Time-of-flight PID upgrade of CMS for hard probes in dense QCD matter in the high-luminosity LHC era

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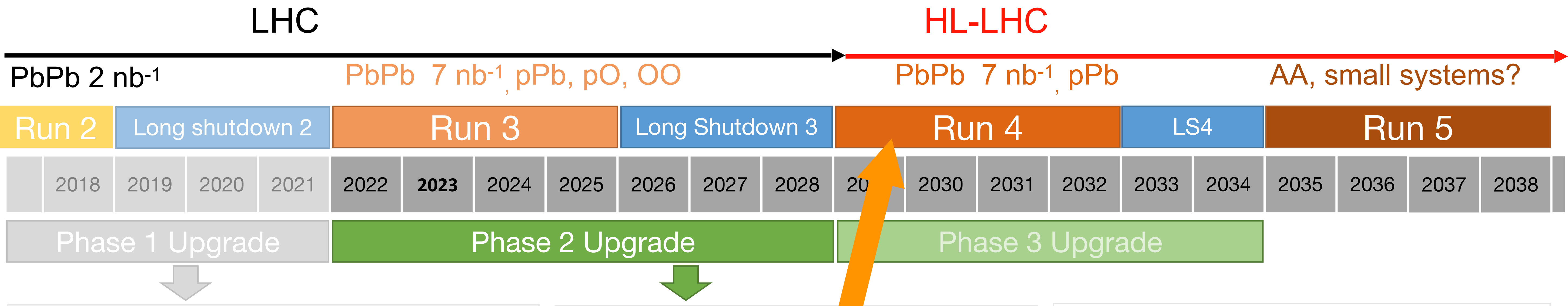
For the CMS Collaboration

Laboratory for Nuclear Science

12th International Conference on Hard and Electromagnetic Probes of High-Energy Nuclear Collisions, Nagasaki, Japan

MIT HIG is supported by US DOE-NP

LHC Timeline and CMS Upgrades



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 30 GB/s (in 2024)
  - 50 kHz MinBias rate (6x of 2018)
  - 30 kHz UPC

CMS Phase 2 for Run 4

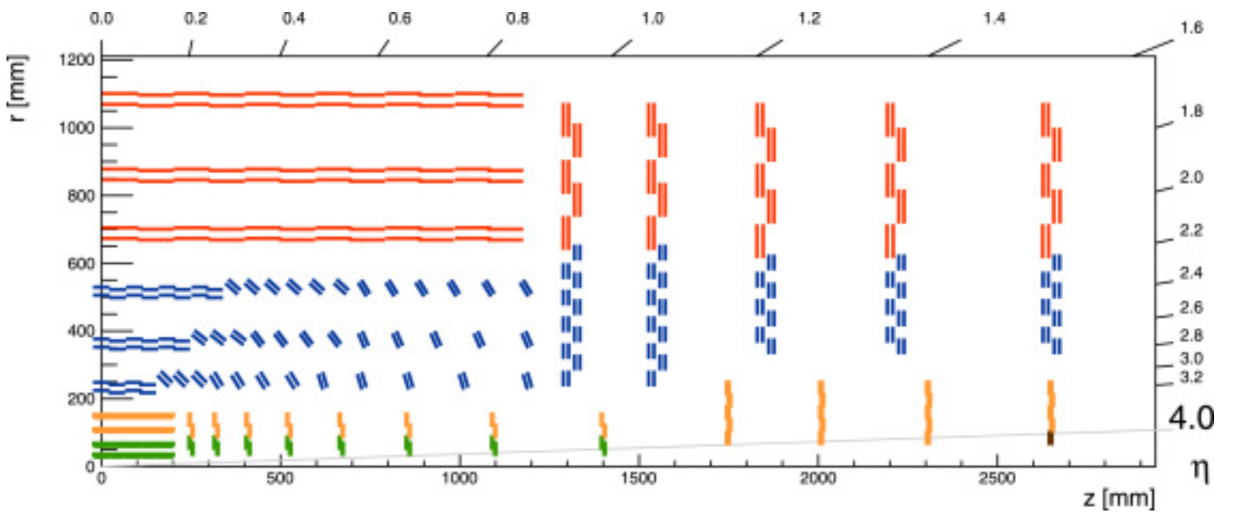
- Tracker **$|\eta|<4$**
- Muon ID up to **$|\eta|<2.8$**
- High Granularity Calorimeter
- MIP timing detector
  - 4D vertexing (x, y, z, t)
  - **p/K/π PID (CMS MTD)**
- L1 trigger update: 750 kHz for CMS
- DAQ: 60 GB/s for CMS
- L1 track triggers
- ZDC

CMS Run 5

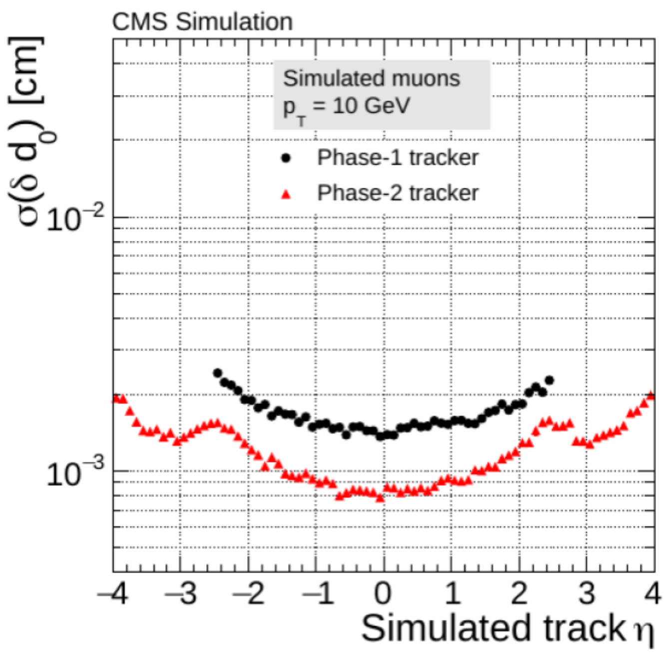
- Record smaller ion collisions at the highest rate delivered by LHC
- Possible further upgrade to be defined, e.g.:
  - Additional timing layers
  - Forward calorimeters
  - Extend muon coverage
  - …

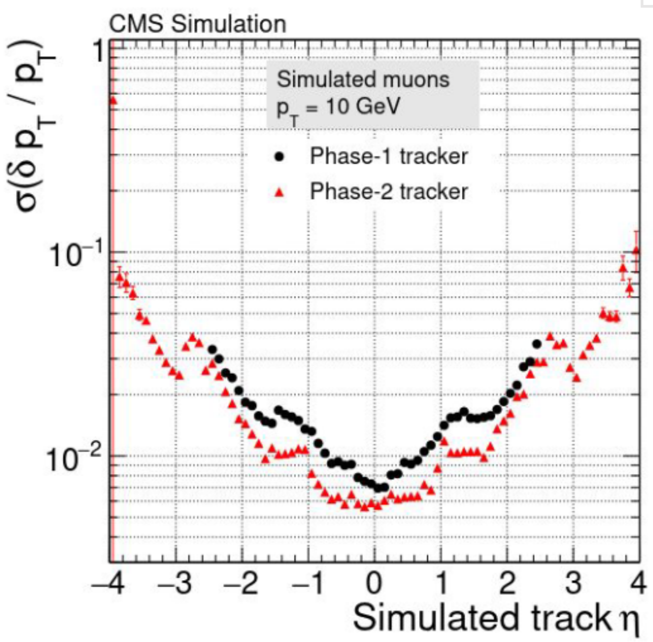
Phase 2 upgrade: Tracking System

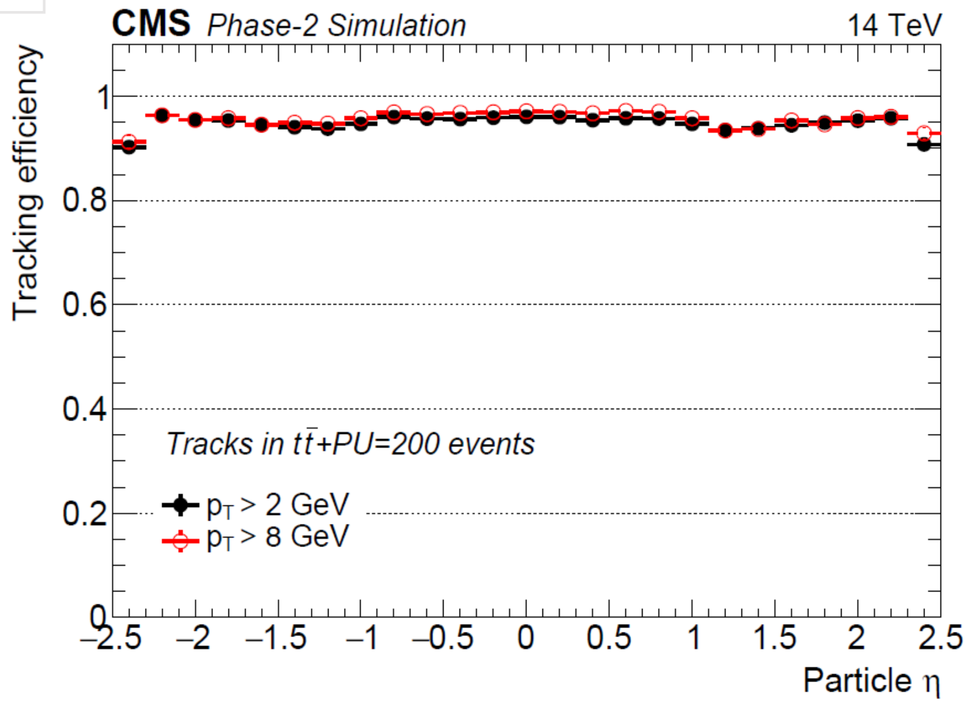
- Charged particle reconstruction up to **|η|<4**
- At <Pile-Up>=200 (heavy-ion like):
  - Efficiency > 90%, fake rate < 3%
- Significantly better p_T and d_0 resolution
  - Improvement on HF hadron and b/c-jet tagging
  - Level-1 track trigger



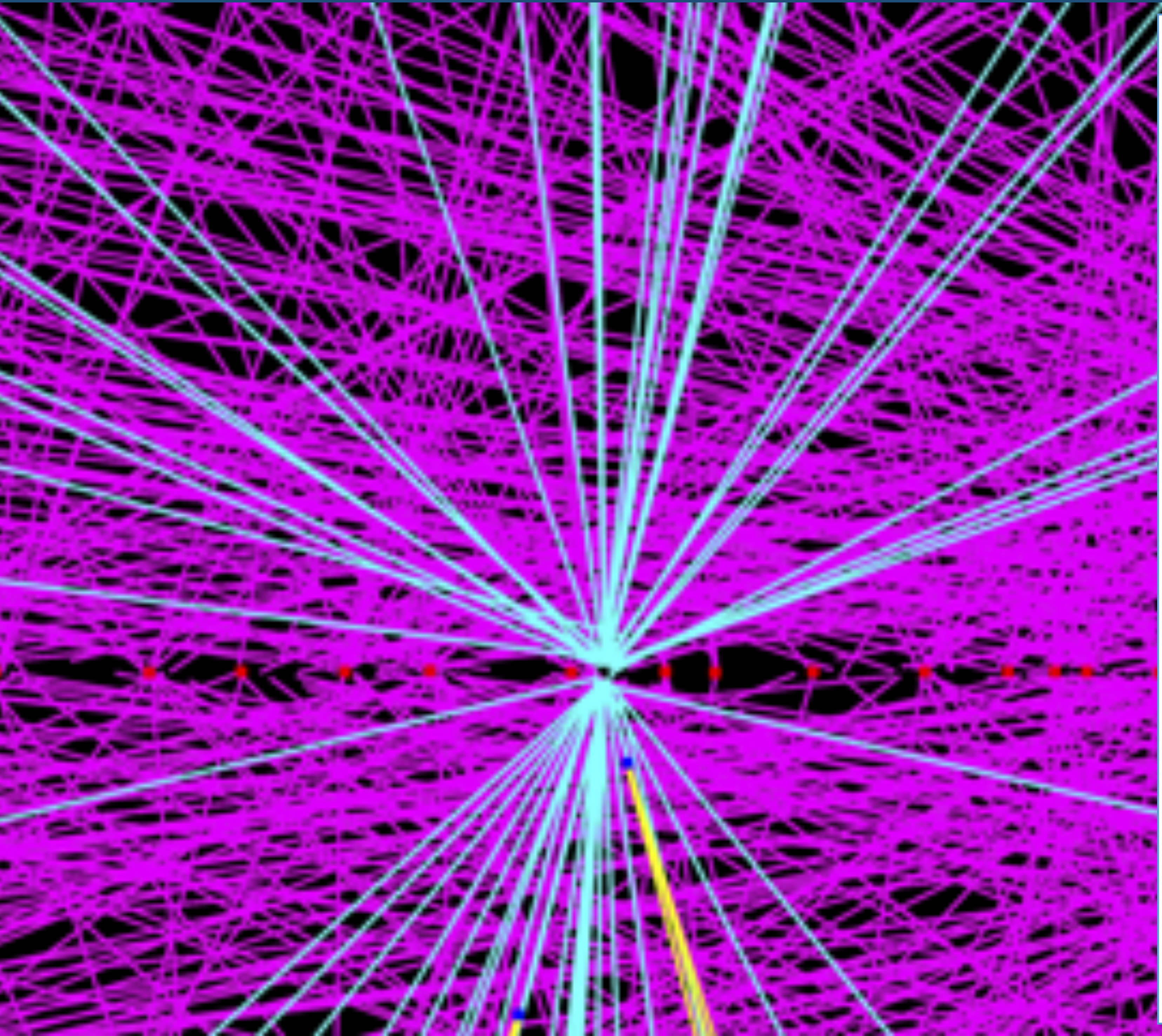
CMS-TDR-014

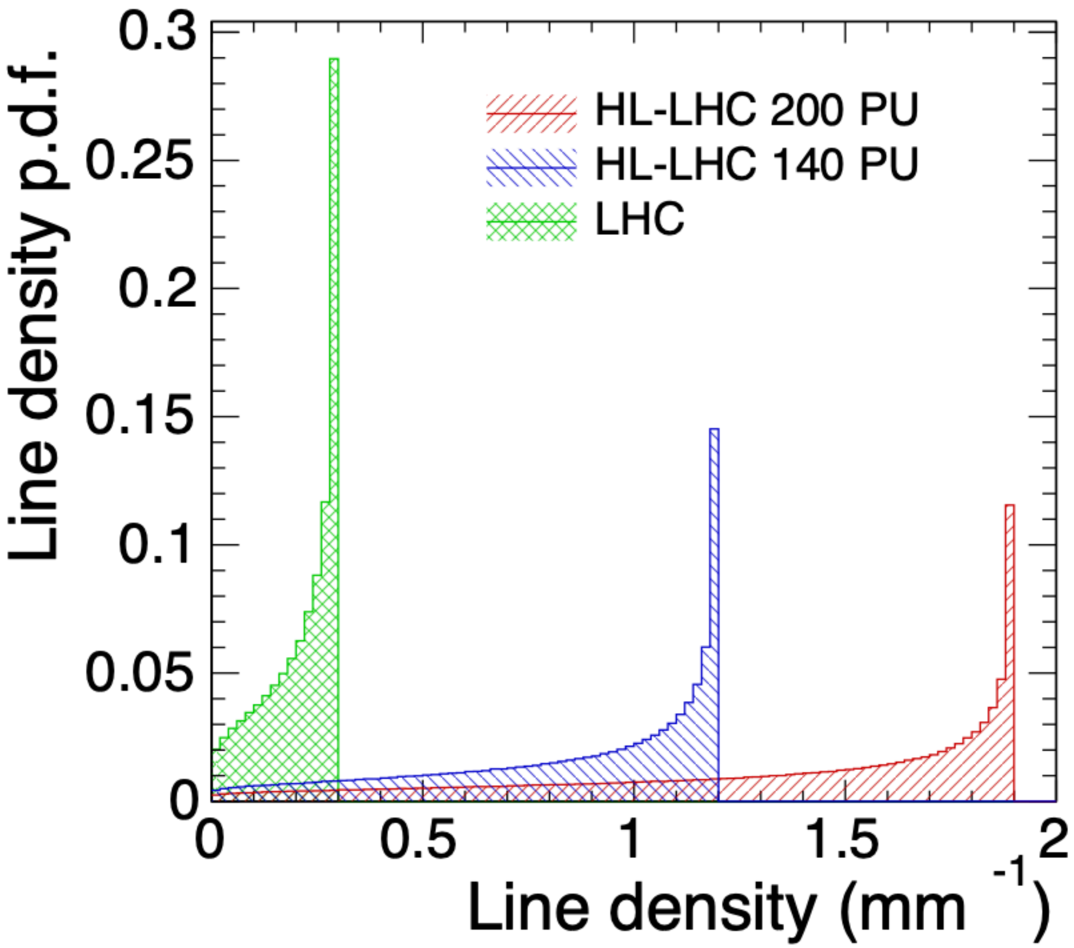






"4D" Tracking in pp at the HL LHC



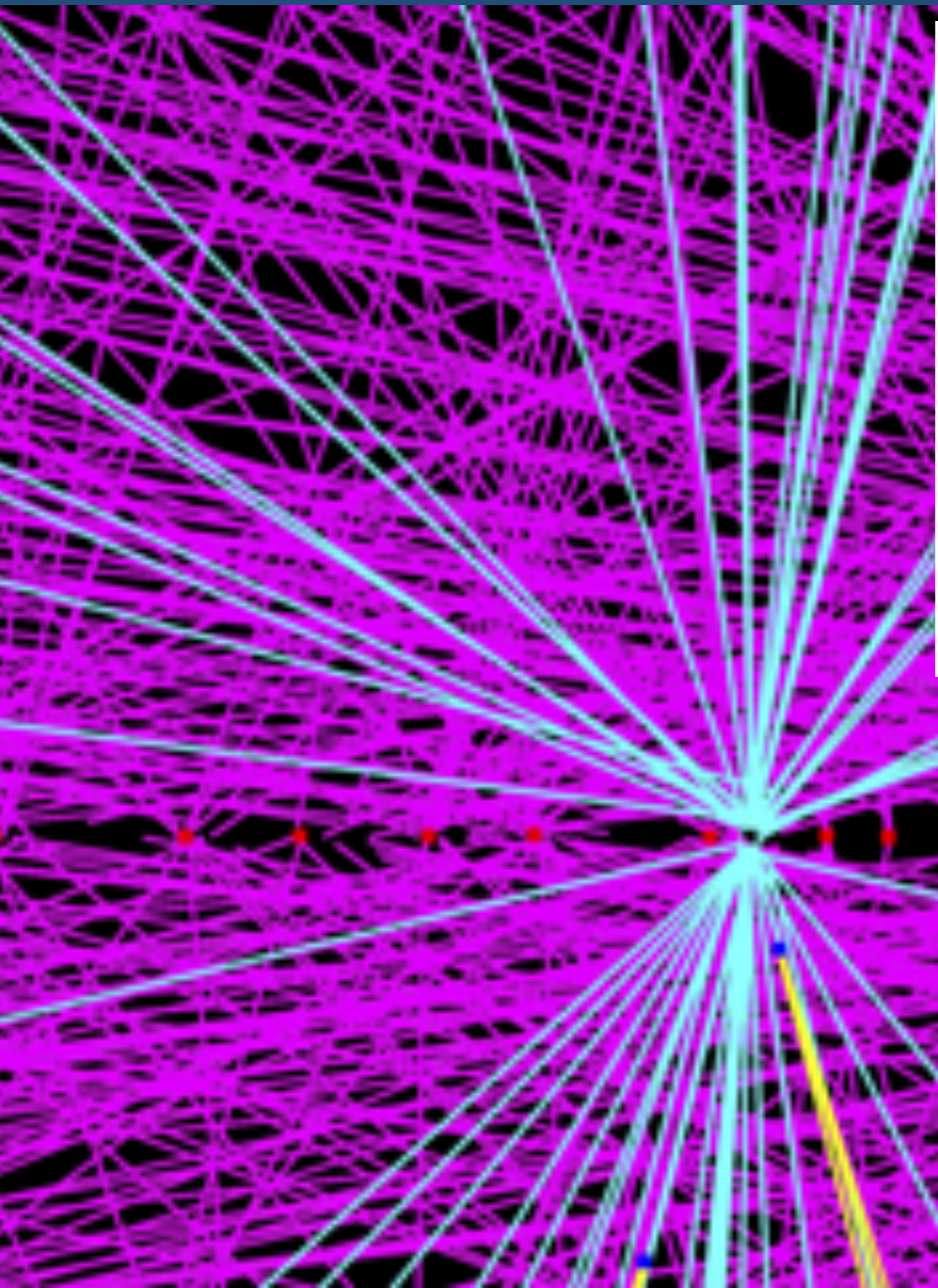


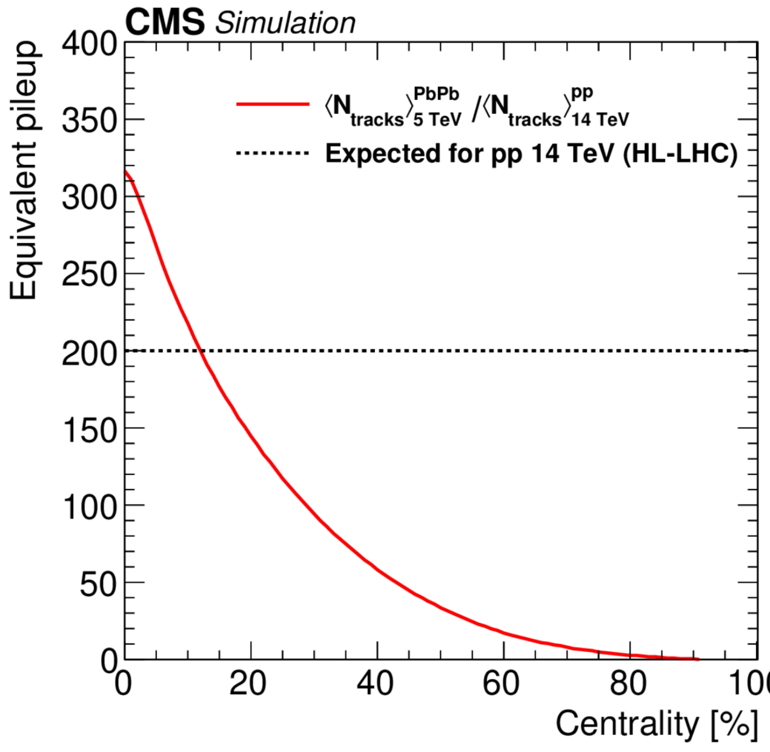
HL-LHC: Increase luminosity to 5×10^{34}/cm$^{-2} \cdot$ s^{-1}

