Heavy ions w/ CMS in the HL-LHC era

Matt Nguyen, et al.

Prospectives QGP-France

December 10th, 2019

Document scope

- CMS will be almost completely rebuilt for Run 4 (2026+)
- The objective of the “Phase II upgrades” is to maintain current performance for an average pile-up of ~ 200 (currently ~ 50)
- The Phase II upgrades enhance the physics potential for heavy ions

Existing projections mostly focus on the statistical reach of the Run 3+4 data
arXiv:1902.10229

Heavy ion physics with the Compact Muon Solenoid

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Abstract
The capabilities of the CMS experiment for heavy ion physics have been well established over the course of the first two Runs of the LHC (2010 – 2018). Pivotal discoveries in the field emerged from the CMS heavy-ion program, such as the sequential suppression of the Υ states in PbPb collisions, as well as the surprising evidence of collectivity seen in high multiplicity pp collisions. The CMS detector will be dramatically upgraded for the high-luminosity era, which is set to begin around 2025. This document outlines the prospects for future measurements in heavy-ion collisions with the upgraded CMS detector.

Our document rather focuses on the impact of the upgrades, which can be mostly inferred from high PU pp simulations

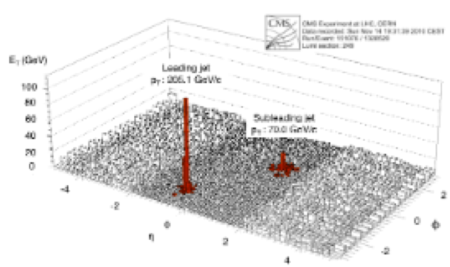
The CMS-HI program

Since the start of Run 1, CMS has emphasized studies of:

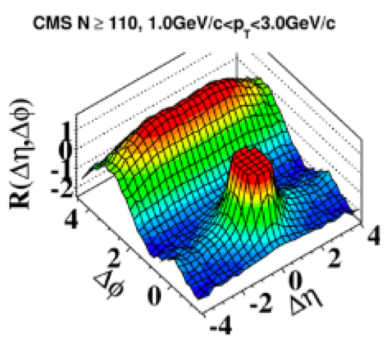
- High p_T physics, particularly jet quenching
- Quarkonia and electroweak bosons
- Flow and correlations, especially in small systems

} Key French contributions

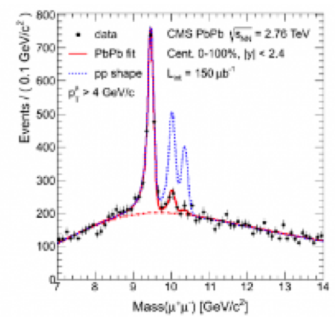
… leading to some of the most notable results in the field:



