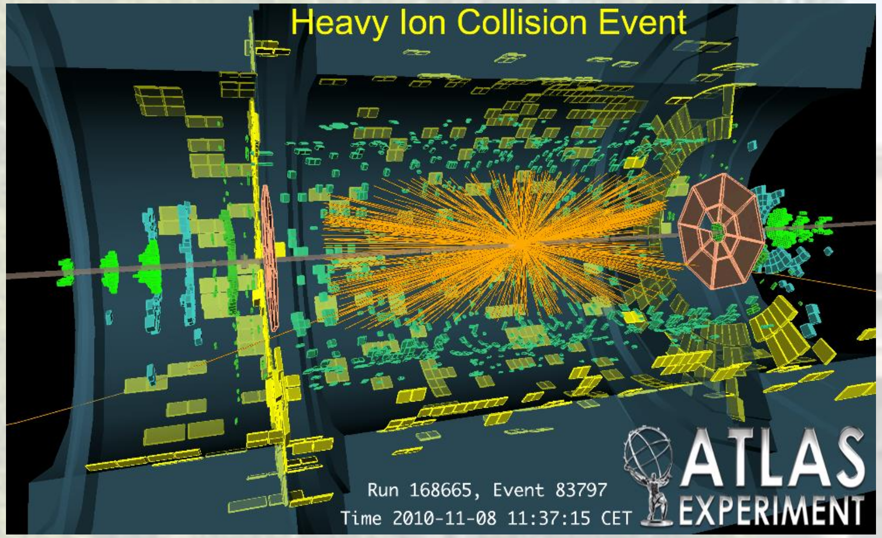
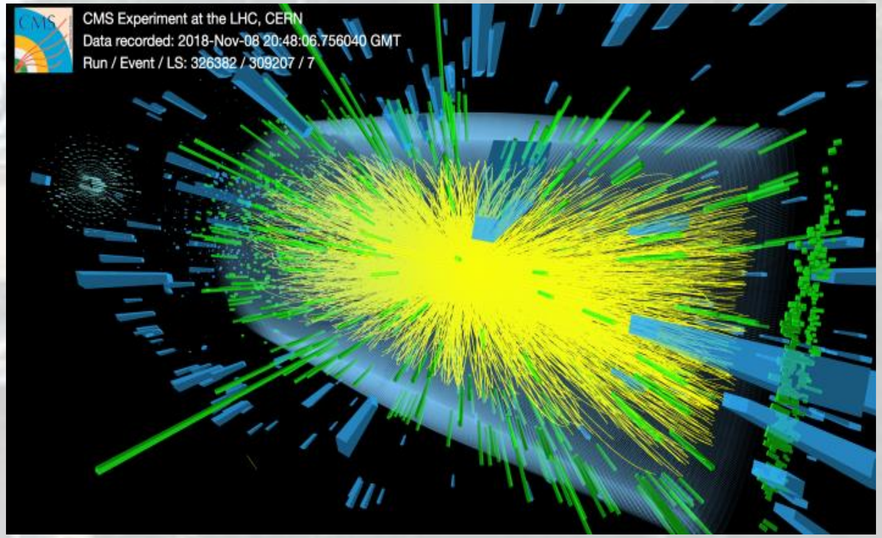
CMS and ATLAS Heavy Ion Physics at Run 3+4 and Beyond



Yen-Jie Lee

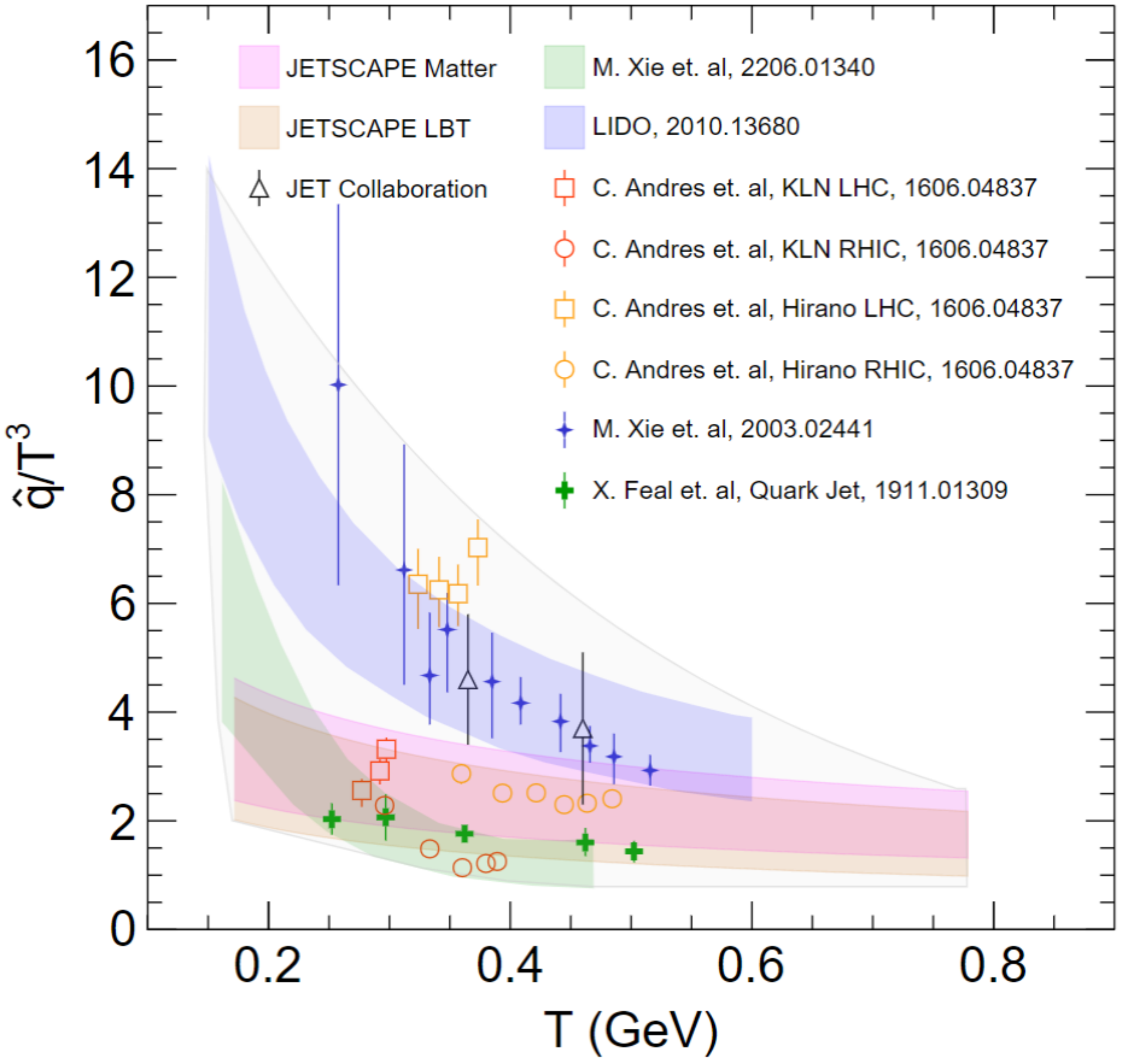


QCD Town Meeting
MIT, Cambridge, MA

23 September, 2022

MIT HIG group's work was supported by US DOE-NP

QGP Transport Properties with RHIC and LHC Run 2 Data



Compilation by YJL, Michael Winn, Liliana Apolinario arXiv:2203.16352
Progress in Particle and Nuclear Physics, 103990 (2022)

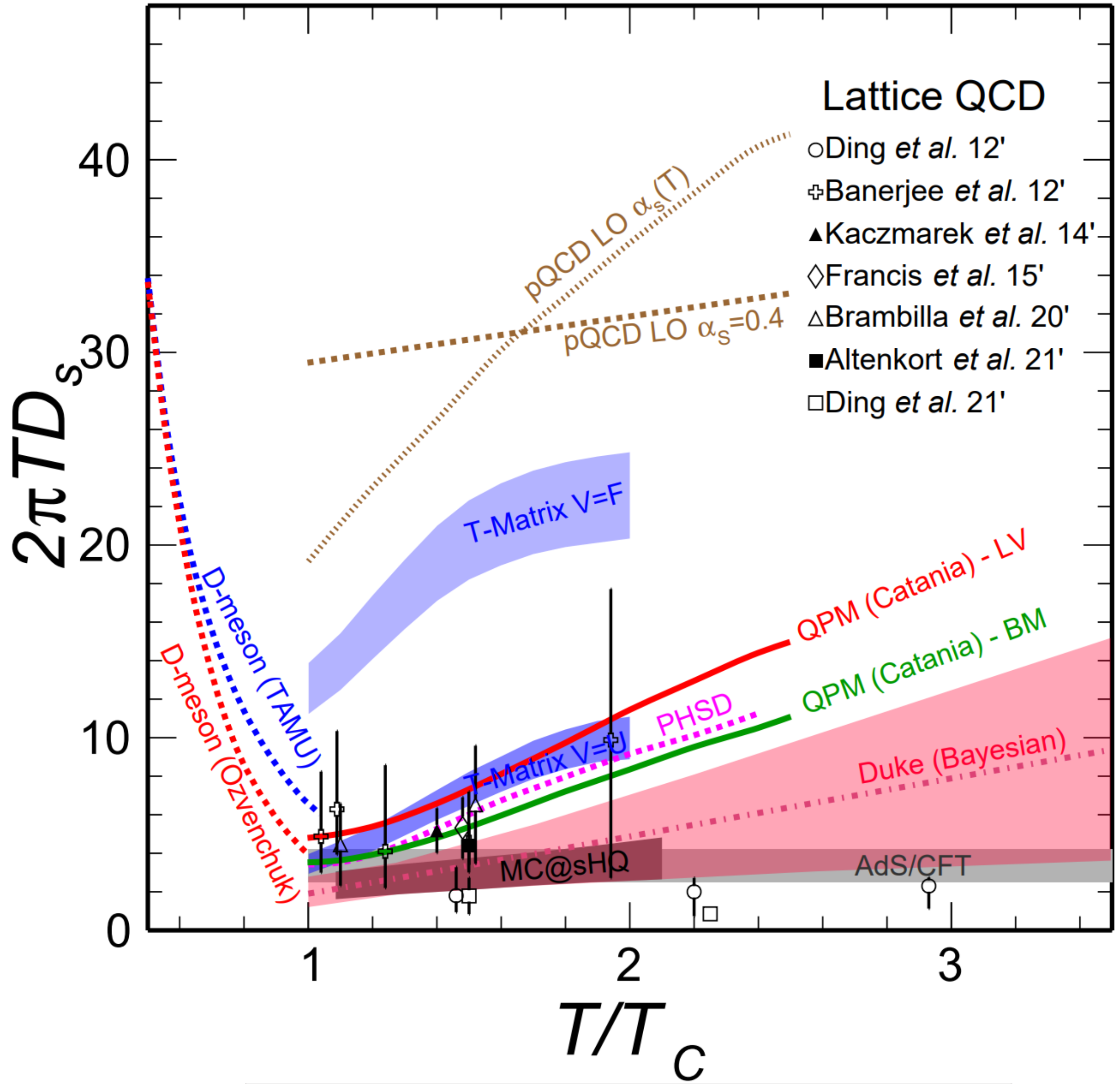
Jet Quenching Parameter $\hat{q}$

- Extracted mainly from charged hadron spectra R_{AA} data
  - Some analyses included γ-hadron and di-hadron data
- $\hat{q}/T^3$: decreasing trend vs. T
- Extracted values differ by up to a factor of 7

Remaining Issues:

- Different jet quenching mechanisms in theoretical models
- Different QGP media used in calculations
- Hadron re-scattering in the hadron gas phase
- Hadronization of fast moving partons

QGP Transport Properties with RHIC and LHC Run 2 Data



Xin Dong, YJL, Ralf Rapp, Ann.Rev.Nucl.Part.Sci. 69 (2019) 417-445

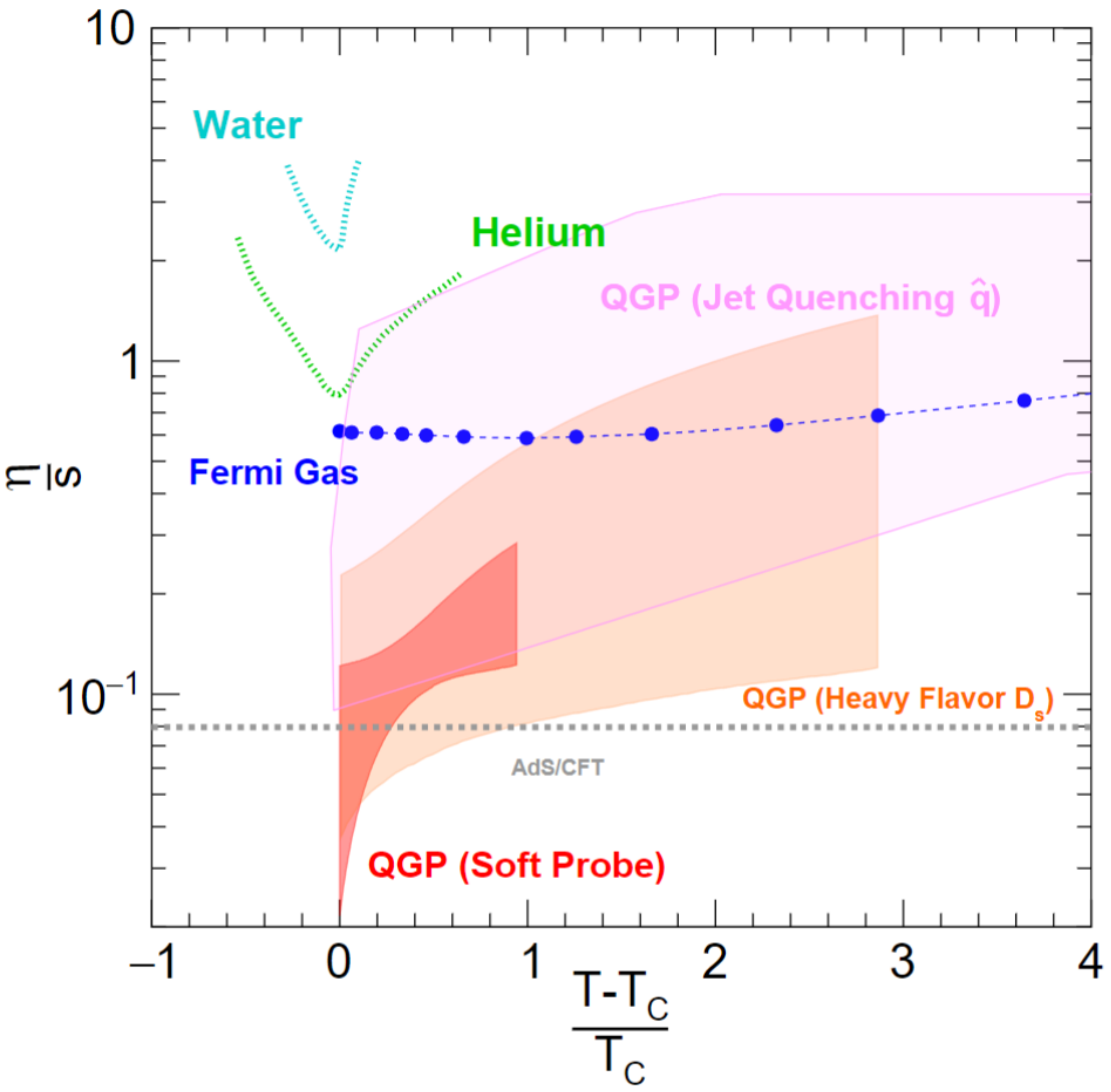
Charm diffusion coefficient D_s

- Bayesian analysis from D meson R_{AA} and v_2
- pQCD calculations at LO are ruled out by the data
- Non-perturbative calculations with a potential close to the HQ free energy from LQCD are not viable
- Increasing trend of $2\pi TD_s$ vs. T in various models

Remaining Issues:

- Hadronization of charm quarks
- Charm diffusion mechanism
- Different QGP media used in various calculations
- Precision of the experimental data

Medium Properties from Soft and Hard Probes



Compilation by YJL, Michael Winn, Liliana Apolinario arXiv:2203.16352
Progress in Particle and Nuclear Physics, 103990 (2022)

Specific viscosity has been extracted from **soft probes**

- Via identified hadron dN/dη, $<p_T>$, v_2, v_3 and v_4
- Main uncertainties from initial state and early time dynamics

To get the big picture of the QGP properties with Run 2 + RHIC data, one could compare the inputs from soft and hard probes:

- **HQ D_s** could be related to specific viscosity by

$$\frac{\eta}{s} = \frac{D_s(2\pi T)}{4\pi k}$$

R. Rapp, H. van Hees, 0903.1096
X. Dong, YJL, R. Rapp, 1903.07709

Where the scale factor k ranges between 1 (strong-coupling limit) and 2.5 (weak coupled)

- **Jet quenching parameter $\hat{q}$** could be related to specific viscosity in the limit of multiple soft scattering by

$$\frac{\eta}{s} = C\frac{T^3}{\hat{q}}$$

Where the scale factor C is varied between 1.25 and 2.5

A. Majumder, B. Muller, Xin-Nian Wang PRL 99 (207) 192301
B. Muller PRD 104 (2021) 7, L071501

Medium properties extracted from **Jet Quenching** and **Open Heavy Flavor** are consistent with the results from **Soft Probes**, but within rather large uncertainties

LHC Timeline and CMS/ATLAS Upgrade

LHC → HL-LHC

PbPb 2 nb^{-1}	PbPb 7 nb^{-1}, pPb, pO, OO		PbPb 7 nb^{-1}, pPb		AA, small systems?
Run 2 (2018)	Long shutdown 2 (2019–2021)	Run 3 (2022–2025)	Long Shutdown 3 (2026–2028)	Run 4 (2029–2032)	LS4 (2033–2034)	Run 5 (2035–2038)

2018 | 2019 | 2020 | 2021 | **2022** | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 | 2031 | 2032 | 2033 | 2034 | 2035 | 2036 | 2037 | 2038

Phase 1 Upgrade | Phase 2 Upgrade | Phase 3 Upgrade

CMS Performance in Run2/3

- 2016: Major upgrade of L1 trigger
- 2017: 4-Layer Pixel Detector
- 2018 Performance:
  - pp L1 100kHz
  - PbPb L1 **35kHz** (3x of 2015)
  - DAQ: 6 GB/s
    - Up to **8.8 kHz** MinBias events to tape (27x of 2015)
- Run3: DAQ 17 GB/s
  - 25 kHz MinBias rate (3x of 2018)

CMS/ATLAS Phase 2 for Run 4

- Tracker **|η|<4**
- Muon ID up to **|η|<2.8**
- High Granularity Calorimeter
- MIP timing detector
  - 4D vertexing
  - **p/K/π PID (CMS MTD)**
- L1 trigger update: 750 kHz for CMS
- DAQ: 51 GB/s for CMS
- L1 track triggers
- ZDC

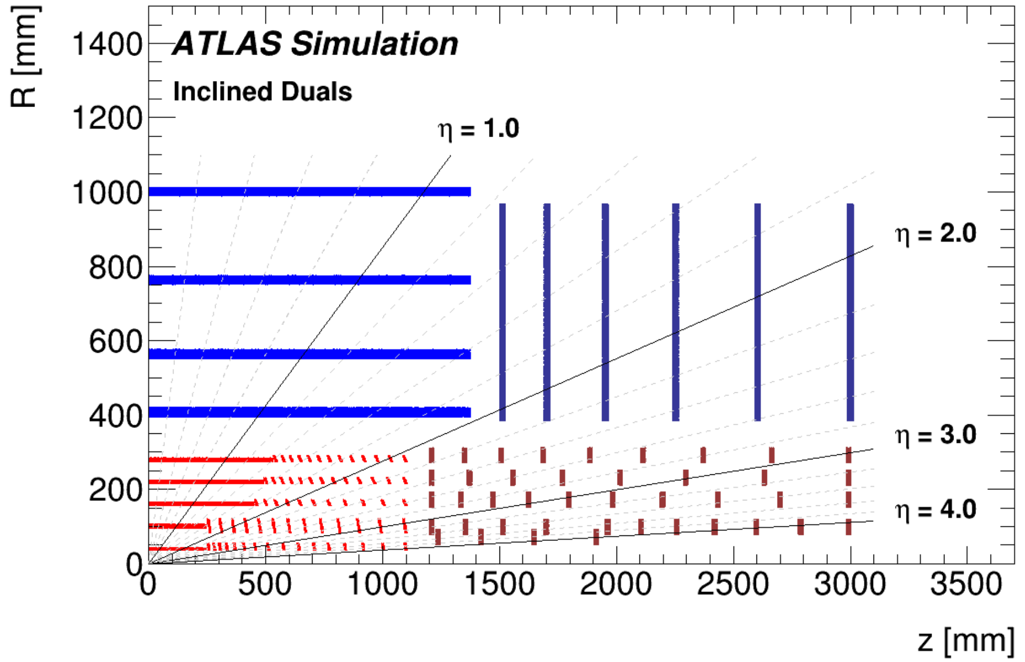
CMS/ATLAS Run 5

- Record smaller ion collisions at the highest rate delivered by LHC
- Possible further upgrade to be defined, e.g.:
  - Additional timing layers
  - Forward calorimeters
  - Extend muon coverage
  - …

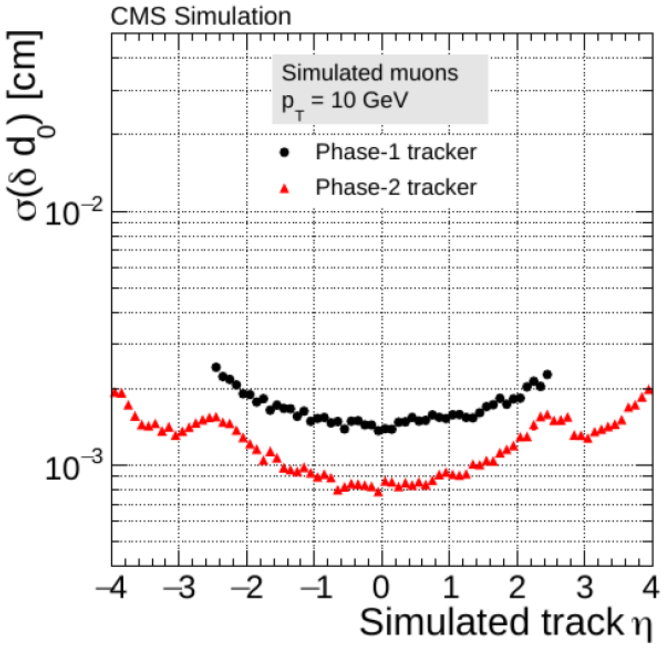
Phase 2 CMS & ATLAS Tracking System

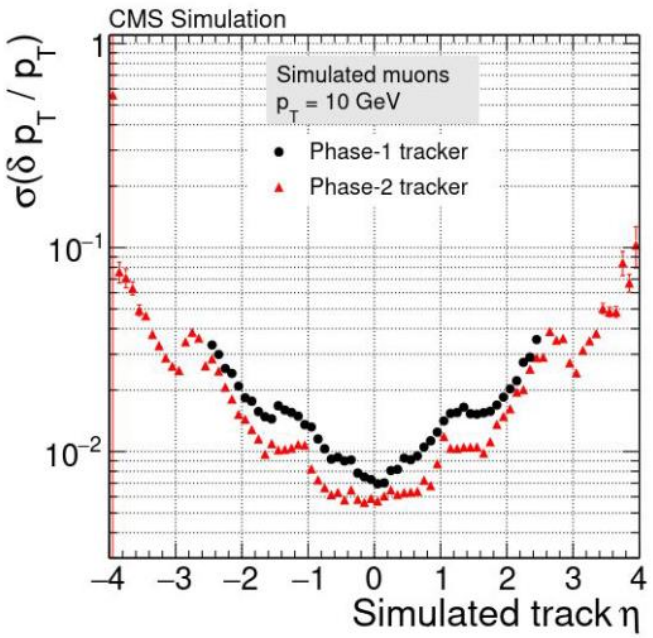
- Installation before Run 4
- Charged particle reconstruction up to **$|\eta|<4$**
- At <Pile-Up>=200 (heavy-ion like):
  - Efficiency > 90%, fake rate < 3%

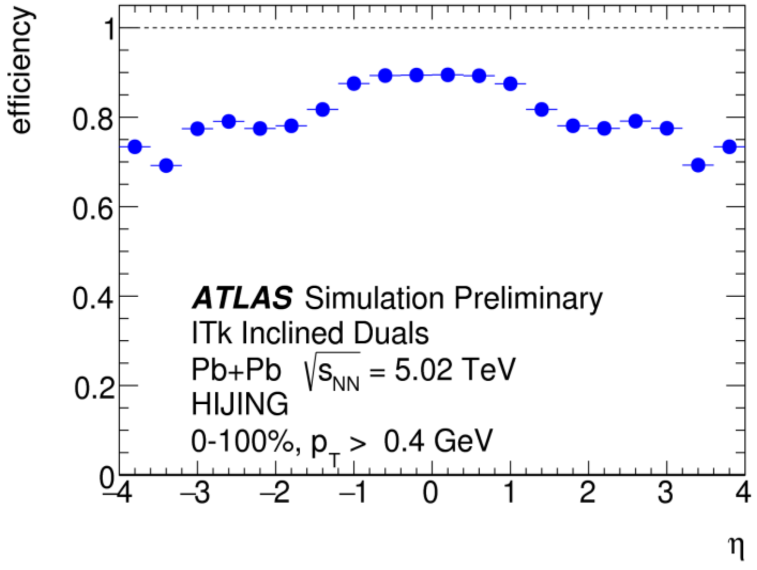
- Significantly better p_T and d_0 resolution
  - Improvement on HF hadron and b/c-jet tagging
  - Possibility to employ L1 track trigger

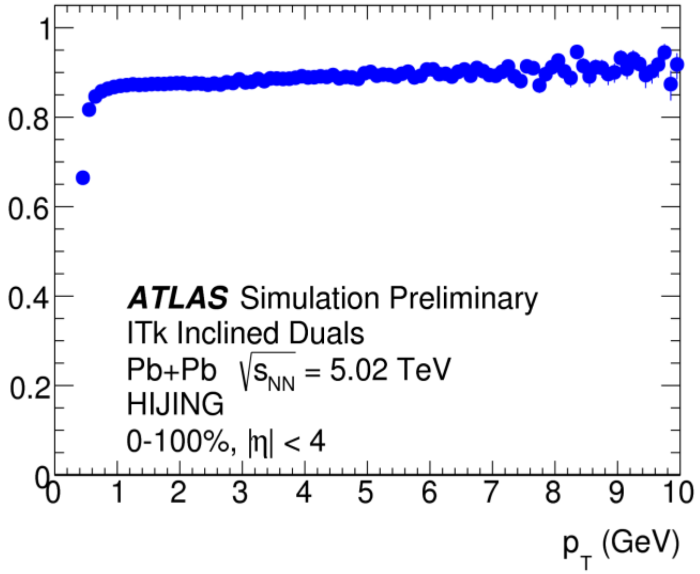


ATL-PHYS-PUB-2018-020







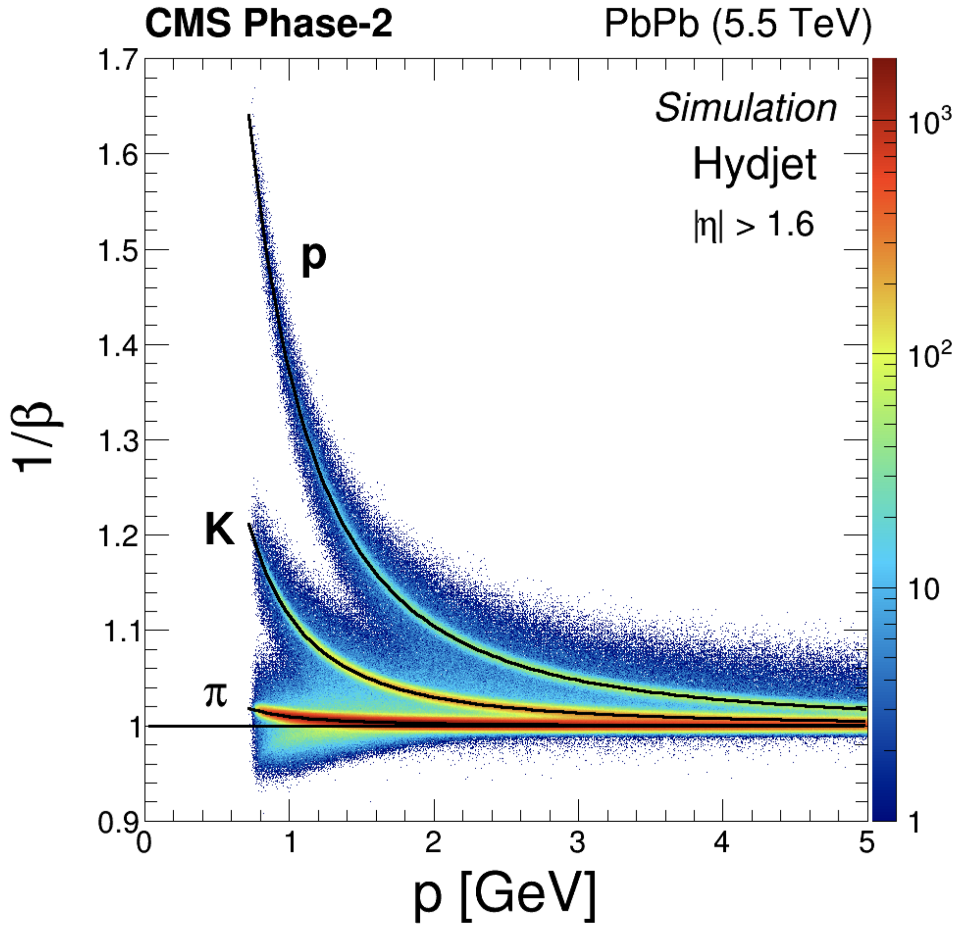


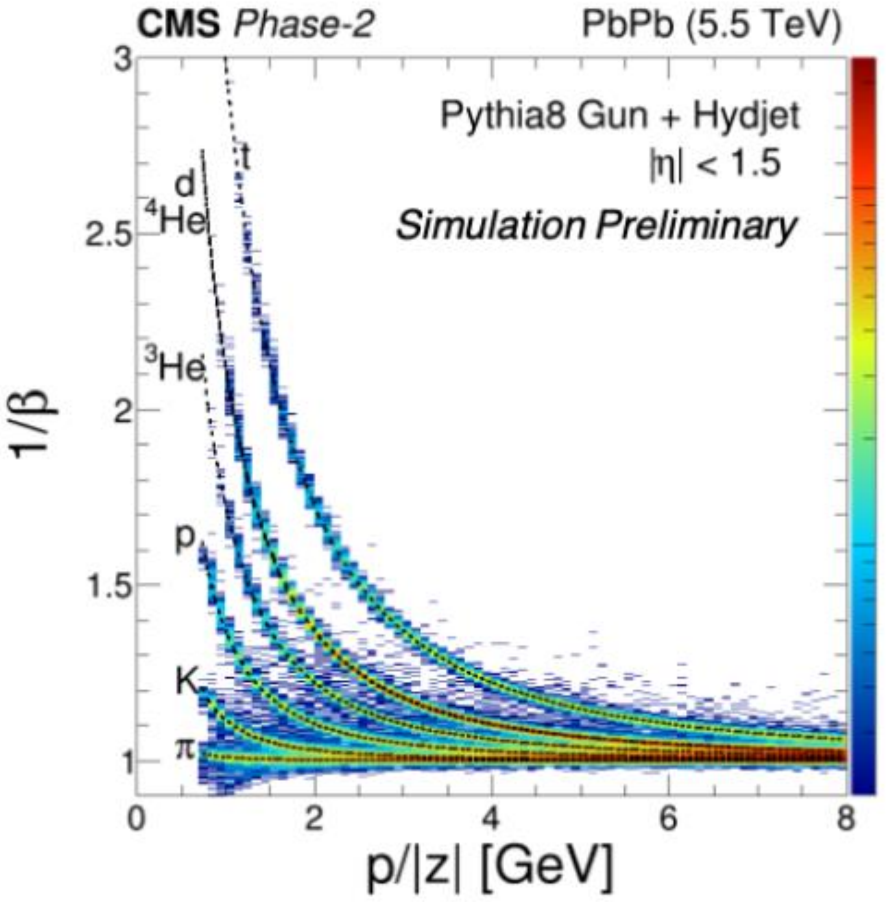
CMS MIP Timing Detector (MTD)

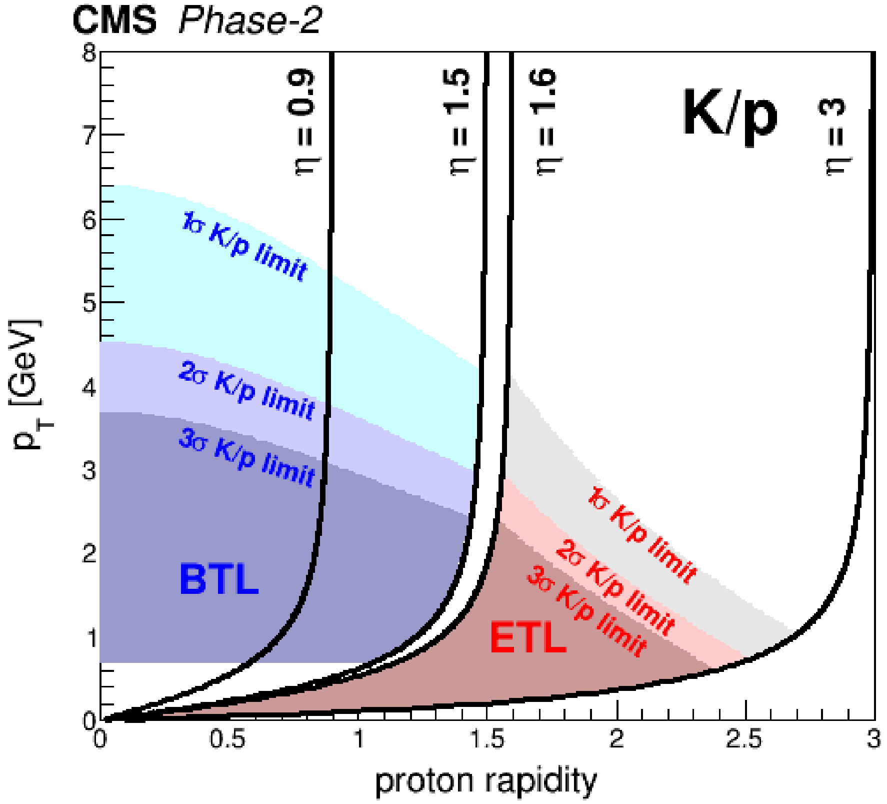
p/K/π separation

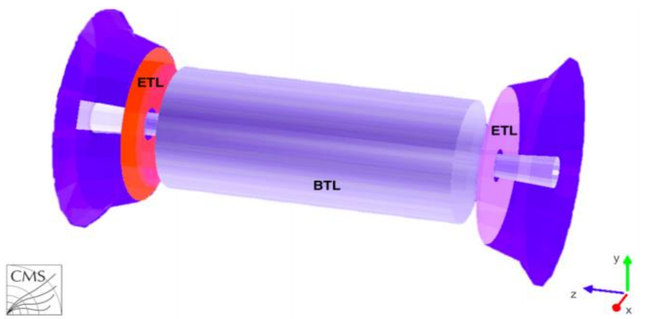
Light ion identification

MTD TDR



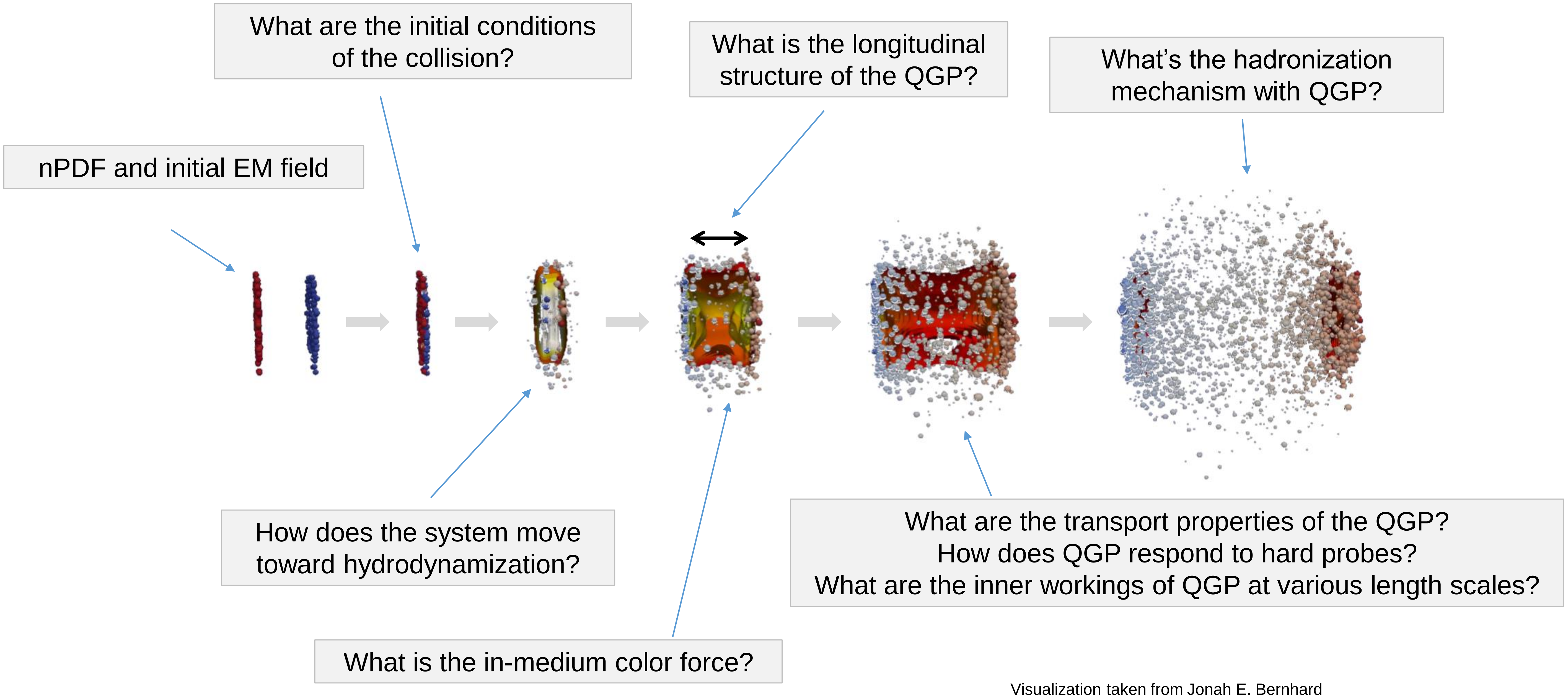






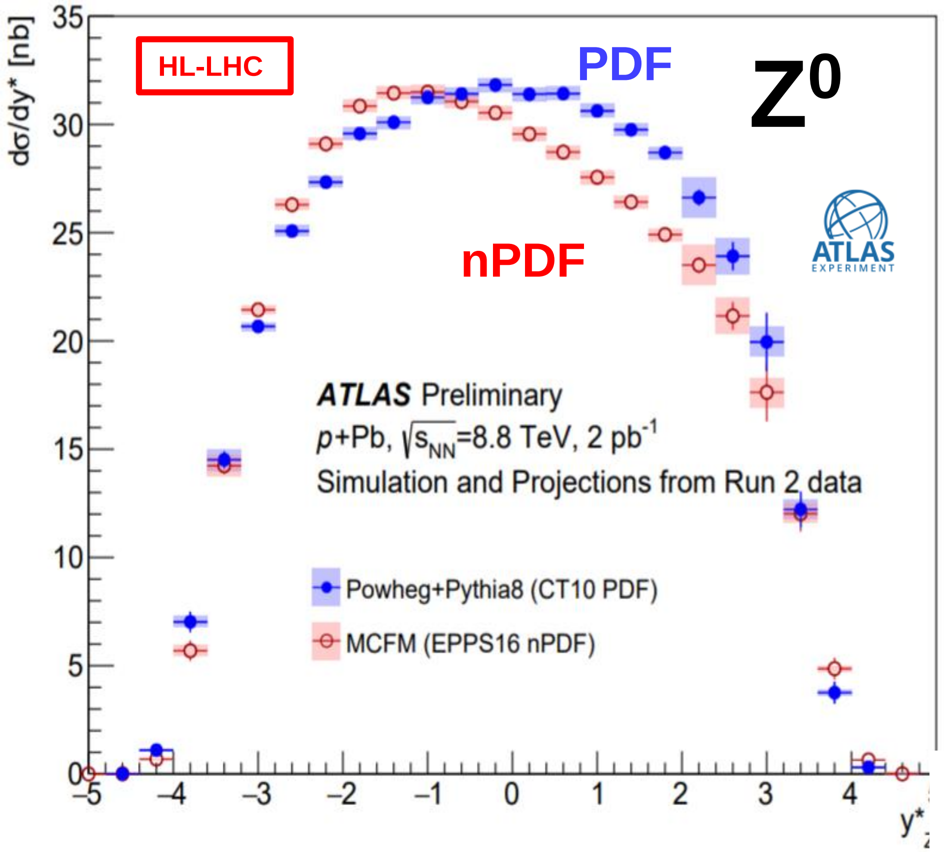
- Unique hermetic particle identification coverage by CMS MTD
- **Crucial Upgrade** for CMS Heavy Flavor Program with heavy ion collision

