QGP-France

Etretat 2-5 juillet 2018

PROSPECTIVES QGP – SMALL SYSTEMS

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What is a small system for QGP physics?

- The name « small systems » appeared at LHC Run I, it is now a session at Quark Matter, it is a recent aspect of heavy-ion physics

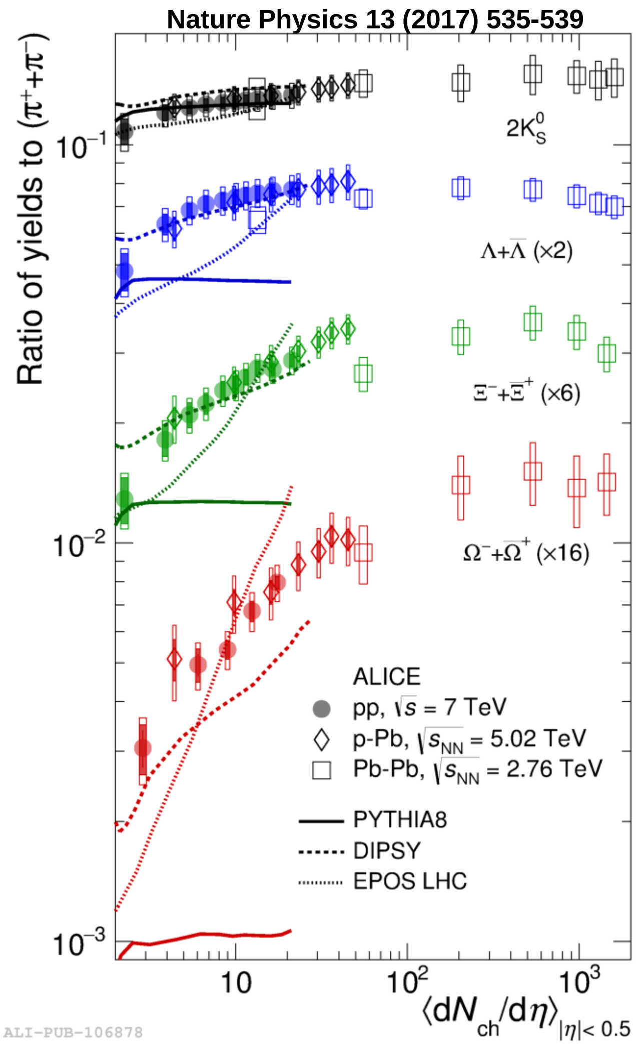
- It is a « fourre-tout » that sometimes refers to new phenomenon between RHIC and LHC connected to pp and p-A systems

- A nonofficial translation could be ”system *a priori too small* to show characteristics of heavy ion physics and however in which we observe them, at least some ”.

- Caveats « a priori too small » is not defined ...

What is a small system for QGP physics?

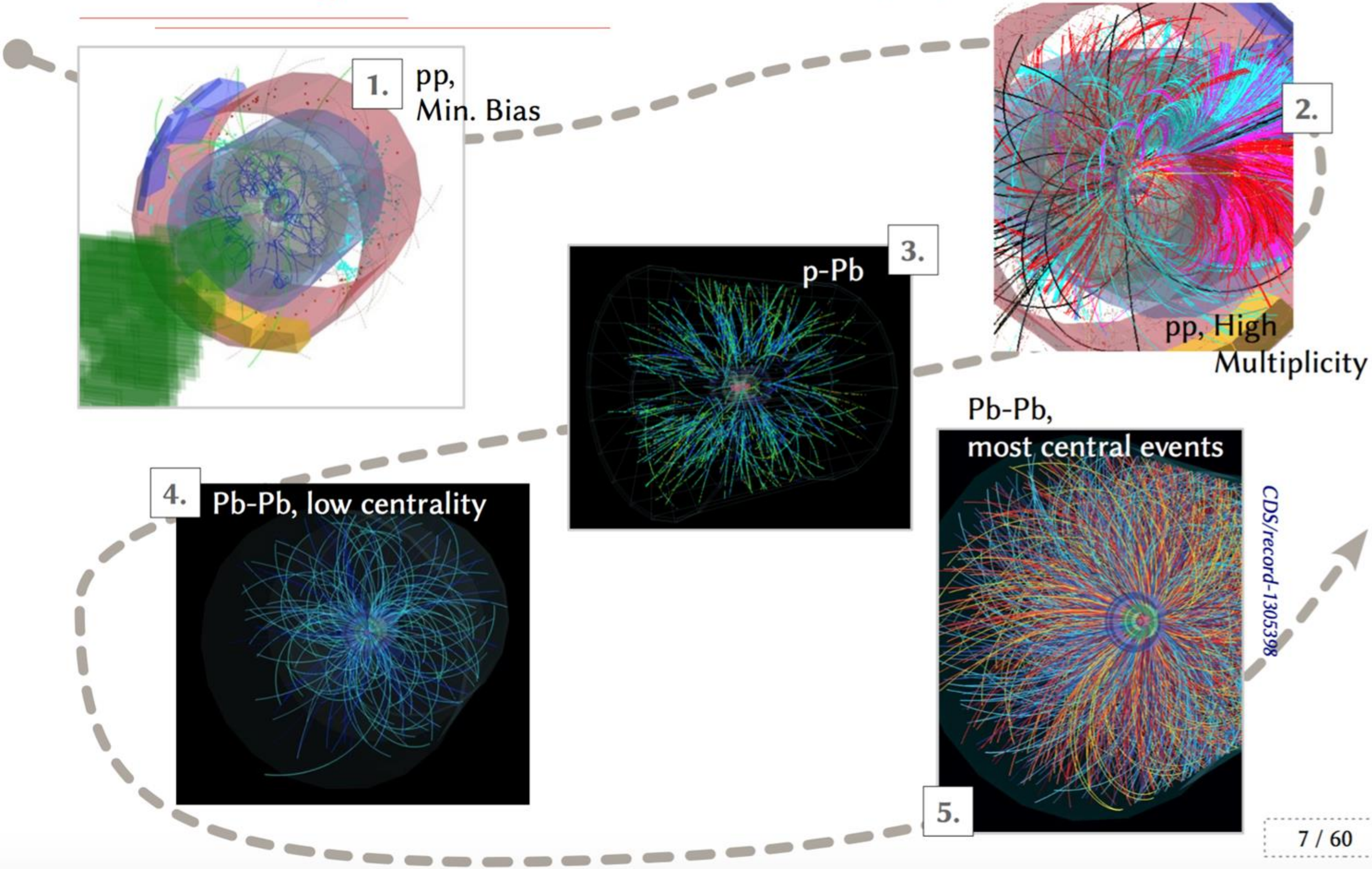
- "A priori small" refers to system size: protons in initial stage
- But with sometimes a final state looking like a large system, at least for charged particle multiplicity
- For LHC RUN 1+2 energies, idea of reference system still valid for pp minimum bias. High multiplicity events represent a small contribution to the total cross section
  $O(10^{-4})$ in statistics



pp/pA/AA at the same multiplicity, is it the same behavior, role of geometry?

How is done the transition from small to large ?

I.3 – Exp^{al} intro : continuum of physics ?



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Quark-Gluon Plasma

- Is the measurement the consequence of the evolution of a hydrodynamic fluid?
- Warning: hydro application do not necessarily imply QGP
- Hydro requires R_e >> 1 => small $\frac{\eta}{s}$, with R_e the Reynolds number:

