FCC hadron detector meeting
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# Muon Detector Studies

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# Introduction (to our group)

**Strong participation to both detectors and physics in ATLAS experiment since the beginning**

- Muon trigger chamber (TGC) construction and operation
- Run coordination of ATLAS experiment
- Upgrade on NSW, Electronics, LAr trigger (Phase-I), MDT trigger (Phase-II)
- Higgs discovery for $H\rightarrow\gamma\gamma$ in Run 1, evidence for $H\rightarrow\tau\tau/bb$ at Run 2
- SUSY searches : squark/gluino, stop, EW gauginos/higgsinos
- Exotics searches : high-$p_T$ tops/W/Z, coordination

**Plan to contribute to**

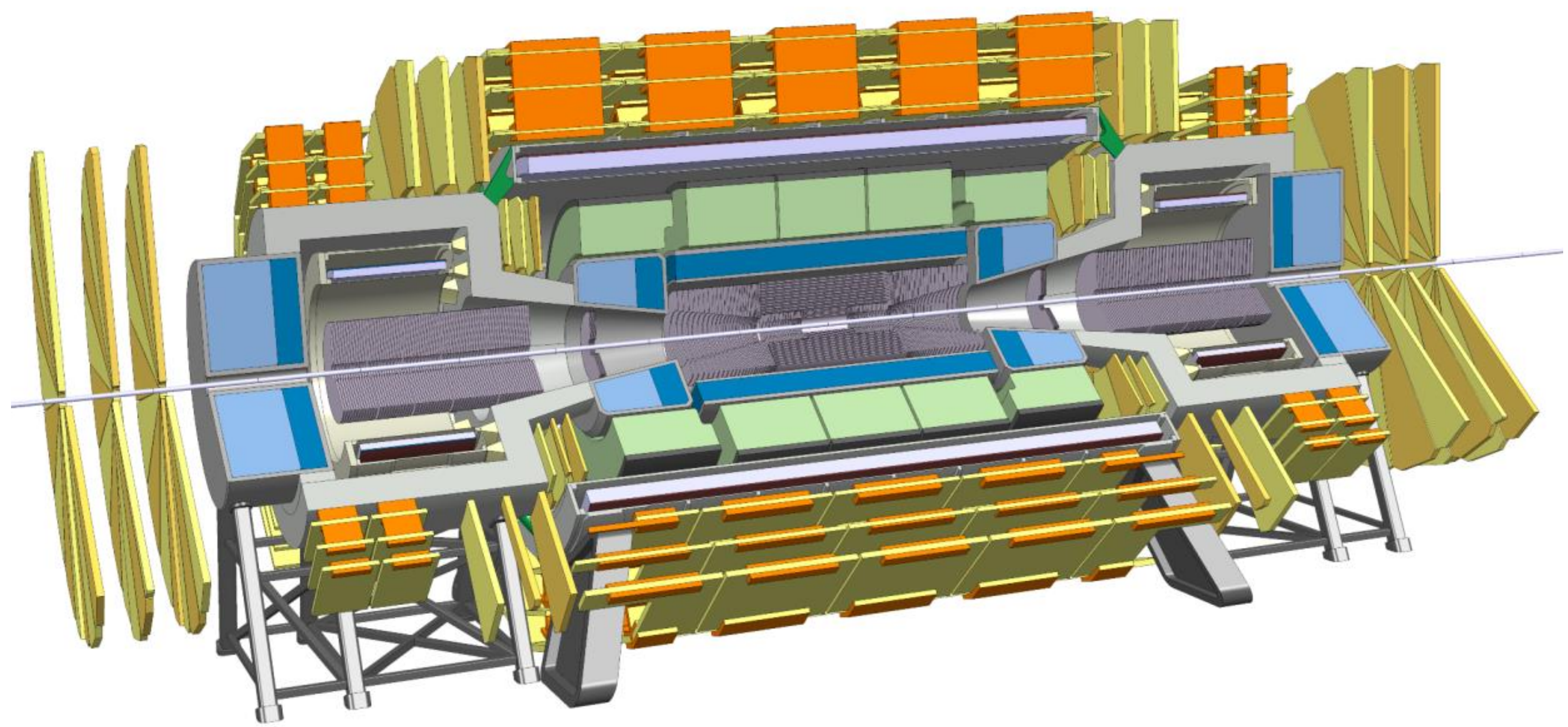
- conceptual design of muon detectors and muon performance at high-$p_T$
- sensitivity studies for SUSY electroweak gauginos ($\rightarrow$FCC Week at Berlin)
- sensitivity studies for HH production

**for CDR**

**Any feedback appreciated!!**

# $FCC_{hh}$ Reference Design for CDR

- 4T 10m barrel solenoid
- 4T forward solenoids
- No shielding coil
- “Barrel muon” region : 6.5m<r<9.0m, |z|<13 m

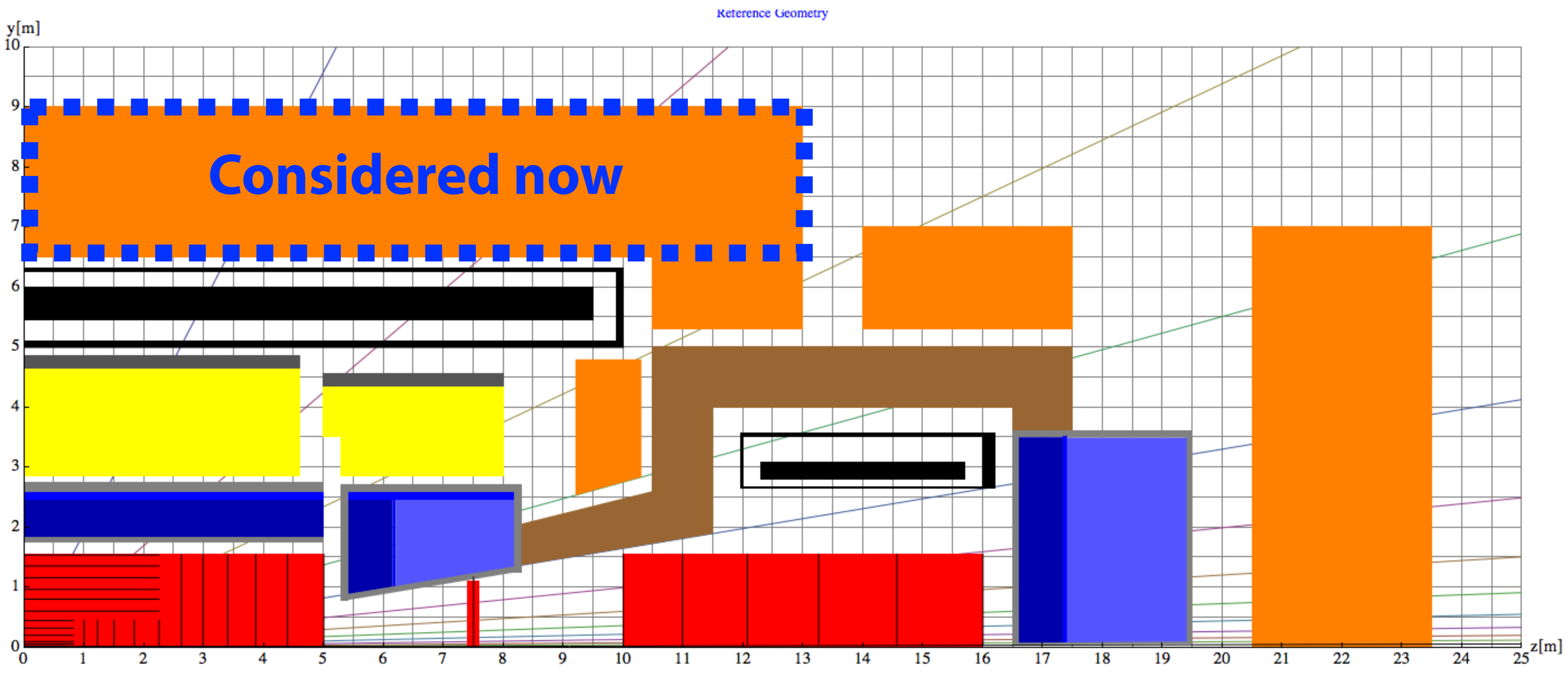


## Muon detector design goal

<10% standalone (combined) momentum resolution up to ~3(20) TeV with 50μm position and 70μrad angular resolution

Our initial goal is to confirm this using “ATLAS-like” muon detector with reference geometry and FCCSW simulation

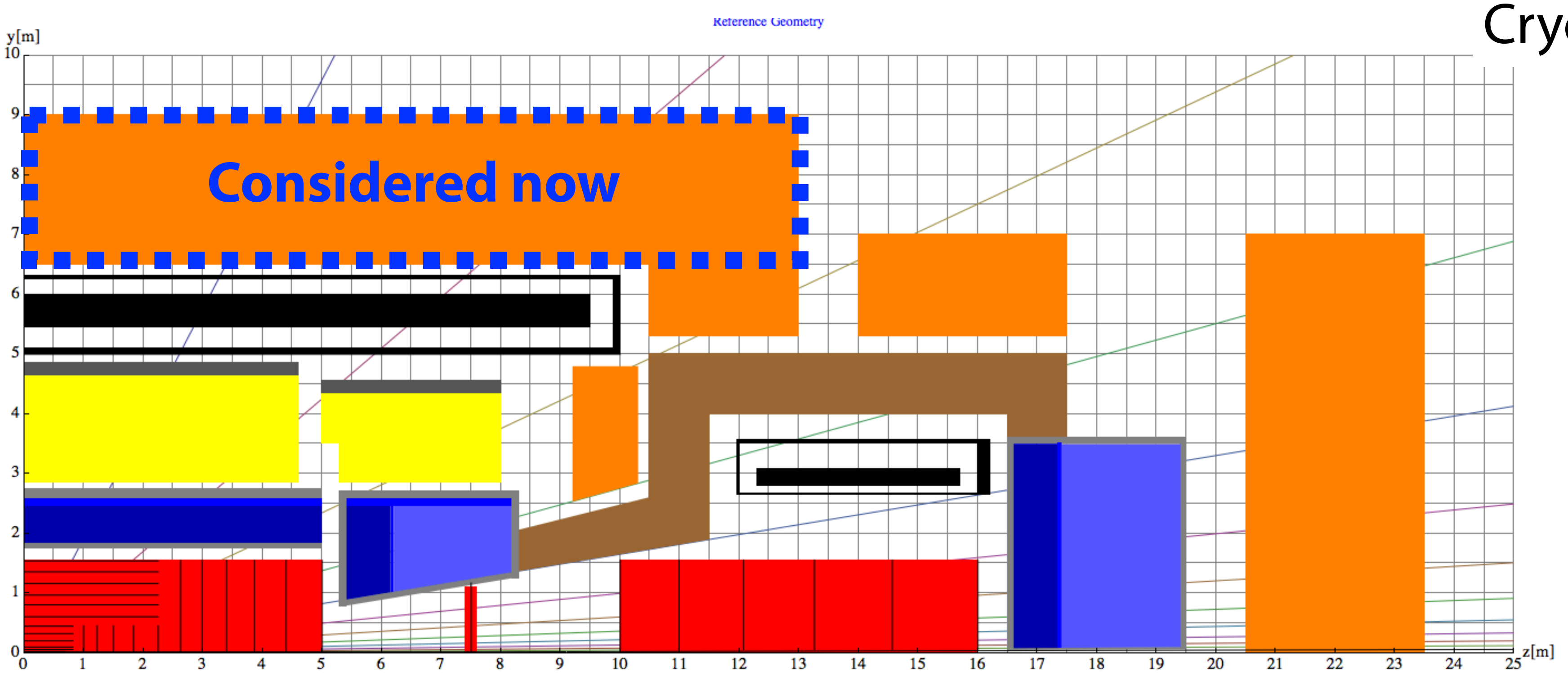
# FCChh Muon Detector

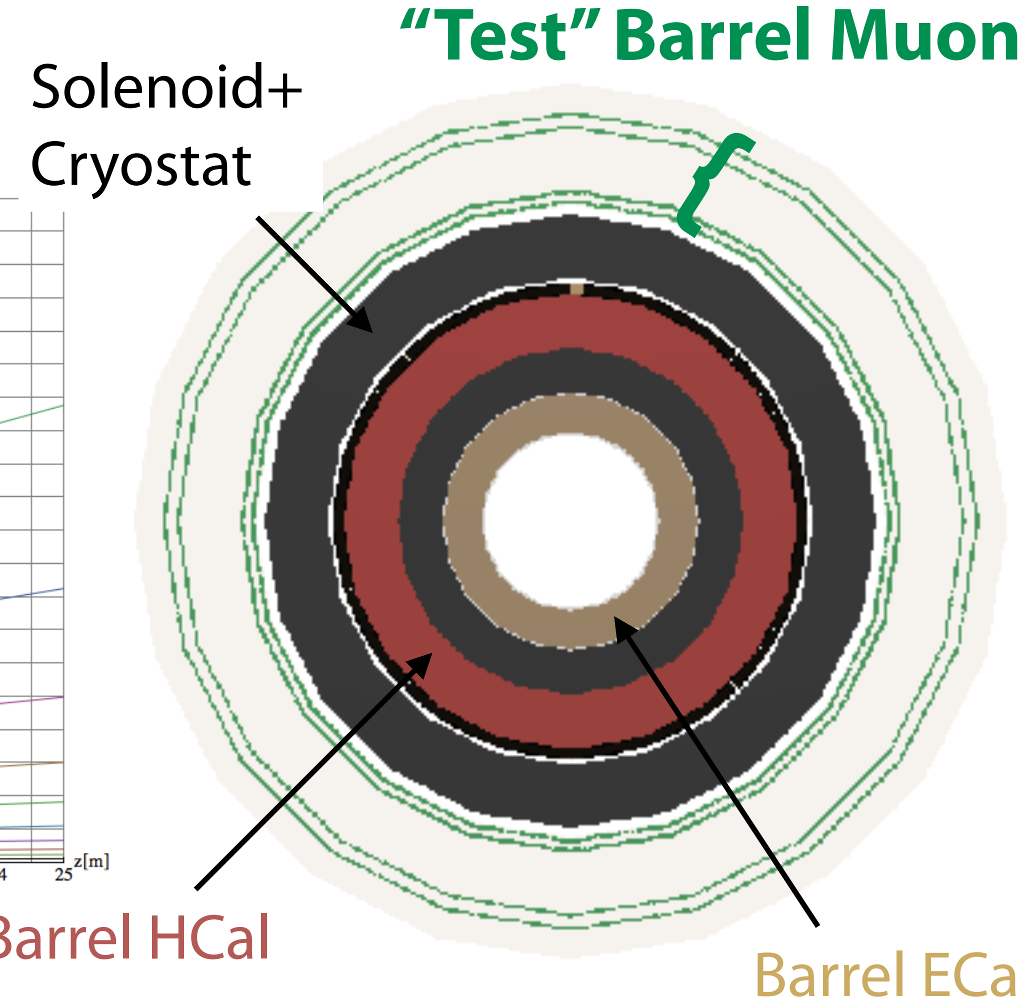



Status :

