CMS Experiment at the LHC, CERN
Data recorded: 2018-Nov-08 20:48:06.756040 GMT
Run / Event / LS: 326382 / 309207 / 7

Particle Identification at the CMS experiment

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India+ lecture

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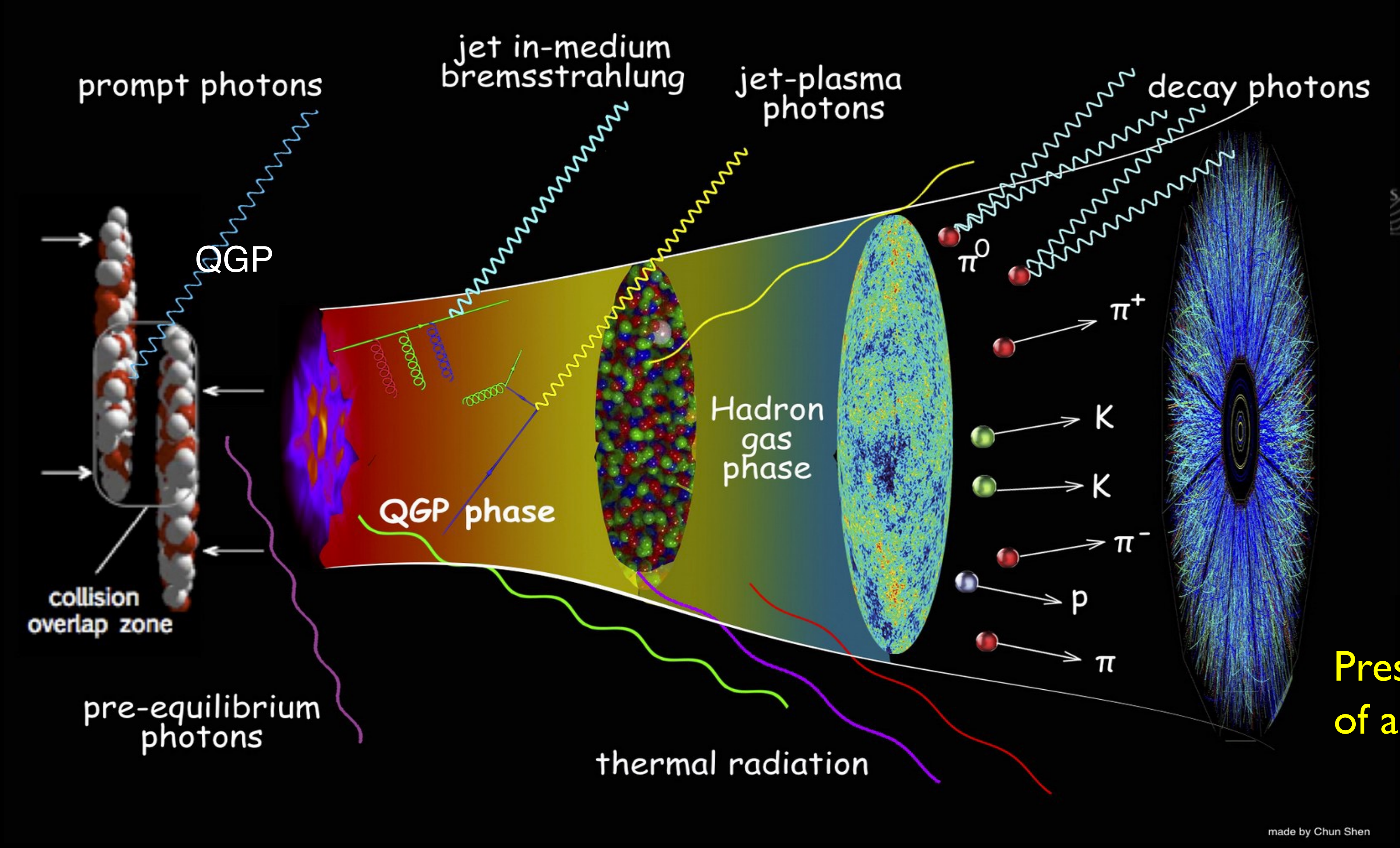
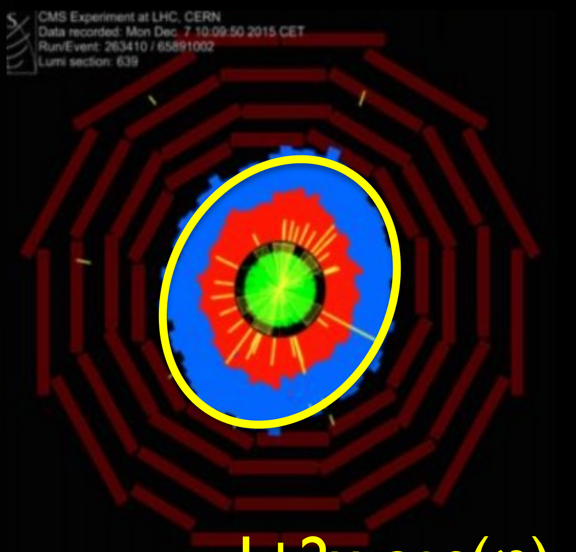
Outline

- CMS experiment at the LHC
  - Sub-detector systems
  - Particle Identification technique and performance
- Highlights of results with PID from ion runs 1 and 2
  - Collectivity in small systems
  - Heavy flavor physics
- Upgrades for the High Luminosity LHC (2029) on PID

“Little Bangs” in the laboratory



Elliptic flow (v_2)

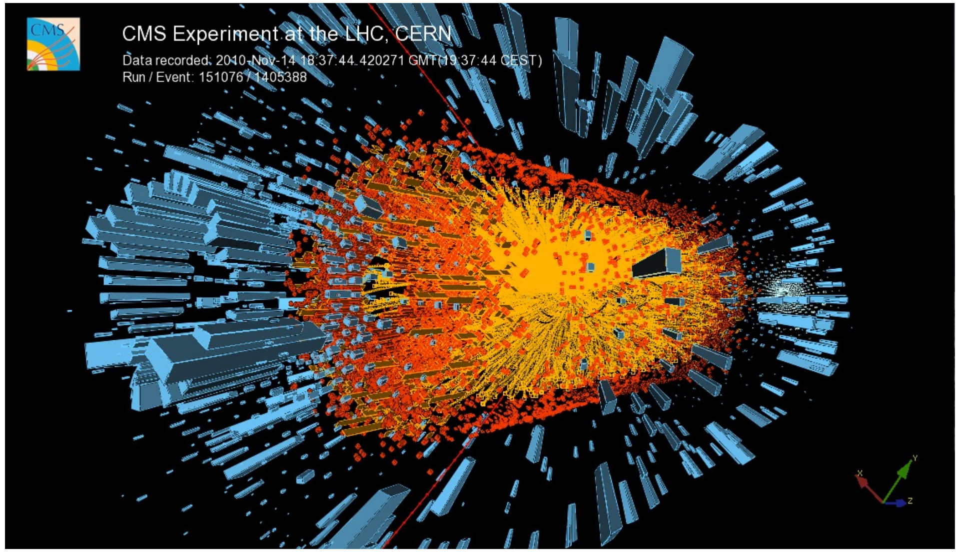


$\sim 1+2v_2\cos(\varphi)$

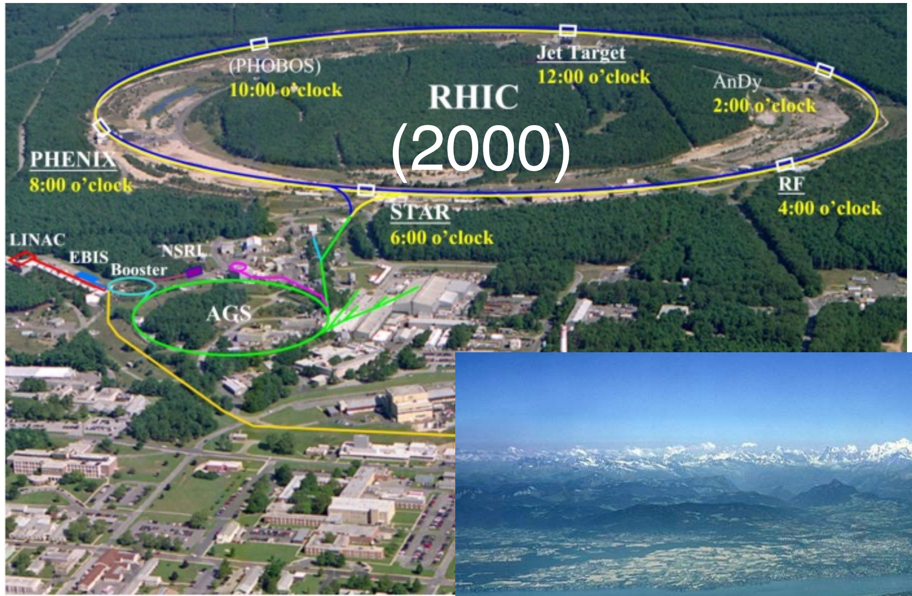
Pressure-driven expansion of a liquid-like QGP

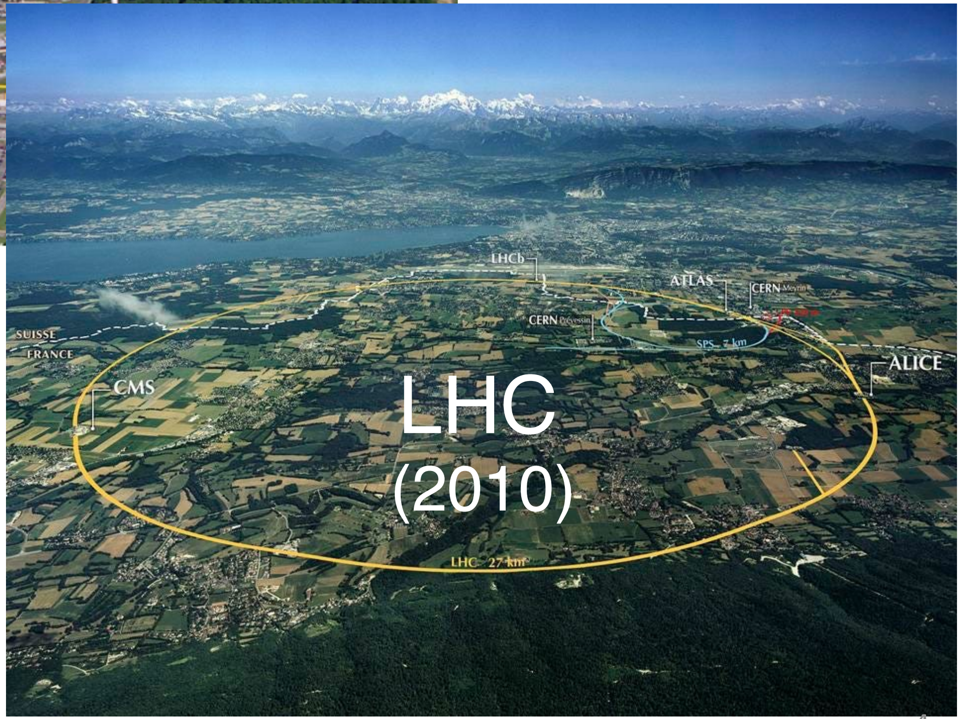
“Little Bangs” in the laboratory

Heavy Ion Collisions



Most violent collisions



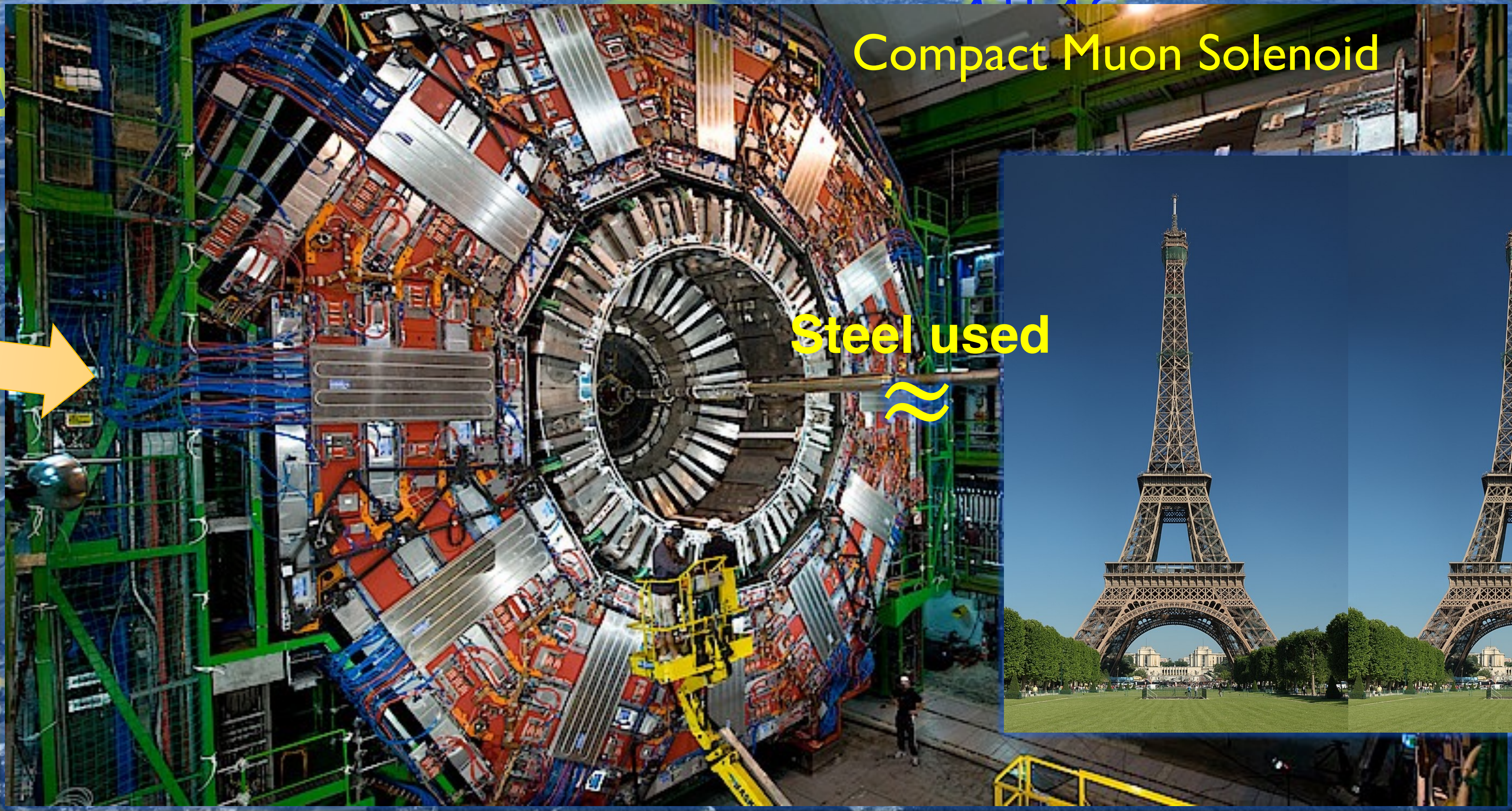


Re-creating the Little Bangs!

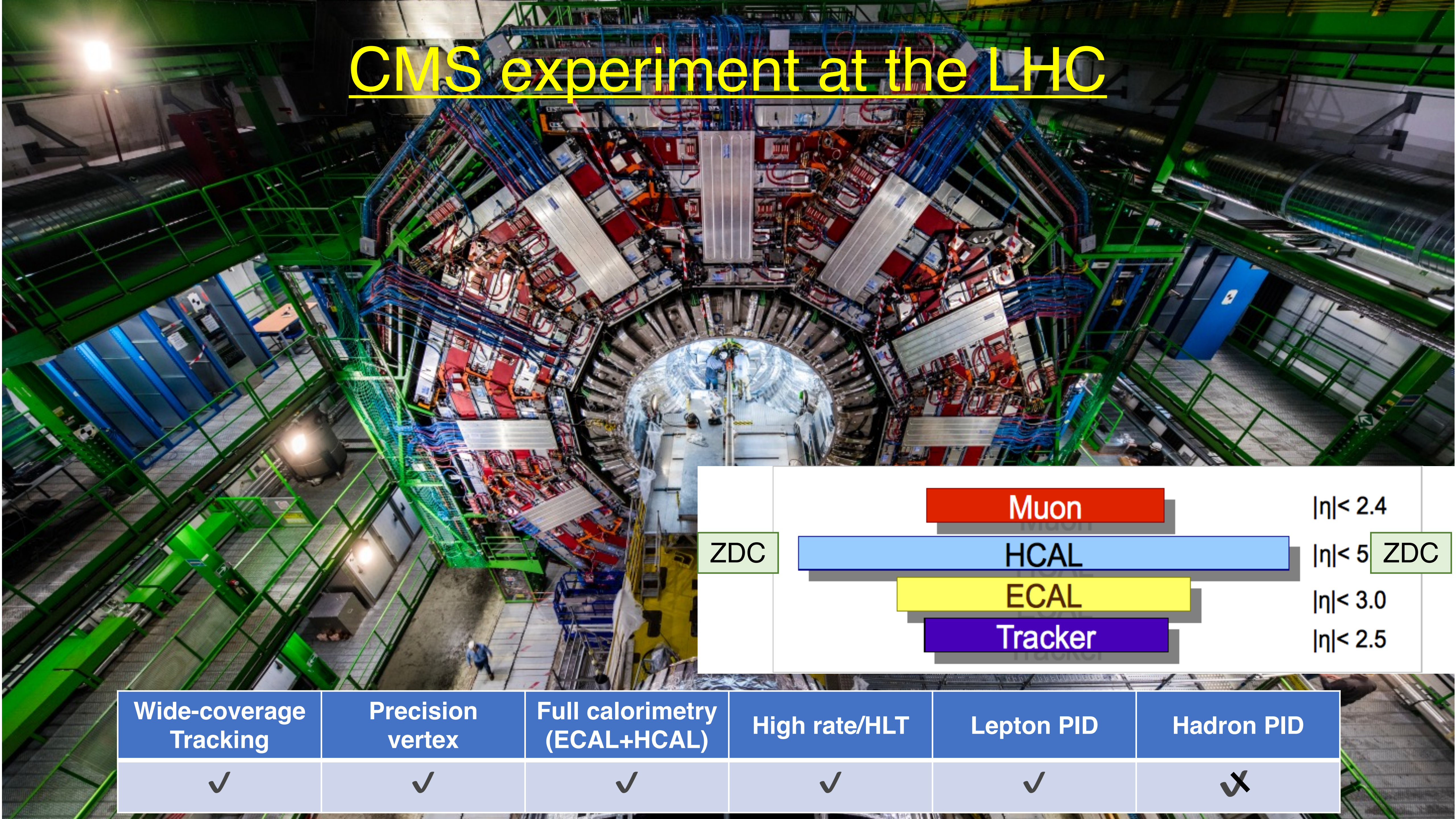
Large Hadron Collider at CERN
– energy frontier of nuclear and particle physics

(85% pp and 15% heavy ions)

Topic today

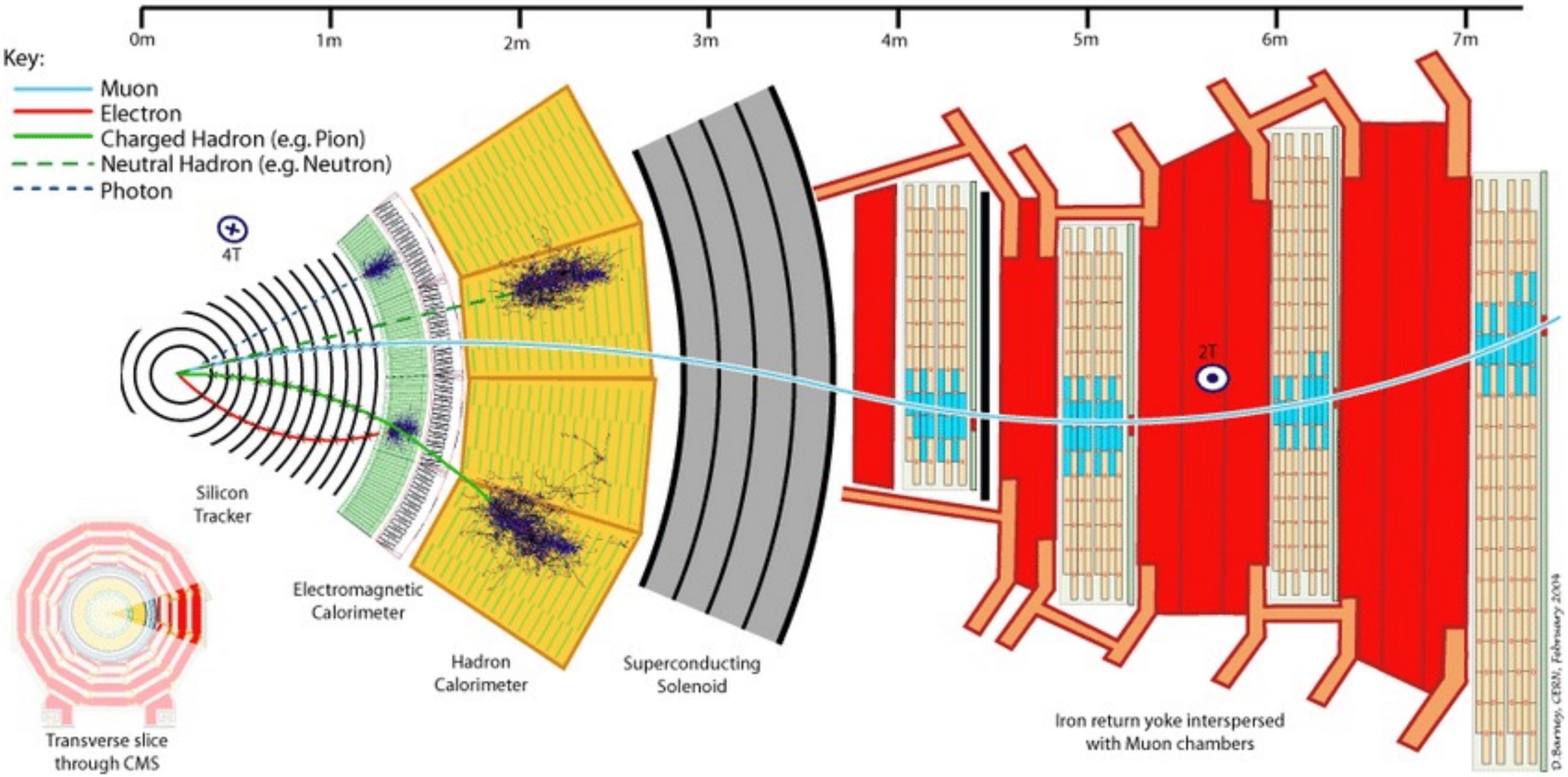


CMS experiment at the LHC



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

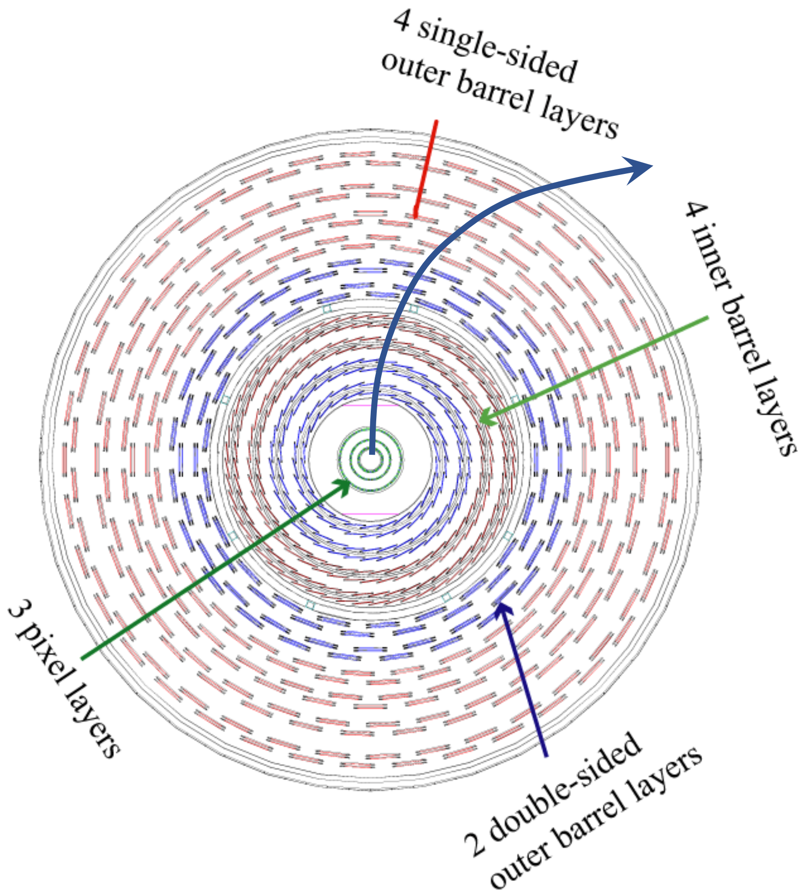
QGP detectors at the LHC (present)

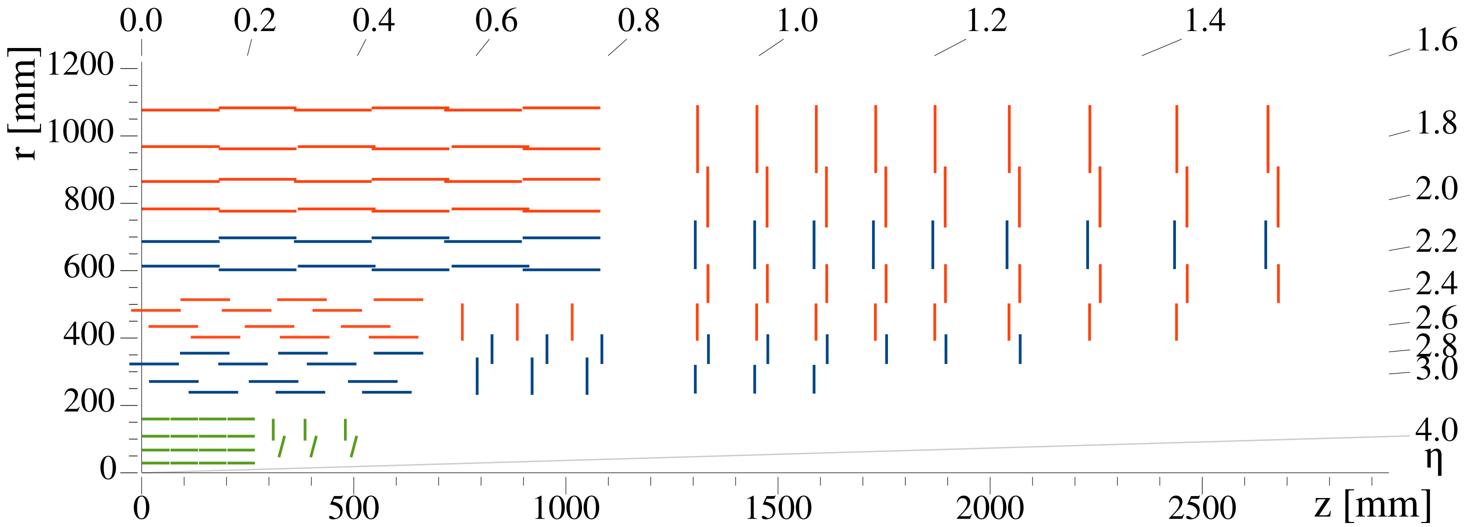


The All Silicon Tracker

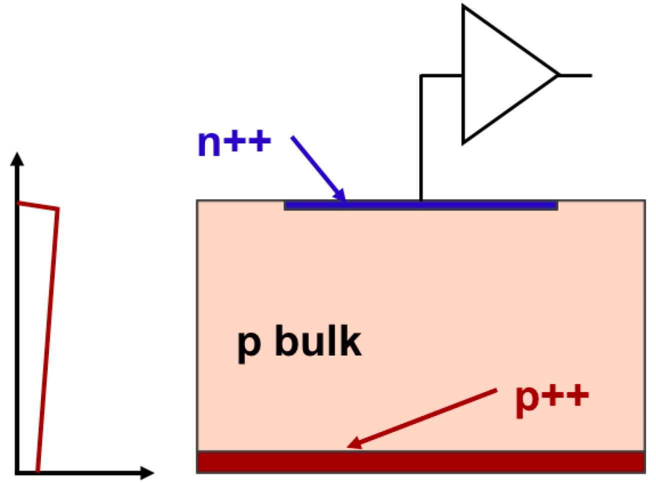
220 m^2 of Silicons!

The All Silicon Tracker





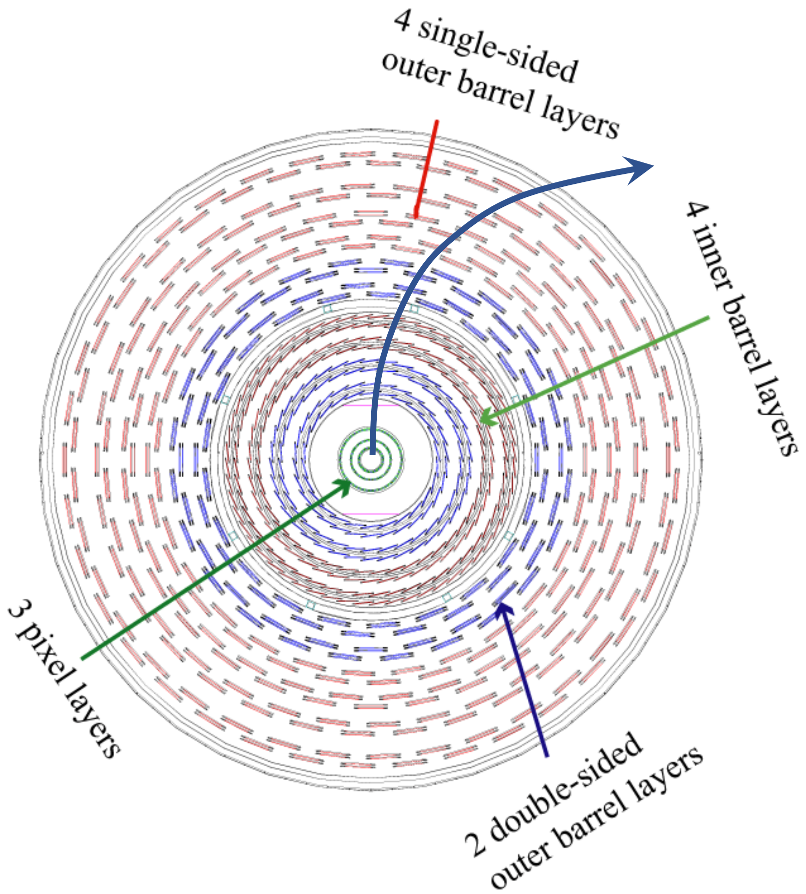
$$\frac{\sigma_{p_T}}{p_T} = \sqrt{\frac{720}{N+4}}\frac{p_T\sigma_x}{\left(0.3L^2B\right)}$$



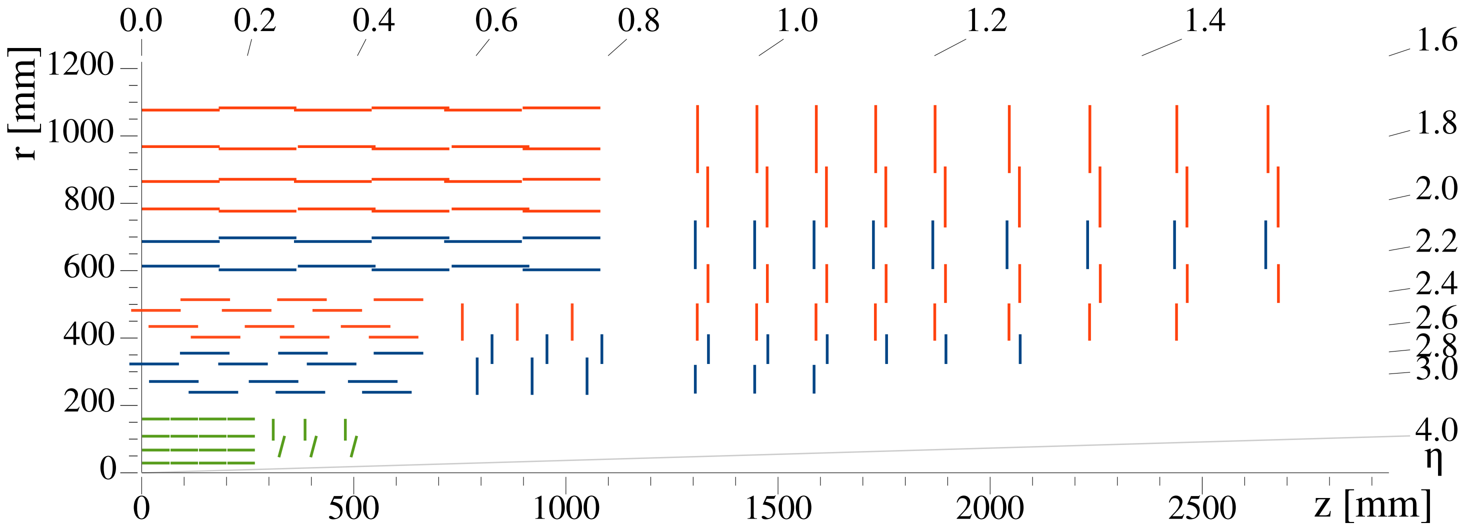
E field Traditional Silicon detector

Measure hit position and dE/dx

The All Silicon Tracker



$$\frac{\sigma_{p_T}}{p_T} = \sqrt{\frac{720}{N+4}}\,\frac{p_T\sigma_x}{\left(0.3L^2B\right)}$$



Silicon Pixels: 66 Mpix

Barrel (4) and Forward (3)

100 × 150 μm pixels

➢ $(\sigma_{r\phi}, \sigma_z) = (13, 25)\ \mu m$

Silicon Strips: 10 M channels

Tracker Inner Barrel (4)

+ Tracker Inner Disks (3)

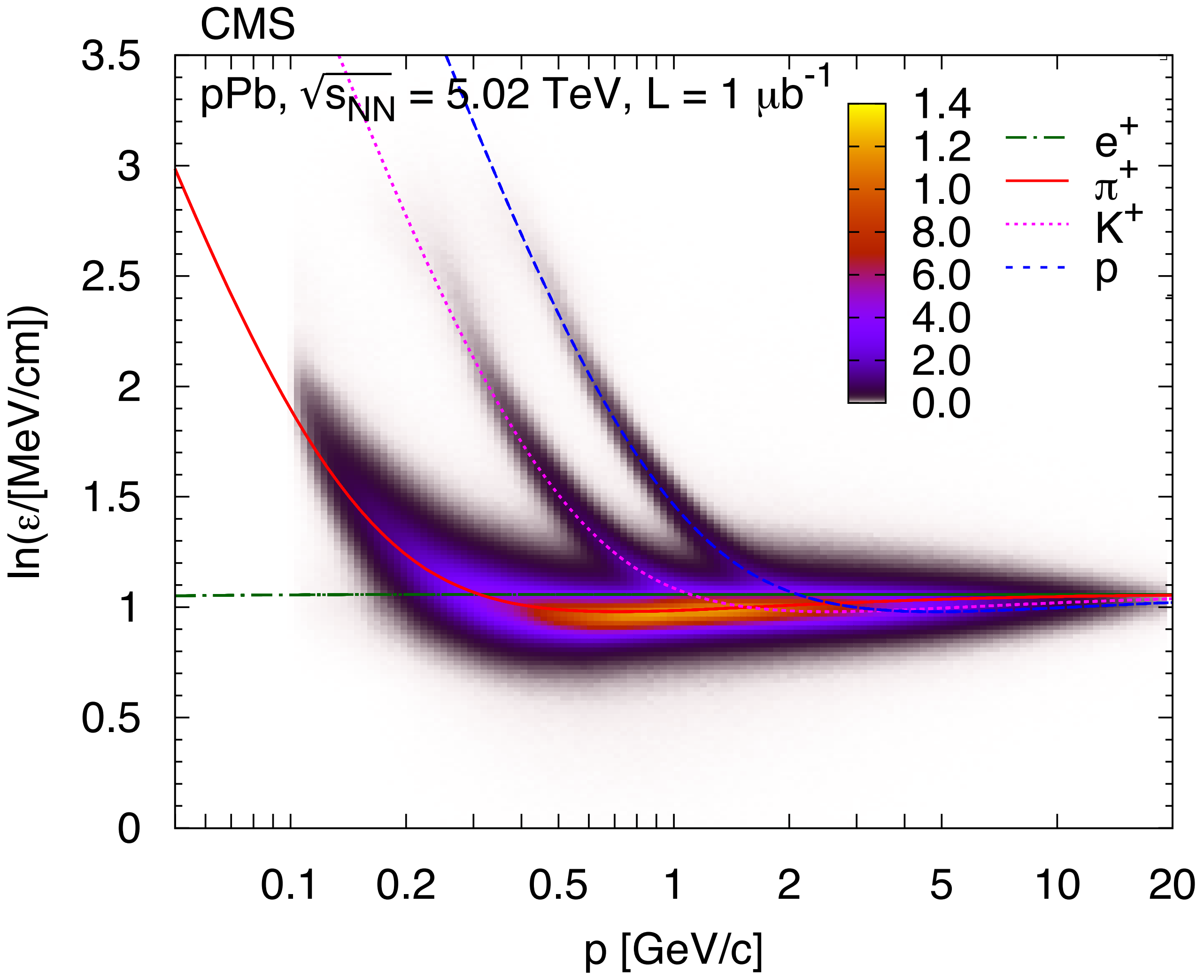
Tracker Outer Barrel (6)

Tracker Endcap Disks (9)

