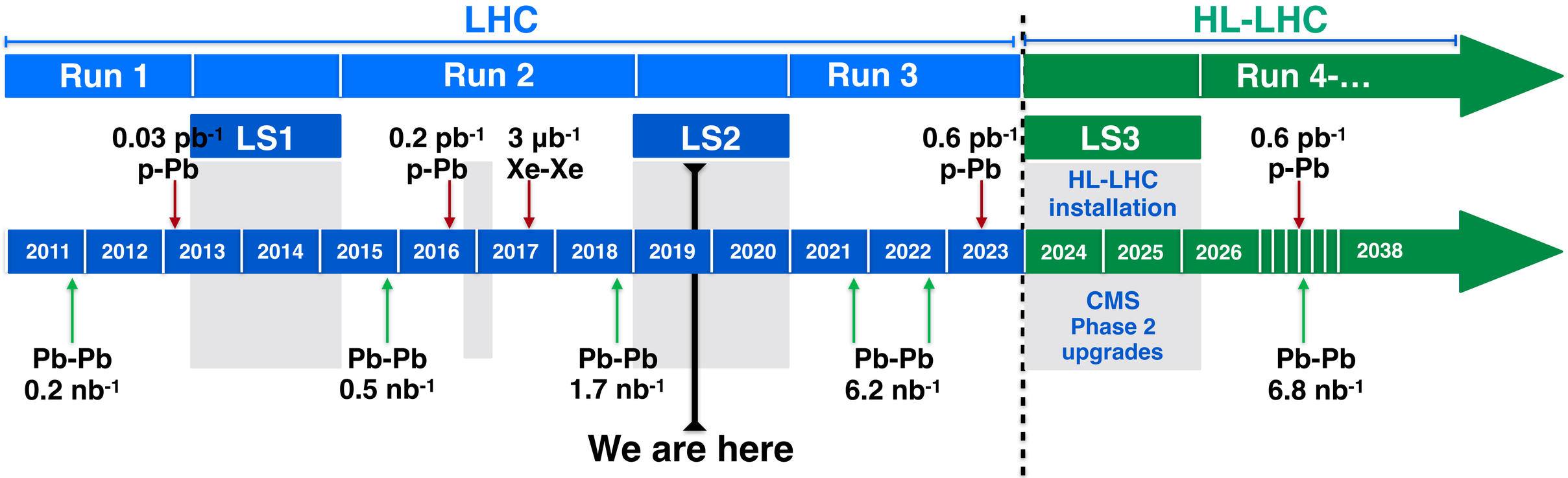
New opportunities in HI physics at HL-LHC with a MIP Timing Detector at CMS

Andre Ståhl
on behalf of the CMS Collaboration

T.W. Bonner Laboratory, William Marsh Rice University

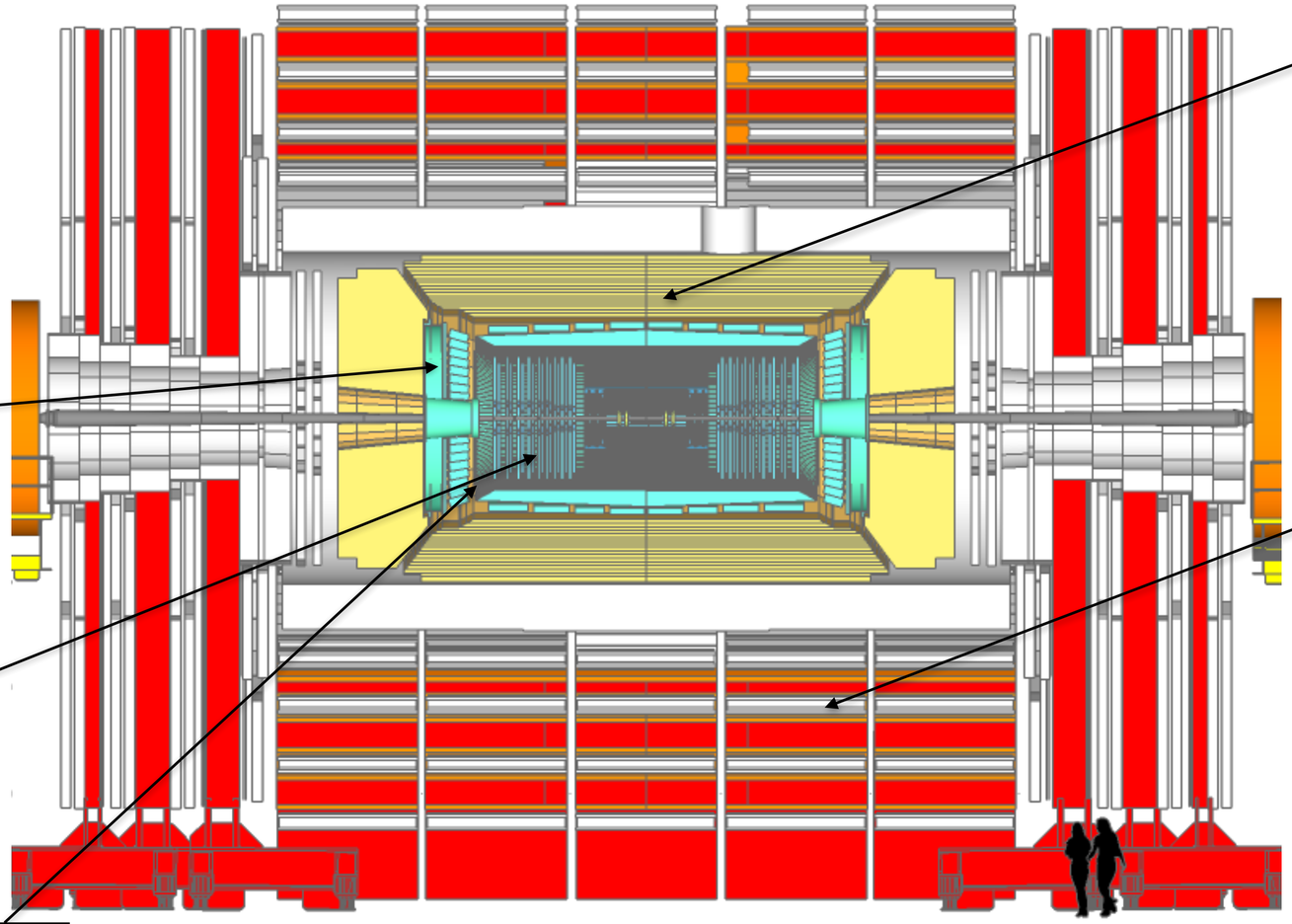
28th International Conference on
Ultra-relativistic Nucleus-Nucleus Collisions

Heavy Ion Program at LHC



- Successful HI program at LHC: Pb-Pb, Xe-Xe and p-Pb, with all 4 main LHC experiments participating.
- By the end of Run 3+4, we expect an increase of 5-7x HI data.
- CMS major upgrade for High Luminosity LHC will bring new opportunities for the HI programme.

CMS Phase 2 upgrades for HL-LHC

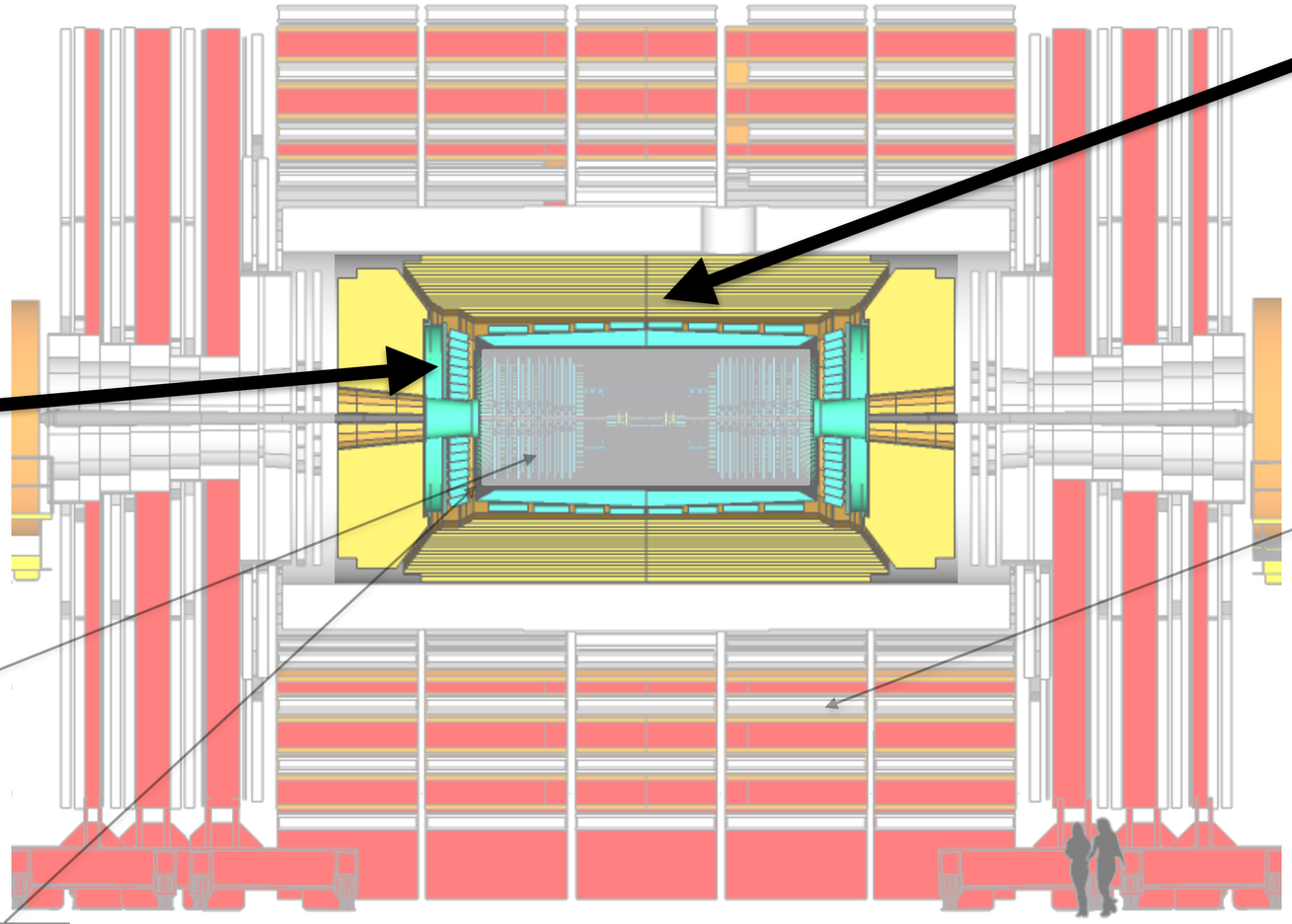


CMS Phase 2 upgrades for HL-LHC

Trigger / HLT / DAQ

Barrel Calorimeters
- Replace FE/BE electronics

New Endcap Calorimeters
- Radiation tolerance
- High granularity



Muon Systems

New Tracker

New MIP Timing Detector

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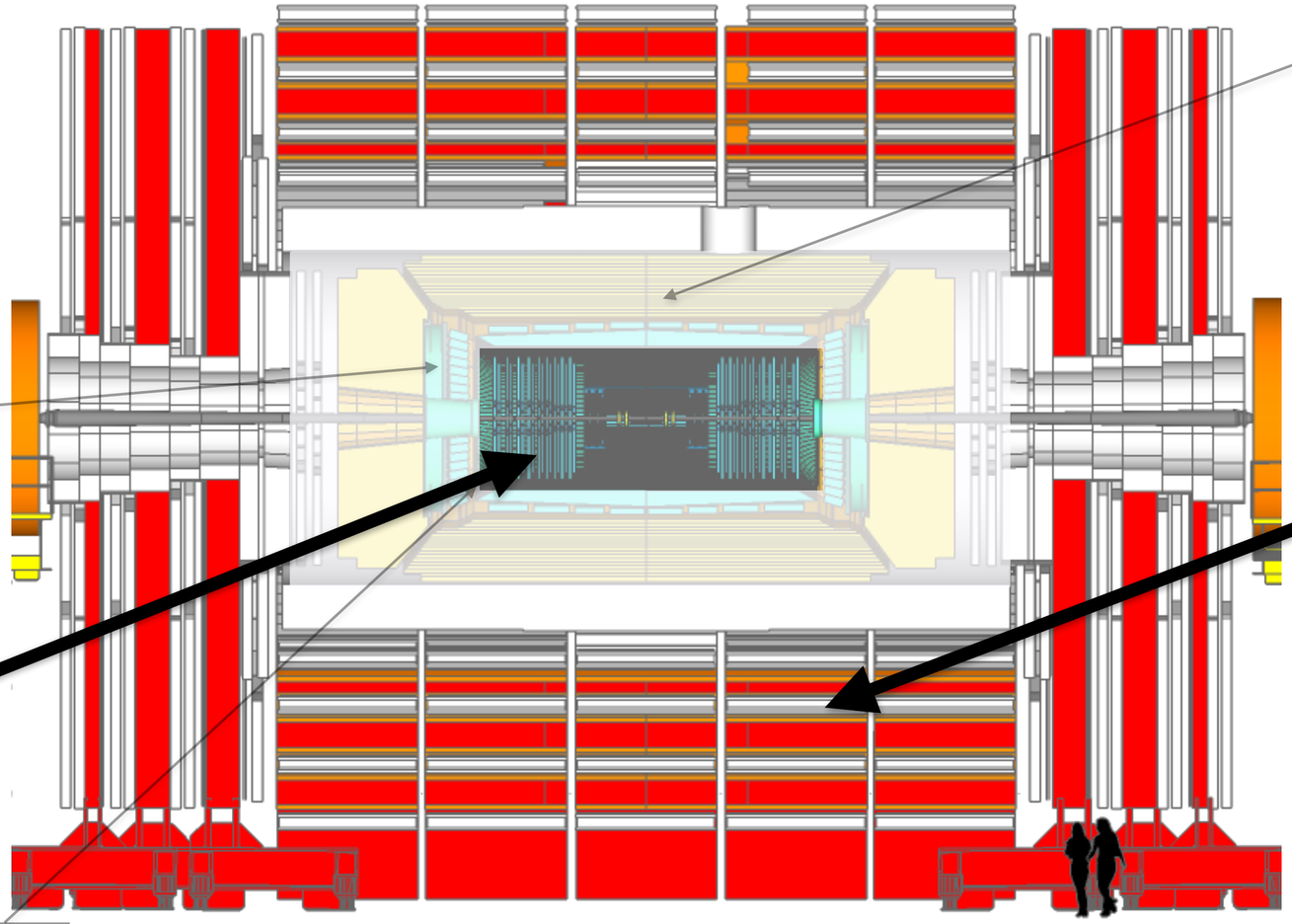