Dijet p_T imbalance
PRC 84 (2011) 024906
726 citations



Ridge in pp
JHEP 1009 (2010) 091
810 citations

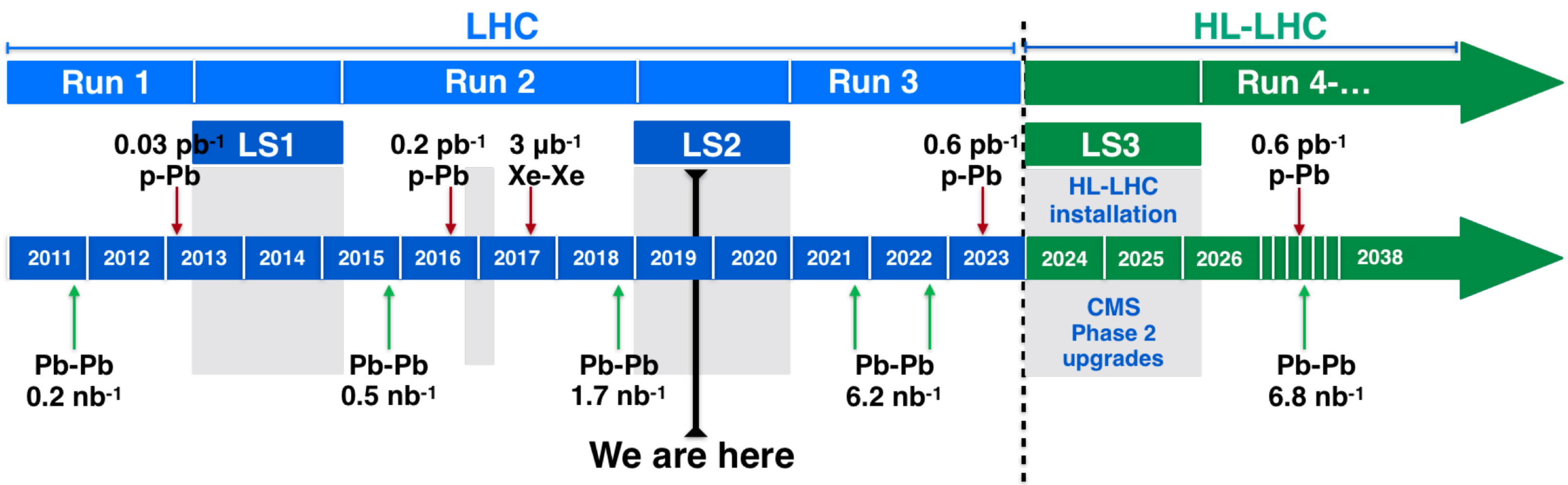


Υ "melting"
PRL 109 (2012) 222301
310 citations

Increasingly, emphasis also on other topics

- Open heavy flavor (D and B mesons)
- Forward and UPC physics

The HL-LHC era



Year	Systems, $\sqrt{s_{NN}}$	Time	L_{int}
2021	Pb–Pb 5.5 TeV	3 weeks	2.3 nb^{-1}
	pp 5.5 TeV	1 week	3 pb^{-1} (ALICE), 300 pb^{-1} (ATLAS, CMS), 25 pb^{-1} (LHCb)
2022	Pb–Pb 5.5 TeV	5 weeks	3.9 nb^{-1}
	O–O, p–O	1 week	500 μb^{-1} and 200 μb^{-1}
2023	p–Pb 8.8 TeV	3 weeks	0.6 pb^{-1} (ATLAS, CMS), 0.3 pb^{-1} (ALICE, LHCb)
	pp 8.8 TeV	few days	1.5 pb^{-1} (ALICE), 100 pb^{-1} (ATLAS, CMS, LHCb)
2027	Pb–Pb 5.5 TeV	5 weeks	3.8 nb^{-1}
	pp 5.5 TeV	1 week	3 pb^{-1} (ALICE), 300 pb^{-1} (ATLAS, CMS), 25 pb^{-1} (LHCb)
2028	p–Pb 8.8 TeV	3 weeks	0.6 pb^{-1} (ATLAS, CMS), 0.3 pb^{-1} (ALICE, LHCb)
	pp 8.8 TeV	few days	1.5 pb^{-1} (ALICE), 100 pb^{-1} (ATLAS, CMS, LHCb)
2029	Pb–Pb 5.5 TeV	4 weeks	3 nb^{-1}
Run-5	Intermediate AA	11 weeks	e.g. Ar–Ar 3–9 pb^{-1} (optimal species to be defined)
	pp reference	1 week	

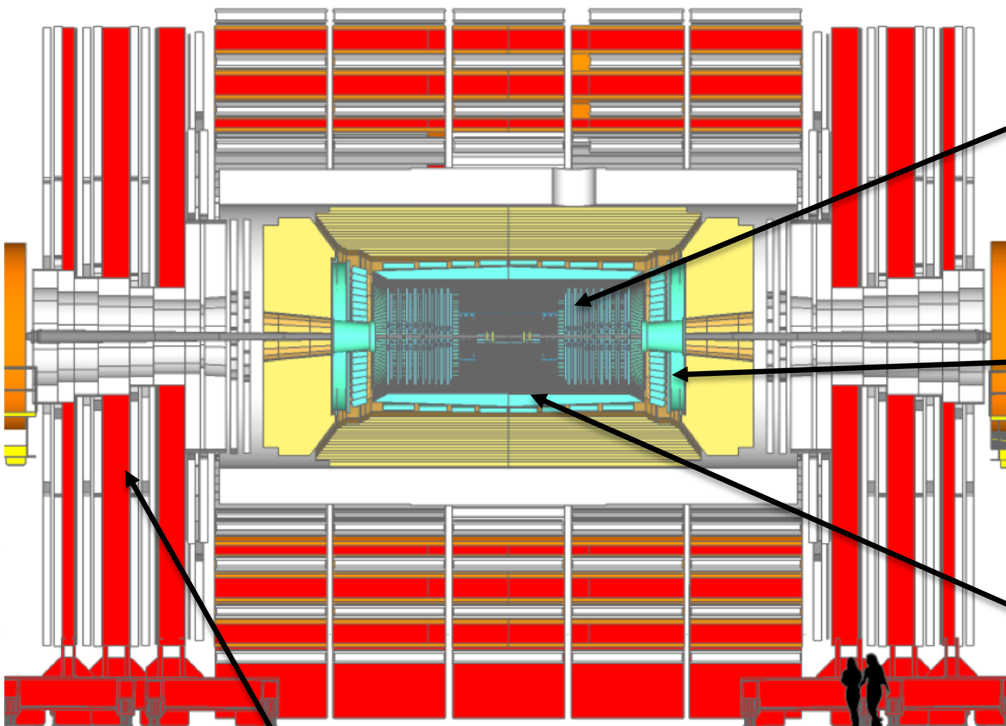
Compared to ALICE

- 1x PbPb*
- 2x pPb
- 10x pp reference

*Note that CMS emphasizes triggered data, while ALICE will write all events in Run 3+
However, in 2018 CMS recorded 4B MB events (1/3 of lumi) and will likely continue to do so

