# Photon(*) timing with micro-channel plates

Tommaso Tabarelli de Fatis
Università di Milano-Bicocca and INFN

*On behalf of the i-MCP collaboration*

(*) from 511 keV to O(1) TeV
*[detection of optical photons well known]*

# i-MCP Collaboration

- **High energy photons:**
  - **Università di Milano Bicocca and INFN, Italy**
    - L.Brianza, A. Ghezzi, C.Gotti, P.Govoni, A.Martelli, B.Marzocchi, S.Pigazzini, T.Tabarelli de Fatis, N.Trevisani
  - **Università di Roma "Sapienza" and INFN, Itlay**
    - F.Cavallari, D.Del Re, S.Gelli, C.Jorda Lopez, P.Meridiani, G.Organitini, R.Paramatti, L.Perinié, S.Rahatlou, C.Rovelli, F.Santanastasio
  - **Buderk Institute of Nuclear Phyiscs (BINP) Novosibirsk, Russia**
    - A.Barinyakov, M.Barniakov
- **PET photons:**
  - **INFN, Sezione di Cagliari, Italy**
    - D. Brundu, A.Cardini, V.Fanti
  - **INFN, Sezione di Ferrara, Italy**
    - G. Zavattini
  - **Università di Milano Bicocca and INFN, Italy**

# Research opportunity …

- **Micro Channel Plates known for superior time performance:**
  - Compact devices with small transit time
- **Conventional usage:**
  - TOF systems with ions
  - Amplification stage in photomultipliers (optical photon detection)

## …quest for high-resolution timing of photons

### 1. $E_\gamma \sim 10$ GeV –1 TeV

- Pileup mitigation with combined time and vertex reconstruction
  - Feasibility being considered for HL-LHC (ATLAS and CMS)

### 2. $E_\gamma \sim 0.5$ MeV

- Photon detection in positron-emission tomography
  - TOF-PET systems

# 1. Timing of high-energy photons

## Use case: pileup mitigation at HL-LHC

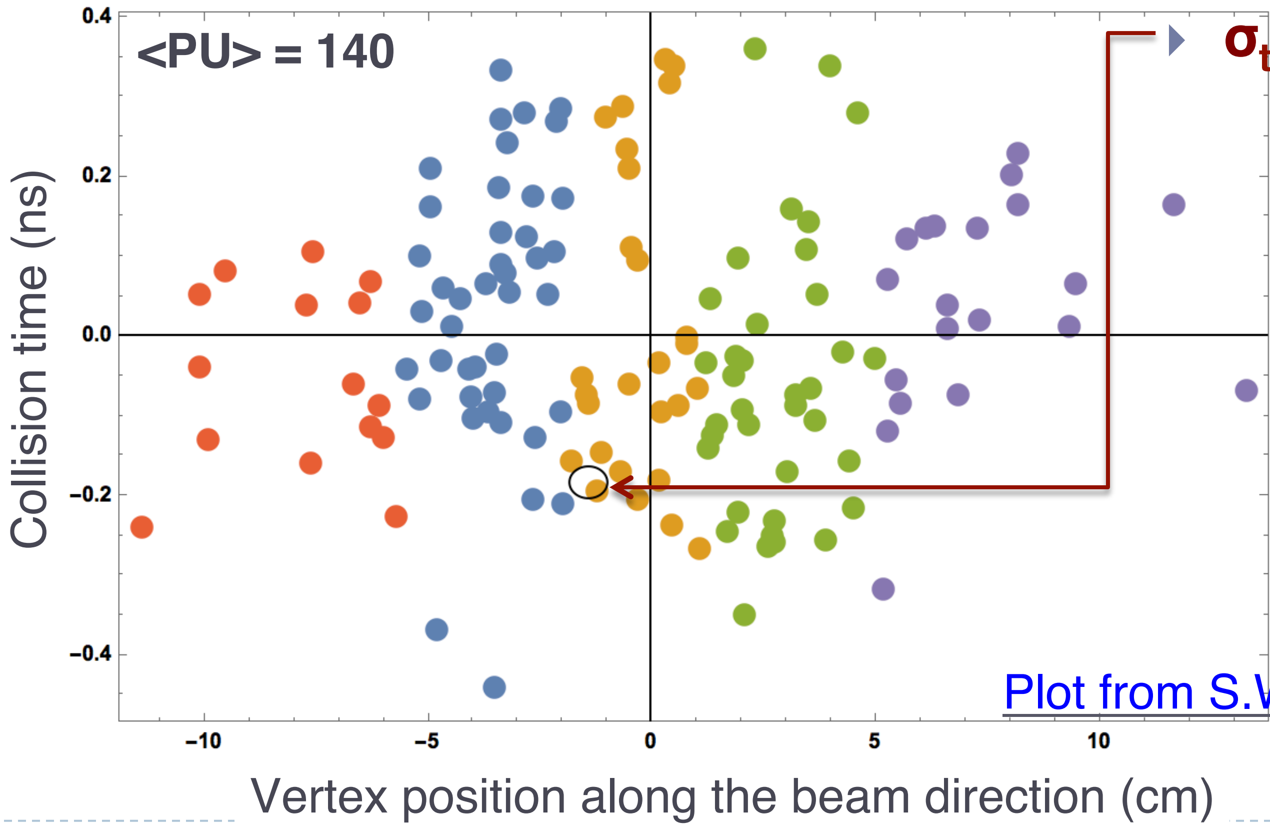
- **High Luminosity (HL) requires higher rate of concurrent collisions per beam crossing (BX)**
  - Due to the bunch structure of hadron colliders
- **At HL-LHC ~ 140-200 pileup collisions per BX**
  - Spread (rms) along the beam axis **~ 6 cm**
  - Spread (rms) in time (same BX) **~ 160 ps**

(Bunch length)

S.Fartoukh, Phys.Rev.STAB.17.111001

# Dissect collisions with time

- **Individual (charged) particle association to an event vertex becomes strained**
  - About **10%** of vertices merged at **140 pileup** (baseline optics)
- **'Effective *pileup*' similar to current LHC for ~20 ps resolution**
  - *[or can read this as "with better timing could stand even higher pileup"]*