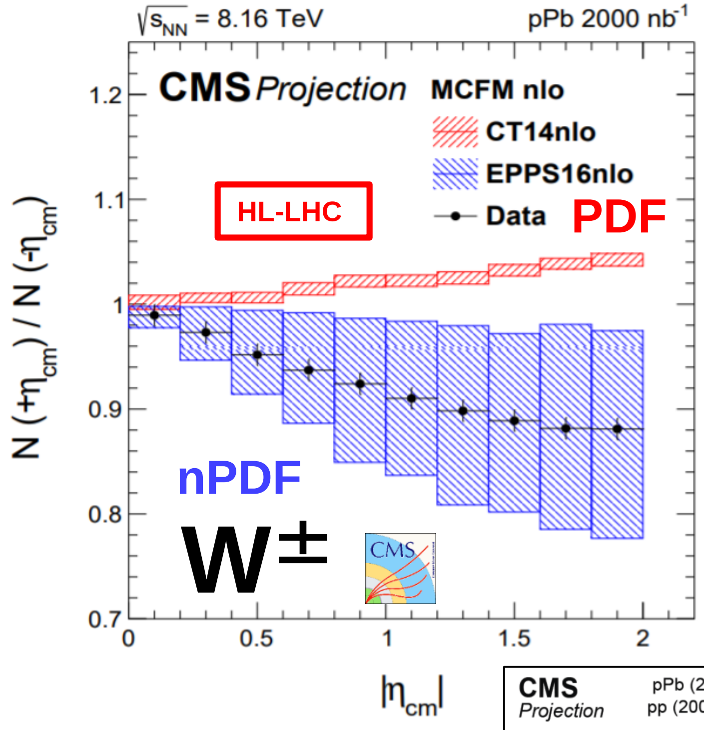
Open Questions

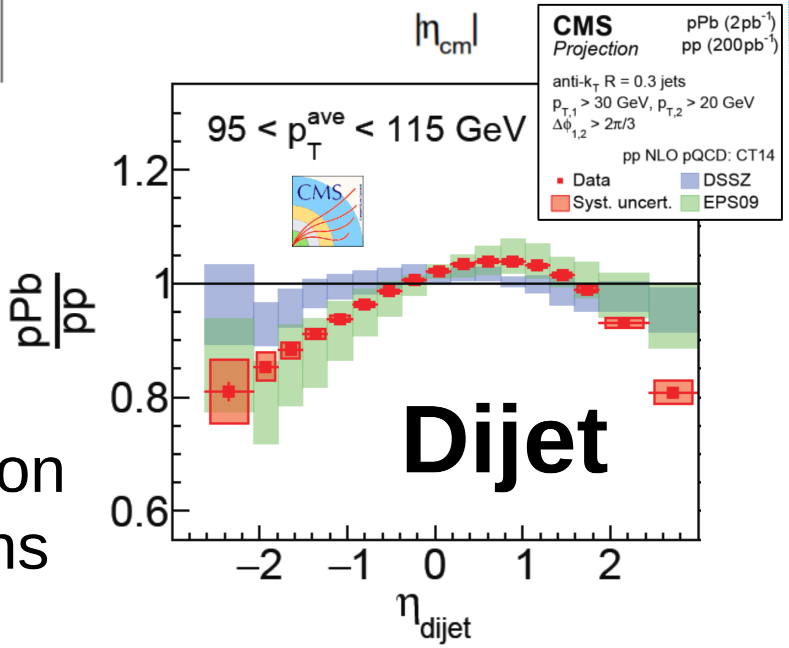


Visualization taken from Jonah E. Bernhard
arXiv:1804.06469

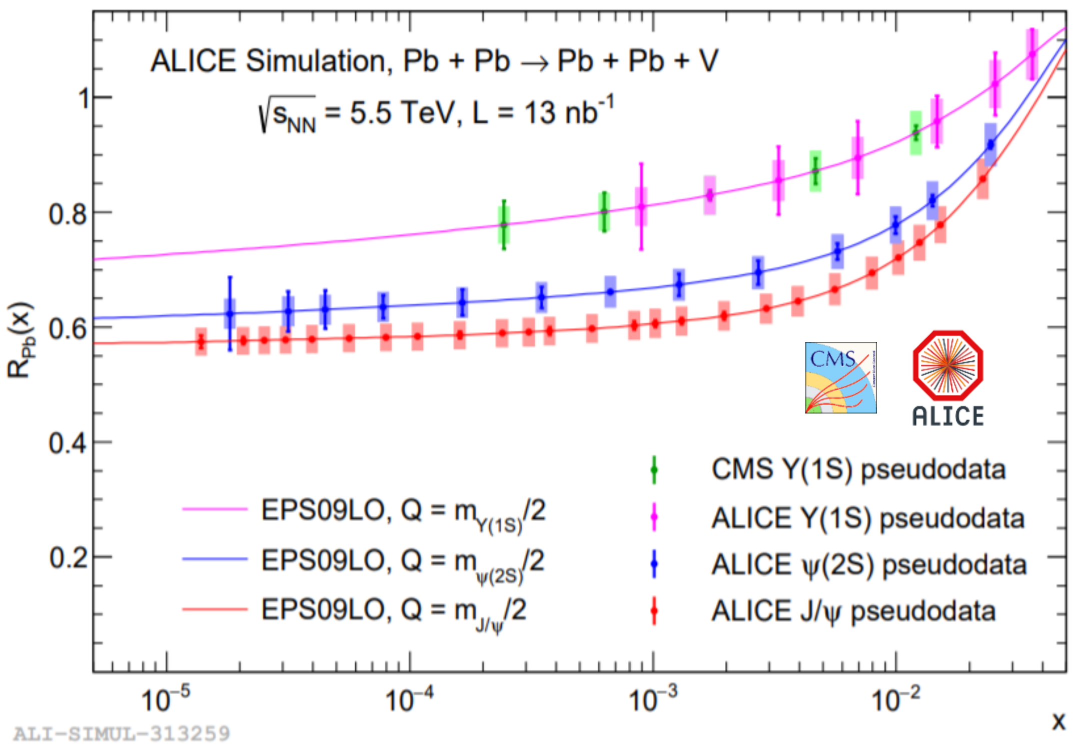
nPDF Constraint from pPb and UPC





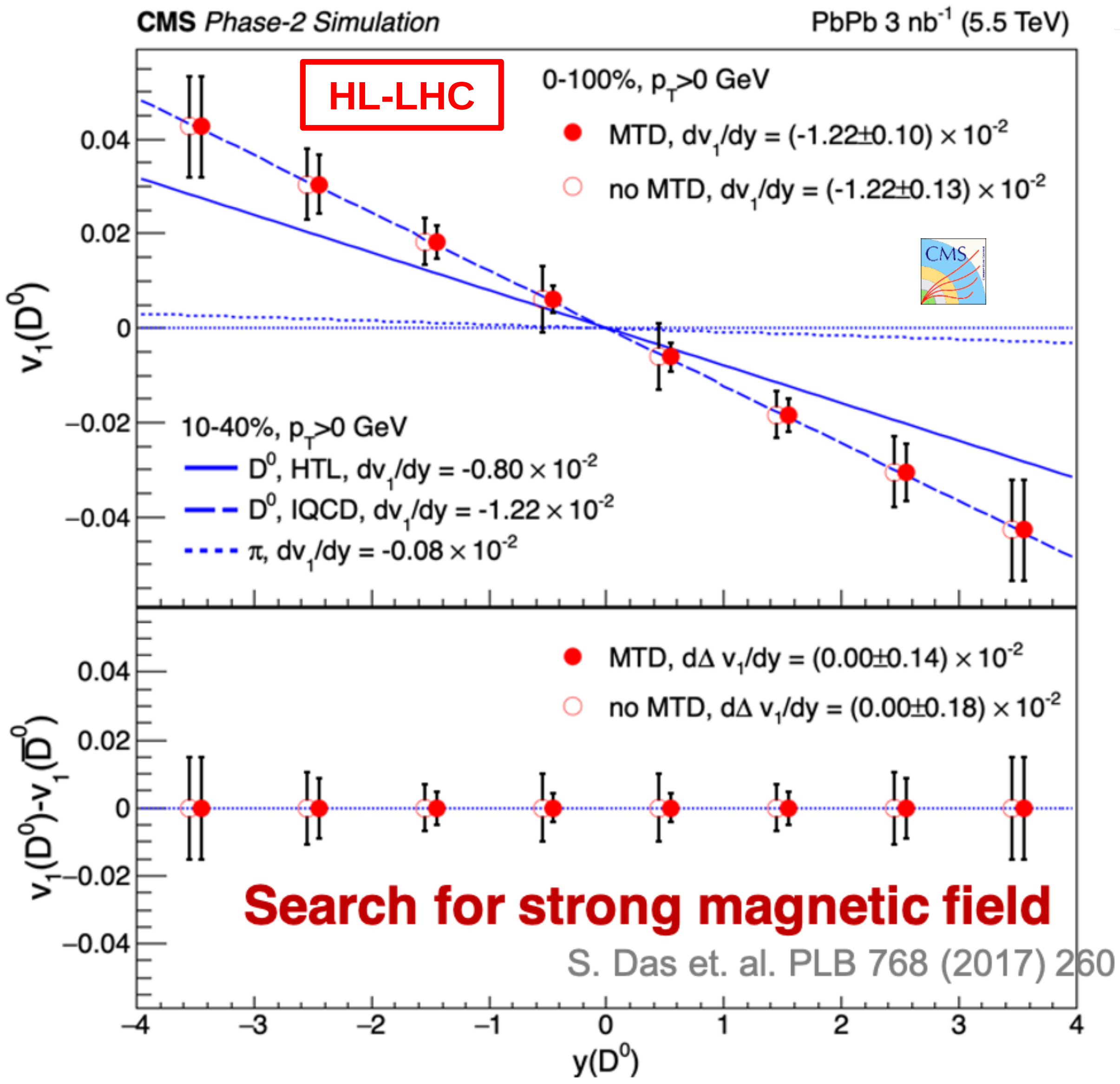


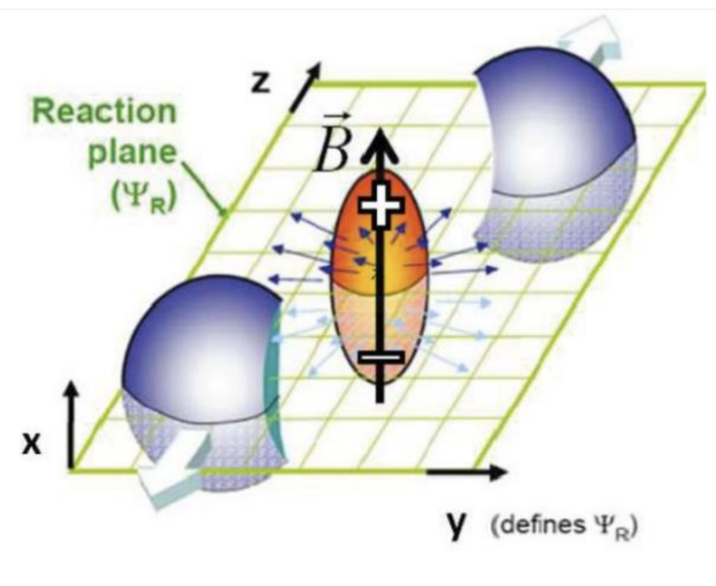
- Strong constraints on nPDF from electroweak boson, Drell-Yan and dijet cross-section measurements in pPb collisions

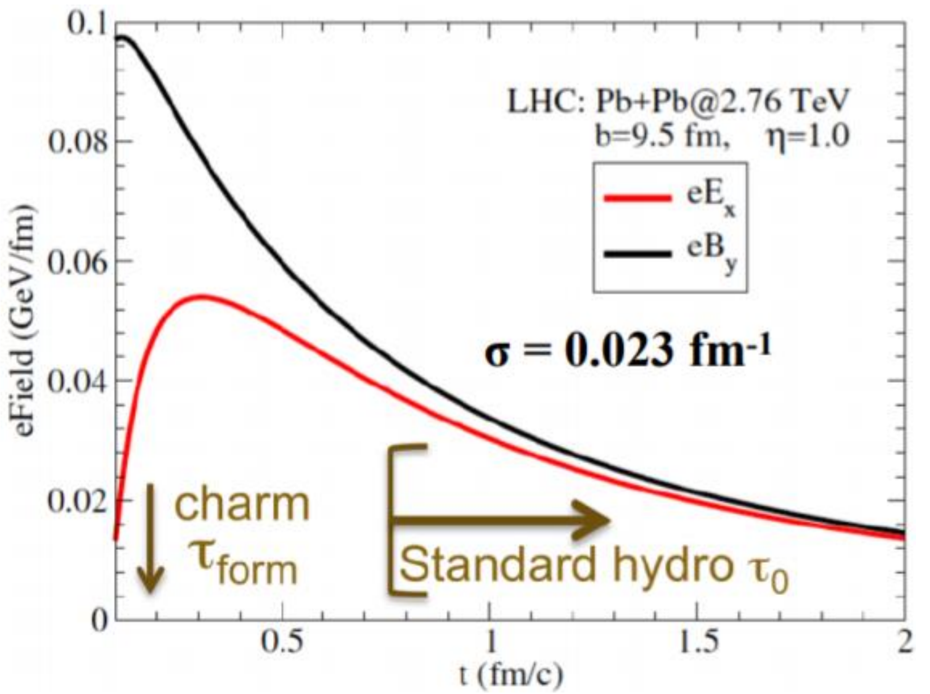


- Ultra-Peripheral PbPb Collisions (UPC): **γ+Pb** collisions!
- **Complementary to EIC efforts**
- HL-LHC data: Precise measurements of ϒ(1S), J/ψ and ψ(2S) over a **very wide x range**, test **Q dependence** of nuclear modifications

Initial Magnetic Field with D^0 Directed Flow v_1





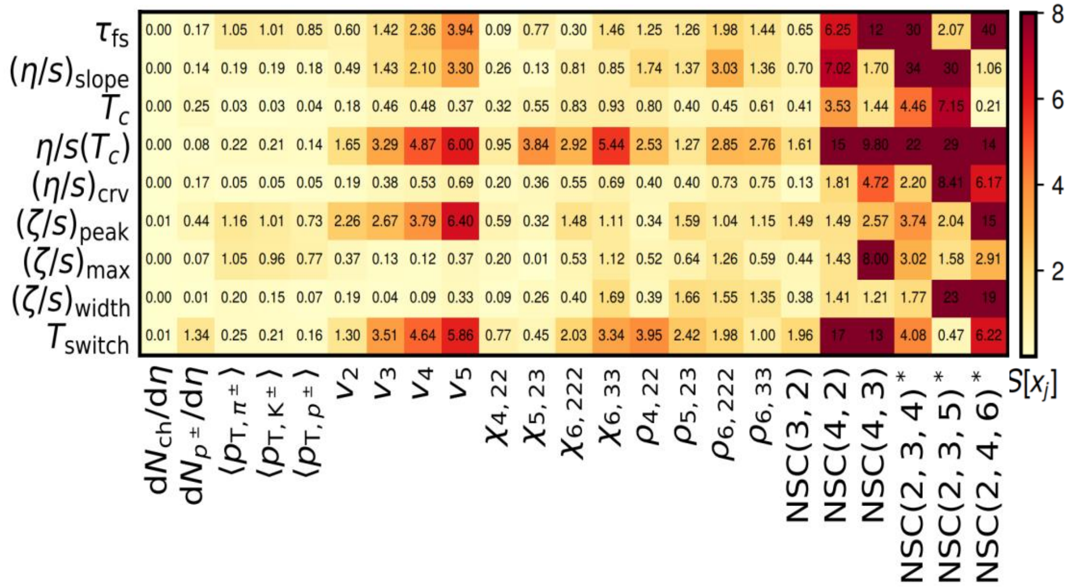


$$\frac{2\pi}{N}\frac{dN}{d\phi} = 1 + \sum_{n=1}^{\infty} 2v_n \cos[n(\phi - \Psi_n)]$$

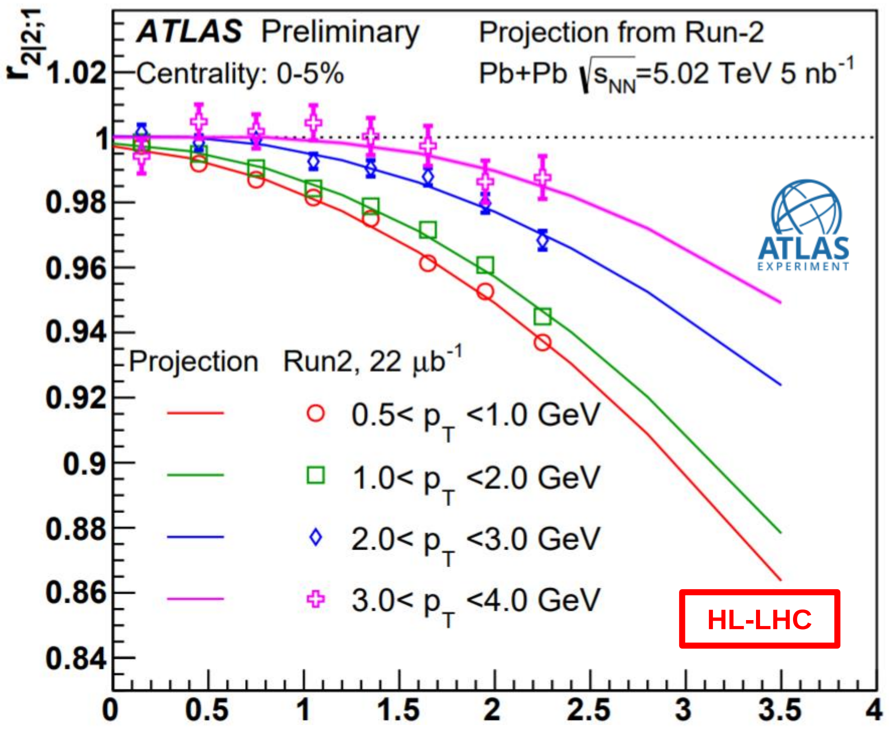
- Strong initial electromagnetic field in heavy ion collisions inducing a vorticity in the reaction plane.
- The resultant effects entails a significant directed flow (v_1) and the effects increase vs. D^0 rapidity
- MTD and the large acceptance CMS tracker could provide high precision measurement of D^0 v_1 over 8 units of D^0 rapidity.

Extraction of QGP Properties with Soft Probes

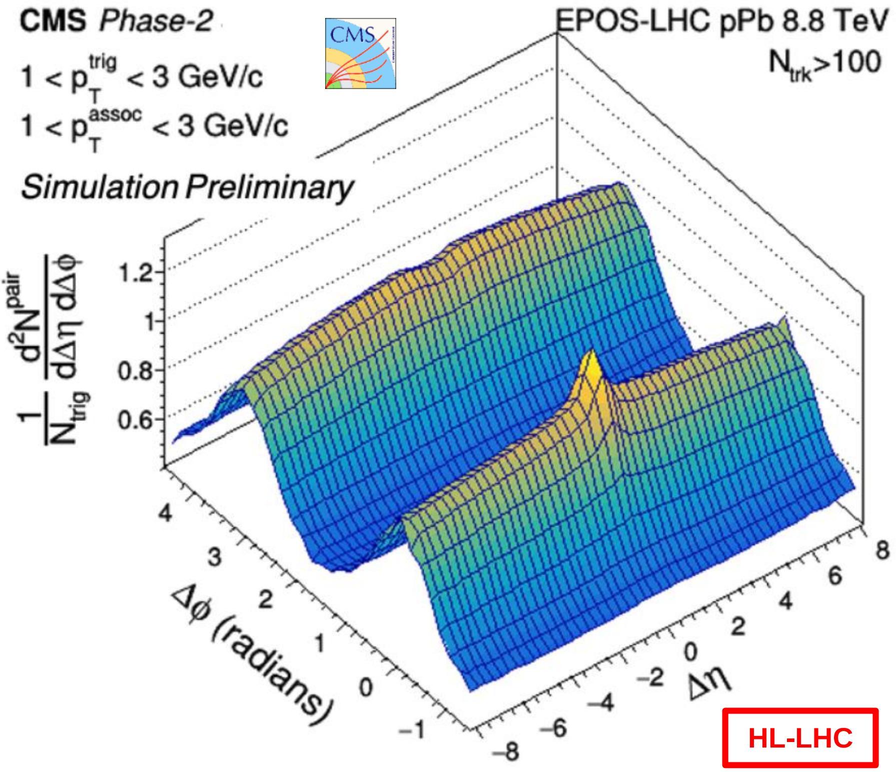
- Unprecedented high precision and differential measurements of flow harmonics and their event-by-event fluctuations: New constraints on the QGP initial density profile, formation time, properties and hadronization



arXiv: 2111.08145

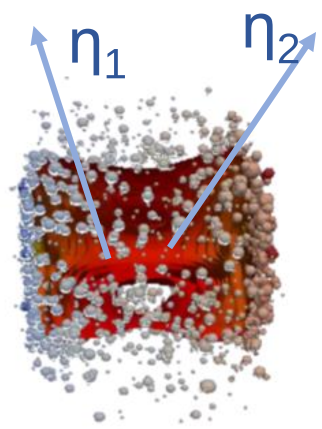


$$r_{n|n;1}(\eta) = \frac{\langle \mathbf{v}_n(-\eta)\mathbf{v}_n^*(\eta_{\text{ref}})\rangle}{\langle \mathbf{v}_n(\eta)\mathbf{v}_n^*(\eta_{\text{ref}})\rangle}$$



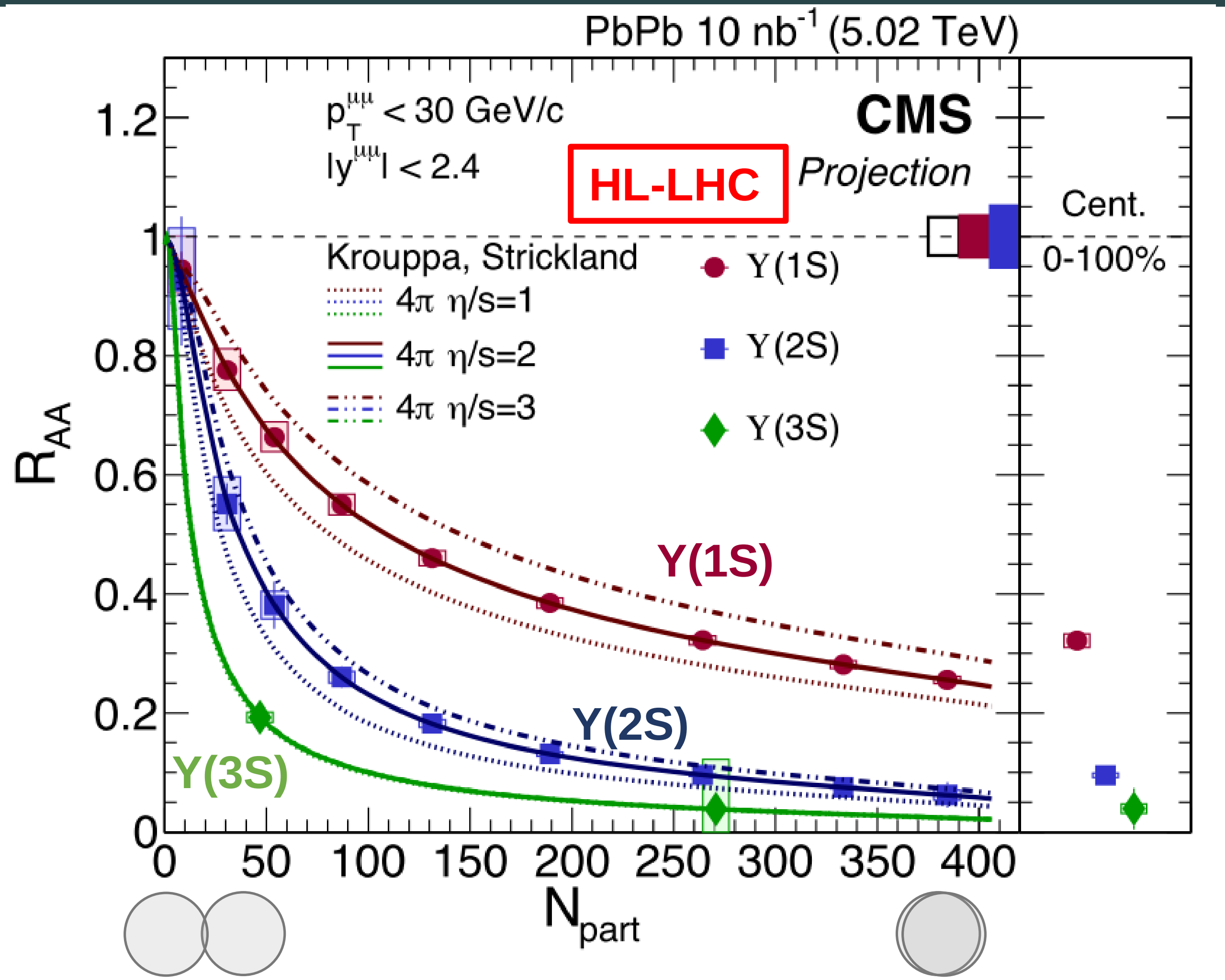
CMS DP2021_037

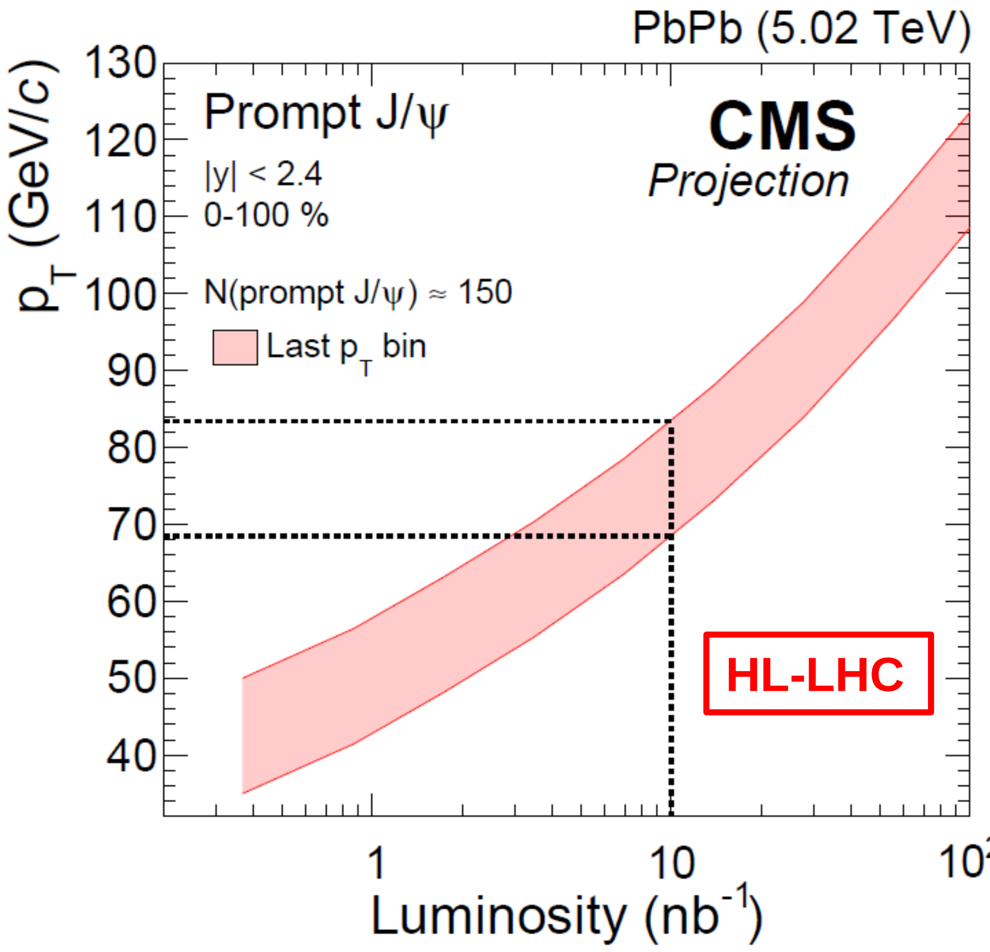
|Δη| up to **8**



- Pseudorapidity dependence of the flow measurements over **a wide η window** enabled by ATLAS and CMS tracker upgrade
  New insights into the longitudinal structure of QGP (event-plane decorrelation)

Quarkonia Production in PbPb Collisions

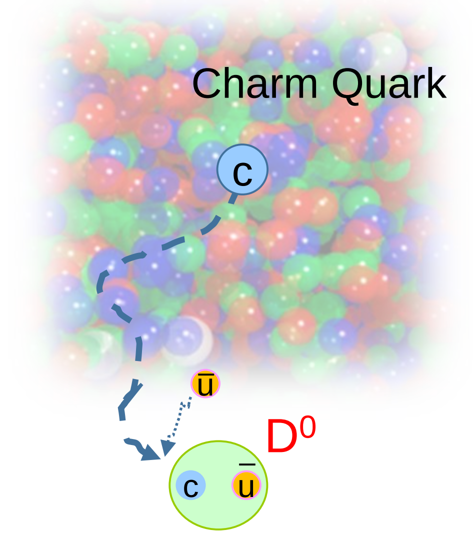


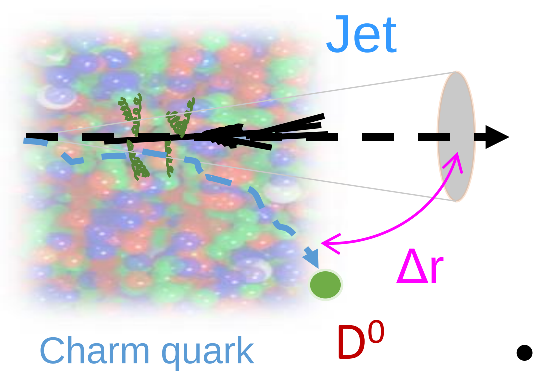


- Significant improvement on the Υ(nS) R_{AA}
- Sensitive to the medium properties such as η/s and temperature

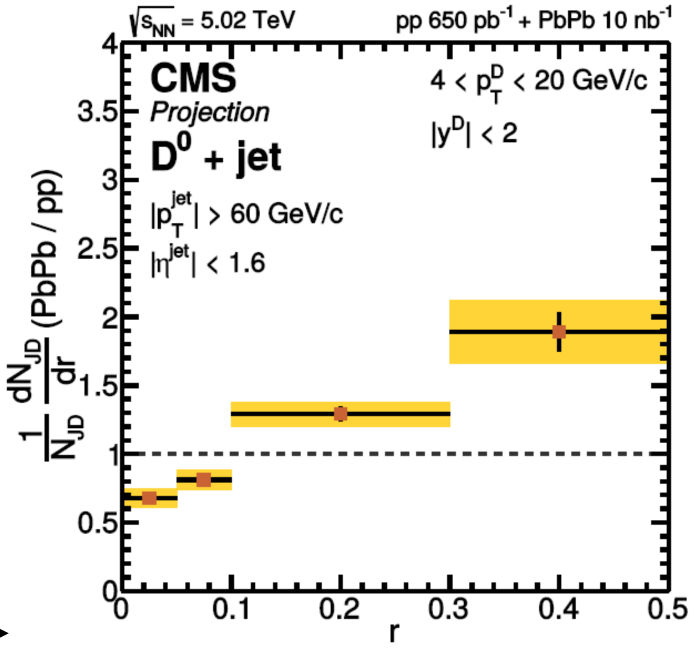
- High p_T reach of prompt J/ψ up to ~ 80 GeV
- Hadronic decays of Quarkonia enabled by CMS MTD such as J/ψ, ψ(2S) and $\eta_c \rightarrow p\bar{p}$