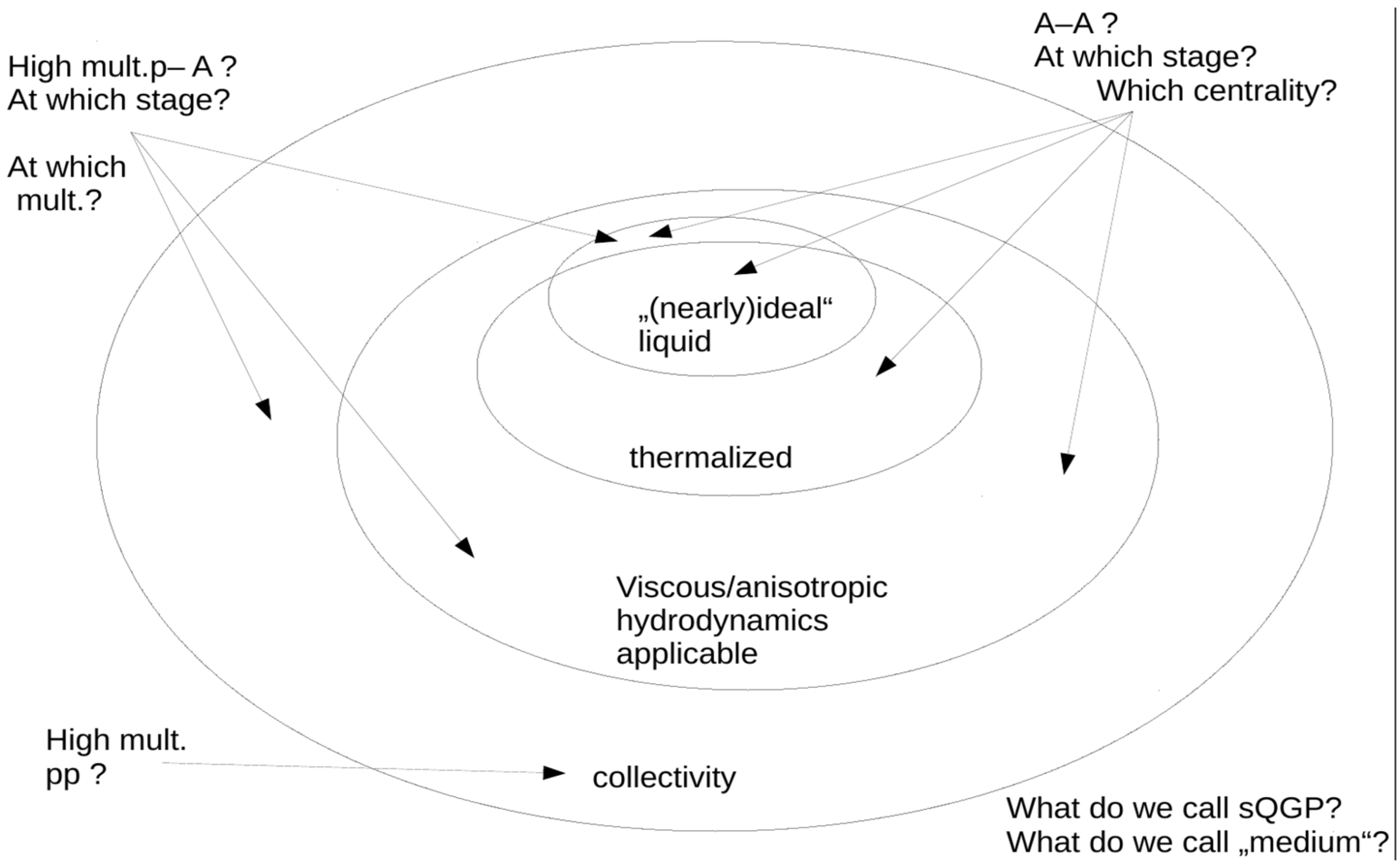
$$R_e = \frac{\mathrm{R}v}{\nu} = \frac{\mathrm{R}v}{\eta/\rho} = \frac{\mathrm{R}vT}{\eta/s}$$

R: characteristic spatial dimension
v: characteristic velocity
$\nu = \frac{\eta}{\rho}$: kinematic velocity
η: shear viscosity
s: entropy density

- Small η/s (<0.2) is a feature of observed QGP

Quark-Gluon Plasma

Which system is suited to test properties of thermal QCD
as described by Lattice QCD ?



Courtesy of M. Winn

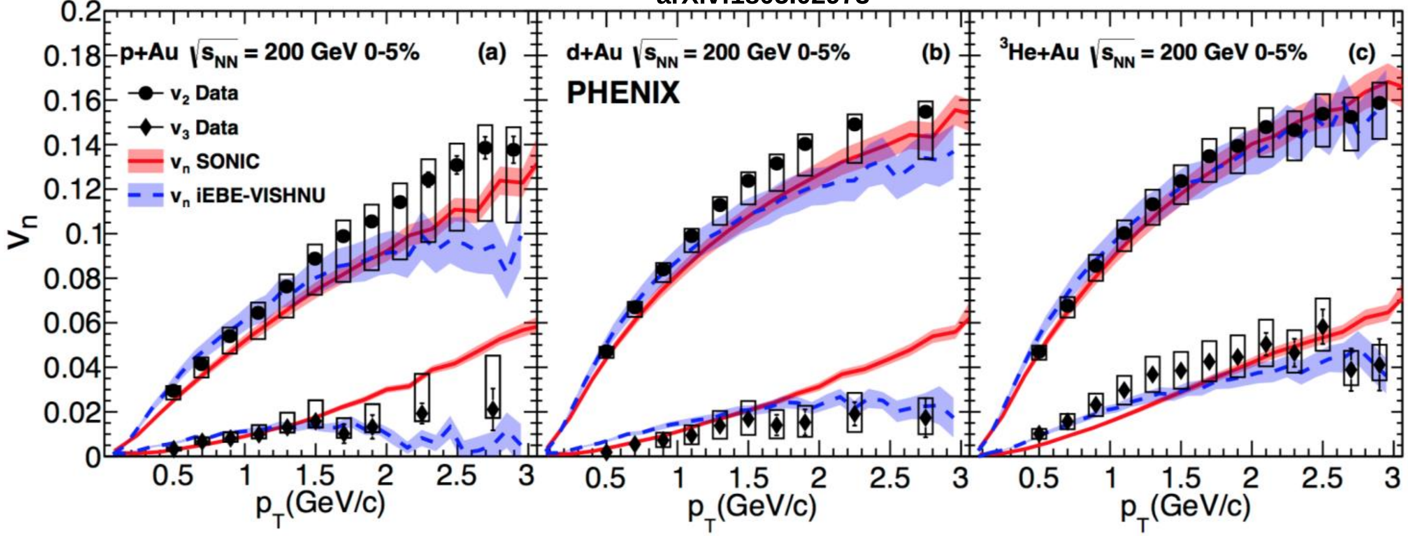
Sign of QGP in small systems at LHC ?

Table prepared by the WG small systems from the HL/E-LHC working group
See the yellow report, in preparation, for references (140)

Observable of effect	Pb-Pb	pPb (high mult)	pp (high mult)
SOFT Probes			
low p_T spectra ("radial flow")	yes	yes	yes
Intermediate p_T ("recombination")	yes	yes	yes
HBT radii	R_{out}/R_{side}~1	$R_{out}/R_{side} \lesssim 1$	$R_{out}/R_{side} \lesssim 1$
Azimuthal anisotropy (v_n) (2 prt. correlations)	v_1-v_7	v_1-v_5	v_2-v_4
Characteristic mass dependence	v_2-v_5	v_2-v_3	v_2
Higher order cumulants	"4~6~8 " + higher harmonics	"4~6~8 " + higher harmonics	"4~6 "+ higher harmonics
Event by event v_n distributions	n=2-4	Not measured	Not measured
Event plane and v_n correlations	yes	yes	yes
HARD Probes			
Direct photons at low-p_T	yes	Not measured	yes
Jet Quenching	yes	Not observed	Not observed
Quarkonia	J/Ψ regeneration / Υ supression	suppressed	Not measured
Heavy-flavor anisotropy	yes	yes	Not measured

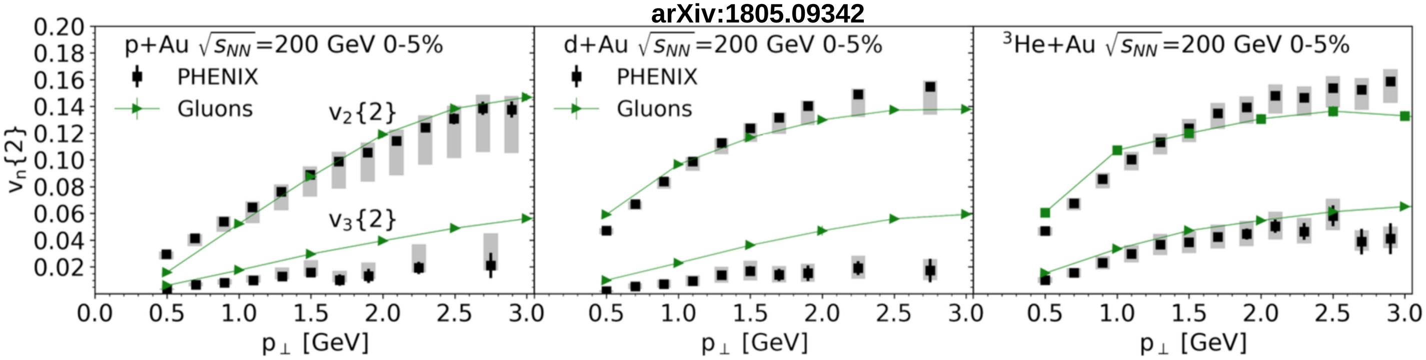
Sign of QGP in small systems at RHIC?