- **$\sigma_t$~20 ps ≈ $\sigma_z$~6 mm**
- Not competitive with tracking resolution
- Sufficient to separate overlaps in orthogonal time-z view

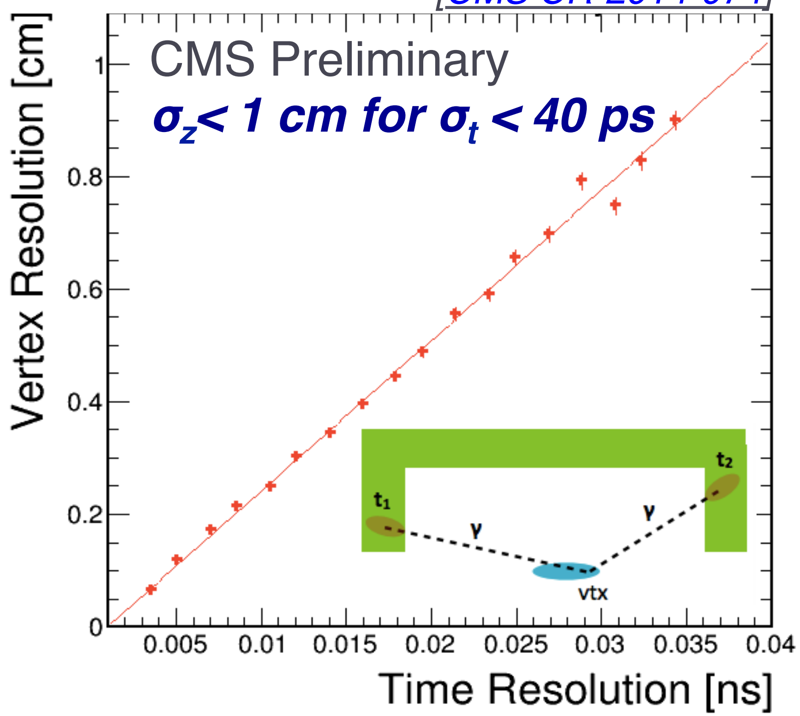
Plot from S.White, ArXiv 1409.1165

# Use of timing at pileup 140

## 1. Location of H→γγ vertex

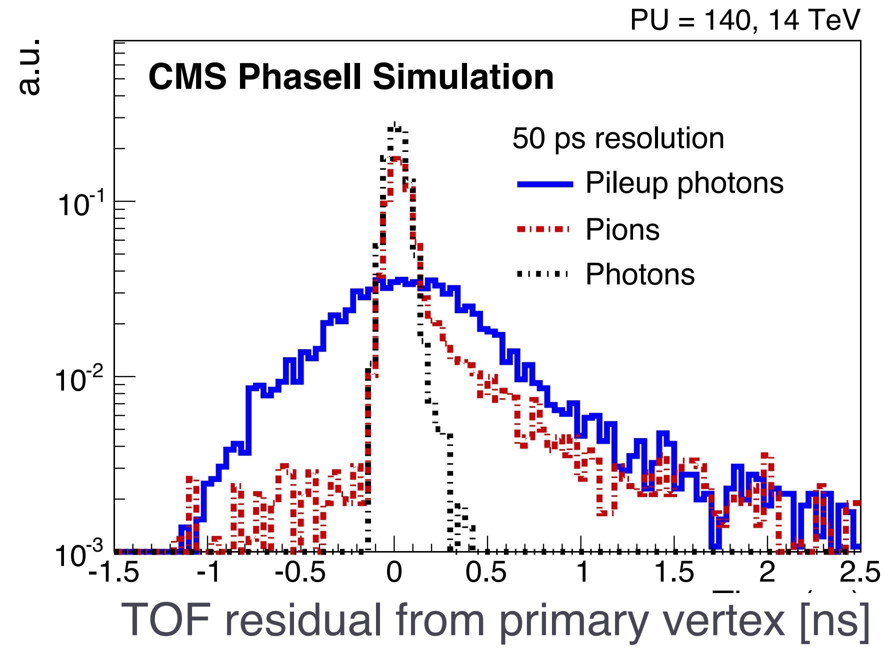
- *Vertex ID efficiency from event kinematics <50% for gg-fusion*
- Triangulation of two high $p_T$ photons (60 GeV) only

[CMS CR-2014-074]




## 2. General PU mitigation:

- Removal of pileup photons from isolation cones, jets, …
- *Need time of low energy photons*
- *Need time of vertices*
  - [from low-energy deposits associated to charged tracks]



# Requirements and concepts for HL-LHC / FPP-collider

- **Timing of photons to ~20 ps**
- **Timing of vertices (< 20 ps) from charged particles**
  - [ Deposits in calorimeters associated to charged particles]

- Granularity of order 1 $cm^2$ (time-walk, occupancy, shower size)
- Active area of order 10 $m^2$ (endcap) for ~$10^5$ channels
- **Rate capability: $10^6$-$10^7$ Hz**
- **Radiation hardness: 10 Mrad – $10^{15}/cm^2$**

I. **Shower Max –** *dedicated layer(s) embedded in the EM calorimeter or from the full longitudinal EM energy profile*
   - *[ and* Timing Layer *– for tracks in front of a calorimeter system ]*

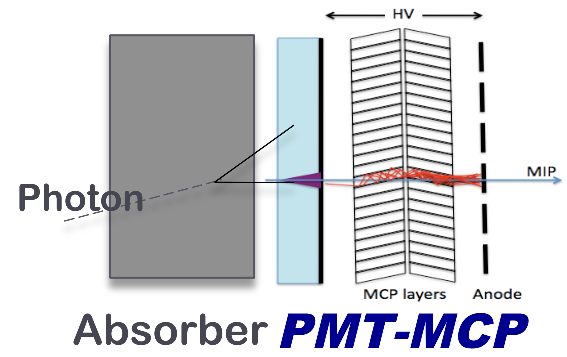
II. **Pre-shower –** *front compartment of an EM calorimeter*
   - *Balance low occupancy MIP identification with EM showering*
   - *Separate quest for precision timing from calorimeter technology*

# MCP in shower detection and timing

- Attractive due to recent technological progress in MCP production (ALD) with impact in production cost and lifetime (LAPPD)