Phase II upgrades

Trigger / HLT / DAQ
Track info. in L1
L1/HLT rate x7.5
DAQ: 6 $\rightarrow$ 60 GB/s



New silicon tracker
Improved granularity
Lighter material budget
$|\eta| < 2.4 \rightarrow |\eta| < 4$

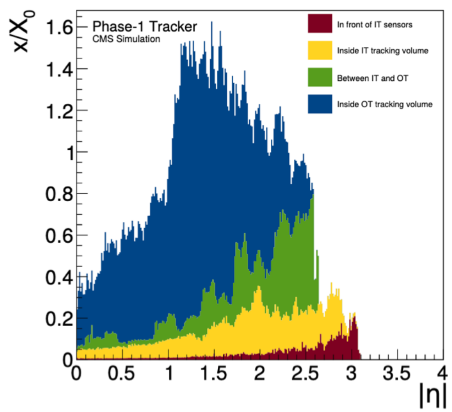
New endcap calorimeters (HGCal)
Unprecedented granularity
$|\eta| < 3$

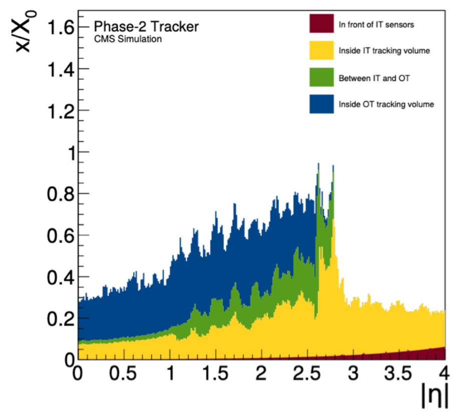
New MIP Timing Detector (MTD)
Precision timing
$|\eta| < 3$