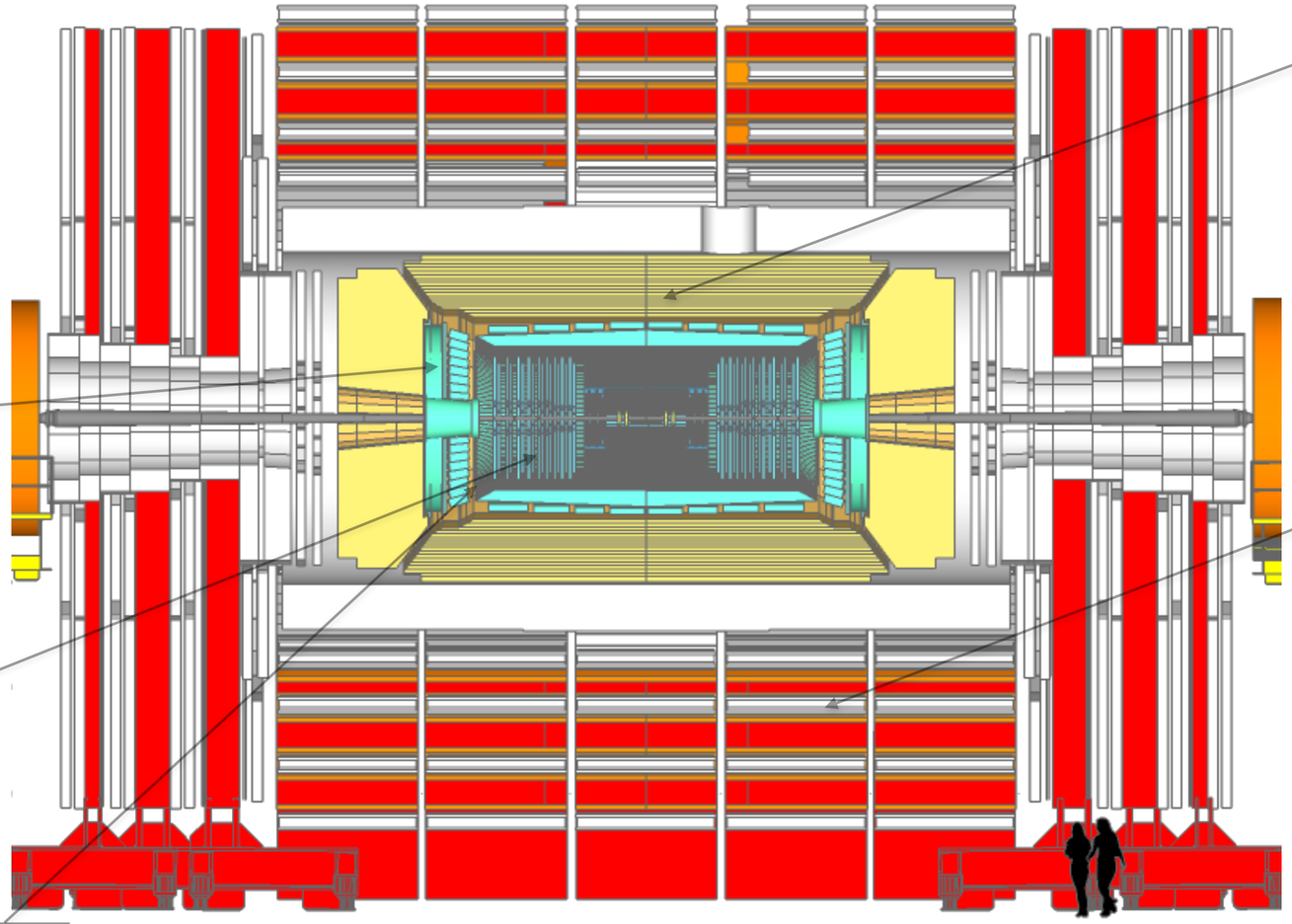
Muon Systems
- $|\eta| < 2.4 \rightarrow |\eta| < 3.0$

New Tracker
- Radiation tolerance
- High granularity
- $|\eta| < 2.4 \rightarrow |\eta| < 4.0$

New MIP Timing Detector

CMS Phase 2 upgrades for HL-LHC

Trigger / HLT / DAQ
- Track info. in L1
- L1/HLT rate x7.5
- DAQ: 6 → **60 GB/s**



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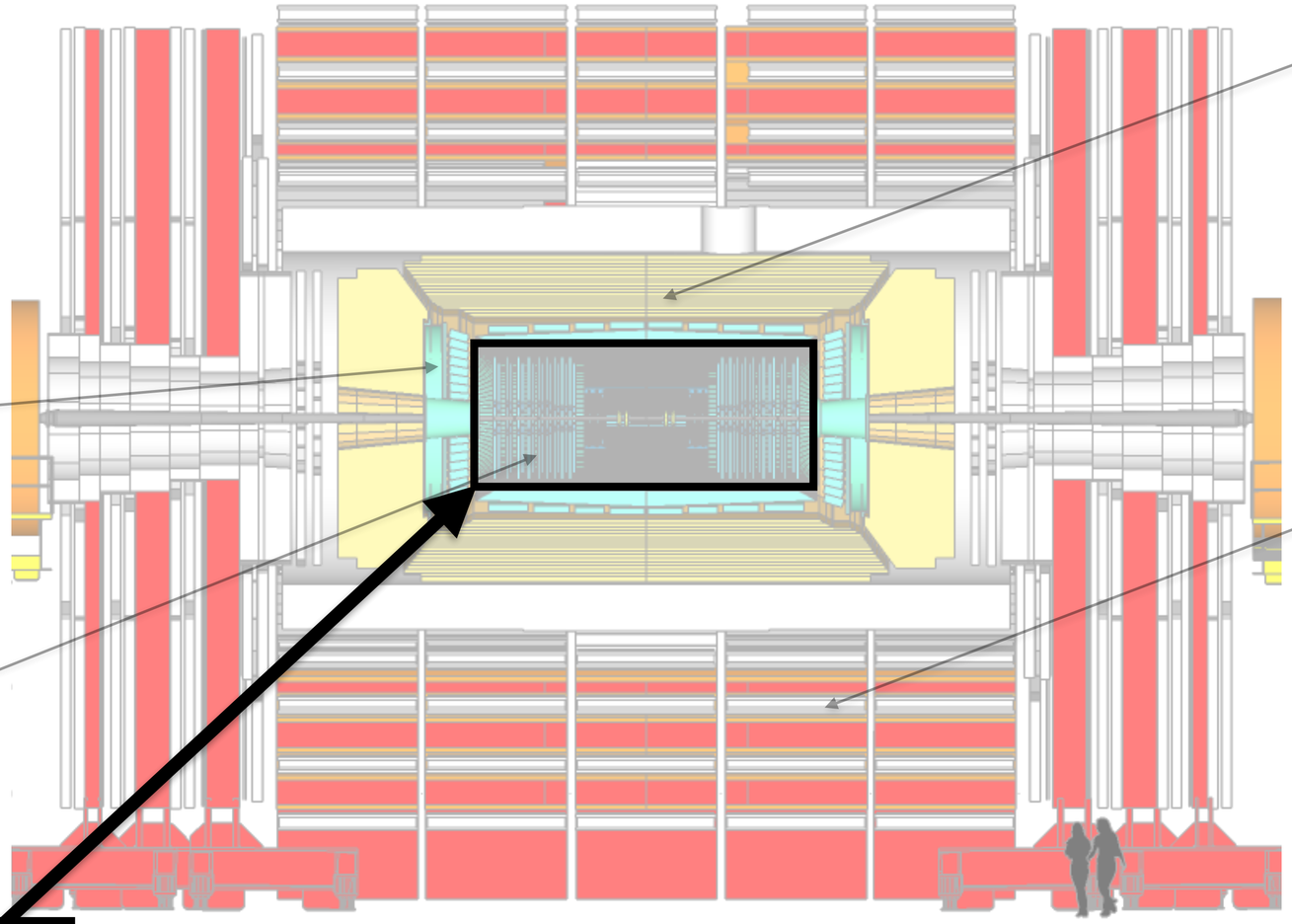
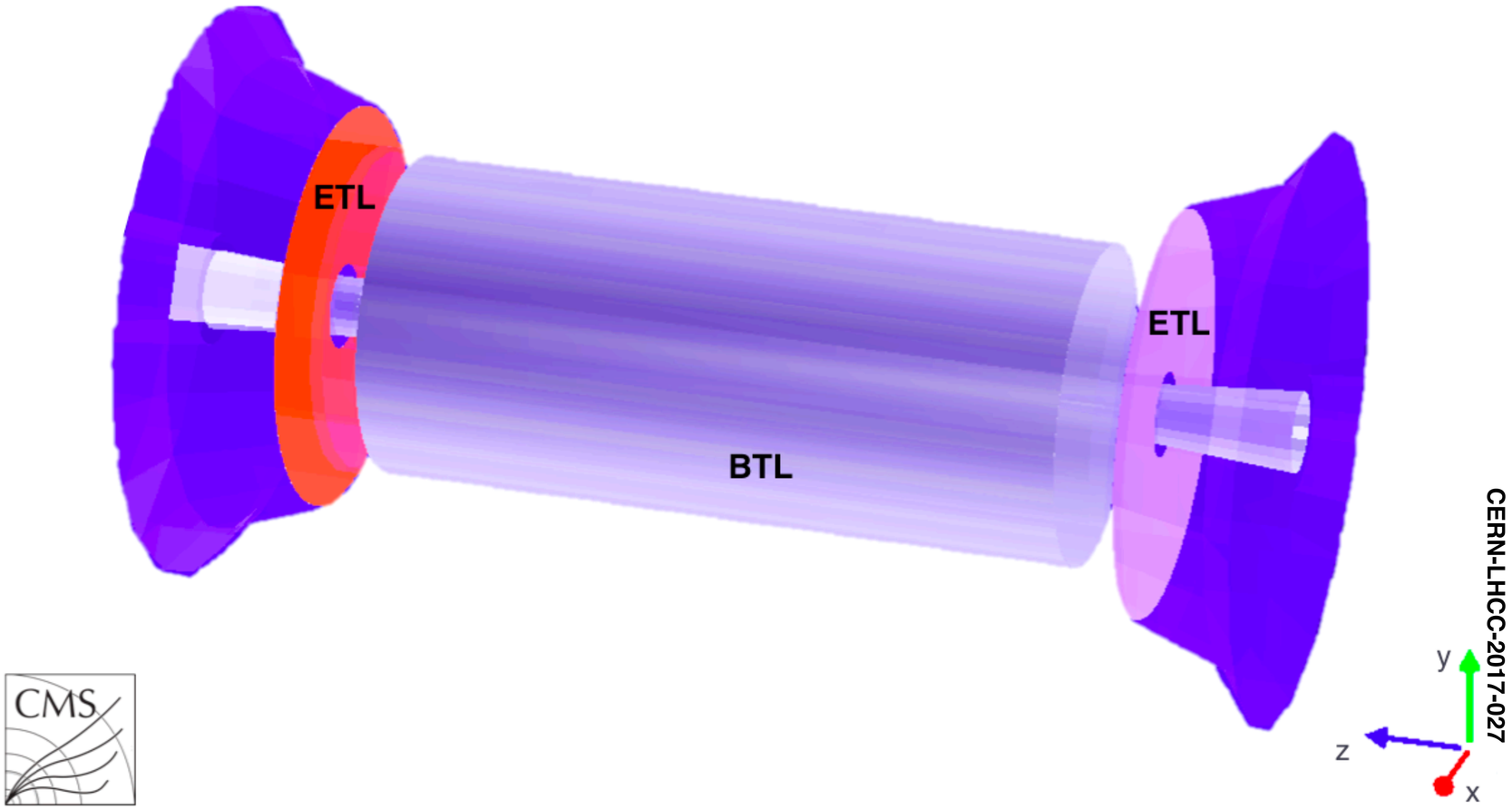


New MIP Timing Detector
- Precision timing
- $|\eta| < 3.0$

Conceptual design

CMS MIP Timing Detector (MTD)



- One barrel section (BTL) and two end-cap disks (ETL).
- Coverage for tracks: p > 0.7 GeV at $|\eta| < 3.0$, and time resolution: ~30 ps
- Installation planned for HL-LHC: 2022 for BTL and 2024 for ETL.