~100 μm pitch,

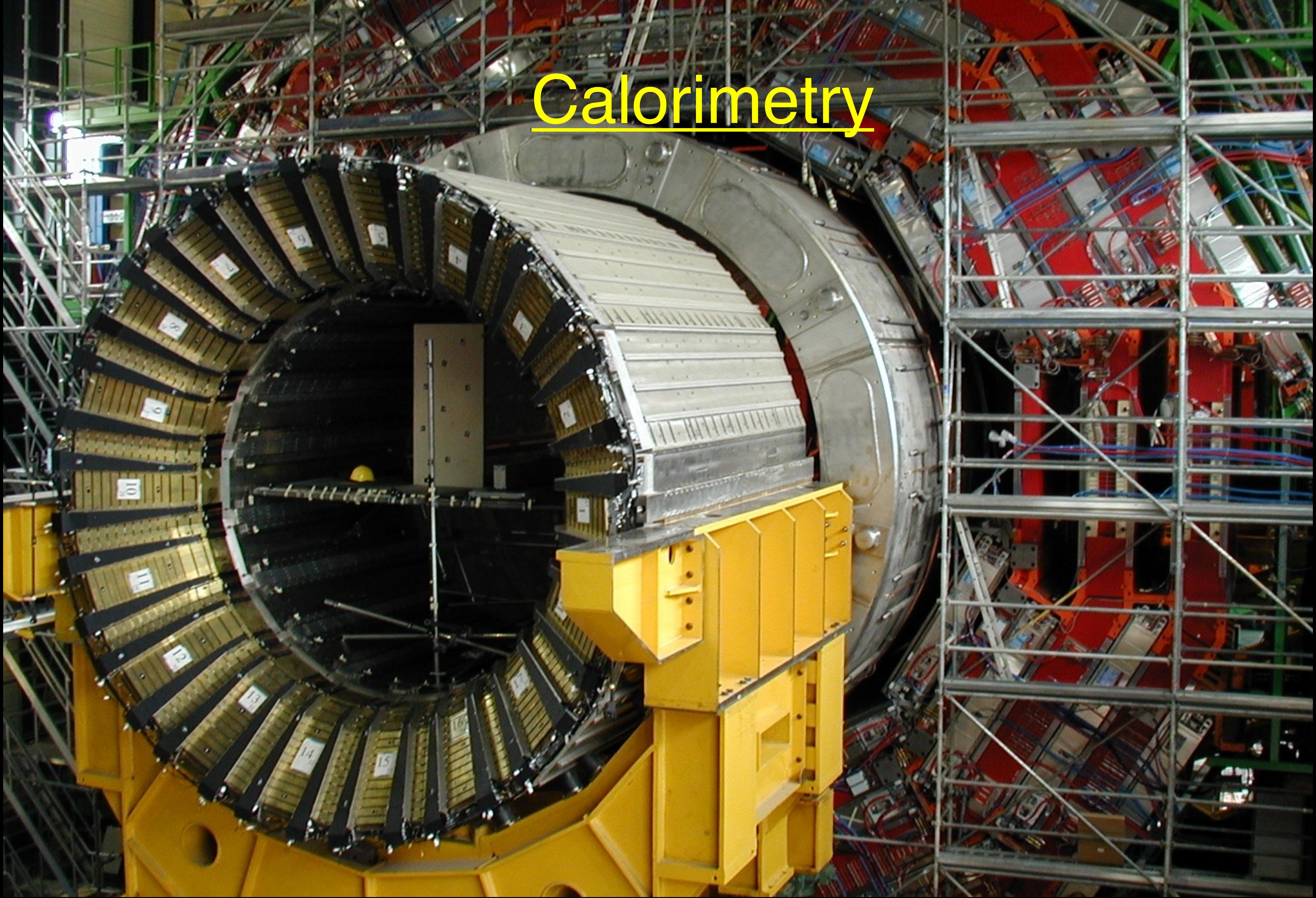
➢ σ_x ~ 20-40 μm

The All Silicon Tracker



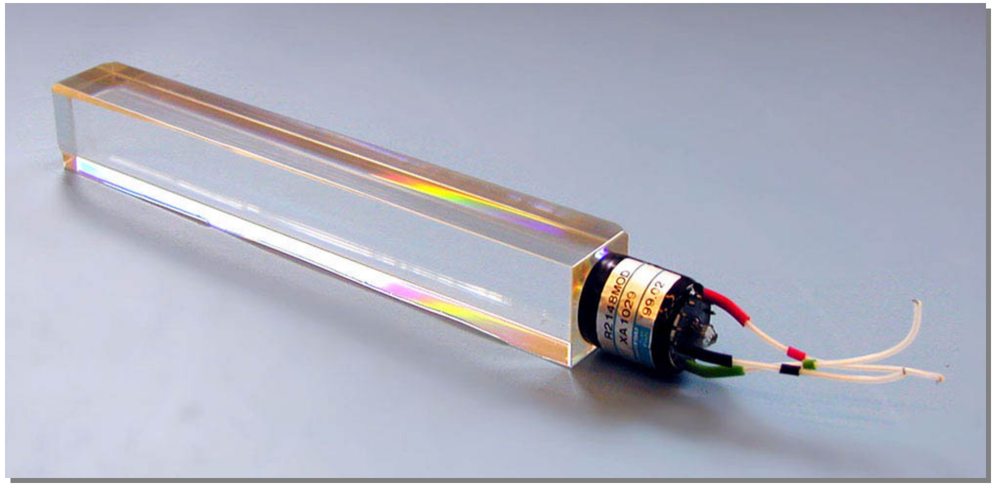
dE/dx PID up to p ~ 1.5 GeV

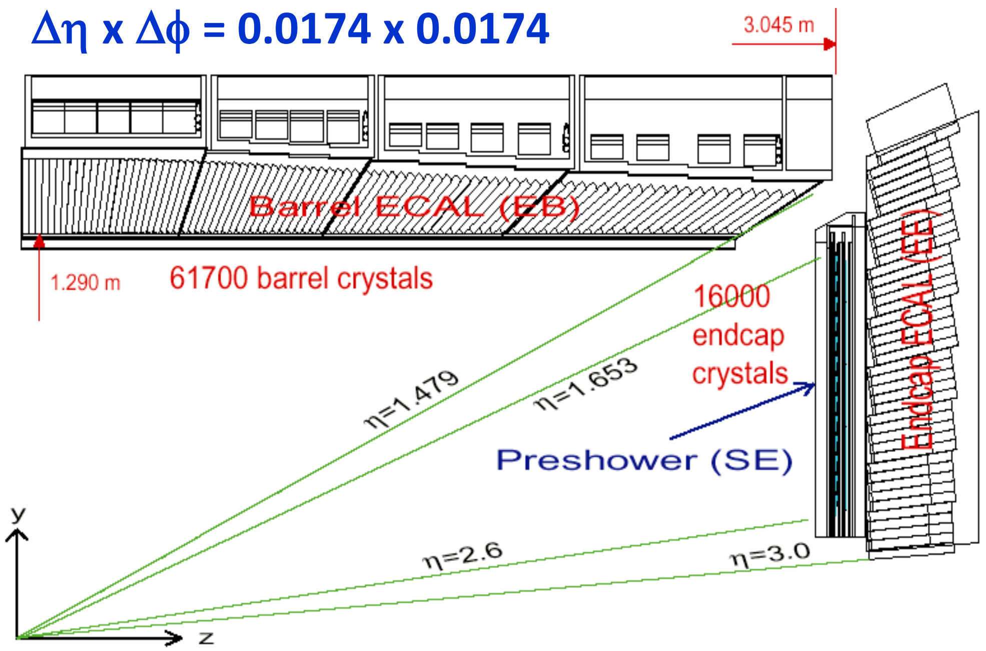
Calorimetry

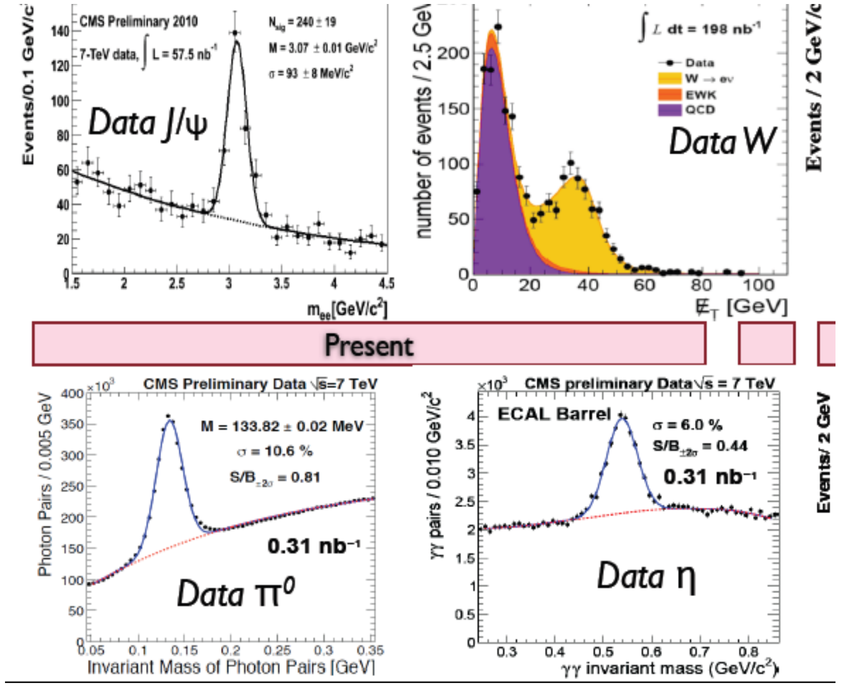


Eletromagnetic calorimeters

- Homogenous calorimeter
- ~76,000 $PbWO_4$ crystals
  - $2.3 \times 2.3 \times 23\ cm^3$, 3 lbs
- Radiation hard, dense, and fast
- B field and radiation require novel electronics APD, VPT





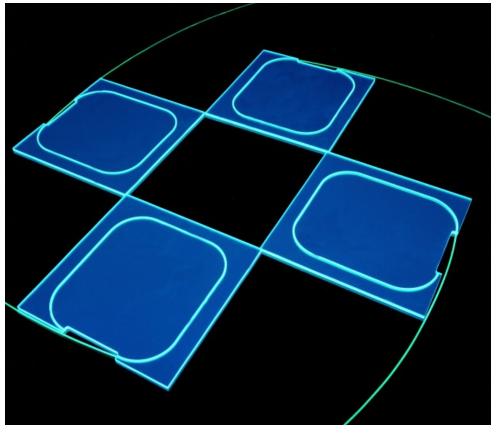


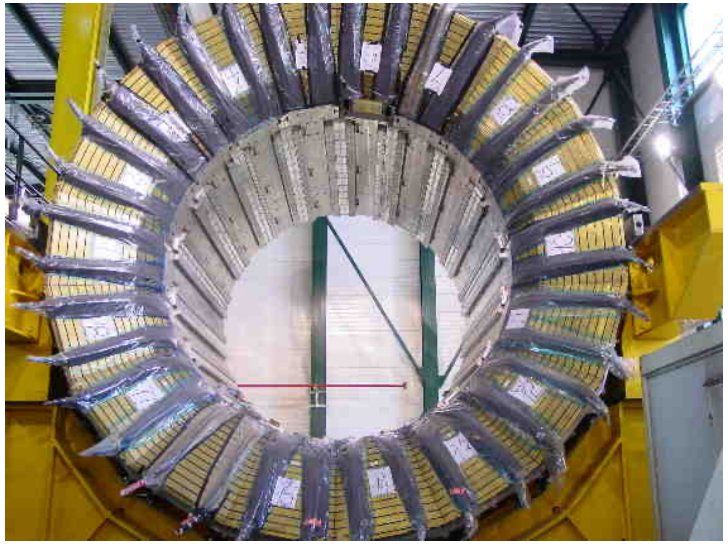
Eletromagnetic calorimeters

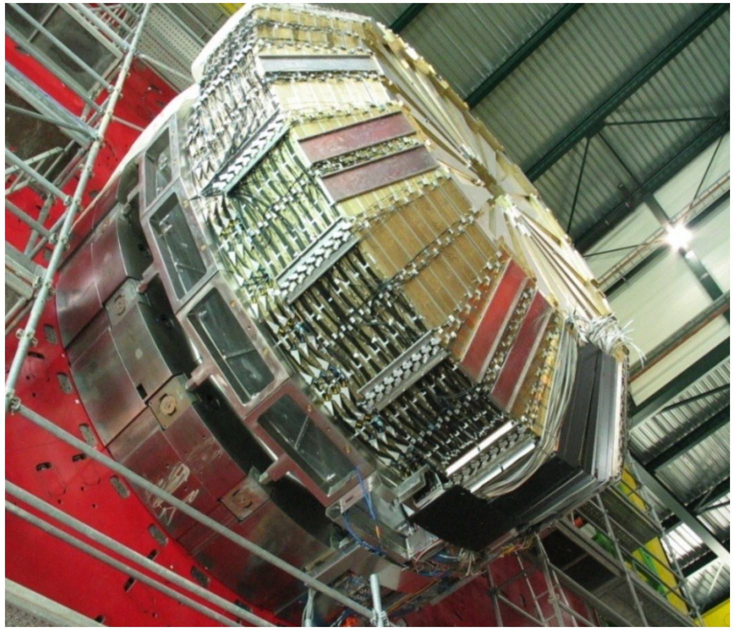
Endcap ECAL

Hadronic calorimeters

- Sampling calorimeter with Barrel, Endcap, and Forward
- HCAL Barrel (HB) and Endcap (HE):
  - Brass absorber from Russian artillery shells (non-magnetic)
  - Scintillating tiles with wavelength shifting (WLS) fiber
  - Read out by SiPMs
  - Tower size is $\Delta\eta\times\Delta\phi$ = 0.087× 0.087
    - Corresponds to 5x5 ECAL crystal grid
- HCAL Forward
  - Steel absorber
  - Cherenkov light from Quartz Fibers
  - Read out with PMTs



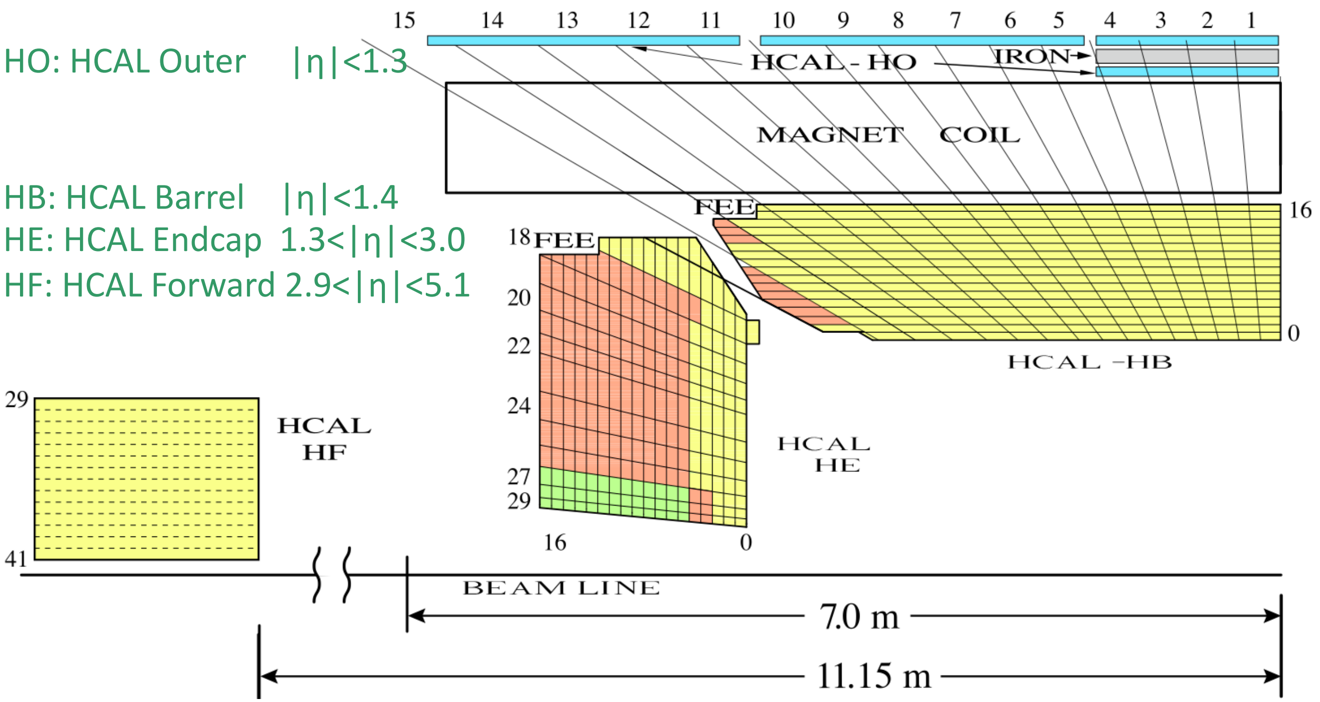


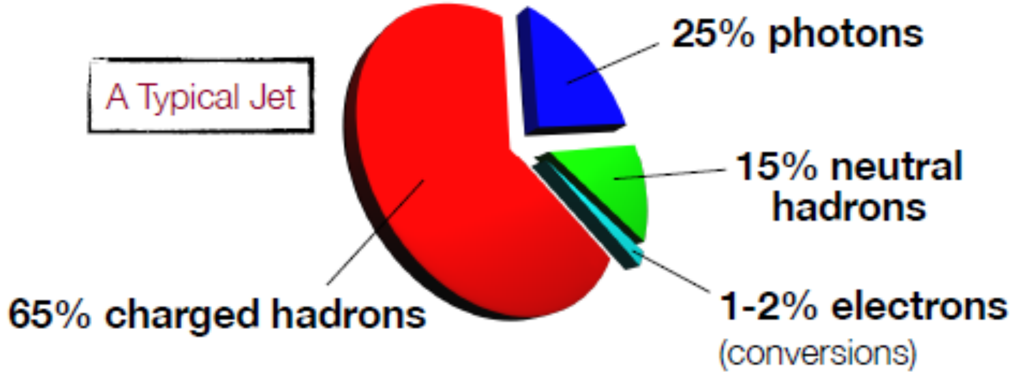


Hadronic calorimeters

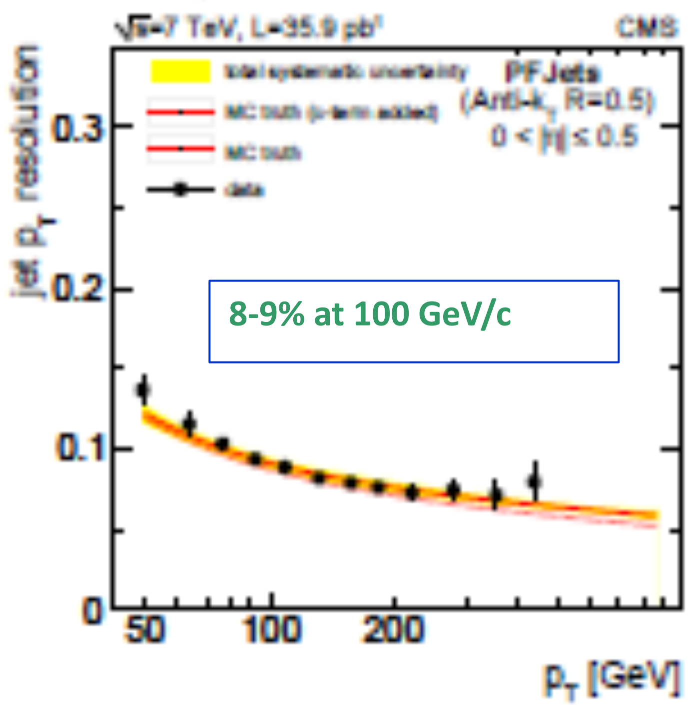
HO: HCAL Outer |η|<1.3

HB: HCAL Barrel |η|<1.4
HE: HCAL Endcap 1.3<|η|<3.0
HF: HCAL Forward 2.9<|η|<5.1





Jet Resolution



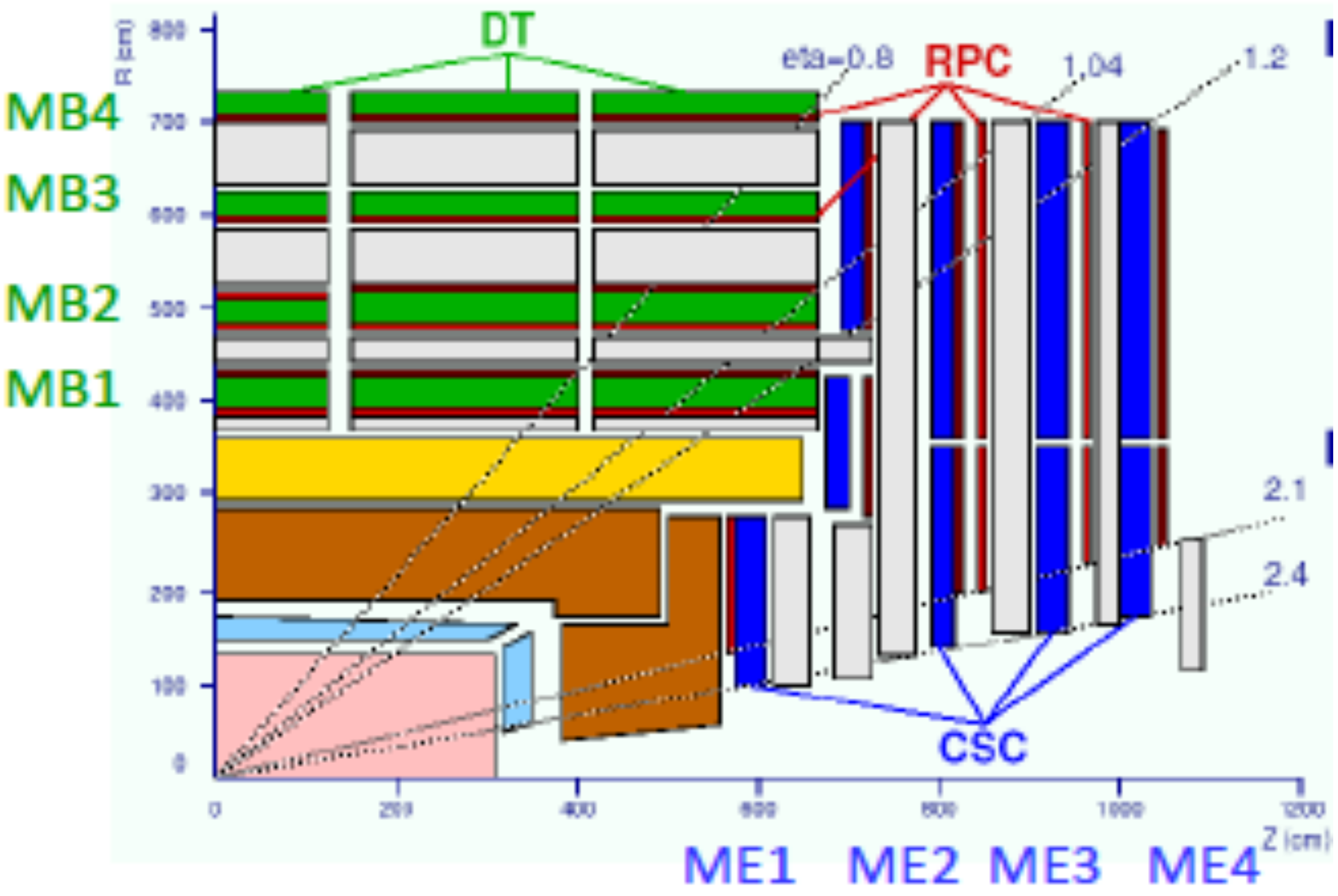
The Muon System

The Muon System

Three ionizing gas technologies:

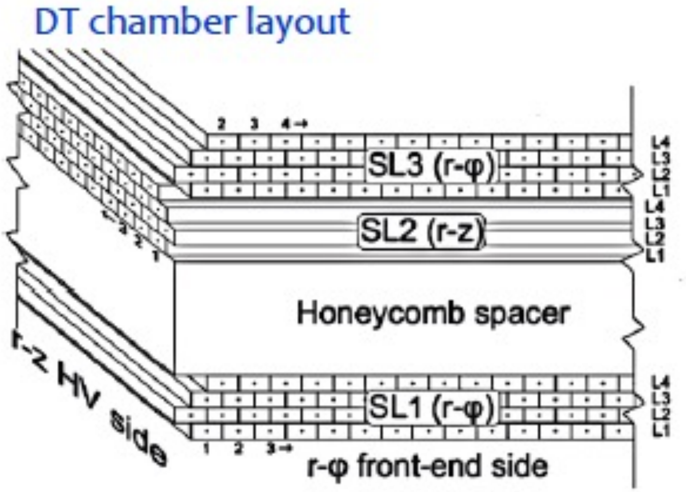
- Drift Tube (Barrel)
- Resistive Plate Chamber (Barrel, Endcap)
- Cathode Strip Chamber (Endcap)

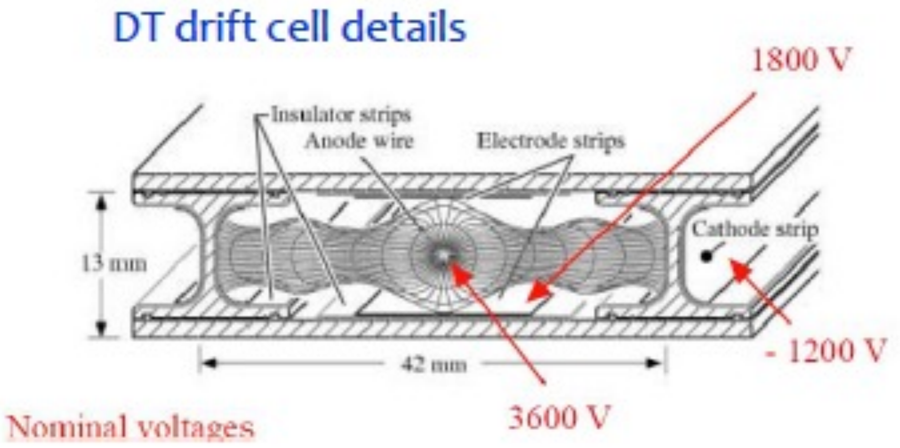
Each unit η is covered by two

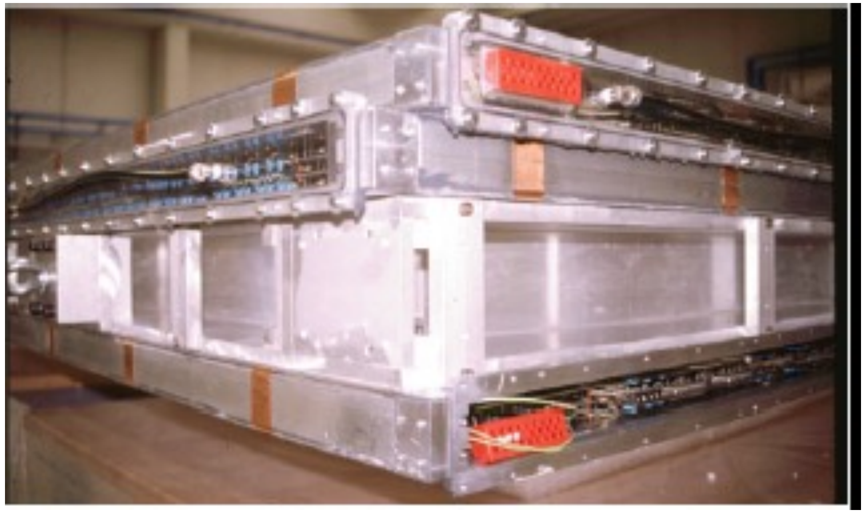


Drift Tubes (barrel)

- Timing of ionization signal with known drift velocity gives spatial position
  - Gas : Ar (85%) + CO_2 (15%)
  - σ_t ~ few ns gives σ_x ~250 µm resolution
  - Known field shaping is critical
- 250 chambers in CMS barrel
- 12 (8) layers in MB1-MB3 (M4)
  - 44 spatial measurements, over 3 *m*

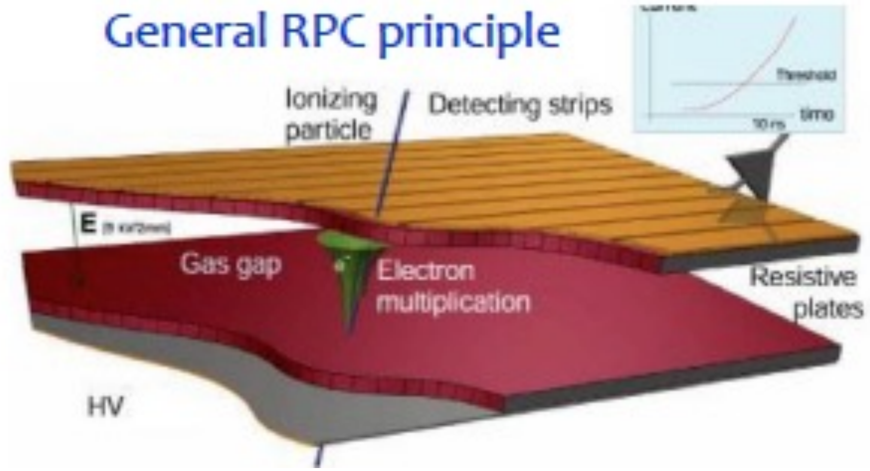


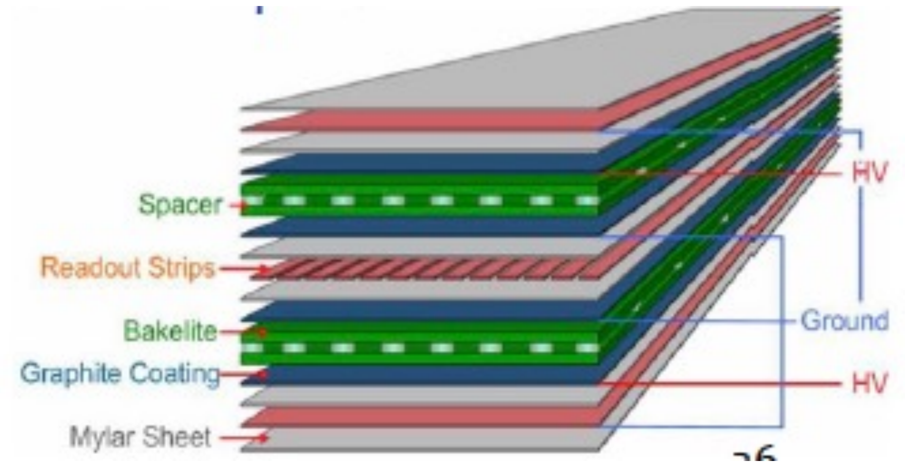




Resistive Plate Chambers (barrel, endcap)

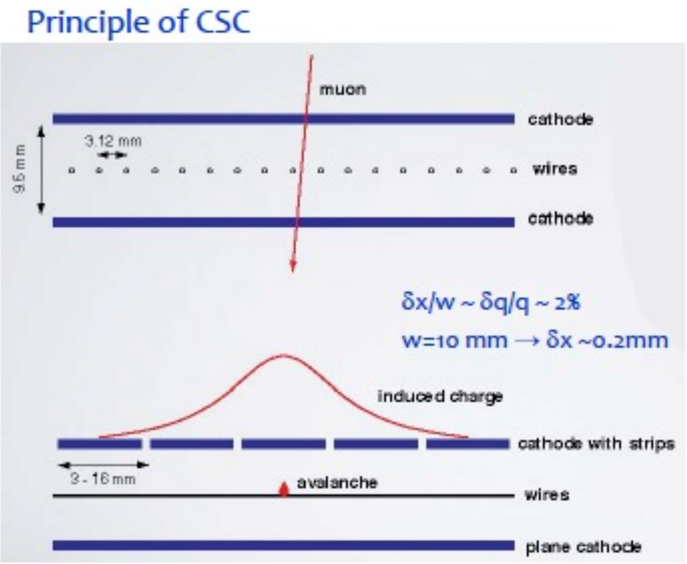
- 480 barrel + 576 endcap chambers
- Large area, fast signal with modest resolution for triggering
- Charge induced onto external strips
- Bakelite ρ~10^{10} Ω-cm
  - Transparent to signal
  - Quenches avalanche
  - Double gap, each 2 mm, 9.6 kV, for high ε
- Modest gain for rate capability and longevity
- Gas mix: $C_2H_2F_4$/isoC_4H_{10}/SF_6 95.2/4.5/0.3%

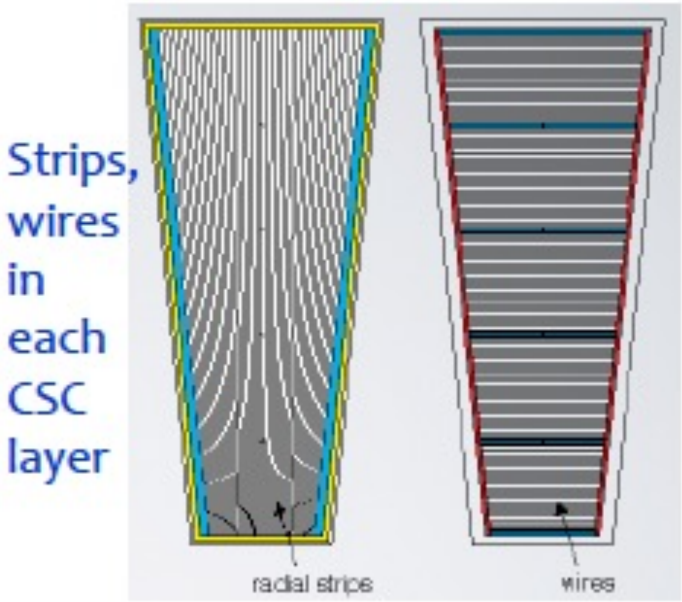




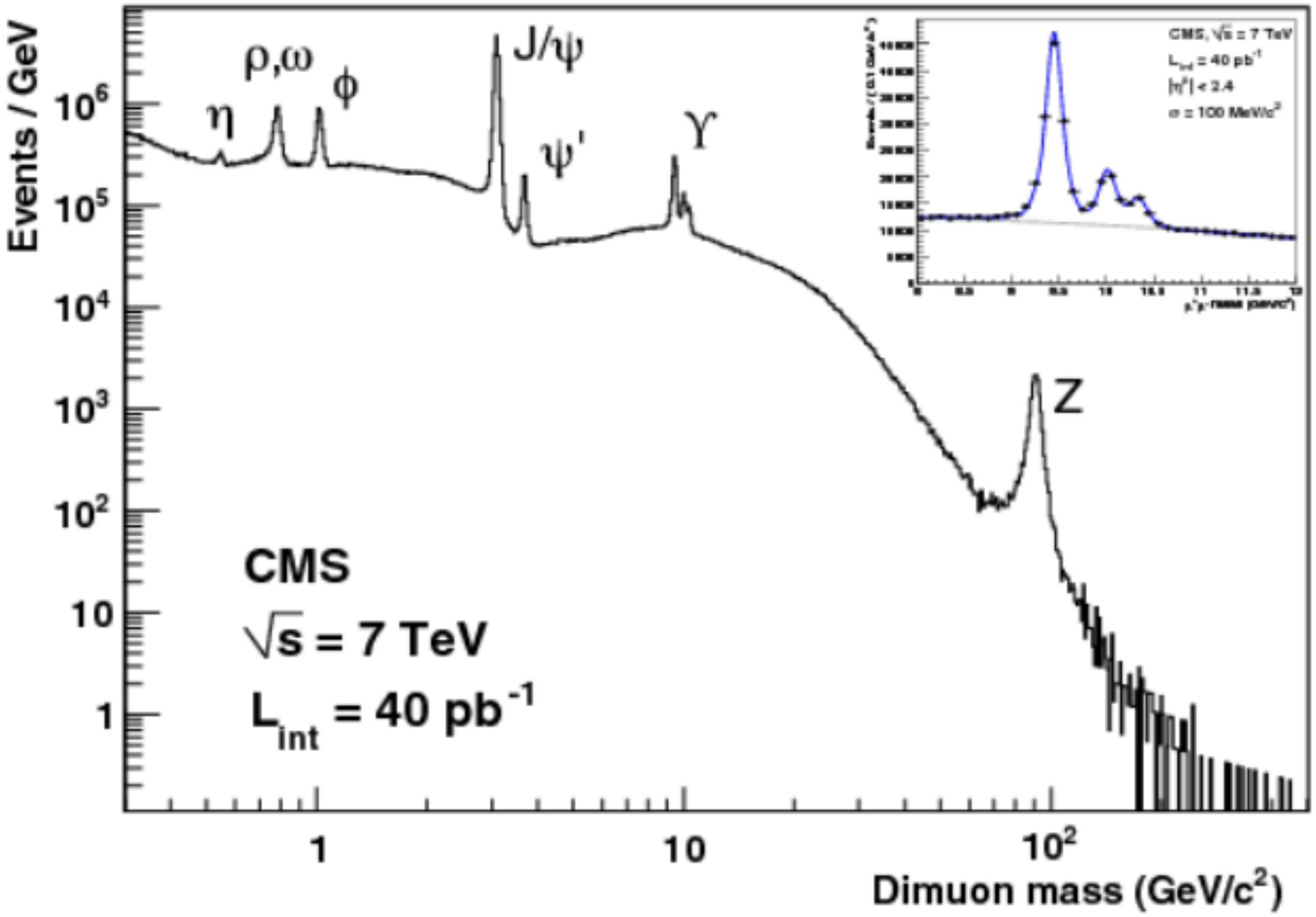
Cathode Strip Chambers (endcap)

- 540 chambers in CMS endcaps
- Precise interpolation of charge induced on cathode strips gives ~200 µm accuracy
- 6 layers in *z*
  - precision ϕ from cathode strips
  - coarse *r* from anode wires

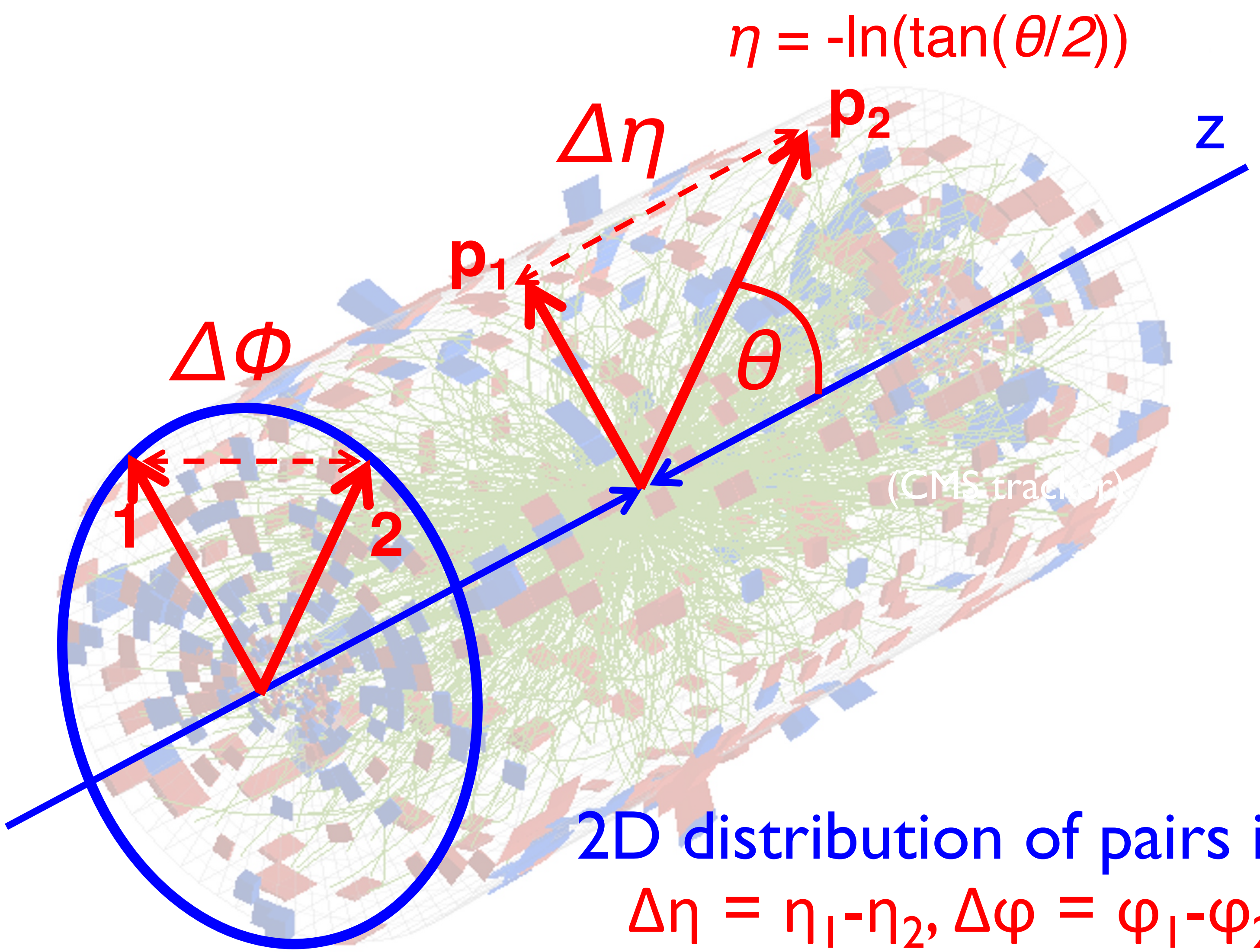




Compact ***Muon*** Solenoid!

