# Unravelling the hadronic collision structure with Large-Scale System and Energy Scan


*<u>By alphabetic orders :</u>*

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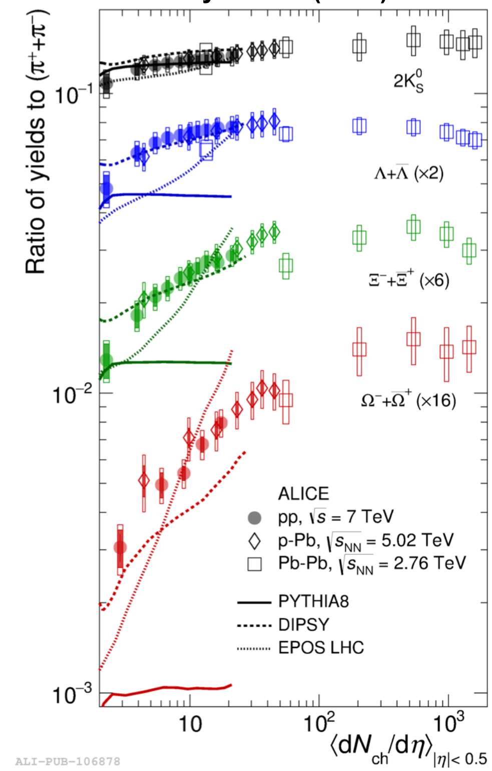
# Small systems @ Etretat 2018

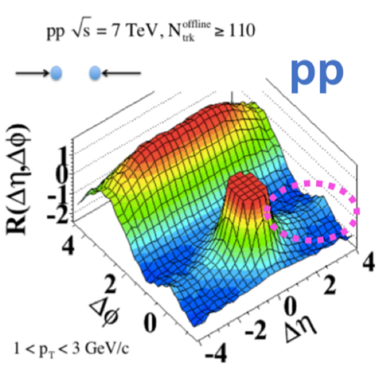
**"Something" is at play in high multiplicity small system (pp, p-Pb) events**

- Signature of QGP/Collective features observed in the soft sector
- No QGP signature in the hard sector up to now
- Smooth transition from low to high mult

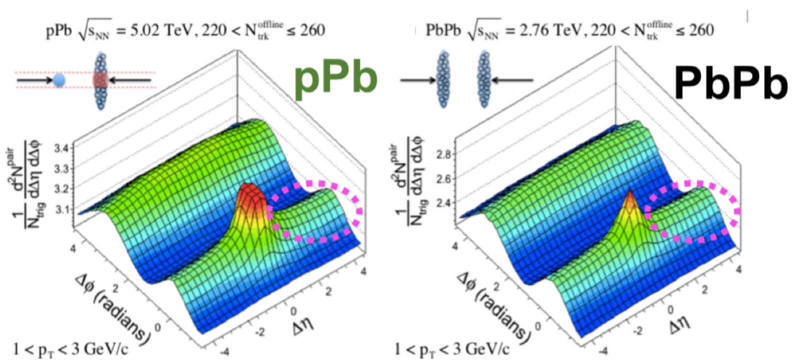
See table prepared by the WG small systems from the HL/E-LHC working group (~140 refs)
[arXiv:1812.06772](arXiv:1812.06772) [arXiv:1602.09138](arXiv:1602.09138)

Nature Physics 13 (2017) 535-539

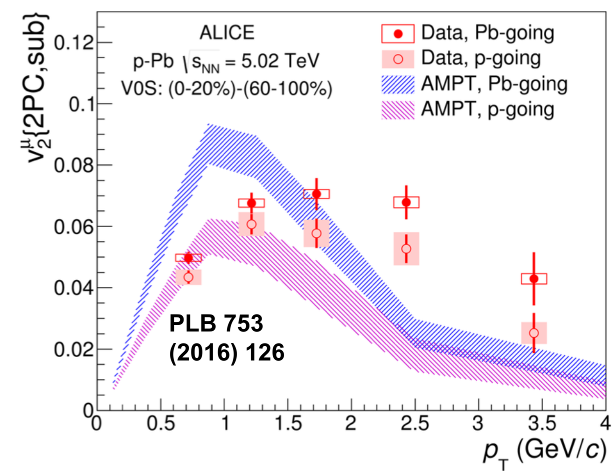



CMS, JHEP09 (2010) 091




CMS, PLB 724 (2013) 213



# ”Something”?

- Is there QGP droplets in small systems ?
- Or is it specific features of the dynamic at play in those very specific events that we miss ?
- Or a combination : the specific dynamic allow to reach the needed high energy density for the QGP phase transition ?
- Change of paradigm not Pb-Pb (complex) vs. pp (elementary)
- Always keep in mind in the discussion that high multiplicity events represent a small contribution to the total cross section [O($10^{-4}$) in statistics at LHC]

**Recent concept of « small systems » highlight more fundamental questions of QCD :the structure of the hadronic collision and the onset of collectivity.**

**Can we describe all hadronic collision with one picture ?**

# Strategy: systematic comparisons

To explore fundamental QCD questions raised by small systems:

- System scan
  Cover a wide range of systems (pp, pA, AA and eA) 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 multiplicty as AA

- Perform all measurements in multiplicity classes, multiplicity differential or find a new scaling quantity for systematic comparisons

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

- Systematic data/data and data/theory comparisons from all systems and all energies in similar multiplicity classes or system size estimator
  RIVET like initiative of importance to ease systematic comparisons

# Strategy: define a system size estimator

- Need to develop a program with systematic comparisons of standard QGP measurements at different energies, systems, multiplicities
  To go beyond the Glauber model of HIC

- Few thoughts

  - 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 : role of size, similar multiplicity in smal and large volume is not similar energy density …

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 ?

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

How to define the size ?
Let’s take the HBT radius …
… yes, but induce other caveats

# Strategy: define a system size estimator

- Need to develop a program with systematic comparisons of standard QGP measurements at different energies, systems, multiplicities
 To go beyond the Glauber model of HIC

- Few thoughts

**Opacity :**
measuring the transverse system size *R* in units of mean free path at the time τ = *R* at which collectivity is built up.

$$\hat{\gamma} = R^{\frac{3}{4}} \gamma \, (\varepsilon_0 \tau_0)^{1/4}$$

$\hat{\gamma}$ can be varied :

- by changing the geometrical size of the system *R* (centrality class in heavy ions)
- by changing the mean free path, varying the density ε0τ0 (multiplicity selection in pp :more dense or dilute systems)

**CERN-TH-2018-115,** arXiv:1805.04081

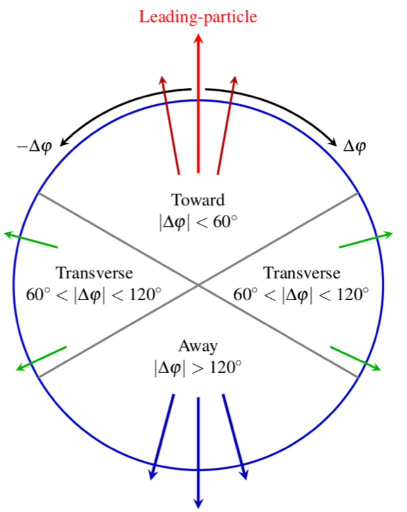
# Strategy: define a system size estimator

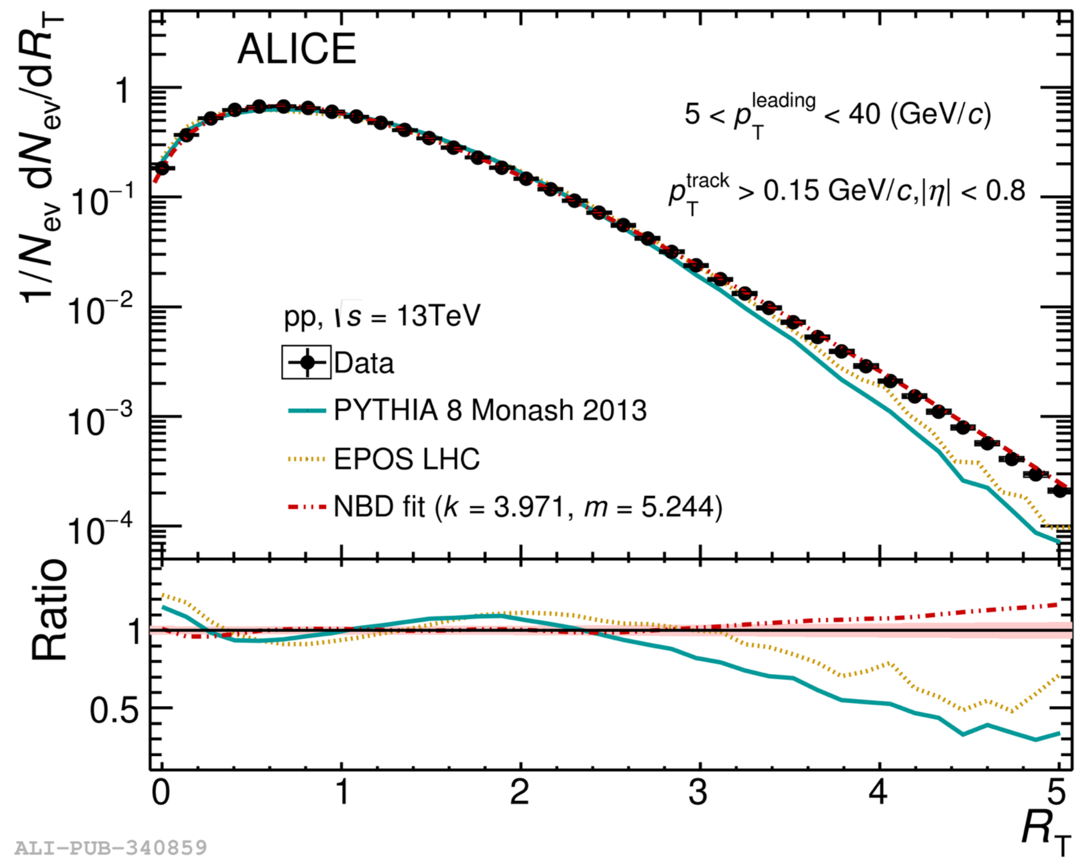
- Need to develop a program with systematic comparisons of standard QGP measurements at different energies, systems, multiplicities
  To go beyond the Glauber model of HIC