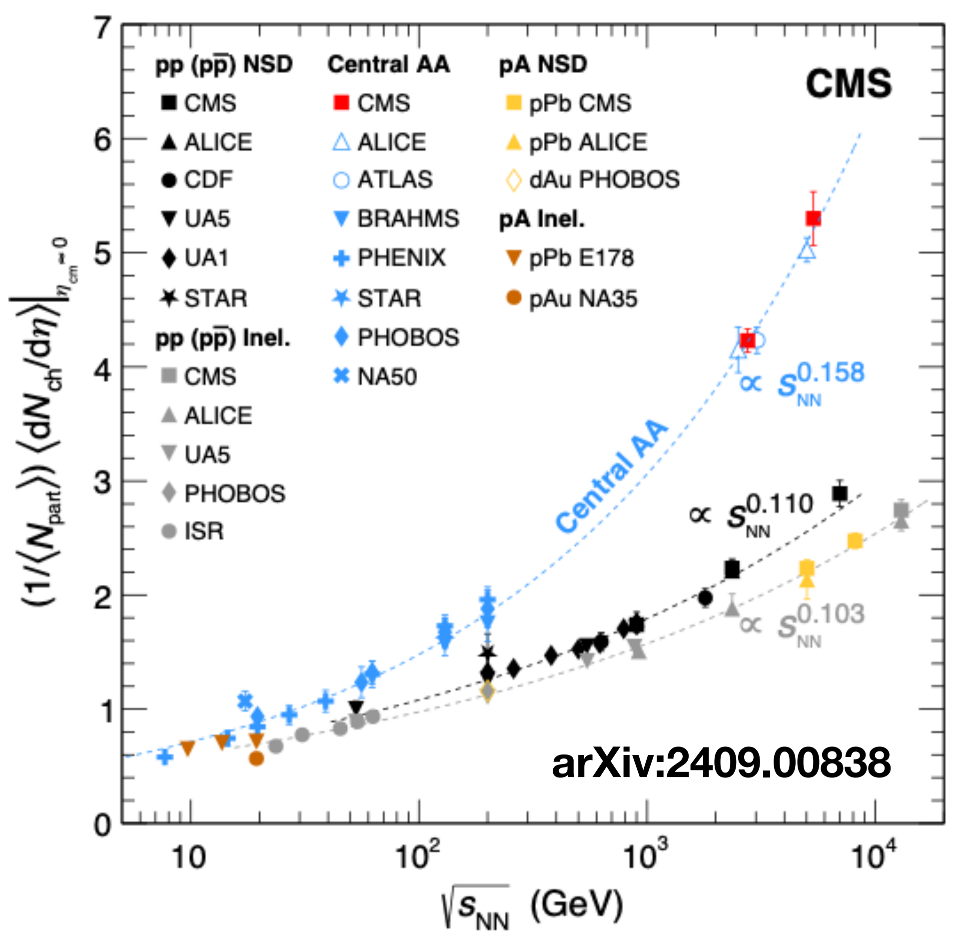
→ average pileup of 140 (up to 200)

→ Line density of pileup vertices comparable to optimal track-vertex association window - O(mm)

“4D” Tracking in pp at the HL LHC





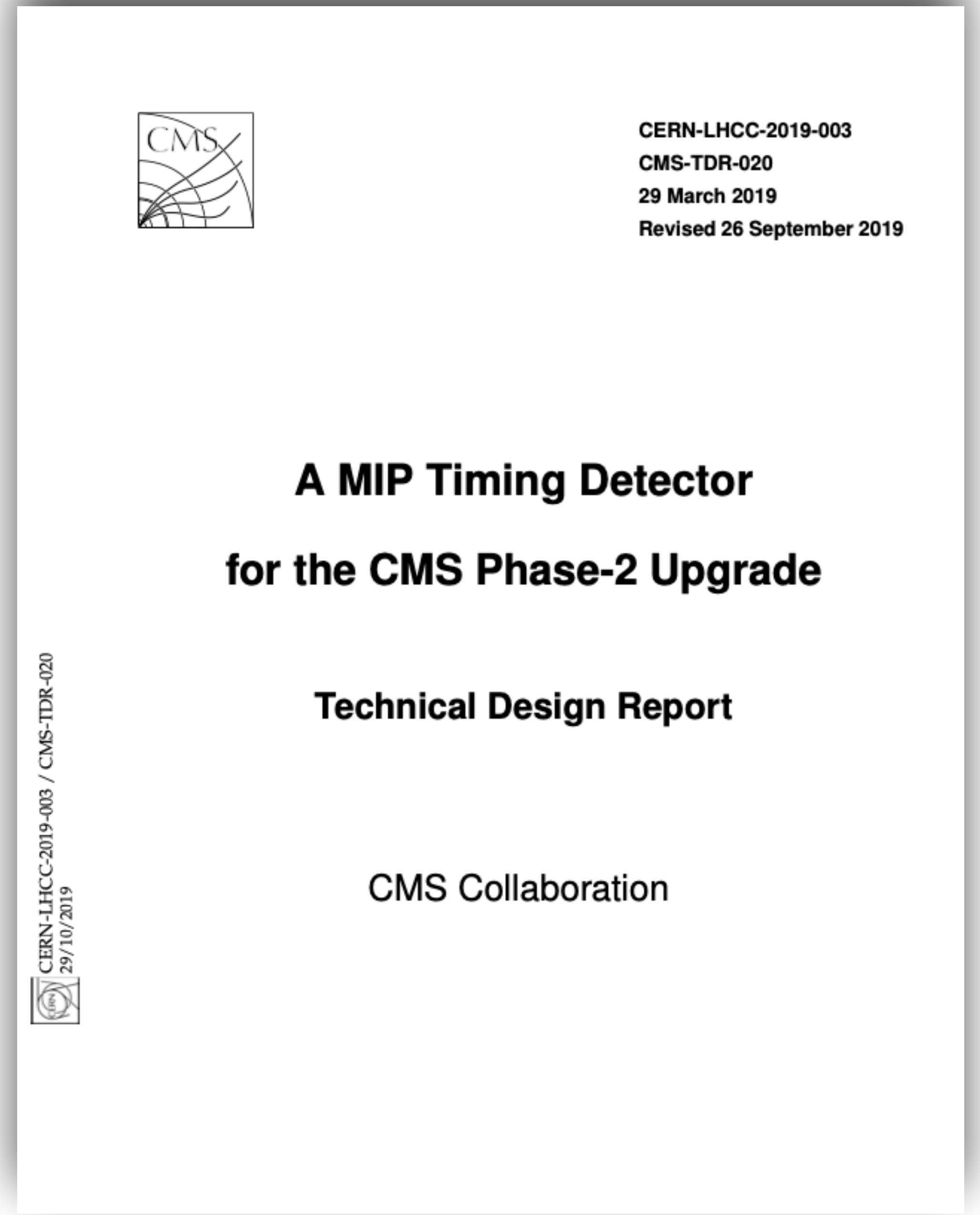


HL-LHC: Increase luminosity to $5 \times 10^{34} / \mathrm{cm}^{-2} \cdot \mathrm{s}^{-1}$

→ average pileup of 140 (up to 200)

→ total number of particles per bunch crossing similar to PbPb at 5.36 TeV

Phase 2 upgrade: MIP Timing Detector (MTD)


CERN-LHCC-2019-003
CMS-TDR-020
29 March 2019
Revised 26 September 2019

A MIP Timing Detector

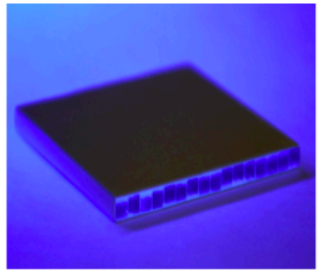
for the CMS Phase-2 Upgrade

Technical Design Report

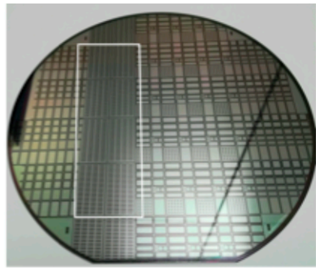
CMS Collaboration

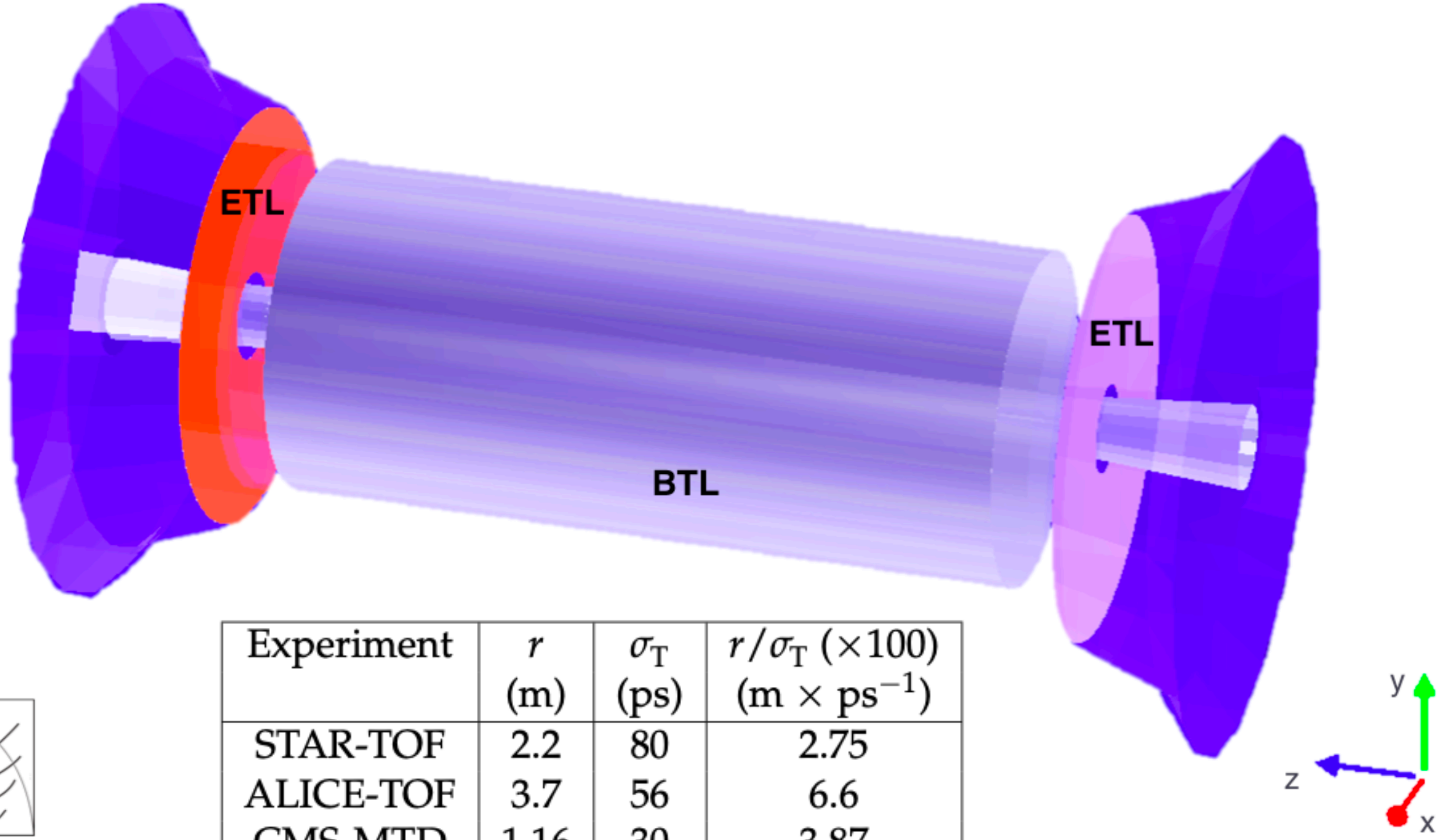
CERN-LHCC-2019-003 / CMS-TDR-020
29/10/2019

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



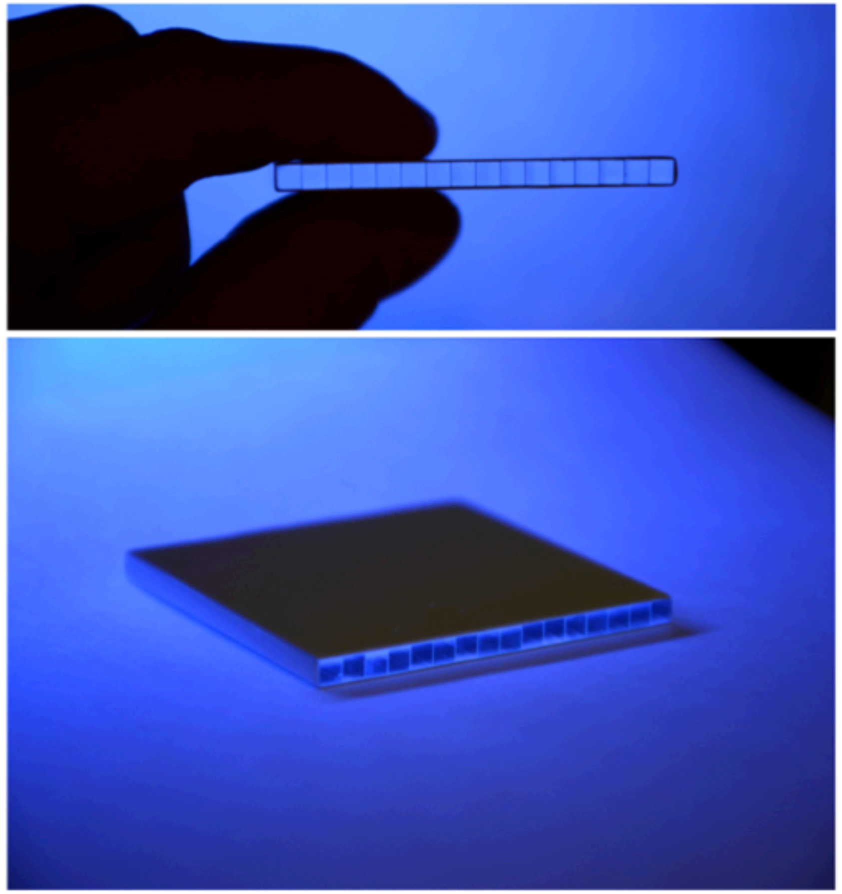
ETL: Si with internal gain (LGAD):
- On the CE nose: $1.6 < |\eta| < 3.0$
- Radius: 315 < R < 1200 mm
- Position in z: ±3.0 m (45 mm thick)
- Surface ~14 m^2; ~8.5M channels
- Fluence at 4 ab^{-1}: up to $2x10^{15}$ n_{eq}/cm^2

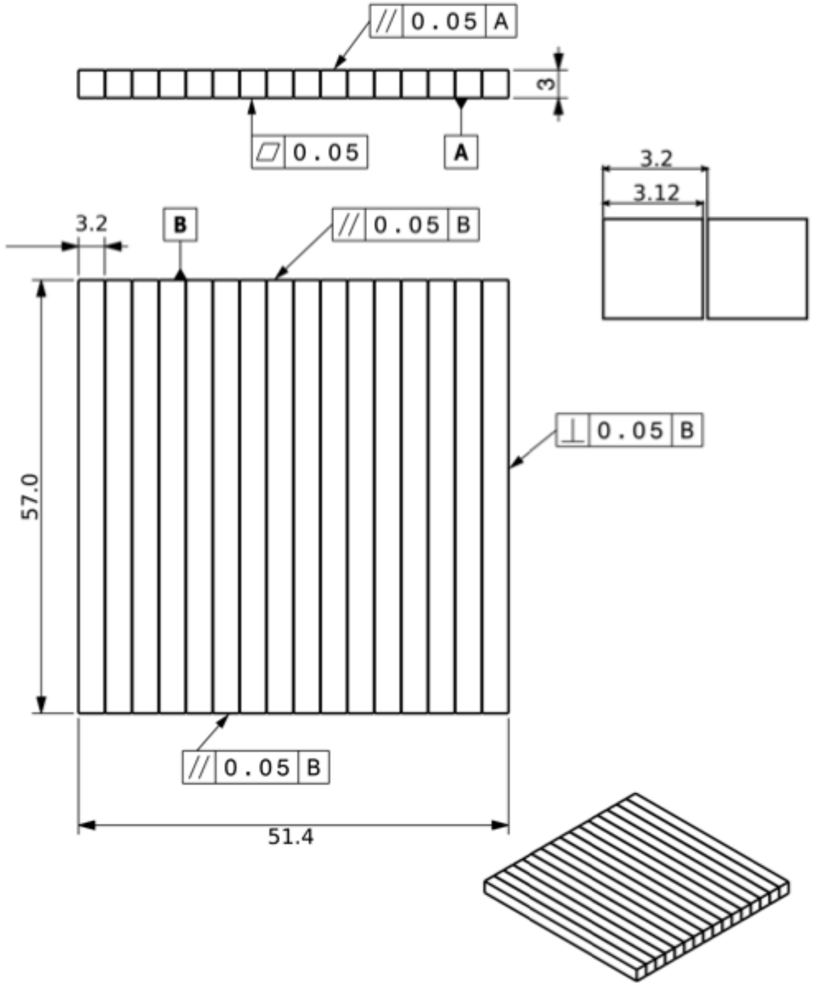




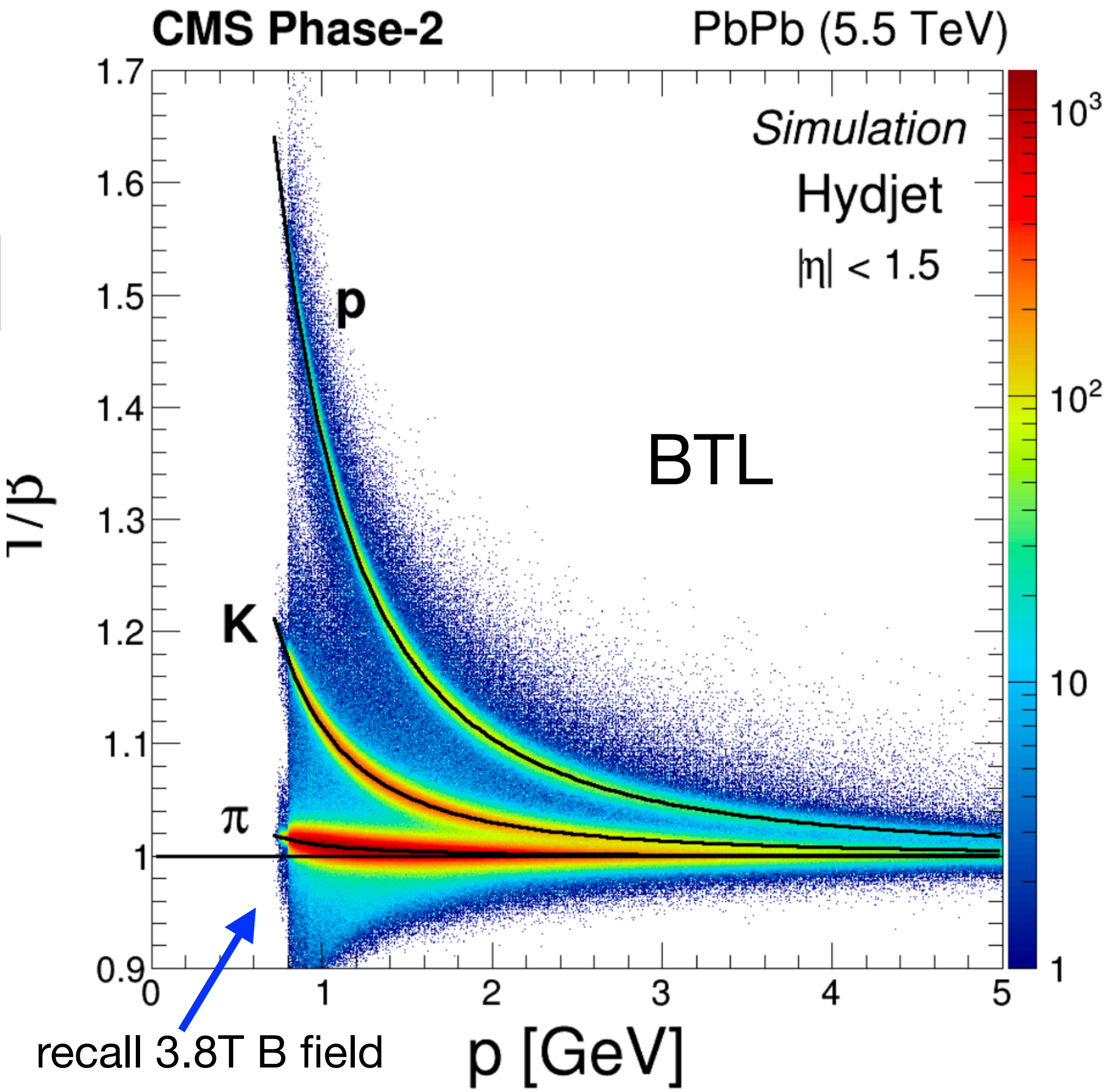
Experiment	r (m)	σ_T (ps)	r/σ_T ($\times 100$) ($m \times ps^{-1}$)
STAR-TOF	2.2	80	2.75
ALICE-TOF	3.7	56	6.6
CMS-MTD	1.16	30	3.87

MTD: Barrel Timing Layer (BTL)