- DD4hep description of muon detector & geometry in FCCSW 0.8.1
  - Only Barrel region is considered with SimpleLayeredCylinder geometry
  - Implementing ATLAS "MDT-like" (w/o tube) gas detector :

# FCChh Muon Detector

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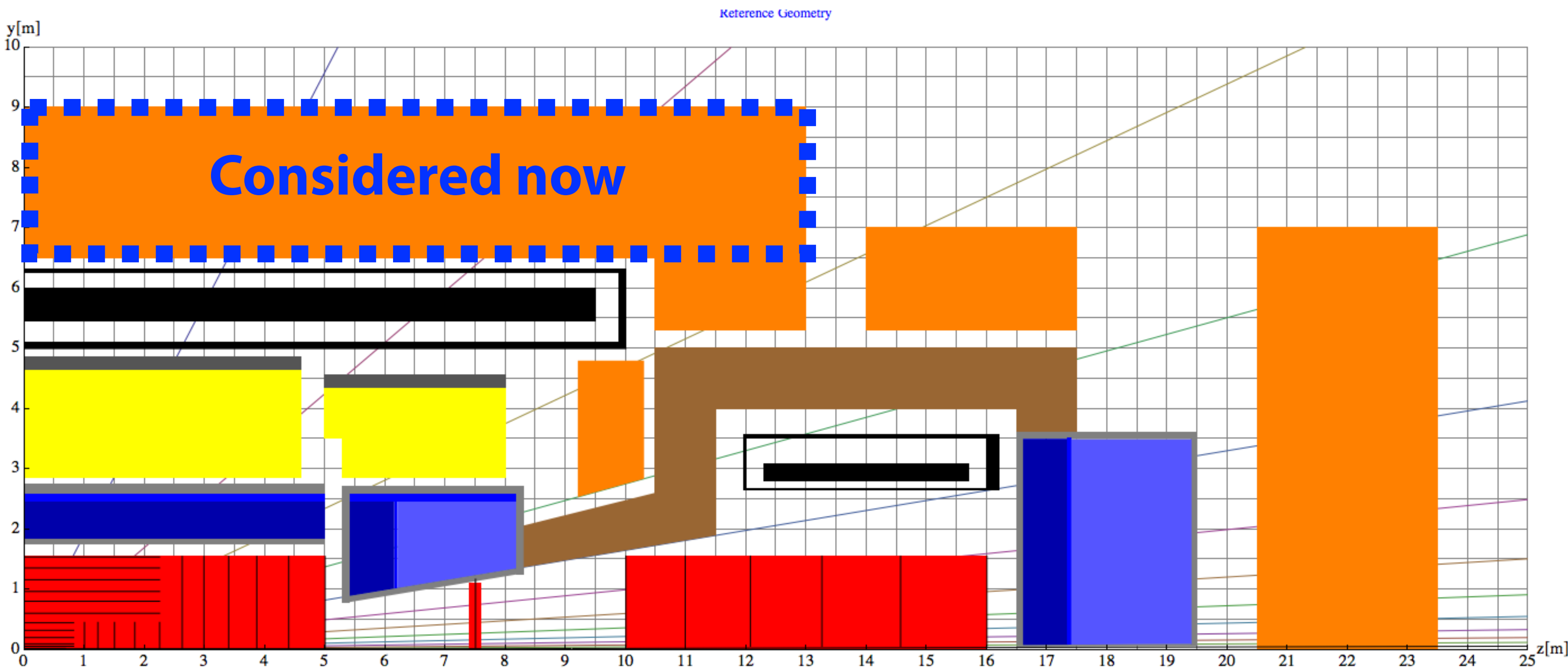
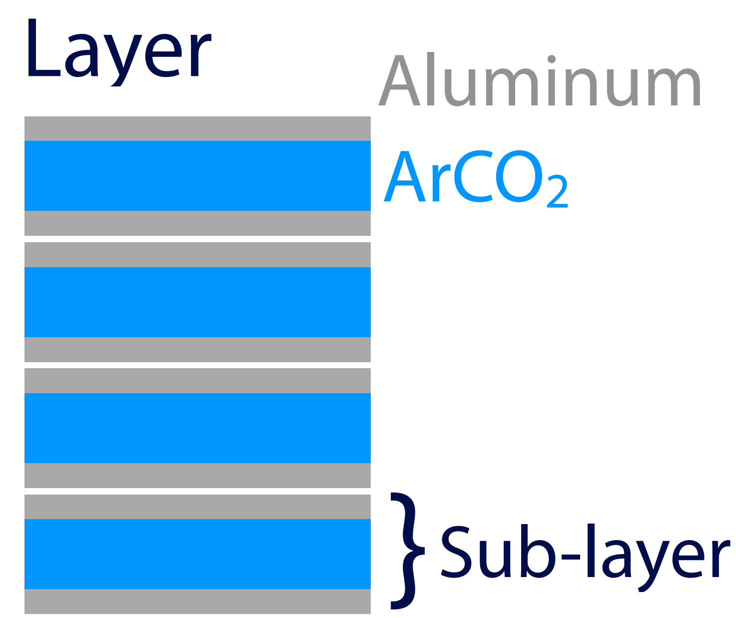
  - Implementing ATLAS "MDT-like" (w/o tube) gas detector :
    - 2 or 3 stations, 2 layers per station, 3-4 sub-layers per layer

| #stations | distance between stations | #layers/ station | distance between layers | #sub-layers |
|---|---|---|---|---|
| 2 | 1.2m | 2 | 12, 22cm | 4/4/3/3 |
| 2 | 2.4m | 2 | 12, 22cm | 4/4/3/3 |
| 3 | 1.1m | 2 | 12, 22, 22cm | 4/4/3/3/3/3 |

# FCChh Muon Detector

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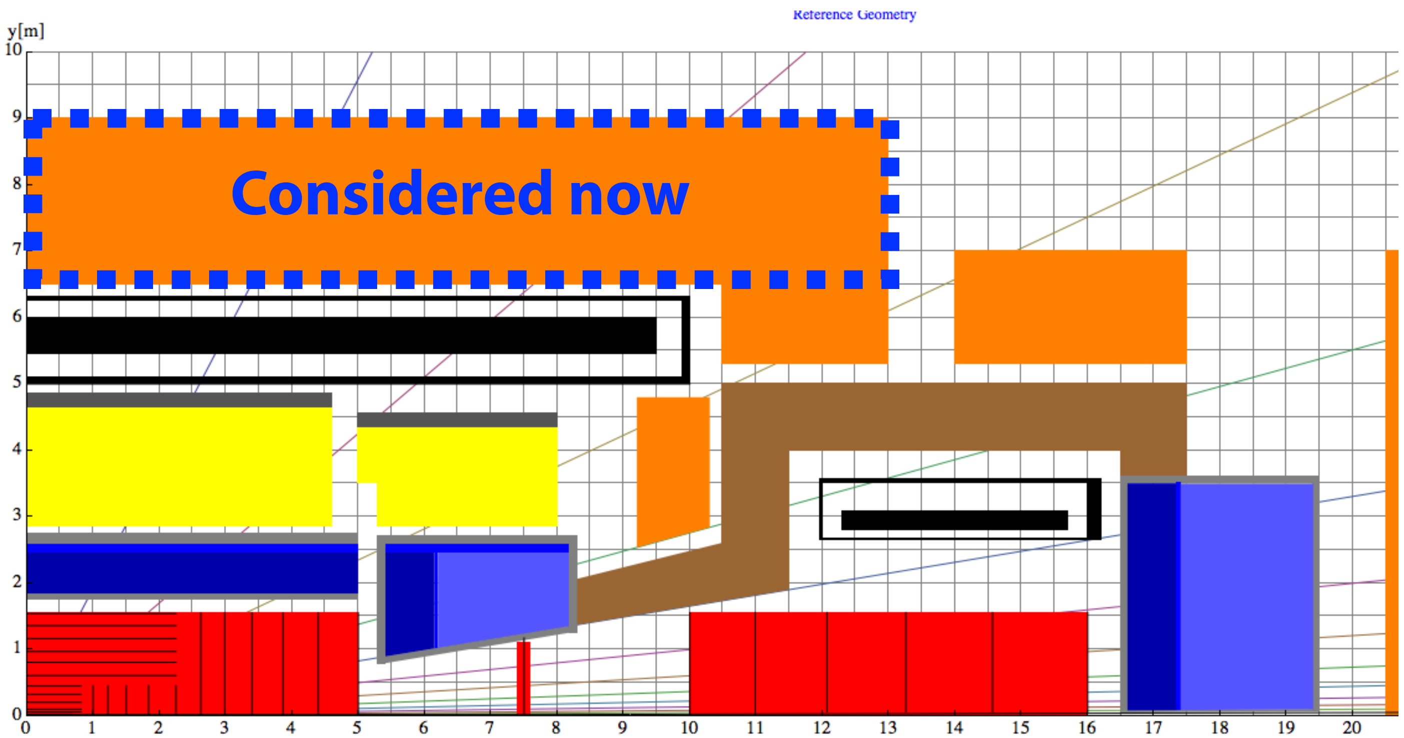
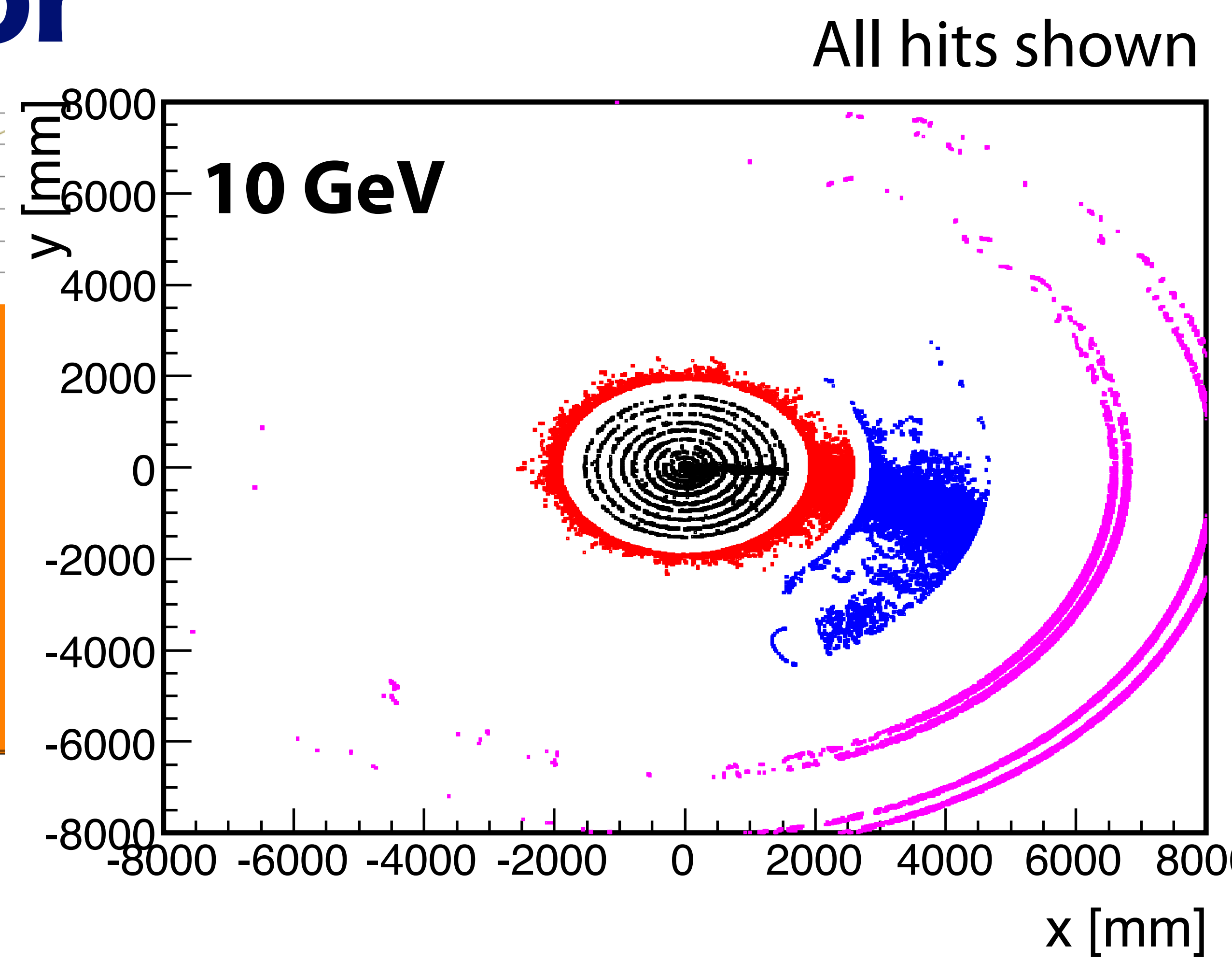
  - Only Barrel region is considered with SimpleLayeredCylinder geometry
  - Implementing ATLAS "MDT-like" (w/o tube) gas detector :
    - 2 or 3 stations, 2 layers per station, 3-4 sub-layers per layer
    - first 2 layers consist of 4 sub-layers; the rest 3 sub-layers
    - Each sub-layer made of Al (0.3mm) - Gas (2cm, 93% Ar, 7% $CO_2$) - Al (0.3mm)

