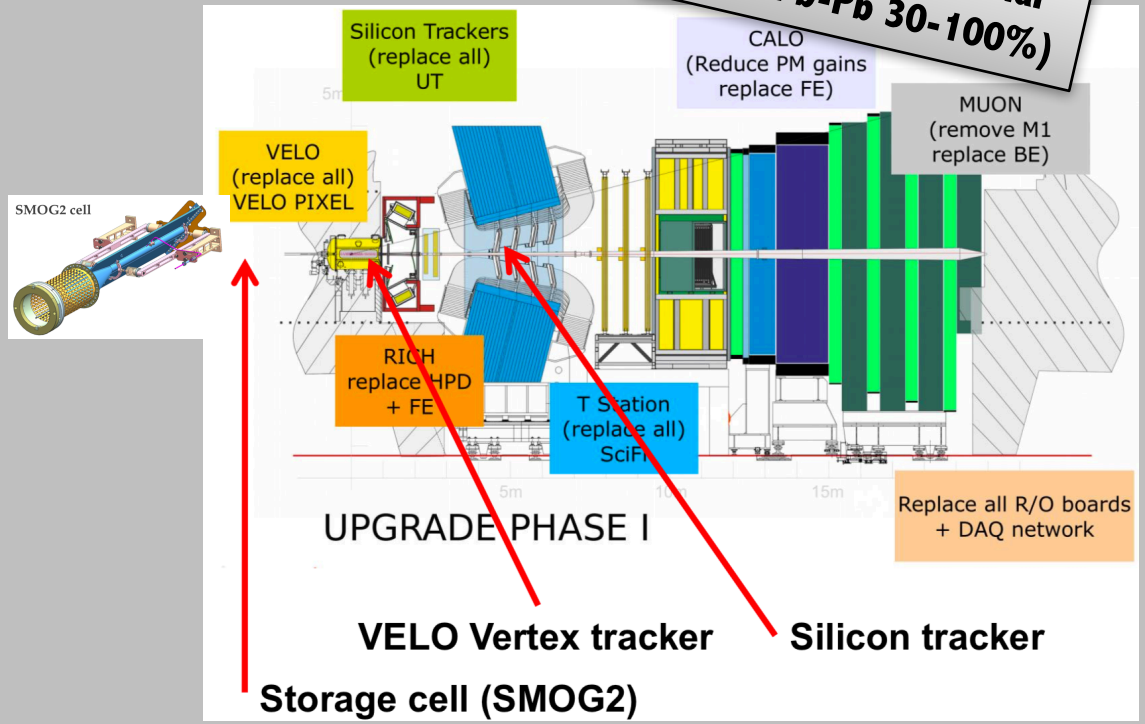
A. Govinda Stahl Leiton (CMS)

LHCb LS2 Upgrade (2021)

- Ongoing LS2 upgrade:
  - Tracker with higher granularity
    → **Pb-Pb 30-100%**
  - New **storage cell for fixed-target collisions** at up to x100 higher rates (p … Ne … Xe)

- Proposal for phase-2 upgrade for Run 5 (2031)
  - Increased readout rate and granularity → **central Pb-Pb**
  - Extended PID performance

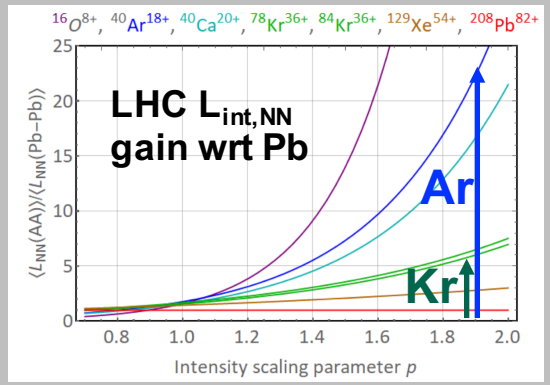
Faster, more granular (goal: Pb-Pb 30-100%)



P. Di Nezza

Extending the LHC HI programme

- Run3+4 sample will also tease us with potentially new directions, just to name a few:
  - Differential Z-jet balance studies
  - HF baryons with >1 HQ, XYZ states, hyper-nuclei A>5 or with charm?
  - Differential thermal radiation studies
  - Physics with top quarks
  - …
- Major $L_{int,NN}$ increase could be achieved with lower-A nuclei: Kr-Kr or Ar-Ar give up to x7 or x25 wrt Pb-Pb
  - In exchange of milder QGP effects, but overall gain
- HL-LHC ws Proposal: high-rate HI in Run 5 with lower-A

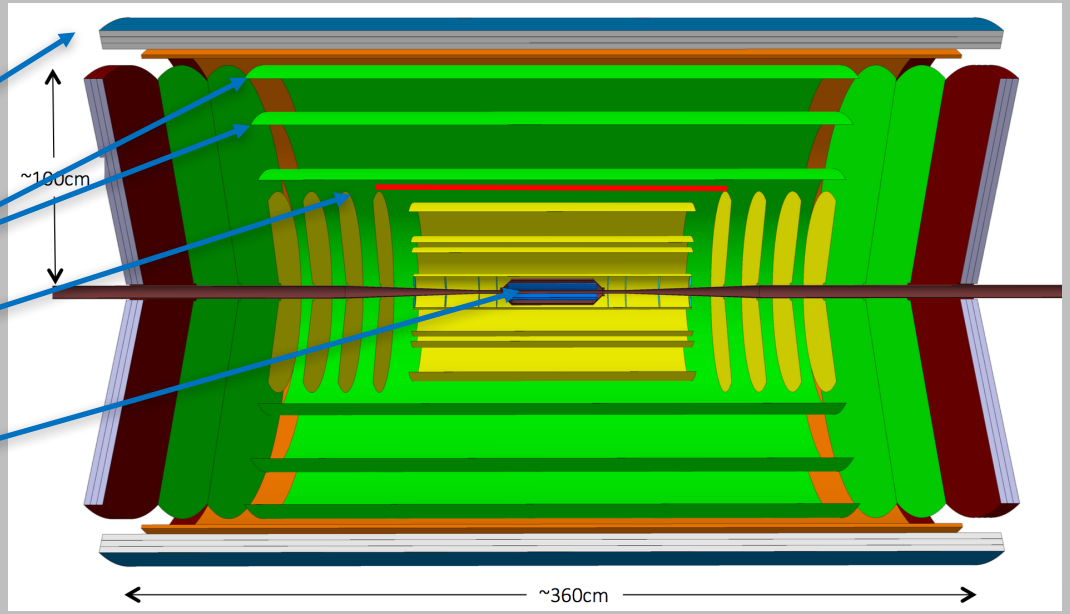


arXiv:1812.06772

”Si-only” HI experiment for LHC Run 5 (>2031?)