Barrel Timing Layer (BTL)

Design:

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

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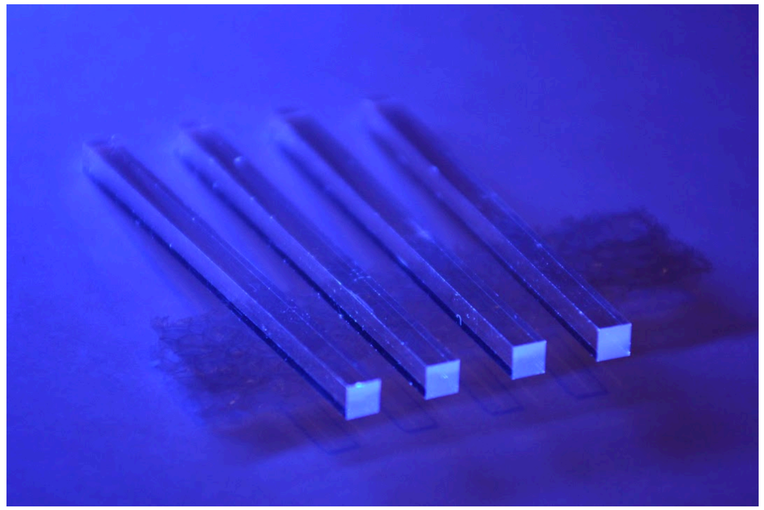
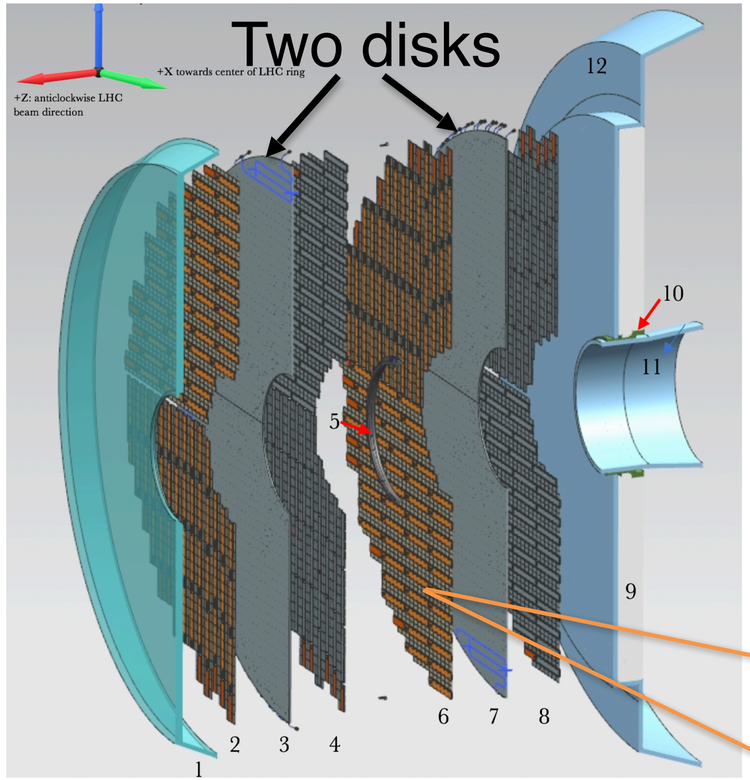
Sensors:

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



Endcap Timing Layer (ETL)



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Design:

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

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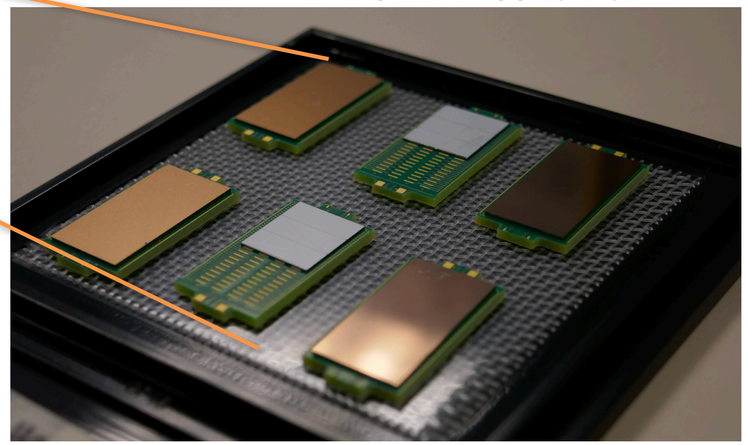


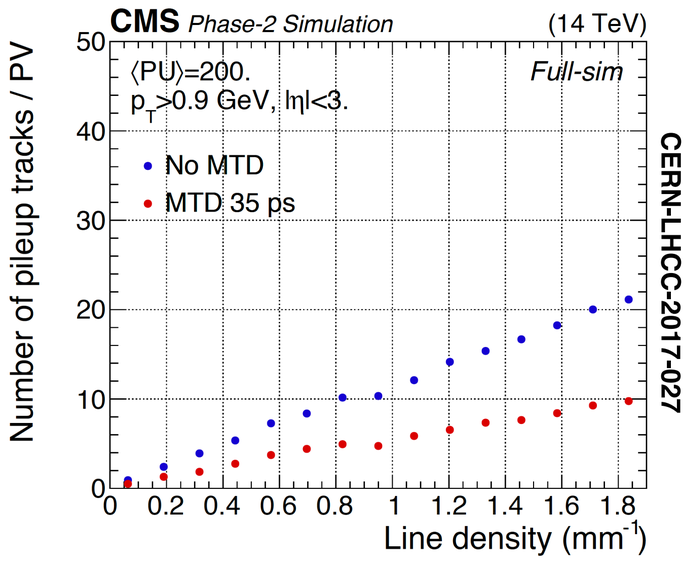
Sensors:

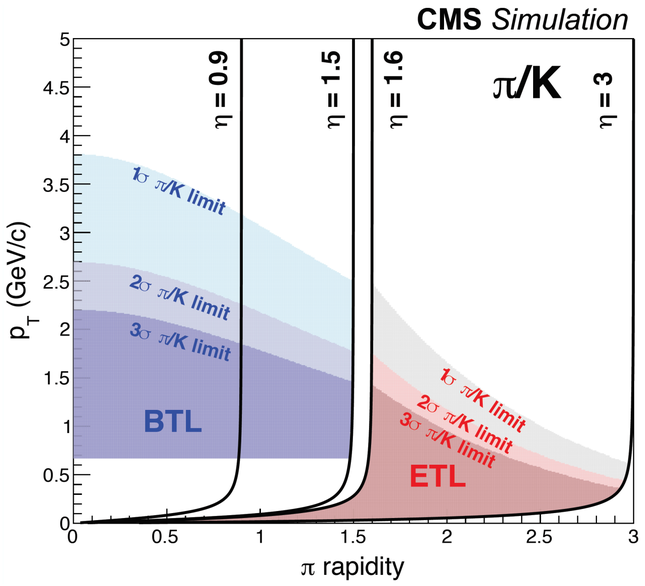
- **Ultra fast silicon detectors:**
  - Low gain avalanche diodes optimised for precision timing.

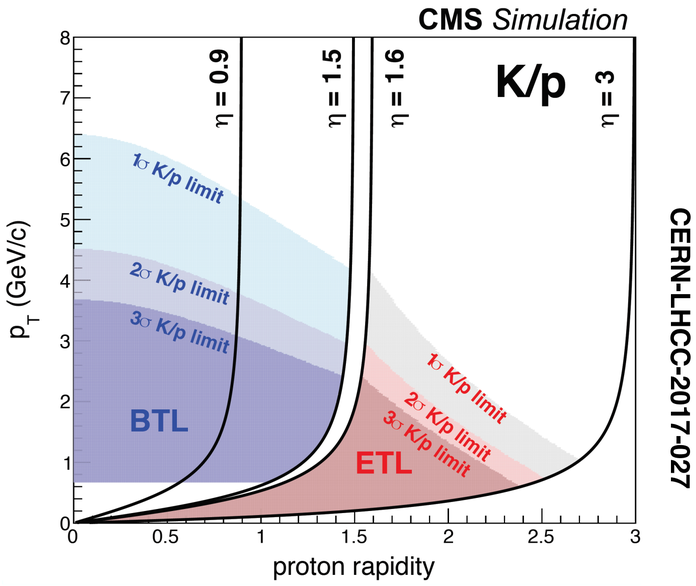
Applications and performance

Applications of CMS MTD

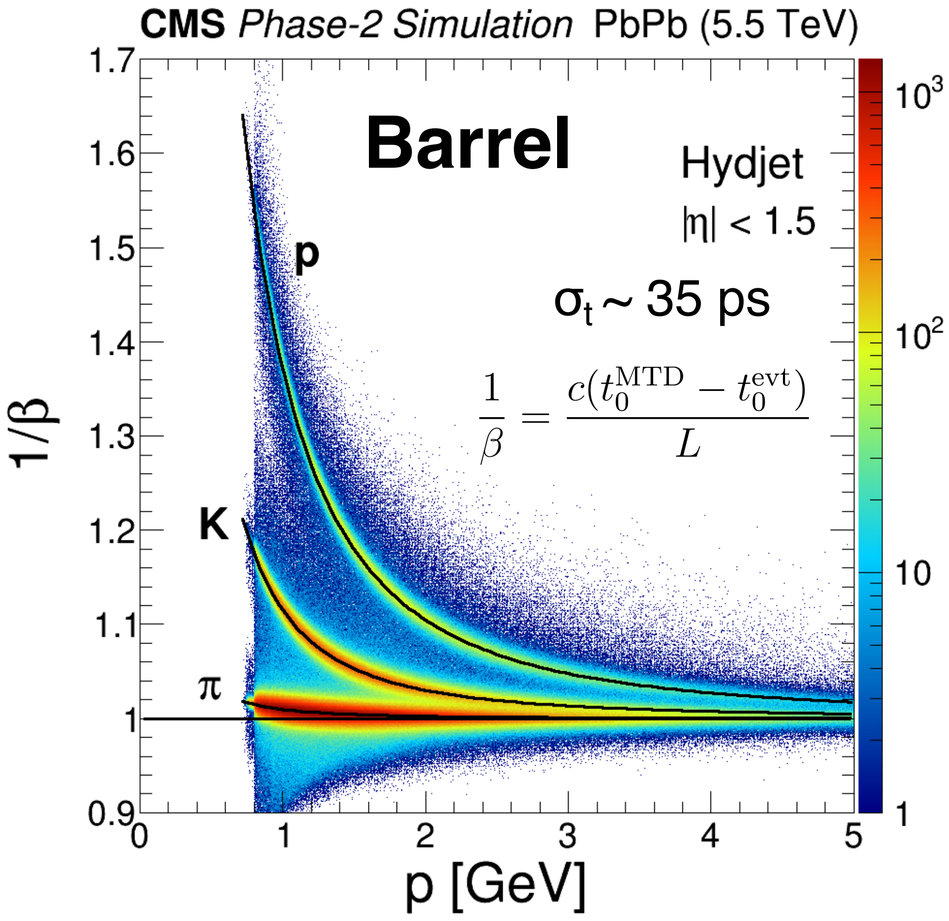
- Time compatibility for track-vertex association:
  - Suppress impact of pile-up in pp collisions.
- 4D vertex reconstruction:
  - Improved reconstruction of displaced products (B decays) or long-lived particles (BSM).
- Measurement of velocity of low p_T hadrons:
  - Particle identification via Time-of-Flight (TOF) of charged hadrons (π, K, p) down to p = 0.8 GeV.

