XIII International Conference on New Frontiers in Physics
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Precision timing at CMS – *the MIP Timing Detector*

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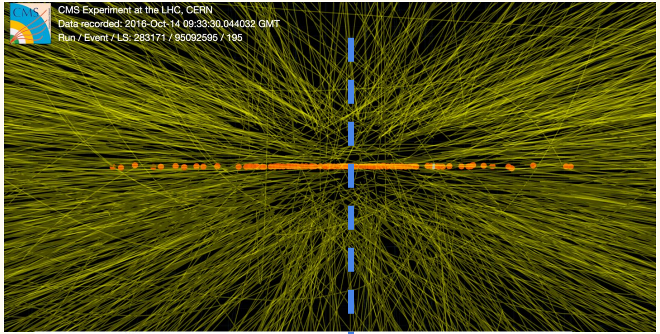
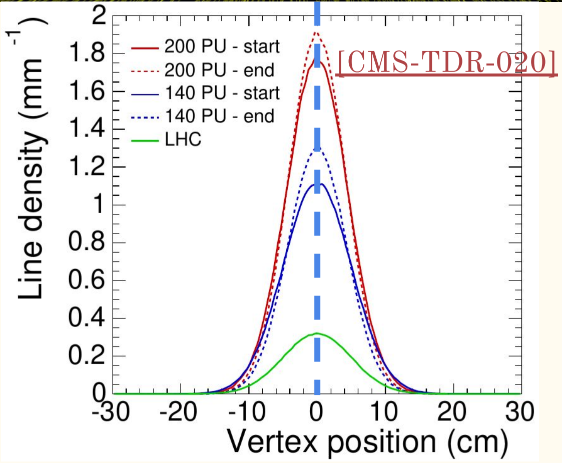
(on behalf of the CMS Collaboration)

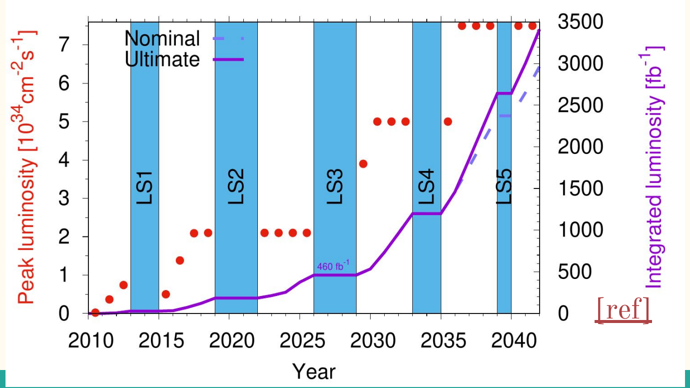
The high luminosity LHC

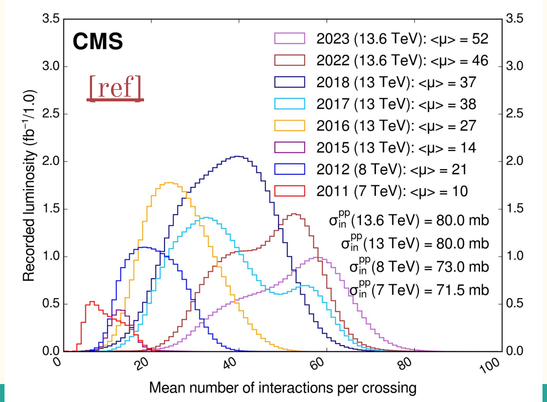
- The high luminosity era of the LHC
  - Baseline
    - $5x10^{34}$ instantaneous luminosity
    - 140 pileup vertices (average)
  - Ultimate
    - $7.5x10^{34}$ instantaneous luminosity
    - 200 pileup vertices (average)
- New challenges
  - Increased particle multiplicity
  - Increased pileup and line density
  - High radiation dosage: >3000 fb^{-1} towards end-of-operation (EoO)

[2016 high pileup fill: ~100 pileup vertices]



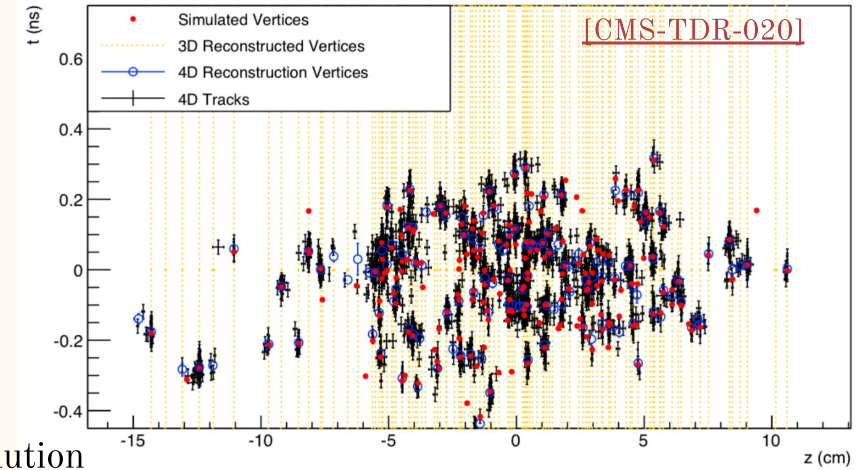




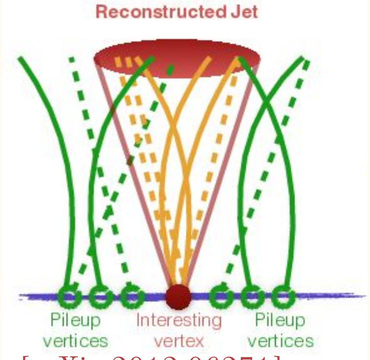


Precision timing to the rescue

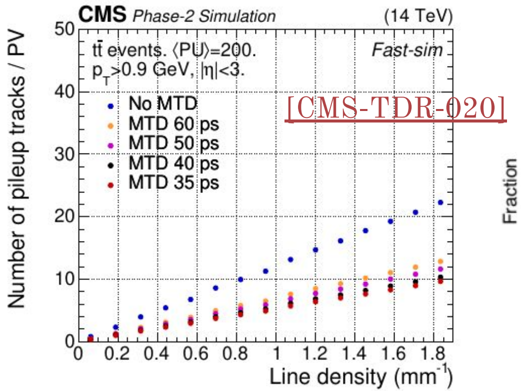
- High pileup and line-density will degrade reconstruction
  - Increased incorrect track-vertex association
  - Degraded kinematics reconstruction, identification, tagging, etc.
- Simply positional information not enough
- Use temporal information
  - Vertices with same position, but different time
  - Need to achieve good precision – few 10s of ps resolution



