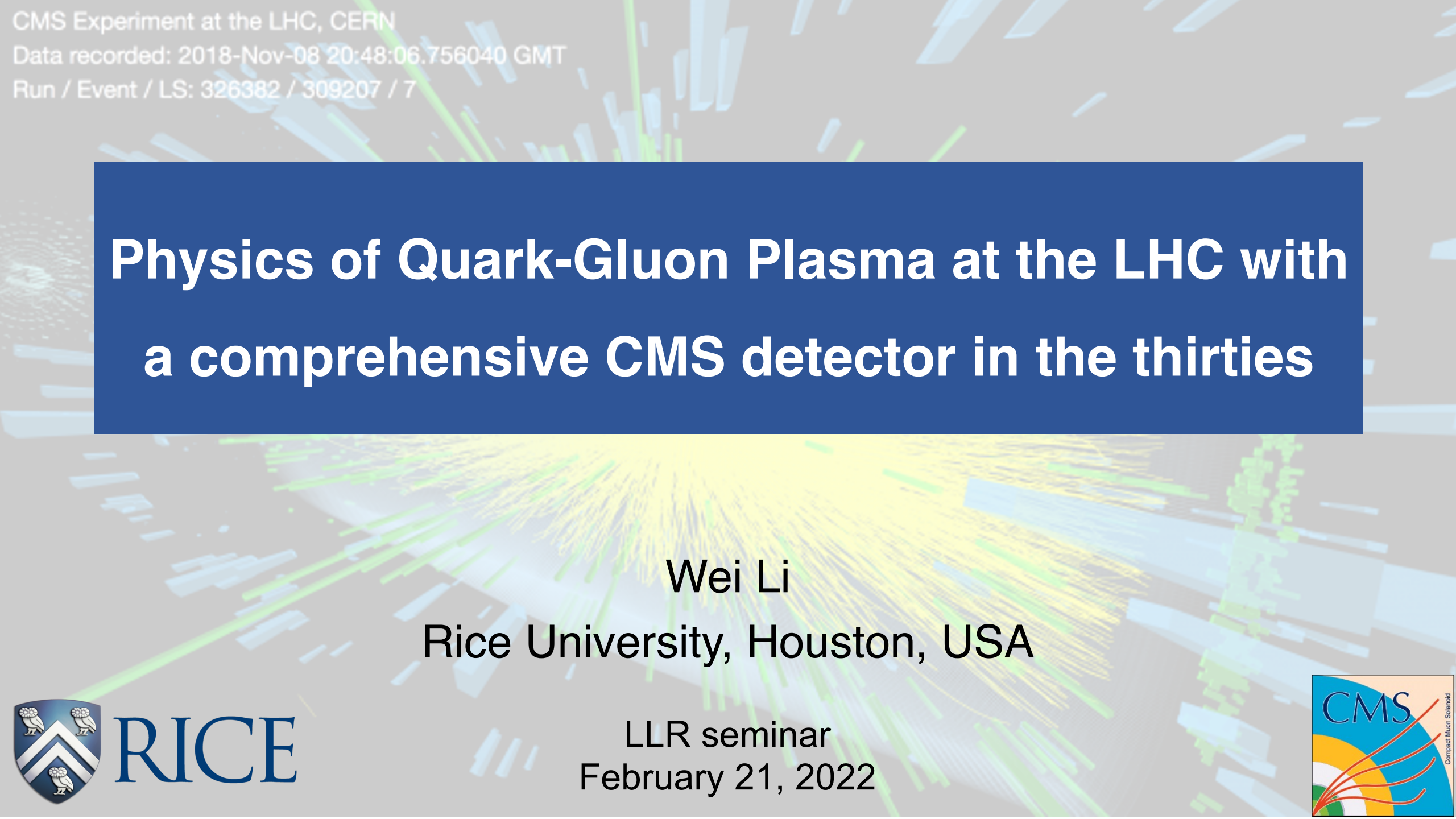


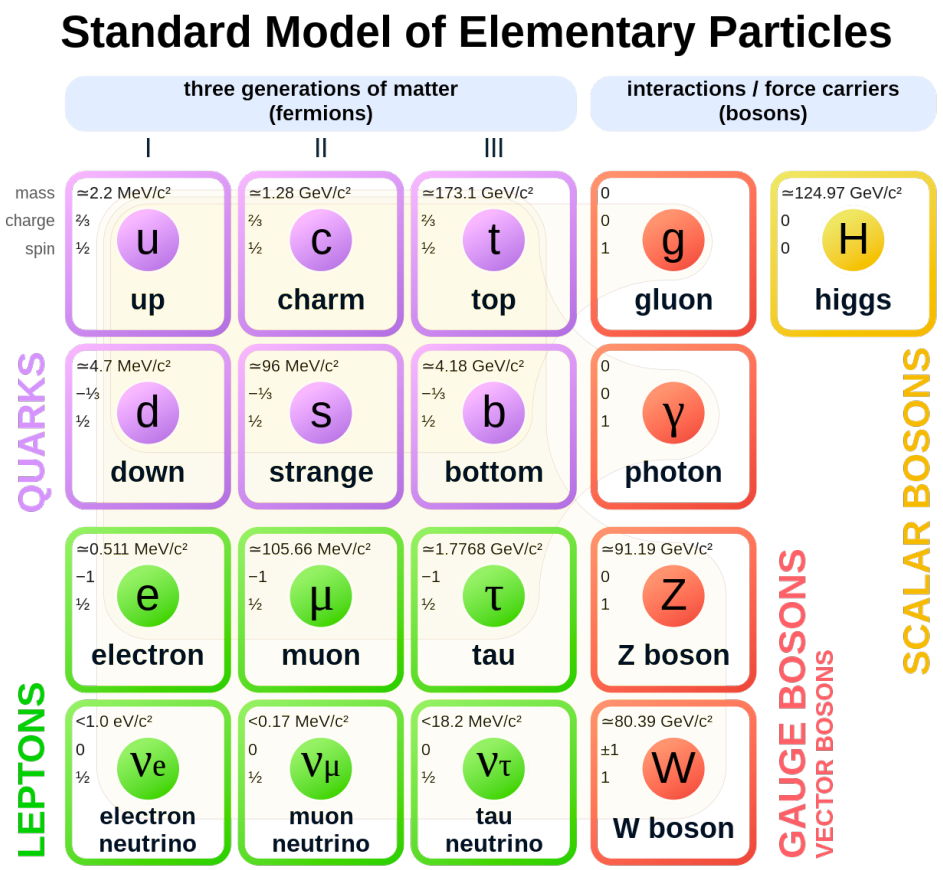
Physics of Quark-Gluon Plasma at the LHC with a comprehensive CMS detector in the thirties

Wei Li
Rice University, Houston, USA

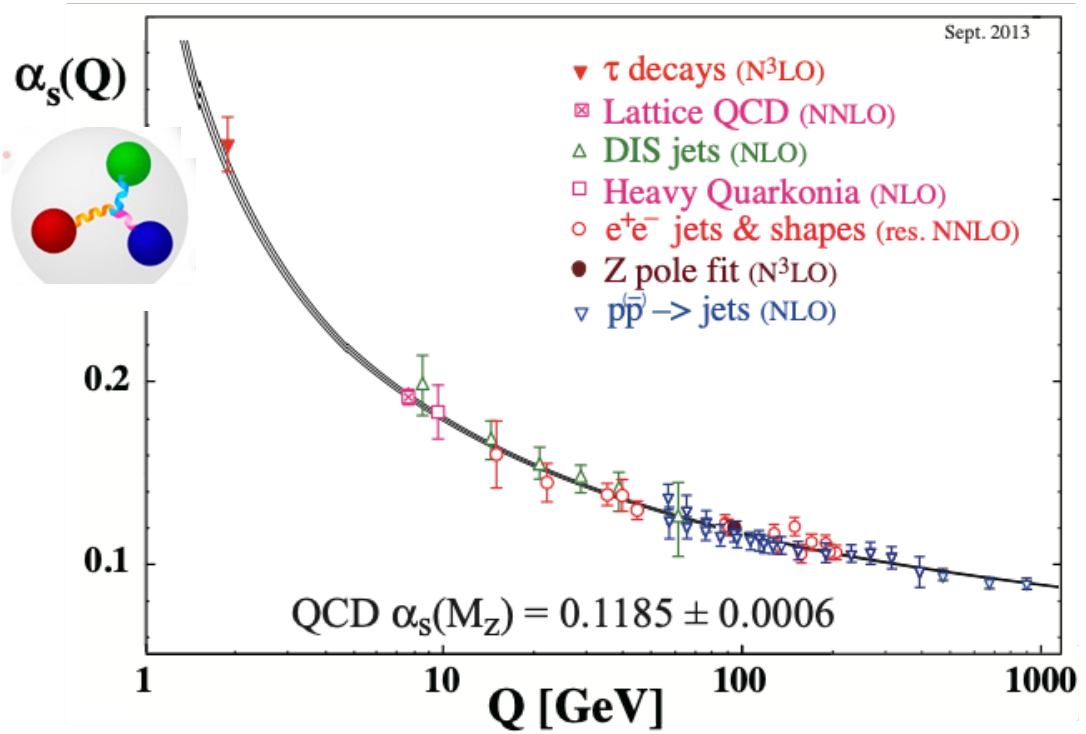
LLR seminar
February 21, 2022

Rice University, Houston, TX

The Standard Model and QCD



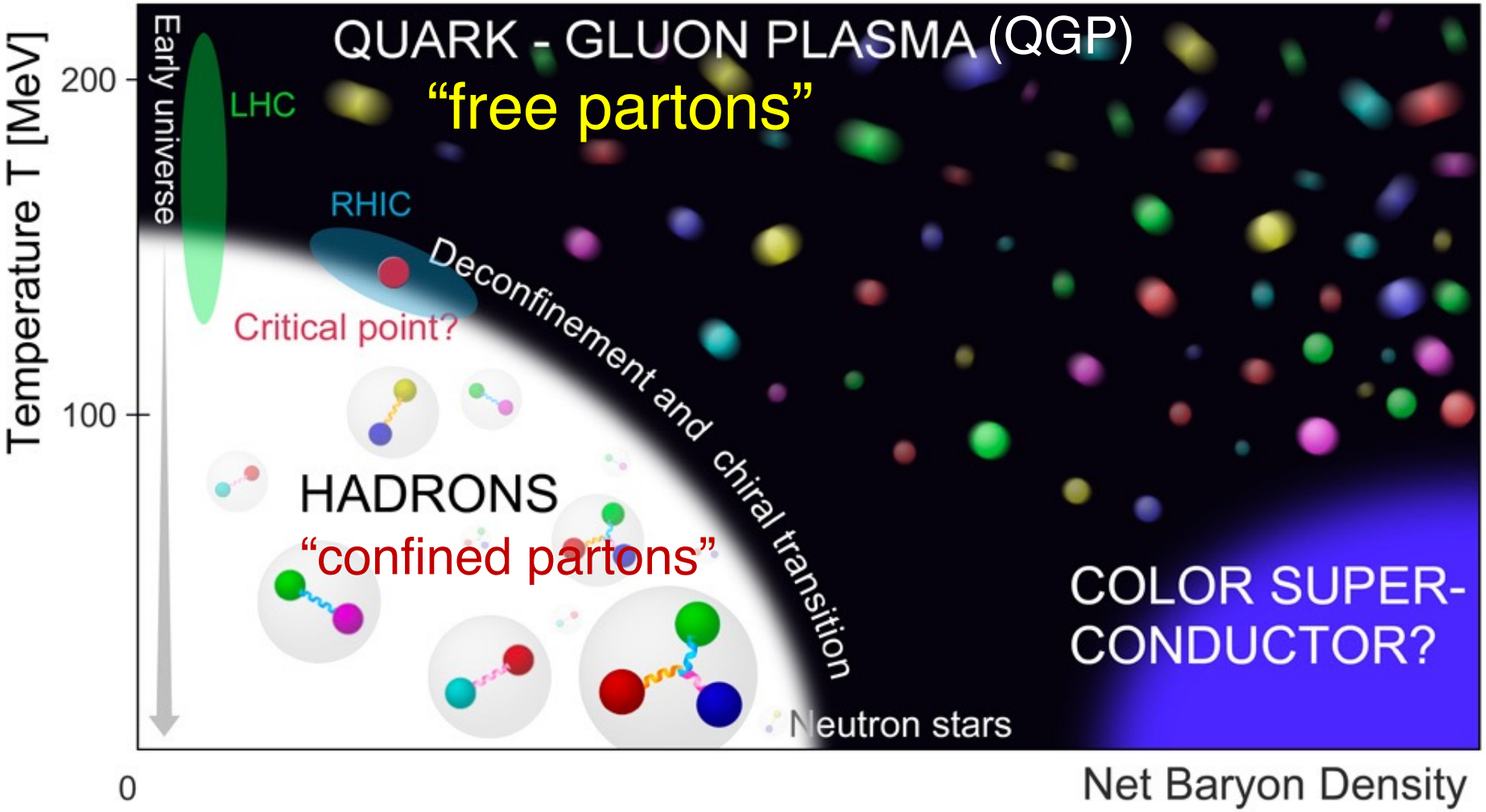
Quantum Chromodynamics (QCD)



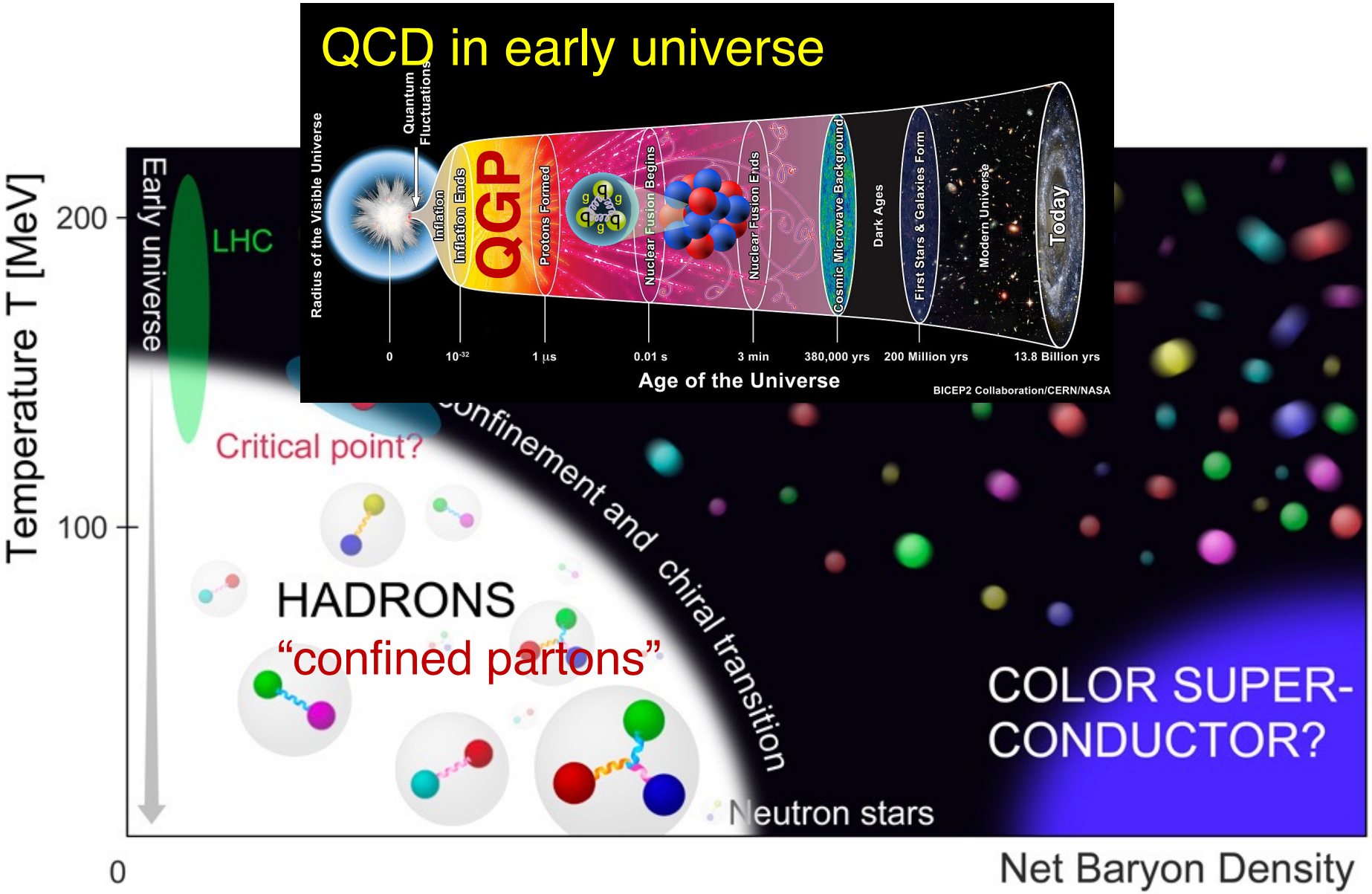
(QCD became the Physics 101…)

Scale-dependent behaviors

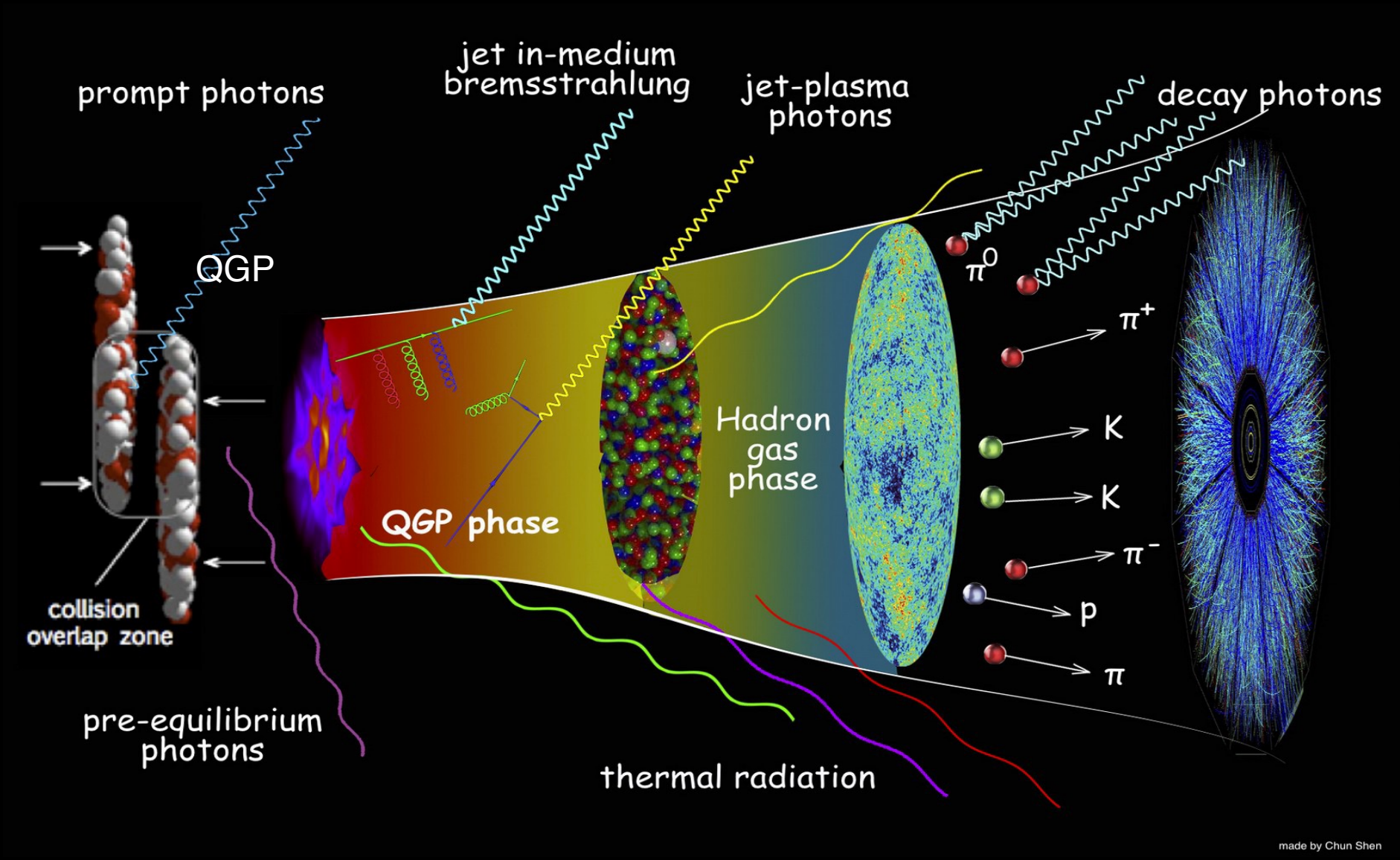
Emergence and phases of QCD matter



Emergence and phases of QCD matter

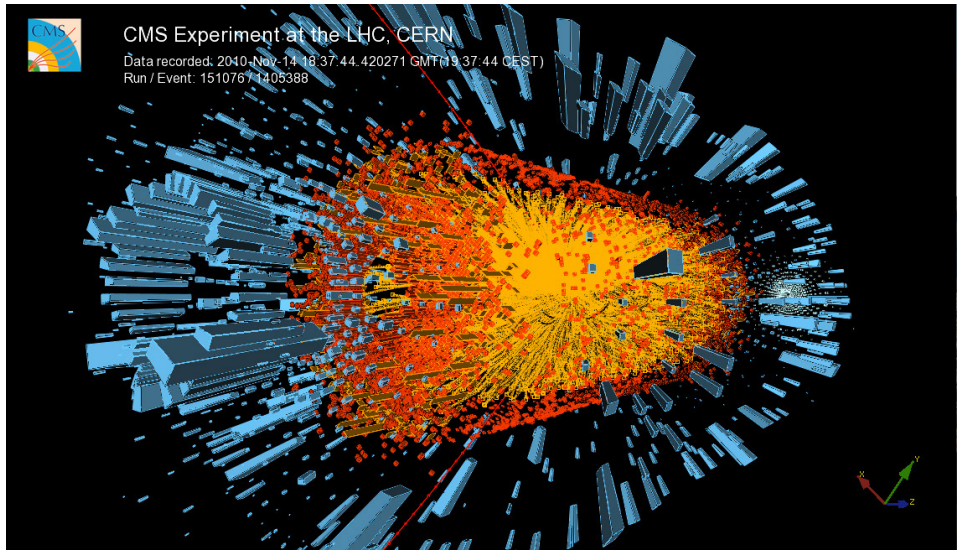


“Little Bangs” in the laboratory

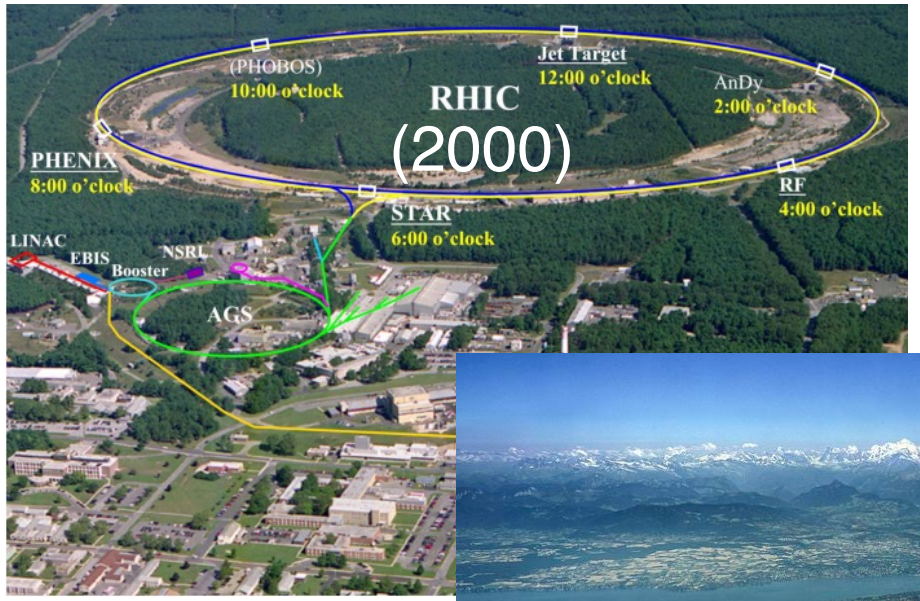


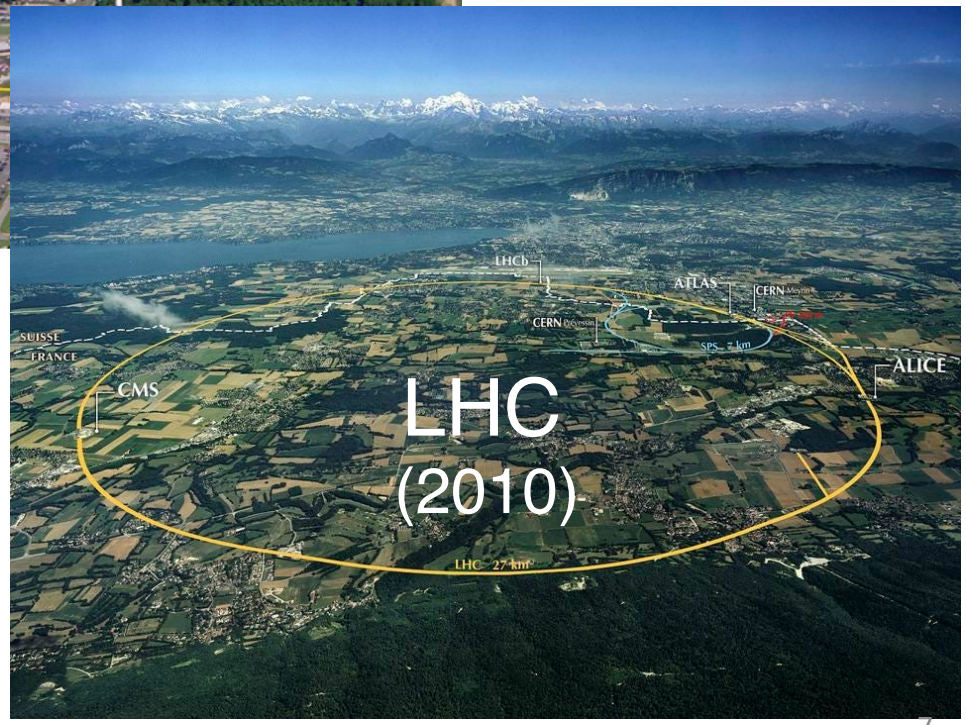
“Little Bangs” in the laboratory

Heavy Ion Collisions



Most violent collisions

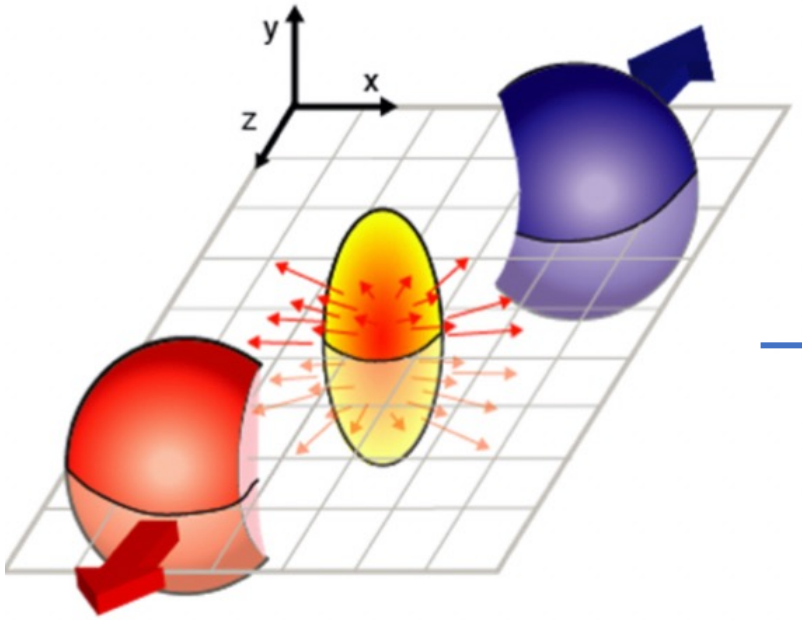




Re-creating the Little Bangs!