arXiv:1805.02973



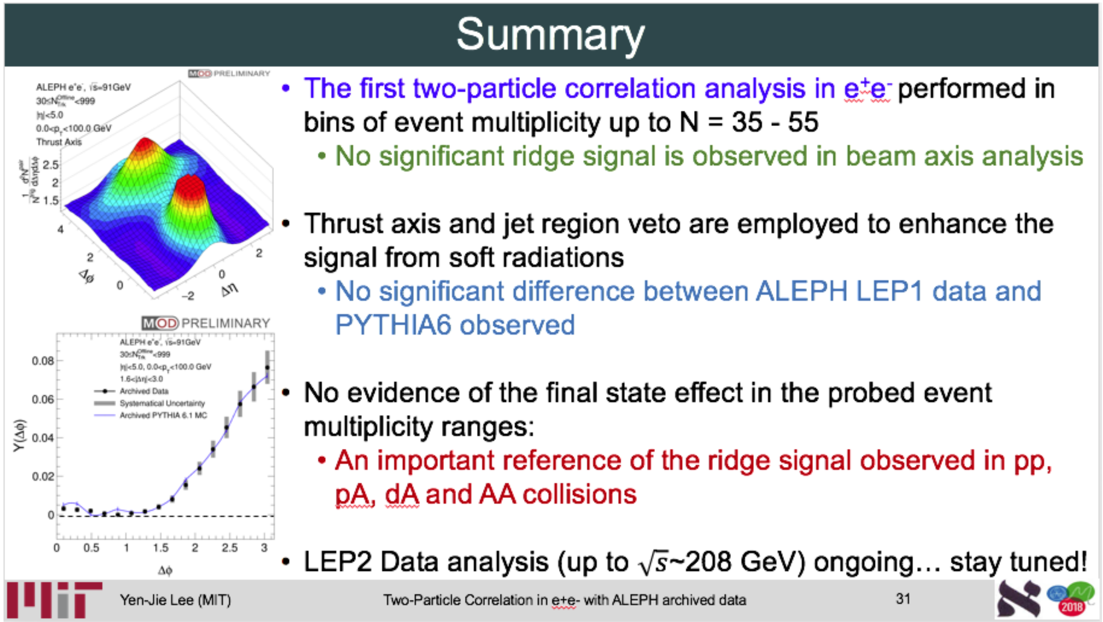
- PHENIX claim for QGP in small systems …

arXiv:1805.09342



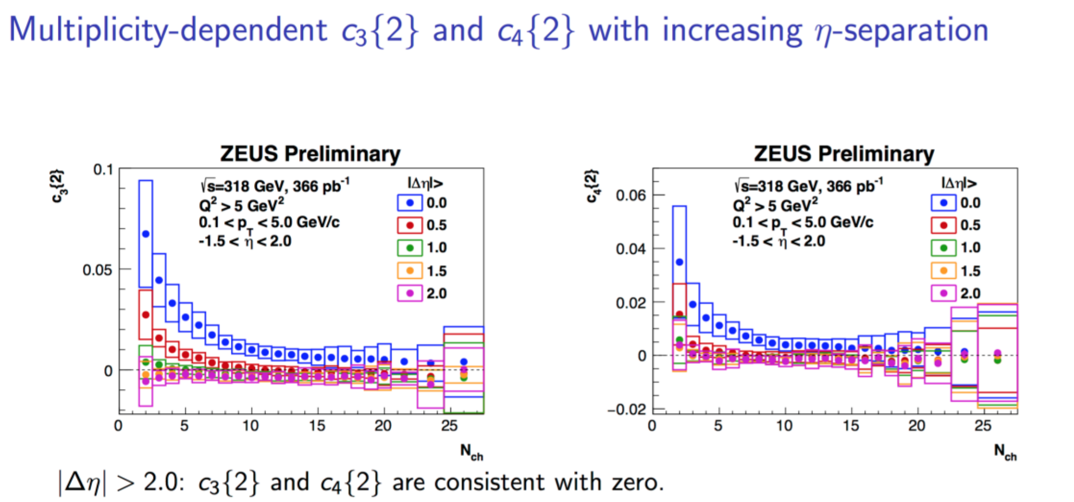
- … also explained by CGC.

Sign of QGP in very small systems ?



QM2018, Yen-Jie Lee

- ➢ LEP e^+e^- $\sqrt{s}$=91 GeV
- ➢ High mult = 55 particles in $|\eta|<5$
- ➢ No ridge observed, compatible with PYTHIA



QM2018, Jacobus Onderwaater

- ➢ HERA ep $\sqrt{s}$=318 GeV
- ➢ High mult = 35 particles in $-1.5<\eta<2$
- ➢ No observation of 2-particle correlations, compatible with Ariadne (dipole cascade model) and Lepto (Lund string)

Questions: "QGP droplets" ?

- What is the smallest (in terms of size and energy content) droplet of QGP to which a fluid dynamical description can be applied?

- When one selects high multiplicity final states in p/dA collisions or pp collisions, what features of the initial state or of the subsequent dynamics are being selected? If by selecting high multiplicity final states one is selecting collisions in which droplets of QGP are formed, how large are the protons in the initial states of the selected collisions? And, how large are the droplets of QGP that are formed?

Thoughts on opportunies from high-energy nuclear collisions https://arxiv.org/abs/1409.2981

- Est-ce que les mécanismes d'équilibration du système sont encore plus efficaces qu'anticipé et rendent l'équilibration jusqu'à la thermalisation possible même dans les plus petits systèmes en collision ? Ou bien est-ce que d'autres mécanismes entrent en jeu et miment un comportement collectif même dans les collisions noyau-noyau ?

Document ALICE, CS IN2P3

Questions: QGP droplets / hard probes in medium interaction

- How is the onset of collective bulk dynamics in small systems correlated with hard probes of the medium, such as jet quenching and quarkonia?

Thoughts on opportunies from high-energy nuclear collisions https://arxiv.org/abs/1409.2981

Questions: Initial state

- Si des phénomènes collectifs sont possibles dans les petits systèmes, quels sont les mécanismes qui permettent d'atteindre la densité d'énergie normalement associée à la transition de phase ?

- Quelles sont les variables les plus pertinentes pour différencier les collisions d'ions lourds, i.e. le nombre et la nature exacte des participants dans l’état initial (nucléons, clusters partoniques, partons, condensat de couleur, ...) ?

Document ALICE, CS IN2P3

Questions: Unified description of hadronic collisions

- How does collectivity emerge as a function of system size and energy density? What are the relevant scales (time, energy, size) controlling the degree of collectivity observed in the final state?

- To which extent can a collective effect observed in a larger system be reduced to a superposition of more elementary collisions? Can this experimentally be studied by selecting events in which properties of either the smaller system or new collective effects are enhanced?

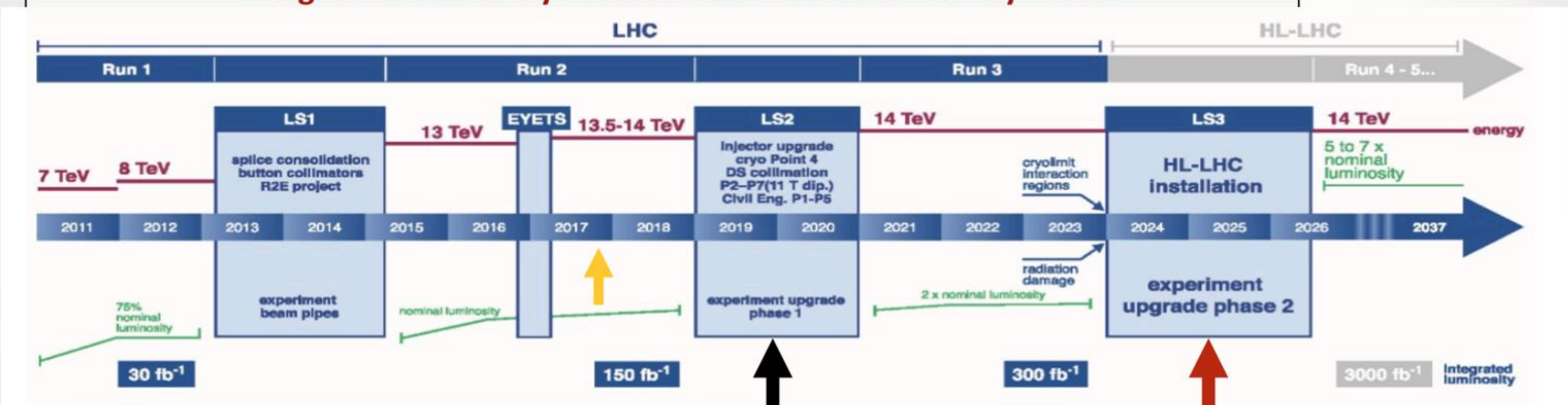
Thoughts on opportunies from high-energy nuclear collisions https://arxiv.org/abs/1409.2981

After LS2: Run 3+4

LHC upgrades (LIU + HL-LHC): parameters and timeline

Nominal LHC: $\sqrt{s}$ = 14 TeV, L= 1x10^{34} cm^{-2} s^{-1}
Integrated luminosity to ATLAS and CMS: 300 fb^{-1} by 2023 (end of Run 3)

HL-LHC: $\sqrt{s}$ = 14 TeV, L= 5x10^{34} cm^{-2} s^{-1} (levelled)
Integrated luminosity to ATLAS and CMS: 3000 fb^{-1} by ~ 2035



LS2 (2019-2020):

