# Benchmark Channel Characterization
&
# Tracker Geometries for FCC-hh


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# Overview & Plans

- In order to define the general properties of a future FCC-hh detector we need to make a parallel progress in analyses of physics benchmark channels together with the preparation of various software tools for detector & physics studies …
- **Current status & summary since the last meeting on April 29th:**
  - **M.Mangano** presented an overview of physics benchmark channels for FCC-hh detector, internally known as a "long physics list":
    - Completion of physics studies in Higgs sector (Higgs properties & dynamics) wrt. HL-LHC & FCC-ee
    - Exploration of the highest energy objects kinematically accessible @ 100 TeV
    - Other physics: e.g. signals at the O(1-10TeV) scale, coverage of possible gaps left by HL-LHC (e.g. signals from compressed spectra, or with displaced tracks), etc.
  - The plan is to "shorten" the list to most important benchmarks and characterize them by fall 2015 (M. Mangano, H. Gray, F. Moortgat) → discussion today

# Overview & Plans

- **H.Gray & F.Moortgat** presented the DELPHES card proposal for generic hadron detector...
  - To define these parameters realistically, necessary input from sub-detector physics experts (& dedicated software) is needed. Plus, it's important to realize that the physics output will form back the requirements on the detector design …
- Several detector designs presented by **W.Riegler** the last time:
  - Twin Solenoid + Dipole, $BL^2$ scaled (CMS-like approach)
  - Toroid + Dipole, $BL^2$ scaled (ATLAS-like approach)
  - …
  - For current status see **W.Riegler's presentation**
  - Possible tracker studies & determination of $p/p_T$ resolution will be presented **here**
- **The plan** is to provide the parametric simulation chain: generator (Madgraph, Pythia, … → Delphes) within the FCC framework soon → see ideas of **C.Helsens** & presentation of **B.Hegner**

  **+** discuss the DELPHES input card today → **H.Gray & F.Moortgat's presentation**

# Overview & Plans

- **Final plan:** **perform the physics results for the benchmark channels using the DELPHES description by end of 2015**

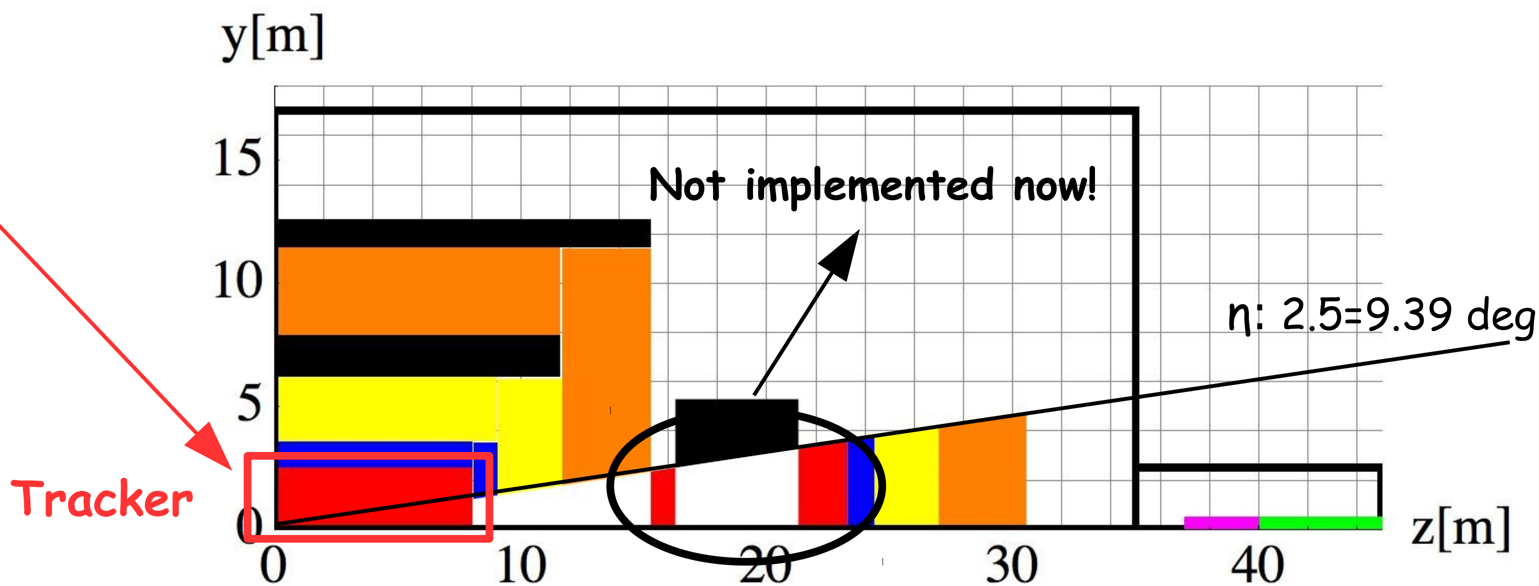
# How to start with detector design studies?

- **In general several ways how to study & optimize detector:**
  - Full simulation → **FCC Geant4 simulation** (A.Salzburger, J.Hrdinka, A.Zaborowska)
  - "Analytical" simulation with some mathematical simplifications → **CMS tkLayout**
  - Parametric simulation → **DELPHES, ...**
- **Why CMS tkLayout? Key features:**
  - **Pros:**
    - Analytical & parametric simulations help us quickly define detector requirements → in parallel, naturally comes the full simulation approach + the tracker is a good starting point to optimize, then we can continue with ECAL, ...
    - 3D model of a tracker implemented in ROOT TGeo structure, TXT input
    - Analytical calculation of track parameters (p/pT resolution, impact parameters) for MIP-like particles in given magnetic field + covariance matrices; particle movement disentagled in R-Phi & Z plane → math. simplification (verified for CMS tracker) → VERY FAST
    - Material budget calculations, Hit maps/occupancies estimation, …

# CMS tkLayout for FCC-hh?

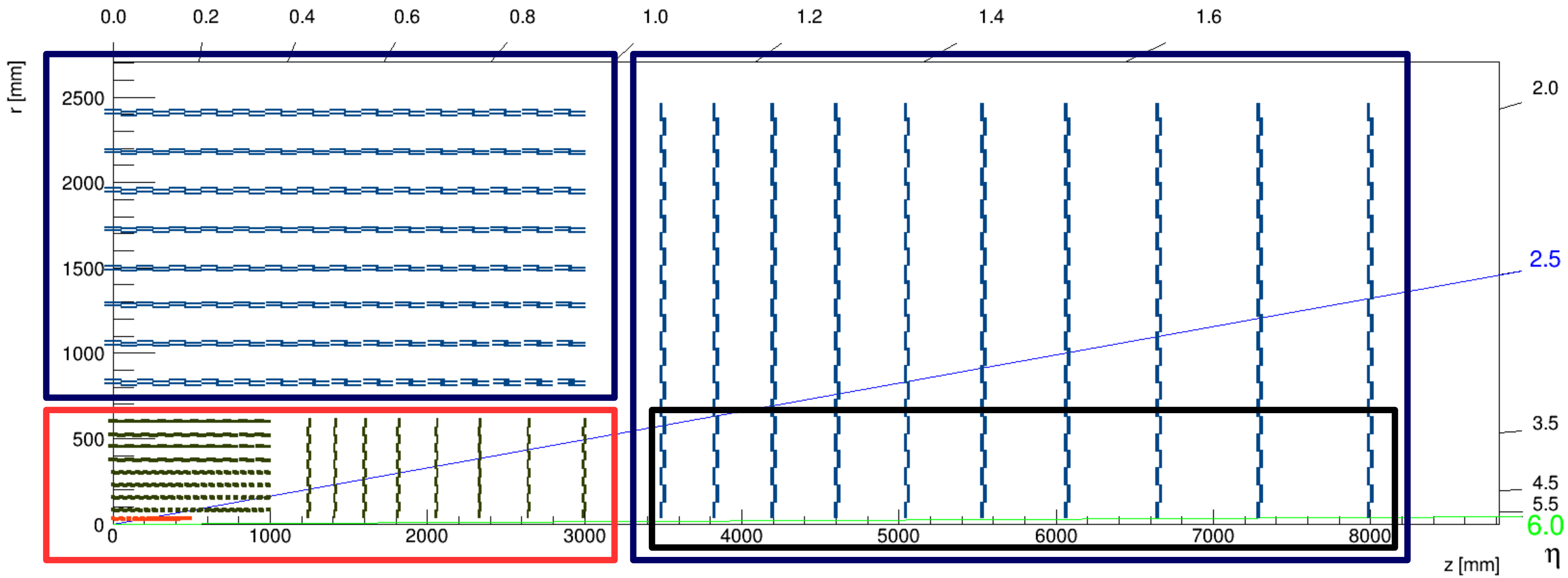
  - Output in XML files & mini-web html structure → FCC-hh web-based results on http://fcc-tklayout.web.cern.ch/fcc-tklayout
- **Cons:**
  - Only solenoidal field implemented → not currently possible to simulate forward region with dipole (plans to implement it → but very tricky - "broken" symmetry)