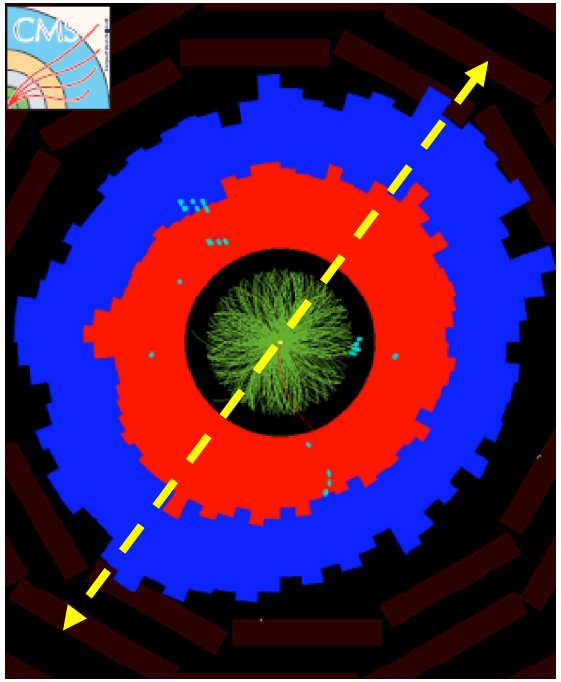
Discovery of a “perfect” QGP liquid

Initial State Geometry:



Pressure-driven expansion

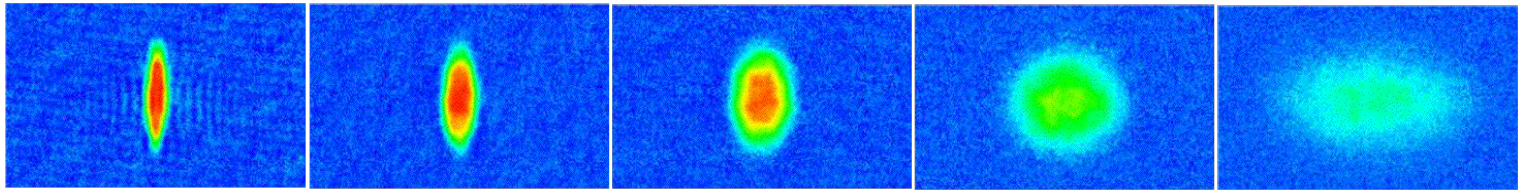
Final State Anisotropy:



“Elliptic flow”

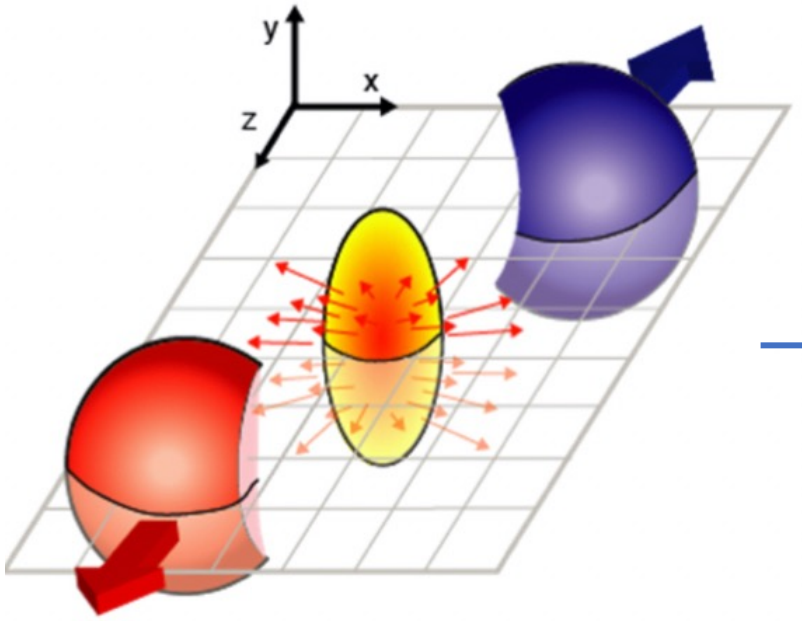
^{6}Li gas T=10^{-7}K

Time



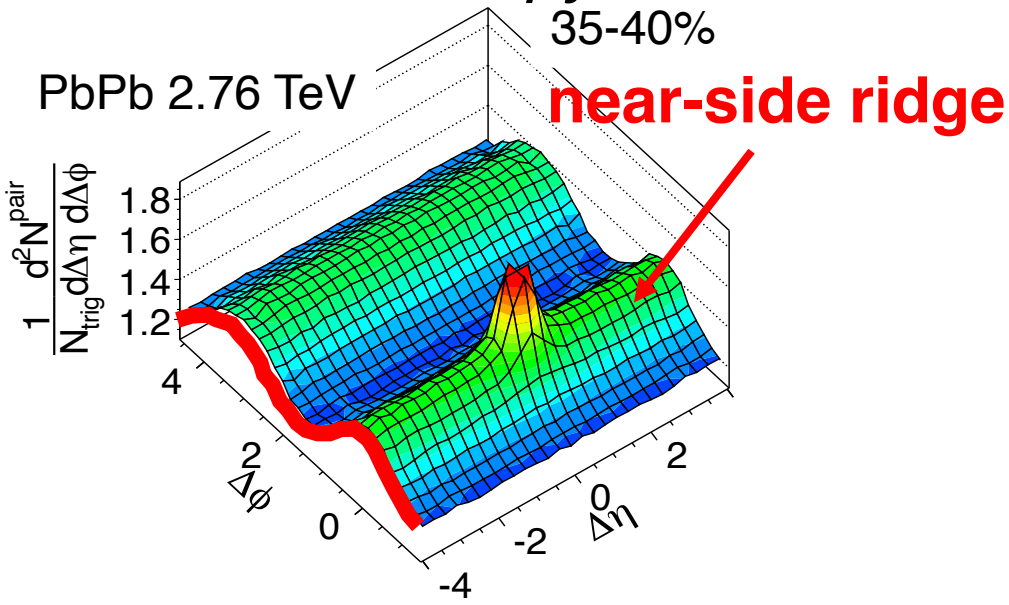
Discovery of a "perfect" QGP liquid

Initial State Geometry:



Pressure-driven expansion

Final State Anisotropy:

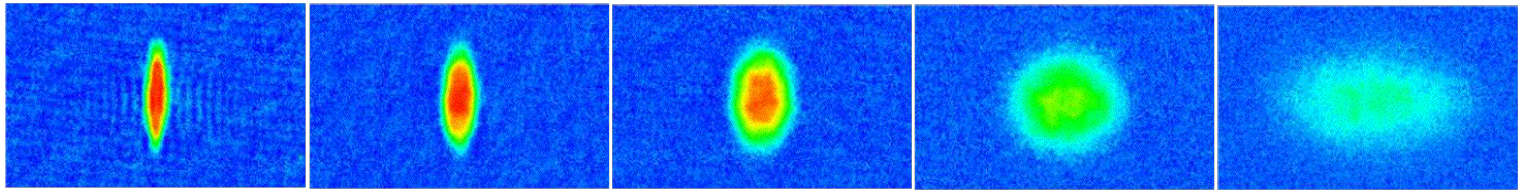


$$\frac{dN^{pairs}}{d\Delta\phi} = \frac{N^{pairs}}{2\pi}\left(1 + \sum_n 2v_n^2 \cos(n\Delta\phi)\right)$$

"Elliptic flow"

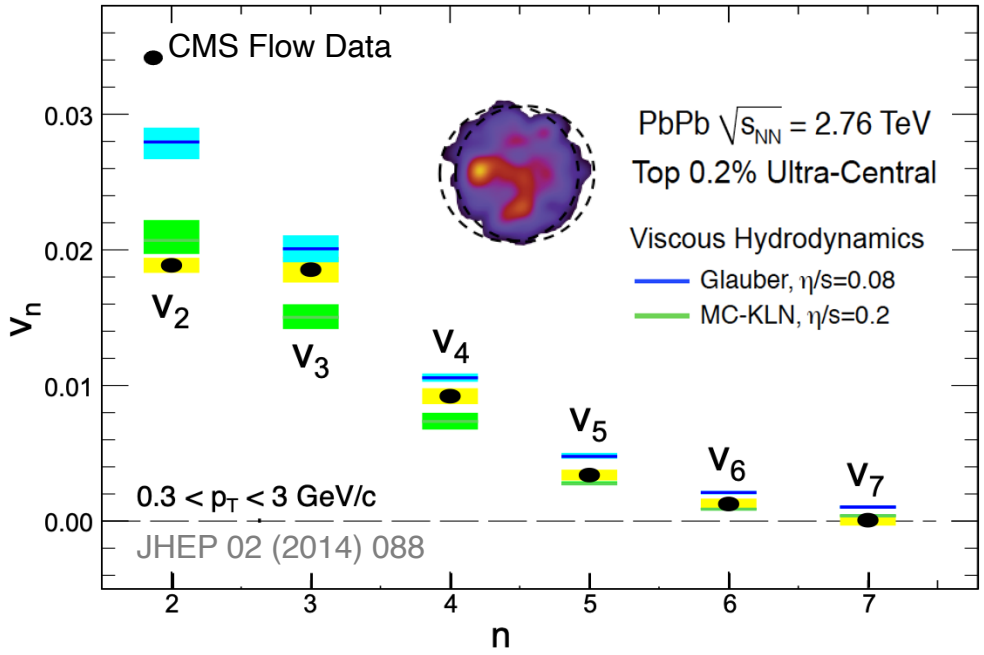
^{6}Li gas T=10^{-7}K

Time ⟶

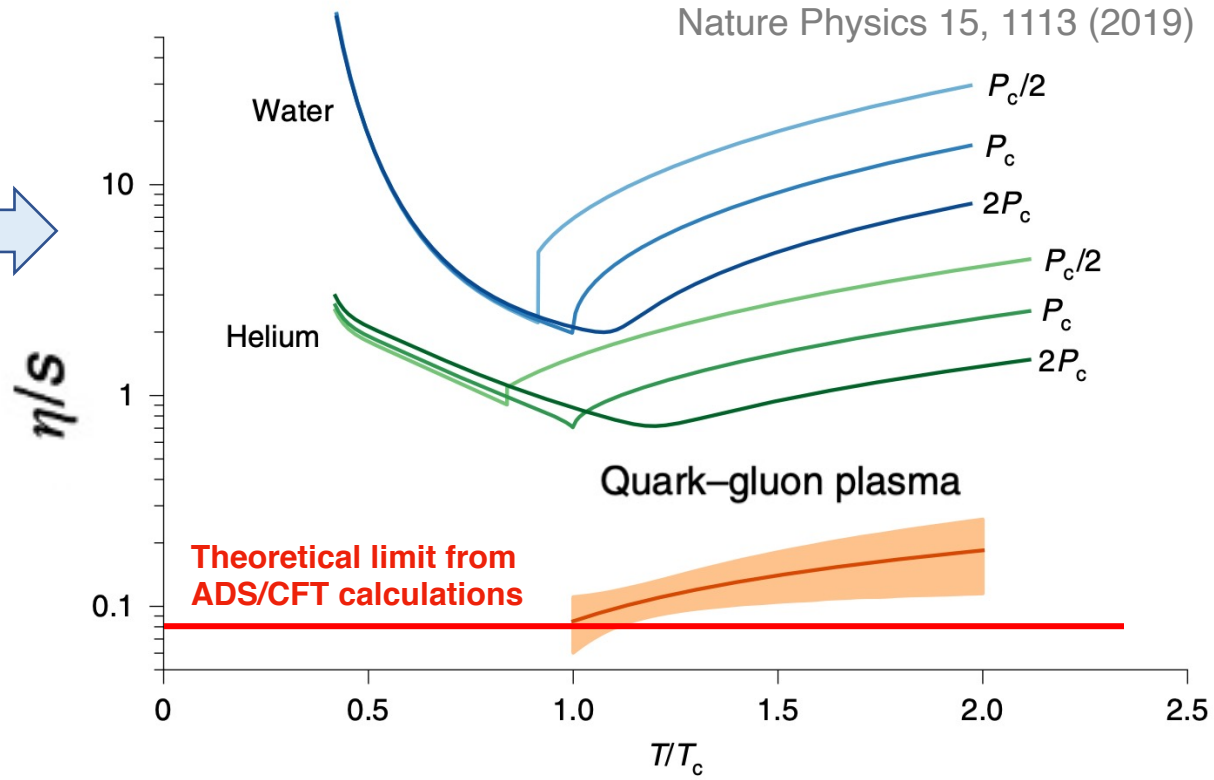


Discovery of a “perfect” QGP liquid

Elliptic (v_2) and high-order (v_n) flow described by viscous hydro.



Shear viscosity to entropy density

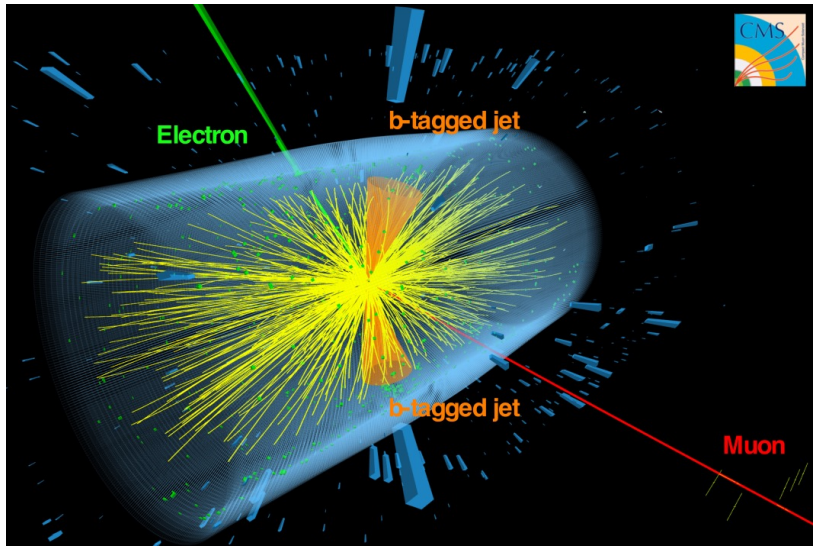


QGP is *strongly coupled*, which flows with little momentum dissipation (near theoretical limit), and it is *opaque* to energetic color probes.

“Little Bangs”

2000: RHIC

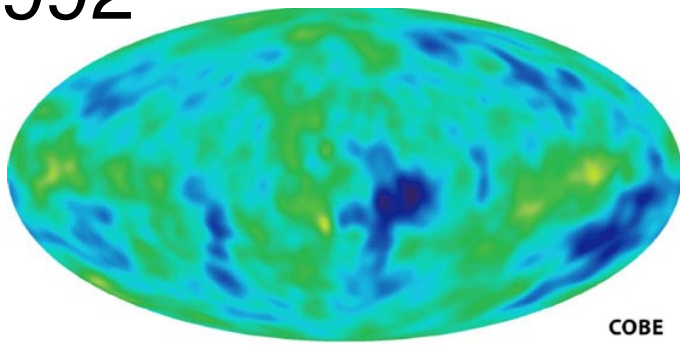
2009: LHC **Precision era**



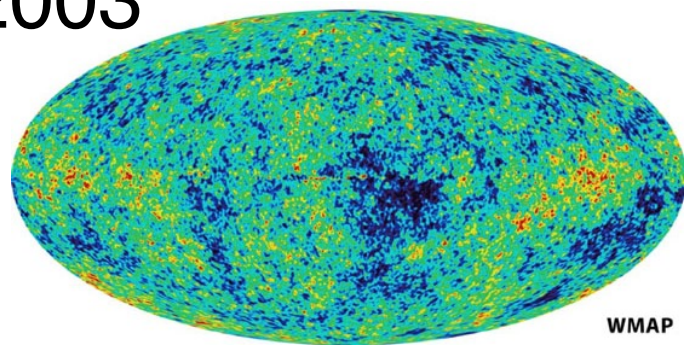
t

The Big Bang

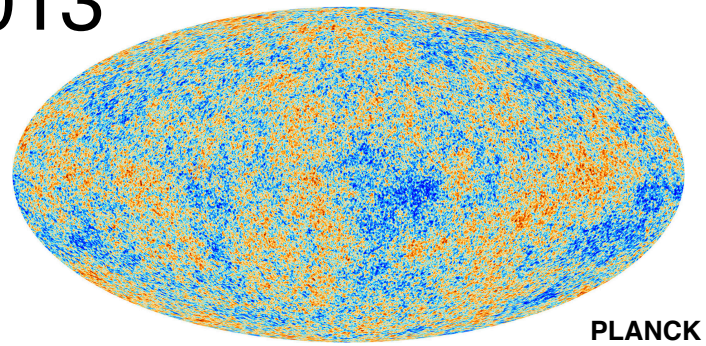
1992



2003



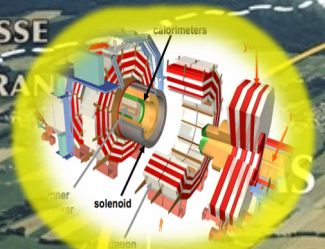
2013



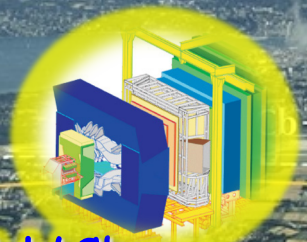
Heavy Ion Program at Large Hadron Collider, CERN

Topic today

PbPb 5 TeV

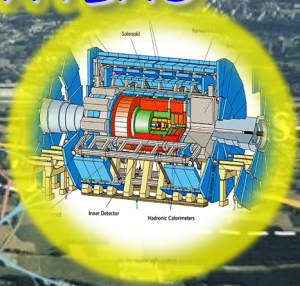


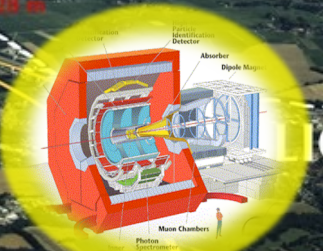
CMS



LHCb

ATLAS





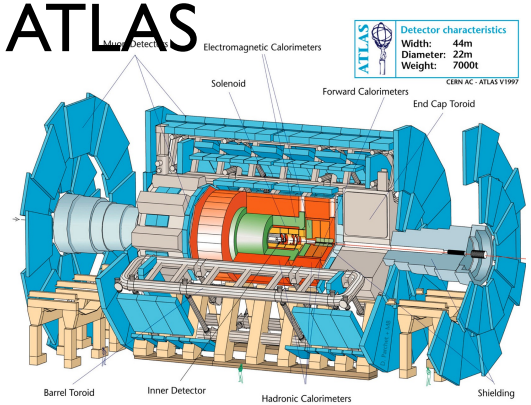
ALICE

All experiments are participating in the heavy ion program with amazing results

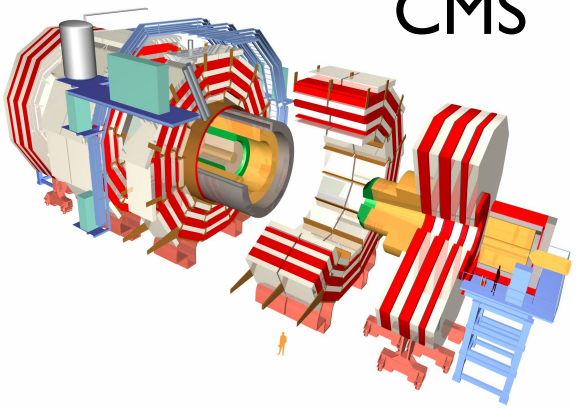
QGP detectors at the LHC (present)

Wide coverage tracking (|η|<2.4) and full calorimetry (|η|<5)

ATLAS



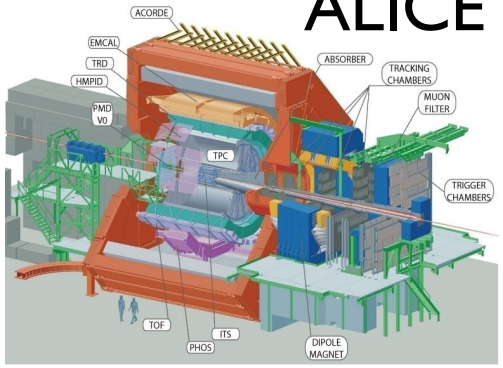
CMS



Excellent hadron PID over wide p_T coverage

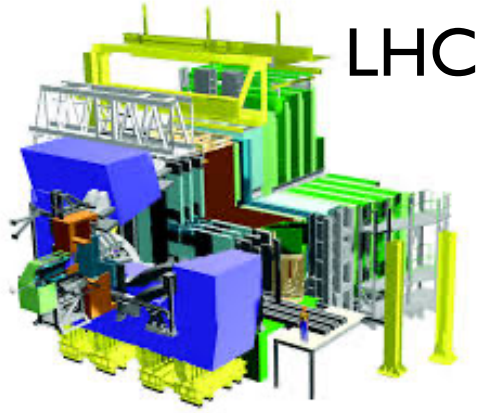
Mid-rapidity

ALICE



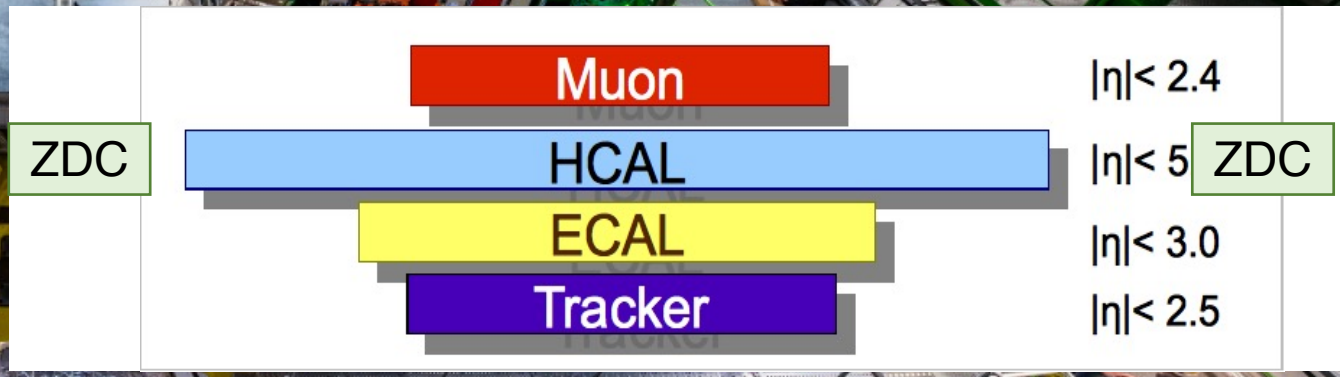
Forward rapidity

LHCb



Excellent complementarities but no one detector for all

CMS experiment at the LHC

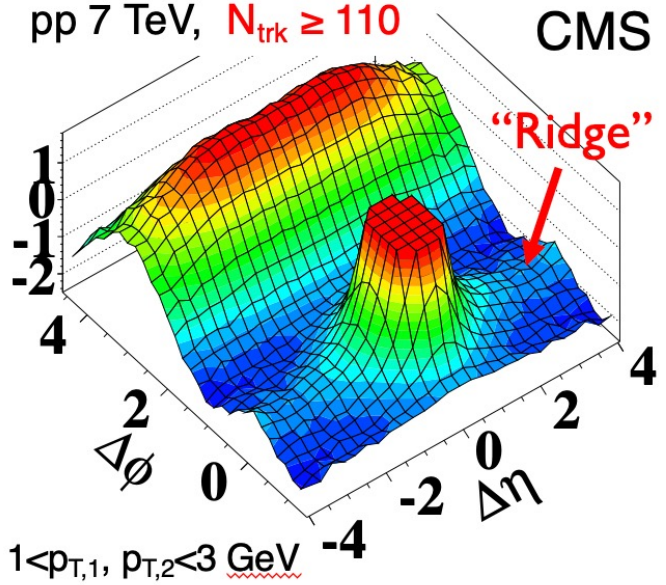


Wide-coverage Tracking	Precision vertex	Full calorimetry (ECAL+HCAL)	High rate/HLT	Lepton PID	Hadron PID
✓	✓	✓	✓	✓	x