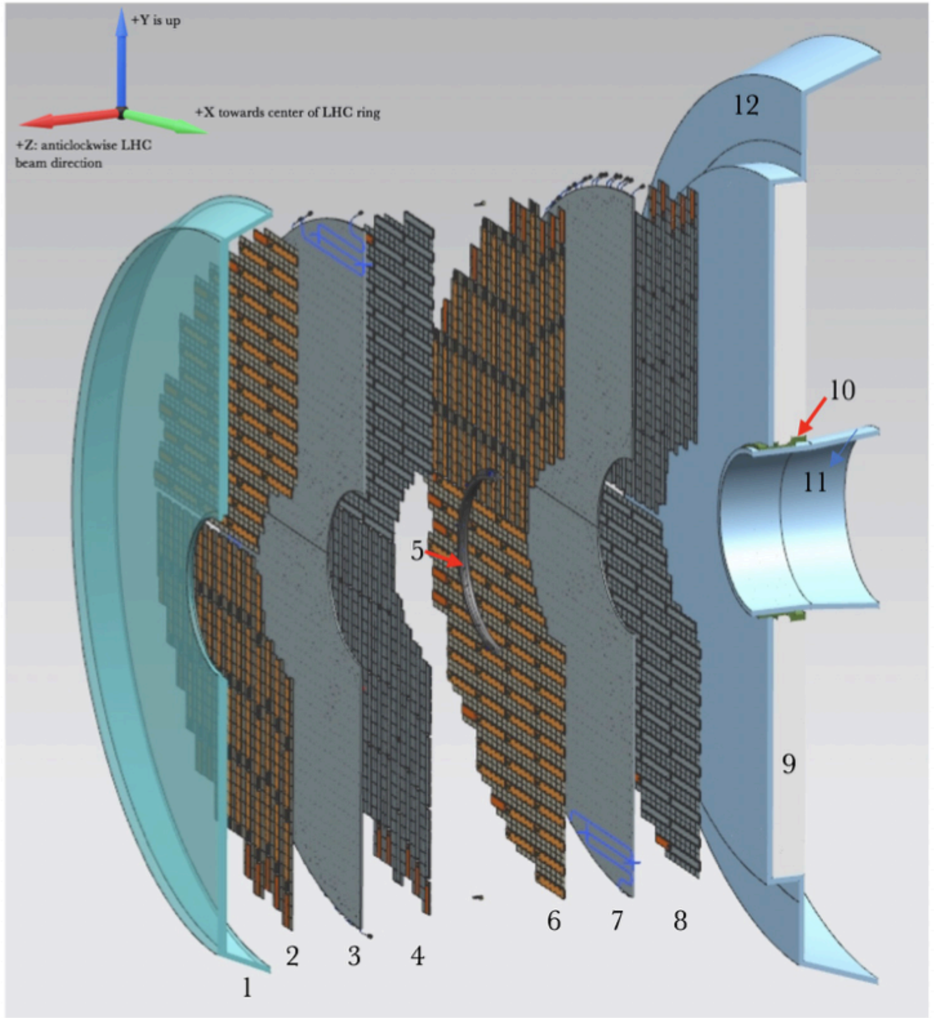




57mm LYSO bars w/ SiPM readout



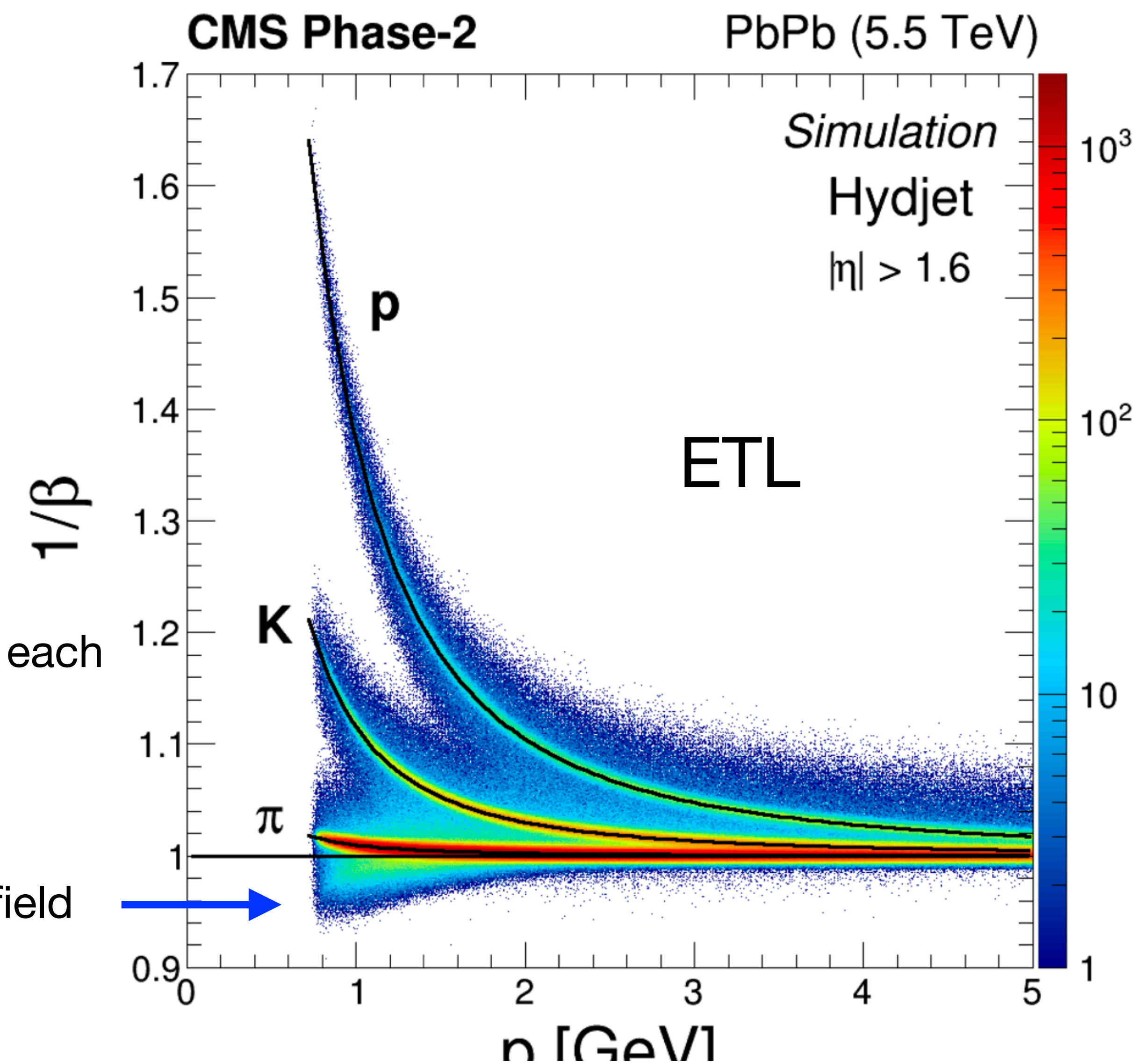
MTD: Endcap Timing Layer (ETL)



1: ETL Thermal Screen
2: Disk 1, Face 1
3: Disk 1 Support Plate
4: Disk 1, Face 2
5: ETL Mounting Bracket
6: Disk 2, Face 1
7: Disk 2 Support Plate
8: Disk 2, Face 2
9: HGCal Neutron Moderator
10: ETL Support Cone
11: Support cone insulation
12: HGCal Thermal Screen

Si LGAD sensors
8000 modules with 4 sensors each
8M channels

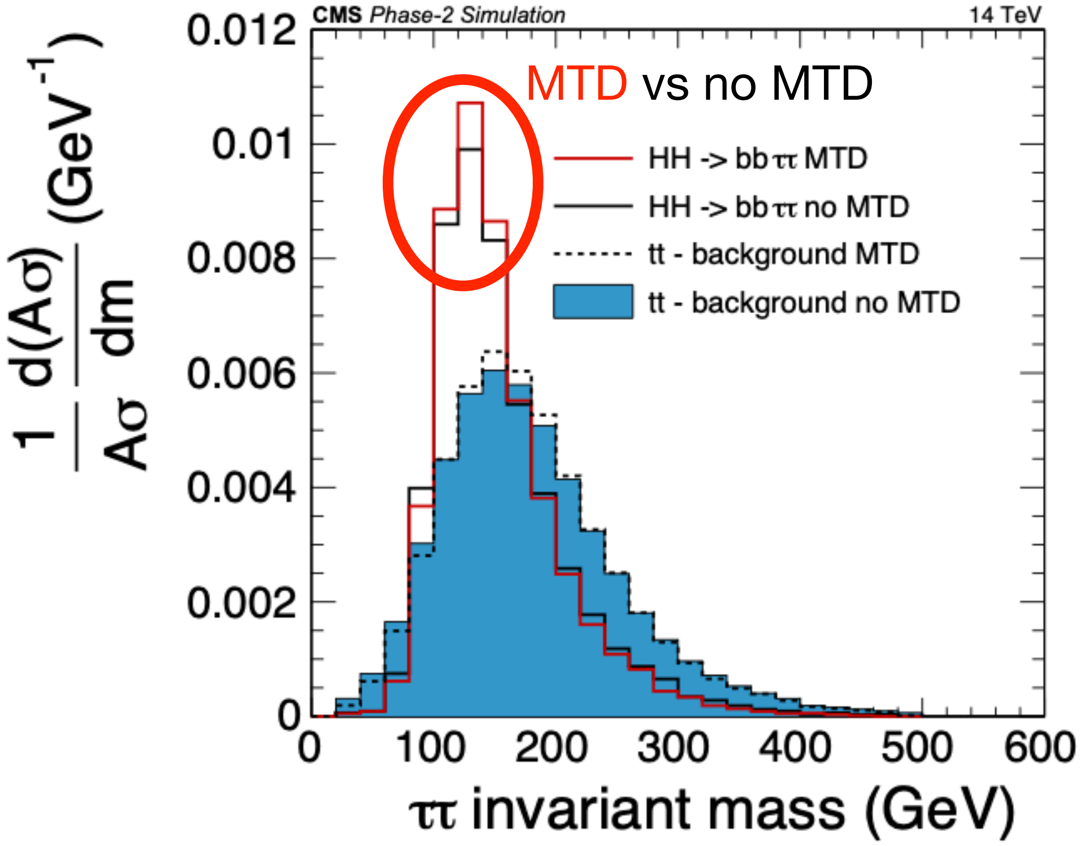
recall 3.8T B field

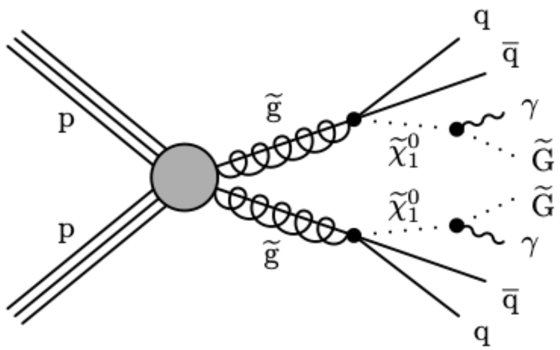


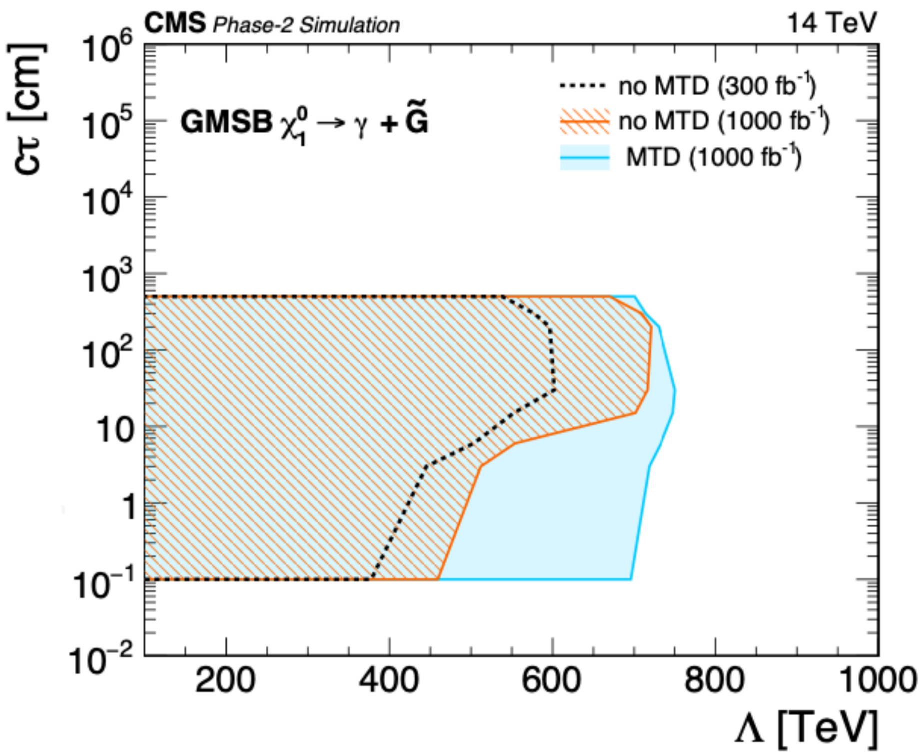
CMS HI effort on ETL supported by US DOE

UIC RICE Laboratory for Nuclear Science THE UNIVERSITY OF KANSAS OAK RIDGE National Laboratory

MTD Physics Impact - pp







	Expected significance	
Di-Higgs decay	No MTD	MTD
bbbb	0.88	0.94
bb$\tau\tau$	1.3	1.48
bb$\gamma\gamma$	1.7	1.83
bbWW	0.53	0.58
bbZZ	0.38	0.42
Combined	2.4	2.63

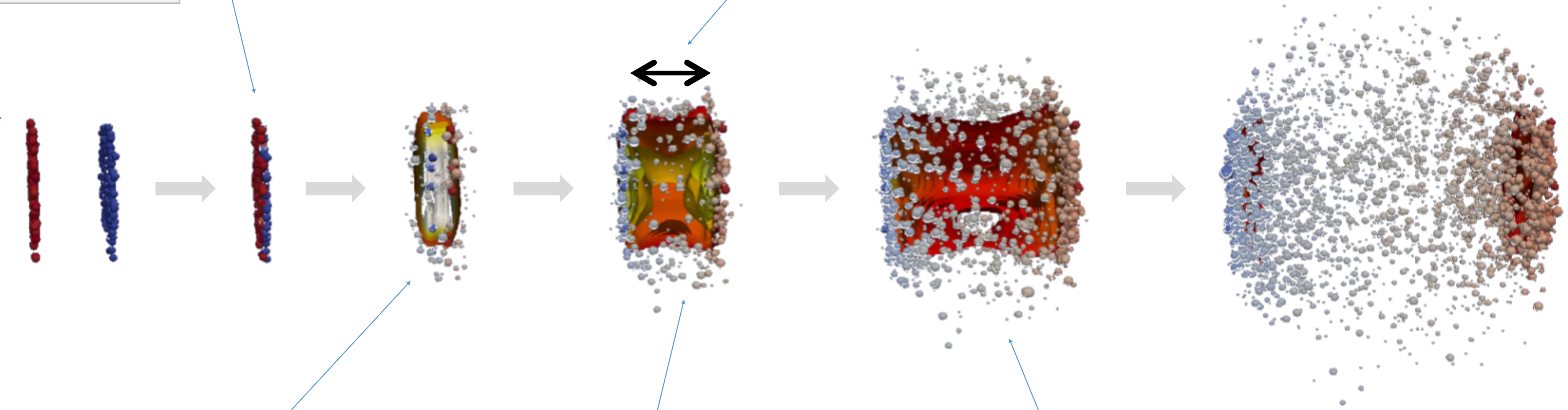
MTD Physics Impact - heavy ions

Initial conditions

QGP longitudinal structure

Hadronization mechanism

nPDF and initial EM field



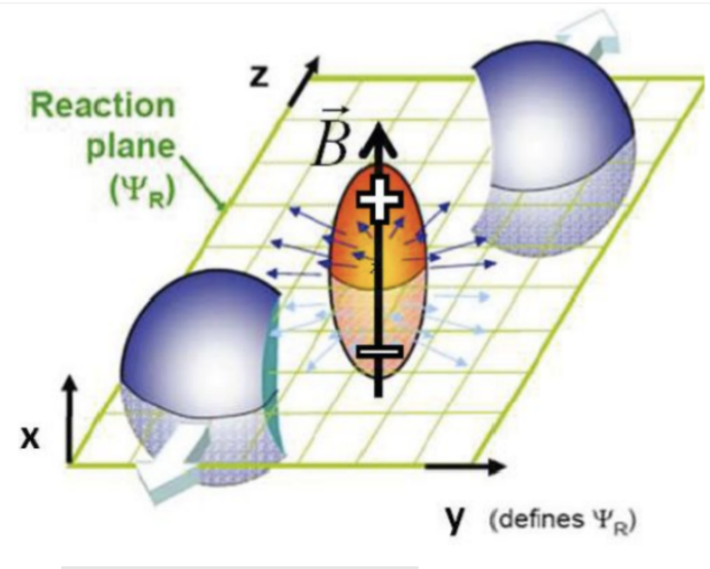
Hydrodynamization

QGP Transport properties
QGP response to hard probes
Microscopic structure of QGP

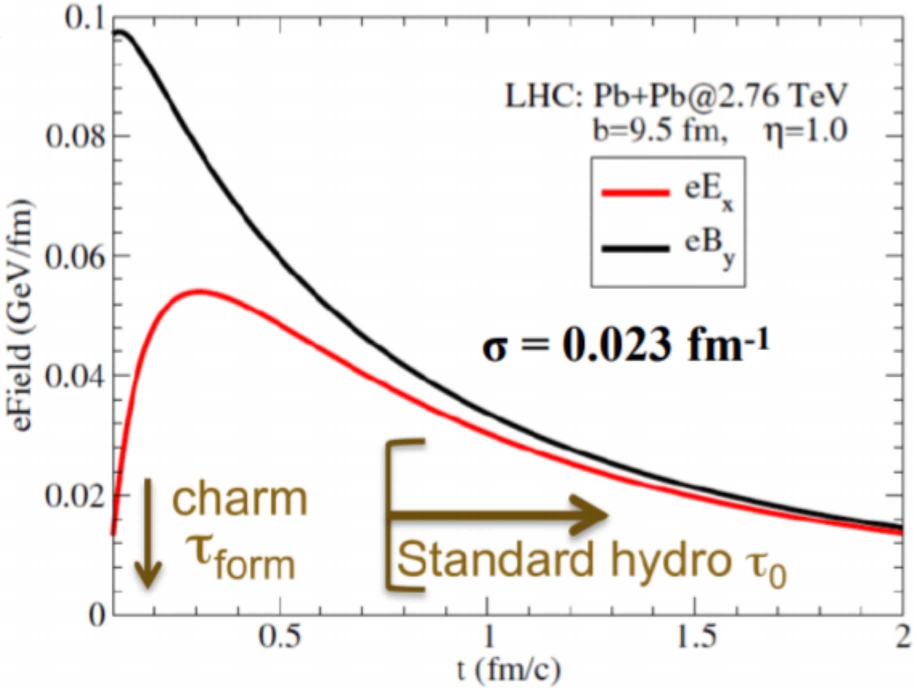
In-medium color force

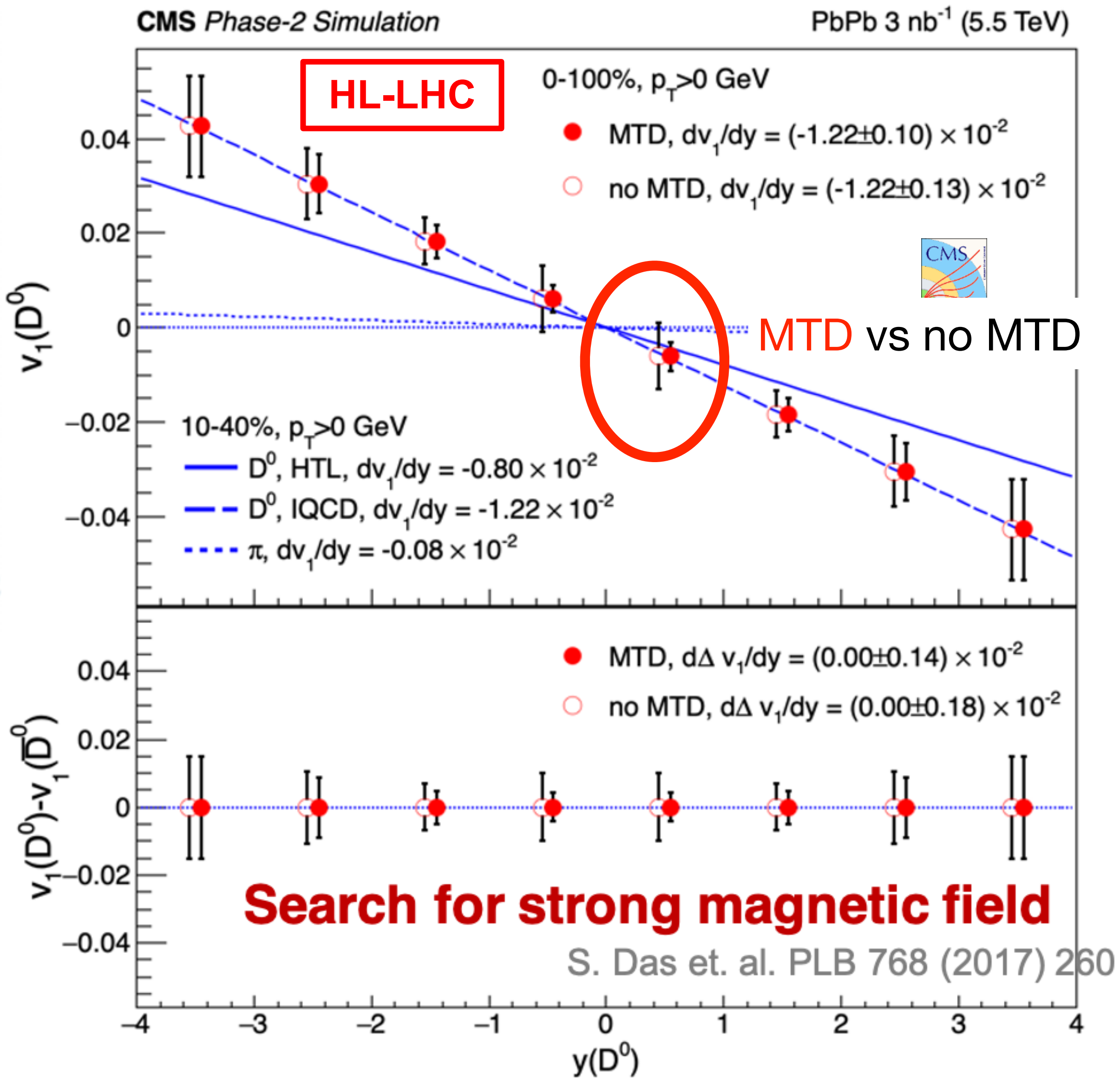
Visualization taken from Jonah E. Bernhard
arXiv:1804.06469

Initial EM Fields



CMS DP_2021_037

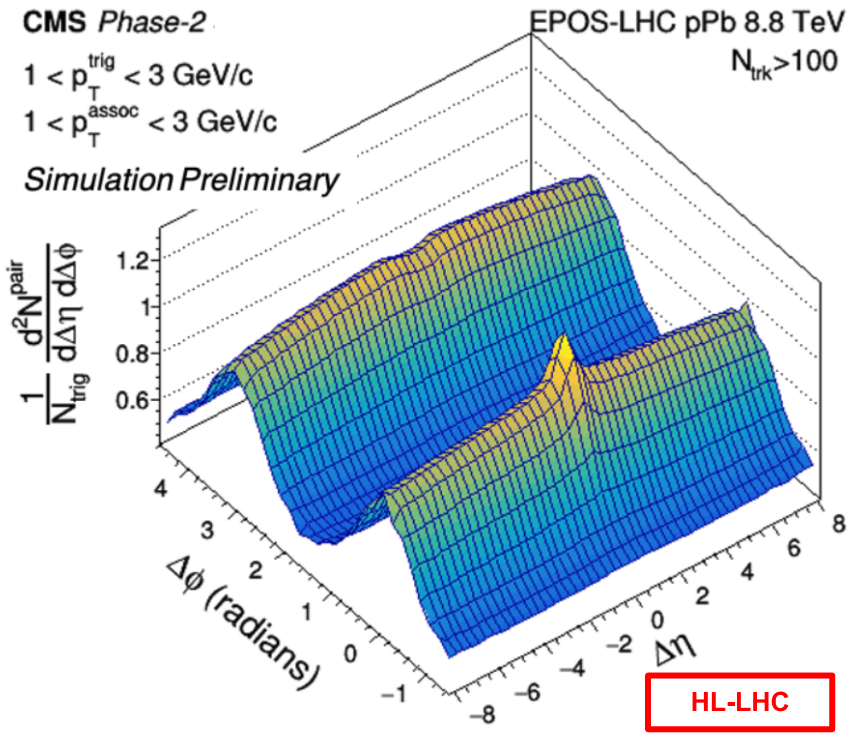




- Initial EM fields result in significant D^0 directed flow (v_1) with characteristic rapidity dependence
- MTD + CMS tracker provide precise measurement of D^0 v_1 over **8 units** of D^0 rapidity.