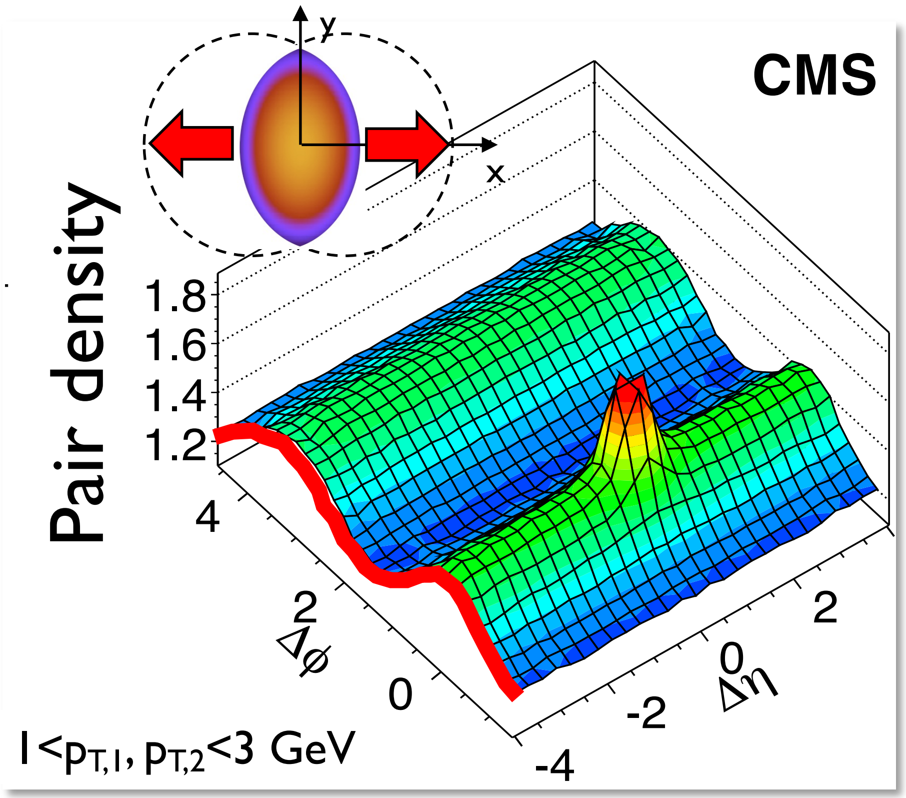


Two-particle correlations and Collective Flow

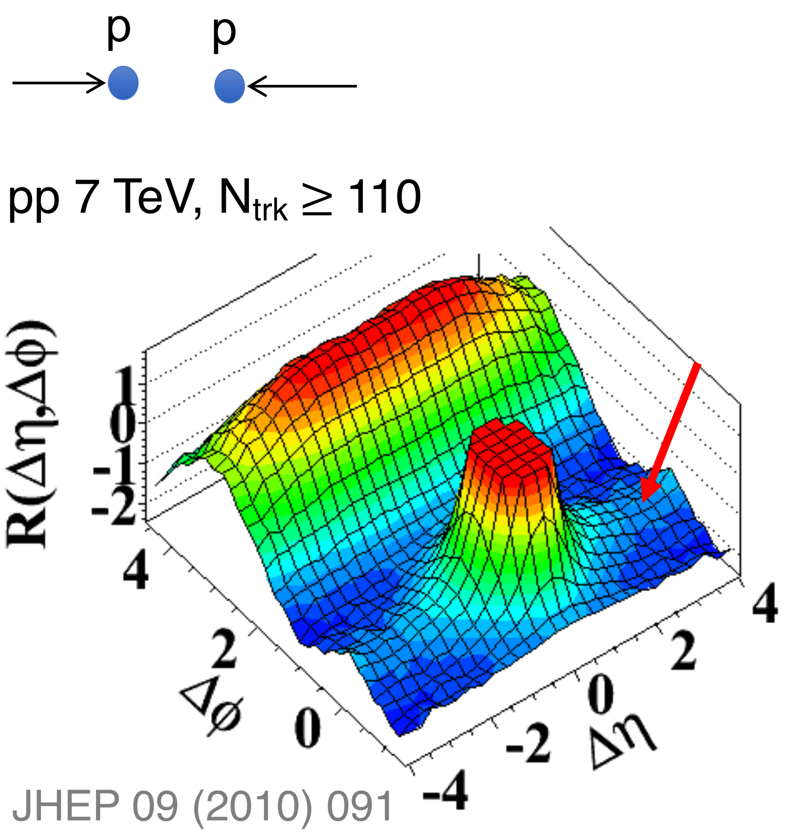


2D distribution of pairs in
$\Delta\eta = \eta_1 - \eta_2$, $\Delta\varphi = \varphi_1 - \varphi_2$

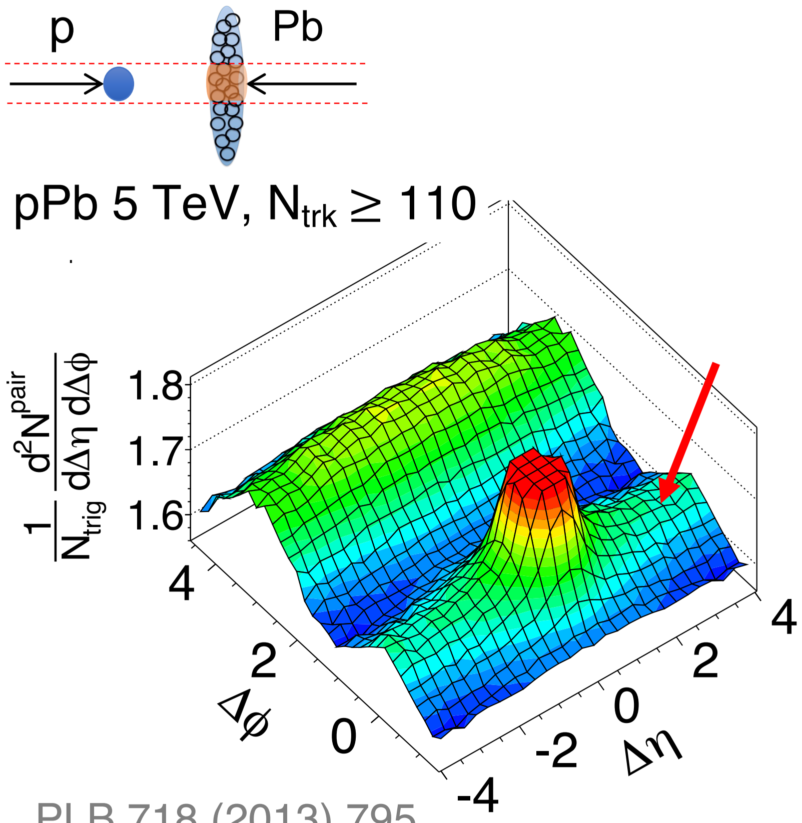
PbPb 35-40% centrality



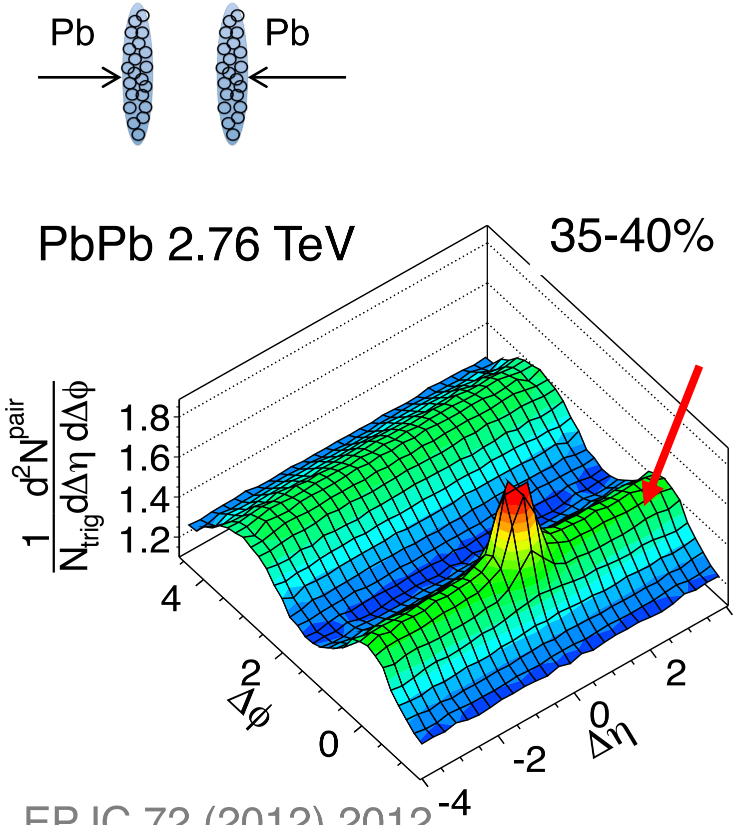
Discovery of "QGP" in small systems



JHEP 09 (2010) 091



PLB 718 (2013) 795

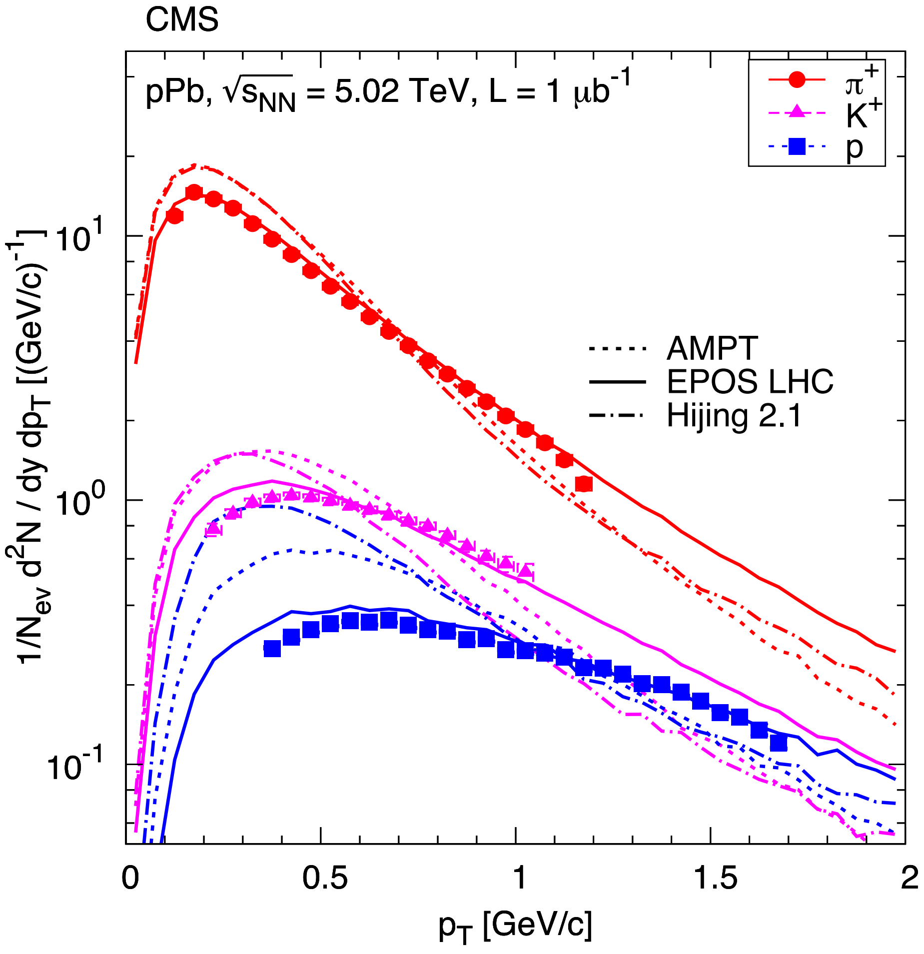


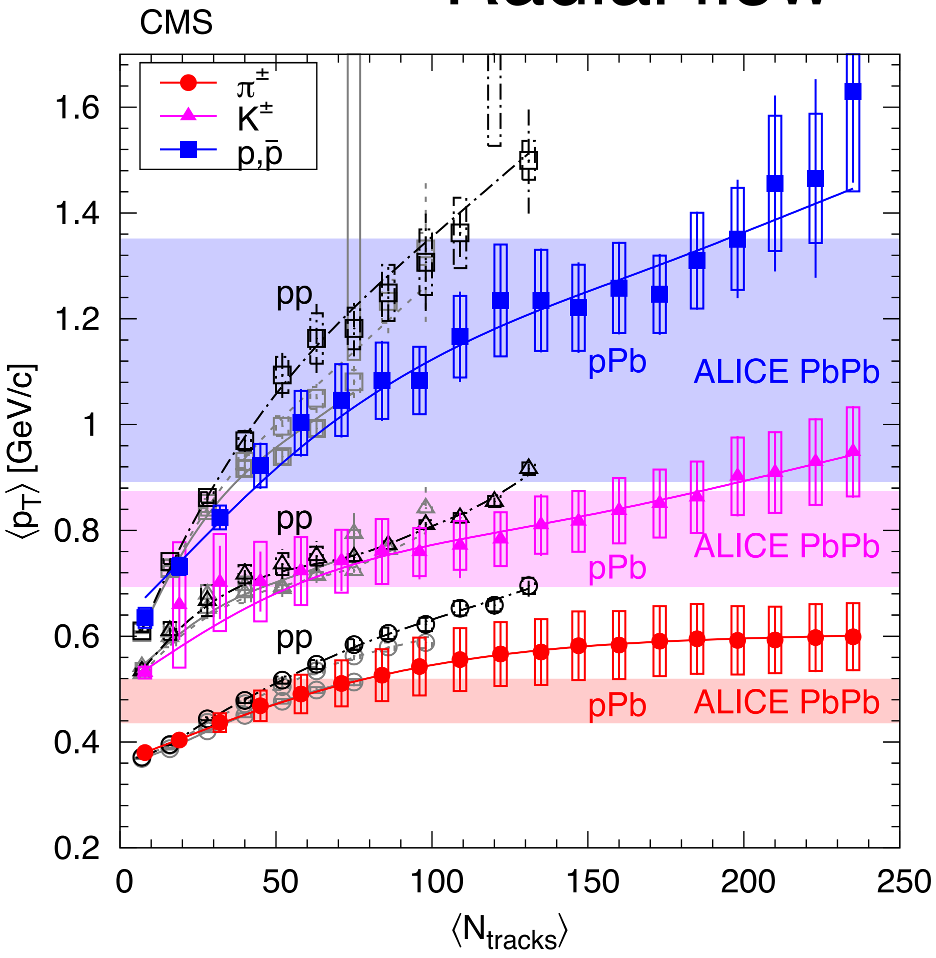
EPJC 72 (2012) 2012

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

PID spectra in small systems

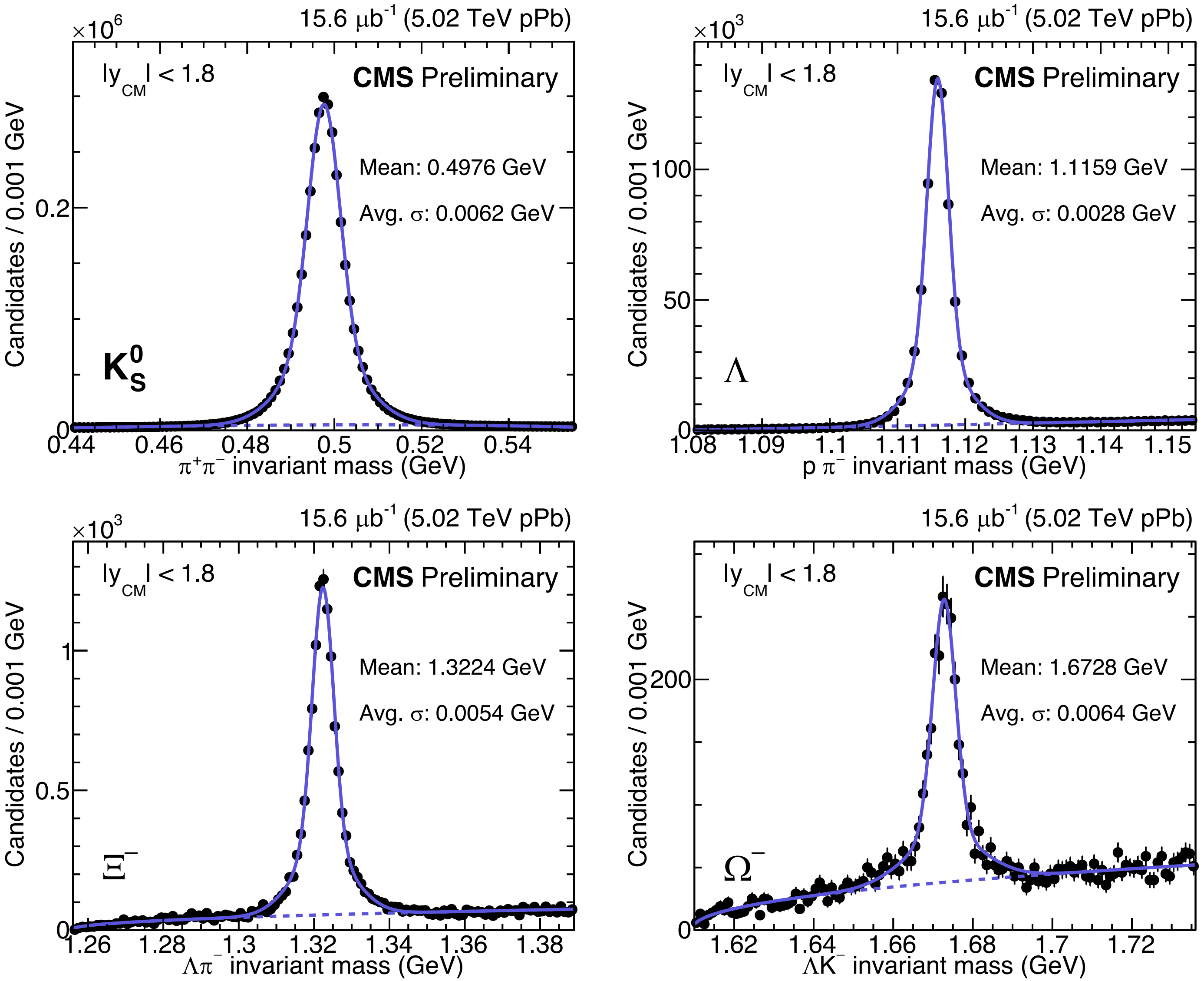
"Radial flow"



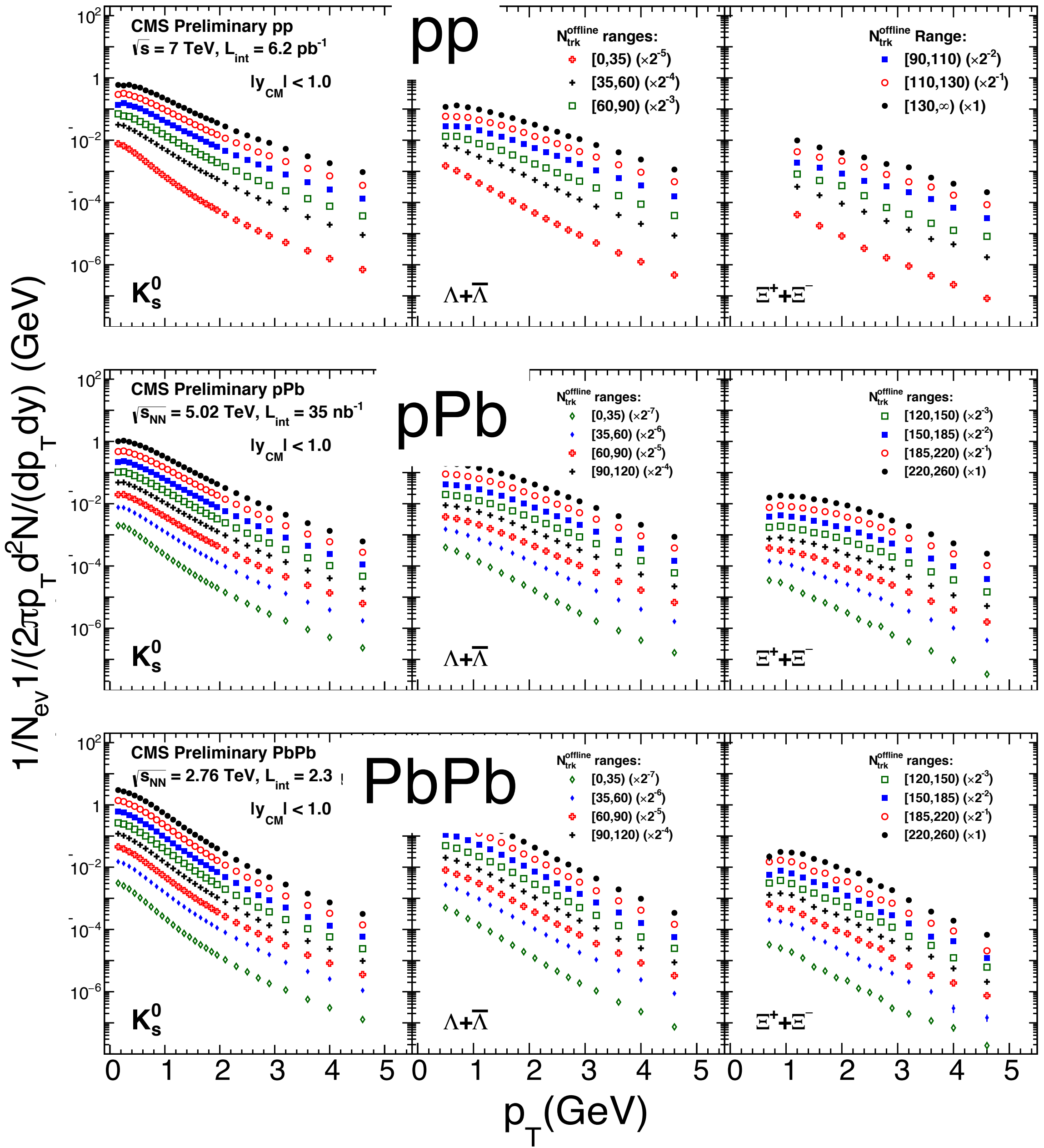


PID spectra in small systems

Topological reconstruction of strange hadrons over wide p_T and η ranges (no PID of pi/K/p)



Spectra and “radial flow” in small systems

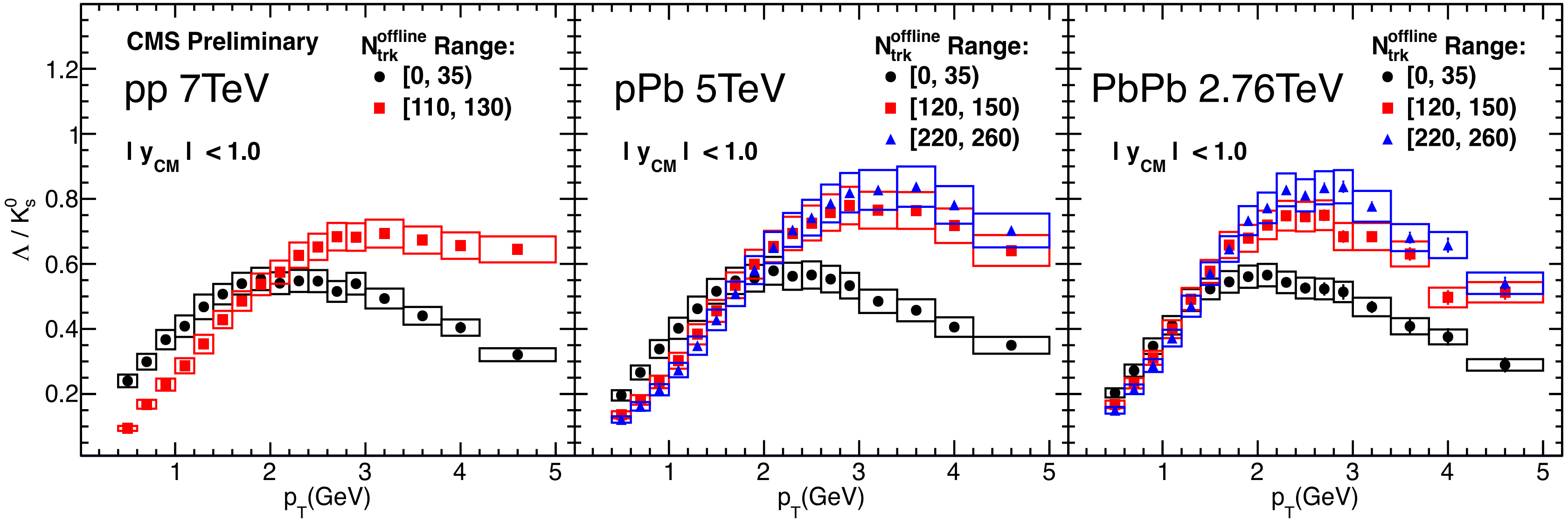


$|y_{cm}|<1$

How does spectra shape evolves with

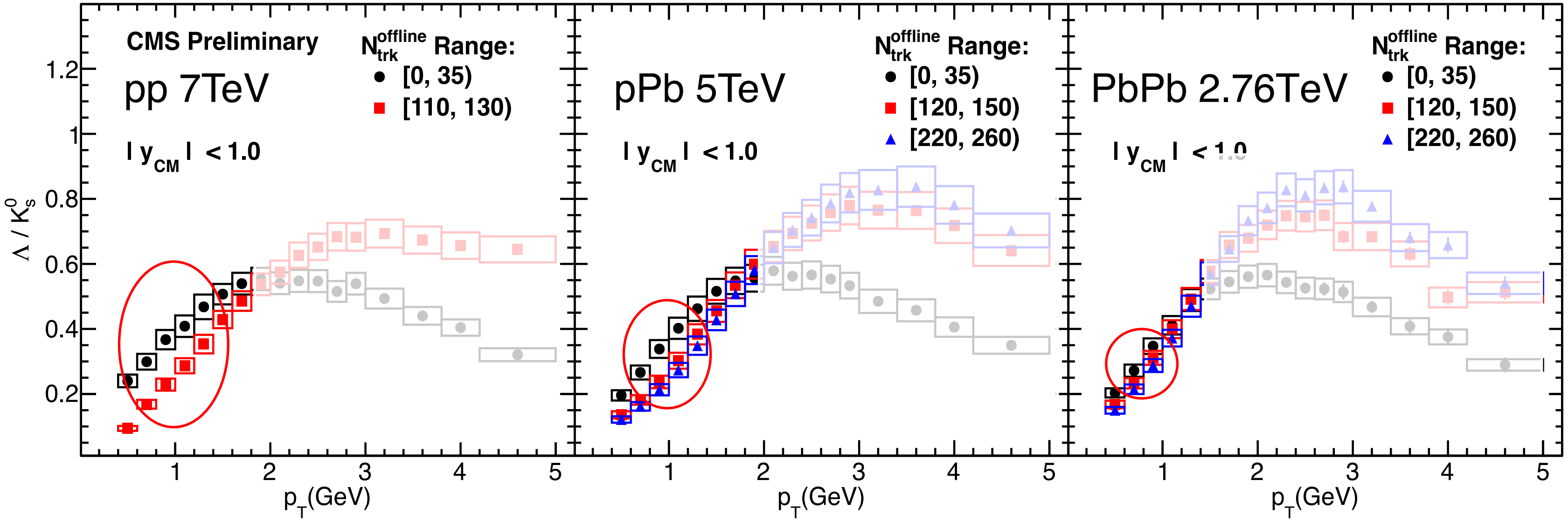
- particle species
- N_{trk}
- system size
- particle rapidity

Baryon-to-meson ratios



- Baryon/meson enhancement in high-multiplicity events

Baryon-to-meson ratios

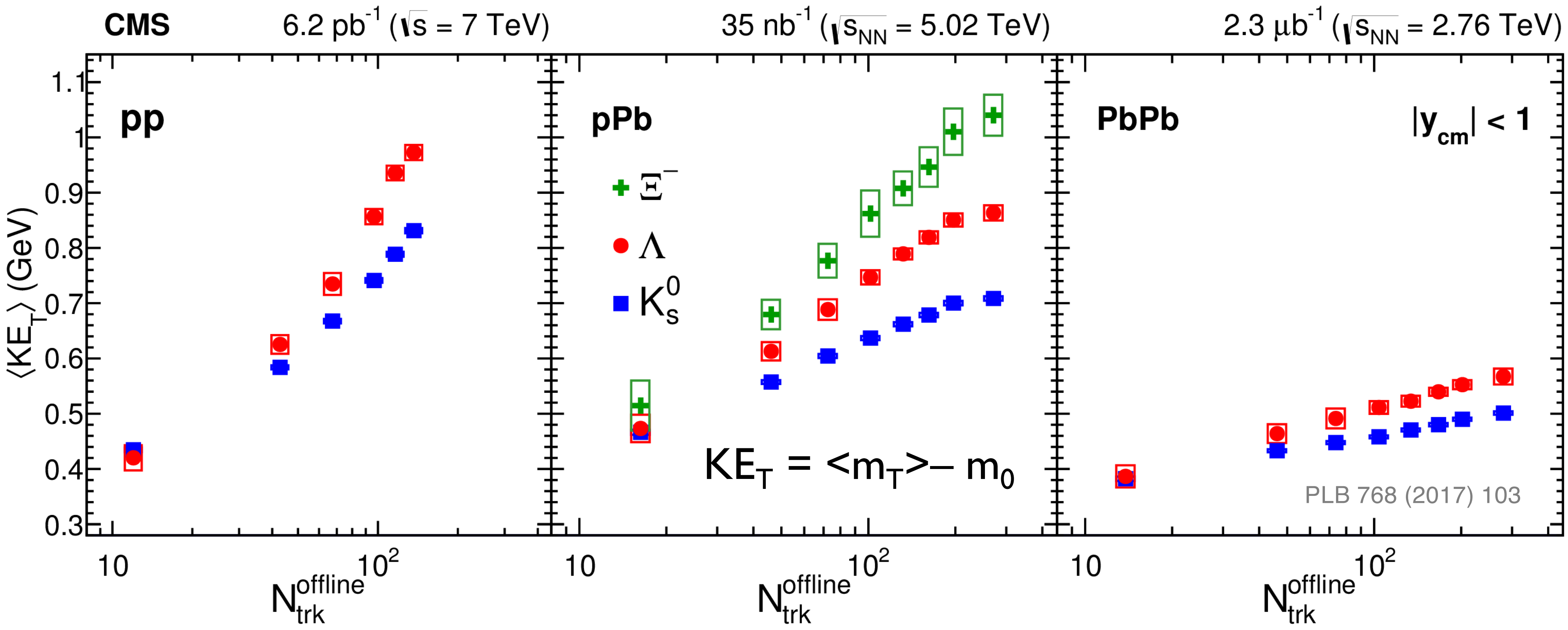


- Baryon/meson enhancement in high-multiplicity events
- From low- to high-multiplicity events

  Larger separation in smaller system

  ⇨ Larger radial flow?