Seminal results from CMS

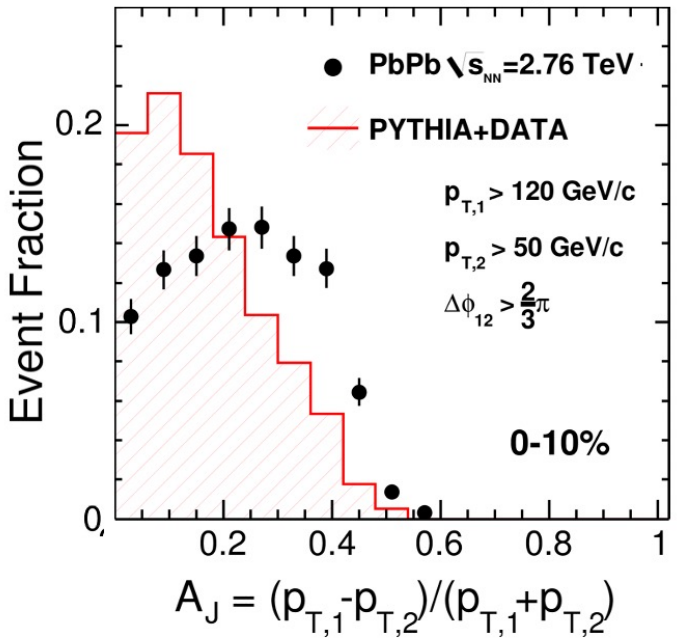
Tiniest QGP droplet

JHEP 09 (2010) 091



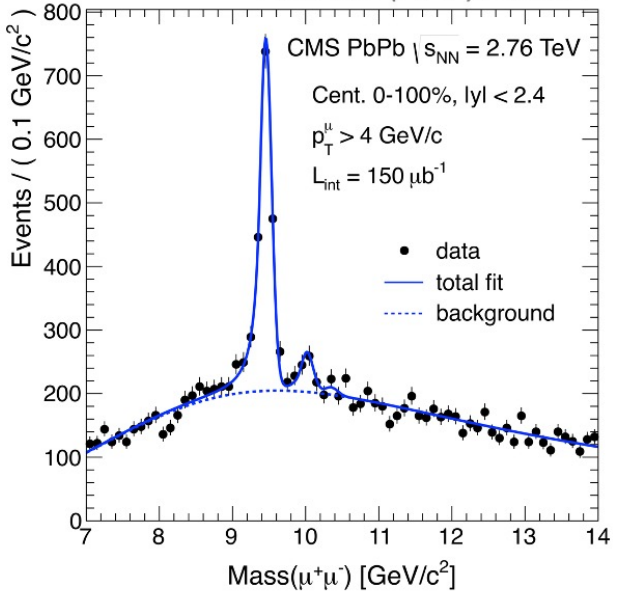
Quenching of full jets

PRC 84 (2011) 024906



QGP thermometer

PRL 109 (2012) 222301

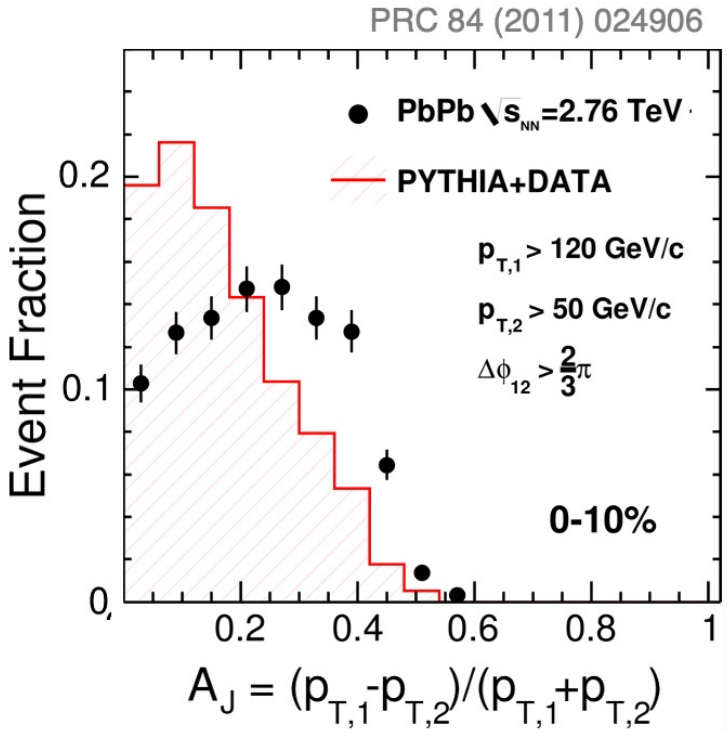


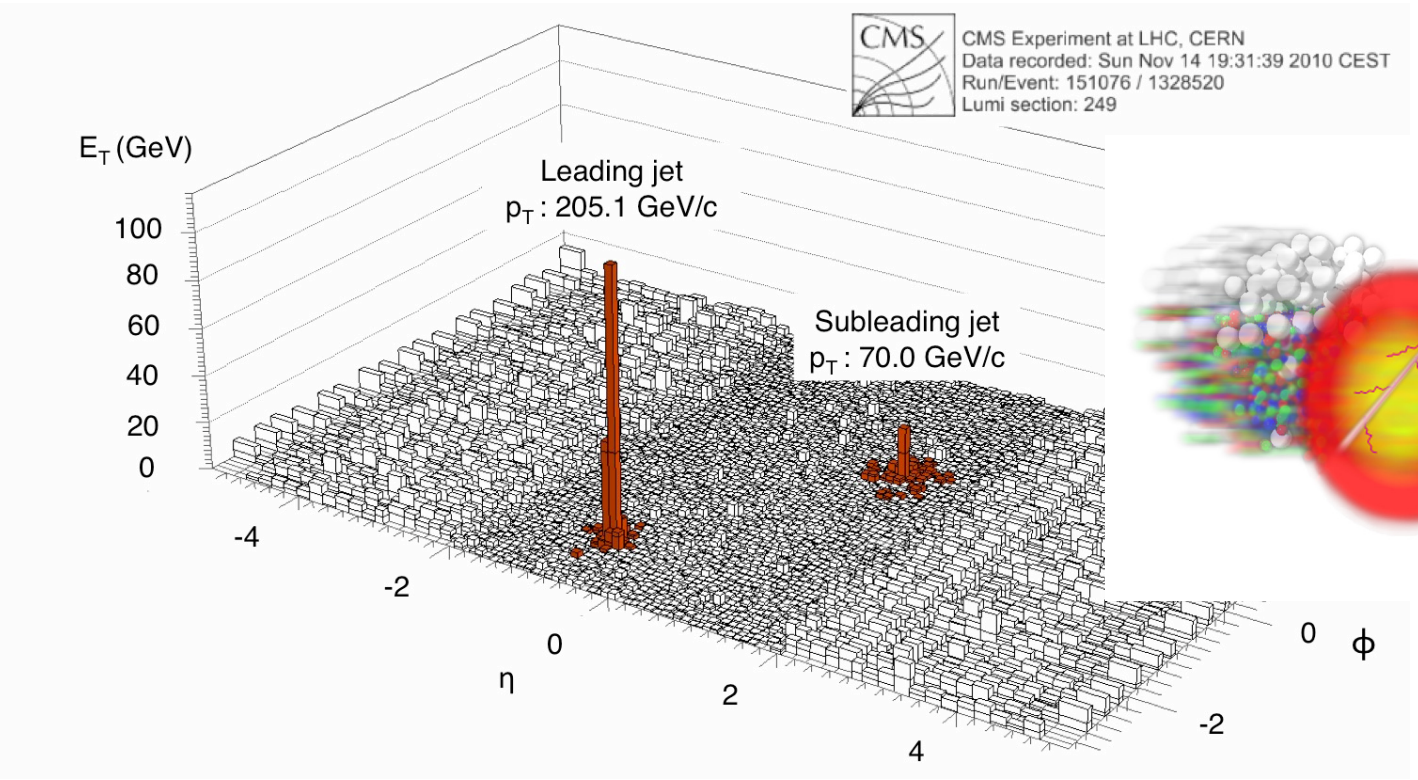
Wide-coverage Tracking	Precision vertex	Full calorimetry (ECAL+HCAL)	High rate/HLT	Lepton PID	Hadron PID
✓	✓	✓	✓	✓	x

Exploiting the strengthens of CMS detector!

QGP tomography with hard probes

Di-jets





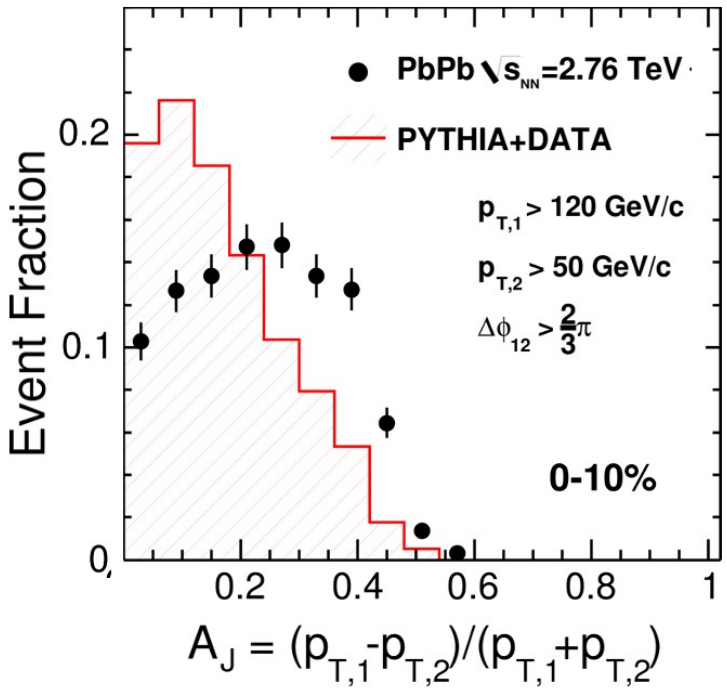
Gluon dominant

New era of jet quenching studies with a multitude of hard probes

QGP tomography with hard probes

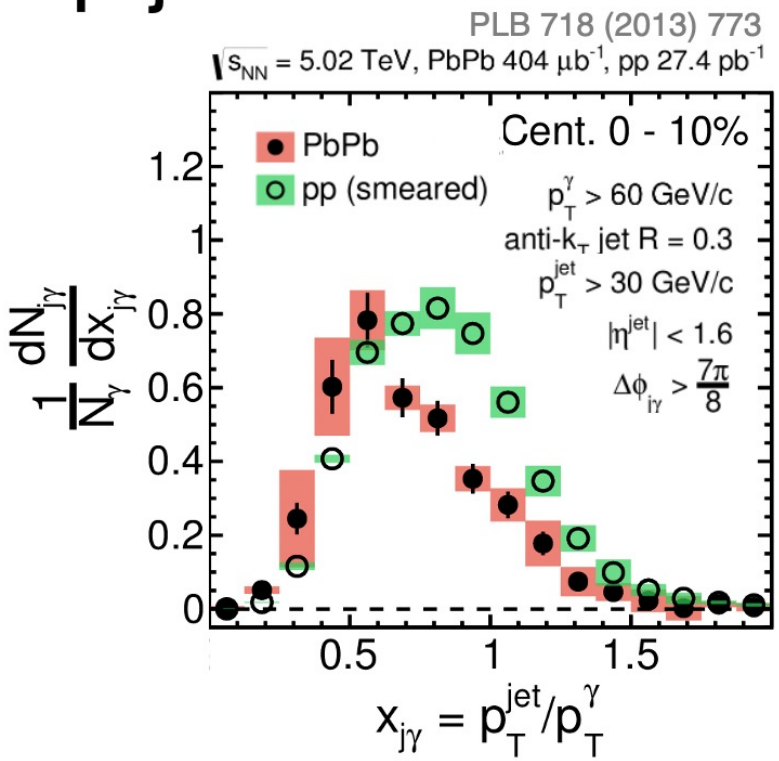
Di-jets

PRC 84 (2011) 024906



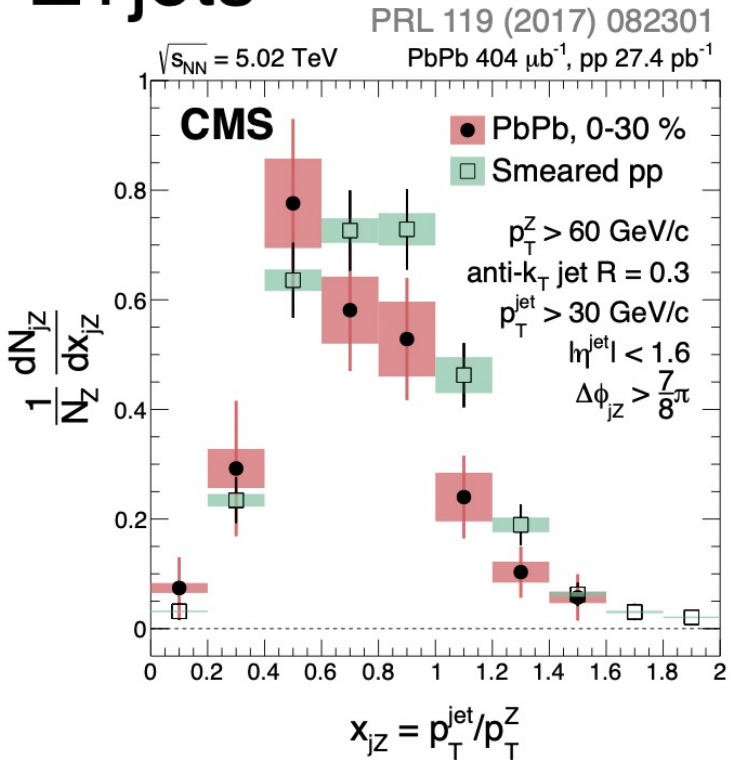
γ+jets

PLB 718 (2013) 773



Z+jets

PRL 119 (2017) 082301



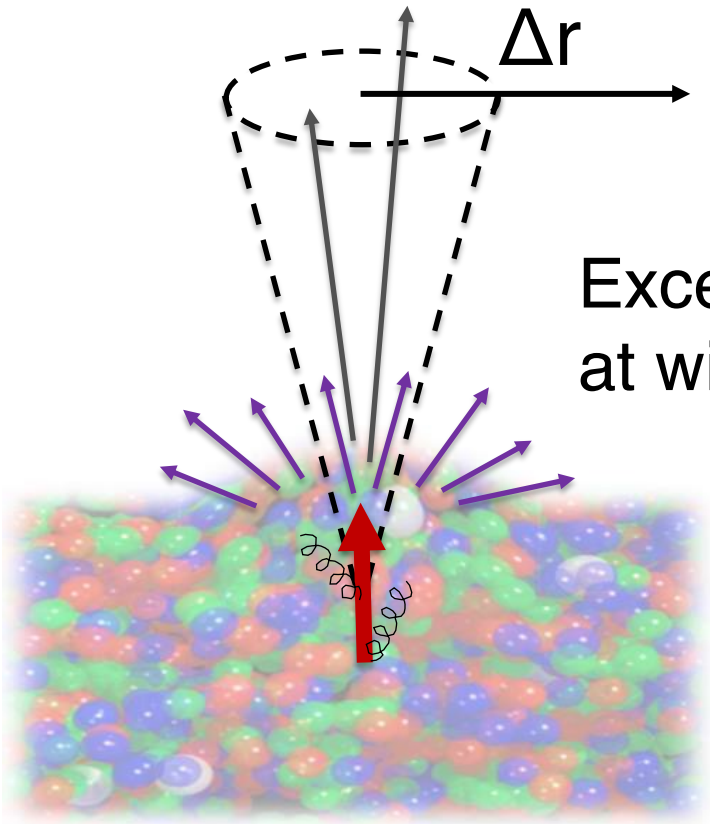
Gluon dominant

Quark dominant

New era of jet quenching studies with a multitude of hard probes

QGP tomography with hard probes

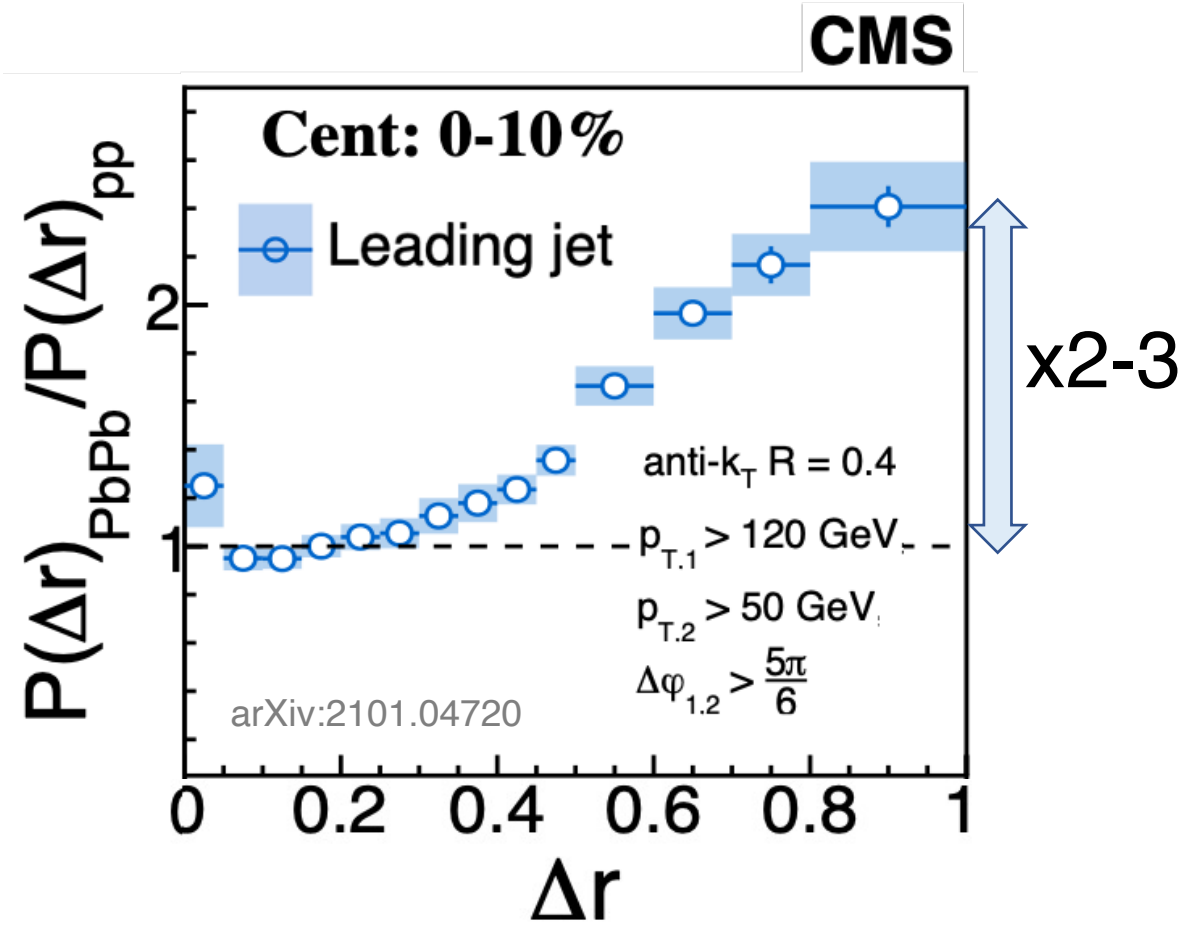
Detailed energy profile around jets over wide angle (from di-jets, γ+jets, Z+jets)



Excess of energy at wide angles

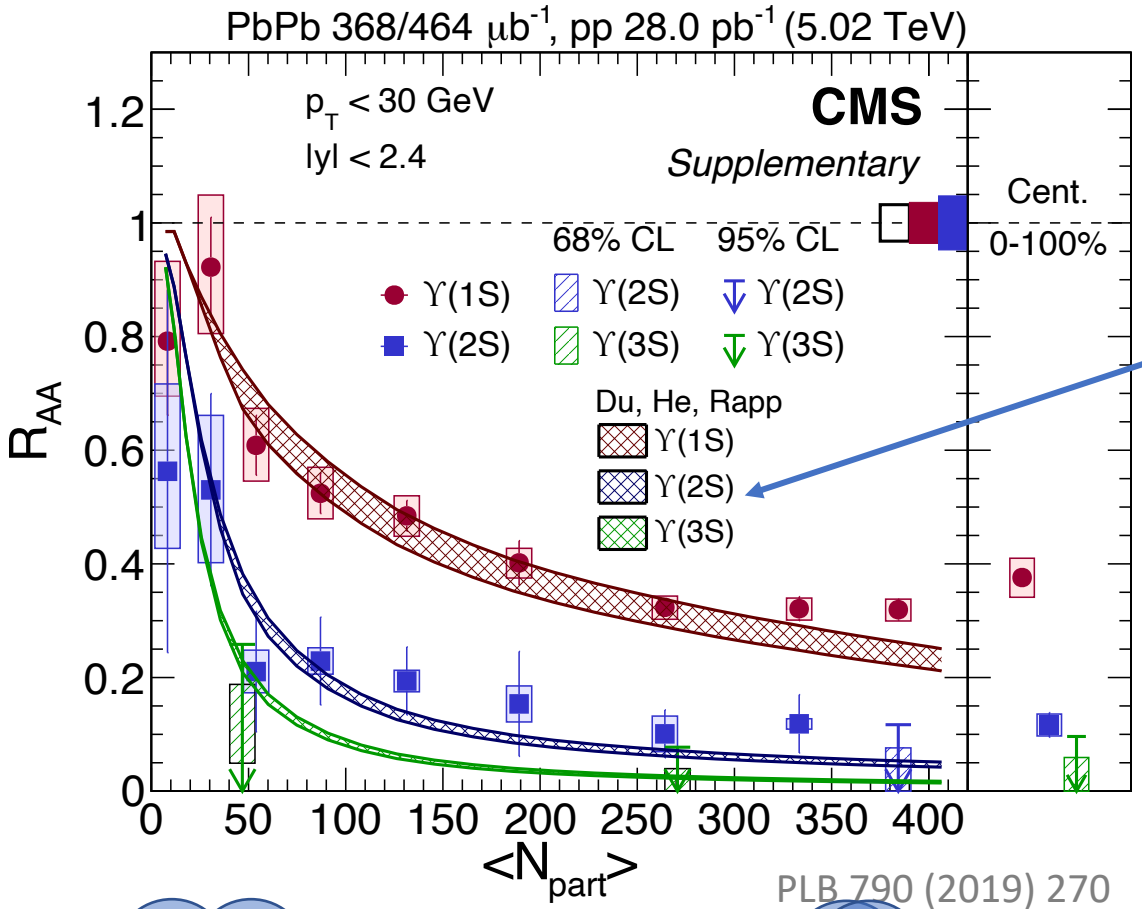
– How?

