Time-of-Flight detector for the ATLAS Forward Proton system

IFJ Department Seminar

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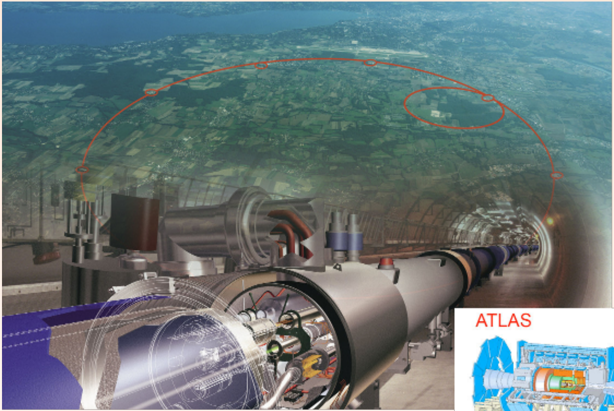
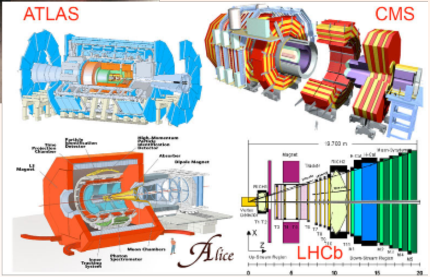
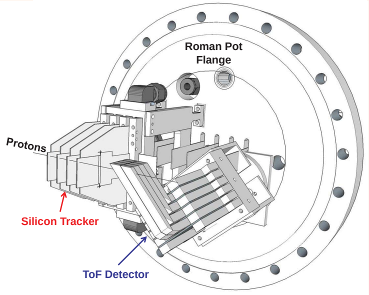
LHC – no need to introduce

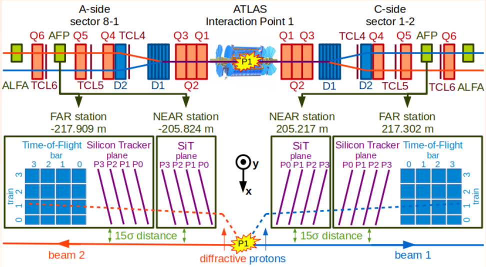




AFP project

- **A**TLAS **F**orward **P**roton
- Forward detector focused on diffraction protons
- Placed in a "Roman Pot" (RP) $\sim 210\,\mathrm{m}$ from IP (Interaction Point) of ATLAS
- 3D pixel detektor + ToF (only far stations)

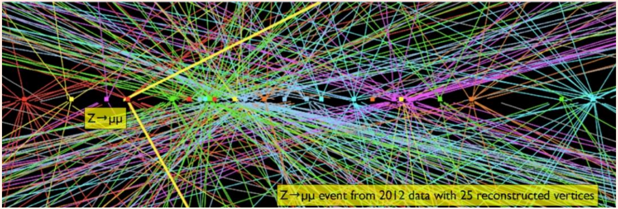




- My work is focused on the Time-of-Flight (ToF) subdetector

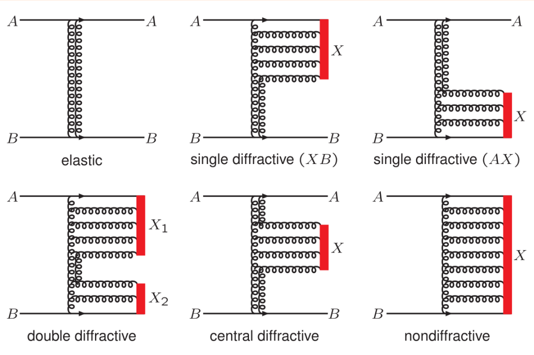
ToF design – motivation, requirements

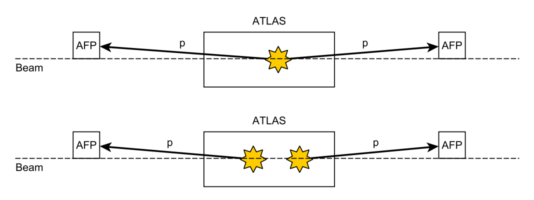
- Fast timing Cherenkov detector
- Purpose:
  - assign protons detected by AFP to individual collisions in IP1
    $\rightarrow$ time determines position and allows pairing with proper vertex