High Precision Measurement of HQ Diffusion

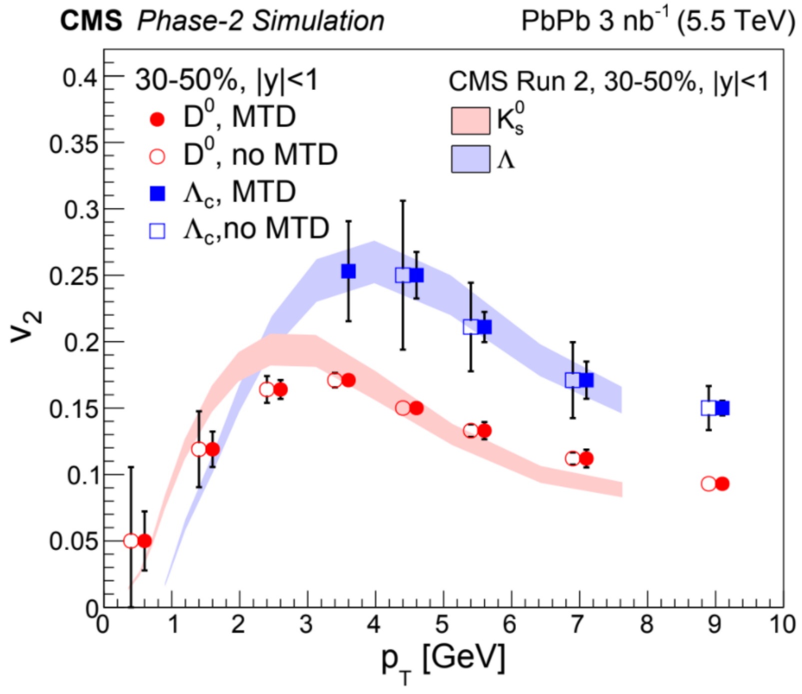




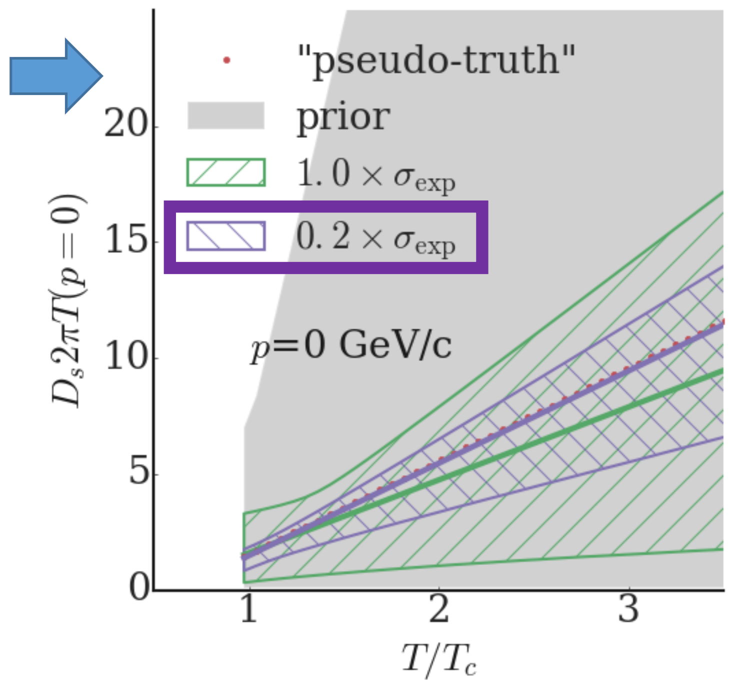
Jet-D^0 Correlation



D^0 and Λ_c v_2

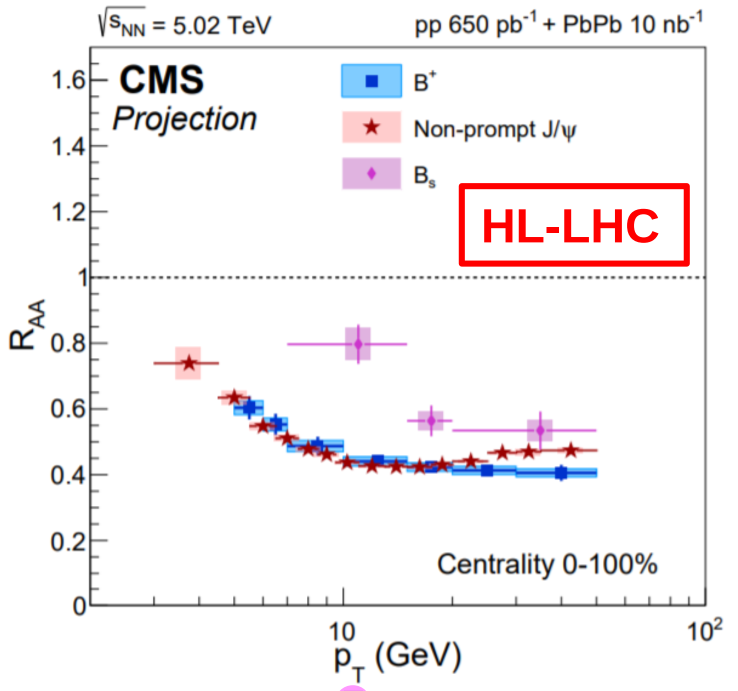


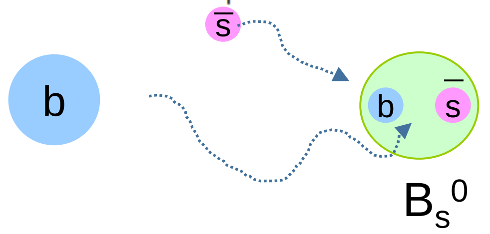
D_s vs. T



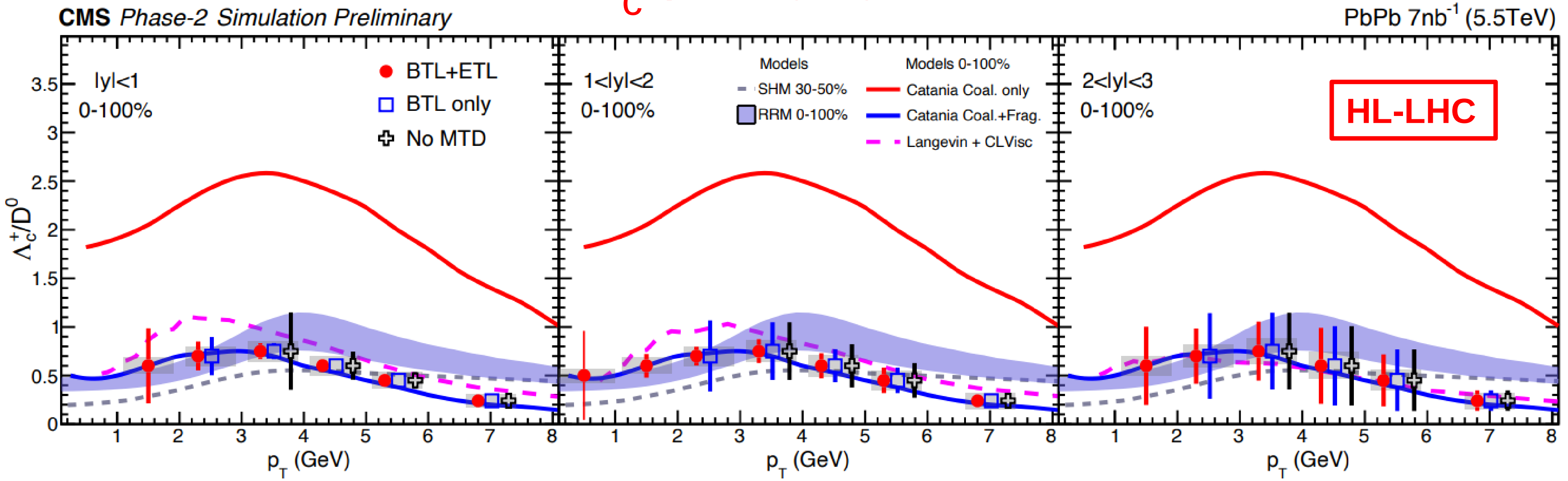
- Large improvement on the Λ_c and D^0 v_2 measurements with CMS MTD
- Direct observation of charm diffusion with D^0-Jet correlation
- Strong constraint on the HQ diffusion coefficient $\mathbf{D_s}$

Heavy Quark Hadronization

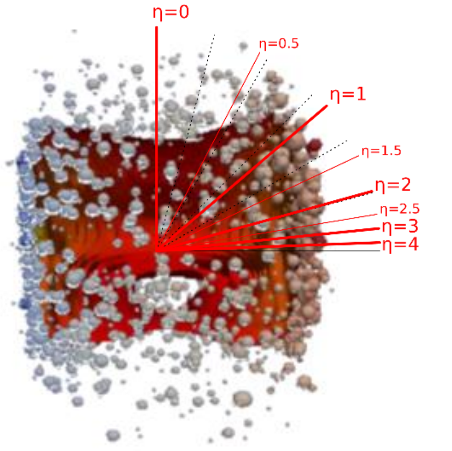




Λ_c^+/D^0 ratio



|y|<1 1<|y|<2 2<|y|<3



- Precise measurement of Λ_c, B_c, B_s, D_s and D^0 for HQ hadronization
- First observation of Λ_b in PbPb

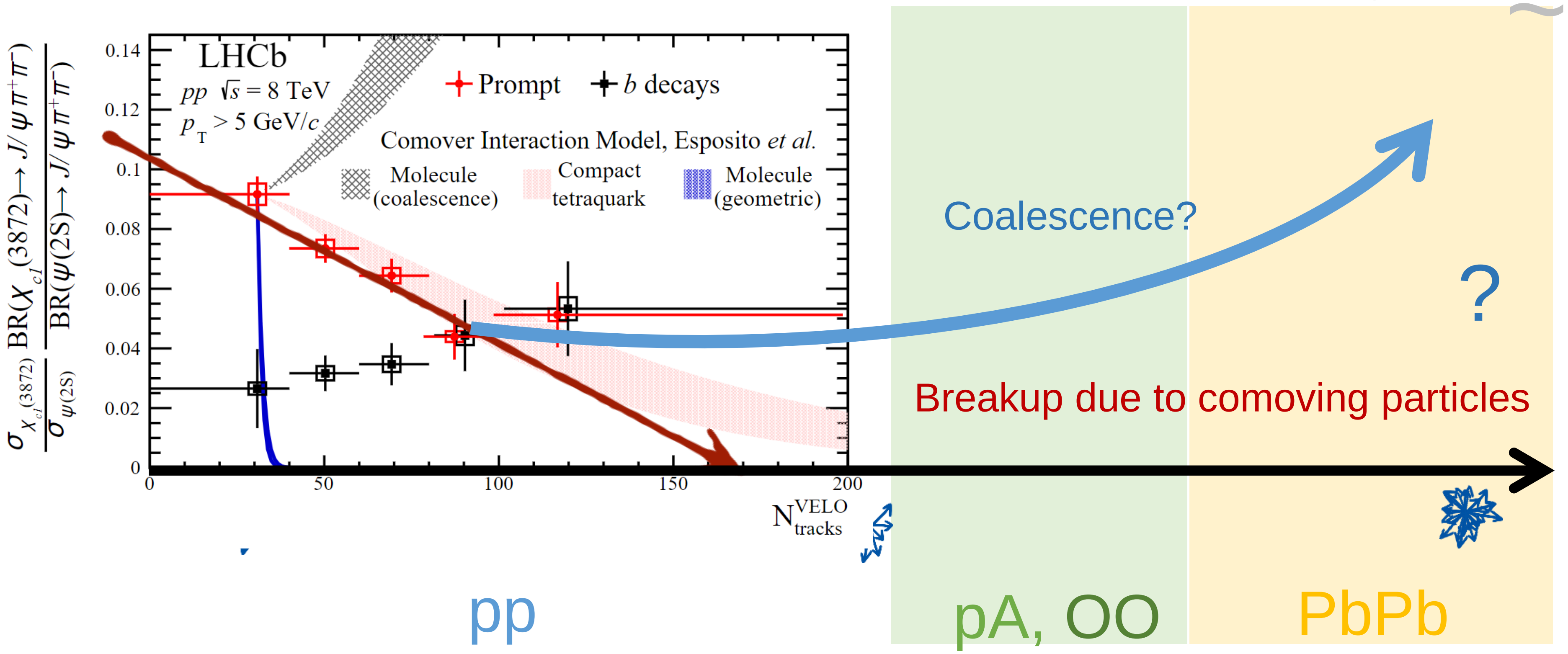
- High precision Λ_c^+/D^0 ratio over a wide rapidity range down to p_T ~0 : toward **total charm cross-section**
- Unique capability of CMS due to the large tracker and MTD acceptance

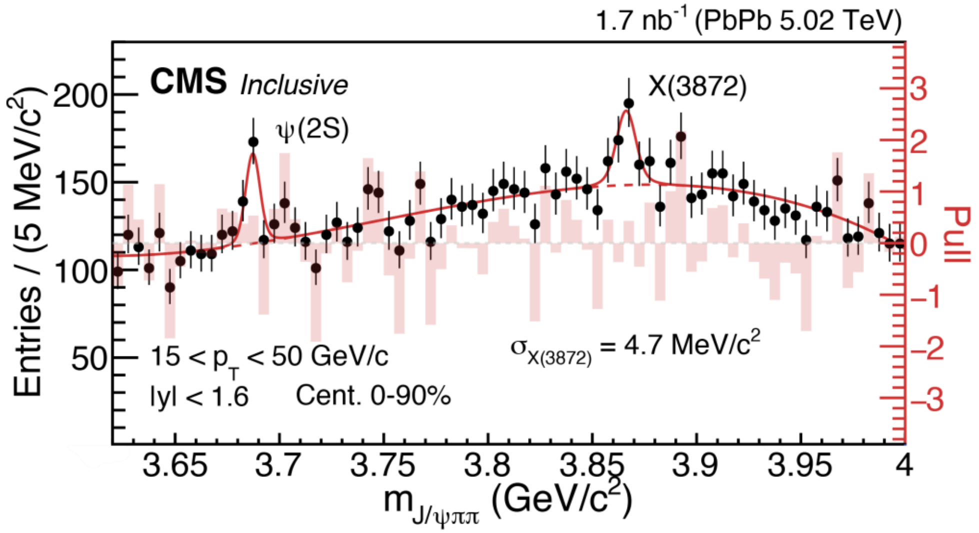
*Except for the Langevin+CLVisc model, all other models shown assume boost invariant in the longitudinal direction, and thus have no rapidity dependence.

New Frontier of Hadronization Study: Exotic Hadron

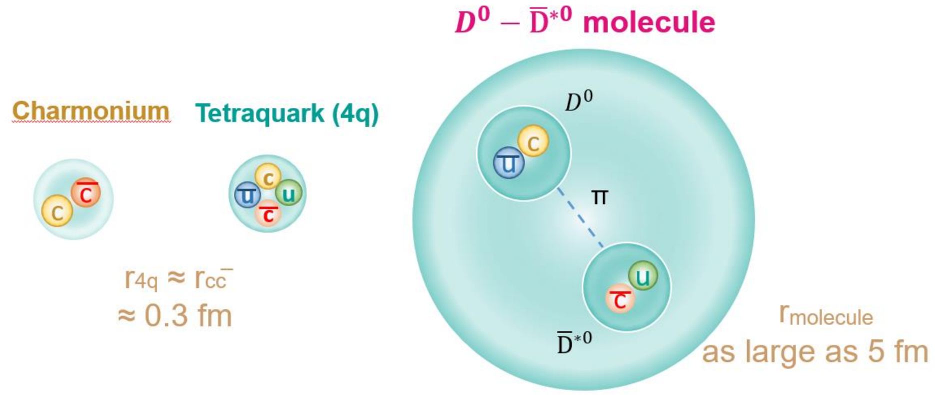
CMS PbPb

$$\rho^{PbPb} = 1.08 \pm 0.49\,(\text{stat}) \pm 0.52\,(\text{syst})$$



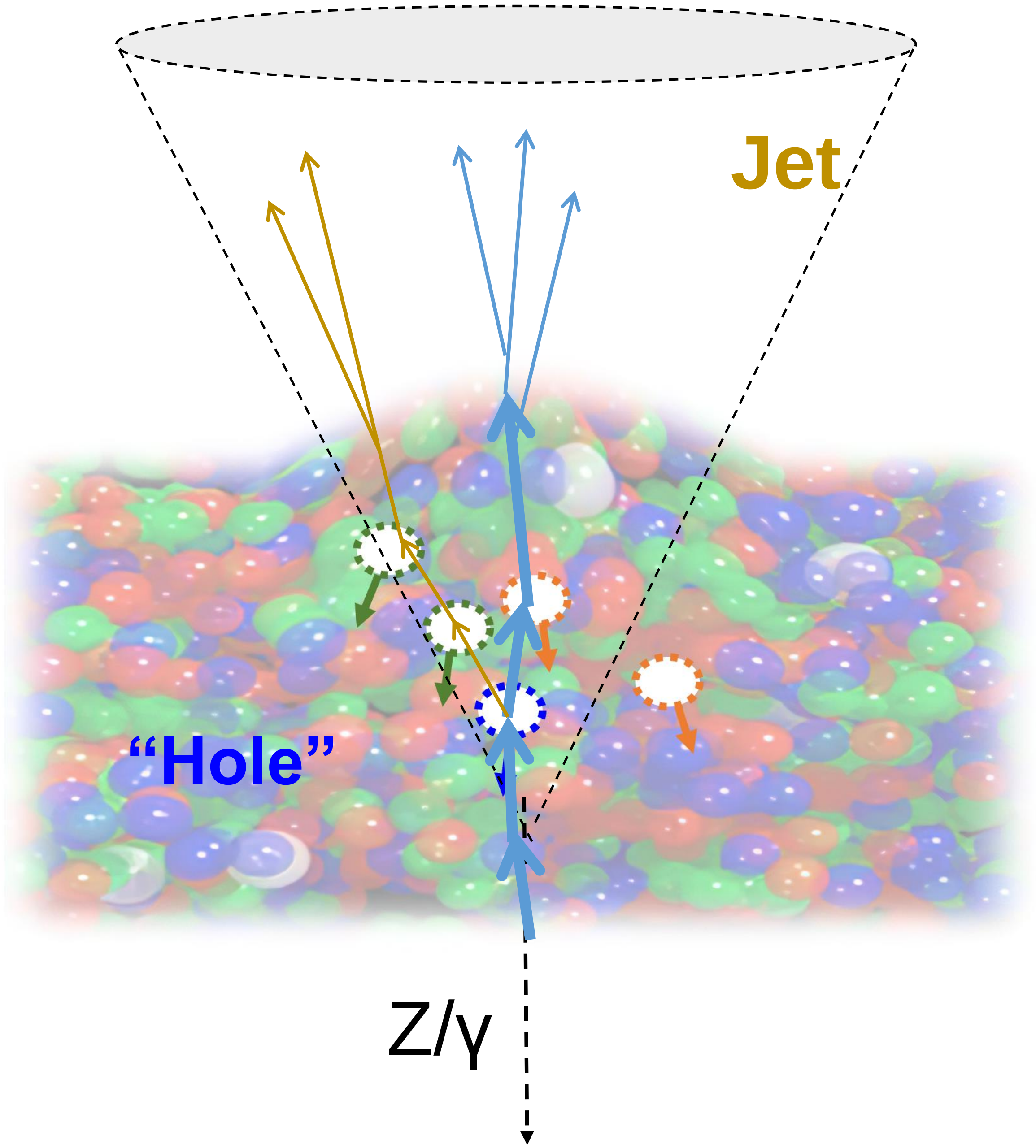


The first evidence of X(3872) in HI



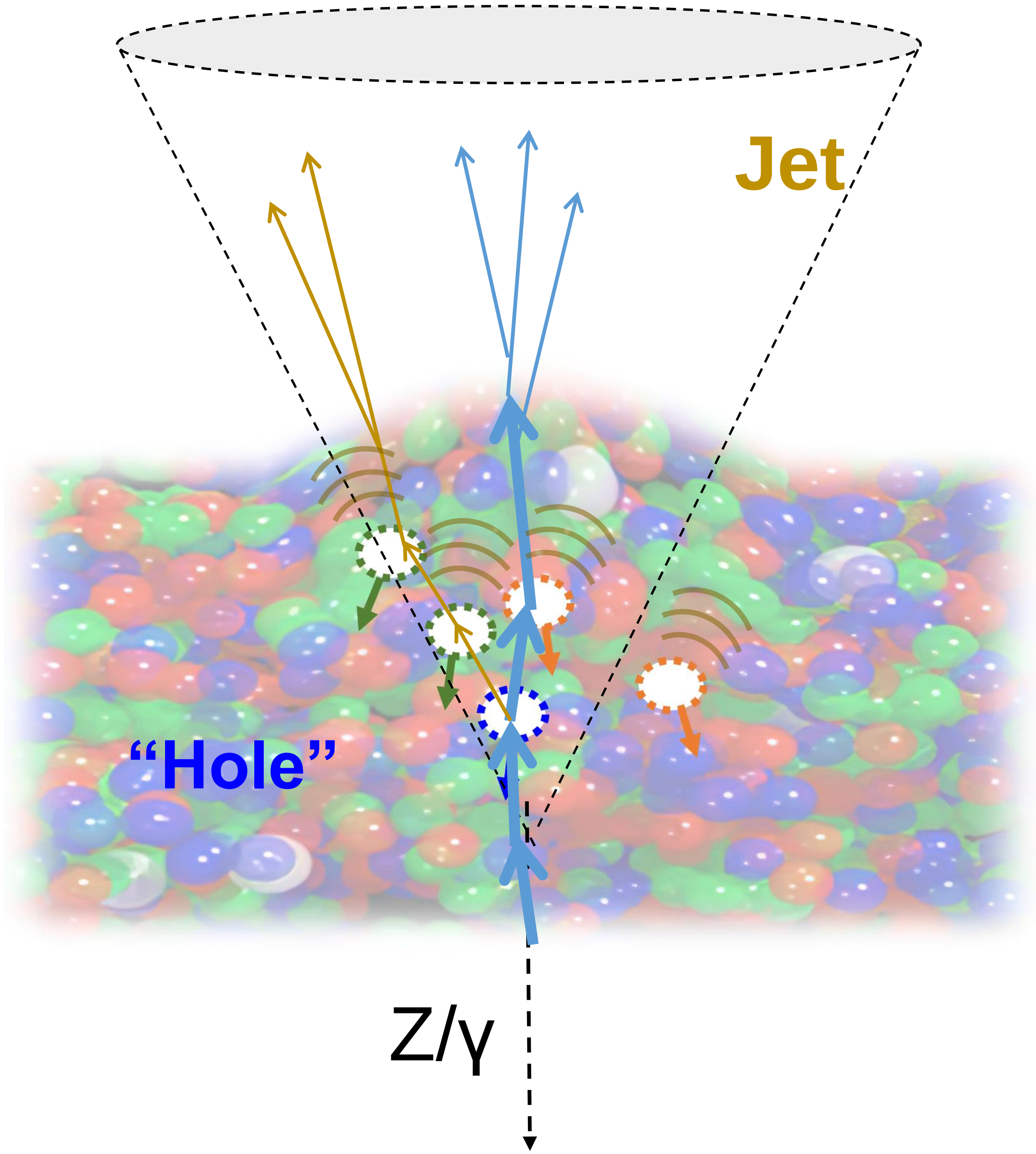
- Observation **of X(3872) in PbPb is expected (>5 σ) in Run3**
- Run3+4: Differential studies
  - Centrality dependence: Probe the structure of X(3872) with QGP
- Search for other exotic hadrons such as T_{cc} and doubly charmed baryons such as Ξ_{cc}

QGP Transport Properties and Structure with Jets



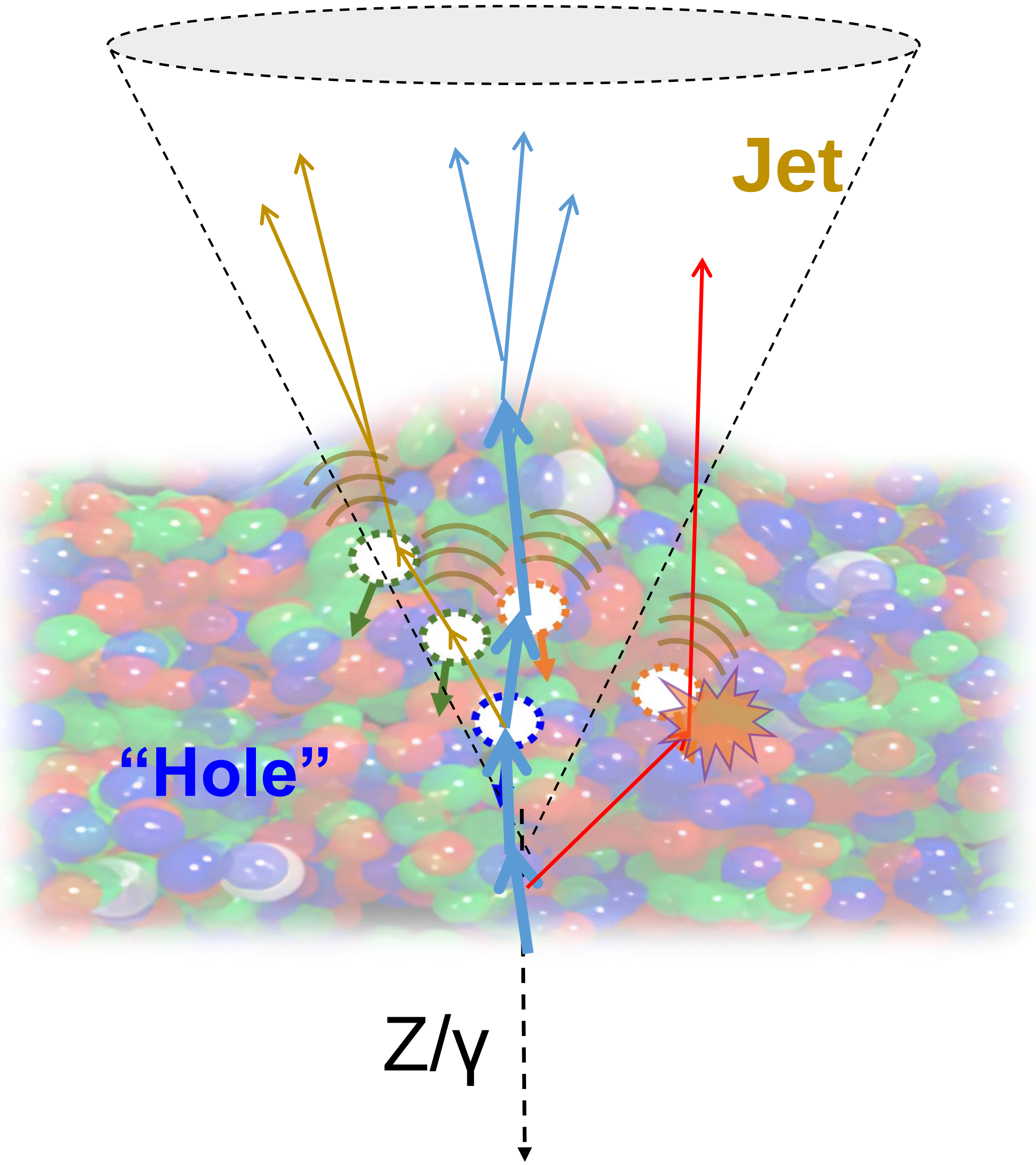
- Jet broadening effects from multiple soft scattering ($\hat{q}$)

QGP Transport Properties and Structure with Jets



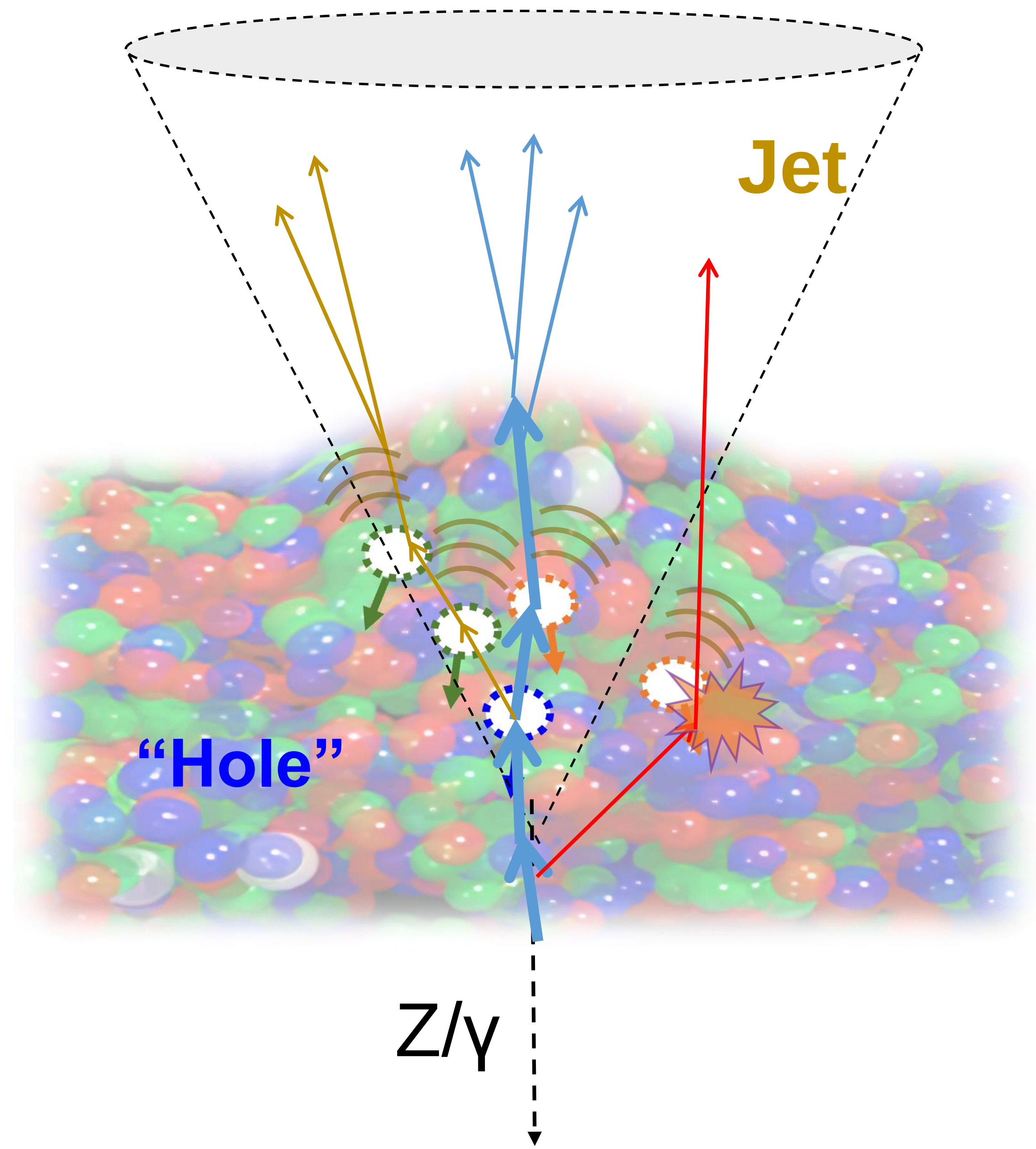
- Jet broadening effects from multiple soft scattering ($\hat{q}$)
- Contribution from medium response
- Reveal medium recoil (the propagation of QGP holes)

QGP Transport Properties and Structure with Jets

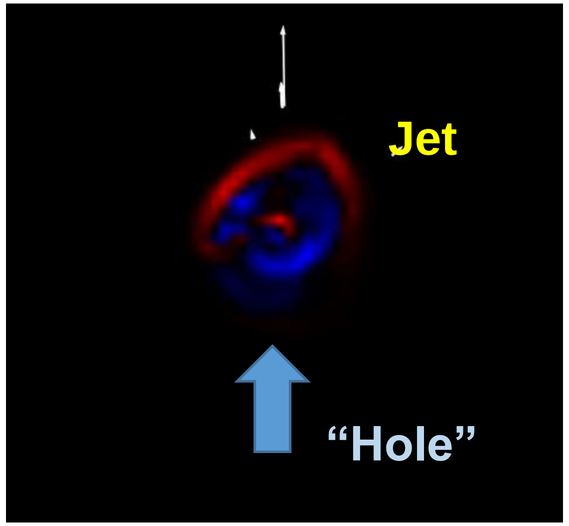


- Jet broadening effects from multiple soft scattering ($\hat{q}$)
- Contribution from medium response
- Reveal medium recoil (the propagation of QGP holes)
- With the precise understanding of the phenomena above, one could reveal the QGP structure with Moliere scattering

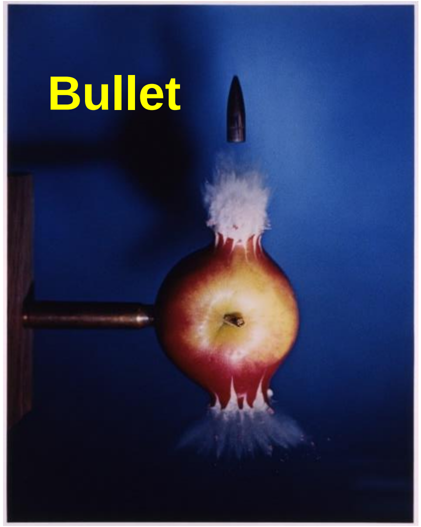
QGP Transport Properties and Structure with Jets