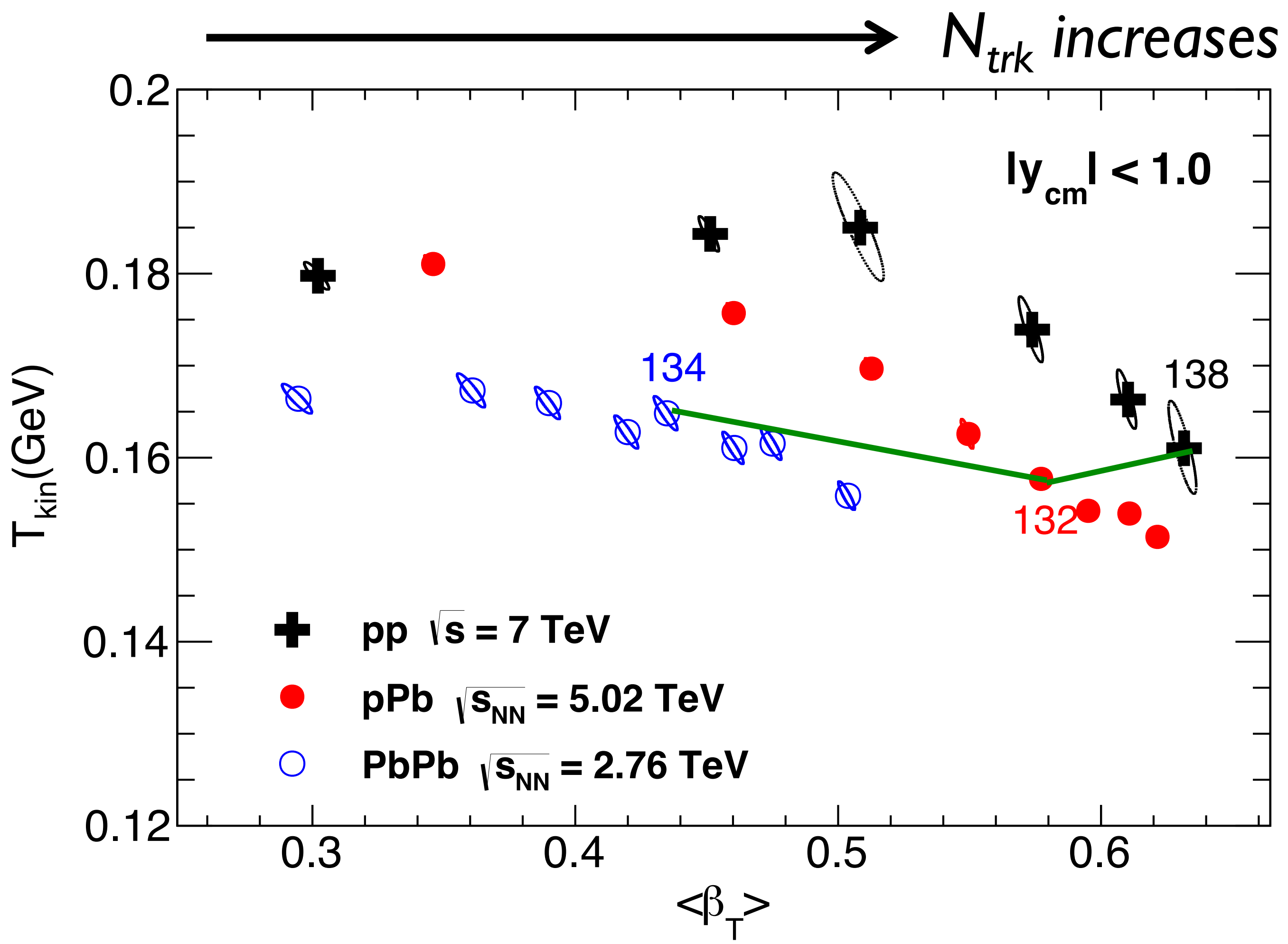
Spectra and "radial flow" in small systems



Mass-dependent splitting of KE_T as N_{trk} increases, faster in small systems

– common velocity field

Spectra and “radial flow” in small systems

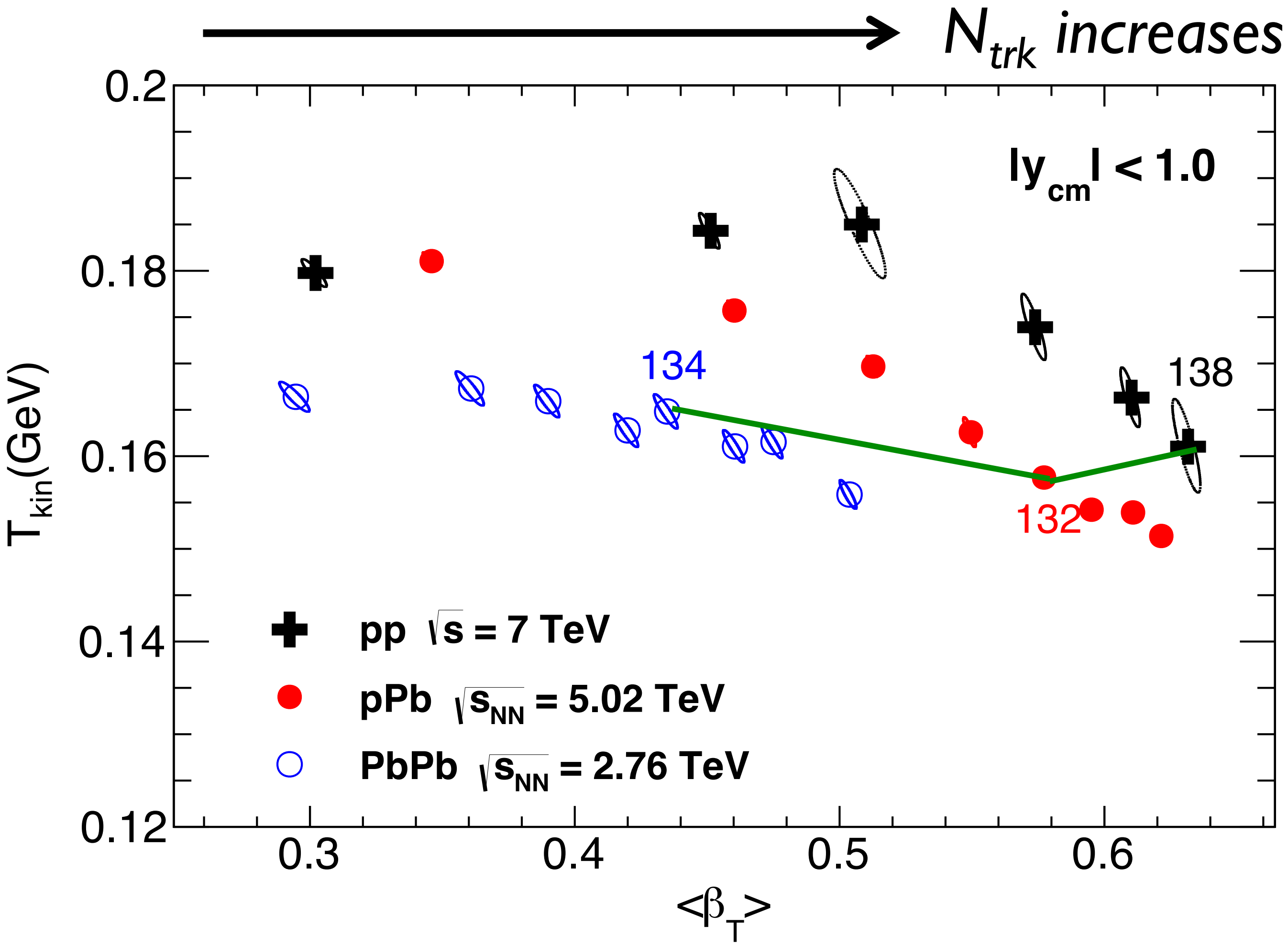


Simultaneous Blast-Wave fits:

$$\boxed{\langle\beta_T\rangle_{pp} > \langle\beta_T\rangle_{pPb} > \langle\beta_T\rangle_{PbPb}}$$

for similar N_{trk}

Spectra and "radial flow" in small systems



Simultaneous Blast-Wave fits:

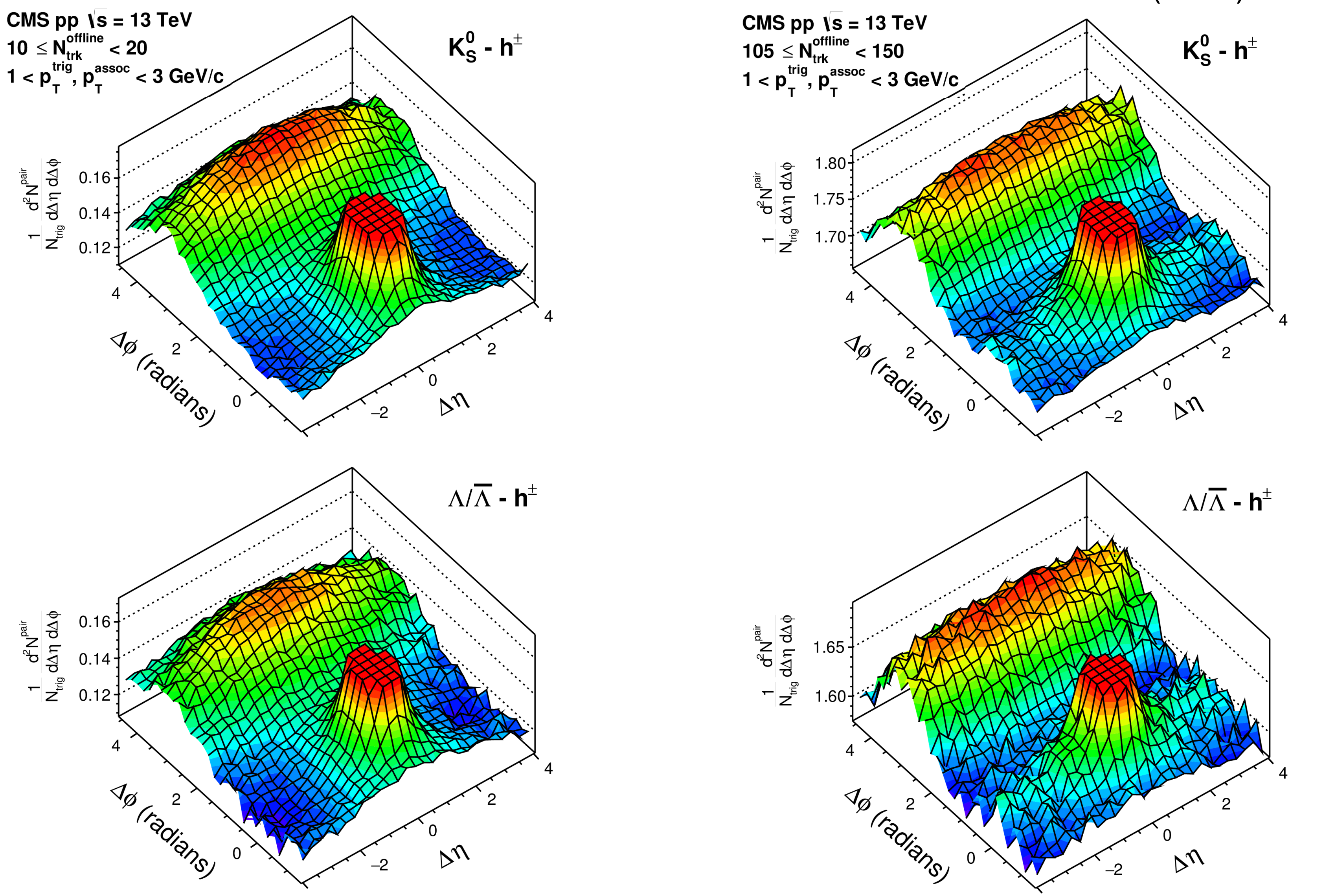
$$\boxed{\left\langle \beta_T \right\rangle_{pp} > \left\langle \beta_T \right\rangle_{pPb} > \left\langle \beta_T \right\rangle_{PbPb}}$$

for similar N_{trk}

Smaller QGP more explosive?!

Flow in small systems with PID

PLB 765 (2017) 193



Anisotropy flow in small systems

Mass ordering of v_2

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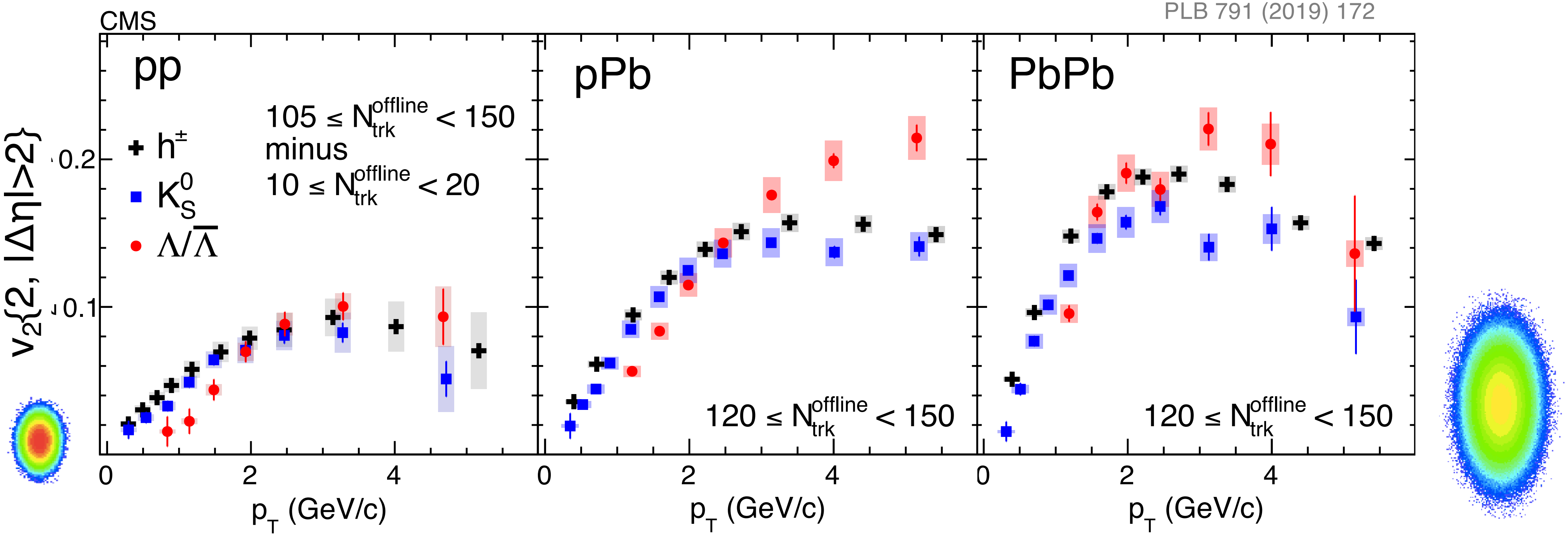
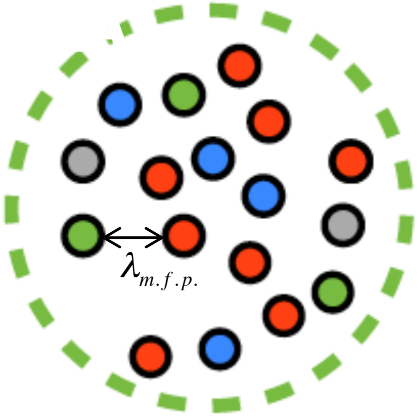


Smaller QGP more explosive?!

Keep pushing to extreme domains:

<u>Heavy</u> quark collectivity in <u>small</u> systems

AA



Shrink the system size

pp/pA

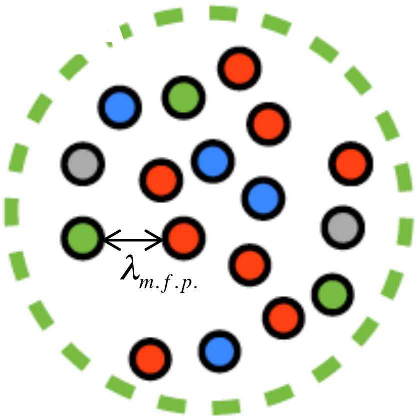
$$\boxed{L >> \lambda_{m.f.p.}}$$

$$\lambda_{m.f.p.} \sim \frac{1}{g^4 T}$$

Keep pushing to extreme domains:

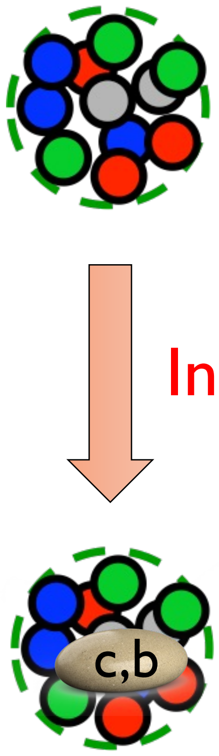
<u>Heavy</u> quark collectivity in <u>small</u> systems

AA



Shrink the system size

pp/pA



Increase $\lambda_{m.f.p.}$

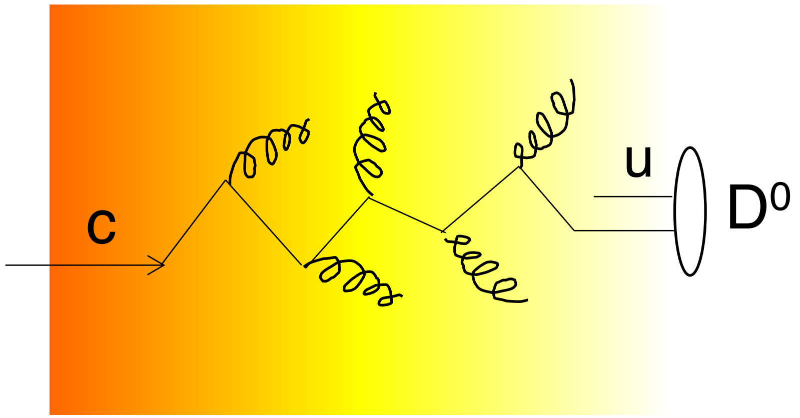
$$\boxed{L >> \lambda_{m.f.p.}}$$

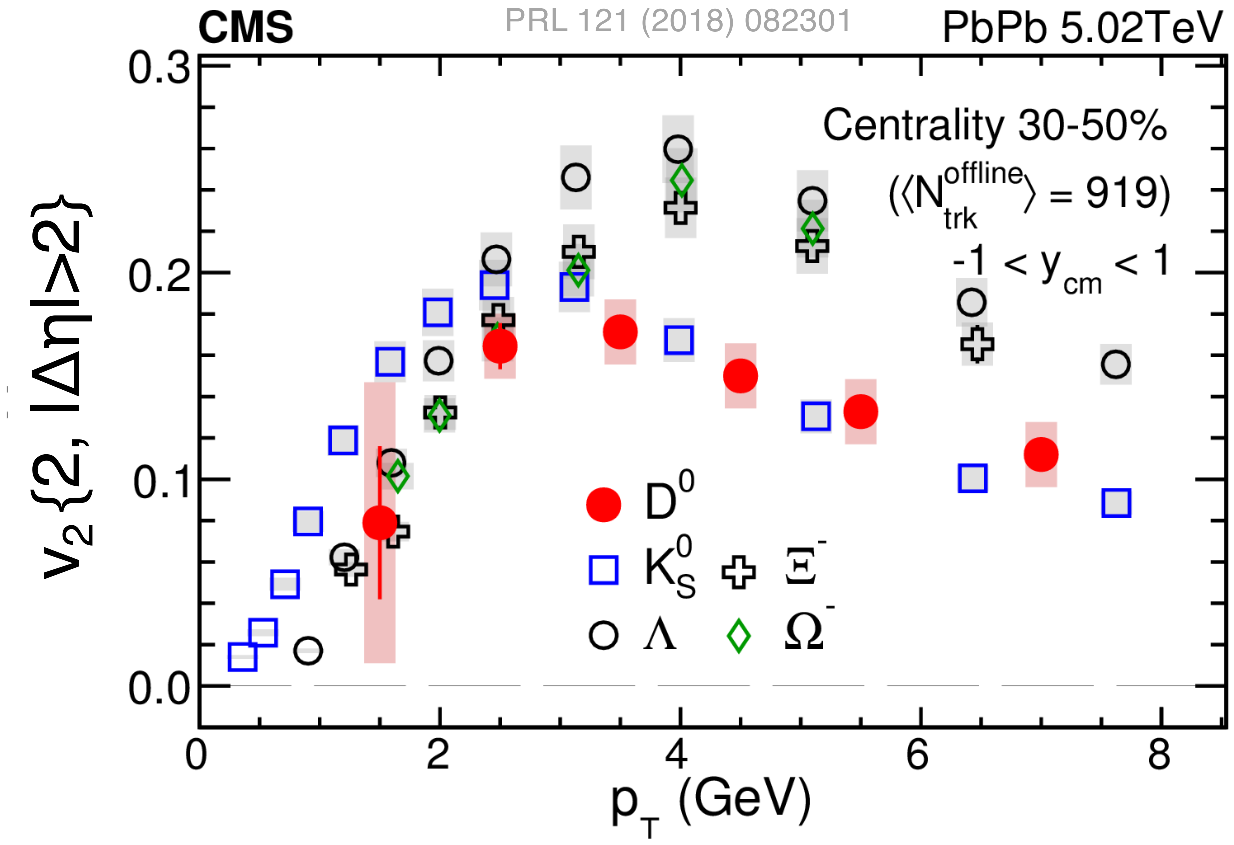
$$\lambda_{m.f.p.} \sim \frac{1}{g^4 T}$$

Heavy flavor hadrons (D, B, J/ψ, …)

- ➢ Perturbative scale
- ➢ Produced at early stages

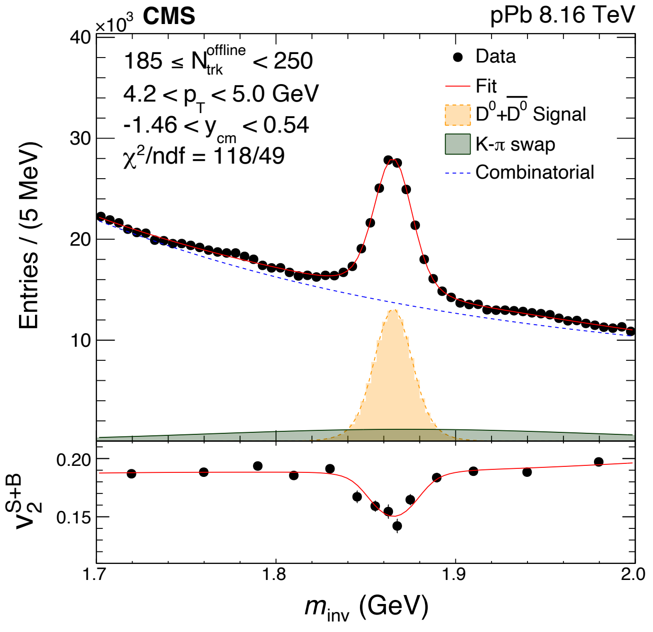
Heavy quark collectivity in large AA systems



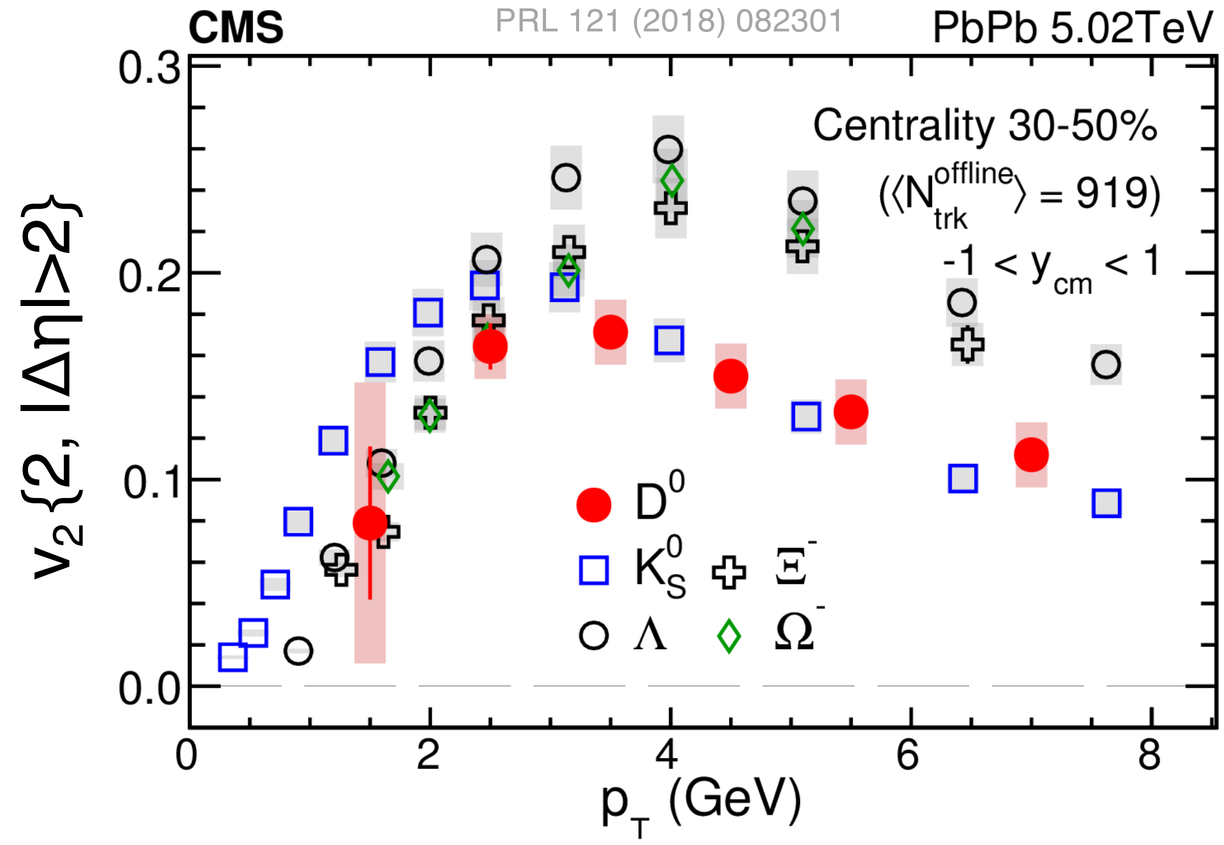


Strong charm flow similar to light flavor in AA at RHIC and the LHC

Heavy quark collectivity in large AA systems



No PID of pions, kaons

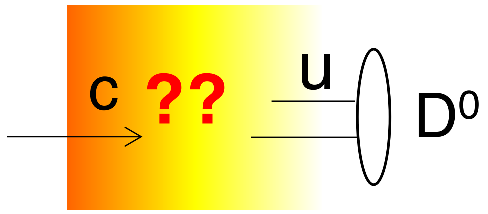


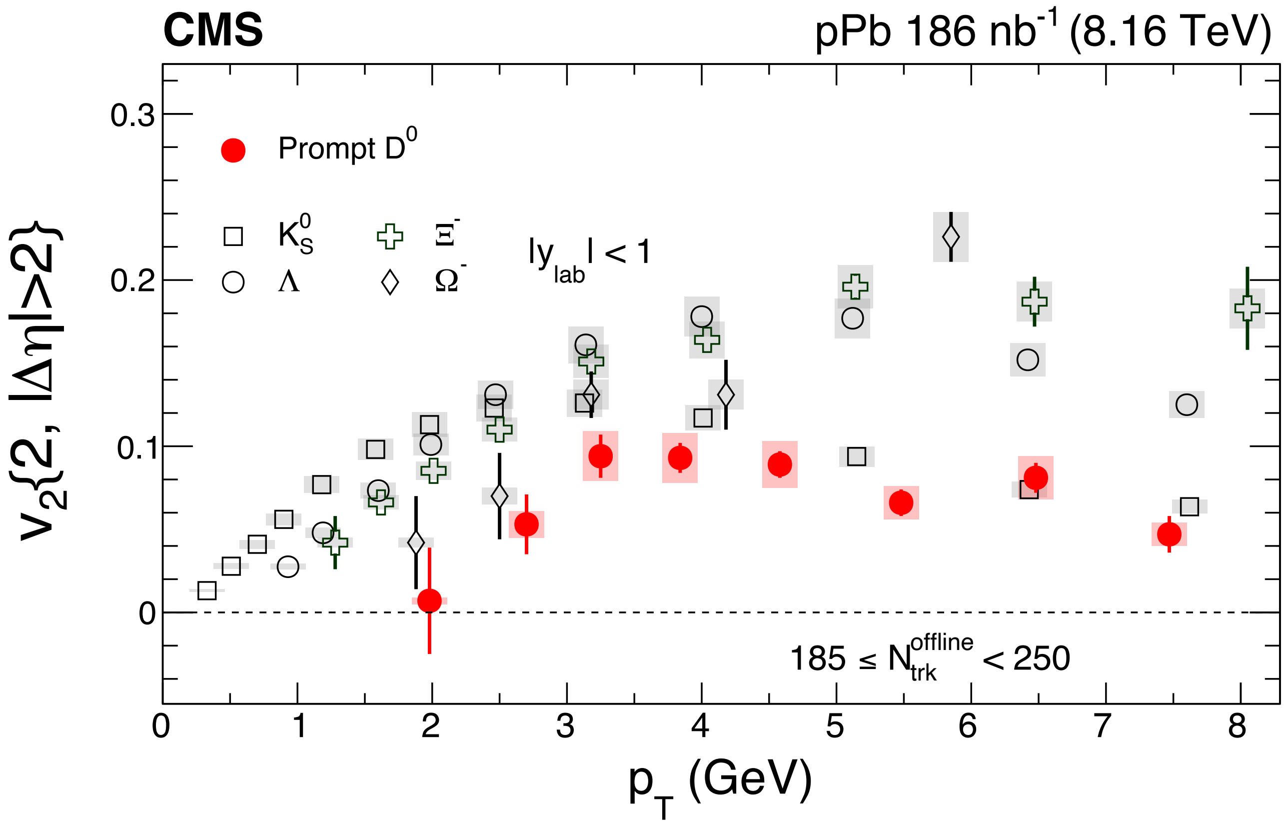
Strong charm flow similar to light flavor in AA at RHIC and the LHC

Heavy quark collectivity in small systems

Shrink the system size: N_{trk} ~ 900 ⟶ N_{trk} ~ 200

In small systems?



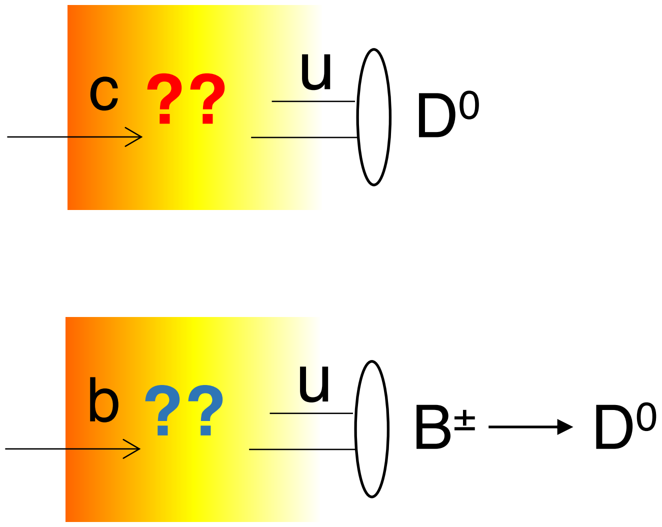


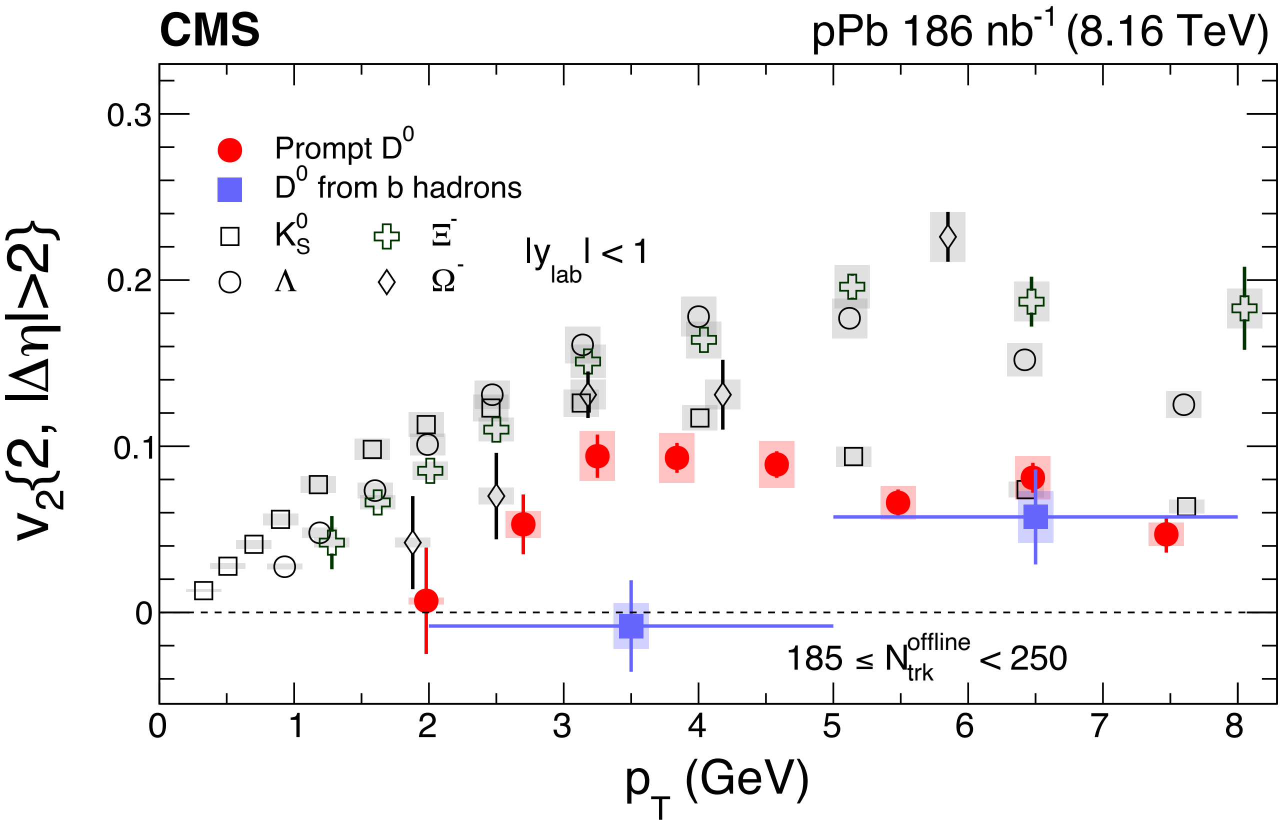
✓ Strong charm flow, maybe some indication < v_2(K)

Heavy quark collectivity in small systems

Shrink the system size: $N_{trk} \sim 900 \longrightarrow N_{trk} \sim 200$

In small systems?





Charm *vs.* Beauty

✓ Strong charm flow, maybe some indication < v_2(K)

✓ Beauty flow < charm flow (flavor hierachy)?!

Heavy quark collectivity in small systems

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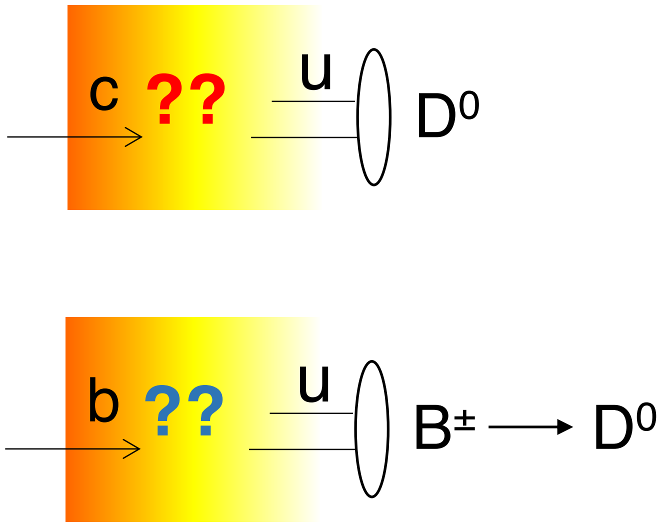
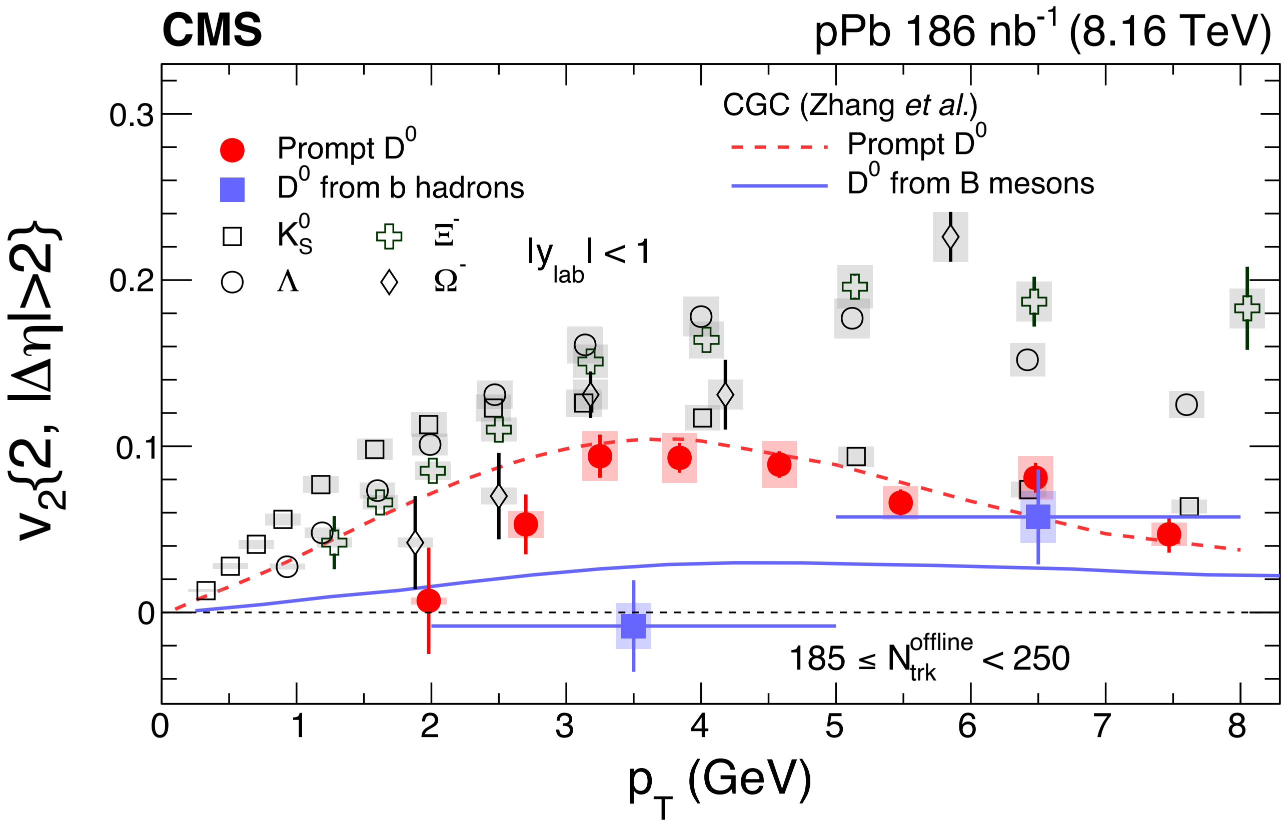
In small systems?





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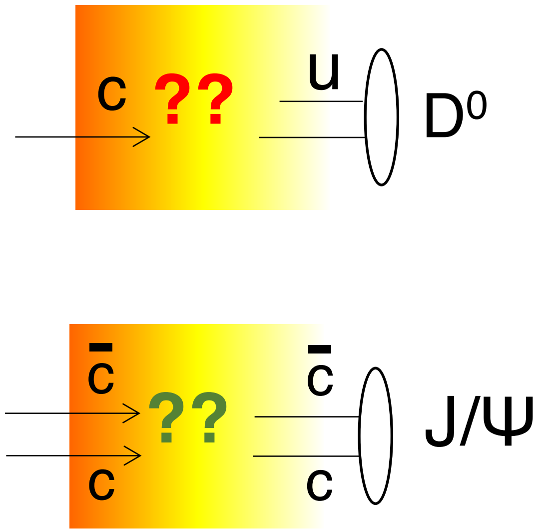
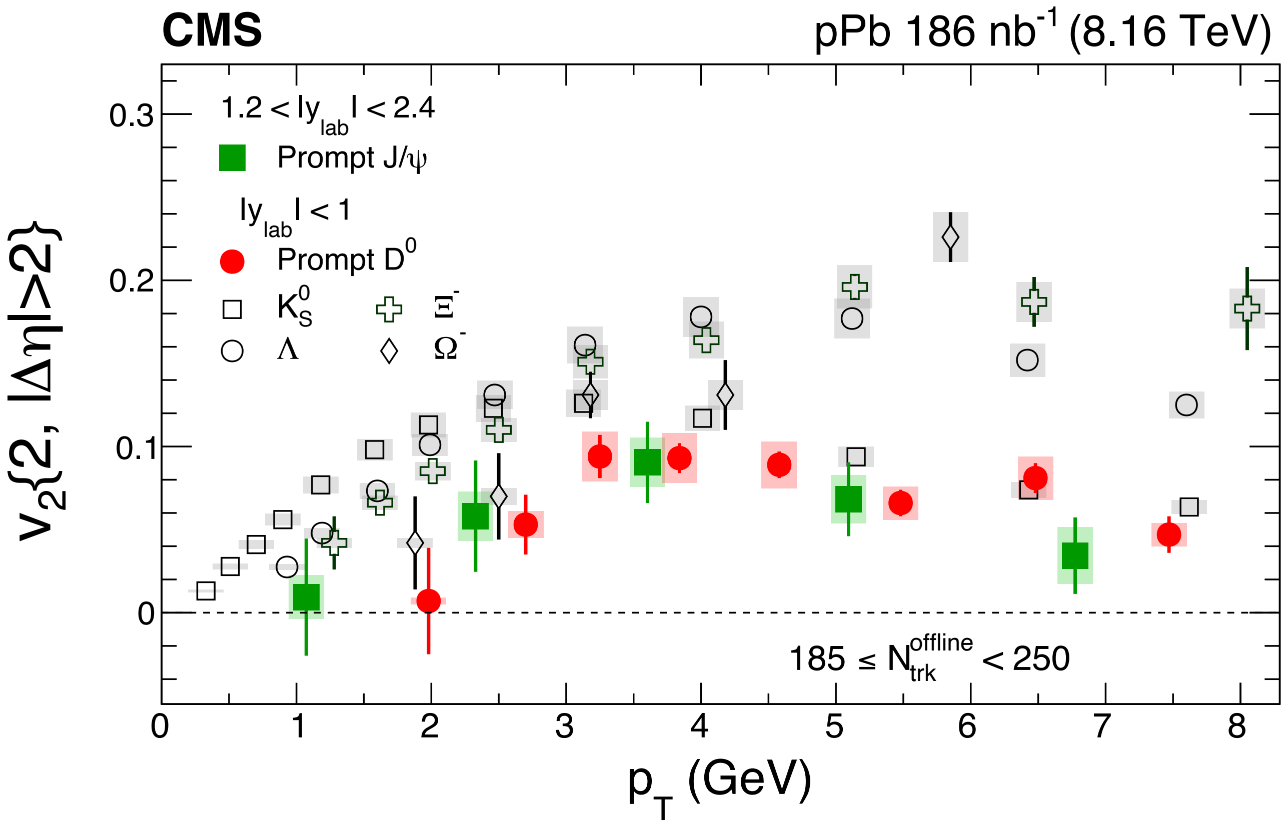


Open *vs.* Hidden



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✓ (Surprisingly!?) large J/ψ v2 signal → ISC needed?