- Few thoughts

**New classifier :**
**Relative transverse activity**

$$R_T = \frac{N_{ch}^{transverse}}{< N_{ch}^{transverse} >}$$

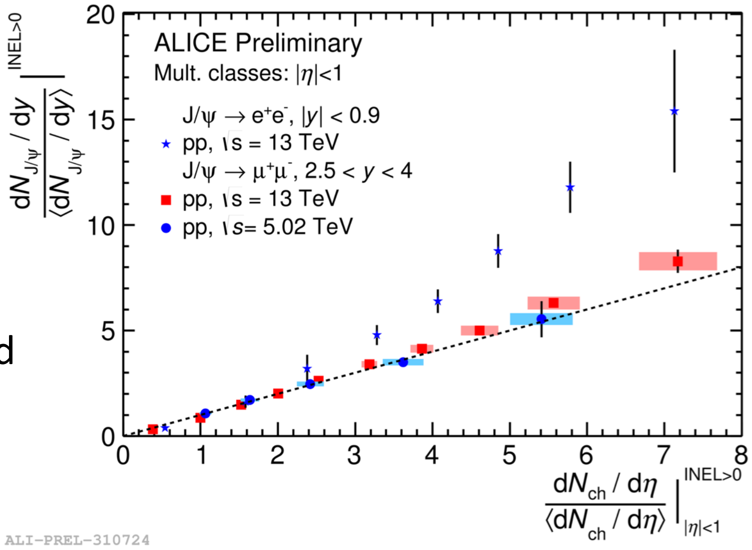


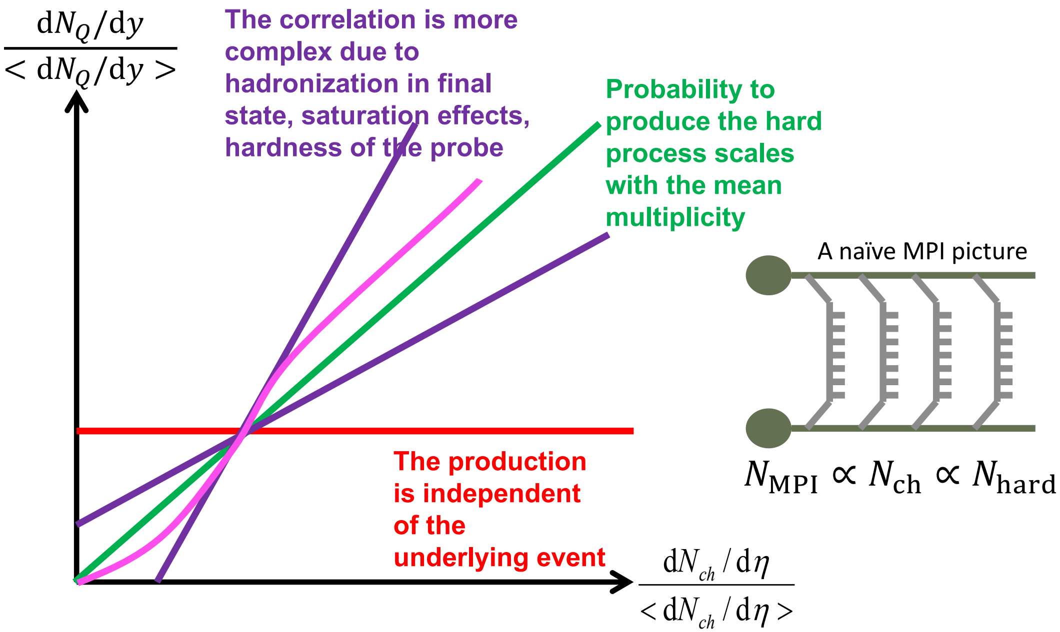



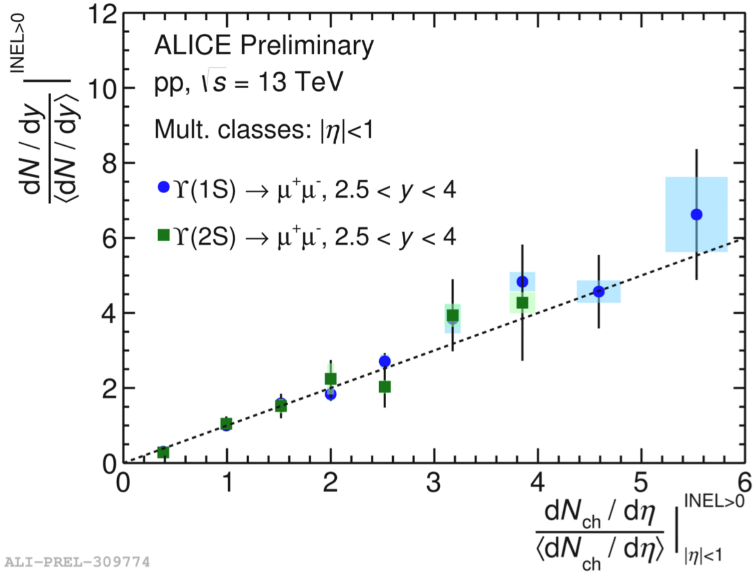
# The multiplicity differential initial state

- **Soft-hard correlations**: measurement of quarkonium and single muon production as a function of the charged-particle multiplicity for various systems and energies (first proposed Nucl.Phys.Proc.Suppl. 214 (2011) 181-184 )

- Goal to understand the **initial state** of hadronic collisions, potentially in terms of Multi-Parton Interactions (MPI) and to study the specific regime of **high multiplicity**

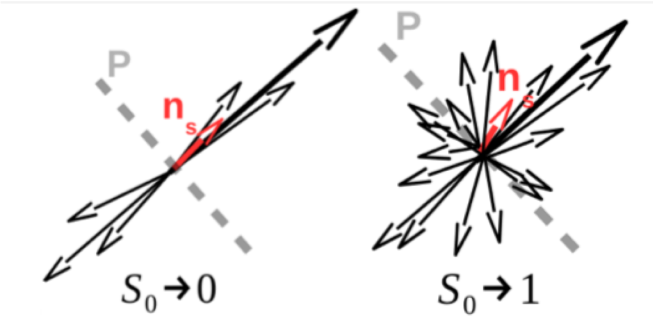


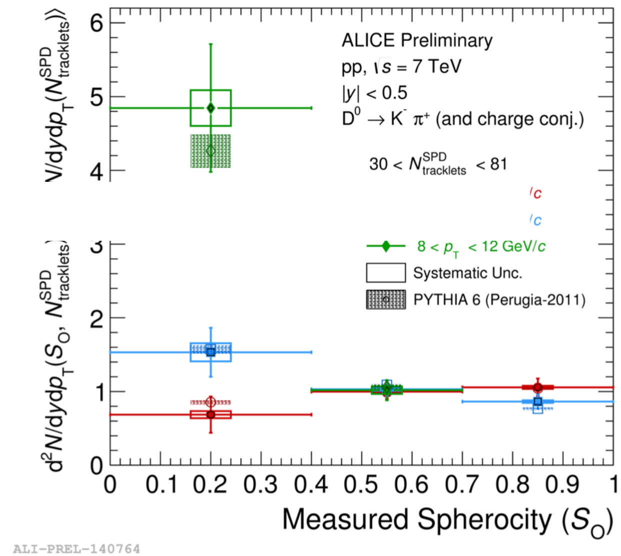
# Strategy: new measurements (ideas)

- **Spherocity analysis connected with hard probes**
  Measures spherocity of hard probes triggered events

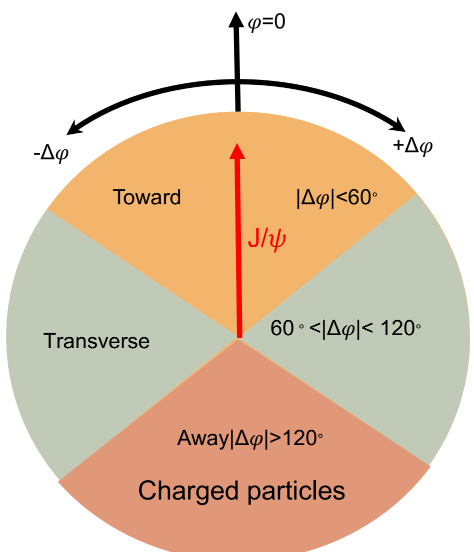


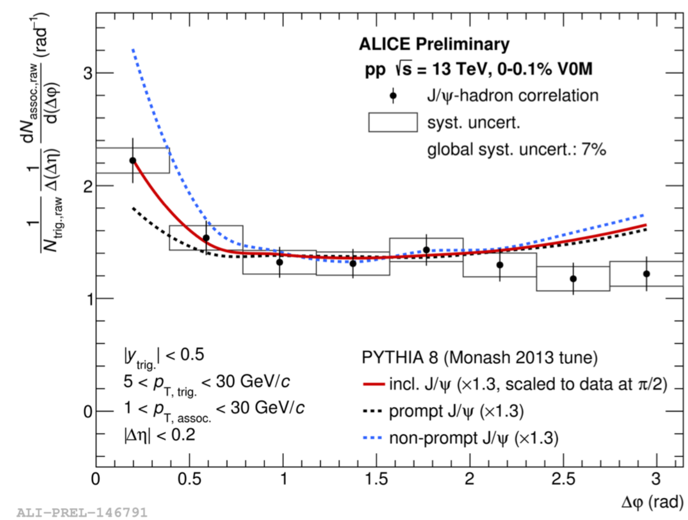

$$S_0 = \frac{\pi^2}{4} \min_{\vec{n}=(n_x,n_y,0)} \left( \frac{\sum_i |\vec{p}_{T_i} \times \hat{n}|}{\sum_i p_{T_i}} \right)^2$$

$$S_0 = \begin{cases} 0 \text{ "jetty" limit (hard events)} \\ 1 \text{ "isotropic" limit (soft events)} \end{cases}$$