- Fast, ultra-thin detector with precise tracking and timing
  - Exploit higher NN lumi with intermediate-A nuclei
  - Ultimate performance for (multi-)HF, thermal radiation and soft hadrons (<50 MeV)

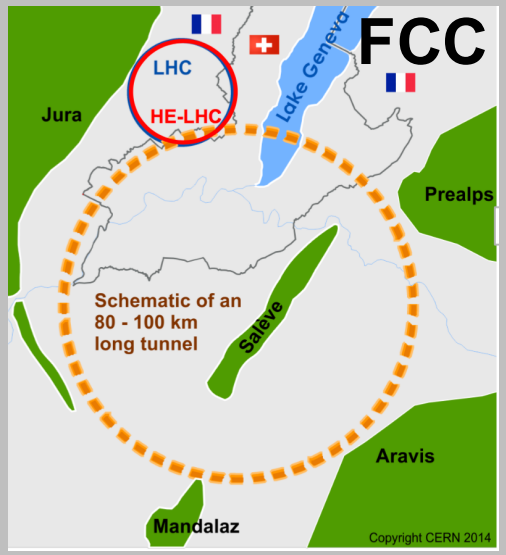
- All-pixel tracking and PID detector $|\eta|<4$
- Pre-shower layers with W+pixels for ID high-*p* electrons
- Timing layers σ~25 ps for t.o.f. ID of hadrons and low-*p* electrons
- Insertable converter layer for photon detection
- Innermost layers inside the beam pipe

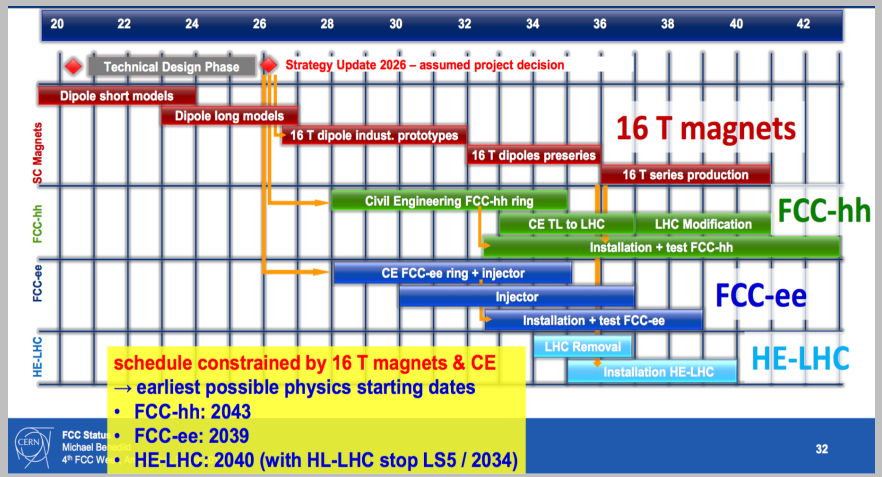


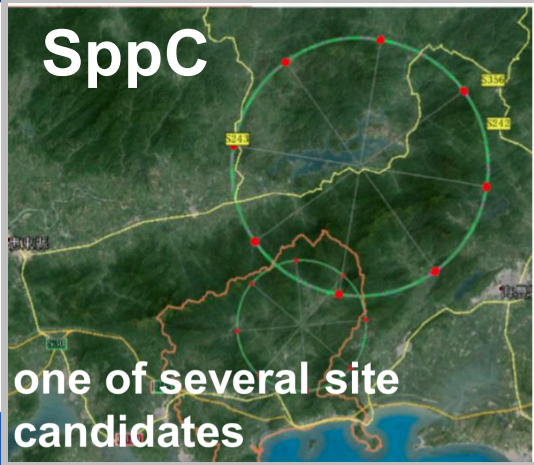
arxiv:1902.01211

Far future: HIs in a 100 km collider? FCC / SppC

- 100 km tunnel: one of the options for HEP in the 2040s-50s
- Two studies: CERN-FCC (CDR done), Chinese SppC (pre-CDR)
- Both could start as e^+e^- Higgs/W/Z/top-factories
- AA and eA operation in baseline design







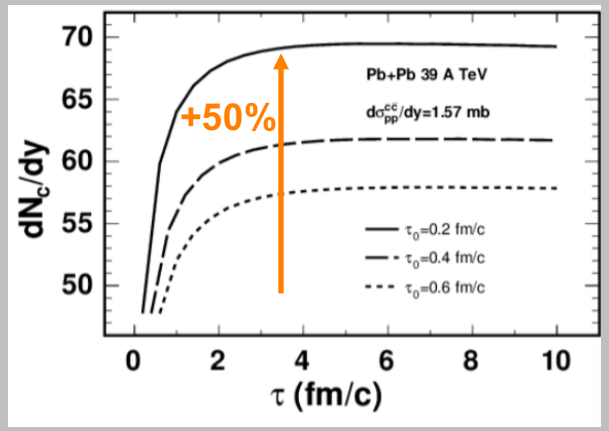
FCC CDR:
https://fcc-cdr.web.cern.ch

SppC pre-CDR:
http://cepc.ihep.ac.cn/preCDR/volume.html

Far future: HIs in a 100 km collider? FCC / SppC

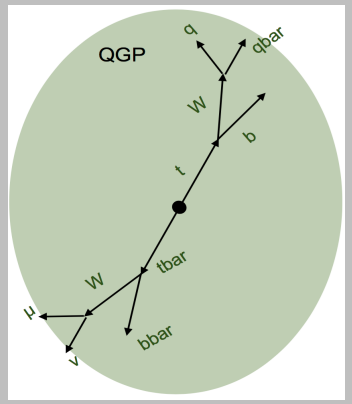
- FCC-hh HI performance: Pb-Pb $\sqrt{s_{NN}}$ = 39 TeV
- >100 nb^{-1}/month in ultimate luminosity scenario: **~ 10x full LHC L_{int} per month!**
- QGP from LHC to FCC: volume x2, energy density x3, initial T_0 up to 0.8-1 GeV!

Thermal charm?



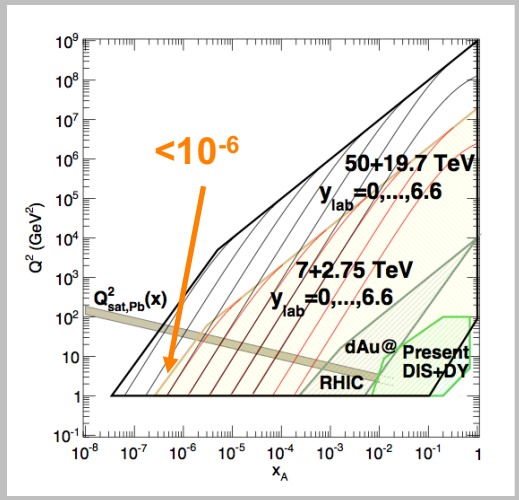
Ko, Liu, JPG43 (2016) 12, 125108
Zhou et al., PLB758 (2016) 434