- ❑ LHC Injectors Upgrade (LIU)
- ❑ Civil engineering for HL-LHC equipment @ P1,P5
- ❑ 11 T dipoles P7
- ❑ Phase-1 upgrade of LHC experiments

LS3 (2024-2026):

- ❑ **HL-LHC installation**
- ❑ Phase-2 upgrade of ATLAS and CMS

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ECFA meeting, CERN report, Fabiola Gianotti
https://indico.cern.ch/event/667672/contributions/2729660/attachments/1559939/2455491/PECFA-2017.pdf

Warning : heavy ions and particle physics timeline

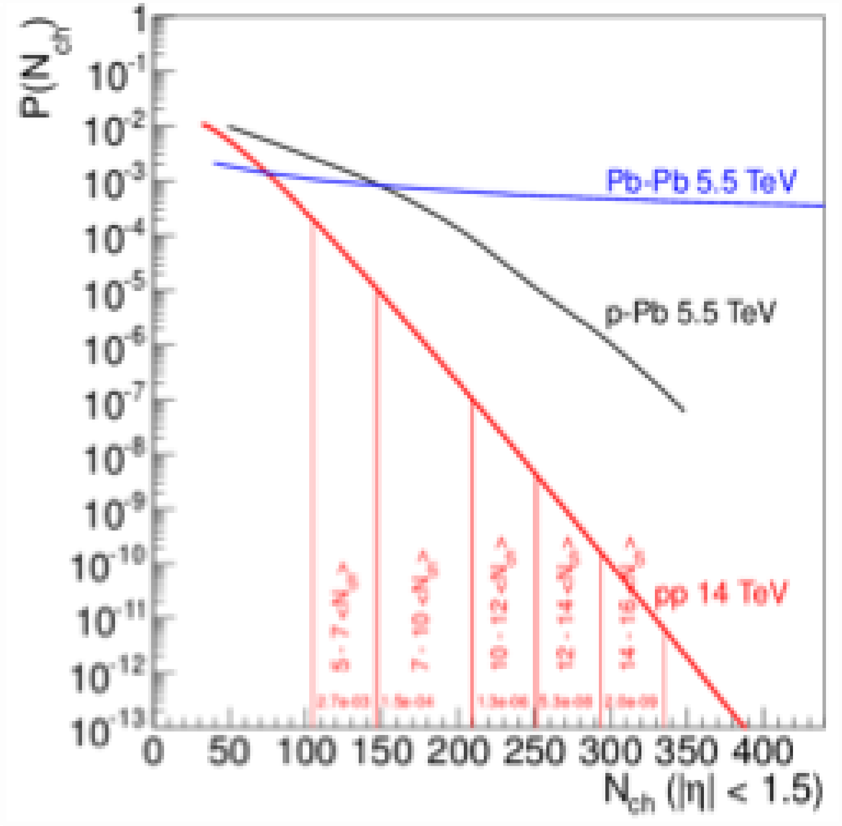
- For the heavy-ion community HL-LHC starts at RUN 3 (2021-2023)
- For the particle physics community HL-LHC starts at RUN 4 (2026-2028)

In the following, timeline with run number for clarity : 3+4 and 5+6

Simulations prepared for the Yellow report (HL-LHC working group) are based on RUN 3+4 estimates

Run 3+4

- Increase in energy, pp to 14 TeV, important for high mult in small systems
- Increase in luminosity, also important for high mult in small systems
- The yellow report will contain predicted number of events at a given multiplicity based on extrapolated multiplicity distribution
- Run 3+4 running conditions are favorable for small systems studies in high multiplicity environment (statistics hungry), be carefull of pile-up

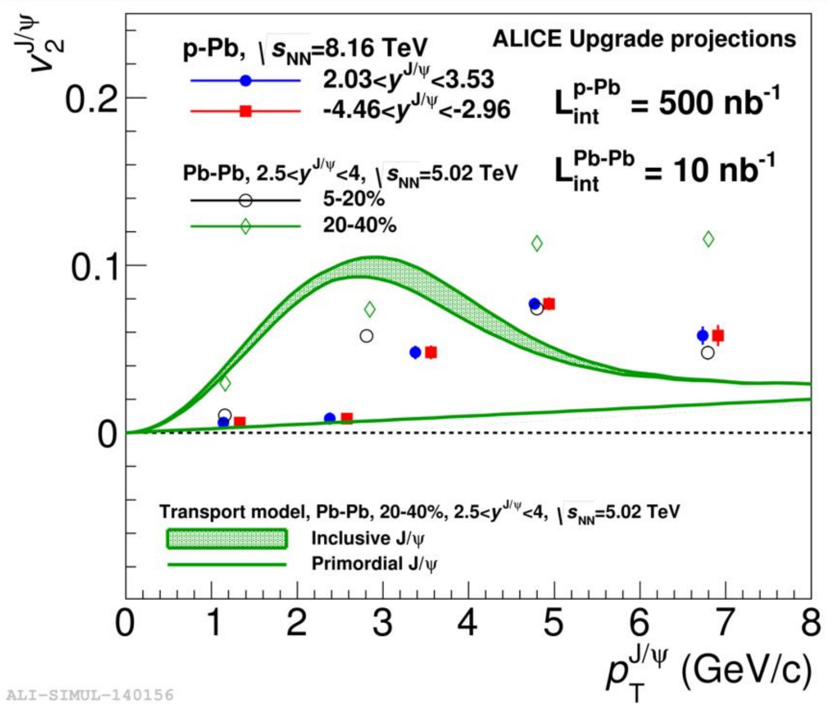


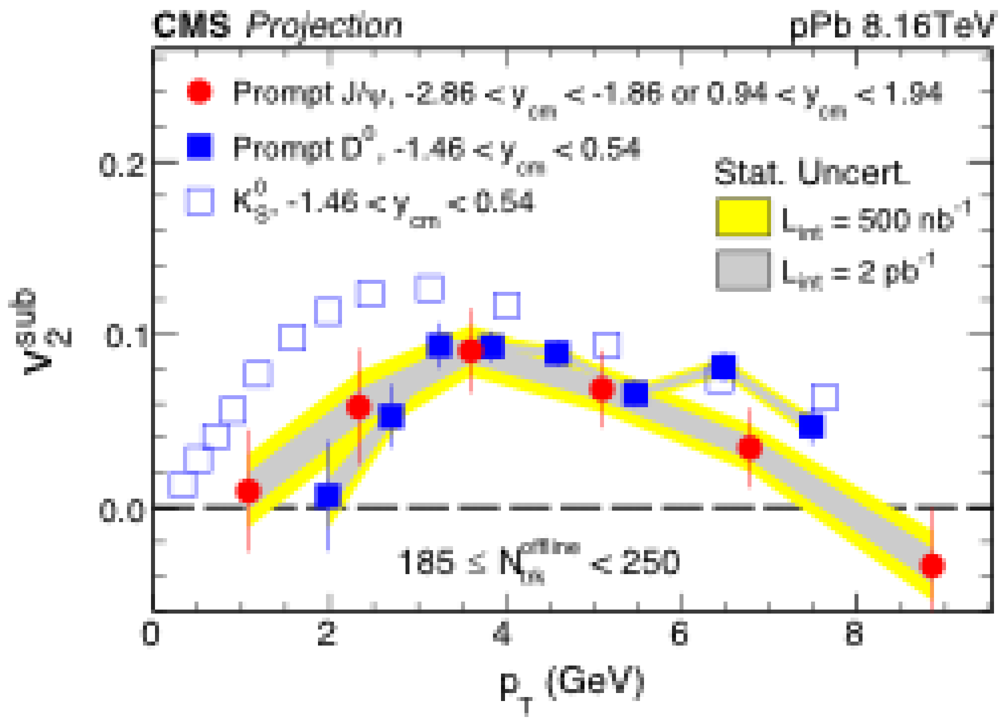
Run 3+4: Flow/Correlations

https://indico.cern.ch/event/686494/contributions/3034636/attachments/1670133/2678939/HEHLLHCWorkshop_v3.pdf

- Precise control over IS (geometry/fluctuations) and FS effects
- Onset of collectivity
- Test various description (hydro, CGC)

- Non-flow v_n measurements
- Symetric cumulants w and wo subevents
- ID v_n (light, strange, charm, beauty)