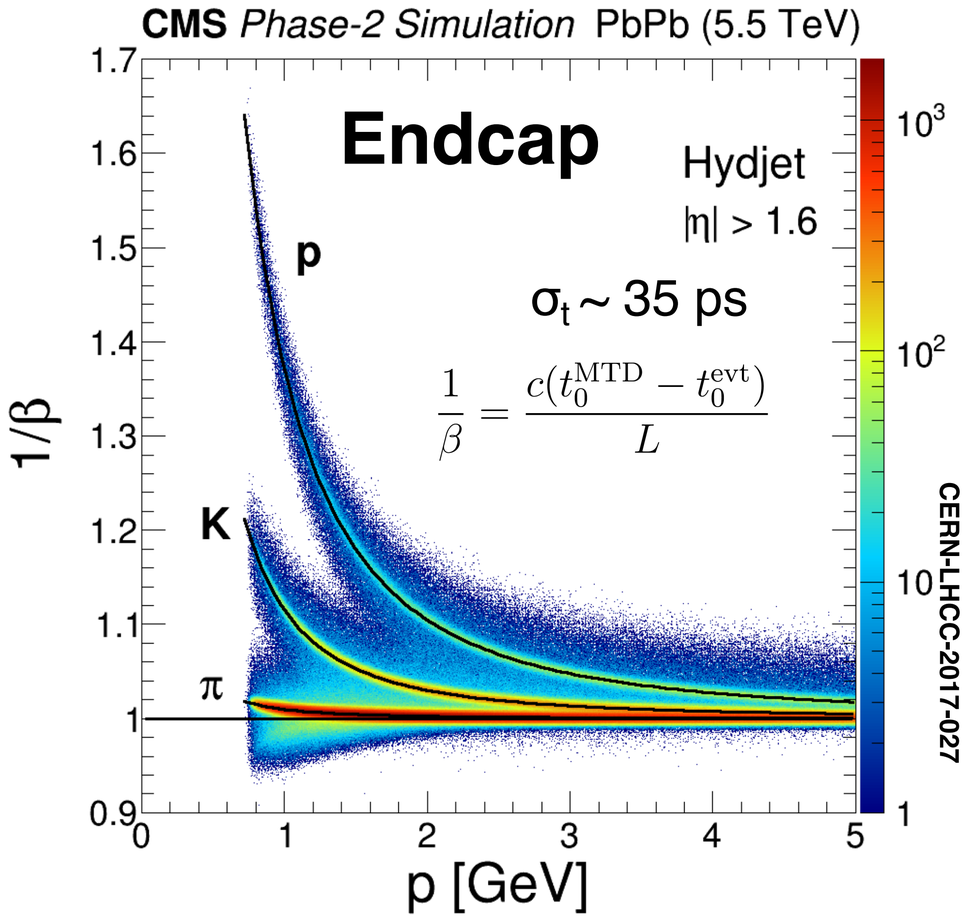






TOF-PID performance with MTD

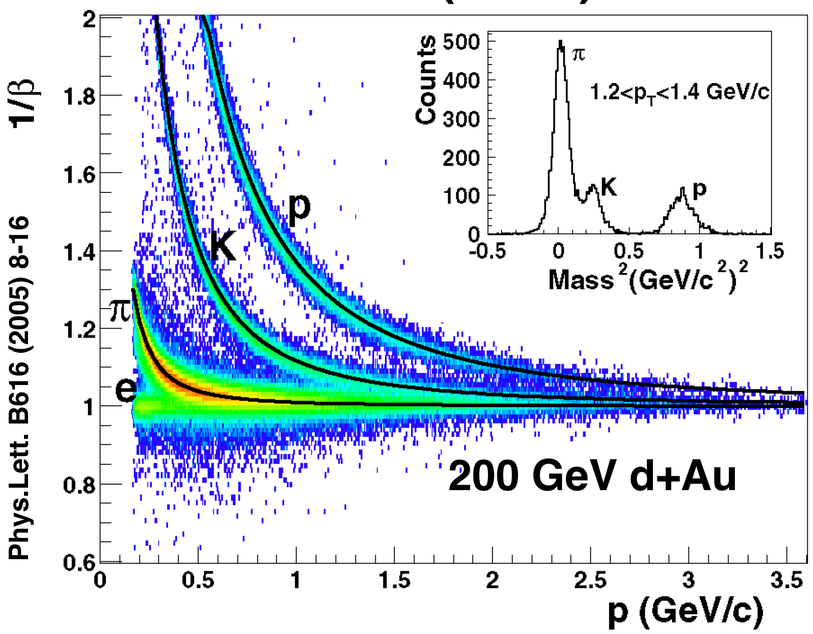




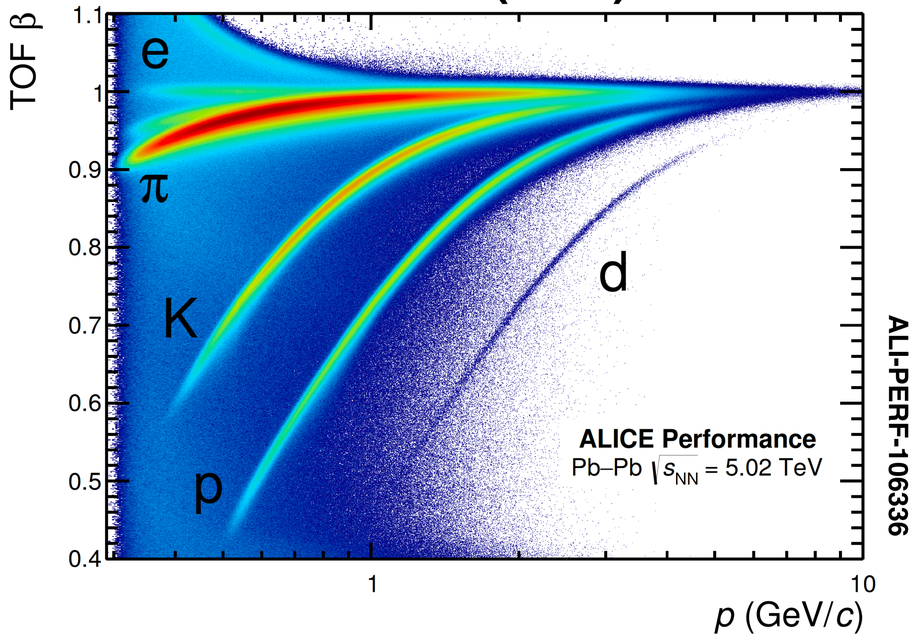
- Clear identification of π/K up to p ~ 2.5 GeV and p/K up to p ~ 5 GeV.
- Hermetic coverage over |η| < 3

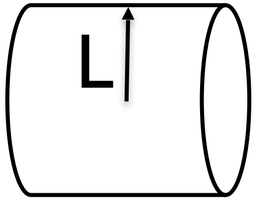
TOF-PID comparison with ALICE and STAR

STAR (RHIC)



ALICE (LHC)





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

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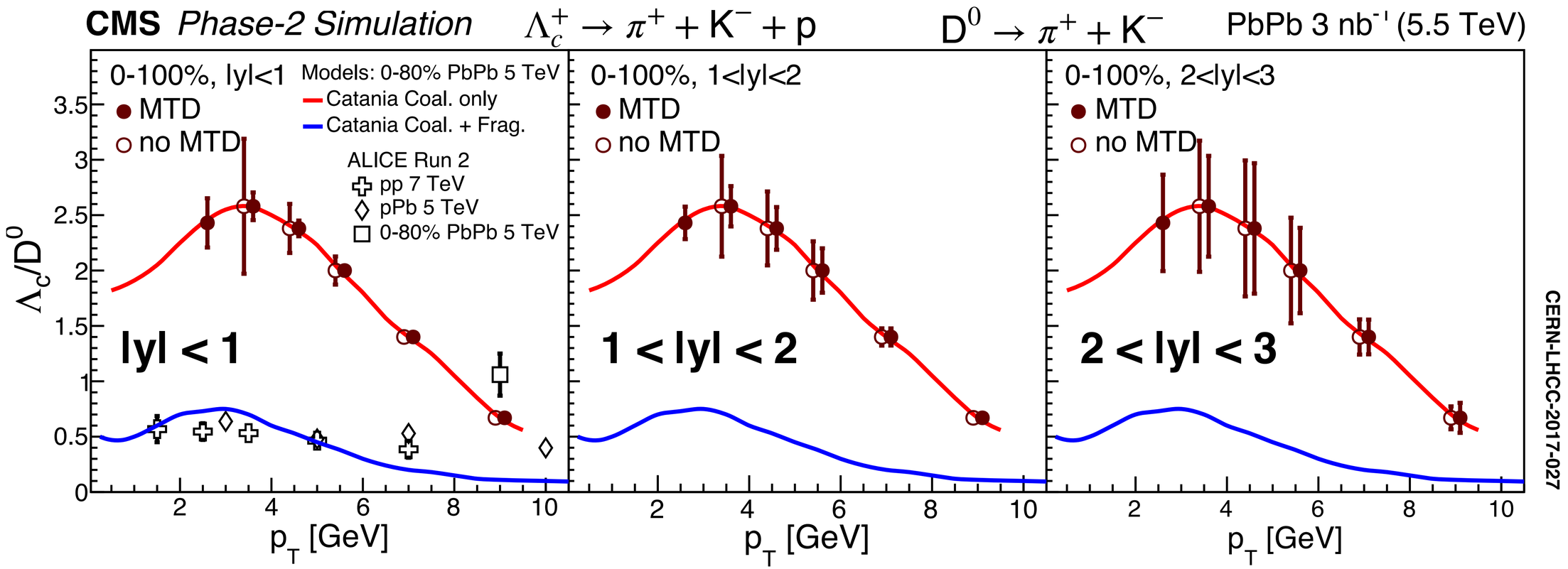
- Competitive momentum coverage compared to ALICE and STAR
- **Unique wider rapidity coverage**

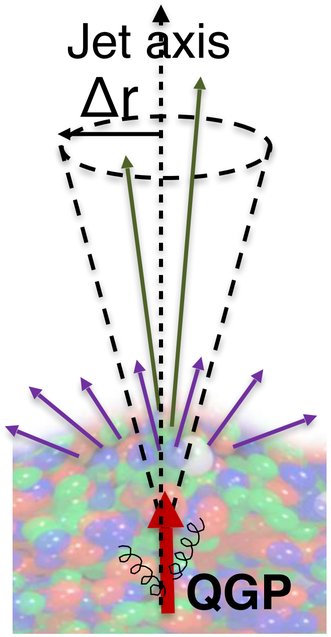
Physics impact

Heavy quark dynamics in QGP



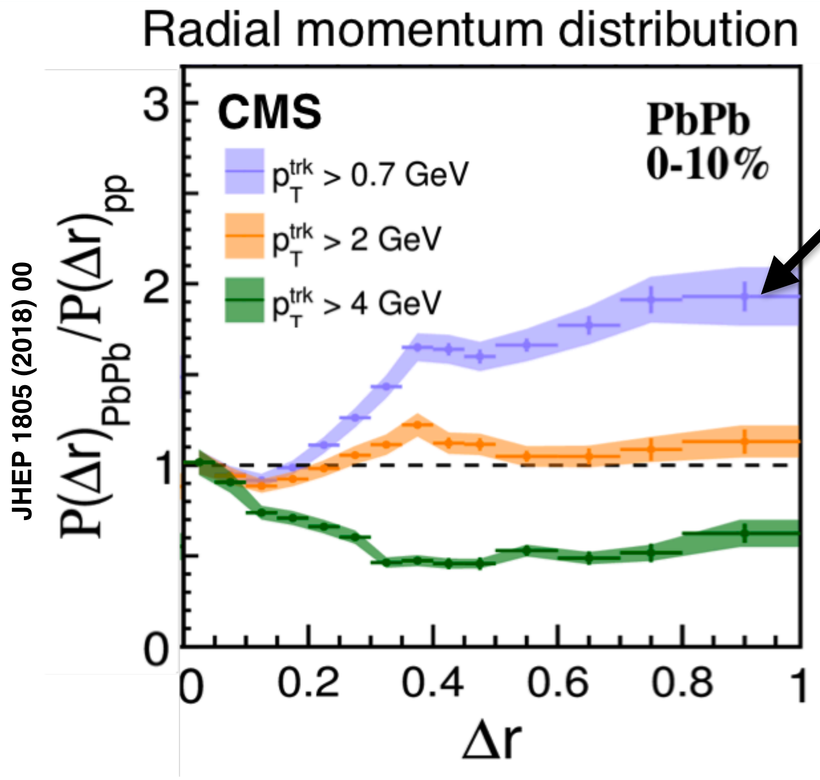
- CMS will be able to study c- and b-hadrons over 6 units of rapidity ($|\eta| < 3$) with MTD.
- Measurements of the production yield and correlation will constrain the 3D HF dynamics in QGP.

QGP response to parton energy loss

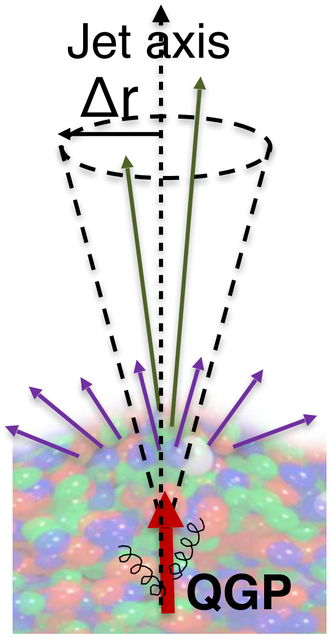


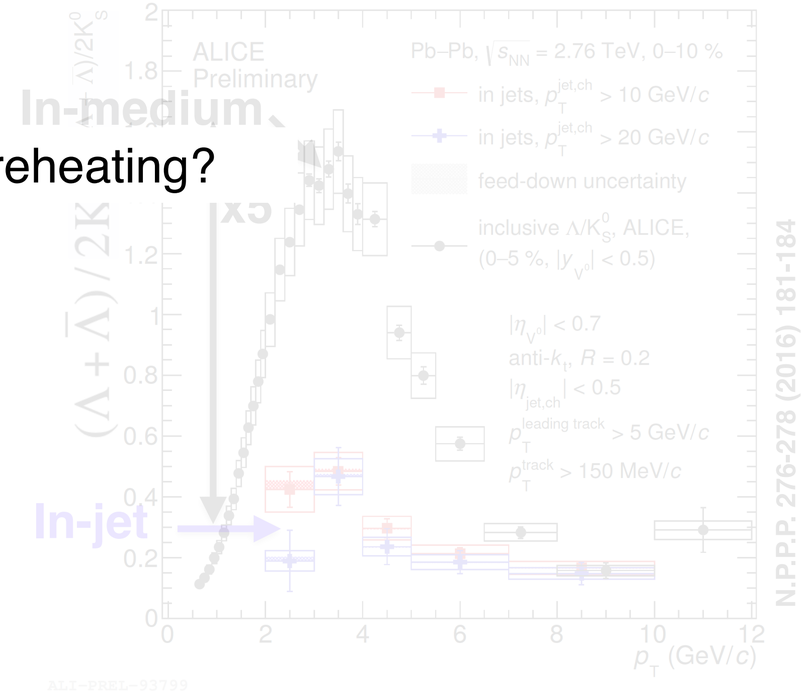
- CMS HL upgrades + MTD provides a unique opportunity to measure baryon-to-meson ratios differential in jet radii, distinguishing between QGP medium effects and jet fragments.

QGP response to parton energy loss



Jet fragmentation or medium reheating?