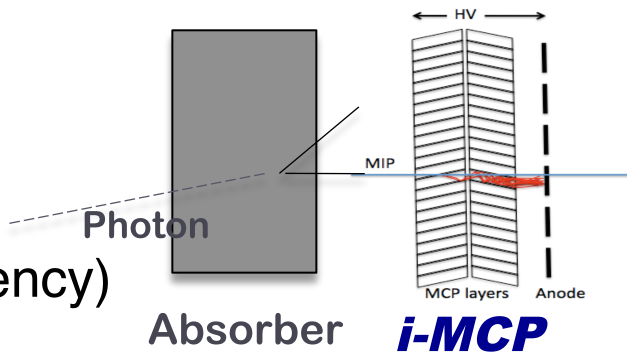
**1. PMT-MCP:**

- High efficiency to MIPs through Cerenkov emission in the optical window
- 20-30 ps in shower detection at beam tests
  - [A.Ronzhin et al, NIM A 759 (2014) 65]




**2. Ionization-MCP:**

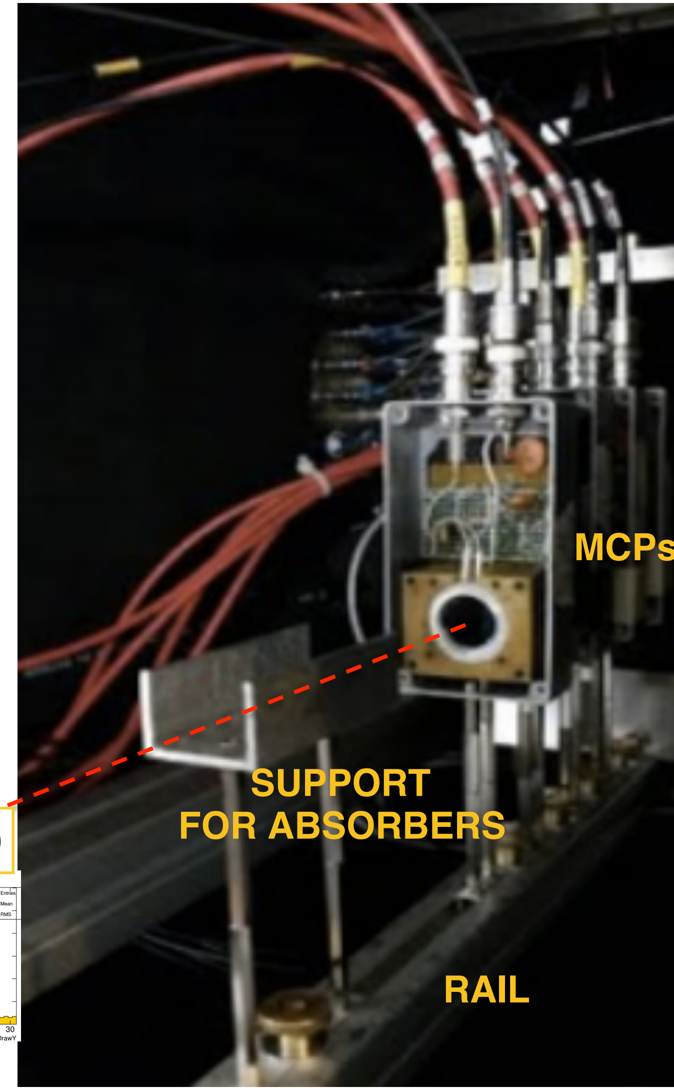
- First proposal for calorimetry (no timing): *[A. A. Derevshchikov et al. Preprint IFVE 90-99, Protvino, Russia, 1990.]*
- Studied for muon detection (limited efficiency) *[Bondila et al., NIM A 478 (2002) 220]*



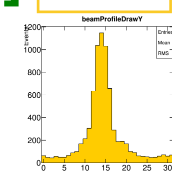

- Appealing with high MIP multiplicity (showers or jets)
- No photocathode → robust design / assembly / potentially rad-hard
- Not studied in depth recently
  - *[indirect study in A.Ronzhin et al., NIM A 759 (2014) 65]*

# Test setup and MCP configurations

- **Cosmic-ray muons test bench**
- **Election beam tests**
  - 500 MeV electrons (BTF-LNF, Italy)
  - 20-50 GeV electrons (CERN SPS)
- **Double and triple layer MCPs**
  - Ekran FEP (BINP Novosibirsk)
  - Planacon-Photonis XP85-015
- **i-MCP operation:**
  - Retarding bias to the photocathode to prevent photoelectron collection
- **Hodoscope [ for beam centering]:**
  - x and y with 1 mm pitch
- **DAQ based on CAEN V1742**
  - DRS4 chip (PSI) set to 5GS/s