- The DELPHES needs input → as a starting geometry **CMS-like FCC-hh tracker simulated** (see Werner's talk):



# TkLayout results for "Baseline" option

- **Geometry (starting "guess"!)**
  http://fcc-tklayout.web.cern.ch/fcc-tklayout/FCChh_Option1/index.html:

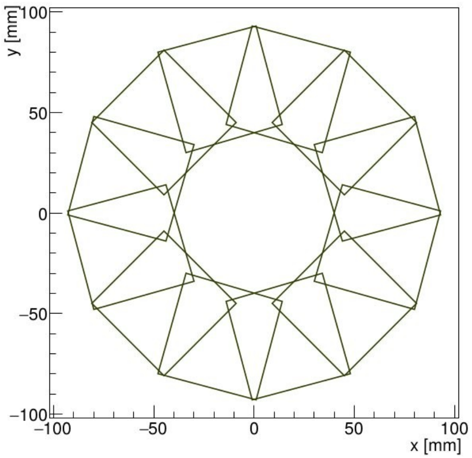



Pixel detectors: 25x25 um2, 100um thick Si sensors

**Strip detectors**: 50x50 um2, 200um thick Si sensors (**black area** → not optimal → needs to be changed for pixelated sensors)

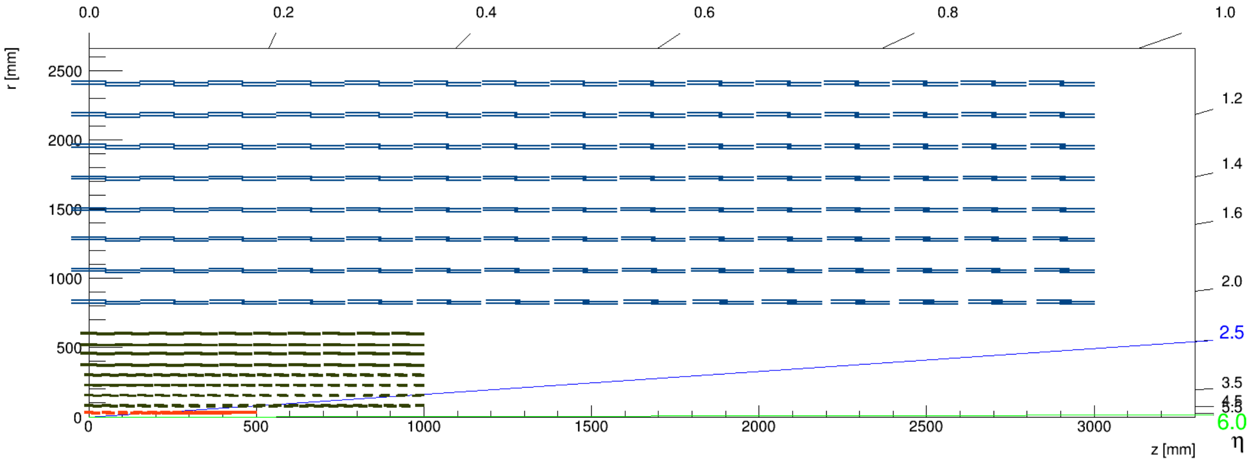
# TkLayout results for "Baseline" option

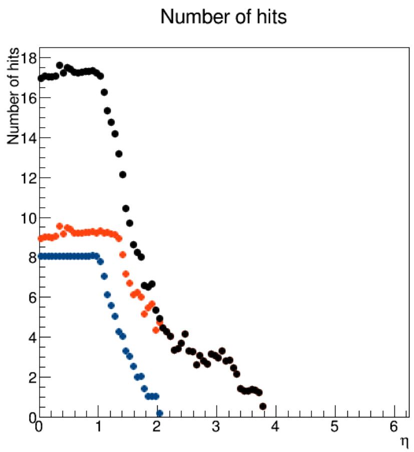
- **Geometry:**
  http://fcc-tklayout.web.cern.ch/fcc-tklayout/FCChh_Option1/index.html:
  - 4 eta regions defined:
    - BRL: 0.0 – 1.5
    - ENDCAP: 1.5 – 2.5
    - FWD: 2.5 – 4.0
    - VFWD ("insanely" forward): 4.0 – 6.0
  - **Remark**: Disc arrangement using "squared" sensors problematic @ low radii → needs to be rearranged → still in progress:
    - Squared-like or hexagonal-like structure?

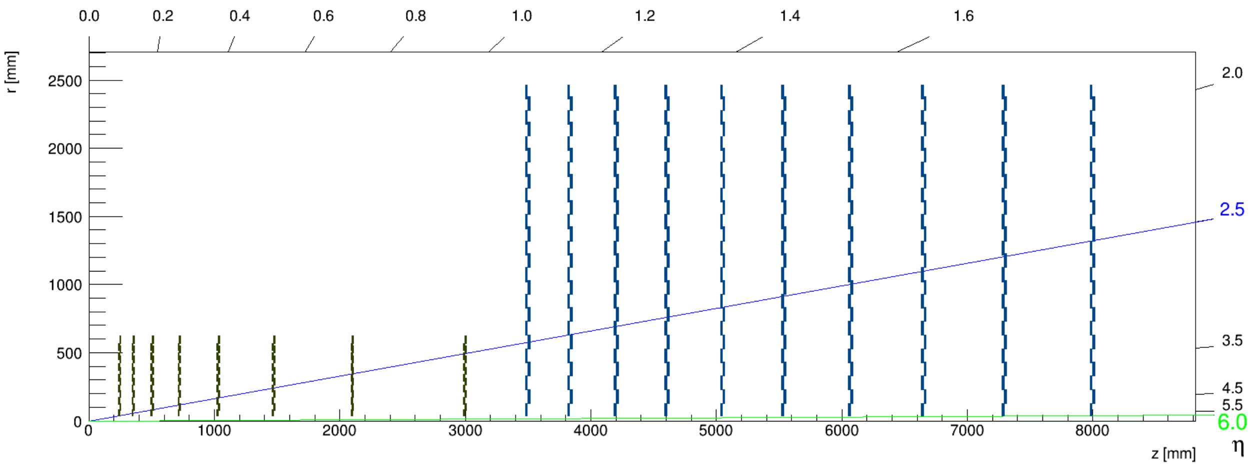


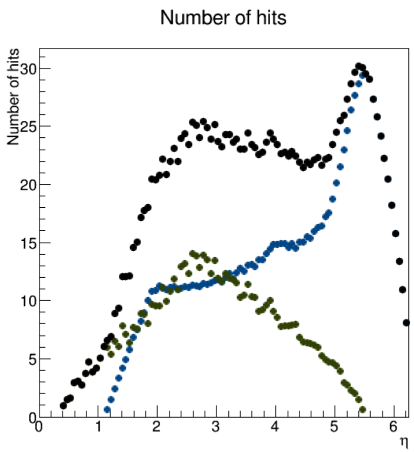
# TkLayout results for "Baseline" option