Extended muon coverage
$|\eta| < 2.4 \rightarrow |\eta| < 2.8$

Hermetic coverage at forward rapidity
→ high complementarity with ALICE/LHCb

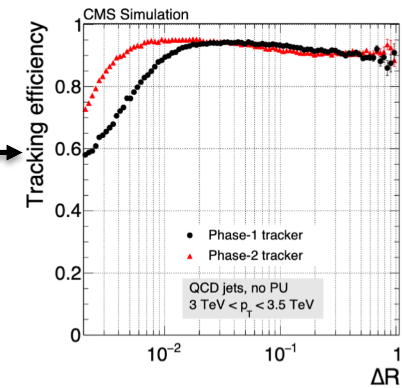
Tracker upgrade

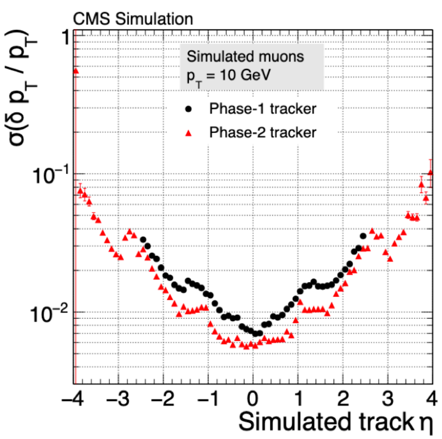


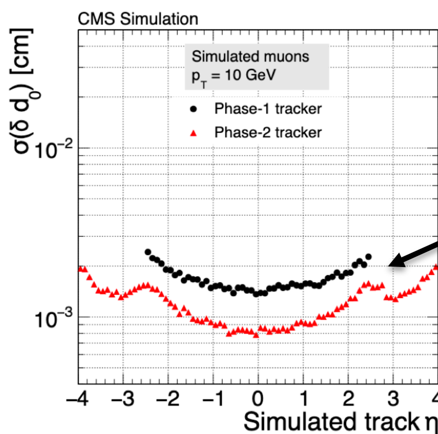


Reduced material budget by up to 2x
→ improved tracking efficiency in AA

… as evidenced by the improved separation of nearby tracks





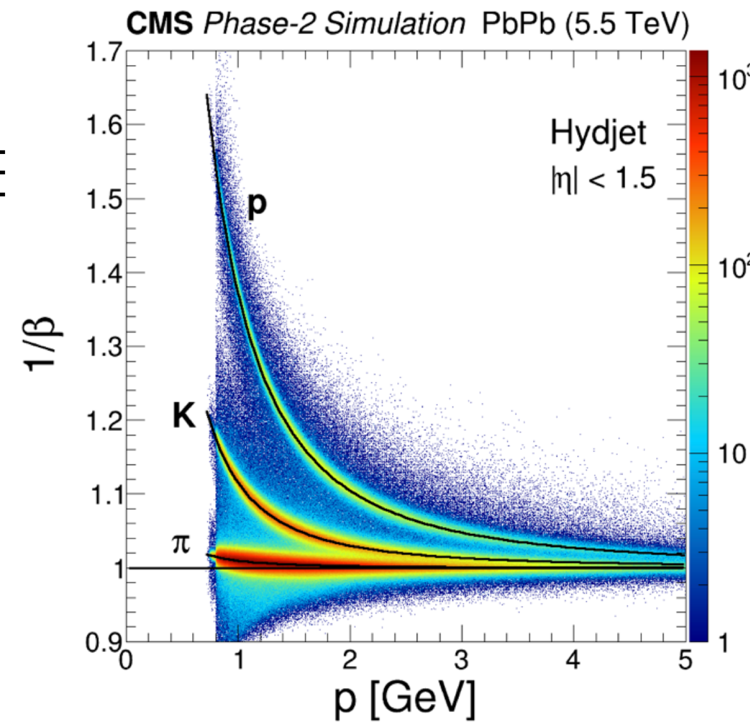


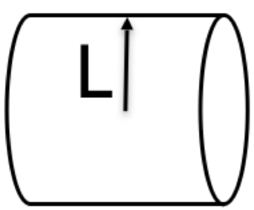
Improved p_T resolution by about 25%
→ Improved mass resolution for resonances

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

MIP timing detector (MTD)

- Timing resolution of 30 – 40 ps
  → comparable PID to STAR/ALICE
  - Protons identifiable up to p ≈ 5 GeV
  - Pion and kaons up to p ≈ 2.5 GeV
- Pile-up rejection in high lumi pp
- Triggering on high multiplicity pp collisions in low PU data



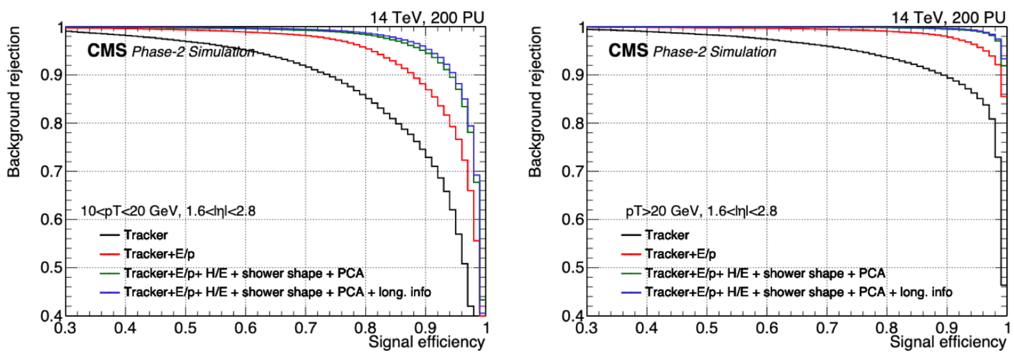


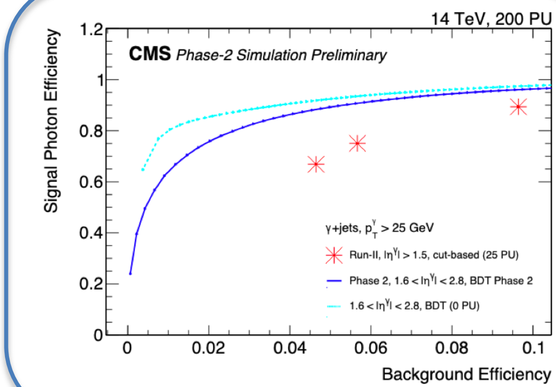
Experiment	η coverage	L at $\eta = 0$ (m)	σ_T (ps)	L/σ_T ($\times 100$)
CMS	$\lvert\eta\rvert < 3.0$	1.16	30	3.9
ALICE	$\lvert\eta\rvert < 0.9$	3.7	56	6.6
STAR	$\lvert\eta\rvert < 0.9$	2.2	80	2.2

CERN-LHCC-2017-027

High granularity calorimeter (HGCal)