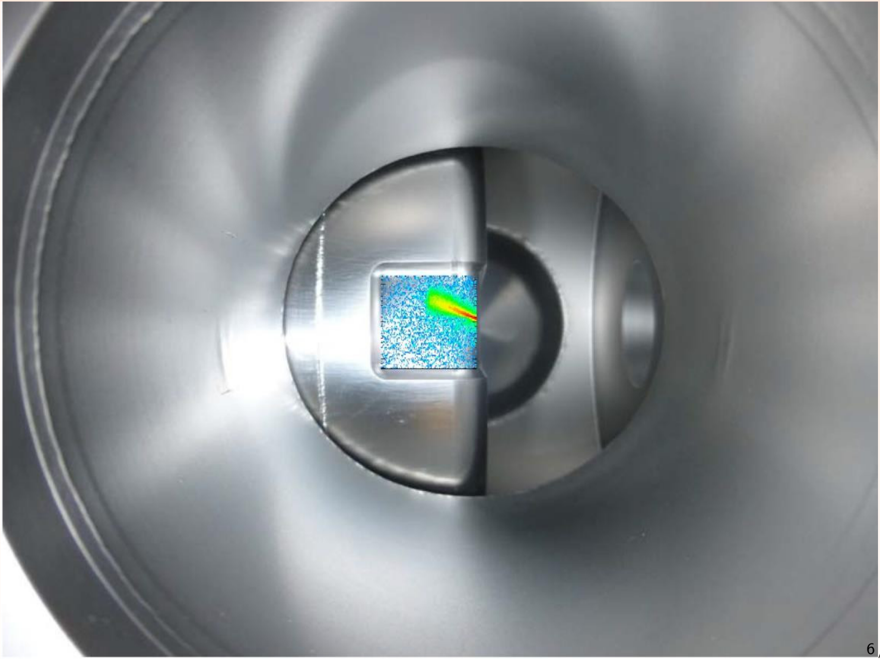
- Requirements:
  - timing: best case 10 ps resolution, 30 ps initially
    10 ps $\rightarrow$ spatial 3 mm
  - radiation hardness (forward region, few mm from LHC beam)
  - cover entire AFP tracker
  - segmentation (multi-proton detection)
  - detection rate 5 MHz (Run 2) up to $>$ 20 MHz (Run 3)
  - L1 trigger signal

Double tag events



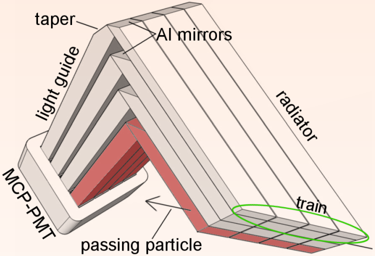


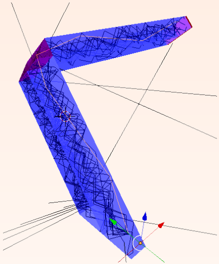
AFP in the beamline



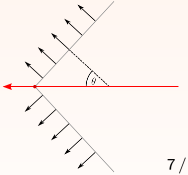
ToF design – optical part

- 4x4 matrix of bars made of quartz glass, L shape
  - bars are tilted 48° from the LHC beam (Cherenkov angle θ)
  - each bar originally glued from two parts using Epotek 305
- Photonis miniPlanacon XPM85112 MCP-PMT (16 channels)
- Typically $\sim$ 100 photons from a bar reach a PMT channel
  $\Rightarrow \sim 15 - 20$ photoelectrons



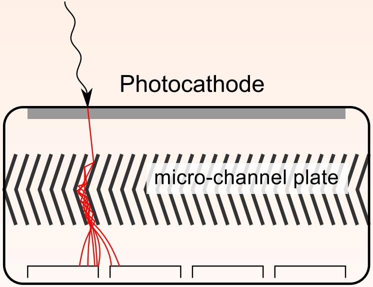


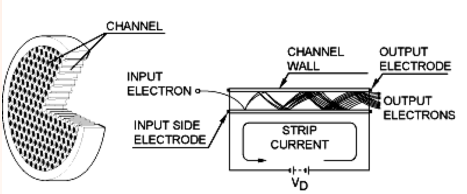
- Particle passes through "train" ($n = 4$ bars)
  $\rightarrow$ 4 (mostly) independent measurements
  $\rightarrow$ ideal case: $\frac{1}{\sqrt{n}}$ resolution improvement