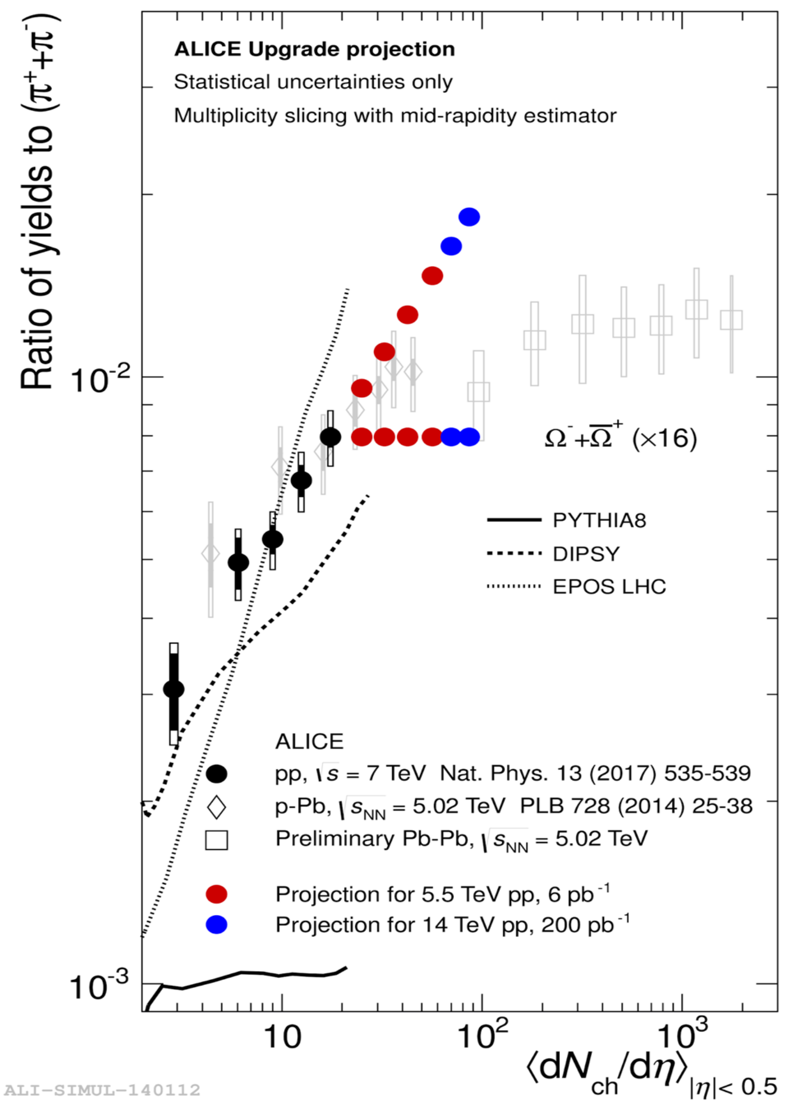




Run 3+4: Strangeness enhancement

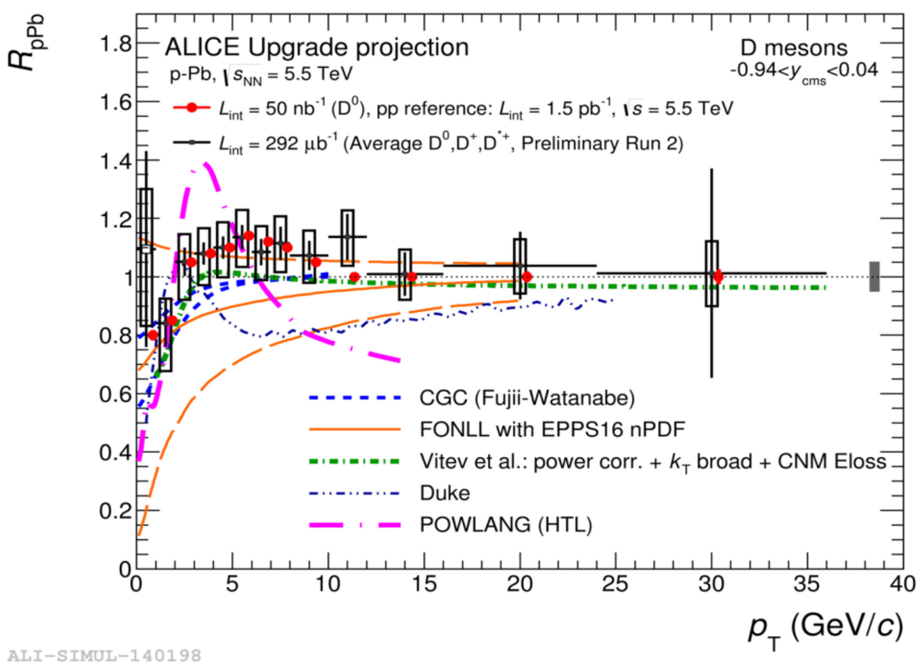
https://indico.cern.ch/event/686494/contributions/3034636/attachments/1670133/2678939/HEHLLHCWorkshop_v3.pdf

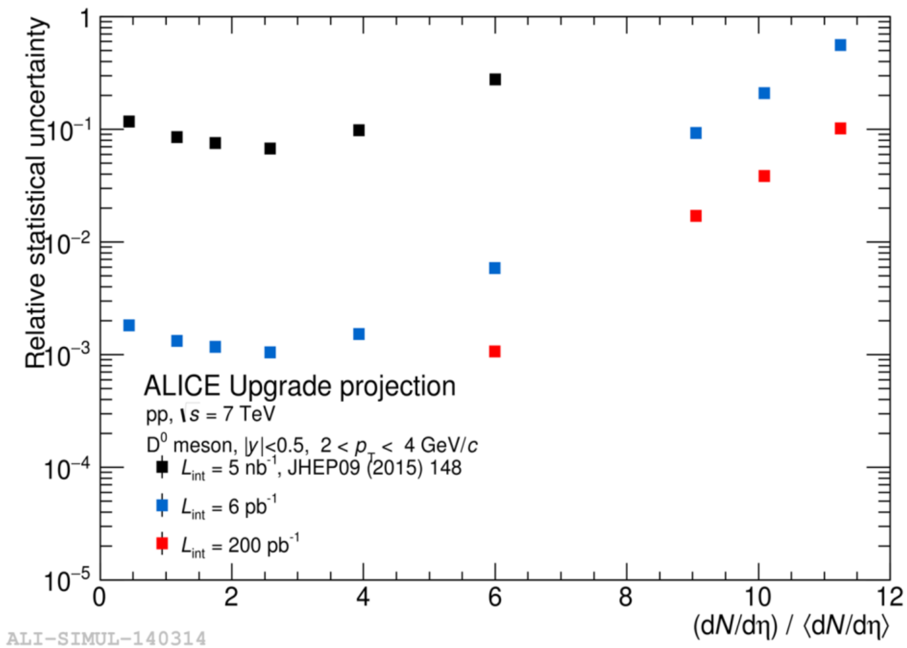
- Smooth transition between pp, pPb and PbPb
- Is the grand canonical limit reached?



Run 3+4: D measurements

- Large increase of precision help to reach high multiplicities and data/theory comparison





Run 3+4: Open questions

1) What is the best system size estimator?

- Multiplicity is the measured quantity (caveats: experimental estimator has to be well defined)

- Multiplicity is protected from theoretical biases (N_{part}, N_{coll} from Glauber models ...)

- But hard to compare to formal calculation and first principle

- What about initial energy density or multiplicity per volume unit ?

Bjorken estimates

$$\varepsilon \sim \frac{n\pi}{\tau_0 A} \frac{3}{2} \frac{dN_{ch}}{d\eta}\bigg|_{\eta=0}$$

Multiplicity per volume unit

$$\frac{N_{ch}}{\pi R^3}$$

Problem of the definition of the normalization size in pp and p-Pb (*A* or *R* or ?)

Run 3+4: Open questions

2) Role of geometry / system size on hydro evolution in small system

pp high mult has a small size

Hydro can be applied out of equilibrium even if R_e do not satisfied the condition R_e >>1

3) Energy loss definition

How to define jet-medium interaction in small systems

Energy loss proportional to system size => in small system, effect is small

How to define the reference ?

Ideas: jet asymmetry, jet substructure, Z-jet, photon-jet

4) Global interpretation and systematic data/theory comparison

Rivet, see for example the workshop Rivet for Heavy Ion (21-24 Aout)

https://indico.cern.ch/event/735911/

Run 3+4 physics program with planned detector upgrades is very promising for small systems

What's next ?

Dreaming of an ideal physics program for small systems

To explore fundamental QCD questions raised by small systems:

- System scan

  Cover a wide range of systems (pp, pA and AA) with various nucleus
  O-O as a ”light heavy-ion” a good candidate

- Energy scan

  Cover a wide range of energy with pp and pA at the same energy as AA

- Perform all measurements in multiplicity classes, multiplicity differential

  The highest multiplicity classes are the more interesting for small systems, analysis are statistic consuming => Dedicated triggers and high lumi

- Go toward more exclusive observables (soft-hard correlations) full tomography of the final state

- Systematic data/data and data/theory comparisons from all systems and all energies in similar multiplicity classes

What's next ?

Dreaming of the ideal detector for small systems: *ALICMSb*

1. Hermeticity = large η coverage

2. Tracking low $p_T > 0$ GeV/c
   = low B field
   = low material budget

3. PID over a large p_T range
   No TPC (slow), No Cerenkov (material budget)

4. Electromagnetic and hadronic calorimeter

5. Muon chambers 4π

6. Computing ressources

What's next ? LHC Run 5/6

ALICE upgrades ?