- **Underlying event studies with a c/b content as a leading particle**



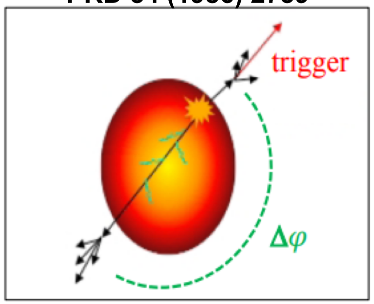



# Strategy: new measurements (ideas)

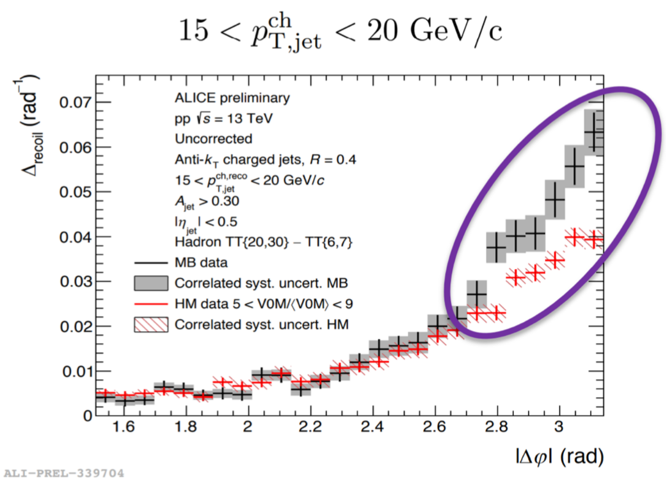
- **How to define jet-medium interaction in small systems ?**
  Energy loss proportional to system size => in small system, effect is small
  How to define the reference ? Ideas: jet asymmetry, jet substructure, Z-jet, photon-jet

- **Role of acoplanarity (jet deflection)**

PRD 34 (1986) 2739




- Change in the $\Delta_{\mathrm{recoil}}$ observed in pp when selection High Multiplicity events (HM)
- Usually interpreted as deflection in a dense medium (QGP)
- Need to investigate the description of the associated UE, MPI dynamics, final states interactions, …

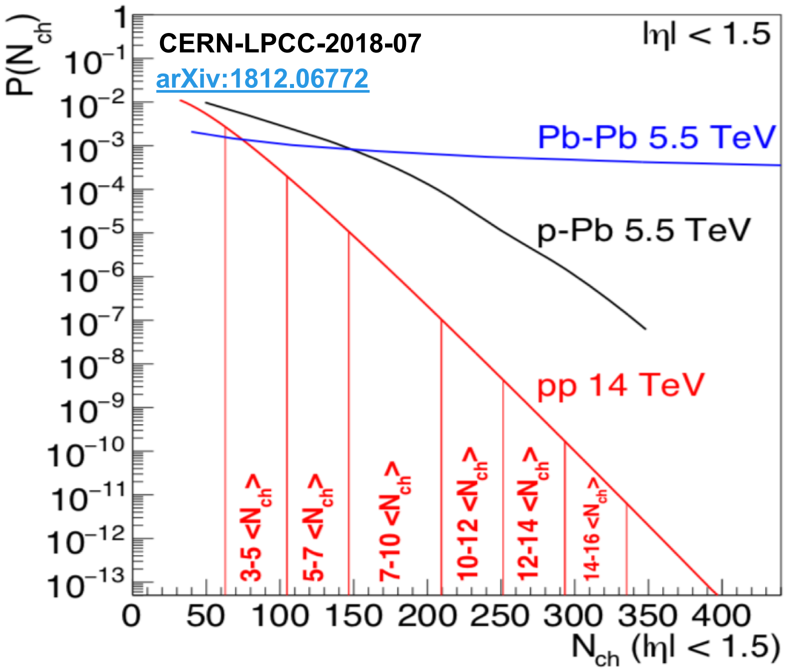


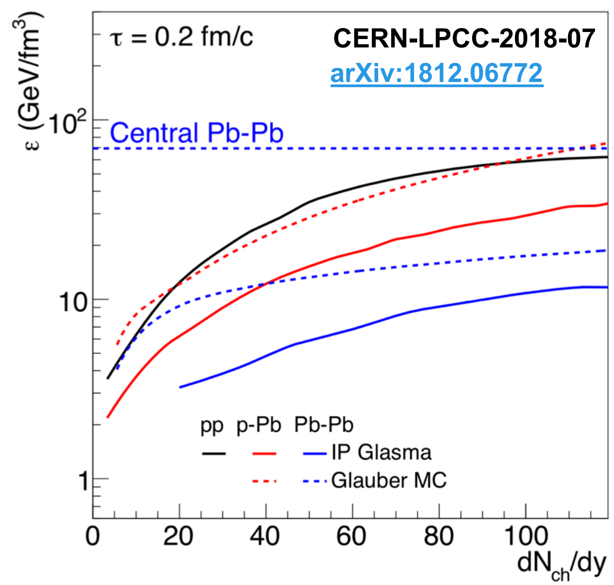

- **Jet fragmentation in multiplicity bins (pp and pA)**
  Is the jet fragmentation influenced by the dense environment, even without QGP ?

- **High-$p_{\mathrm{T}}$ flow measurement with charged ID particles.**

# 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
- Run 3+4 running conditions are favorable for small systems studies in high multiplicity environment (statistics hungry), be careful of pile-up
- The new ALICE continuous readout, data taking and upgrades will open possibilities for new measurements and possible correlations
- CMS PID, already at at RUN4
- LHCb upgrades
- Few examples of expected improvement in the following



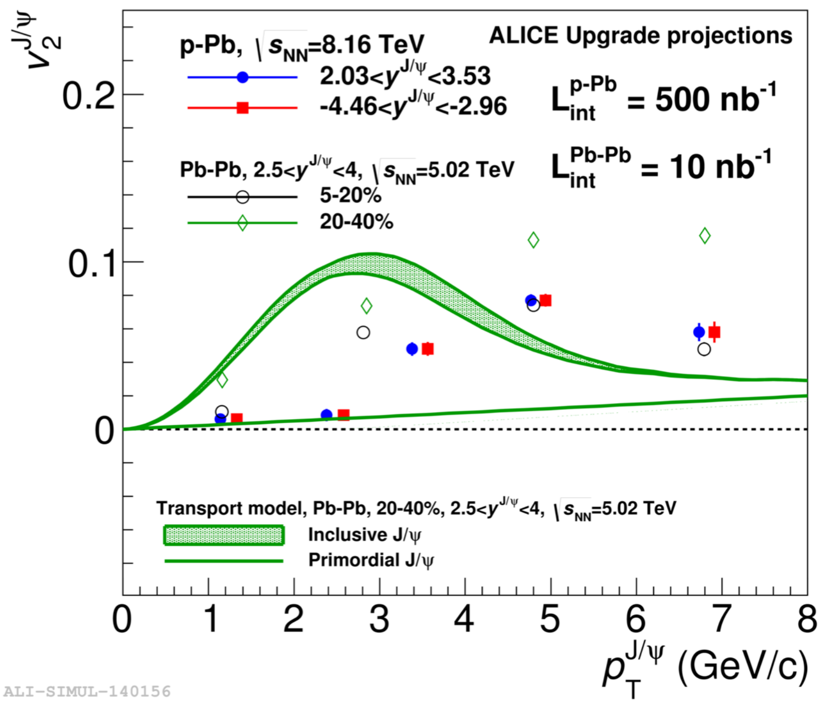



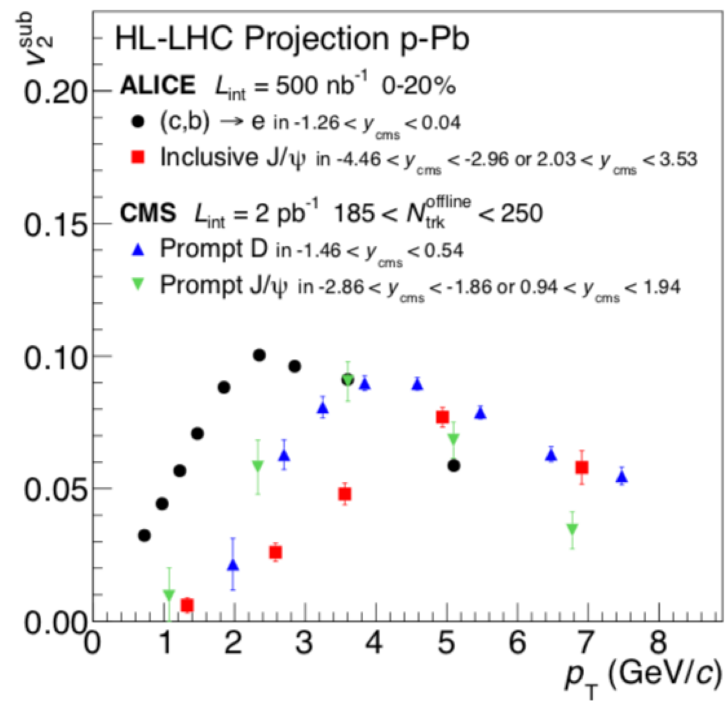
# Run 3+4: Flow/Correlations

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)