New hard probes



Apolinario, Milhano, Salam, Salgado,
PRL120 (2018) 23, 232301

Smallest-x ever



A. Dainese et al., arXiv:1605.01389

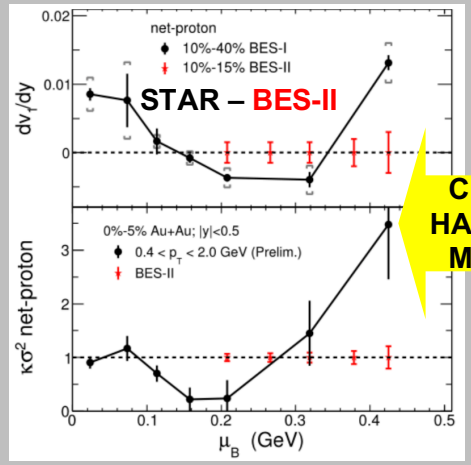
Outline

- Future AA/QGP research directions: high energy or high (B-)density
- eA colliders as precision cold-QCD machines
- Overview of low energy / high-μ_B facilities & experiments
  - HIAF, J-PARC, NICA, FAIR, SPS, RHIC-BES2
- Overview of high energy facilities & experiments
  - RHIC, LHC, FCC/SppC
- Selected physics objectives
  - Critical fluctuations and endpoint
  - QGP constituents and d.o.f.
  - Transport properties
  - Hadronisation
  - Thermal radiation


MONTH DAY YEAR HOUR MIN
AUG 27 2027 AM PM 12 50
DESTINATION TIME
MONTH DAY YEAR HOUR MIN
NOV 09 2019 AM PM 10 20
PRESENT TIME
MONTH DAY YEAR HOUR MIN
OCT 26 1985 AM PM 01 20
LAST TIME DEPARTED
CALIFORNIA
OUTATIME

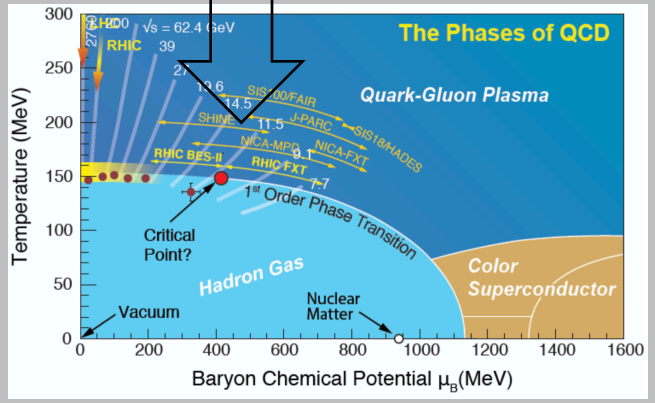
Critical fluctuations and search for critical point

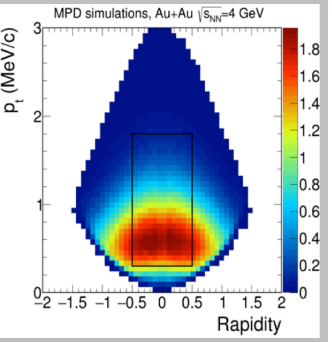
Main tool: net baryon fluctuations → needs high statistics and large acceptance

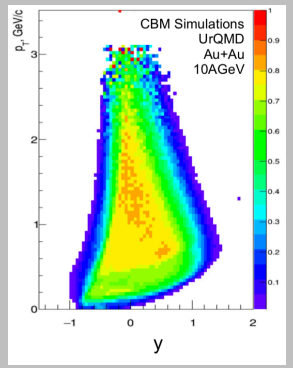


CBM
HADES
MPD

Systematic scan of high-μ_B region, for the first time with very high luminosity: BES-II, SIS100, NICA







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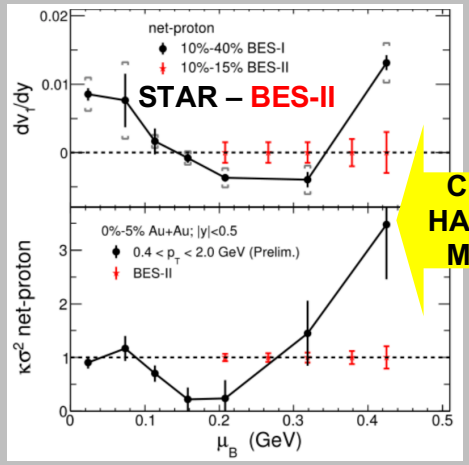

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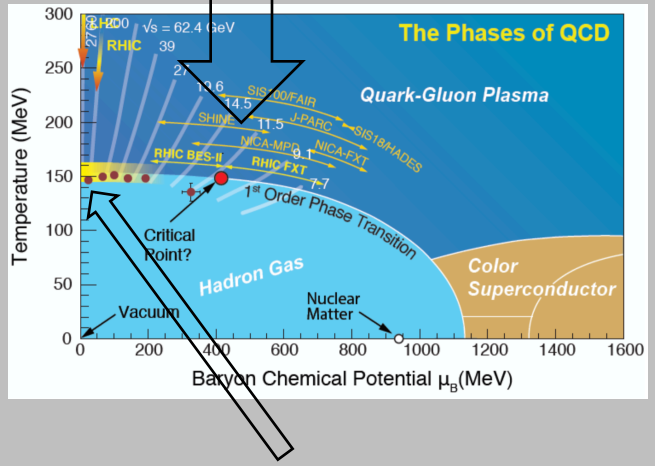
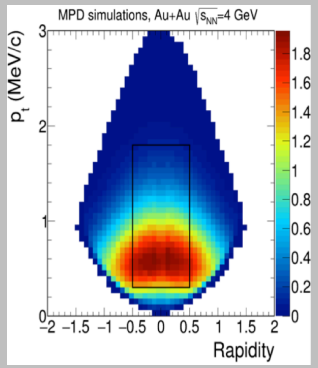
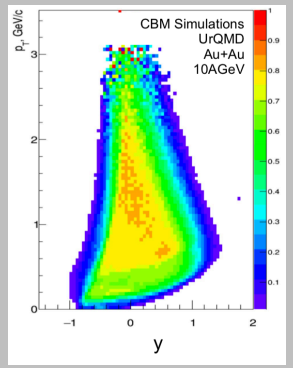
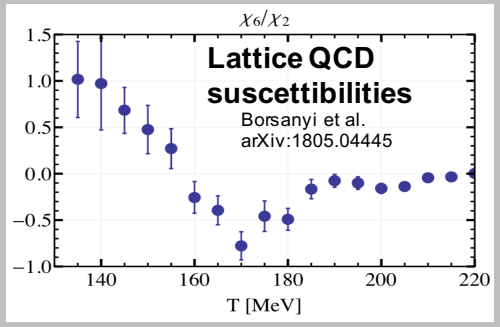
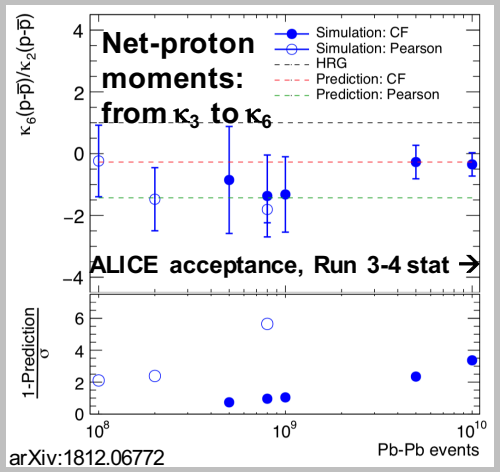




