Heavy ions w/ CMS @ the HL-HLC: Assessment & Prospects

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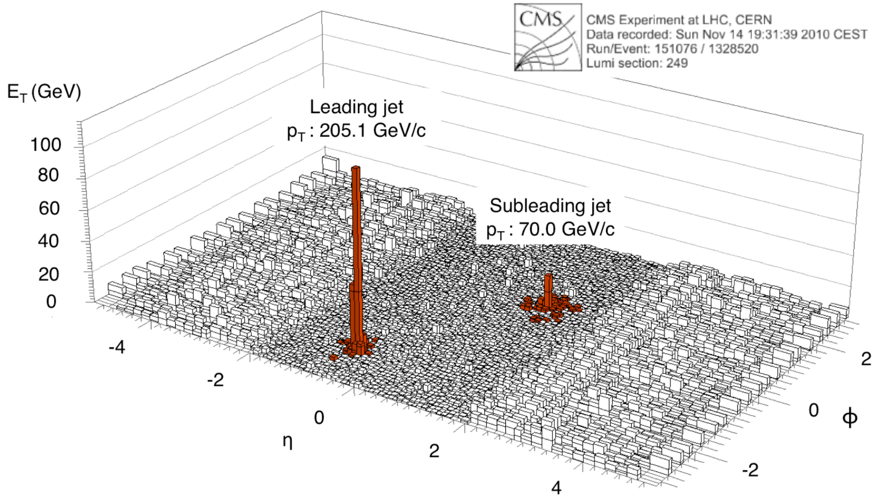
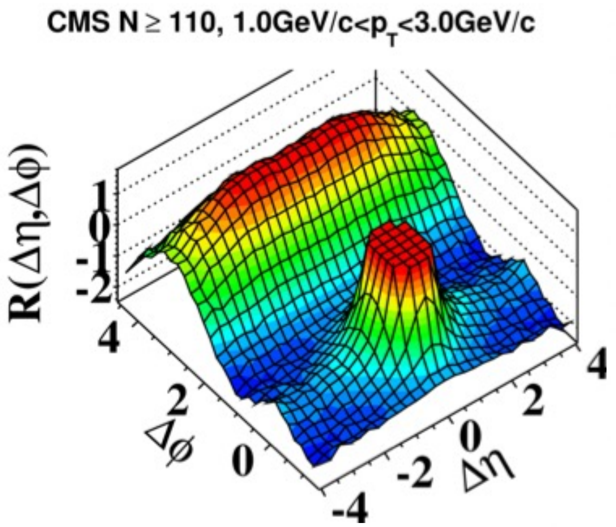
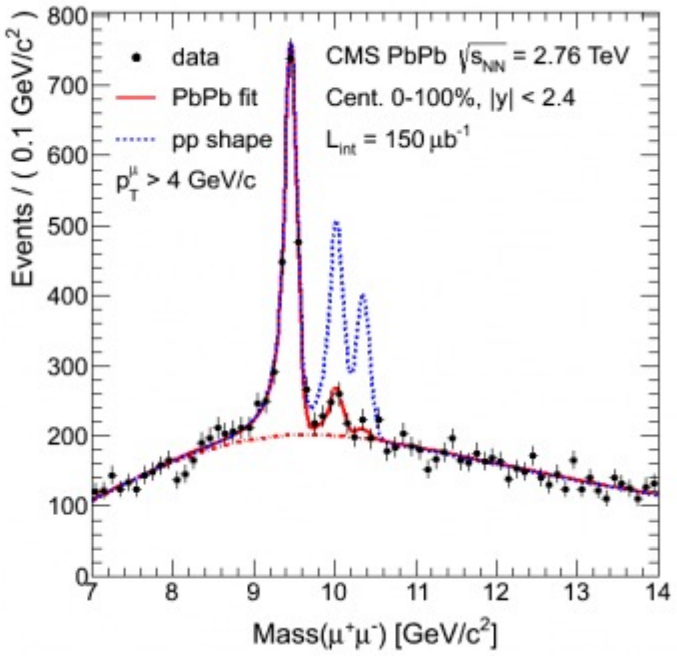
Heavy ion program in CMS

Conceived to profit from CMS's
- High rate
- Large acceptance
- High B field / precision tracking

Several of the most 'iconic' heavy-ion results from the LHC:







Anomalous dijet imbalance, w/ highly quenched recoil jets

Long range ridge correlations, showing flow effects in small systems

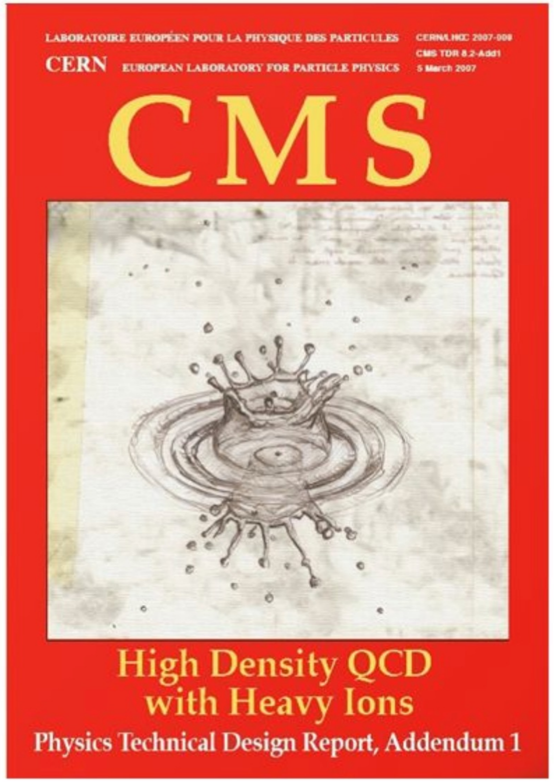
"Melting" of quarkonium states, w/ characteristic binding energy dependence

PRC 84 (2011) 024906

JHEP 09 (2010) 091

PRL 109 (2012) 222301

Some historical perspective



CERN-LHCC-2007-009

CMS Physics Technical Design Report: Addendum on High Density QCD with Heavy Ions

D. d'Enterria , M. Ballintijn , M. Bedjidian [1] , D. Hofman , O. Kodolova , C. Loizides , I. P Lokthin , C. Lourenço , C. Mironov , S. V Petrushanko , C. Roland , G. Roland , F. Sikler , G. Veres Details

1 IPNL - Institut de Physique Nucléaire de Lyon

Main concern for heavy ions w/ CMS:

High occupancy in first layer of strip tracker

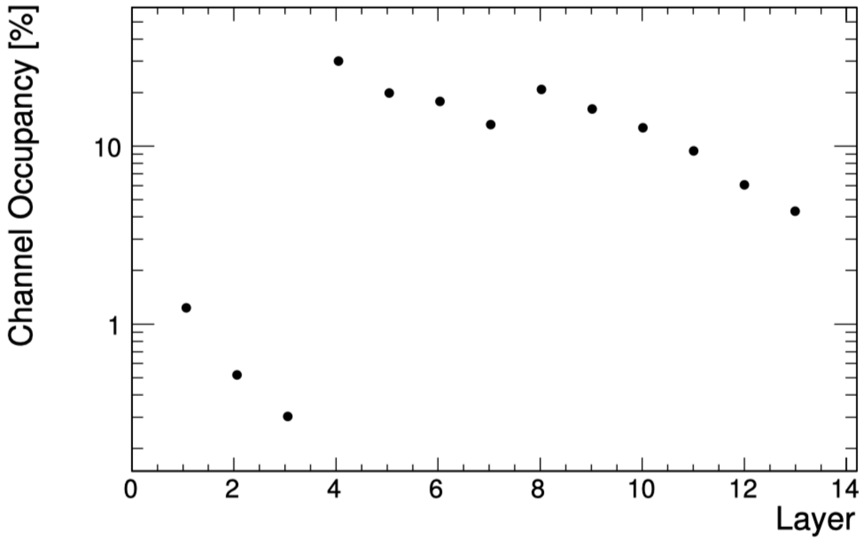


Figure 3.1: Channel occupancy in the barrel region as a function of tracker detector layer: 1–3 are pixel layers; 4–7 are inner strip layers; and 8–13 are outer strip layers [165].

The strip tracker occupancy & large material budget is one of the main drawbacks

→ To this day, our charged hadron tracking efficiency is typically limited to around 75%

(This will improve for Run 4)