- Geometry: Barrel versus end-cap → R or Z pos. optimized to cover eta



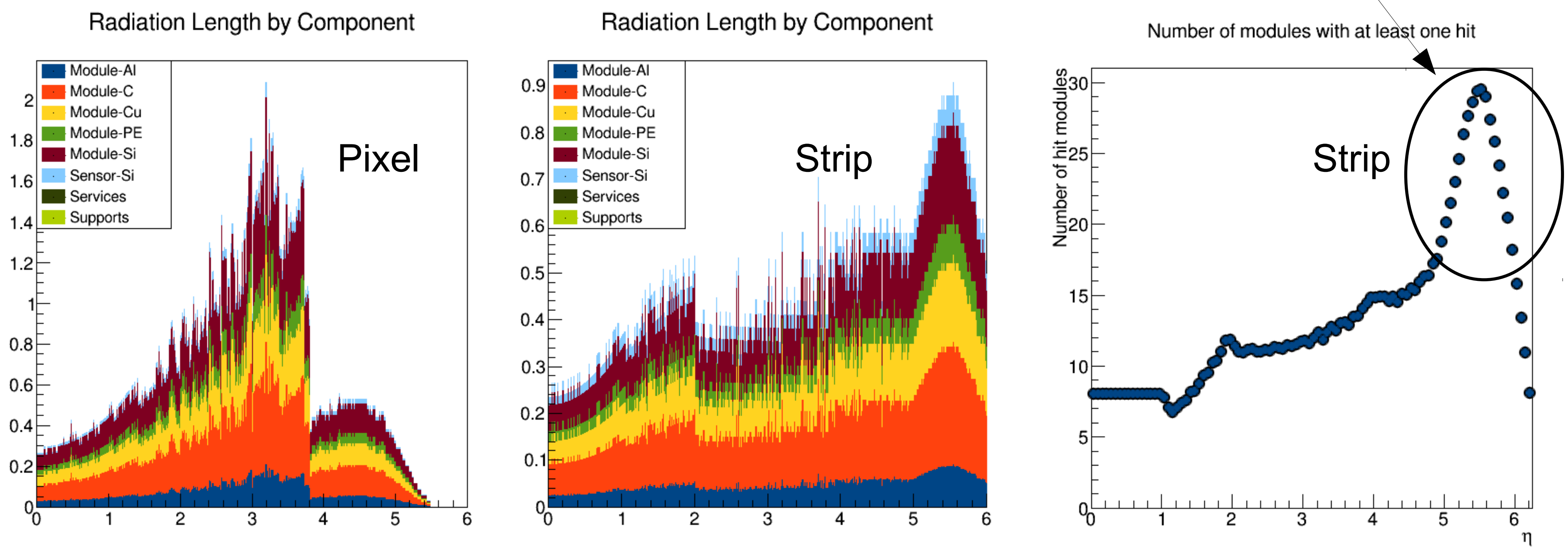



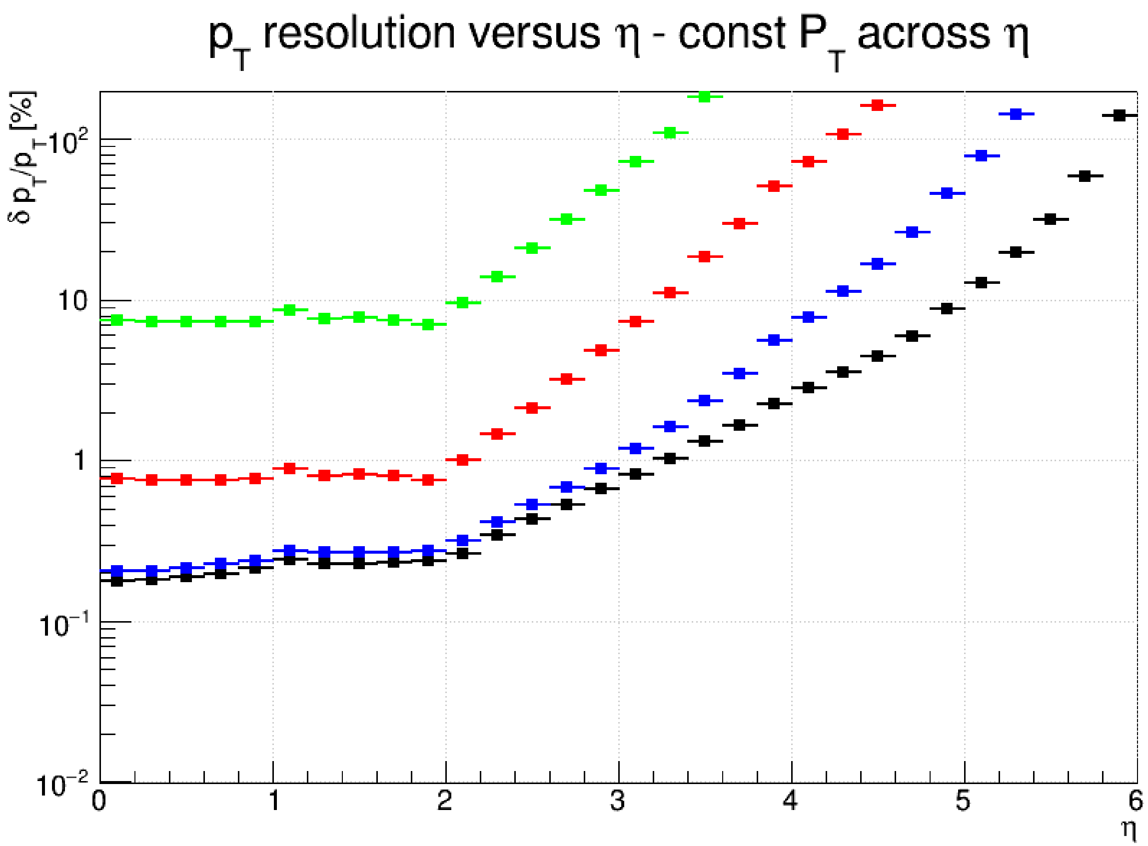
# TkLayout results for "Baseline" option

- **Material budget ($t_{module}$=0.43cm, 20% Si, 42% C, 2% Cu, 6% Al, 30% Plastic):**
  http://fcc-tklayout.web.cern.ch/fcc-tklayout/FCChh_Option1/materialSTD.html
  http://fcc-tklayout.web.cern.ch/fcc-tklayout/FCChh_Option1/materialPXD.html
  - Currently only detector modules implemented, no services, no support structures!
  - Not ideal disc arrangement now @ low radii → huge increase in number of hits



# TkLayout $p_T$ resolution for given $p_T$

- **Track resolution in 6T magnetic field (no dipole in FWD region):** http://fcc-tklayout.web.cern.ch/fcc-tklayout/FCChh_Option1/errorsTRK.html
  - **$p_T$ resolution versus eta for $p_T$ = 10GeV, 100GeV, 1TeV, 10TeV**




**Compared to CMS:**

- 4 → 6T (factor of 1.5)
- ~1m → ~2.5m

→ factor of ~ 3.8 improvement

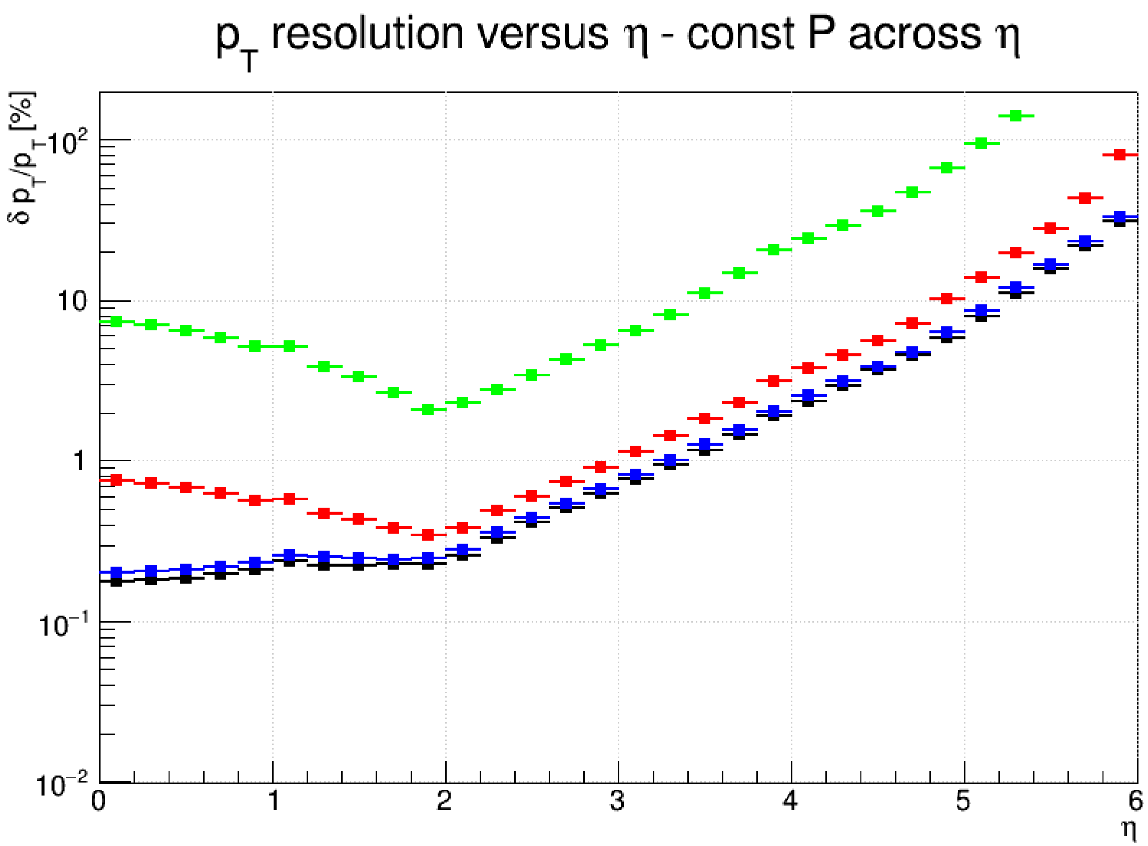
**Resolution for low $p_T$:**

- $X/X_0$ = 3% per layer
- MS dominated:

$$\frac{\Delta p_t}{p_t} \approx \frac{0.0542}{\beta\, B[T]\, L[m]} \sqrt{\frac{X_{tot}}{X_0}}$$

# TkLayout $p_T$ resolution for given p

- **Track resolution in 6T magnetic field (no dipole in FWD region):** http://fcc-tklayout.web.cern.ch/fcc-tklayout/FCChh_Option1/errorsTRK.html
  - **$p_T$ resolution versus eta for p = 10GeV, 100GeV, 1TeV, 10TeV**



# TkLayout tracker studies: Summary & Outlook

- **Summary:**
  - TkLayout adapted for FCC-hh detector studies (fcc branch)
  - First option ("guess") based on CMS general design implemented
  - Calculated track resolution, but … the design is still far from reality!
  - All plots & numbers are available at: http://fcc-tklayout.web.cern.ch/fcc-tklayout

    Q1: Shall we keep the web page public or private?