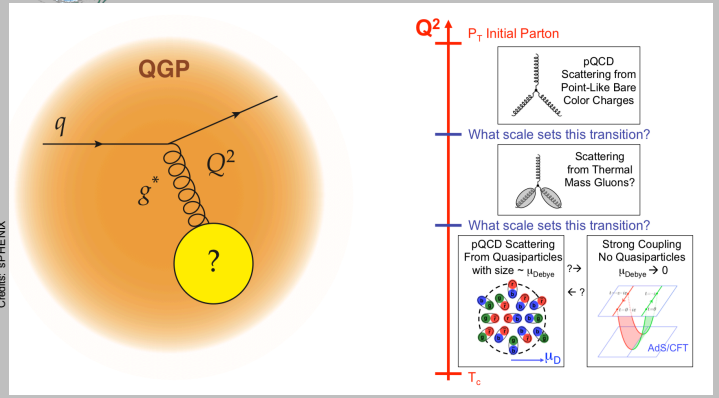


Precise characterisation of phase transition via high order (>3) moments at the LHC





QGP constituents



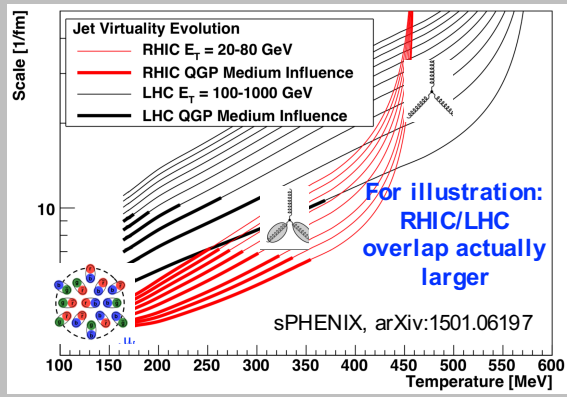
Credits: sPHENIX

What are the relevant degrees of freedom vs. scale Q and Temp?

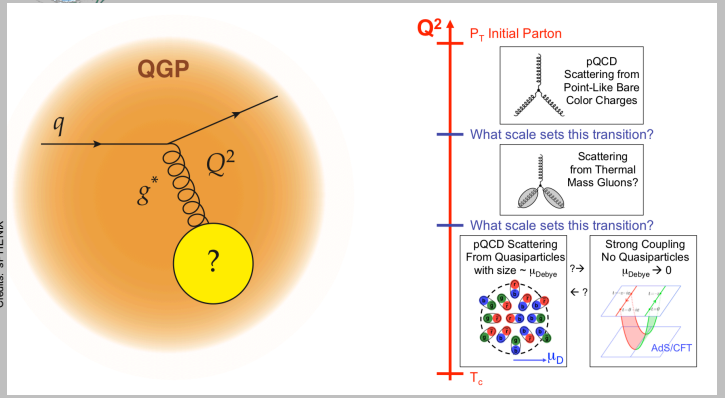
- High-Q: point-like color charges?
- …: thermal quarks and gluons?
- Low-Q: quasi-particles?

→ Probes with broad range of scales

→ Complementarity RHIC / LHC



QGP constituents



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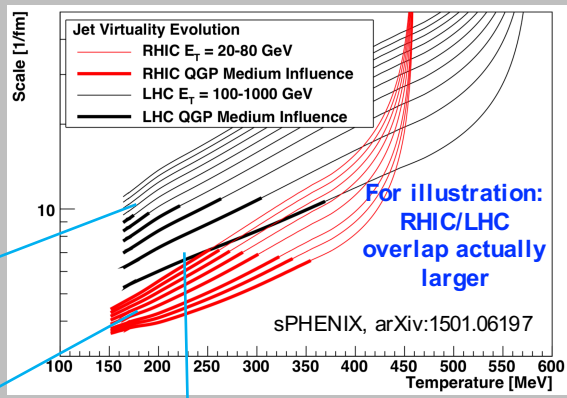
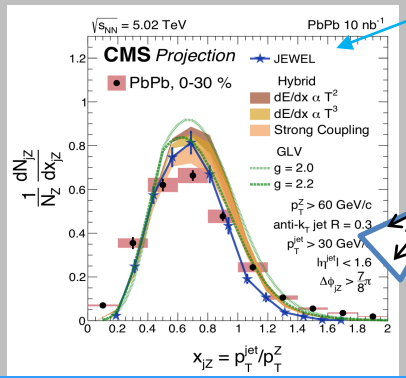
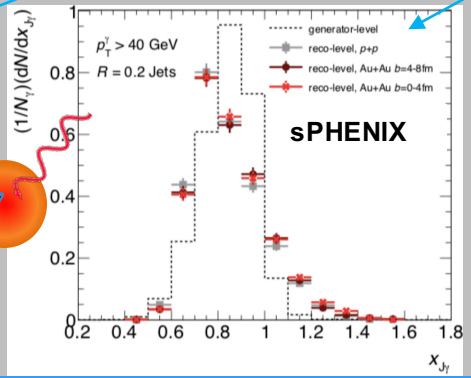


→ High-precision **γ/Z/h-jet** momentum and angular (de)correlation studies at RHIC and LHC

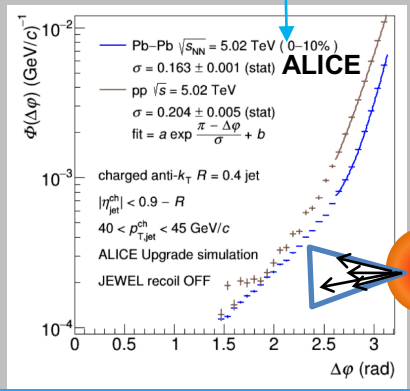
High-Q/High-T:



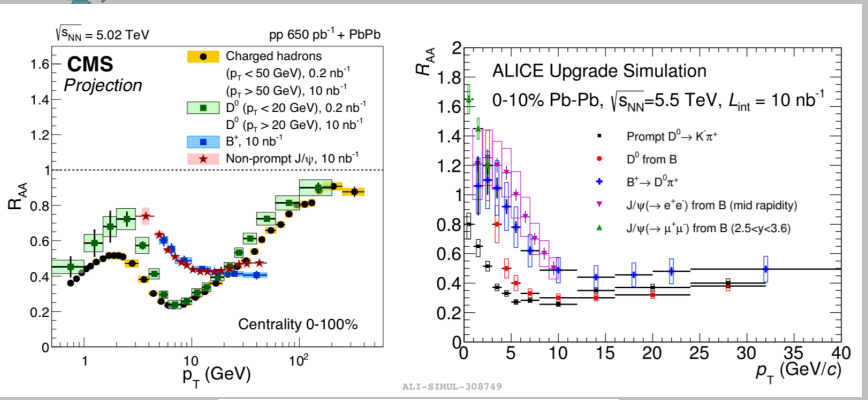
Low-Q/Low-T:

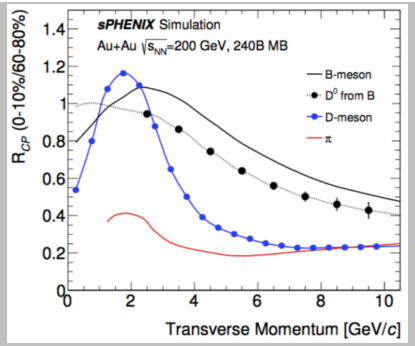


Low-Q/High-T:



QGP transport properties



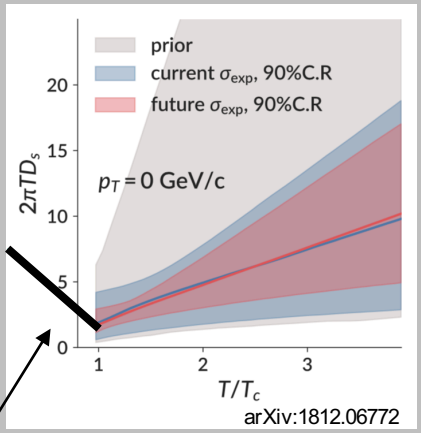


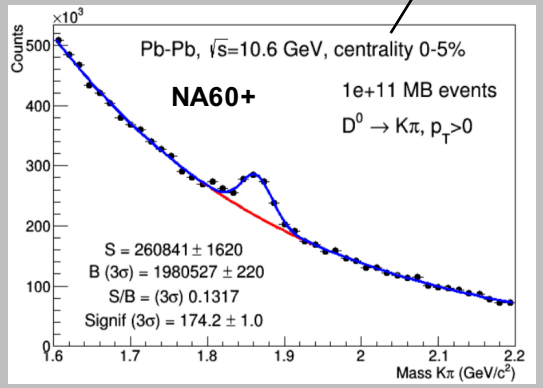
D and B at LHC and RHIC

→ **Heavy quark diffusion coefficients** $2\pi TD_S(T)$

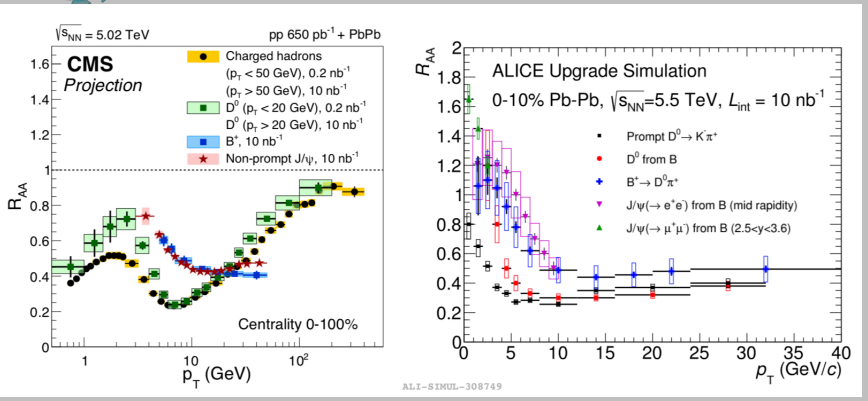
- e.g. Bayesian analysis with modified Langevin (Bass et al.)

$2\pi TD_S$ in hadronic matter ($T<T_c$) with NA60+ at SPS?





QGP transport properties and density … vs time



D and B at LHC (Runs3+4)

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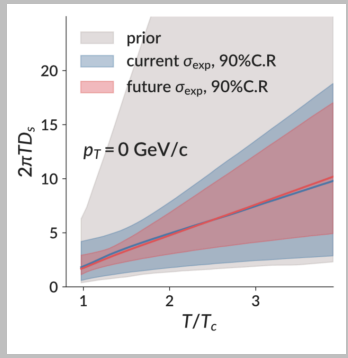
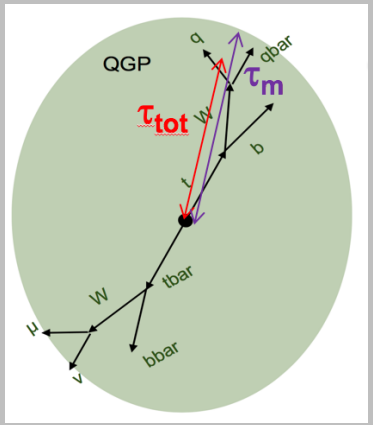
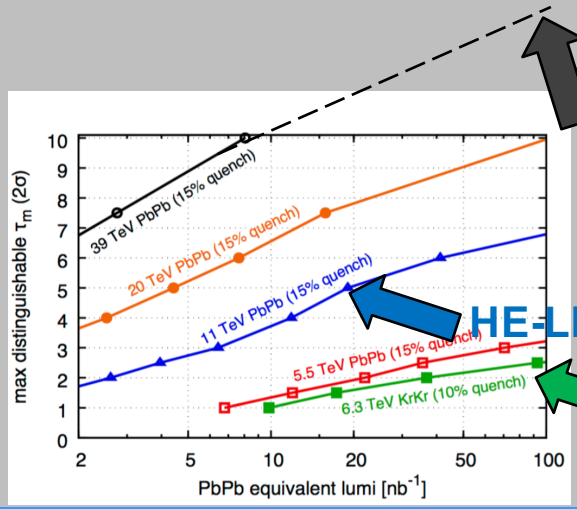




Boosted top decay chain

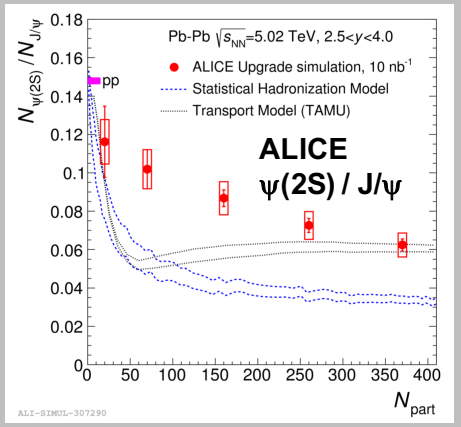
→ $\bar{q}q$ from W probes the QGP with delay τ_{tot} of up to