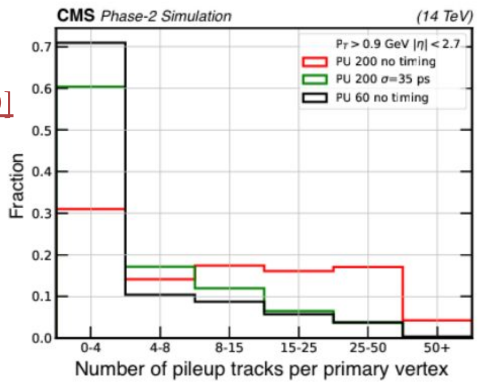
[CMS-TDR-020]



[arXiv:2012.06271]



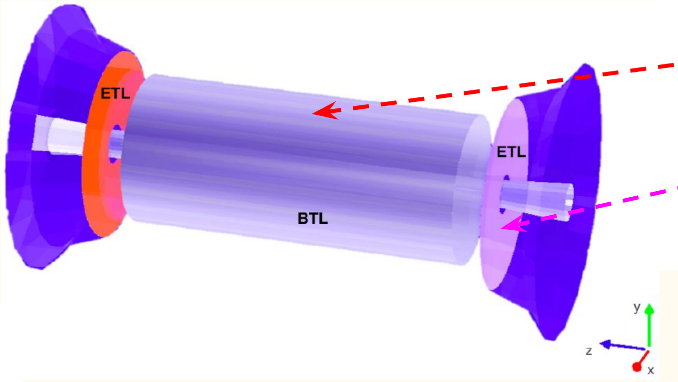
[CMS-TDR-020]

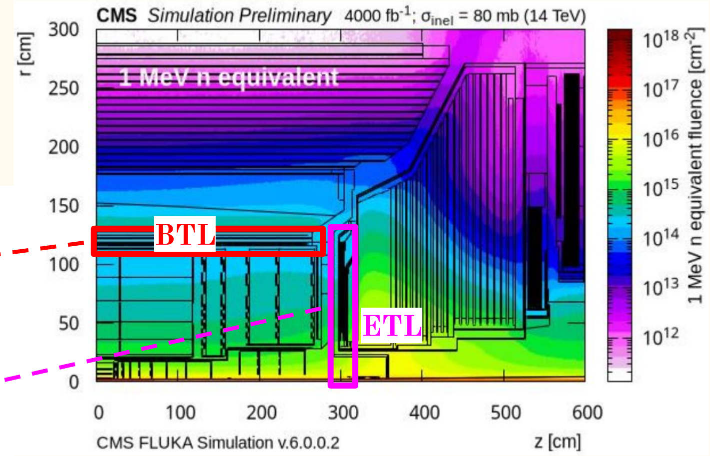


The MIP Timing Detector (MTD) – an overview

[CMS-DP-2023-087]

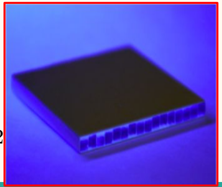
- Technology guided by radiation hardness
  - Others include segmentation/channels (low occupancy), readout, cost, schedule





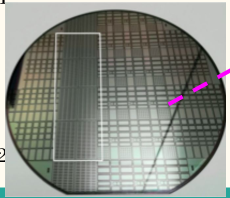
Barrel Timing Layer (BTL)

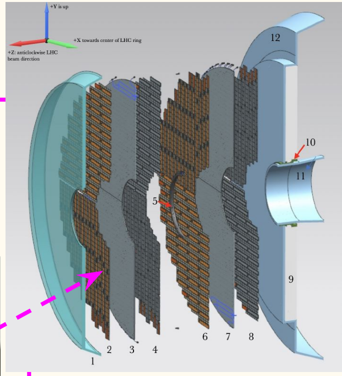
- LYSO scintillator crystal bars
  - High light output, short decay time
- SiPM readout
- ~38 m^2 active area
- ~332K channels
- $|\eta| < 1.45$
- Fluence at 4 ab^{-1}: ~2×10^{14} n_{eq}/cm^2



Endcap Timing Layer (ETL)

- Silicon with internal gain (LGAD)
  - Fast, radiation hard
- 2 double-faced disks in each endcap (1.7 hits per track on average)
- ~14 m^2 active area
- ~8.5M channels
- $1.6 < |\eta| < 3$
- Fluence at 4 ab^{-1}: ~2×10^{15} n_{eq}/cm^2

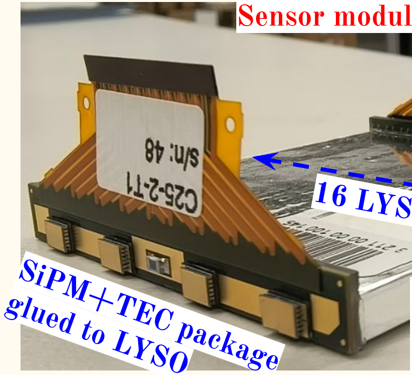


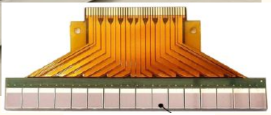


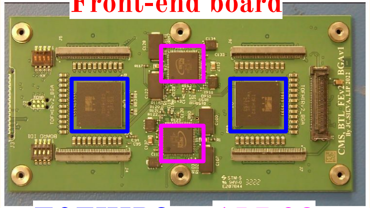
Barrel Timing Layer (BTL)

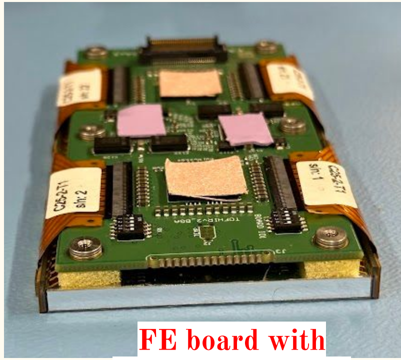
BTL modules

- Cerium doped Lutetium-based scintillation crystal
  - $Lu^{1.8}Y.^{2}SiO^{5}$:Ce or LYSO:Ce
  - Fast response
    - $<$100 ps rise time
    - ~40 ns decay time
  - High light output: 40 photons per keV
  - Dense: 0.86 MeV/mm for MIP
- BTL sensor module
  - 16 LYSO bars
  - Bar axis along azimuthal direction (ϕ)
  - Each bar is $3.75\times3.12\times54.7$ mm^3
  - SiPM readout at both ends of bar
    - 25 µm cell size
    - Cooled with thermo-electric coolers (TECs)
- Front-end (FE) board
  - SiPM signal acquisition and digitization with TOFHIR2 ASIC [arXiv:2404.01208]
  - SiPM biasing regulated with ALDO2 ASIC [arXiv:2203.16098]