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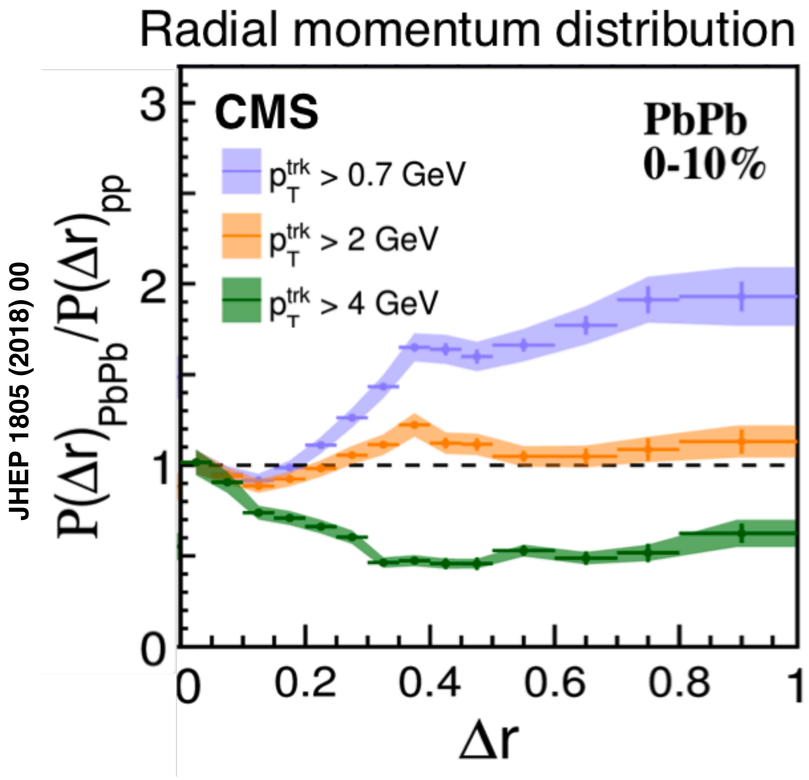

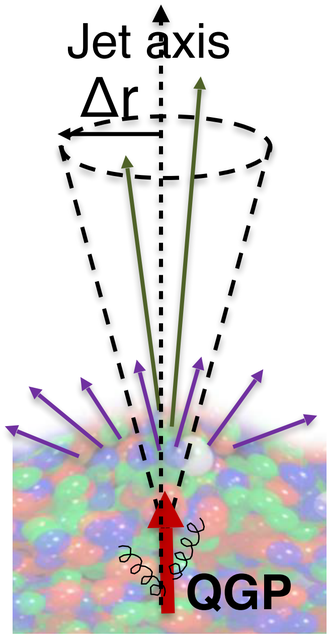

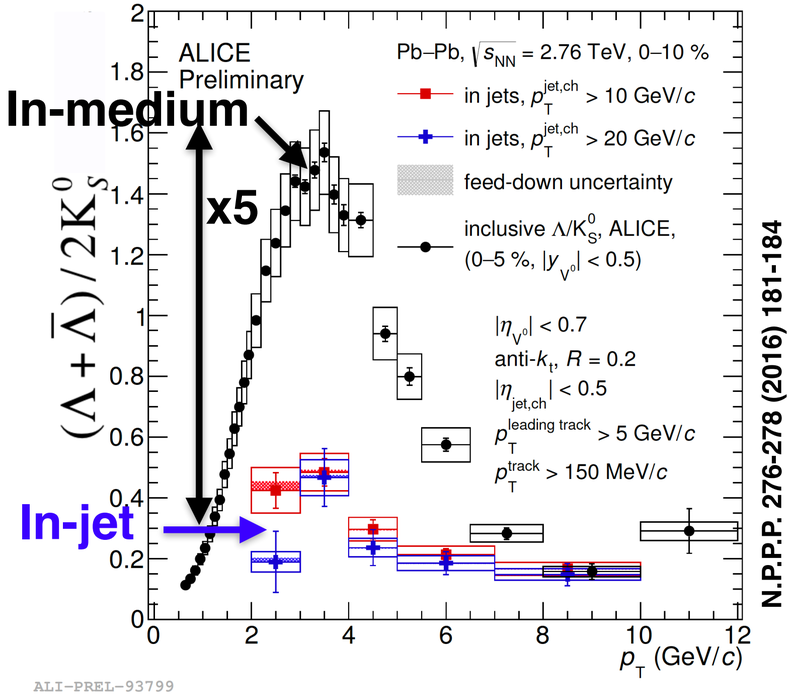

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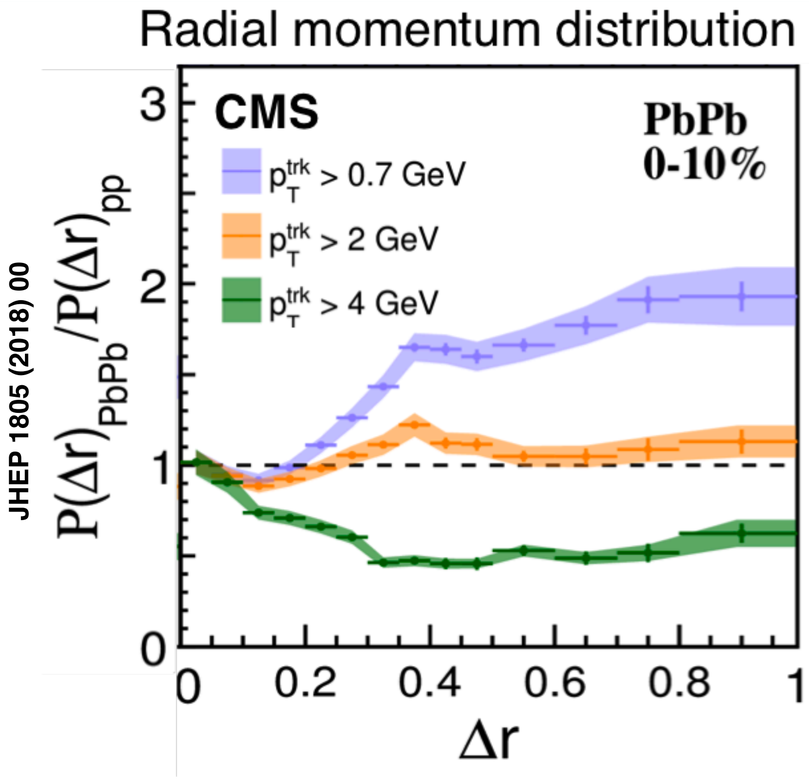

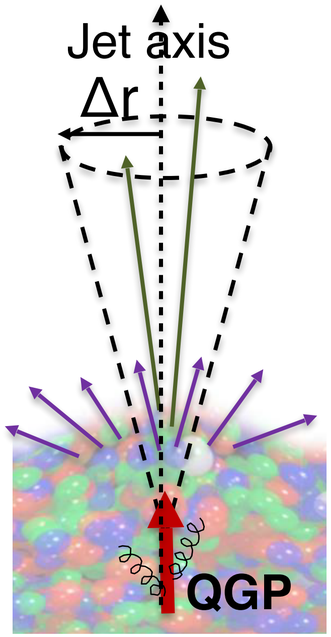

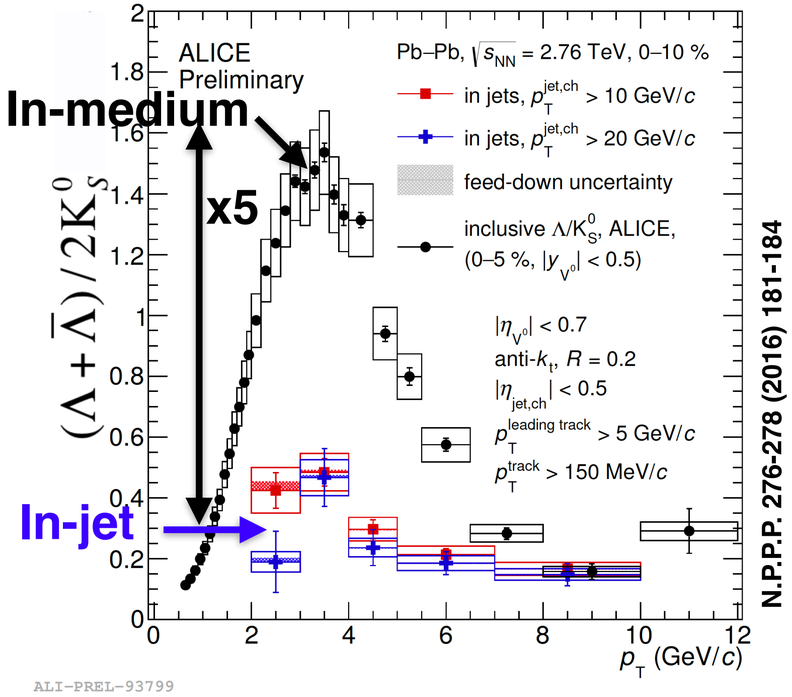

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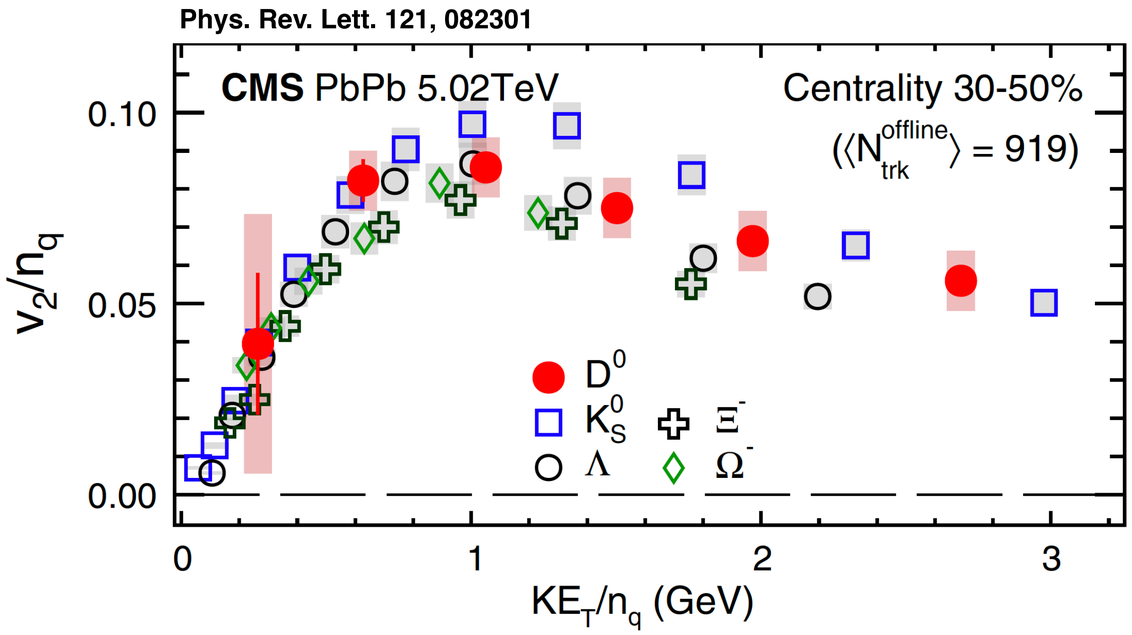
Universal scaling of elliptic flow



- MTD will allow to derive the v_2 of charm baryons and to measure precisely the N_q-scaling of v_2 in the charm quark sector:

$$v_2(\Lambda_c) = \frac{3}{2}\, v_2(D_0)?$$

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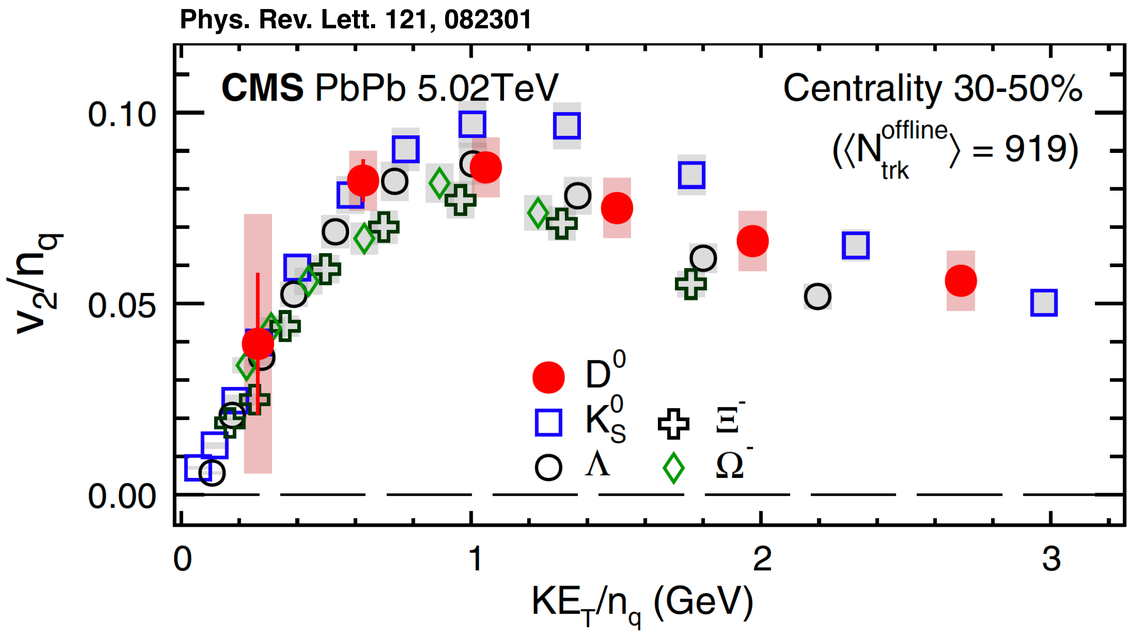