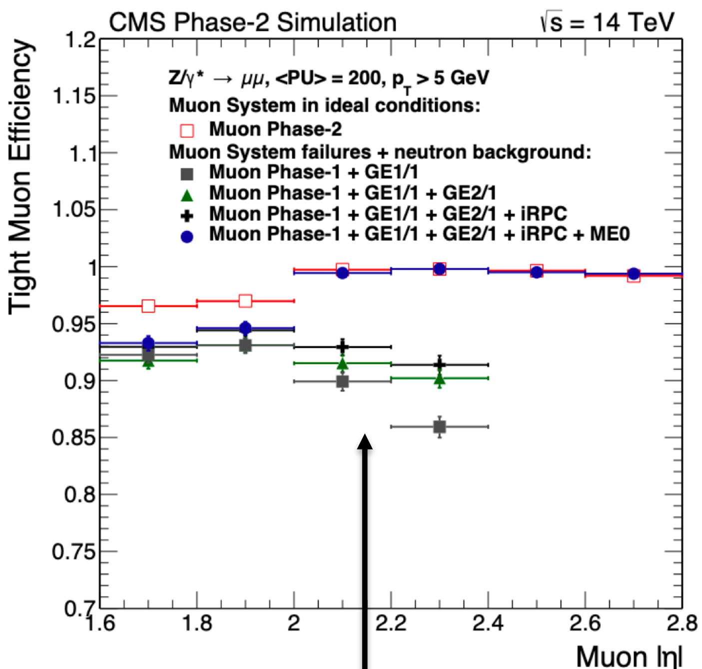
- Unprecedented transverse and longitudinal sampling
  → "particle flow calorimetry"
- Isolated electrons: 95% efficiency for background rejection of 100x at $p_T > 20$ GeV





- Isolated photons: 90% efficiency for background rejection of 20x $p_T > 25$ GeV
- Comparable jet performance to barrel region:
  e.g., for substructure, soft drop mass resolution of ~ 10%

Muon upgrades



Extension to $|\eta| < 2.8$ with GEM detectors

Further redundancy in forward region ($1.2 < |\eta| < 2.8$) → improve matching to tracks from silicon tracker, where the occupancy is largest

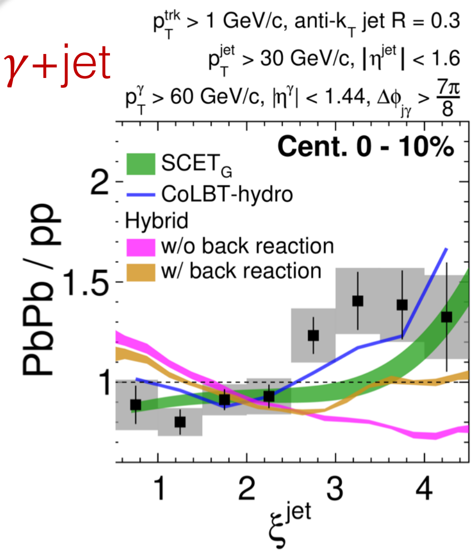
(Thoughts on)
physics performance

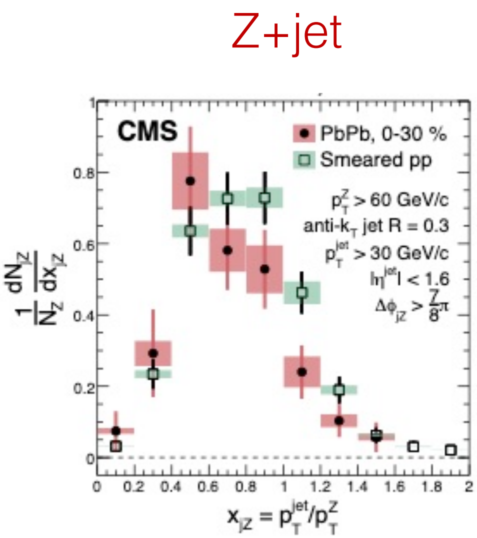
… while we wait for Phase II simulations with heavy ions

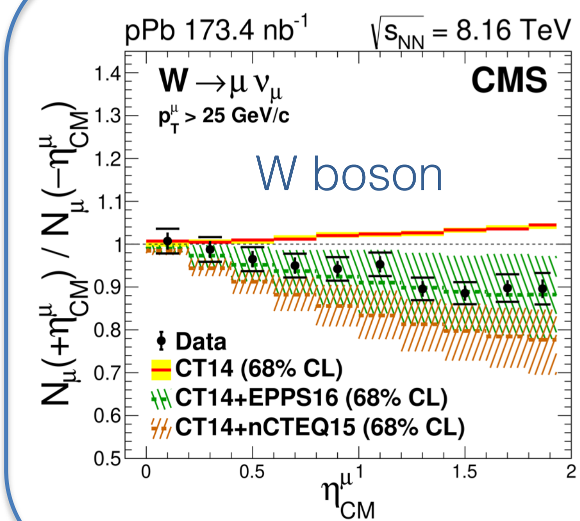
Precision quenching & nPDFs

Large acceptance, hermetic detectors essential for precise measurements of:

- Jet quenching in AA with γ+jet and Z+jet balancing
  → to fully constrain entire energy of the recoiling jet
- nPDFs with dijets and with weak bosons
  → to probe the forward region, which is most sensitive to nuclear effects