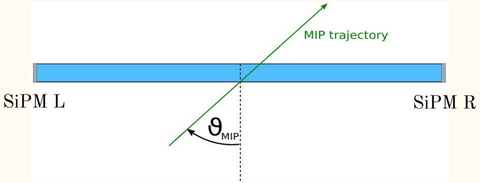




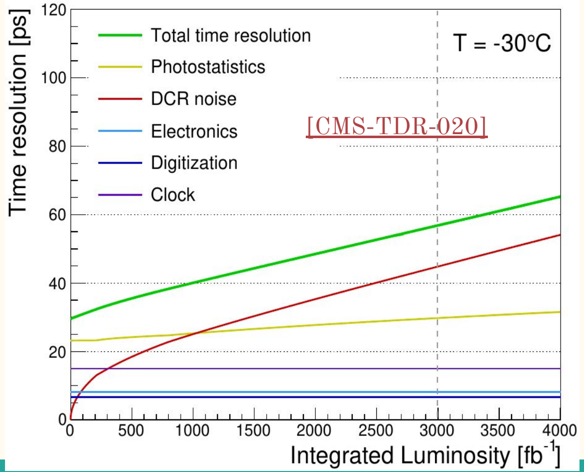


BTL performance [1]

- Dual readout
  - Bar (average) time ~independent of impact point
  - Improves resolution by $\sqrt{2}$
- Number of photoelectrons (N_{phe}) is the driving factor behind resolution
- Dark current rate (DCR) dominant at end-of-operation



$$t_{avg} = (t_L + t_R)/2$$
$$\sigma(t_{avg}) = \sigma(t_{L,R})/\sqrt{2}$$

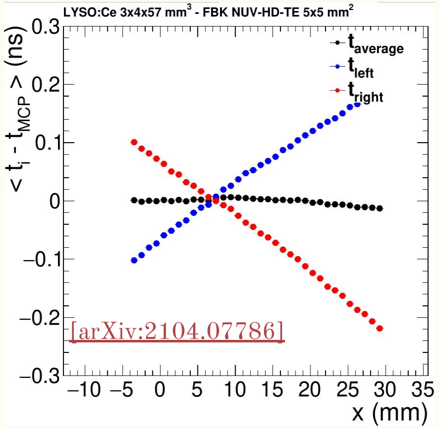


$$\sigma_t^{BTL} = \sigma_t^{clock} \oplus \sigma_t^{digi} \oplus \sigma_t^{ele} \oplus \sigma_t^{phot} \oplus \sigma_t^{DCR}$$

$$\sigma_t^{\,ele} \propto \sigma_{noise} \;/\; N_{phe}$$

$$\sigma_t^{\,DCR} \propto \sqrt{DCR} \;/\; N_{phe}$$

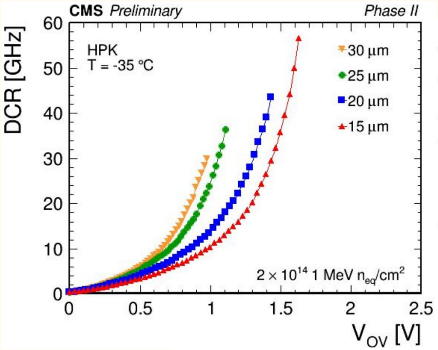
$$\sigma_t^{phot} \propto \sqrt{\frac{\tau_r \tau_d}{N_{phe}}} \propto \sqrt{\frac{\tau_r \tau_d}{E_{dep} \cdot LY \cdot LCE \cdot PDE}}$$

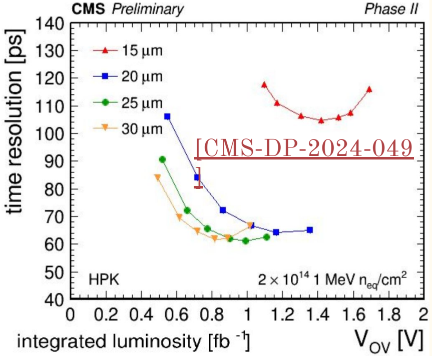


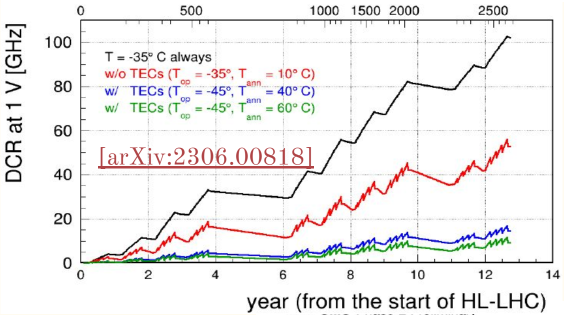
BTL performance [1]

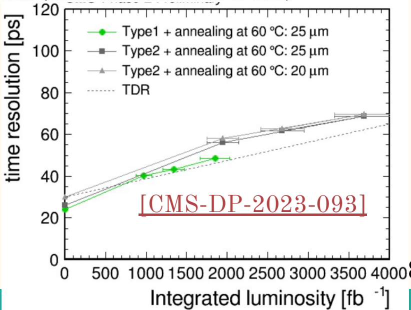
$\sigma_t^{DCR} \propto \sqrt{DCR} / N_{phe}$

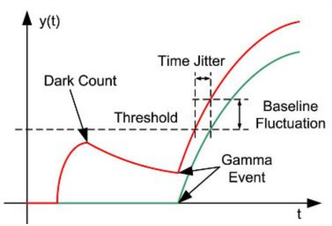
- Mitigating DCR
  - Tradeoff between gain, photon detection efficiency (PDE), power consumption
    - Optimized SiPM cell size – 25 μm for BTL
    - Reduction of over-voltage over lifetime
  - CO_2 cooling at -35 °C
    - TECs used to reach -45 °C at SiPM [CMS-DP-2024-037]
  - In-situ annealing (heat by reverse biasing TECs) at 60 °C
  - TOFHIR2 signal processing
    - Differential leading edge discriminator (DLED) [A. Gola *et al.*]
    - Preserves fast leading edge, reduces tail and slow (correlated) baseline fluctuations



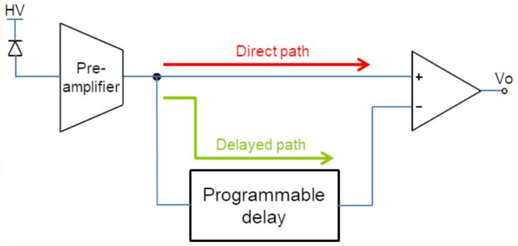




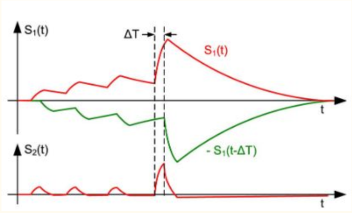




DLED input



$hf(t) = f(t) - f(t + \delta t)$

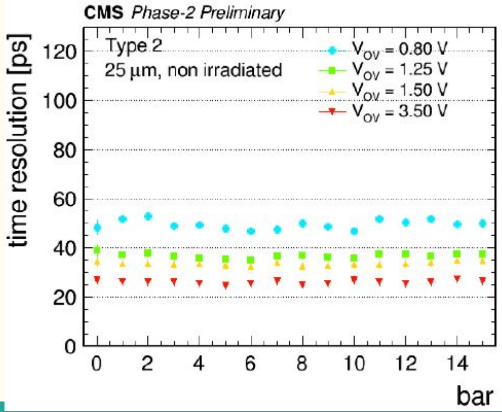


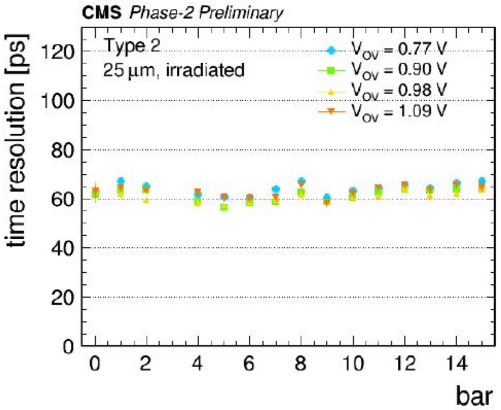
DLED output

BTL performance [3]