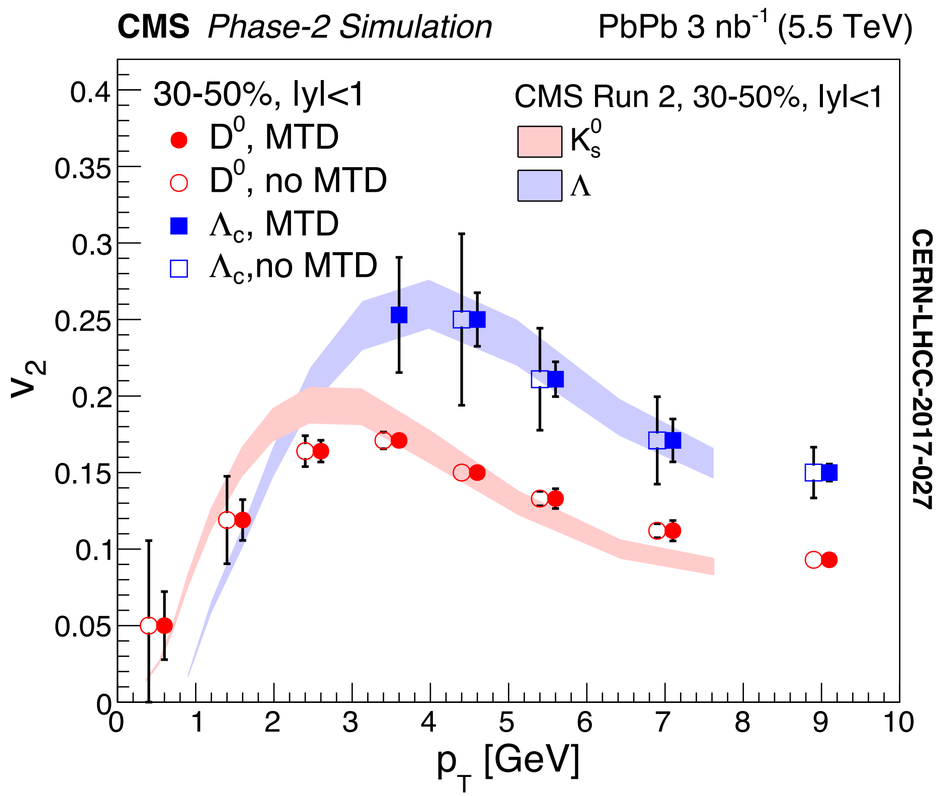

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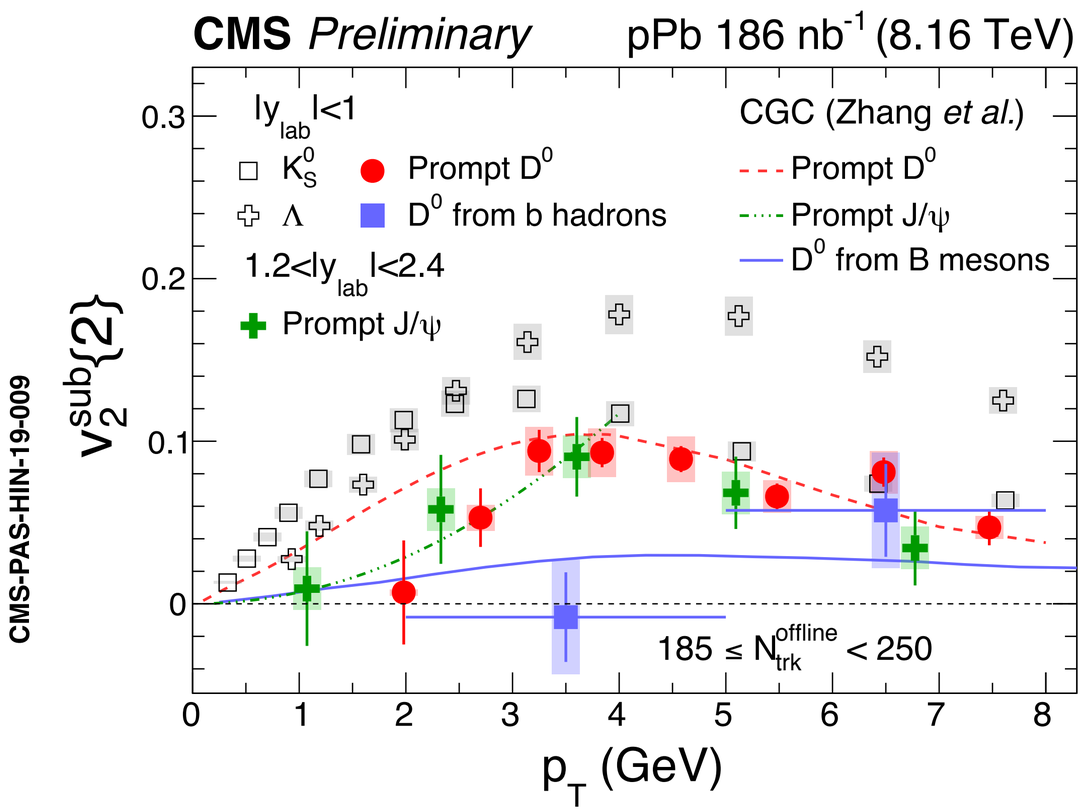
Origin of collectivity in small systems



- Collect more data by triggering on high MIP-multiplicity with MTD.
- Reduce the HF background using TOF-PID, allowing to measure v_2 down to very low p_T for a variety of HF hadrons in small systems.

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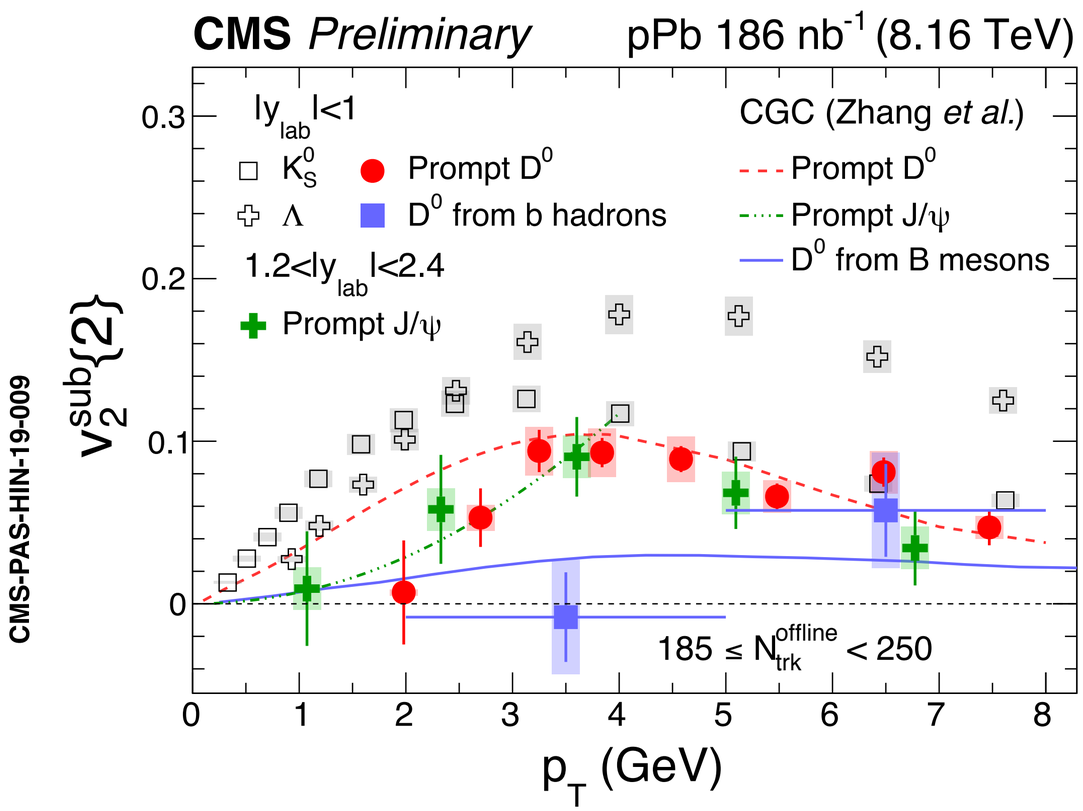

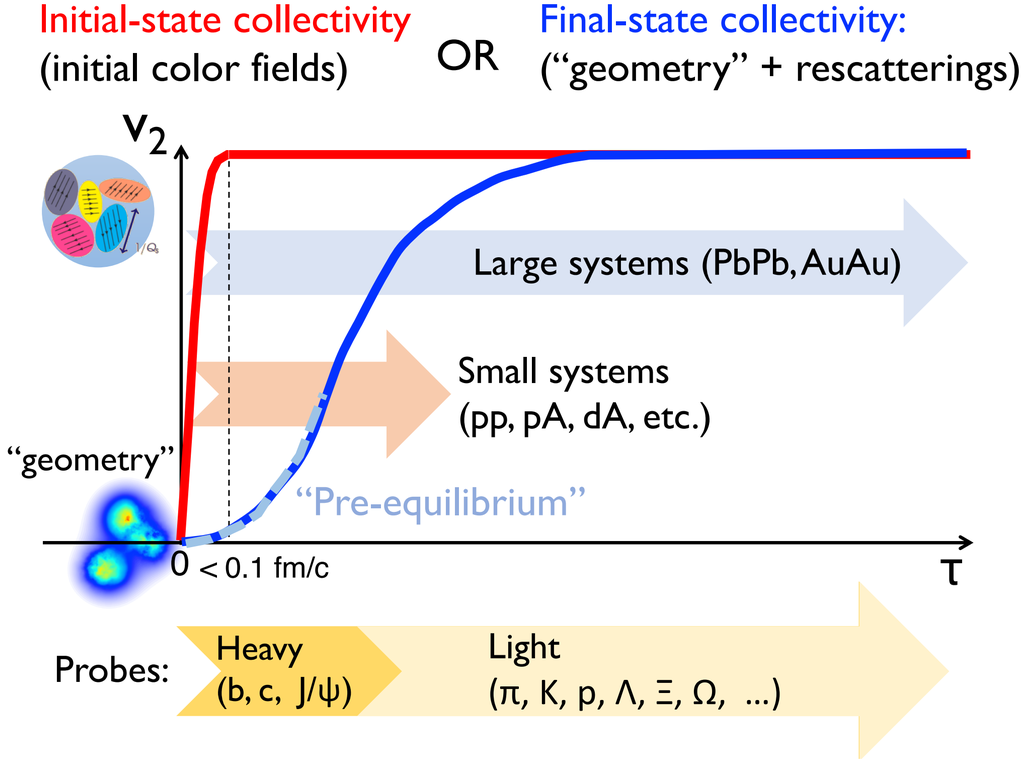

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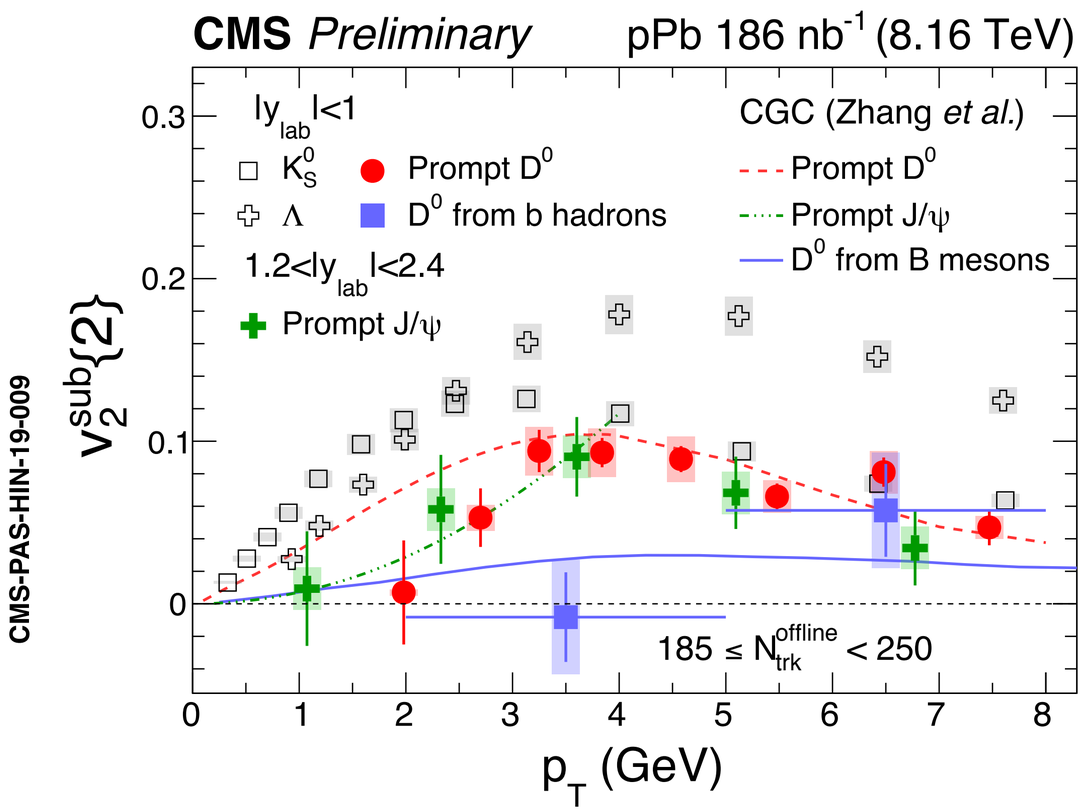