Low p_T tracking

A recent analysis

CERN-LHCC-2007-009

PRC 98 (2018) 044902

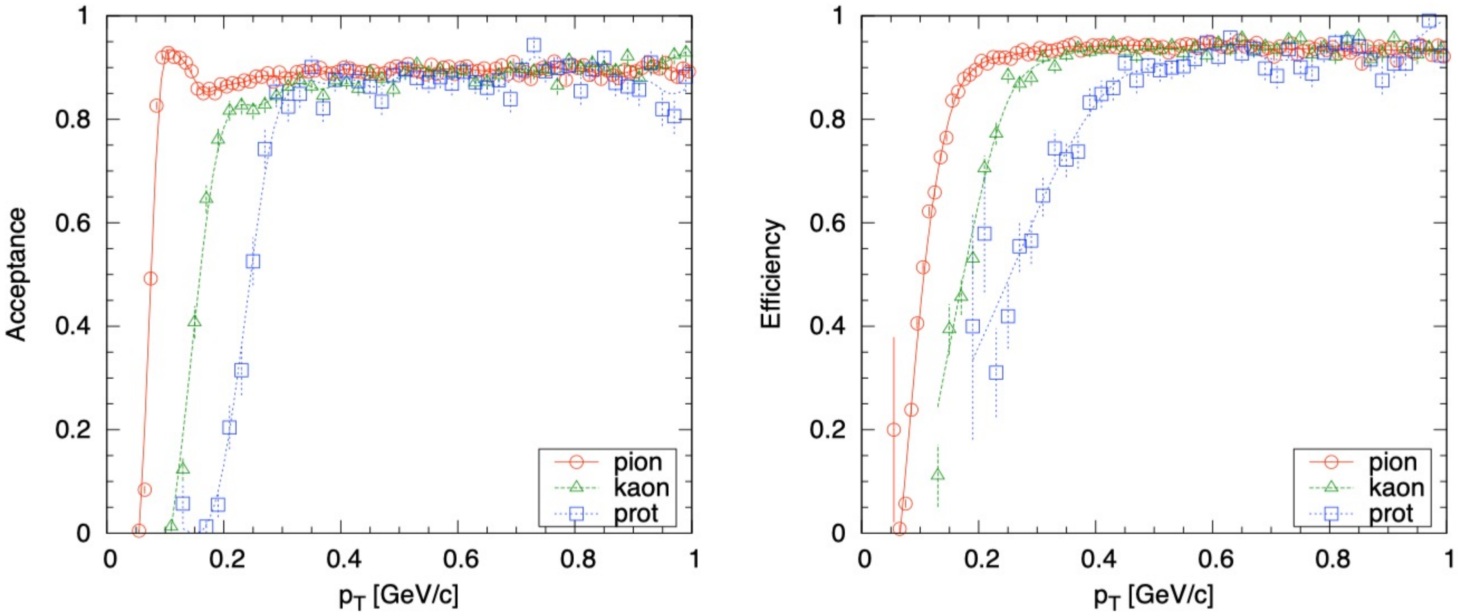
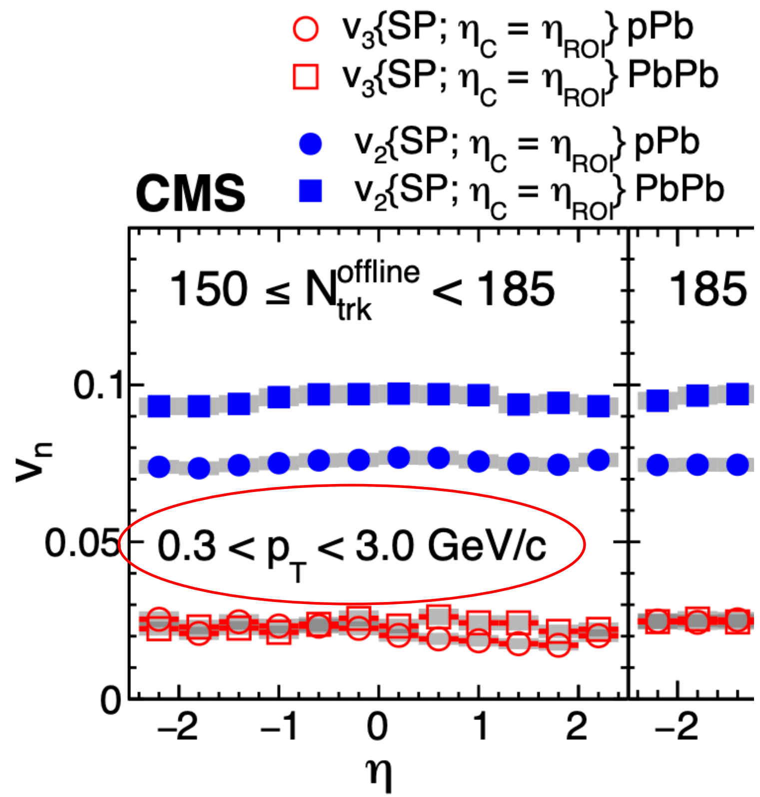
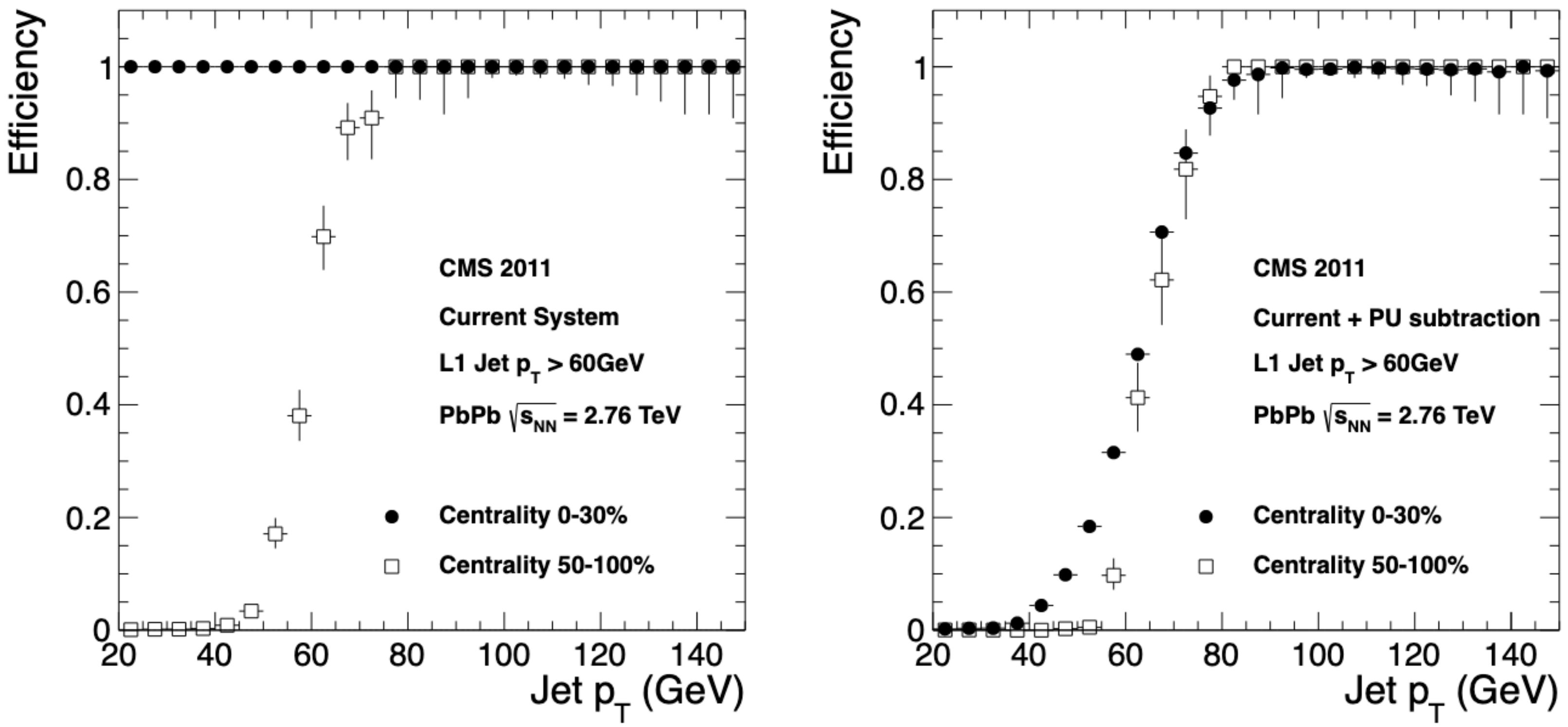


Figure 3.3: Acceptance (left) and efficiency (right) as a function of p_T, for tracks in the rang
$|\eta| < 1$. Values are given separately for pions (circles), kaons (triangles) and (anti)proton
(squares).



- Below about 1 GeV, better performance is achieved using pixel-only tracks than using the full pixel+strip tracker
- Ideally, hadrons reach the outer pixel layer down to ~ 100 MeV, but a bit worse in practice due to energy loss
- CMS publishes results with pixel tracks down to 300 MeV; 200 MeV might be feasible w/ some effort

A “heavy-ion upgrade”: Level-1 calo trigger

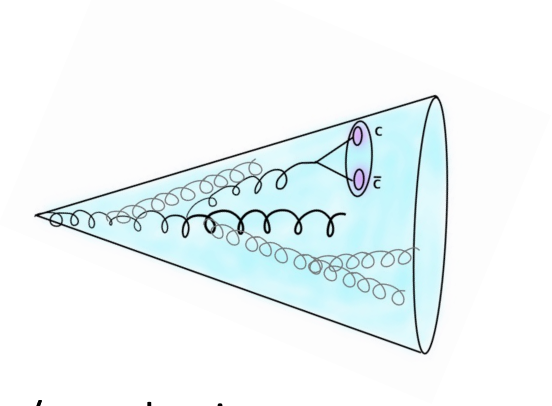


CMS-TDR-012

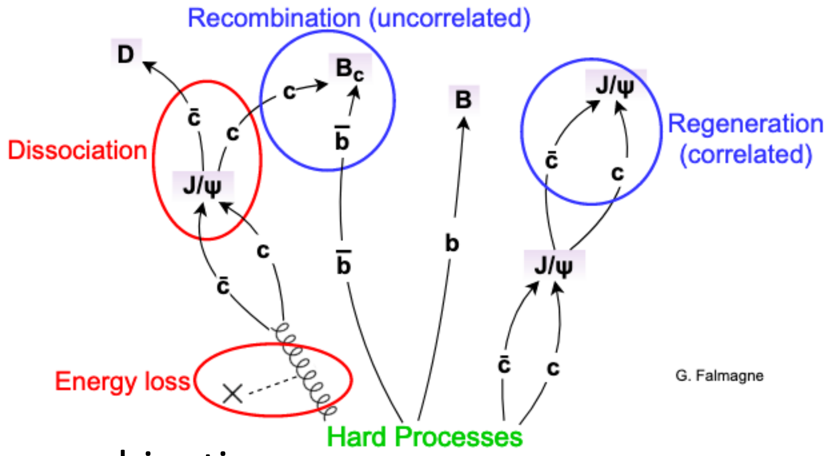
UE subtraction at L1 (hardware-level) was driven in part by heavy-ion program

We would not be able to record the full rate of high p_T jets without this upgrade