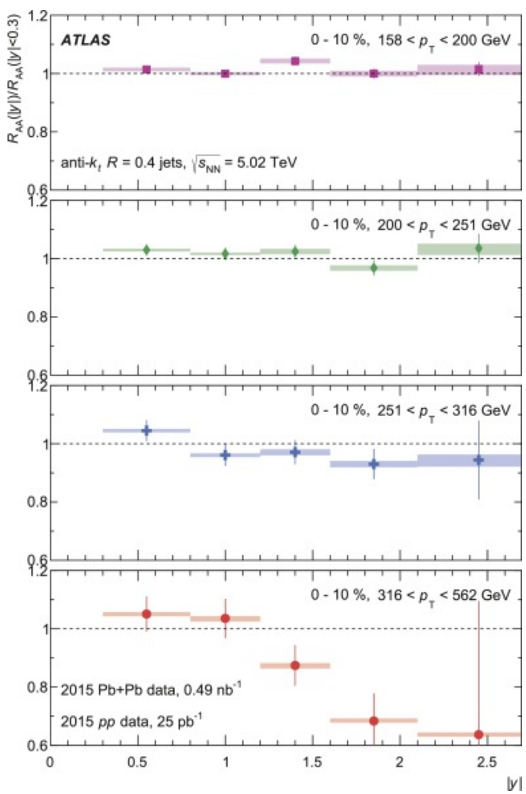


Phase II features full particle flow (tracker+HGCal+muon) to $\eta \approx 3$

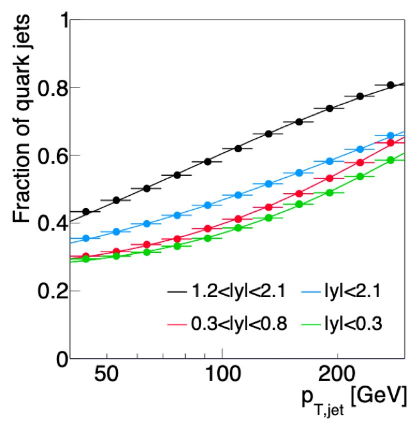
Current detector goes to $\eta \approx 2.4$, but often limited by poor endcap performance

Flavor dependence of jet quenching

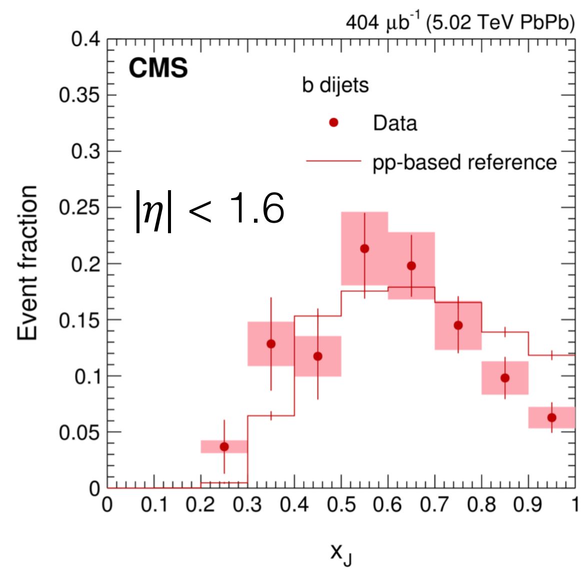
Quark vs gluon jets



Large η R_{AA} at high p_T sensitive to changing q:g



Direct flavor tagging



b-dijet p_T imbalance would benefit from b-tagging to $|\eta|$ = 3

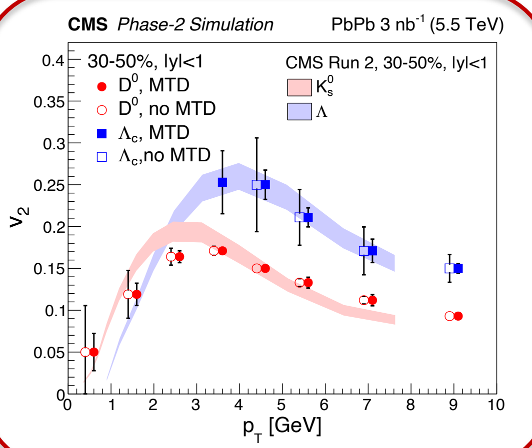
Large acceptance also crucial for Z→ bb, ttbar, etc.