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

QGP: Longitudinal structure

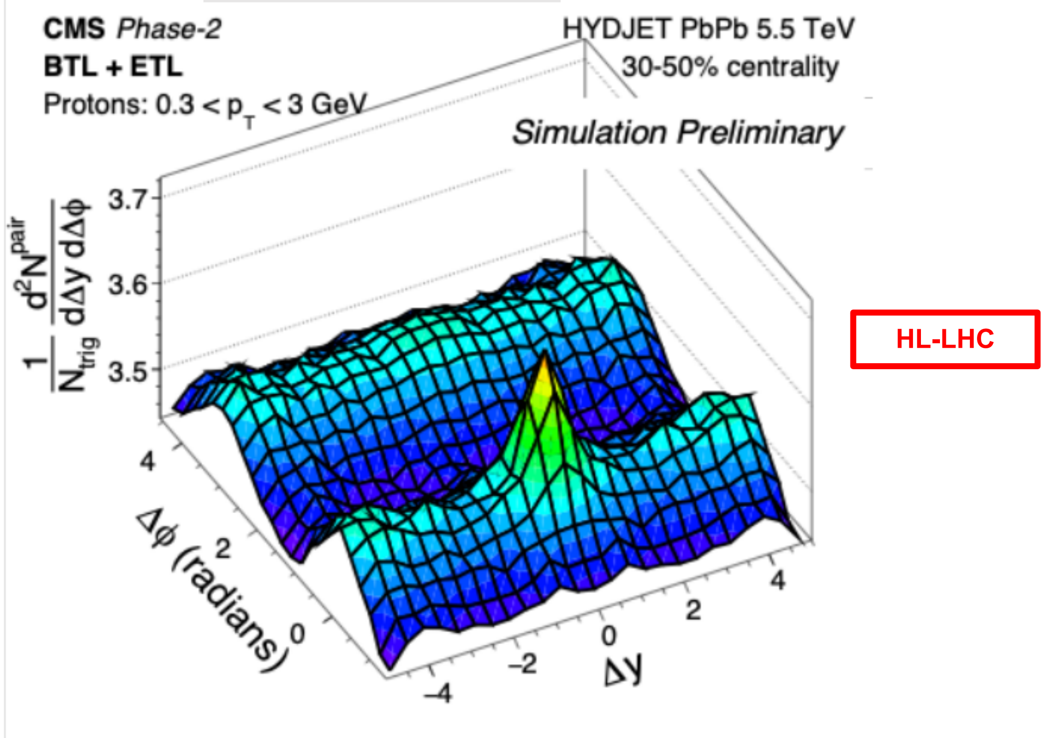


arXiv: 2111.0814

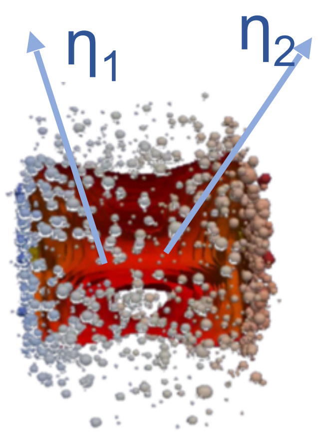
CMS DP2021_037

|Δη| up to **8**

CMS DP_2021_037

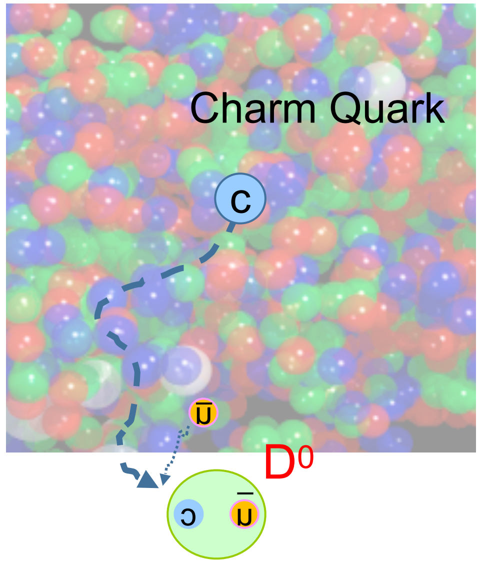


MTD: Proton correlations over |Δη| to ~**5**

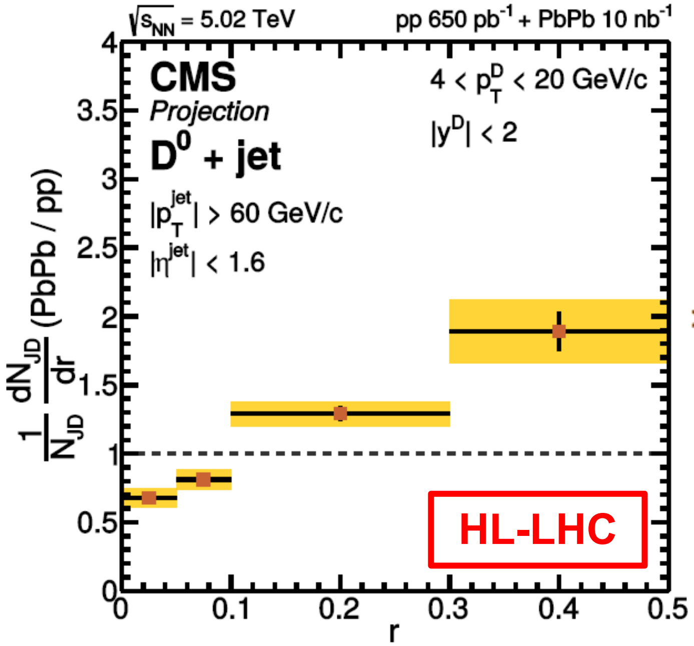


- Pseudorapidity dependence of the flow measurements over **a wide η window** enabled by CMS tracker upgrade
  New insights into the longitudinal structure of QGP (event-plane decorrelation)

QGP: In-medium color force

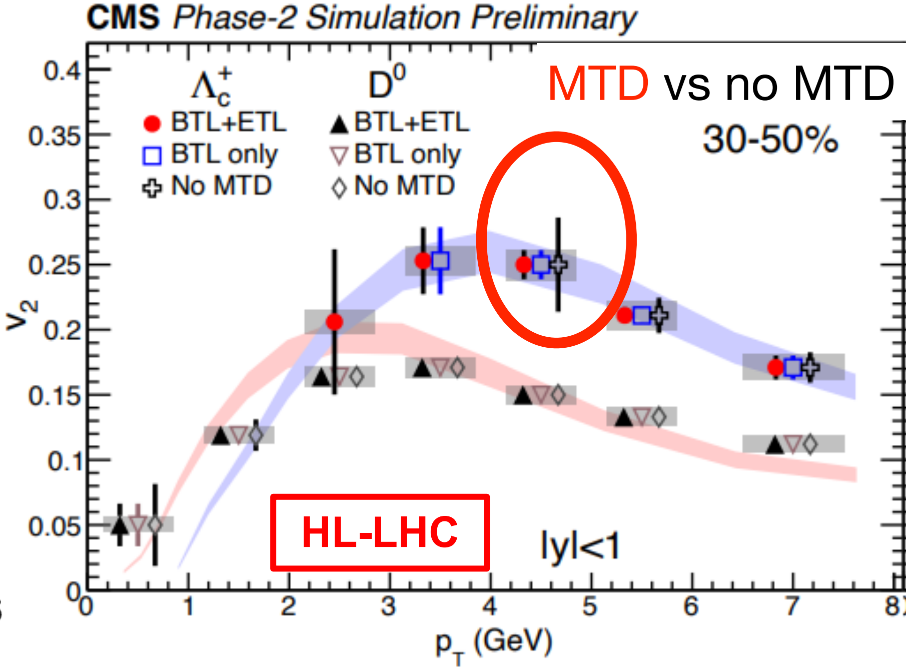


Jet-D0 Correlation



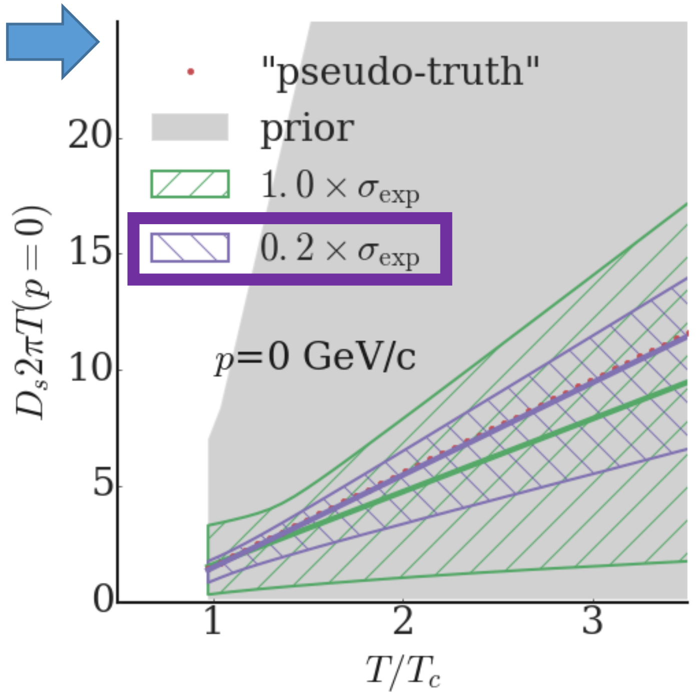
CMS PAS-FTR-18-025

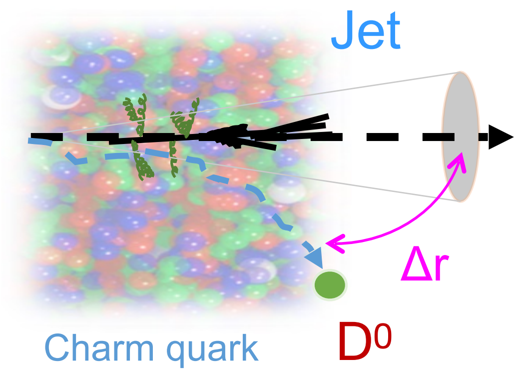
D0 and Λ_c v_2



CMS DP_2021_037

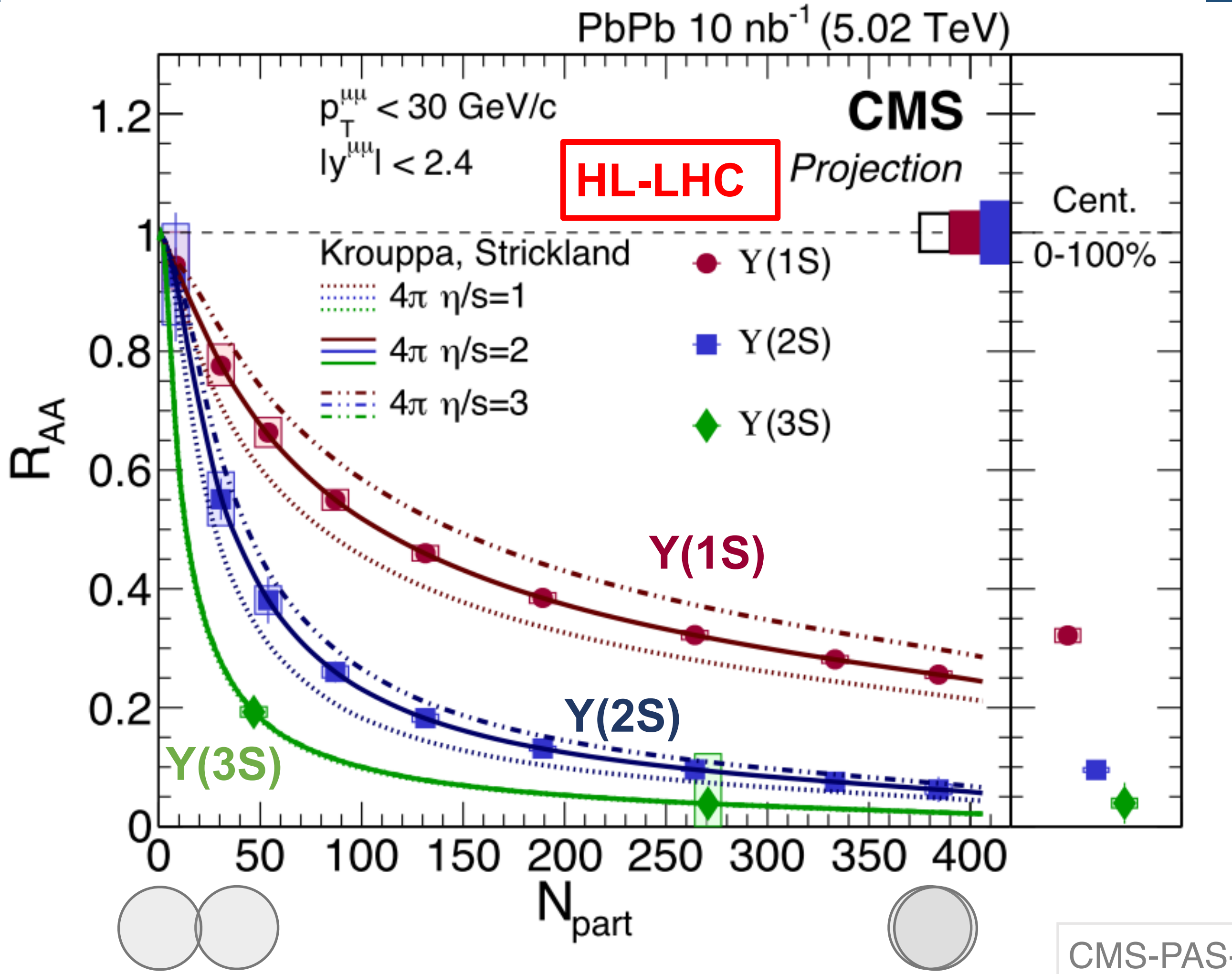
D_s vs. T

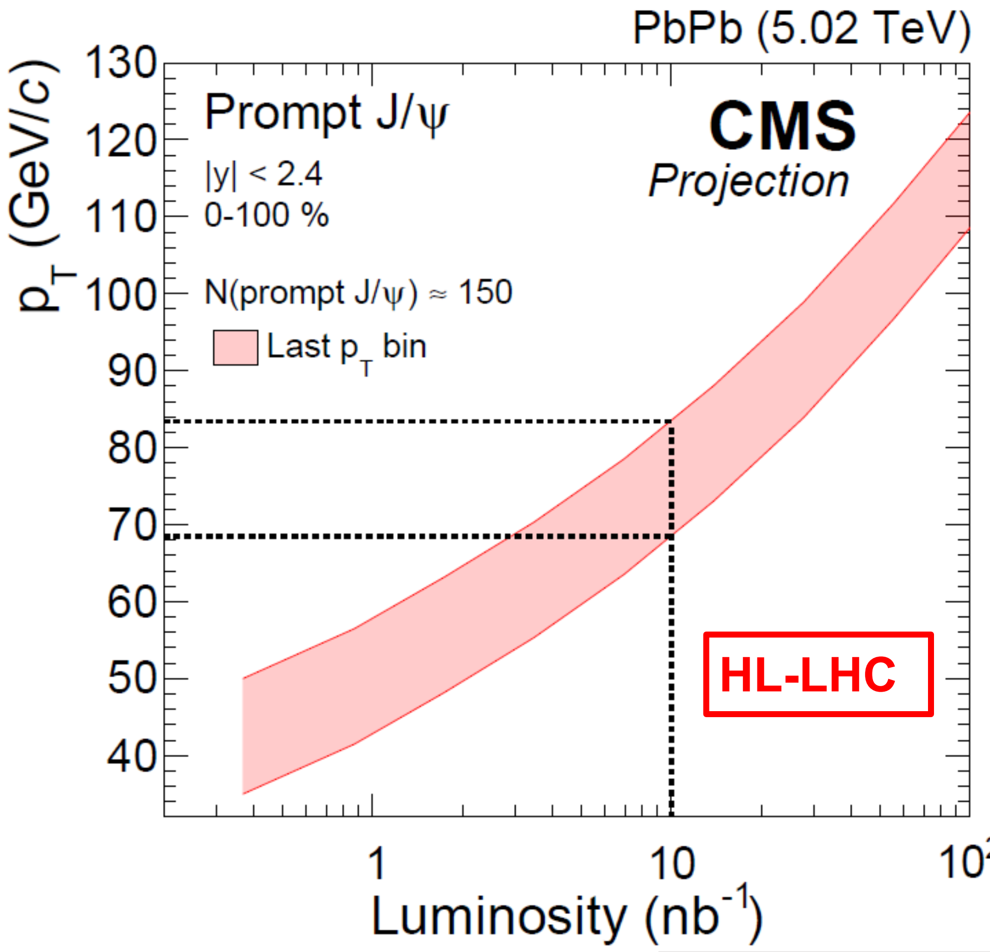




- Large improvement on the Λ_c and D0 v_2 measurements with CMS MTD
- Direct observation of charm diffusion with D0-Jet correlation
- Strong constraint on the HQ diffusion coefficient $\mathbf{D_s}$

QGP transport: Quarkonia





CMS-PAS-FTR-17-002

CMS-PAS-FTR-18-024

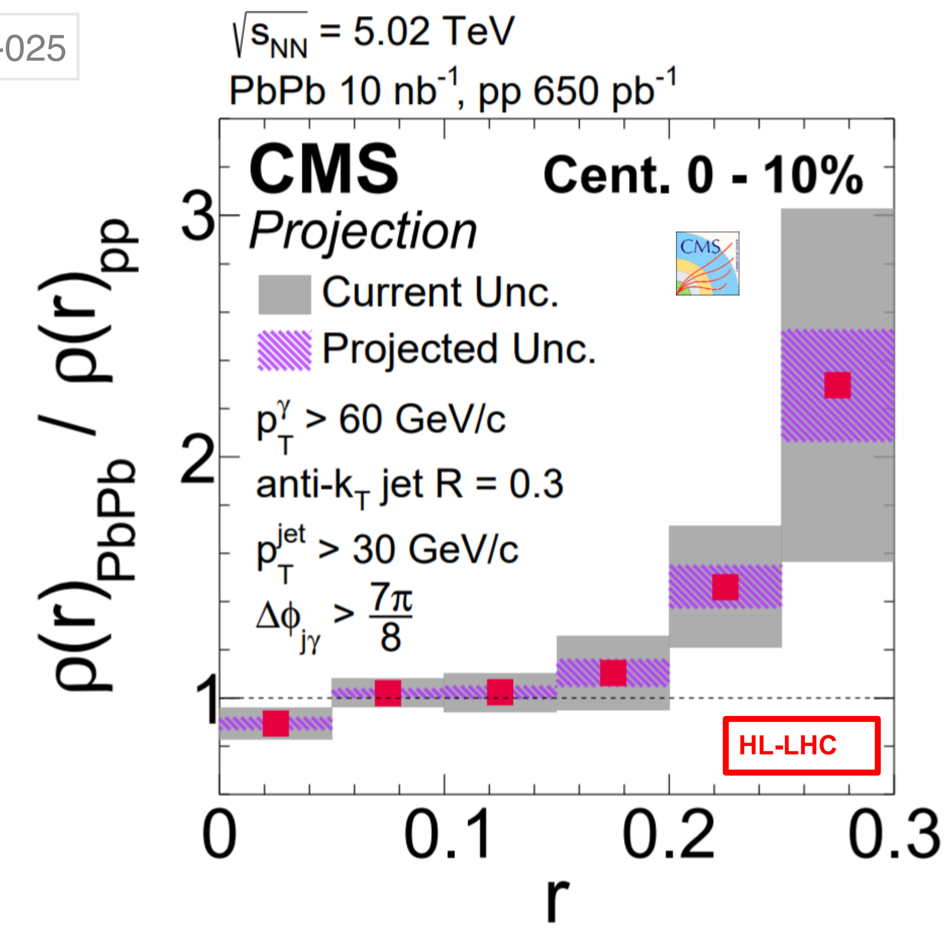
- Significant improvement on the ϒ(nS) R_{AA}
- Sensitive to the medium properties such as η/s and temperature; provide strong constraints in the future Bayesian analyses.