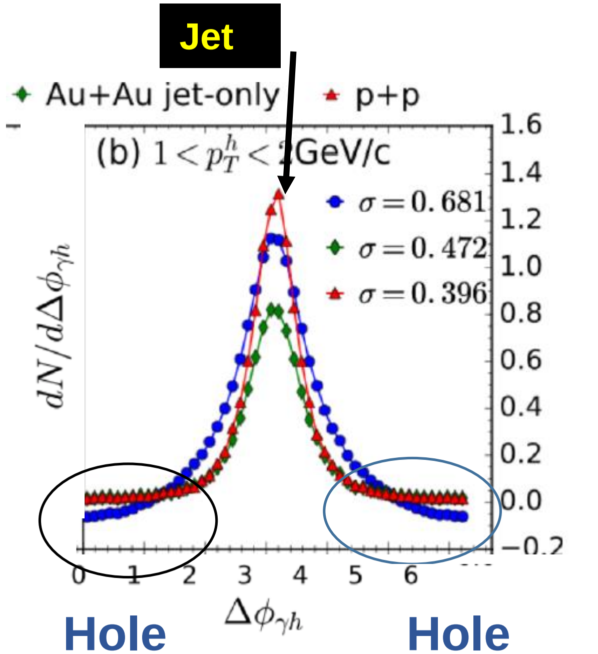
Tan Luo, Xin-Nian Wang (CoLBT)



wake



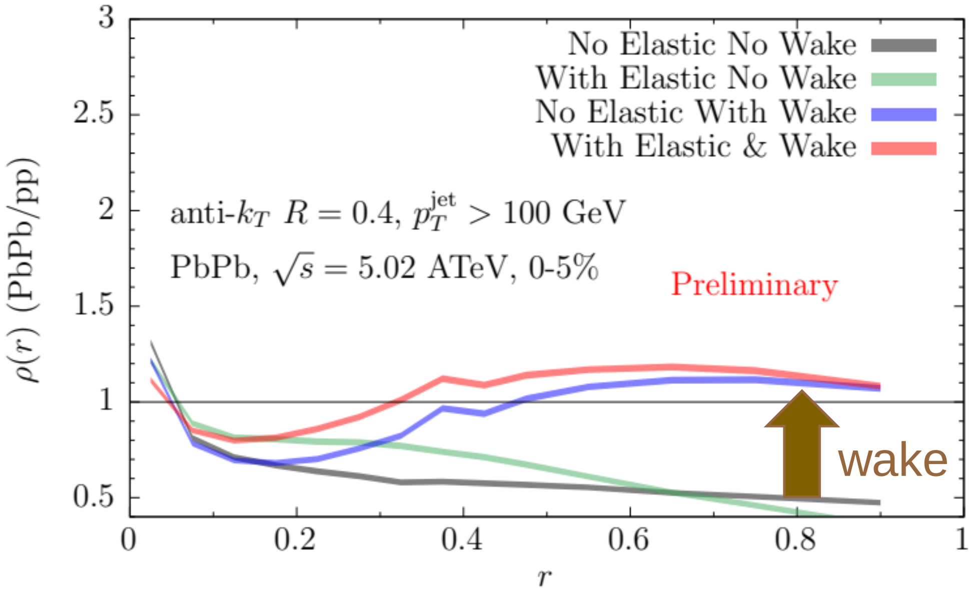
Hole



medium response / wake

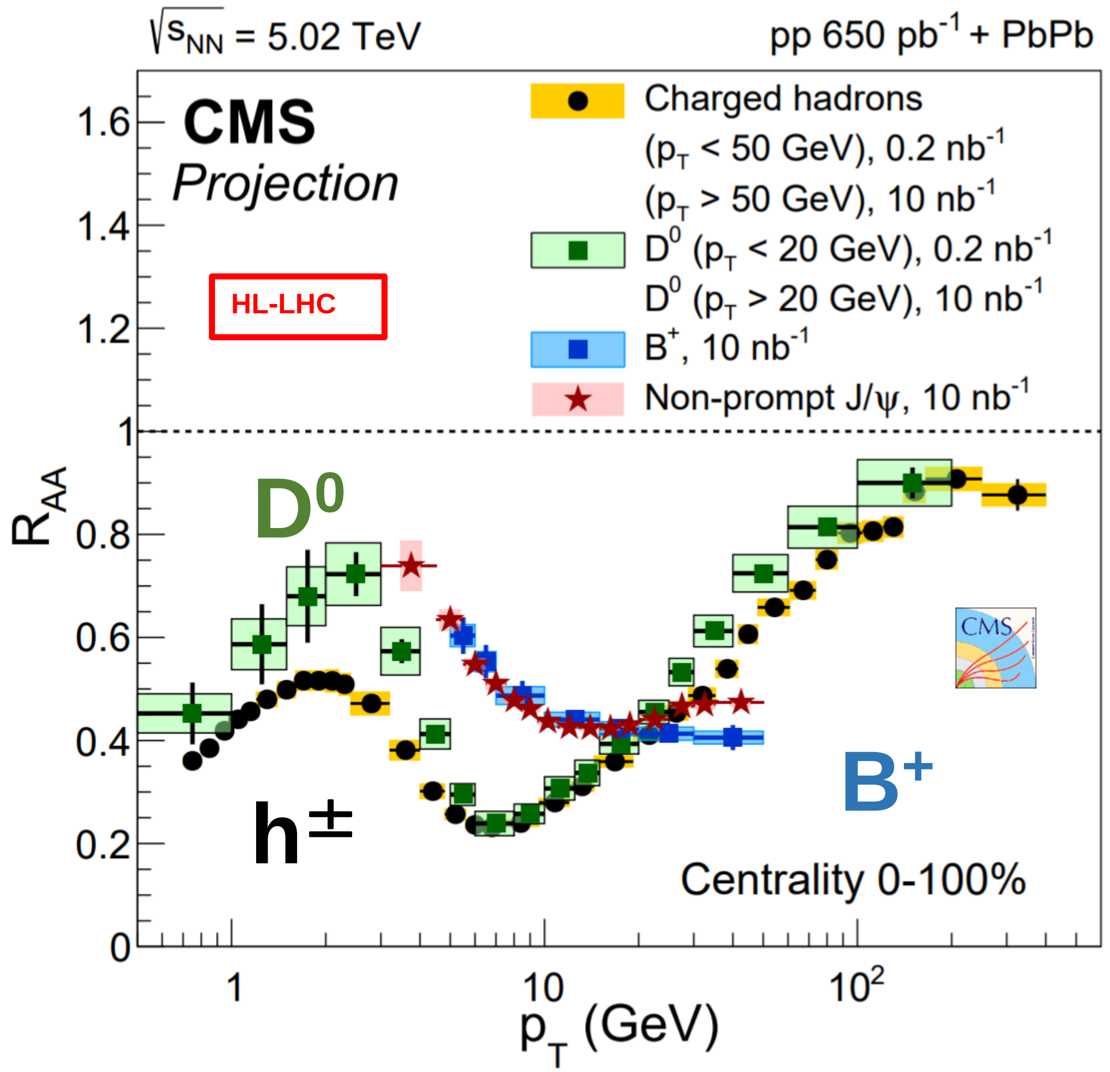
Low p_T particles at large angle

arXiv:2208.13593
Hulcher, Pablos, Rajagopal

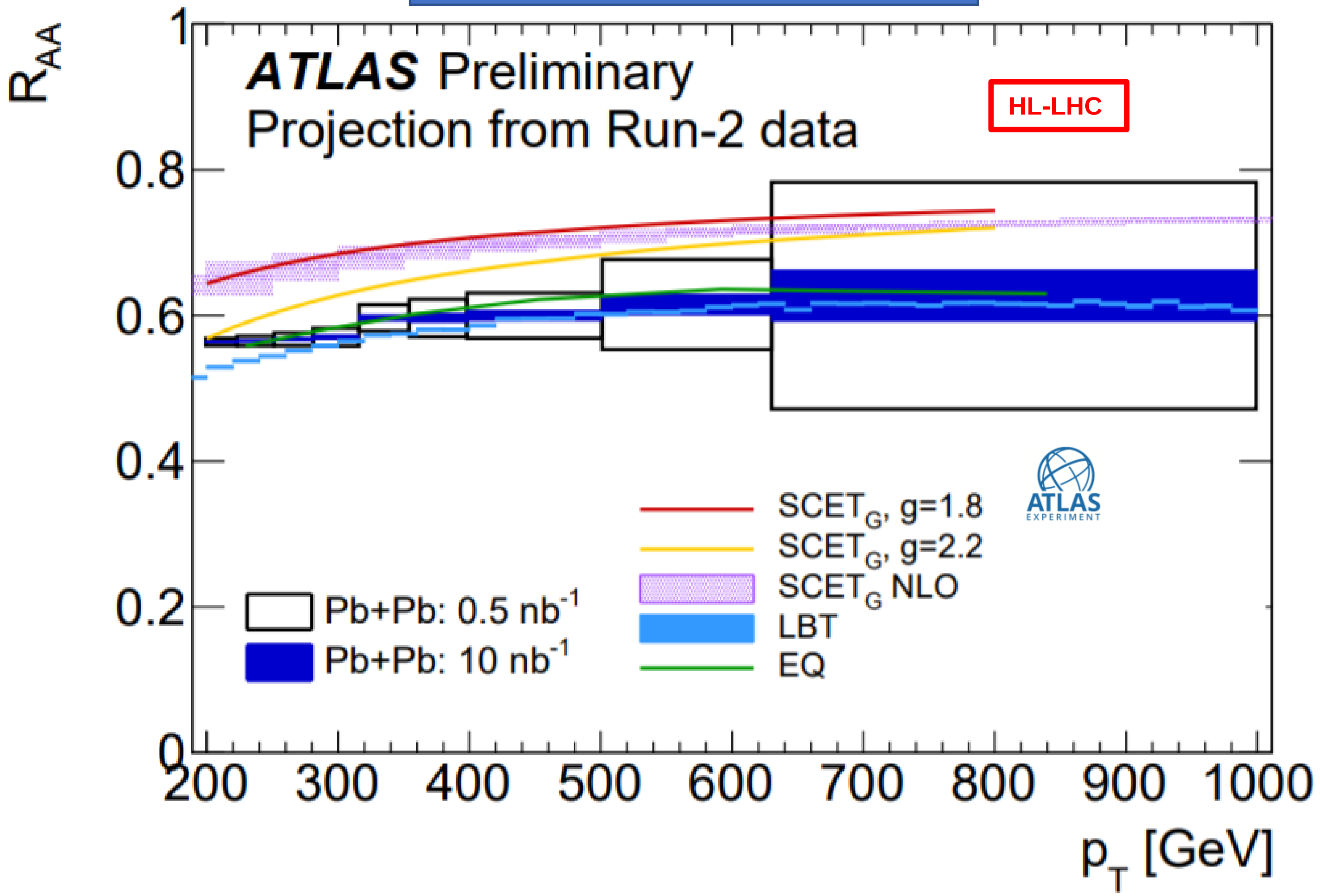


Jet Quenching up to 1 TeV in PbPb

(Heavy Flavor)Hadron R_{AA}



Jet R_{AA}

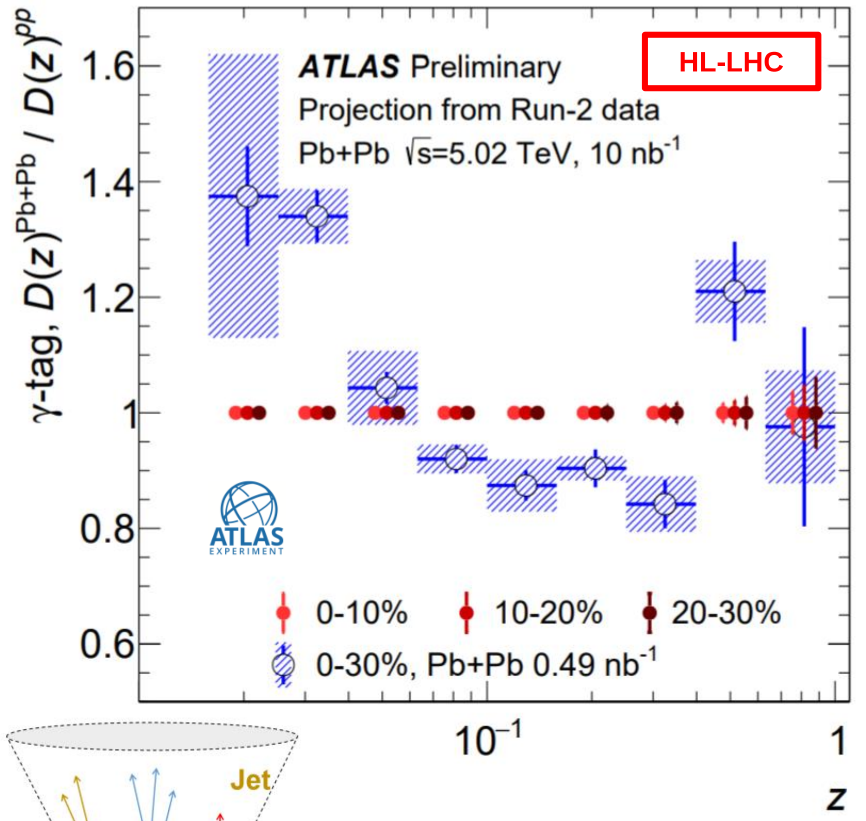


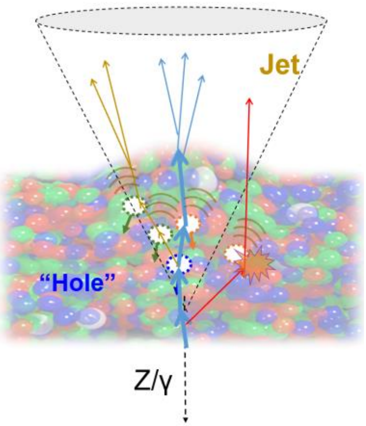
- Precise measurement of light and heavy flavor hadron R_{AA} up to **0.4** to **1 TeV**

- High p_T reach of charged hadrons and jet R_{AA} up to **~ 1 TeV**
- The excitement is that the quenched energy / medium response will be significant compared to UE energy density!

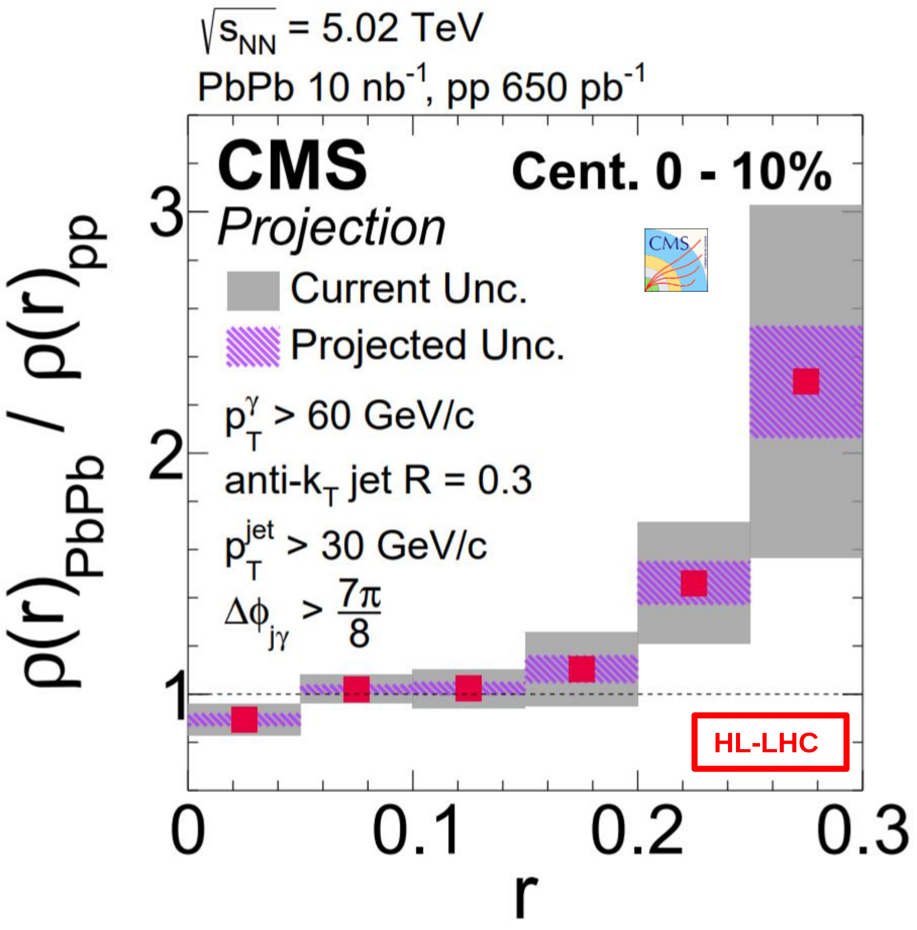
Photon-Tagged Jet Structure in PbPb

Modification of Jet Fragmentation Function

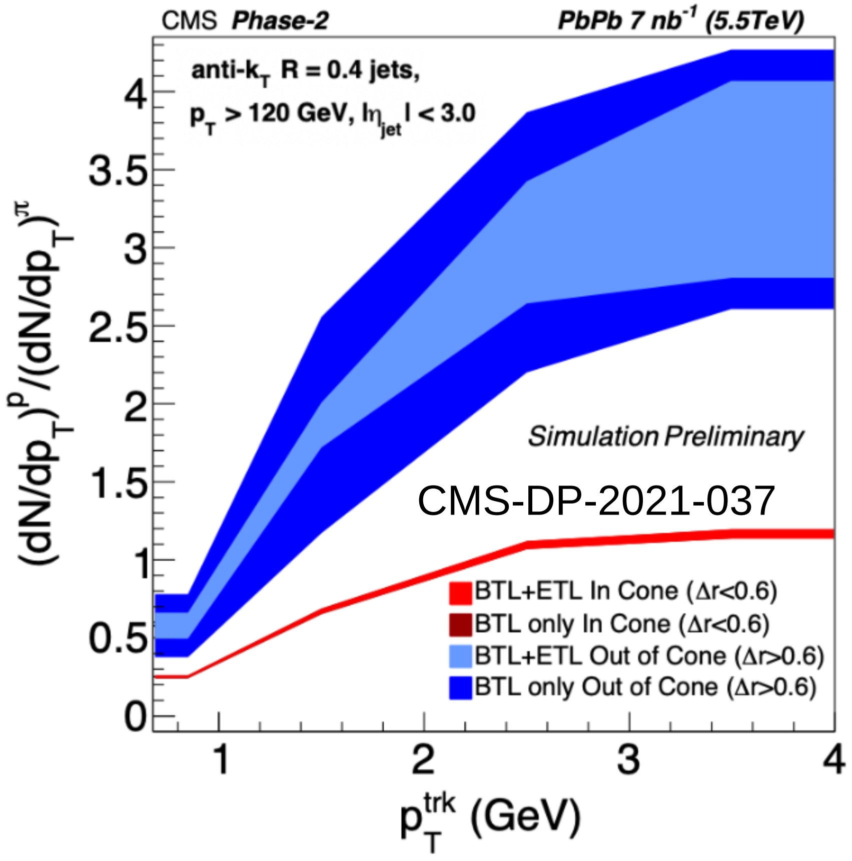




Modification of Jet Shape



p/π ratios **in** **and** **out** **of jet cone**

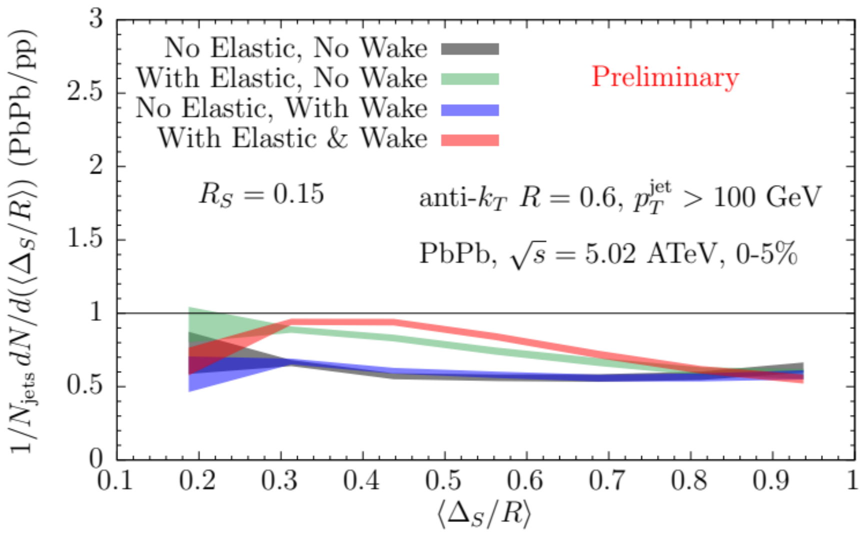


- Reveal jet broadening effect from multiple soft scattering and medium response
  - Photon-tag reduced “survival bias” which narrows the inclusive jet shape
- Particle composition in the QGP wake

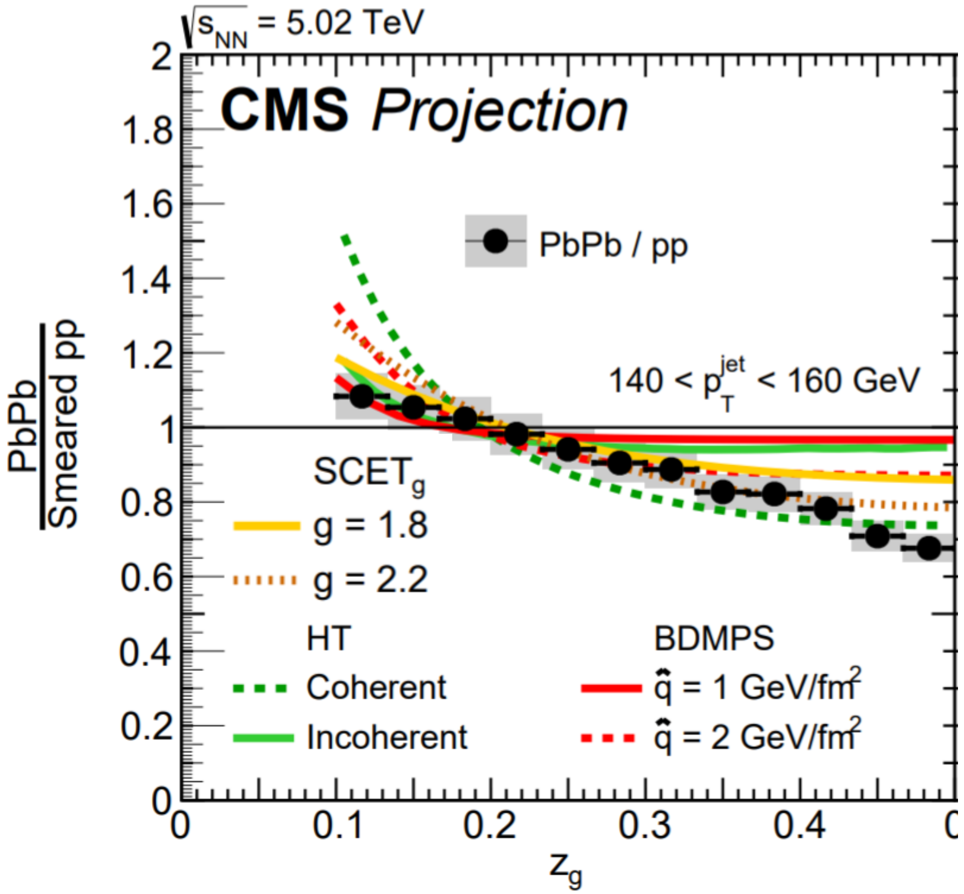
Jet Substructure and D^0-Jet Correlations

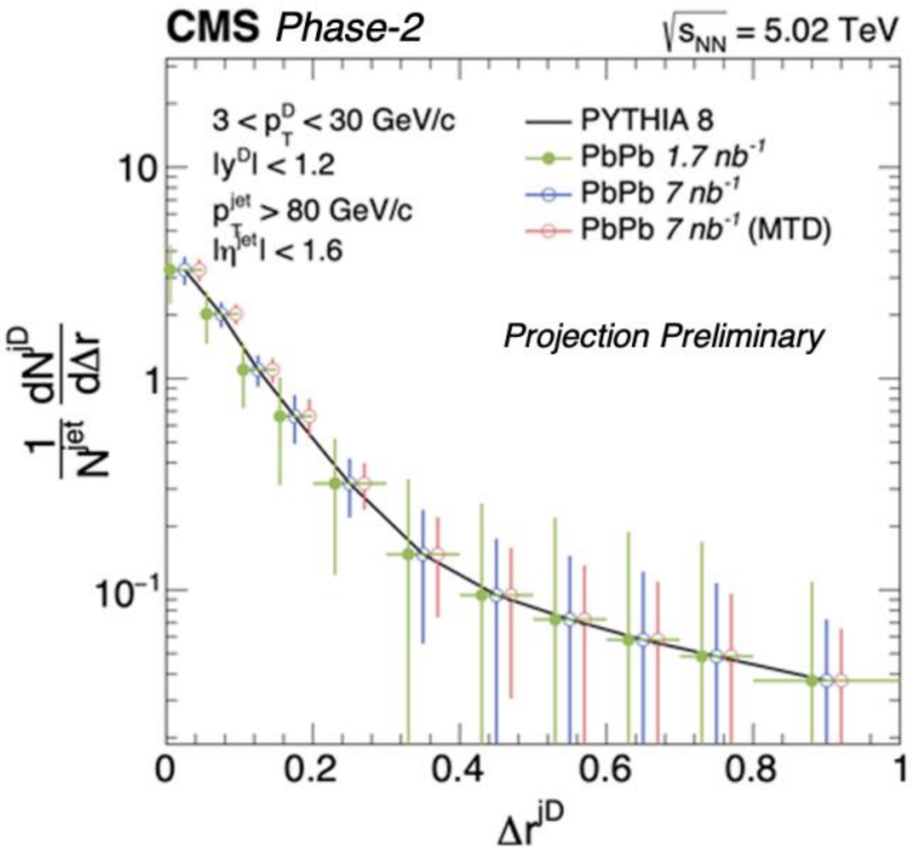
Moliere scattering

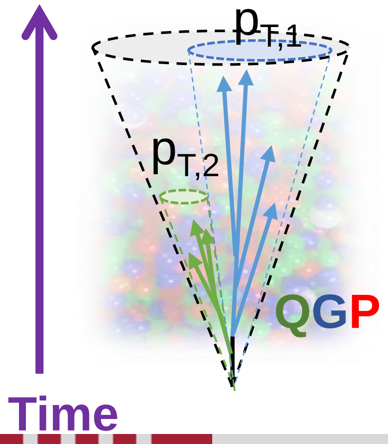
"Sprout" more subjets



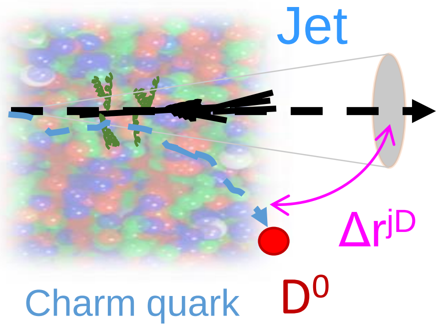
arXiv:2208.13593
Hulcher, Pablos, Rajagopal





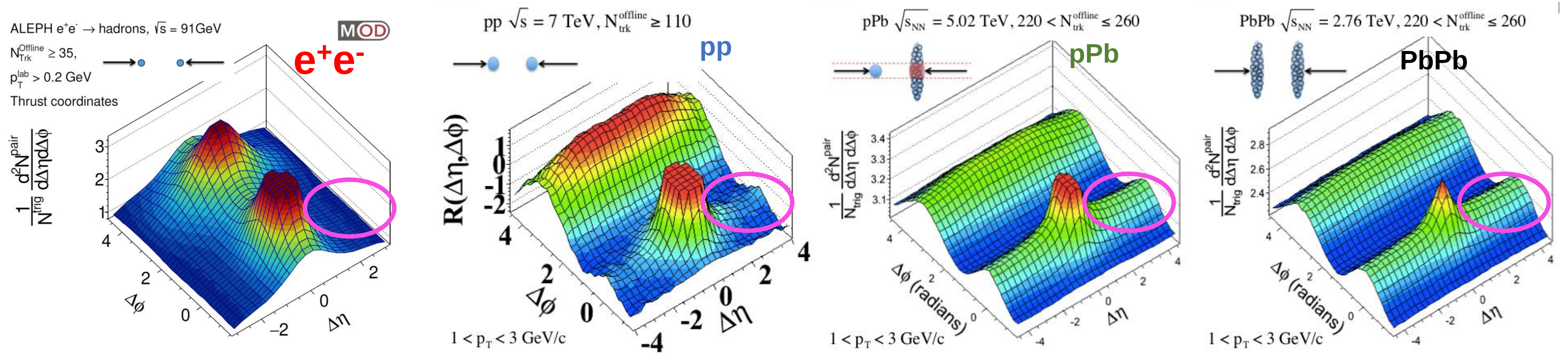


With Run 3+4 data, jet substructure observables such as Z_g and subjet multiplicity could be measured with high precision



D^0-Jet angular correlation
- D^0 as a proxy of heavy quark
- Search for **large angle scattering**

Small System



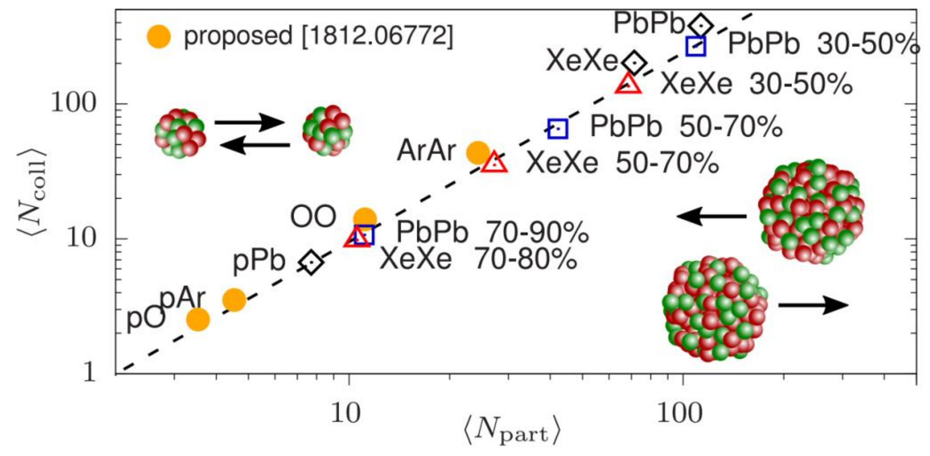
PRL 123 (2019) 21, 212002

JHEP 09 (2010) 091

PLB 718 (2013) 795

- Flow-like phenomena in high multiplicity pp and pPb collisions, not yet observed in e^+e^- and ep
- Strangeness enhancement from ALICE
- OO: provide unique opportunity to smoothly connect pPb and PbPb

A. Huss et al, PRL 126 (2021) 19,192301

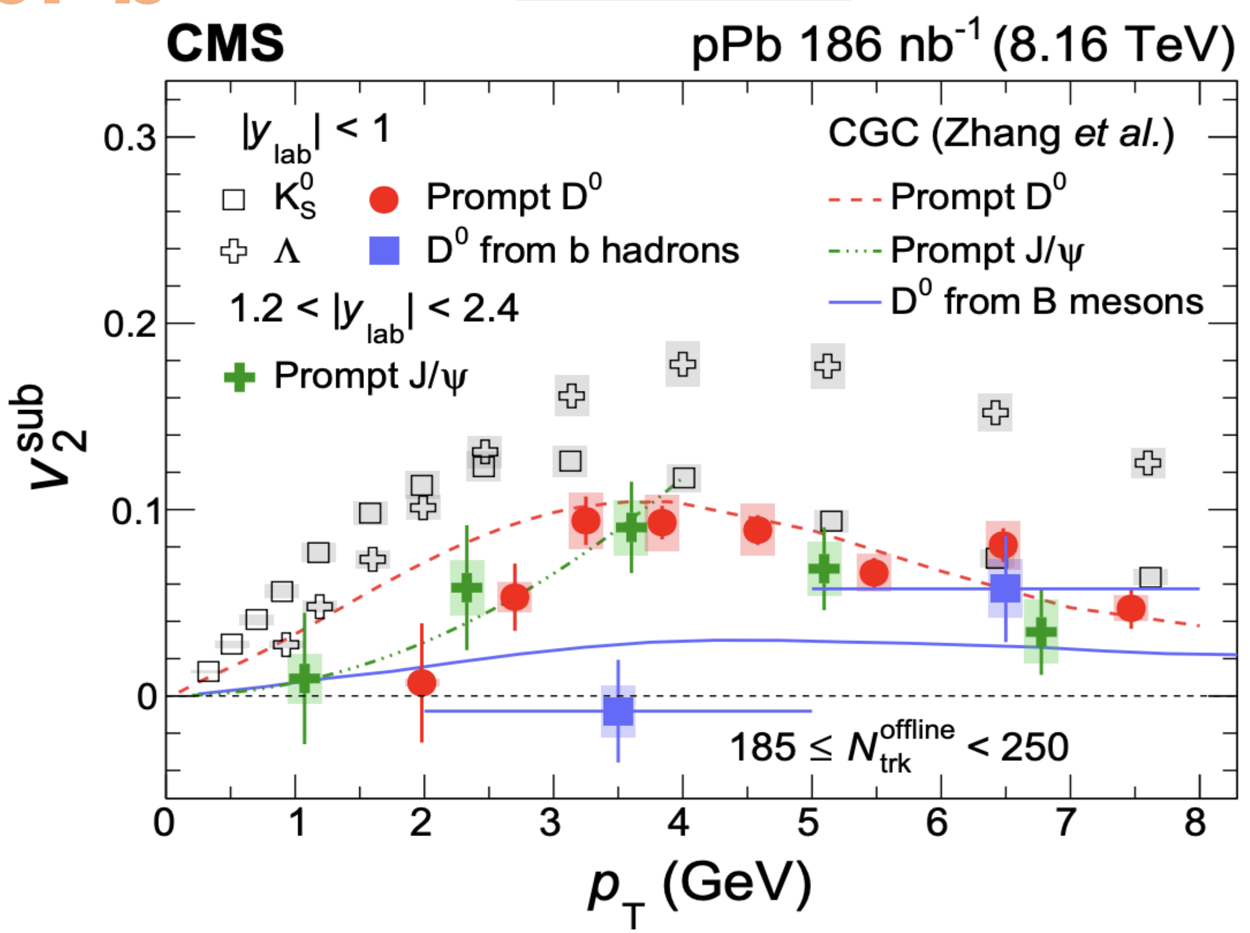


e+e-:
ALEPH LEP1: YJL+ PRL 123 (2019) 21, 212002
Belle: Y.-C. Chen+ PRL 128 (2022) 14, 142005
ep:
ZEUS I. Abt+ JHEP 04 (2020) 070

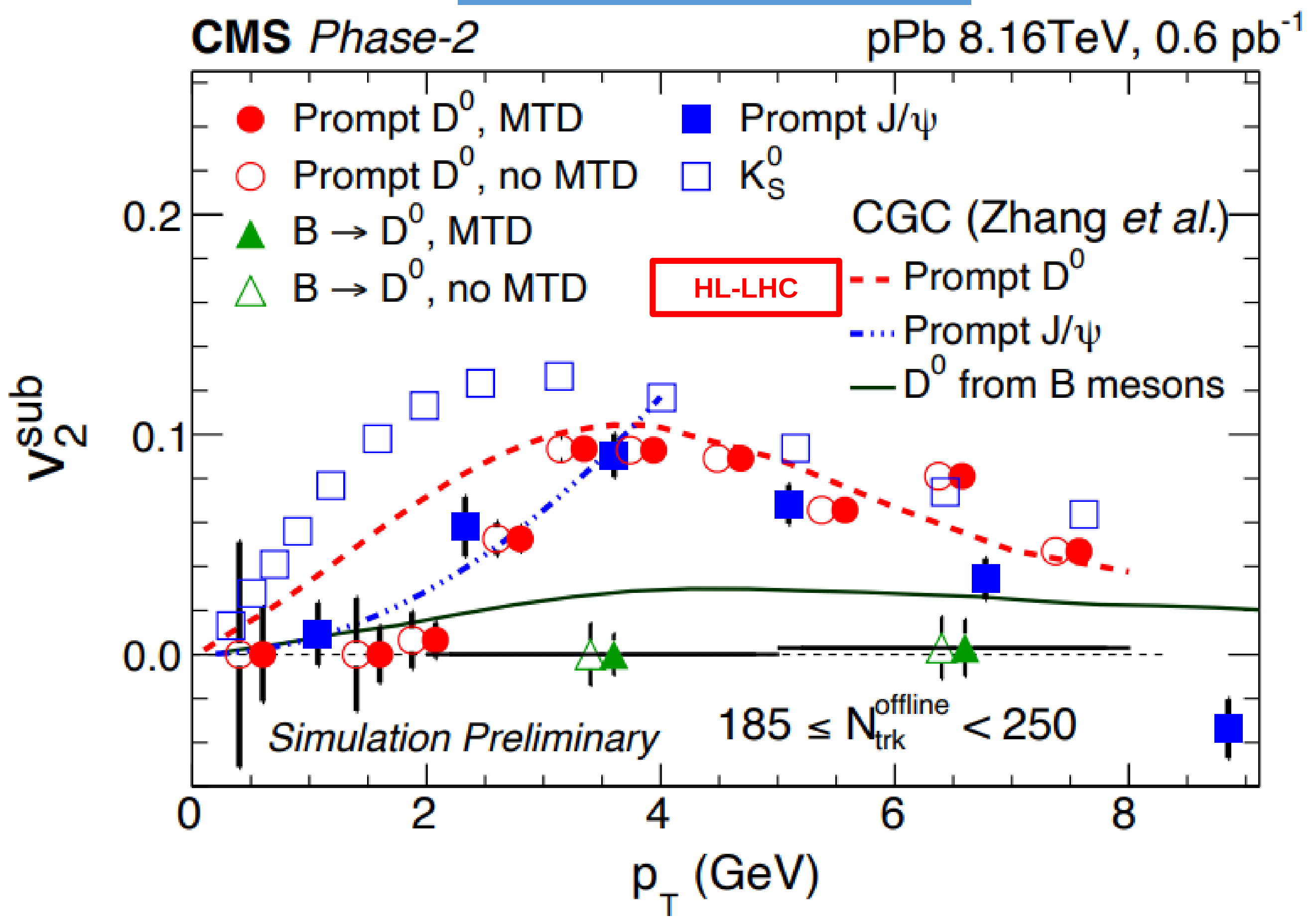
Collectivity in Small System

pPb

CMS Run 2

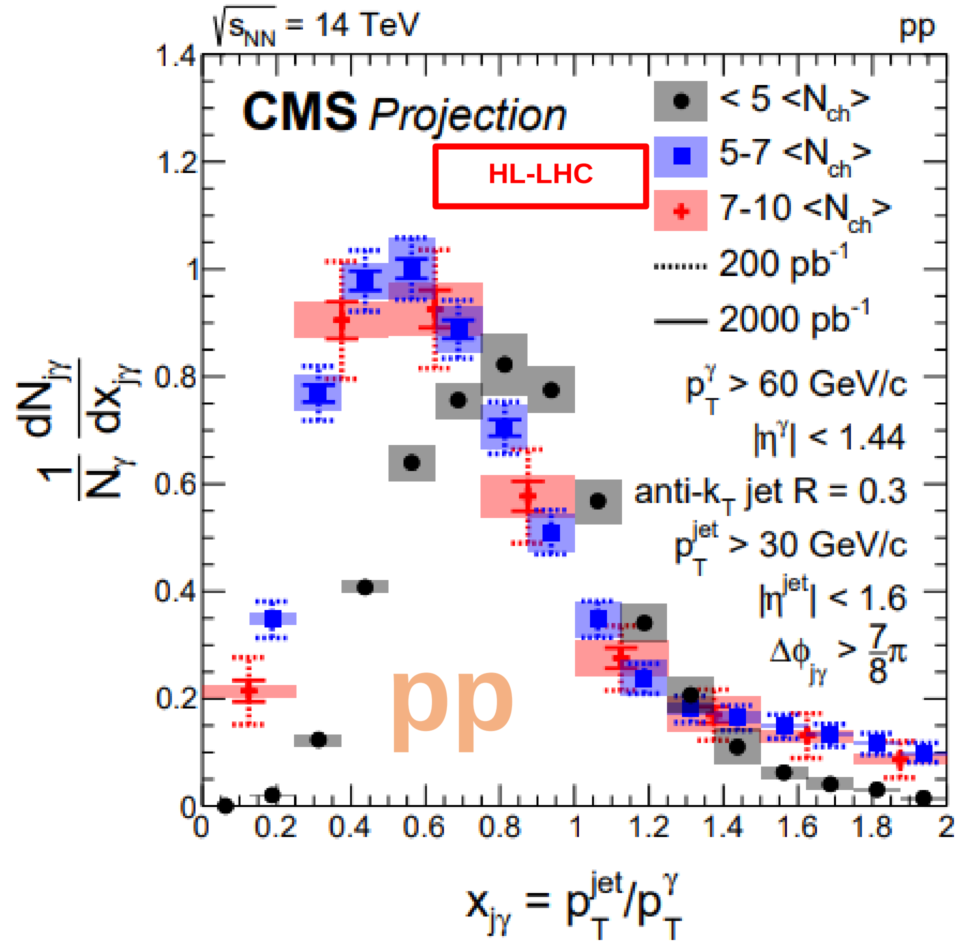


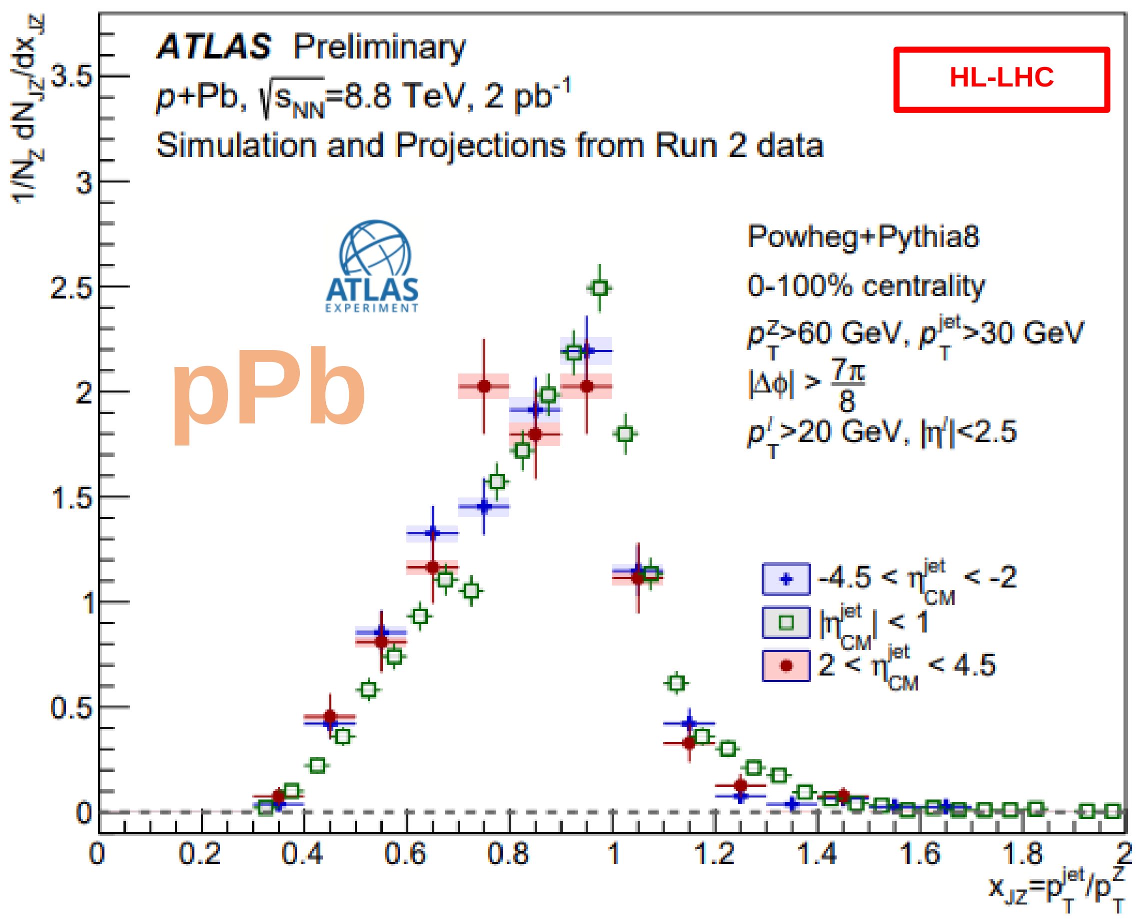
CMS 1-year with MTD



- With MTD: Unprecedented precision could be achieved with fast CMS tracking and DAQ system
- Detailed characterization of the heavy flavor hadron collective behavior in high multiplicity proton-proton and proton-lead collisions