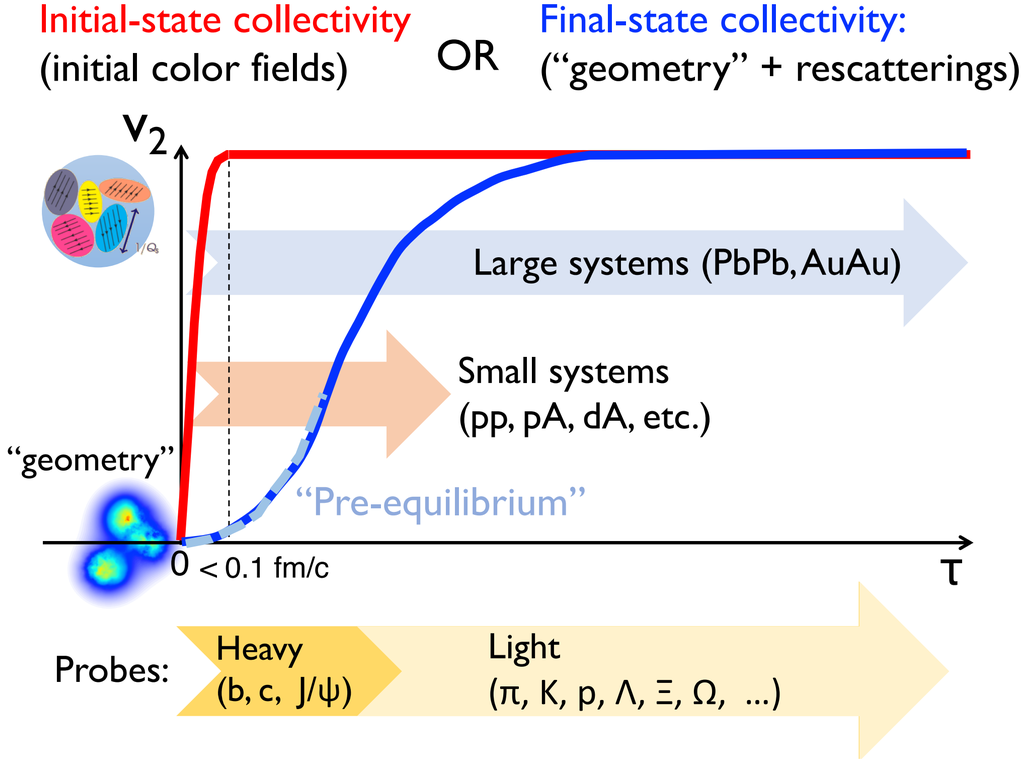

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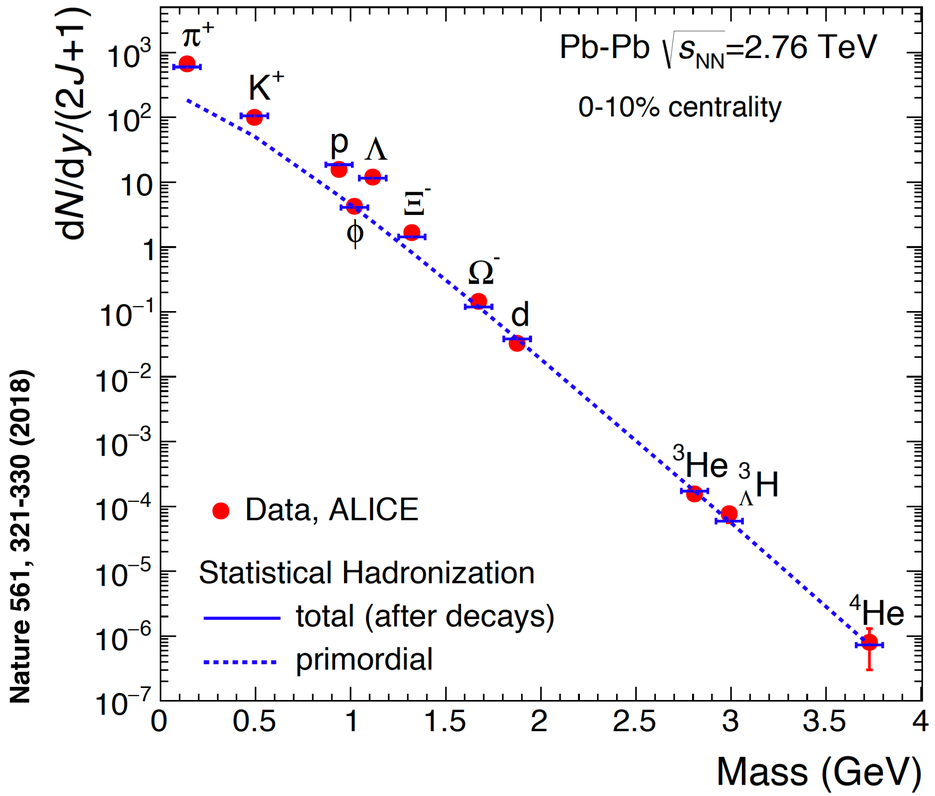
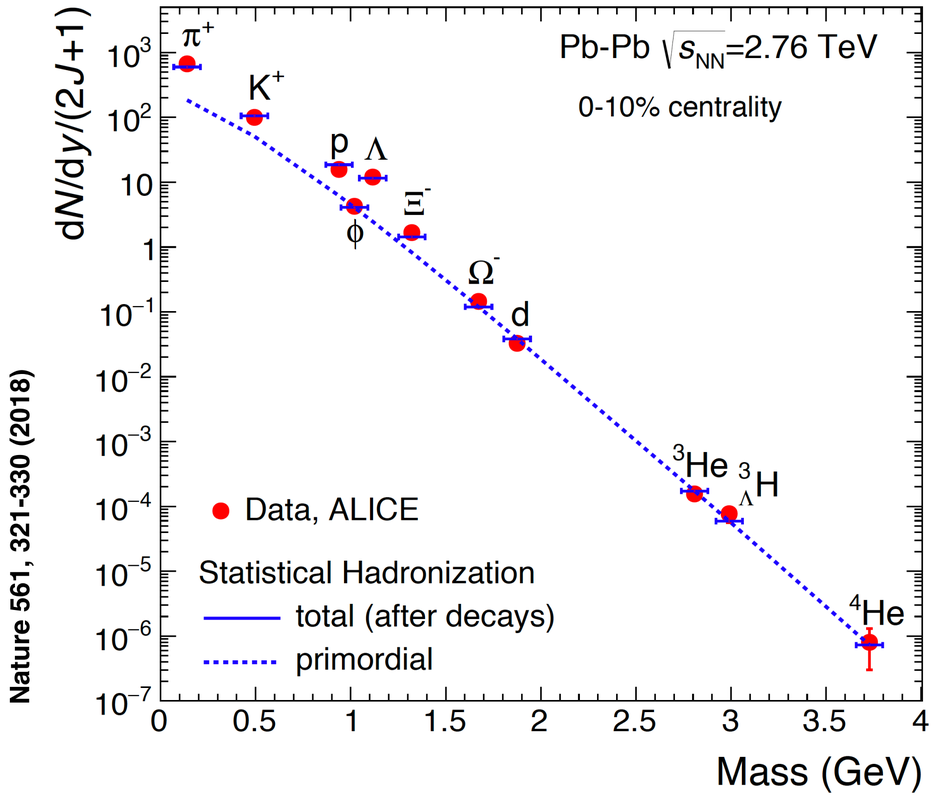
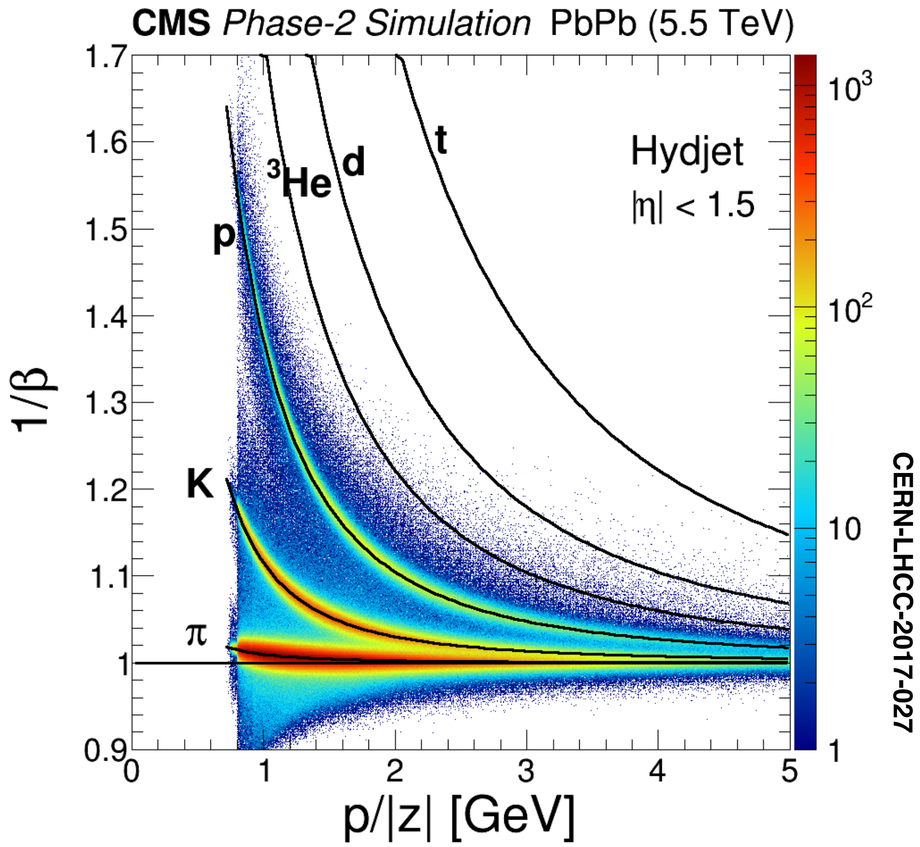
Light (hyper-) nuclei production



- Light (d, ^{3}He, t) and hyper ($^3_\Lambda$He, $^3_\Lambda$H) nuclei can be identified over a wide kinematic range via TOF using MTD.
- Also provide insights for dark matter searches and astrophysics.

Light (hyper-) nuclei production





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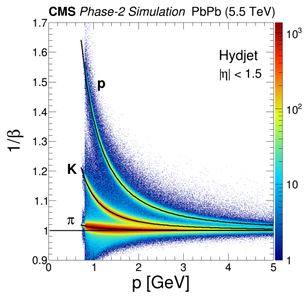
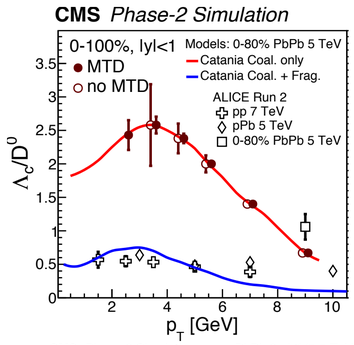
SUMMARY

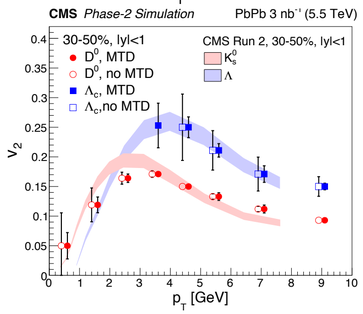
CMS will add a new precise MIP timing detector for HL-LHC

For more details check: CERN-LHCC-2017-027



MTD will bring a completely new capability to CMS: particle identification via time-of-flight





High impact on CMS Heavy Ion physics program:

- Heavy quark dynamics in QGP → D $p_T > 0$ GeV and Λ_C $p_T > 3$ GeV
- QGP response to parton energy loss
- Universal scaling of elliptic flow
- Origin of collectivity in small systems
- Light (hyper-) nuclei physics
- …. among other topics

Thank you for your attention!

Acknowledgement

U.S. DEPARTMENT OF ENERGY

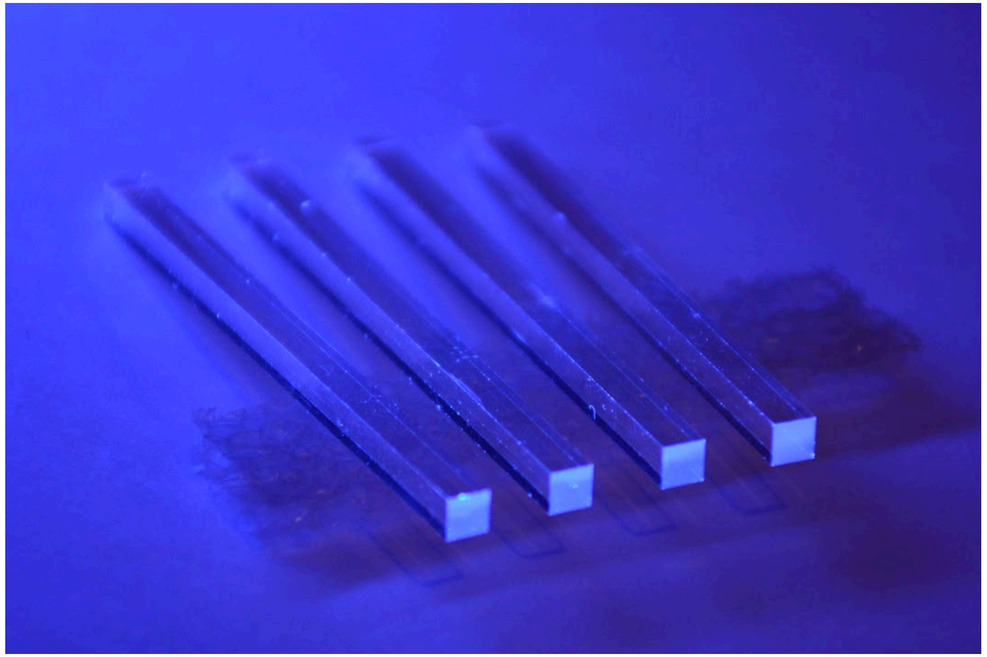
Office of Science

Alfred P. Sloan FOUNDATION

THE Welch FOUNDATION

BACKUP

Lutetium-Yttrium Oxyorthosilicate crystal



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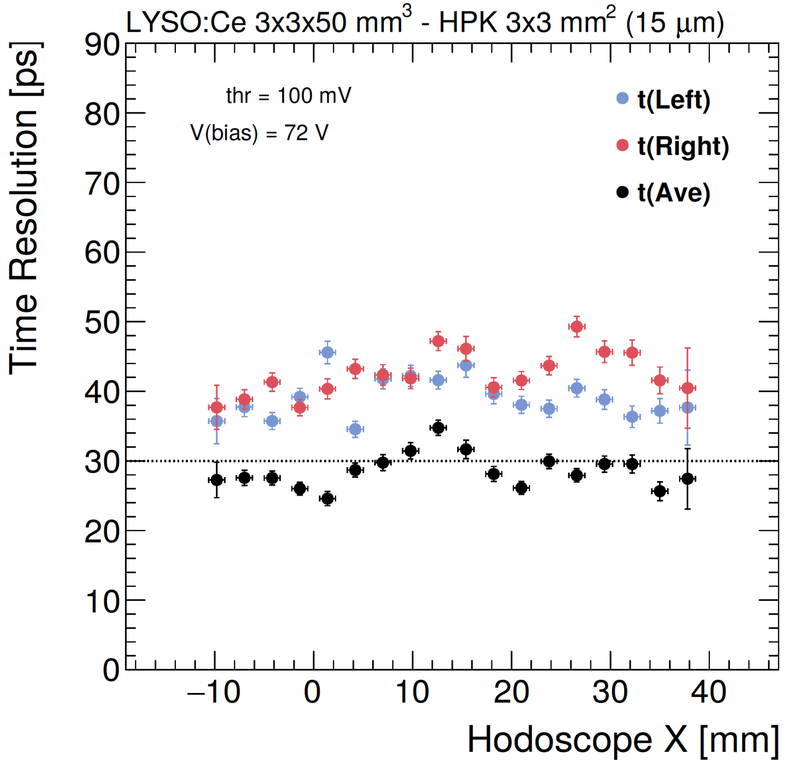

