Jetting through the Quark Soup

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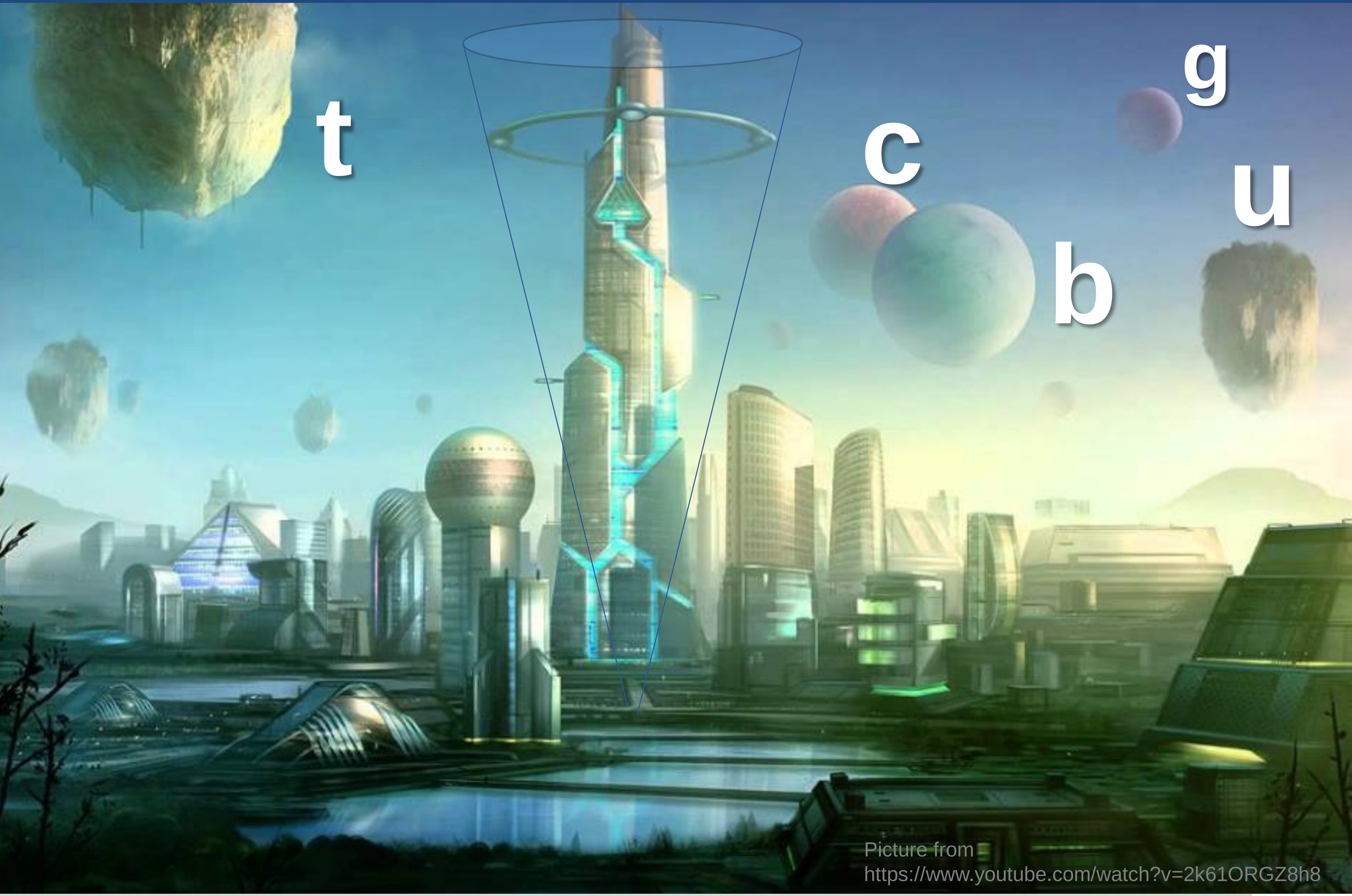
Lecture 5
Future Direction and Open Questions

Outline

- Lecture 1
  Why do we study relativistic heavy ion collisions?
- Lecture 2
  How do we measure jets in heavy ion collisions?
- Lecture 3
  Parton energy loss and its parton flavor dependence
- Lecture 4
  Modification of jet substructure and medium response
- Lecture 5
  ➡ Open questions and future direction

Outlook


t
c
g
u
b
Picture from
https://www.youtube.com/watch?v=2k61ORGZ8h8

Open Questions

- Why is the system hydrodynamize so fast? How does the strongly interacting medium emerge from an asymptotic free theory?

Start from "un-thermalized" objects and see how they are hydrodynamized / thermalized in the Quark Soup

- What is the initial transverse fluid velocity and the role of the pre-hydrodynamization phase? When is QGP formed?

Study hard probes with different formation time
Final a way to "turn off" temporarily the interaction with QGP

- How does the QGP hadronize?

Study the hadronization of a hard scattered partons and heavy quarks

- Can we see quasi particles (quarks and gluons) in the Quark Gluon Plasma ? Can we see medium response?

Shoot colored objects through the QGP

- Are we completely wrong?!

Extract medium properties with probes

Current Status

- Why is the system hydrodynamize so fast? How does the strongly interacting medium emerge from an asymptotic free theory?

We have a large set of jet and heavy flavor meson measurement: hints of hydrodynamization / thermalization of the hard probes

- What is the initial transverse fluid velocity and the role of the pre-hydrodynamization phase? When is QGP formed?

We could study TOP or boosted W or Z to turn off the jet quenching temporarily

- How does the QGP hadronize?

Exciting results from heavy flavor mesons and Quarkonia which shows modified hadronization. Modified jet fragmentation function.

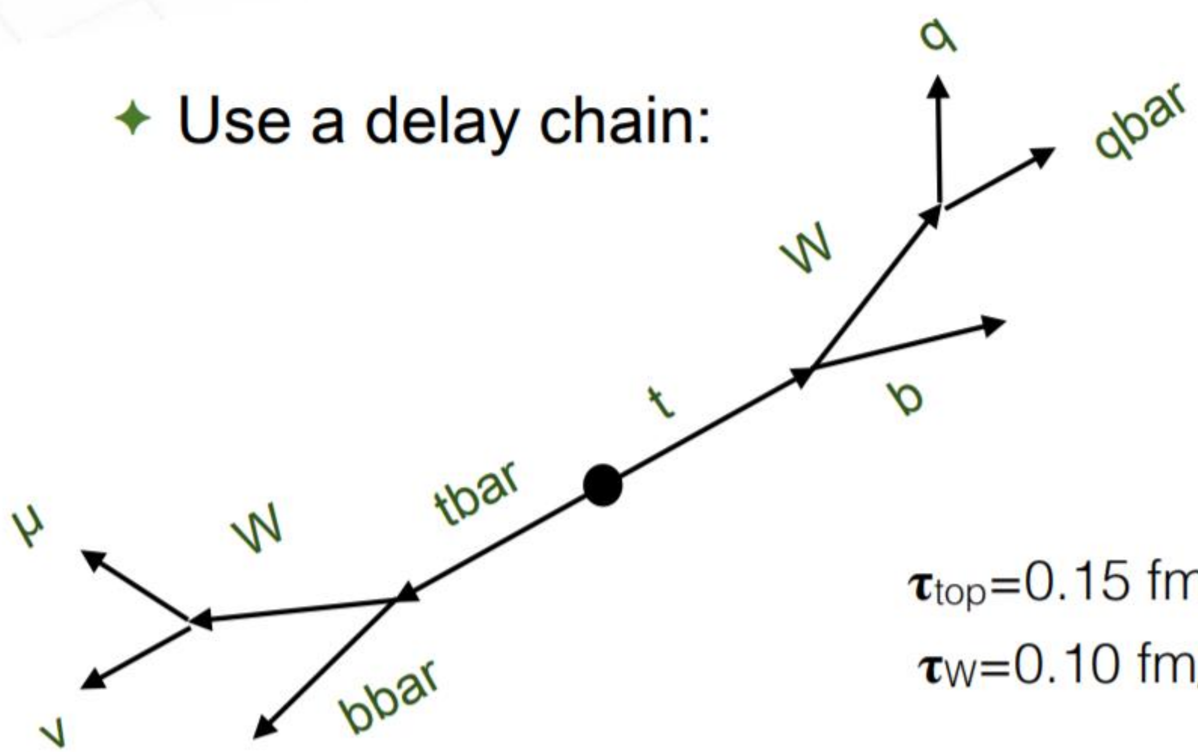
- Can we see quasi particles (quarks and gluons) in the Quark Gluon Plasma ? Can we see medium response?