Search for Jet Quenching in Small Systems

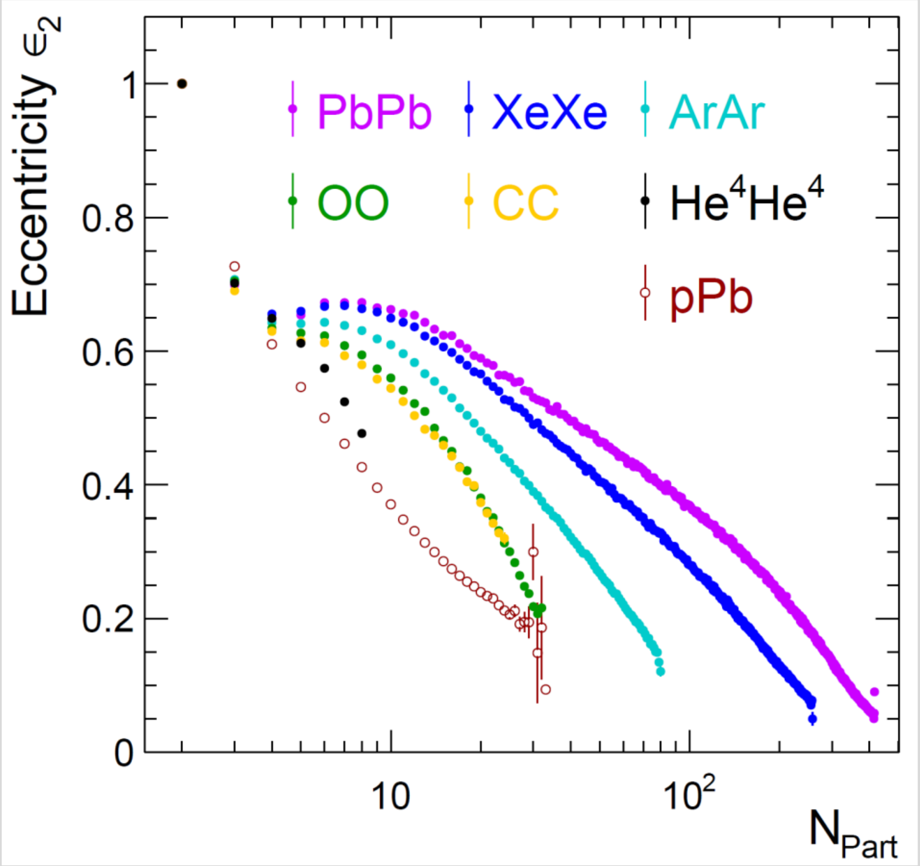




- High statistics pp and pPb data could provide a large sample of electroweak boson-tagged jets for the study of jet quenching in small systems.
- OO collisions: opportunity to search for jet quenching in small AA system

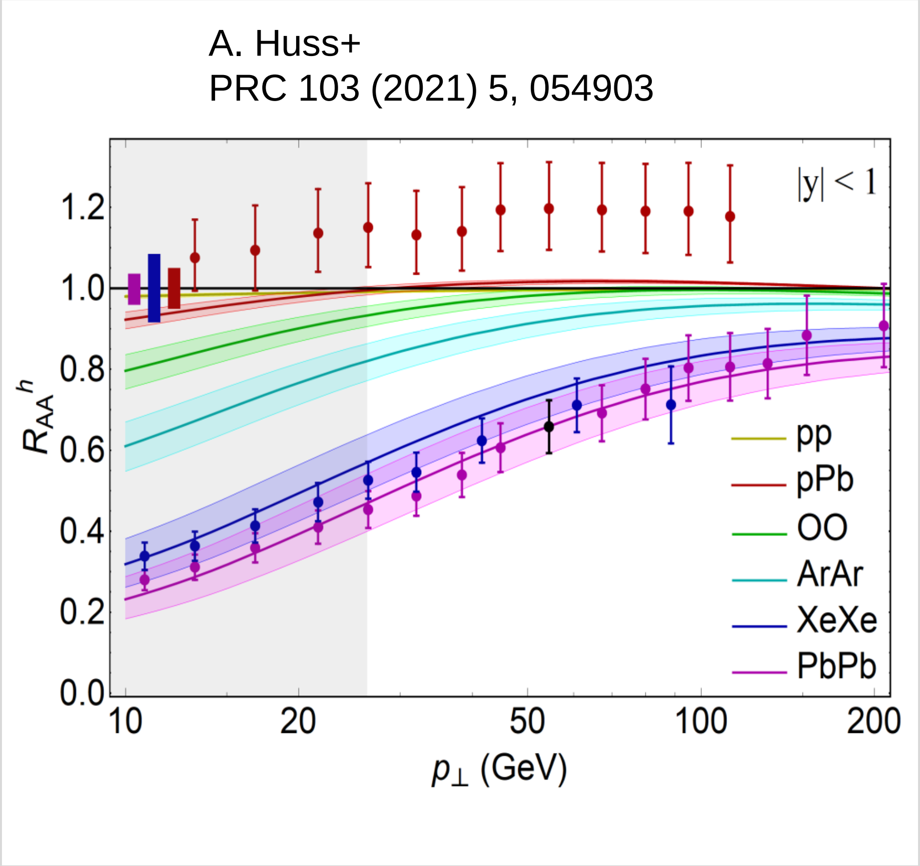
OO Collisions and System Size Scan

Flow



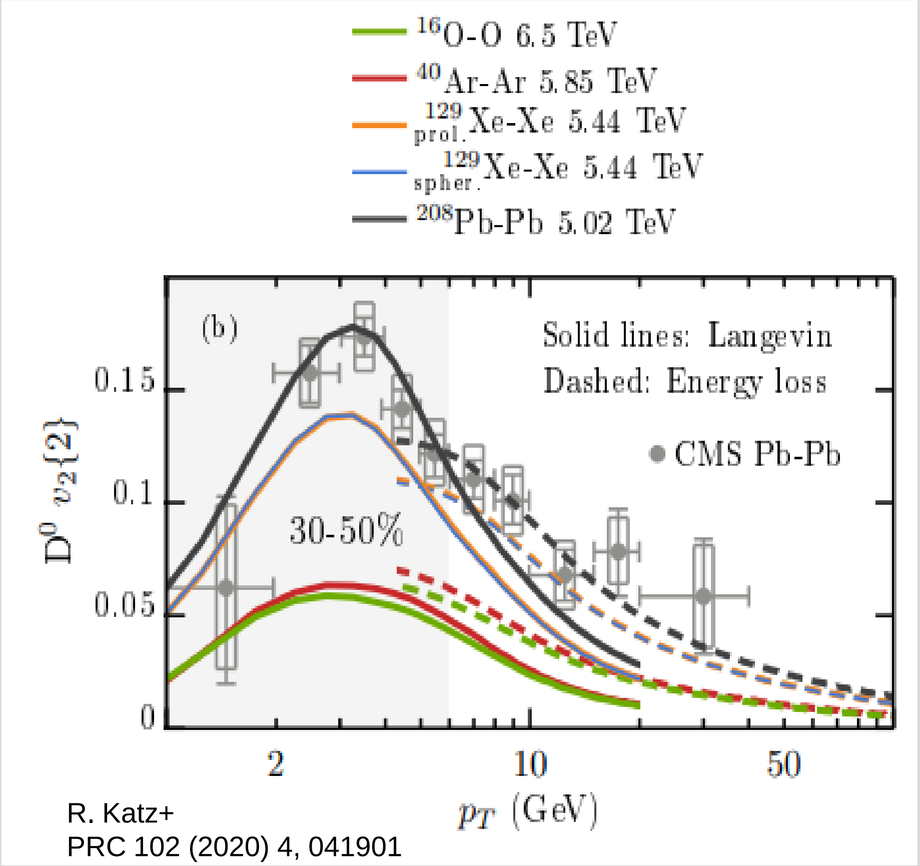
New opportunity to sample QGP droplets on the eccentricity ε_2 and N_{part} phase space

Jet Quenching



- Significant jet quenching effect predicted in **OO** and **ArAr**

Charm Diffusion

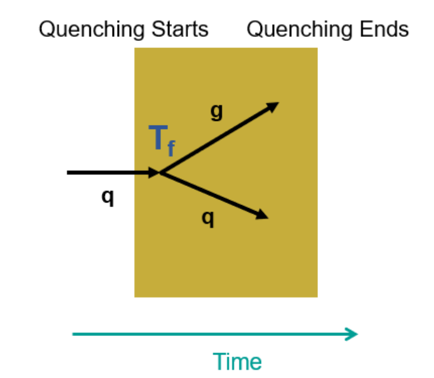


- Different D^0 v_2 in various systems in 30-50% centrality

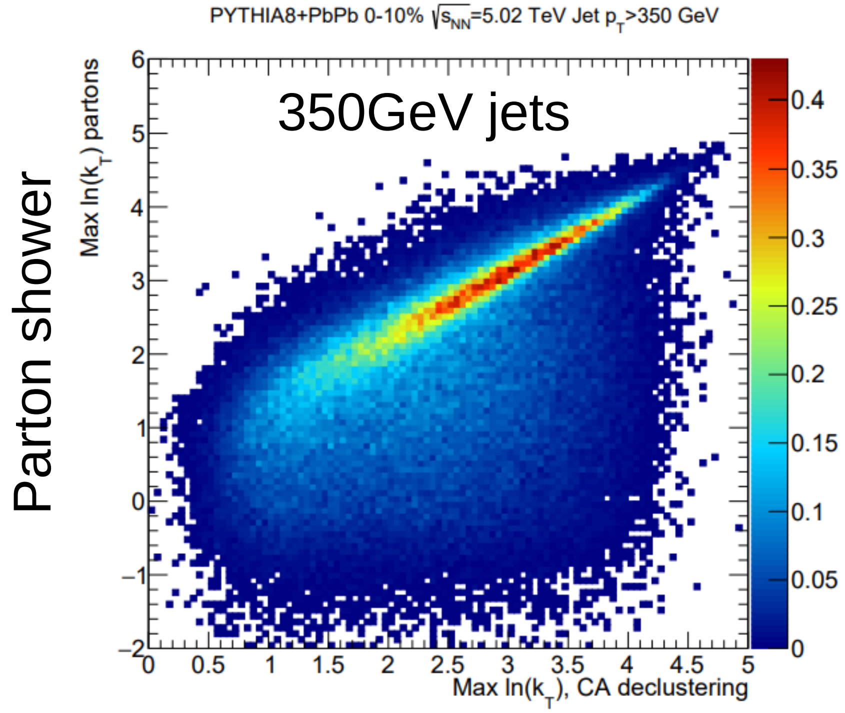
See also: Isobar white paper arXiv 2209.11042
Jiangyong Jia's talk

Probing the QGP Evolution

Formation Time (T_f) Tagging

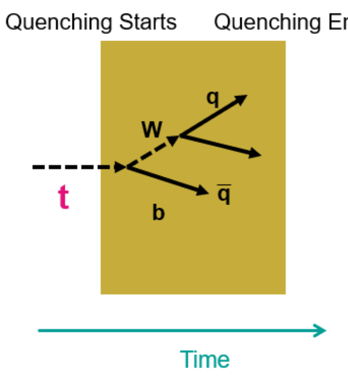


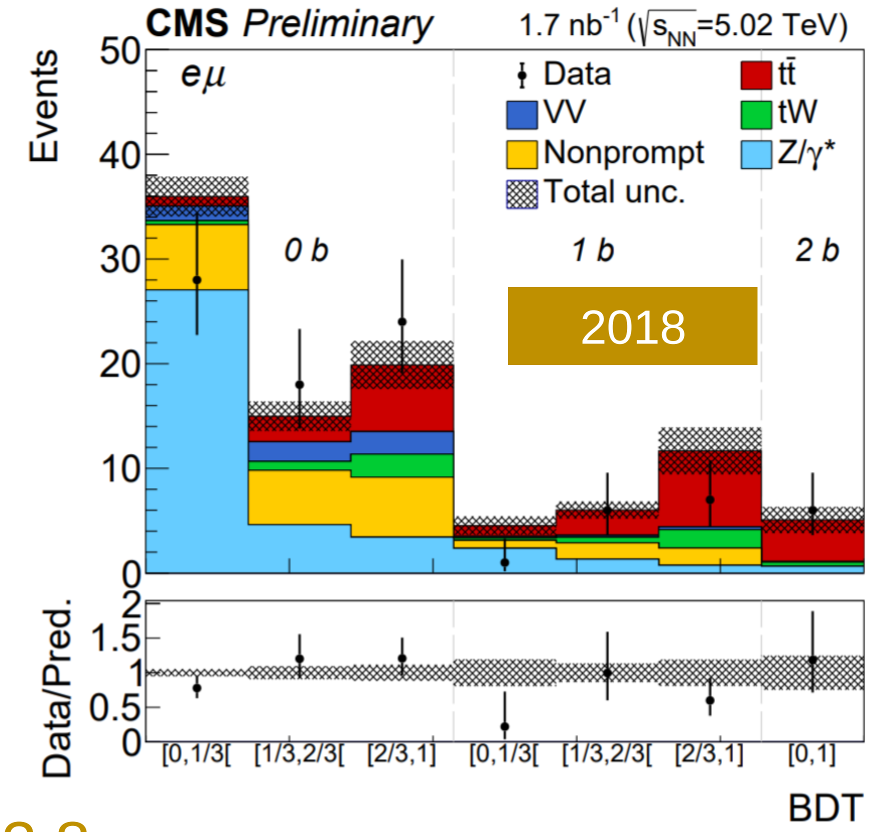
Yi Chen, YJL,
EMMI Jet RRTF



Hadron level (C-A declustering)

Boosted Top





Modification of jet structure and correlations through interactions with QGP constituents

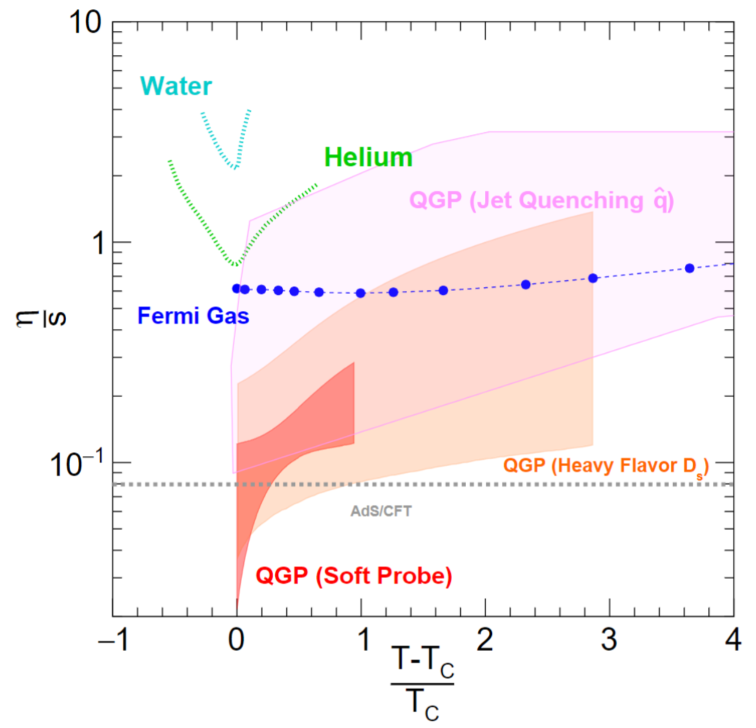
2018 data: 3.8σ

Observation of Top production in Run 3

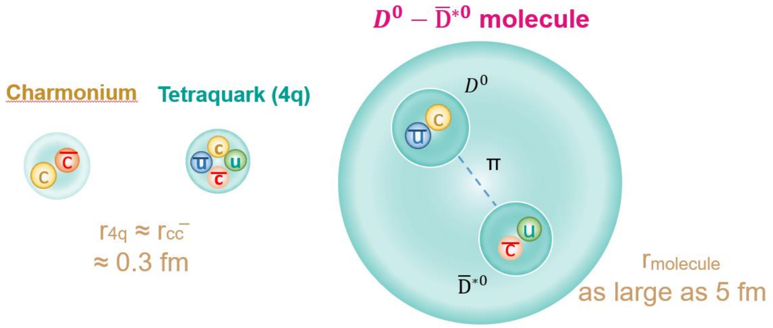
- First proof-of-principle measurement with Run 3 and 4 data.
- To fully exploit the top and high p_T jet probes, much higher statistics needed

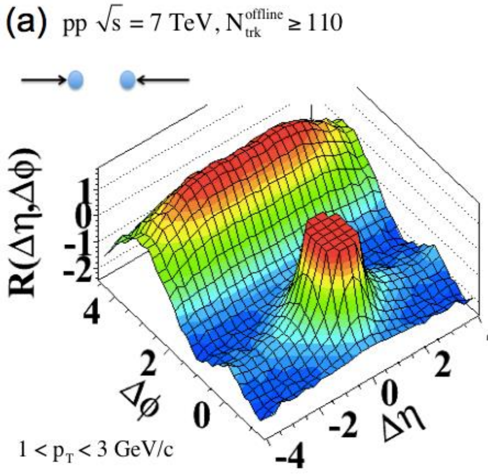
Summary

- ATLAS/CMS Run 3+4 data will provide
  - **New constraints on the nPDF** from high precision electroweak bosons, UPC Quarkonia in PbPb, forward HF hadrons and dijets in pPb
  - Improve the understanding of **initial energy density profile** and the **underlying dynamics of hydrodynamization**
  - **Precise determination of medium properties** such as temperature, viscosity and transport coefficients through multiple probes
  - Reveal **microscopic structure of QGP**
  - Probe the **nature of X(3872)** with QGP and high multiplicity pp and pPb



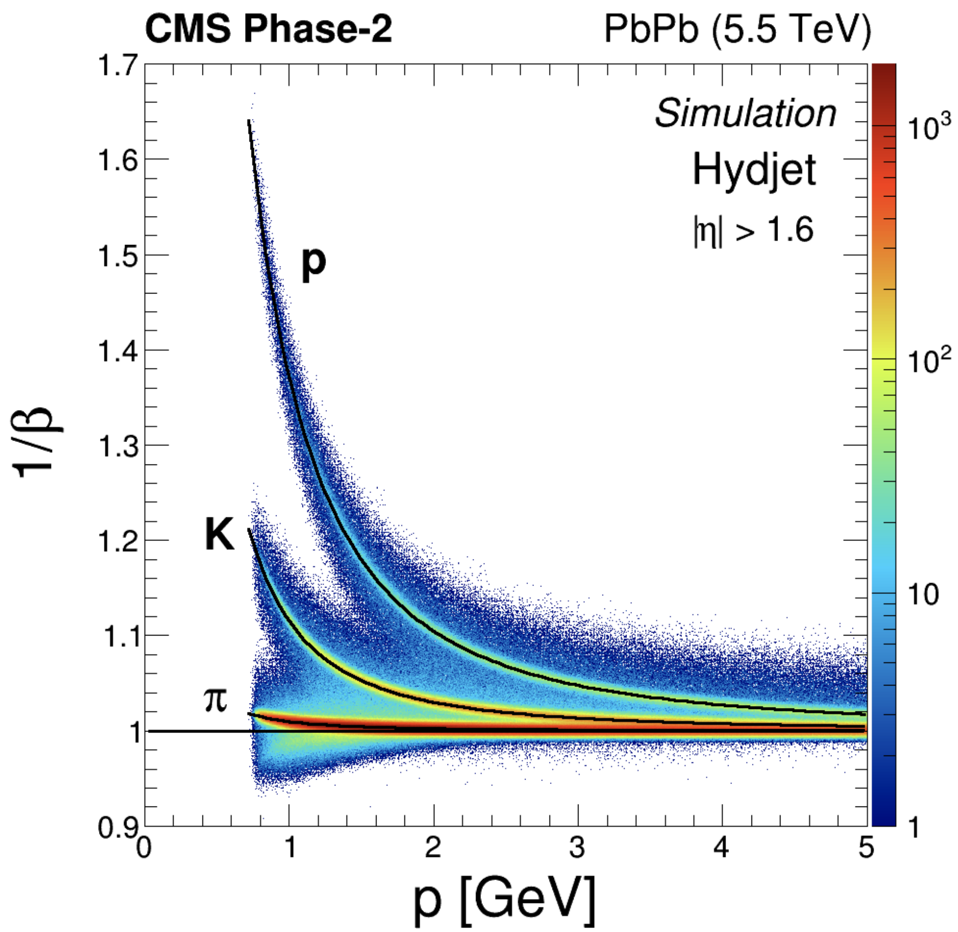
- System Size Scan:
  - Opportunity to sample QGP droplets on the eccentricity ε_2 and N_{part} phase space
  - Stress tests to the **Heavy Ion Standard Model**
  - Further Constraints on QGP properties from soft and hard probes

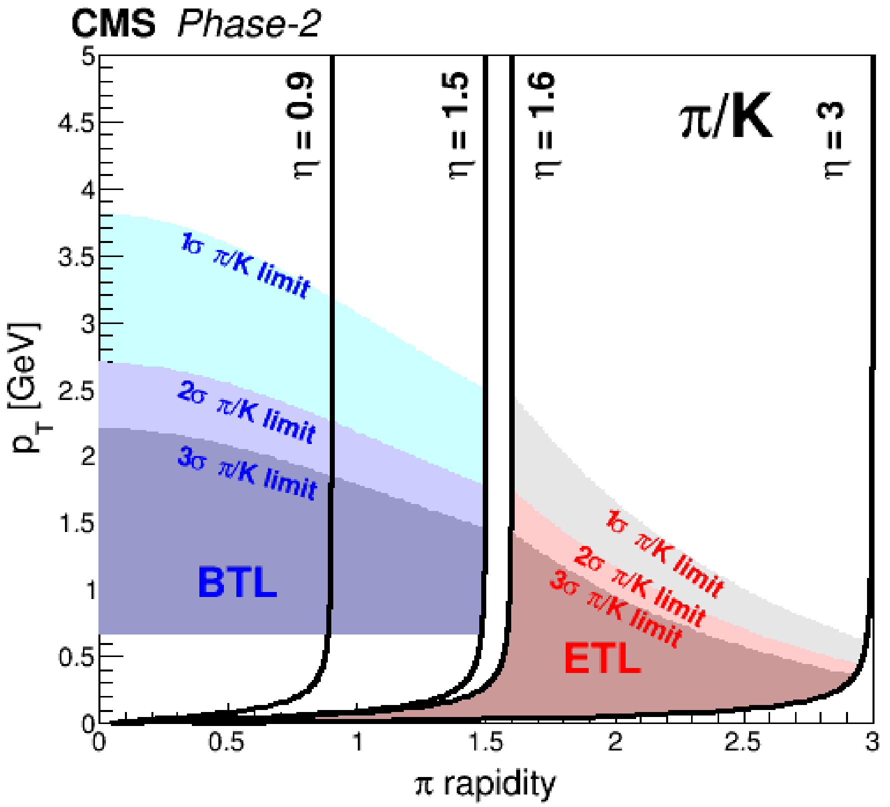




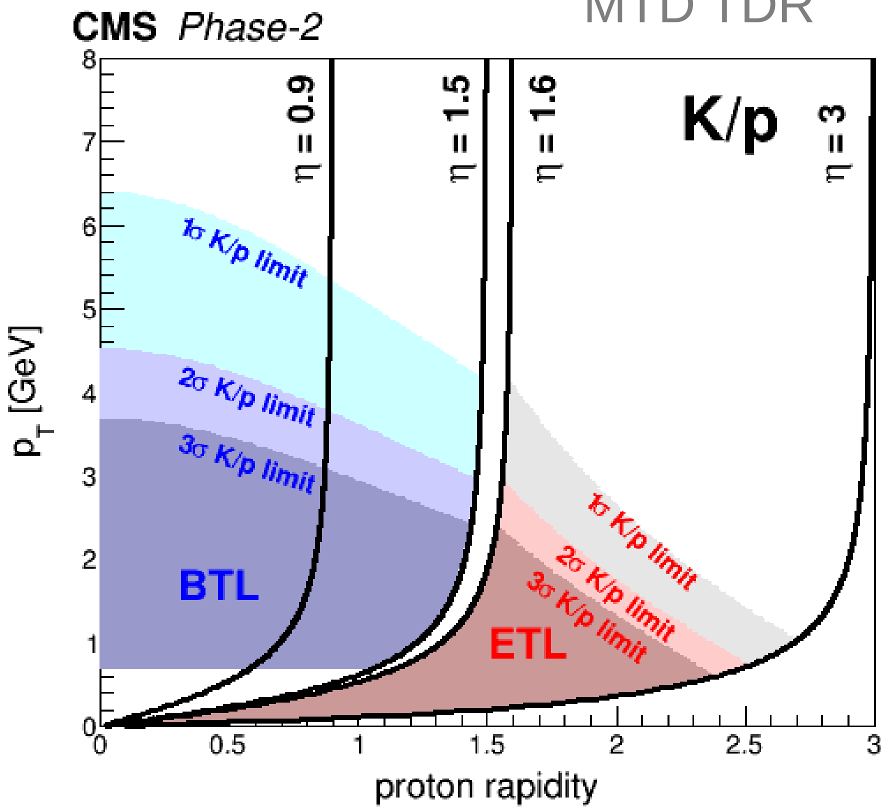
Backup Slides

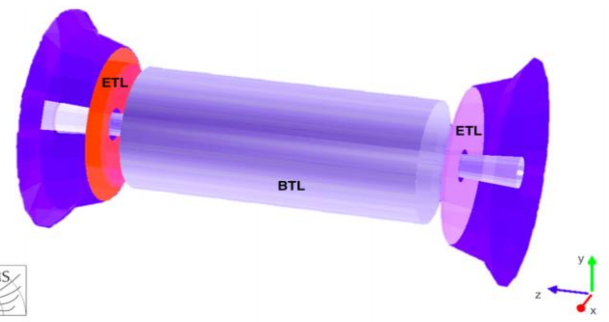
CMS MIP Timing Detector (MTD)





MTD TDR

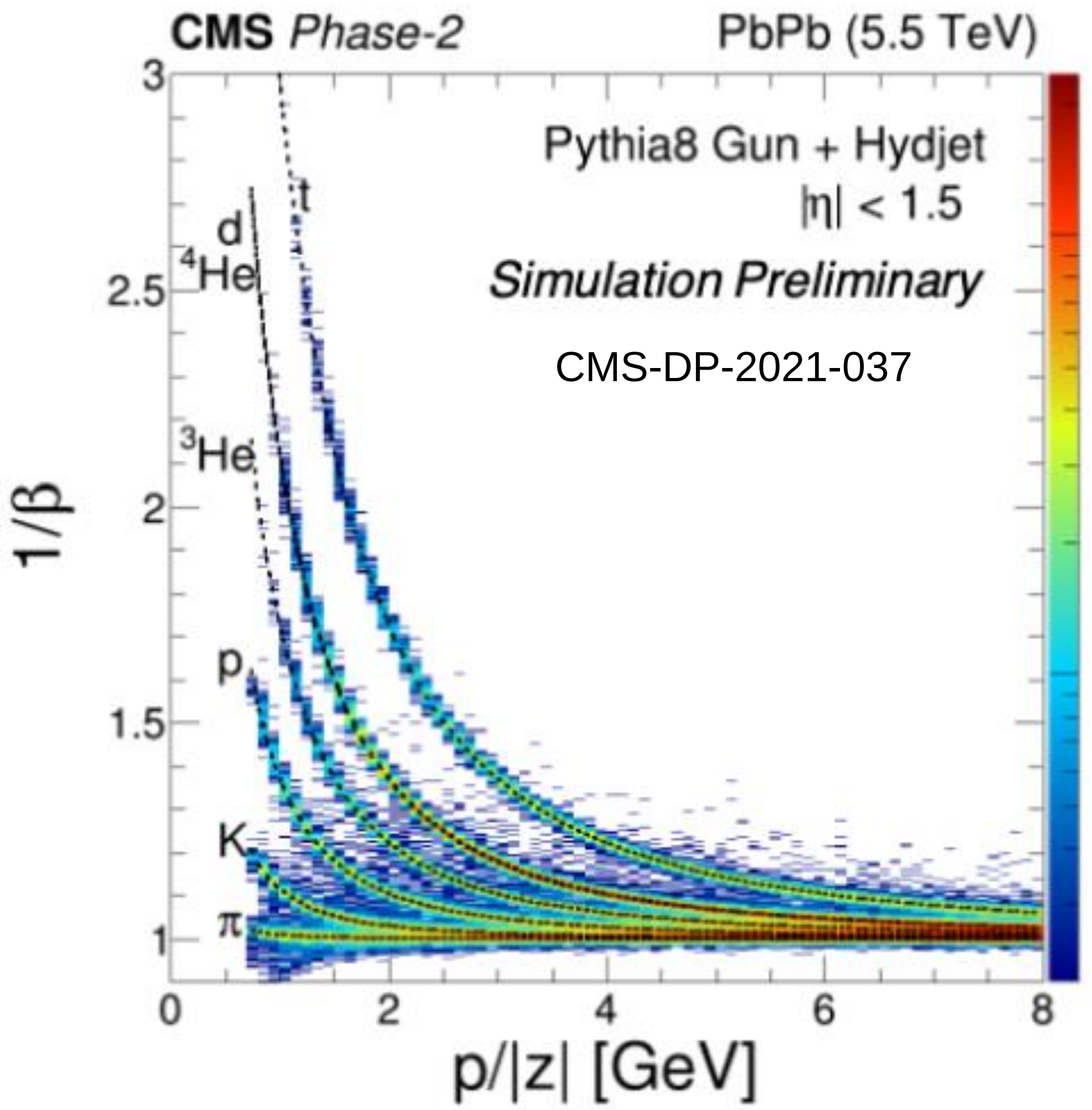


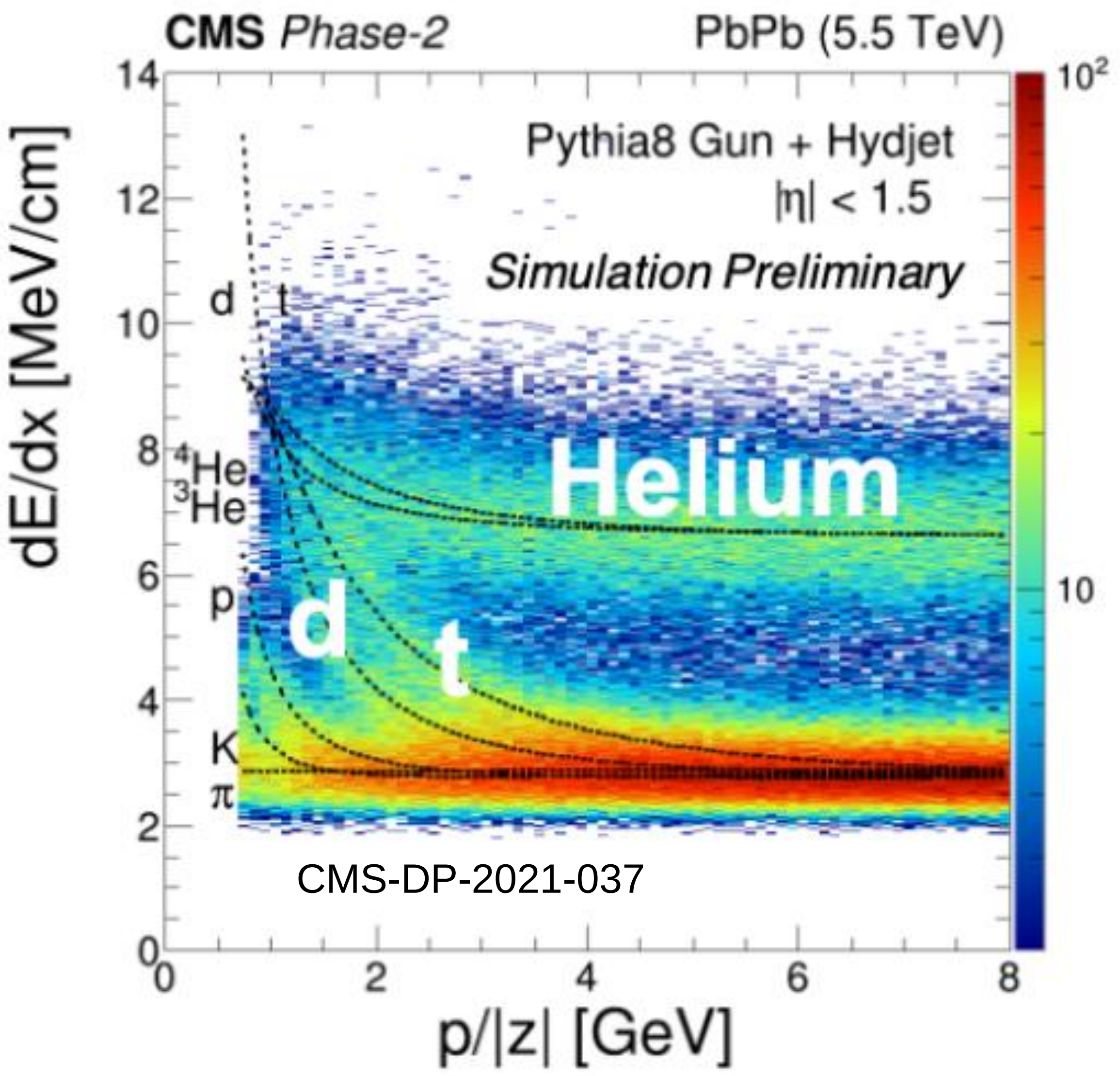


- Unique hermetic particle identification coverage by CMS MTD
- **Crucial Upgrade** for CMS Heavy Flavor Program with heavy ion collision