- 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 $\eta_c \rightarrow p\bar{p}$

QGP: Transport properties and medium response

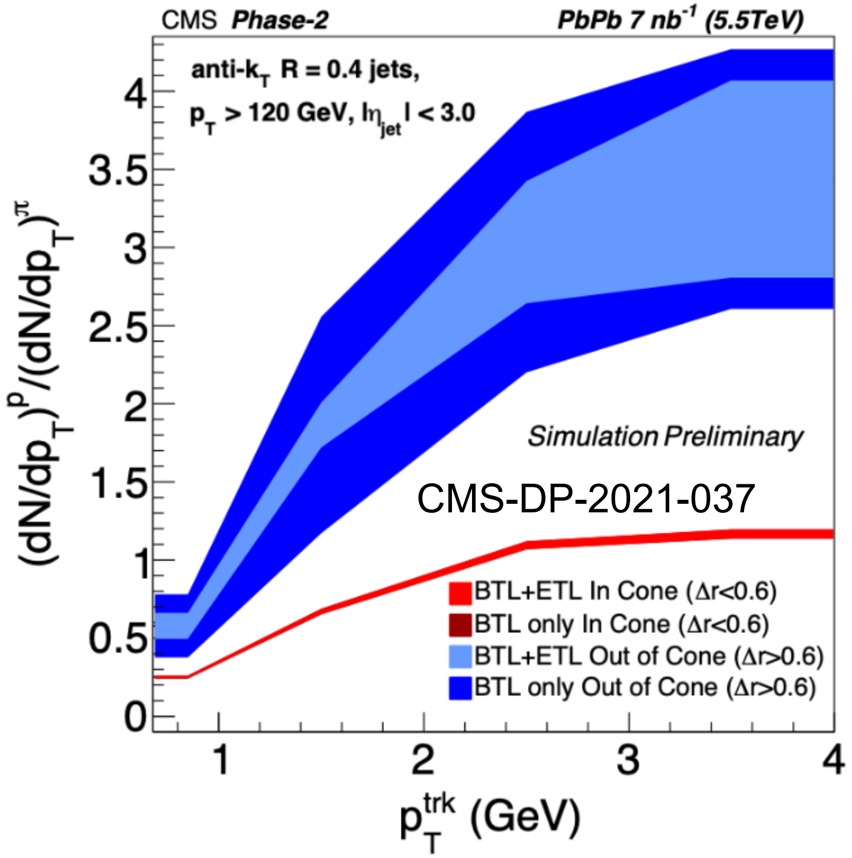
CMS PAS-FTR-19-025

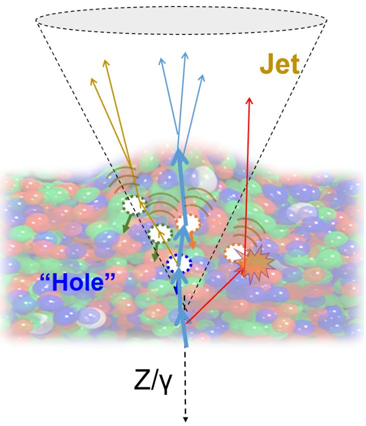
Modification of Jet Shape



p/π ratios in and out of jet cone

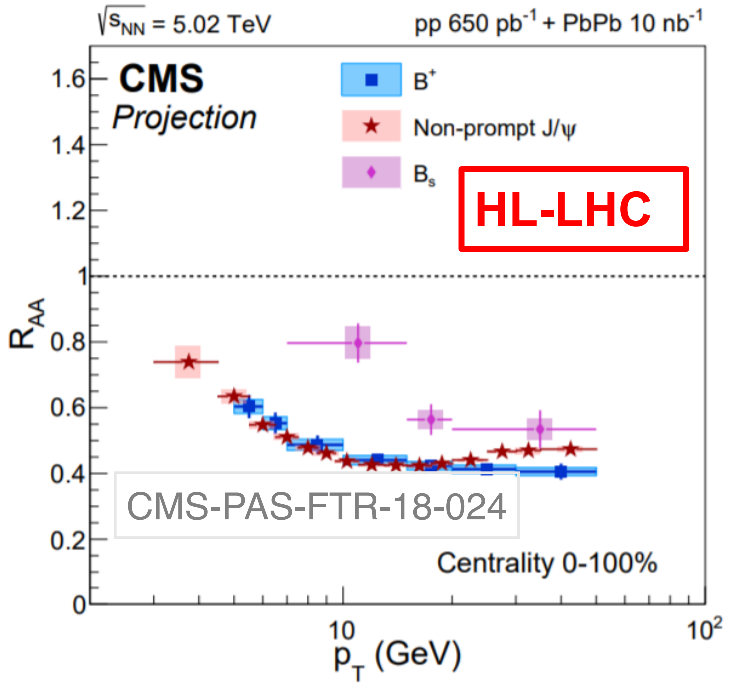
HL-LHC





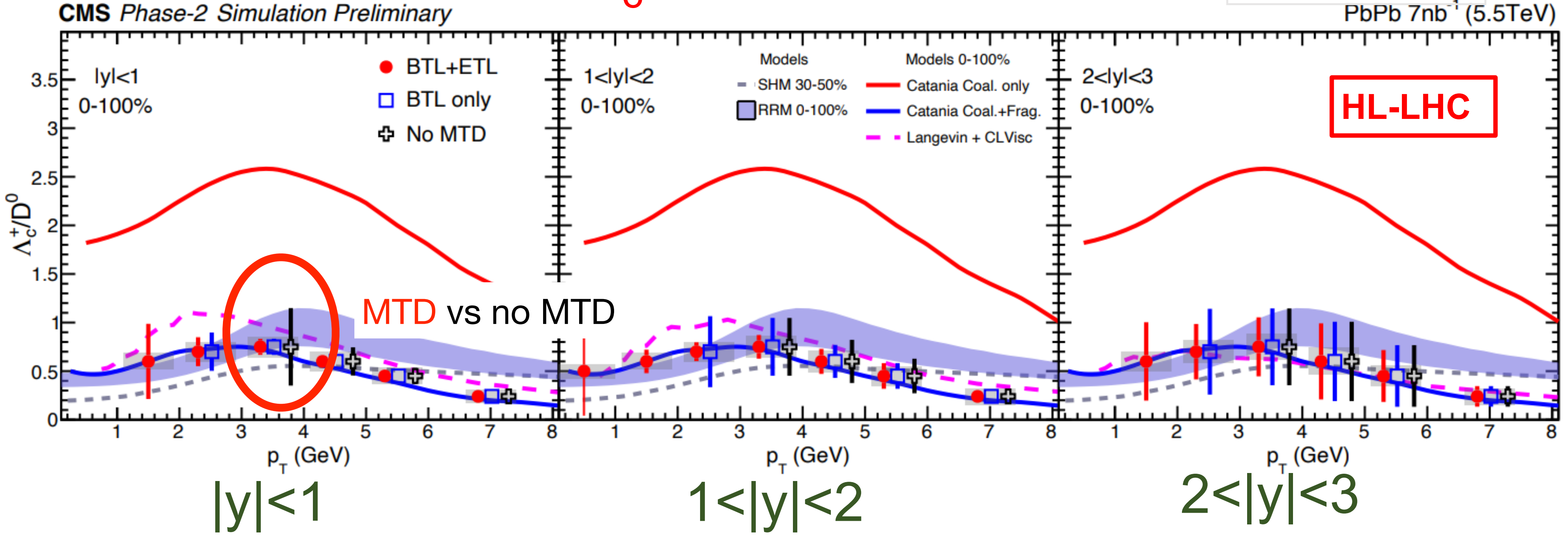
- Reveal jet broadening effect from multiple soft scattering and medium response
  - Photon-tag reduced "survival bias" which narrows the inclusive jet shape
- **Particle composition in the QGP wake**

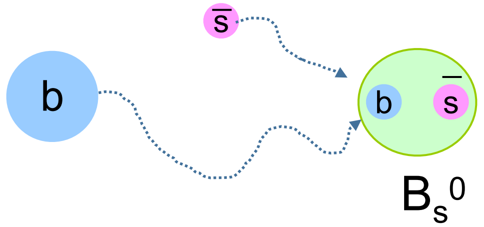
Hadronization: Heavy quarks



Λ_c^+/D^0 ratio

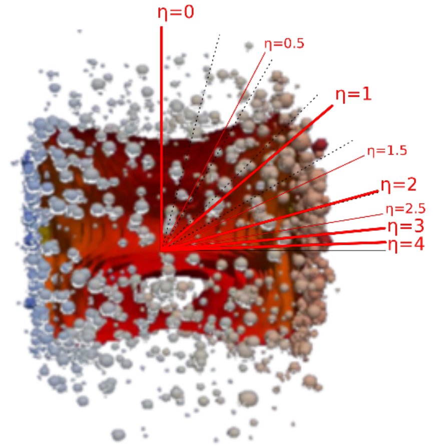
CMS DP_2021_037





- 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 thanks to the large tracker and MTD acceptance

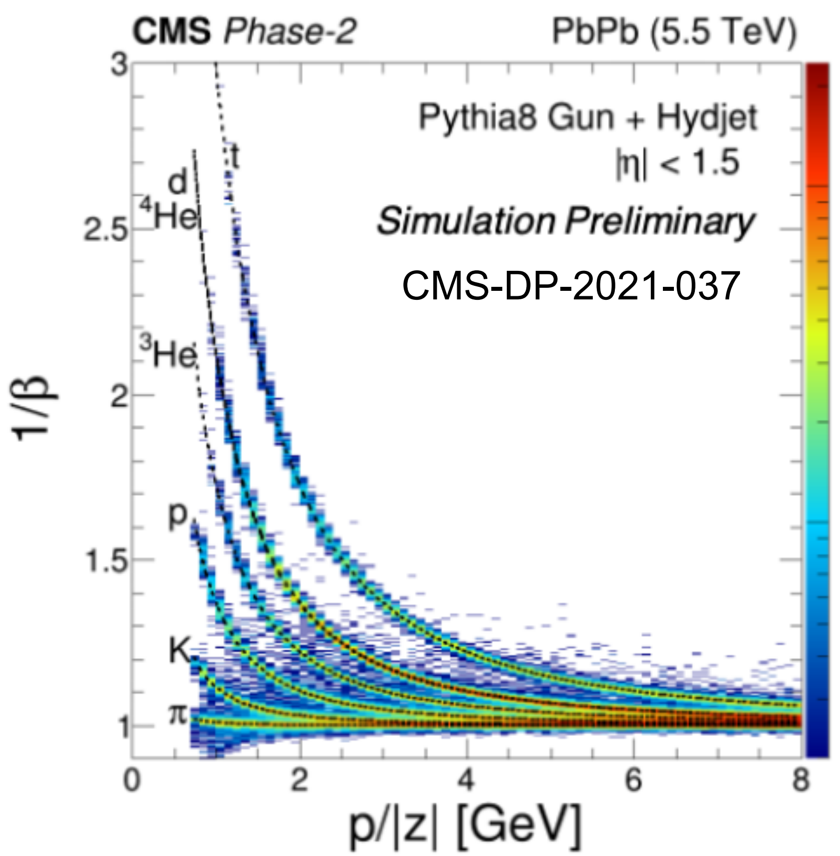


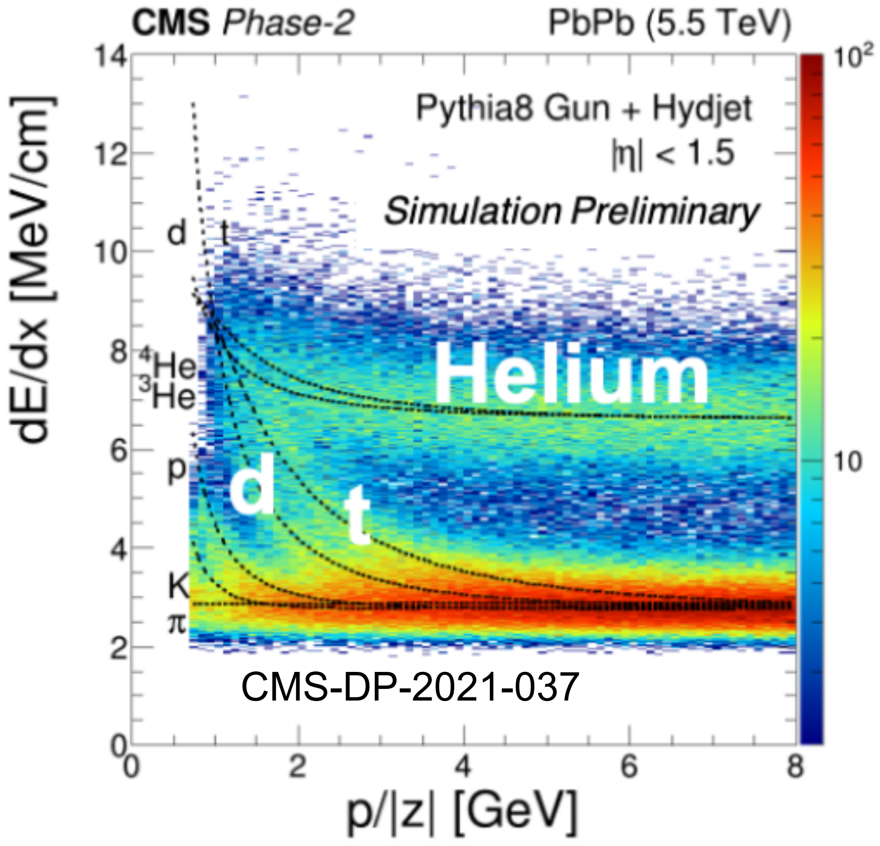
*Except for the Langevin+CLVisc model, all other models shown assume boost invariant in the longitudinal direction, and thus have no rapidity dependence.

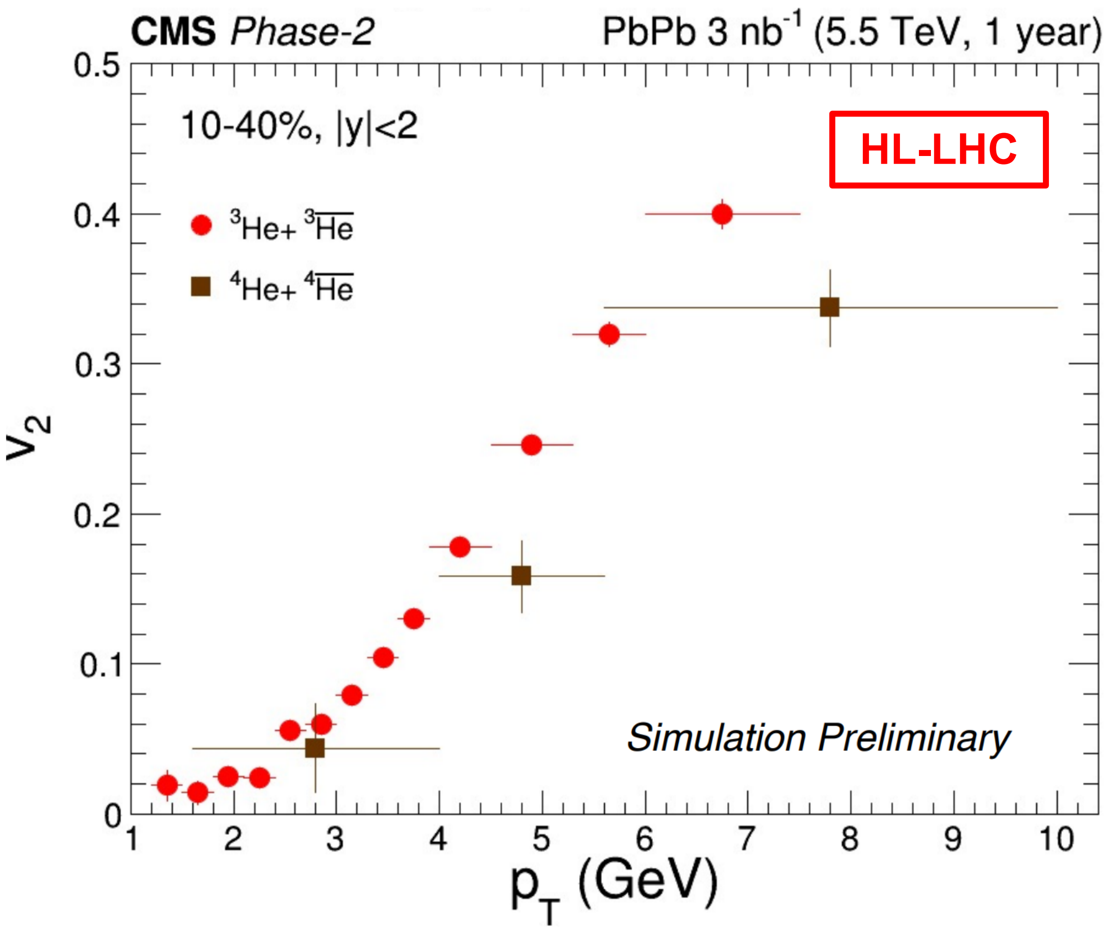
Hadronization: Light nuclei

- PID with Time of Flight with MTD and dE/dx from pixel detector
- High accuracy measurement of **d**, **t**, **^{3}He** and **^{4}He** v_2

CMS DP_2021_037

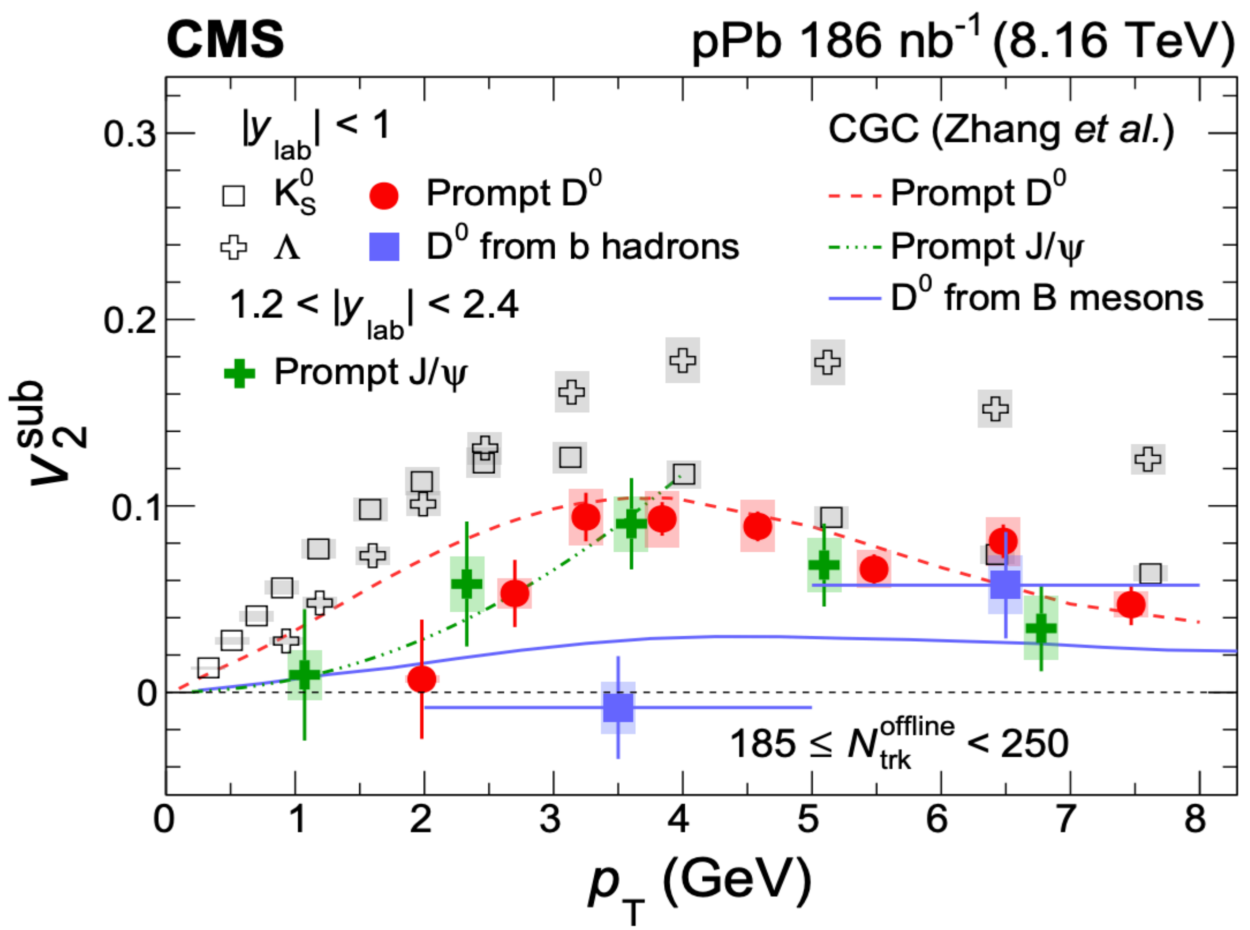




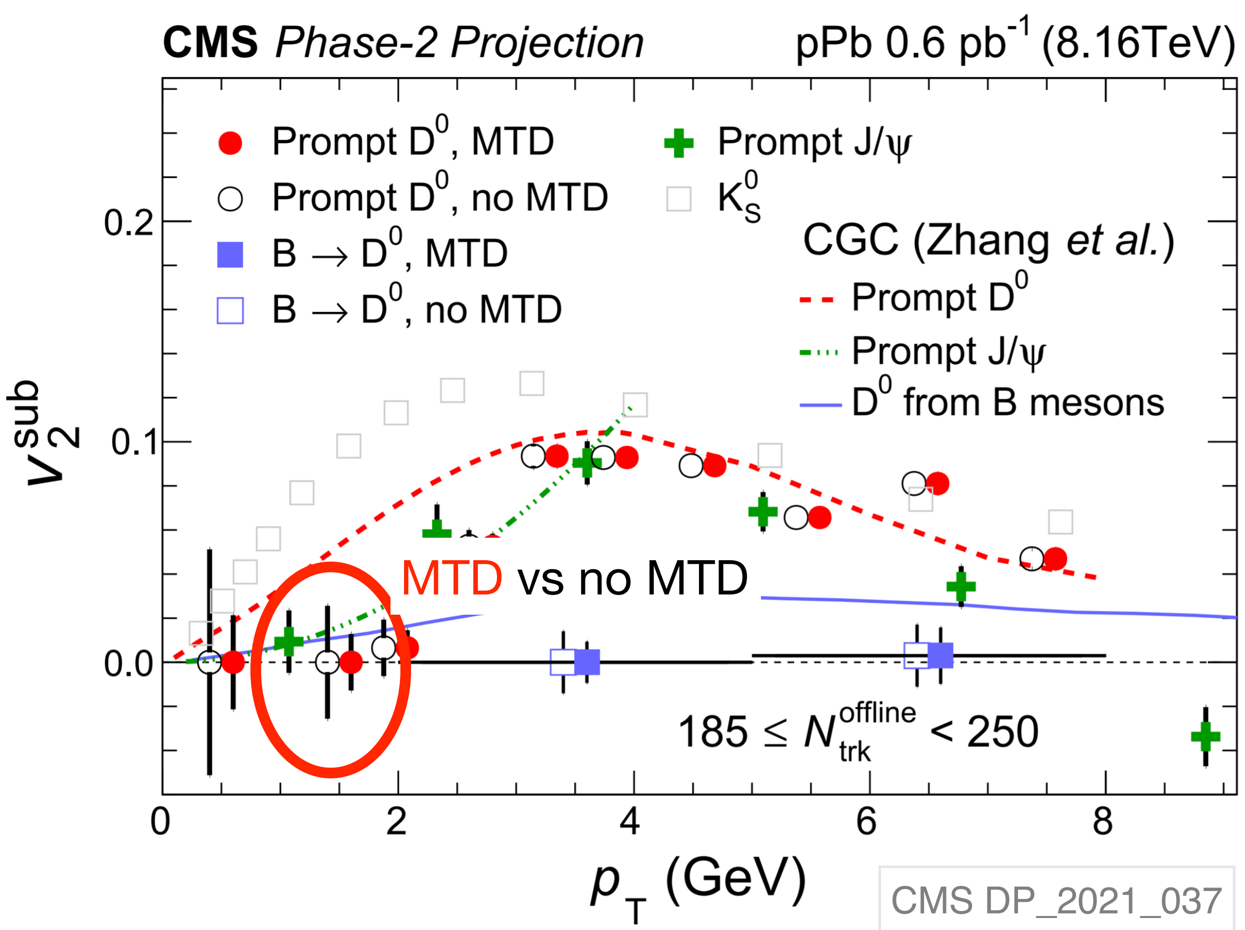


QGP (?): Collectivity in Small System

Run 2: PLB 813 (2021) 136036



CMS 1-year with MTD

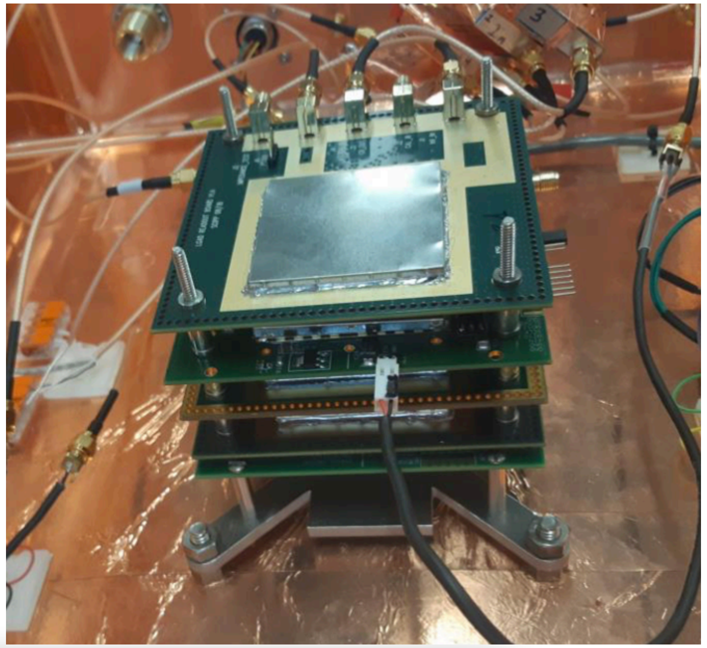


CMS DP_2021_037

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

MTD: towards construction (ETL)