Radial energy dist. in PbPb / pp

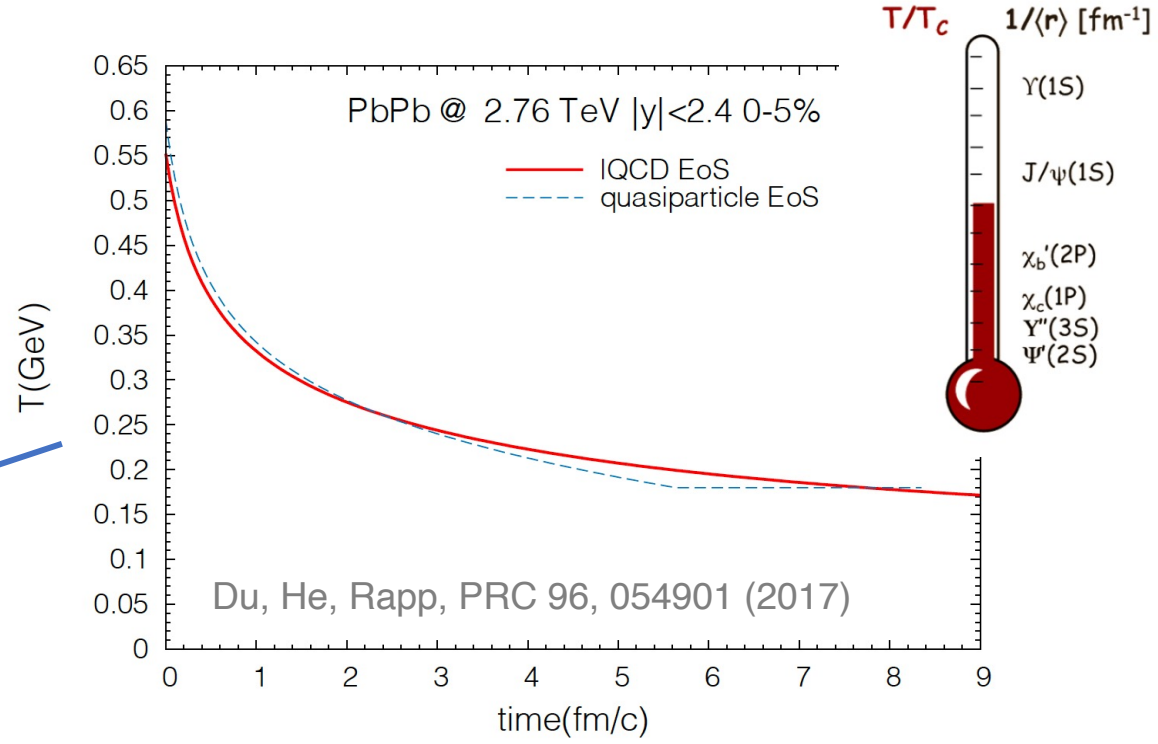


QGP thermometer with Quarkonia

Sequential Υ(nS) suppression

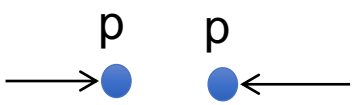


PLB 790 (2019) 270

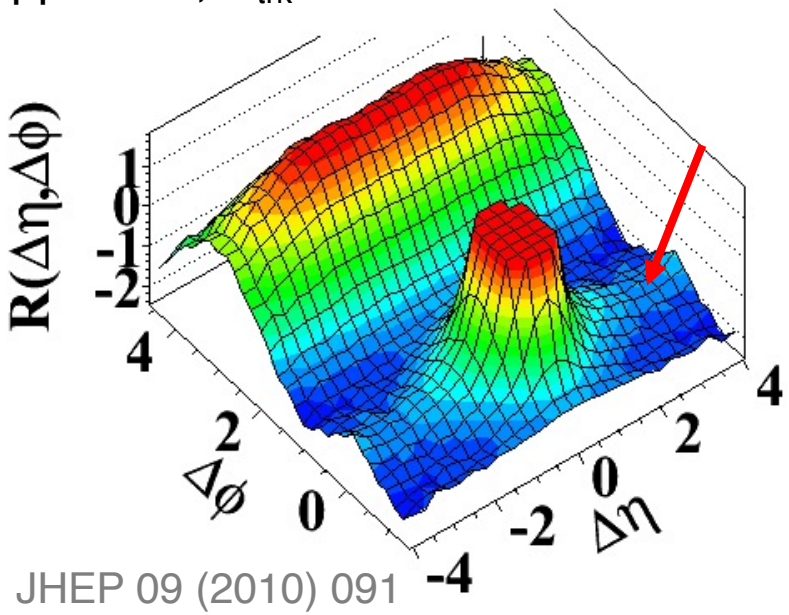


Precise constraints to QGP temperature profile and evolution

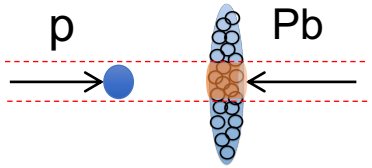
Discovery of “QGP” in small systems



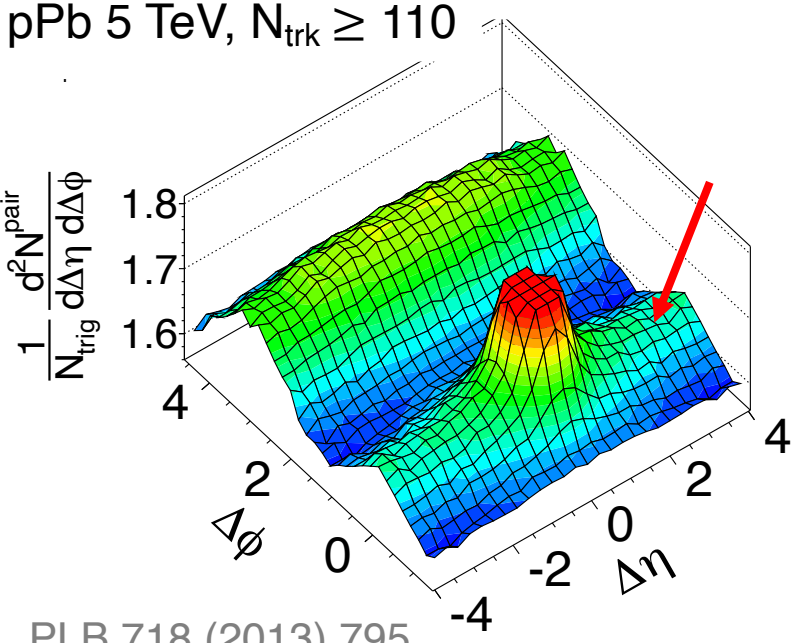
pp 7 TeV, $N_{trk} \geq 110$



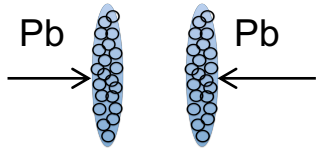
JHEP 09 (2010) 091



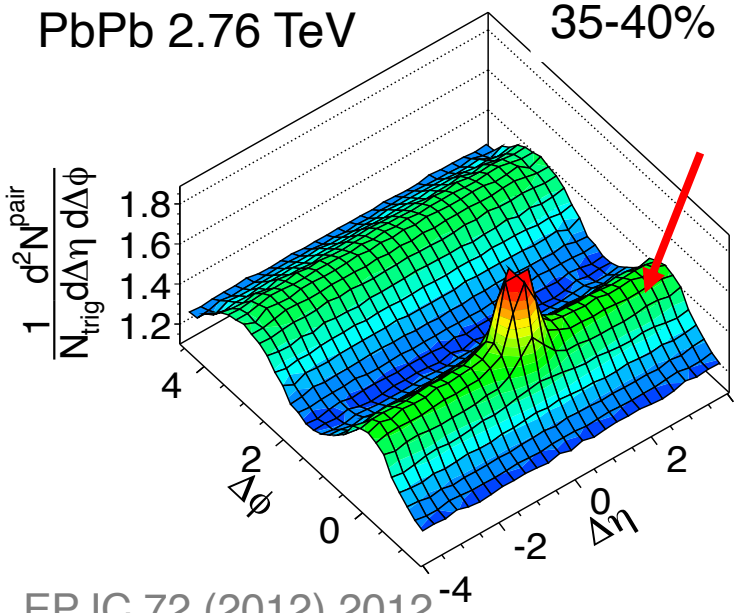
pPb 5 TeV, $N_{trk} \geq 110$



PLB 718 (2013) 795



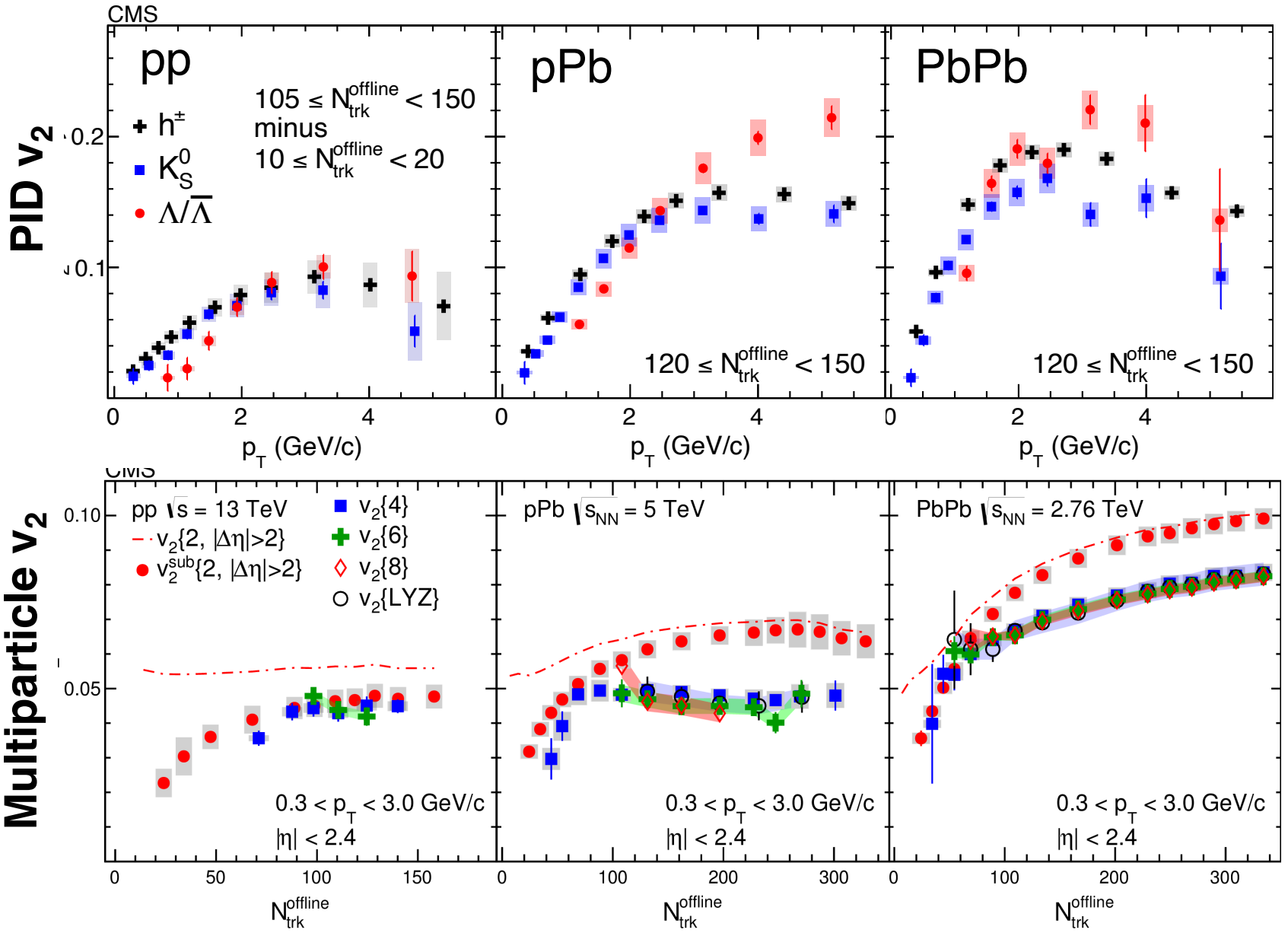
PbPb 2.76 TeV 35-40%



EPJC 72 (2012) 2012

Opened a new era of QCD studies in the high density limit

Discovery of "QGP" in small systems



A multi-year program on small systems:

PLB 724 (2013) 213
PLB 742 (2015) 200
PRL 115 (2015) 012301
PLB 768 (2017) 103
PLB 765 (2017) 193
PRL 120 (2018) 092301

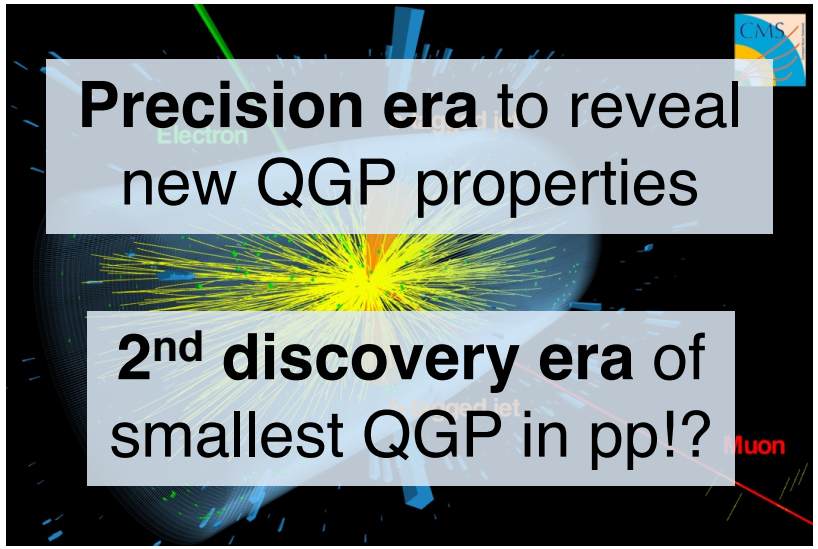
Everything flows!?

Tiniest QGP or … ?

“Little Bangs”

2000: RHIC

2009: LHC

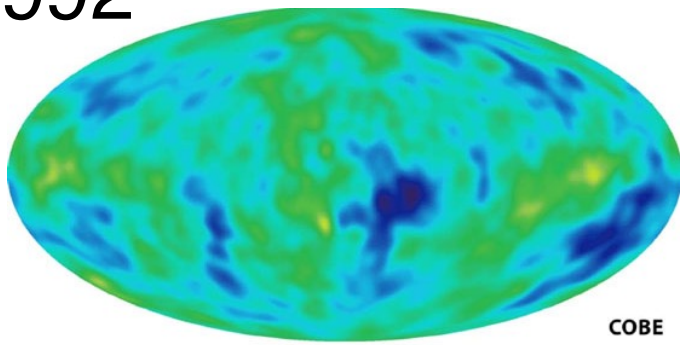


What’s next ???

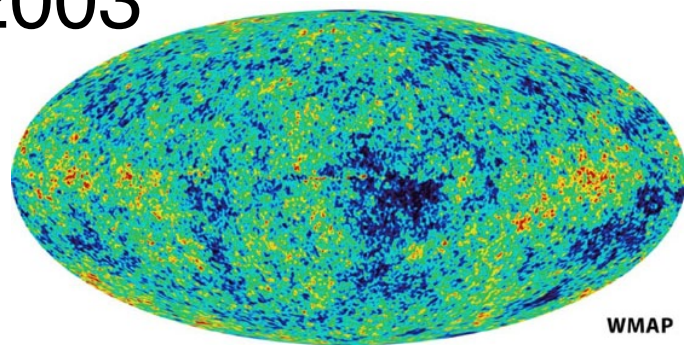
t

The Big Bang

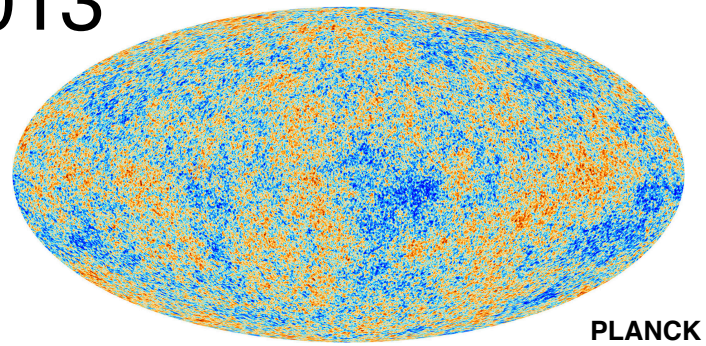
1992



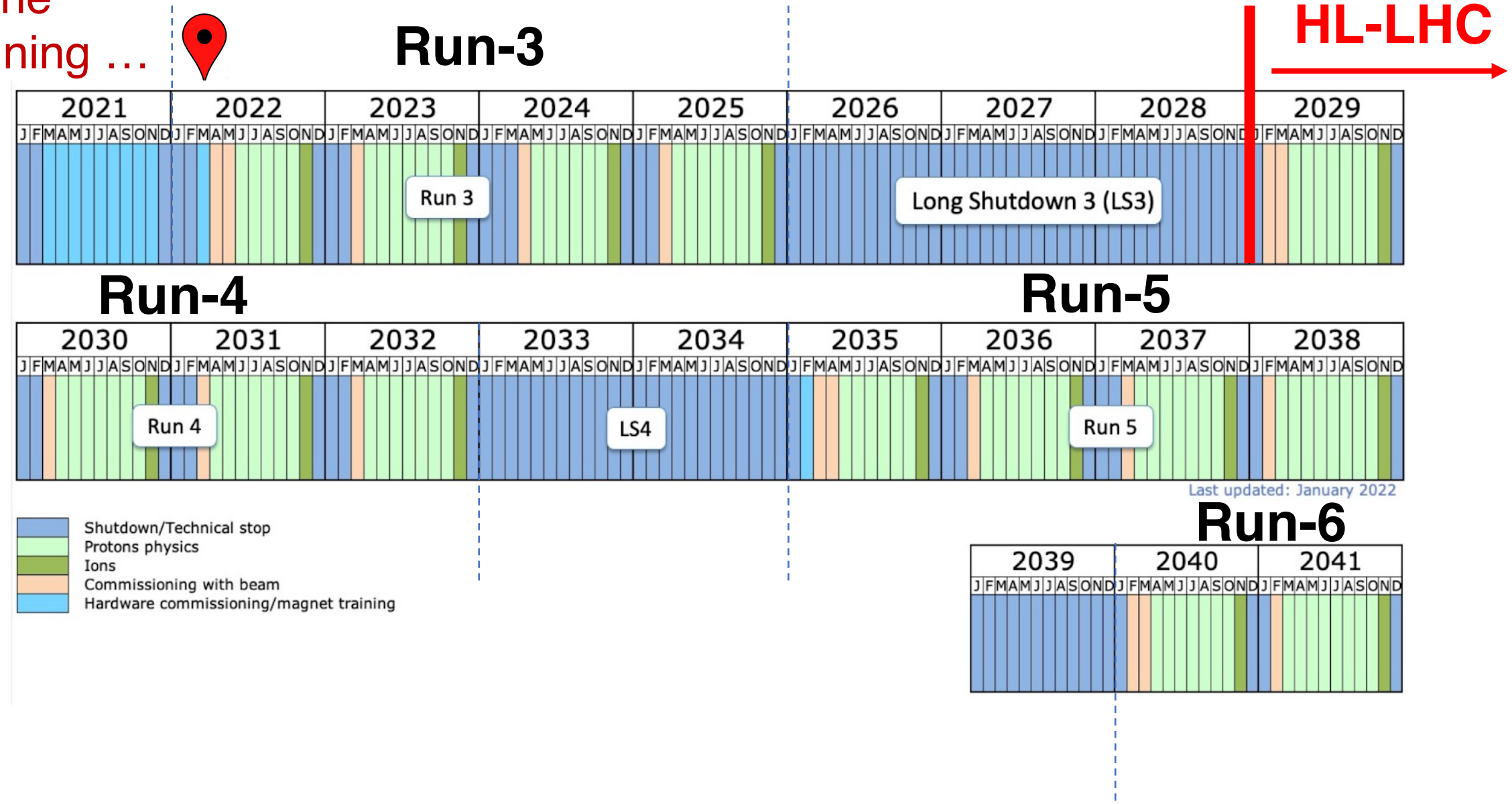
2003



2013



Just the beginning …



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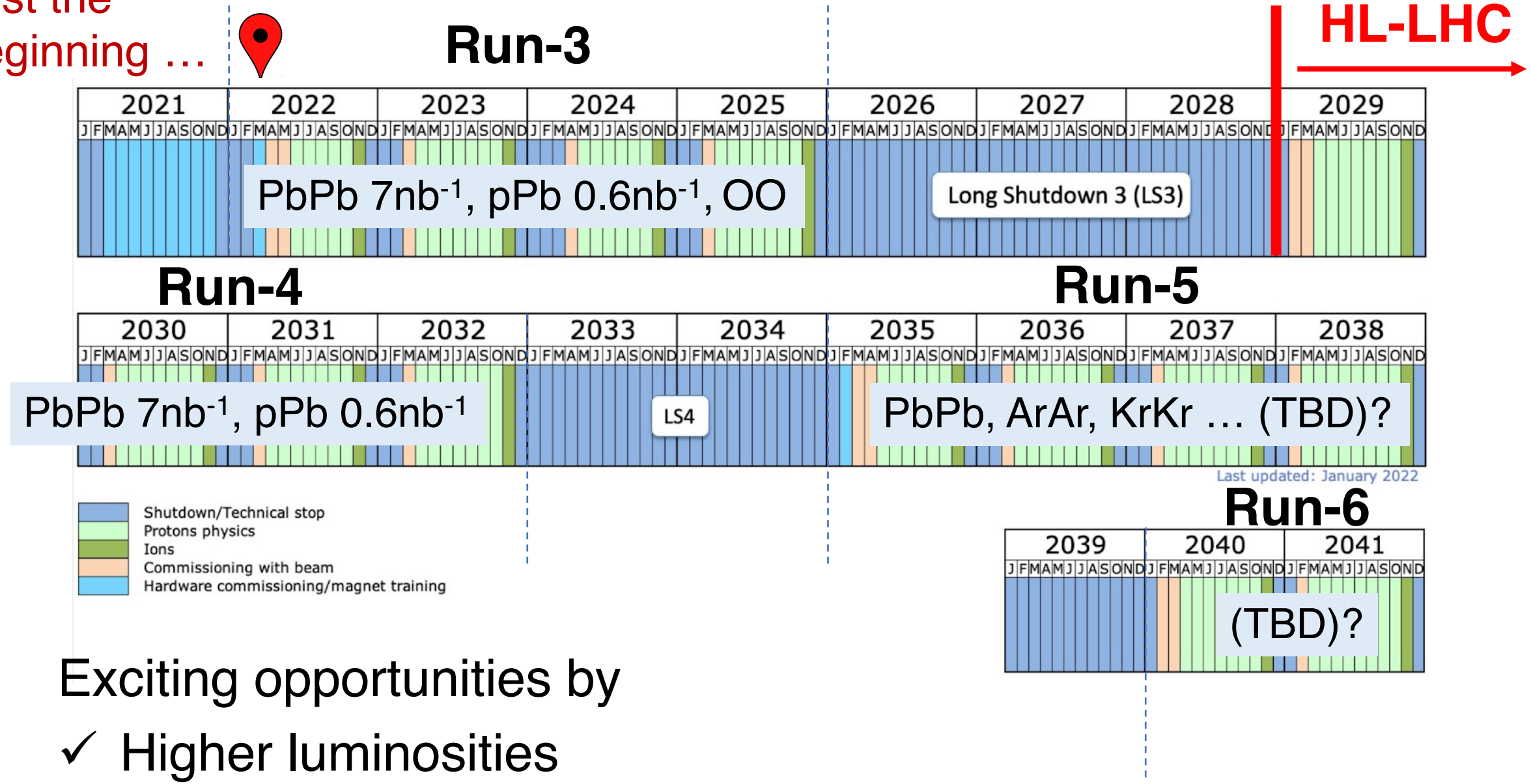
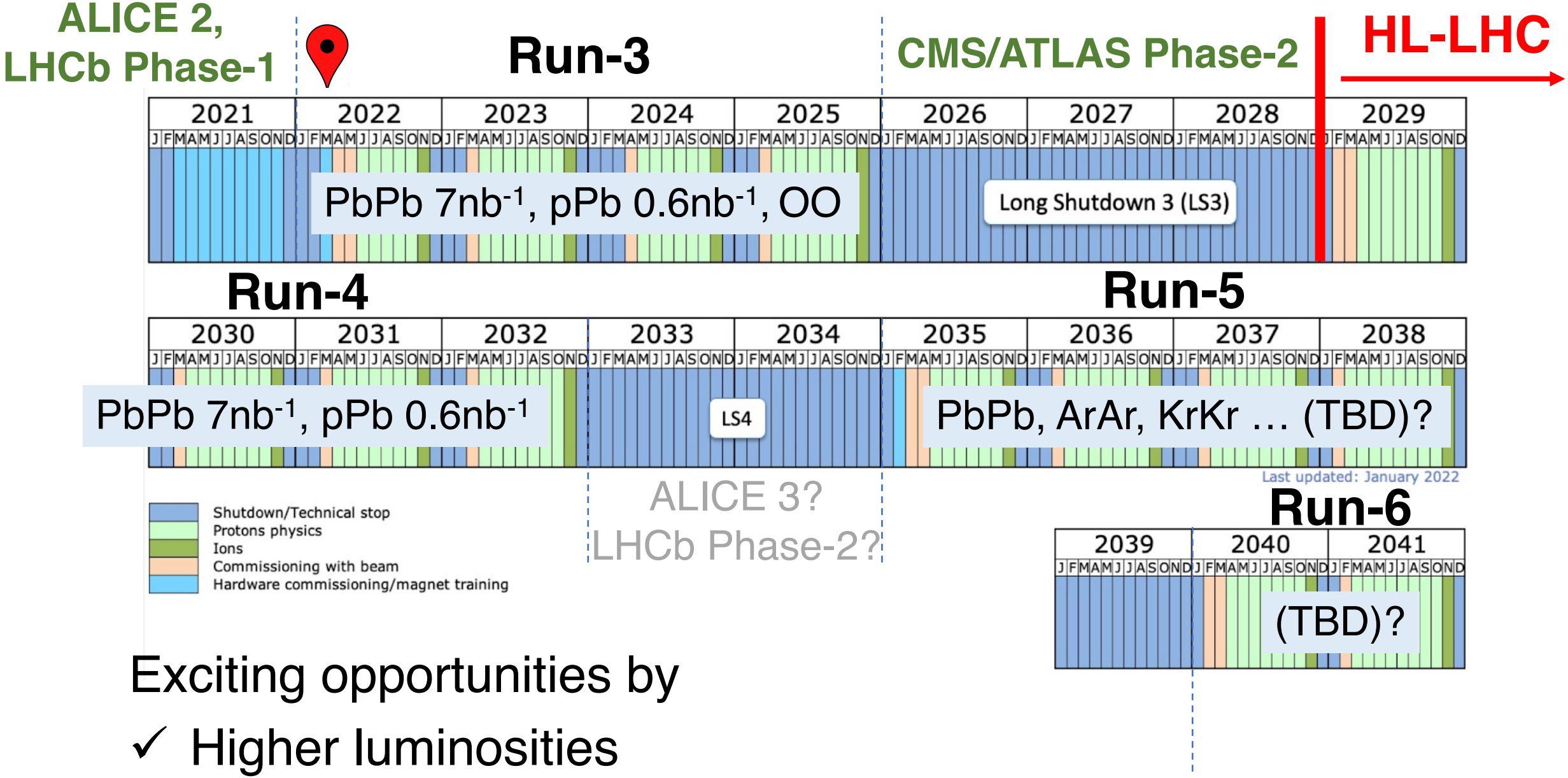


Exciting opportunities by

✓ Higher luminosities



Exciting opportunities by

- ✓ Higher luminosities
- ✓ **Upgraded apparatus by new technology!**

CMS Phase-2 upgrades for HL-LHC

Wider coverage, better precision, higher rate, and …

Table 1: Main features of CMS detector at present and Phase 2 upgrades.

Subdetector	CMS present	CMS Phase-2
Inner Tracker	$\|\eta\| < 2.4$, 100×150 μm^2 pixel size	$\|\eta\| < 4$, 50×50 μm^2 pixel size
Calorimeter	Low-granularity	High-granularity end-cap with silicon sensors
Muon detector	$\|\eta\| < 2.4$	$\|\eta\| < 2.8$
L1 trigger bandwidth	30 kHz for PbPb, 100 kHz for pp and pPb	750 kHz (pass through all PbPb events)
DAQ throughput	6 GB/s	60 GB/s

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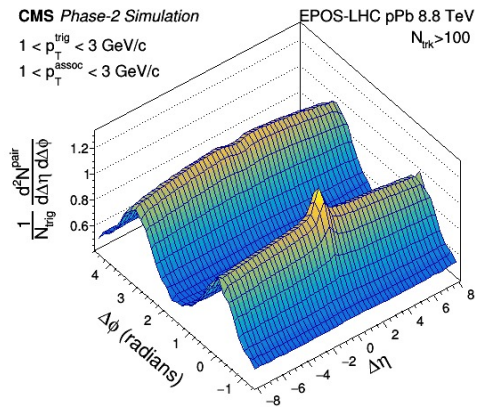

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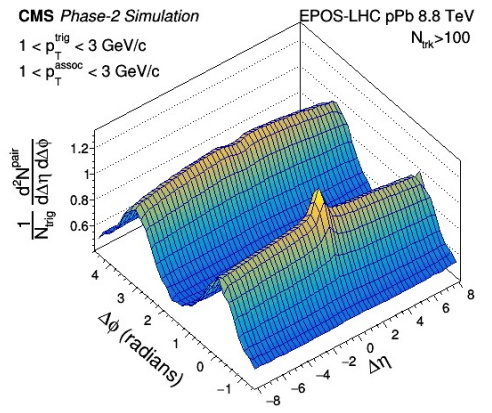

all PbPb evts read out

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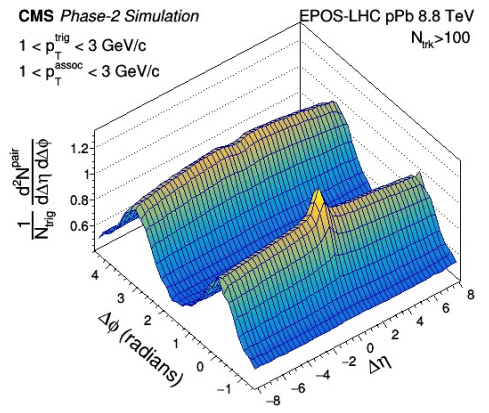

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Time-of-flight for Particle ID	**N/A**	**MTD for charged hadron PID over $\|\eta\| < 3.0$**

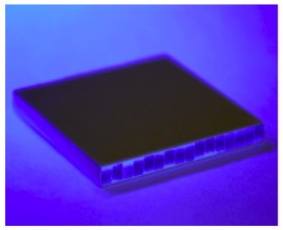
all PbPb evts read out

Approaching particle-by-particle true-level event info.