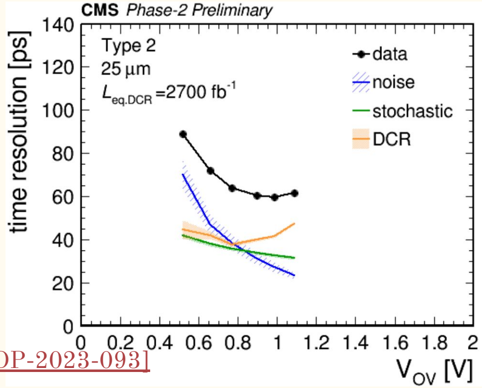
- Mitigating photostatistics uncertainty
  - Fast response crystal – low rise (τ_r) and decay times (τ_d)
  - Dense crystal – high deposited energy (E_{dep}) by MIP
  - High light yield (LY) crystal
  - Large light collection efficiency (LCE)
    - Probability that a photon reaches the SiPM w/o escaping or being absorbed
  - Large photon detection efficiency (PDE) of the SiPM
- Good module performance at test-beam
  - Excellent uniformity

$$\sigma_t^{\text{phot}} \propto \sqrt{\frac{\tau_r \tau_d}{N_{\text{phe}}}} \propto \sqrt{\frac{\tau_r \tau_d}{E_{\text{dep}} \cdot \text{LY} \cdot \text{LCE} \cdot \text{PDE}}}$$





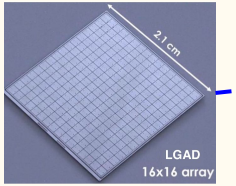
[CMS-DP-2023-093]

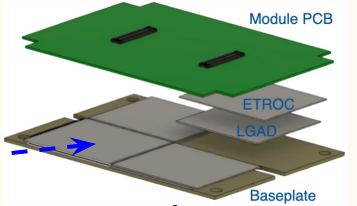


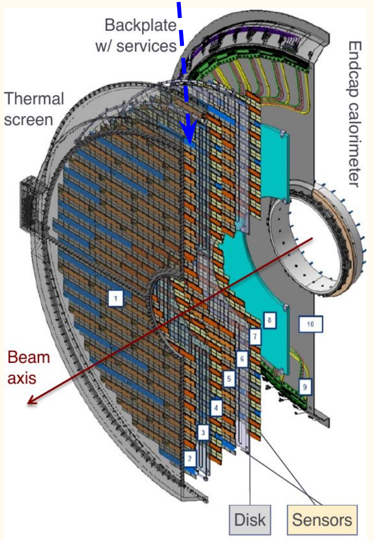
Endcap Timing Layer (ETL)

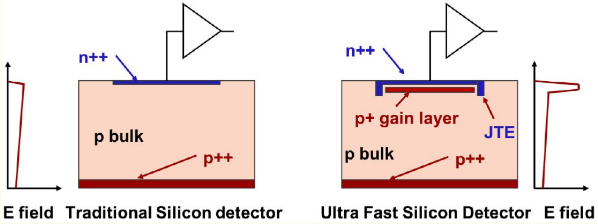
ETL modules

- Ultra Fast Silicon Detector (UFSD) [arXiv:1704.08666]
  - Low Gain Avalanche Detector (LGAD) technology [G. Pellegrini *et al.*]
  - Thin gain layer (~1 μm) with moderate doping (~10^{16} atoms/cm^3), high E field O(100) kV/cm
  - Gain ~10-30 – good for S/N
  - Thin sensor active layer (~50 μm)
    - Fast rise time
    - Low Landau fluctuation (non-uniform charge deposition)
    - Target: signal > 8 fC at EoO (10^{15} n_{eq}/cm^2 in the innermost region)
  - Small sensor size (1.3×1.3 mm^2 pixel)
    - Low sensor capacitance
    - Arranged in 16×16 pad array









$$\sigma_t^2 = \sigma_{\text{Jitter}}^2 + (\sigma_{\text{Total ionization}} + \sigma_{\text{Local ionization}})^2 + \sigma_{\text{Distortion}}^2 + \sigma_{\text{TDC}}^2$$

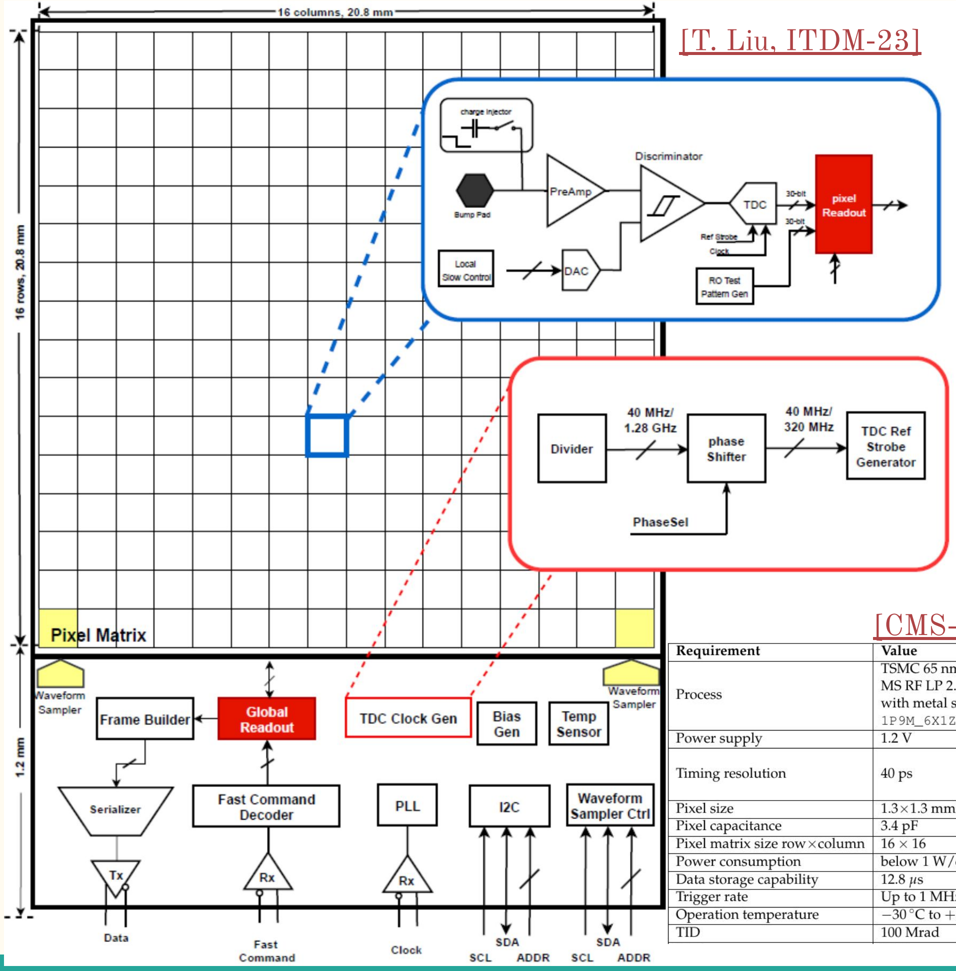
Landau (~30 ps for 50 μm)