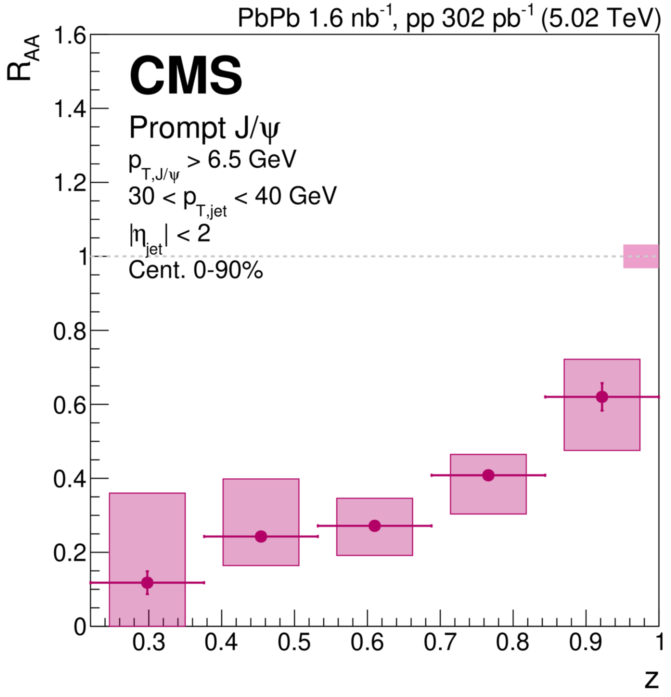
Recent contributions from LLR

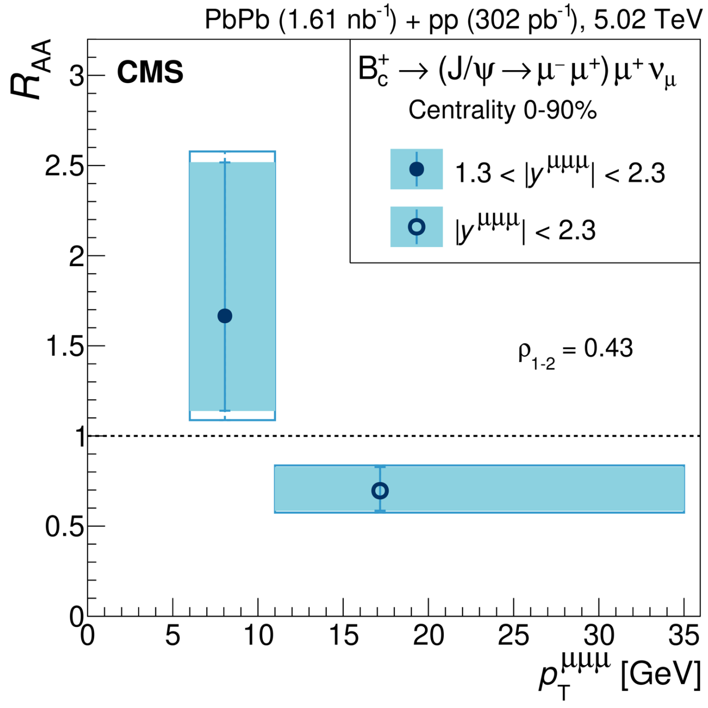


J/ψ-in-jets
Jet quenching w/ quarkonium



B_c meson
A sensitive probe of recombination

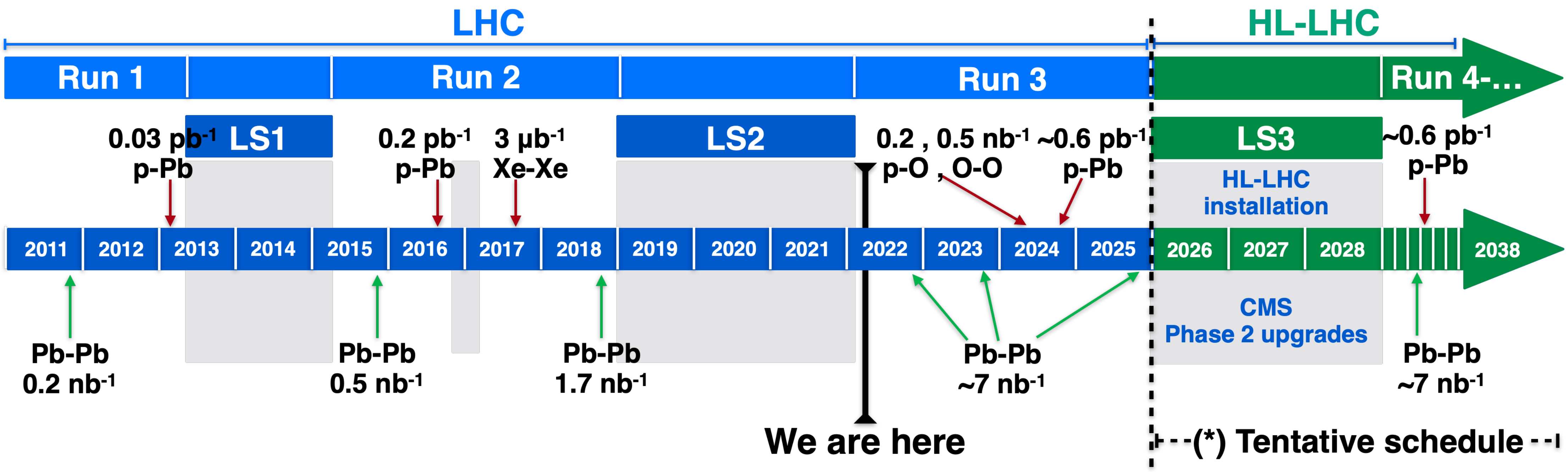




PLB 825 (2021) 136842

PRL 128 (2022) 252301

Heavy ion program for CMS



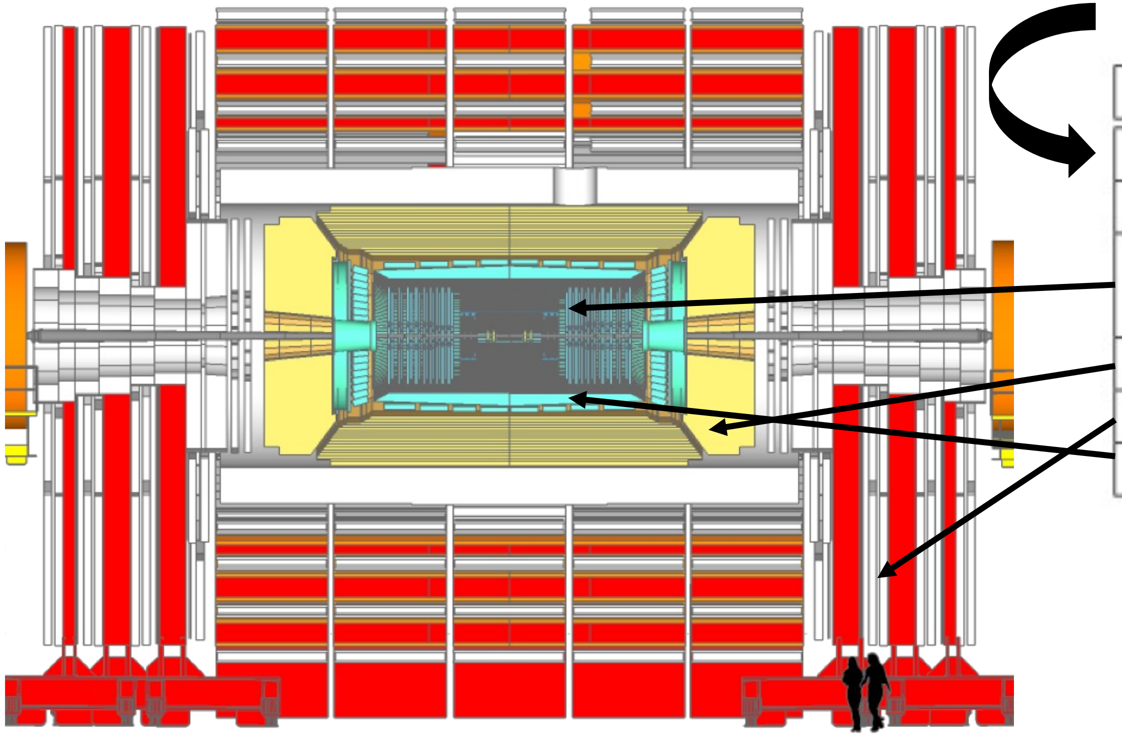
Expect to augment our AA and pA data by a factor of 3 in Run 3

Similar luminosity again in Run 4, but with a vastly upgraded detector

Phase 2 upgrades of CMS

Designed for pile-up of 200 → similar multiplicity to central PbPb collisions

Features larger rapidity coverage, better precision & higher rate



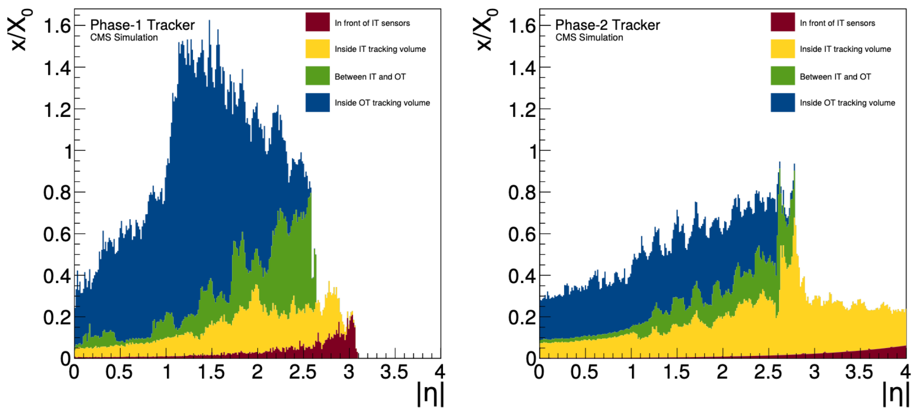
Goal: Record **all** PbPb events (<50% in Run 3)

Subdetector	CMS present	CMS Phase II
L1 bandwidth	30 kHz for PbPb	750 kHz (all PbPb events)
DAQ throughput	6 GB/s	60 GB/s
Inner tracker	$\|\eta\| < 2.4$ $100\times150\ \mu m^2$ pixels	$\|\eta\| < 4$ $50\times50\ \mu m^2$ pixels
Endcap calorimeter	Low granularity	High granularity
Muon system	$\|\eta\| < 2.4$	$\|\eta\| < 2.8$
Time-of-flight	N/A	PID for $\eta\| < 3$

Tracker upgrade

Complete replacement of pixel and strip tracker

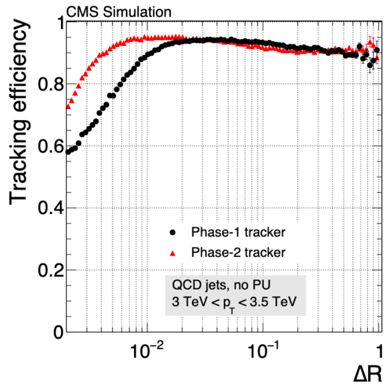
100 x 150 → 50 x 50 μm^2 pixel size
Tracking out to $|\eta| < 4$!!