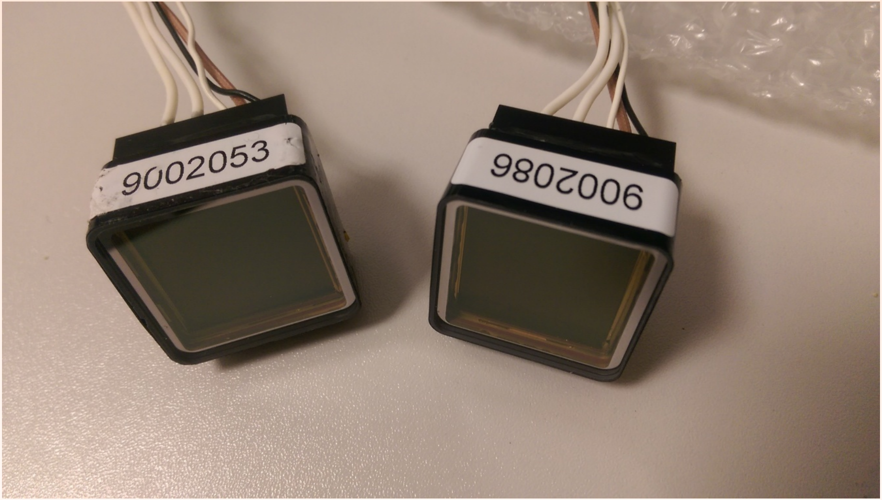


MCP-PMT

- Compact photomultiplier, main element is microchannel plate (MCP), microchannels typically a couple $\mu\mathrm{m}$
- Pixelization of readout purely by anode pad segmentation
- MPossible sharing of charge across channels (near boundaries)
- Main advanatges: compact construction, timing resolution, operation in strong magnetic fields (up to few T)



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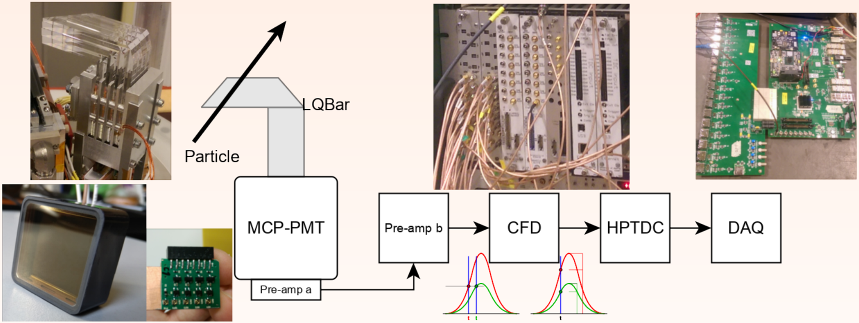
ToF design – electronics

PMT signal is processed by wideband electronics (fast edged $< 1\,\mathrm{ns}$)

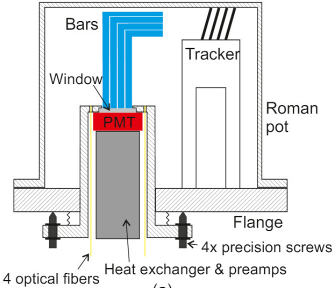
- Two preamp stages: $16.5/19\,\mathrm{dB}$ gain ($6.7\times/9\times$ amplitude)
- CFD – Constant Fraction Discriminator
- HPTDC – High Performance Time to Digital Converter ($24.4\,\mathrm{ps}$/bin)
- DAQ system



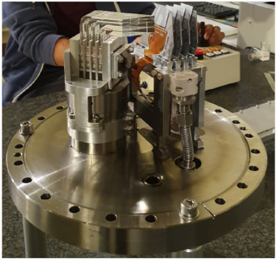
Summary of introduced AFP-ToF upgrades

Mechanical solution

- PMT placement reworked – now all HV outside vacuum
- Strong focus on shielding from outside interference
- Easier precision alignment of the ToF bars
- No signal feedthroughs, access to first stage amps without opening the pot
- Much better cooling of components originally in vacuum
- Integration of artificial light source for testing purposes