# FCChh Muon Detector

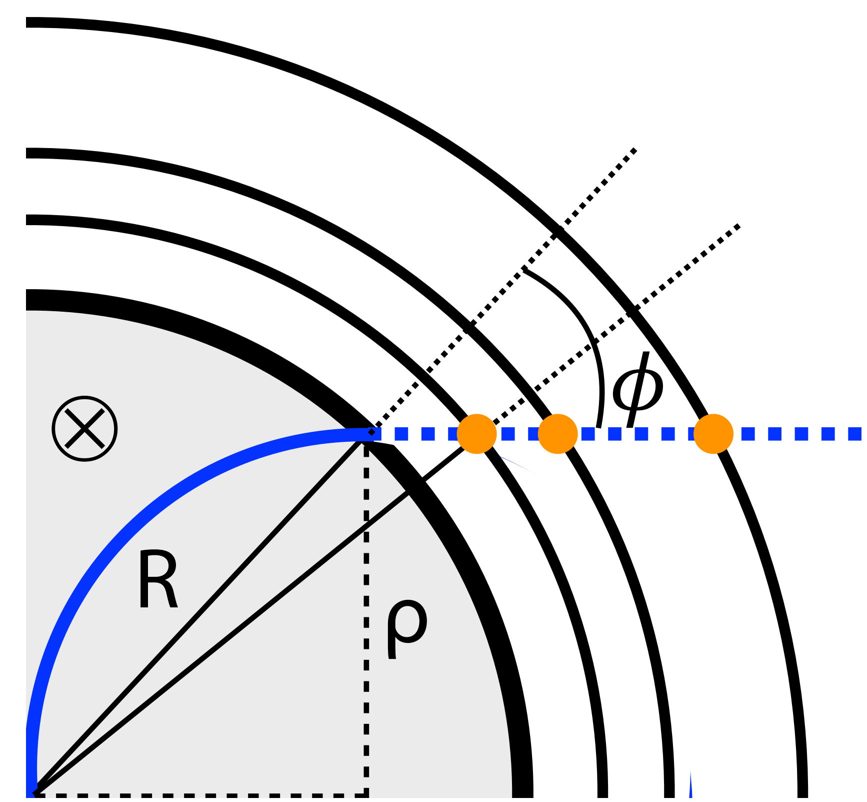



## Status :

- Test momentum measurement in full simulation (FCCSW 0.8.1)
  - Single muon events:
    - Single μ⁻ with a fixed energy at $\eta=0$, $\phi=0$
    - Beam pile, ID (TkLayout option 3), ECal, HCal, Solenoid + Muon detector
    - 4 Tesla field within R = 6 m
  - Muon standalone (based on angle at exit from magnetic field)
  - Only hits used → Need to develop digitization scheme
  - Preliminary calorimeter reconstruction for muon energy deposits

# Muon Reconstruction

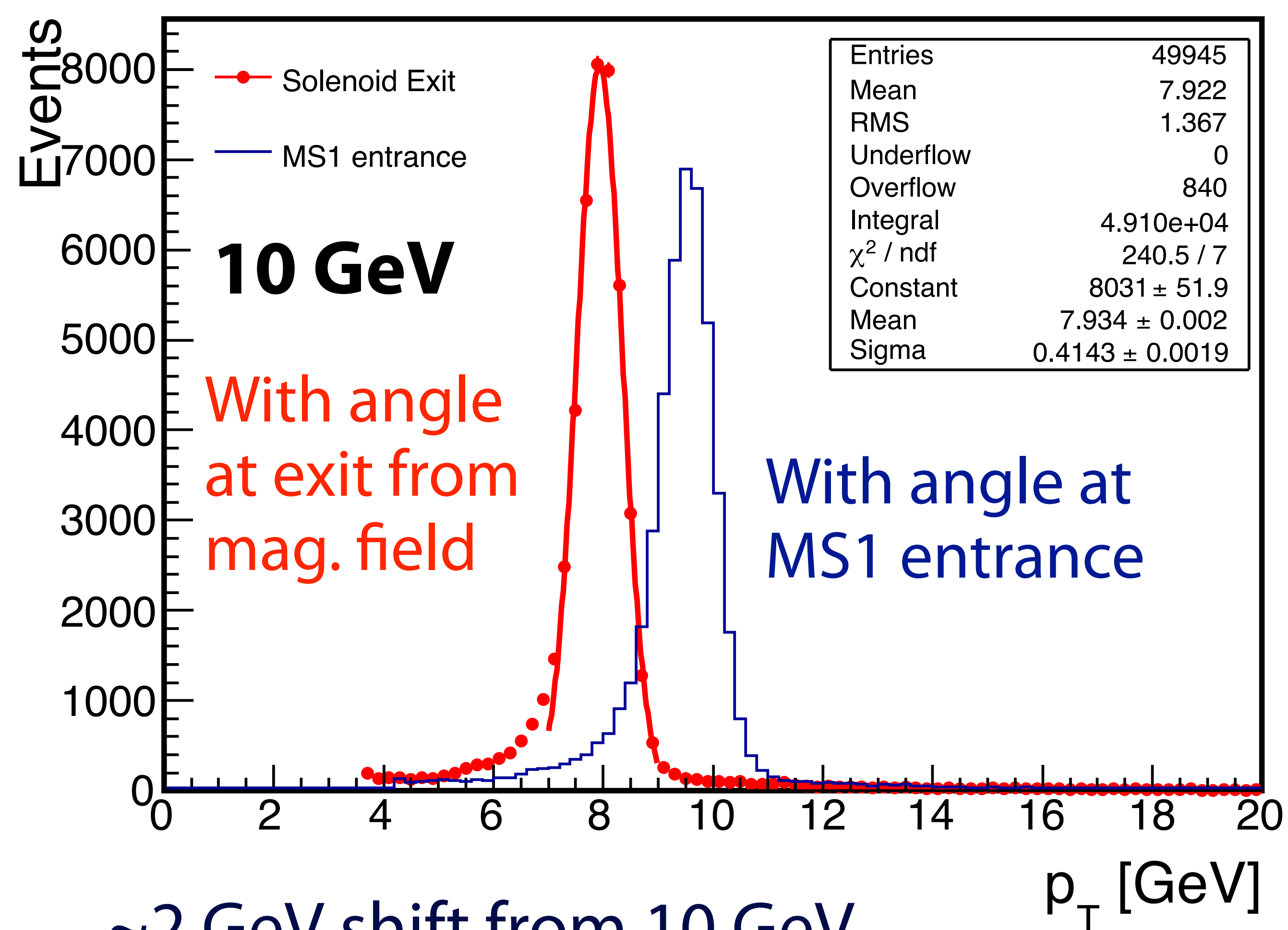



## Extract muon $p_T$ from angle

- Calculate average hit position in each of 4 layers
- Perform linear fit and extrapolate the fit to the point where the muon exits from the magnetic field
- Get the angle $\phi$ at exit
- Get $p_T$ from $p_T = 0.3B\rho$ and $\cos(\pi/2-\phi) = R/(2\rho)$

## Remarks

- Use hits; No digitization yet
- "Average" hit could be inaccurate
- No return field in muon spectrometer region (i.e, straight muon track)