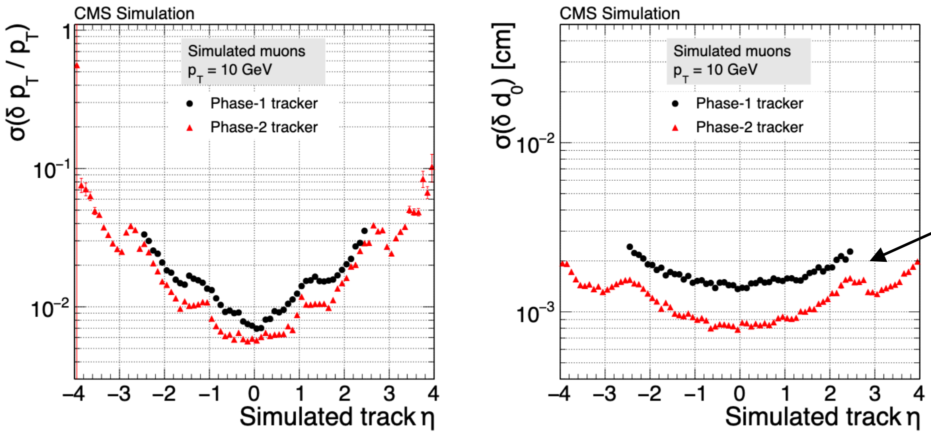


CMS-TDR-014

Reduced material budget by up to 2x
→ improved tracking efficiency in PbPb

… as evidenced by the improved separation of nearby tracks





Improved p_T resolution by about 25%
→ Improved mass resolution for resonances

Impact parameter resolution improved by 40%
→ Improved heavy flavor measurements
(B/D hadrons & b/c-jet tagging)

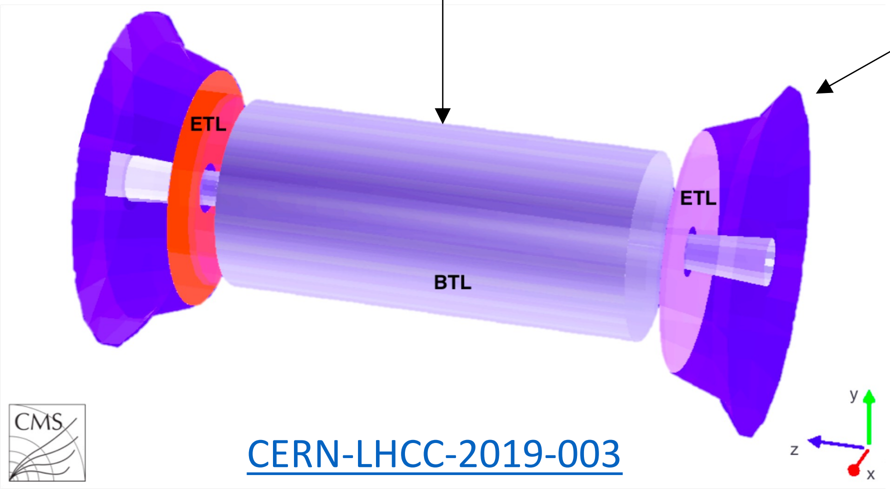
MIP timing detector (MTD)

LGAD is a novel technology, planned for CMS, ATLAS & EIC

Large contributions from CMS-HI

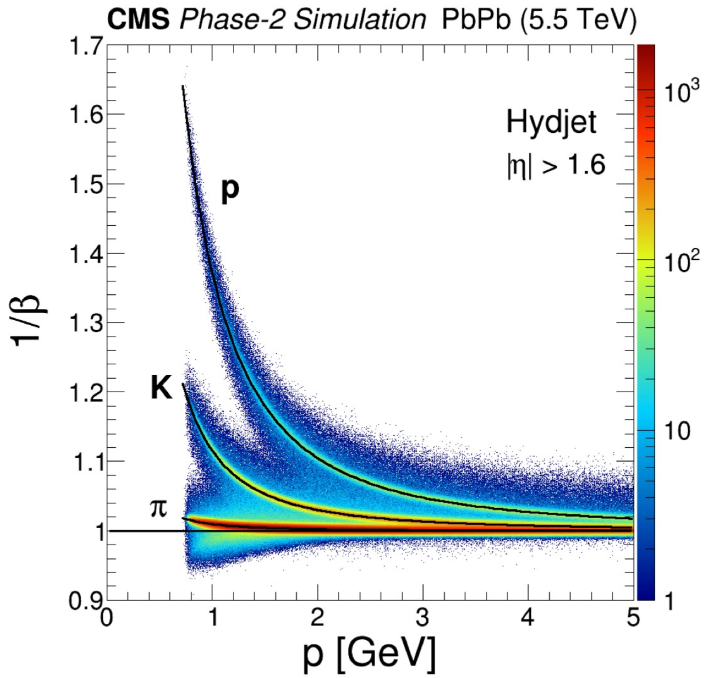
Barrel Timing Layer (BTL)
Coverage: $|\eta| < 1.45$, $p_T > 0.7$ GeV
Timing resolution: ~ 30 ps
Tech: Scintillator + Si photo-multiplier

Endcap timing layer (ETL)
Coverage: $1.6 < |\eta| < 3.0$, $p > 0.7$ GeV
Timing resolution: ~ 30 – 40 ps
Tech: Silicon w/ internal gain (LGAD)

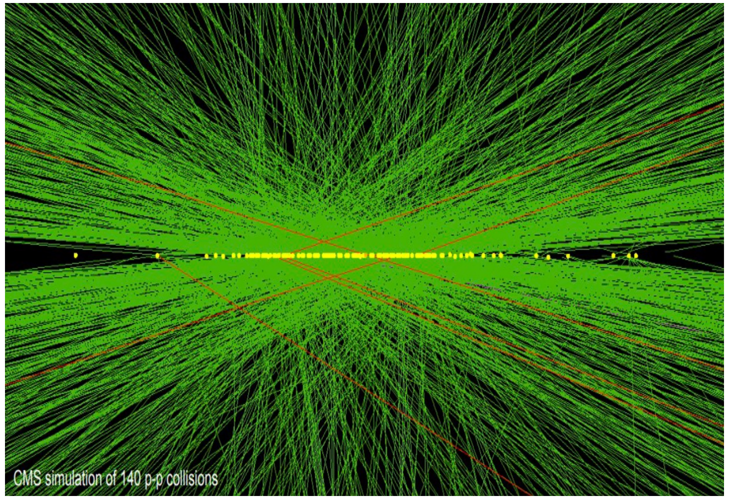


CERN-LHCC-2019-003

Particle identification



Pile-up mitigation



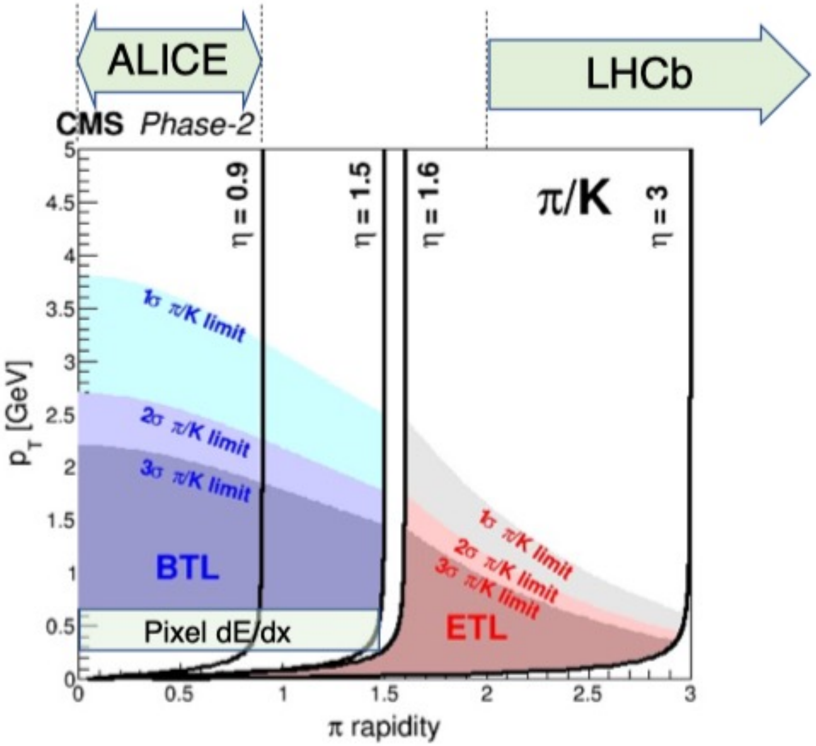
PID coverage

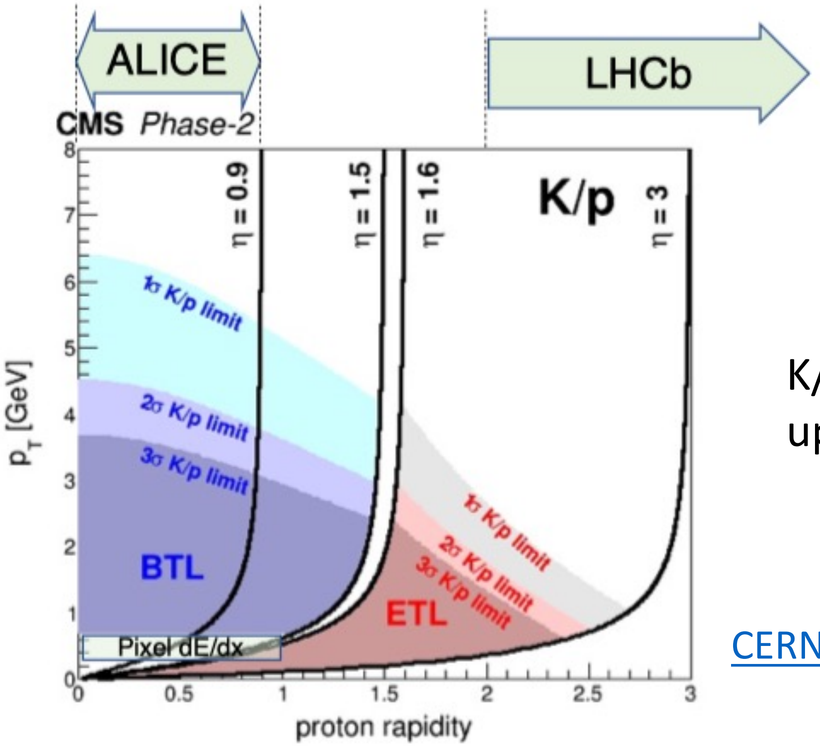
Experiment	η coverage	r (m)	σ_T (ps)	r/σ_T (x100)
CMS	$\|\eta\| < 3.0$	1.16	30	3.87
ALICE	$\|\eta\| < 0.9$	3.7	56	6.6
STAR	$\|\eta\| < 0.9$	2.2	80	2.75