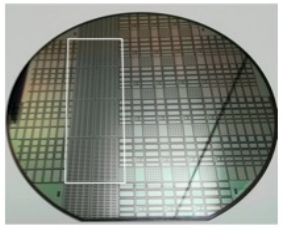
Toward a comprehensive QGP detector

CMS Mip Timing Detector (MTD)

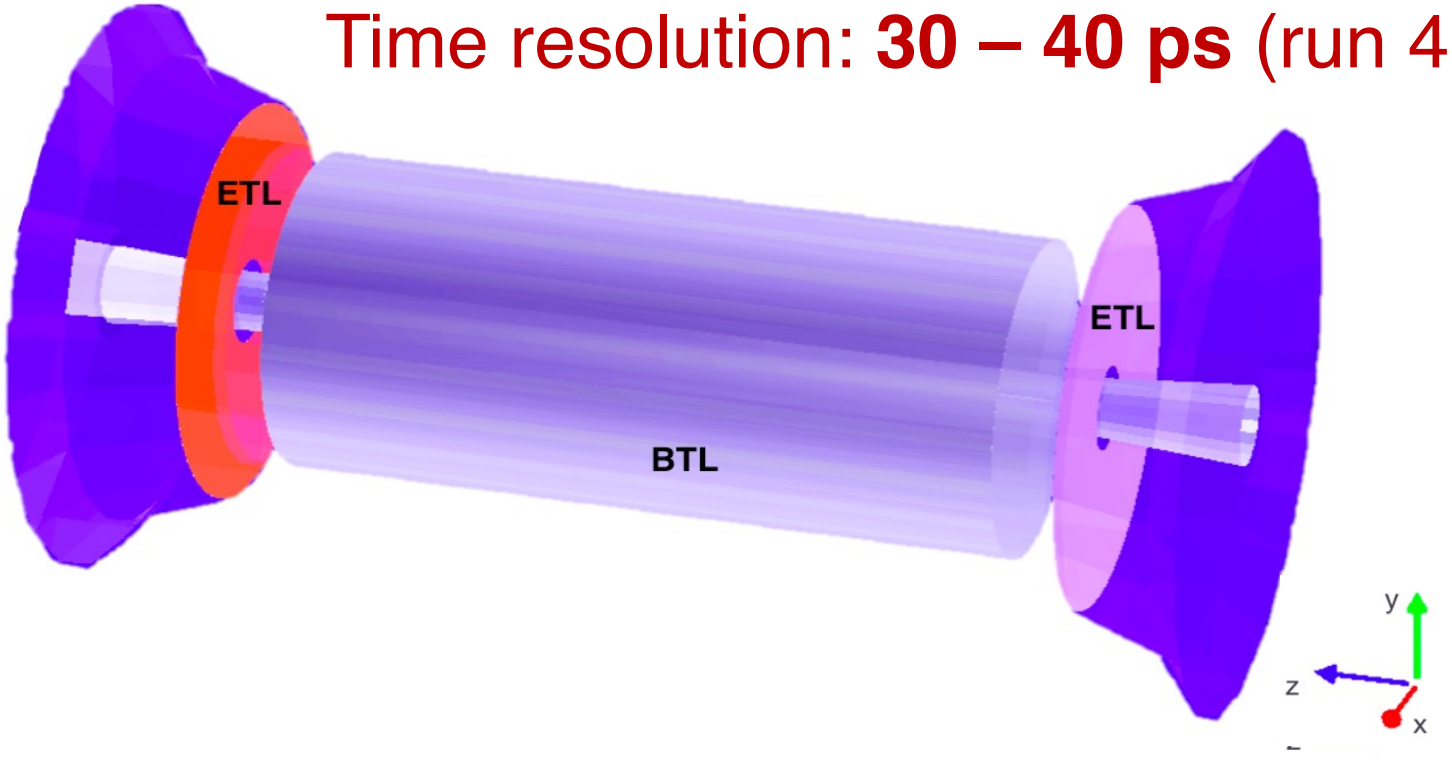
BTL: LYSO bars + SiPM readout:
- TK / ECAL interface: $|\eta| < 1.45$
- Inner radius: 1148 mm (40 mm thick)
- Length: ±2.6 m along z
- Surface ~38 m^2; 332k channels
- Fluence at 4 ab^{-1}: $2x10^{14}$ n_{eq}/cm^2



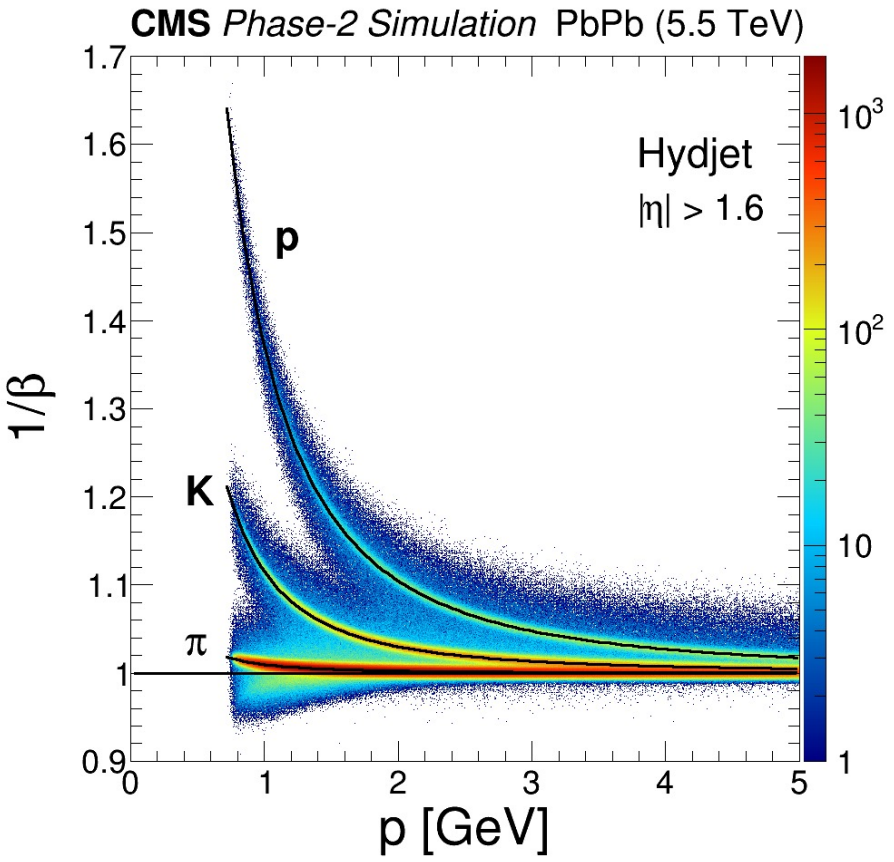
ETL: Si with internal gain (LGAD):
- On the CE nose: $1.6 < |\eta| < 3.0$
- Radius: $315 < R < 1200$ mm
- Position in z: ±3.0 m (45 mm thick)
- Surface ~14 m^2; ~8.5M channels
- Fluence at 4 ab^{-1}: up to $2x10^{15}$ n_{eq}/cm^2



Time resolution: **30 – 40 ps** (run 4)



Time-of-flight PID



CERN-LHCC-2017-027

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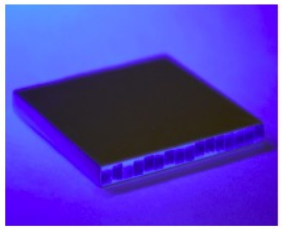

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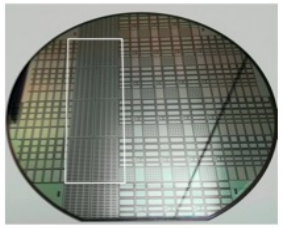
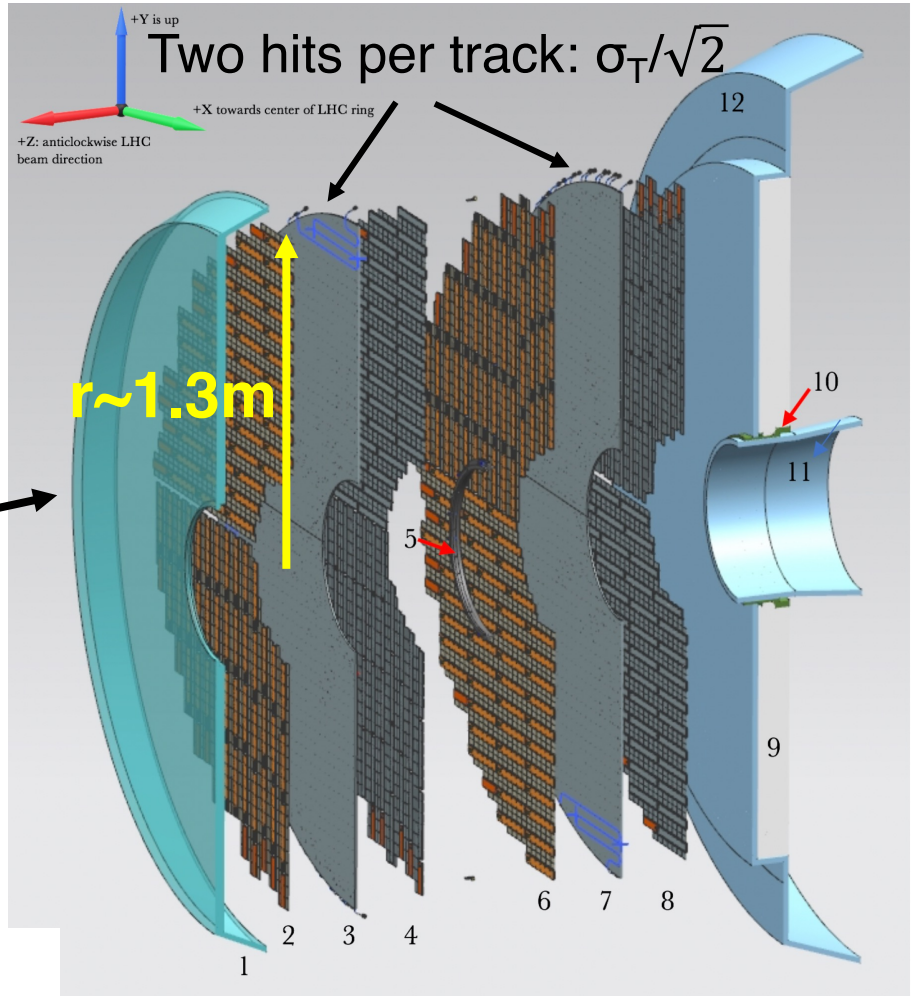


Time resolution: **30 – 40 ps** (run 4)

Major contributions by heavy ion groups in ETL

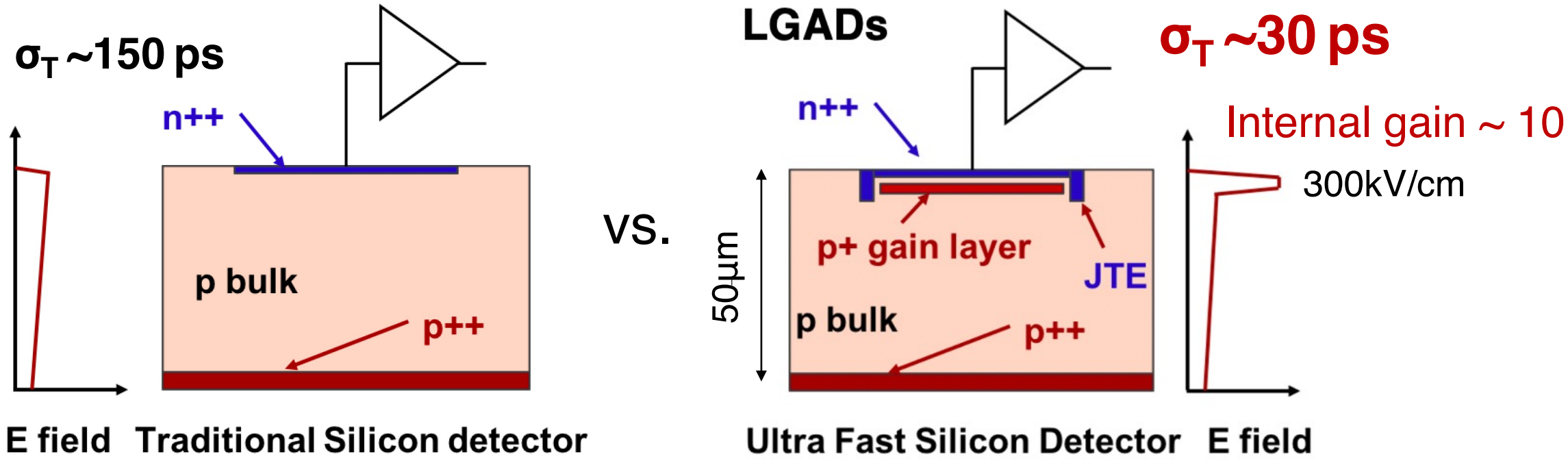
Endcap timing layer



CERN-LHCC-2017-027

Low Gain Avalanche Diodes (LGADs)

High E field → larger, faster signal → better timing resolution

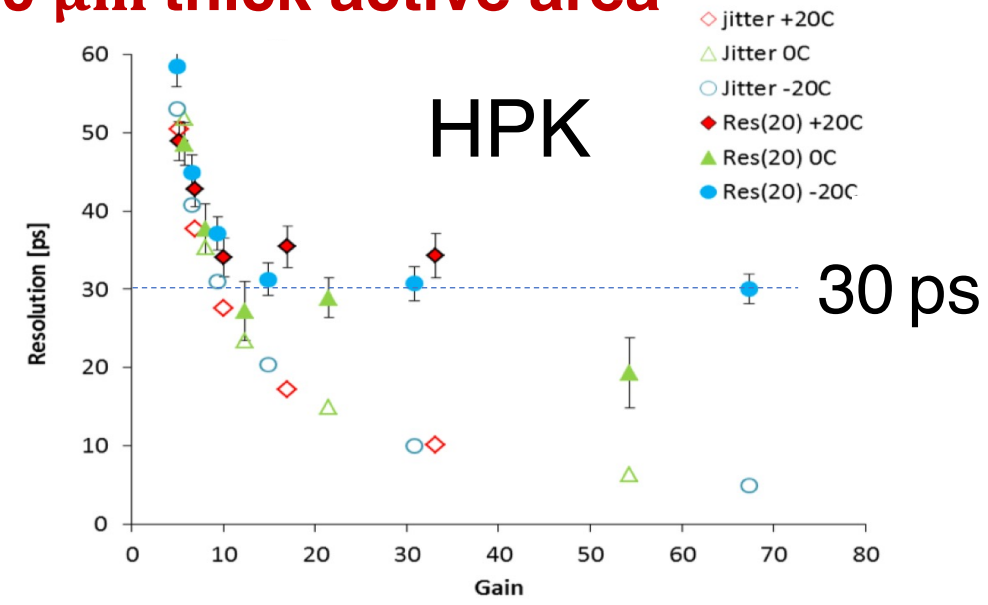


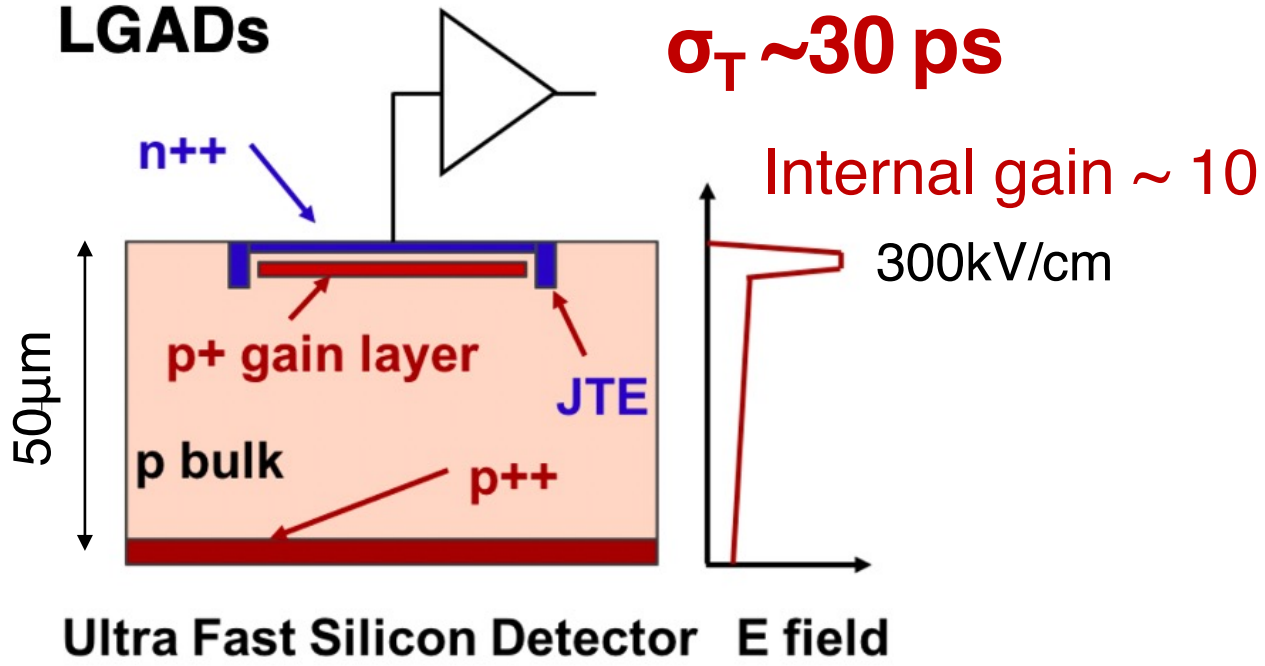
Precision timing and position – technology of the future tracker!

Low Gain Avalanche Diodes (LGADs)

High E field → larger, faster signal → better timing resolution

50 μm thick active area



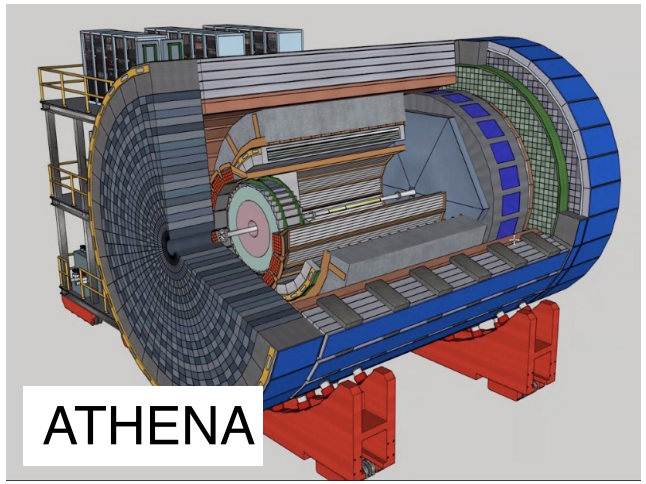


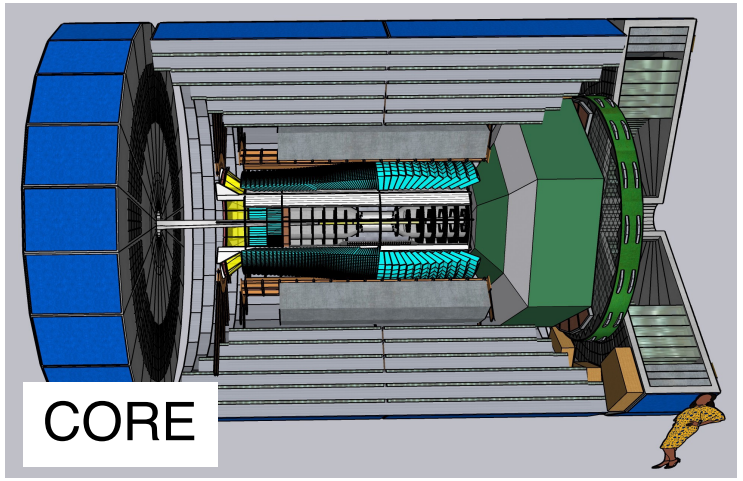
Prototype LGADs+ASICs: **42-46 ps** in beam tests

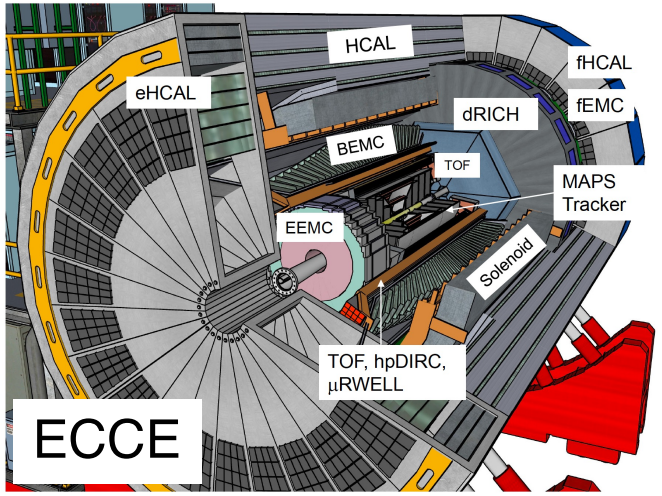
Precision timing and position – technology of the future tracker!

LGADs for electron-ion collider (EIC): 2030+

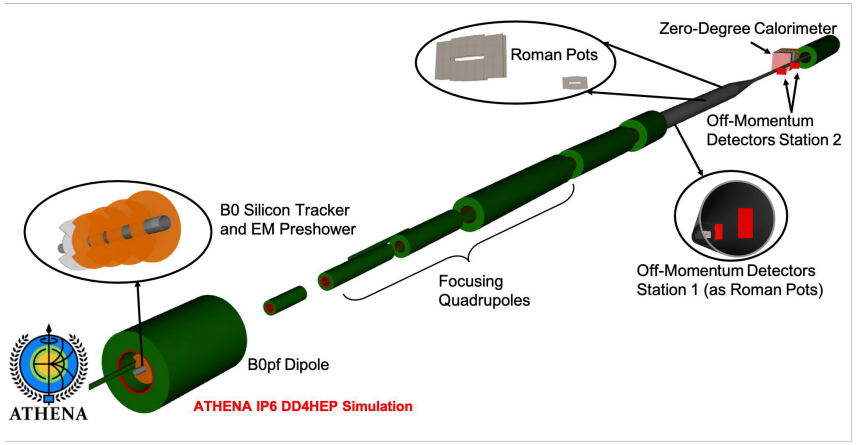
Central detector proposals this year:







Far forward/backward:

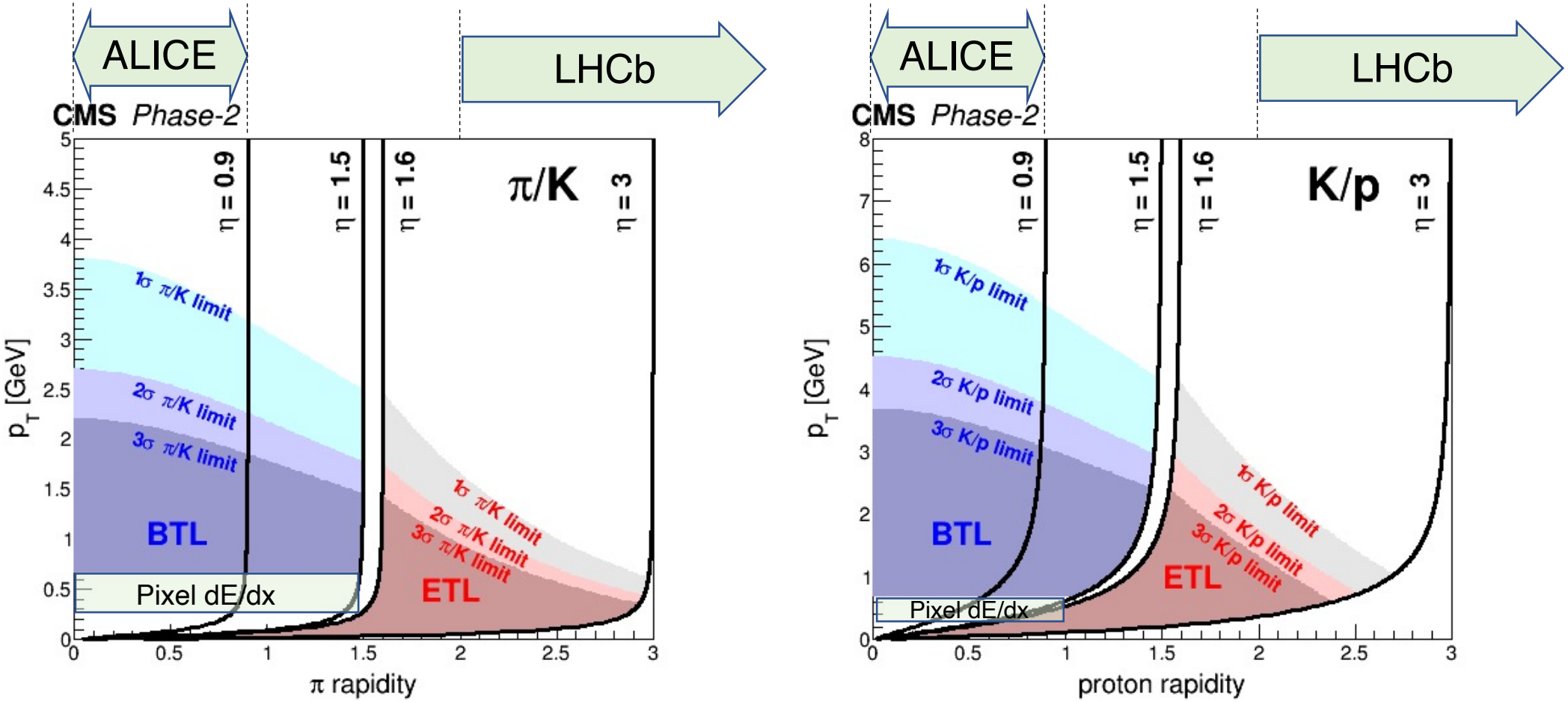


LGADs in all 3 detector proposals!

- TOF-PID for central regions
- Far forward/backward trackers

Proposal selection by ~ March – April

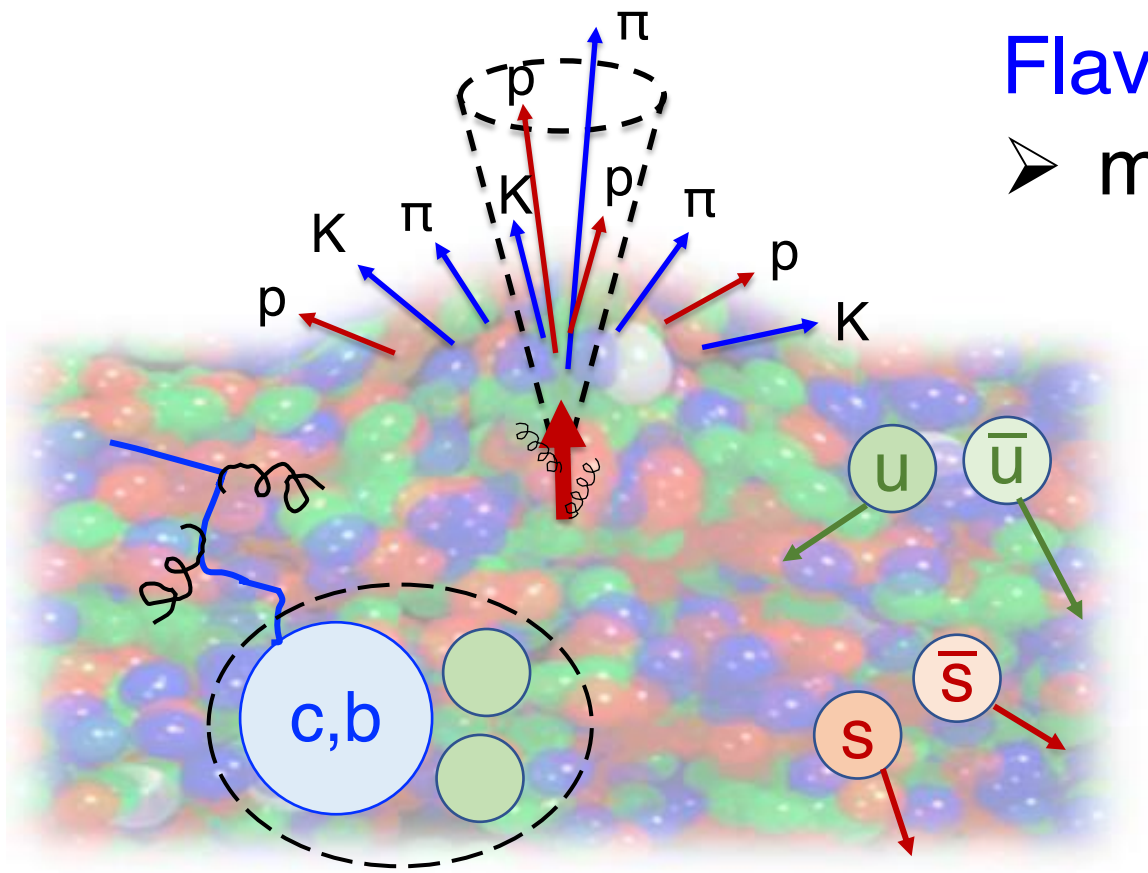
TOF particle ID with CMS MTD



- **Unique** hermeticity in PID with CMS-MTD (**|η|<3**)
- **Complementarity** to ALICE (**|η|<0.9**) and LHCb (**2<η<5**)

Physics of QGP with CMS-MTD

"Tracing the flavors"



Flavor composition in and outside a jet

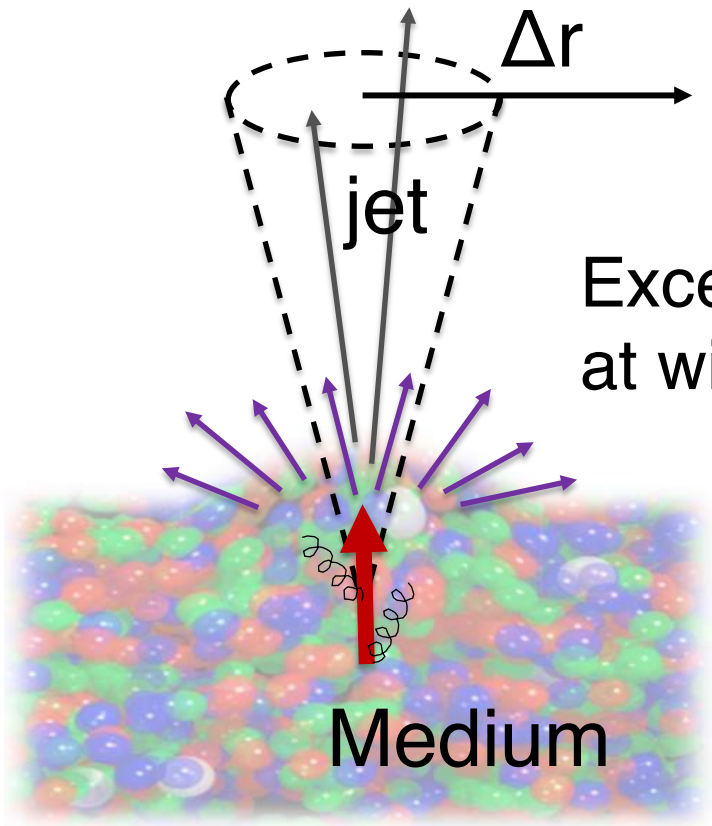
- medium response to energy loss

Diffusion of multi-scale probes:

- Charm, bottom: "Brownian motion"
- Light flavor: evolution of net-B, S, Q

Medium response to jet quenching

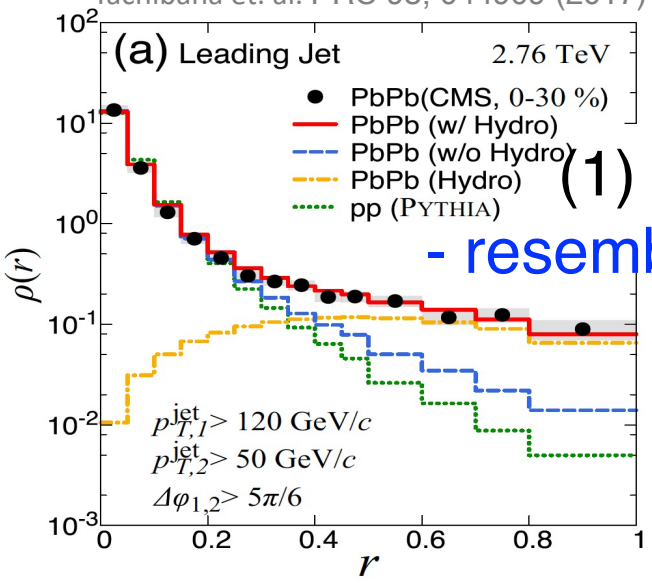
Detailed energy profile around jets over wide angle (from di-jets, γ+jets, Z+jets)



Excess of energy at wide angles

– How?