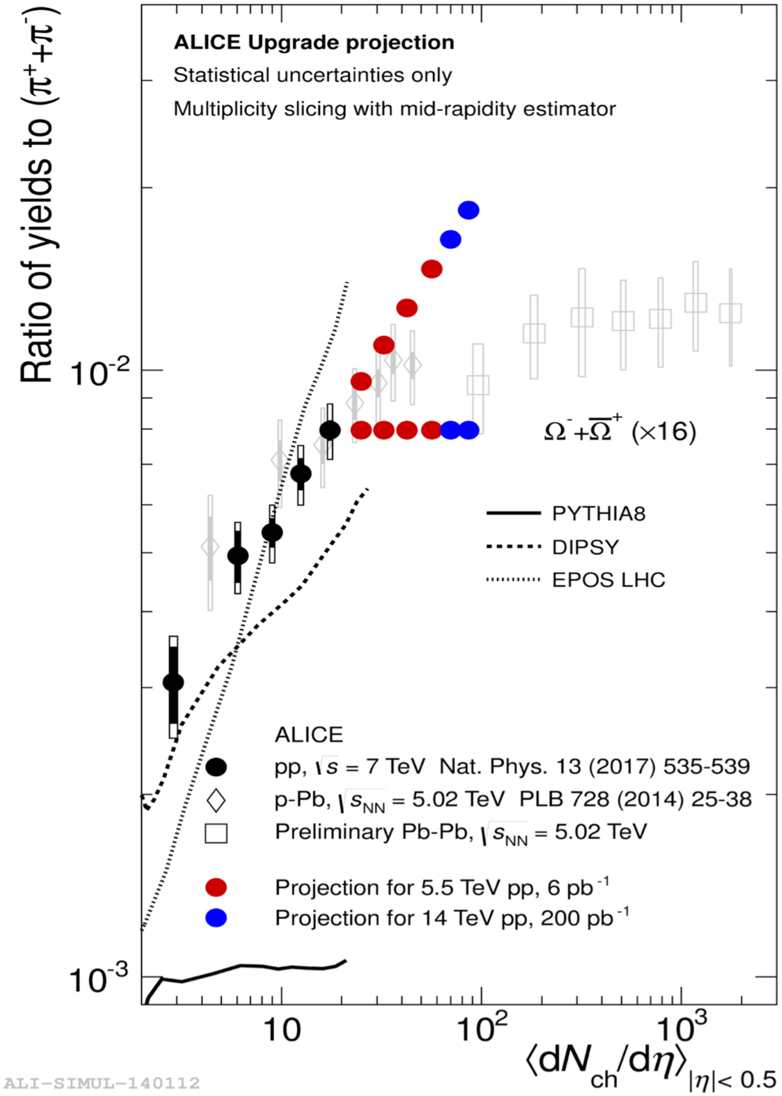


# Run 3+4: Strangeness enhancement

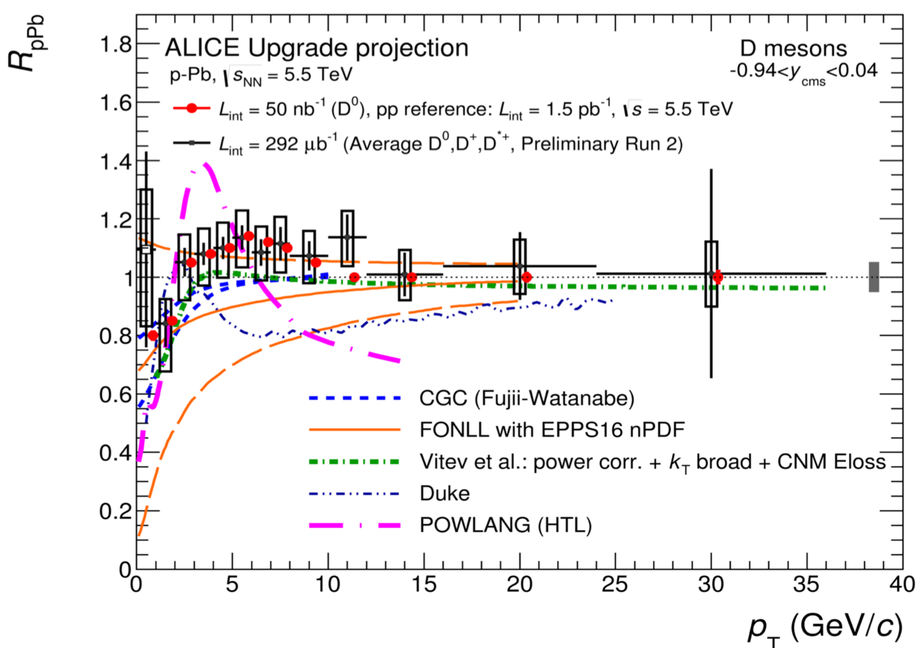
https://indico.cern.ch/event/686494/contributions/3034636/attachments/1670133/2678939/HEHLLHCWorkshop_v3.pdf

- 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

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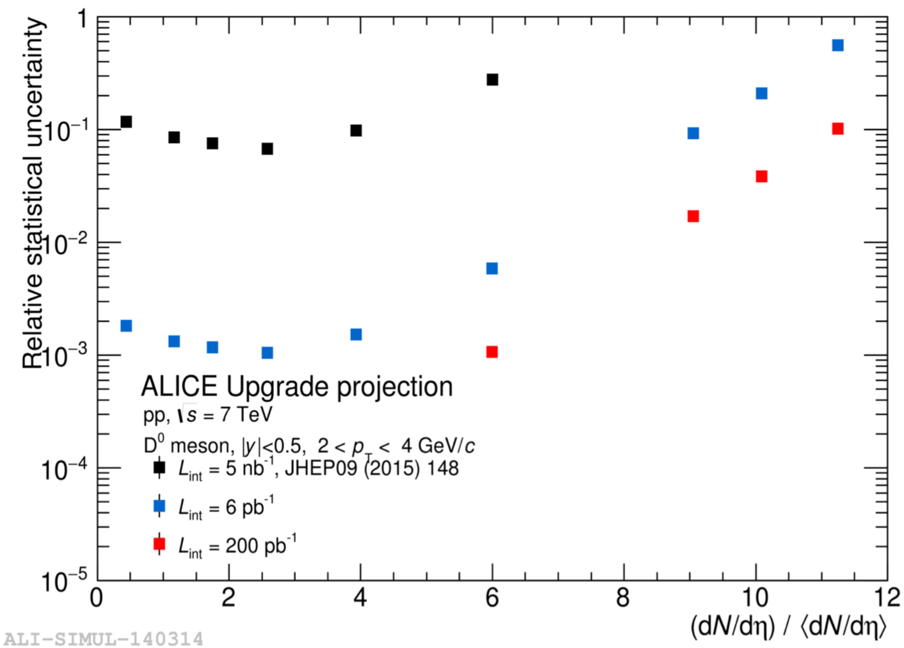



ALI-SIMUL-140314

# Enlarge the program

- LHC Run 3-4 will be a great playground for small systems physics
- But will not solve all the open questions
  - Is a multiplicity hadronic event the same independently of the energy of the collisions ?
  - Is a multiplicity hadronic event the same independently of the size of the system ?
- An Ideal physics program would scan a very wide range of energy and systems scanning all multiplicities up to LHC central Pb-Pb => Not possible
- Large-scale collisions system and energy scan,
  having the goal to reach the highest possible multiplicity classes

# Go lower in energy with high multiplicities Fixed target at LHC, horizon 2025

- $\sqrt{s}$ = 115 GeV for pp, pd,pA and $\sqrt{s}$ = 72 GeV for Pbp, Pbd, PbA
- Benefit of fixed target : high luminosity => high stat
- 2 programs with different implementations, see dedicated contributions

LHCb

- Gas target
- Already running with SMOG
- Upgrade SMOG 2 a Run 4 (x100)

ALICE

- Project under development, foreseen at RUN4
- Solid Target versatility From Be (A=9, Z=4) to W (A=184,Z=74) Consideration of Ca, C, Os, Ir, Ti, Ni, Cu

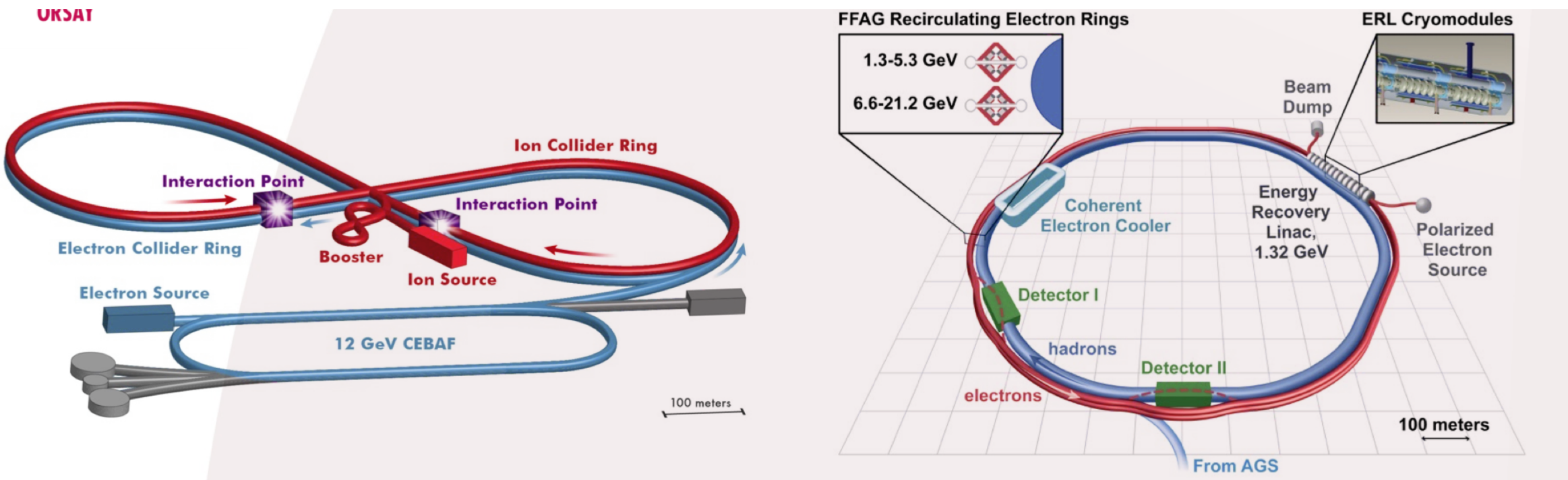
- Multiplicity class reached with the available luminosity to be estimated with the two set-up

If high multiplicities are reached at lower energy (below RHIC)
The small system bridge between RHIC and LHC
**Energy and system scan to study the onset of collectivity**

arXiv.org:1807.00603

# Drastic system scan: electrons EIC, horizon 2030

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




- Interest for small systems
  - Initial state (CGC, nPDF)
  - Hadronization
  - Centrality definition
  - Jet fragmentation
  - What is the highest multiplicity reached ?
  - The control experiment or not yet?