$$\sigma_{\text{Jitter}} \propto \frac{e_n C_{\text{d}}}{Q_{\text{in}}}\sqrt{t_{\text{rise}}}$$

Pixel readout – the ETROC ASIC

- ASIC requirements
  - Low power (<4 mW/channel at EoO)
  - Fast rise time, low noise
  - Contribution to resolution < 40 ps
  - Radiation hard (100 Mrad total ionizing dose)
- The ETROC ASIC [arXiv:2011.01222]
  - 65 nm technology
  - Bump-bonded to LGAD
  - Time of arrival (TOA) and Time over threshold (TOT) measured by single TDC
  - TOT used for time-walk correction
- Prototypes
  - ETROC0 – single channel
  - ETROC1 – 4x4 channel
  - ETROC2 – 16×16 channel
- ETROC3 – final version

[T. Liu, ITDM-23]

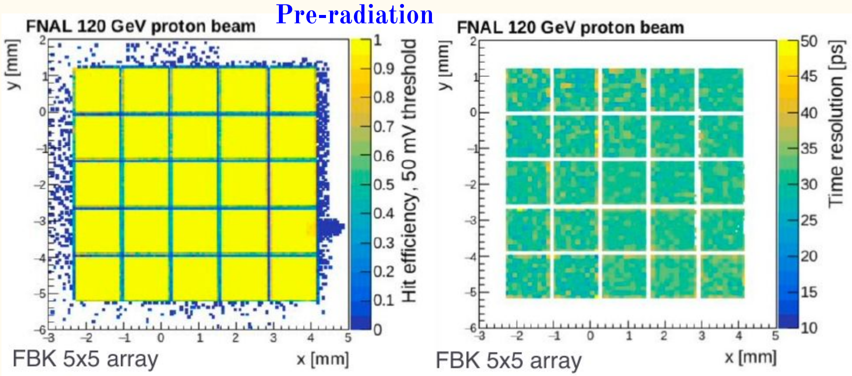


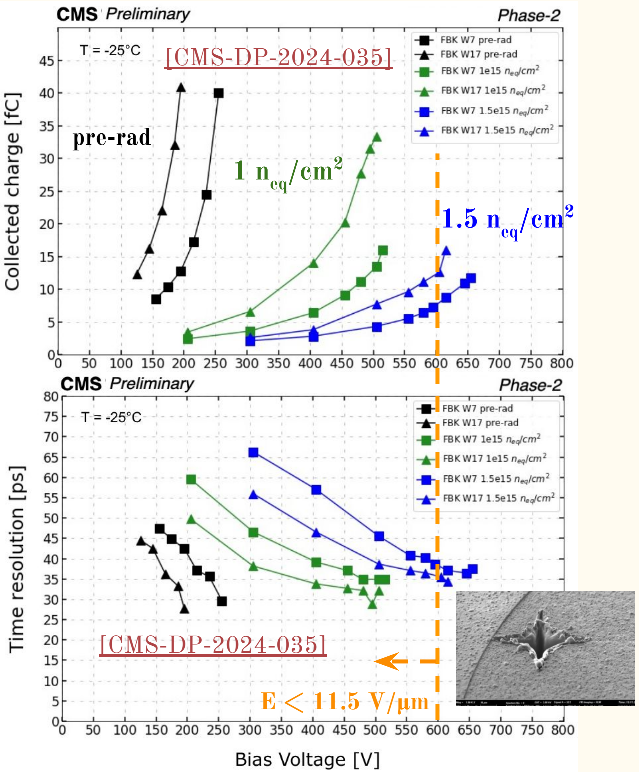
[CMS-TDR-020]

Requirement	Value
Process	TSMC 65 nm MS RF LP 2.5 V with metal stack 1P9M_6X1Z1U_RDL (CERN)
Power supply	1.2 V
Timing resolution	40 ps
Pixel size	1.3×1.3 mm^2
Pixel capacitance	3.4 pF
Pixel matrix size row×column	16 × 16
Power consumption	below 1 W/chip
Data storage capability	12.8 μs
Trigger rate	Up to 1 MHz
Operation temperature	−30 °C to +20 °C
TID	100 Mrad

ETL performance [1]

- Sensor optimization with different vendors
- Good efficiency and resolution (pre-radiation)
- Impact of radiation damage can be mitigated by increasing bias voltage
  - Observed sparking damage for electric field > 11.5 V/µm
  - Target performance of ~45 ps (EoO) can still be reached below this field