    Q2: Shall we summarize geometry options here?

- **Outlook:**
  - Implement **simplified** geometry, which can be realistically used for all benchmark physics studies (just necessary technical details will be taken into account):
    - **Baseline:** CMS-like detector structure with more realistic services & support structure → will study its influence on overall "low" pT physics

      Q1: Do we agree?

      Comment: Let me remind you that the resolution depends on MB, e.g. for 1 GeV particles ...

# TkLayout tracker studies: Summary & Outlook

- Implement **other possible design options** & study their general impact on physics:
  - Equidistant layers/discs versus double layers/discs (sharing common infra-structure)
  - Tilted geometry layout versus standard disc structure

  Q1: Do you have in mind other important options?

  Q2: Is it acceptable to start with CMS upgrade phase 2 modules? In my opinion, it's the most realistic material estimate of detector modules we have now.

  Q3: Produce automatic output to DELPHES in a text format?

- Study occupancy in background & full pile-up.

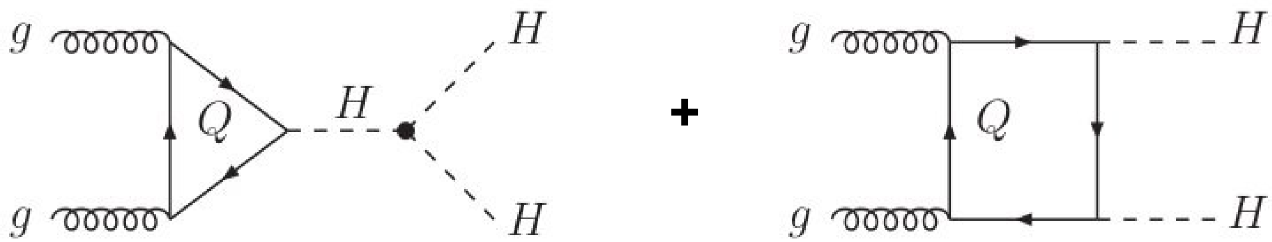
  Q: Are there some estimates how shall we proceed with the background?

- Implement a dipole field in the FWD region to see the interplay between BRL & FWD region in terms of resolution

  Comment: Quite tricky procedure, being discussed with authors of tkLayout now ...

# Physics benchmark: *gg* → HH

- **Physics benchmark channel:** **HH production through gluon-gluon fusion**




  - **Studied H (125GeV) decay channels:**
    - $H \rightarrow b\bar{b}$, $H \rightarrow \gamma\gamma$ (BR= 0.263%)
    - $H \rightarrow b\bar{b}$, $H \rightarrow W^+W^-$ ($W \rightarrow e, \mu$), one W off-shell (BR= 24.8%)
    - $H \rightarrow bb$, $H \rightarrow \tau^+\tau^-$ (BR= 7.29%)
    - NLO production cross section @100TeV = 1417.83 fb, see **arXiv 1212.5581v2**
  - **Strategy:**
    - Use Madgraph (C.Helsens) → Decay in Pythia (Z.Drasal) … (missing link to DELPHES → see Clement's presentation) … DELPHES

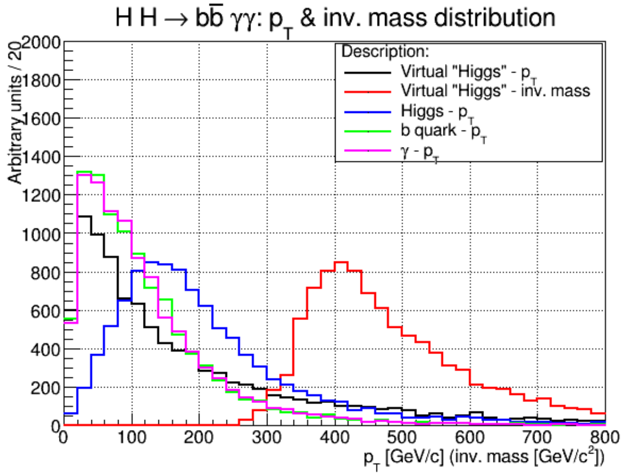
      Madgraph files @ https://test-fcc.web.cern.ch/test-FCC/LHEevents.php

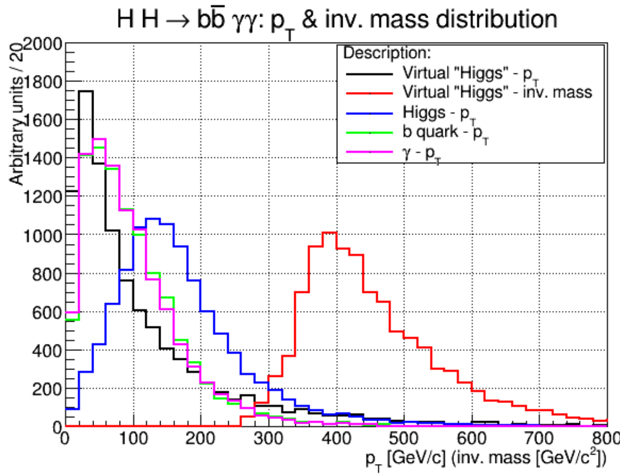
# Physics benchmark: *gg* → HH

– **Strategy contd.:**
  - Start with true information → study kinematics & invariant mass resolution versus applied $p_T$ cuts, geometric acceptance (eta coverage), E cuts, reconstructed missing $E_T$, b-tagging, $\tau$-reconstruction)
  - Continue with DELPHES and study impact of various detector effects …
  - Crosscheck results with LHC @ 13TeV versus FCC-hh @ 100 TeV

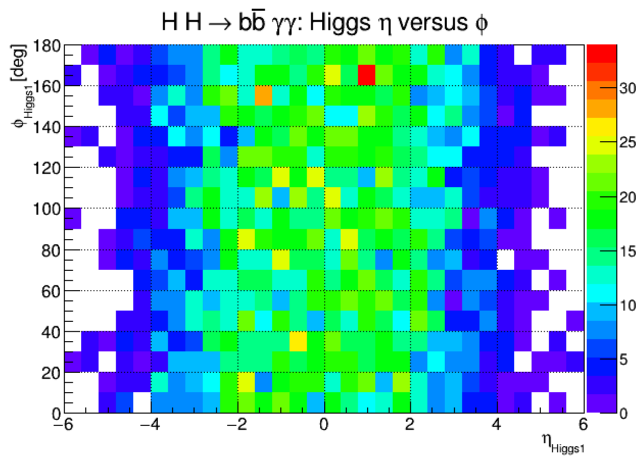
# Results for decay mode: $H \rightarrow b\bar{b}$ + $H \rightarrow \gamma\gamma$

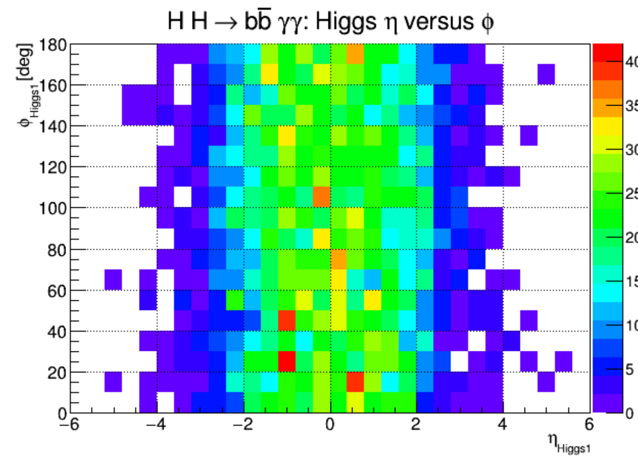
- $P_T$ spectrum & Higgs invariant mass for 100TeV versus 13TeV machine



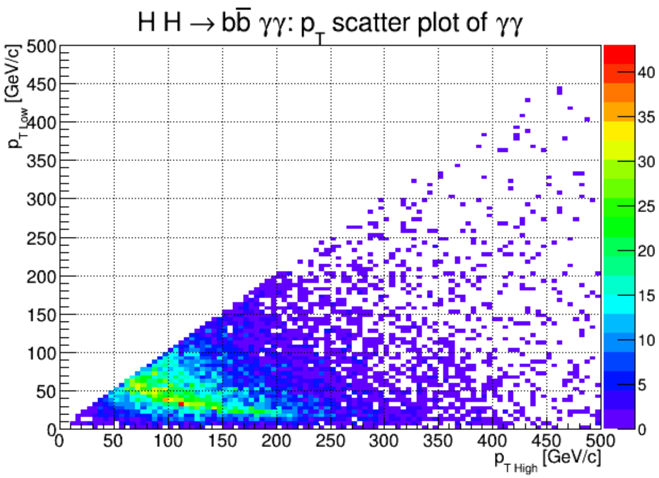

- Required geometric acceptance for Higgs particles:

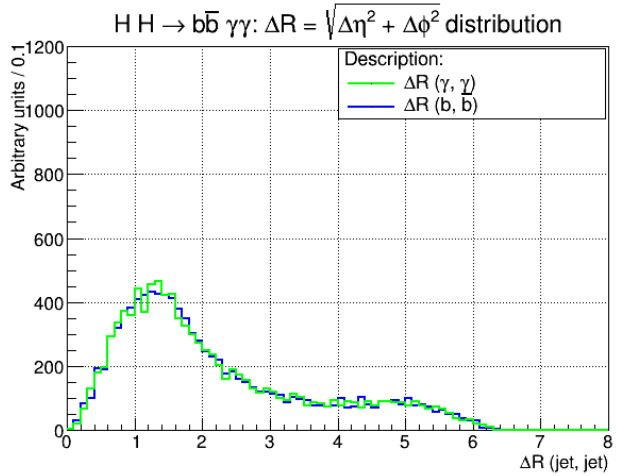


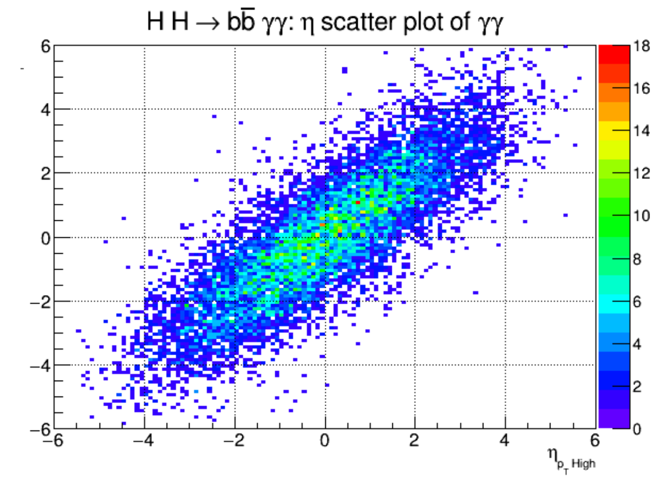



# Results for decay mode: $H \to b\bar{b}$ + $H \to \gamma\gamma$

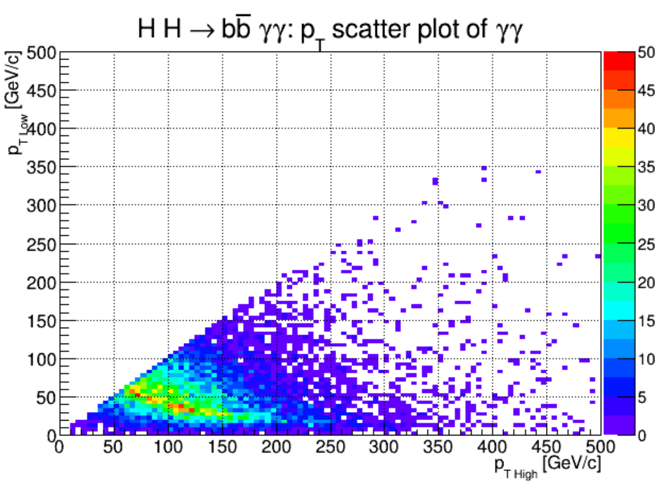
– $P_T$ spectrum, jet isolation & eta spectrum for 100 TeV machine

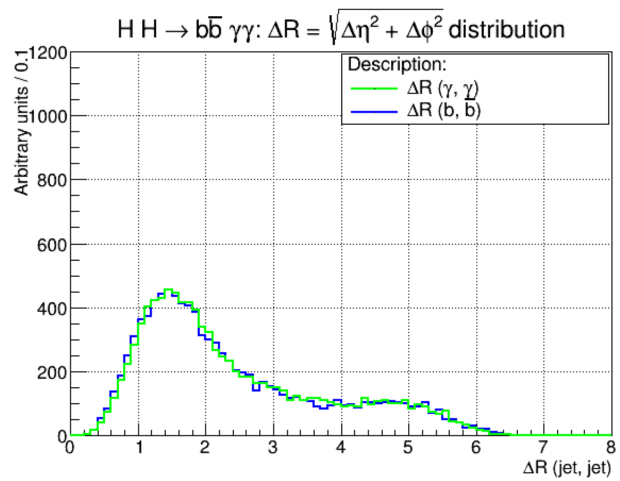


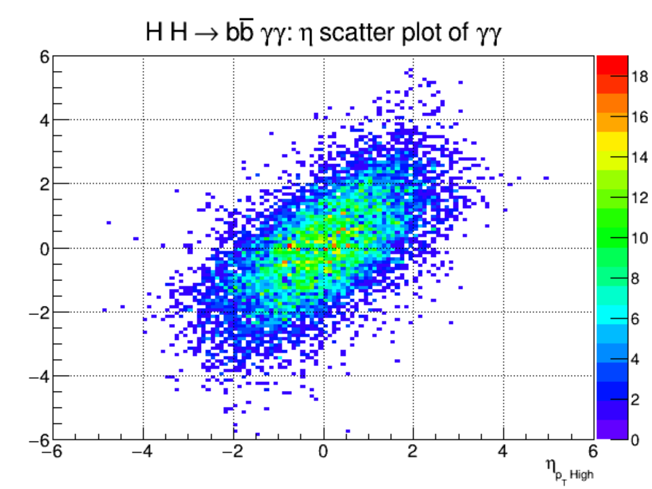




– **For 13 TeV machine:**

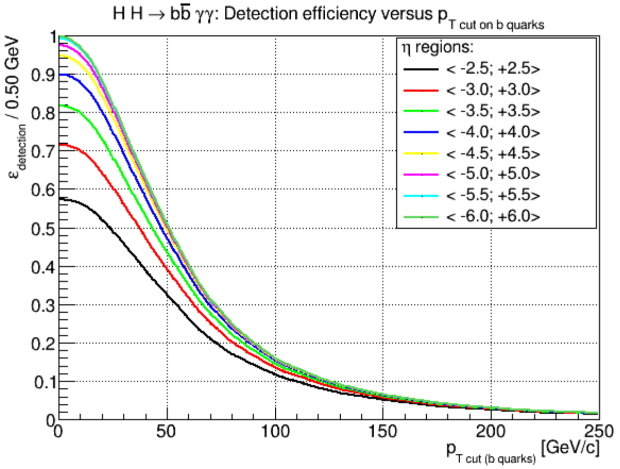


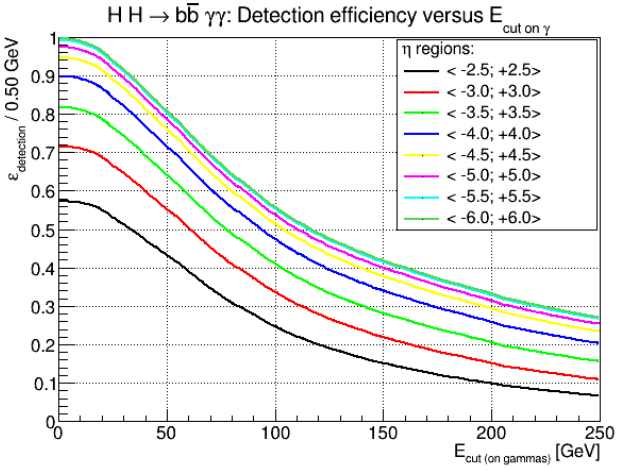



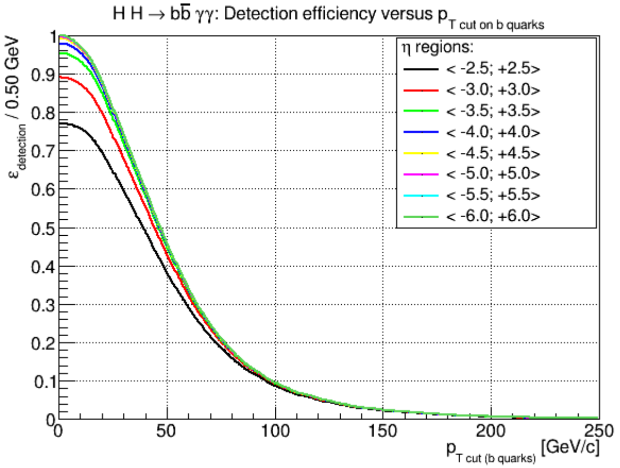
# Results for decay mode: $H \to b\bar{b}$ + $H \to \gamma\gamma$