- Not yet an official proposal
- for a 4π compact silicium detector with very low momentum resolution (p_T > 20 MeV) with PID and TOF
- Ideal for charged tracks, photons and electrons

LHCb upgrades ?

- Not yet an official Expression of Interest,
- plan to run with the actual CMS/ATLAS lumi (10^{34} pile-up 30/40) with the HLT developed for Run 3/4 (very fine event topology selection)
- Providing reconstruction software development LHCb could be able to measure central heavy ion collisions at Run 5/6.

What's next ? LHC Run 5/6

CMS upgrades ?

- Hermeticity with low material budget.
- Potential for dedicated run at "low" lumi and low B field (low p_T).
- Tagger = TOF PID at low pile-up ?

  Already planned for Run 4 p/K/π with 0.7 <p_T< 3-4 GeV/c

  https://indico.cern.ch/event/726024/

ATLAS upgrades ?

- Not evaluated

Can we develop a physics program for small systems (example of p-Xe, O-O, p-O) and energy scan at Run 5/6 ?

What's next ? Fixed target at LHC

- <u>AFTER program</u>

arXiv.org:1807.00603

- $\sqrt{s}$ = 115 GeV for pp, pd,pA and $\sqrt{s}$ = 72 GeV for Pbp, Pbd, PbA
- High luminosity => high stat
- 2 programs: LHCb (already existing with SMOG) and ALICE
- Multiplicity class reached with the available luminosity to be estimated

If high multiplicity reached at lower energy (below RHIC), interesting system scan to study the onset of collectivity

- LHCb in RUN 3+4: increase by a factor 100 with SMOG2 (see F. Fleuret talk on Monday)

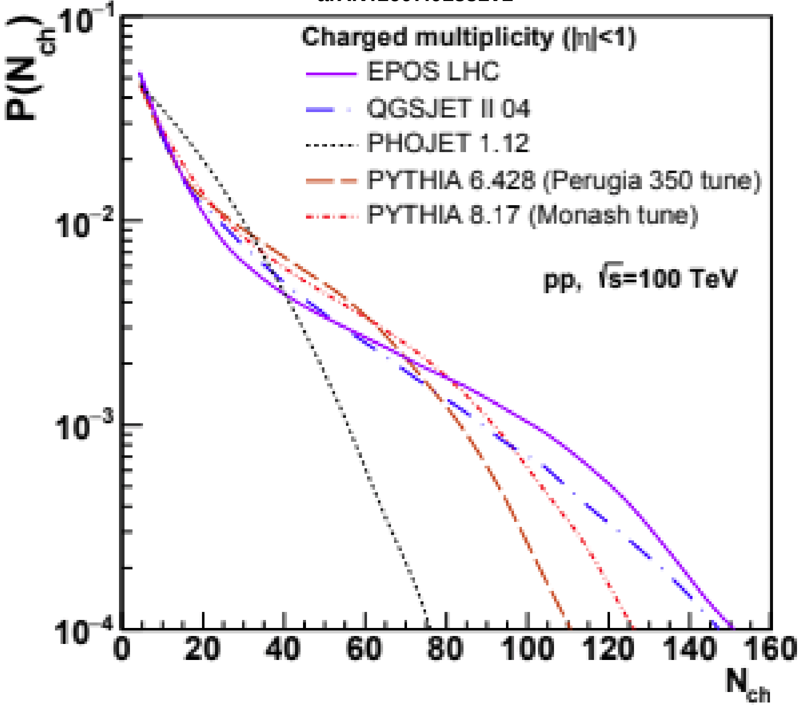
What's next ? CERN HE-LHC/FCC/SPPS

- Essential for small system study: increase in multiplicity, increase in energy density => Increase in collision energy

- Future colliders at energies greater than LHC: natural continuation of small systems study

  - HE-LHC; upgrade LHC with FCC technology, 27 TeV, earliest possible physics starting date : 2040*
  - FCC-hh, **100 TeV**, earliest possible physics starting date : 2043*
  - SPPS, chinese project at **100 TeV**, FCC like

Physics at a 100 TeV pp collider: Standard Model processes
arXiv:1607.01831v1

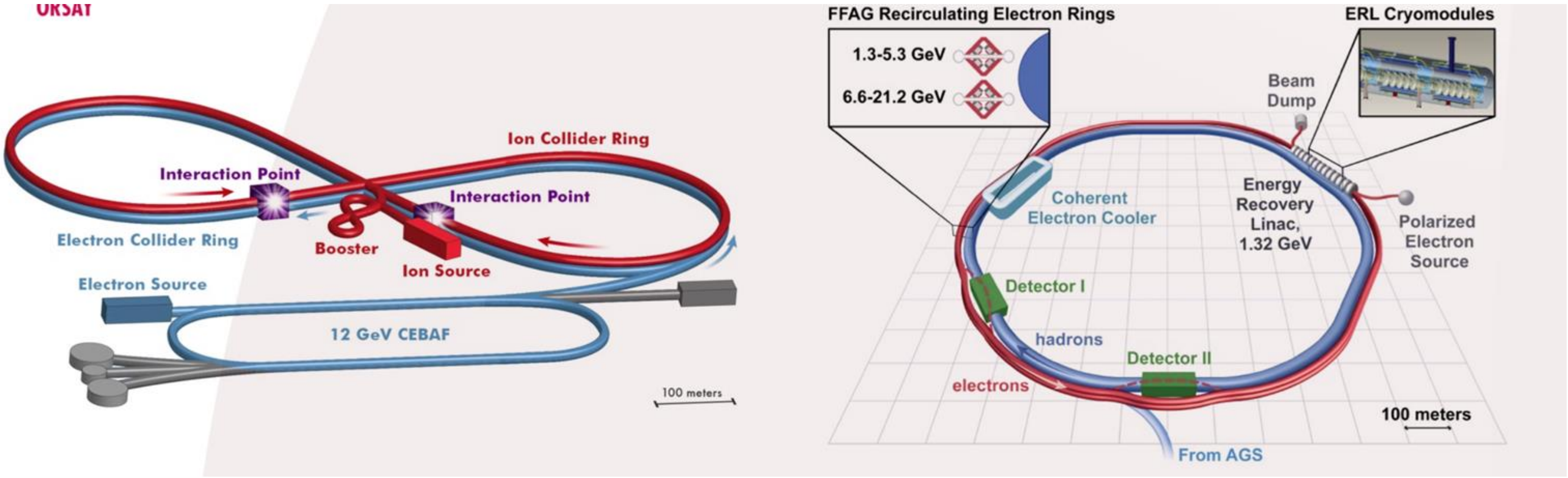


Starting physics in 20 to 30 years, but machine design, detector design is starting now!
Full simulation in preparation

* ECFA meeting, FCC report, Michael Benedikt
https://indico.cern.ch/event/667672/contributions/2730846/attachments/1560446/2456317/171117_FCC-Status_Berlin_ap.pdf

What's next ? EIC

- Electron Ion Collider, first physics beam in 2027 (~10 years)



- Interest for small systems
  - Initial state (CGC, nPDF)
  - Hadronization
  - Centrality definition

La communauté française sur cette thématique

- L’ensemble des analyses « QGP » contribuent à la « physique des petits systèmes »

- Auxquels ont peu ajouter pp/pA en fonction de la multiplicité ou dans des bins de hautes multiplicités

- Très forte corrélation avec les autres groupes de travail

- Un élément important est l’interprétation des données : mise en perspective, comparaison systématique, comparaison avec la théorie
  Contribue à une redéfinition du sujet : vision d’ensemble des collisions hadroniques

La communauté française a contribué activement à la question des petits systèmes au niveau expérimental et théorique.

Conclusions

- Recent concept of « small systems » enlight more fundamental questions on QCD and the onset of collectivity in hadronic collisions

- Run 3+4 with energy (pp 14 TeV) and luminosity increase will provide statistics increase to test pp/p-Pb in high multiplicity classes and Pb-Pb

- Ideal future for small systems
    - System scan
    - Energy scan
    - Analysis in multiplicity classes
    - Systematic data/data data/theory comparisons

Potential for a physics program to study small systems at Run 5/6 up to FCC!