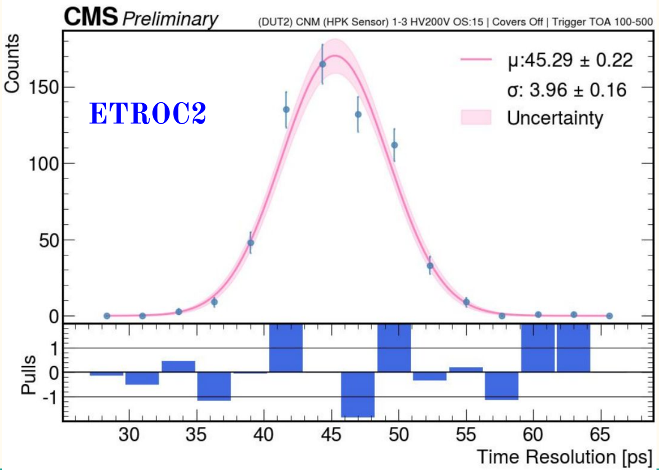


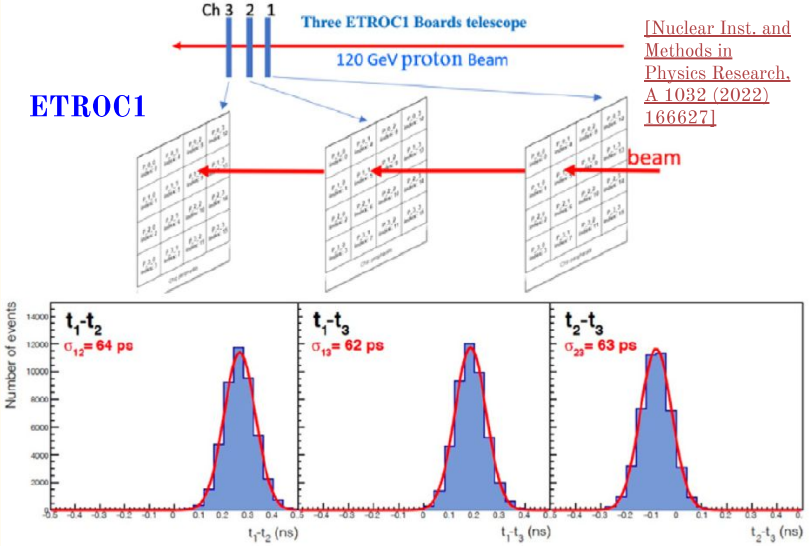


[Courtesy: F. Cossutti, ICHEP-24 , F. Golf, Pisa-24]

ETL performance [2]

- 4x4 LGAD+ETROC1
  - ETROC wire bonded to LGAD
  - Resolution 42-46 ps
- 16x16 LGAD+ETROC2
  - ETROC bumb bonded to LGAD
  - Resolution 45 ps
  - Consistent with ETROC1 results





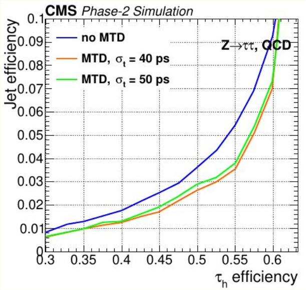
[Nuclear Inst. and Methods in Physics Research, A 1032 (2022) 166627]

$$\sigma_i = \sqrt{0.5 \cdot (\sigma_{ij}^2 + \sigma_{ik}^2 - \sigma_{jk}^2)}$$

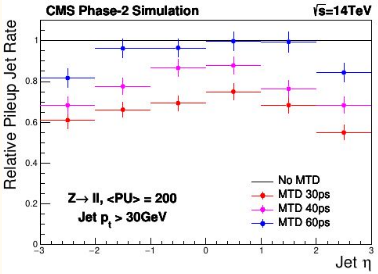
Physics benefits

Physics benefits

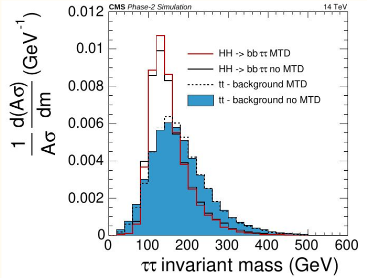
Reconstruction improvements

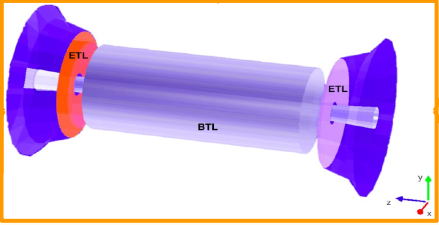


Pileup mitigation

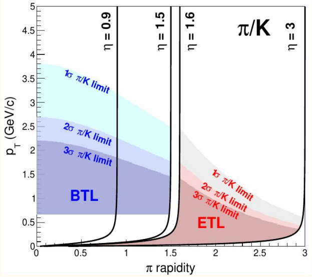


Standard model measurements

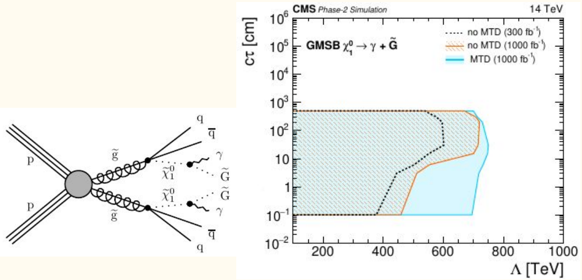




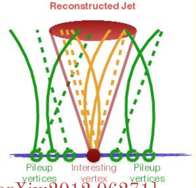
Particle identification (PID)



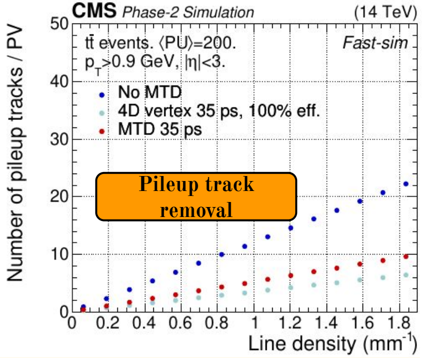
New physics searches



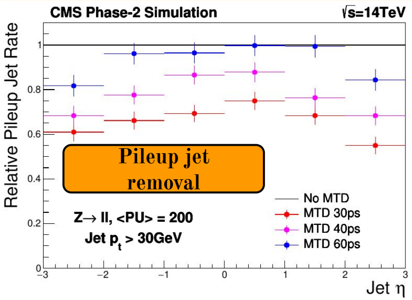
Pileup mitigation and reconstruction improvements



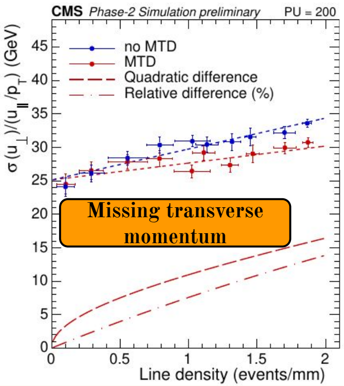
[arXiv:2012.06271]



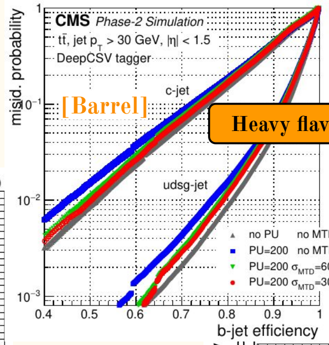
Pileup track removal



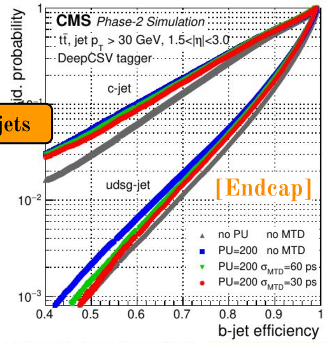
Pileup jet removal



Missing transverse momentum

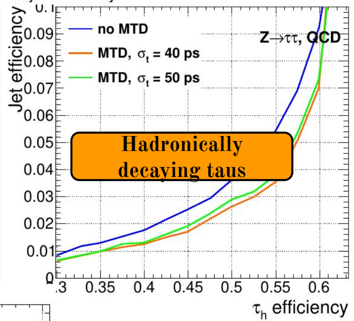


[Barrel]