- Testbeam campaign with LGAD/ETROC telescope
- Irradiation studies
- Mechanical design
- LGAD sensors request for bids going out ~today
- Assembly starting in 2027

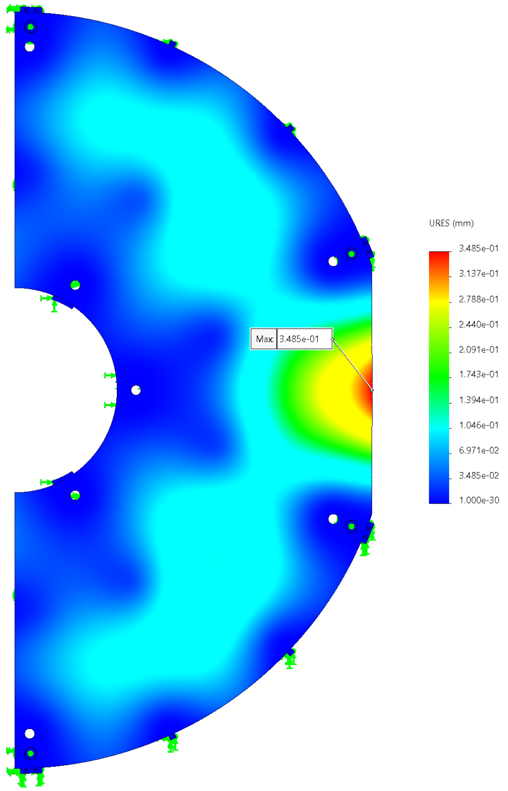


DRAFT LHCC/P2UG Recommendations

Recommendations for CMS

- The LHCC and the P2UG congratulate CMS on the technical progress in all areas of the challenging Phase II upgrade projects, in particular on the successful transition to preproduction for the BTL, the completion of the BTL Tracker Support Tube and the excellent results of the ETL module test obtaining 45ps timing resolution.

MTD: towards construction (ETL)



With all spacers and standoffs: Horizontal gravity sag: 0.35 mm

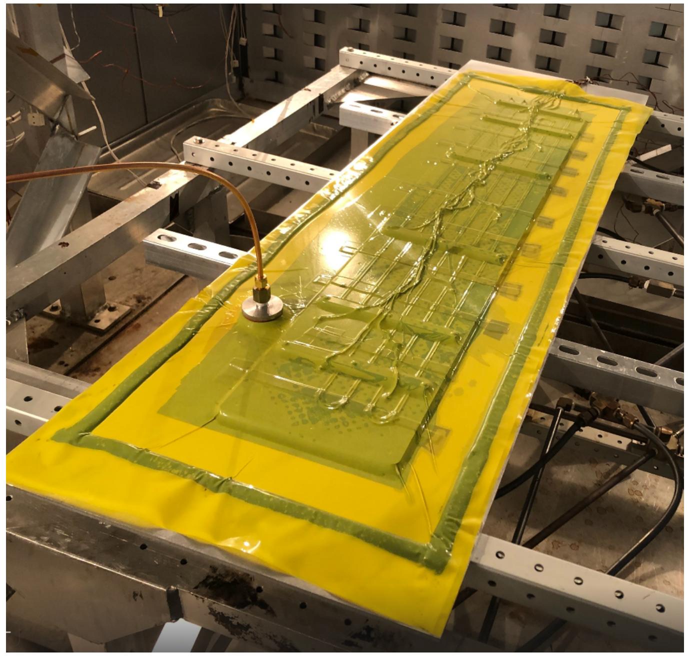
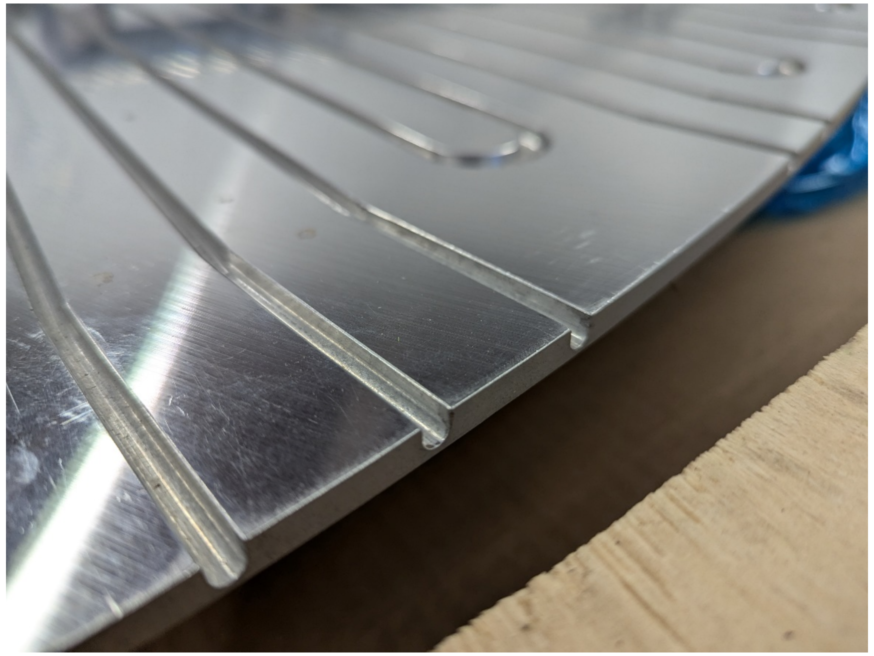
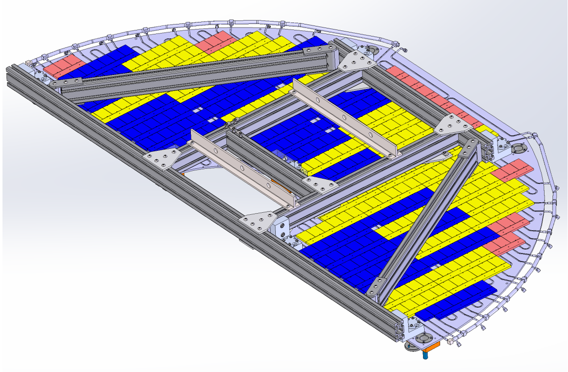


Plate vacuum-bagged in soldering oven



Half dee machining



Picture frame and spider frame mechanical design

Recent work on ETL mechanical design (CMS HI groups)

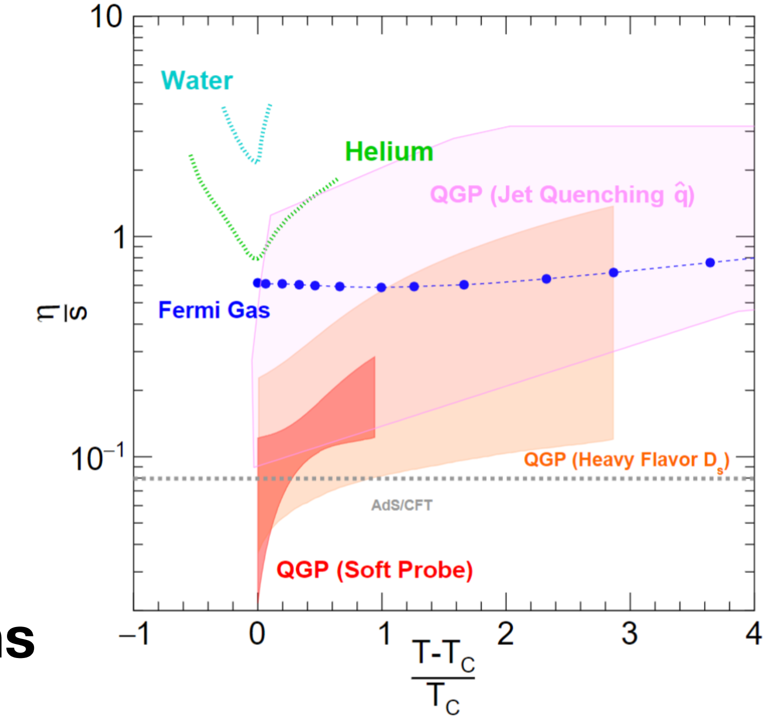
In lieu of a summary: Open HF with CMS Phase 2

	2018 PbPb 1.7 nb^{-1} (Run 2)		Run 3 (3nb^{-1})		**Run 4 MTD (3nb^{-1})**		
Observables	p_T min (GeV)	|y| coverage	p_T min (GeV)	|y| coverage	**p_T min (GeV)**	**|y| coverage**	**MTD Gain**
D^0 R_{AA}	2	1	1	1	**0**	**3**	**Up to 2.4**
D_s R_{AA}	6	1	5	1	**2**	**3**	**>3**
Λ_c R_{AA}	6	1	5	1	**< 2**	**3**	**Up to 6**
B->D R_{AA}	2	2	2	2	**0**	**3**	**Up to 2.4**
B^+ ($D^0\pi$) R_{AA}	Not accessible		~15	1	**Close to 0**	**3**	**>3**
Total charm cross-section	Not accessible		Not accessible		**First measurement**		
D^0 v_2	0.5	1	0.5	1	**0**	**3**	**Up to 2.4**
D_s v_2	6		5		**2**	**3**	**>3**
B->D^0 v_2	~2		~2		**Close to 0**	**3**	**Up to 2.4**
Λ_c v_2	~6		~6		**2-3**	**3**	**Up to 6**
Photon-D^0	Not accessible		Proof of principle	1.2	**First measurement**	**3**	**Up to 2.4**
Jet-D^0	D^0 p_T > 4 GeV	2	D^0 p_T > 4 GeV	2	**D^0 p_T > 0 GeV**	**3**	**Up to 2.4**
D^0D^0bar p_T> 5 GeV	Proof of principle		First measurement		**Precise measurement**	**3**	**Up to 1.4**
D^0D^0bar p_T> 2 GeV	Not accessible		Not accessible		**First measurement**	**3**	**Up to 2**

Summary

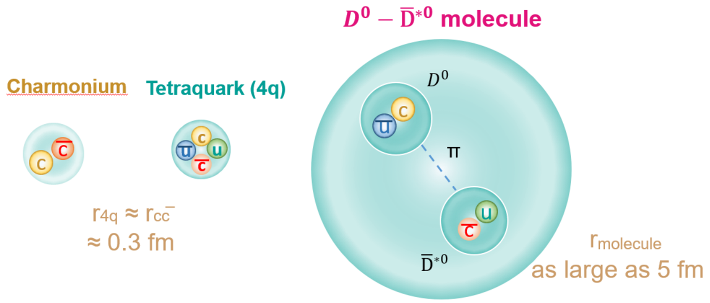
CMS Phase II Upgrade

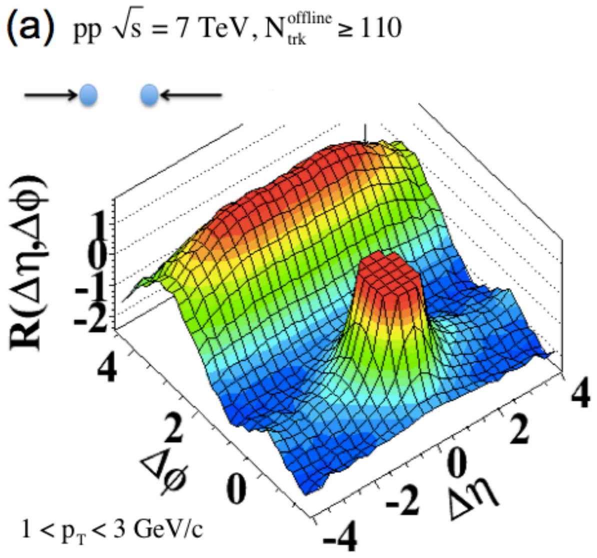
- Large acceptance and high performance tracker |η|<4
- Particle and light nucleon identification with CMS MTD + Pixel
- Improvement on the secondary vertex resolution
- L1 track trigger capability



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 studies of exotic hadron in high multiplicity pp, pPb and PbPb UPC





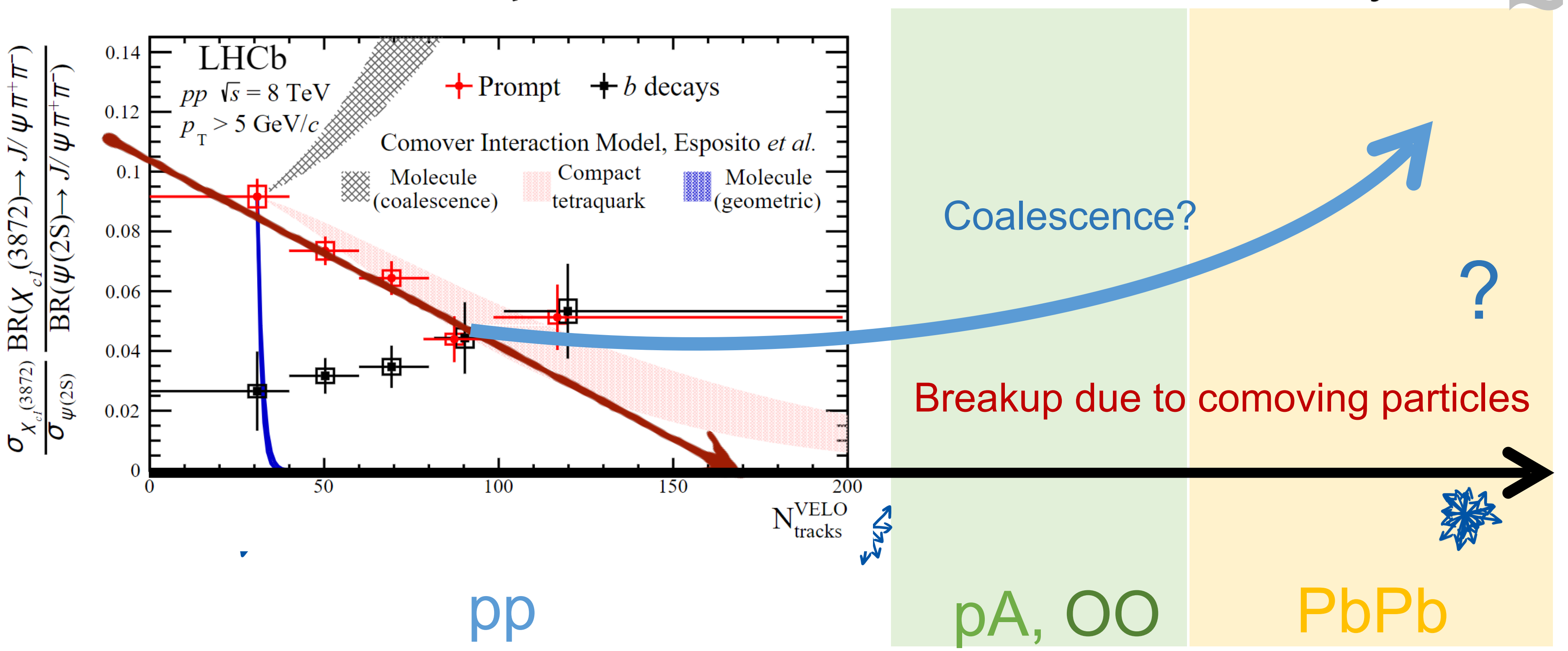
BACKUP

Hadronization (+transport): QCD exotica

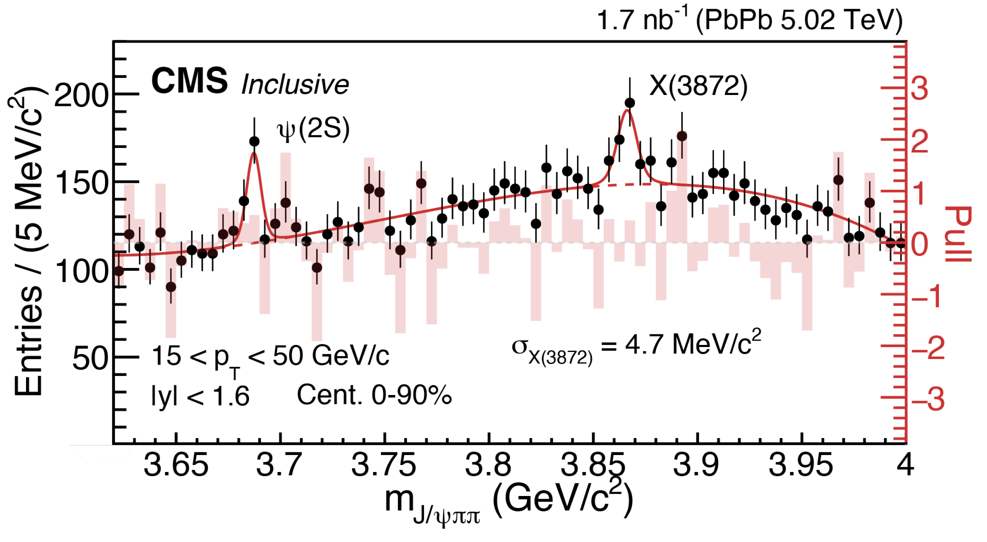
LHCb
PRL 126 (2021) 9, 092001

CMS PbPb

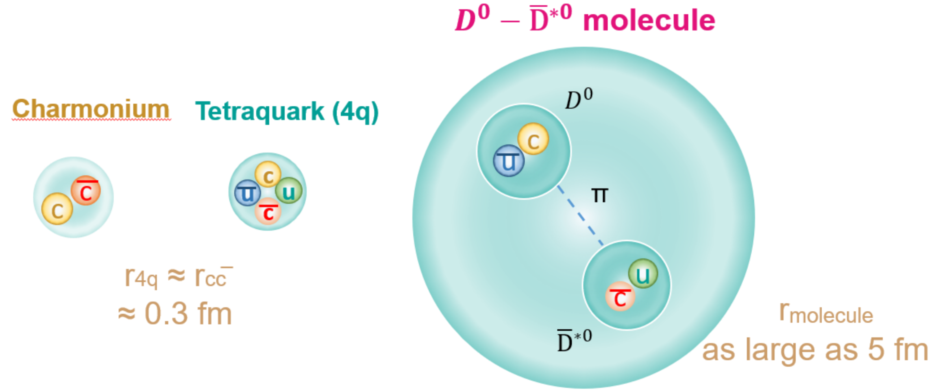
$$\rho^{\mathrm{PbPb}} = 1.08 \pm 0.49\,(\mathrm{stat}) \pm 0.52\,(\mathrm{syst})$$



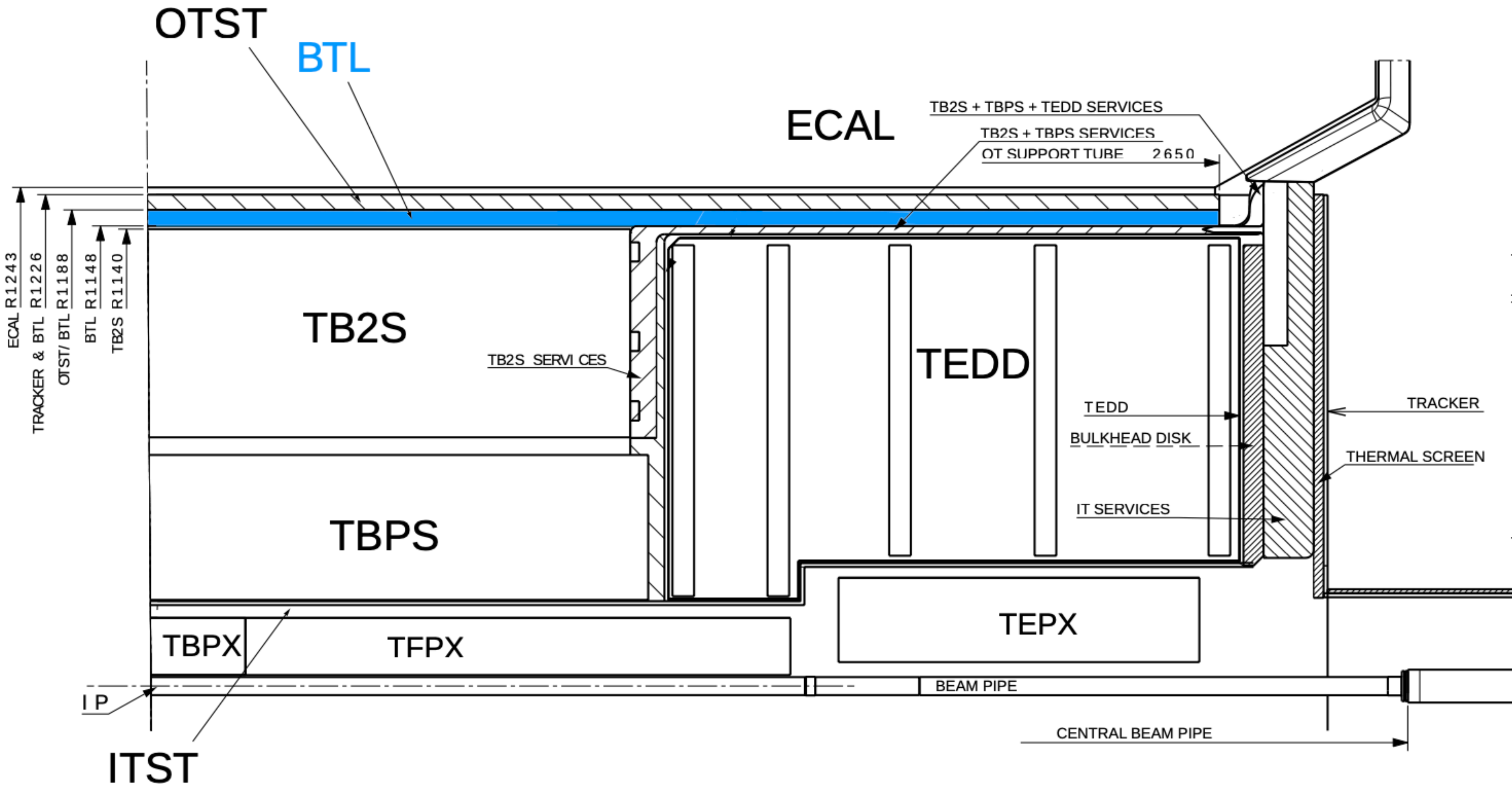
CMS
PRL 128 (2022) 032001



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}
- Exotic hadron production in UPC events