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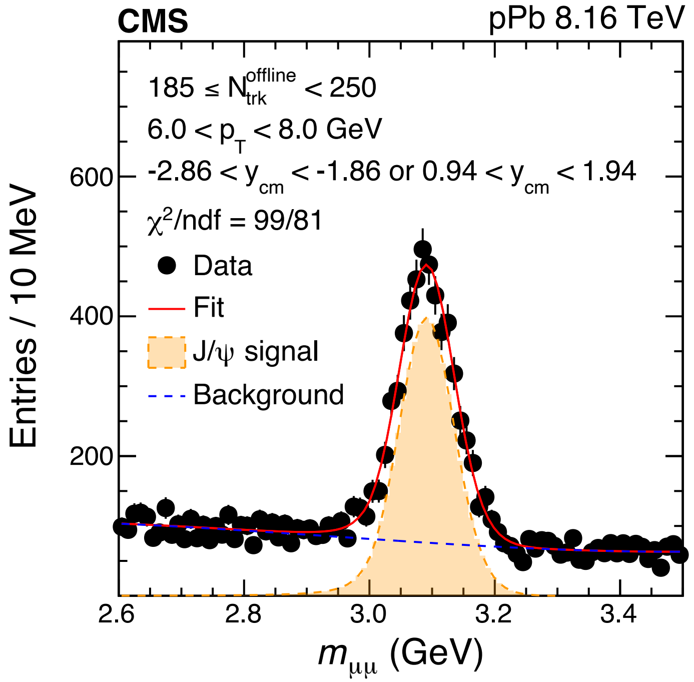
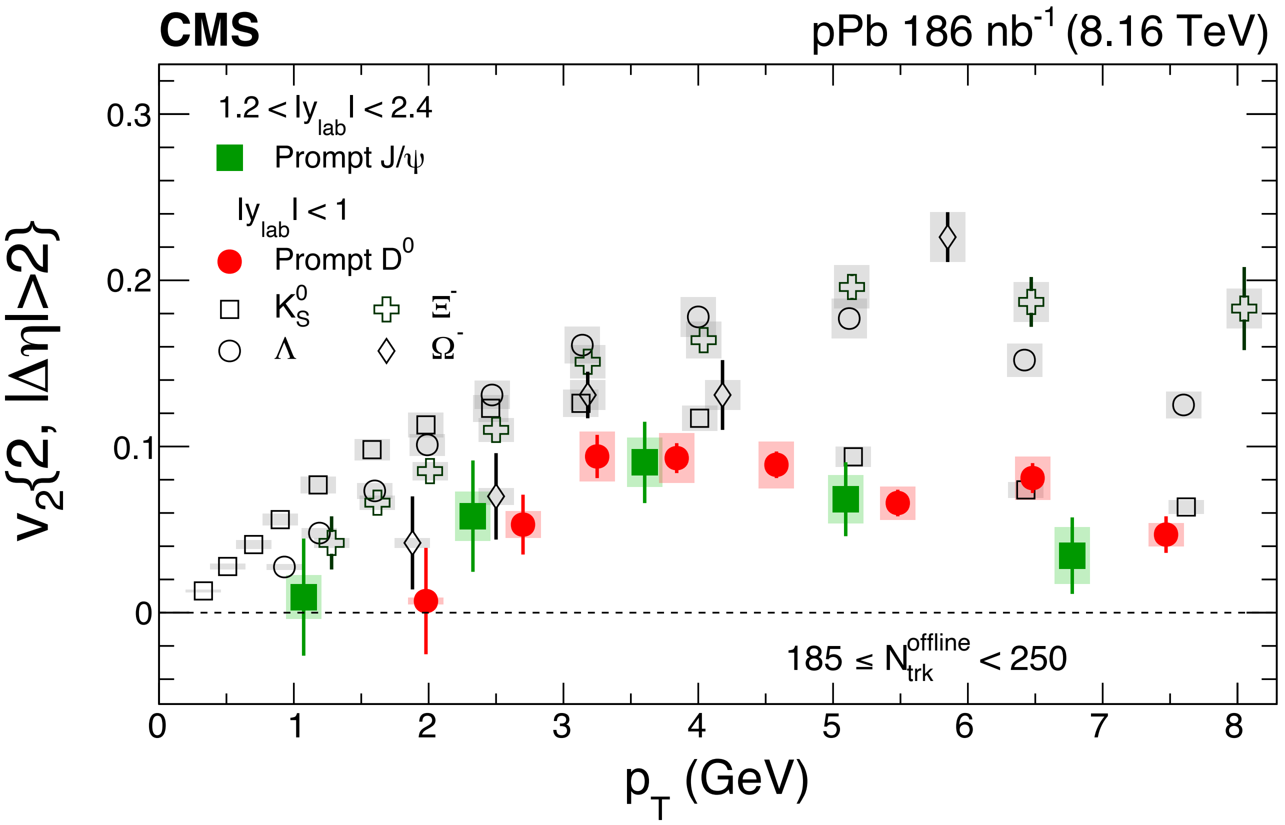
In small systems?



Open *vs.* Hidden



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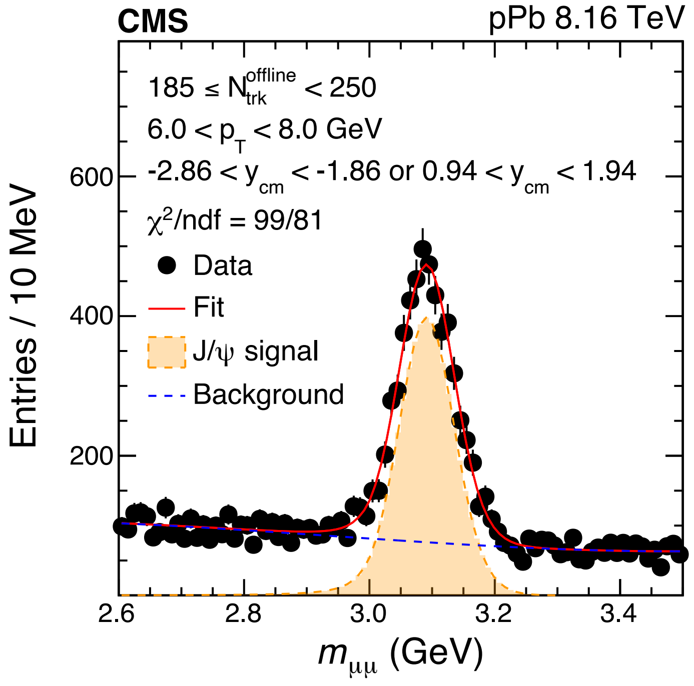
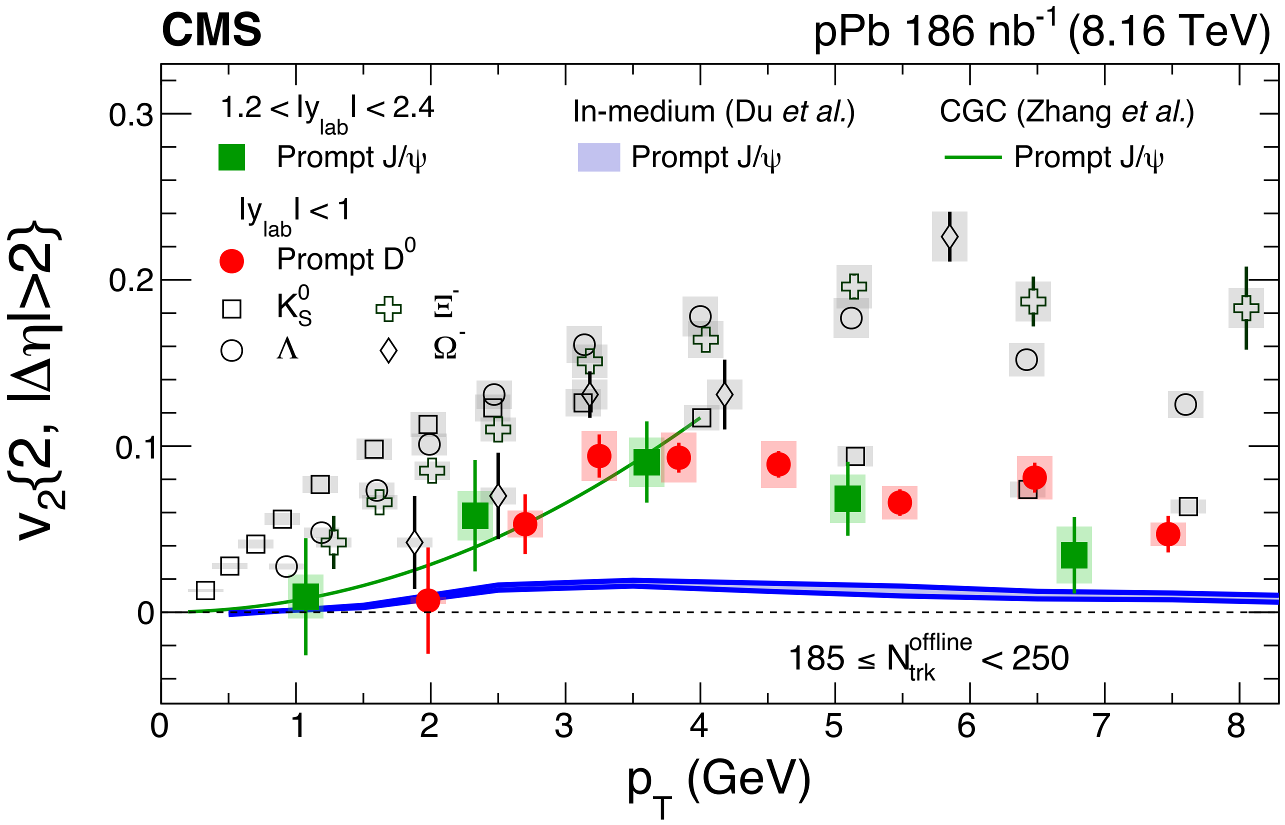
In small systems?





Open *vs.* Hidden

✓ Strong charm flow, maybe some indication < $v_2(K)$

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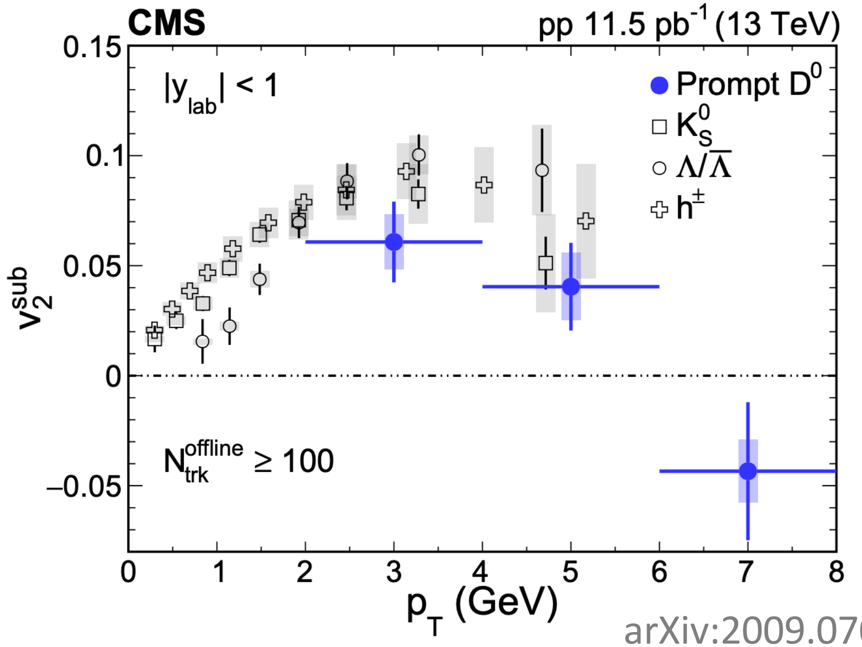
Heavy quark collectivity in small systems

Summary and outlook

	pp		pPb	
	v_2	yield	v_2	yield
Open Charm Meson	✓	✓	✓	✓
Open Beauty Meson	✓	✓	✓	✓
Open Charm Baryon	x	✓	x	✓
Open Beauty Baryon	x	x	x	x
Charmonia	x	✓	✓	✓
Bottomonia	x	✓	x	✓

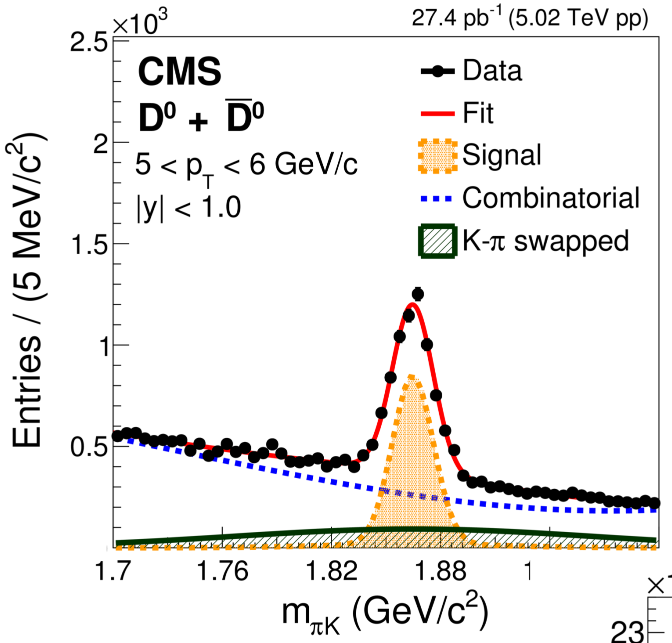
Most ✓ to be improved with better precision

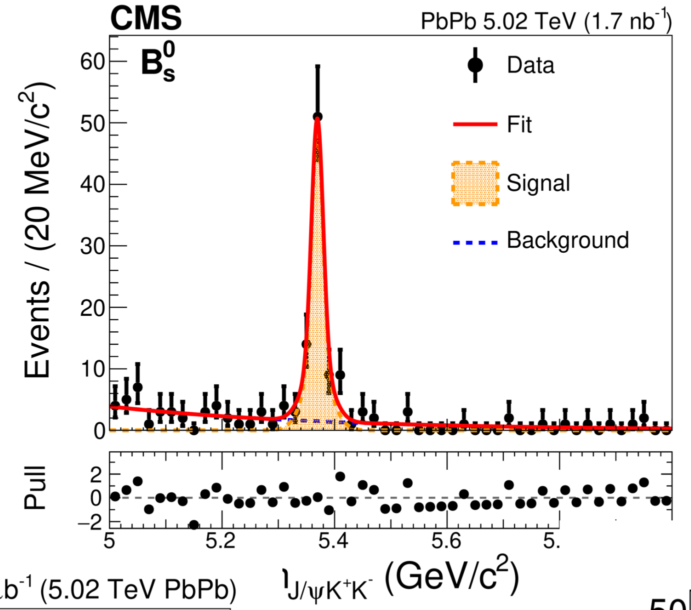
Prompt D^0 in HM pp

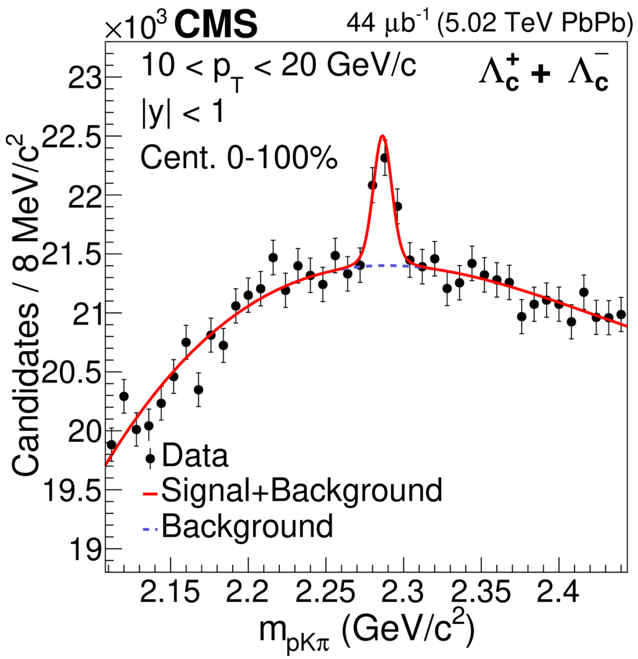


arXiv:2009.07065

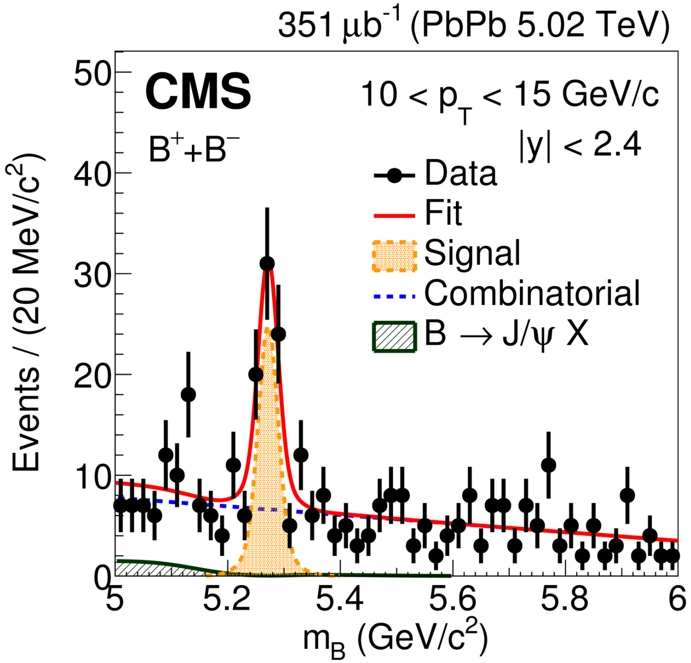
A comprehensive open heavy flavor program



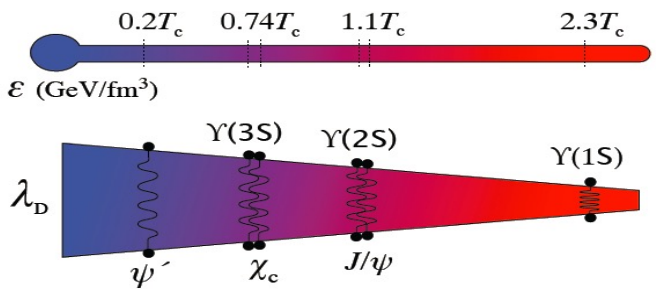




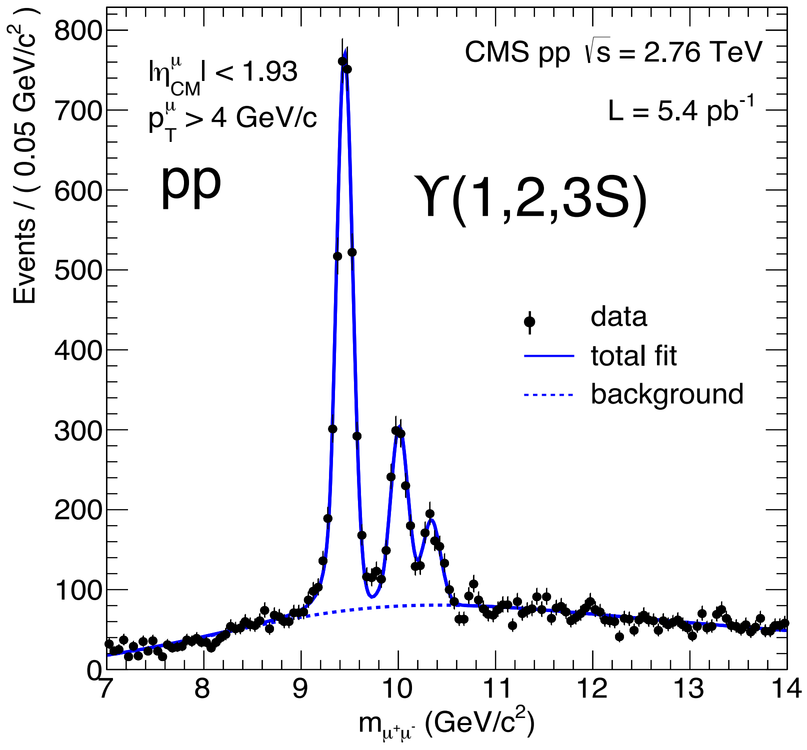
All done without hadron PID!

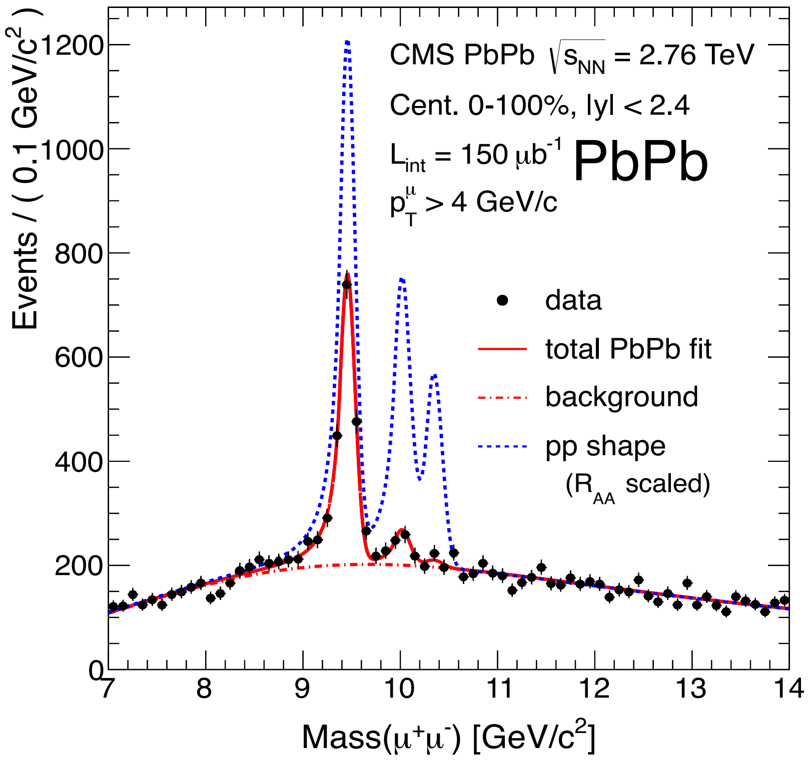


QGP thermometer with Quarkonia

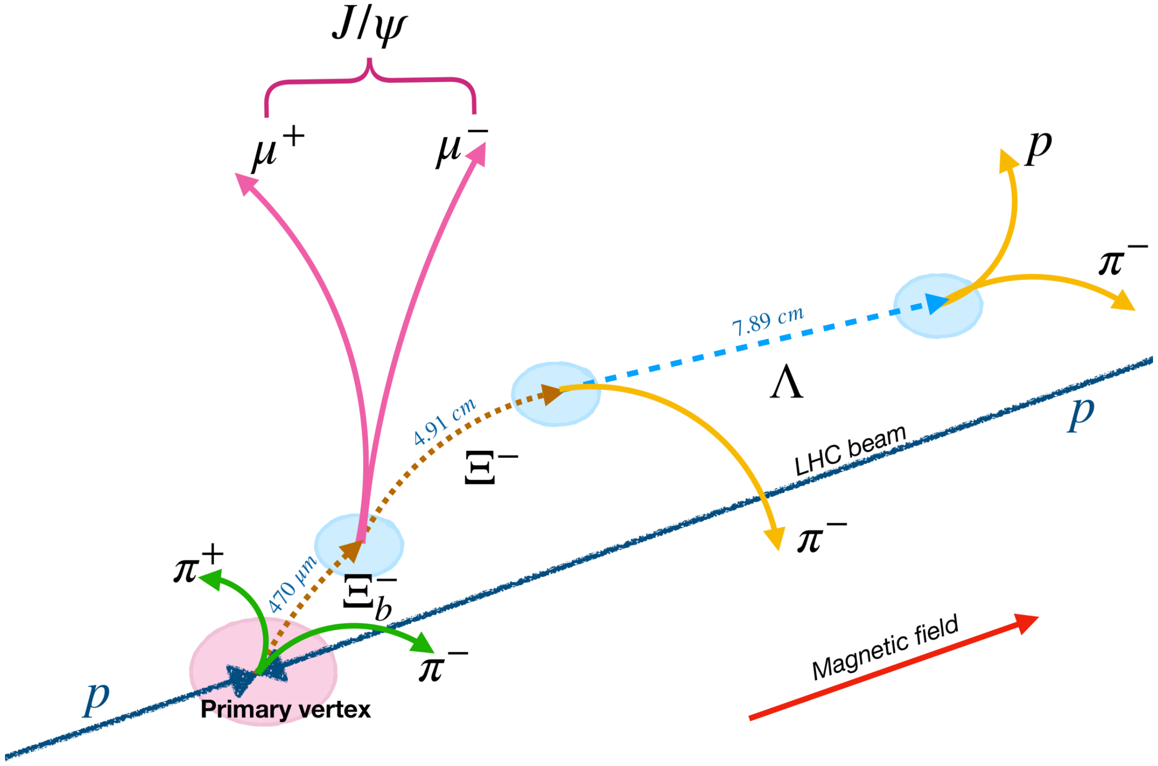


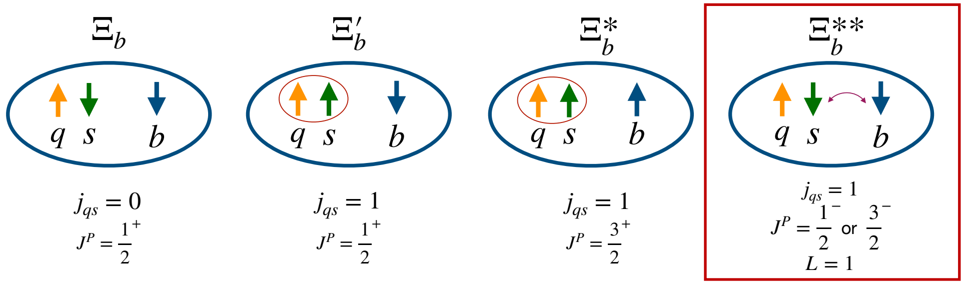
Sequential melting directly visible!

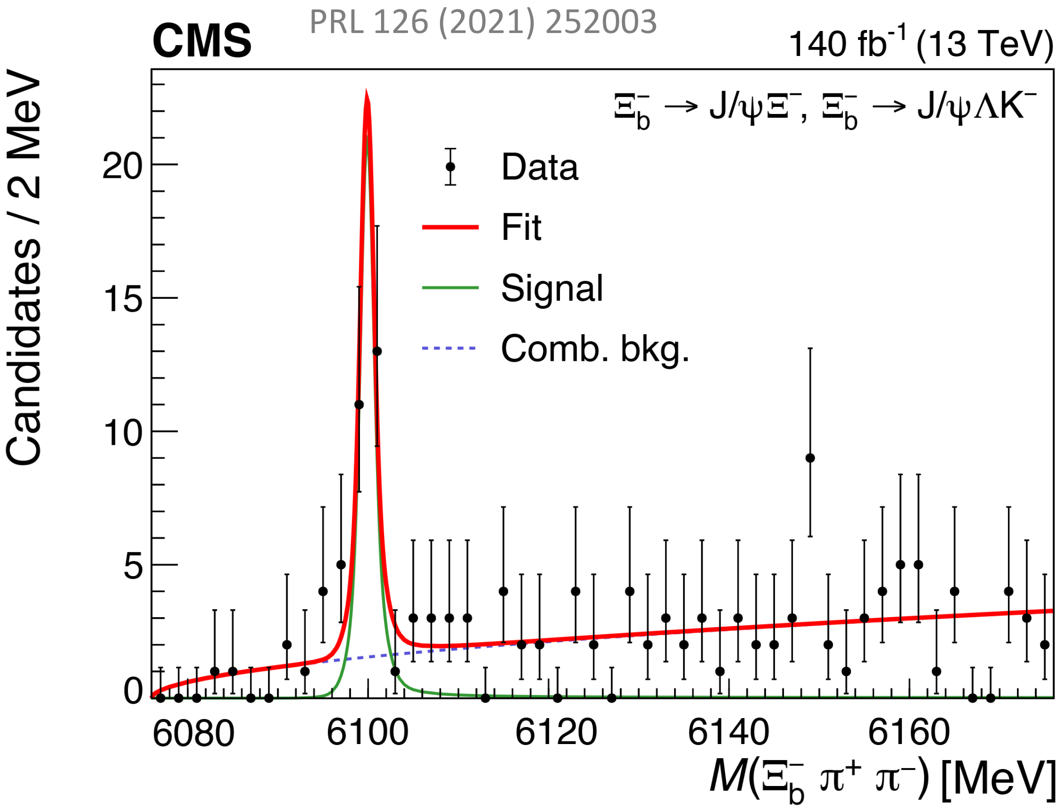




A new excited beautiful strange baryon!





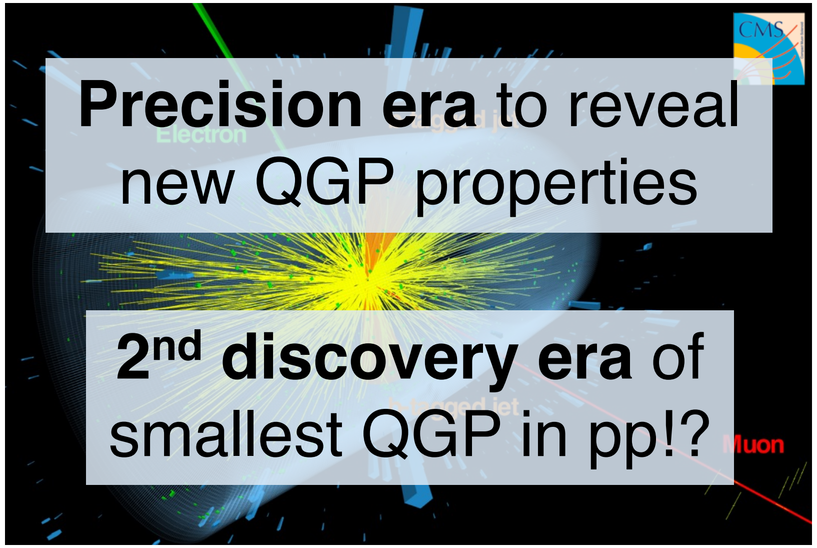


“Little Bangs”

2000: RHIC

1st discover era of perfect QGP liquid

2009: LHC



Precision era to reveal new QGP properties

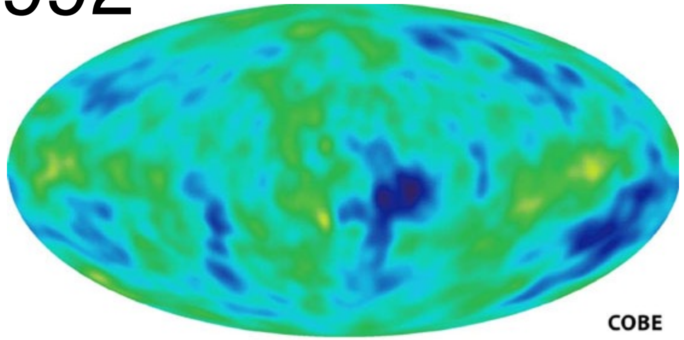
2nd discovery era of smallest QGP in pp!?

What’s next ???