# At LHC Run 5/6, horizon 2030

- LHC experiments are planning upgrades

- Particle physics experiments will open phase space for heavy ion studies, examples :
    - Centrality reconstruction for LHCb
    - CMS PID

- ALICE proposal for for a $4\pi$ compact silicium detector with very low momentum resolution ($p_T > 20$ MeV) with PID and TOF

- Need for a system scan and higher multiplicities measurements to be determined for small systems

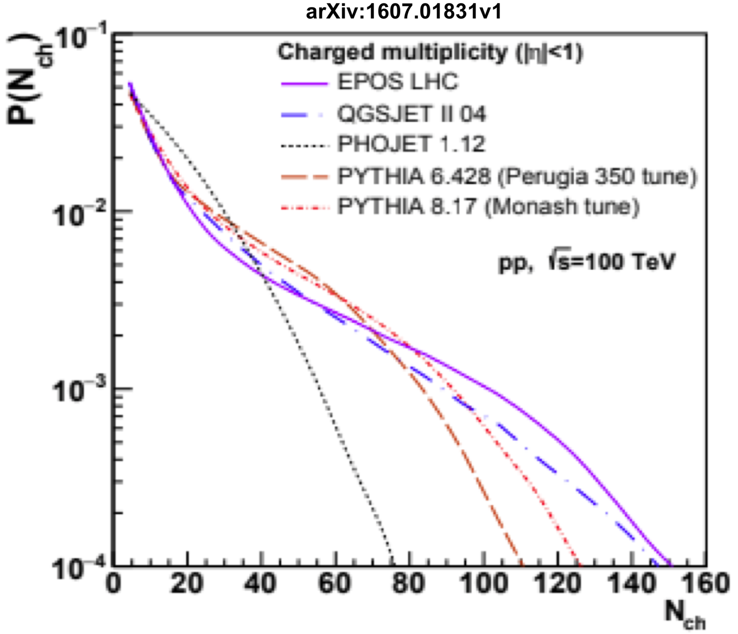
# Go higher in energy
# CERN HE-LHC/FCC/SPPS: the far future

- Increase in multiplicity, increase in energy density, increase in collision energy
- Future colliders at energies greater than LHC: natural continuity for small systems studies

  - 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

**The ultimate energy scan!**

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!
**Small system physics case to be developed!**

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

# Impact for the community

- Not an additional project, a change of paradigm to exploit the foreseen facilities
- Any new insight on a universal description of hadronic collisions would bring significant outcome on the theory side
- This field has a strong impact for the event generator community: modeling of hadronic collisions in PYTHIA, EPOS, HERWIG, DISPY, …
- Could even impact the modelling of minimum bias pp collisions
- Could be of importance the particle physics community:
  - Rare events with high number of charged particles have specific dynamics
  - High $Q^2$, mass, $p_T$ selected particle bias the selection towards those type of events
  - This physics will impact the underlying event description of the particle physics community

# Unravelling the hadronic collision structure with Large-Scale System and Energy Scan

(the conclusions)
(from the document)

1) On a short time scale, **fully exploit LHC for RUN3 and beyond** with multi-differential measurements and, in particular correlation studies ;

2) For the medium and long time scale, complementary paths are of high interests and need to be investigated to conduct this ambitious program
   - **Fixed Target@LHC** possibilities to study high multiplicity events at lower than RHIC and LHC energies but with high luminosity and target versatility (RUN 4)
   - Prepare a physics case for high multiplicity pp and pA @**FCC**, and consider a heavy-ion program in this context ;
   - **EIC** to study a high multiplicity environment with fixed initial conditions ;

3) Conserve a French **network for Hadronic physics** as a natural *forum* for exchange among experiments and theoreticians.

# 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

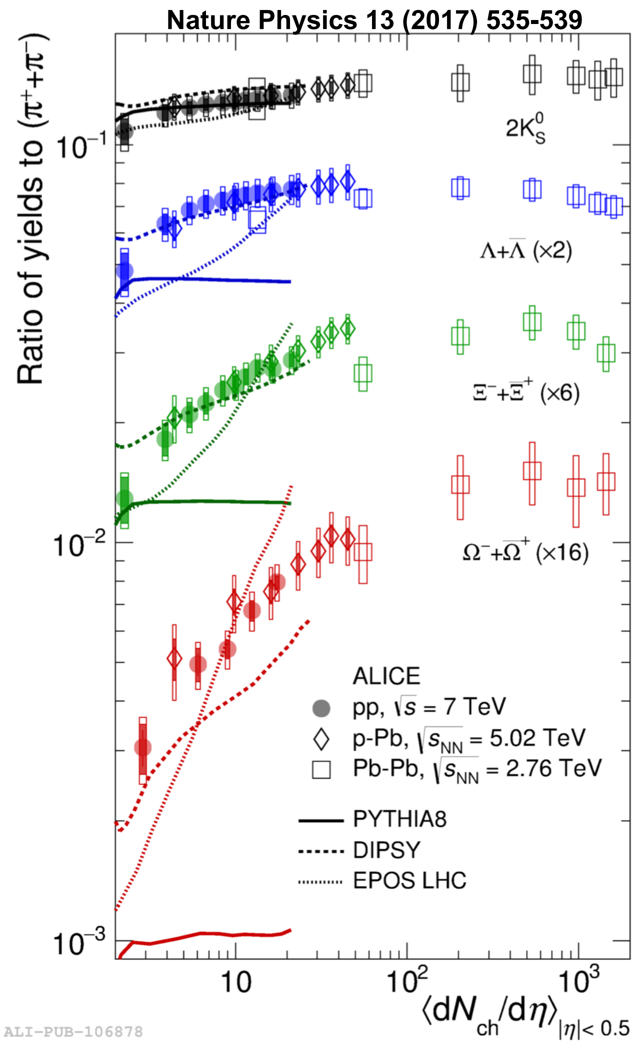
- It is a « fourre-tout » that sometimes refers to new phenomenon between RHIC and LHC connected to pp and p-A systems

- 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?

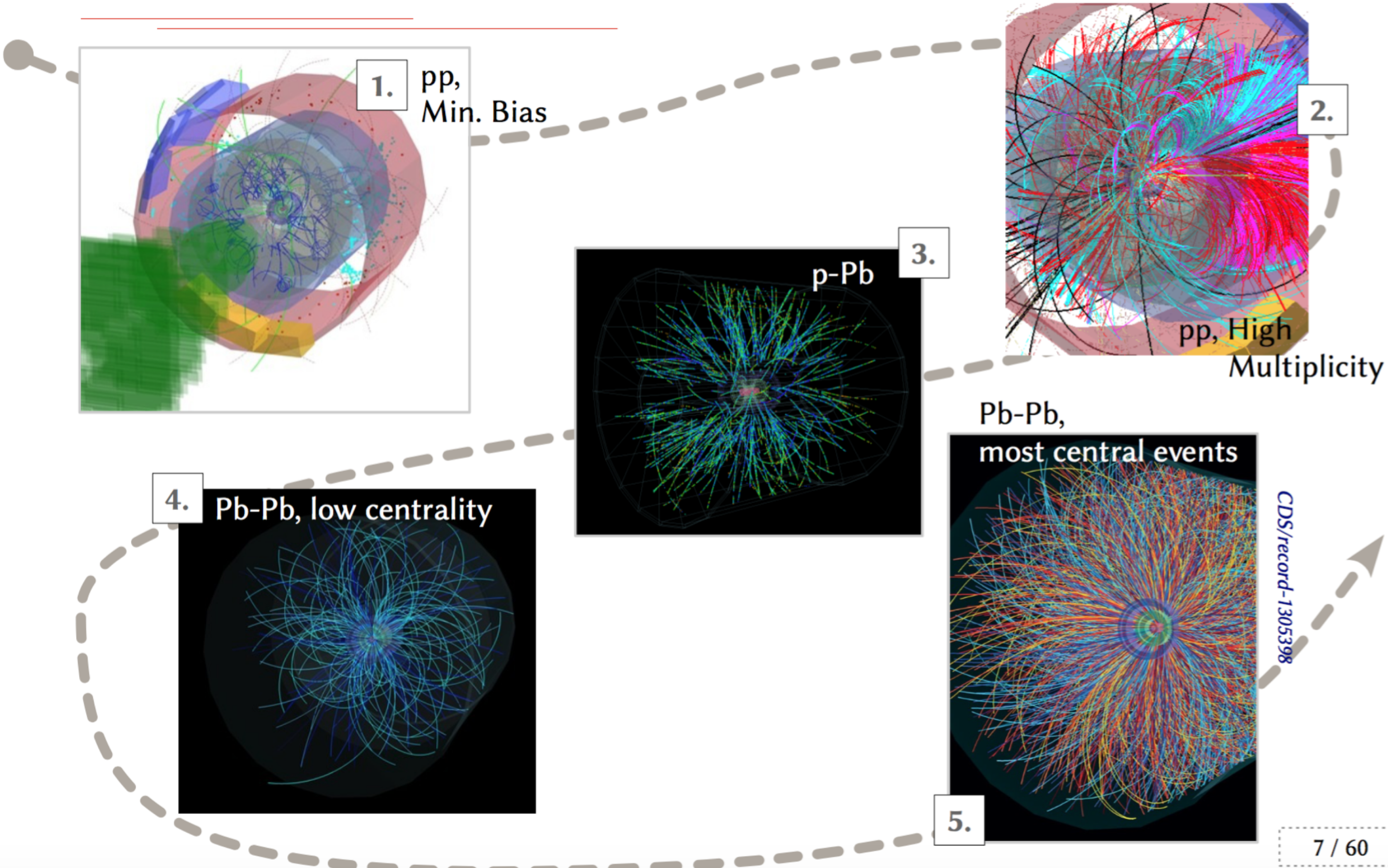
- ”A priori small” refers to system size: protons in initial stage
- But with sometimes a final state looking like a large system, at least for charged particle multiplicity
- For LHC RUN 1+2 energies, idea of reference system still valid for pp minimum bias. High multiplicity events represent a small 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 ?