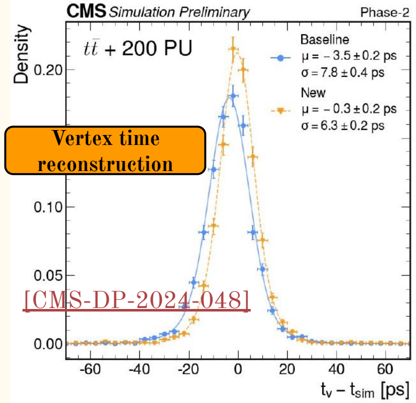
[Endcap]

Heavy flavor jets



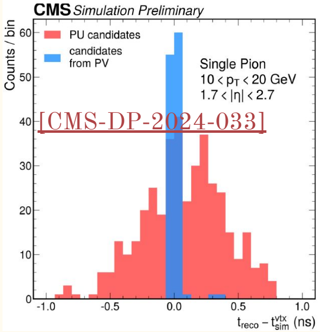
Hadronically decaying taus

[CMS-TDR-020]



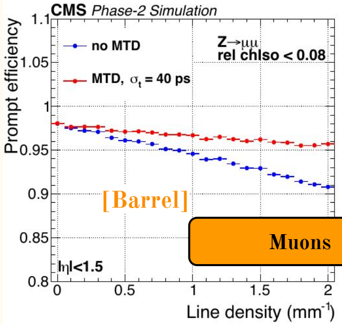
Vertex time reconstruction

[CMS-DP-2024-048]

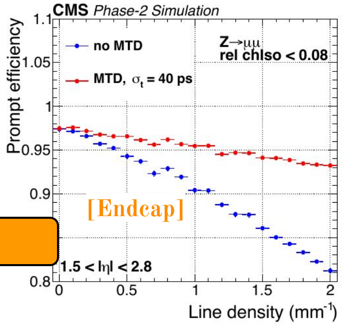


[CMS-DP-2024-033]

Charged hadron time (MTD+HGCAL)

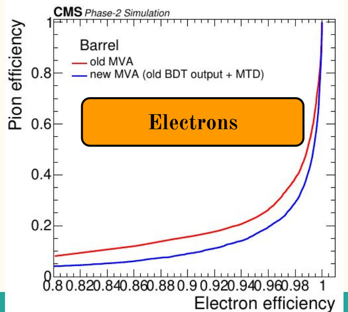


[Barrel]



[Endcap]

Muons



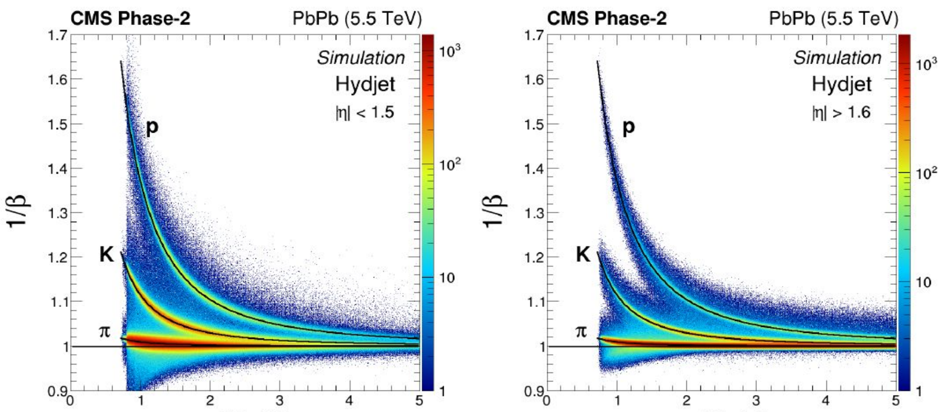
Electrons

Time of flight – particle identification (PID)

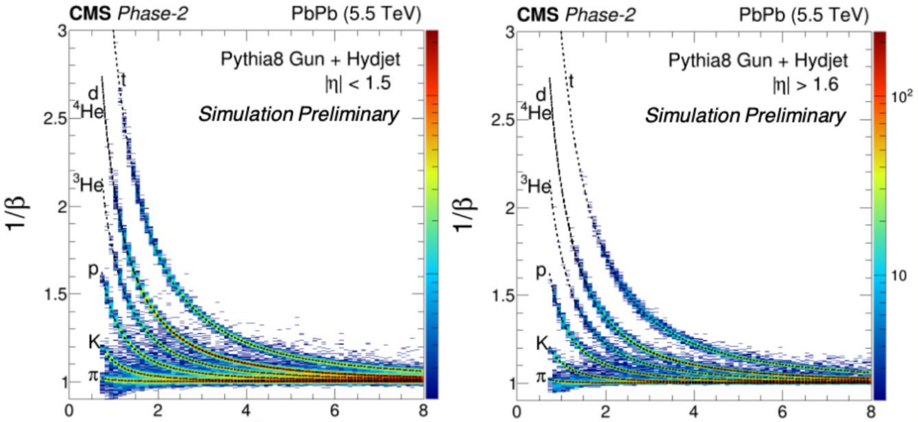
- Time of flight capability in PbPb collisions – new at CMS!
- Proton/Kaon separation up to ~5 GeV
- Pion/Kaon separation up to ~3 GeV

$$\frac{1}{\beta} = \frac{c(t_0^{\mathrm{MTD}} - t_0^{\mathrm{evt}})}{L}$$

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



[CMS-TDR-020]



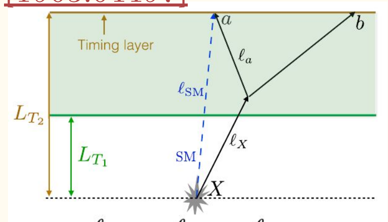
[CMS-DP-2021-037]

Measurements and searches

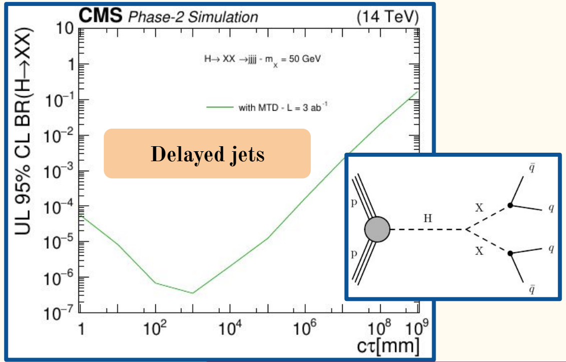
	Signal increase (%)		Expected significance	
Di-Higgs decay	BTL	BTL+ETL	No MTD	MTD
bbbb	13	17	0.88	0.95
$bb\tau\tau$	21	29	1.3	1.6
$bb\gamma\gamma$	13	17	1.7	1.9
bbWW			0.53	0.58
bbZZ			0.38	0.42
Combined			2.4	2.7