QGP is smooth with the current probes. Hint of medium response.

- Are we completely wrong?! **Still need to do our homework…**

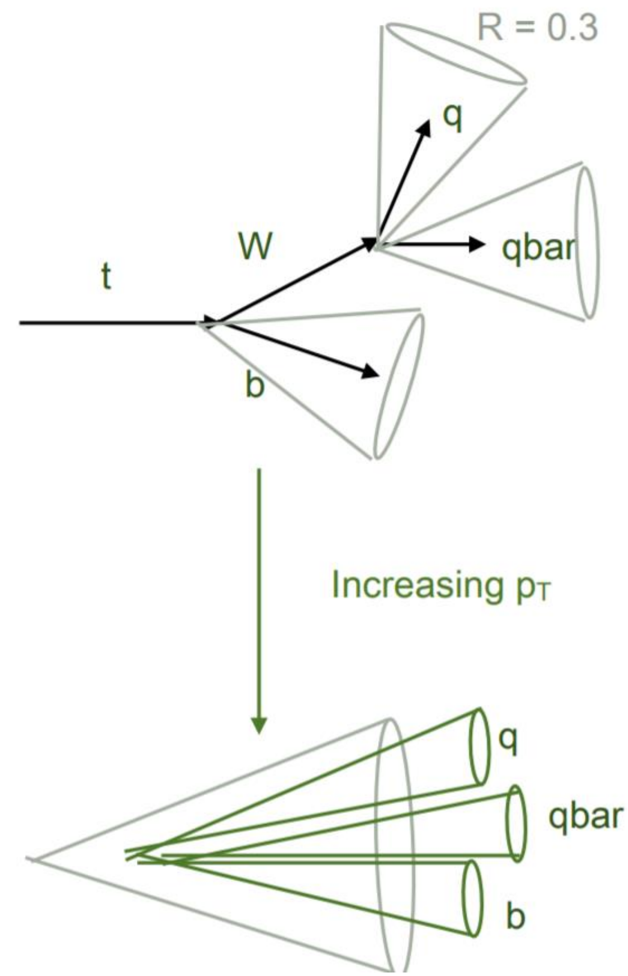
TOP Production

- Use a delay chain:



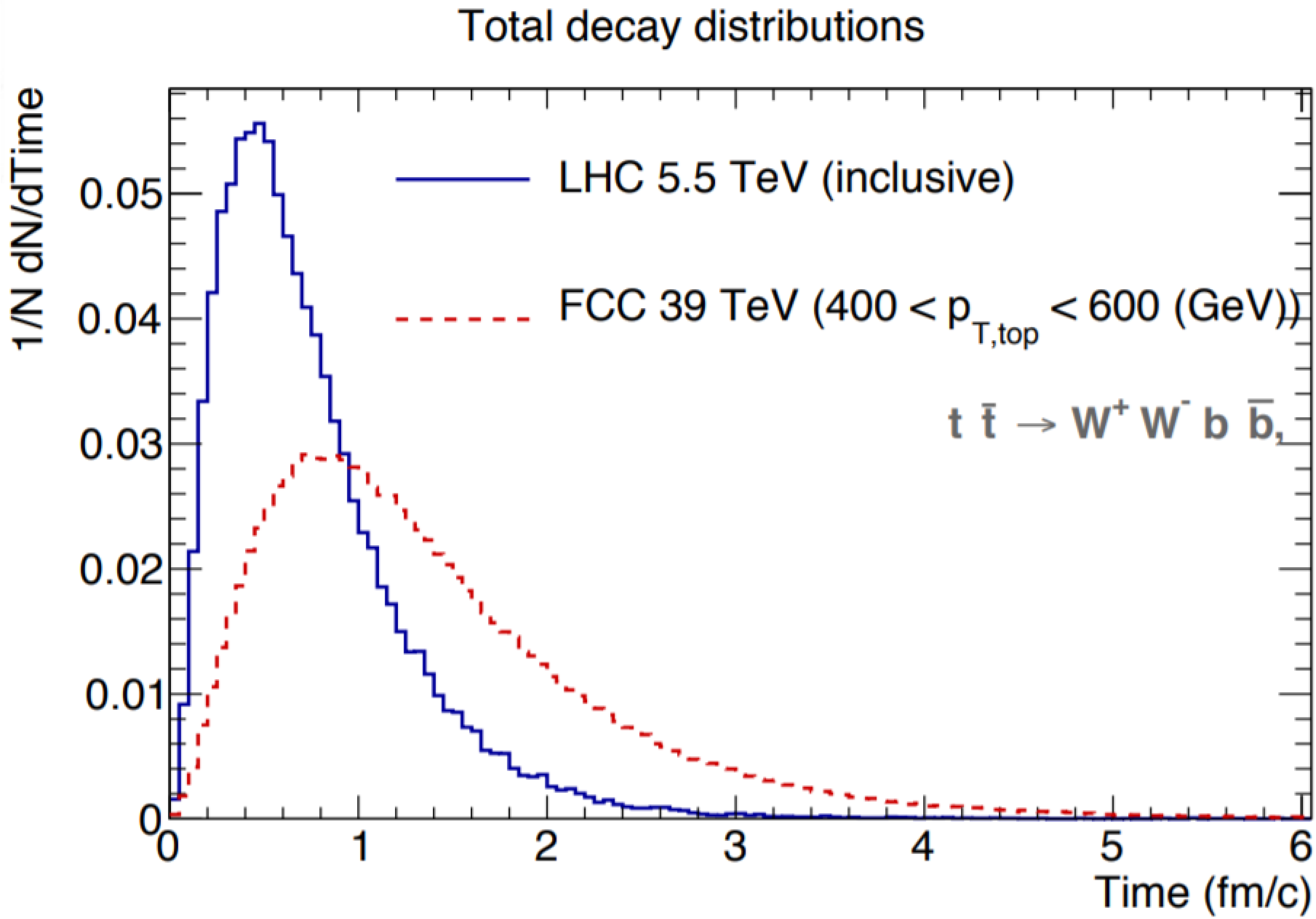
τ_{top}=0.15 fm/c

τ_W=0.10 fm/c



Liliana Apolinário (LIP)