Large acceptance PID: $|\eta| < 3$

Complementary w/ ALICE & LHCb

π/K separation
up to p ≈ 2.5 GeV





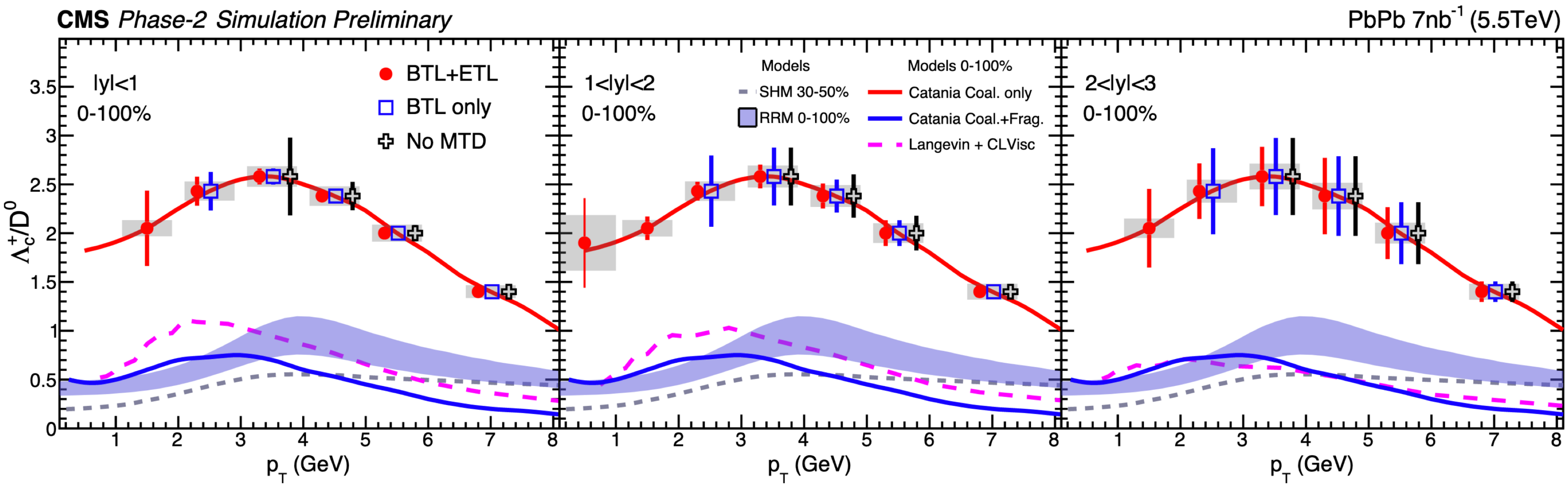
K/p separation
up to p ≈ 5 GeV

CERN-LHCC-2019-003

Combined with dE/dx from pixel detector, **π/K/p coverage down p_T = 300 MeV**!

Charm measurements w/ PID

CMS-DP-2021-037

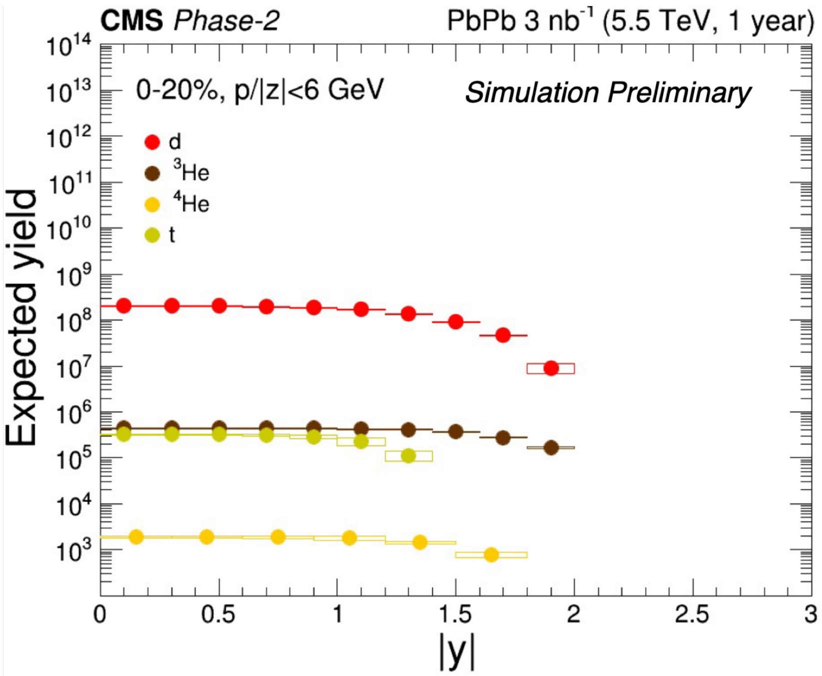


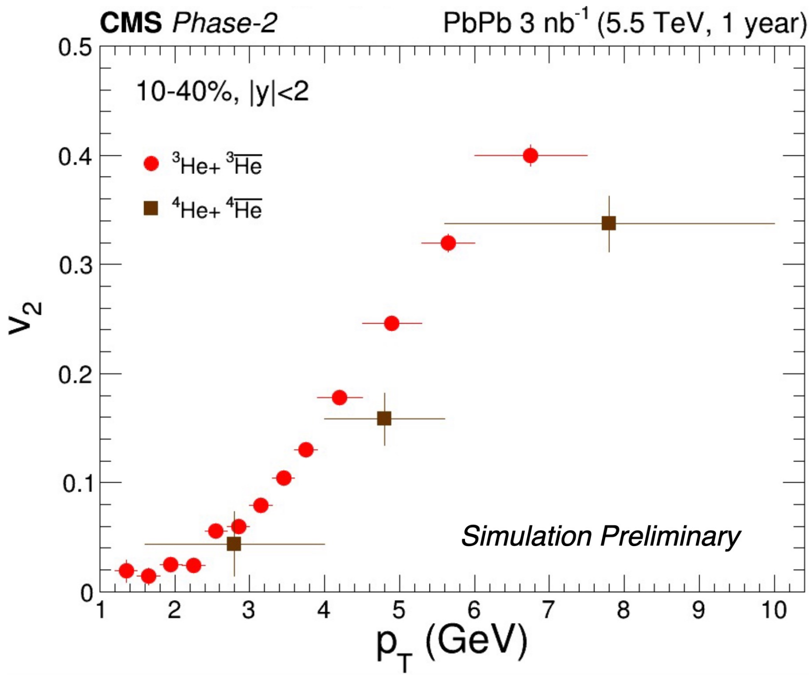
Charm and beauty hadron measurements over six units of pseudorapidity ($|\eta| < 3$)

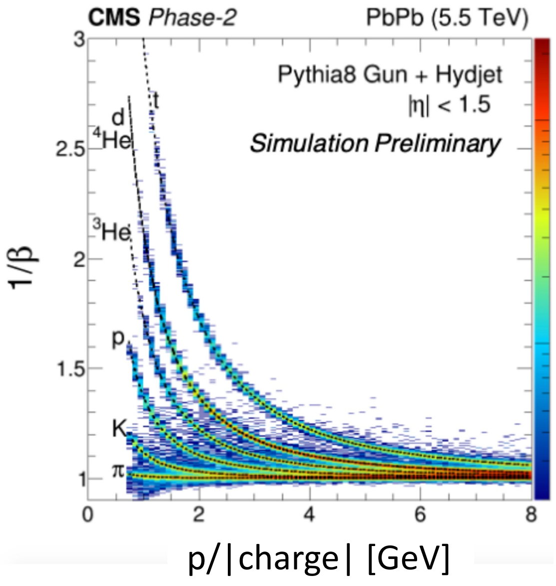
Λ_c and D mesons down to $p_T = 0$ in the η range not covered by other experiments

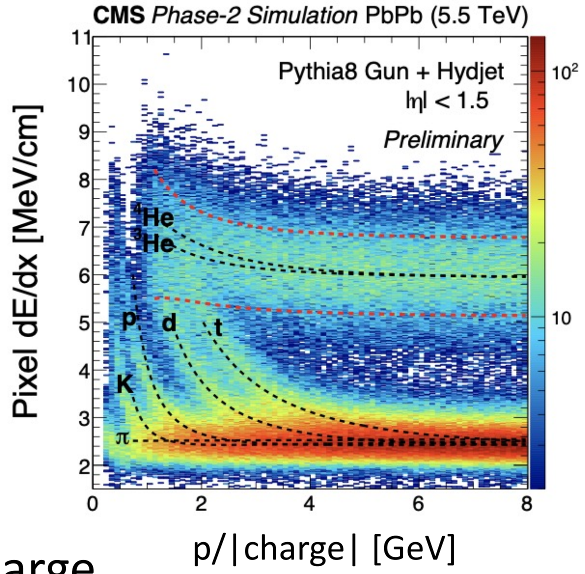
Light nuclei production in PbPb

Light nuclei are sensitive probes of statical hadronization and flow









Combination of MTD + pixel dE/dx can identify d, t, He^3 & He^4

Relies on pixel dE/dx to separate deuteron from ^{4}He by their charge

[CMS-DP-2021-037](CMS-DP-2021-037)