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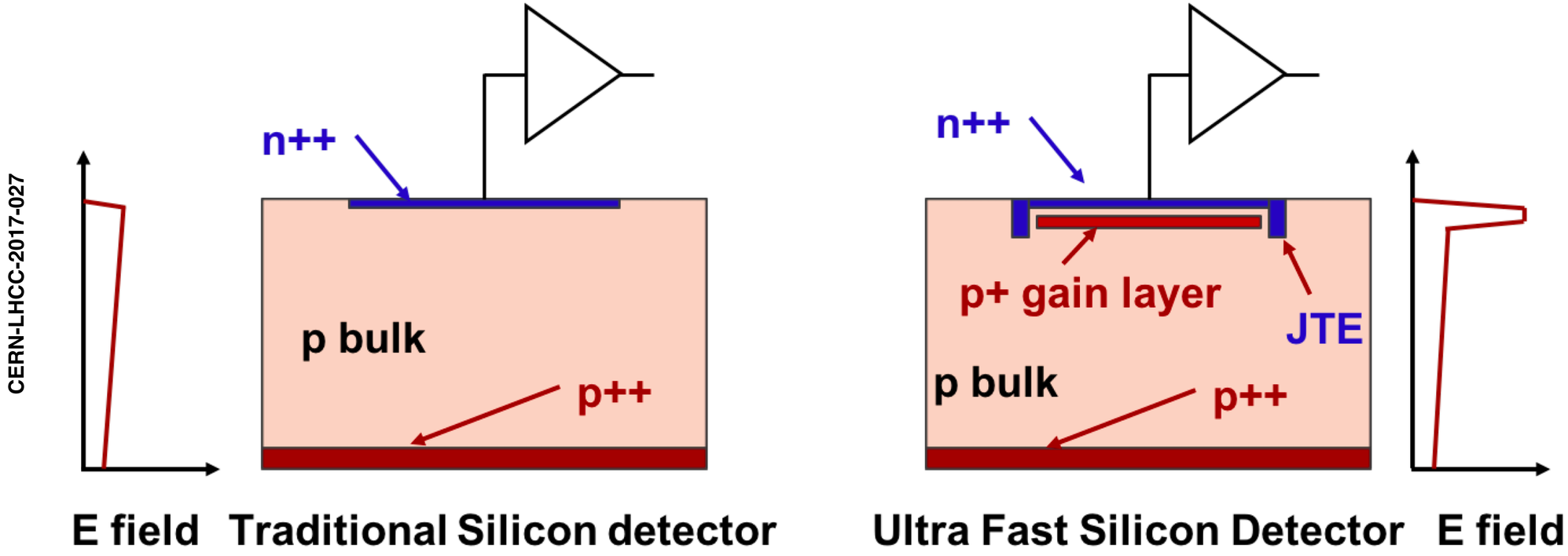
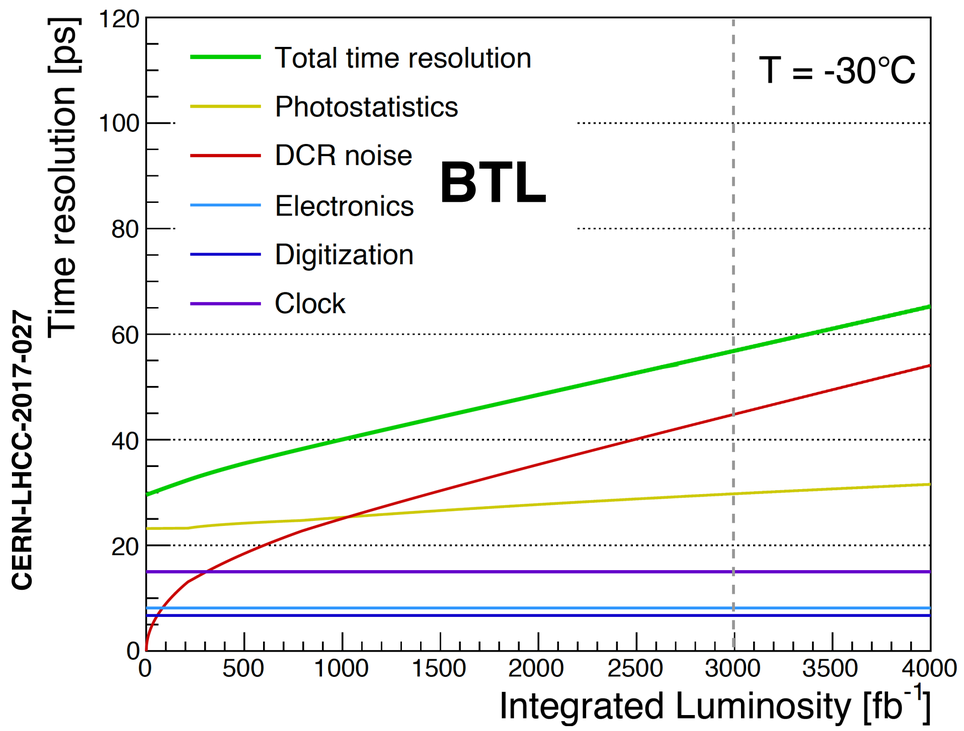
- LYSO:Ce crystal bar size: 3 x 3 x 50 mm^3 and time resolution: ~30 ps.
- LYSO:Ce optimal due to their high light yield (40k photons/MeV), fast scintillation rise time (<100 ps) and short decay time (~40 ns). Also, the light wavelength (420 nm) matches the sensitive range of SiPMs.

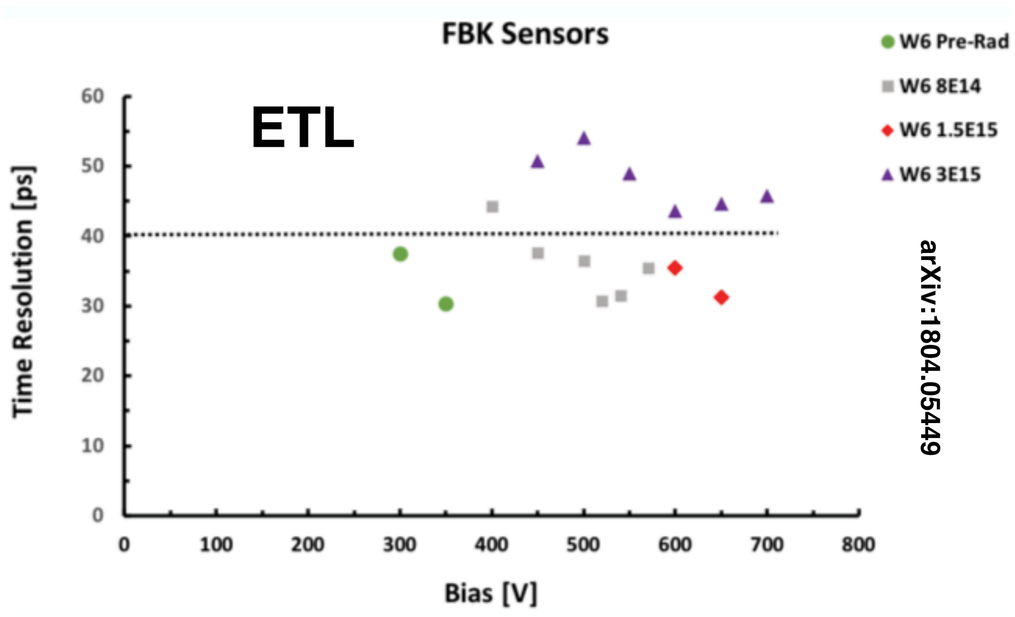
Ultra Fast Silicon Detector



- LGAD sensor pixel size: 1.3 x 1.3 mm^2 and time resolution: 30-50 ps.
- Extra *p*-type implant near the *n*-electrode generates a large electric field, resulting in an electron-avalanche effect that offers a gain factor of 10-30.
- Additional gain allows to extract signals with thinner pixels (depths of 30-50 µm), resulting in: low noise, large slew-rate and fast rising pulse.

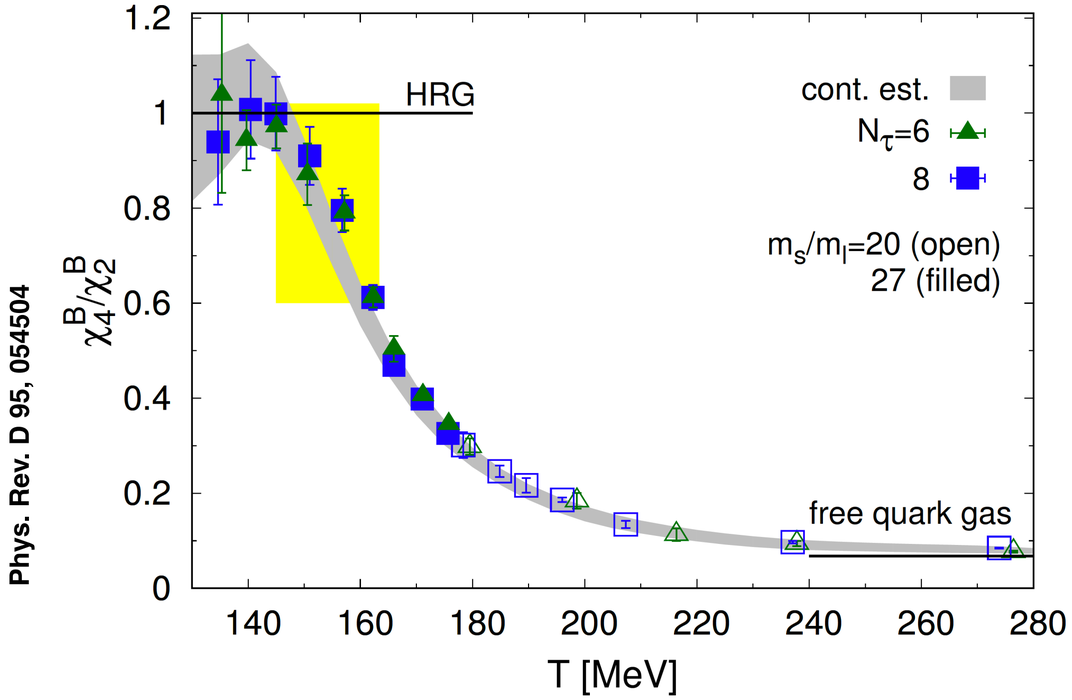
Impact of radiation damage

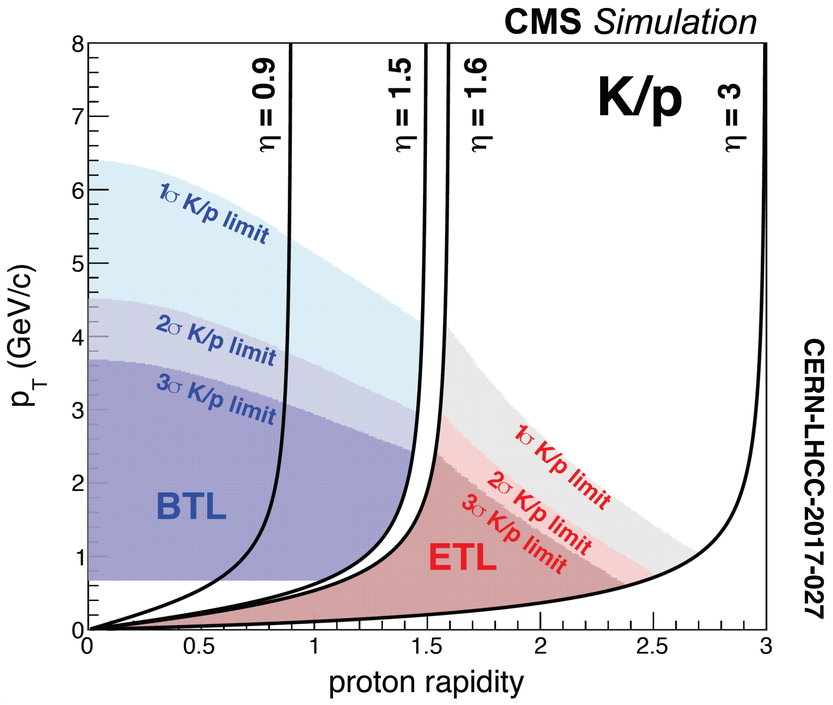




- **BTL**: Radiation damage leads to worse time resolution up to 60 ps by the end of Run 4. Dominated by the dark count rate (DCR) noise of SiPMs.
- **ETL**: The UFSD is also affected by radiation dose, however the time resolution can be recovered by increasing the bias voltage.

Fluctuations of conserved charges





- Can be studied experimentally by measuring the higher cumulants of net strangeness or baryon number (κ_n).
- The PID capabilities of MTD allows to measure the net kaon and proton cumulants in a **wide rapidity range**, directly testing the lattice QCD calculations at LHC energies.

Preliminary proposal of future HI runs

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	

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CMS Detector