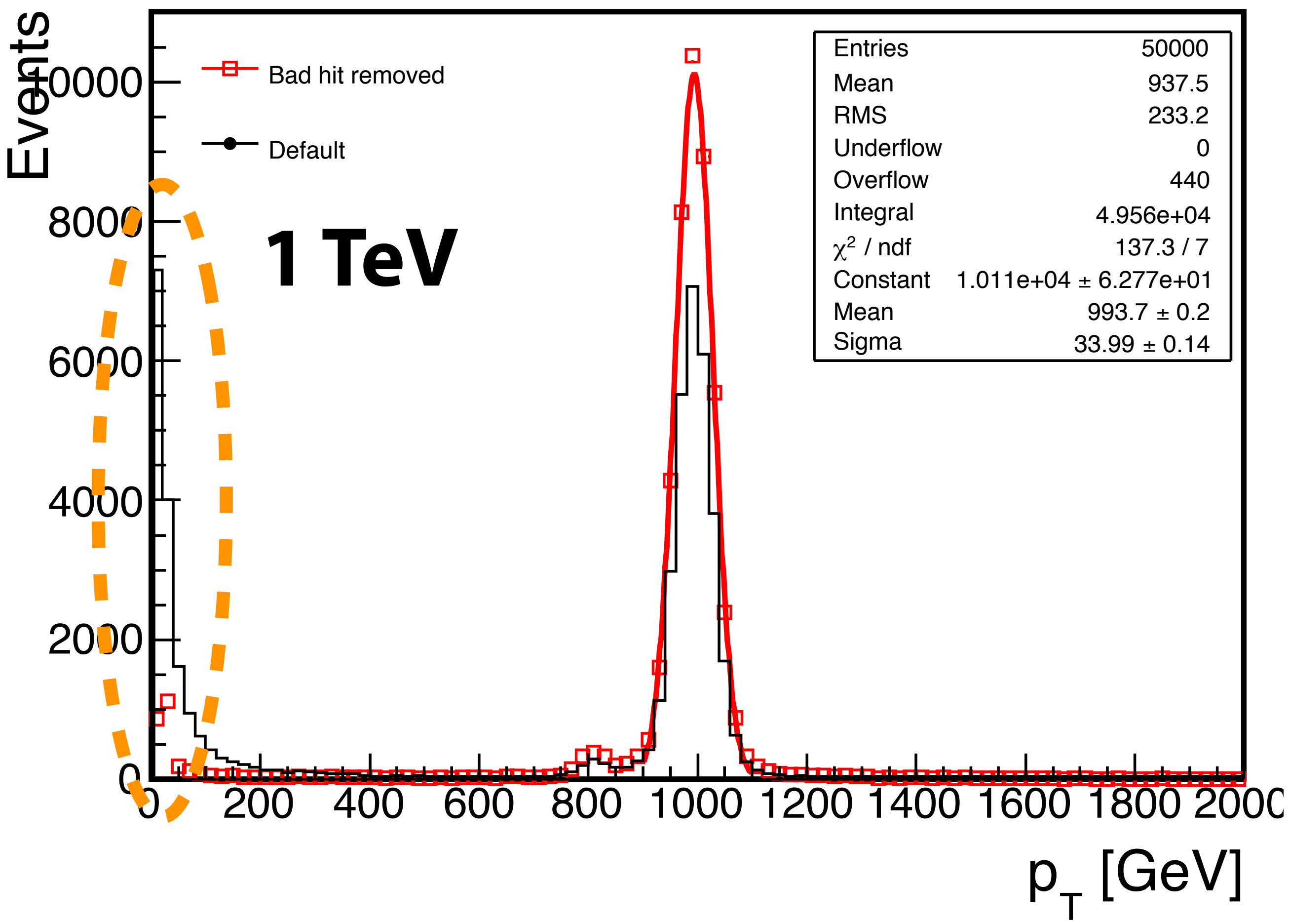


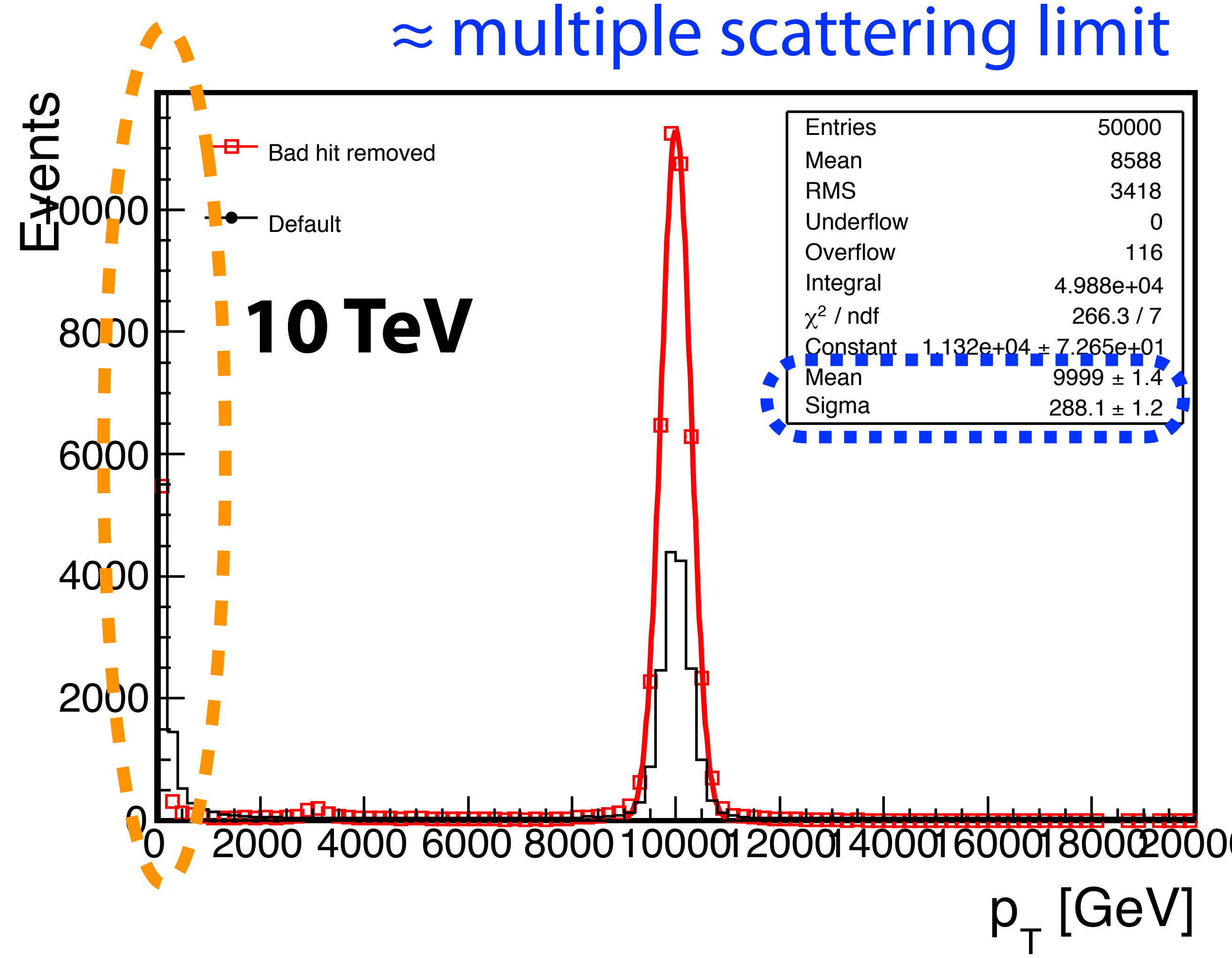

~2 GeV shift from 10 GeV

→ Energy loss in calorimeter

# "Ideal" Momentum Resolution

~3% resolution at 10 TeV
≈ multiple scattering limit



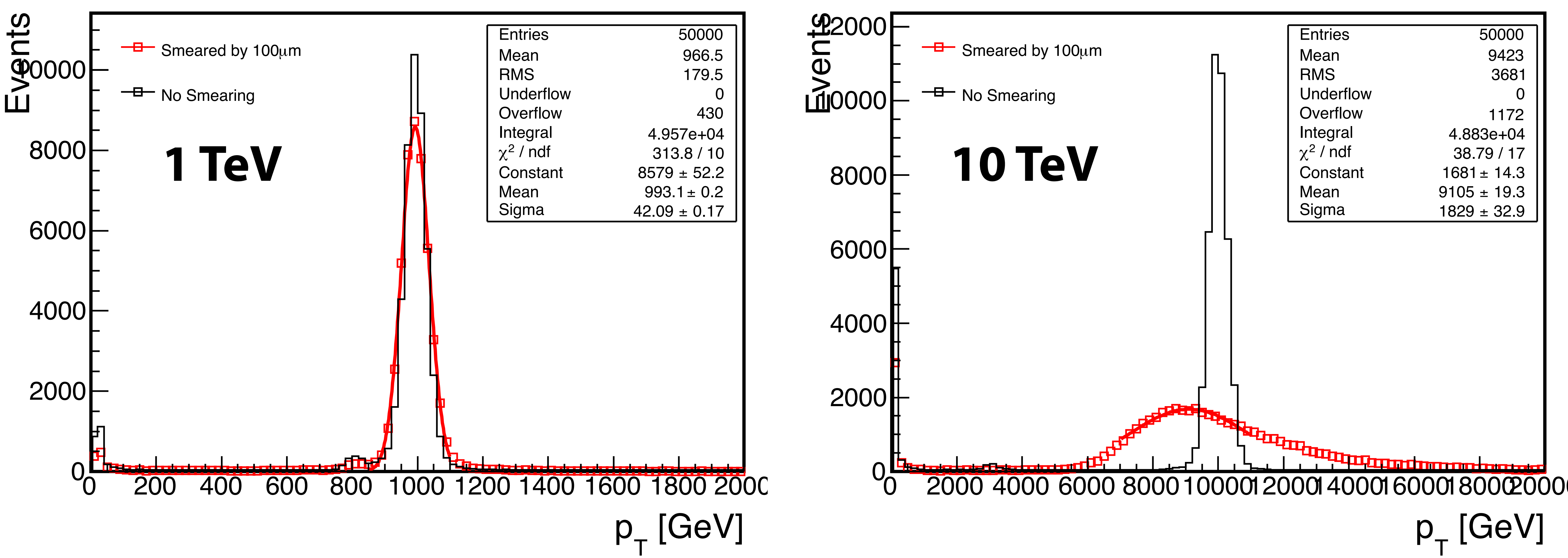




Many low $p_T$ events observed ➔ Appear to be caused by displaced hits

- displaced hits seem to have
  - no strong correlation with hit energy
  - no strong correlation with calorimeter energy deposit (next slide)
- If displaced hits are removed (red histograms), the fit can converge better

➔ To be understood

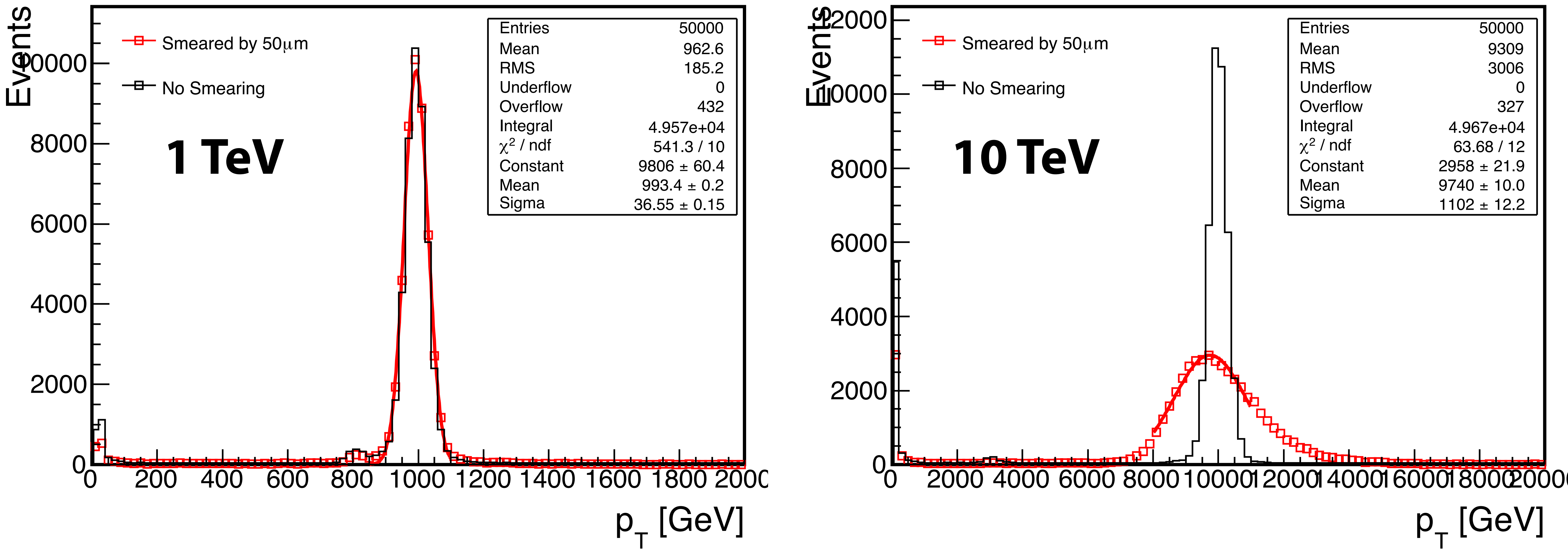
# “Realistic” Momentum Resolution




Smeared *event-by-event* (x, y) hit positions separately by adding a shift of Gauss(0, **100μm**) per layer

- No significant effect on $p_T$ resolution at $p_T^{\mu}$ <100 GeV
- $p_T$ resolution : ~3.4(**2.9**)% → ~4.2(**20.1**)% at $p_T^{\mu}$ = 1(10) TeV

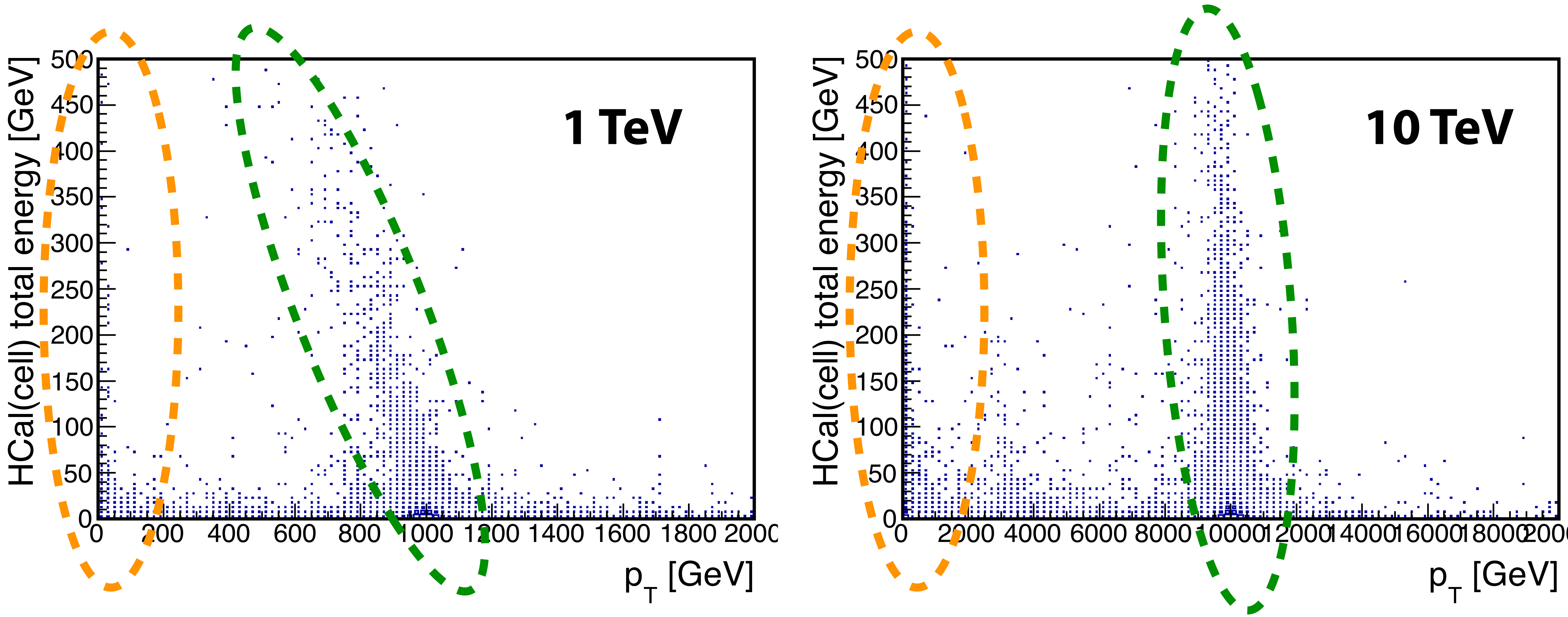
# “Realistic” Momentum Resolution




Smeared *event-by-event* (x, y) hit positions separately by adding a shift of Gauss(0, **50μm**) per layer

- No significant effect on $p_T$ resolution at $p_T^{\mu}$ <100 GeV
- $p_T$ resolution : ~3.4(**2.9**)% → ~3.7(**11.3**)% at $p_T^{\mu}$ = 1(10) TeV