# Quark-Gluon Plasma

- Is the measurement the consequence of the evolution of a hydrodynamic fluid?

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- Warning: hydro application do not necessarily imply QGP

- Hydro requires $R_e$ >> 1 => small $\frac{\eta}{s}$, with $R_e$ the Reynolds number:

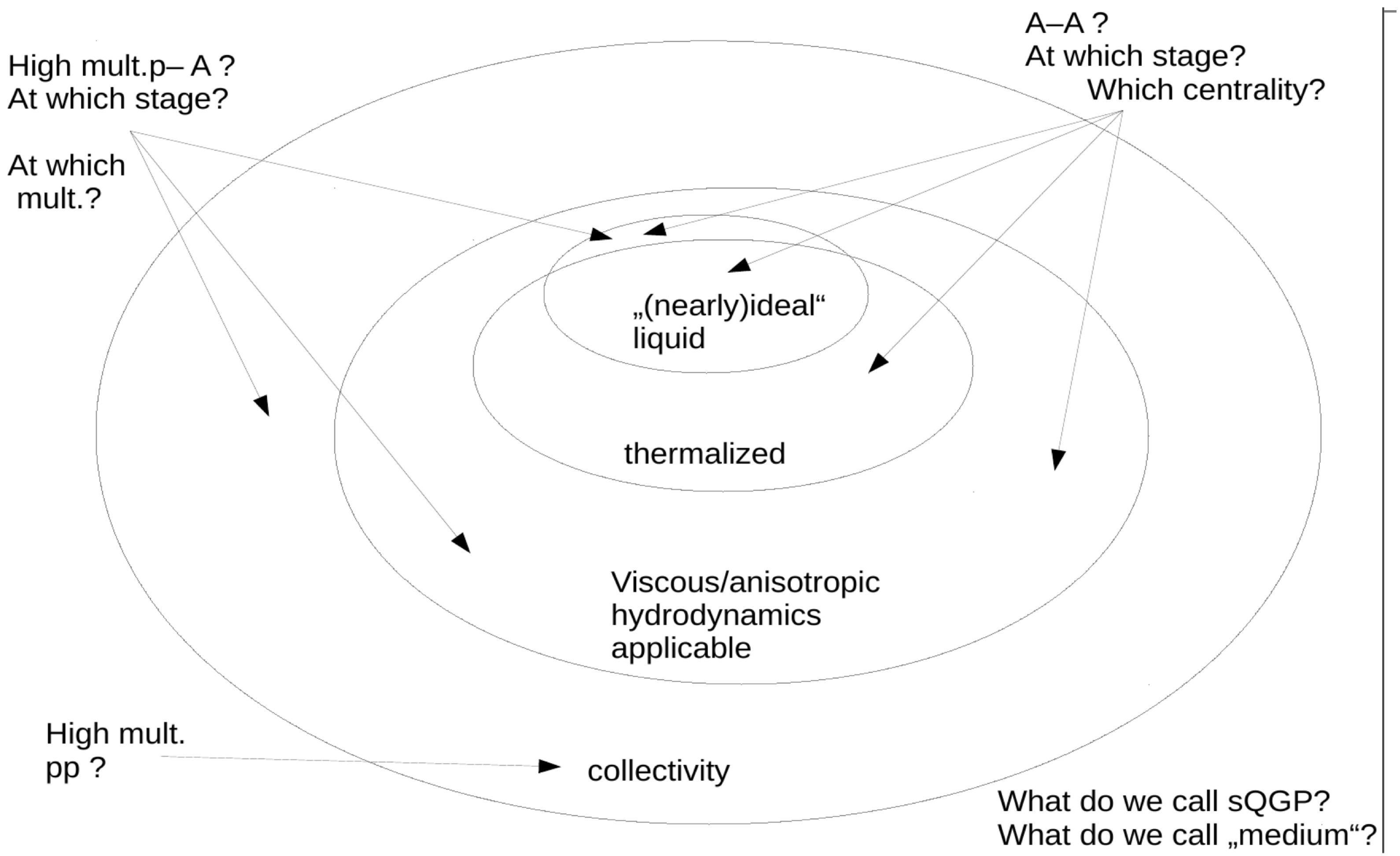
$$R_e = \frac{\mathrm{R}v}{\nu} = \frac{\mathrm{R}v}{\eta/\rho} = \frac{\mathrm{R}vT}{\eta/s}$$

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

- Small $\eta/s$ (<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

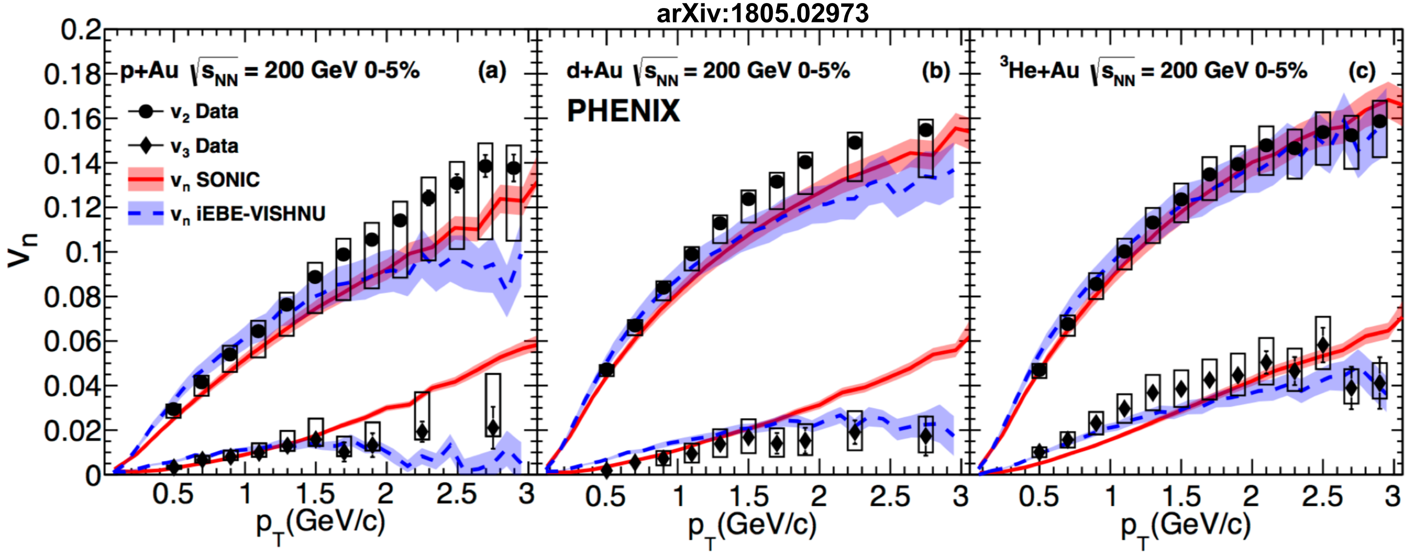
# Sign of QGP in small systems at LHC ?

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 / Y supression | suppressed | Not measured |
| Heavy-flavor anisotropy | yes | yes | Not measured |

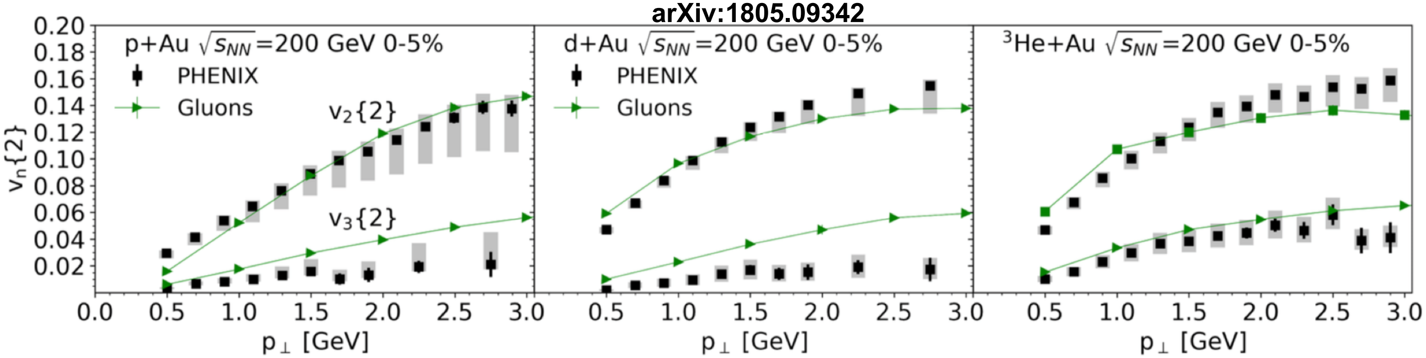
# Sign of QGP in small systems at RHIC?

arXiv:1805.02973




- PHENIX claim for QGP in small systems …

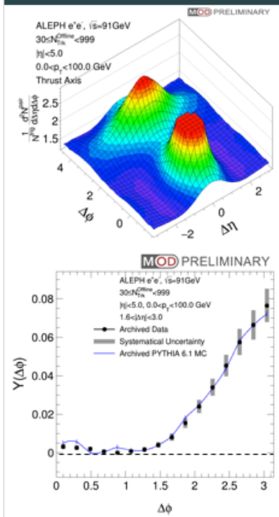
arXiv:1805.09342




- … also explained by CGC.