Tachibana et. al. PRC 95, 044909 (2017)



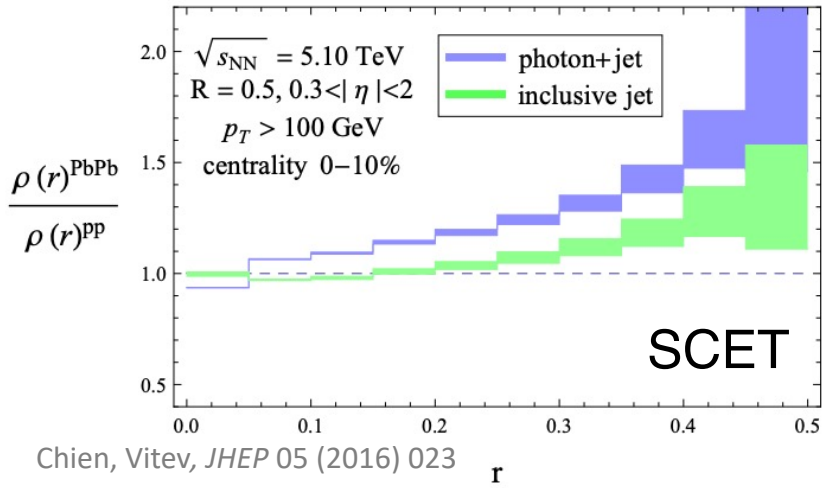
(1) QGP wake?

- resembling the medium

VS.

(2) Medium induced splitting?

- resembling the jet



Chien, Vitev, *JHEP* 05 (2016) 023

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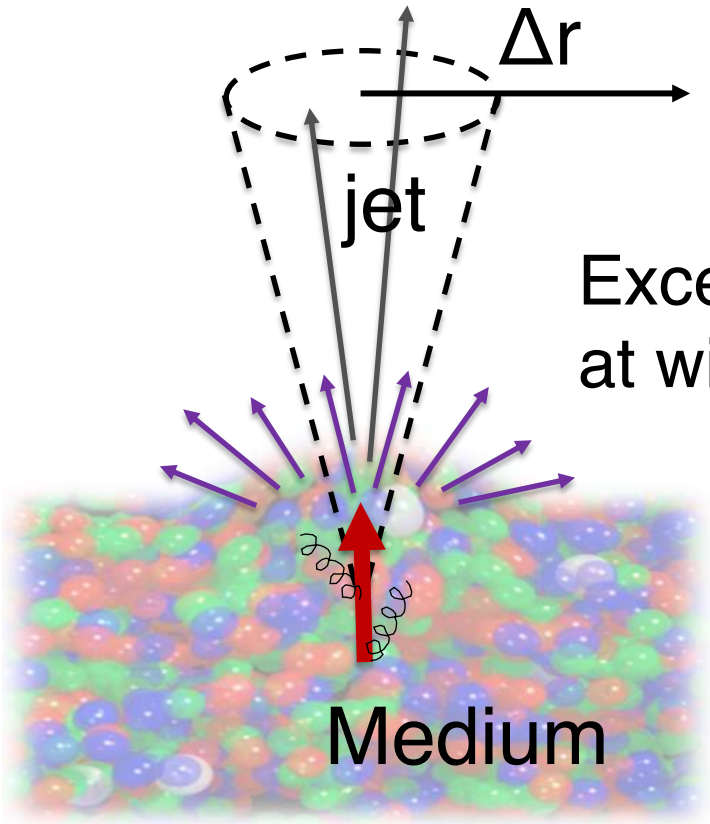

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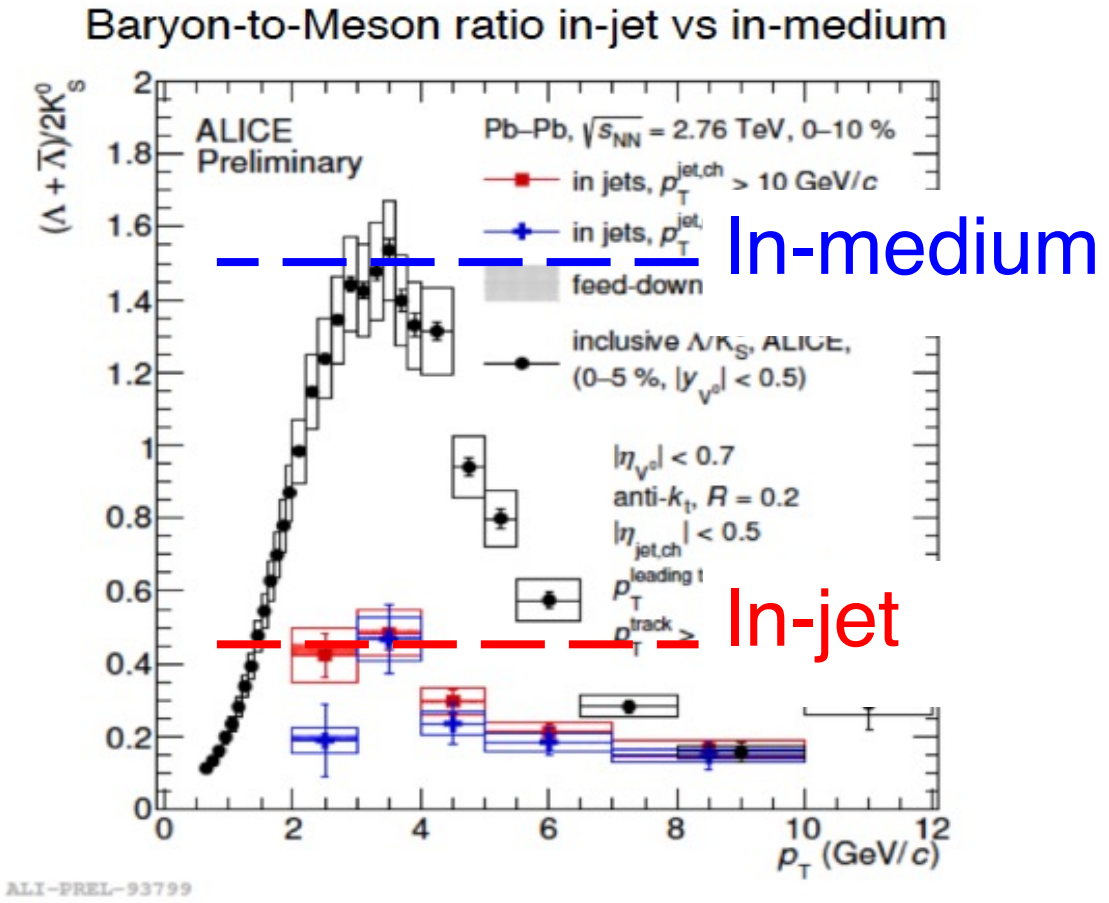
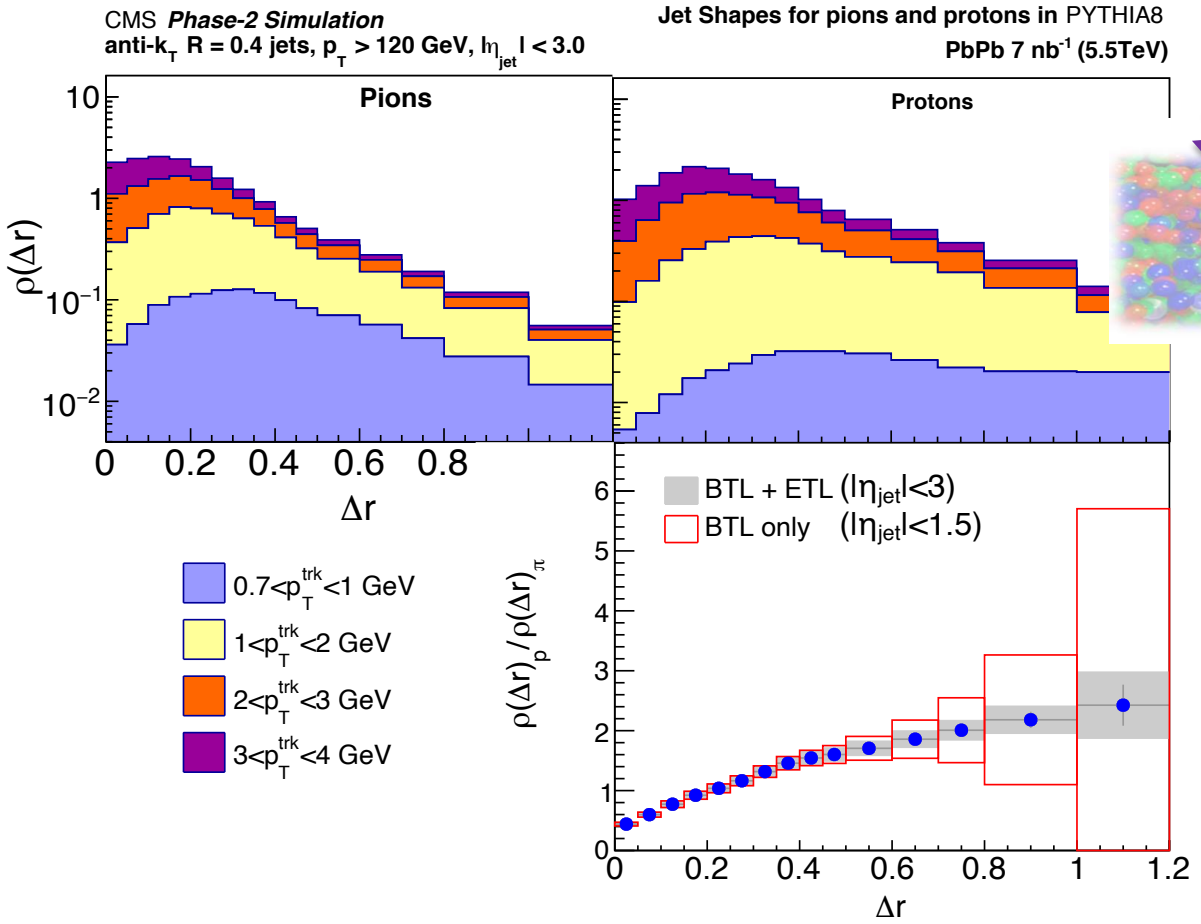
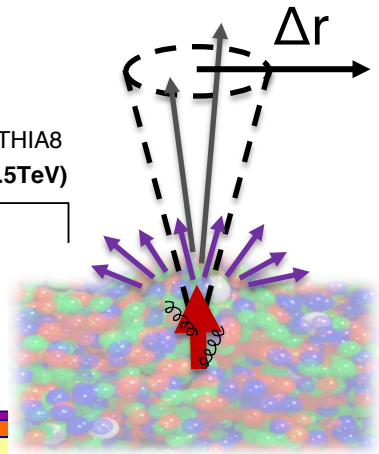


Need baryon-to-meson ratios **differential in Δr to Δr > 1**!

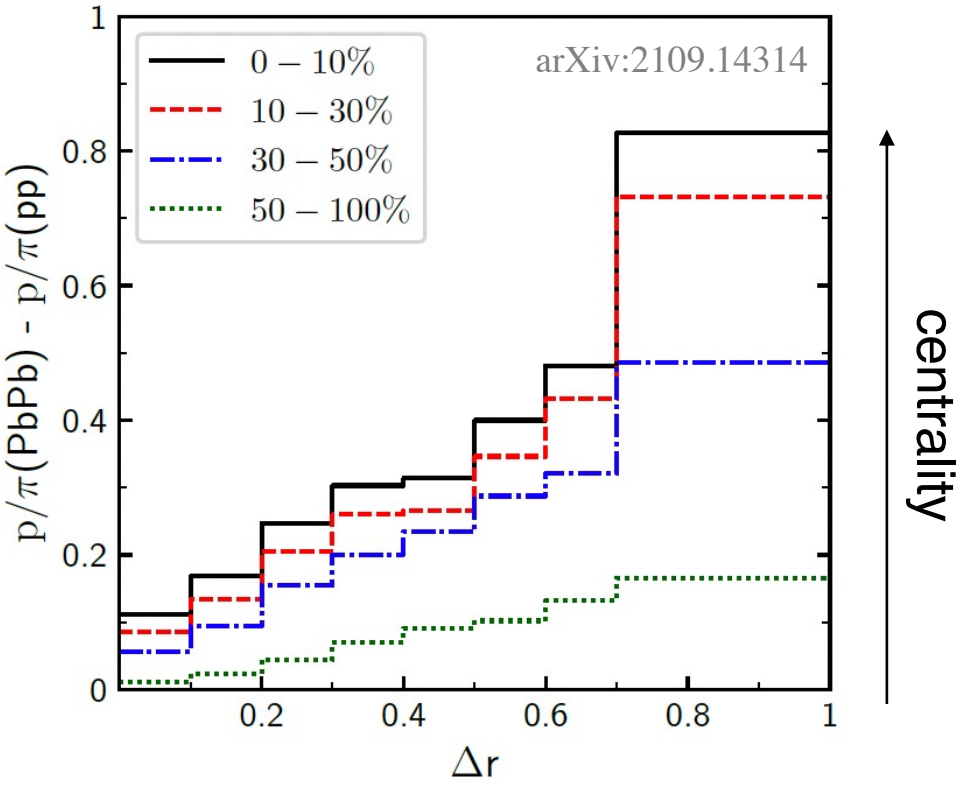
Medium response to jet quenching

CMS simulation with PYTHIA8





Prediction by QGP wake model

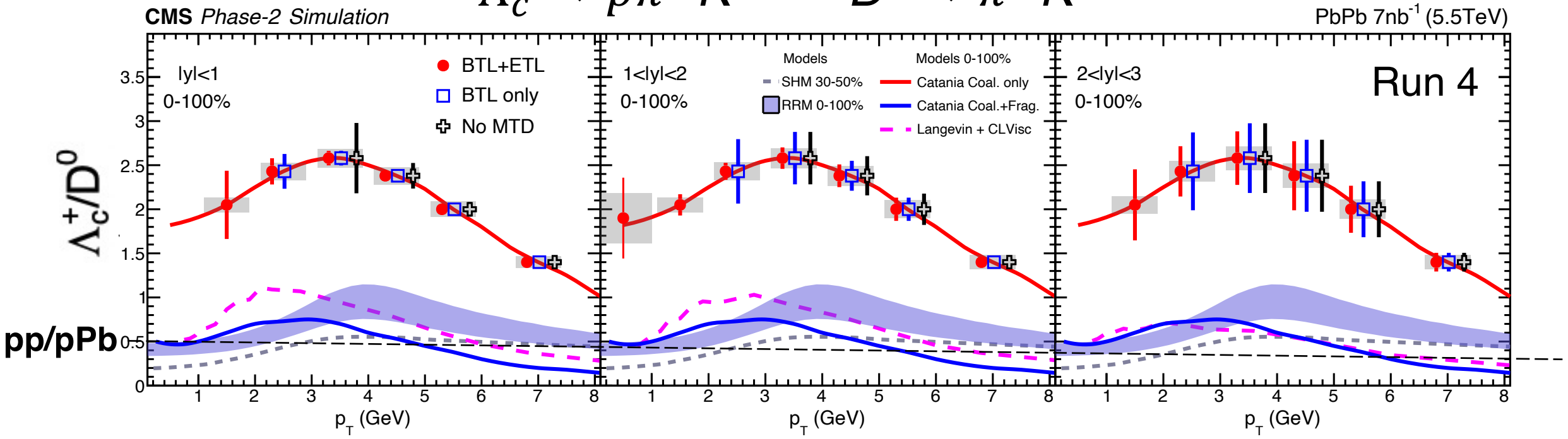


Unique measurement only possible by CMS with the MTD!

(3+1)D heavy flavor dynamics in QGP

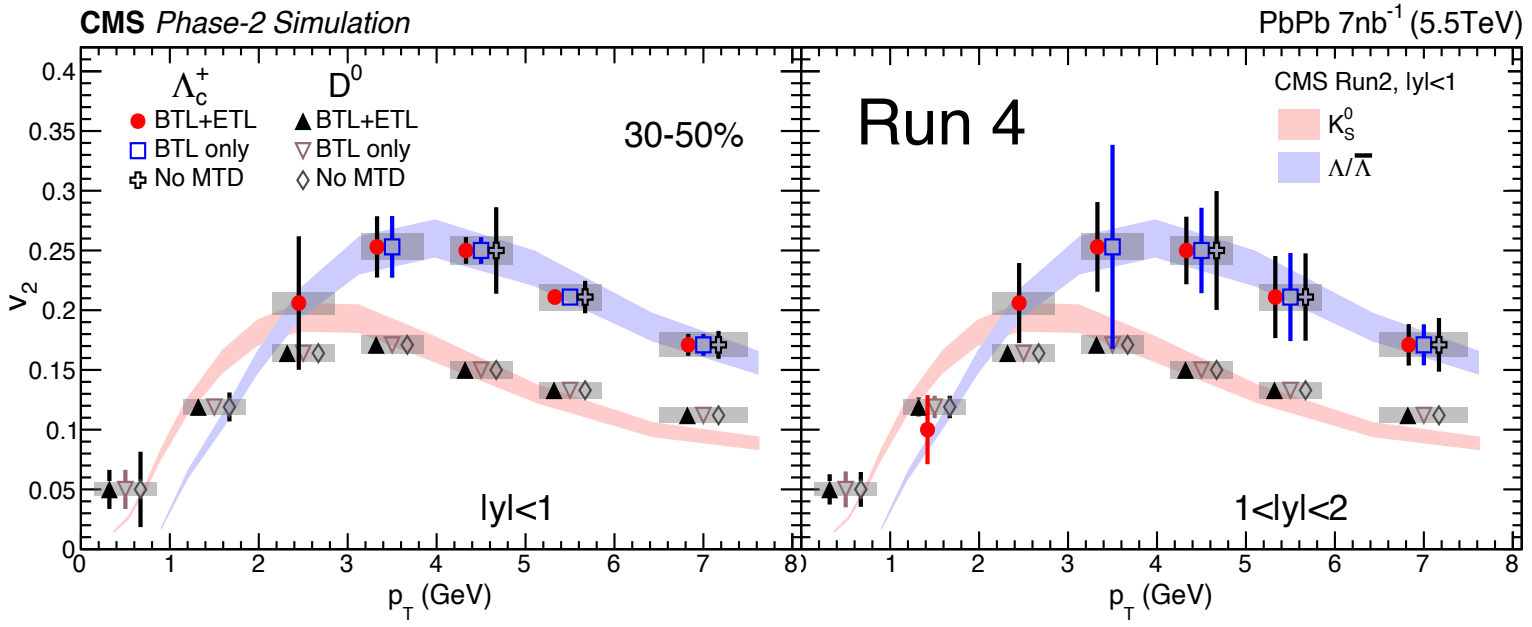
Constrain HF dynamics with a variety of hadrons ($D/D_s/\Lambda_c$, $B/B_s/\Lambda_b$) with high precision and wide acceptance coverage (3-D) **by MTD**

A benchmark $\Lambda_c^+ \to p\pi^+K^-$ $D^0 \to \pi^+K^-$



(3+1)D heavy flavor dynamics in QGP

Elliptic flow of charm baryon vs meson



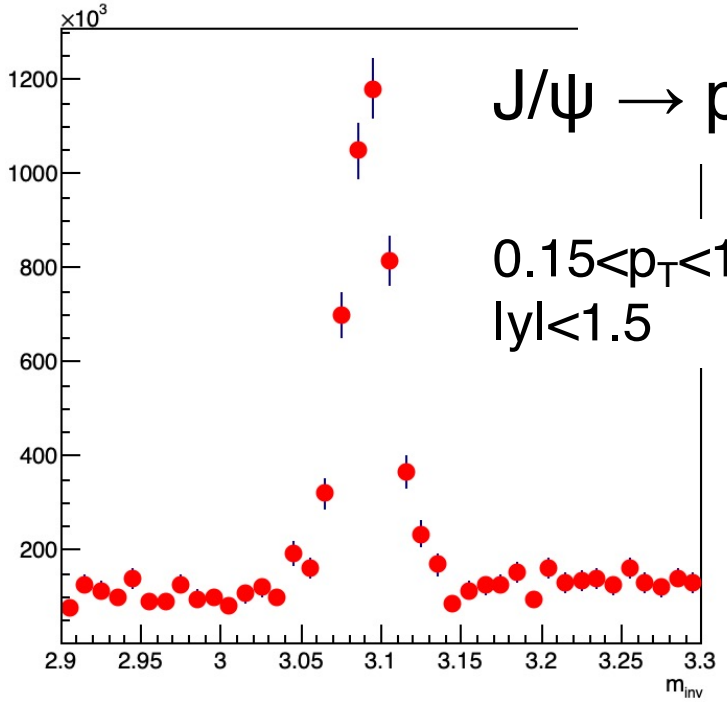
Naïve NCQ scaling in the charm sector?

$$\frac{v_2(\Lambda_c)}{v_2(D^0)} = \frac{3}{2}\ ?$$

MTD to test HF dynamics and hadronization with a variety of hadrons ($D/D_s/\Lambda_c$, $B/B_s/\Lambda_b$) with high precision and wide kinematics coverage

Quarkonia and Exotica with MTD

CMS-MTD simulation



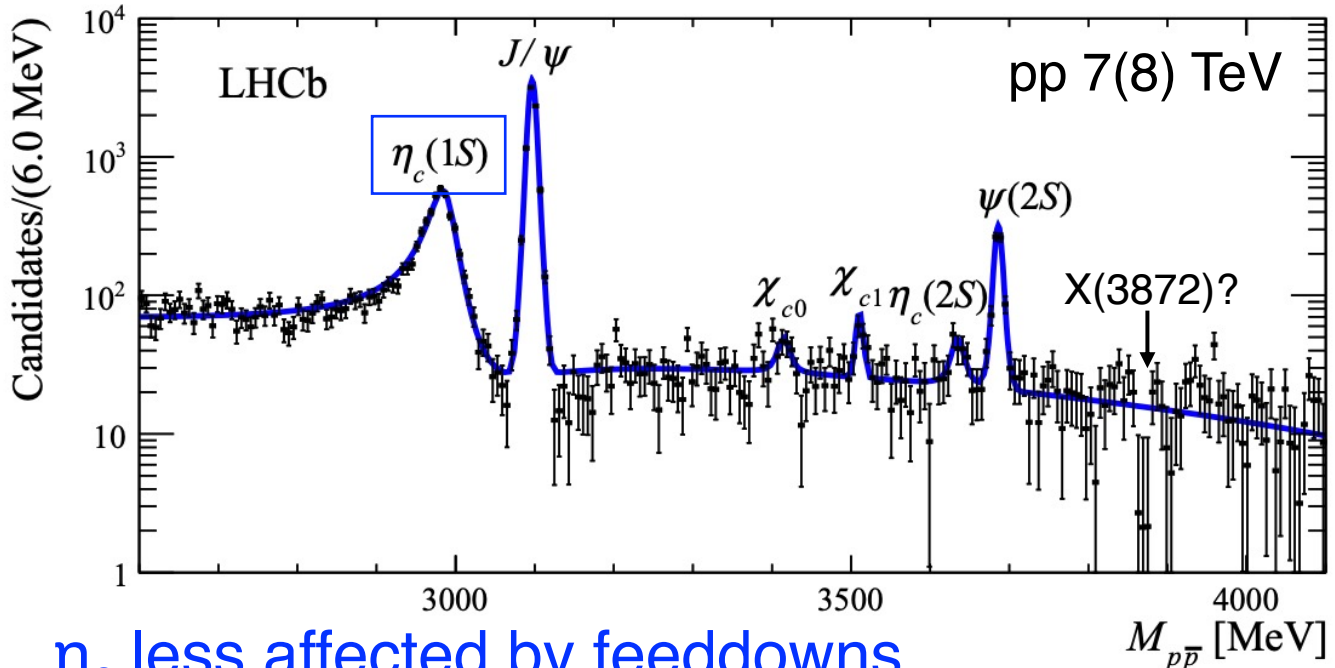
$J/\psi \rightarrow p\bar{p}$

$0.15<p_T<1.3$ GeV

$|y|<1.5$

(not accessible by $\mu^+\mu^-$)

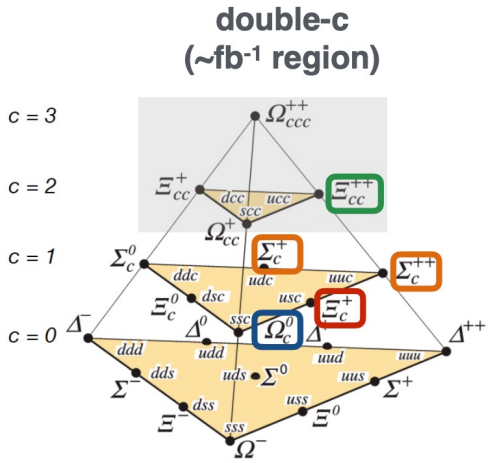
Phys. Lett. B 769 (2017) 305



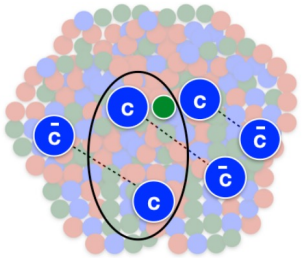
η_c less affected by feeddowns

Opportunities in quarkonia and exotica with hadronic decays in pp and AA!