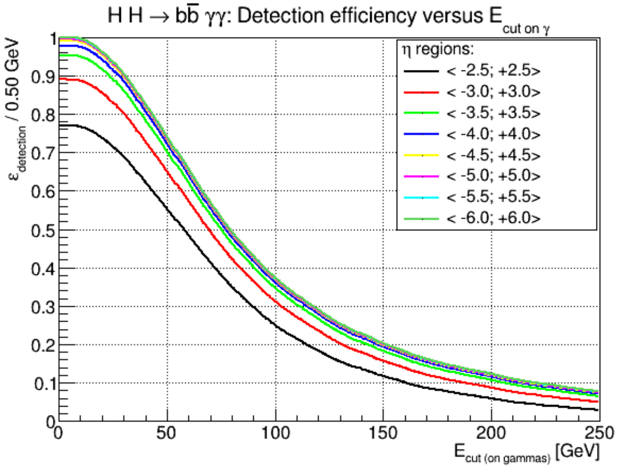
- Apply $P_T(b\bar{b})$, E ($\gamma\gamma$) cuts versus eta acceptance for 100 TeV machine



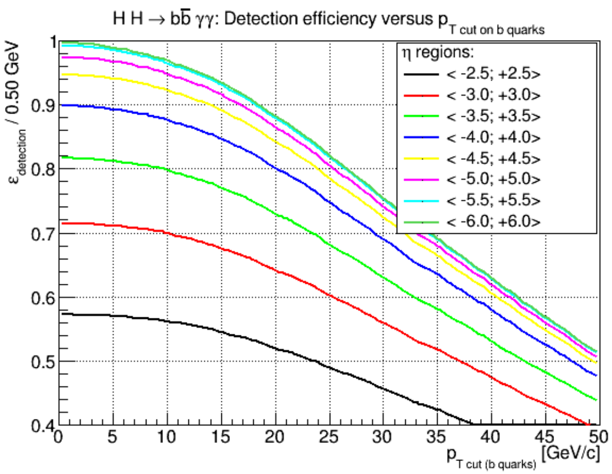

- For 13 TeV machine:

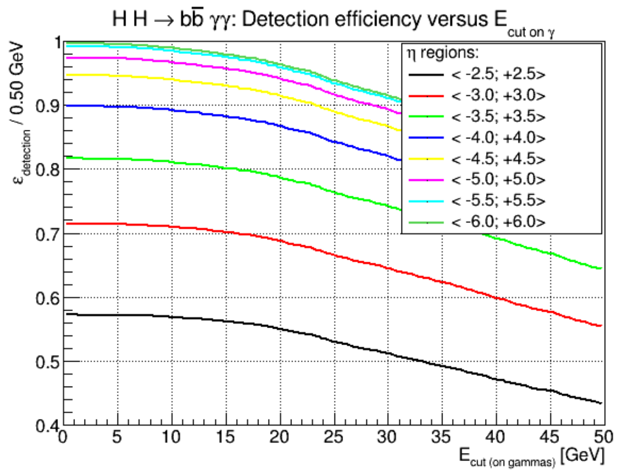


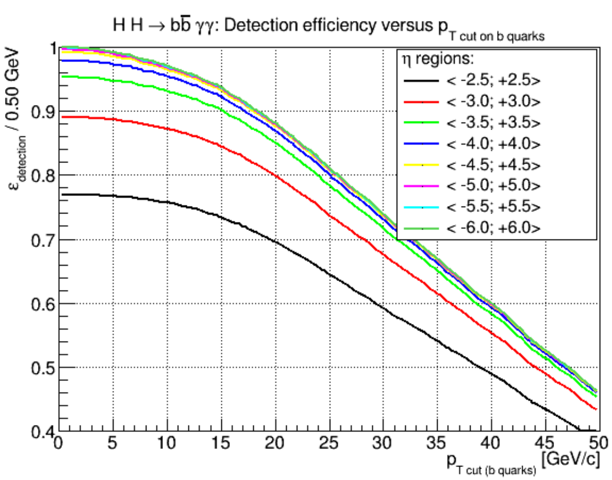
# Results for decay mode: $H\rightarrow b\bar{b}$ + $H\rightarrow\gamma\gamma$

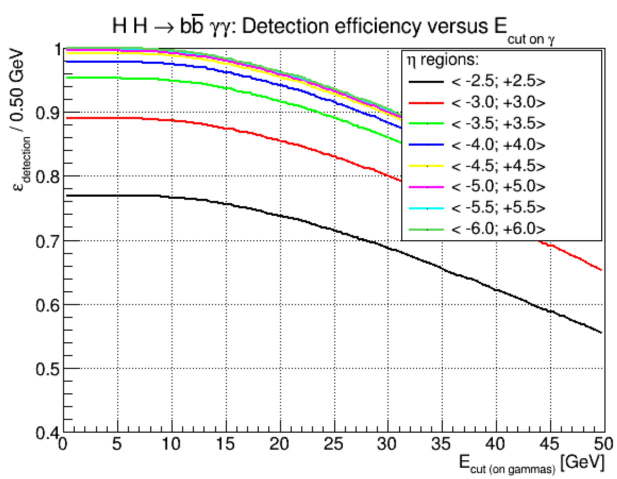
- Cuts in detail & numbers for 100 TeV machine




- For 13 TeV machine:




## Efficiency (b quarks) [%]

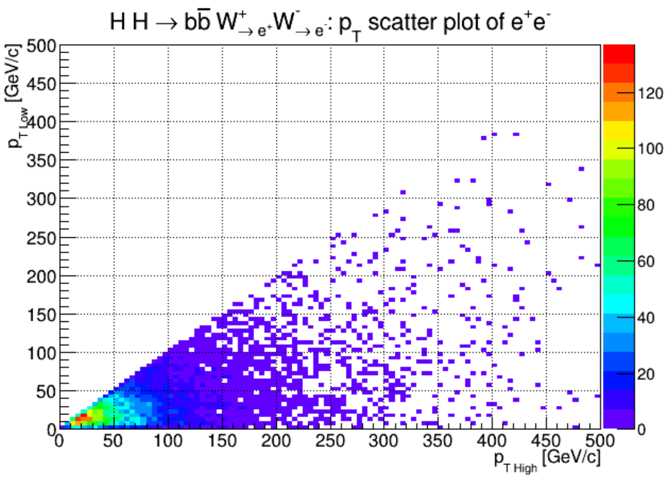
| $p_T(b)$[GeV] ≥ | 0.0 | 5.0 | 10.0 |
|---|---|---|---|
| <-4.5;+4.5> | 94.6 | 94.0 | 92.2 |
| <-5.0;+5.0> | 97.4 | 96.8 | 94.8 |
| <-6.0;+6.0> | 99.6 | 98.8 | 96.8 |

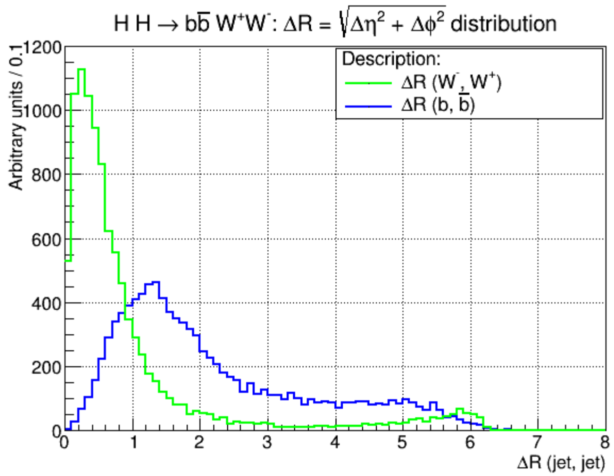
## Efficiency (gammas) [%]

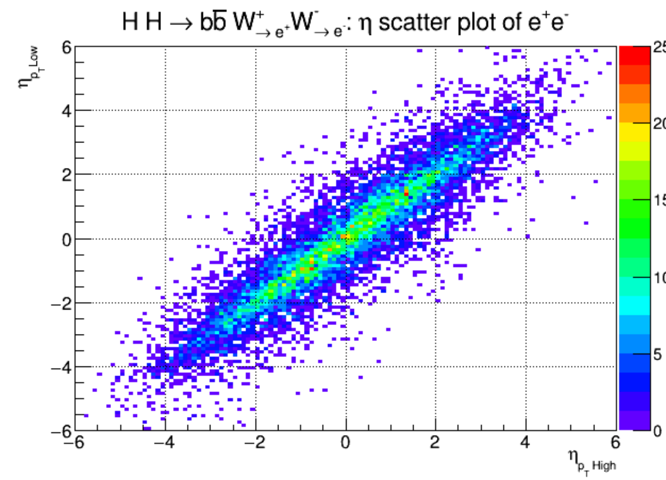
| $E(\gamma)$[GeV] ≥ | 0.0 | 5.0 | 10.0 |
|---|---|---|---|
| <-4.5;+4.5> | 94.6 | 94.6 | 94.0 |
| <-5.0;+5.0> | 97.4 | 97.3 | 96.6 |
| <-6.0;+6.0> | 99.6 | 99.5 | 98.8 |