# Sign of QGP in very small systems ?

## Summary



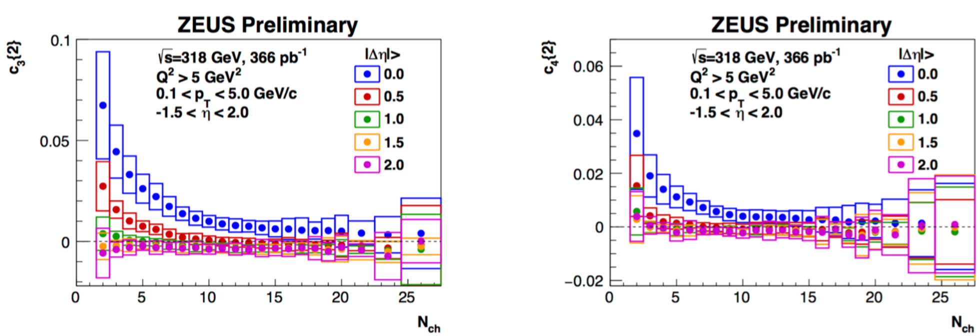

- The first two-particle correlation analysis in $e^+e^-$ performed in bins of event multiplicity up to N = 35 - 55
  - No significant ridge signal is observed in beam axis analysis
- Thrust axis and jet region veto are employed to enhance the signal from soft radiations
  - No significant difference between ALEPH LEP1 data and PYTHIA6 observed
- No evidence of the final state effect in the probed event multiplicity ranges:
  - An important reference of the ridge signal observed in pp, pA, dA and AA collisions
- LEP2 Data analysis (up to $\sqrt{s}$~208 GeV) ongoing… stay tuned!

Yen-Jie Lee (MIT) Two-Particle Correlation in e+e- with ALEPH archived data 31

**QM2018, Yen-Jie Lee**

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

Multiplicity-dependent $c_3\{2\}$ and $c_4\{2\}$ with increasing $\eta$-separation




$|\Delta\eta| > 2.0$: $c_3\{2\}$ and $c_4\{2\}$ are consistent with zero.

**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, ...) ?

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# 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?

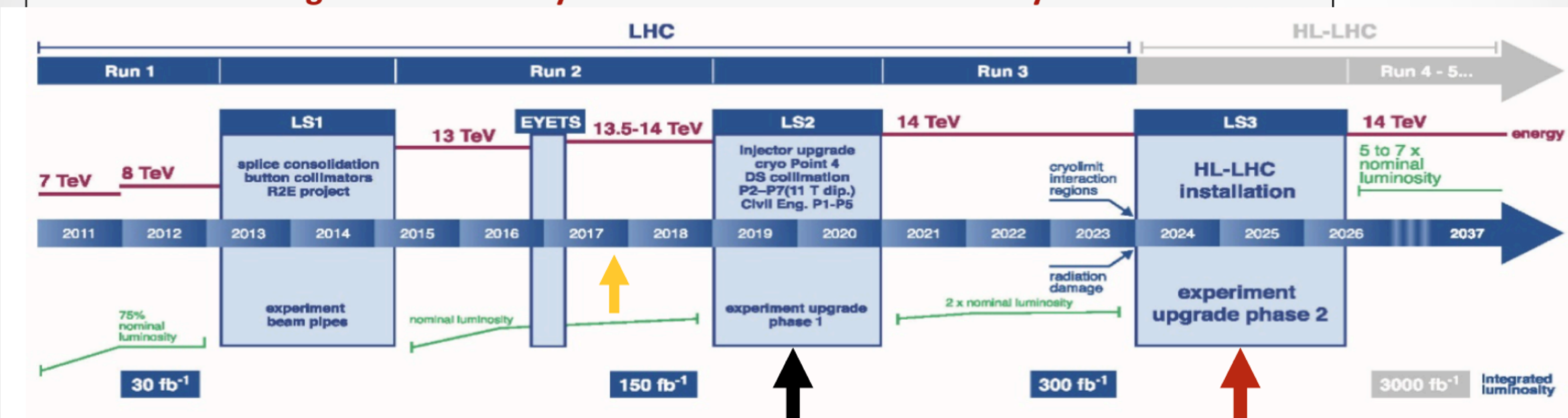
***Thoughts on opportunies from high-energy nuclear collisions*** https://arxiv.org/abs/1409.2981

# After LS2: Run 3+4

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

Nominal LHC: $\sqrt{s}$ = 14 TeV, L= $1\times10^{34}$ $cm^{-2}$ $s^{-1}$
Integrated luminosity to ATLAS and CMS: 300 $fb^{-1}$ by 2023 (end of Run 3)

**HL-LHC: $\sqrt{s}$ = 14 TeV, L= $5\times10^{34}$ $cm^{-2}$ $s^{-1}$ (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

# 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/](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:

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- 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 $\eta$ 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 $4\pi$

6. Computing ressources

# What's next ? LHC Run 5/6

ALICE upgrades ?

- Not yet an official proposal
- for a $4\pi$ 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/$\pi$ with 0.7 <$p_T$< 3-4 GeV/$c$

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

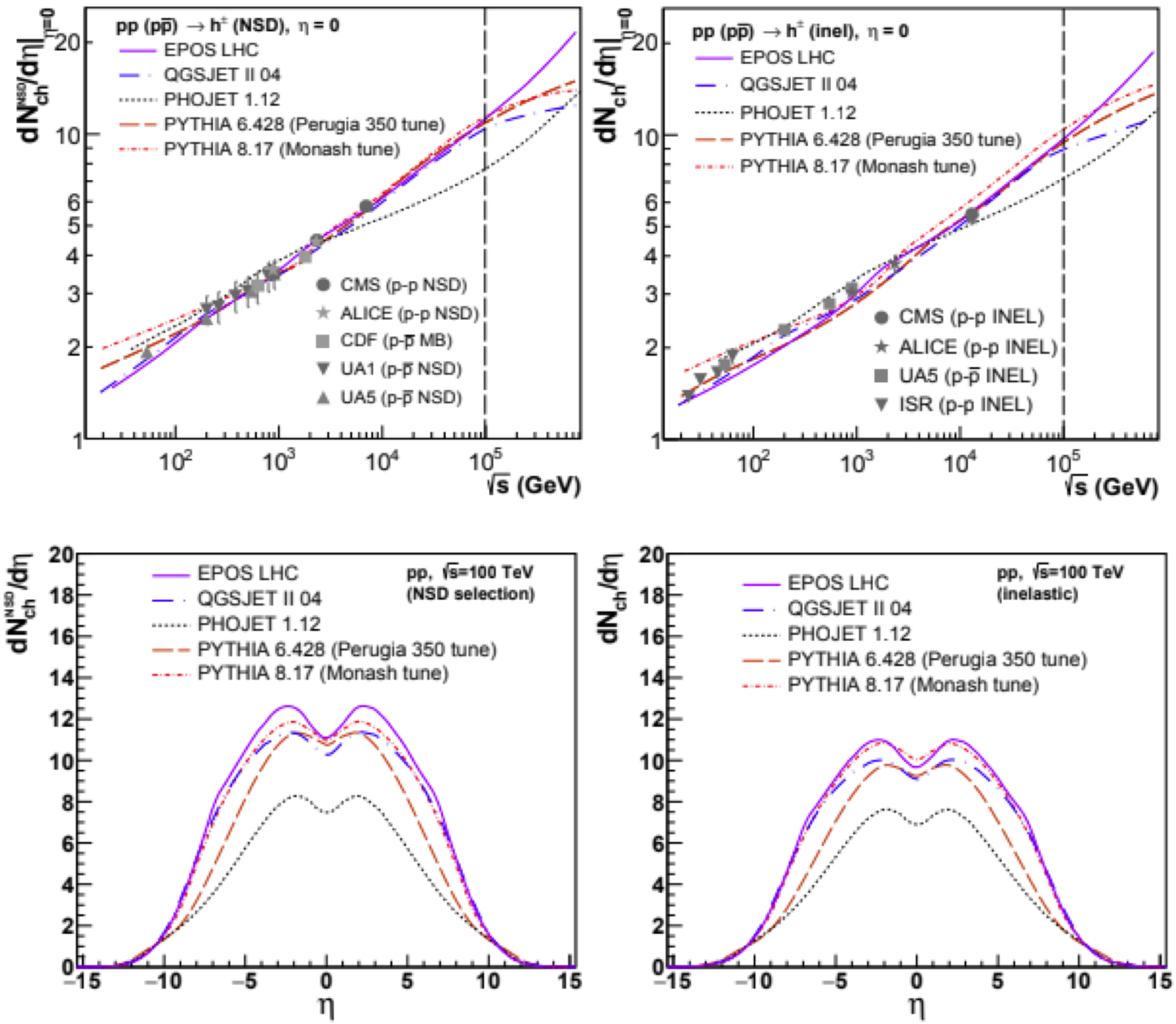
ATLAS upgrades ?