(a)

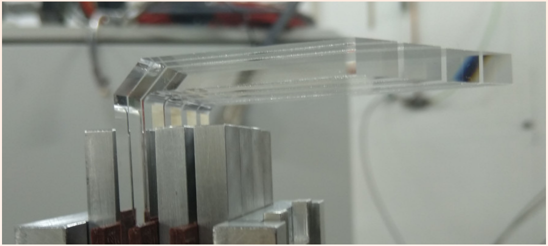


(b)

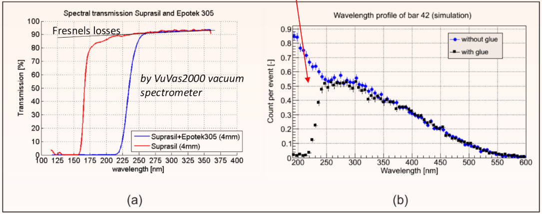
Bars

- Upgrade to glueless construction
  - more light yield, mitigation of degradation from radiation exposure
- Train width optimalization

  chosen 3 mm, 3 mm, 5 mm and 5.5 mm (2 mm too fragile)

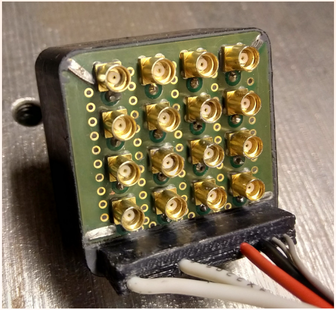


Losses on glue 20% (measurement + simulation)



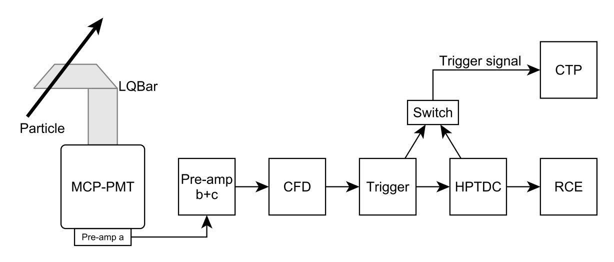
Photomultipliers

- Selected Photonis miniPLANACON XPM85112-S-R2D2
- Long life (withstands high integrated charge)
- Slightly worse TTS ($\sim 40\,\mathrm{ps}$)
- Targeting lowest possible internal resistance
- Custom backend of own production (UP Olomouc)
- HV divider adjusted as well



Electronics

- Amplifiers
  - first stage form factor radically modified (integrated on cables), while keeping the same amplifier element
  - third stage added, remote control of attenuation
- CFD with variable pulse length (amplitude information)
- Trigger module – inserted after CFD, also filters events
- HPTDC
  - FPGA replaced with a more radiation tolerant type (SEU issues)
  - much more precise and capable PicoTDC to be deployed soon

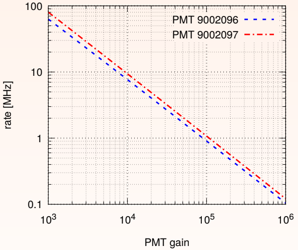


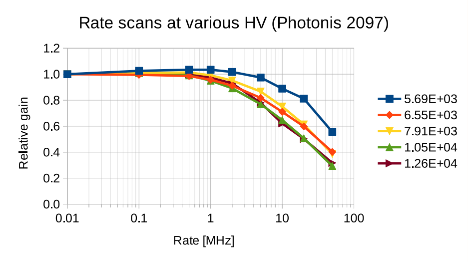
Rate capability concerns

Rate capability – PMT

- Originally insufficient pulse rate capability of the used PMTs (Run 3 up to 20 MHz hit rate, possibly even 60 MHz with showers)
- Optimization of powering scheme and theoretical description of observed rate limitations
  - lower PMT gain means less charge depleted per pulse
  - insufficient amplitude compensated by extra amplifier stage
  - downside: more sensitive to noisy components and interference
  - target PMT gain ~ 2000