Light nuclei factory at CMS

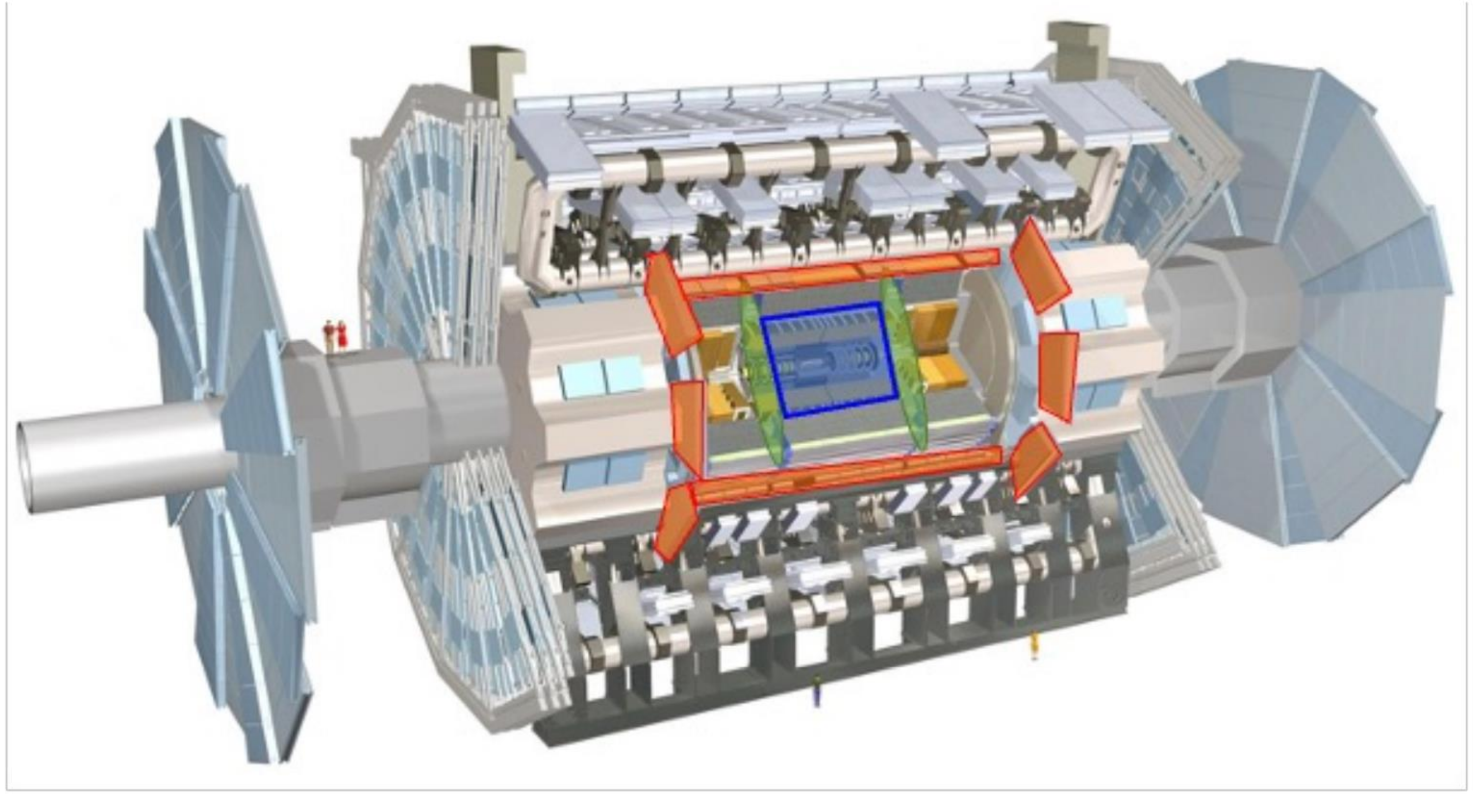
- Time of flight + dE/dx





ATLAS Upgrade

[CERN-LHCC-2015-020]



Upgraded Trigger and Data Acquisition System
- Single Level Trigger with 1 MHz output
- Improved 10 kHZ Event Farm

Electronics Upgrades
- On-detector/off-detector electronics upgrades of LAr Calorimeter, Tile Calorimeter & Muon Detectors
- 40 MHz continuous readout with finer segmentation to trigger

High Granularity Timing Detector (HGTD)
- Precision time reconstruction (30 ps) with Low-Gain Avalanche Detectors (LGAD)
- Improved pile-up separation and bunch-by-bunch luminosity

New Muon Chambers
- Inner barrel region with new RPCs, sMDTs, and TGCs
- Improved trigger efficiency/momentum resolution, reduced fake rate

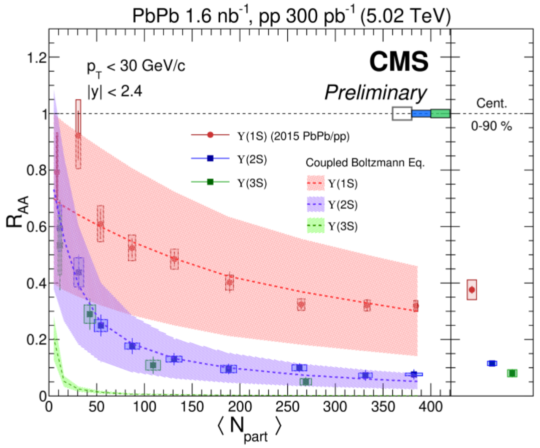
New Inner Tracking Detector (ITk)
- All silicon with at least 9 layers up to |η| = 4
- Less material, finer segmentation

Additional small upgrades
- Luminosity detectors (1% precision)
- HL-ZDC (Heavy Ion physics)

8

ATLAS

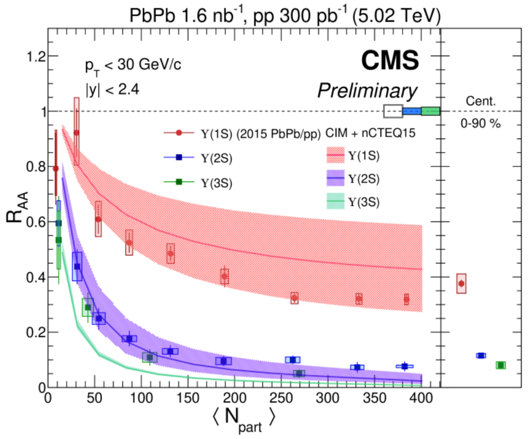
Description of the Υ(nS) data



CMS-PAS-HIN-21-007

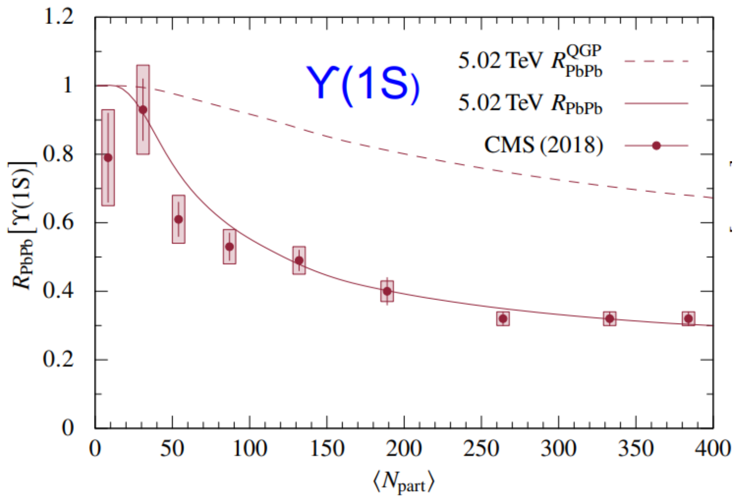
☛ Coupled Boltzmann equations
[JHEP 01 (2021) 046, X. Yao]

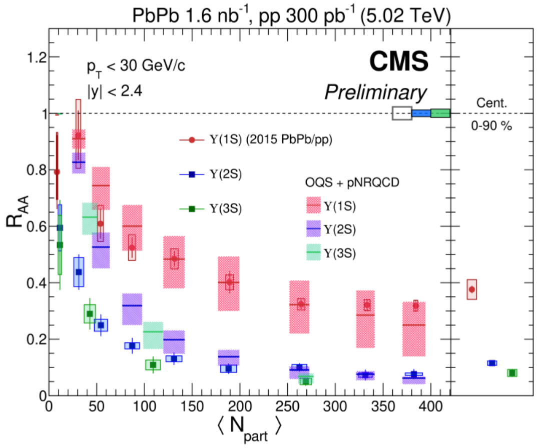
Regeneration missing for Υ(3S)



Comover interaction model ☚
[JHEP 10 (2018) 094, E. G. Ferreiro]

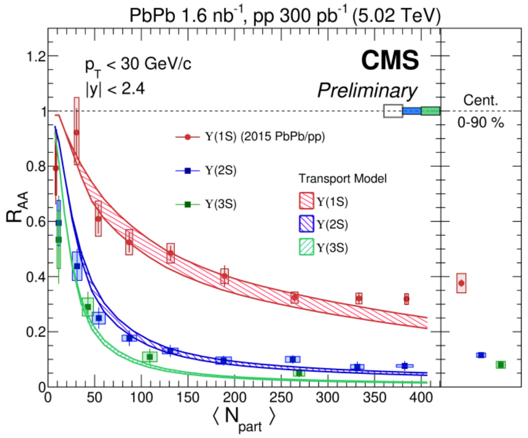
No regeneration contribution





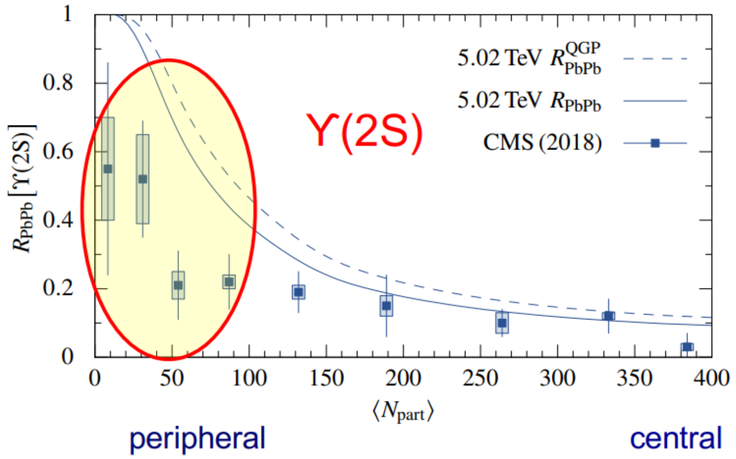
☛ Open-quantum system + pNRQCD
[PRD 104 (2021) 094049, N. Brambilla]

Call for CNM effects?



TAMU transport model ☚
[PRC 96 (2017) 054901, R. Rapp]

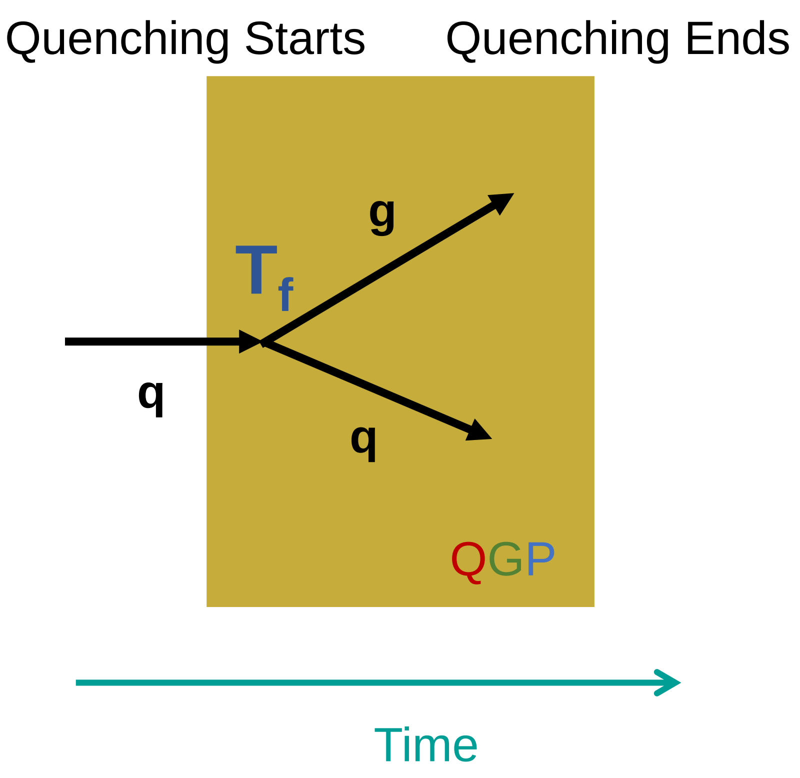
Undershooting data for central events?



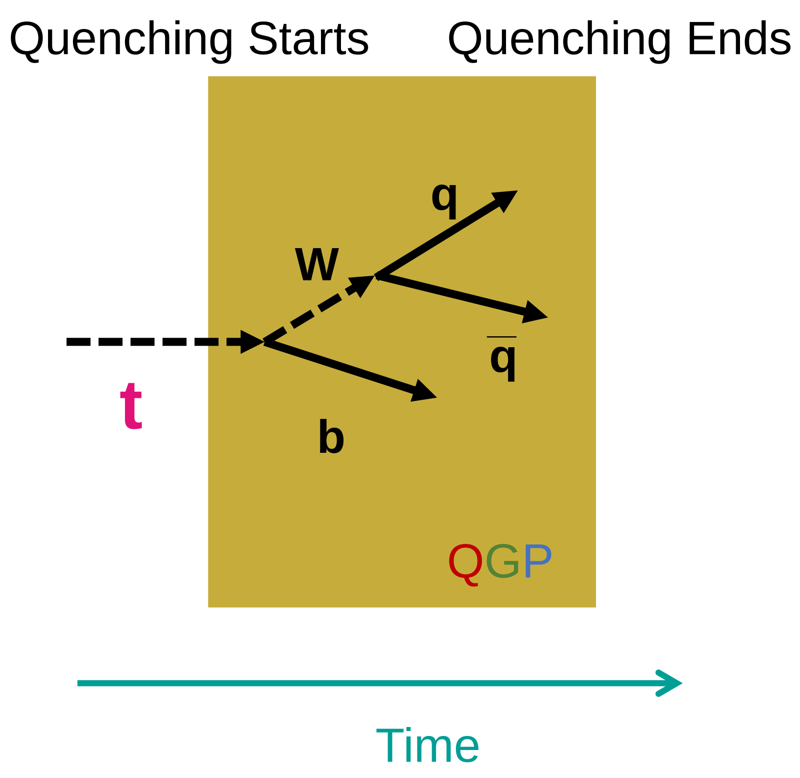
- Reasonable description of the Υ(1S) and Υ(2S) data with very different ingredients
  - Simple vs. full hydro simulation
  - With and without a thermalization (Elena)
- Poorer (and possibly improvable) description of the new 3S data

Probing the QGP Evolution

Formation Time (T_f) Tagging

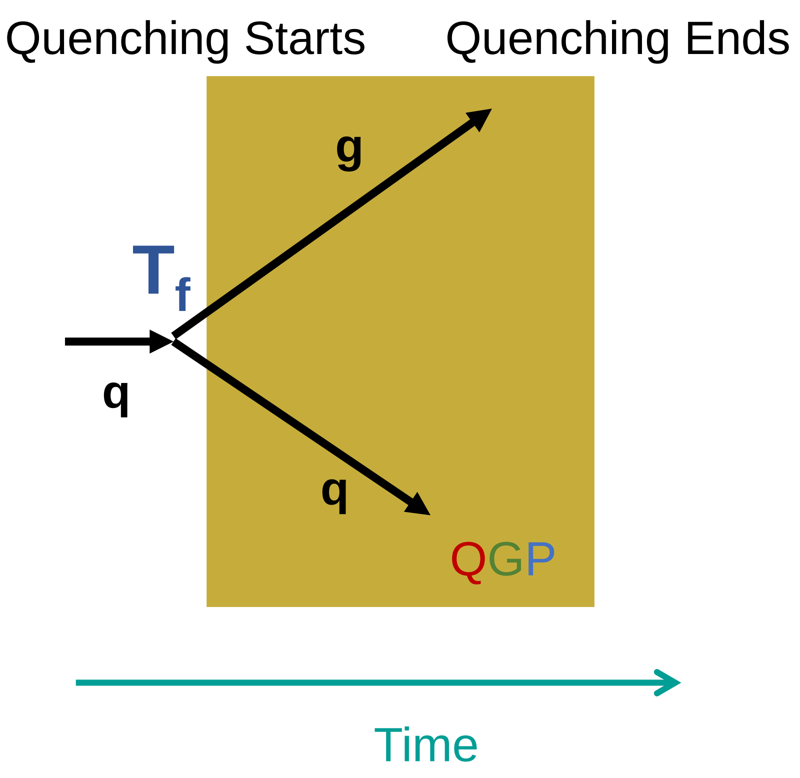


Boosted Top



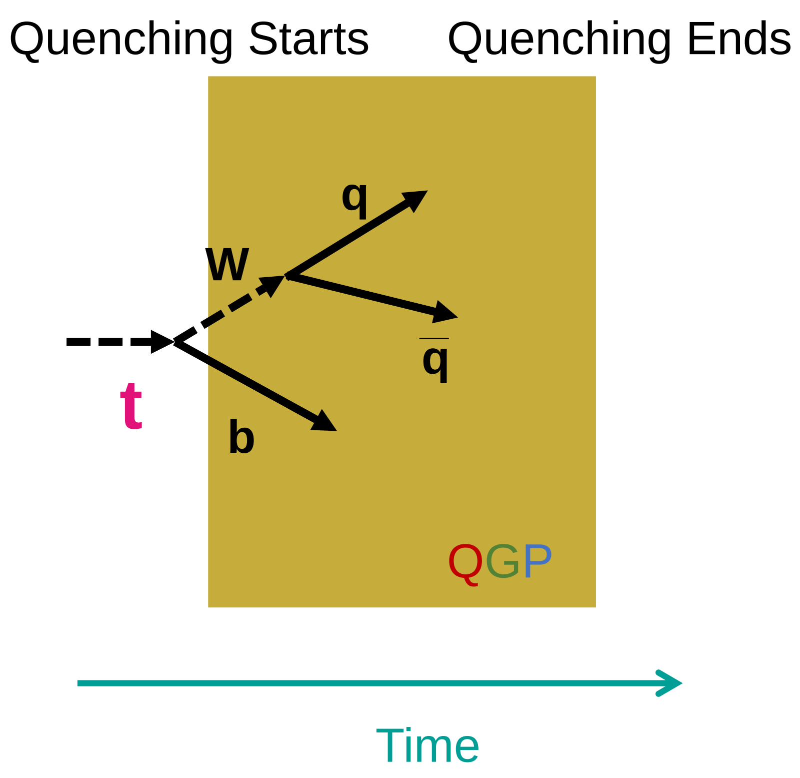
Probing the QGP Evolution

Formation Time (T_f) Tagging



Short formation time

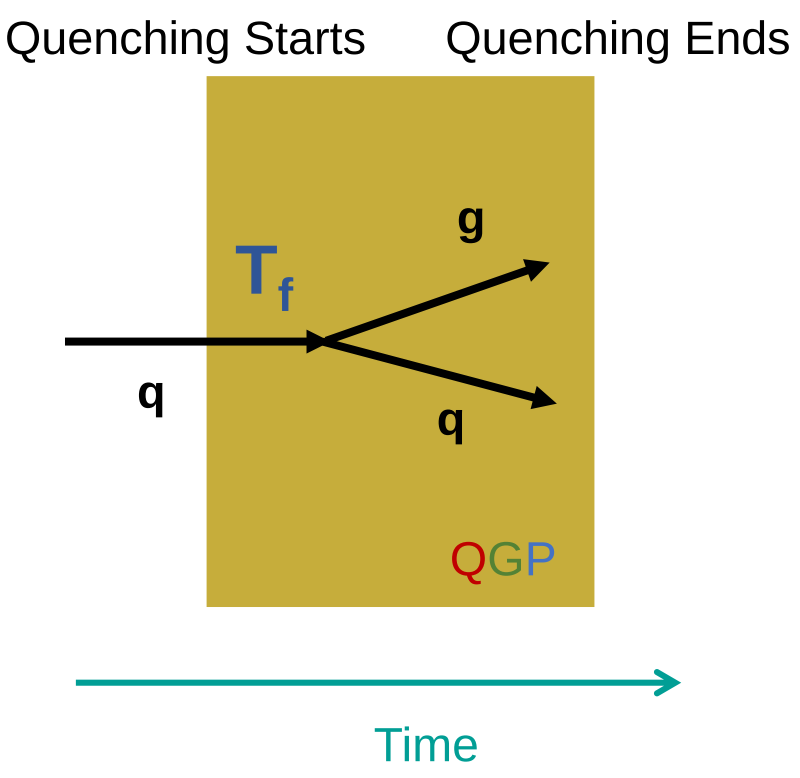
Boosted Top



Low p_T top

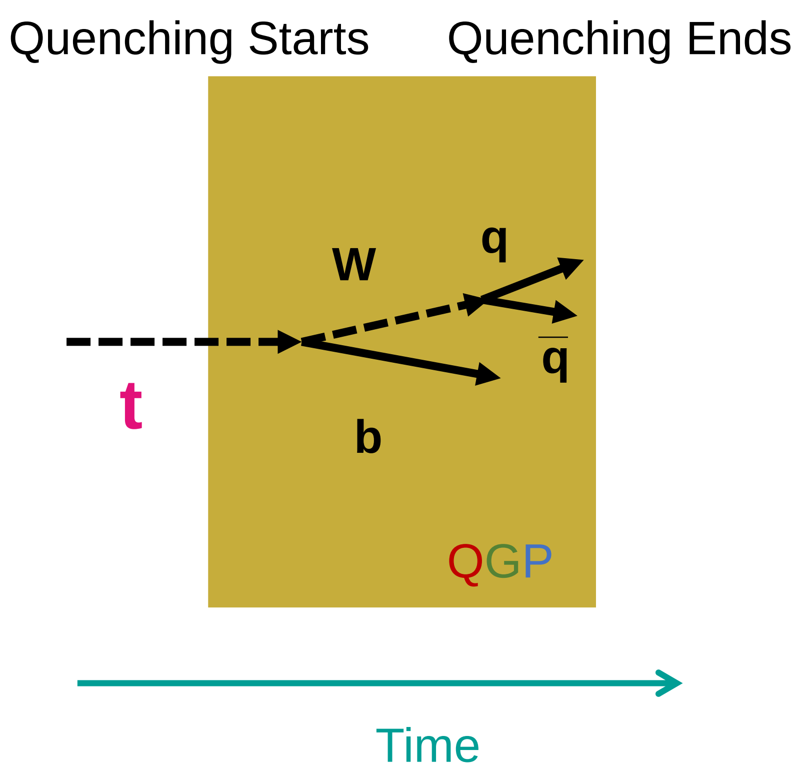
Probing the QGP Evolution

Formation Time (T_f) Tagging



Long formation time

Boosted Top



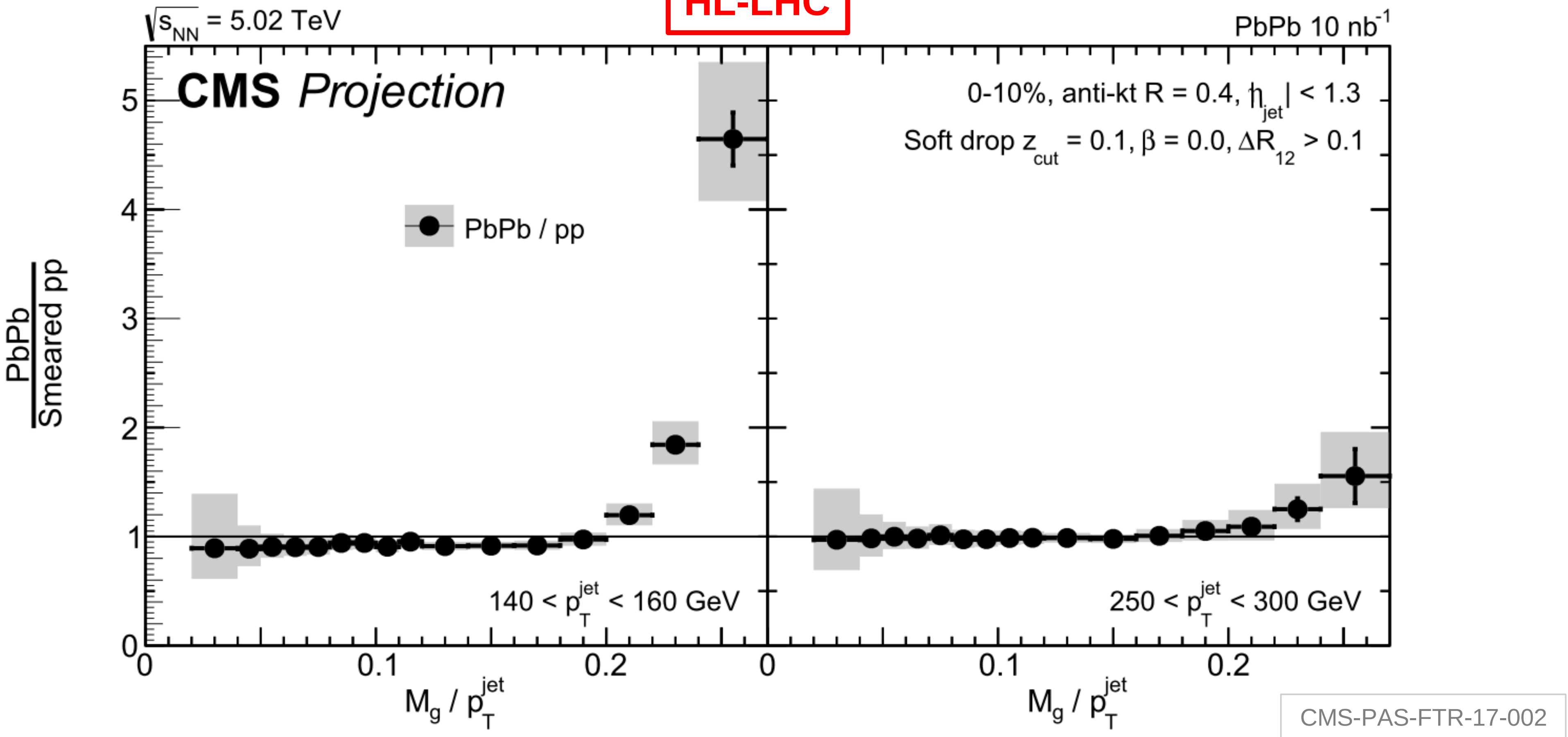
High p_T top

Physics With Run 3+4 and Beyond with CMS and ATLAS

- Strong constraints on the medium properties in the long-wave length limit with soft and hard probes
- Understand the medium wake with high energy jets and search for the direct evidence of medium recoils
- Resolve the intermediate length scale structure in the QGP with Moliere scattering
- Search for evidence of QGP droplets and jet quenching phenomena and comprehensive validation of HI standard model with system size scans

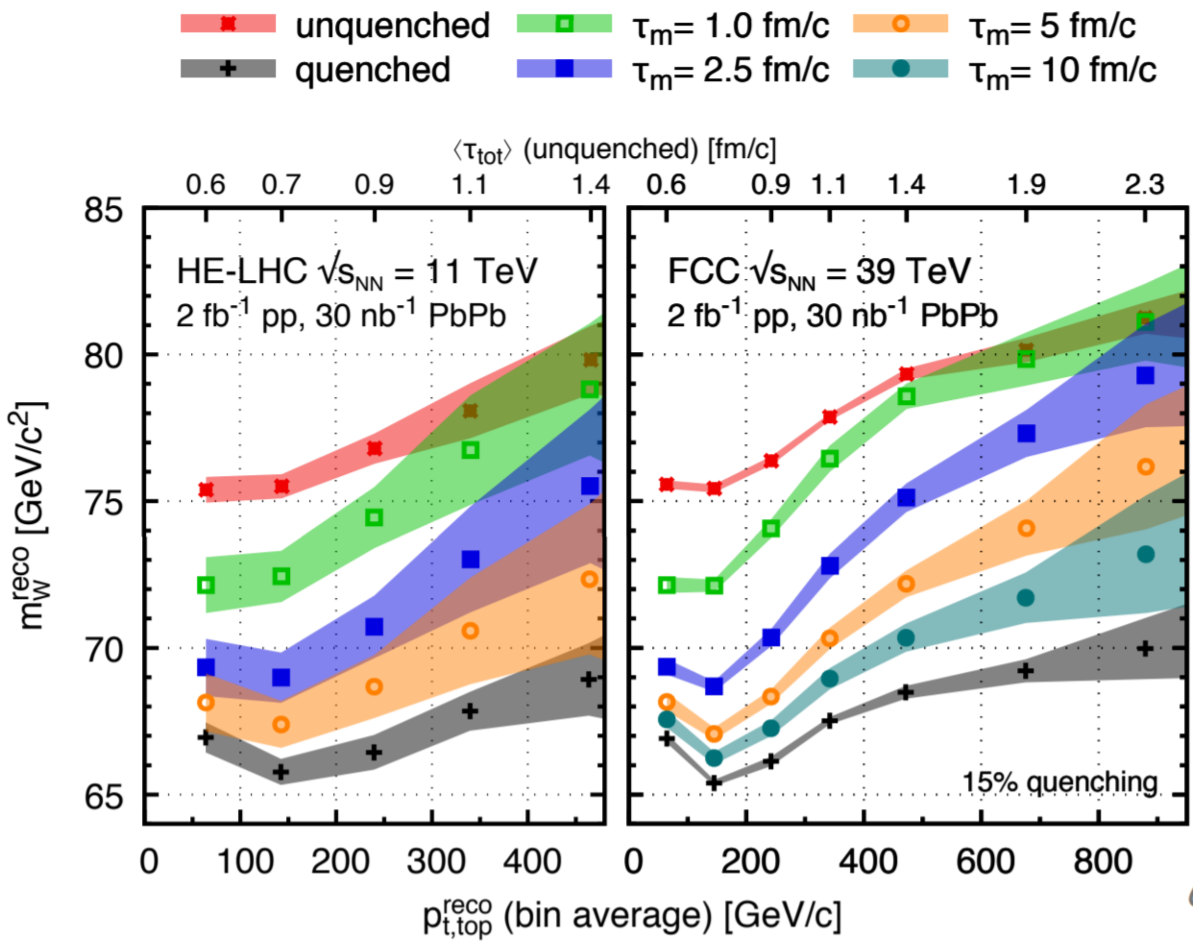
Groomed Jet Mass

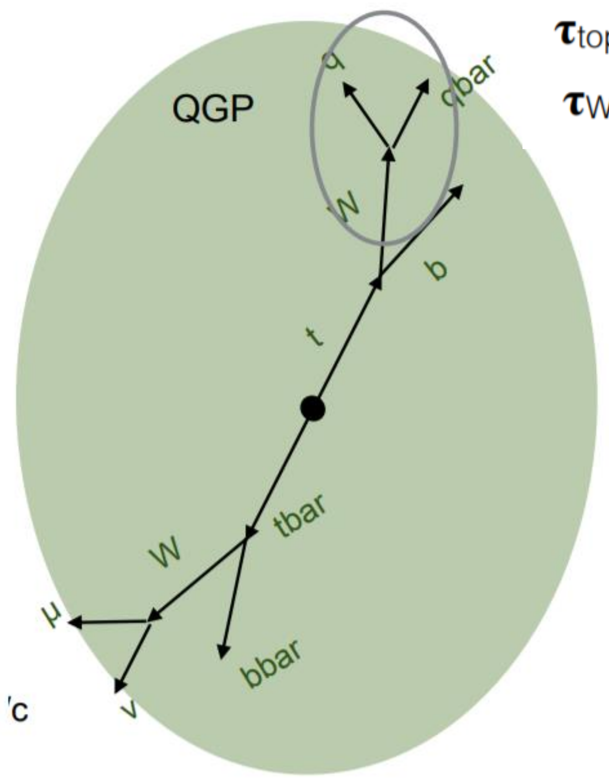
HL-LHC



- High statistics jet sample delivered in HL-LHC:
  - Opening a new era of jet quenching studies with jet substructure
- Use of grooming techniques enable us to study **"Parton Shower Shape Dependence of Jet Quenching"**
- **Stress test on the jet quenching models**

Modification of W mass in Top event





τ_{top}=0.15 fm/c

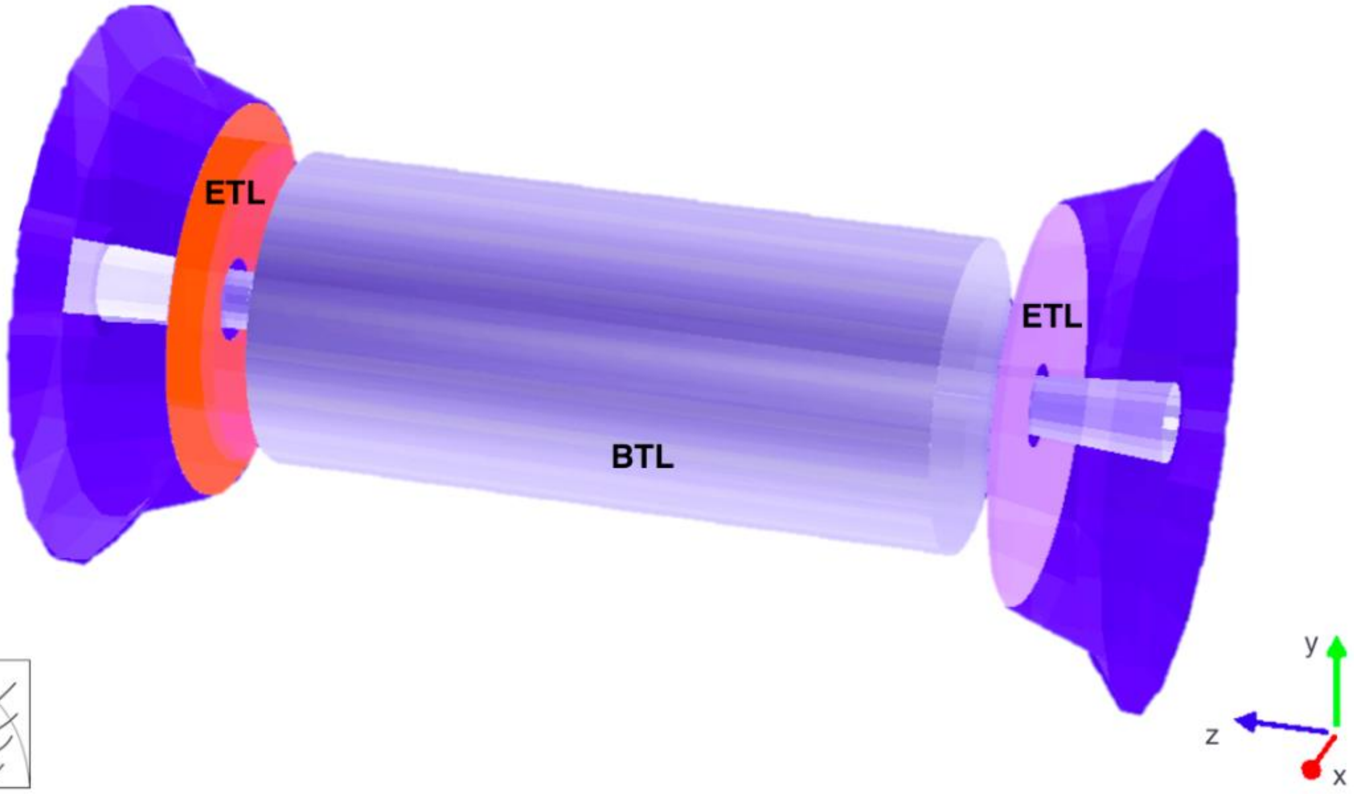
τ_{W}=0.10 fm/c

τ_m : quenching end time

"A Yoctosecond Chronometer." (Gavin Salam)

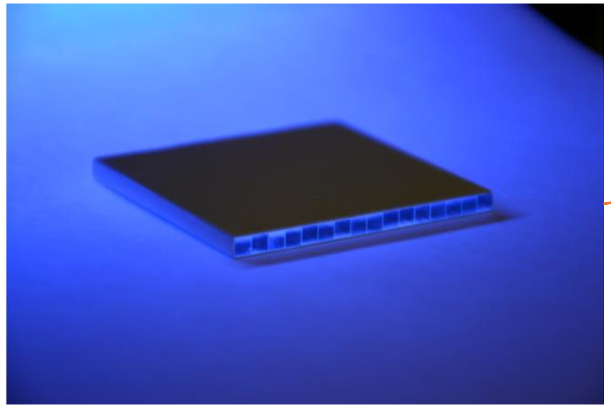
MIP timing detector

- MIP timing detector (MTD)
  - Entirely new proposal
  - **Resolution ~35ps**
  - **Large coverage, |η|<3**
  - Enable new opportunities with PID, benefits to the entire CMS collaborations, Long-lived Particle, PU mitigations, heavy ion physics …