# Muon Momentum vs Calorimeter Energy Deposit



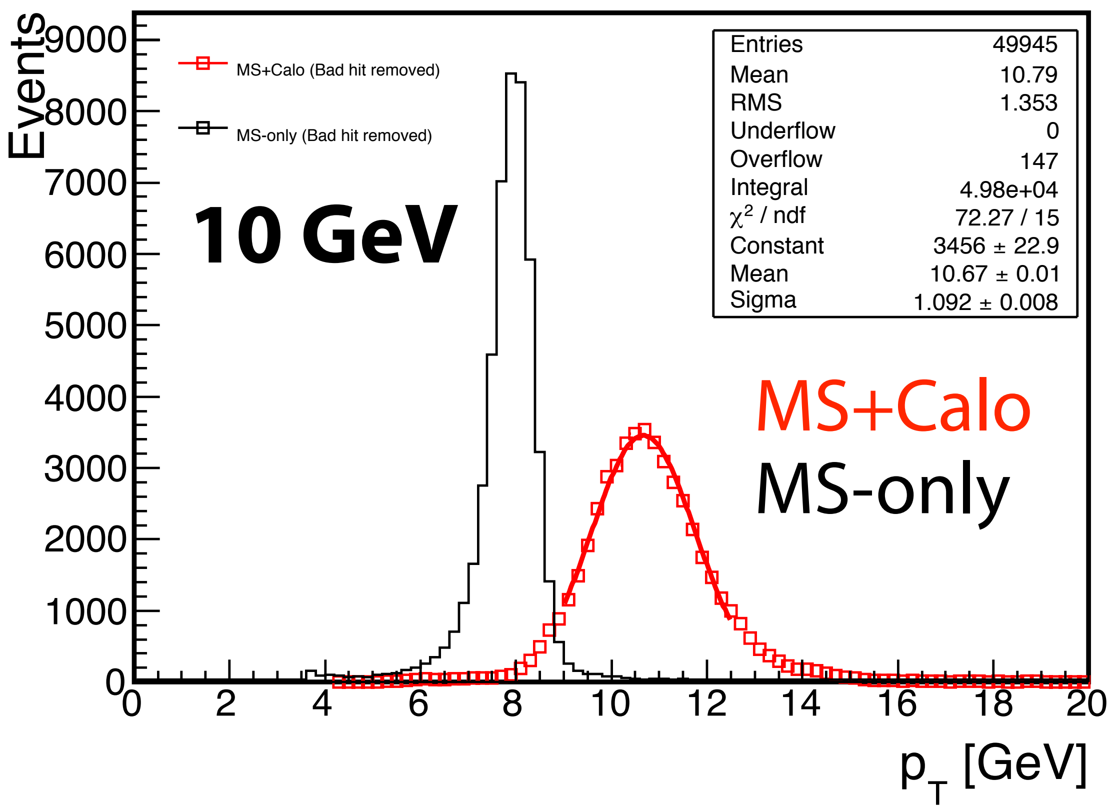

Low $p_T$ events have no strong correlation with calorimeter energy deposit

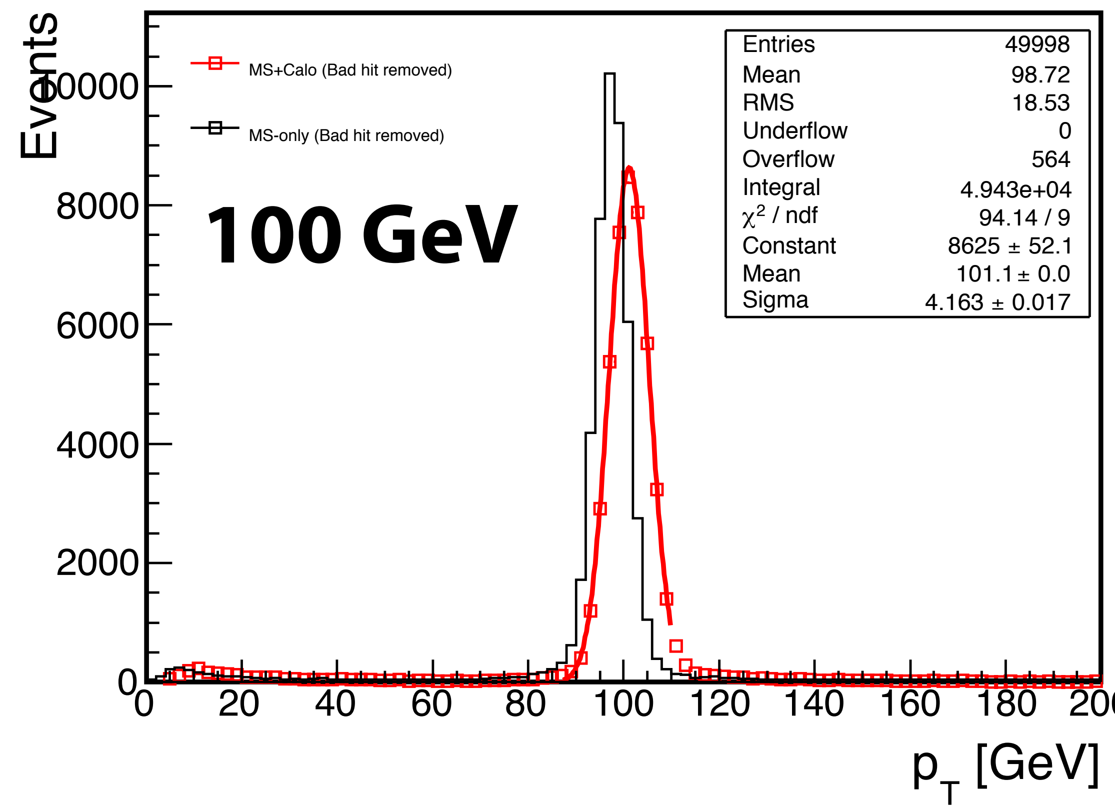
Fraction of lower $p_T$ events around the peak is correlated with calorimeter energy deposit

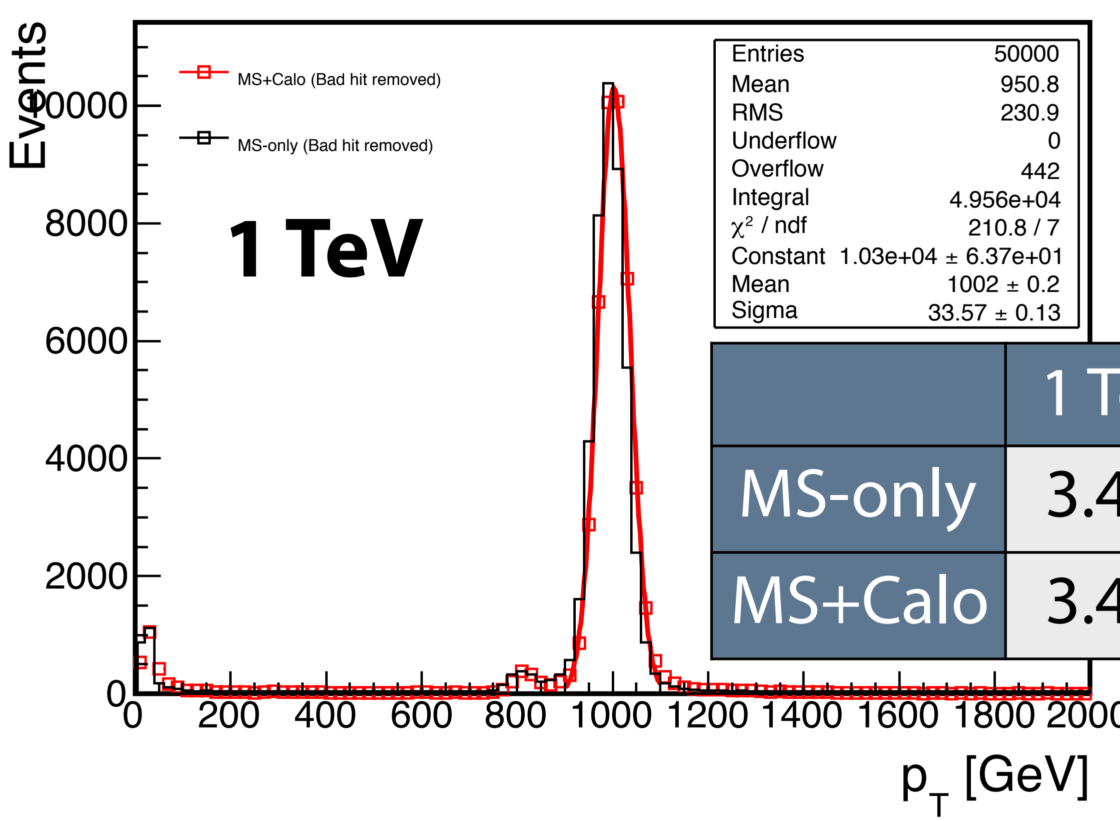
➔ Strategy to reconstruct full muon energy needed

# “Combined” Momentum Resolution

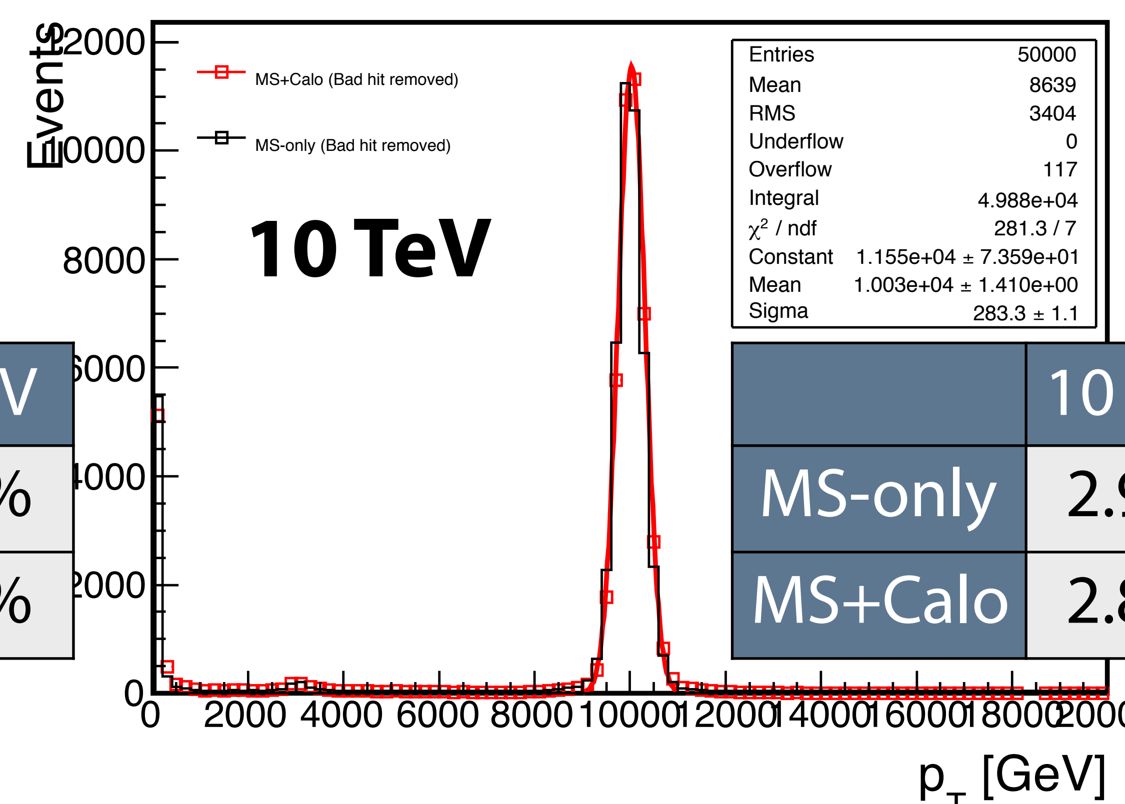
(Naive) combined MS+Calo momentum $= p_T^{reco}(\mu) + E_{cell}(ECal+HCal)$