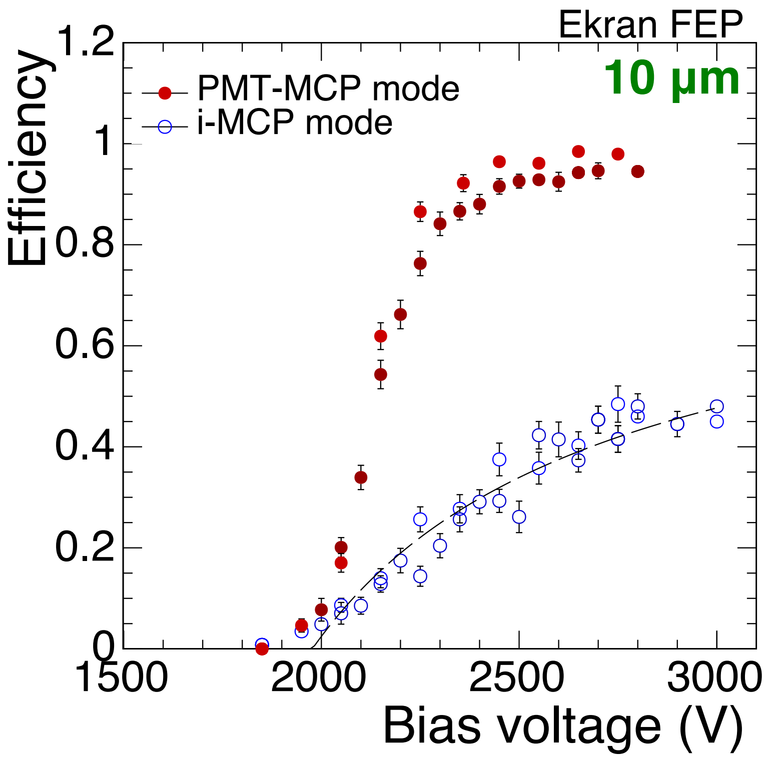


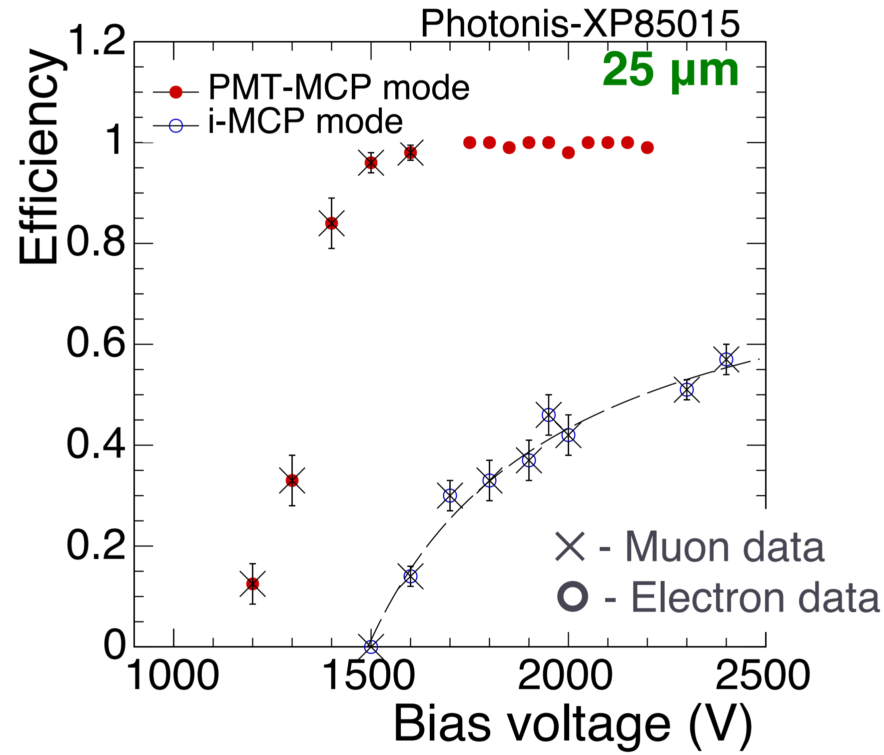

HODO



# Single particle efficiency

- **Double layer MCPs (aspect ratio 1:40)**



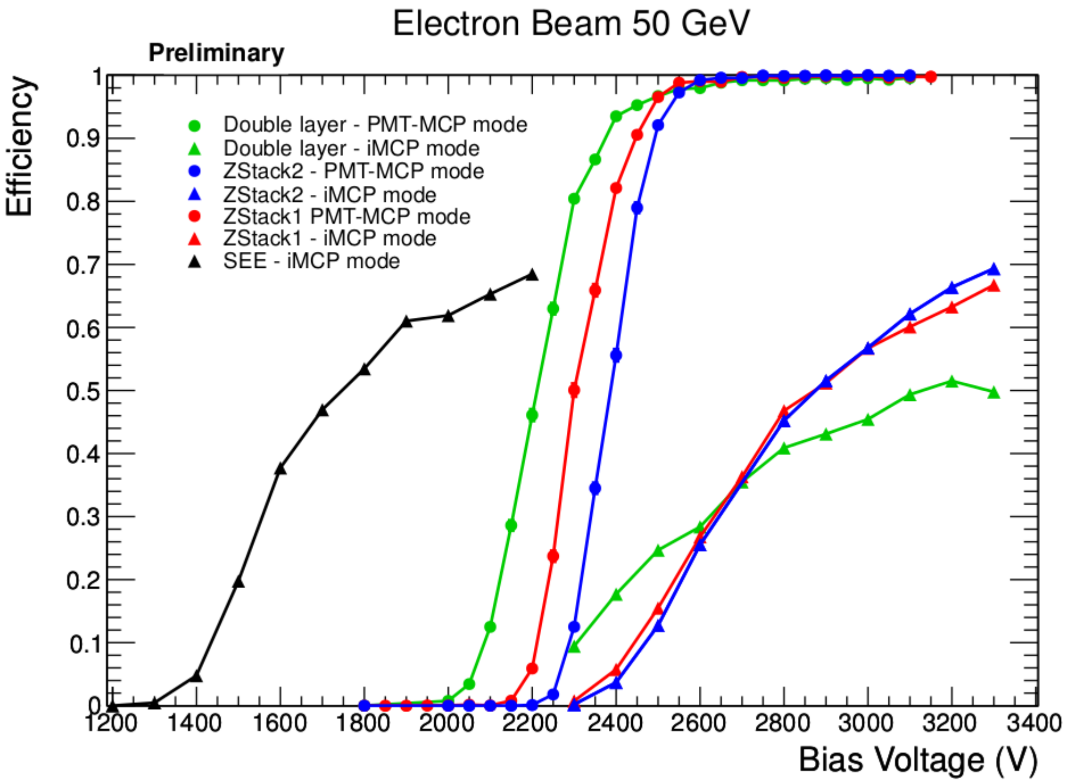

- Efficiency model for i-MCP mode:
  - *s = secondary emission probability over the stack*

$$\varepsilon = s\left(1 - \frac{1}{b\ln(V/V_{th})+1}\right)$$

[L.Brianza et al. arXiv:1504.02728 ]

# Single particle efficiency (II)

- **Ekran FEP (BINP) MCPs with 50 GeV electrons**
  - Same aspect ratio of wafers
  - More pore-crossings in Z-stack