Light nuclei in high-luminosity pp

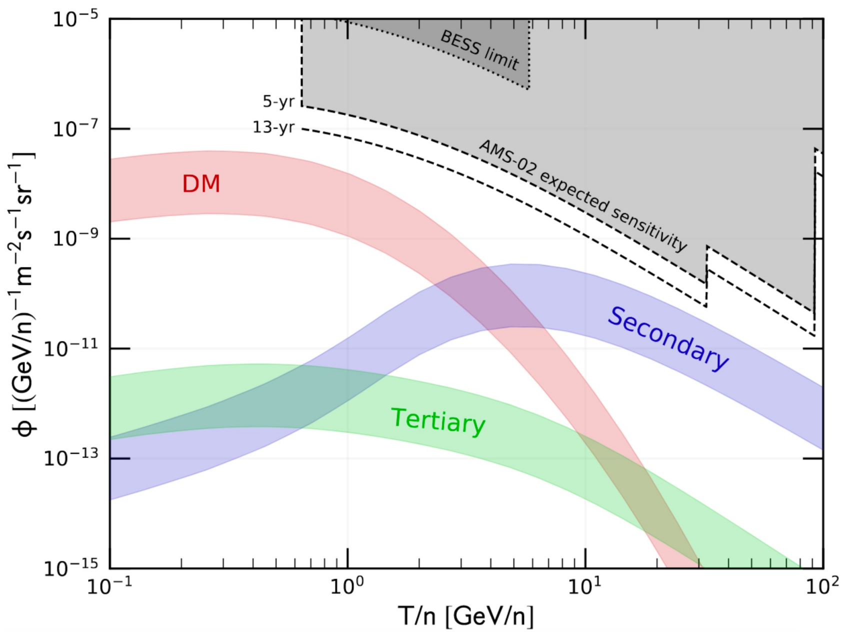
CMS-DP-2021-037

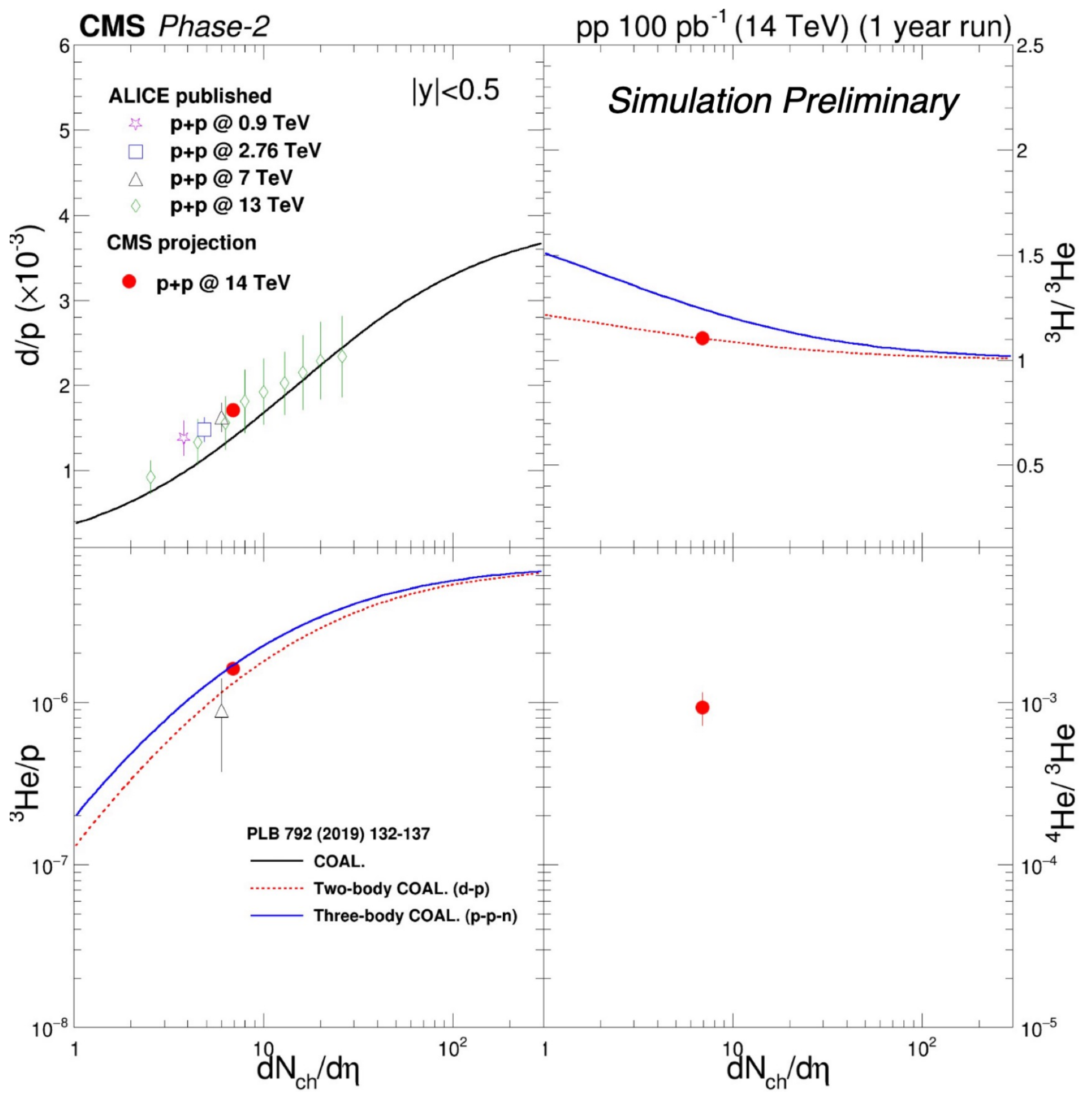
Ultra-precise yield ratios in pp

Input for dark matter searches

Korsmeier et al, PRD 97 (2018) 103011

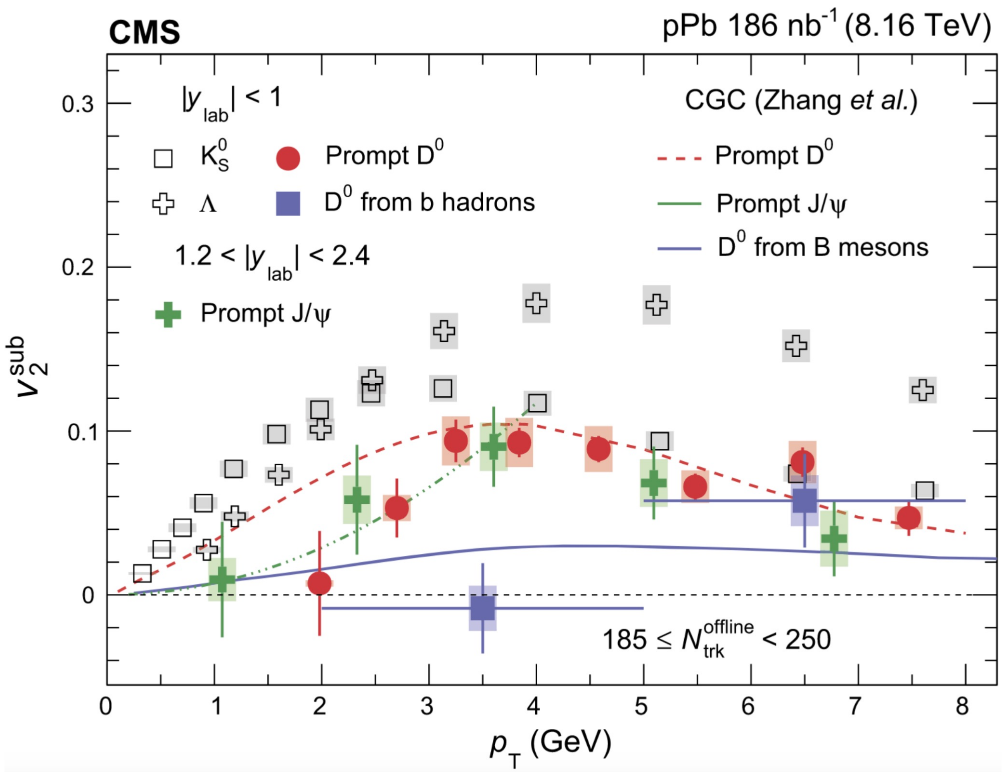
Antihelium flux

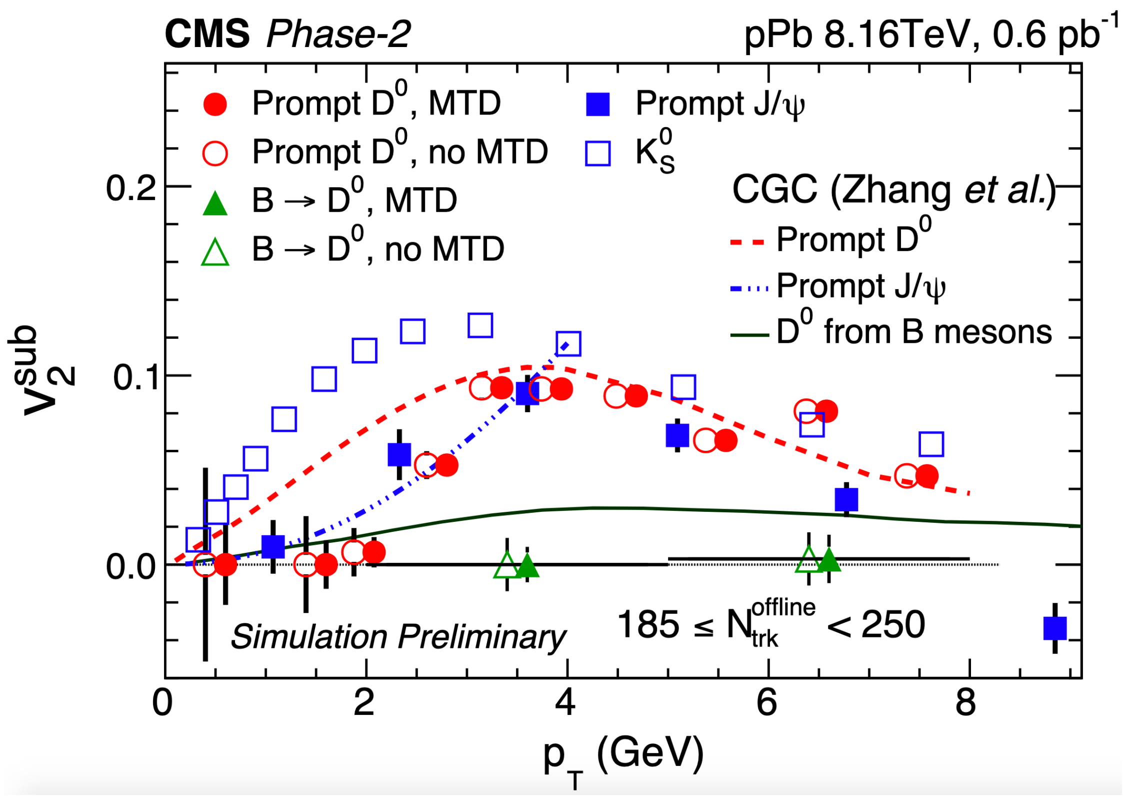




High multiplicity trigger in small systems

PLB 813 (2021) 136036





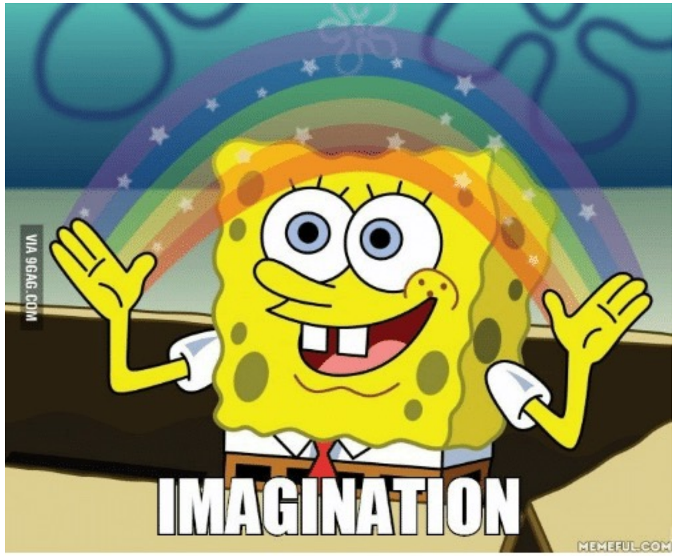
CMS-DP-2021-037

MTD information is accessible to the high-level trigger → select high multiplicity collisions

Turn-on of nuclear effects can be explored w/ precision in small systems