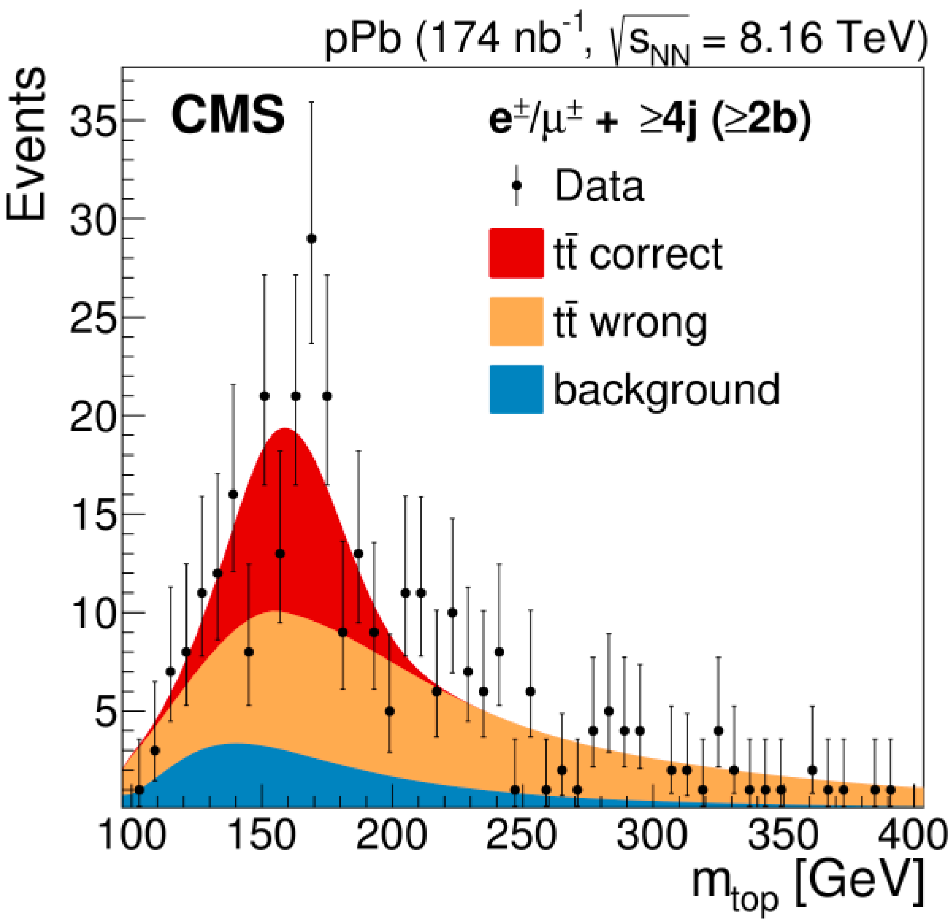
TOP Production



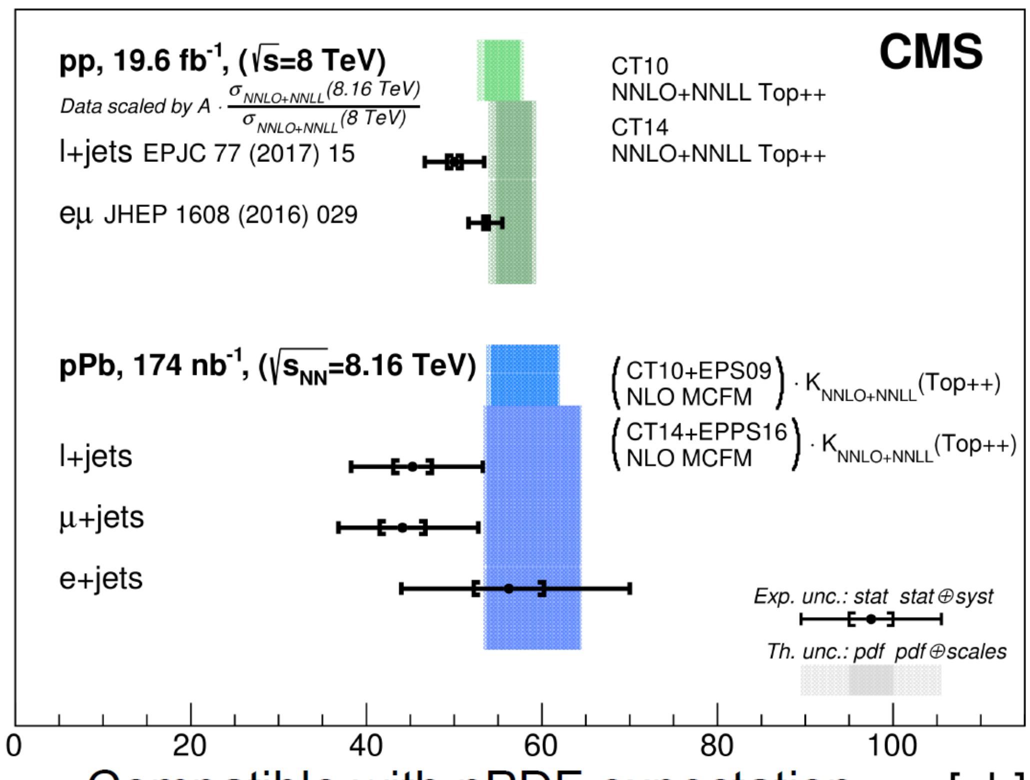
"A Yoctosecond Chronometer." (Gavin Salam)

TOP production in pPb collisions

Reconstructed top mass



Top pair cross section



Compatible with nPDF expectation

Detector Upgrade

- During the HL-LHC period

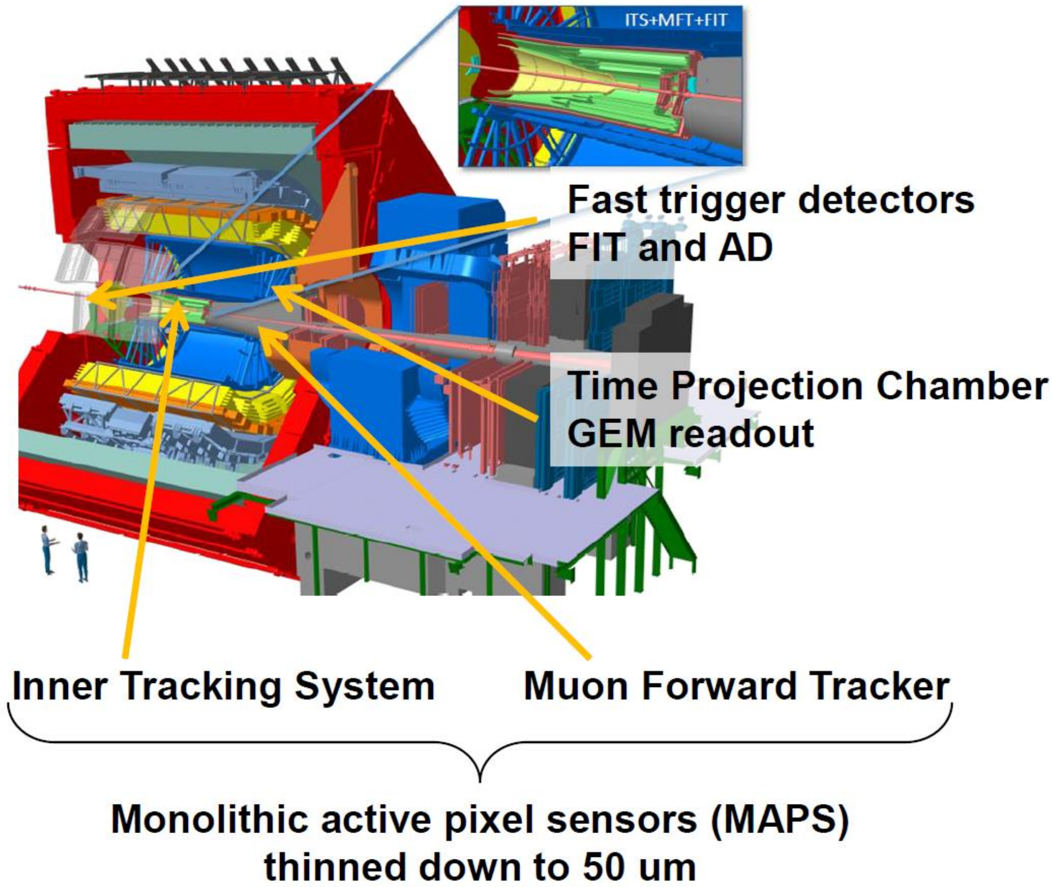
- RHIC experiments during the next 5-10 years

ALICE Upgrade

ALICE @ LHC
(data taking from 2021)

Approved and funded

- Significant upgrade, including
  - increasing data rate by factor 100
  - impact parameter resolution by factor 3
- Collision spacing < TPC drift time
  - No notion of event during data taking
- Continuous data-taking
  - 50 kHz Pb-Pb
  - Offline reconstruction determines which track belongs where
  - Online reduction 3.4 TB/s → 0.1 GB/s
  - 10 nb^{-1} = 10^{11} Pb-Pb events in 2021-29
- Focus on "untriggerable" signals with tiny signal over background



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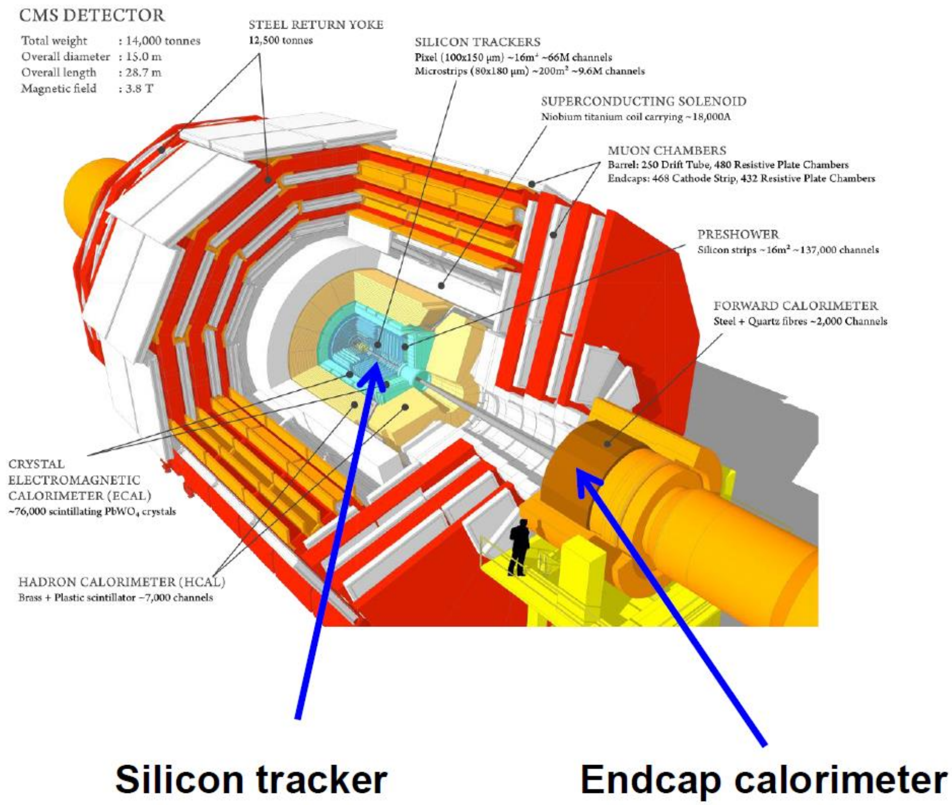
CMS Upgrade