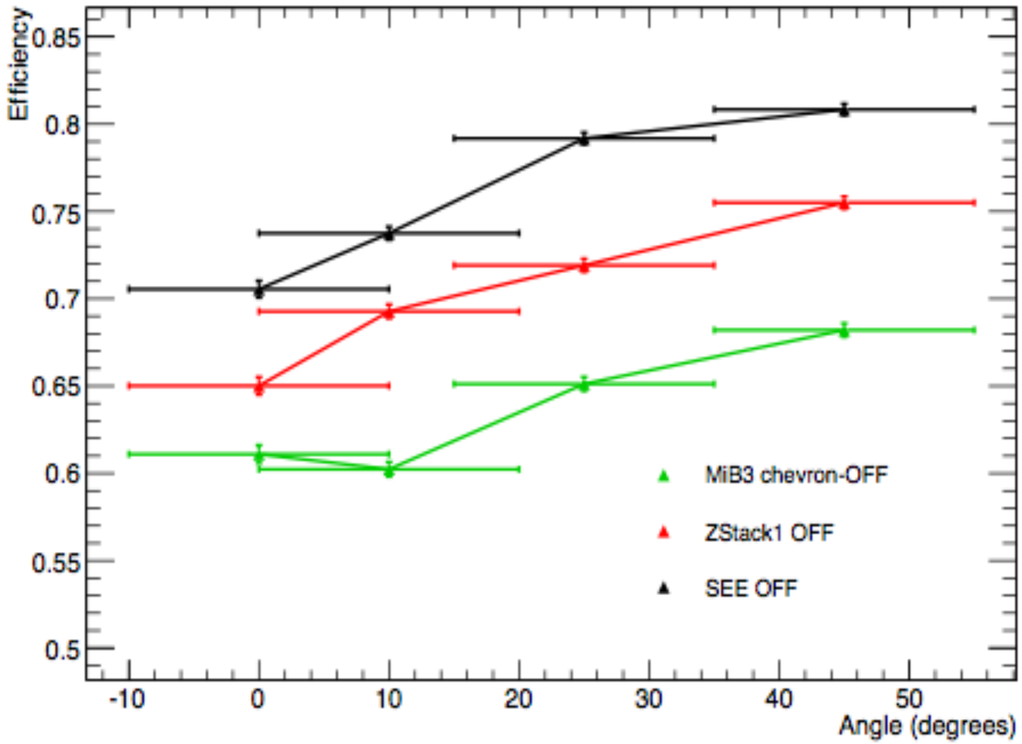



- **i-MCP mode:**
  - Double layer (same MCP as in previous slide)
    - **ε~50%**
  - Double layer with enhanced SE
  - Z-Stack (triple layer)
    - **ε~70%**

- *Next steps: thicker wafers, separate gain/conversion stages, …*

# Efficiency vs angle (single track)

- **Further gain in efficiency at large crossing angles**
  - Bias angle of Ekran FEP MCPS ~ 10-12°
- More channels crossed by single particle
- Higher 'integral' SE emission probability



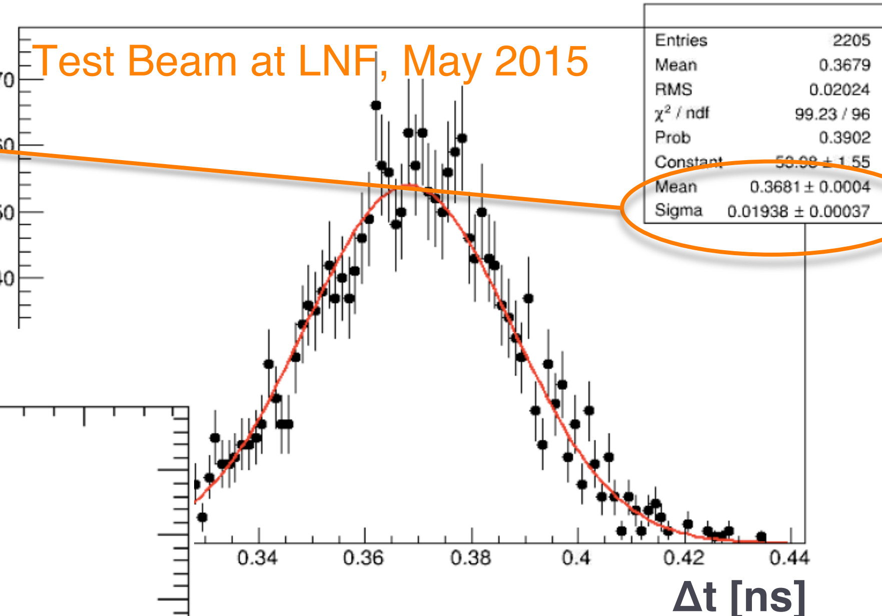

- **Efficiency up by 10%**

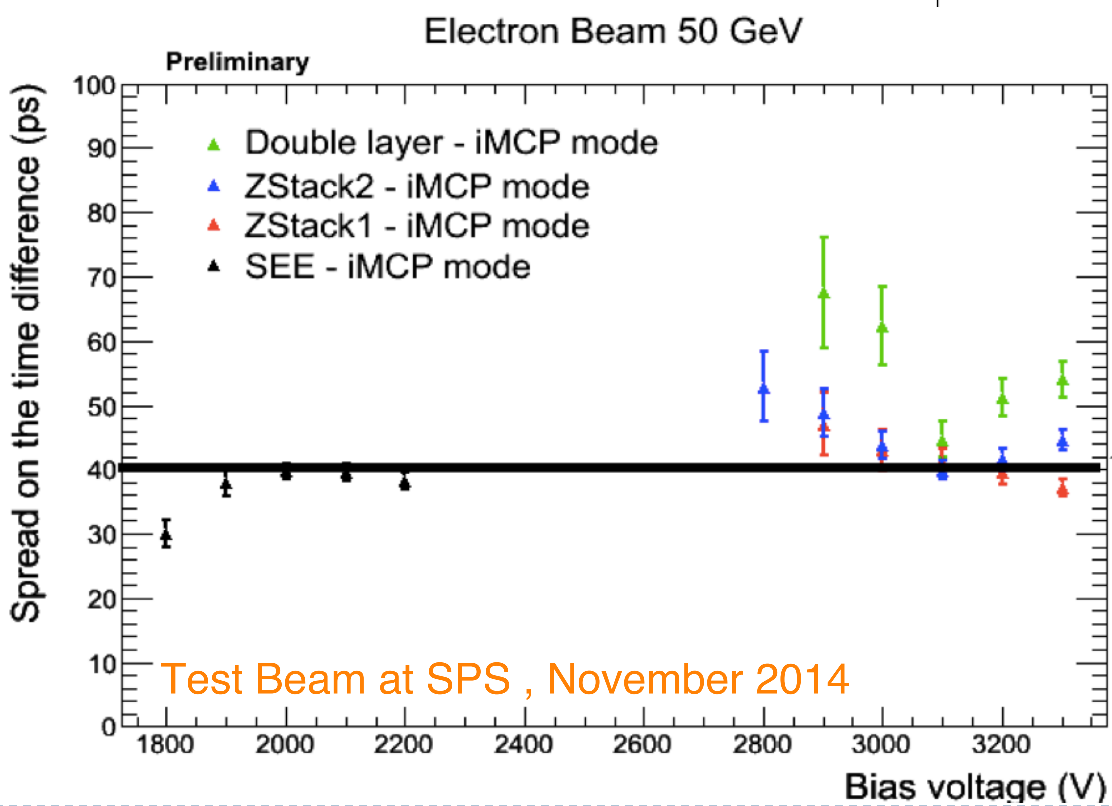
- NOTE: All MCPs scanned together
- Red (Z-Stack) first on beamline
- Showering affects efficiency of downstream MCPs