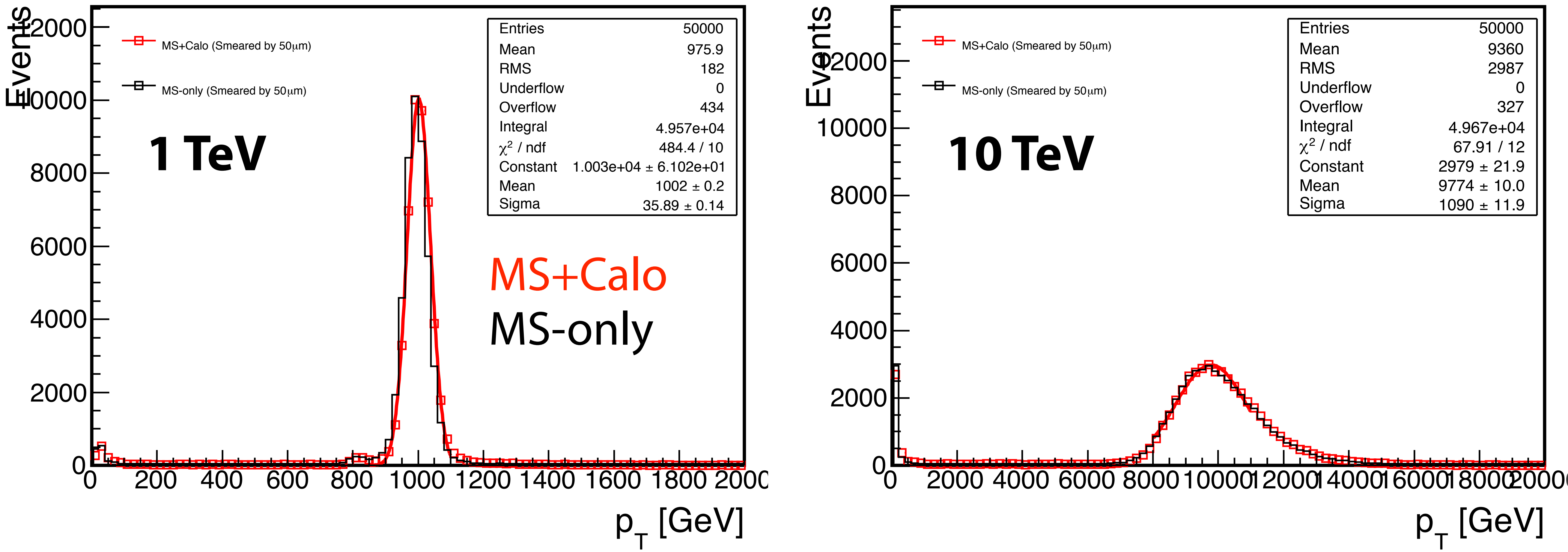

| | 1 TeV |
|---|---|
| MS-only | 3.4% |
| MS+Calo | 3.4% |




| | 10 TeV |
|---|---|
| MS-only | 2.9% |
| MS+Calo | 2.8% |

# “Realistic Combined” Momentum Resolution

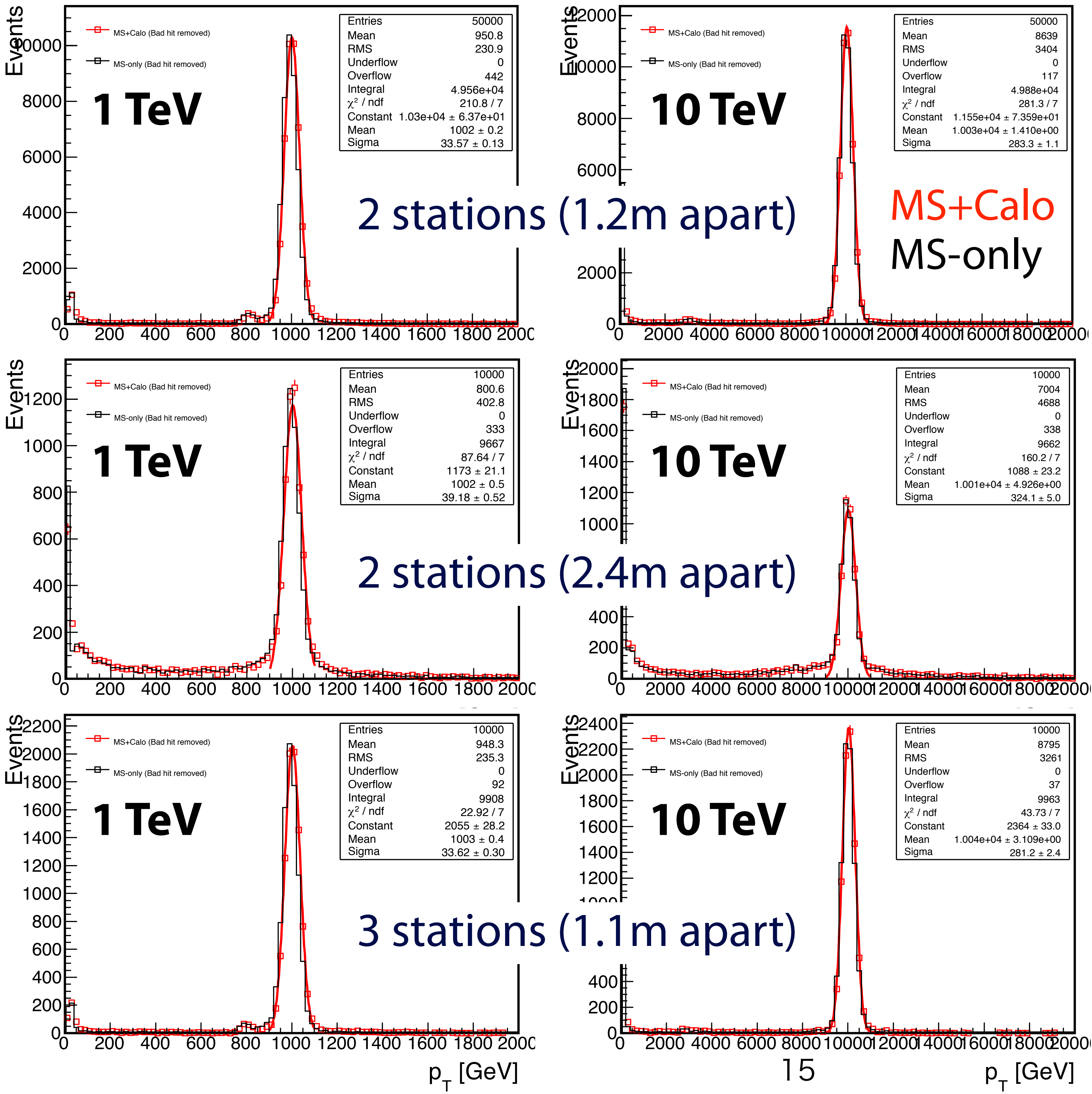
(Naive) combined MS+Calo momentum = $p_T^{reco}(\mu) + E_{cell}(ECal+HCal)$




Smeared *event-by-event* (x, y) hit positions separately by adding a shift of Gauss(0, **50μm**) per layer

- $p_T$ resolution : ~3.7(**11.3**)% → ~3.6(**11.2**)% at $p_T^{\mu}$ = 1(10) TeV for MS-only → MS+Calo

# Different Muon Detector Configurations

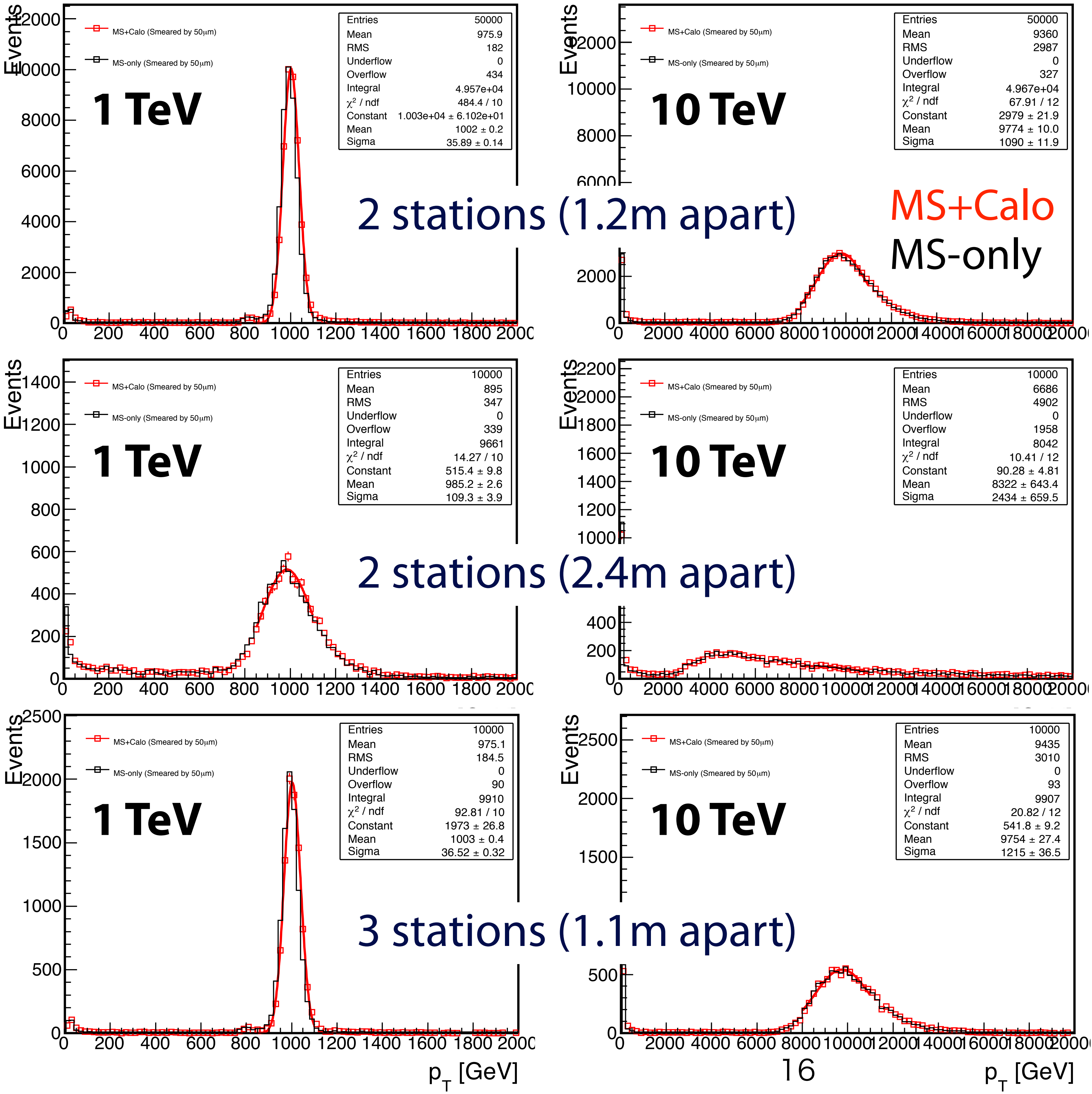



Combined reconstructed muon momentum

| | 1 TeV | 10 TeV |
|---|---|---|
| 2 stations 1.2m | 3.4% | 2.8% |
| 2 stations 2.4m | 3.9% | 3.2% |
| 3 stations 1.1m | 3.4% | 2.8% |

No large difference…

# Different Muon Detector Configurations




Combined reconstructed muon momentum

Smeared *event-by-event* (x, y) hit positions separately by adding a shift of Gauss(0, **50μm**) per layer

| | 1 TeV | 10 TeV |
|---|---|---|
| 2 stations 1.2m | 3.6% | 11% |
| 2 stations 2.4m | 11% | 29% |
| 3 stations 1.1m | 3.6% | 12% |

Significantly worse resolution for 2 stations (2.4m apart)

# Next Steps

## Baseline trigger and muon reconstruction

- Muon reconstruction

  **1) standalone** (close to baseline?)

  2) **combined (ID+Calo+Muon)**

  → ID+muon tracking + calorimeter energy reconstruction

# Next Steps

## Baseline trigger and muon reconstruction

- Muon reconstruction
  - **1) standalone** (close to baseline?)
  - 2) **combined (ID+Calo+Muon)**
    - → ID+muon tracking + calorimeter energy reconstruction
- Trigger
  - 1) timing resolution (bunch-crossing identification)
  - 2) fast and coarse tracking capability
  - → **Considering RPC-like gas chamber as baseline for 25 ns**
    A new idea/technique likely needed for 5 ns (beyond CDR?)