# Results for decay modes: $H \to b\bar{b}$ + $H \to W^+W^-$

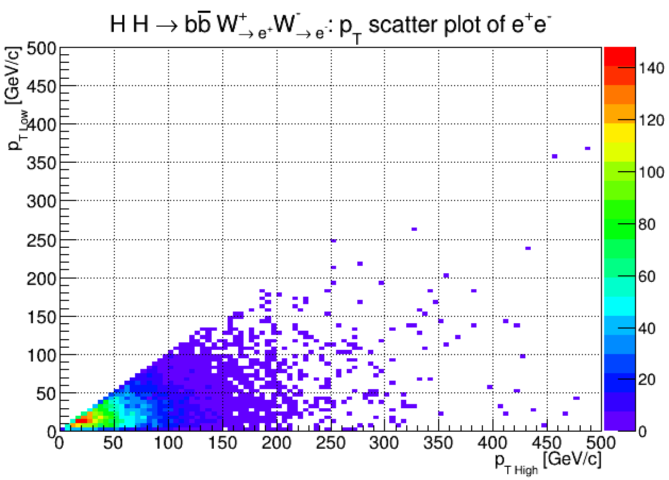
– **WW → ee** ; $P_T$ spectrum, jet isolation & eta spectrum for 100 TeV machine

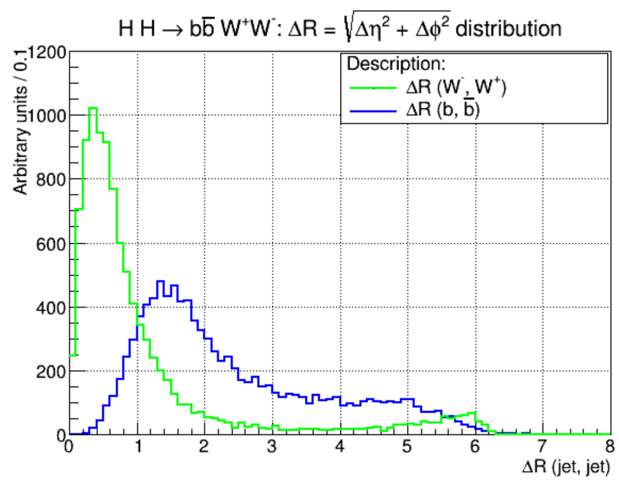


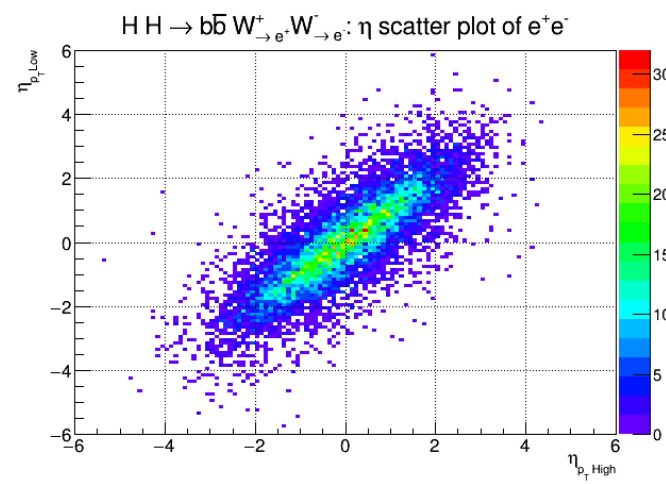




– **For 13 TeV machine**

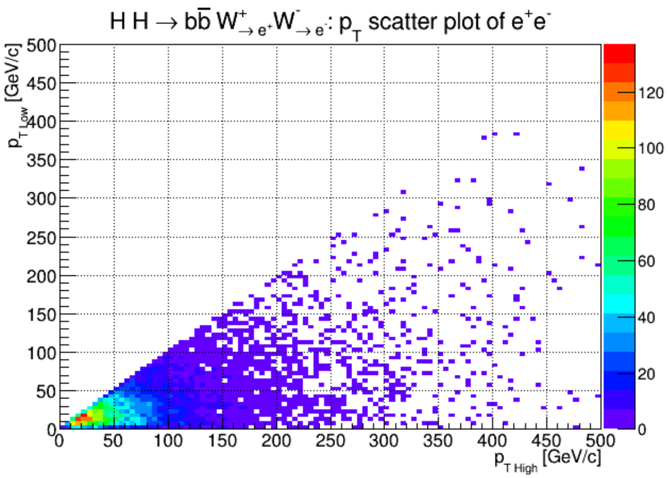


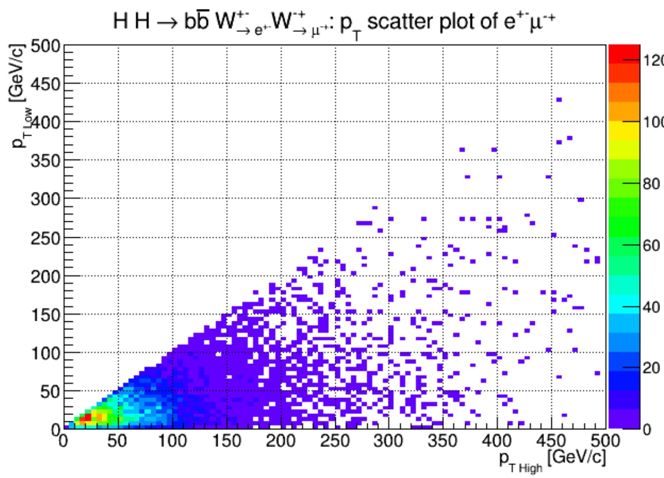



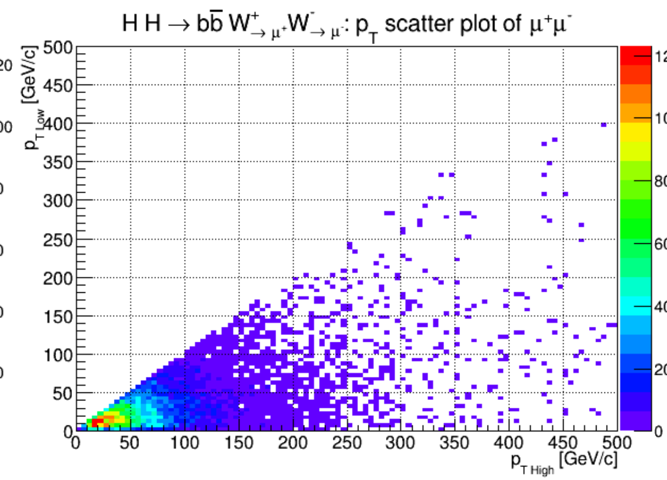



# Results for decay modes: $H \to b\bar{b}$ + $H \to W^+W^-$

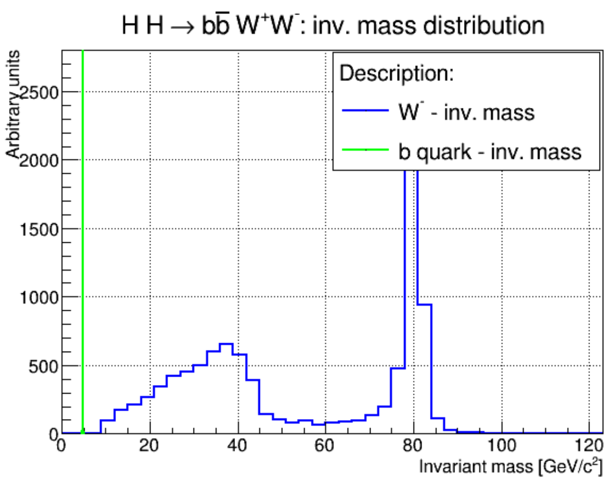
– $WW \to ee$ x $WW \to e\mu$ x $WW \to \mu\mu$ → very similar results (100 TeV machine)