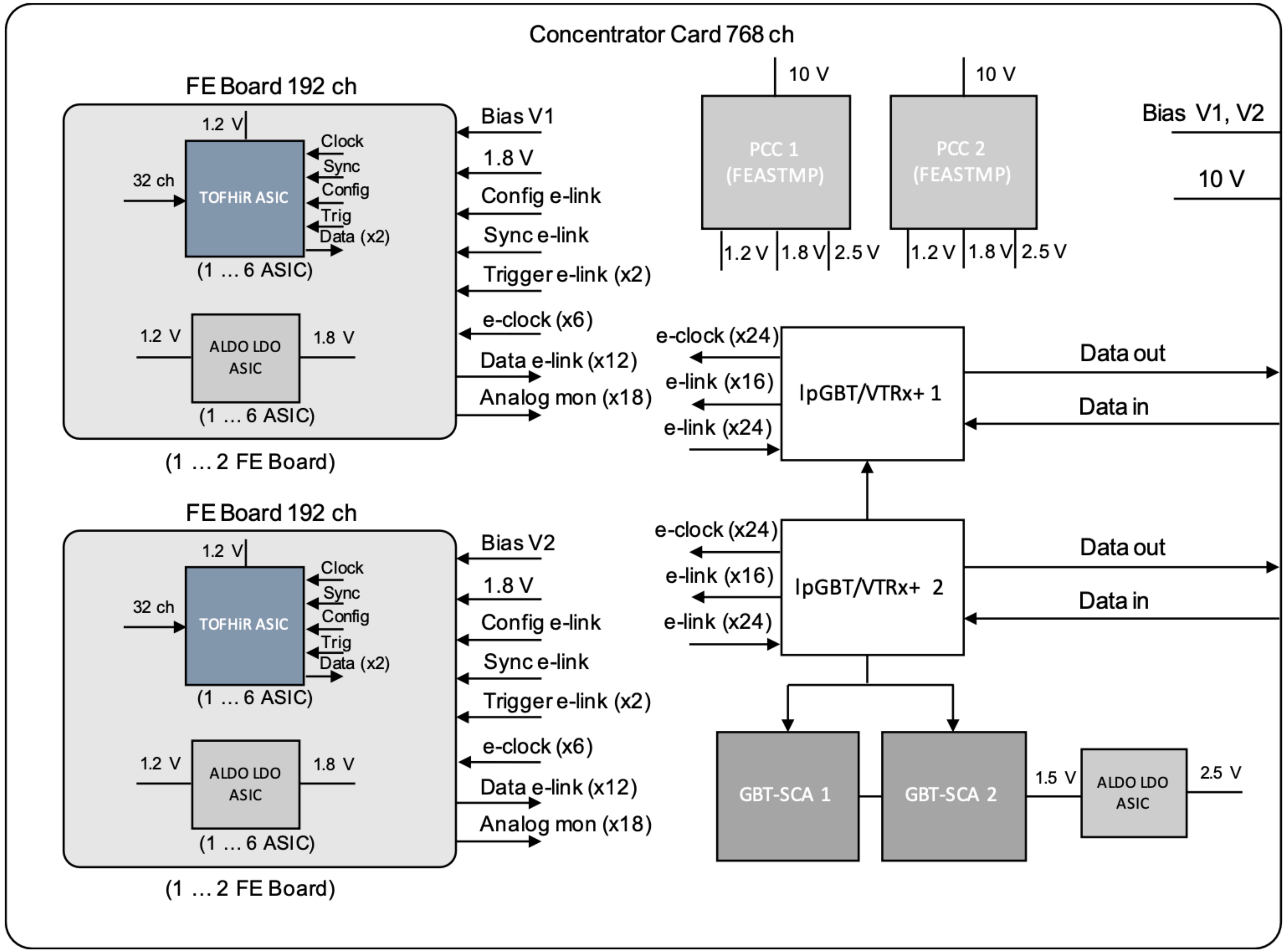


	Module	RU	Tray	Total
Channels (SiPMs)	32	768	4608	331776
Crystals	16	384	2304	165888
ASICs	1	24	144	10368
Modules	-	24	144	10368
Readout units (RU)	-	-	6	432
Trays	-	-	-	72

$\lvert\eta\rvert$ region	**0–0.7**	**0.7–1.1**	**1.1–1.48**
Readout unit ID within tray	1–2	3–4	5–6
Crystal thickness, t [mm]	3.75	3.0	2.4
$\langle t_{\text{slant}} \rangle$ [mm]	4.0	4.3	4.6
SiPM active area [mm^2]	11.2	9.0	7.2
$\langle \Phi_{\text{neq}}^{\text{tot}}(3000\ \text{fb}^{-1}) \rangle$ [cm^{-2}]	1.65×10^{14}	1.75×10^{14}	1.85×10^{14}

- CMS clock distribution: 15 ps;
- Digitization: 7 ps;
- Electronics: 8 ps;
- Photo-statistics: 25–30 ps;
- Noise (SiPM dark counts): negligible at startup, 50 ps after 3000 fb^{-1};

BTL readout unit

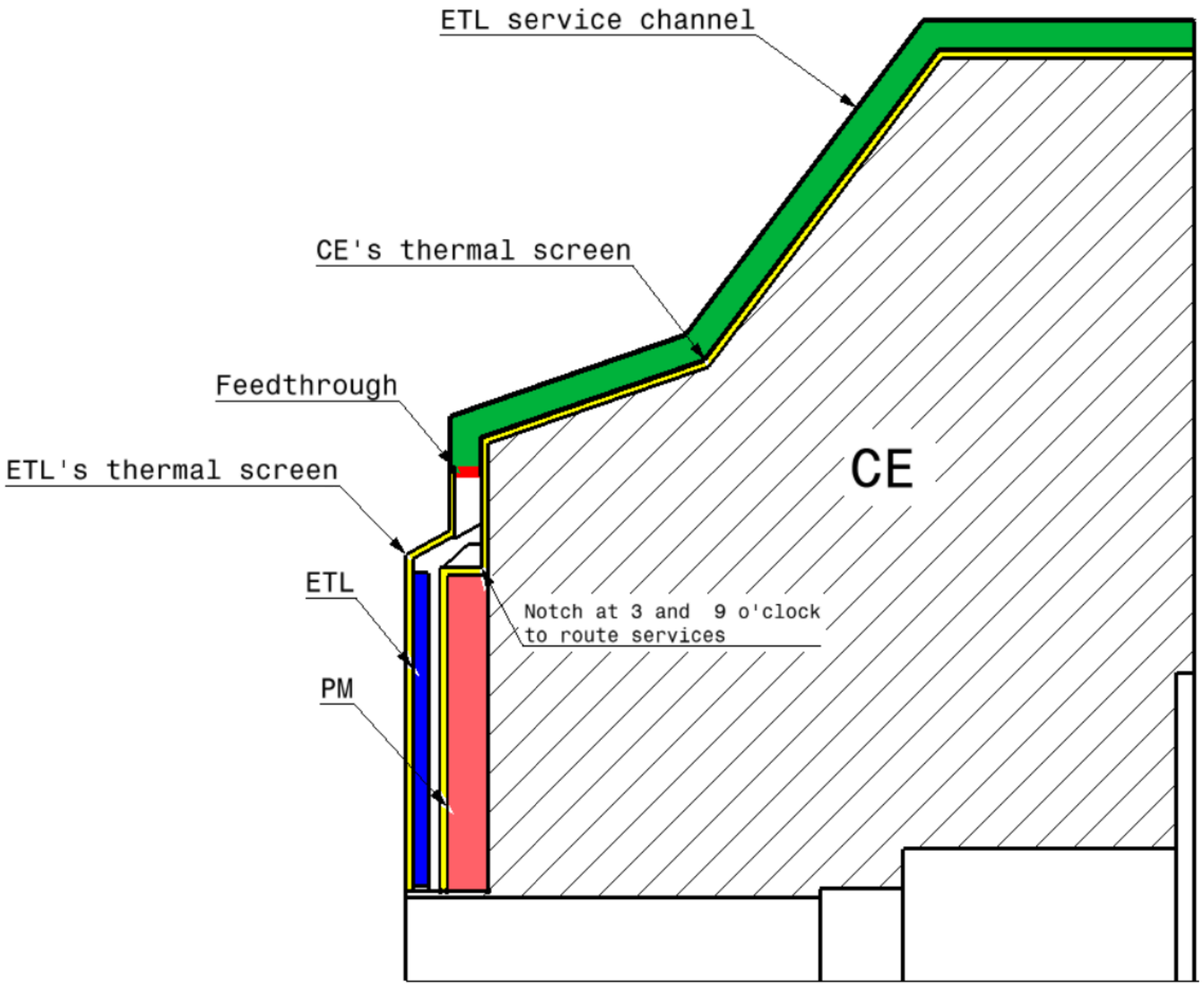


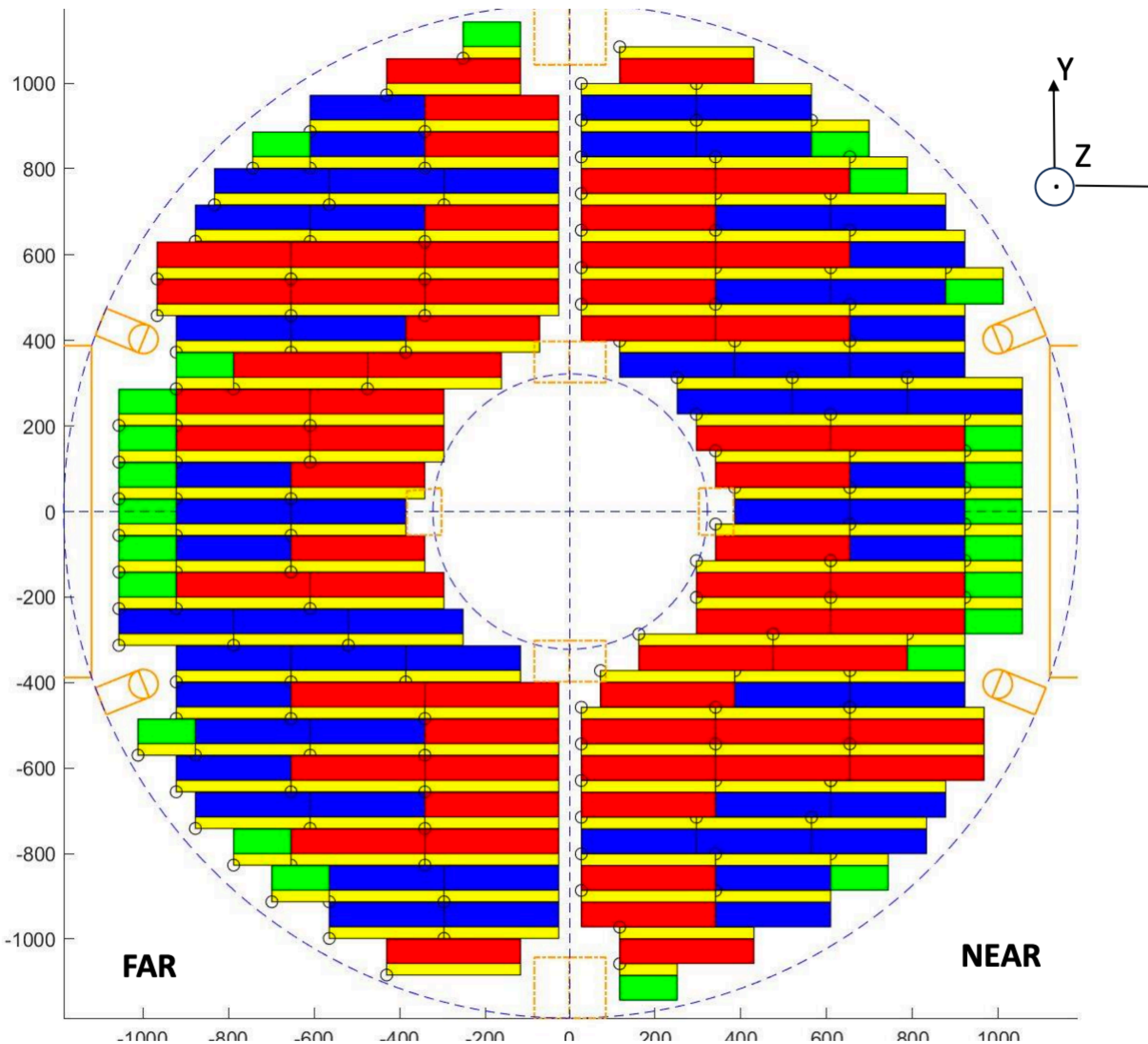
	TOFHIR1	TOFHIR2
Number of channels	16	32
Technology	UMC 110 nm	TSMC 130 nm
Voltage	1.2 V, 2.5 V	1.2 V
Radiation Tolerance	No	Yes
Compatibility with lpGBT	Yes	Yes
I/O links	LVDS	CLPS
L1, L0 Trigger	Yes, No	Yes, Yes
10-bit SAR ADC (MHz)	10	40
Bandwidth (MHz)	350	350
Input impedance (Ω)	6	6
DCR noise filter	No	Yes
Number of TACs and QACs	4	6
TDC bin (ps)	20	20
Reference voltages	External	Internal
Maximum MIP rate/ch (MHz)	1	2.5
Max low E rate/ch (MHz)	3	5
Clock frequency (MHz)	160	160

BTL SiPM candidates

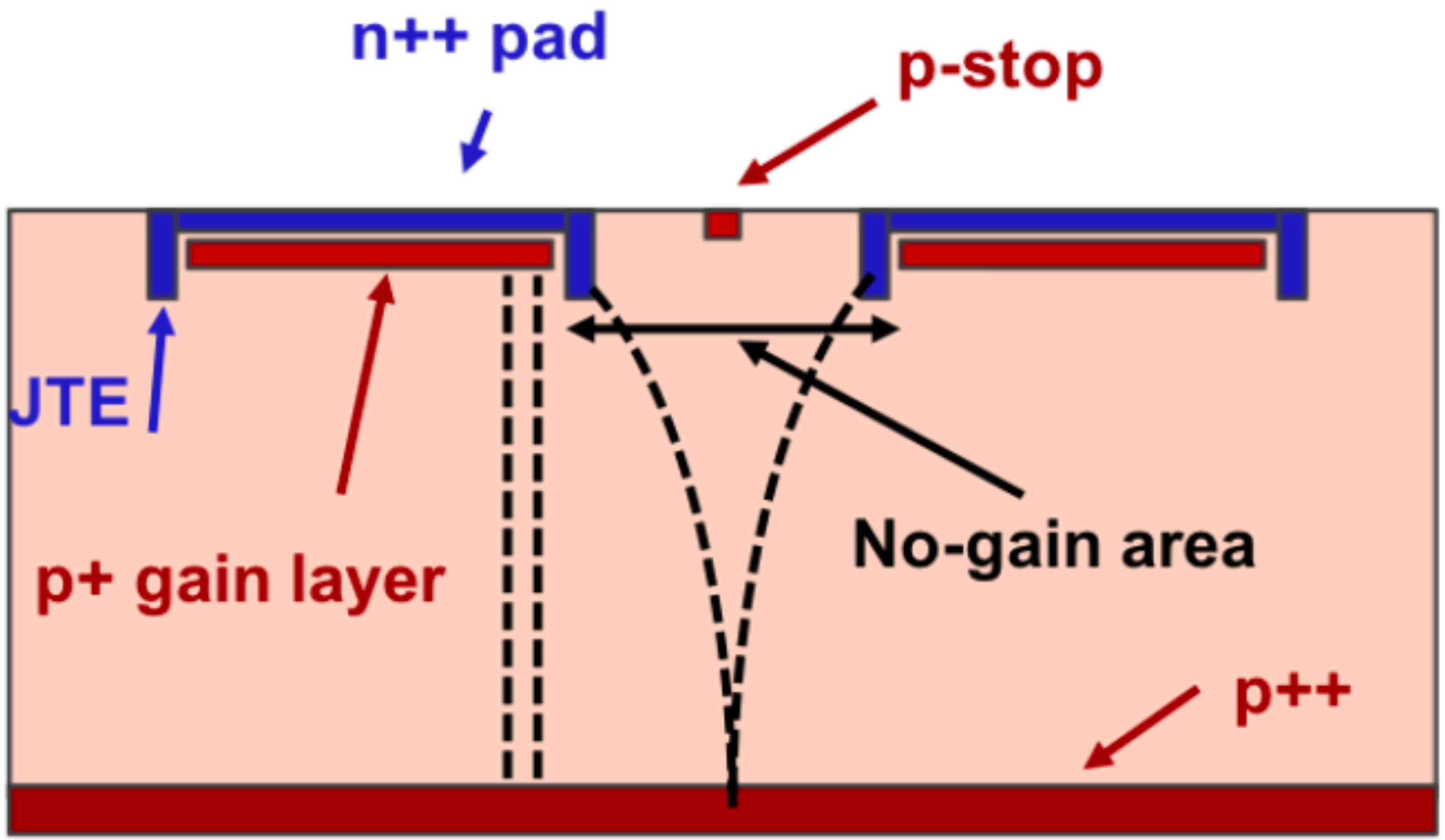
SiPM parameter	Specification	FBK-NUV-HD	HPK-S12572	HPK-HDR2
Active area	–	$\sim 9\ \mathrm{mm}^2$	$\sim 9\ \mathrm{mm}^2$	$\sim 9\ \mathrm{mm}^2$
Cell pitch	$< 20\ \mu\mathrm{m}$	$15\ \mu\mathrm{m}$	$15\ \mu\mathrm{m}$	$15\ \mu\mathrm{m}$
Cell recovery time	< 10 ns	7 ns	8.5 ns	< 10 ns
Capacitance	< 600 pF	530 pF	295 pF	585 pF
Number of cells	> 20k	~ 40k	~ 40k	~ 40k
V_{br} ($-30\,°$C)	–	34.2 V	63.0 V	35.8 V
dV_{br}/dT	–	41 mV/ °C	59 mV/ °C	37 mV/ °C
$\delta V_{br}/10^{13}\ n_{eq}/\mathrm{cm}^2$	≤ 0.2 V	< 0.1 V	0.2 V	< 0.1 V
DCR-T coefficient	–	1.76	1.90	1.79
ENF	< 1.1	< 1.05	1.07	< 1.05
Parameters after 3000 fb^{-1}				
Optimal OV	> 1V	1.6 V	1.5 V	1.2 V
PDE	–	15%	13%	23%
Current/device	–	1.32 mA	0.77 mA	1.30 mA
Static power consumption	≤ 50 mW	50 mW	50 mW	50 mW
Gain	$\geq 1.3 \times 10^5$	2.1×10^5	1.45×10^5	1.55×10^5
DCR/SiPM	–	42 GHz	37 GHz	55 GHz
PDE/$\sqrt{\mathrm{DCR}}$	≥ 2.0	2.3	2.1	3.1