Projections for Run 3+4 exist, but primarily focused on statistical gain CMS-PAS-FTR-17-002

Besides the MTD, full heavy-ion simulations of the CMS Phase 2 detector have not yet been carried out

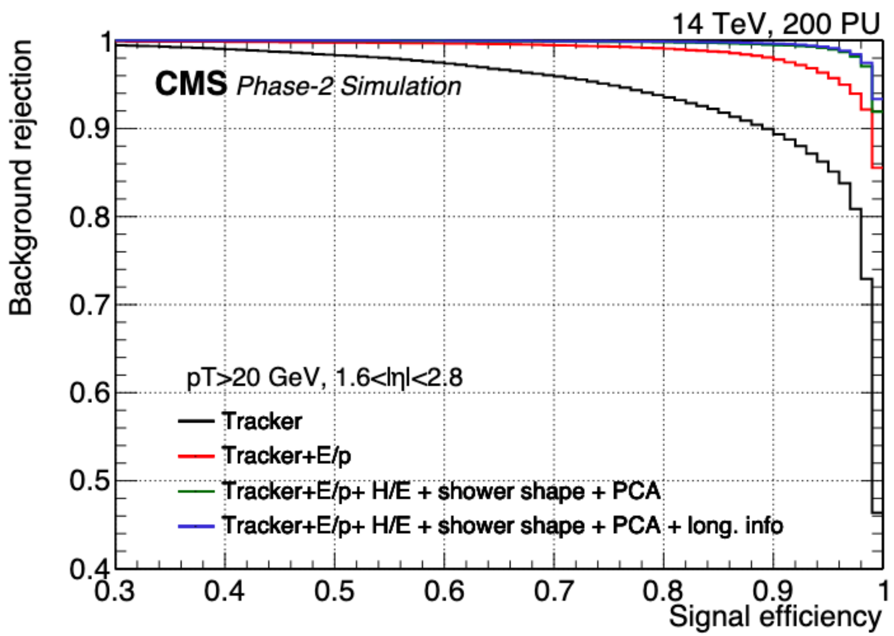


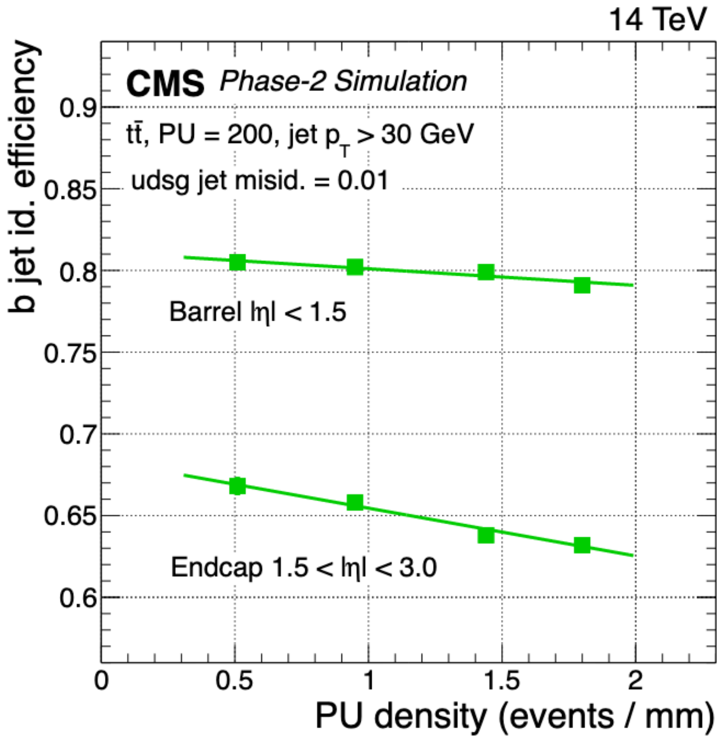
However, one can look at the 200 pile-up studies to anticipate performance improvements in heavy ions

Jets

Tracker + HGCAL = Full particle flow for high precision jets out to |η| ≈ 3 (from 2.4)

CMS-TDR-019





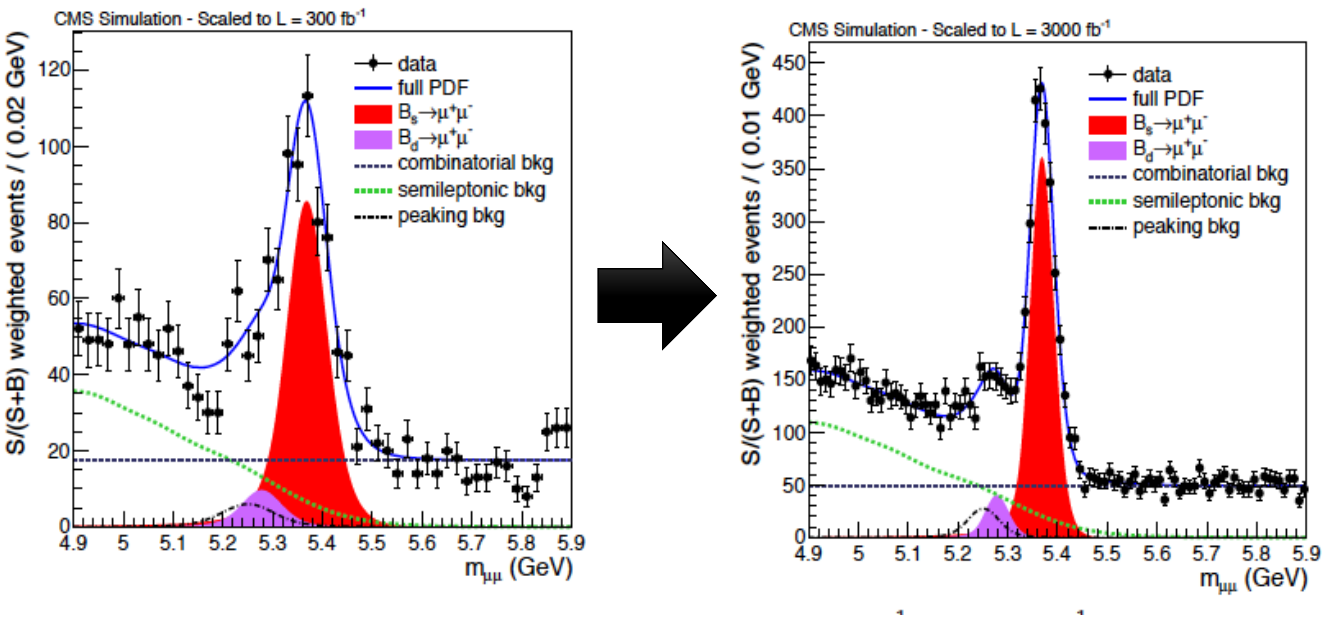
Isolated photons to |η| = 2.8

(currently limited to |η| < 1.44 in heavy ions)

Improved b-tagging,

larger coverage (|η| < 2 → |η| < 3 or 4)