# Next Steps

## Baseline trigger and muon reconstruction

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  - → **Considering RPC-like gas chamber as baseline for 25 ns**
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## Technology

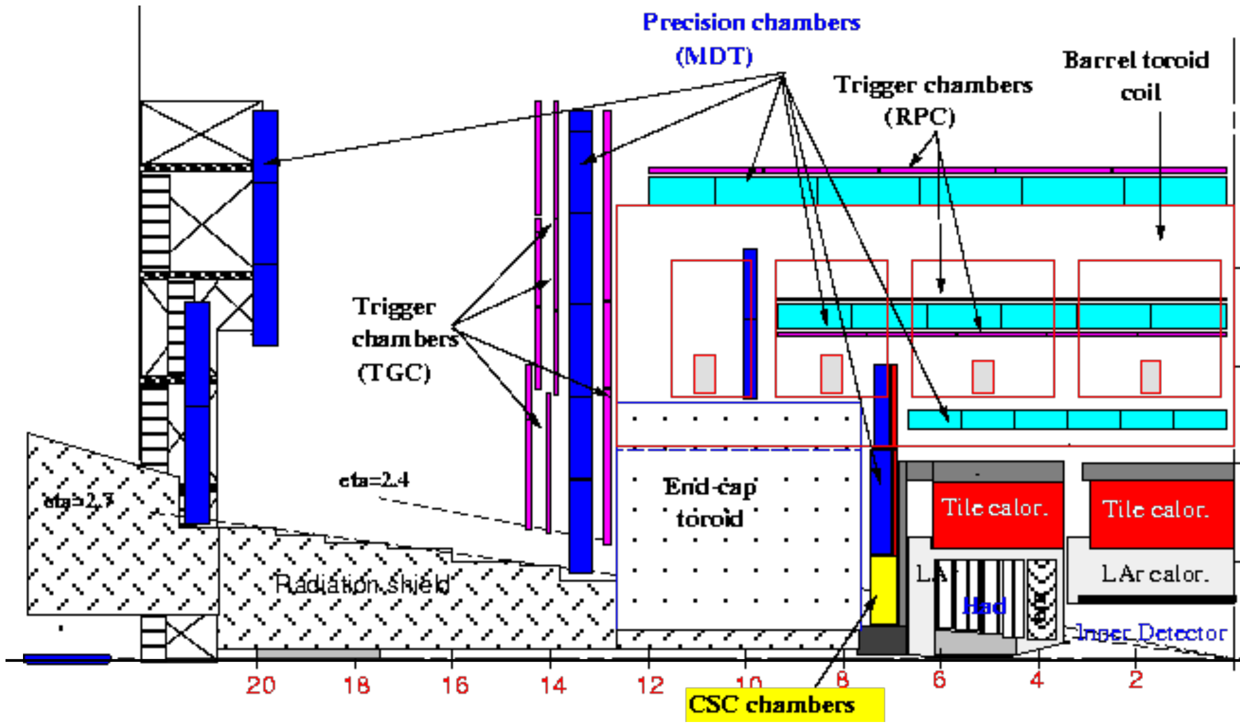
- Material (gas, …), Baseline readout (granularity)

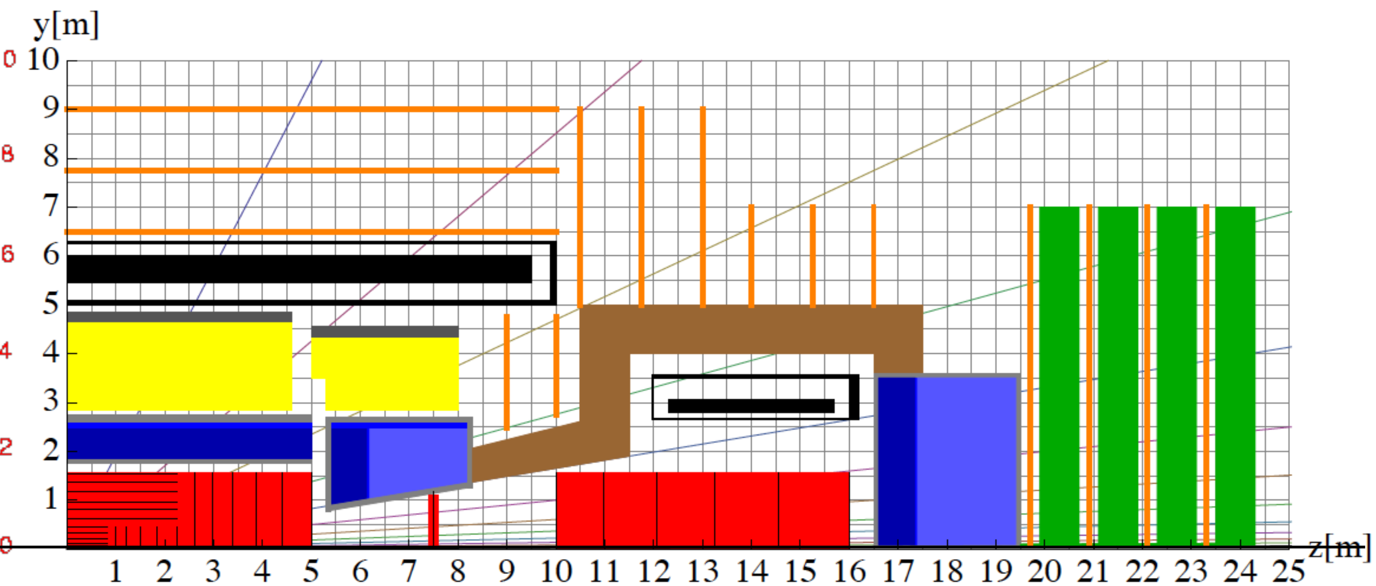
## Baseline design

- #layers, layer distance, sub-layer structure, …
- Forward region
  - 1) time resolution, high-rate capability
  - 2) decreasing readout pitch with increasing $\eta$ for rate reduction?
  - 3) tolerance for high radiation level

# Backup

# Muon Detector Geometry




| ATLAS |
|---|

- $R_{inner\ solenoid}$ = 1.23m
- B = 2T

| FCChh |
|---|

- $R_{inner\ solenoid}$ = 5.45m
- B = 4T

⇒ BR(ATLAS)/BR(FCChh) = 1.23*2 / (5.45*4) = 0.11

$p_T = 0.15BR/\cos(\pi/2-\phi)$

⇒ 10 TeV at FCChh ~ 1.1 TeV at ATLAS (for same angle resolution)

# Single muon simulation

- Single $\mu^-$ with a fixed energy and angle ($\eta$=0, $\phi$=0)
- Beam pile, ID (TkLayout option 3), ECal, HCal, Solenoid + Muon detector
- 4 Tesla field within R = 6 m

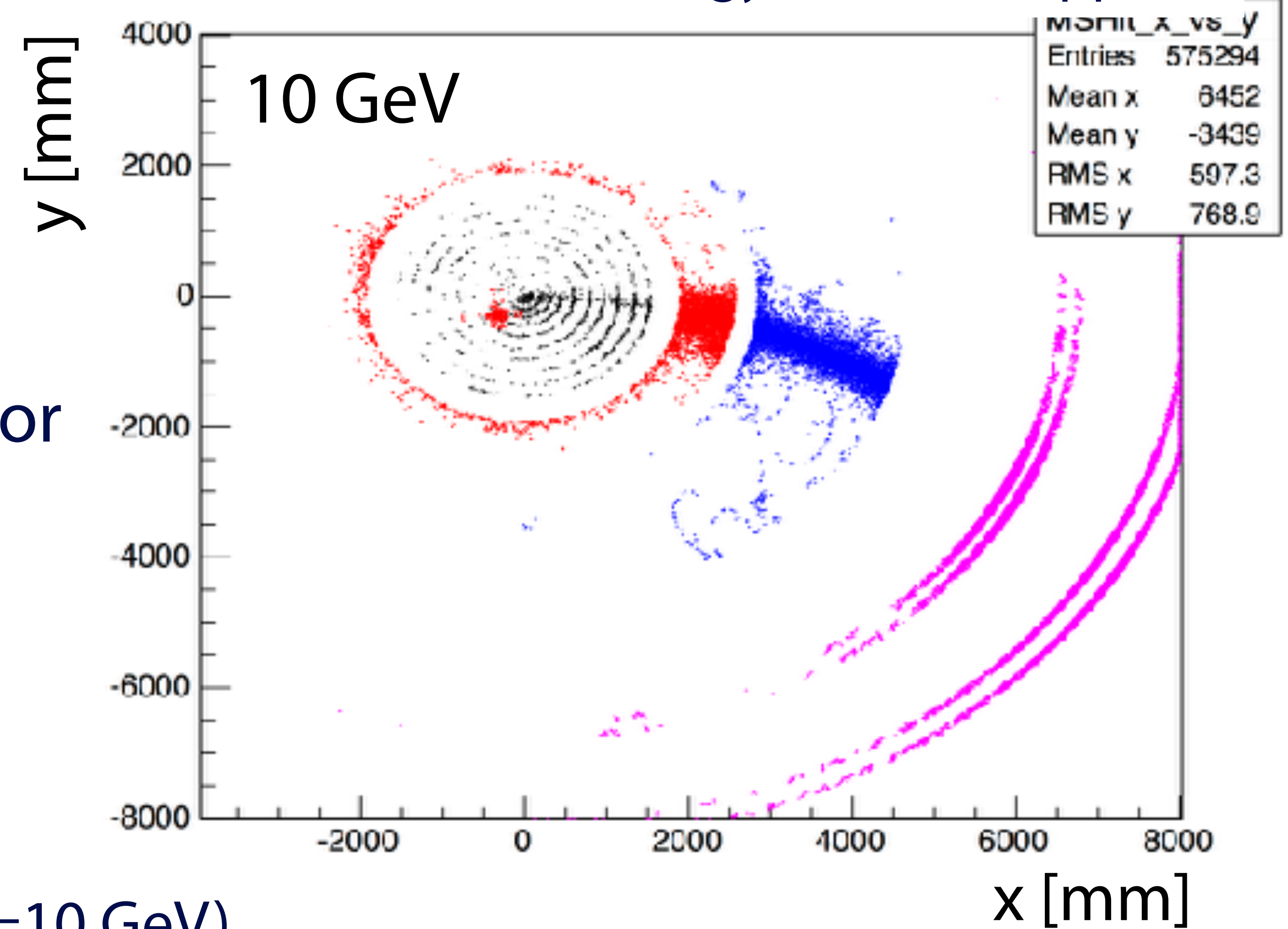
# Multiple scattering

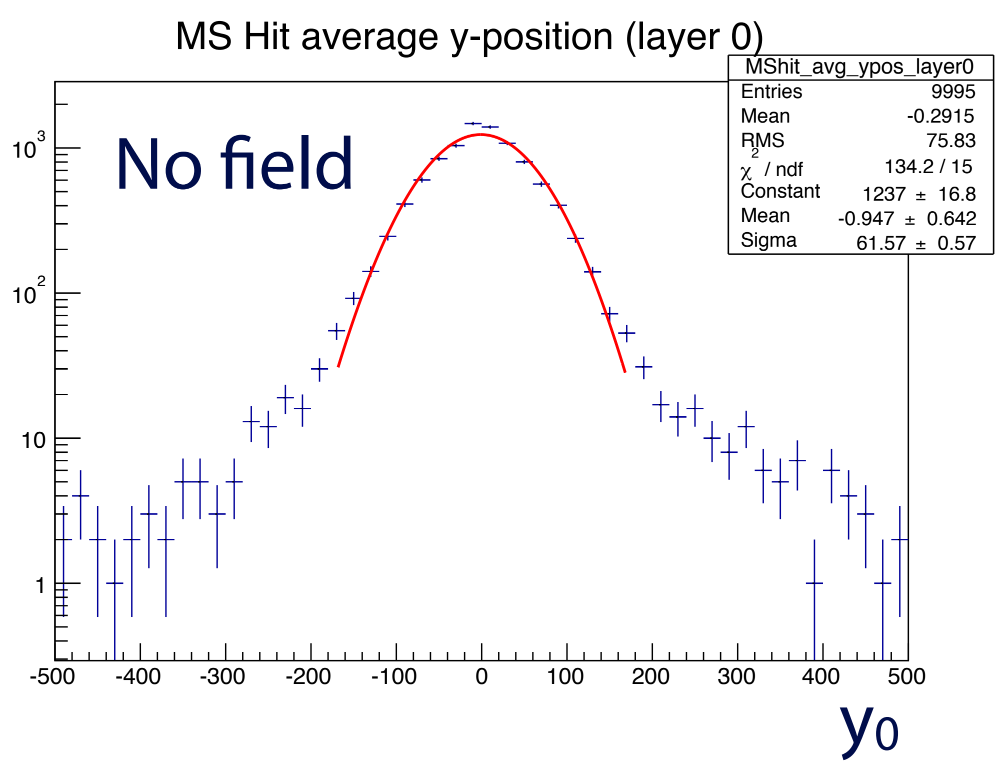
- $x \sim 130 X_0$ at $\eta$=0

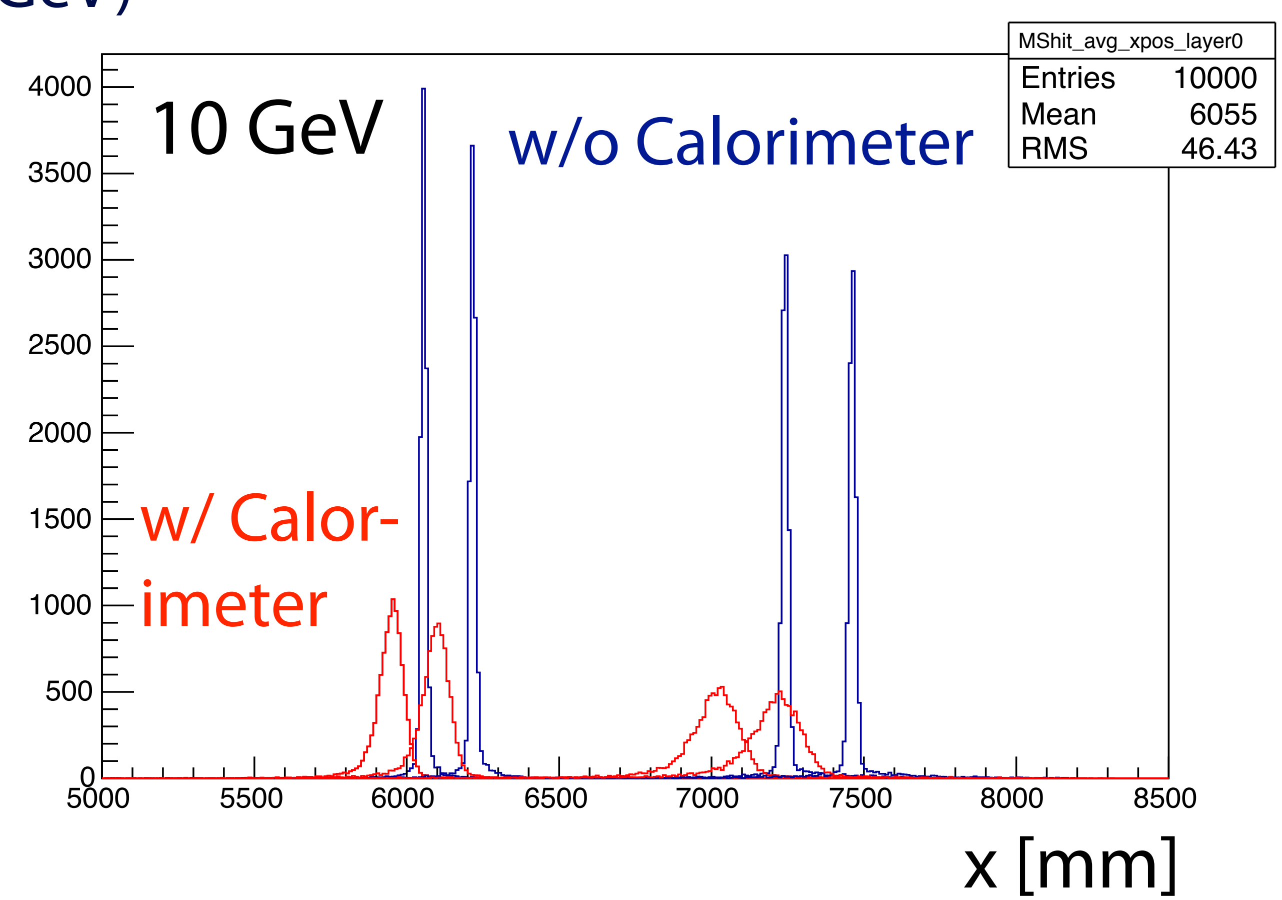
$\Rightarrow \Delta\theta \simeq 0.0136/p_T \sqrt{x/X_0} = 15$ mad ($p_T$ =10 GeV)