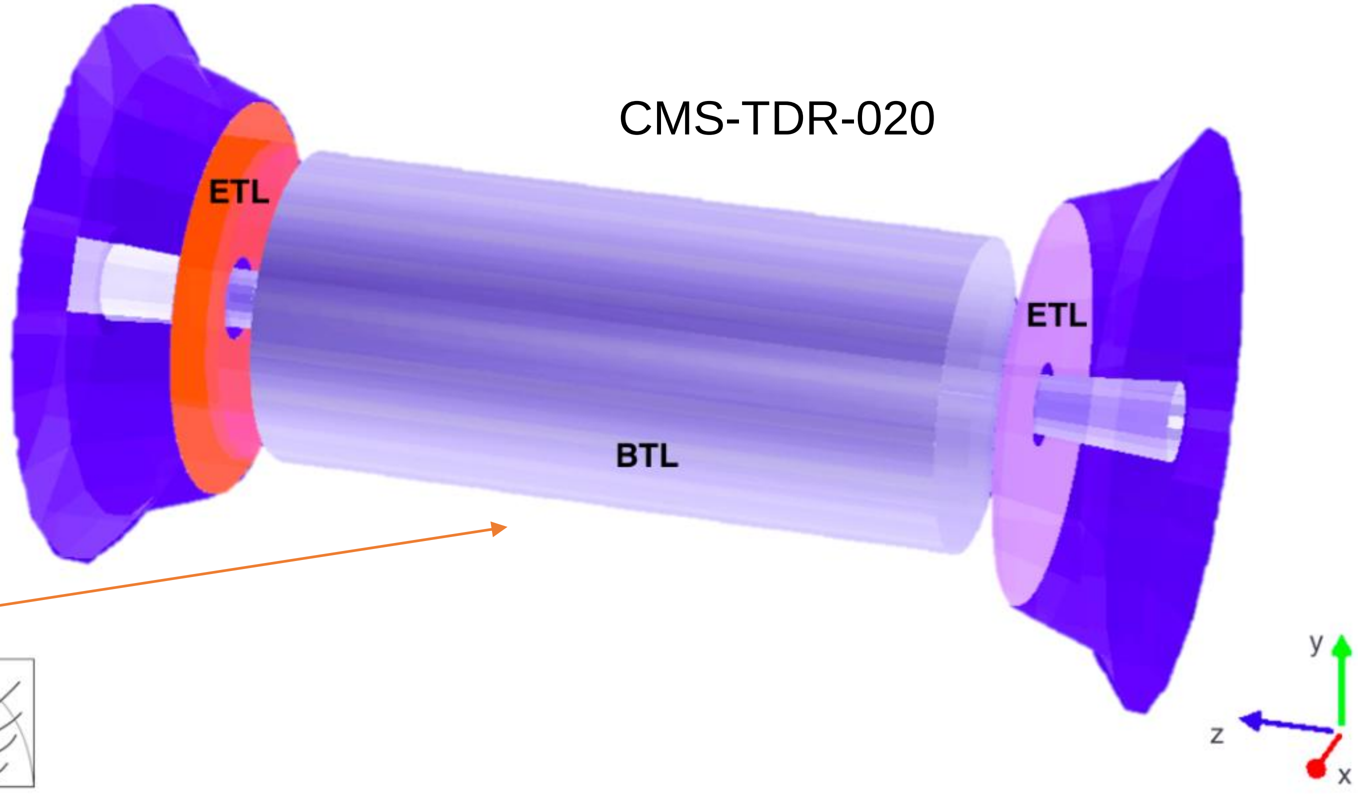


MTD -- Barrel timing layer

- BTL general
  - Resolution ~35ps
  - LYSO bars + SiPM readout
  - |η|<1.45
  - Inner radius: 1148 mm (40mm thicl
  - Length: +/- 2.6 m along z
  - Surface ~38 m^2; 332k channels

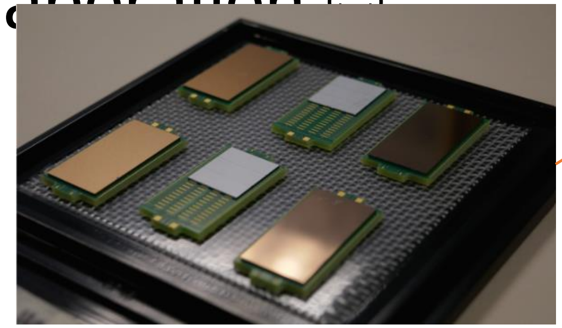


16x1 array of crystal bar

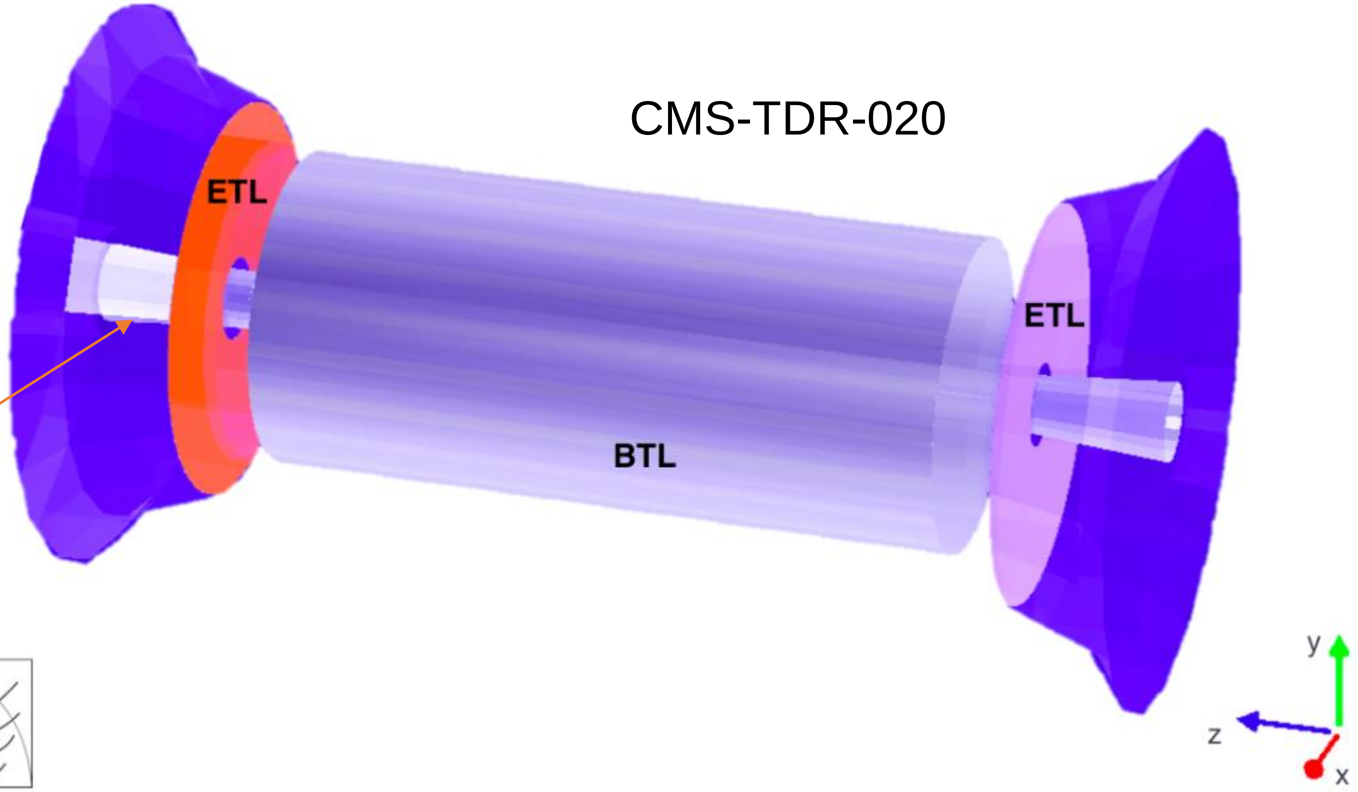


MTD Endcap timing layer

- ETL General
  - Si with internal gain (LGAD)
  - 1.6 < | η | < 3.0
  - Radius: 315 < R < 1200 mm
  - Position in z: +/-3.0 m (45 mm thick)
  - Surface ~14 m^2; ~8.5M channels
- CMS HI contribute half of ETL – efforts from entire CMS collaboration ☺

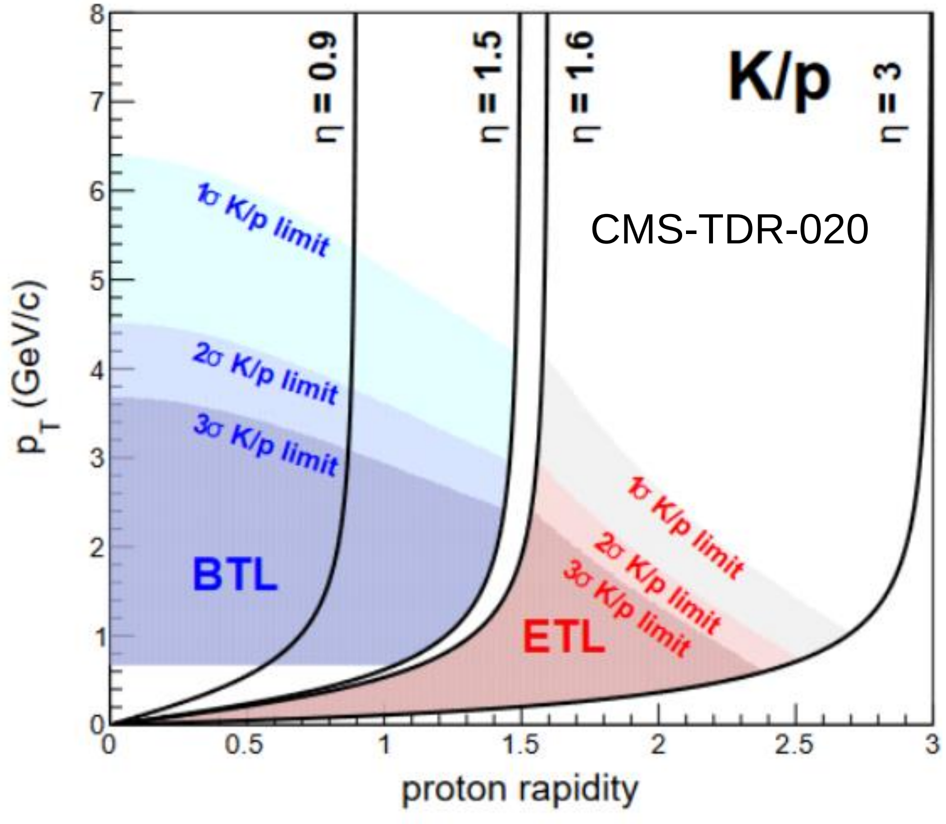


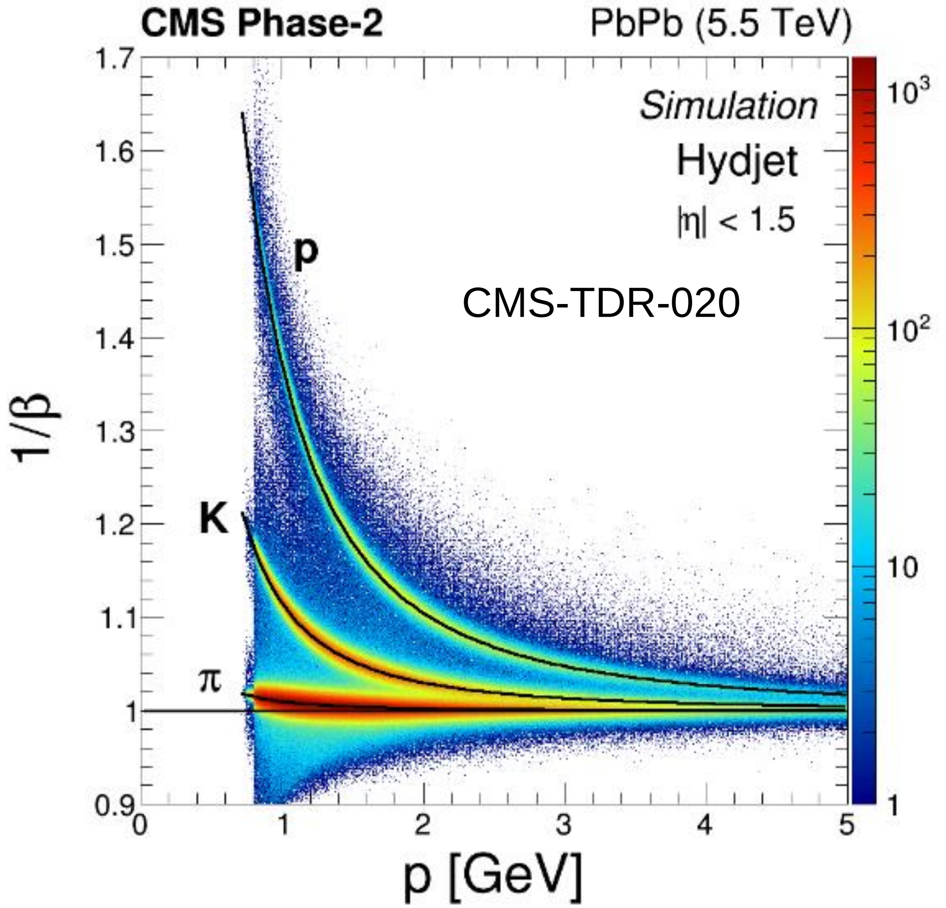
LGAD sensors on PCB

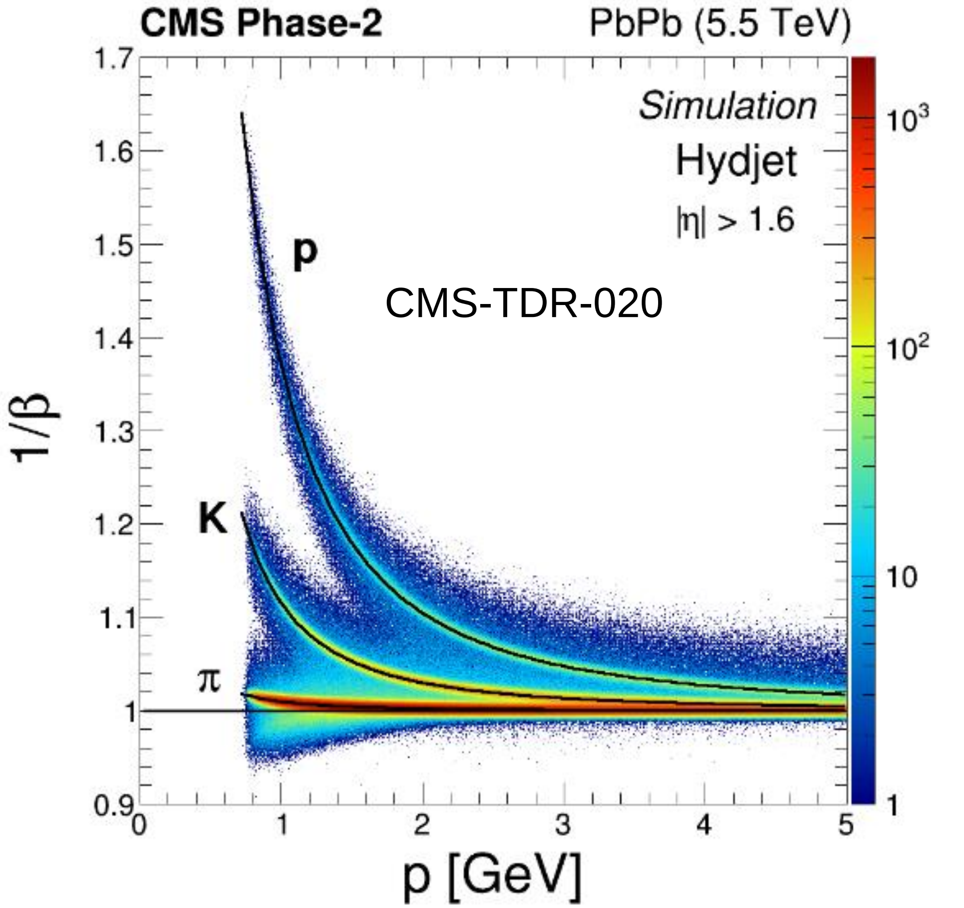


MTD Simulations

- Wide coverage up to 6 units of rapidity
- π/K separation up to 3 GeV
- K/p separation up to 5 GeV

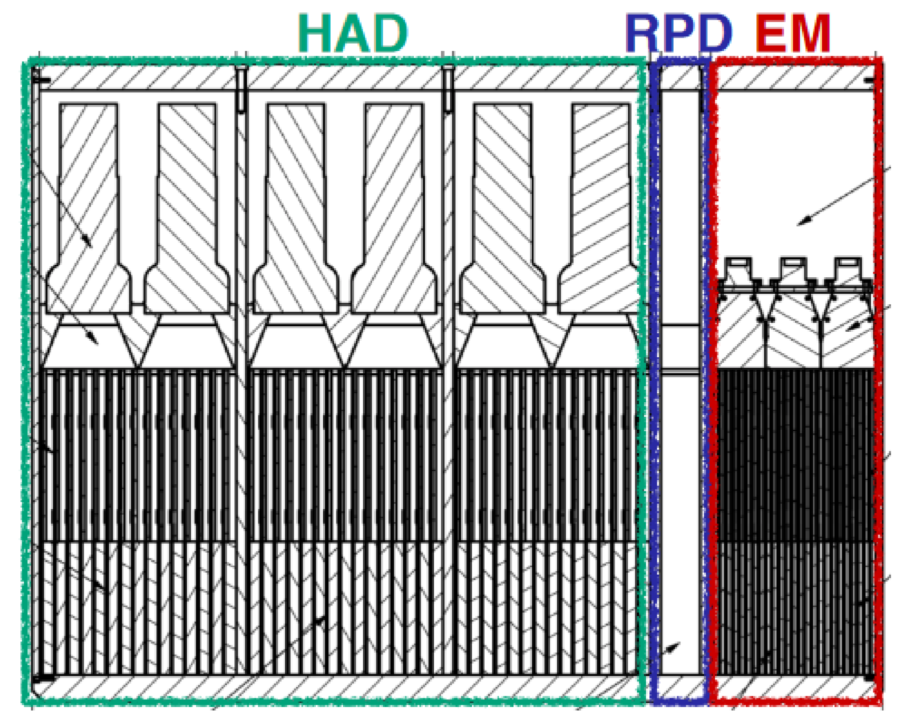


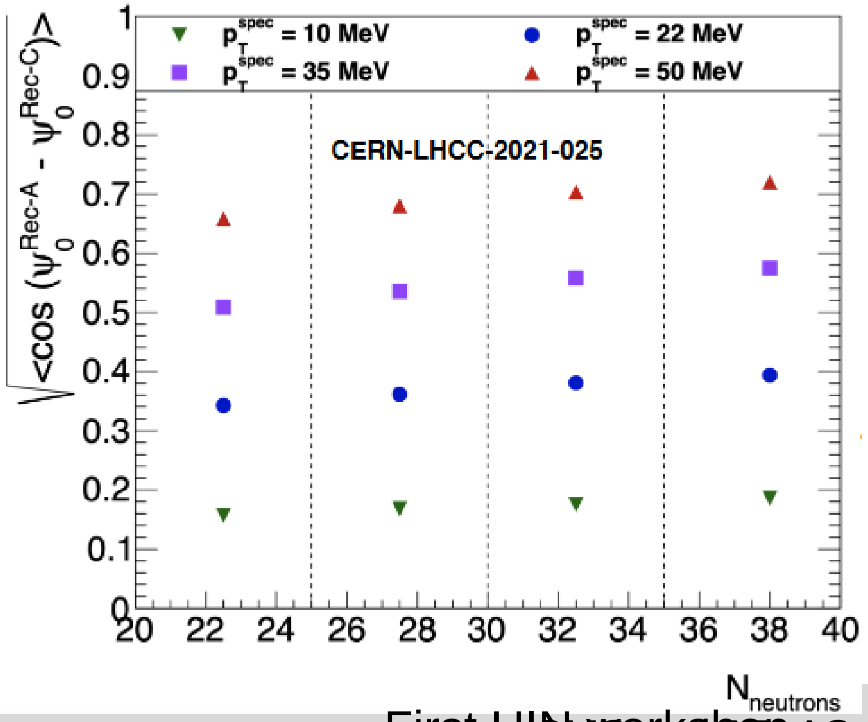


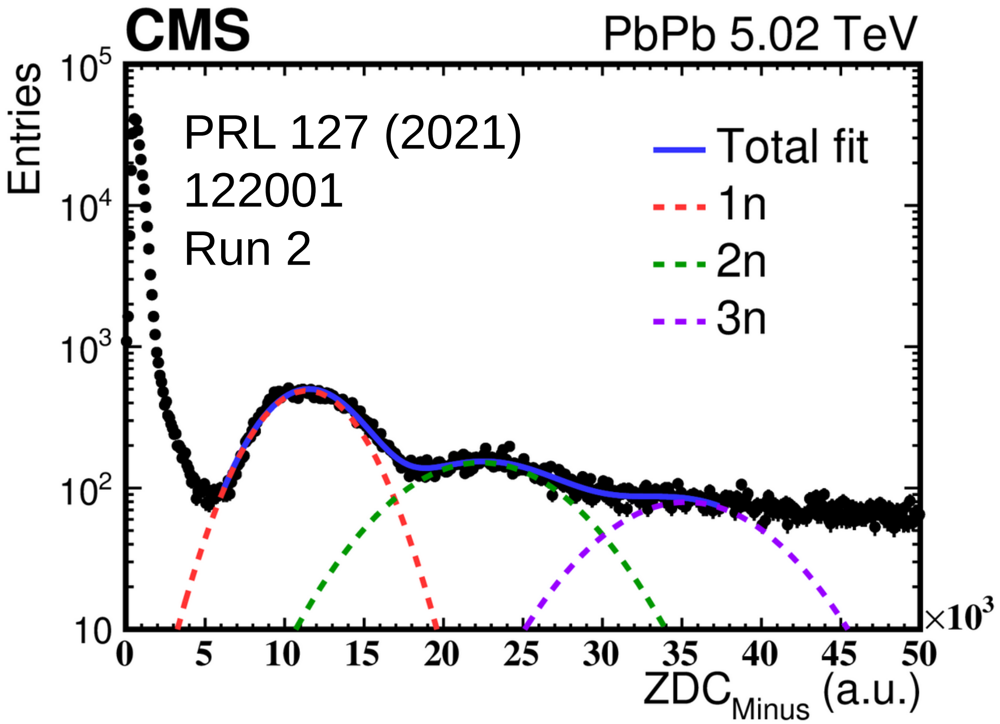


ZDC

- Thinner and finer segmented absorber for neutron/proton
- Separations of number of neutron for UPC
- Potential MB trigger
- v_1 measurements enabled by good resolution of 1st of reaction plane – potential D0 v_1 splitting from magnetic field?

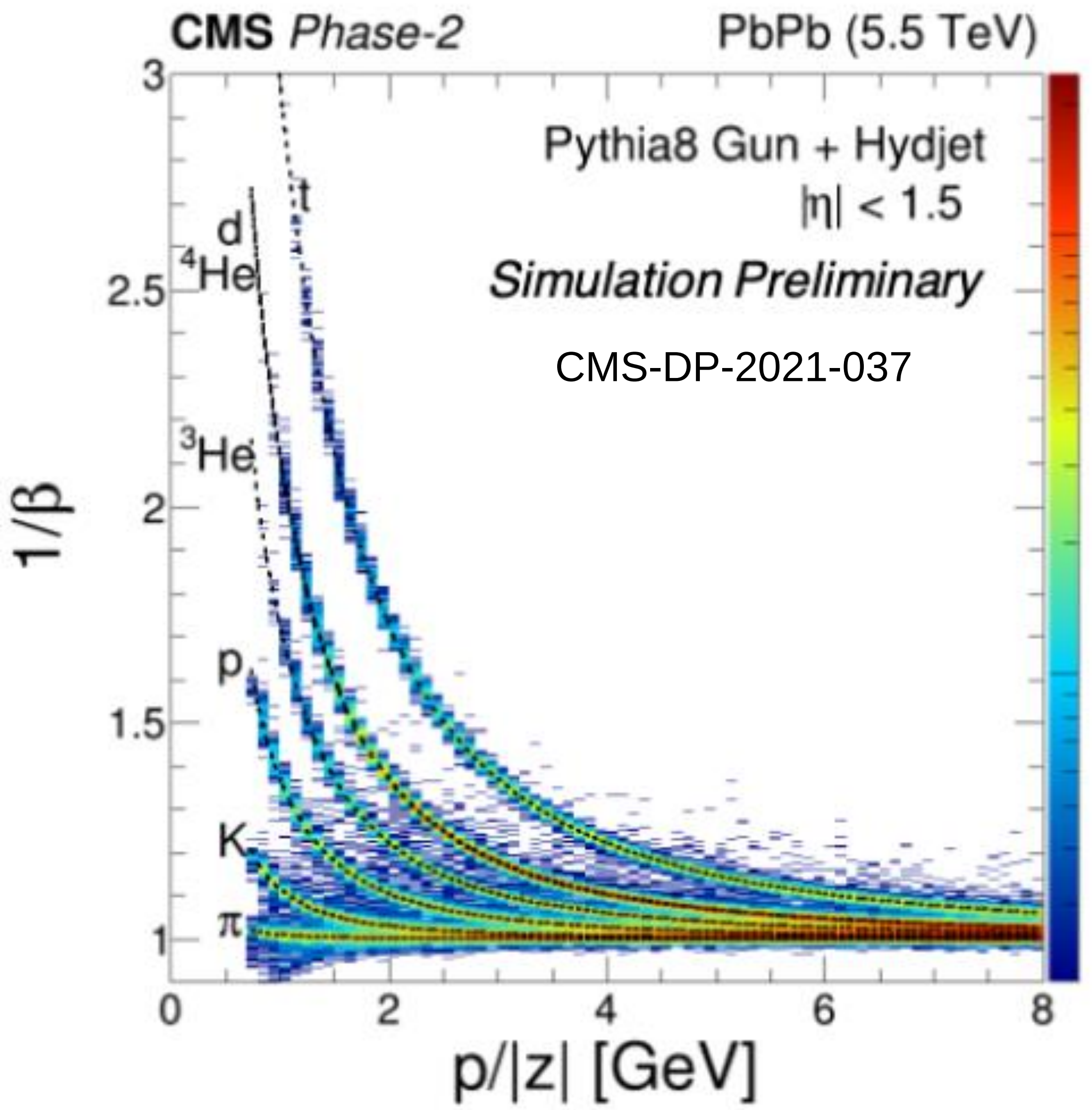


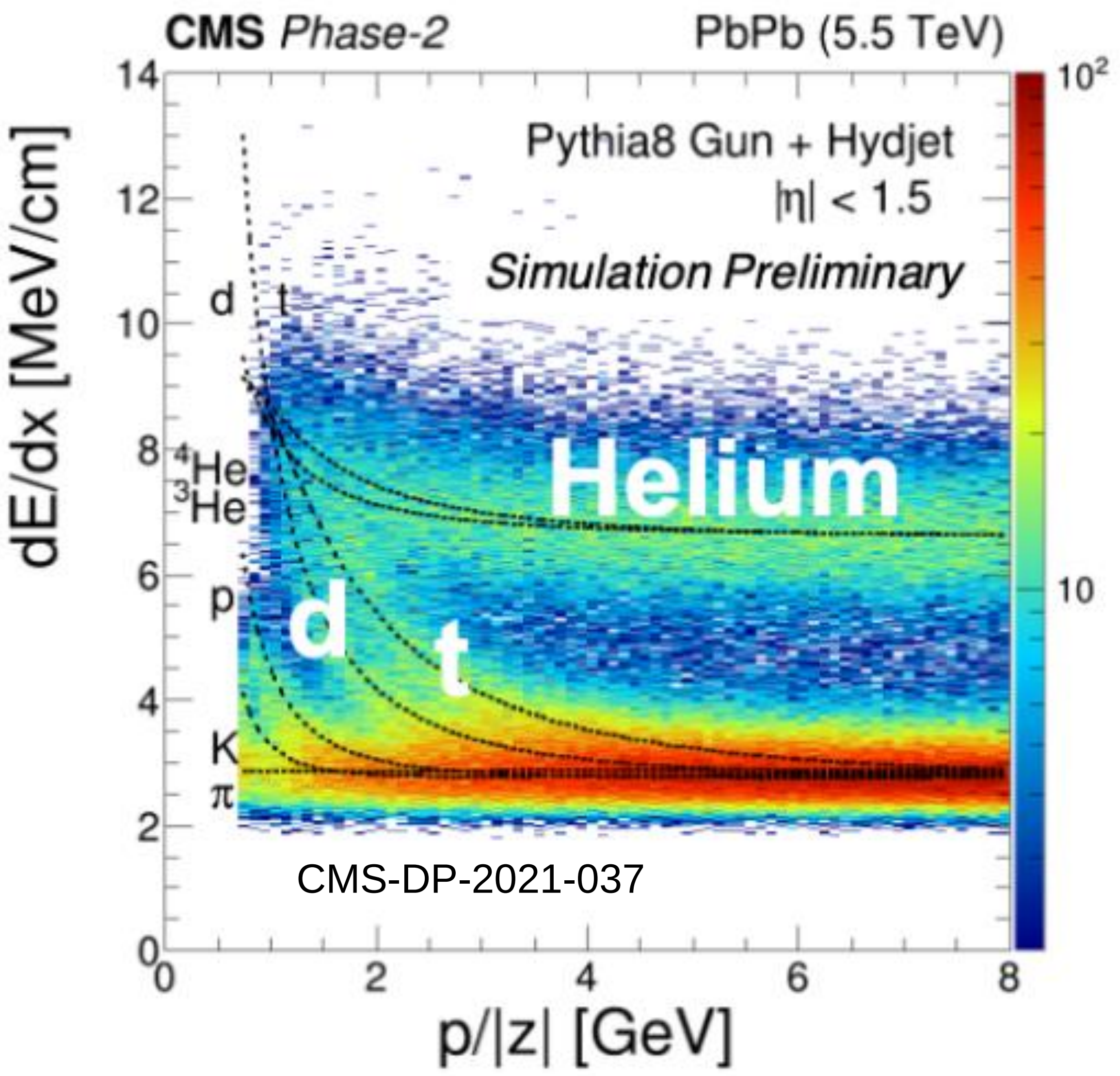




Light nuclei factory at CMS

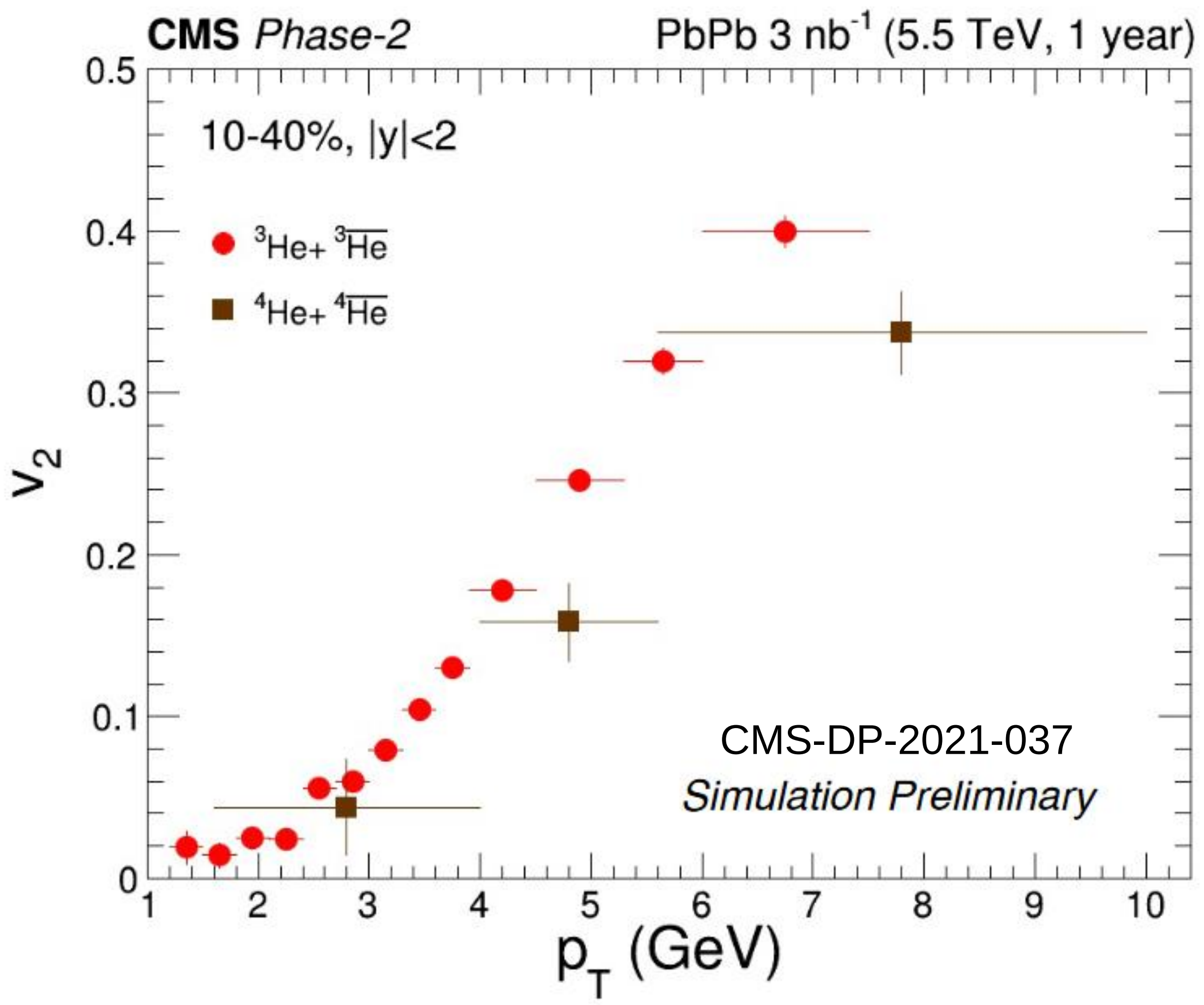
- Time of flight + dE/dx

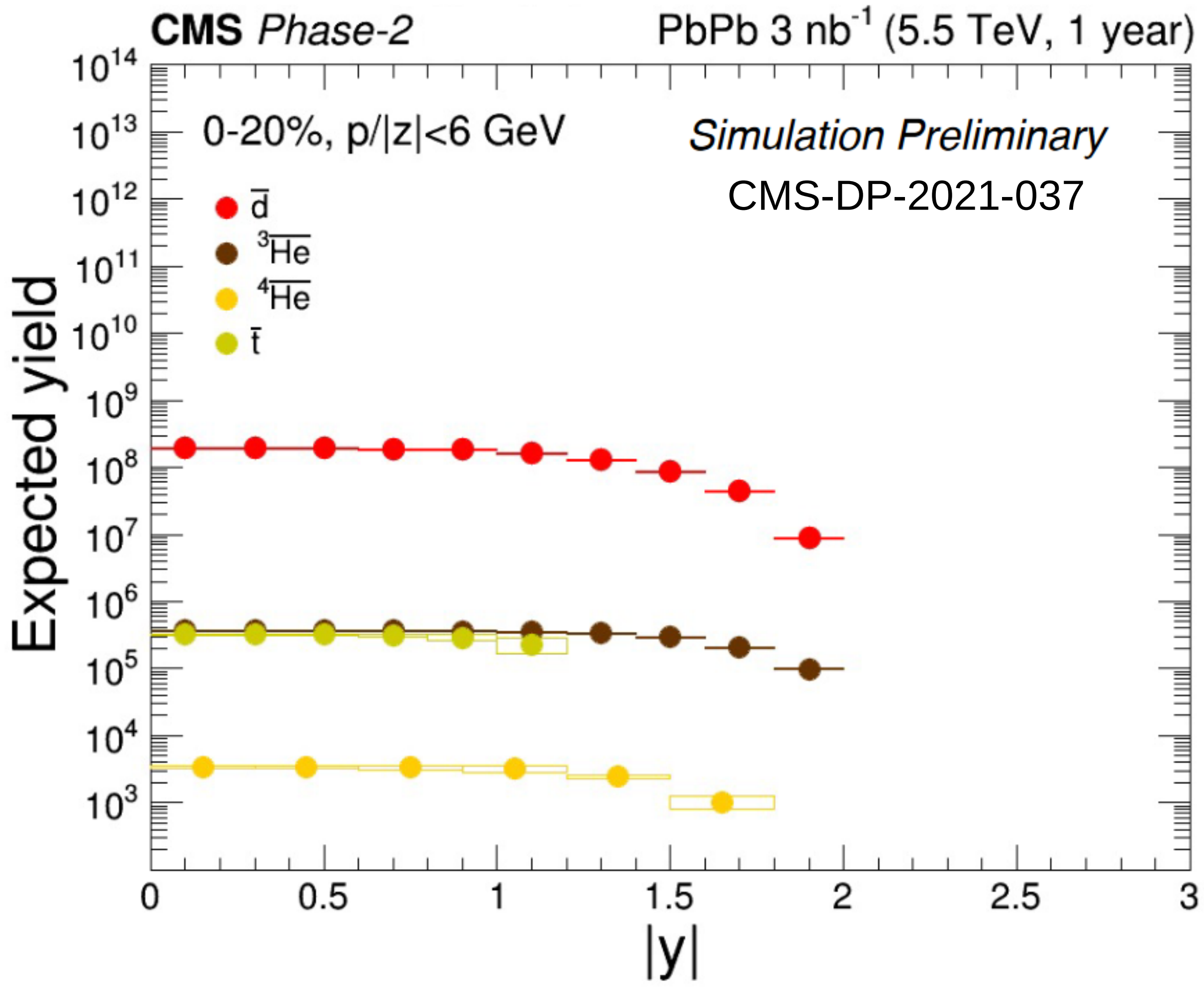




Projections for light nuclei

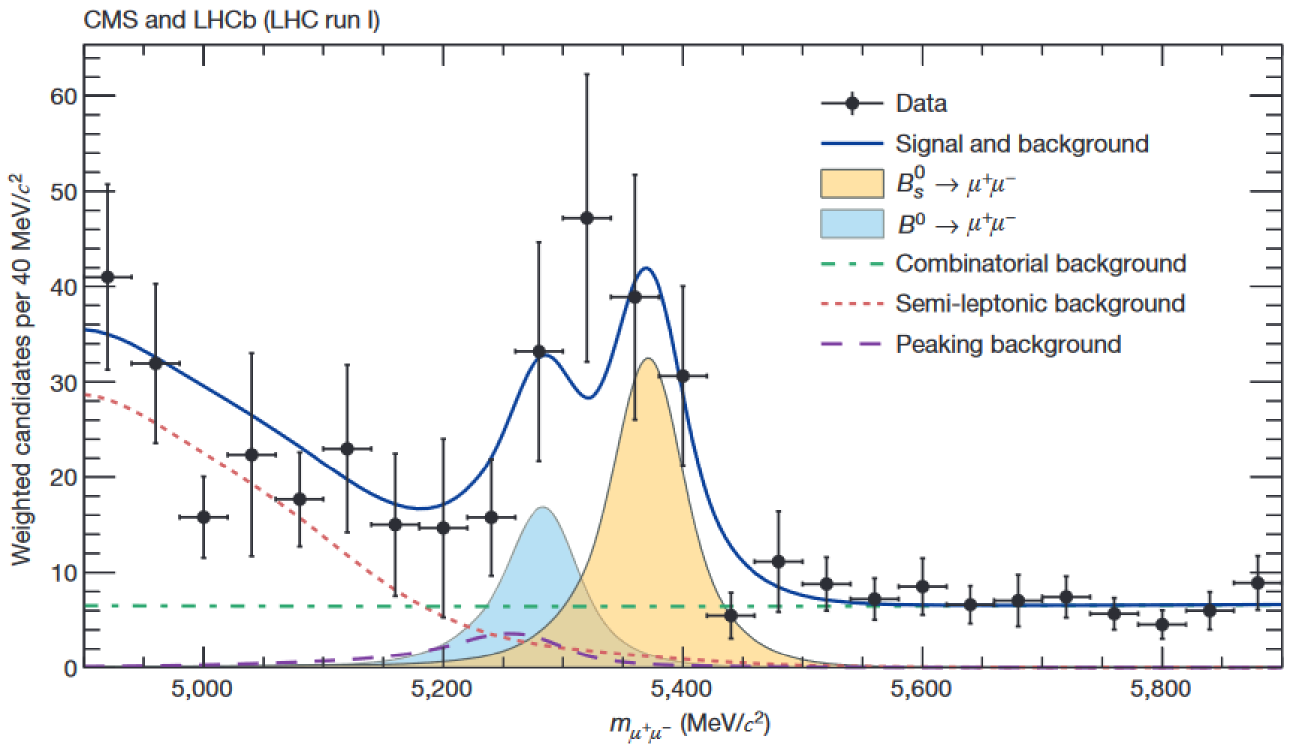
- First CMS measurements of elliptic flow and expected yields