Multi-charm hadrons in QGP with MTD?



Ξ_{cc}, Ω_{cc}

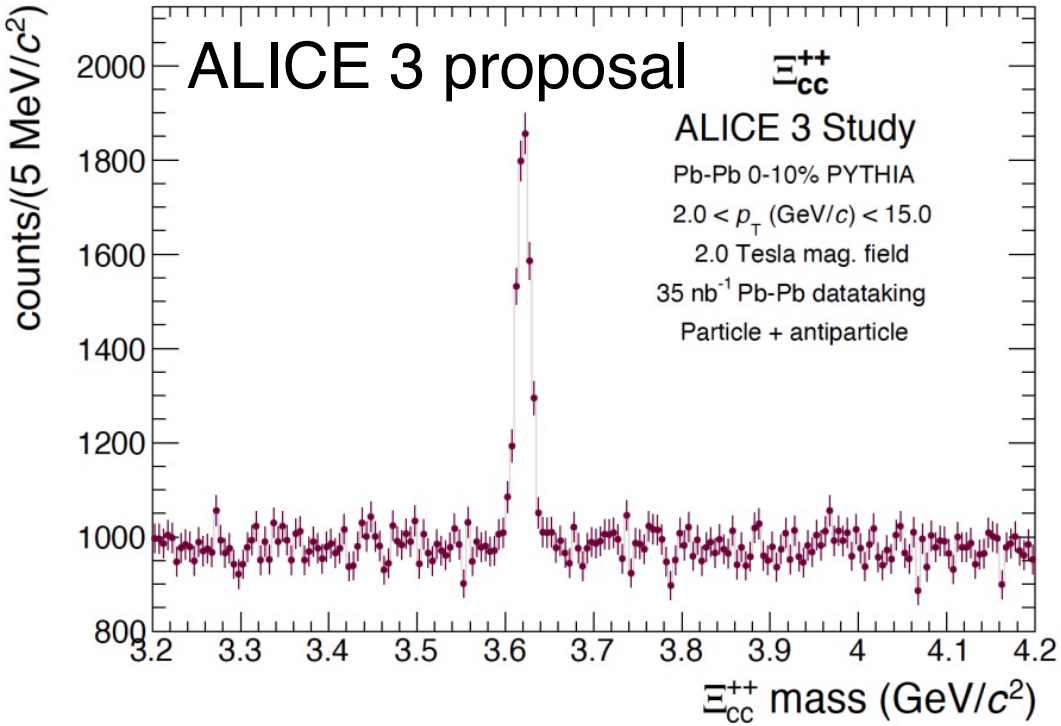


$\Xi^{++}_{cc} \rightarrow \Xi^{+}_{c} + \pi^{+}$ ($c\tau \approx$ 76 μm)

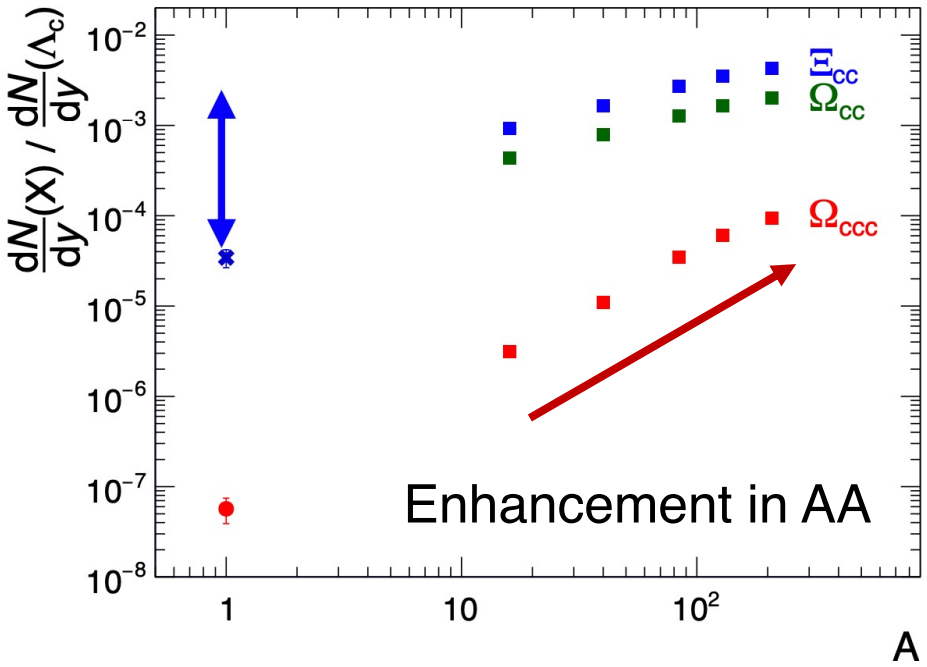
$\Xi^{+}_{c} \rightarrow \Xi^{-} + 2\pi^{+}$ ($c\tau \approx$ 132 μm)

$\Xi^{-} \rightarrow \Lambda + K^{-}$

seen by LHCb in pp



SHM (Andronic et al, JHEP 2021, 35)

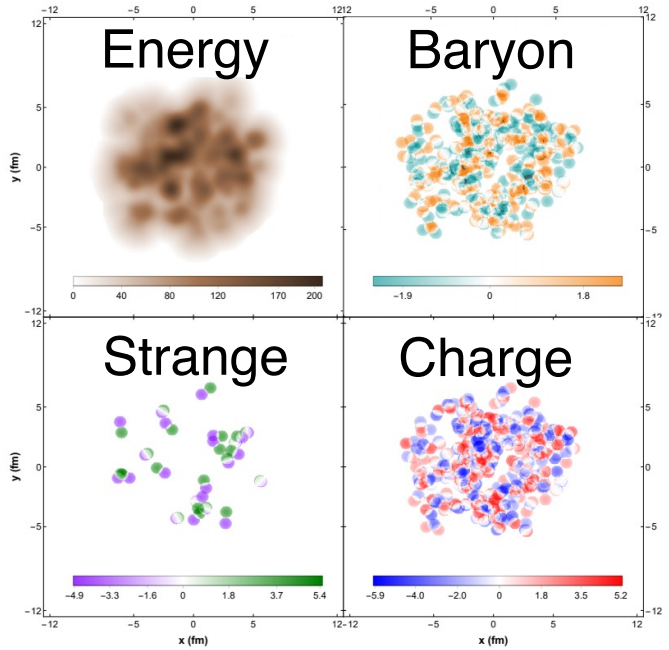


Also accessible by CMS-MTD?
– studies in progress

Light-flavor diffusion: net-B, S, Q

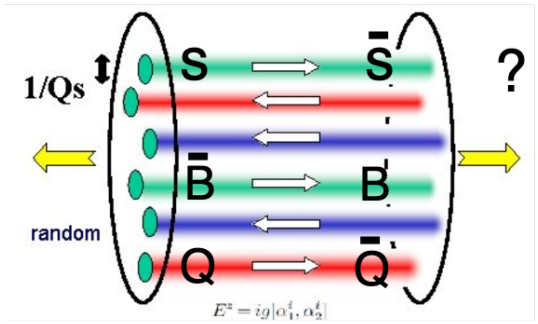
CMS-MTD simulation

Transverse *Initial state*

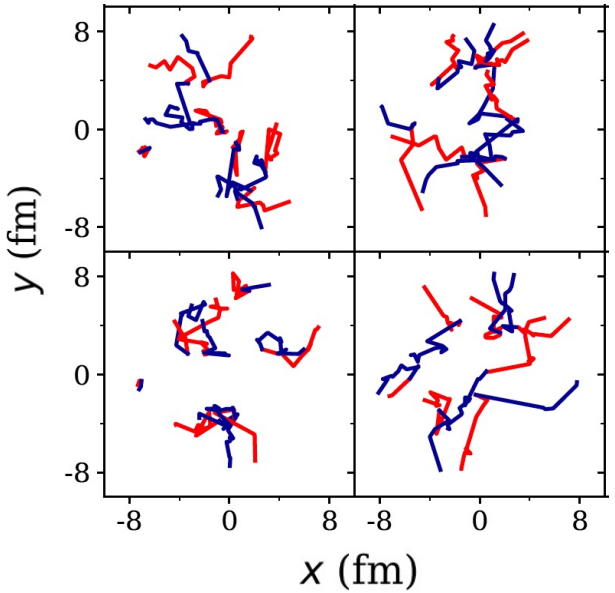


Longitudinal

arXiv:1801.08986,
arXiv:1911.10272



Diffusion in QGP

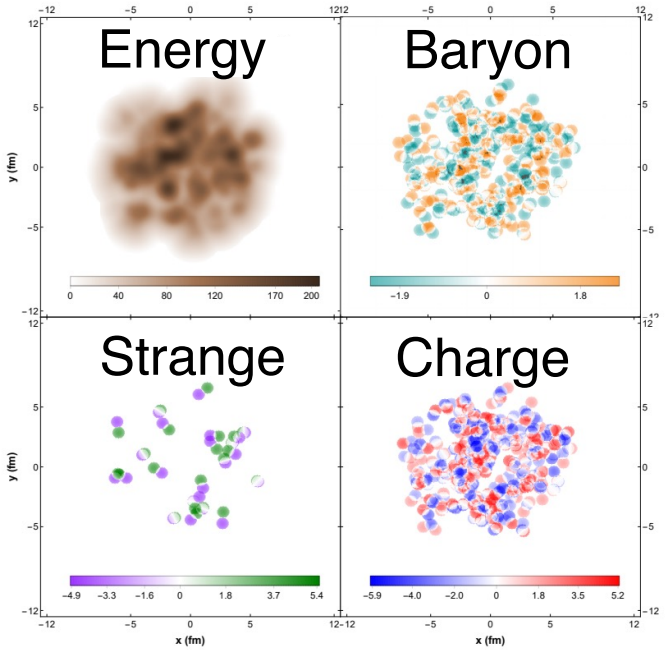


S. Pratt, C. Plumberg:
PRC 104, 014906 (2021)

Light-flavor diffusion: net-B, S, Q

CMS-MTD simulation

Transverse *Initial state*



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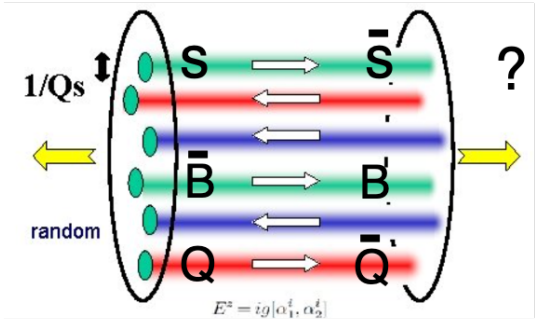
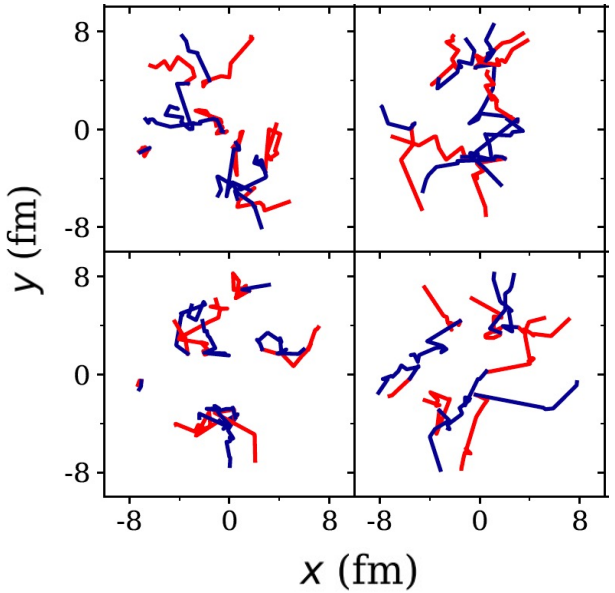
arXiv:1801.08986,
arXiv:1911.10272

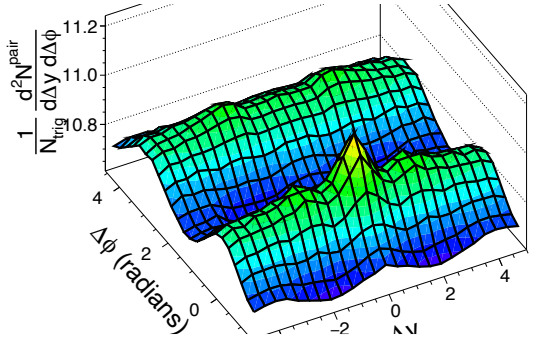


Diffusion in QGP

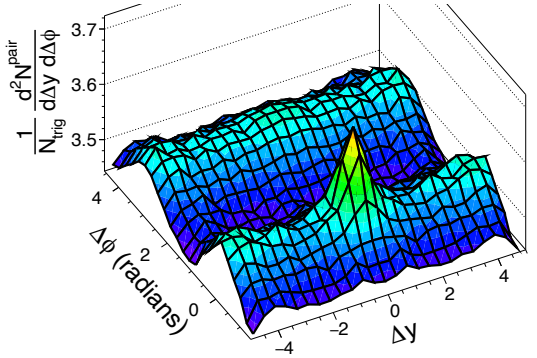


S. Pratt, C. Plumberg:
PRC 104, 014906 (2021)

$K^{+(-)}$-$K^{+(-)}$ vs. K^{+}-K^{-}



p-p vs. p-p̄ *Final state*



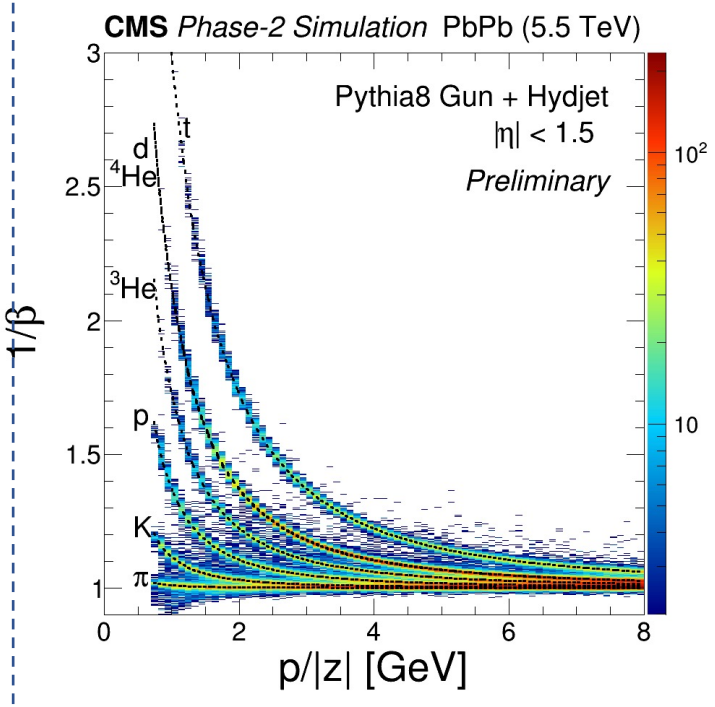
Long-range correlations with both (anti)particle identified

- Search at Δy>2,

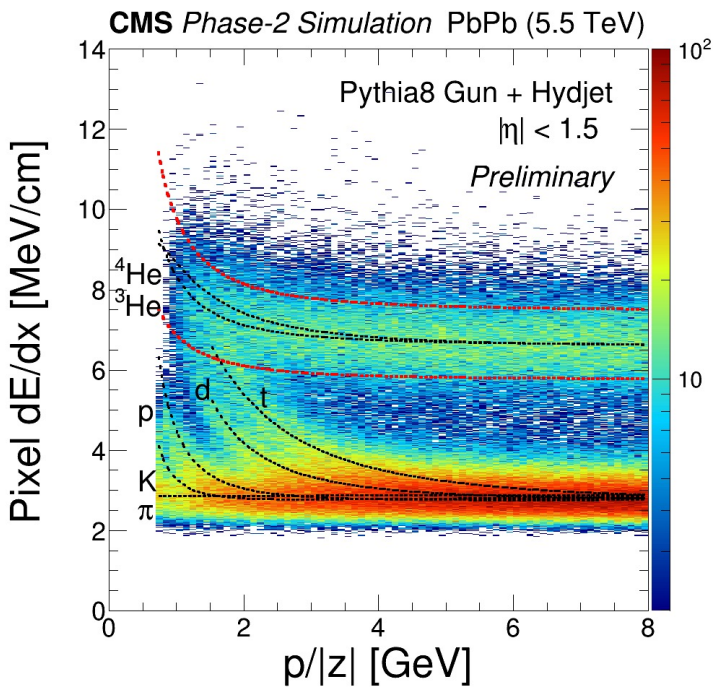
  v_2(SS) - v_2(OS) ∝ $\varepsilon_2^{(\mathcal{X},\mathrm{net})}\{2\} = \sqrt{\left\langle \left(\varepsilon_2^{(\mathcal{X}^+)} - \varepsilon_2^{(\mathcal{X}^-)}\right)^2 \right\rangle}$

A (hyper)(anti)light nuclei factory by MTD

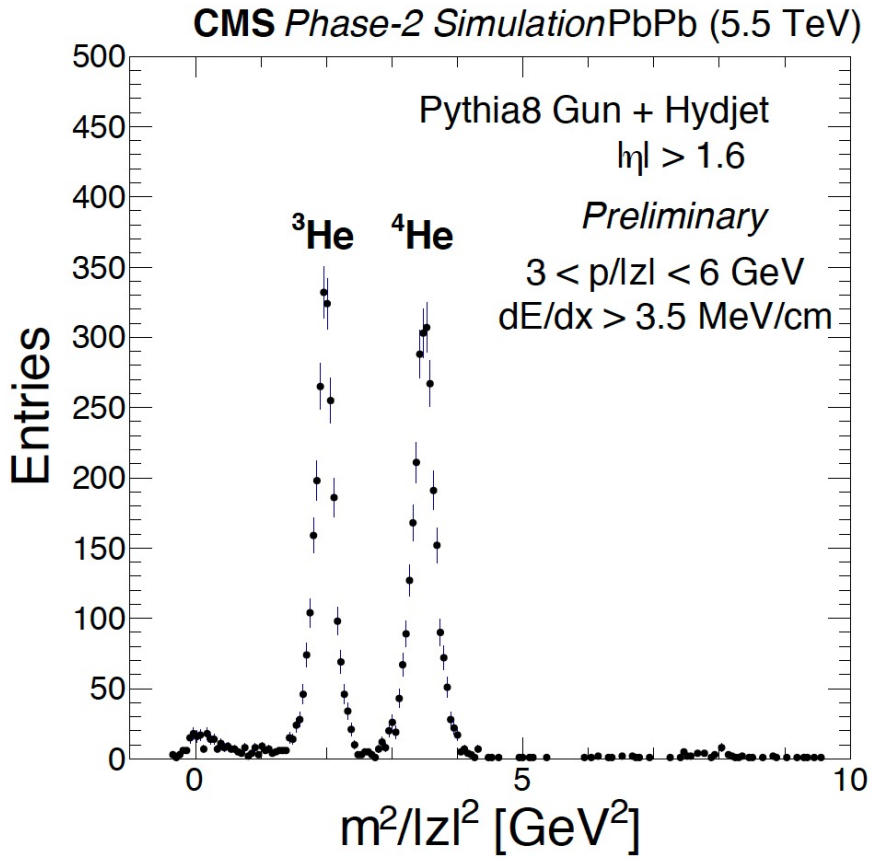
MTD TOF



Pixel tracker dE/dx

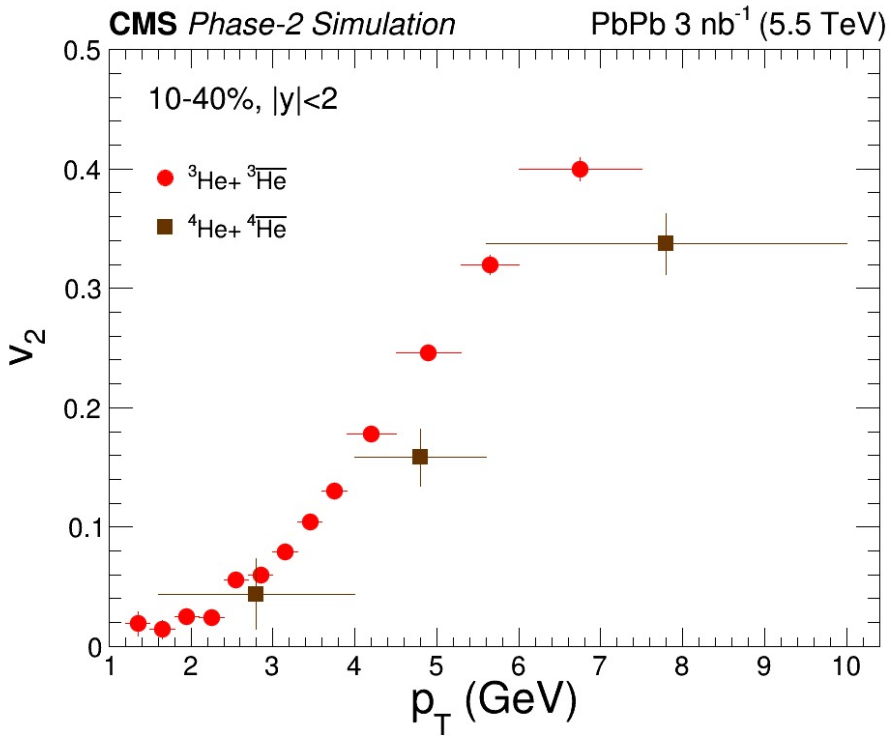


Light nuclei ID in pp/pA/AA



A (hyper)(anti)light nuclei factory by MTD

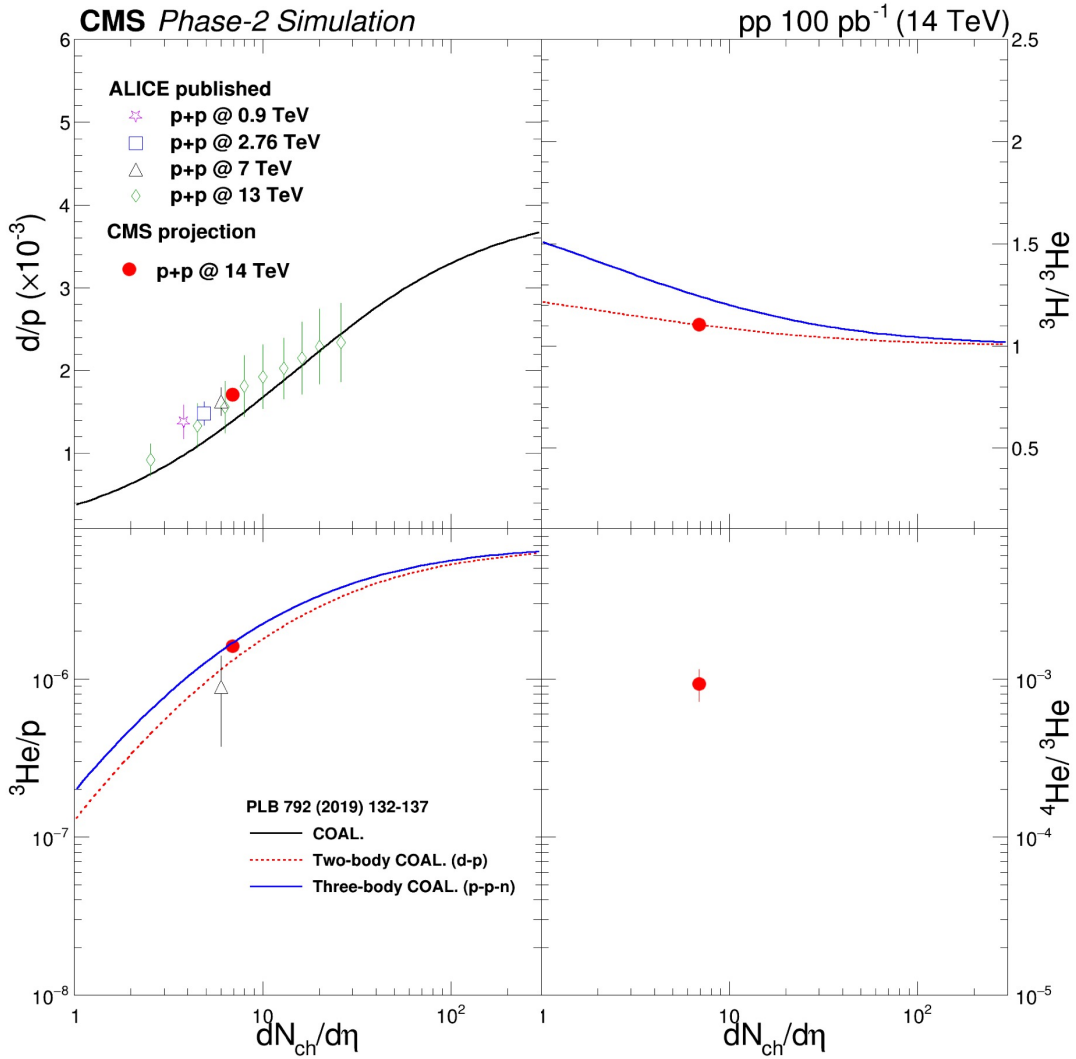
^{3}He/ ^{4}He flow in PbPb



Strong constraints to light nuclei production in pp, pA, AA

(SHM vs. coalescence)

~ 10 trillion/year MB pp recorded

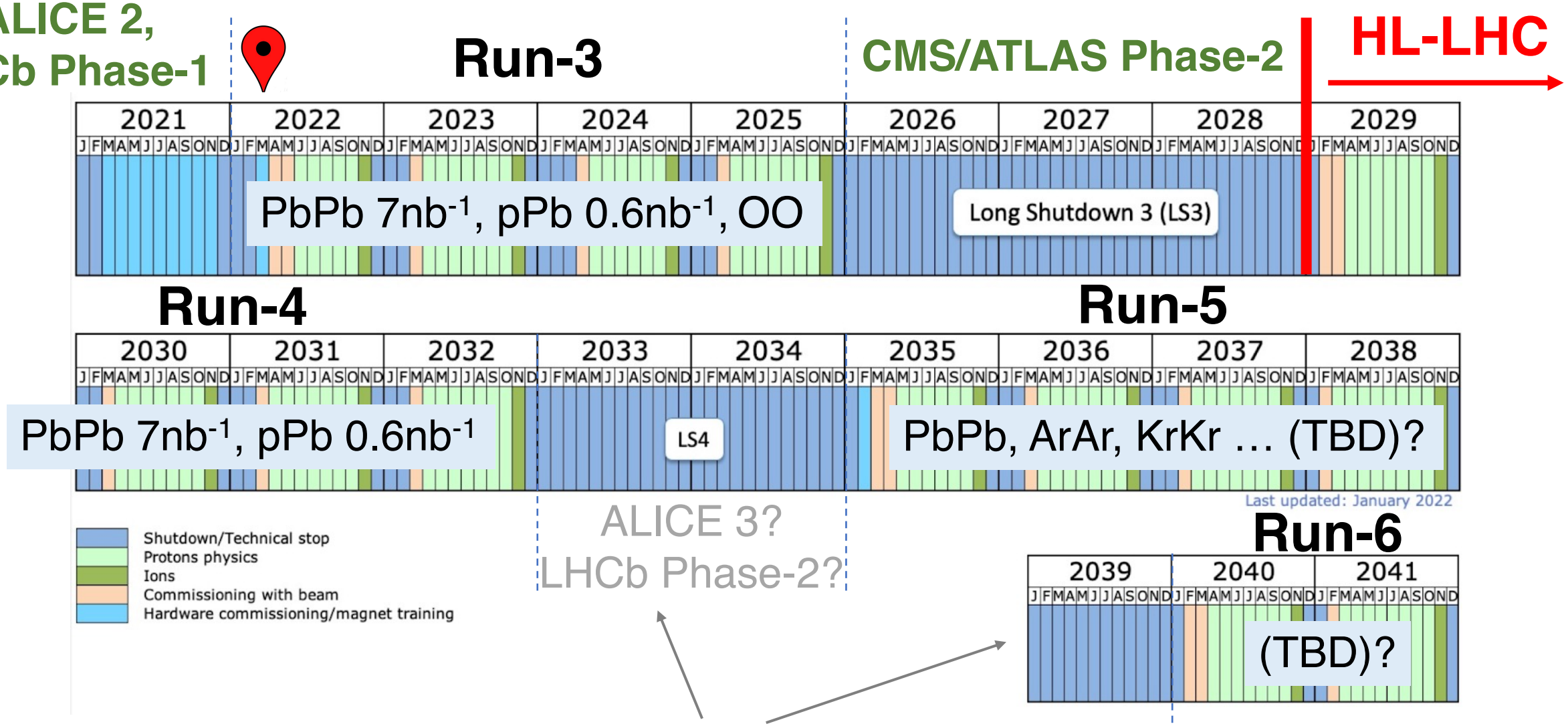


A rich program by CMS and MTD at HL-LHC

Unique science goals	Key observables
QGP medium response to parton energy loss	• Jet-hadron correlations to $\Delta r>1$ with PID
(3+1)D heavy flavor dynamics and hadronization in QGP	• HF baryon/meson yields and collective flow (v_n) vs y, p_T
Fluctuations and transport of conserved quantum charges in QGP	• Long-range PID two-particle correlations in Δy and $\Delta\phi$ • Charge balance function to $\lvert\Delta y\rvert>2$ • High-order cumulants (C_4) vs y_{max}
Origin of collectivity in small system	• LF and HF collective flow (v_n)
Mechanism of light nuclei production over wide phase space	• Light nuclei yields and collective flow (v_n) vs y and p_T

⋮

and be prepared for surprises!