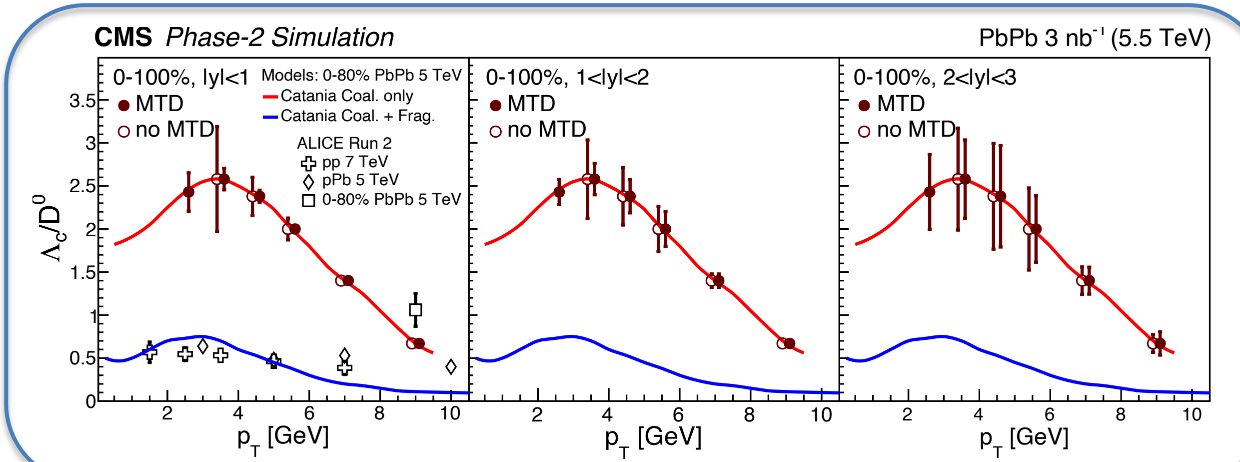
Open heavy flavor

$\Lambda_c \rightarrow \pi + K + p$ is the PID physics case par excellence

Heavy quark dynamics via elliptic flow

Hadronization by recombination from baryon-to-meson ratio





+ Combining w/ other experiments, can measure total charm x-section, e.g., for onia dissociation studies

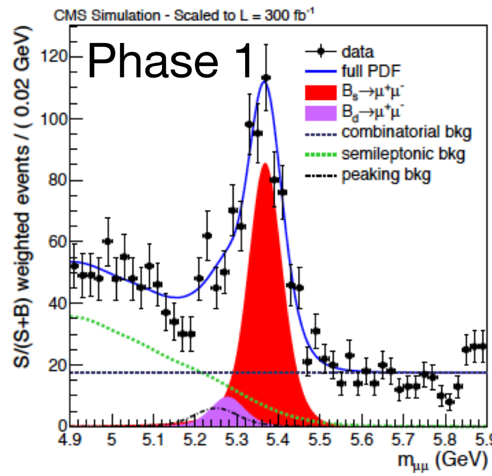
Light nuclei & hyper-nuclei is another interesting PID application

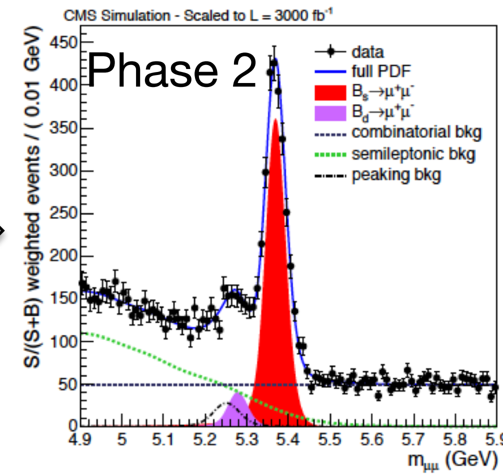
Quarkonia dissociation

Tracker+muon upgrades will improve triggering + reconstruction efficiency

50% gain in mass resolution

B_0/B_s separation



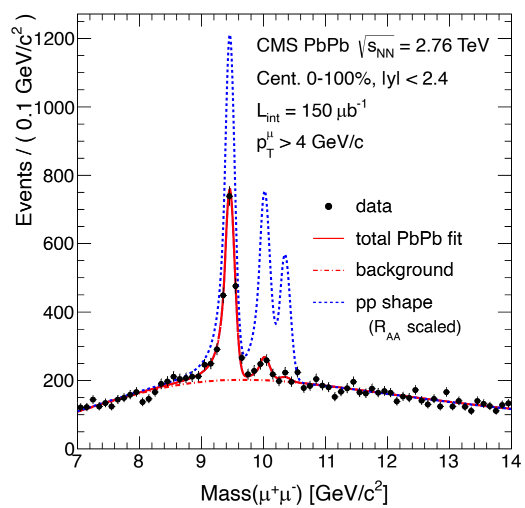


Separation of the ϒ family

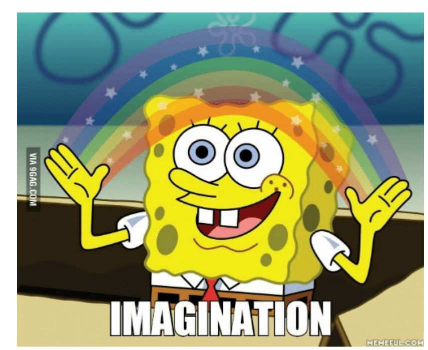
→ Observe the ϒ(3s) (or place more stringent limits)

→ Improve significance of other low S/B peaks: ψ(2s), X(3872), etc.