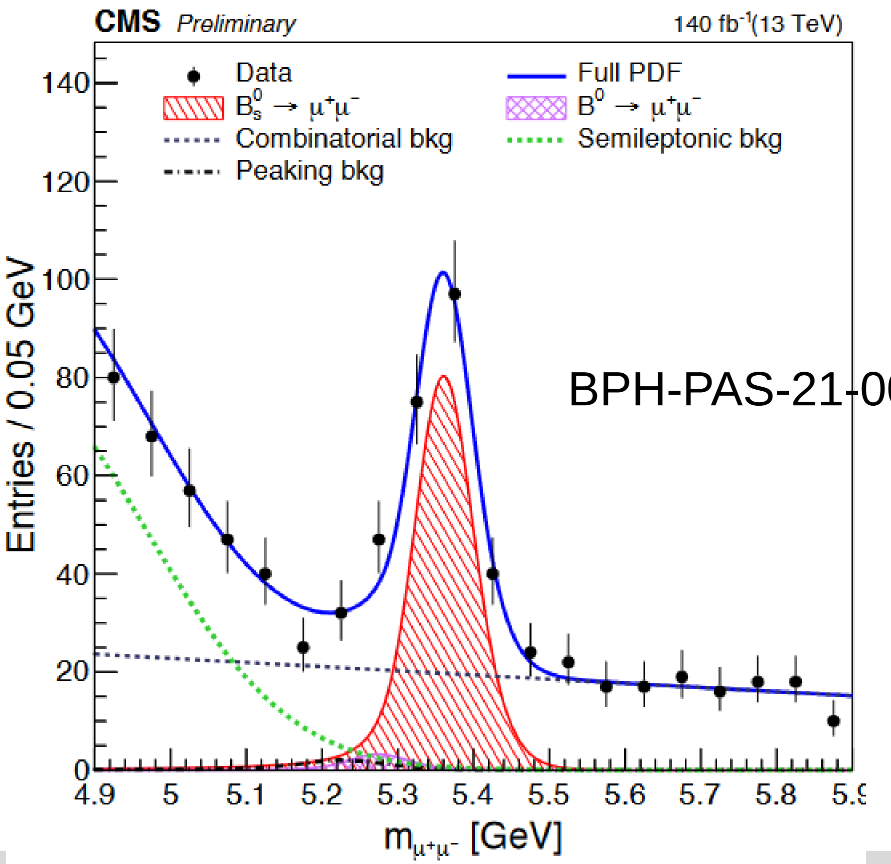




Thoughts beyond upgrade – methodologies

- Better understanding of the detectors (supplied with machine learning?)
  - An example of CMS measurements for rare B_s^0 -> μμ
  - ML deployed in muon identification and signal search (2-3 better rejection of fake than the standard) together with high luminosity – from observation to precisely test Standard Model





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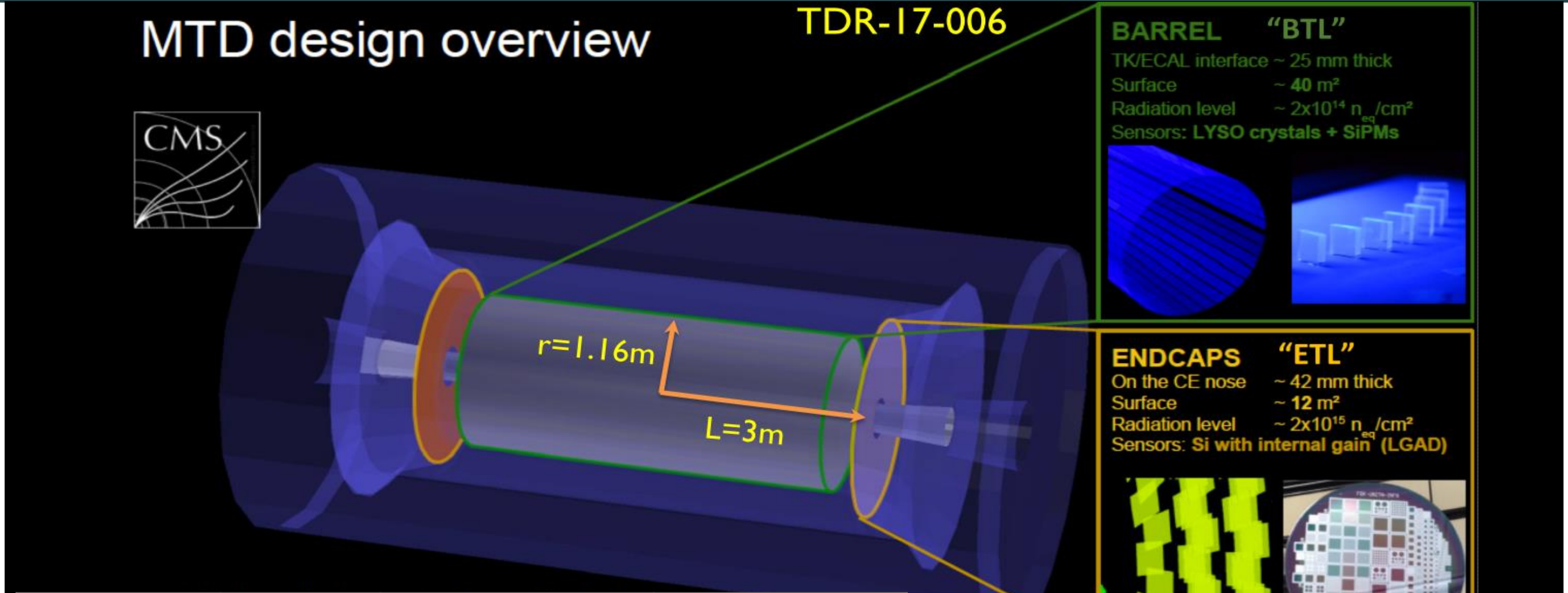
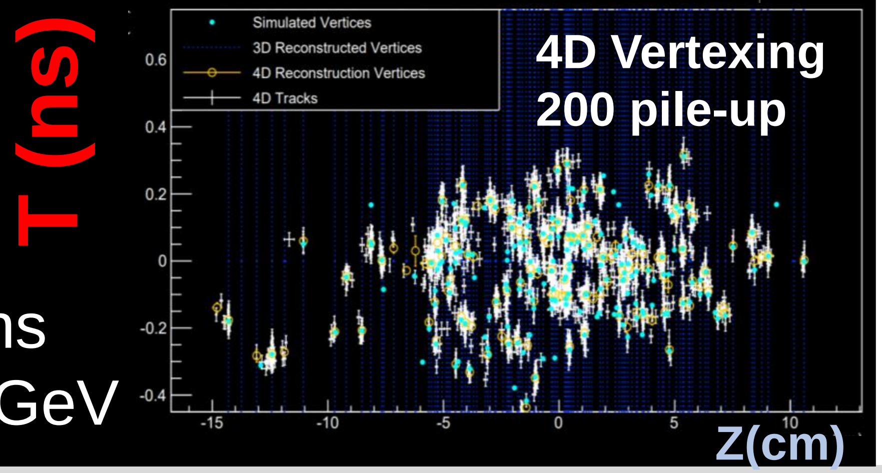
Time of Flight with MIP Timing Detector



	Radius **(r)** (cm)	Time Resolution **(σ)** (ps)	Separation Power **(r / σ)**
STAR	220	80	2.75
ALICE	370	80	4.63
CMS-MTD	116	30	3.87



- 4D vertexing (x,y,**z**,**T**) in high PU pp collisions
- Possible p/K/π separation with $0.7<p_T<3$ GeV

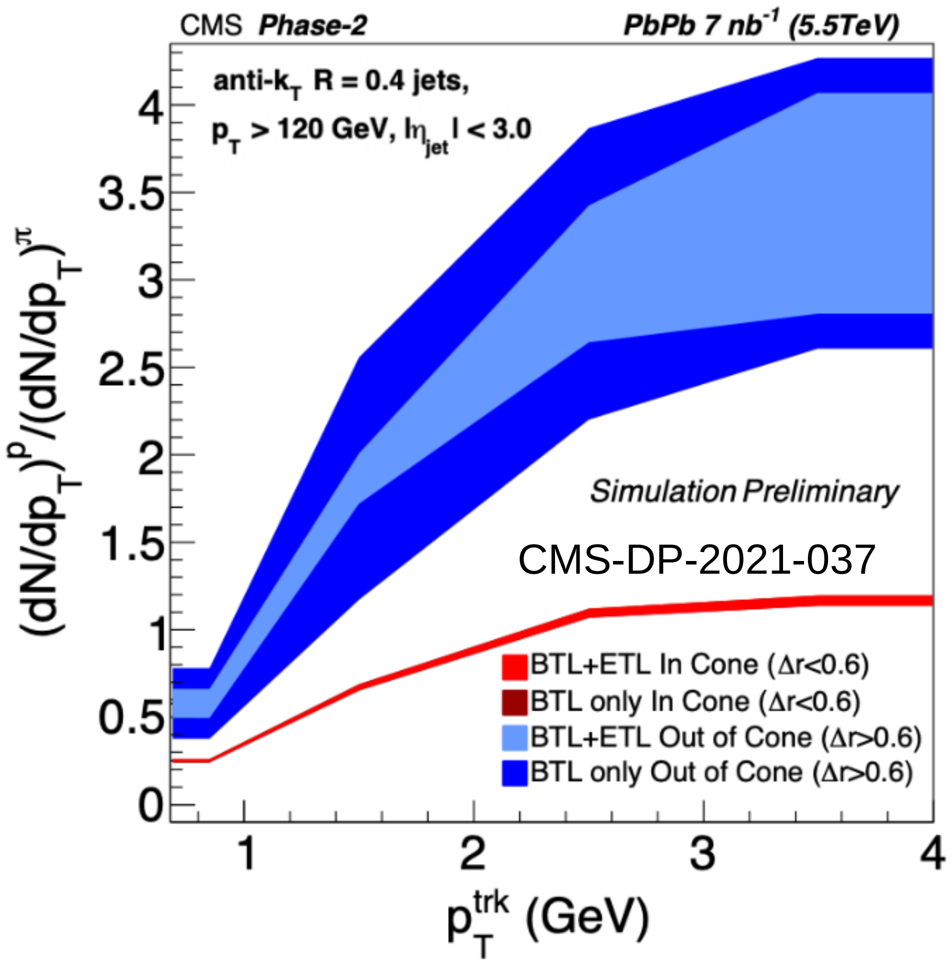
WG5 Report

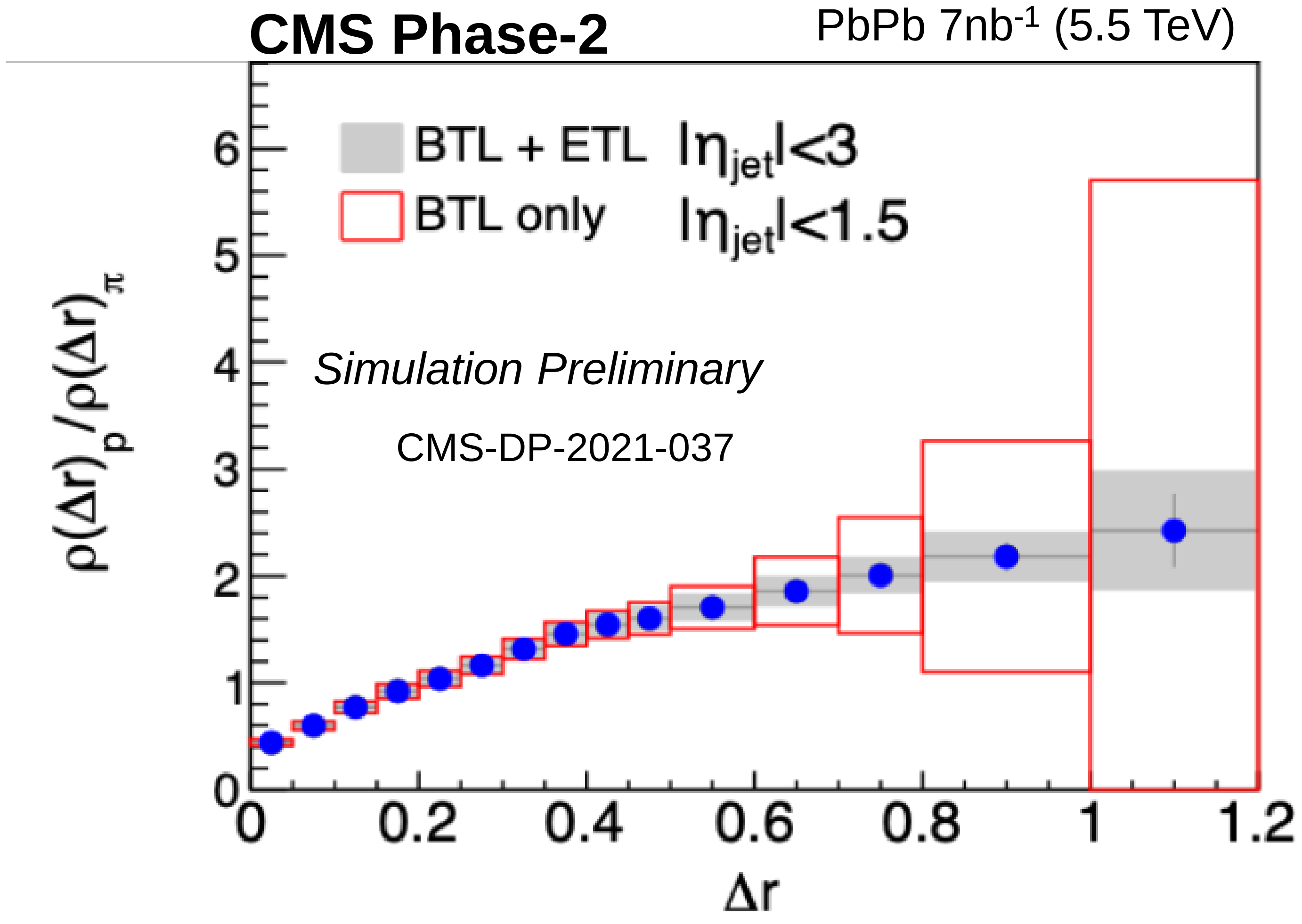
Year	Systems, $\sqrt{s_{NN}}$	Time	L_{int}
2021	Pb–Pb 5.5 TeV	3 weeks	$2.3\ nb^{-1}$
	pp 5.5 TeV	1 week	$3\ pb^{-1}$ (ALICE), $300\ pb^{-1}$ (ATLAS, CMS), $25\ pb^{-1}$ (LHCb)
2022	Pb–Pb 5.5 TeV	5 weeks	$3.9\ nb^{-1}$
	O–O, p–O	1 week	$500\ \mu b^{-1}$ and $200\ \mu b^{-1}$
2023	p–Pb 8.8 TeV	3 weeks	$0.6\ pb^{-1}$ (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	

CMS and ATLAS physics at Run3+4 and beyond

Jet Chemstery

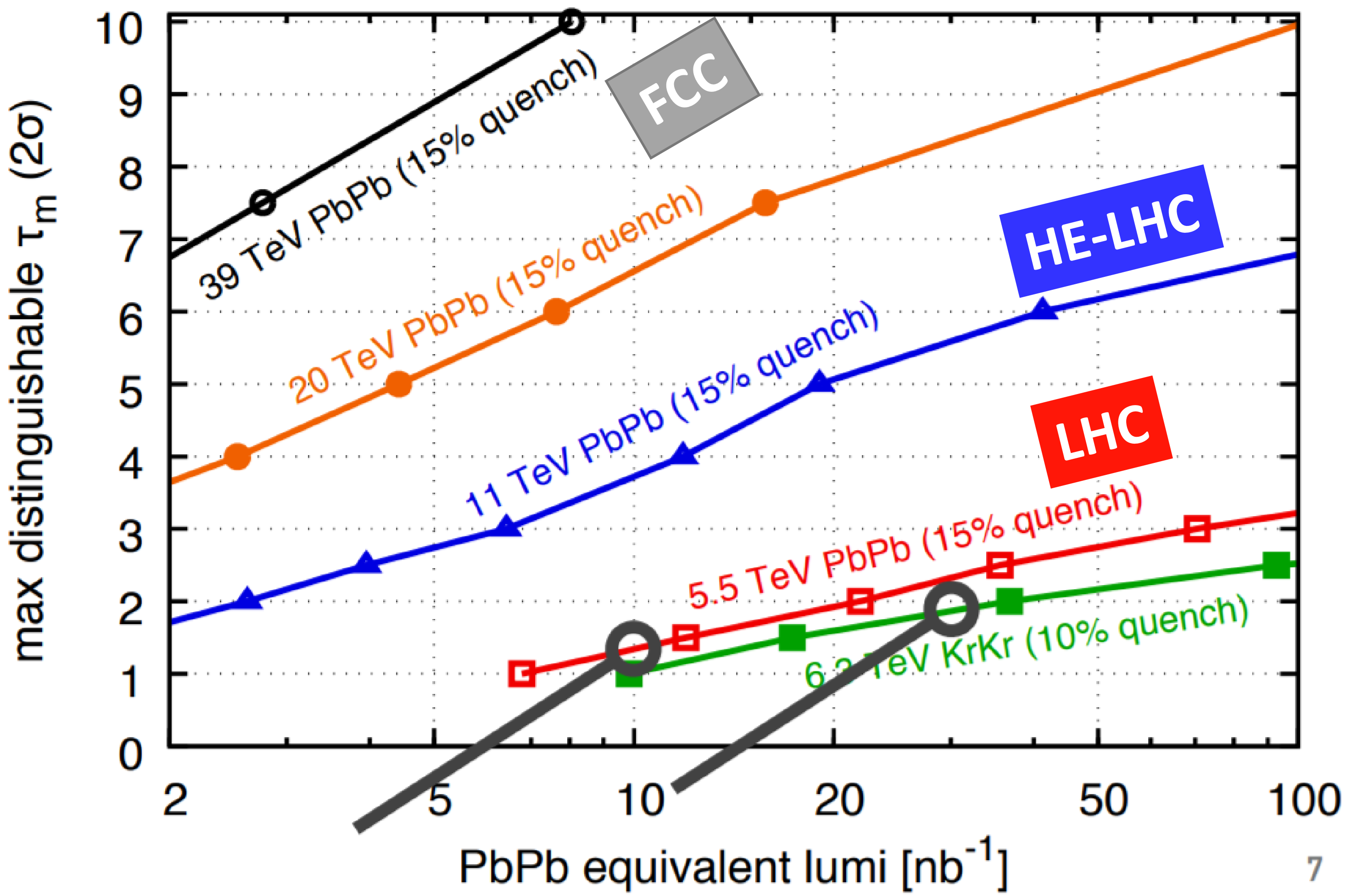
- In- and out-cone hadronizations, fragmentation vs. QGP-related effects
  - Enable measurements of jet – *identified* hadrons correlations with CMS
  - Precision access to large jet radius – benefits from large MTD coverage





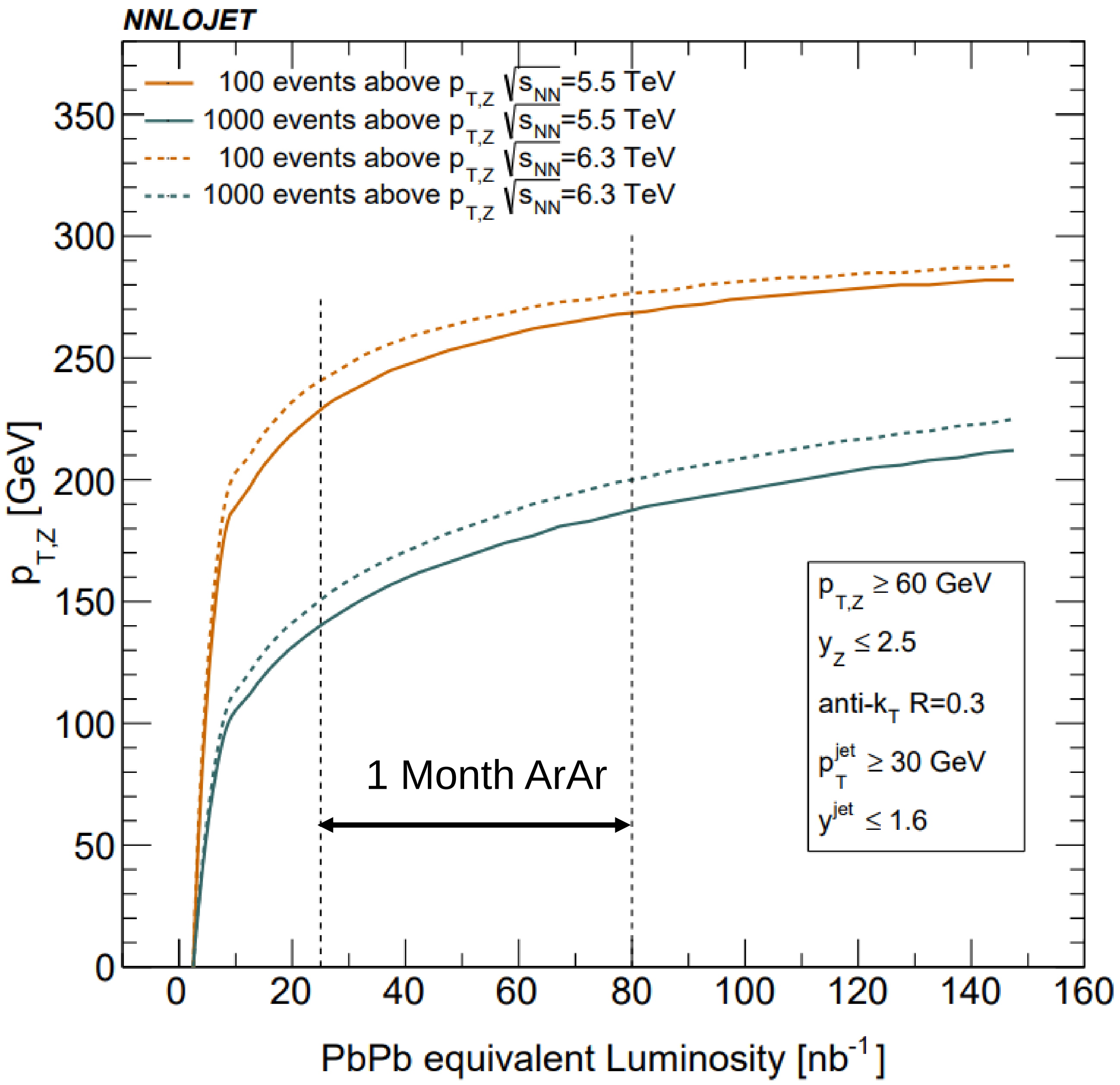
Sensitivity to the Medium End Time

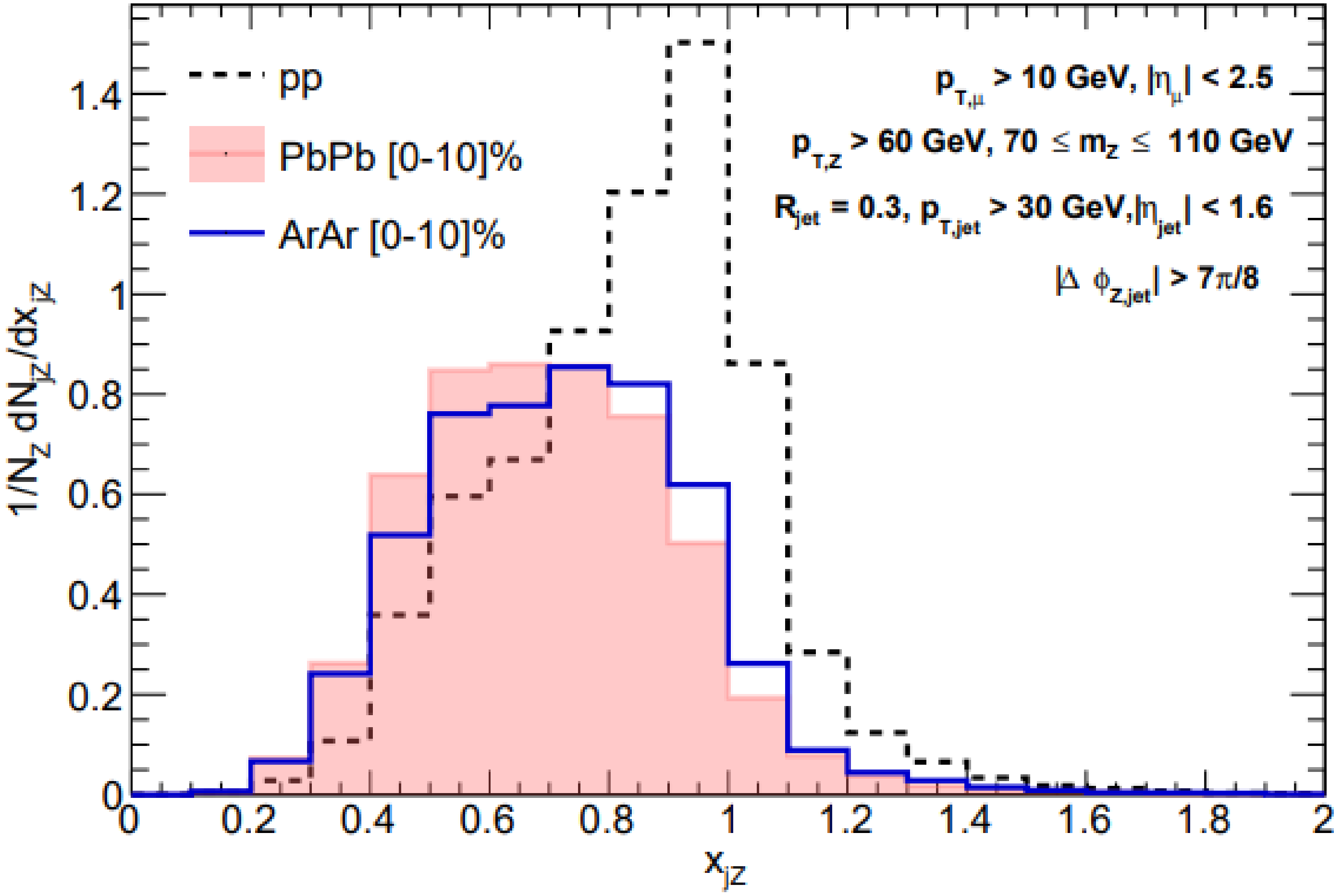
- Sensitivity to medium end time (τ_m):
  - HL-LHC PbPb Program (10 nb^{-1}): 1.4 fm/c
  - 1 month KrKr (30 nb^{-1}): 1.8 fm/c



Full exploitation of this probe only at **FCC energies**

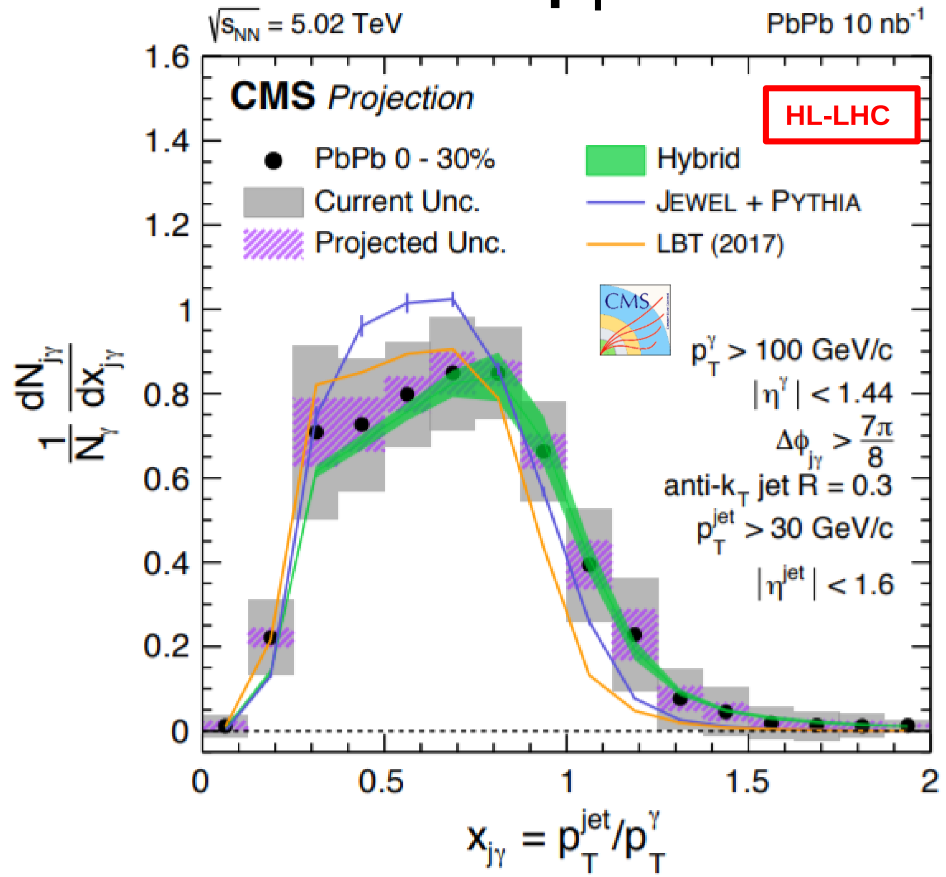
Expected Performance with Lighter Ions in Run 5



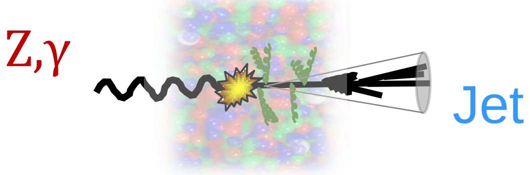


ArAr: a smaller collision system with still sizable jet quenching based on JEWEL

Photon-Jet p_T Ratio

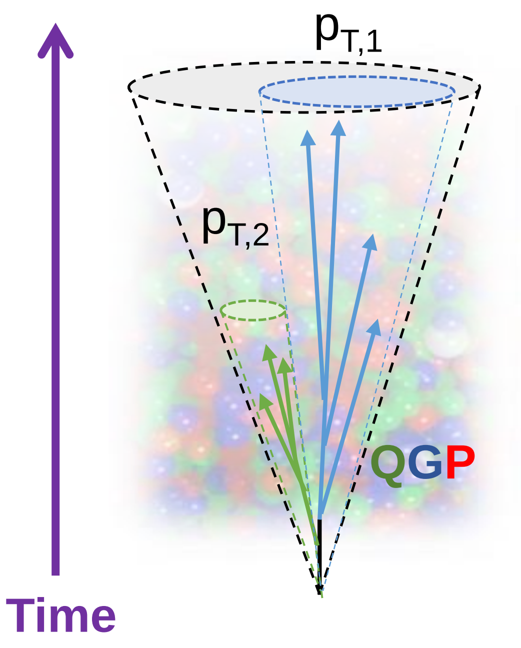


Transverse momentum conservation

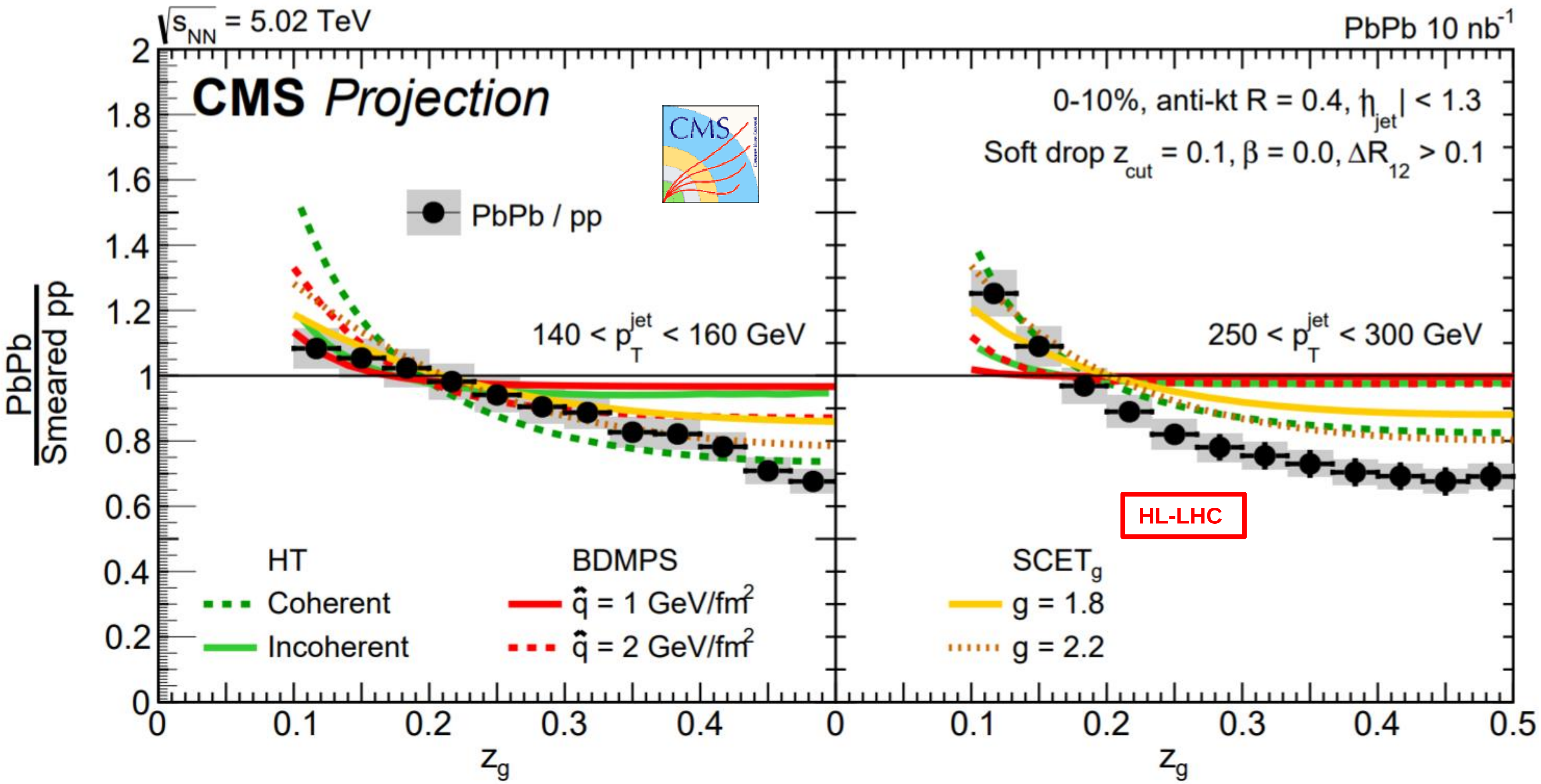


- Quenching reduces boson-jets p_T ratio
- High precision "**absolute energy loss**" measurement at HL-LHC

Subjet Momentum Sharing in PbPb



$$z_g = \frac{p_{T,2}}{p_{T,1} + p_{T,2}}$$



- New era of jet substructure fluctuation studies: **constraints on the QGP scattering power with a completely orthogonal observable** (vs. jet or hadron spectra)
- Grooming techniques enable us to classify jets and to study **"Parton Shower Shape Dependence of Jet Quenching"**