Approved and funded

CMS @ LHC
(data taking from 2026)

- "Phase II" upgrade for high luminosity LHC, including
- Tracker upgrade
  - $|\eta| < 2.5 \rightarrow |\eta| < 4$
- Calorimeter upgrade
  - Endcap: larger granularity
- Trigger and DAQ
- Triggered data-taking in 2021-29
  - 6 kHz Pb-Pb to tape
  - $0.2\ nb^{-1} = 2\ 10^{9}$ MB events
  - $10\ nb^{-1}$ triggered events
- Focus on HF, jets and Y



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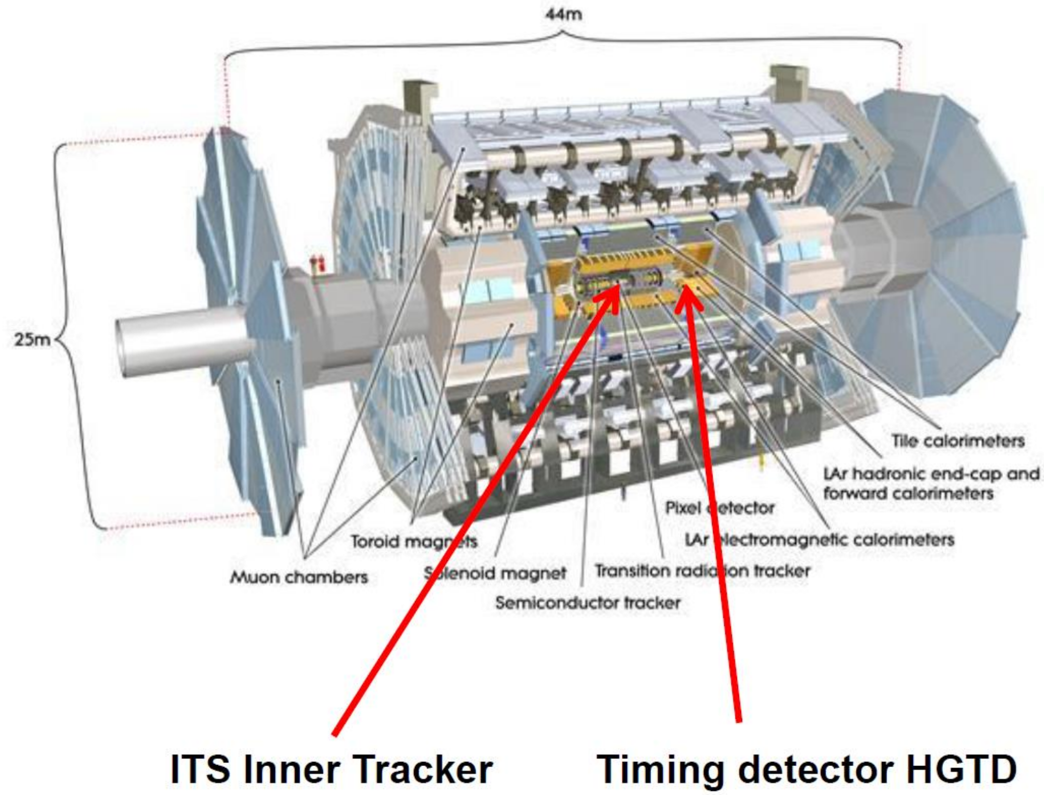
ATLAS Upgrade

Approved and funded

ATLAS @ LHC
(data taking from 2026)

- "Phase II" upgrade for high luminosity LHC, including
- ITK Inner Tracker
  - $|\eta| < 2.7 \rightarrow |\eta| < 4$
- Timing detector HGTD
  - $2.5 < |\eta| < 5$
- Forward calorimeter: granularity
- Trigger and DAQ

- Triggered data-taking in 2021-29
  - 10 nb^{-1} triggered events
- Focus on HF, jets and Υ



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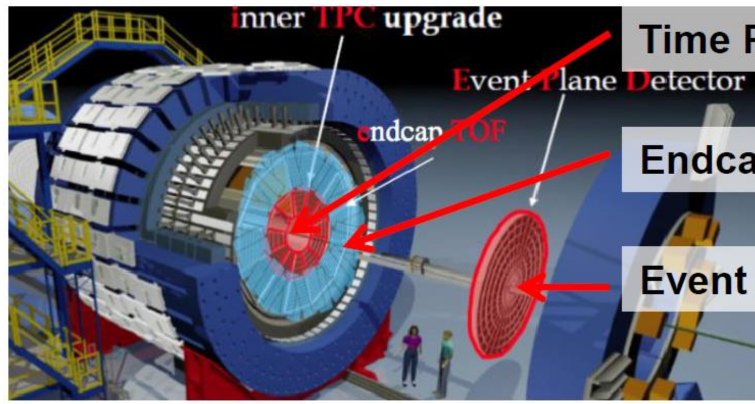
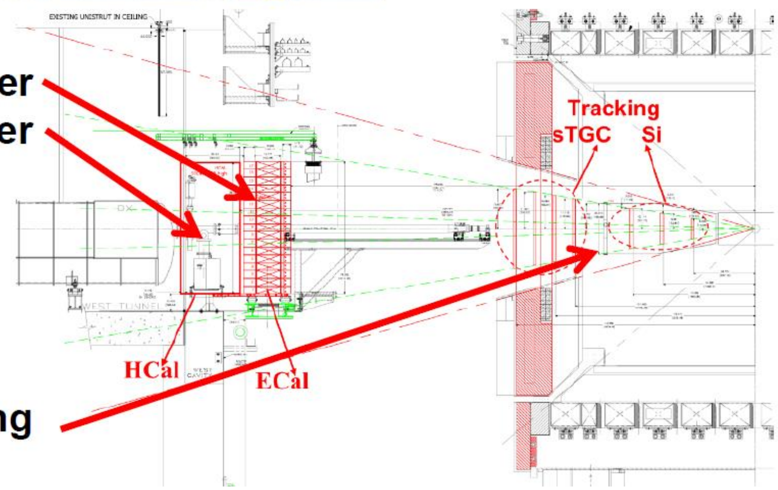
STAR Upgrade

STAR @ RHIC
(data taking from 2019 and from 2022)

- Upgrades for BES-II (2019)
  Approved and funded
  - Extend TPC to $|\eta| < 1.5$
  - TOF to $\eta = -1.6$ (one side)
  - Event plane detectors (already installed)
- Forward upgrade (2022)
  $-4.6 < \eta < -2.5$ **Proposed + R&D**
  - Tracking (Si & sTGC)
  - Calorimeters (EMCal + HCal)
- Data taking
  - 1.4 kHz rate (including TPC)
  - 4 billion Au-Au events / year
- Focus on PID, polarized p beams and forward physics