- Not evaluated

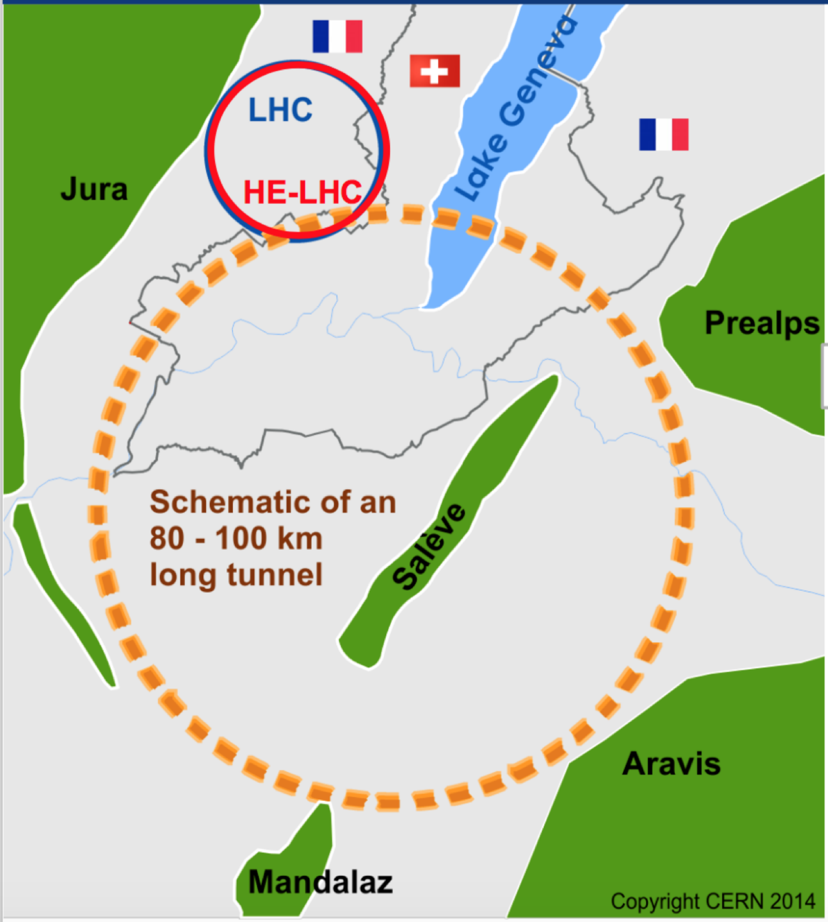
**Can we develop a physics program for small systems (example of p-Xe, O-O, p-O) and energy scan at Run 5/6 ?**

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

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



# Future Circular Collider (FCC) Study

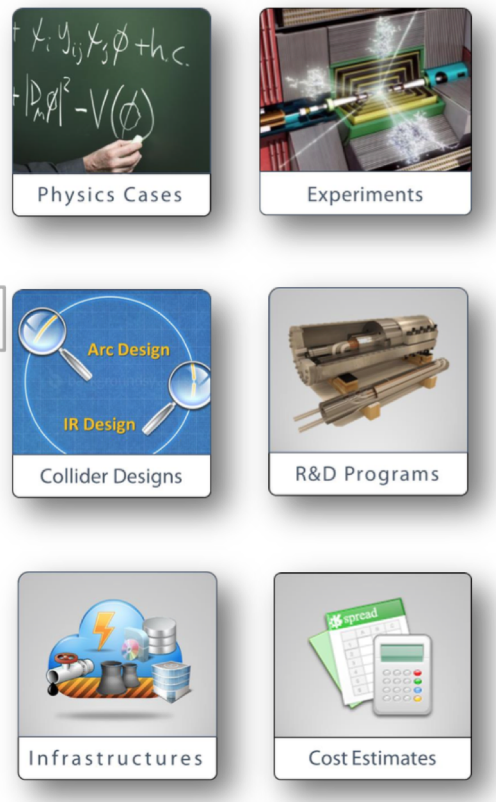



**International FCC collaboration (CERN as host lab) to study:**

- ***pp*-collider (*FCC-hh*)**
  → main emphasis, defining infrastructure requirements

**~16 T ⇒ 100 TeV *pp* in 100 km**

- **~100 km tunnel infrastructure** in Geneva area, site specific
- **$e^+e^-$ collider (*FCC-ee*),** as potential first step
- **HE-LHC** with *FCC-hh* technology
- ***p-e* (*FCC-he*) option,** IP integration, $e^-$ from ERL




* 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)
  ($m_{Z,}$ $m_W$, $m_{top}$ , $\sin^2 \theta_w^{eff}$ , $R_b$ , $\alpha_{QED}$ ($m_z$) $\alpha_s$ ($m_z$ $m_W$ $m_\tau$), 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

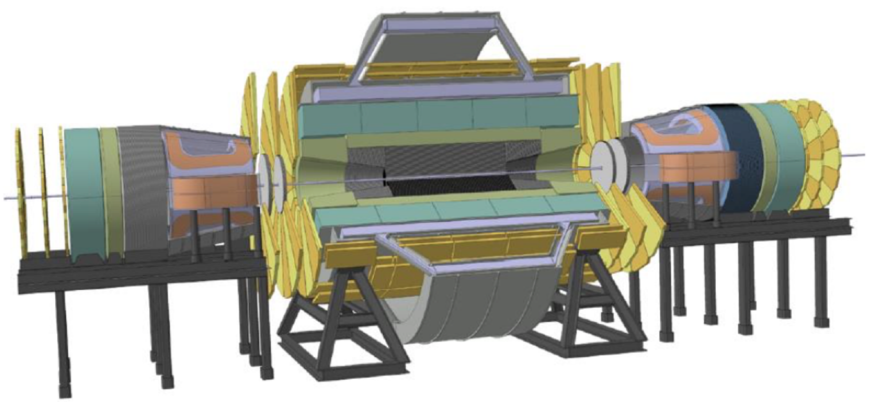
| parameter | Z | WW | H (ZH) | ttbar | |
|---|---|---|---|---|---|
| beam energy [GeV] | 45 | 80 | 120 | 175 | 182.5 |
| beam current [mA] | 1390 | 147 | 29 | 6.4 | 5.4 |
| no. bunches/beam | 16640 | 2000 | 393 | 48 | 39 |
| bunch intensity [$10^{11}$] | 1.7 | 1.5 | 1.5 | 2.7 | 2.8 |
| SR energy loss / 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

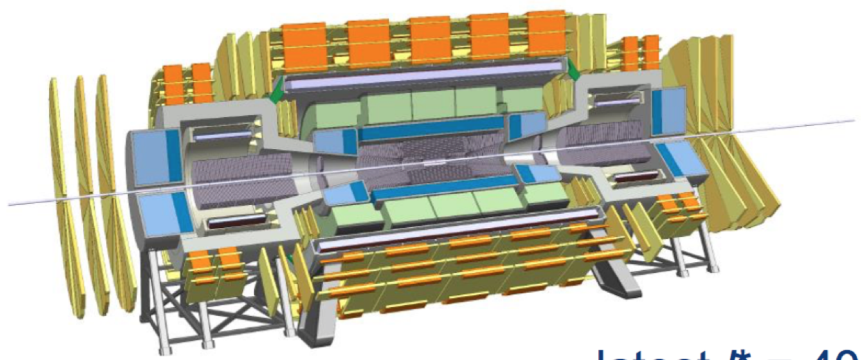
**6 T, 12 m bore solenoid, 10 Tm dipoles, shielding coil**

- 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**

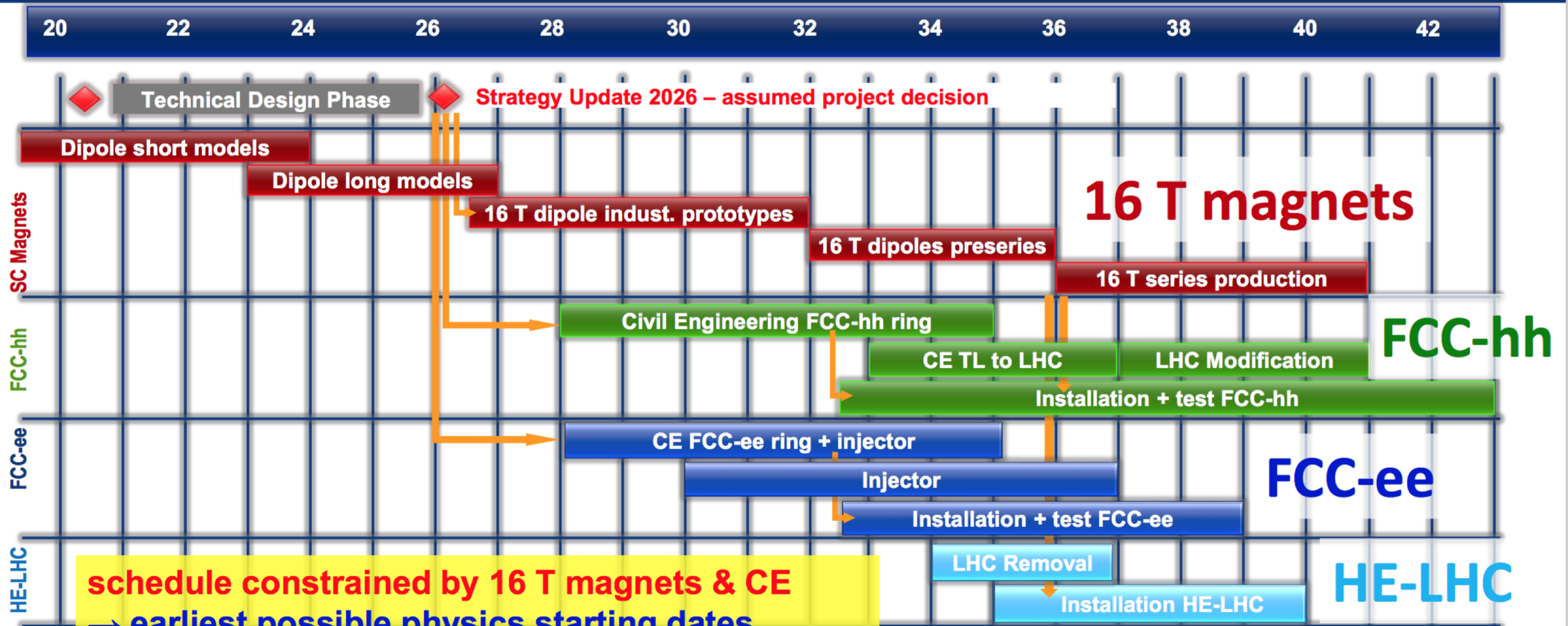
- 14 GJ stored energy
- rotational symmetry for tracking!
- 20 m diameter (~ ATLAS)
- 15 m shaft
- ~1 billion project



latest $l^*$ = 40 m

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

# Technical Schedule for each the 3 Options




**schedule constrained by 16 T magnets & CE**
**→ earliest possible physics starting dates**

- **FCC-hh: 2043**
- **FCC-ee: 2039**
- **HE-LHC: 2040 (with HL-LHC stop LS5 / 2034)**

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