Phase 1

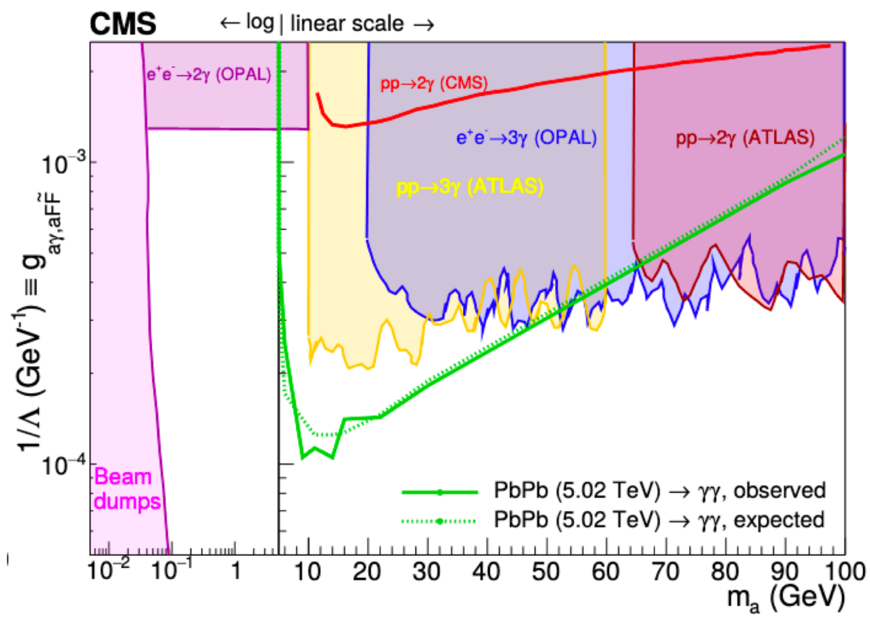


Phase 2



BSM in heavy ions

One example:
γγ from UPCs provides an exclusion limit on axion-like particles (ALPs)



Rate for UPCs of heavy ions ~ Z^4

However, factoring in beam intensity, light-ion collisions become competitive

		$^{16}_{8}$O	$^{40}_{18}$Ar	$^{40}_{20}$Ca	$^{78}_{36}$Kr	$^{129}_{54}$Xe	$^{208}_{82}$Pb
γ	$[10^3]$	3.76	3.39	3.76	3.47	3.15	2.96
$\sqrt{s_{\rm NN}}$	[TeV]	7	6.3	7	6.46	5.86	5.52
$\sigma_{\rm had}$	[b]	1.41	2.6	2.6	4.06	5.67	7.8
N_b	$[10^9]$	6.24	1.85	1.58	0.653	0.356	0.19
ϵ_n	[μm]	2	1.8	2	1.85	1.67	1.58
Z^4	$[10^6]$	$4.1 \cdot 10^{-3}$	0.01	0.16	1.7	8.5	45
$\widehat{\mathcal{L}}_{\rm AA}$	$[10^{30}\,{\rm cm}^{-2}{\rm s}^{-1}]$	14.6	1.29	0.938	0.161	0.0476	0.0136
$\widehat{\mathcal{L}}_{\rm NN}$	$[10^{33}\,{\rm cm}^{-2}{\rm s}^{-1}]$	3.75	2.06	1.5	0.979	0.793	0.588
$\langle\mathcal{L}_{\rm AA}\rangle$	$[10^{27}\,{\rm cm}^{-2}{\rm s}^{-1}]$	8990	834	617	94.6	22.3	3.8
$\langle\mathcal{L}_{\rm NN}\rangle$	$[10^{33}\,{\rm cm}^{-2}{\rm s}^{-1}]$	2.3	1.33	0.987	0.576	0.371	0.164
$\int_{\rm month}\mathcal{L}_{\rm AA}{\rm d}t$	$[{\rm nb}^{-1}]$	$1.17 \cdot 10^4$	1080	799	123	28.9	4.92
$\int_{\rm month}\mathcal{L}_{\rm NN}{\rm d}t$	$[{\rm fb}^{-1}]$	2.98	1.73	1.28	0.746	0.480	0.210

For searches of long-lived particles (LLP) light ions are even more advantageous

Contribution submitted to the update to the European Particle Physics Strategy

arXiv:1812.07688

The message

- CMS has produced some of the most notable heavy-ion results in Runs 1 & 2 of the LHC
- There remain interesting measurements to do with the larger luminosities we'll see in Runs 3+
- The Phase II upgrades enhance the capabilities for heavy-ion physics with the CMS detector
  - Large acceptance, full particle flow to $|\eta| \approx 3$ with
    - Lighter, more granular tracker
    - A state-of-the-art super-granular endcap calorimeter
    - Extended muon coverage
  - New PID capabilities with the MTD detector