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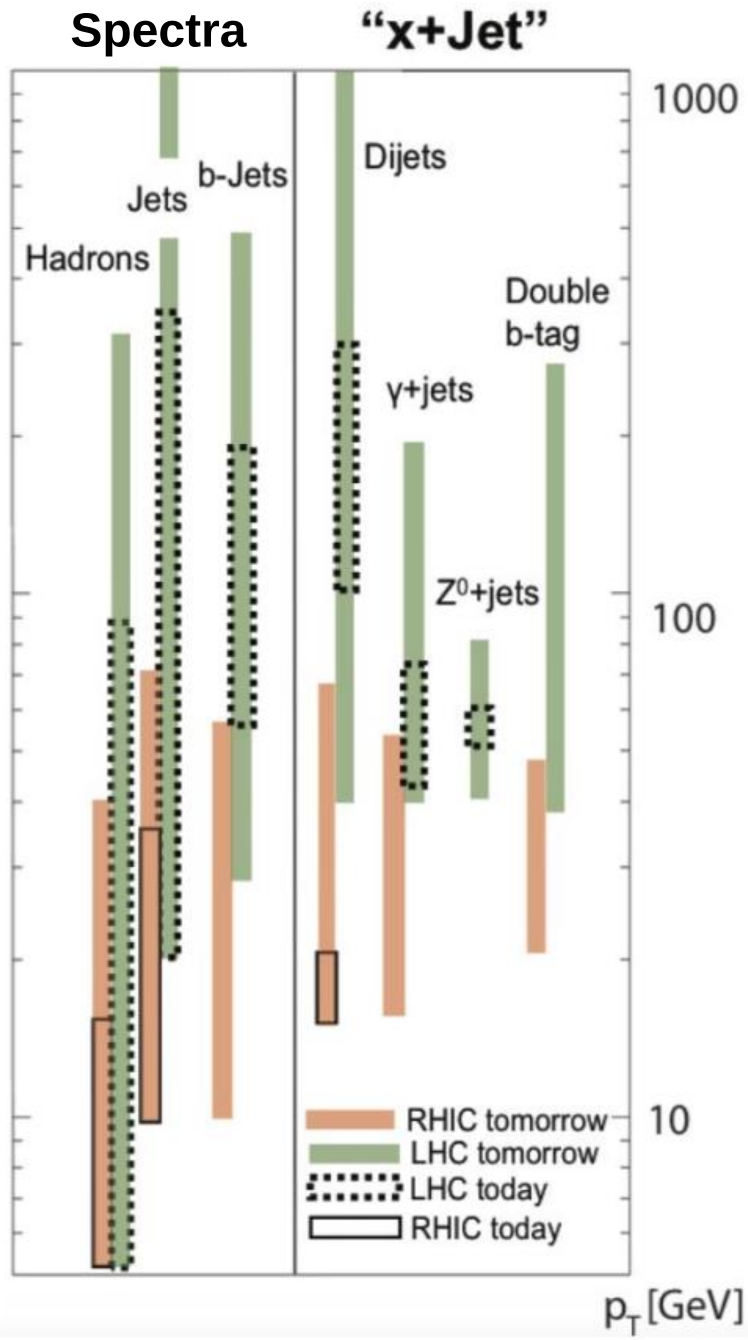
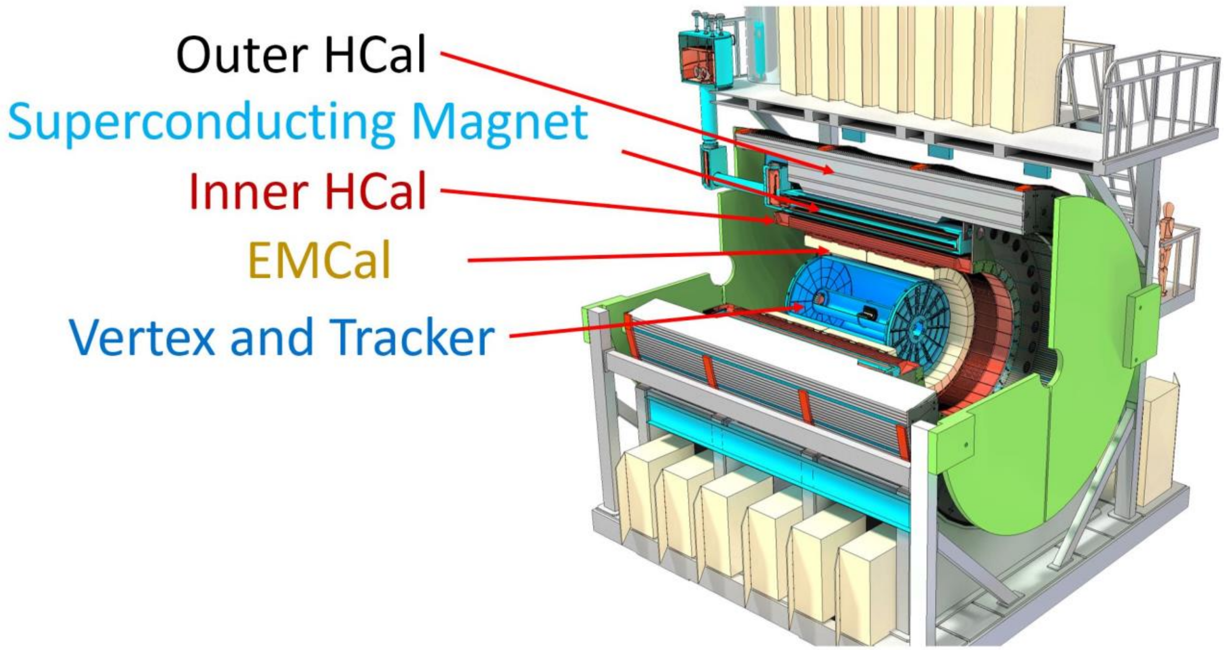
sPHENIX Physics at RHIC

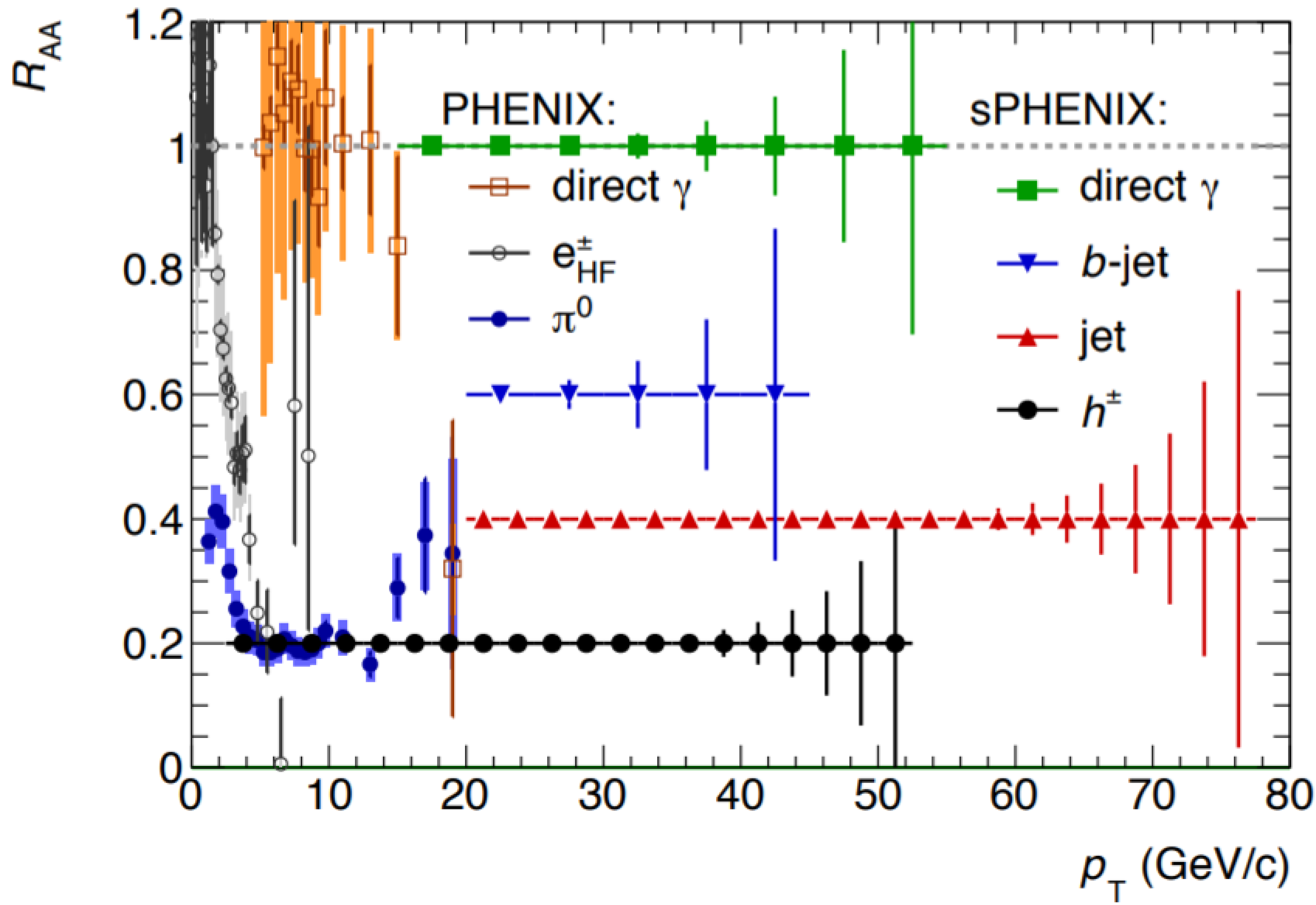


- Jetting through lower temperature Quark Soup from Gold+Gold collisions at 200 GeV
- Direct comparison with LHC data!