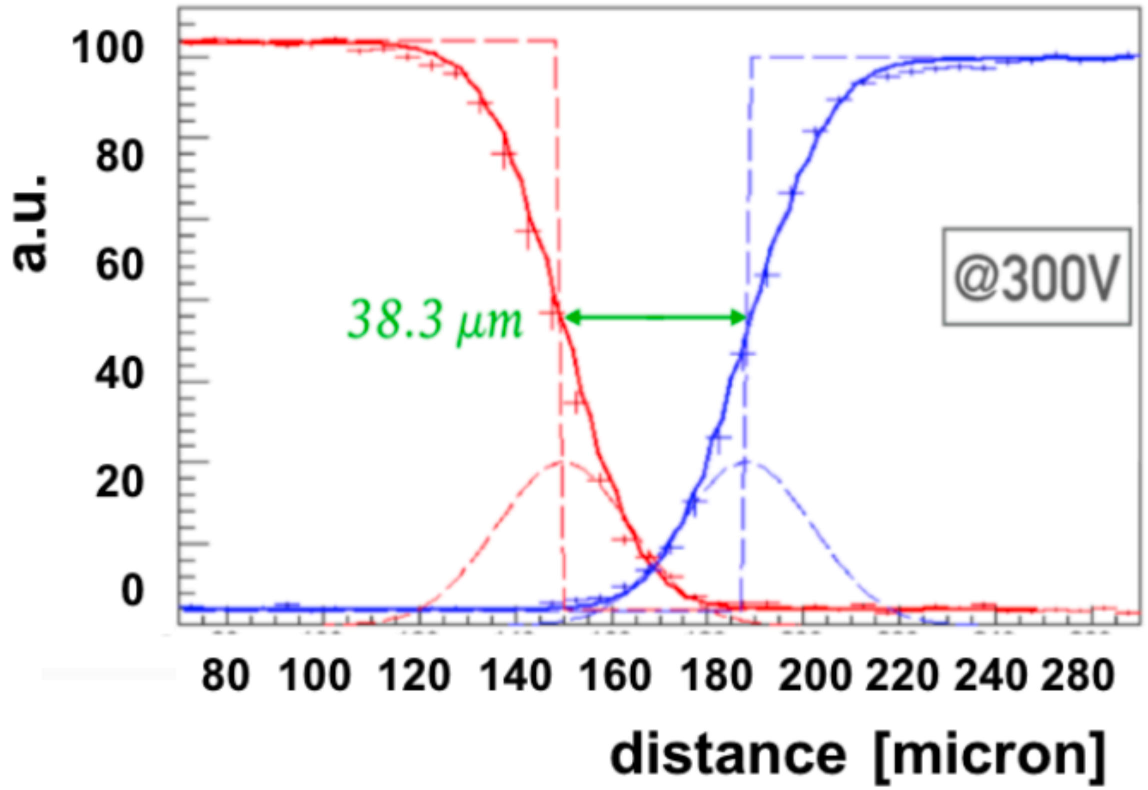
ETL integration





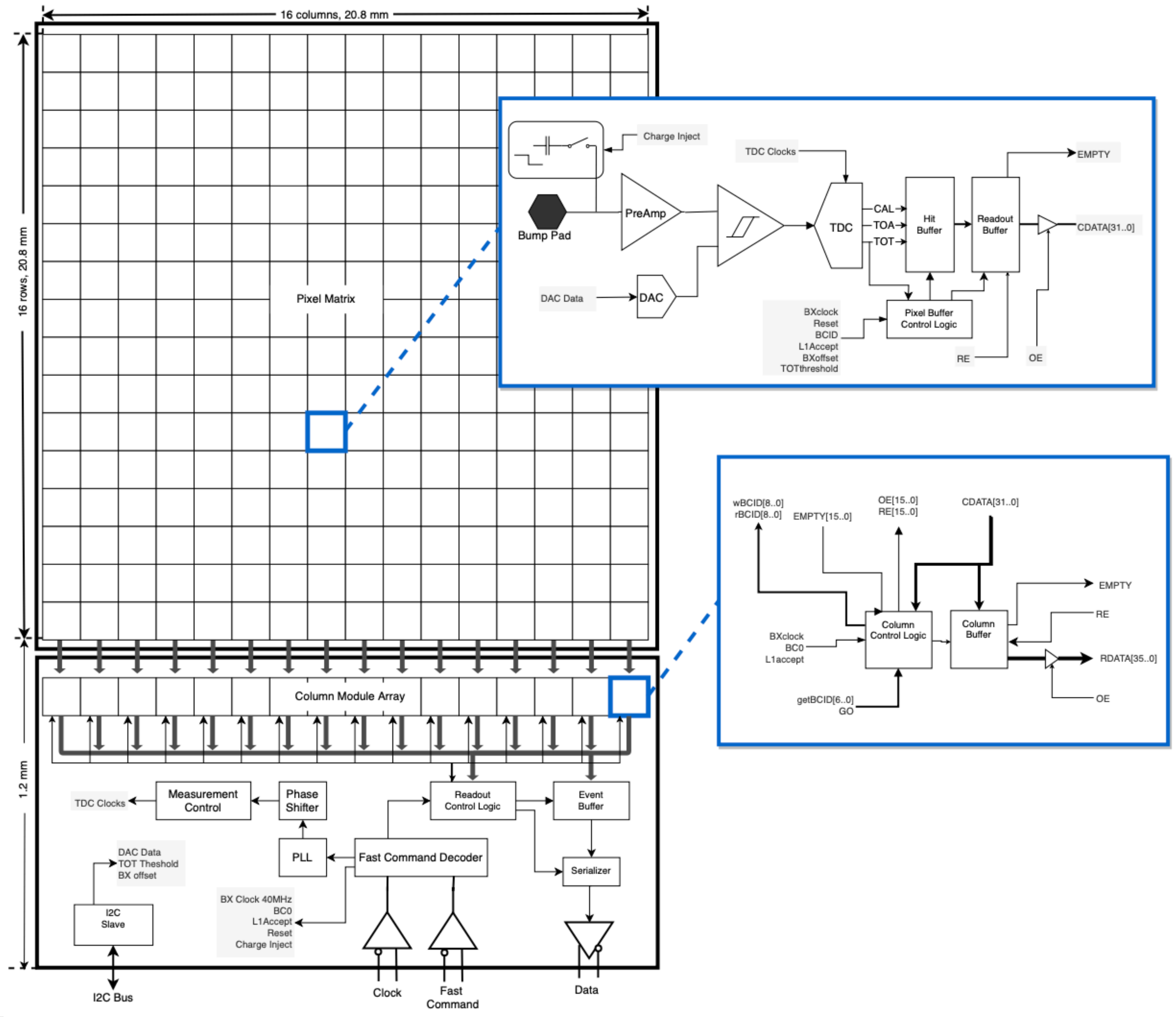
ETL sensor cross-section (schematic)





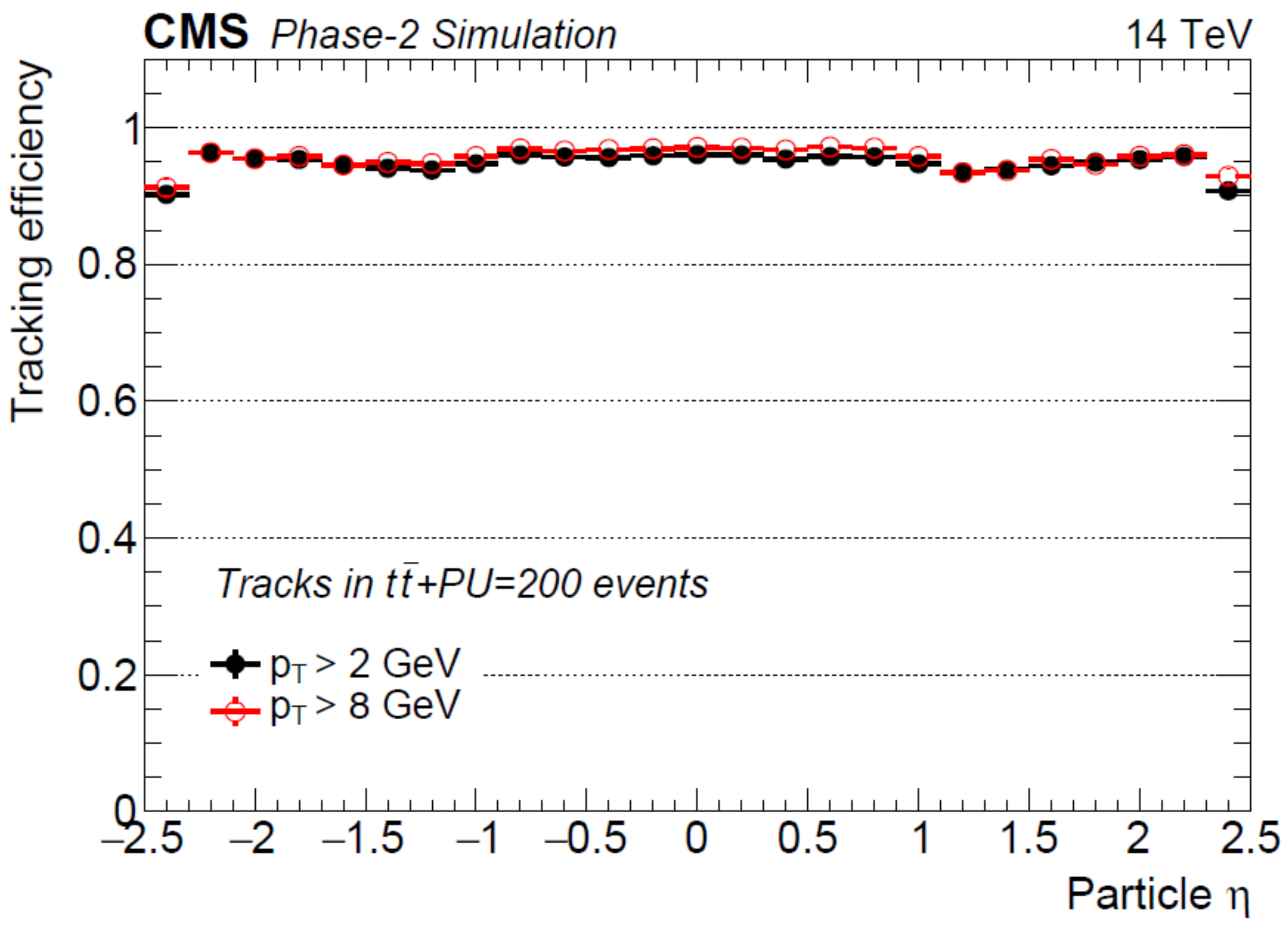
CMS: 1.3mm x 1.3mm pixels

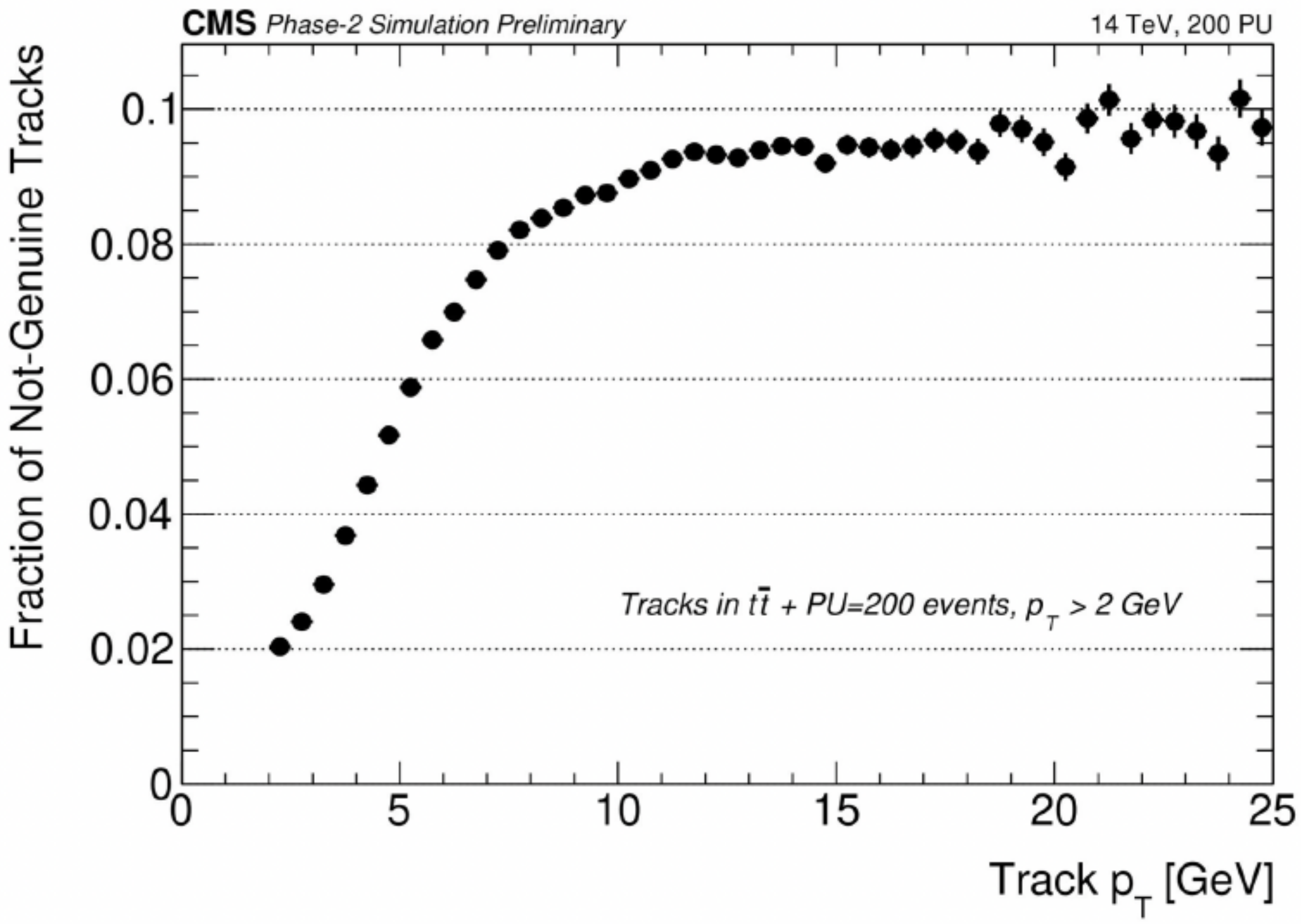
ETROC block diagram



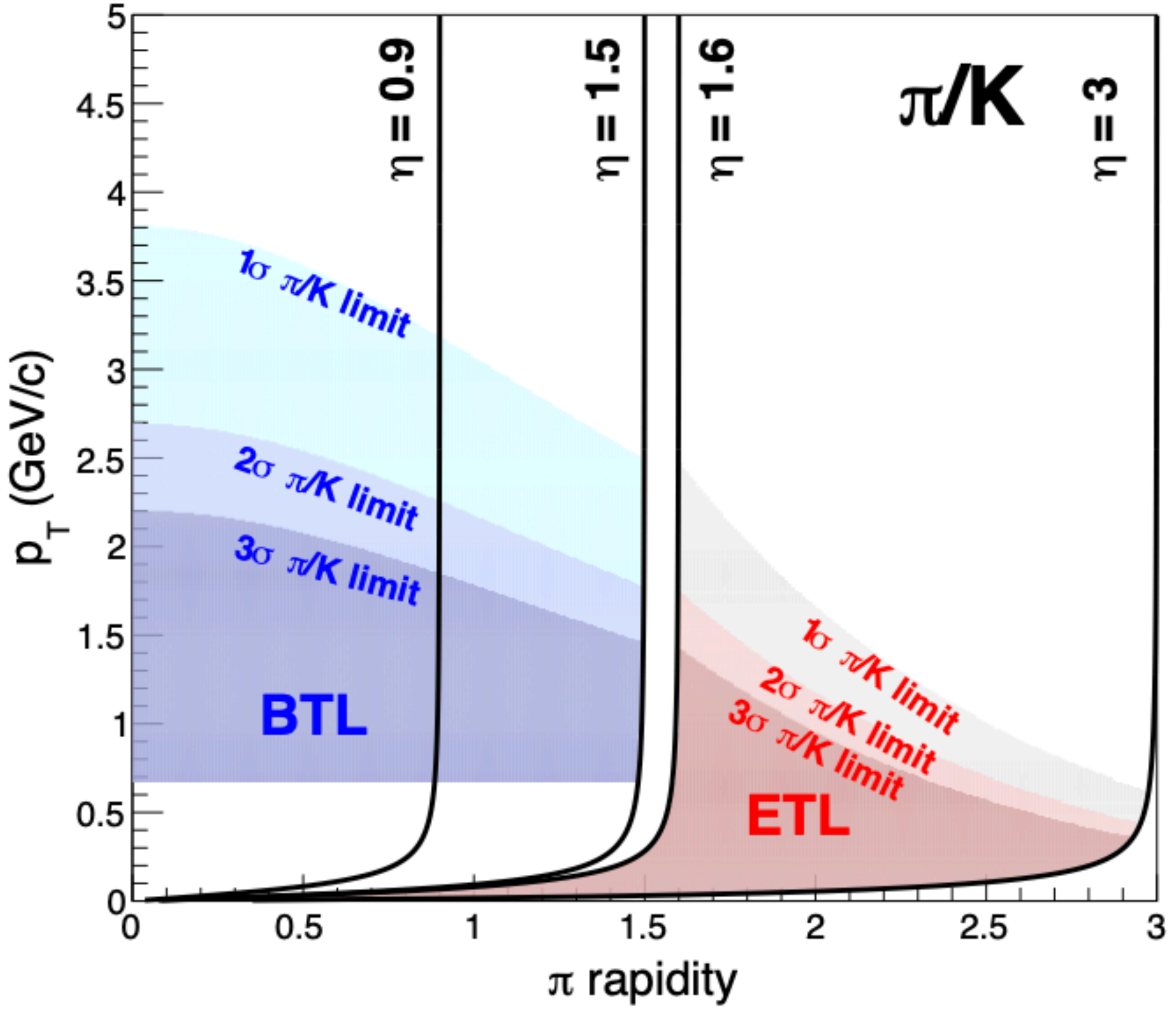
Phase 2 CMS L1 Track Trigger Performance

- Possibility to employ L1 track trigger

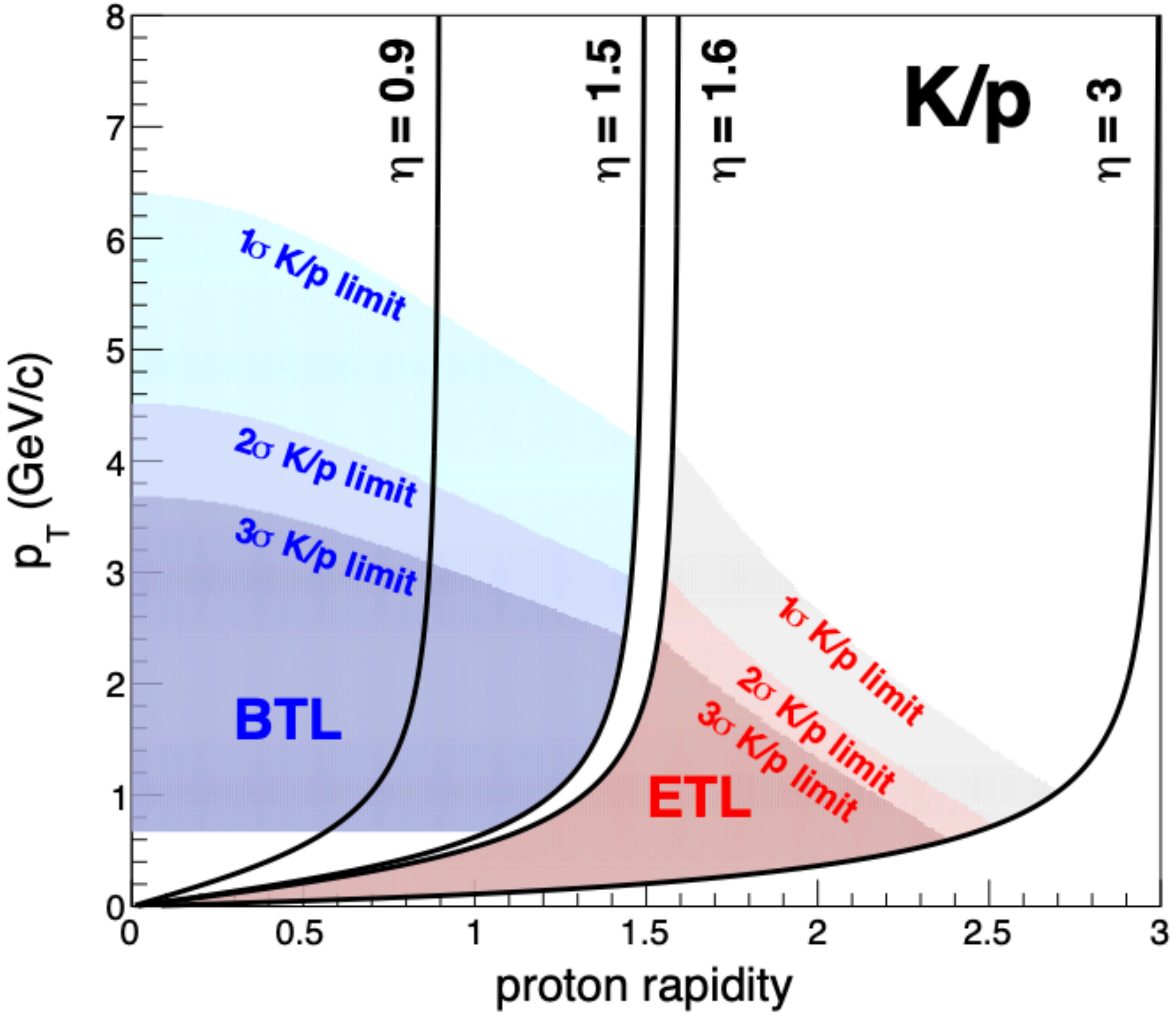




PID limits



π/K
η = 0.9
η = 1.5
η = 1.6
η = 3
1σ π/K limit
2σ π/K limit
3σ π/K limit
BTL
1σ π/K limit
2σ π/K limit
3σ π/K limit
ETL
p_T (GeV/c)
π rapidity



K/p
η = 0.9
η = 1.5
η = 1.6
η = 3
1σ K/p limit
2σ K/p limit
3σ K/p limit
BTL
1σ K/p limit
2σ K/p limit
3σ K/p limit
ETL
p_T (GeV/c)
proton rapidity

Participating CMS institutions (at TDR time)

Tag	Institution name
BY-INP	Institute for Nuclear Problems of Belarus State University, Minsk, Belarus
CN-PKU	Peking University, Peking, China
FI-HIP	Helsinki Institute of Physics, Helsinki, Finland
FR-IRFU	IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
DE-KIT	Karlsruher Institut fr Technologie (KIT), Institut fr Experimentelle Teilchenphysik (ETP), Karlsruhe, Germany
HU-Deb	Institute of Physics, University of Debrecen, Debrecen, Hungary
IT-Ge	INFN Sezione di Genova, Università di Genova, Genova, Italy
IT-MiB	INFN Sezione di Milano-Bicocca, Università di Milano-Bicocca, Milano, Italy
IT-Pd	INFN Sezione di Padova, Università di Padova, Padova, Italy, Università di Trento [c], Trento, Italy
IT-Rm	INFN Sezione di Roma, Sapienza Università di Roma, Rome, Italy
IT-To	INFN Sezione di Torino, Università di Torino, Torino, Italy, Università del Piemonte Orientale [c], Novara, Italy
IT-Ts	INFN Sezione di Trieste, Università di Trieste, Trieste, Italy
LT-ViU	Vilnius University, Vilnius, Lithuania
PT-LIP	Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal
RU-INR	Institute of Nuclear Resaerch (INR), Moscow, Russia
RU-NSU	Novosibirsk State University (NSU), Novosibirsk, Russia
SP-IFCA	Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain
SP-USe	University of Sevilla, Sevilla, Spain
CH-ETHZ	ETH Zurich - Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland
US-BU	Boston University, Boston, USA
US-UCSB	University of California, Santa Barbara - Department of Physics, Santa Barbara, USA
US-Caltech	California Institute of Technology, Pasadena, USA
US-FU	Fairfield University, Fairfield, USA
US-FNAL	Fermi National Accelerator Laboratory, Batavia, USA
US-UIC	University of Illinois at Chicago (UIC), Chicago, USA
US-UI	The University of Iowa, Iowa City, USA
US-KU	The University of Kansas, Lawrence, USA
US-KSU	Kansas State University, Manhattan, USA
US-MIT	Massachusetts Institute of Technology, Cambridge, USA
US-UNL	University of Nebraska-Lincoln, Lincoln, USA
US-NEU	Northeastern University, Boston, USA
US-ND	University of Notre Dame, Notre Dame, USA
US-PU	Princeton University, Princeton, USA
US-Rice	Rice University, Houston, USA
US-UVa	University of Virginia, Charlottesville, USA
US-UW	University of Wisconsin - Madison, Madison, WI, USA