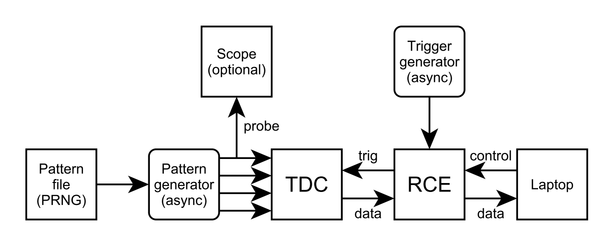
$$f = 0.1 \frac{U_{\mathrm{MCP}}}{16 e g R_{\mathrm{MCP}} N_{\mathrm{pe}}}$$

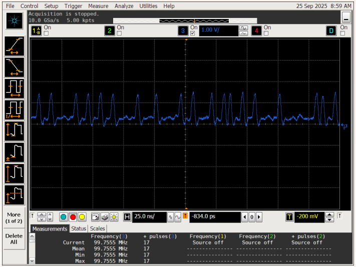


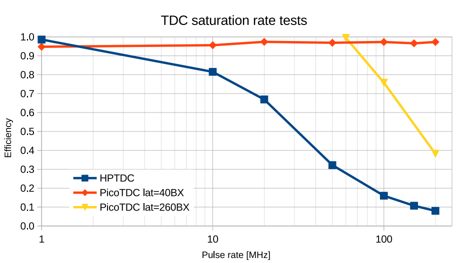


Rate capability – TDC

- HPTDC known limit 8 MHz per channel
- PicoTDC much more capable, > 200 MHz (depends on latency)



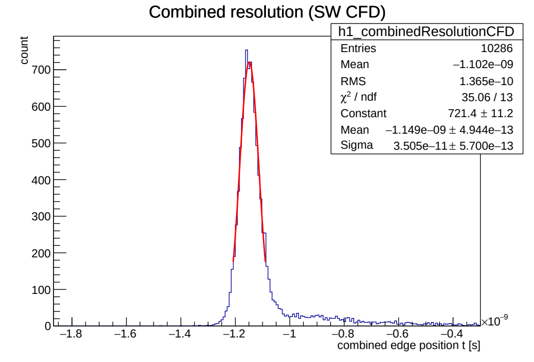




Timing resolution of AFP-ToF

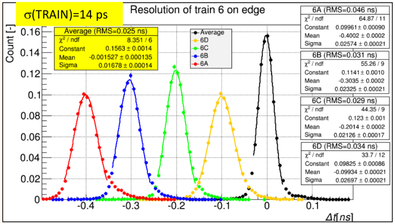
PMT timing resolution

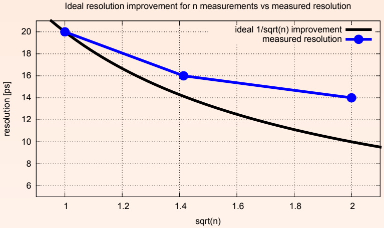
- Very good thanks to short electron paths inside microchannels
- Main characteristic: TTS (transit time spread), typically few tens of ps ($30 - 40\,\mathrm{ps}$ in ones we use)
- TTS histogram shows a tail of electrons bounced off MCP face
- For good results, CFD (HW/SW) is needed, otherwise "time walk"

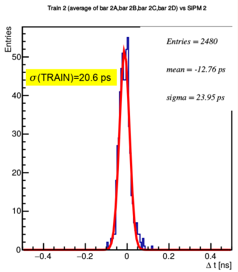


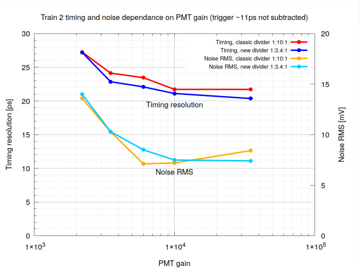
- more photoelectrons $\Rightarrow$ better timing (theoretical limit $1/\sqrt{n}$)

RAW: 20 – 25 ps single channel, 14 – 18 ps 4 ch combined
TDC: 20 – 23 ps 4 ch combined
Newer PMTs (worse TTS) and lower gain impact timing