- ~1-2 fm/c at LHC (Kr)
- ~5 fm/c at HE-LHC
- ~10 fm/c at FCC

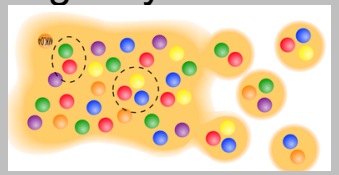


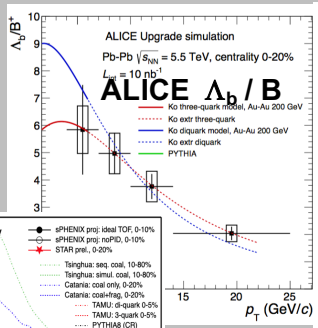
Apolinario, Milhano, Salam, Salgado, PRL120 (2018) 23, 232301

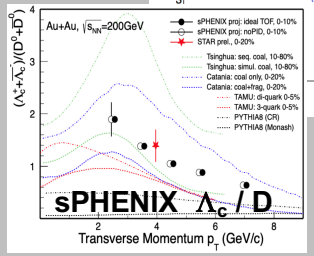
Understanding hadronisation: from HQs

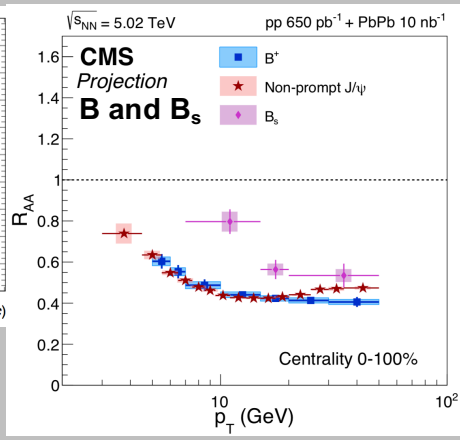


← $c\bar{c}$ un-/re- binding at LHC to probe QCD potential;
c and b baryons to test hadronisation dynamics from small to larger systems →

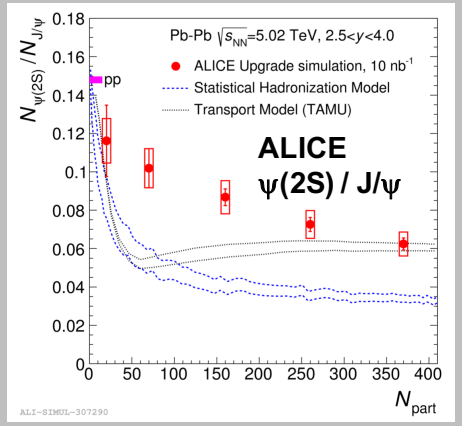








Understanding hadronisation: from HQs to hyper-A



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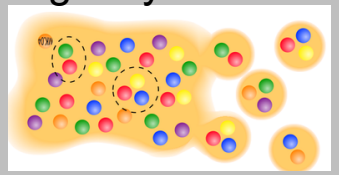
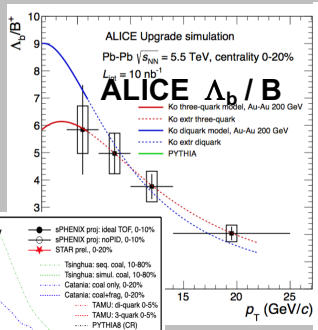
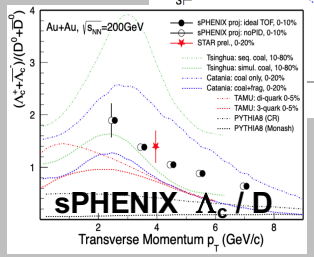
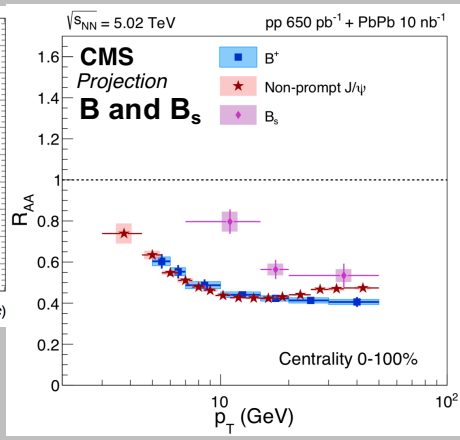
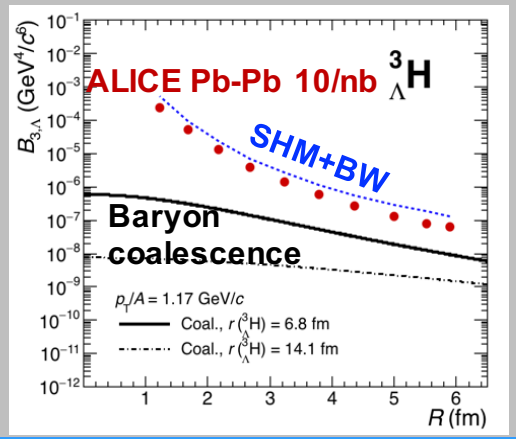


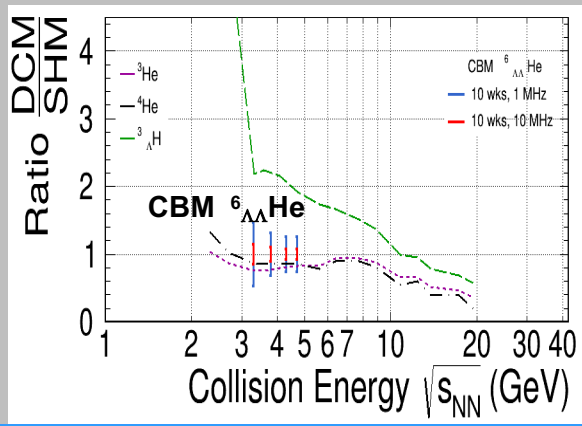








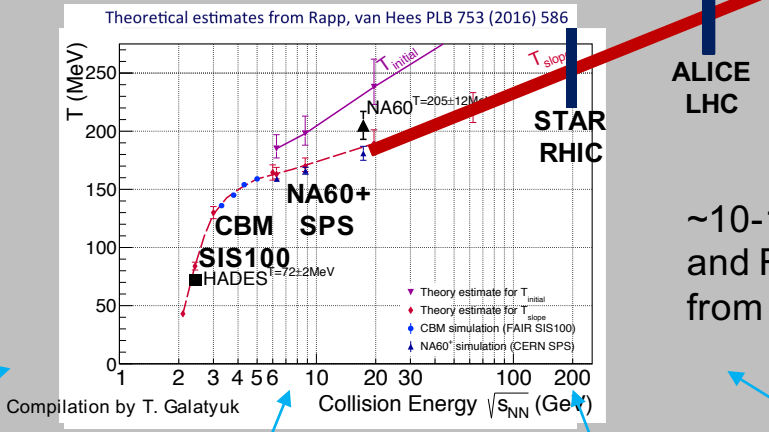
(Hyper-) nuclei (A=3,4) at LHC and up to A=6 at SIS100 to test strange matter properties (→ neutron star EoS)