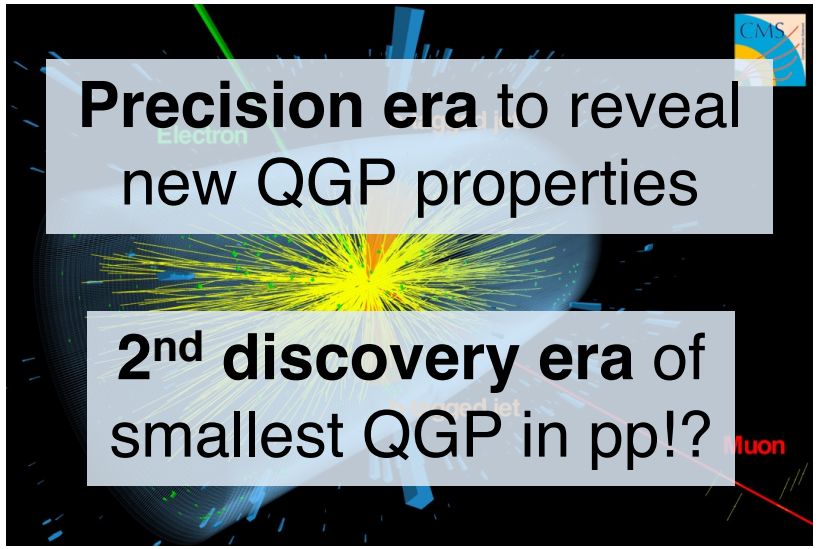


- Potential "phase-3" opportunities?
  - PID for p_T<0.7 at |η|<1.5: iBTL with LGADs? (or lower B to 2T).

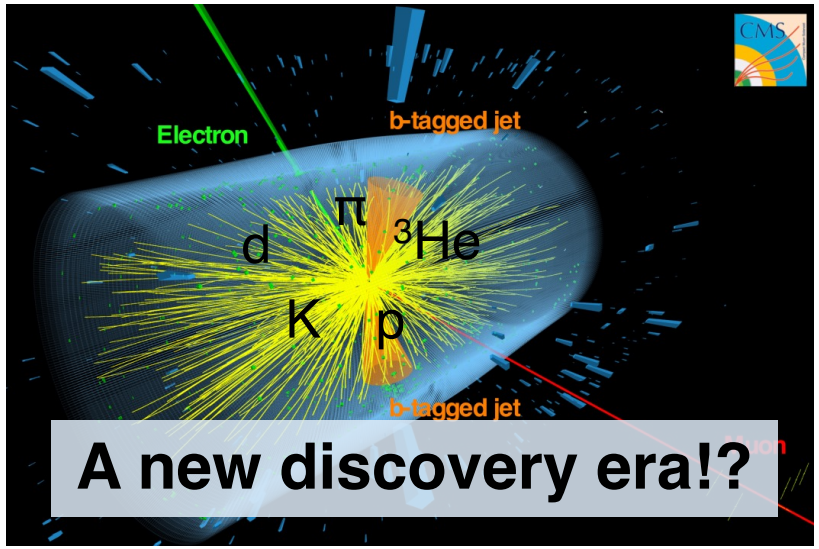
“Little Bangs”

2000: RHIC

2009: LHC



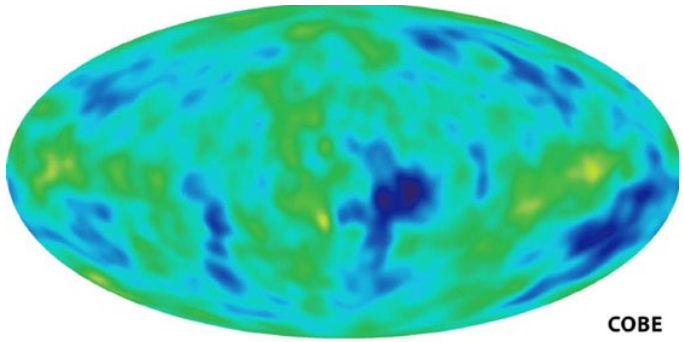
2030+: HL-LHC

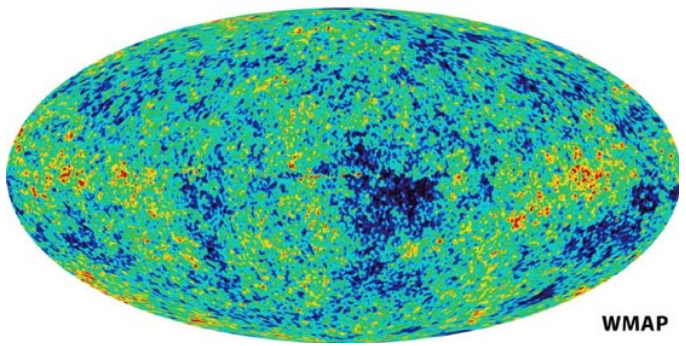


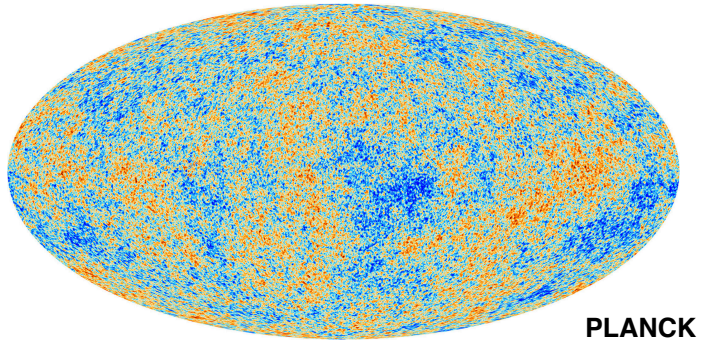
Approaching true-level event info.

t

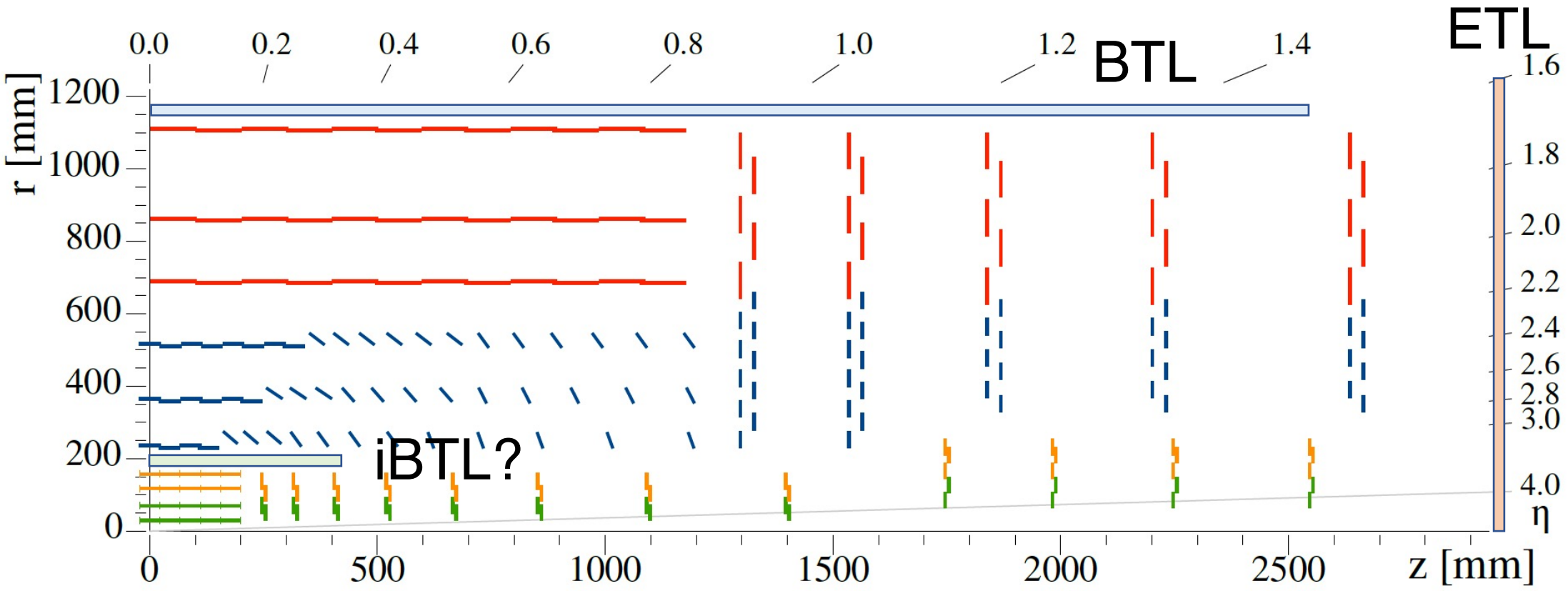
The Big Bang







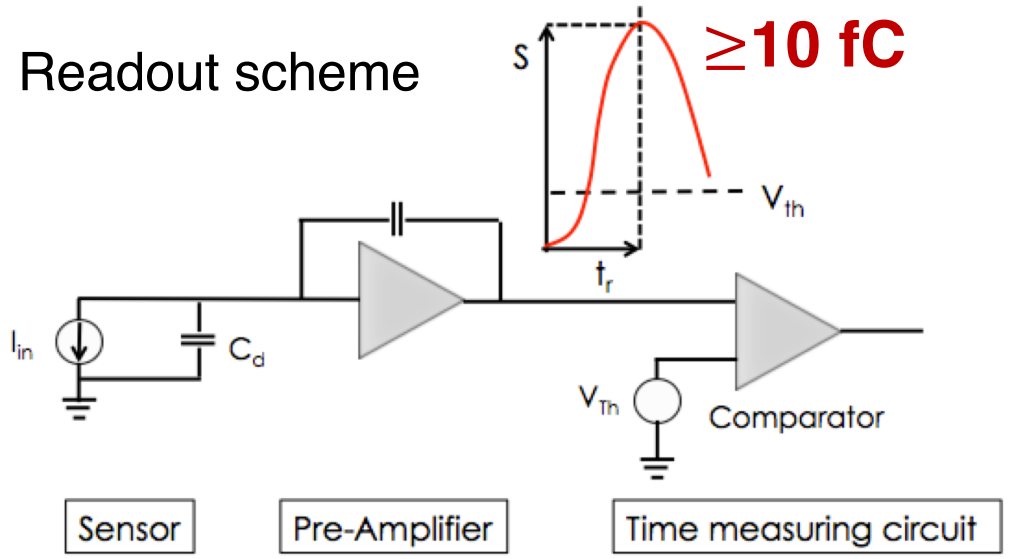
Backups



an iBTL at r=0.2 m using (AC-)LGADs?

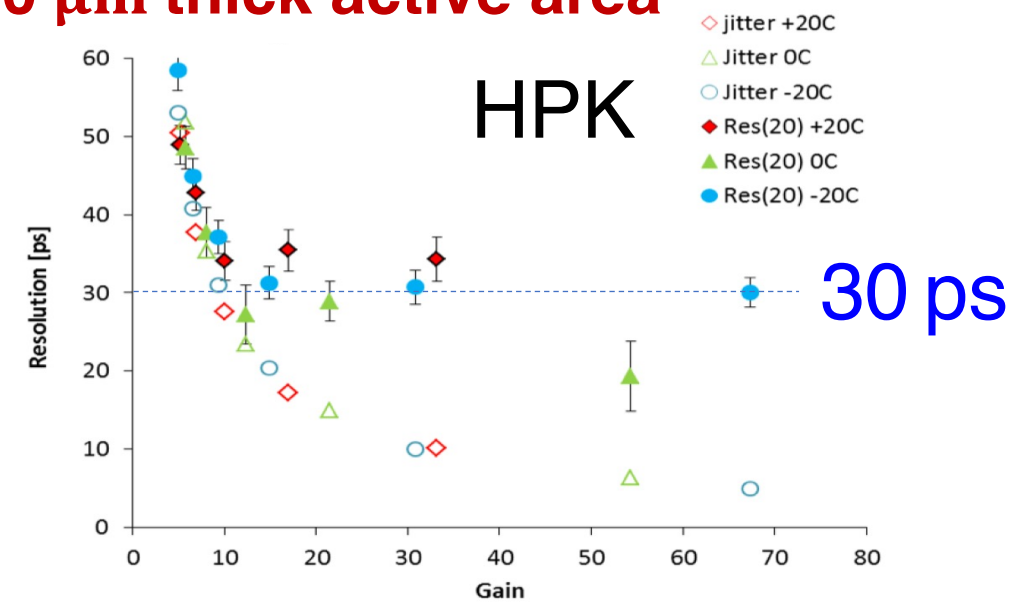
Low Gain Avalanche Diodes (LGADs)

Readout scheme



N. Cartiglia

50 μm thick active area

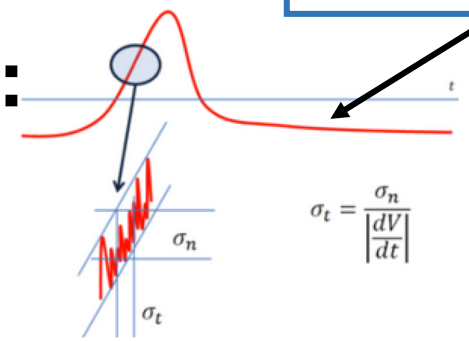


30 ps

$$\sigma_t^2 = \sigma_{jitter}^2 + \sigma_{ionization}^2 + \sigma_{shape}^2 + \sigma_{TDC}^2$$

subdominant

Jitter:

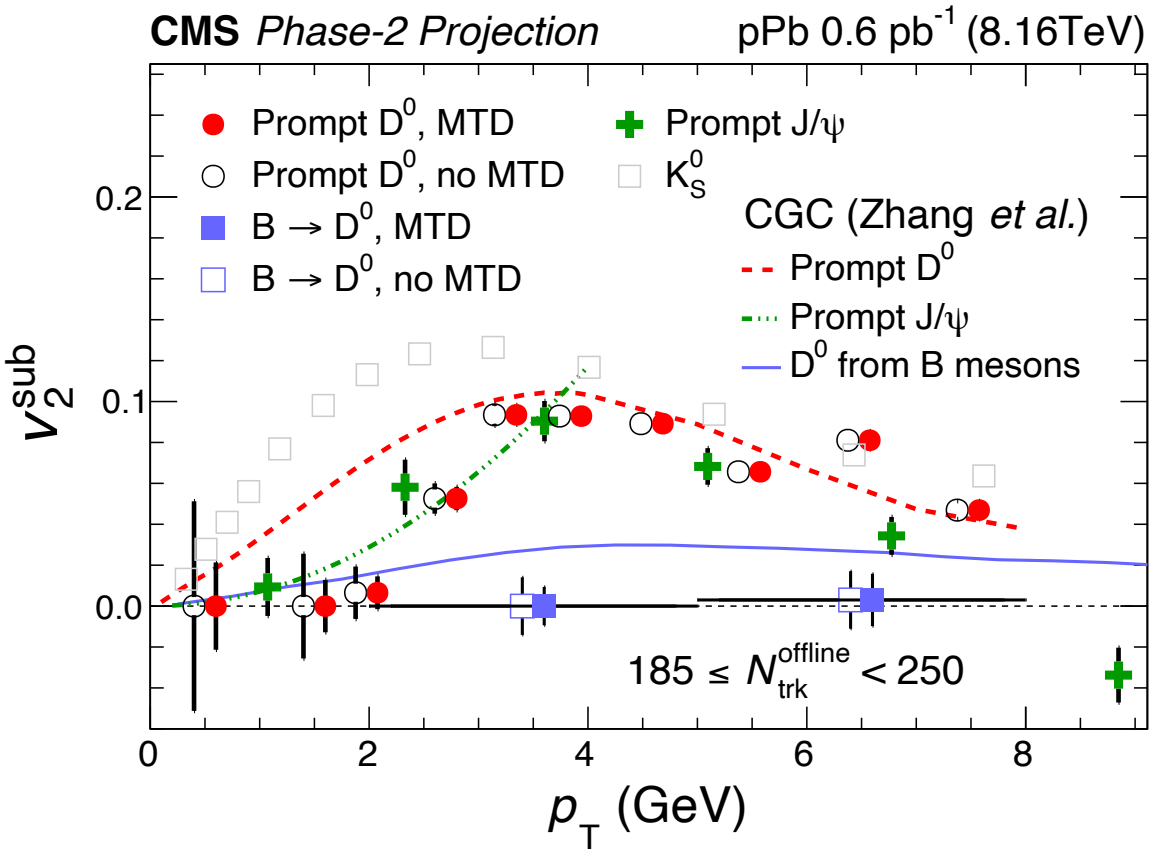


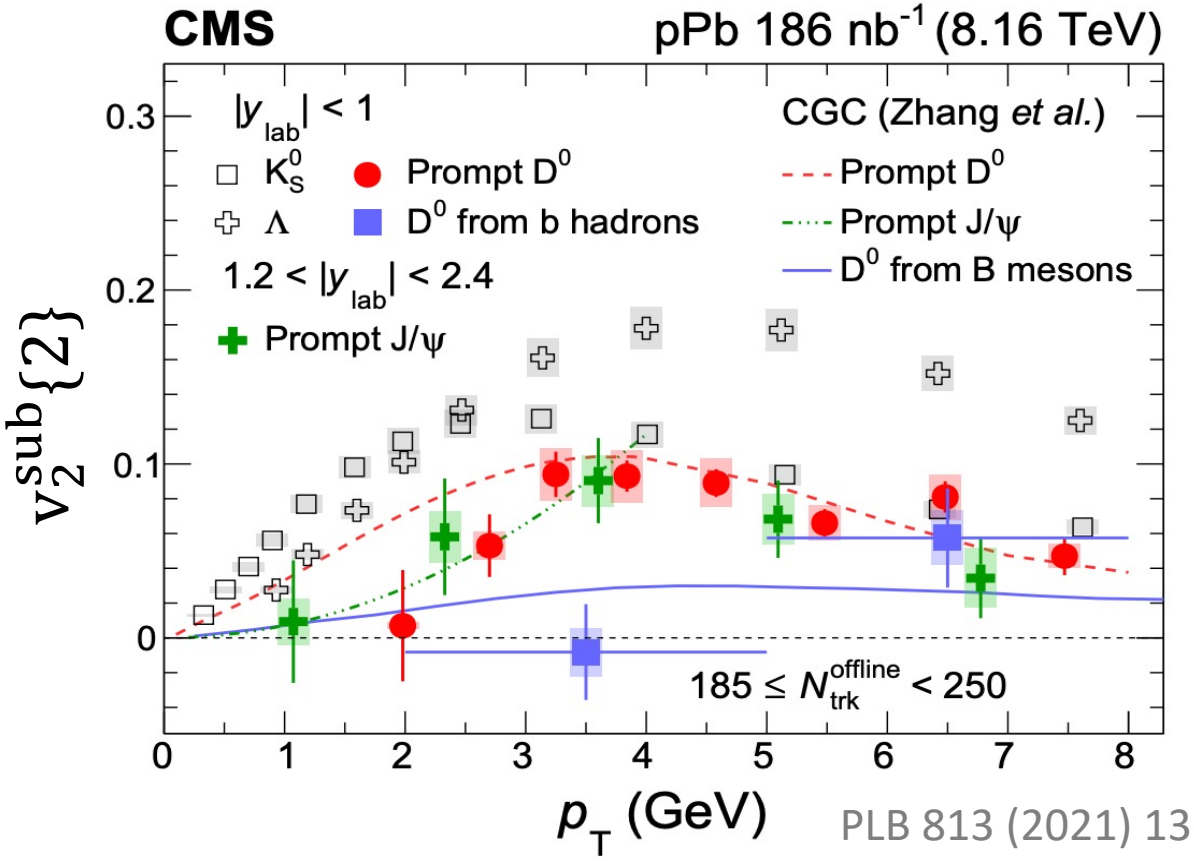
Need large dV/dt

Non-homogeneous energy deposition
– **"Landau noise"**

Emergence of collectivity in small systems

Heavy flavor collectivity at Run 2





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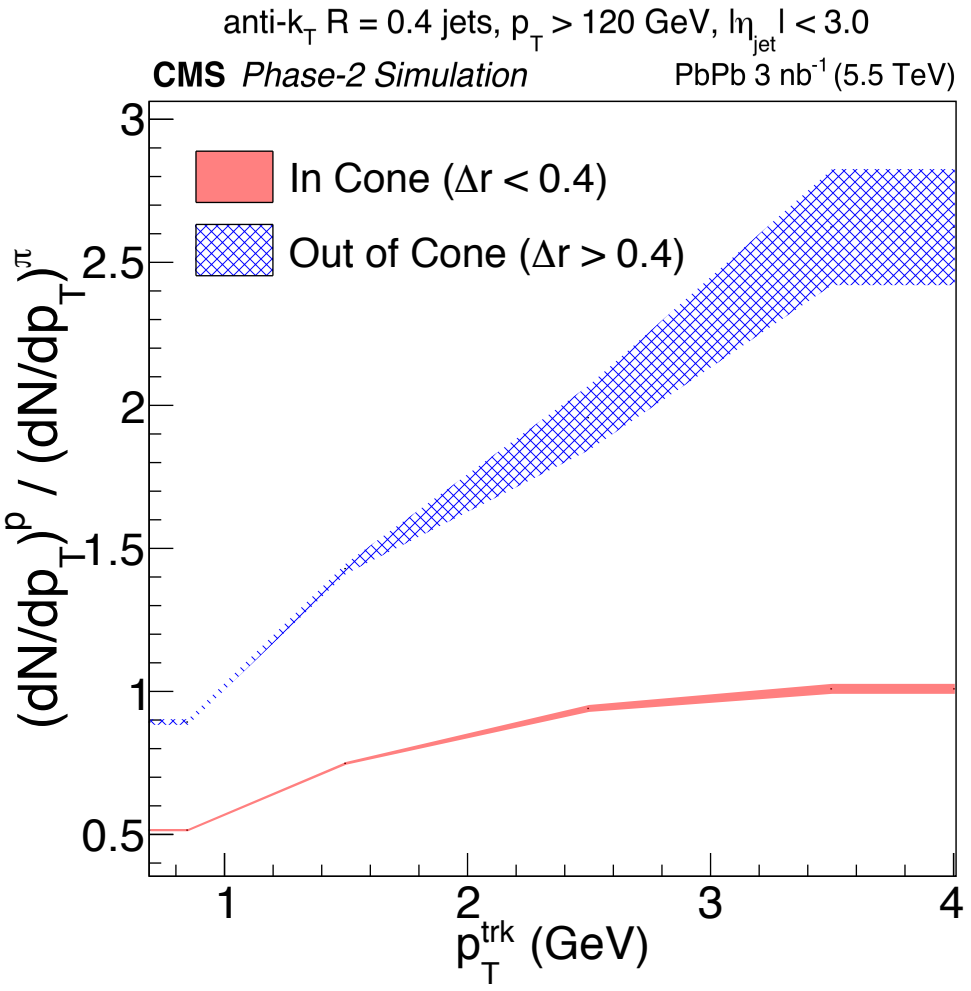
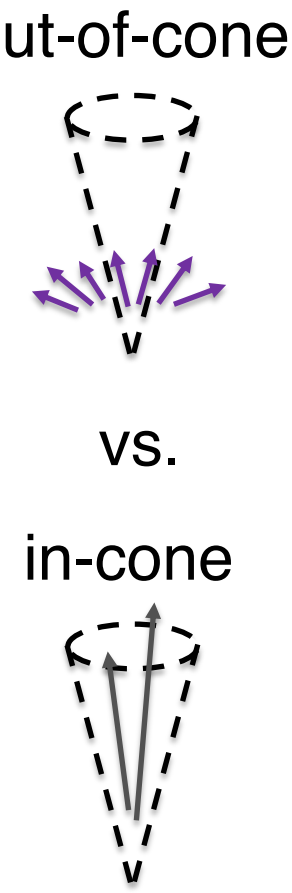
Medium response to jet quenching

Ratios of **PID** Jet yields in-cone vs out-of-cone

Can also be performed with γ/Z+jets





Unique measurement only possible by CMS with the MTD!