$\Delta y \simeq 100$mm at 1st layer

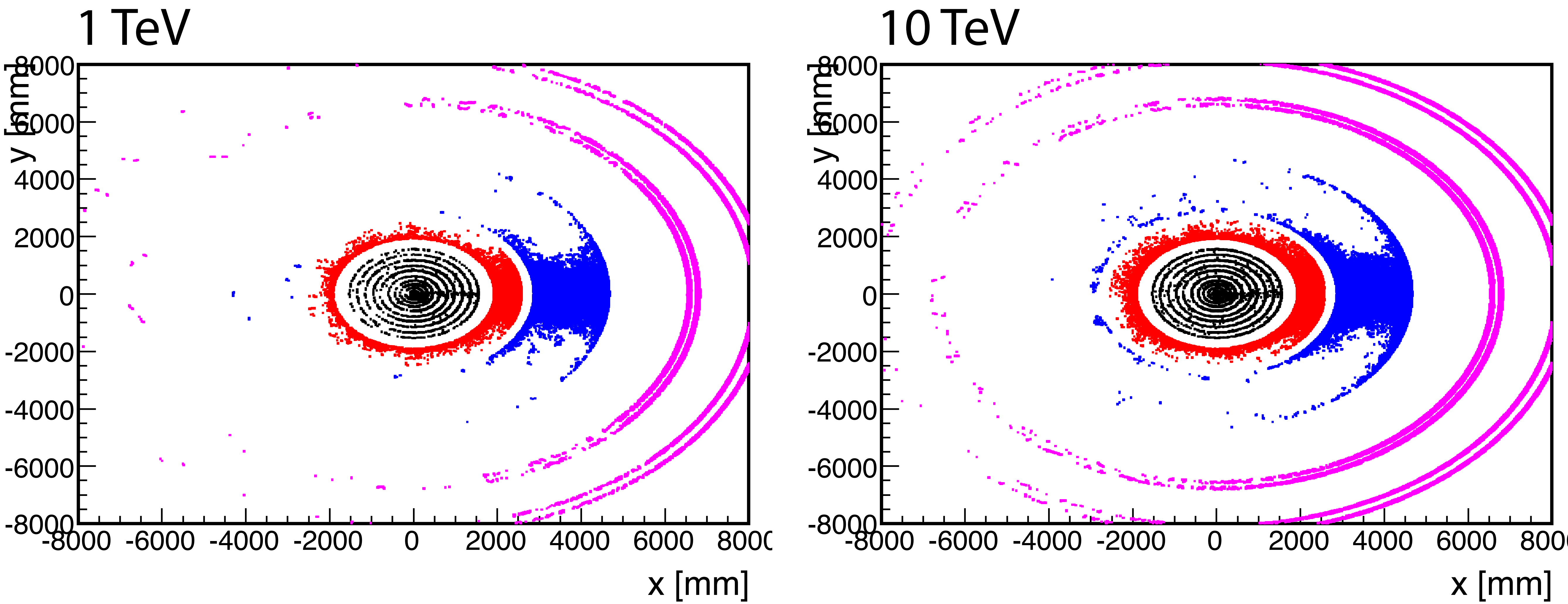
All hits shown (no energy threshold applied)



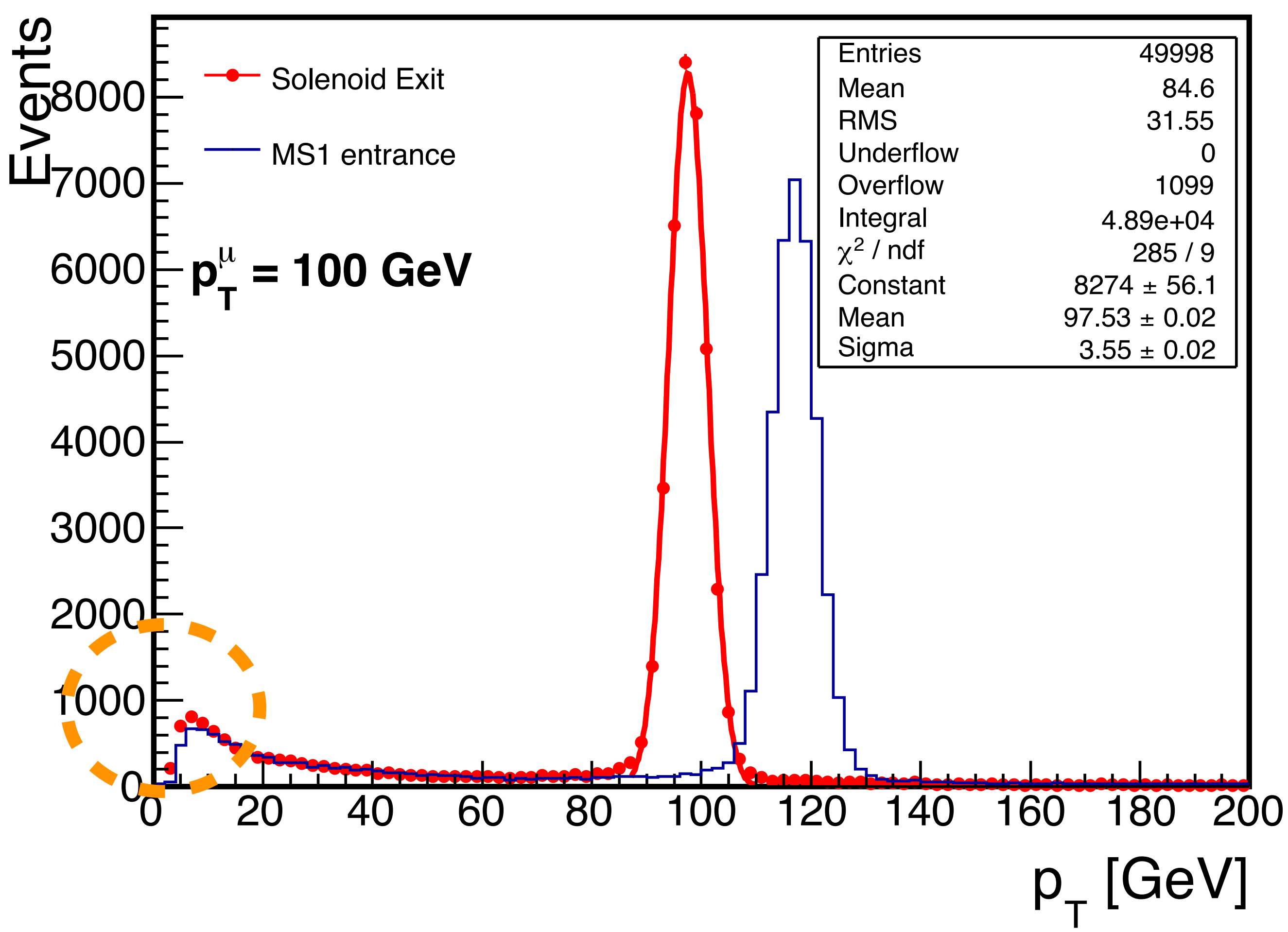



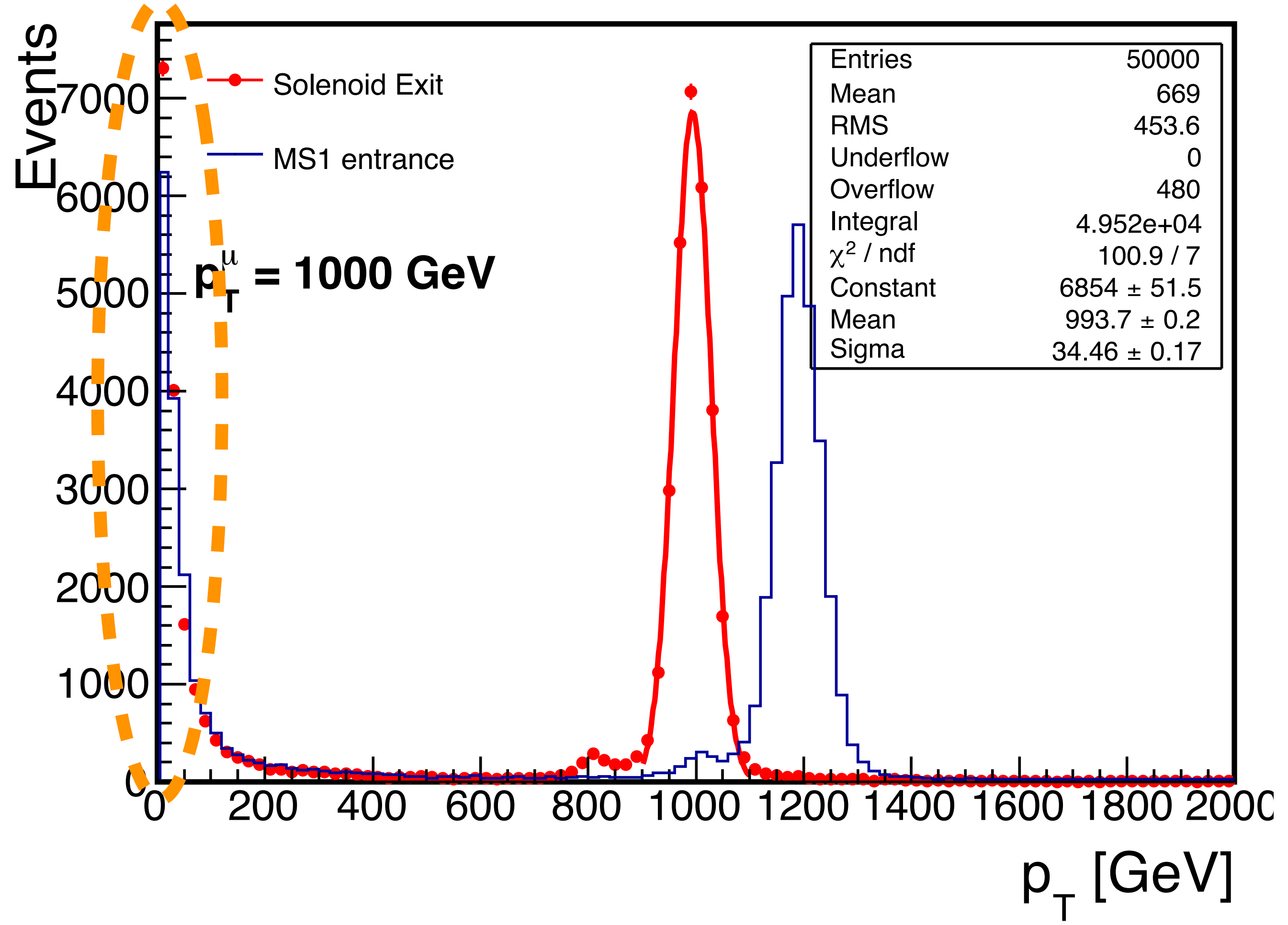



# All hits shown (no energy threshold applied)




Many hits present far away from the impact point




# "Ideal" momentum resolution

- Angle determination very sensitive to fit quality at high $p_T$
  ➔ Often leads to unphysical result
- Sensible result ($p_T^{reco}/p_T^{true}>0.8$) for ~64(35)% of the time at $p_T^\mu$ = 1(10) TeV
  ➔ To be understood
- ~3% resolution at 10 TeV ≈ multiple scattering limit