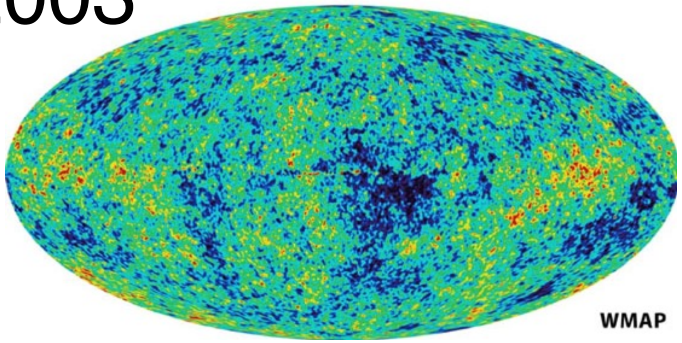
t

The Big Bang

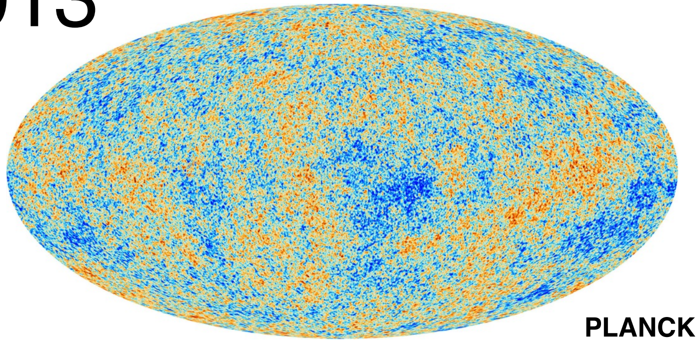
1992

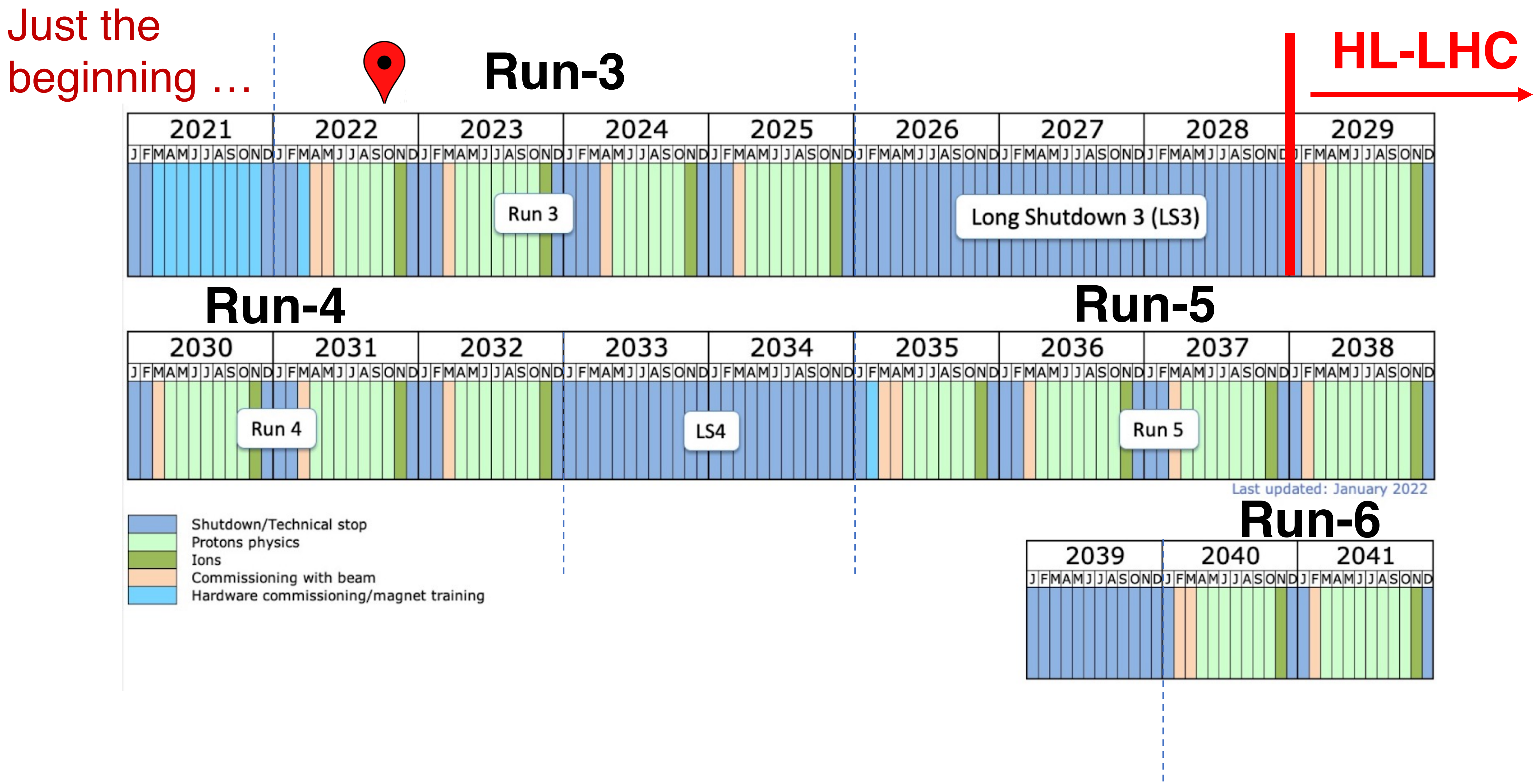


2003



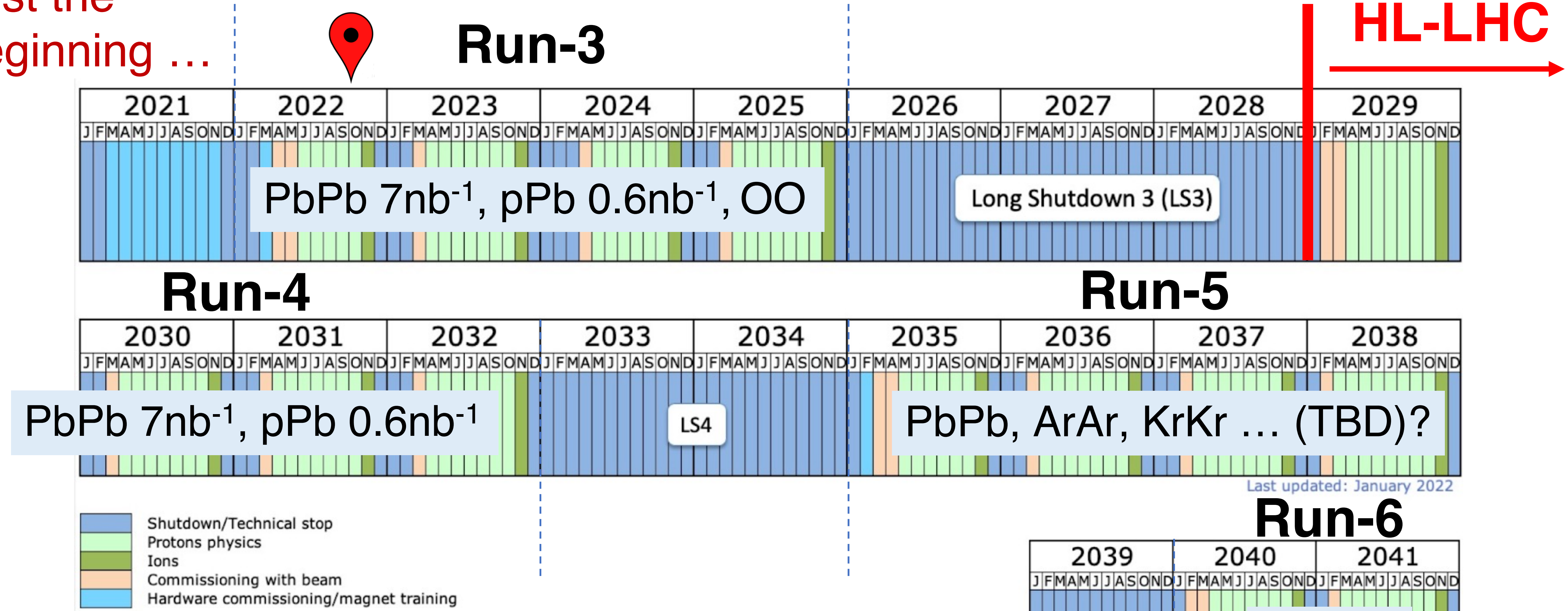
2013

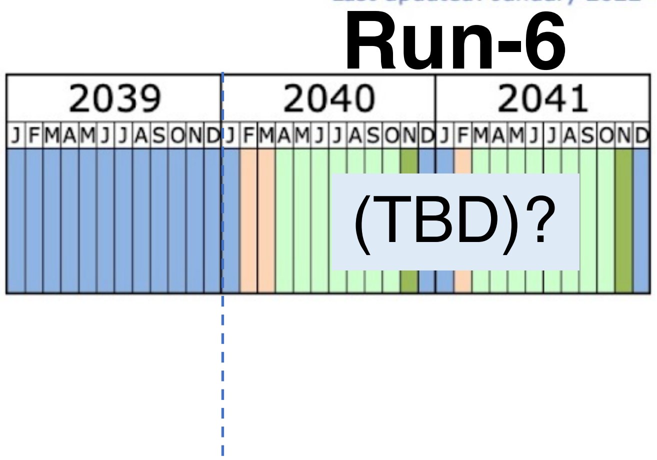




Just the beginning …
Run-3
HL-LHC
2021
2022
2023
2024
2025
2026
2027
2028
2029
Run 3
Long Shutdown 3 (LS3)
Run-4
Run-5
2030
2031
2032
2033
2034
2035
2036
2037
2038
Run 4
LS4
Run 5
Last updated: January 2022
Run-6
2039
2040
2041
Shutdown/Technical stop
Protons physics
Ions
Commissioning with beam
Hardware commissioning/magnet training

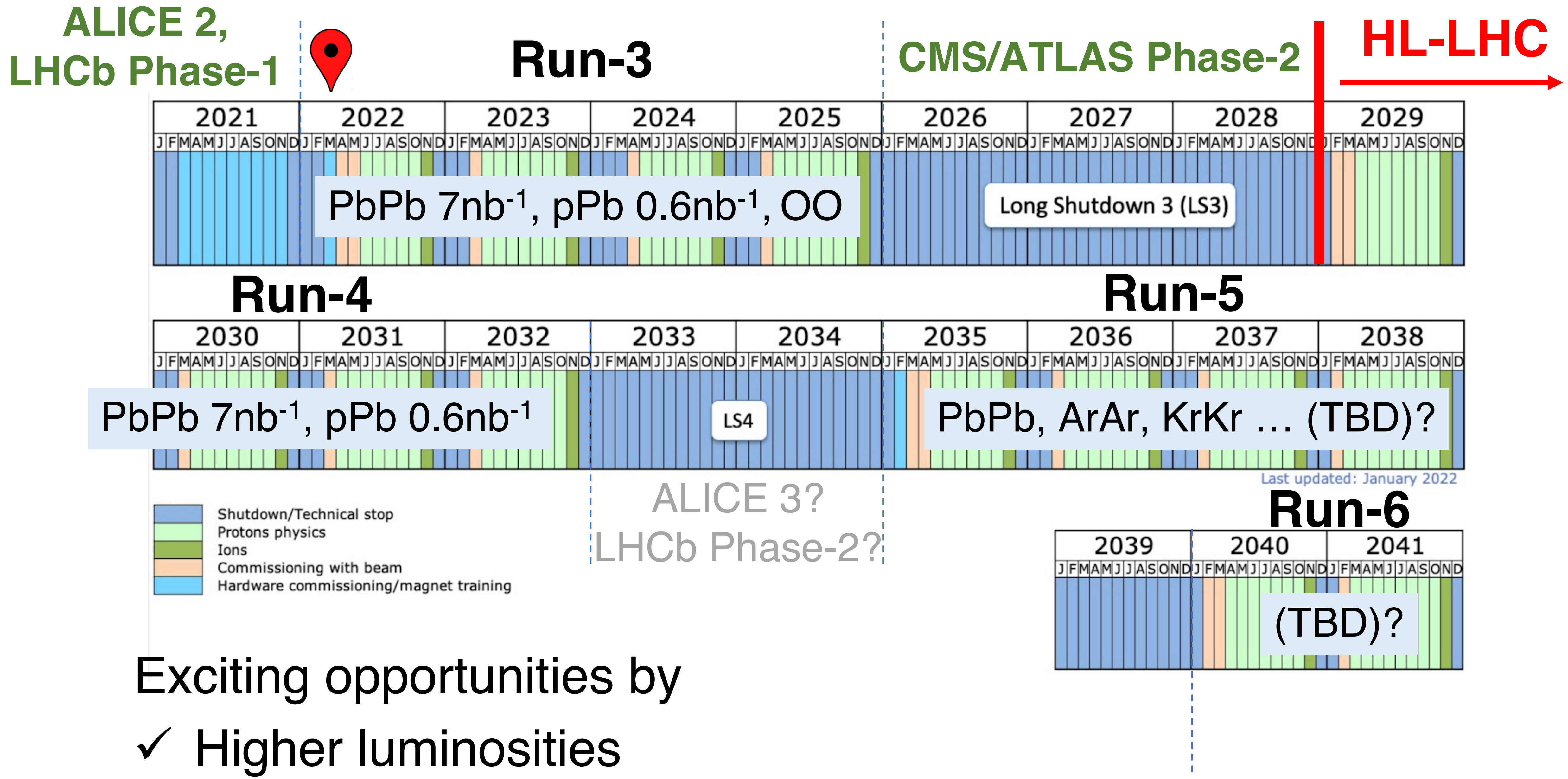
Just the beginning …





Exciting opportunities by

✓ Higher luminosities



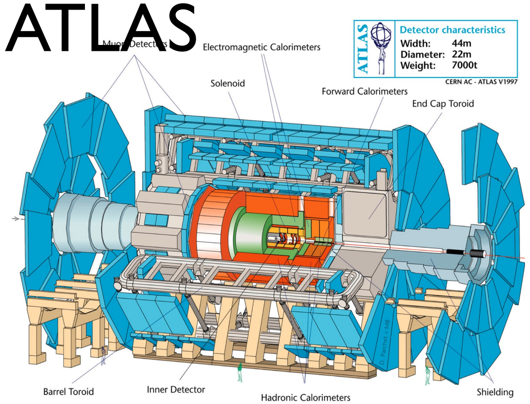
Exciting opportunities by

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

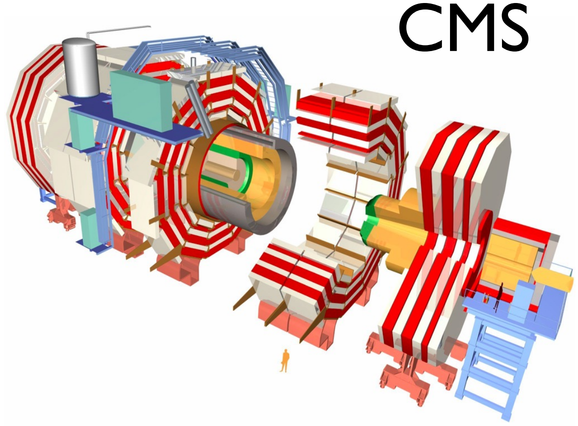
QGP detectors at the LHC (present)

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

ATLAS



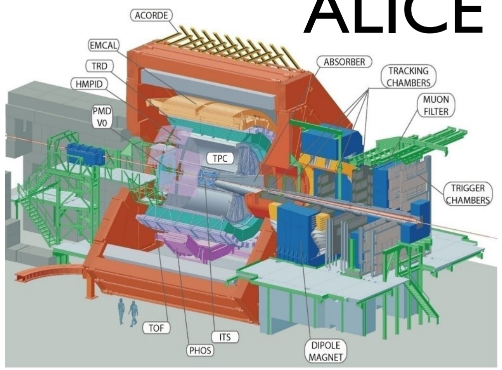
CMS



Excellent hadron PID over wide p_T coverage

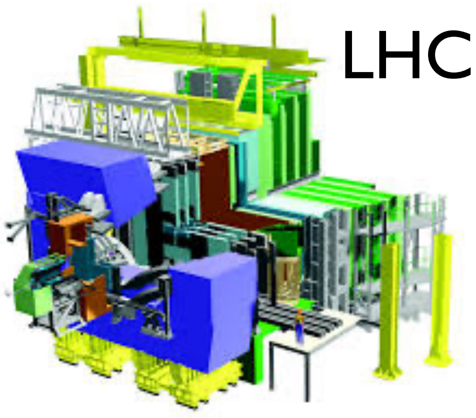
Mid-rapidity

ALICE



Forward rapidity

LHCb



Excellent complementarities but no one detector for all

CMS 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	$\|\eta\| < 2.4$, $100\times150\ \mu m^2$ pixel size	$\|\eta\| < 4$, $50\times50\ \mu m^2$ 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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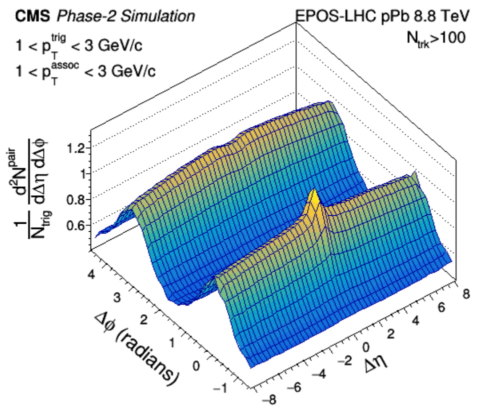

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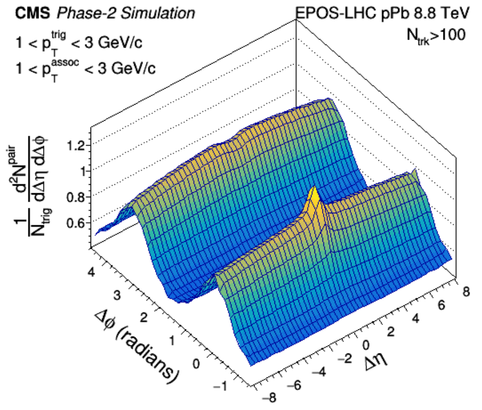

all PbPb evts read out

CMS Phase-2 upgrades for HL-LHC

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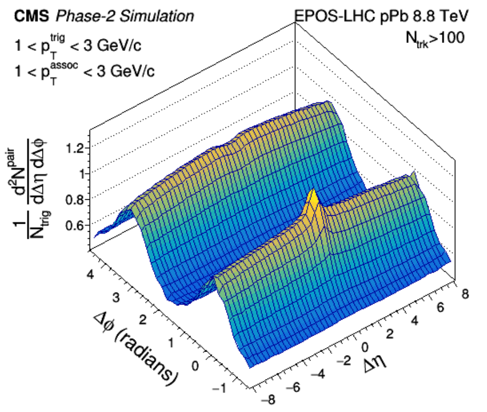

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Time-of-flight for Particle ID	**N/A**	**MTD for charged hadron PID over $\lvert\eta\rvert < 3.0$**

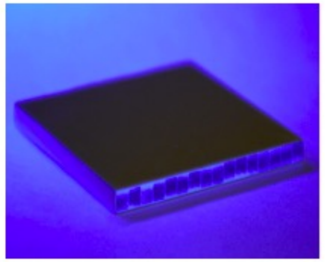
all PbPb evts read out

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

Toward a comprehensive QGP detector

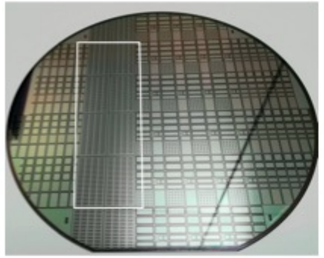
BTL: LYSO bars + SiPM readout:

- 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}: 2×10^{14} n_{eq}/cm^2

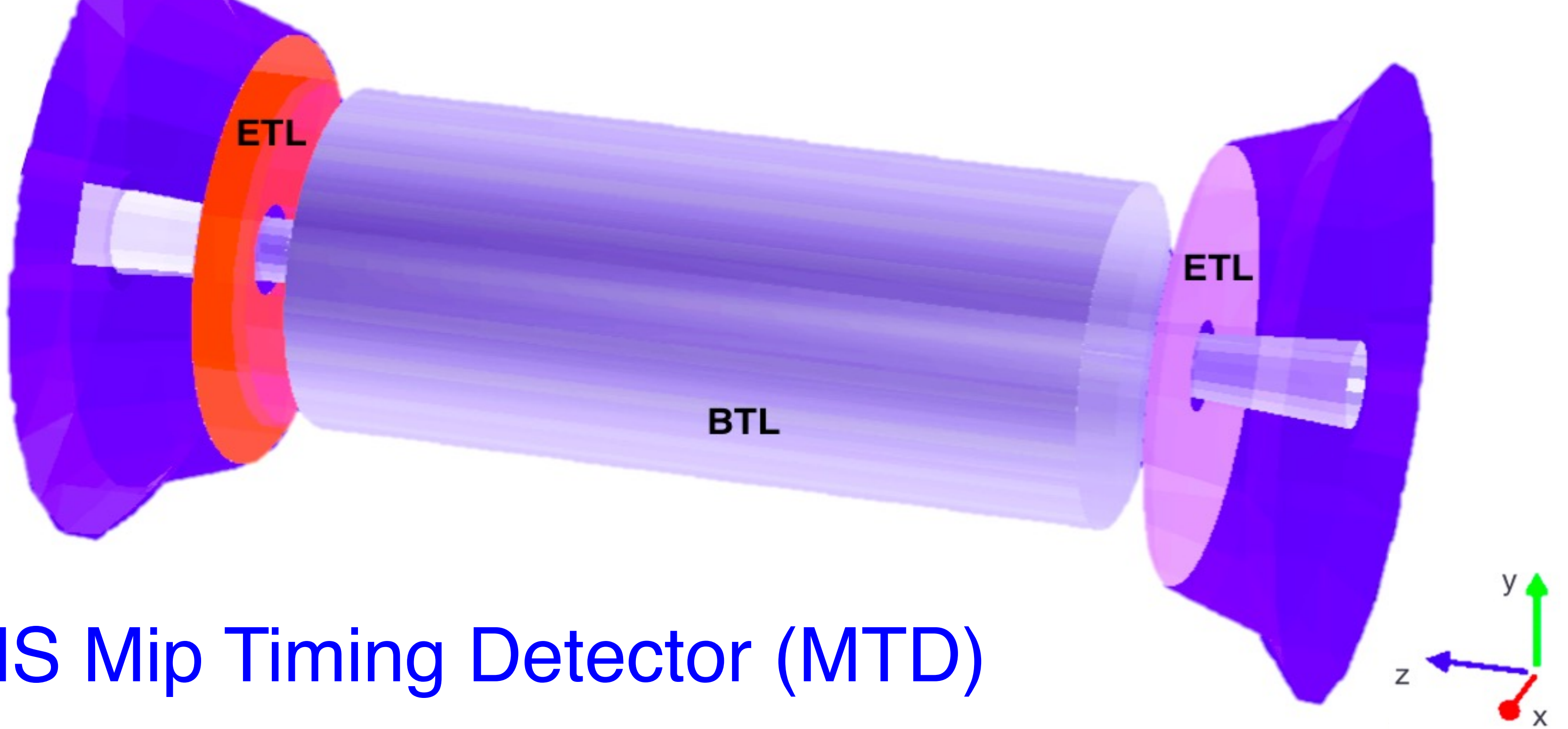


ETL: Si with internal gain (LGAD):

- 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 2×10^{15} n_{eq}/cm^2

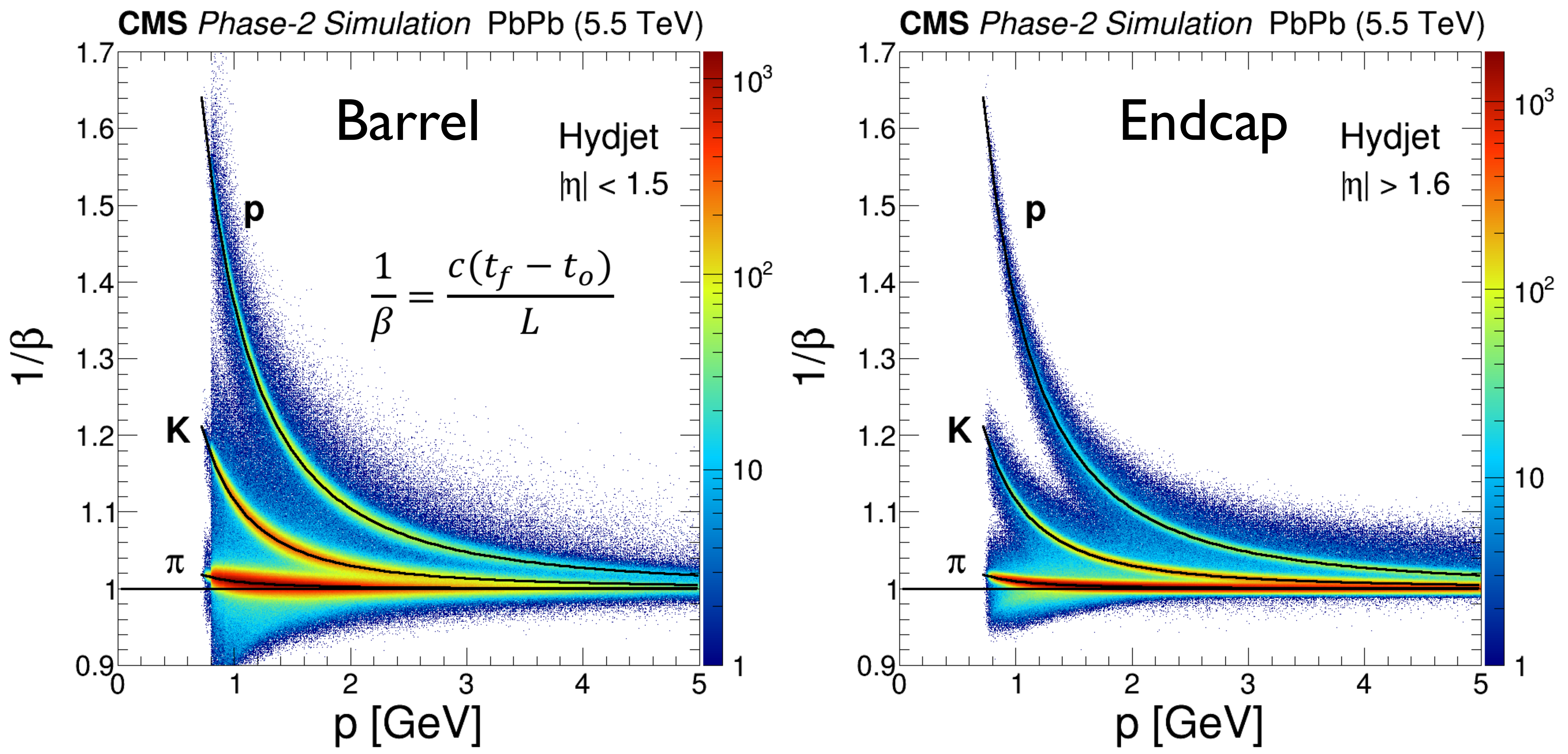


Time resolution: **30 – 40 ps** (run 4)



CMS Mip Timing Detector (MTD)

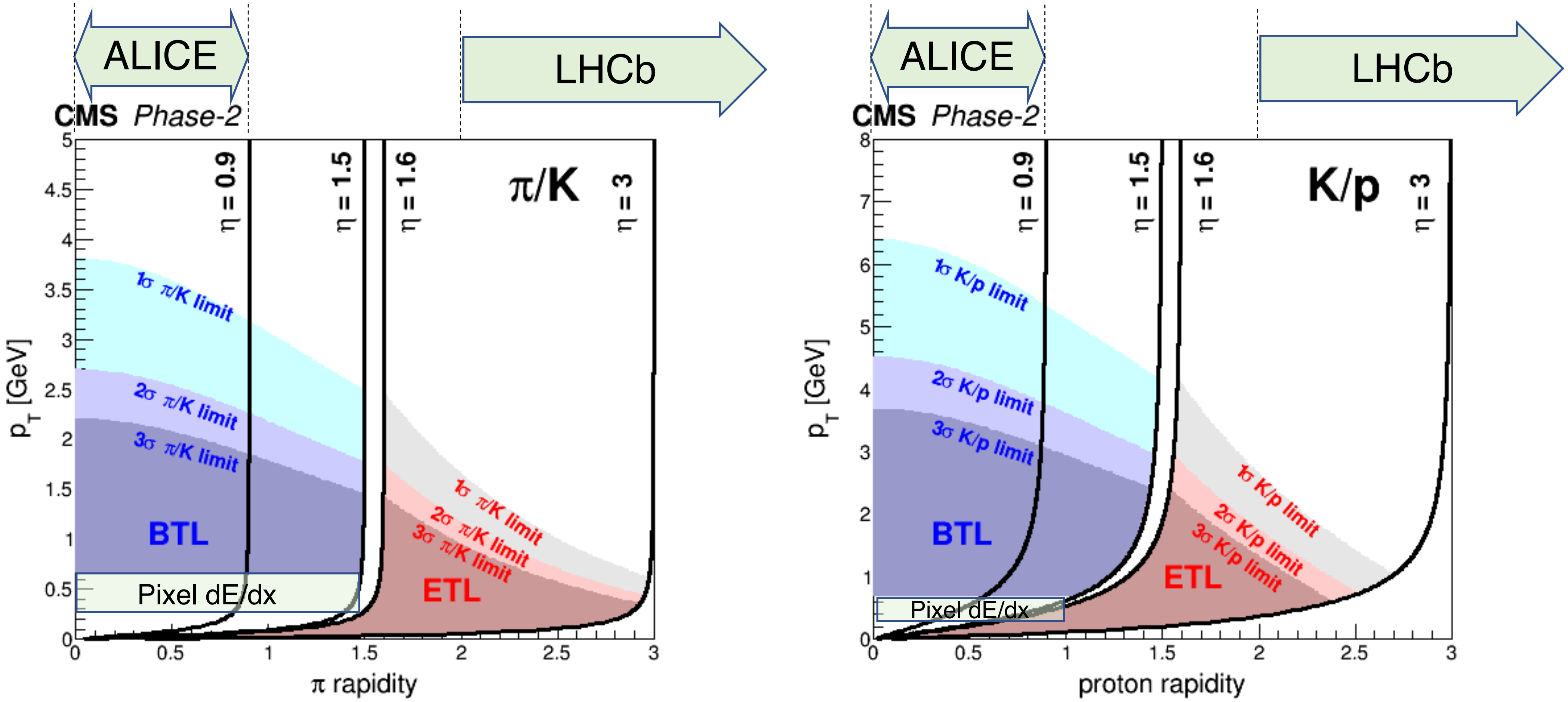
Toward a comprehensive QGP detector



TOP-PID up to p ~ 5 GeV

CERN-LHCC-2017-027

Toward a comprehensive QGP detector



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

Barrel Timing Layer

Design:

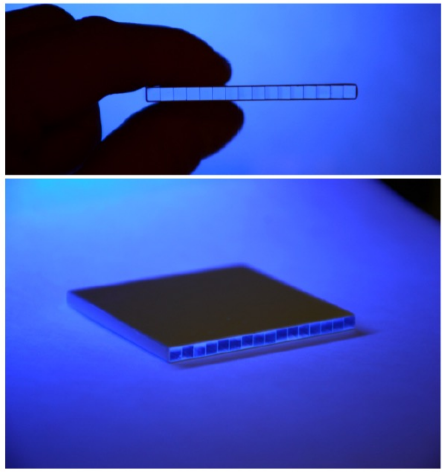
- 72 trays covering a surface of ~38 m^2
- Material budget: < 0.4 X_0
- Rapidity coverage: |η| < 1.5
- Timing resolution: ~ 30 ps

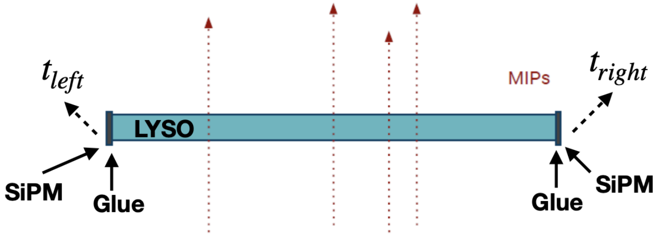
Sensors:

- **L(Y)SO:Ce crystal** bars as scintillator**:**
  - Excellent radiation tolerance, high signal and fast response time.
- **Silicon Photomultipliers** as detectors:
  - Compact, fast and insensitive to magnetic fields.

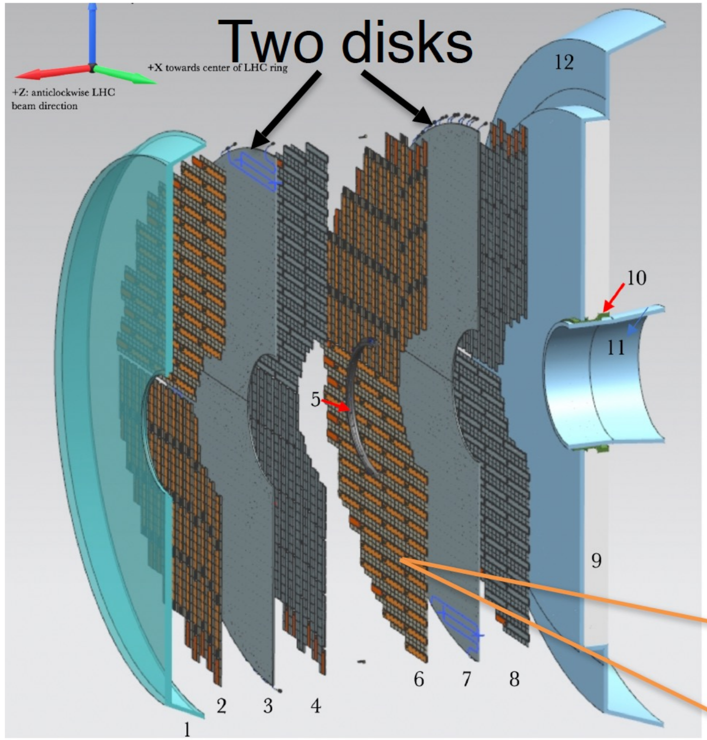
CERN-LHCC-2017-027

LYSO:Ce matrix 1x16





Endcap Timing Layer

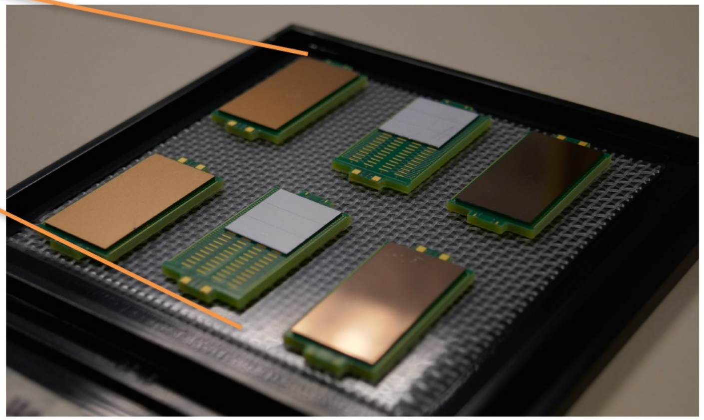


CERN-LHCC-2017-027

Design:

- 2 disks covering a surface of ~14 m^2
- Material budget: < 0.2 X_0
- Rapidity coverage: 1.6 < |η| < 3.0
- x10 higher radiation level than BTL
- Timing resolution: ~ 30-50 ps

CERN-LHCC-2017-027

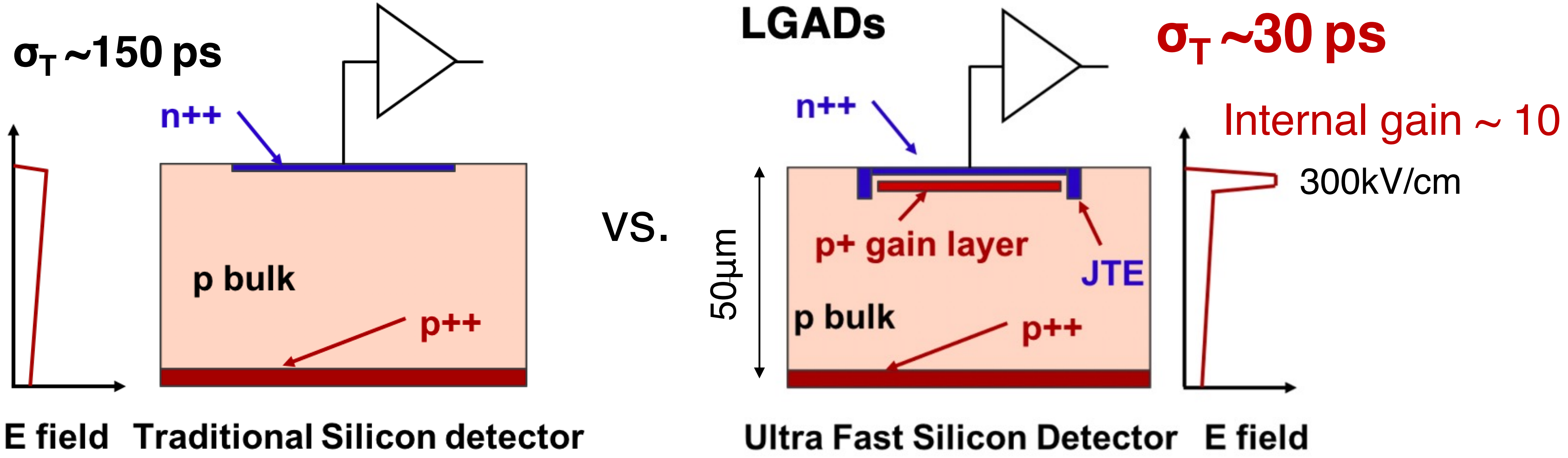


Sensors:

- **Ultra fast silicon detectors:**
  - Low gain avalanche diodes optimised for precision timing.

Low Gain Avalanche Diodes (LGADs)

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

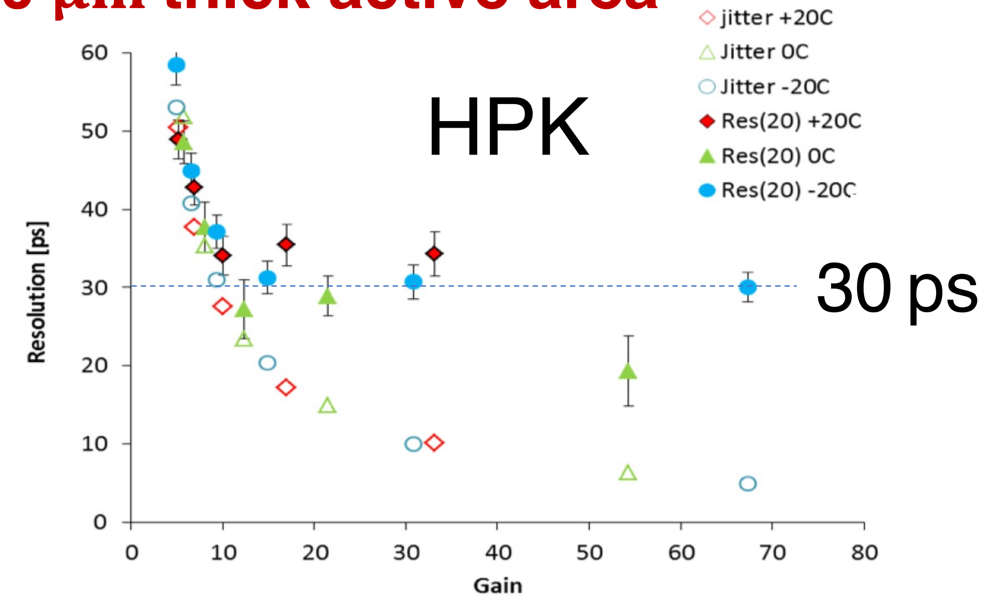


Precision timing and position – technology of the future tracker!

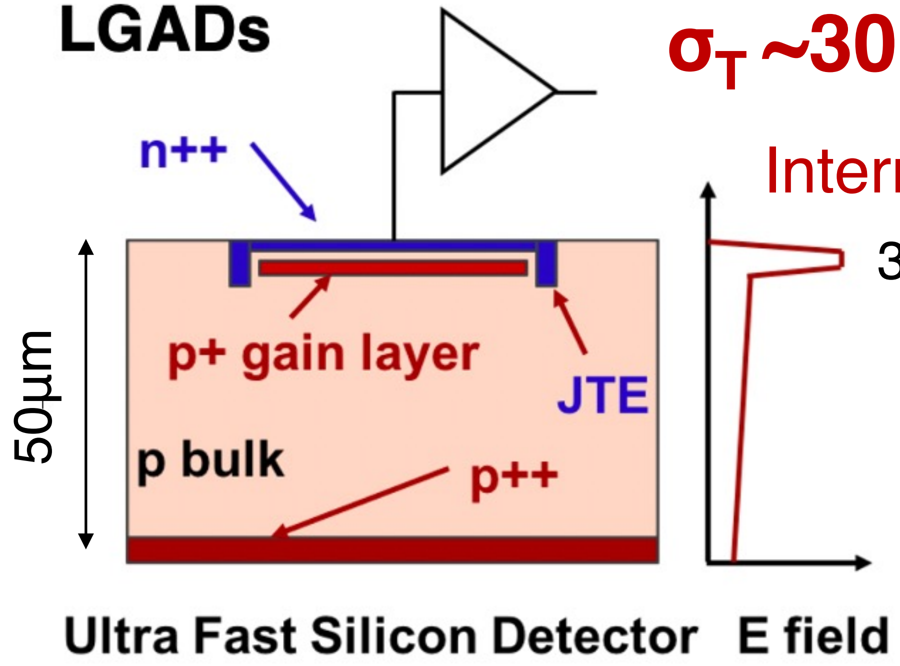
Low Gain Avalanche Diodes (LGADs)

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

50 μm thick active area



σ_T ~30 ps



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

Precision timing and position – technology of the future tracker!