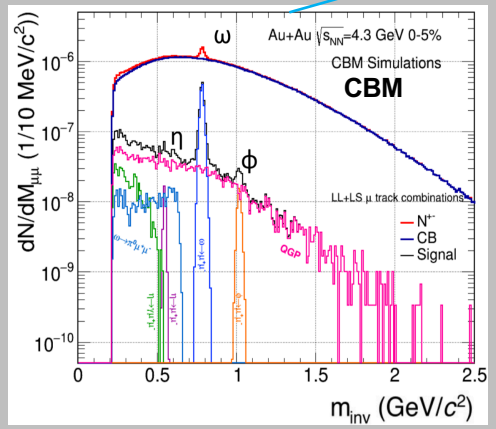


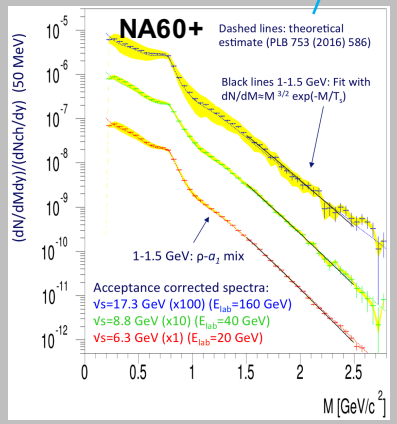
Thermal radiation: → caloric curve of QCD matter

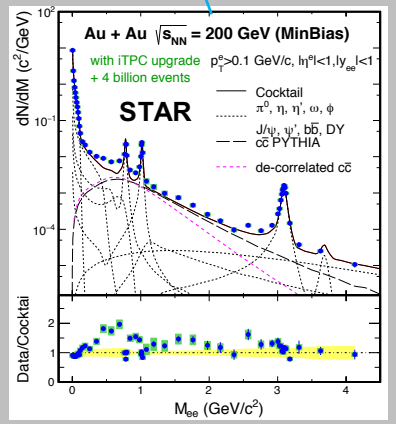
~% uncertainty on T_{eff} at SIS100 and SPS with di-muons from CBM and NA60+

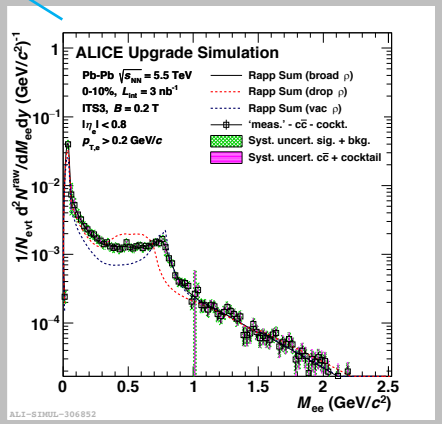
~10-15% uncertainty on T_{eff} at LHC and RHIC energies with di-electrons from ALICE and STAR





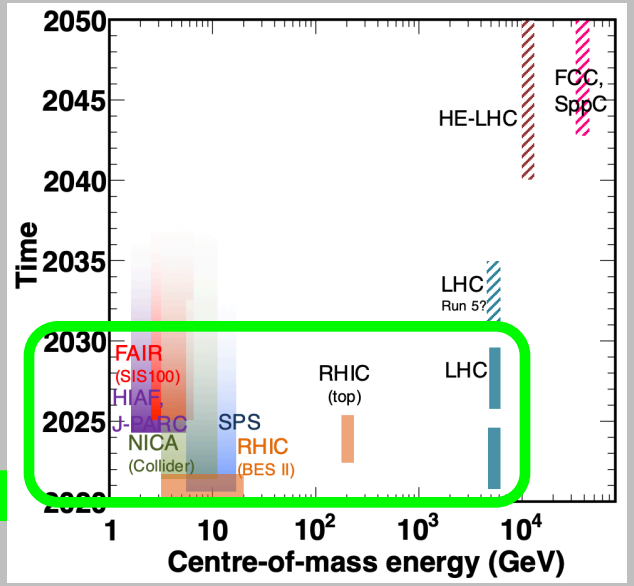






Conclusions

- Today: still in the middle of exploiting the latest/largest LHC Pb-Pb run
- Very rich decade ahead of us:
  - Data from 6-7 facilities
  - From current 7 to 12-14 running experiments
  - Up to x100 higher rates / L_{int}



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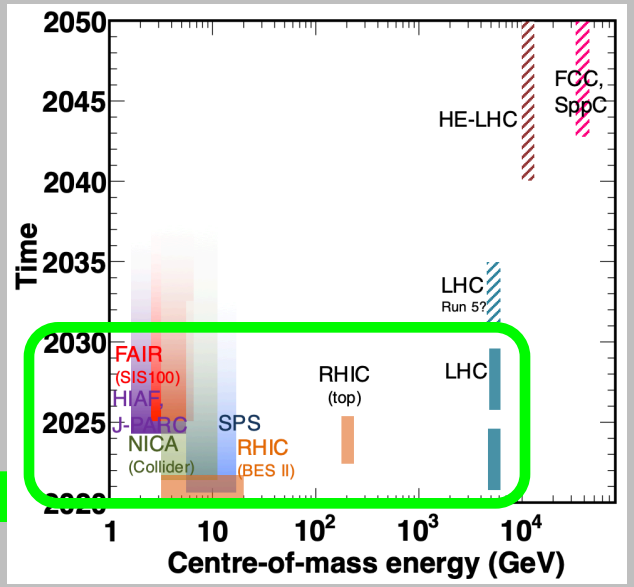

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We are very eager to plug them in ☺

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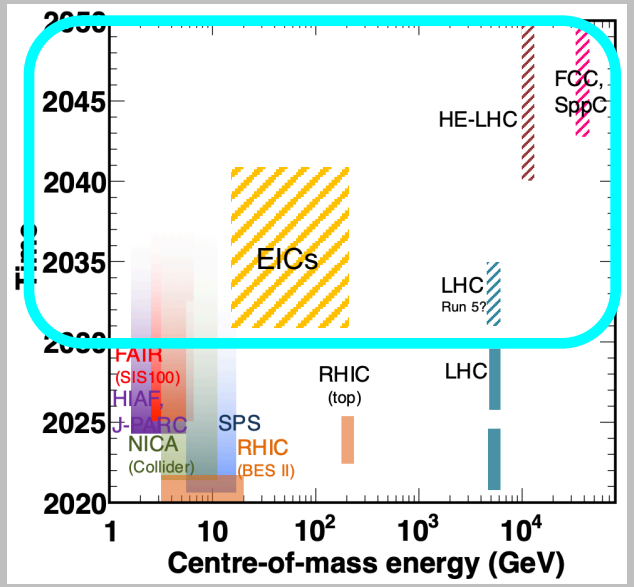
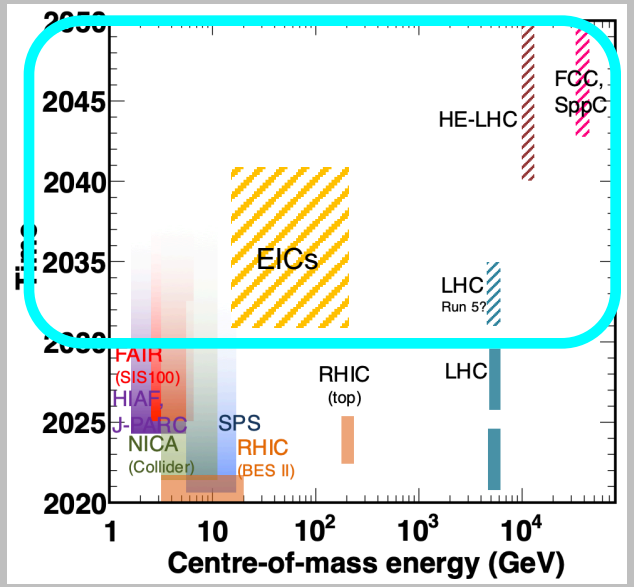