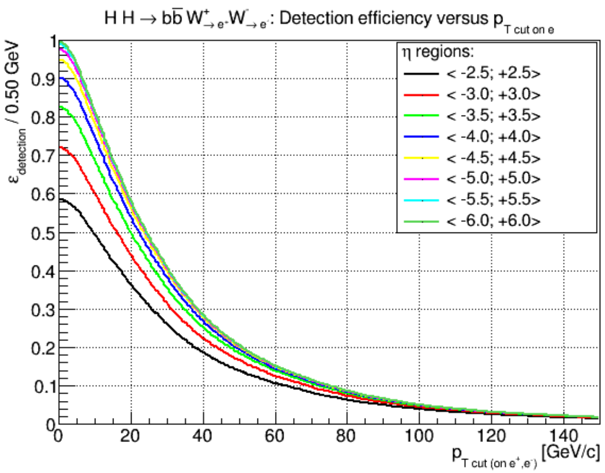



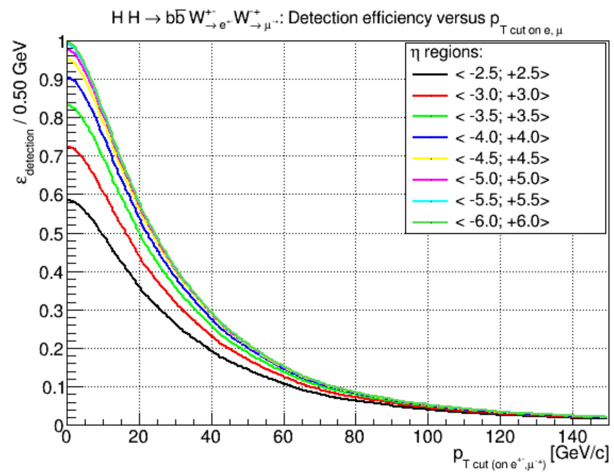

– W invariant mass → one W off-shell:

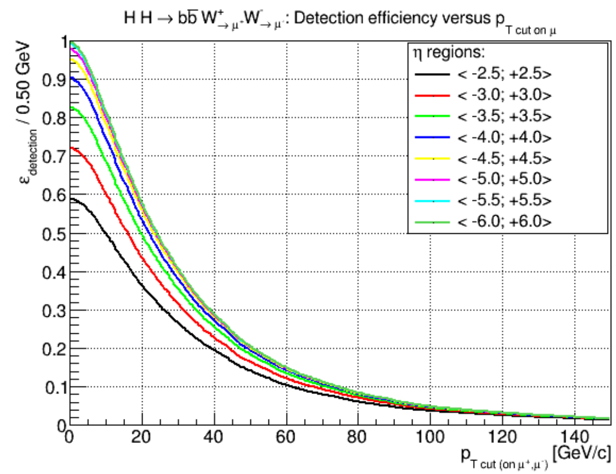


# Results for decay modes: $H \rightarrow b\bar{b}$ + $H \rightarrow W^{+}W^{-}$

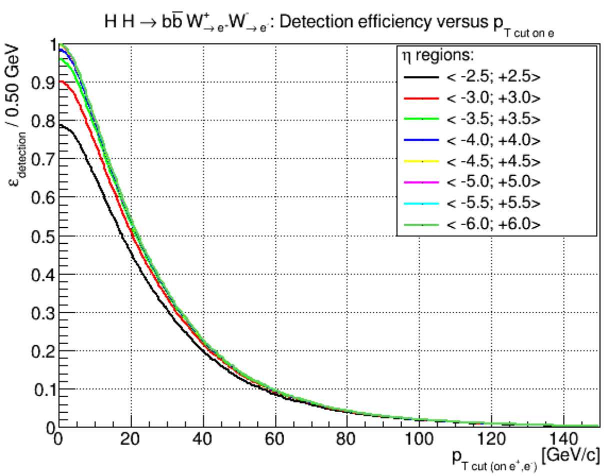
– **WW → ee,eμ,μμ** ; Apply $P_T$ cuts versus eta acceptance for 100 TeV machine



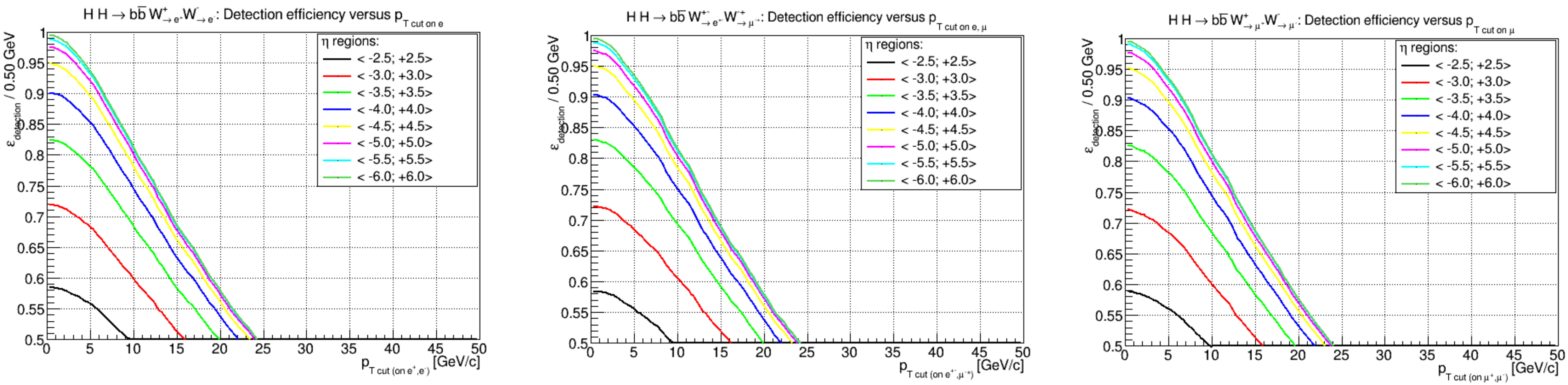




– **For 13 TeV machine**



# Results for decay modes: $H \to b\bar{b}$ + $H \to W^+W^-$

– **WW → ee,eμ,μμ ; Cuts in detail & numbers for 100 TeV machine**

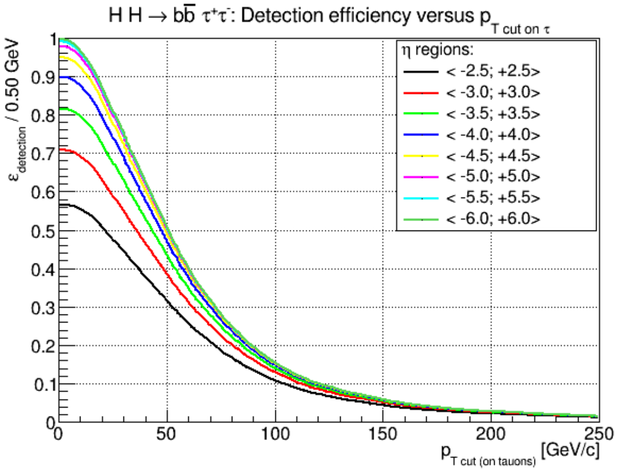


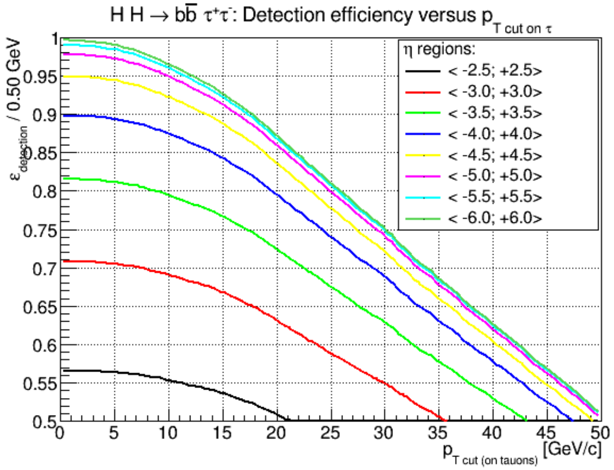

**Efficiency (e,μ) [%] → very similar for all three leptonic decay channels**

| pT[GeV] ≥ | 0.0 | 5.0 | 10.0 |
|---|---|---|---|
| <-4.5;+4.5> | 94.9 | 89.2 | 77.6 |
| <-5.0;+5.0> | 97.6 | 91.6 | 79.6 |
| <-6.0;+6.0> | 99.6 | 93.2 | 80.8 |

# Results for decay mode: $H \rightarrow b\bar{b}$ + $H \rightarrow \tau^+\tau^-$

- Very similar topology as in previous decay channels, but still missing tau lepton decayed to the final states: e,μ
- For demonstration: **Apply $P_T$ cuts versus eta acceptance (100 TeV)**



# gg → HH studies: Summary & Outlook

- **Summary**:
  - The study is far from being complete:
    - b-tagging effects not yet implemented
    - tau reconstruction missing (in progress)
    - $E_T$ reconstruction for W decay channel missing (in progress)
    - but the following can be stated:
  - gg → HH represents a “low” pT physics compared to FCC-hh TeV scale in terms of detector design! So, various channels “in other corners” of TeV scale spectra needs to be addressed to have a realistic picture of our detector
  - Rather than $\eta_{coverage} = <-6.0;+6.0>$, $\eta_{coverage} = <-5.0;+5.0>$ or even $\eta_{coverage} = <-4.5;+4.5>$ seems to be sufficient
  - More crucial are the applied $p_T$ (E) cuts on final leptons (gammas), i.e. detector resolution rather than eta → the degradation in terms of efficiency is very steep!
- **Outlook:** Add study with DELPHES to understand other detector effects