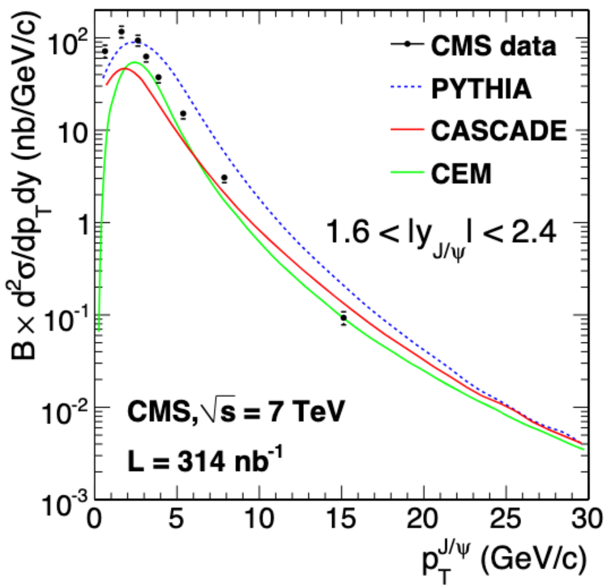
Quarkonia

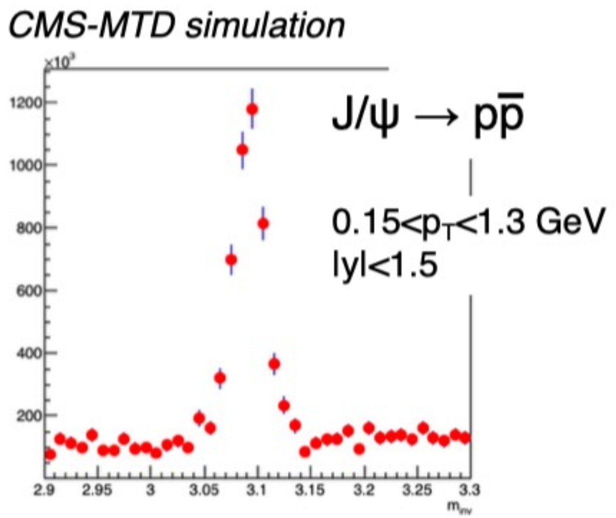


- Improved mass and lifetime resolution w/ the new tracker
- Modest acceptance increase ($|\eta| < 2.4 \rightarrow |\eta| < 2.8$), but in region where low p_T reach is the best
- Speculative: "Calorimeter muon" identification w/ HGCAL to improve low p_T muon reach?

Low p_T J/ ψ reconstruction

Via dimuon in pp



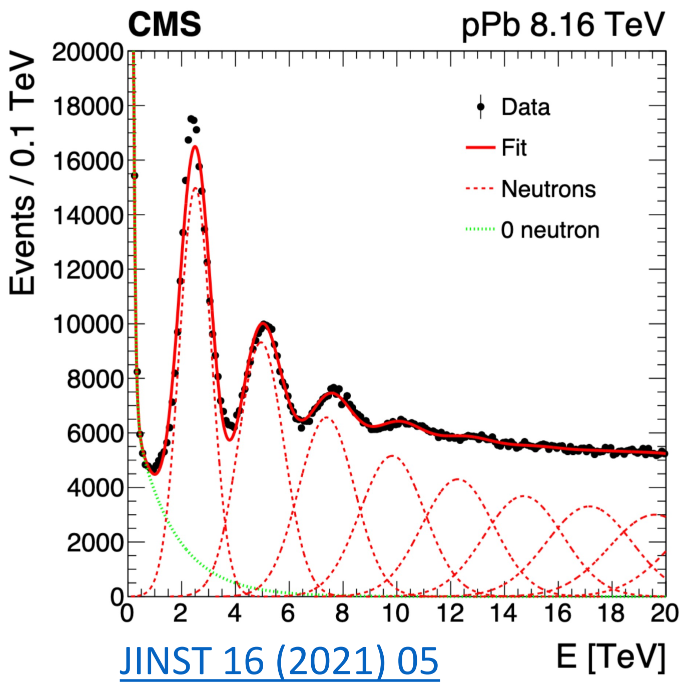


(not accessible by $\mu^+\mu^-$)

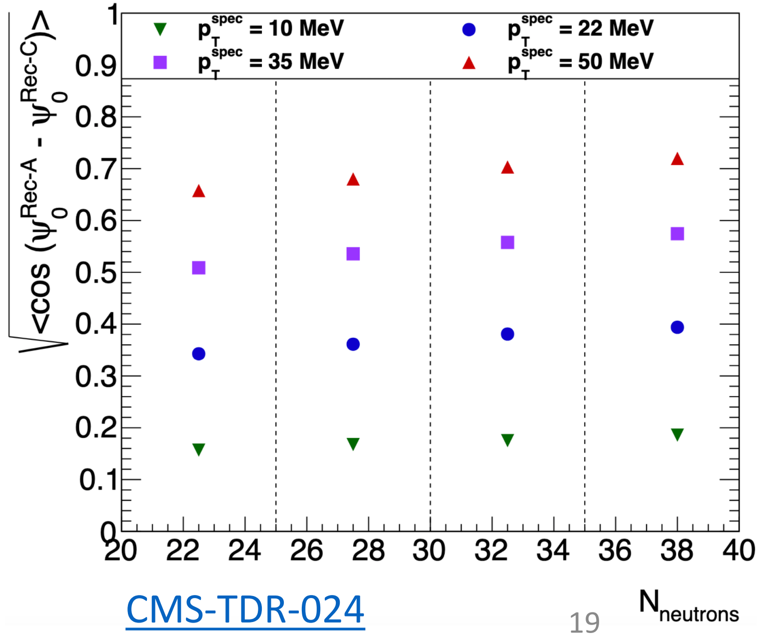
Hadronic channels w/ MTD

Zero degree calorimeters

- ZDCs are an essential part of the HI program
  - Crucial part of heavy-ion min. bias trigger from Run 3 onwards
  - Used to identify & characterize ultra-peripheral collisions
  - Bias estimation for centrality, especially in small systems
  - Exclusively HI detector (removed for high-lumi pp)
- Joint ATLAS & CMS effort: radiation-hard ZDCs for Run 4
- Reaction Plane Detector (RPD), rxn plane & directed flow



JINST 16 (2021) 05



CMS-TDR-024

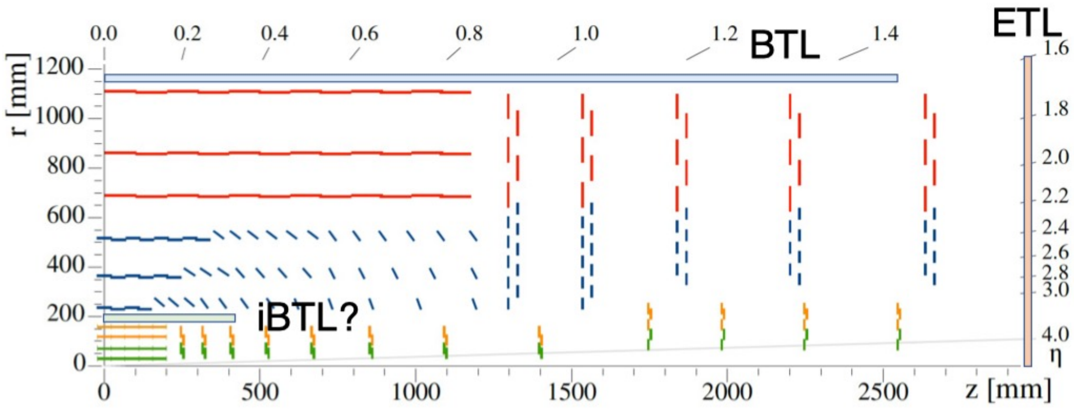
Beyond Run 4

The focus is currently on the Phase II upgrades, but CMS will continue to record HI data in Run 5+

Light-ion collisions featured in long term plan

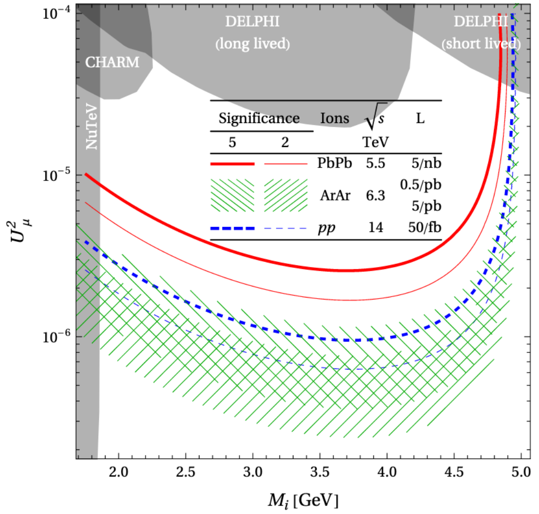
→ System scans of nuclear effects

→ BSM searches

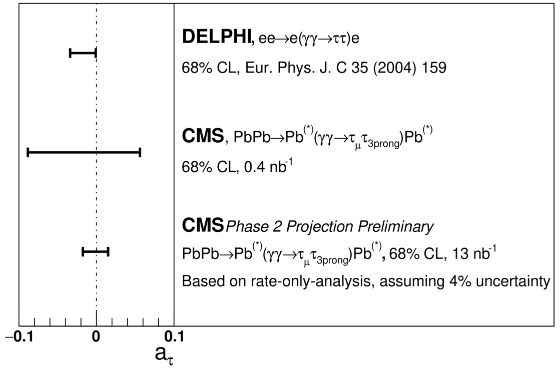


an iBTL at r=0.2 m using (AC-)LGADs?

Magnetic monopole search



τ anomalous magnetic moment



arXiv:2206.05192 (accepted by PRL)

Extending low p_T reach of CMS could be a possibility, if there is a community behind it to build the case

- Add'l PID inside the tracker region down to p = 400 MeV?
- Dedicated low B field run? → Simulations could be done now, but requires personpower

R. Bruce *et al* 2020 *J. Phys. G* **47** 060501

Summary

- CMS will record large datasets in Runs 3 & 4, increasing our integrated luminosity by nearly an order of magnitude

- The Phase II upgrades will be highly beneficial for the HI program
  - Even larger acceptance: Full particle flow (i.e., all subsystems) out to $\eta \approx 3$
  - Lighter tracker: better tracking efficiency, mass & lifetime resolution, etc.
  - New PID capabilities: particularly useful for heavy flavor and light nuclei
  - …

- The prospects for CMS at the HL-HLC have not yet been fully explored