- Next decade also crucial to shape the long-term future of the field:
  - Secure and build an EIC → very broad (cold) QCD programme, strong connection with other communities
  - Pursue LHC Run 5 HI programme → not an extension but a whole new programme, with new observables and possibly a new detector
  - Keep engagement with future collider options, contribute to detector design

Conclusions

- Today: still in the middle of exploiting the latest/largest LHC Pb-Pb run
- Very rich decade ahead of us:
  - Data from 6-7 facilities
  - From current 7 to 12-14 running experiments
  - Up to x100 higher rates / L_{int}



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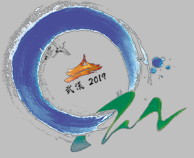
New (and unconventional) ideas welcome!



OUTATIME

INFN

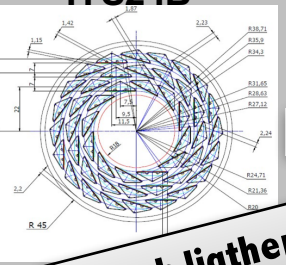
Thank you!

Thanks for inputs and feed-back:
F Antinori, H Caines, T Galatyuk, J F Grosse-Oetringhaus, A Kisiel,
D Morrison, L Musa, G Roland, M van Leeuwen, Z Xu

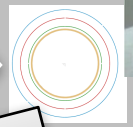
EXTRA SLIDES

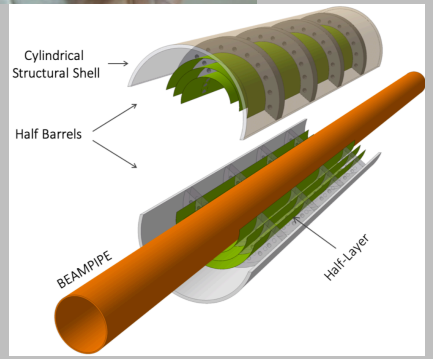
ALICE LS3 possible upgrades (2026)

ITS2 IB



ITS3 IB

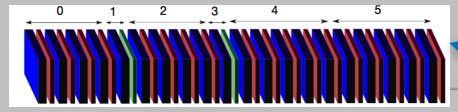


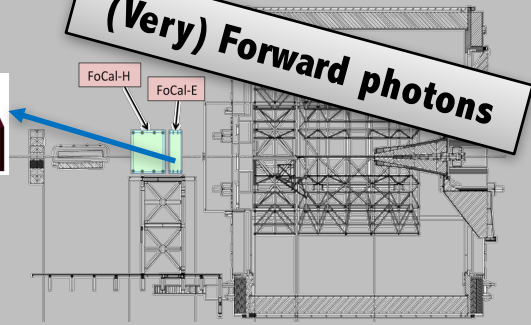


Much ligther and more precise

- ITS3 inner barrel
  - Replace 3 innermost layers with ultra-thin truly cylindrical pixel sensors
  - Material budget down x3
  - x2 better tracking precision
  - Enhance dielectron and HF performance

(Very) Forward photons

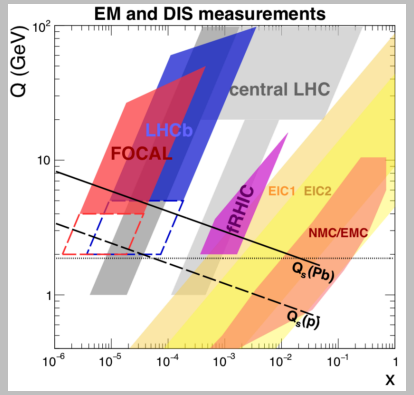




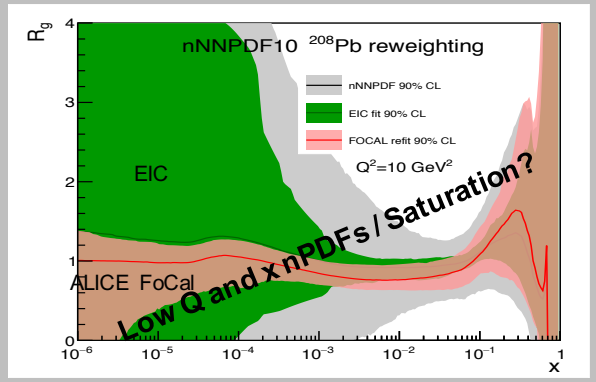
- FoCal at $3.2 < \eta < 5.8$
  - High readout granularity EM calorimeter + H-calorimeter
  - Forward direct photons in p-Pb to probe x down to 5×10^{-6}
  - + forward π^0, jets, J/ψ, UPC
- Fixed-target collisions
  - Exploratory studies for crystal-collimated beam halo on insertable solid target

Nuclear PDFs

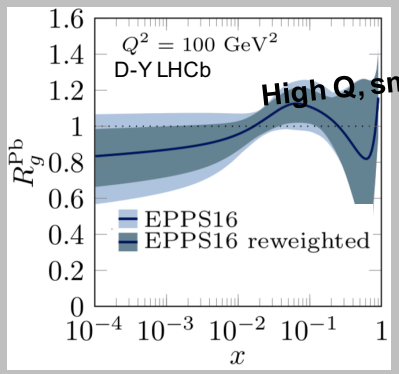
Closer future: LHC, RHIC, EIC → pA $10^{-6}<x<0.2$, eA $10^{-3}<x<1$

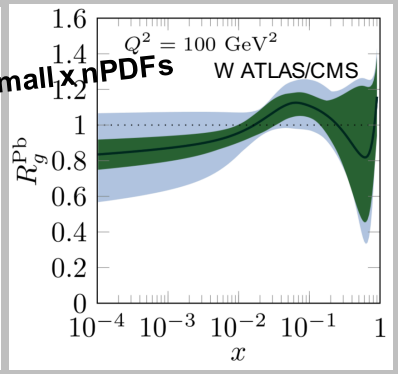


Forward direct γ in p-Pb at LHC, compared to EIC



Drell-Yan and W asymmetry p-Pb at LHC





Further future? LHeC, FCC-hh/he → pA $10^{-7}<x<1$, eA $10^{-6}<x<1$