sPHENIX detector

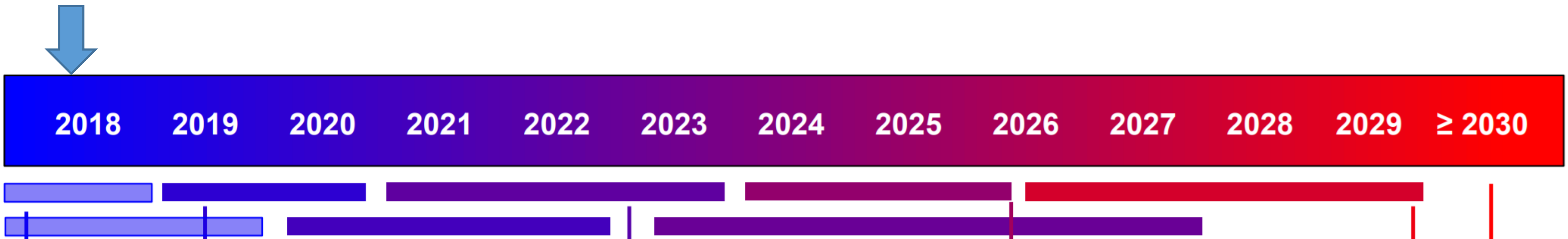


sPHENIX performance



Timeline

We are here



LHC run 2
RHIC run

sPHENIX const.
STAR upgrades

RHIC run
sPHENIX
- **10^{11} events read out**
- **Sampled 50 nb^{-1}**

STAR
- **10^{9} events read out**

Upgrades "LHC LS3"
ATLAS:
- **Tracker (acc x2)**
- **Timing**

CMS:
- **Tracker (acc x2)**
- **Encap Calorimeter**

LHCb:
- **TOF?**

Run5 and 6?
HE-LHC(?)
PbPb at 11 TeV
FCC (?)
PbPb at 39 TeV

Upgrades "LHC LS2"
- **LHC: collimators + injectors**
- **ALICE: Tracking, DAQ (rate x100)**
- **ATLAS: Fast tracker trigger (rate x2)**
- **CMS: pixel detector (rate x2)**
- **LHCb: VELO, tracker, DAQ (rate x10)**

LHC Run 3 + 4 (numbers for Pb-Pb)
- **$L = 6 \cdot 10^{27}\ cm^{-2}s^{-1}$ ~ 50 kHz rate**
- **10 nb^{-1} (ALICE, CMS, ATLAS)**

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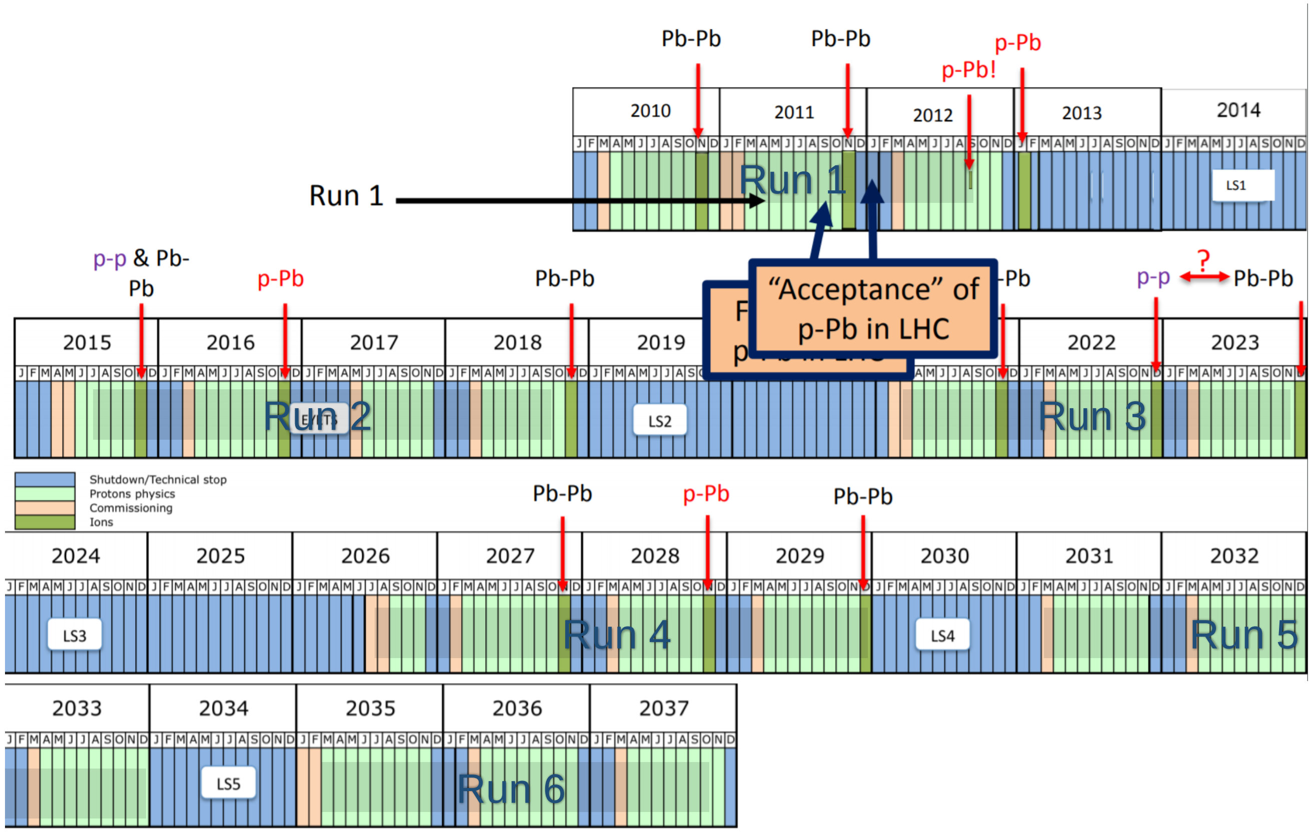
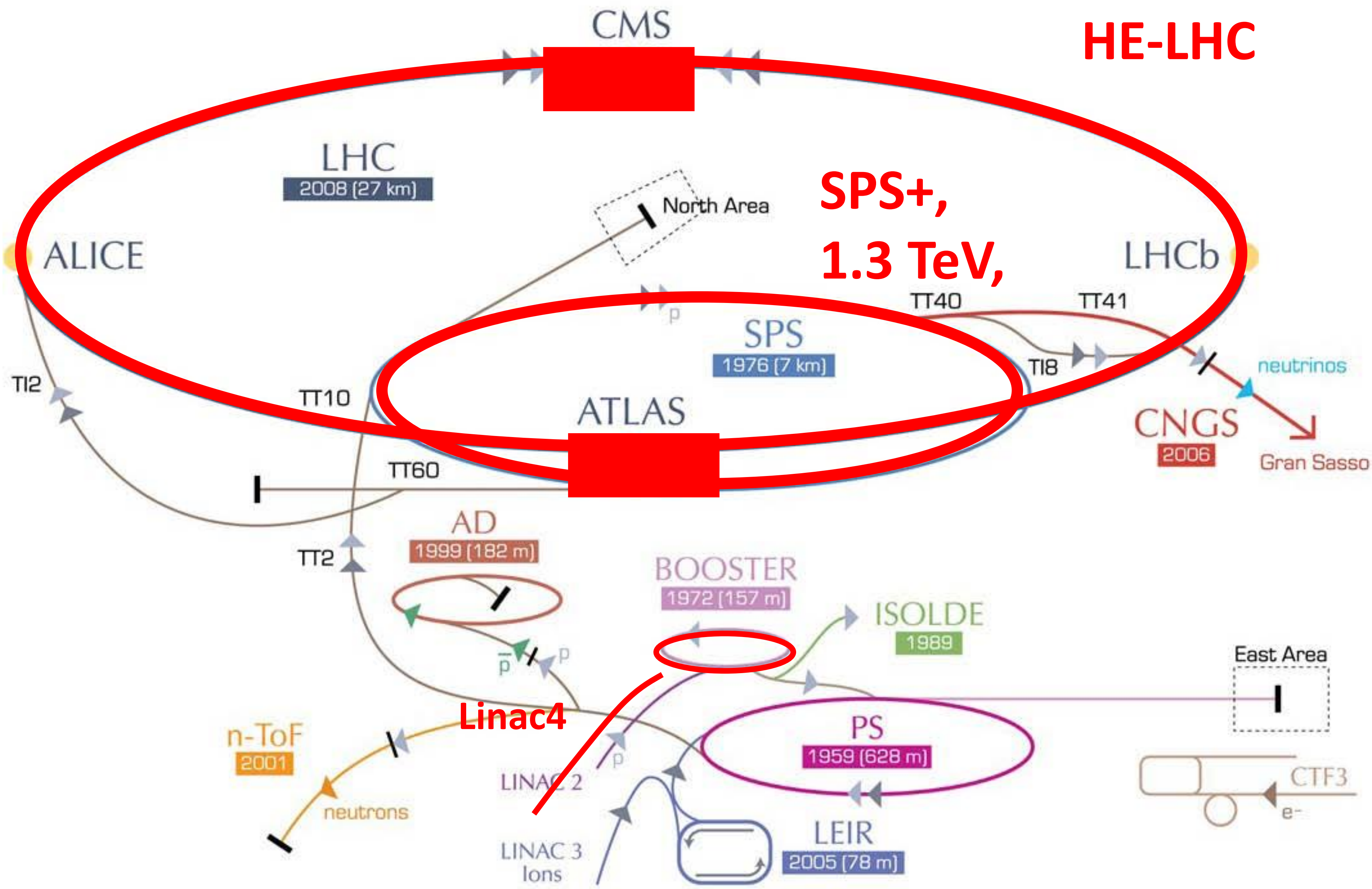
HL-LHC for Heavy Ion