BACKUP

Bibliographie

- Google drive rassemblant divers documents
  https://drive.google.com/open?id=1UrgFlsXKKWYMqsEUdDo_yRQvblgbzTWN

    - Conseil scientifique physique hadronique
    - Liens indico vers les réunions du groupe de travail du CERN WG5
    - Réflexions du Mont St Odile

Run I et II – sondes molles

Vn :

- with {N}-cumulants ? CMS, p-Pb, http://arxiv.org/abs/1502.05382
- v2 PID mass ordering :
  - ALICE v2(pi,K,p) http://arxiv.org/abs/1307.3237
  - CMS, v2(D^0, K0s, Λ, Ξ , Ω) p-Pb : https://arxiv.org/abs/1804.09767

Renforcement de la production l'étrangeté avec dNch/dη ++

<pT>

Run I et II – sondes dures

RpA sonde dures

NOTE :

v2 D0, v2 (J/psi)≠ 0

- ALICE, v2(J/psi): https://arxiv.org/abs/1709.06807
- CMS, v2(D^0, K0s, Λ, Ξ , Ω) p-Pb : https://arxiv.org/abs/1804.09767

Run I et II – corrélations

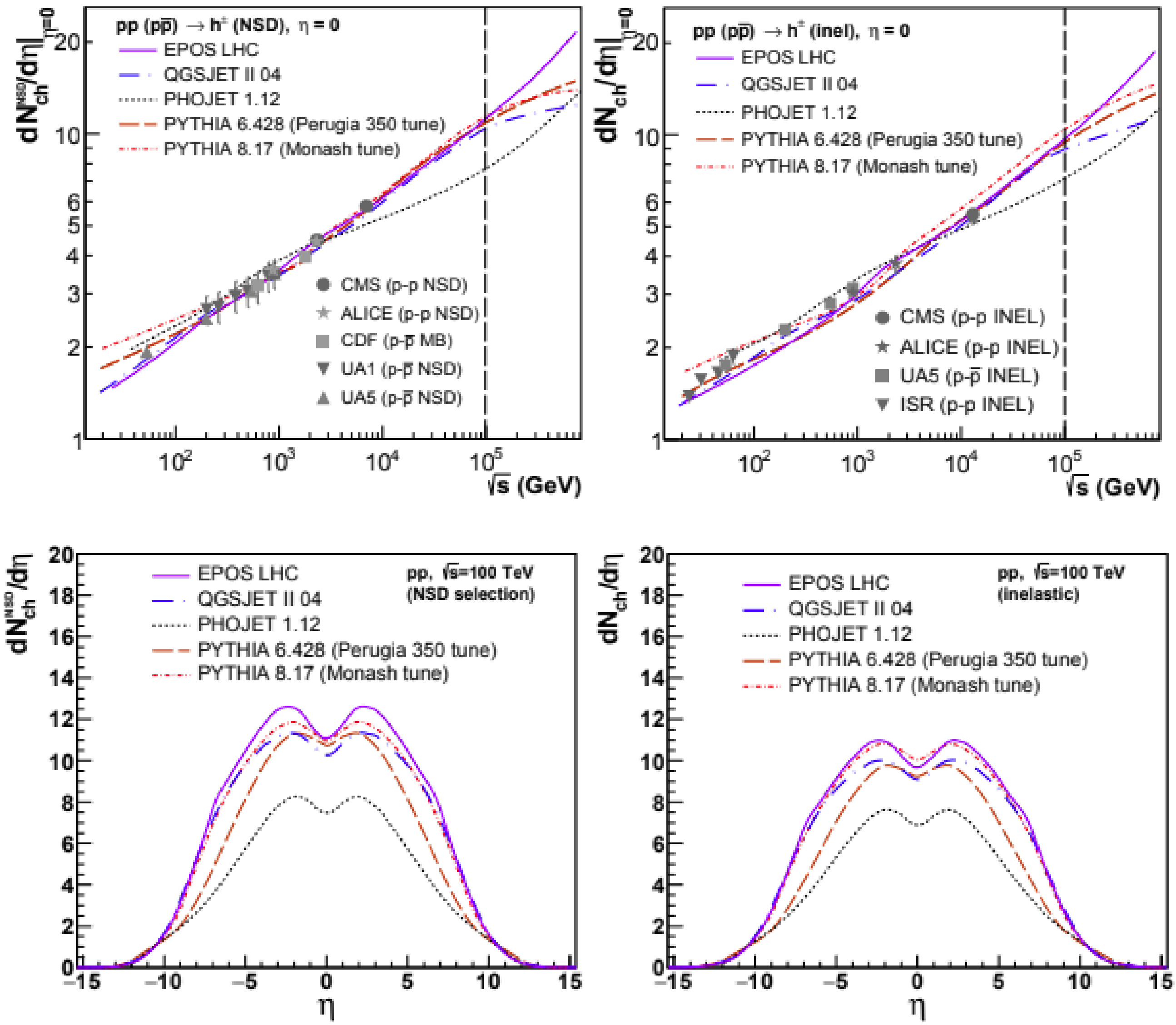
Quarkonia/open charm vs.
mult

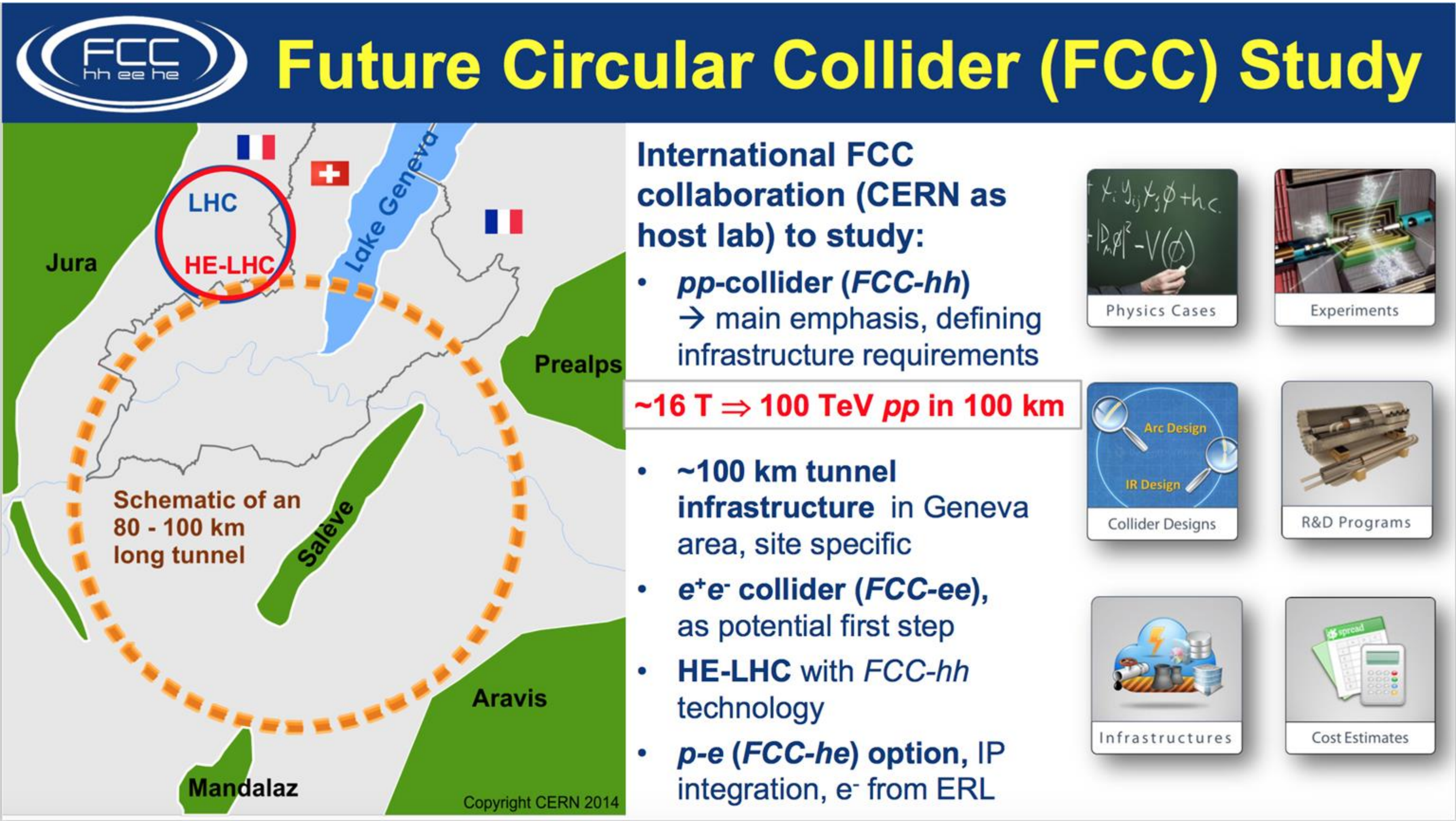
- CMS
ridge

Sphericit
é

What’s next ? CERN HE-LHC/FCC/SPPS

Physics at a 100 TeV pp collider: Standard Model processes arXiv:1607.01831v1





* ECFA meeting, FCC report, Michael Benedikt
https://indico.cern.ch/event/667672/contributions/2730846/attachments/1560446/2456317/171117_FCC-Status_Berlin_ap.pdf

FCC study: physics and performance targets

FCC-ee:

- **Exploration of 10 to 100 TeV energy scale via couplings with precision measurements**
- **~20-50 fold improved precision on many EW quantities (equiv. to factor 5-7 in mass)**
  ($m_{Z,}$ m_W, m_{top} , $\sin^2 \theta_w^{eff}$, R_b , α_{QED} (m_z) α_s (m_z m_W m_τ), Higgs and top quark couplings)

➢ **Machine design for highest possible luminosities at Z, WW, ZH and ttbar working points**

FCC-hh:

- **Highest center of mass energy for direct production up to 20 - 30 TeV**
- **Huge production rates for single and multiple production of SM bosons (H,W,Z) and quarks**

➢ **Machine design for 100 TeV c.m. energy & integrated luminosity $\sim$ 20ab^{-1} within 25 years**

HE-LHC:

- **Doubling LHC collision energy with FCC-hh 16 T magnet technology**
- **c.m. energy = 27 TeV $\sim$ 14 TeV x 16 T/8.33T, target luminosity ≥ 4 x HL-LHC**

➢ **Machine design within constraints from LHC CE and based on HL-LHC and FCC technologies**

* ECFA meeting, FCC report, Michael Benedikt
https://indico.cern.ch/event/667672/contributions/2730846/attachments/1560446/2456317/171117_FCC-Status_Berlin_ap.pdf

FCC-ee collider parameters

parameter	Z	WW	H (ZH)	ttbar	
beam energy [GeV]	45	80	120	175	182.5
beam current [mA]	1390	147	29	6.4	5.4
no. bunches/beam	16640	2000	393	48	39
bunch intensity [10^{11}]	1.7	1.5	1.5	2.7	2.8
SR energy loss / turn [GeV]	0.036	0.34	1.72	7.8	9.21
total RF voltage [GV]	0.1	0.44	2.0	9.5	10.9
long. damping time [turns]	1281	235	70	23	20
horizontal beta* [m]	0.15	0.2	0.3	1	1
vertical beta* [mm]	0.8	1	1	2	2
horiz. geometric emittance [nm]	0.27	0.28	0.63	1.34	1.45
vert. geom. emittance [pm]	1.0	1.0	1.3	2.7	2.7
bunch length with SR / BS [mm]	3.5 / 12.1	3.3 / 7.6	3.1 / 4.9	2.5 / 3.3	2.5 / 3.2
luminosity [10^{34} cm^{-2}s^{-1}]	>200	>30	>7	>1.5	>1.3
beam lifetime rad Bhabha / BS [min]	70 / >200	500 / 20	42 / 20	39 / 24	39 / 25

* ECFA meeting, FCC report, Michael Benedikt
https://indico.cern.ch/event/667672/contributions/2730846/attachments/1560446/2456317/171117_FCC-Status_Berlin_ap.pdf

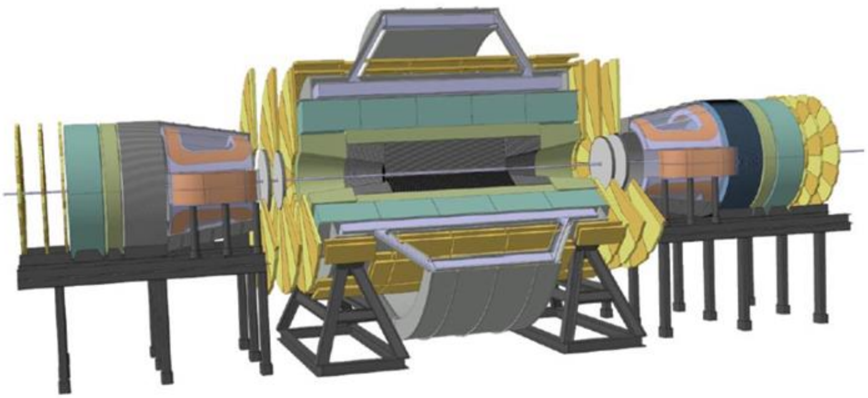
FCC-hh detector – new reference design

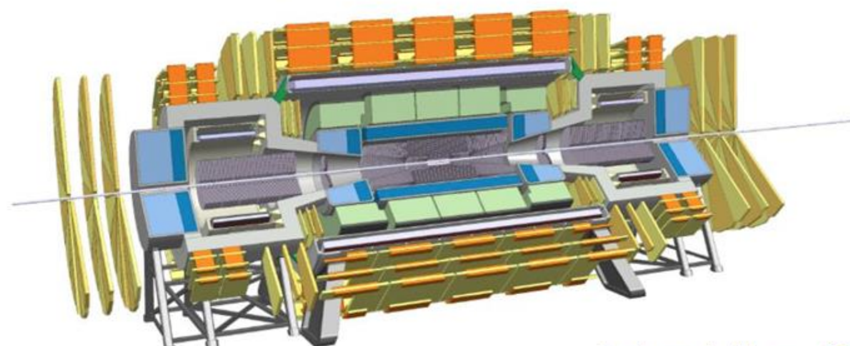
6 T, 12 m bore solenoid, 10 Tm dipoles, shielding coil

- 65 GJ stored energy
- 28 m diameter
- >30 m shaft
- multi billion project

4 T, 10 m bore solenoid, 4 T forward solenoids, no shielding coil

- 14 GJ stored energy
- rotational symmetry for tracking!
- 20 m diameter (~ ATLAS)
- 15 m shaft
- ~1 billion project





latest l^* = 40 m

* ECFA meeting, FCC report, Michael Benedikt
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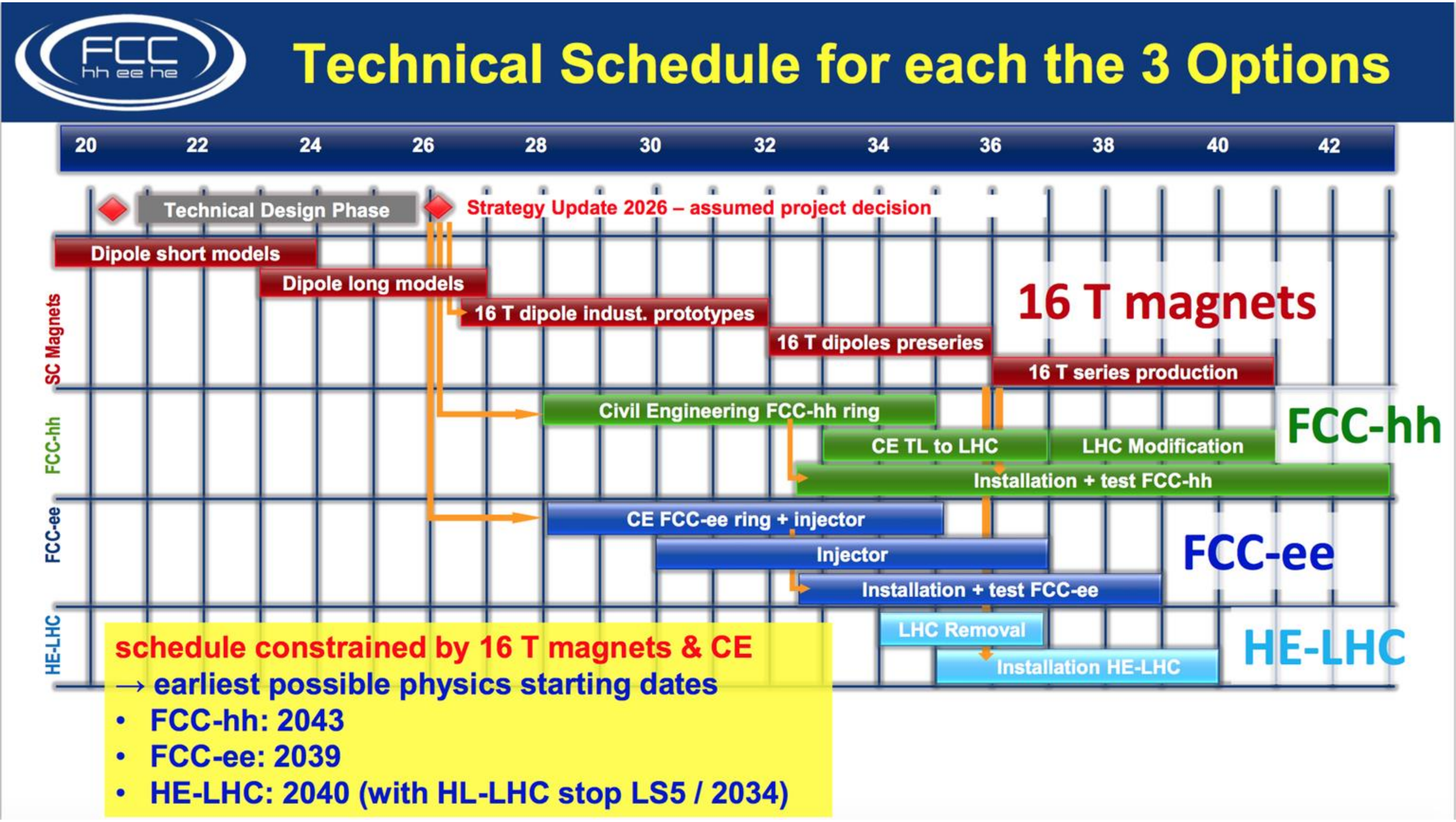

* ECFA meeting, FCC report, Michael Benedikt
https://indico.cern.ch/event/667672/contributions/2730846/attachments/1560446/2456317/171117_FCC-Status_Berlin_ap.pdf