Unique Physics with CMS-MTD

Questions		Measurements
• What is the (3+1)D dynamics of heavy flavors in QGP?	←	Heavy flavor hadrons over wide y ($D/D_s/\Lambda_c$, $B/B_s/\Lambda_b$)
• How does QGP medium response to energy loss?	←	Jet – **identified** hadron correlations over wide angles
• What is origin of collectivity in smallest systems?	←	Correlations with a wide range of identified probes

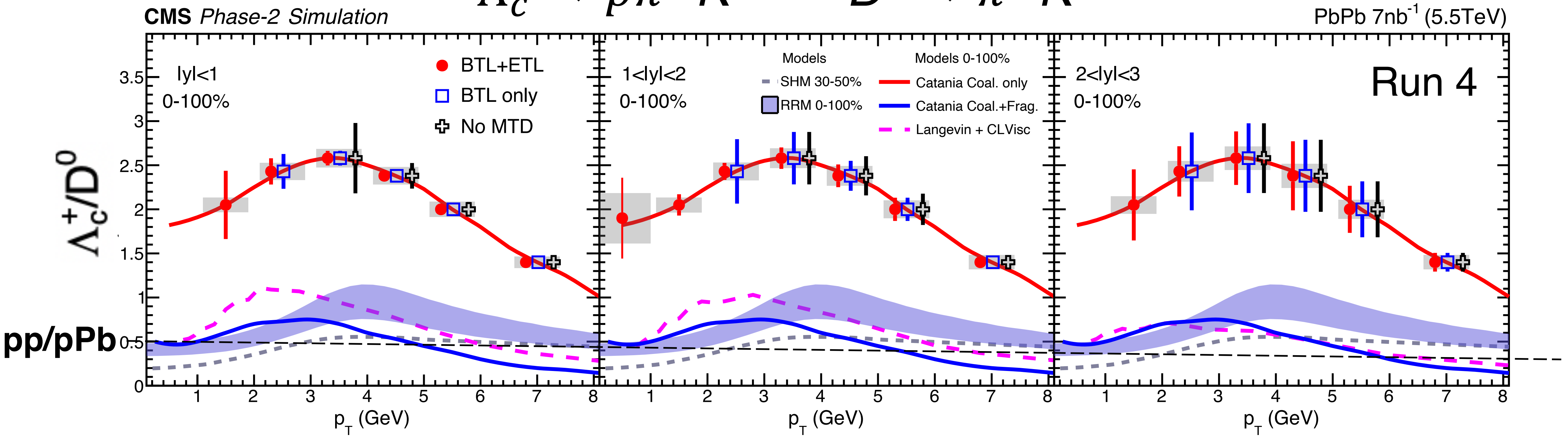
Wide-coverage Tracking	Precision vertex	Full calorimetry (ECAL+HCAL)	High rate/HLT	Lepton PID	Hadron PID
✓	✓	✓	✓	✓	✓ (MTD)

(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**

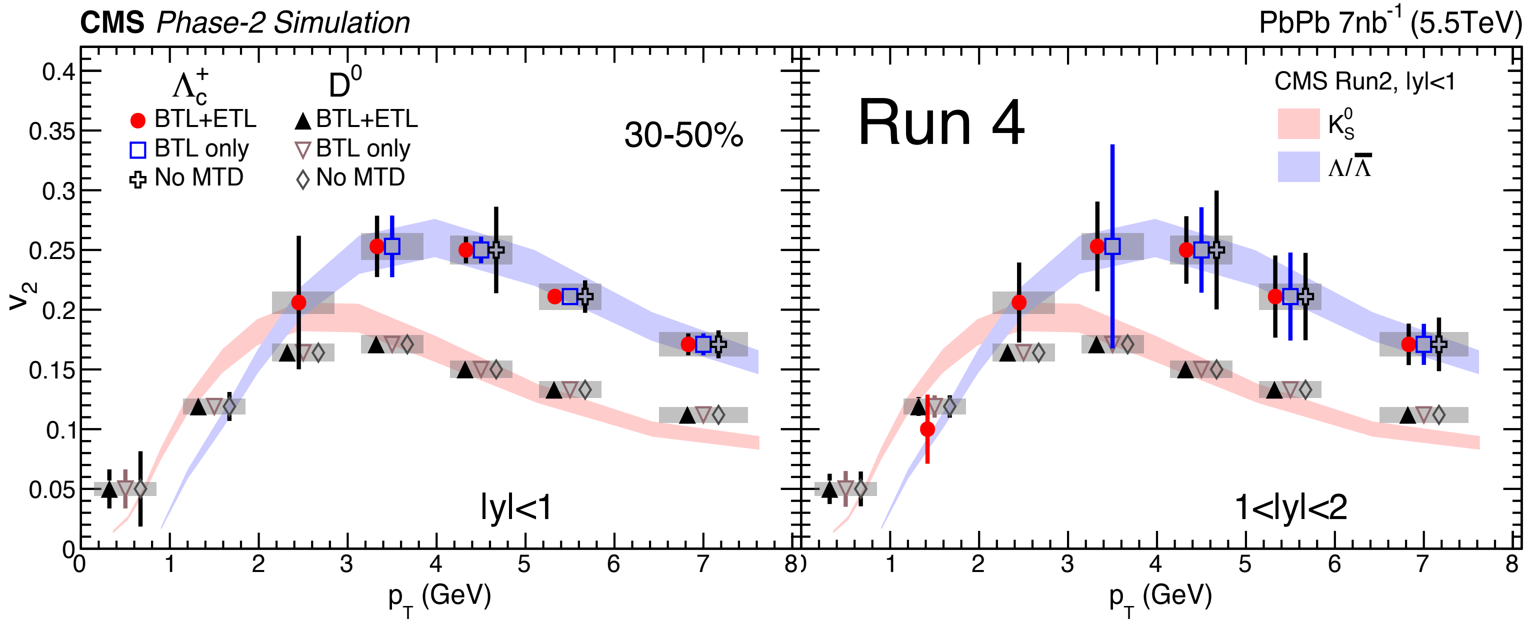
A benchmark

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



(3+1)D heavy flavor dynamics in QGP

Elliptic flow of charm baryon vs meson



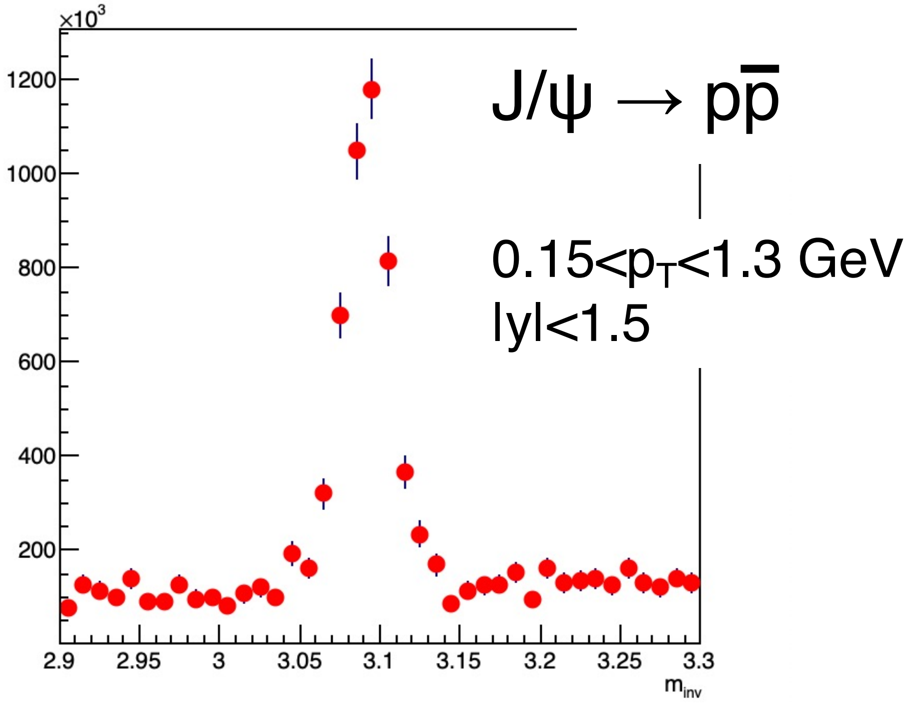
Naïve NCQ scaling in the charm sector?

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

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

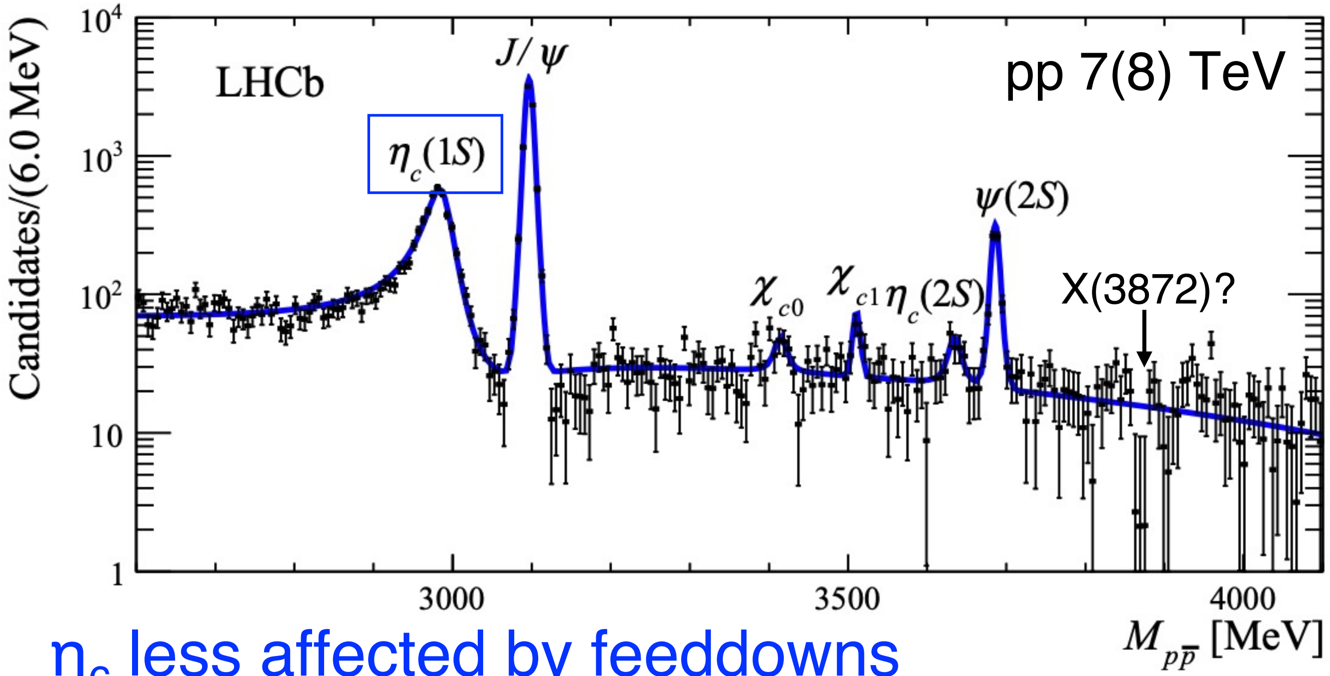
Quarkonia and Exotica with MTD

CMS-MTD simulation



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

Phys. Lett. B 769 (2017) 305

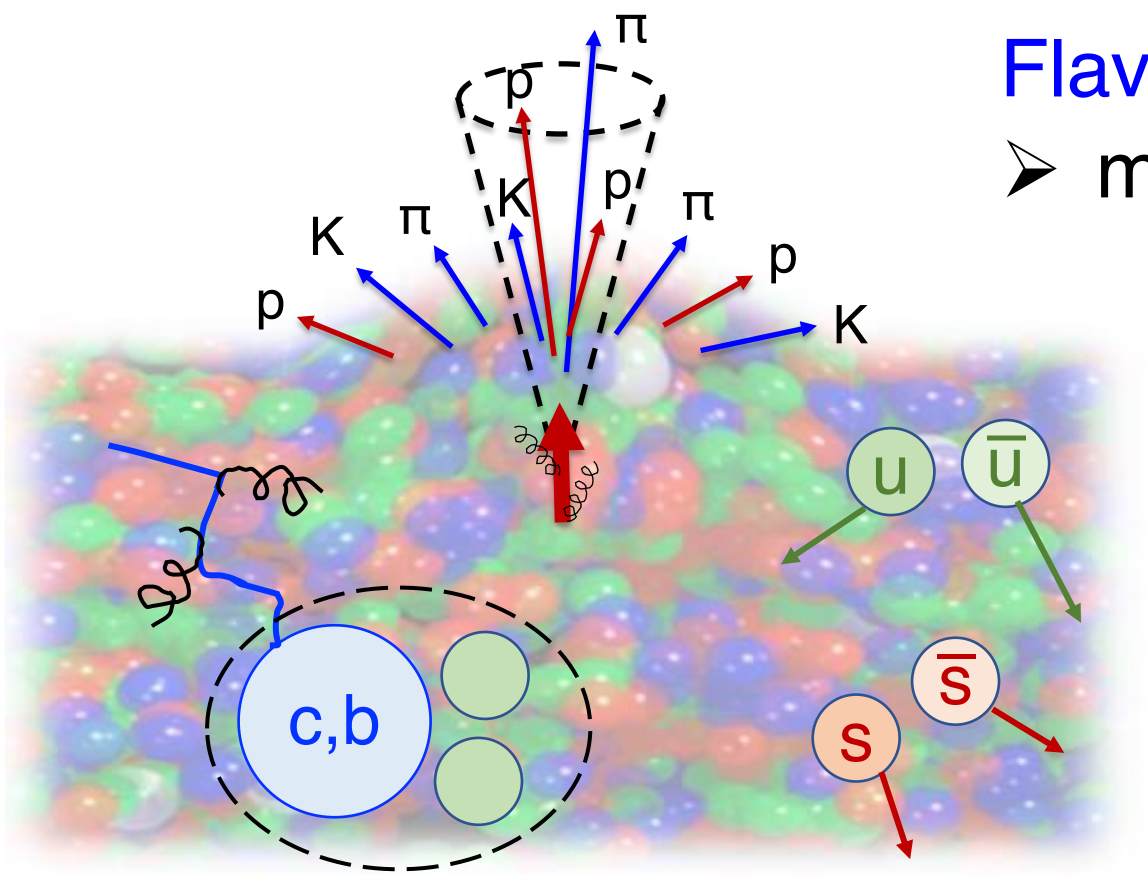


η_c less affected by feeddowns

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

Medium response to jet quenching

"Tracing the flavors"

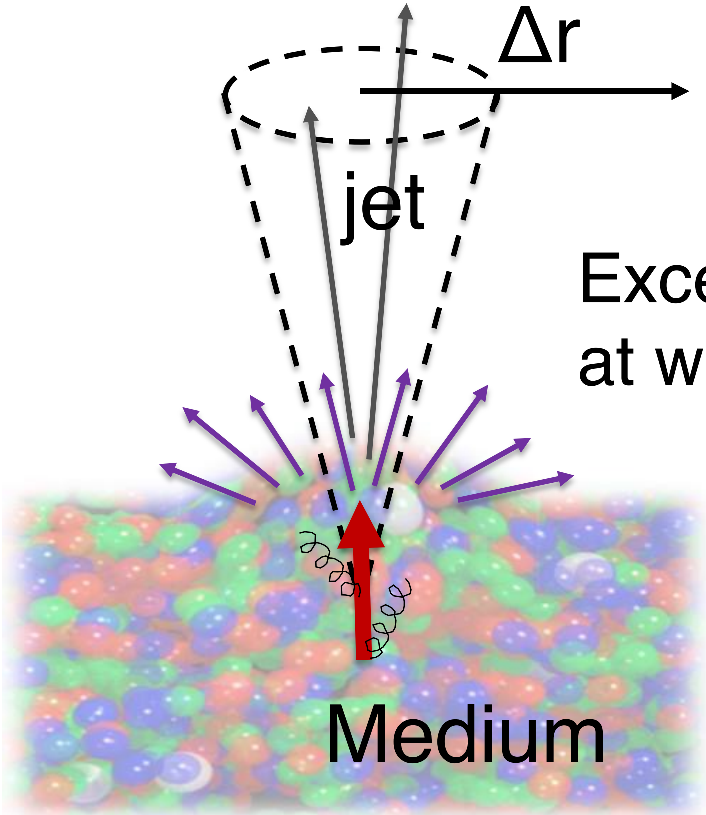


Flavor composition in and outside a jet
- medium response to energy loss

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

Medium response to jet quenching

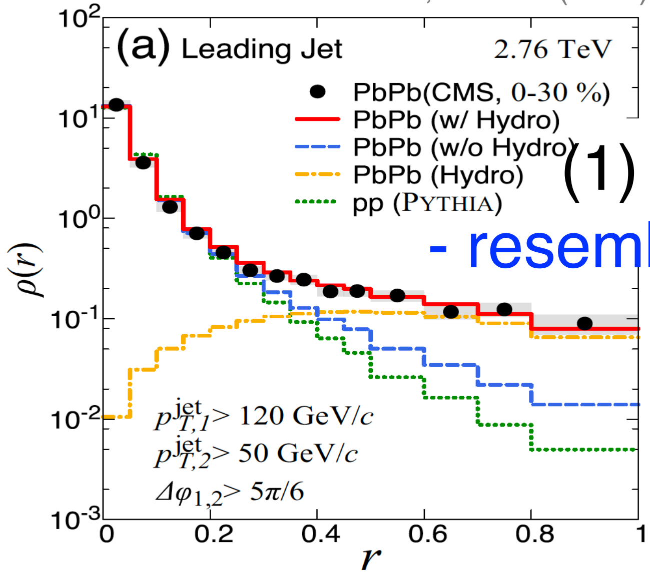
Detailed energy profile around jets over wide angle (from di-jets, γ+jets, Z+jets)



Excess of energy at wide angles

– How?

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



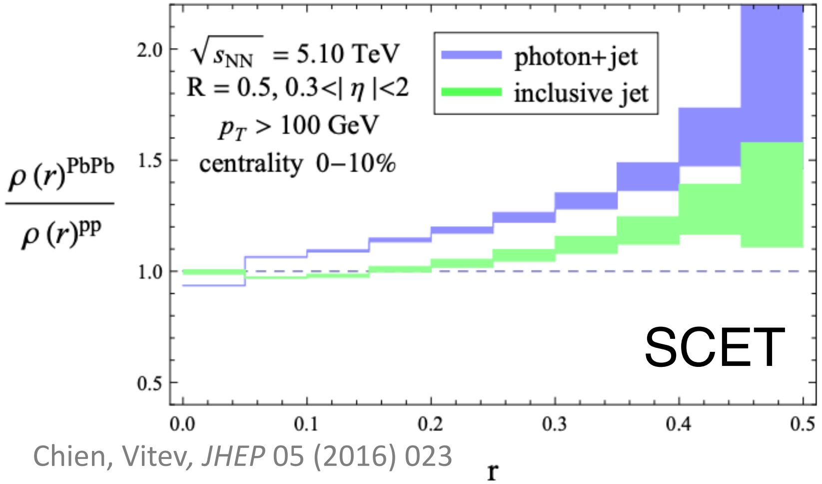
(1) QGP wake?

- resembling the medium

VS.

(2) Medium induced splitting?

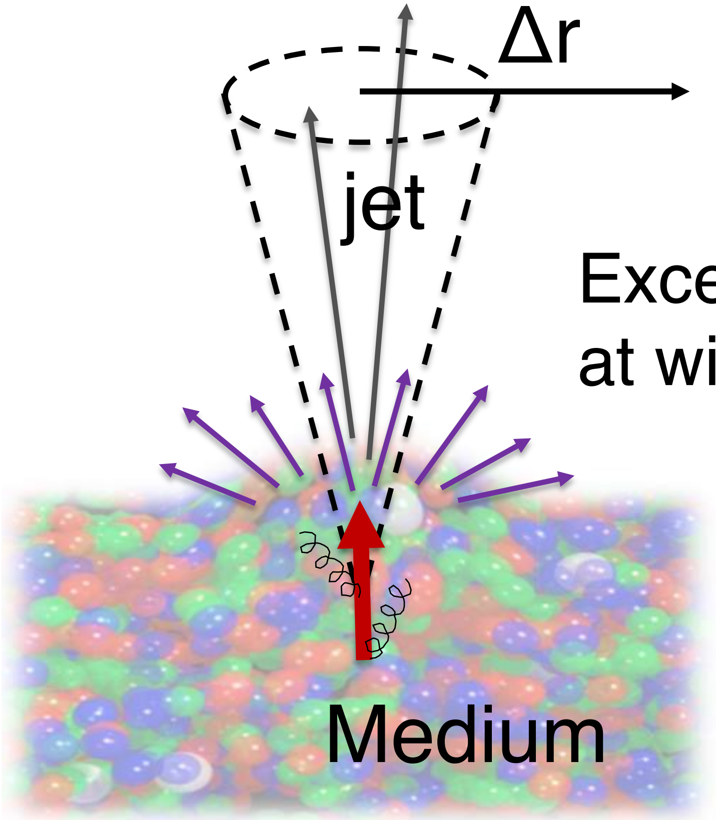
- resembling the jet



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

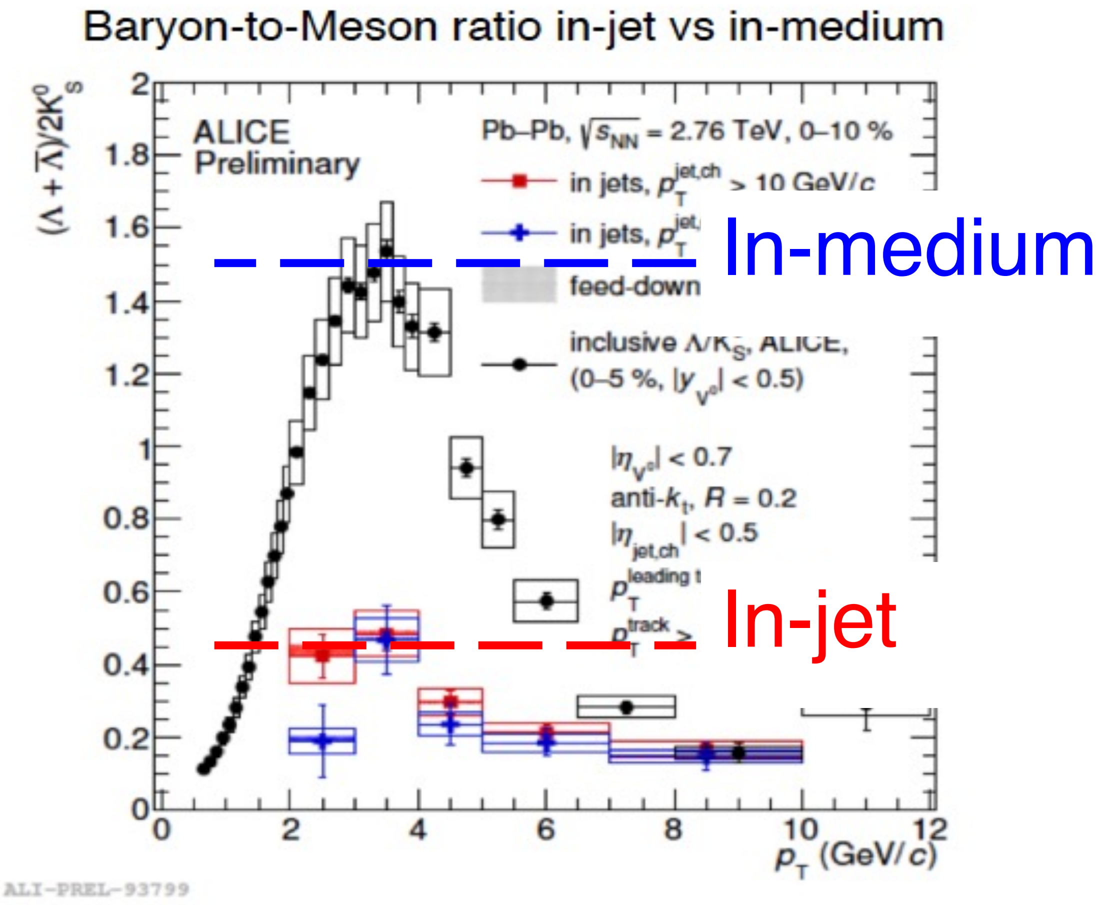
Medium response to jet quenching

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



Excess of energy at wide angles

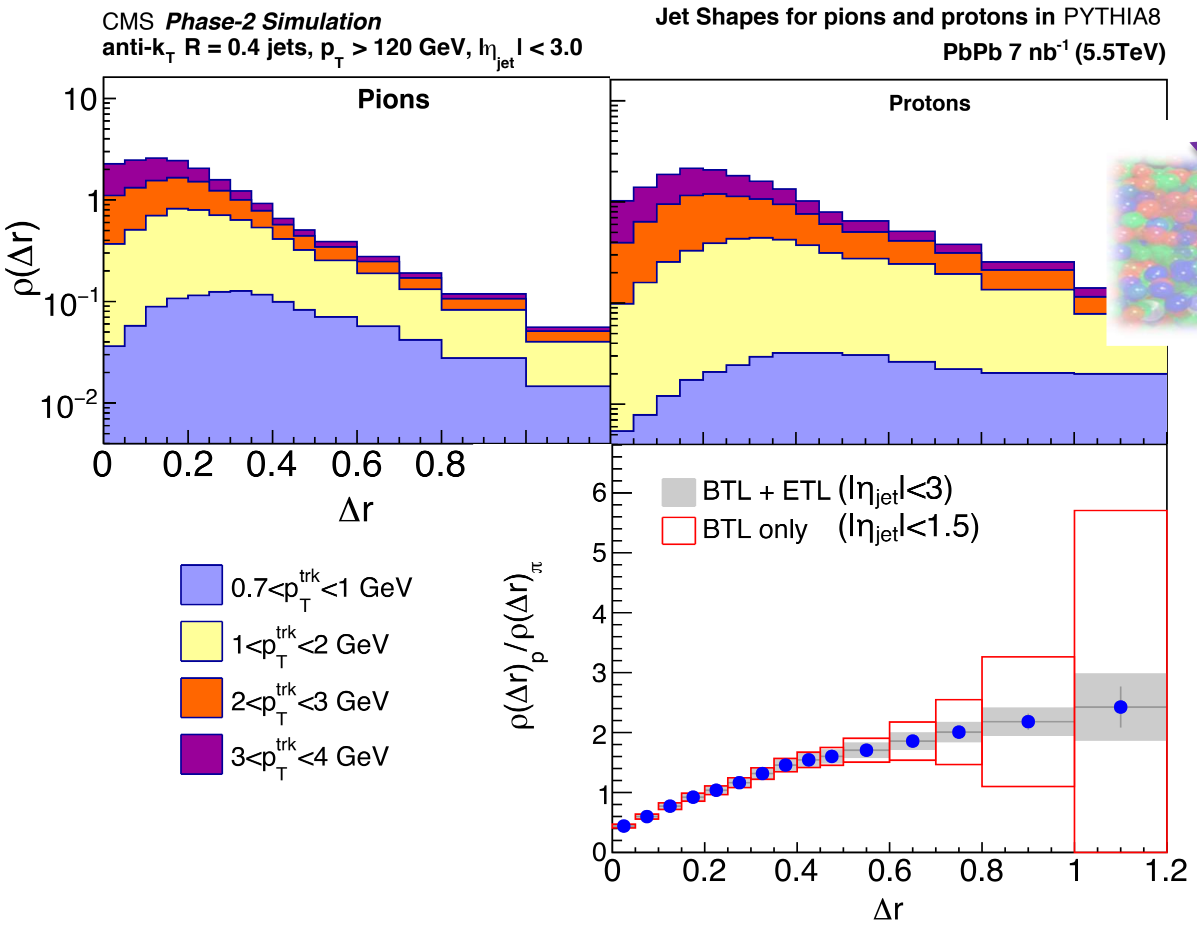
– How?

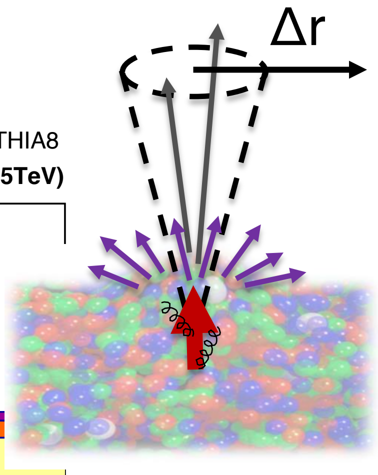


Need baryon-to-meson ratios **differential in Δr to Δr > 1**!

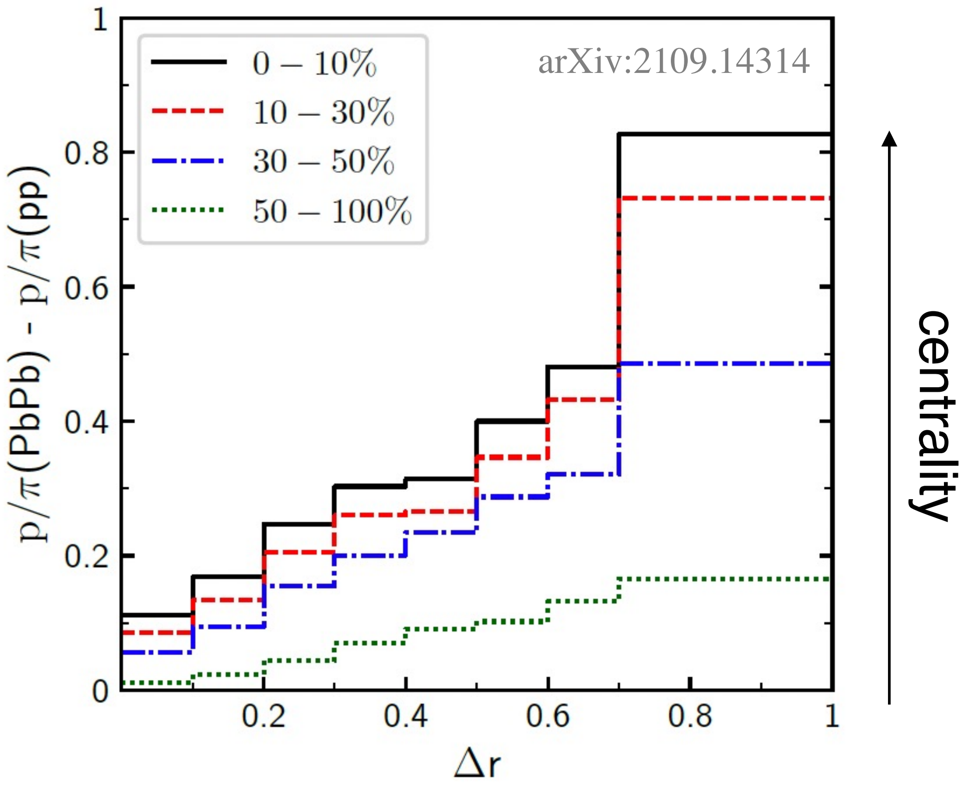
Medium response to jet quenching

CMS simulation with PYTHIA8



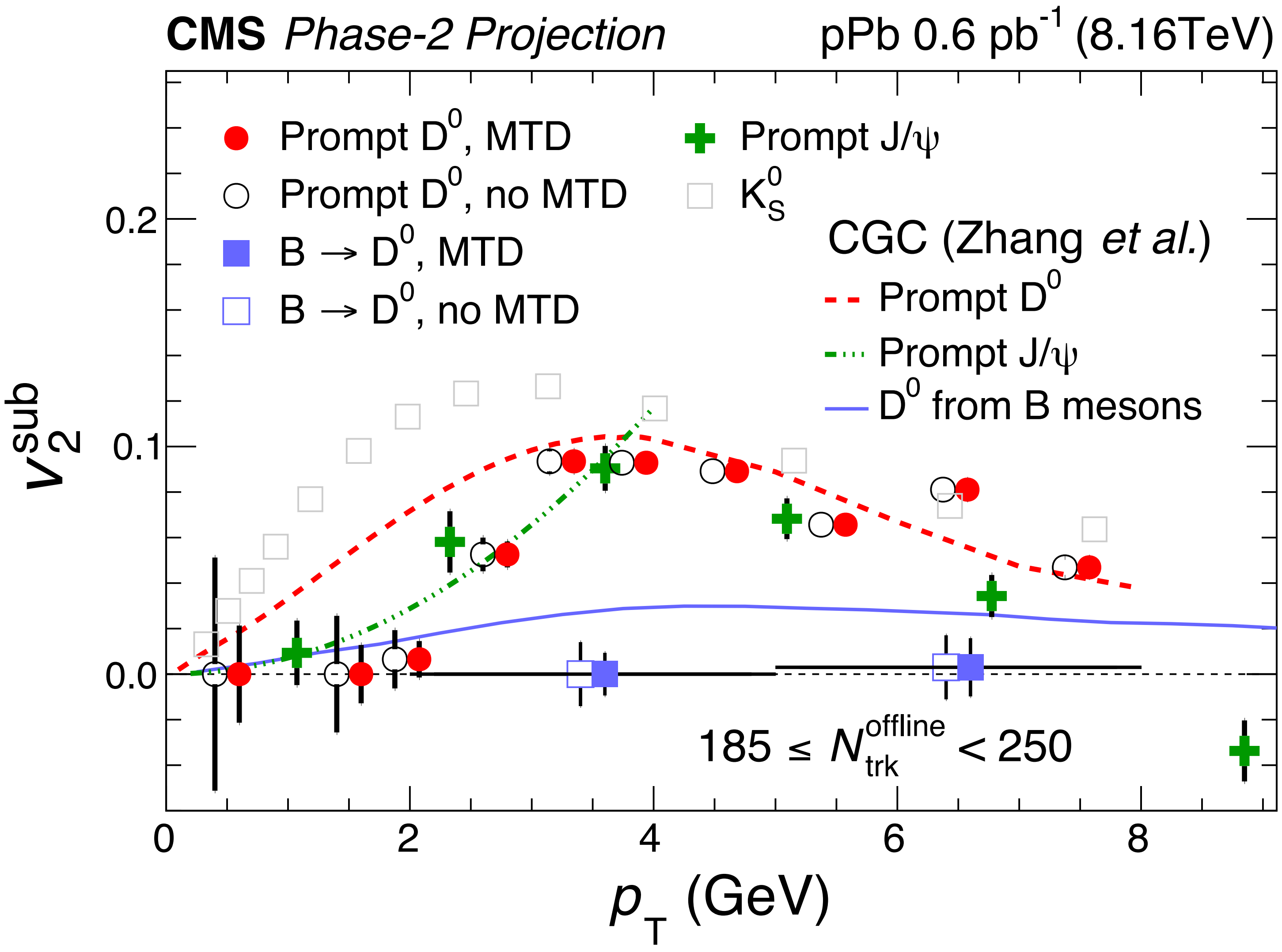


Prediction by QGP wake model



Unique measurement only possible by CMS with the MTD!