- HL-LHC for HI: HL-LHC for HI will start in Run 3!
  - Yellow chapter on HI should include Run 3 and Run 4
  - Current *tentative* schedule based on ALICE Upgrade 2012 LOI
  - We need to come out with good physics plan to motivate HI in Run 5

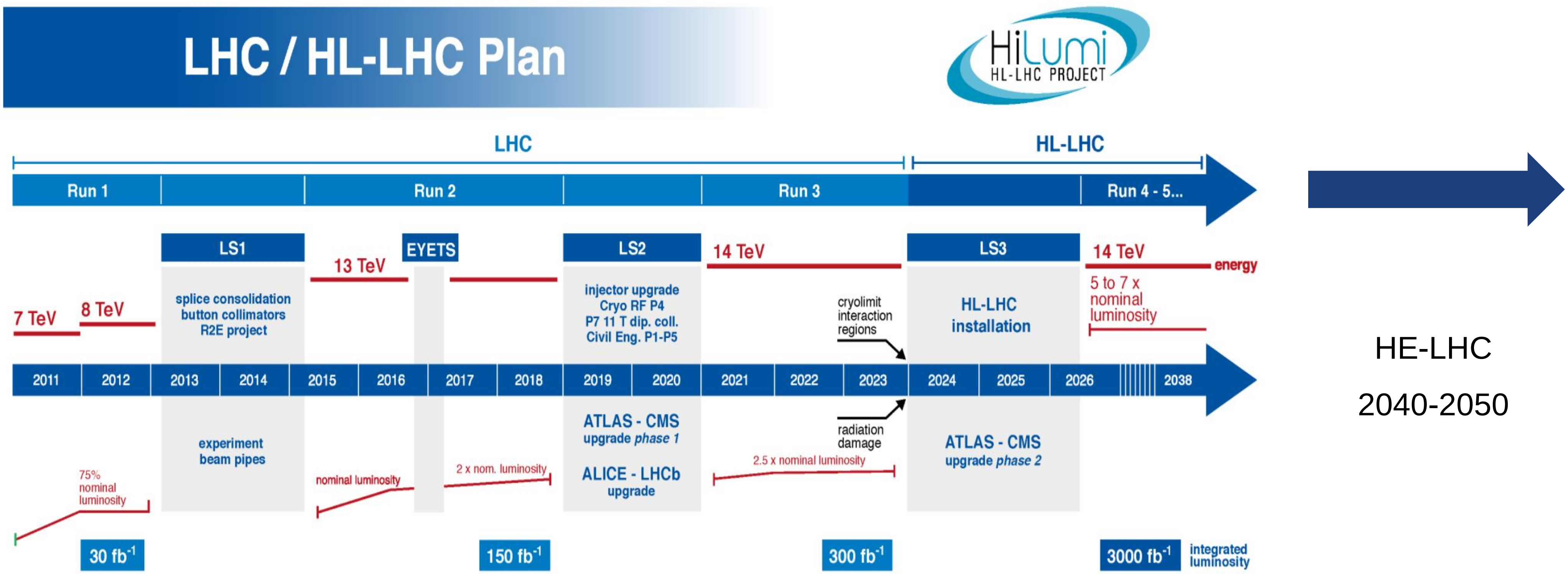


HE-LHC – *LHC modifications*



HE-LHC for Heavy Ion

- HE-LHC: With CM energy in the range of ~28 TeV (for pp) and ~11 TeV (simple minded calculation for PbPb)
  - "*Expect* to have a HI program", deliver physics beam from 2050
  - Discussion with John Jewett: could try to have first rough estimation of possible lumi and energy at HE-LHC for kick-off meeting



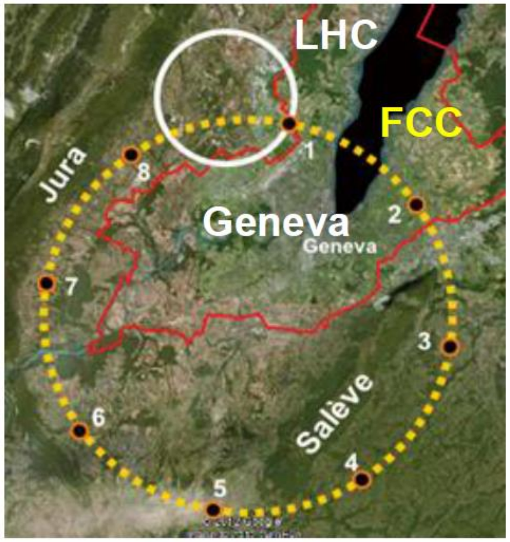
Future collider

Future Collider Projects
(2040-50)

- 100 km circumference
  - $\sqrt{s_{NN}}$ = 39 TeV (Pb-Pb) | 63 TeV (p-Pb) | 100 TeV (pp)

Pb-Pb

$dN_{ch}/d\eta$	3600
V	11000 fm^3
ε (τ = 1 fm/c)	35-40 GeV/fm^3



- Future Circular Collider @ CERN
  - 35-110 nb^{-1} per month (12-40x LHC)
  - Conceptual Design Report by fall 2018
- SPPC in China
  - Combined with e^+e^- machine
  - Funding for R&D available