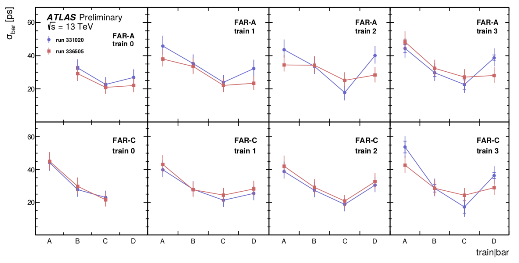


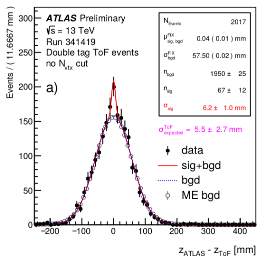




AFP-ToF at LHC (2017) – performance

- Very bad efficiency $< 5\,\%$ (limited PMT lifetime)
- Not suitable for vertex selection, able to determine timing resolution regardless
- Bars $20 - 50\,\mathrm{ps}$, Trains $20 \pm 4\,\mathrm{ps}$ (A) a $26 \pm 5\,\mathrm{ps}$ (C)
- Spatial resolution of vertex matching: $6.2 \pm 1.0\,\mathrm{mm}$

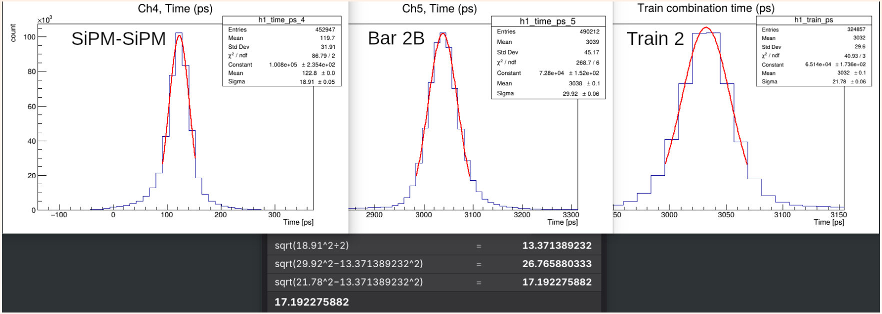




AFP-ToF timing with PicoTDC (Beam Test)

PicoTDC after SiPM (trigger) subtraction:

- SiPM+Pico 13.4 ps
- ToF Train average: 17.2 ps
- PicoTDC single channel: 8-10 ps



Timing resolution contributions

- PMT TTS: $\sim 40\,\mathrm{ps}$
  $+$ number & timing distribution of photons delivered by a bar
  $\rightarrow$ PMT $+$ bar: $20 - 25\,\mathrm{ps}$
- Train combination: $14 - 16\,\mathrm{ps}$

- Amplifiers: $3 - 4\,\mathrm{ps}$
- CFD: $5\,\mathrm{ps}$
- HPTDC: $15 - 17\,\mathrm{ps}$
- PicoTDC: $8 - 10\,\mathrm{ps}$ (uncalibrated)

- Beam Test SiPM timing reference: $11\,\mathrm{ps}$

- At LHC – reference clock: $6\,\mathrm{ps}$ (conservative estimate)

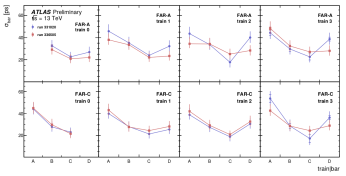
- Final expected resolution:
  $\sim 20 - 30\,\mathrm{ps}$ (HPTDC)
  potentially under $20\,\mathrm{ps}$ (PicoTDC)

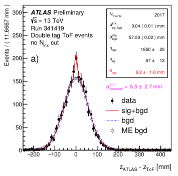
Conclusion

Conclusion

- AFP-ToF has been deployed at the LHC, so far with limited success
- Run2, 2017:
  - poor ToF efficiency of few percent (PMT degraded fast)
  - good timing resolution (21 ps) nonetheless!

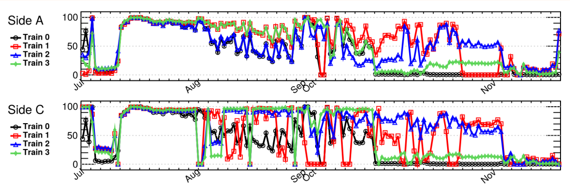
Timing resolution of individual channels, vertex matching distribution





Performance of the ATLAS Forward Proton Time-of-Flight Detector in 2017, ATL-FWD-PUB-2021-002

- Run 3: Limited usefulness due to increased collision intensities
  - plan to deploy PicoTDC for 2026



Thank you for your attention!