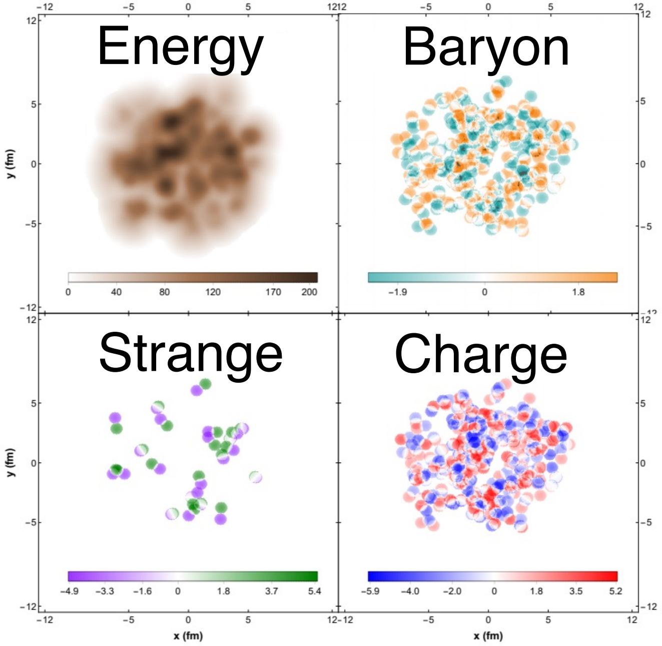
Emergence of collectivity in small systems



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

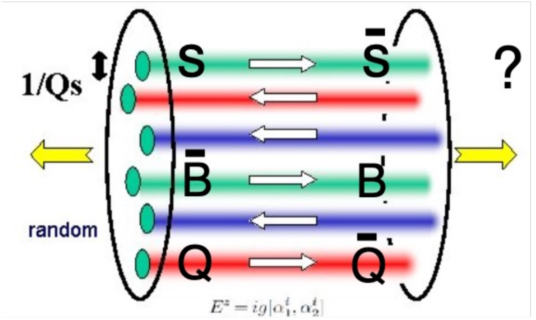
CMS-MTD simulation

Transverse *Initial state*

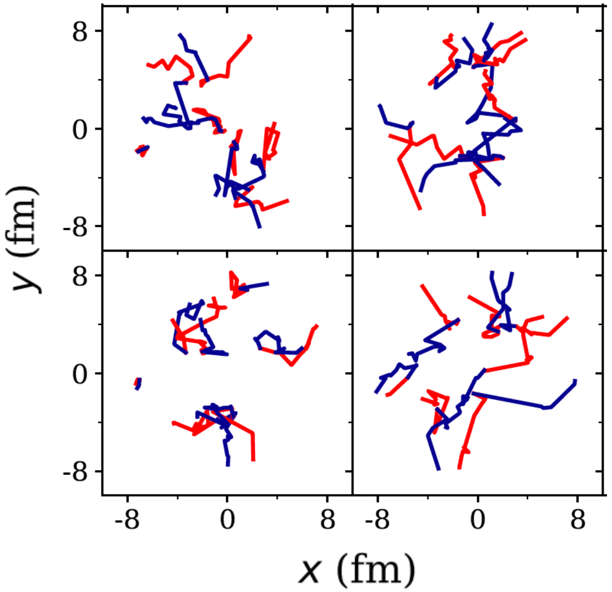


Longitudinal

arXiv:1801.08986,
arXiv:1911.10272



Diffusion in QGP

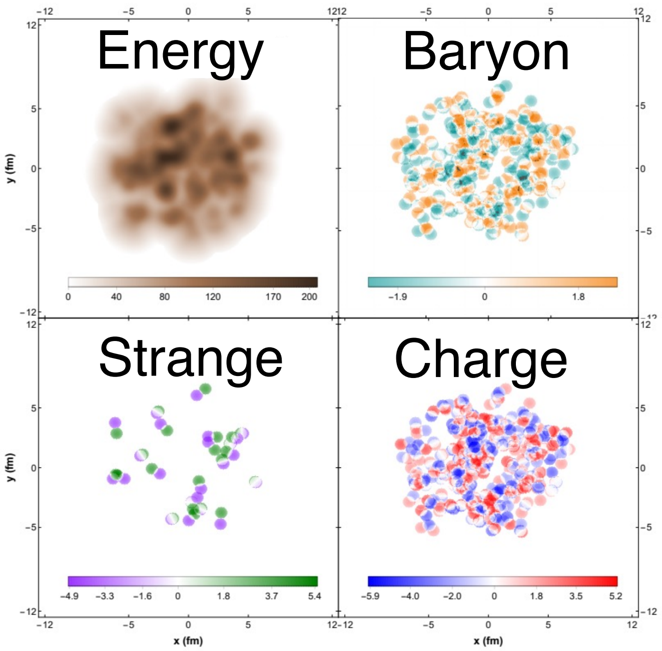


S. Pratt, C. Plumberg:
PRC 104, 014906 (2021)

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

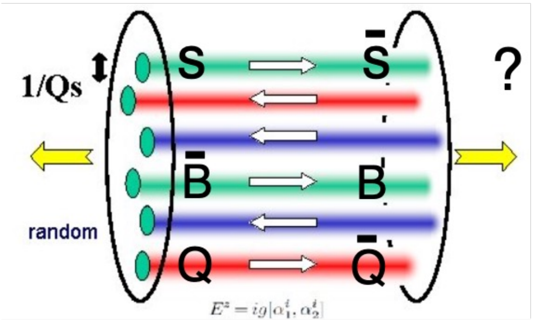
CMS-MTD simulation

Transverse *Initial state*

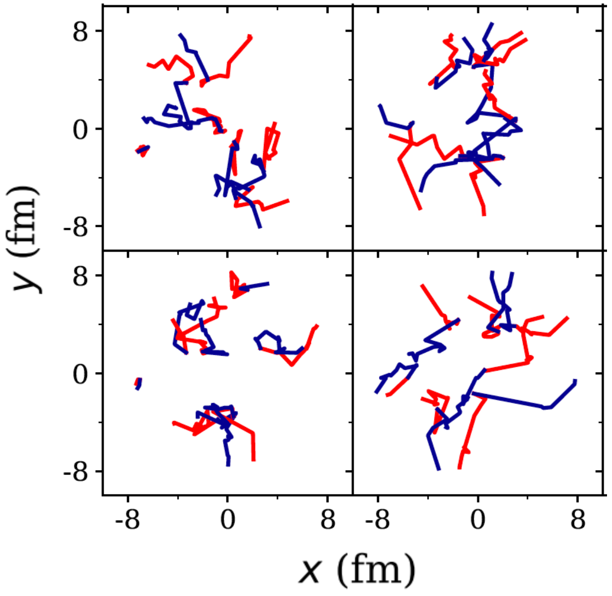


Longitudinal

arXiv:1801.08986,
arXiv:1911.10272

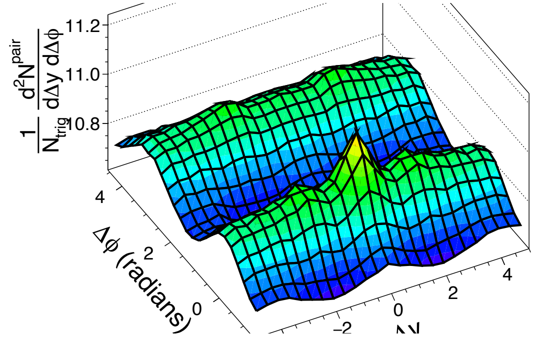


Diffusion in QGP

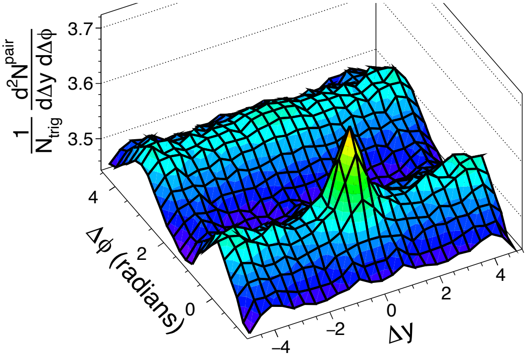


S. Pratt, C. Plumberg:
PRC 104, 014906 (2021)

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



p-p vs. p-$\bar{p}$ *Final state*

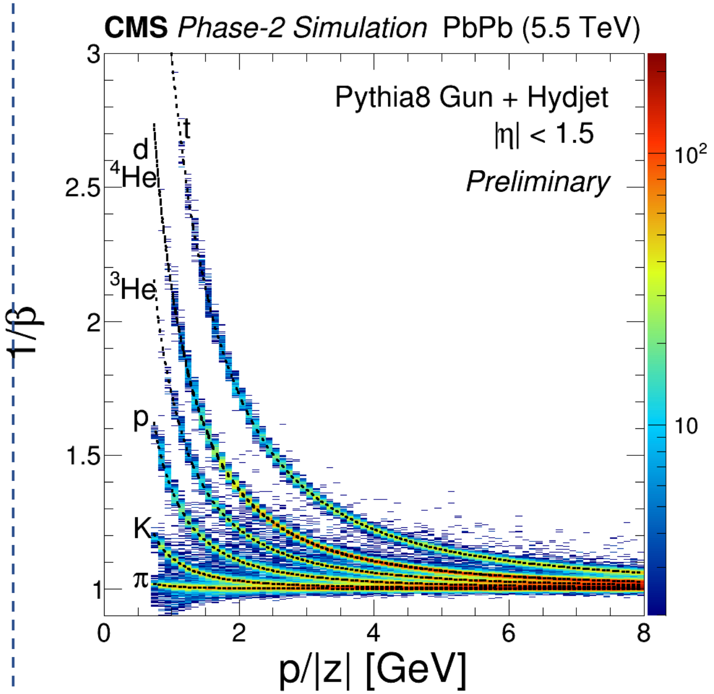


Long-range correlations with both (anti)particle identified

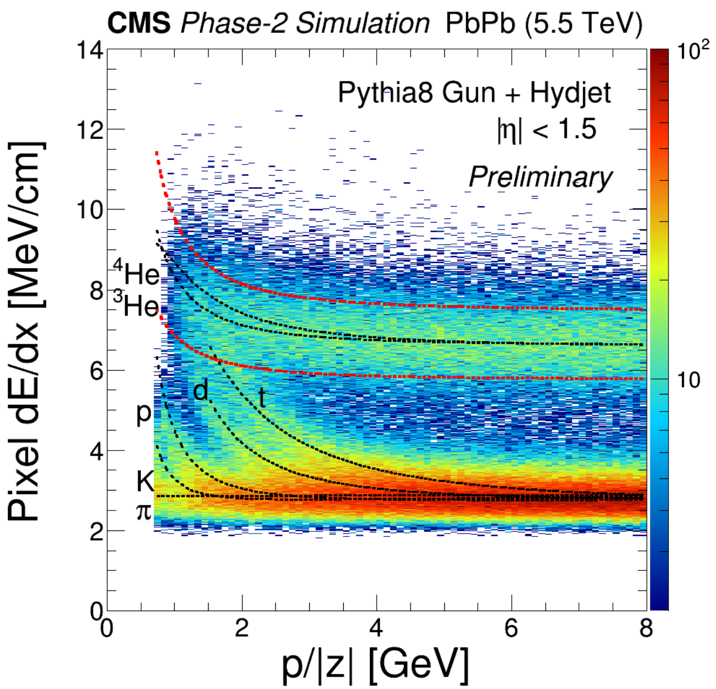
- Search at $\Delta y>2$,
  $v_2(SS) - v_2(OS) \propto \varepsilon_2^{(\mathcal{X},\mathrm{net})}\{2\} = \sqrt{\left\langle \left(\varepsilon_2^{(\mathcal{X}+)} - \varepsilon_2^{(\mathcal{X}-)}\right)^2 \right\rangle}$

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

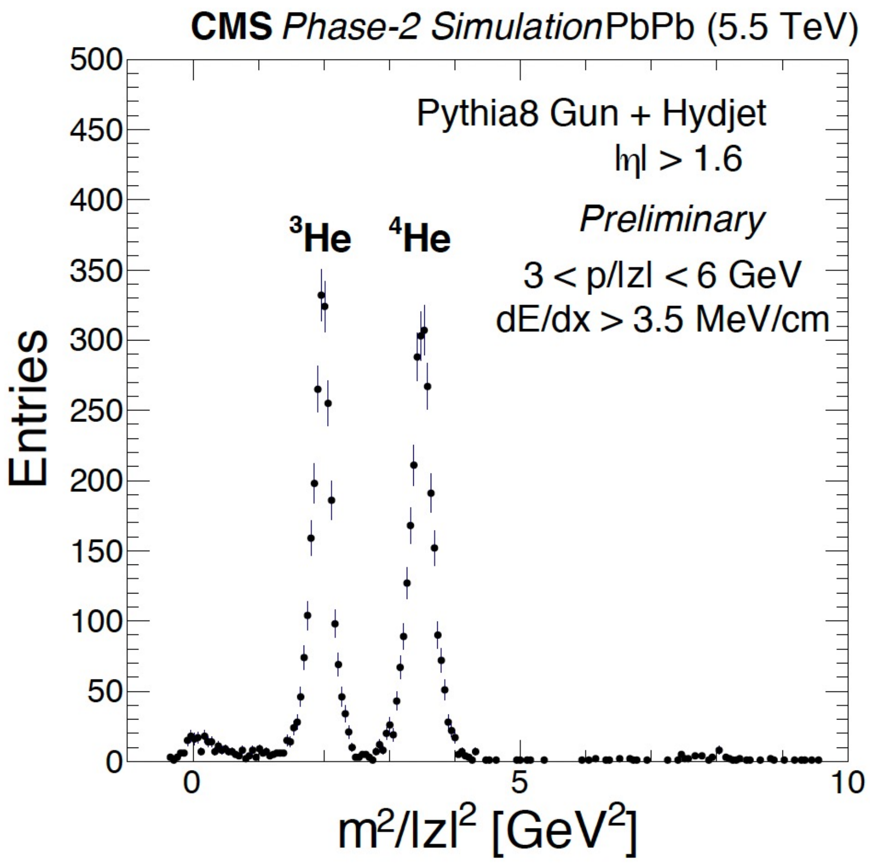
MTD TOF



Pixel tracker dE/dx

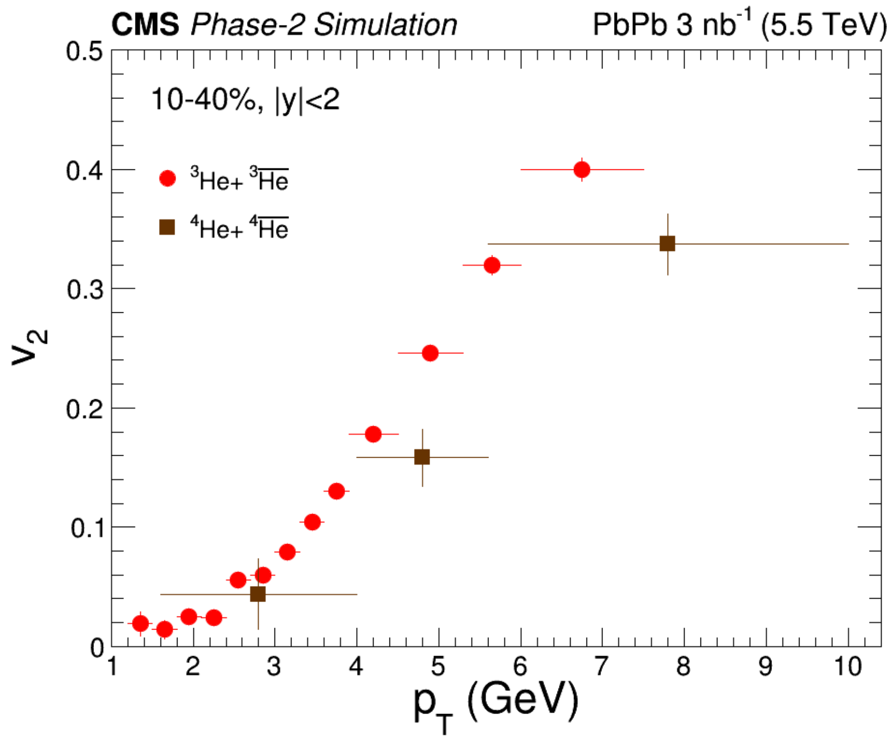


Light nuclei ID in pp/pA/AA



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

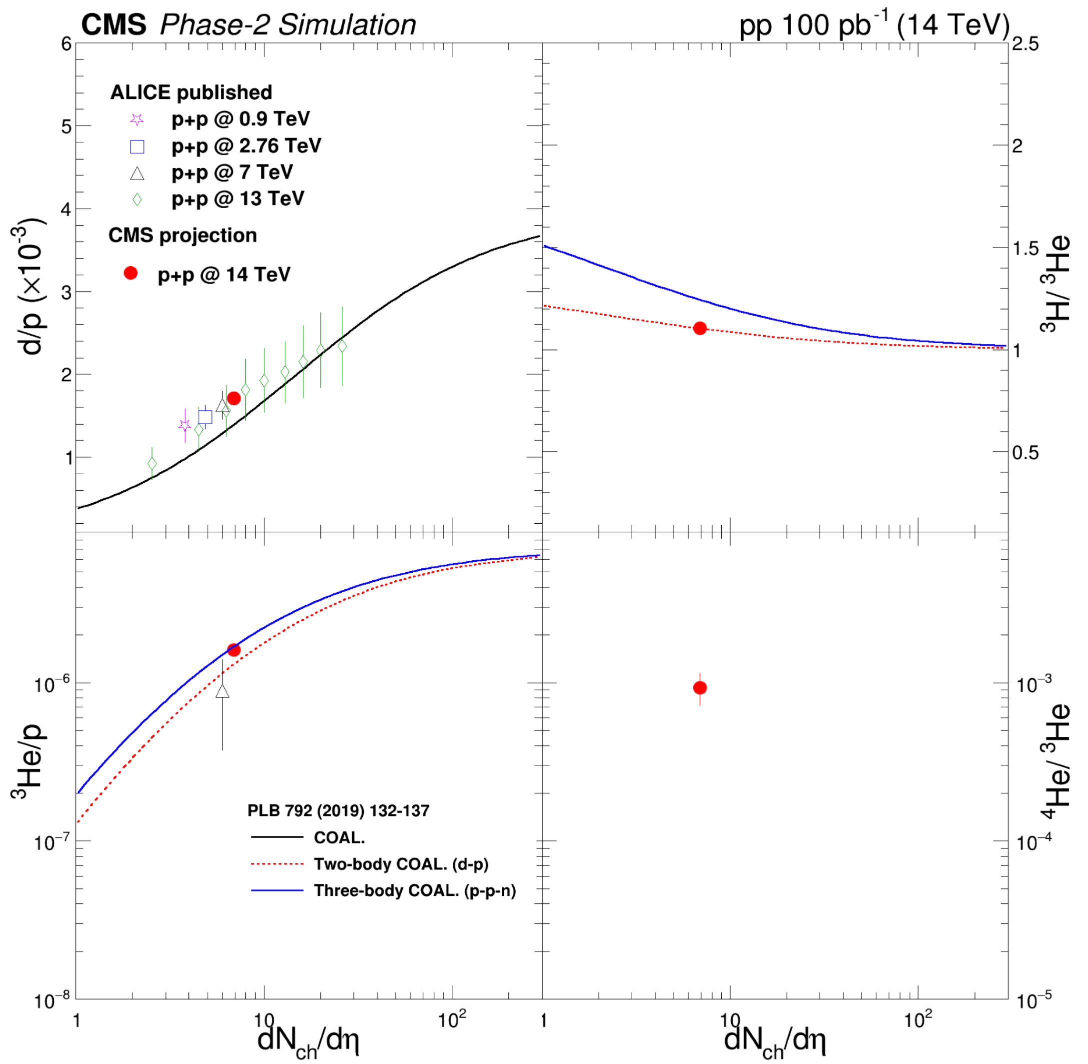
^{3}He/ ^{4}He flow in PbPb



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 $|\Delta y|>2$ • 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

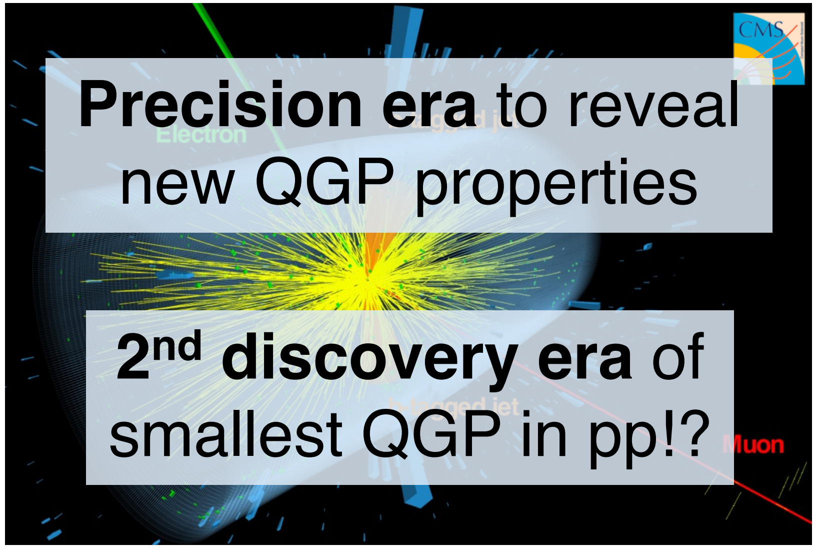
⋮

and be prepared for surprises!

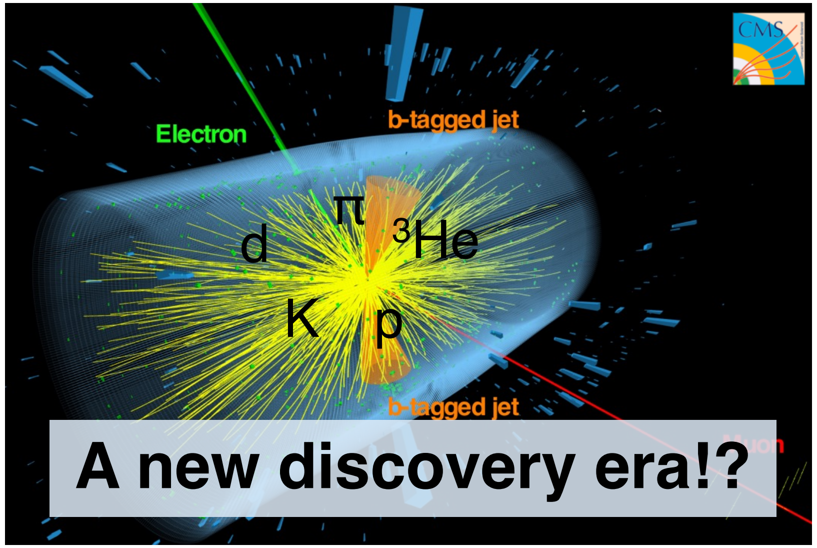
“Little Bangs”

2000: RHIC

2009: LHC



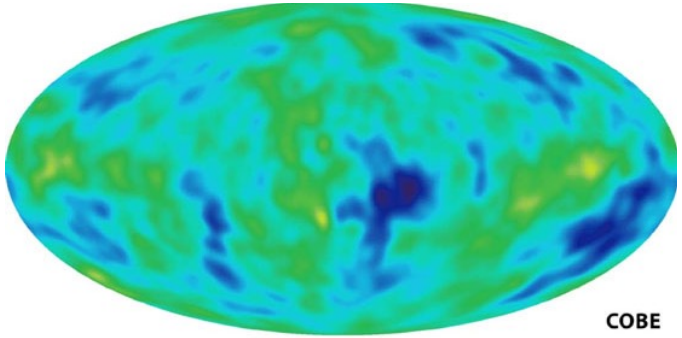
2030+: HL-LHC

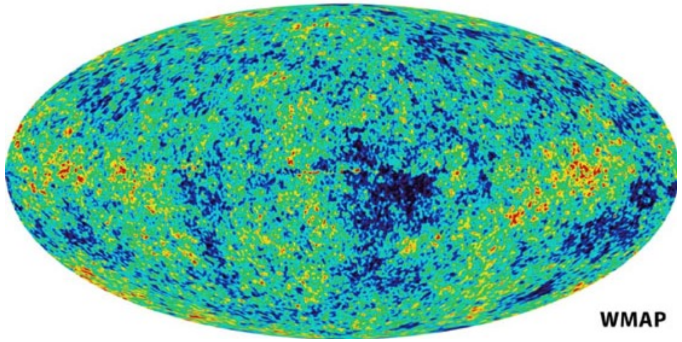


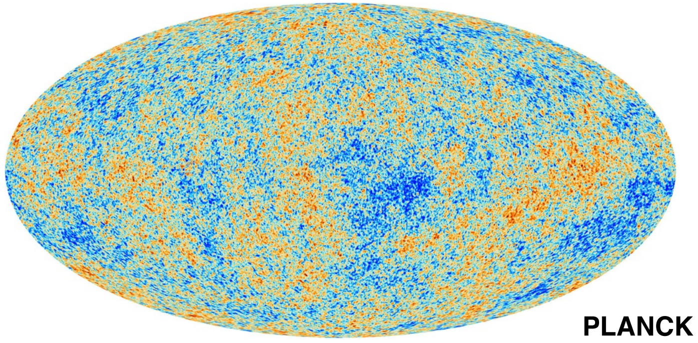
Approaching true-level event info.

t

The Big Bang

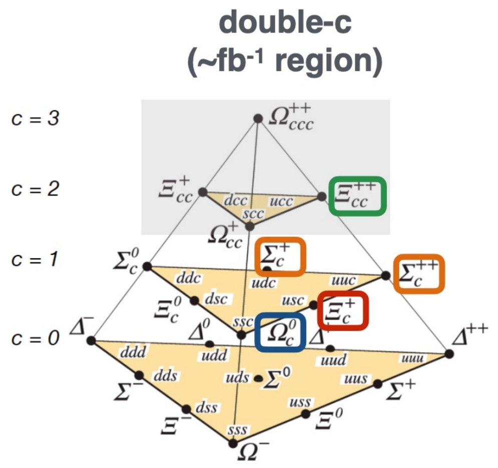


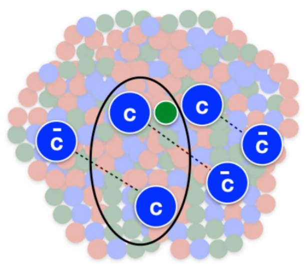




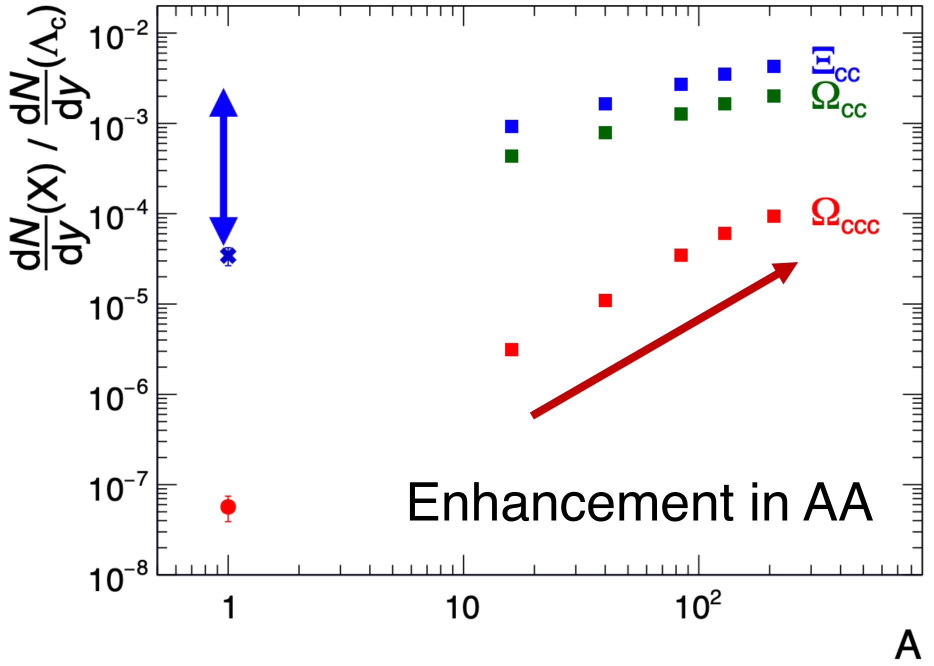
Backups

Multi-charm hadrons in QGP with MTD?





SHM (Andronic et al, JHEP 2021, 35)

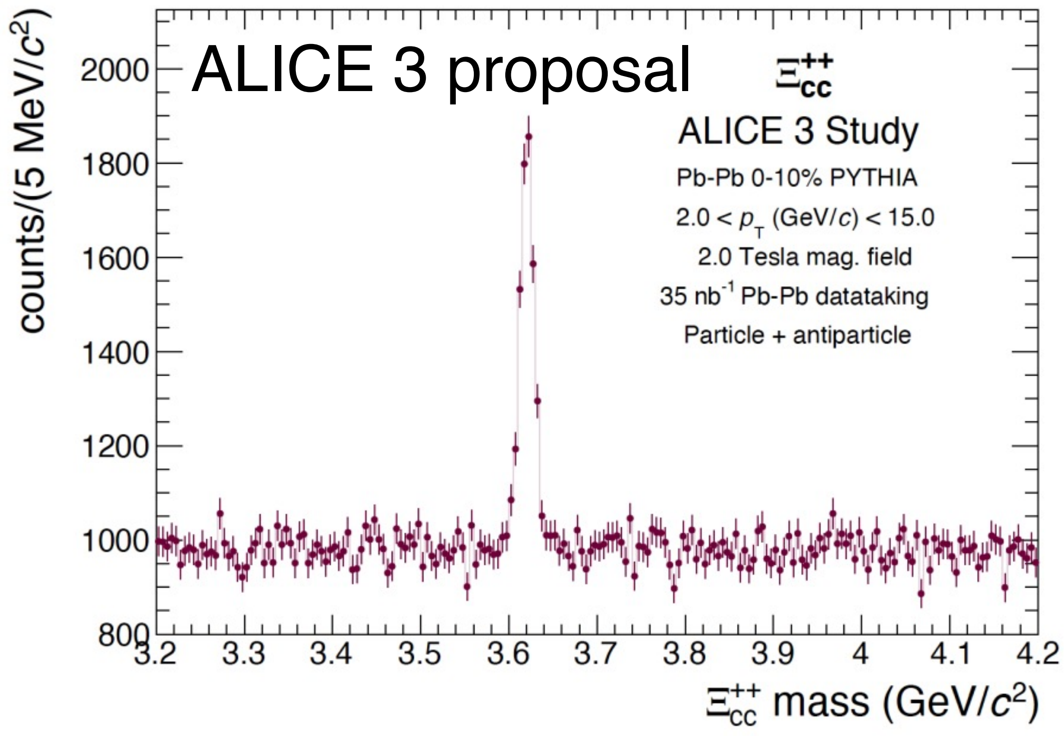


$\Xi^{++}_{cc} \rightarrow \Xi^{+}_{c} + \pi^{+}$ (cτ ≈ 76 μm)

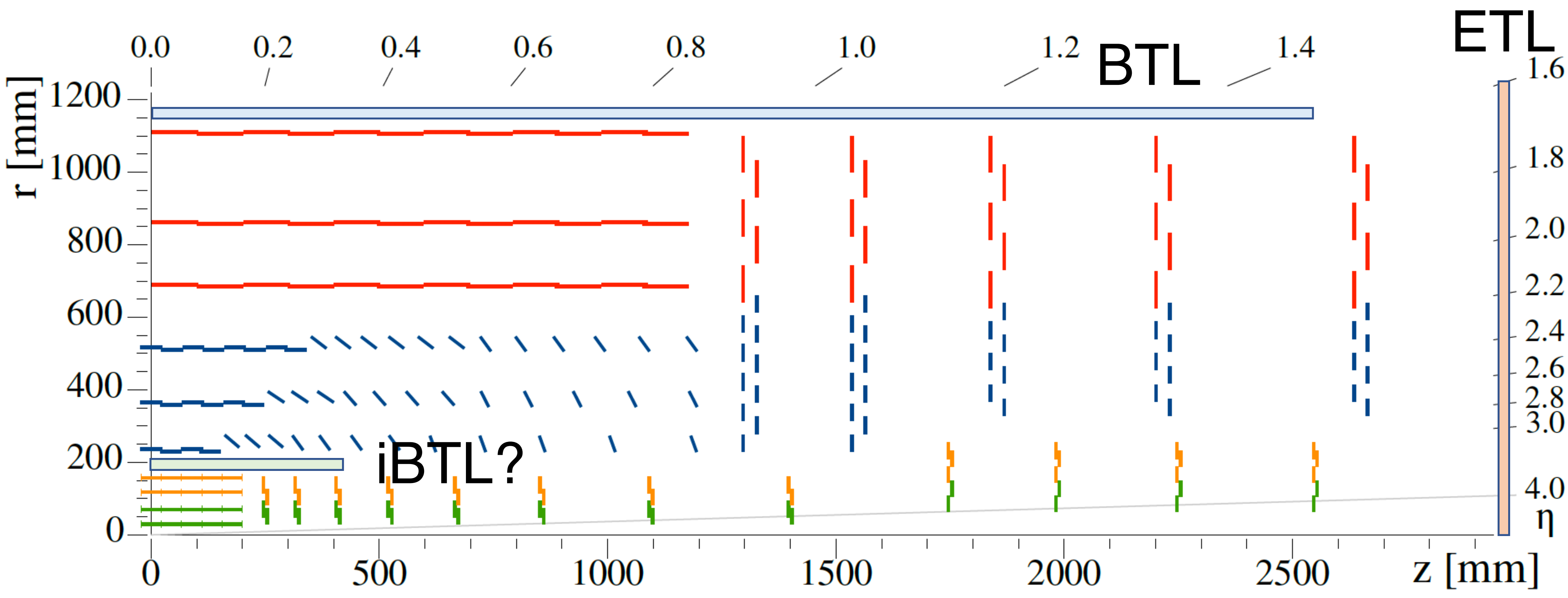
$\Xi^{+}_{c} \rightarrow \Xi^{-} + 2\pi^{+}$ (cτ ≈ 132 μm)

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

seen by LHCb in pp



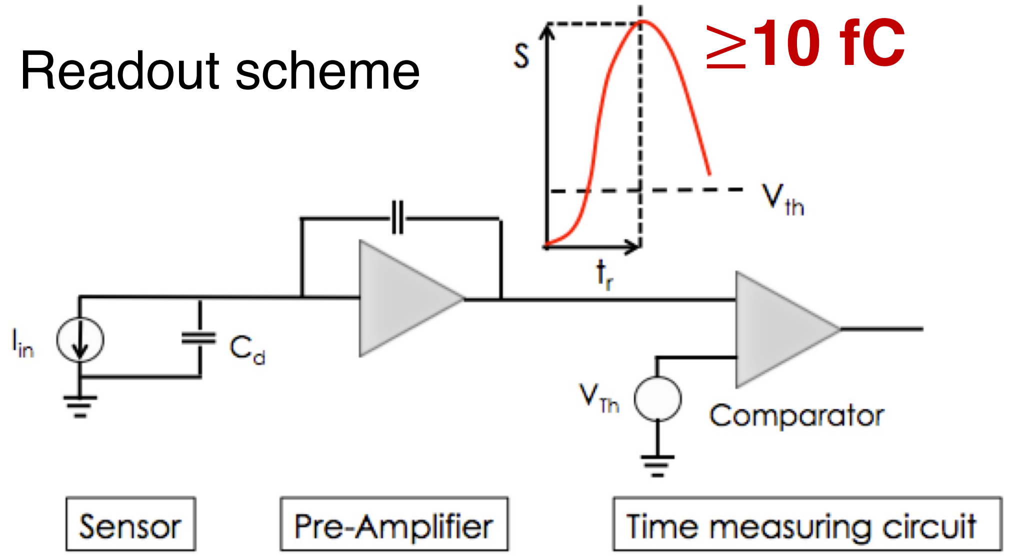
Also accessible by CMS-MTD?
– studies in progress



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

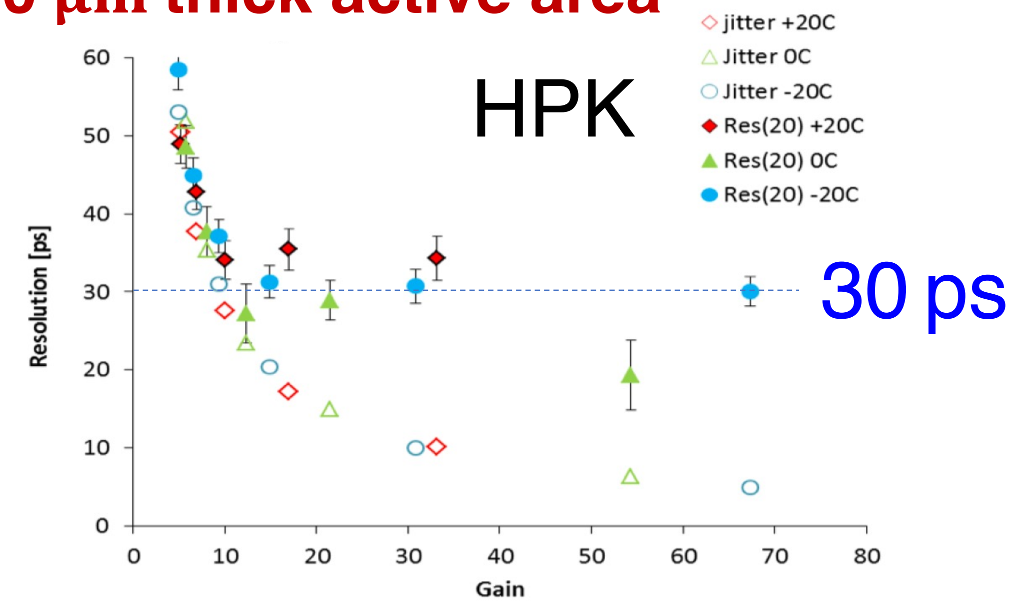
Low Gain Avalanche Diodes (LGADs)

Readout scheme



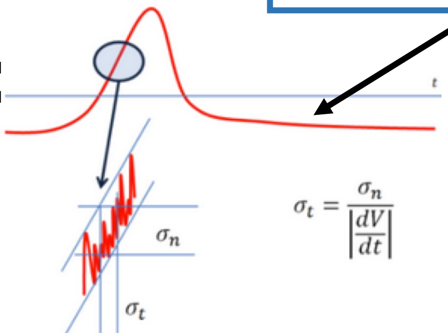
N. Cartiglia

50 μm thick active area



$$\sigma_t^2 = \sigma_{jitter}^2 + \sigma_{ionization}^2 + \underbrace{\sigma_{shape}^2 + \sigma_{TDC}^2}_{\text{subdominant}}$$

Jitter:



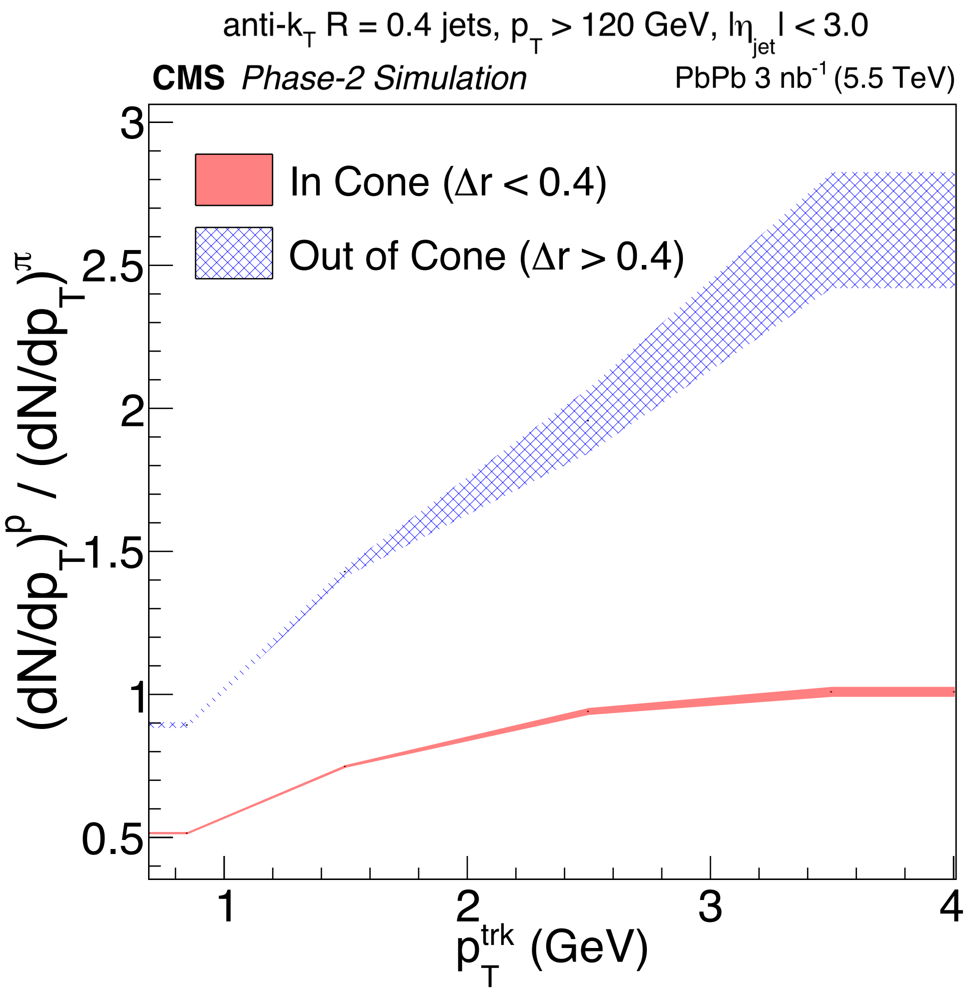
Need large dV/dt

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

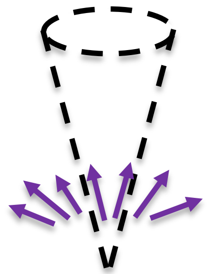
Medium response to jet quenching

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

Can also be performed with γ/Z+jets

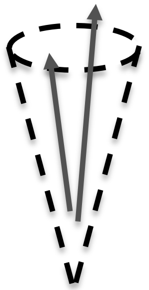


out-of-cone



vs.

in-cone



Unique measurement only possible by CMS with the MTD!