Manqi Ruan, Hard Probes 2016

CEPC-SPPC: Circular Electron Positron Collider – Super Proton-Proton Collider

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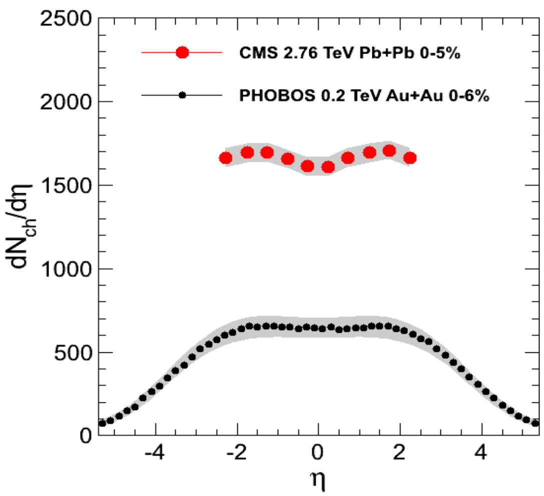
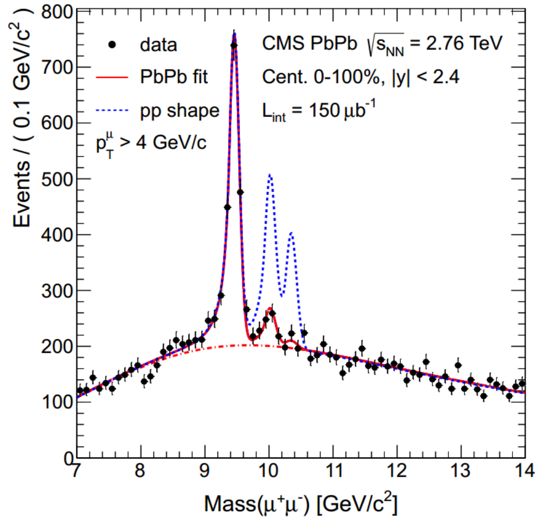
Parameters from LHC to FCC

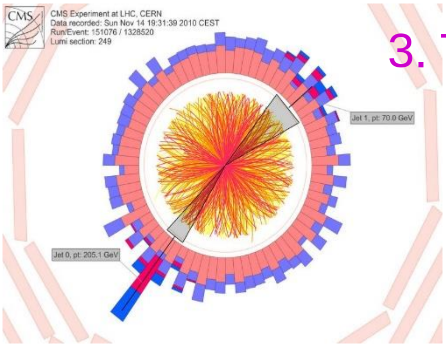
Table 1: Key parameters of LHC, HL-LHC, HE-LHC (tentative), and FCC-hh.

parameter	FCC-hh	HE-LHC	HL-LHC	LHC (pp)
centre-of-mass energy [TeV]	100	25	14	14
injection energy [TeV]	3.3 (1.5?)	0.45	0.45	0.45
ring circumference [km]	100	26.7	26.7	26.7
arc dipole field [T]	16	16	8.33	8.33
number of IPs	2+2	2+2	2+2	2+2
initial bunch population $N_{b,0}$ [10^{11}]	1.0 (0.2)	2.5 (0.5)	2.2	1.15
number of bunches per beam n_b	10600 (53000)	2808 (14040)	2748	2808
beam current [A]	0.5	1.29	1.11	0.58
initial (peak) luminosity/IP [10^{34} cm^{-1}s^{-1}]	5–30	5–34	5 (levelled)	1
max. no. of events per bunch crossing	170–1020 (204)	1070 (214)	135	27
stored energy per beam [GJ]	8.4	1.4	0.7	≈0.4
arc synchrotron radiation [W/m/aperture]	28.4	4.1	0.33	0.17

Summary: Quark Gluon Plasma



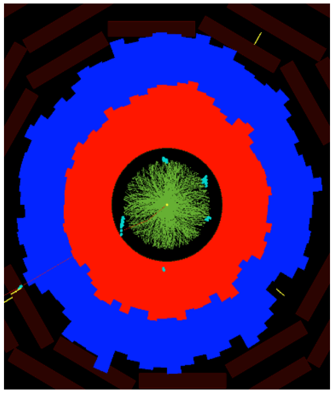




3. The stopping power is very strong O(10GeV/fm)

1. >10x denser than the proton or nuclei

2. 1 Trillion Degree!!!
= 1 million million
(1,000,000,000,000 °C)



4. It flows like perfect fluid!

Signal in pPb collisions?

0°C

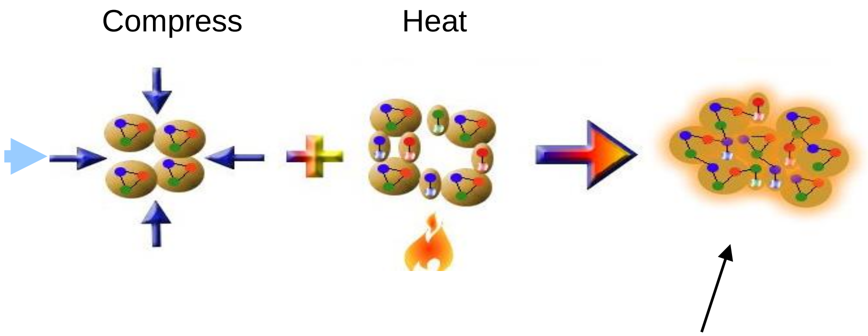
Ice

10°C

Water

>100°C

Steam

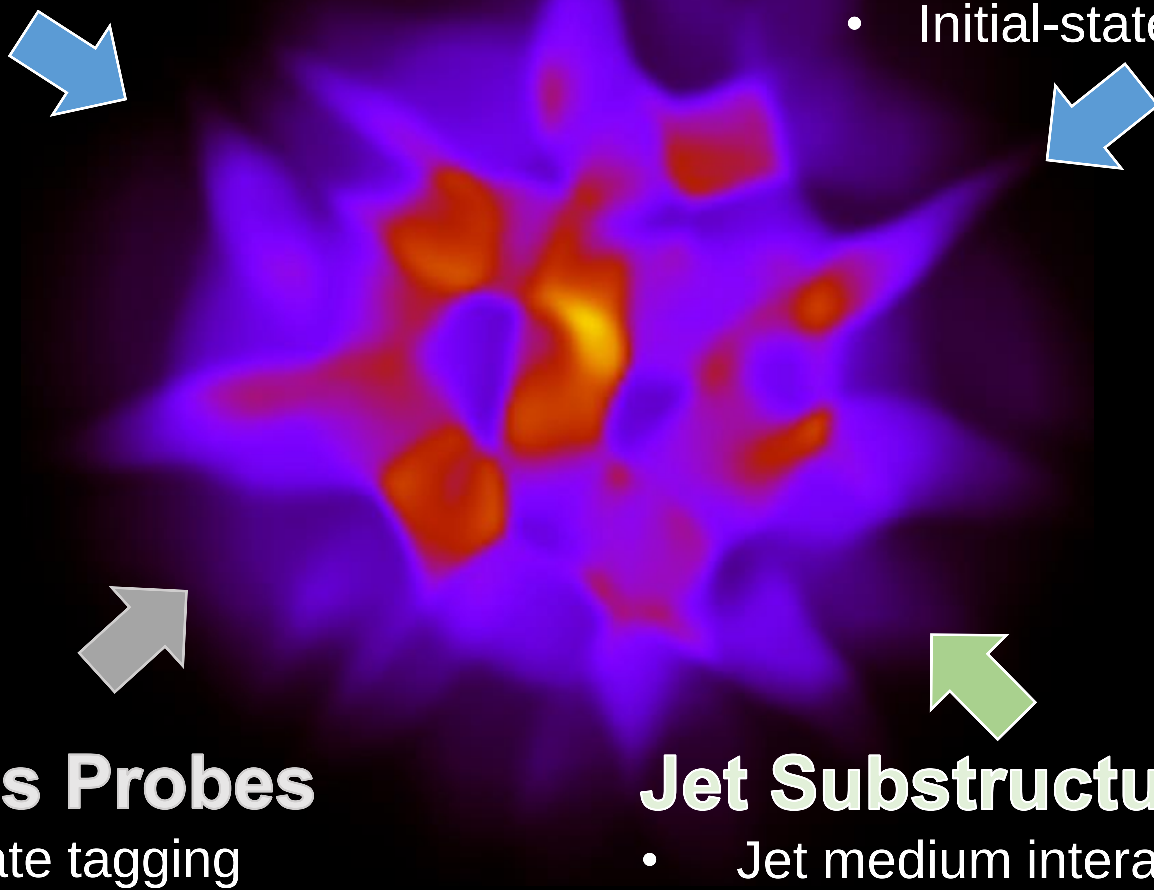


Quark Gluon Plasma

Jetting through the Quark Soup

Particle Multiplicity
- Collision impact parameter
- Energy density

Azimuthal Anisotropy
- Early hydrodynamization <1 fm/c
- Shear viscosity
- Initial-state geometry fluctuation



Colorless Probes
- Initial state tagging
- Parton distributions
- Number of hard scatterings

Jet Substructure and Hadrons
- Jet medium interaction
- Medium gluon density, structure
- Medium scattering power, mean free path, temperature …

Backup slides