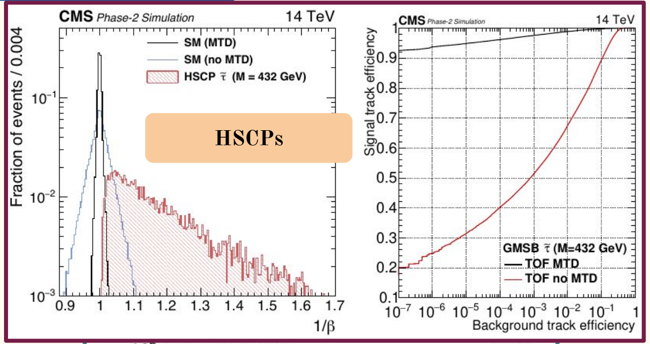
Gain equivalent to ~30% higher integrated luminosity without MTD

[1903.04497]

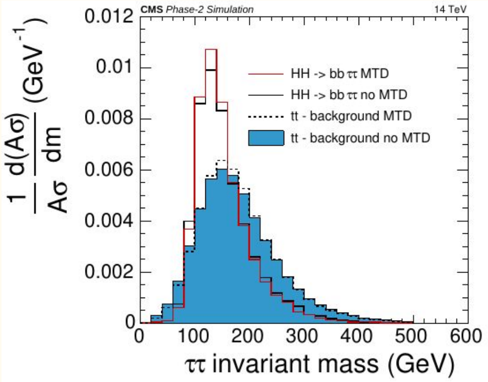


$$\Delta t = \frac{\ell_X}{\beta_X} + \frac{\ell_a}{\beta_a} - \frac{\ell_{SM}}{\beta_{SM}}$$

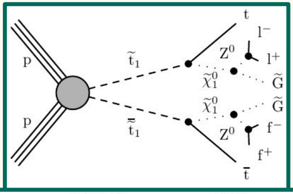


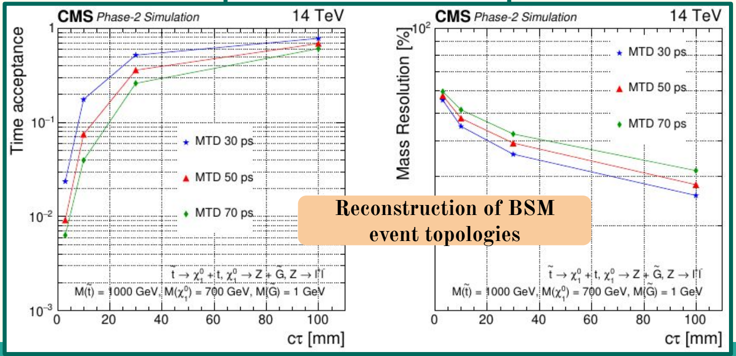


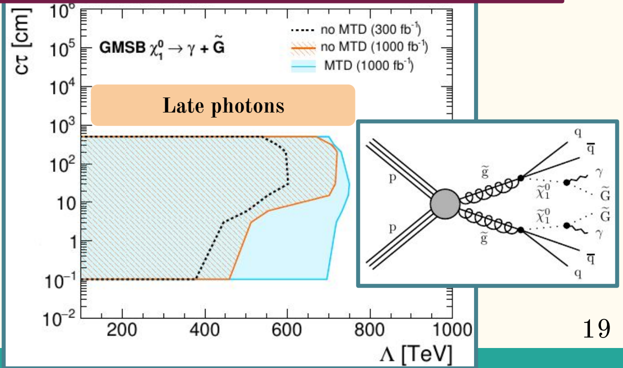
[CMS-TDR-020] [CMS-DP-2022-025]



Better missing momentum resolution
⇒ Better invariant mass resolution





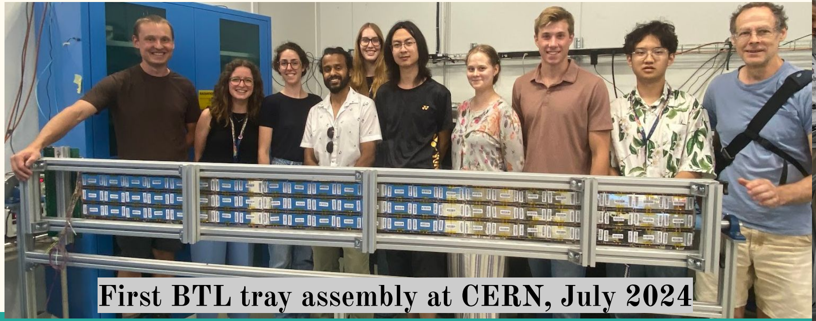


Summary

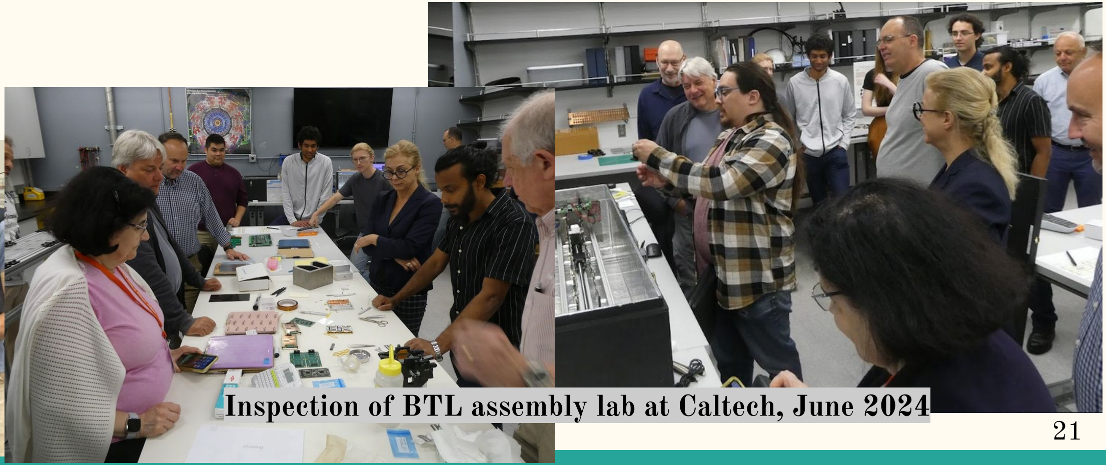
Summary

- The MTD is first detector in CMS solely dedicated for precision timing
  - Challenging, state-of-the-art technologies
  - Tremendous impact on physics results
- BTL design has been fully validated
  - Assembly centers ready – demonstrated capability and throughput
  - Started assembly+construction in July 2024
- ETL design is mature – in final phase of prototyping
  - On track for construction in 2026

ETL Days – Boston, 2022



First BTL tray assembly at CERN, July 2024



Inspection of BTL assembly lab at Caltech, June 2024

Thank you for your attention!