HV = 2200 V (Enhanced SE)
HV = 3200 V (other MCPs)

# Timing performance: single particles

- Two Z-Stack in PMT-MCP mode: **$\sigma_{\Delta t}$~20 ns**
  - SE at the photocathode
  - Same gain for all signals

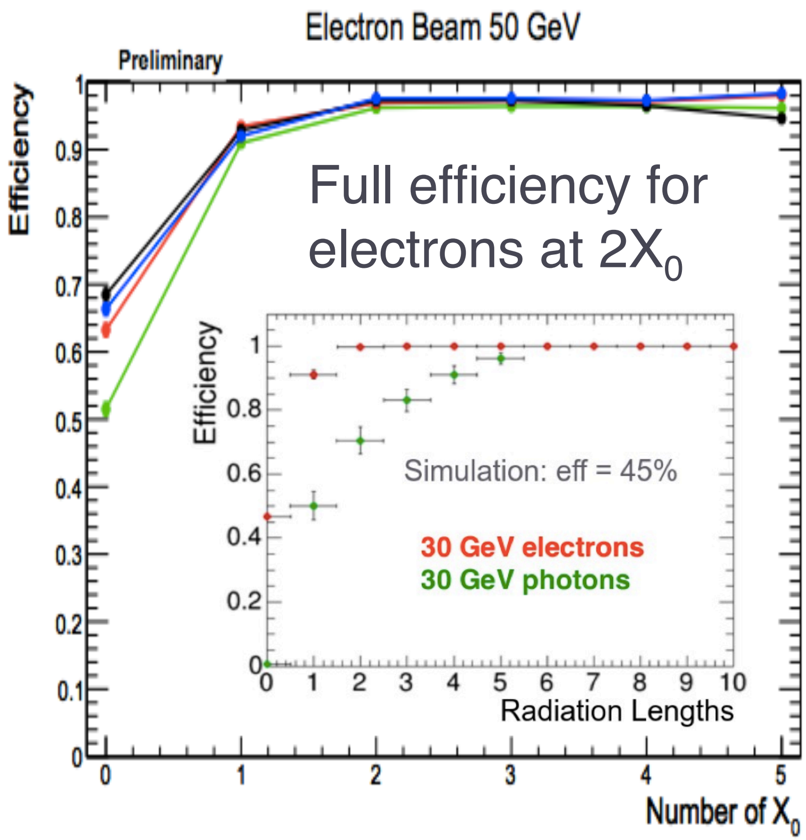


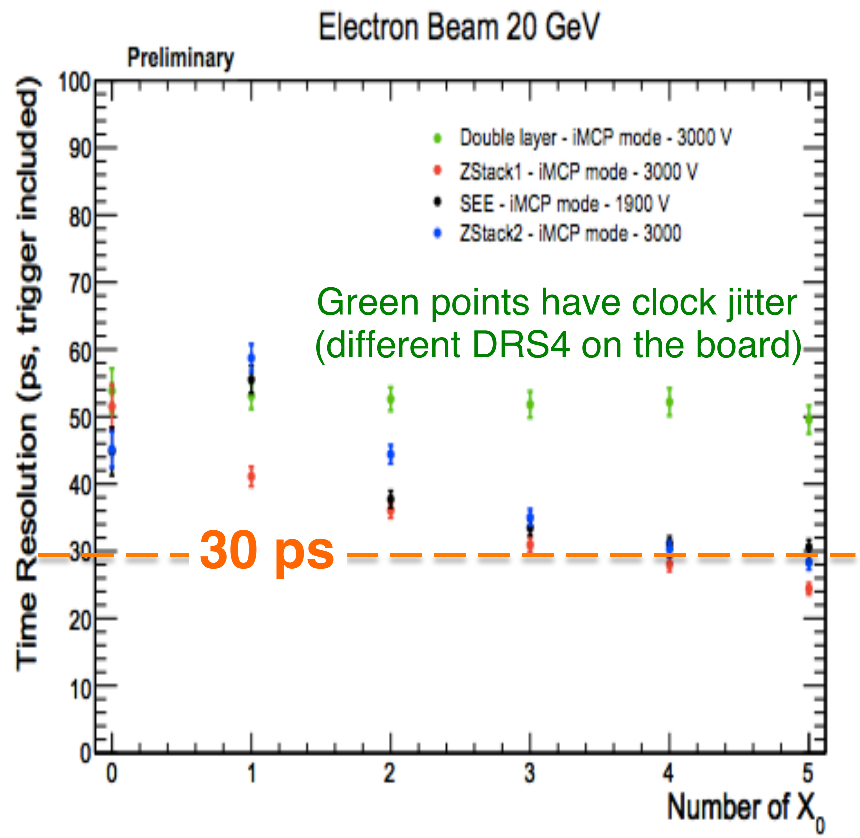




- One i-MCP vs one PMT-MCP: **$\sigma_{\Delta t}$~40 ns**
  - Lower gain than in PMT-MCP mode
  - SE at different depths in the channels

# MCP in shower detection / timing

- **Response vs the shower depth (i.e. multiplicity)**
  - Configurations: double/triple layers, enhanced secondary emission

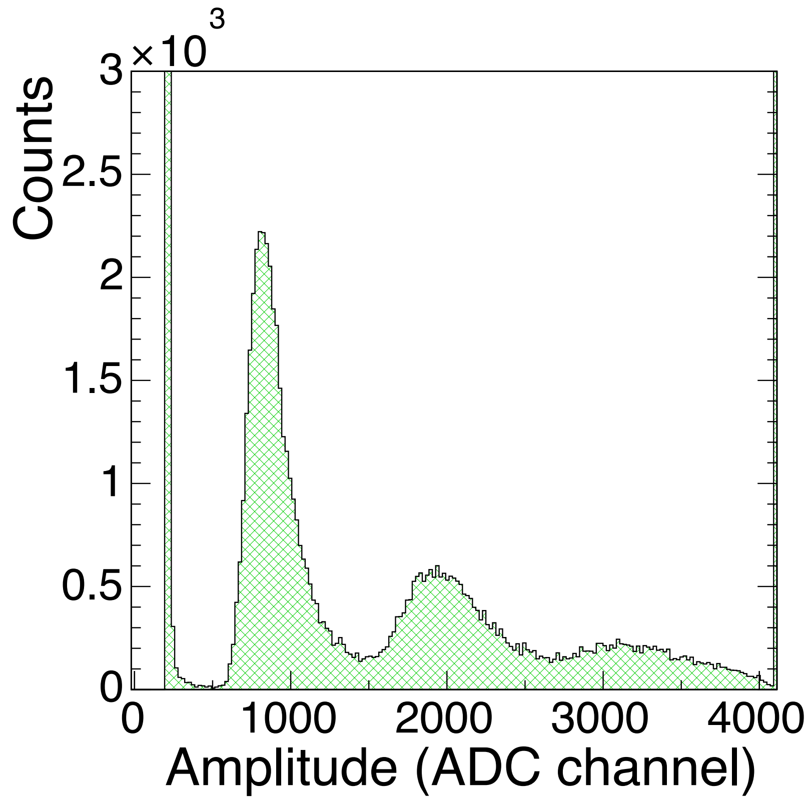


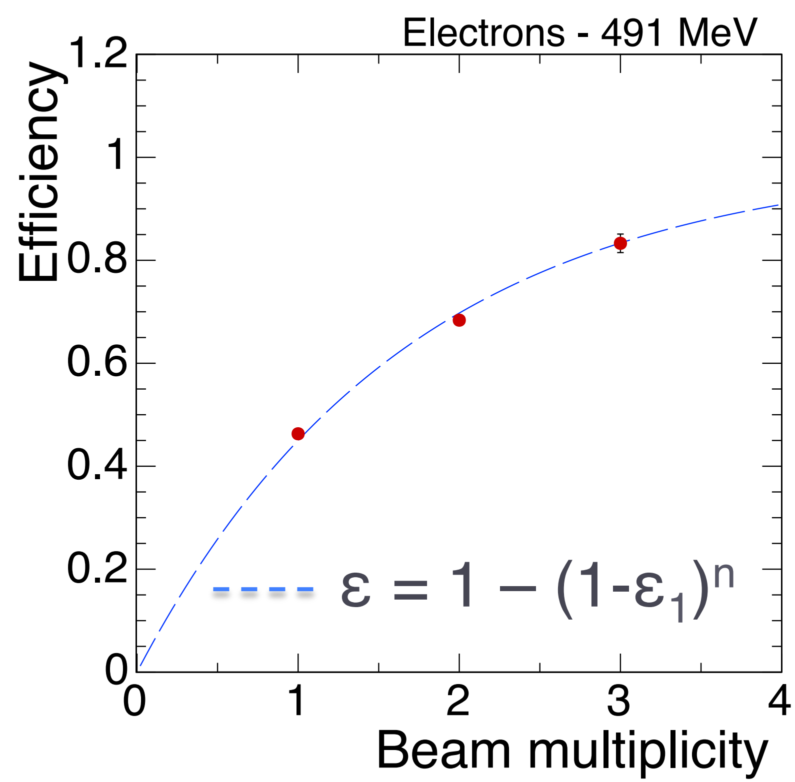




Efficiency to photons requires conversion

# Multiplicity dependence

- **Vertex timing can exploit high track multiplicity in jets:**
  - Full efficiency to MIPs desirable, but not mandatory




- Beam intensity at BTF-LNF tunable to few particles per spill
- Multiplicity from SCI counter / efficiency for at least one electron

# 2. Detection of 511 keV photons

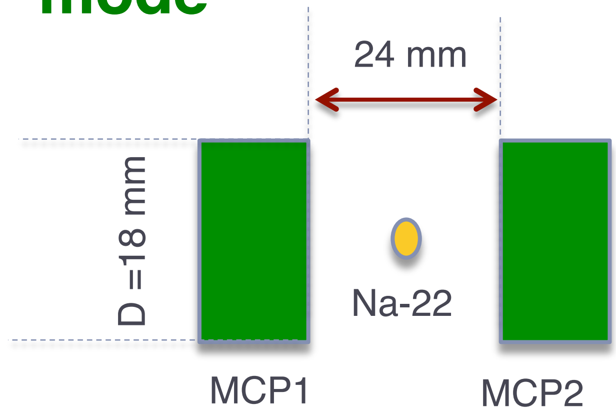
## (Small animal) TOF-PET

- **Test direct conversion of 511 keV in the MCP stack**
  - No information on the energy
  - Potentially high time resolution

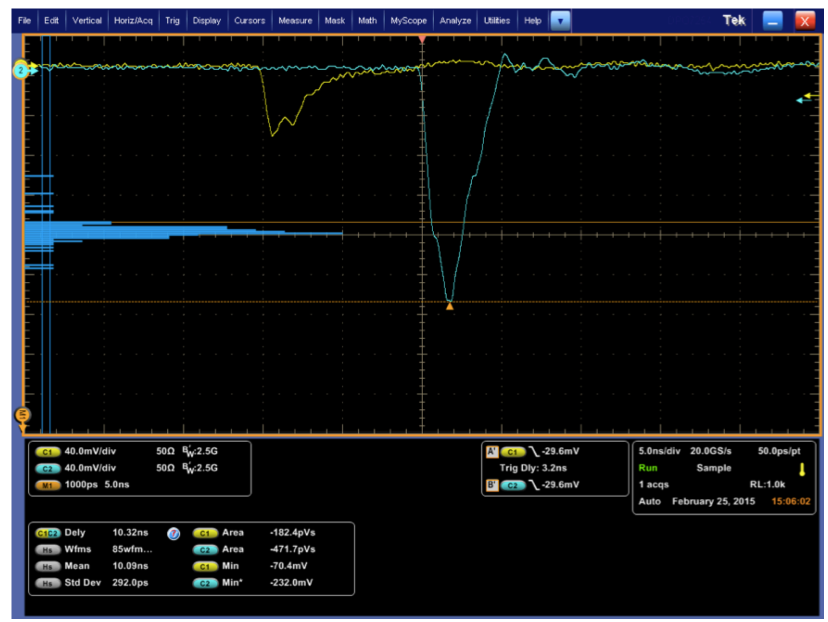
- 60% of "first" interaction due to Compton scattering (even in high-Z materials)

# Test of PET configuration with two MCPs

- **Two PMT-MCPs operated in i-MCP mode**
  - Ekran FEP MCPs – Z-stack
    - Three lead-glass wafers for **~0.6 mm** total thickness
      - Pores ~ 8-12 μm
        Pitch ~ 10-12 μm
    - Retarding bias to inhibit photocathode

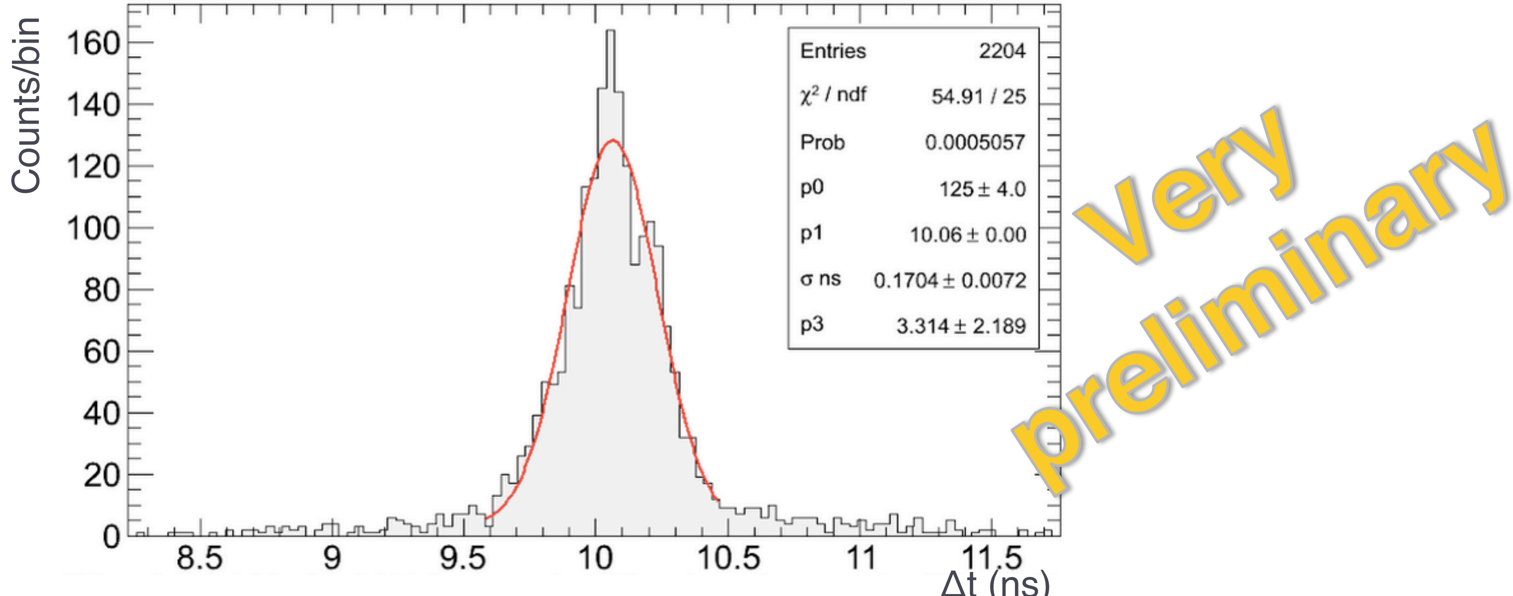



  - Waveforms digitized with Tektronix DPO7254
    - 8-bit digitization at 20 GSample/s, 2.5 GHz input bandwidth
  - Trigger on delayed coincidence within ±10 ns
  - Trigger threshold at **30 mV** (50 Ω load)



# Time resolution and efficiency

- MCPs operated at HV = 2800 V, with trigger threshold at 30 mV
- Offline discrimination with CFD at 50%




- **Time resolution: Δt ~ 170 ps (i.e. 120 ps per photon)**
  - Source of additional time spread
- **Per photon detection efficiency ~ $10^{-3}$**
  - Measured from source activity and setup geometry
  - *Photon conversion probability ~ 1.5%*
  - *Efficiency to MIPs ~ 5—10 % (TB data analysis with 30 mV threshold)*

# Summary and outlook

- **Discussed photon detection with MCPs**
  - Characterized MCP response to single particles and EM showers in PMT-MCPs
    - Retarding bias to photocathode to inhibit photoelectron collection
  - Dependence of efficiency on geometry and operation parameters drives next tests:
    - Stack geometry, aspect ratio
    - High emissivity (test with ALD wafers)
  - *Has to study radiation hardness and magnetic field immunity*
- ***Pre-shower based on i-MCP viable for pileup mitigation***
- ***Preliminary results in detection of 511 keV γ's interesting***