Search for displaced top quark in the tracker of CMS

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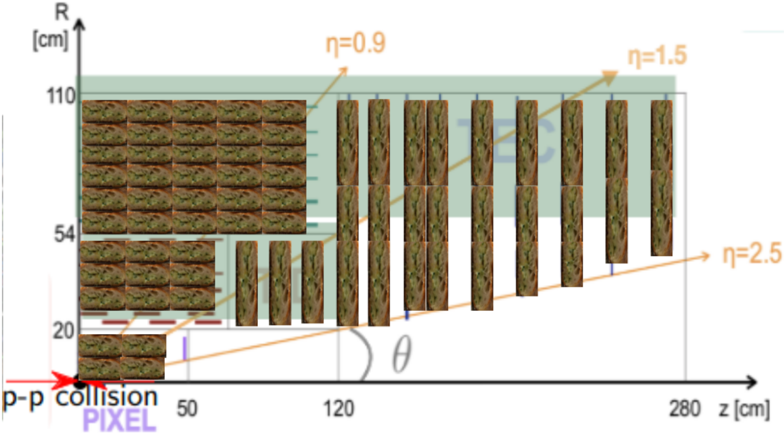
25/10/2023

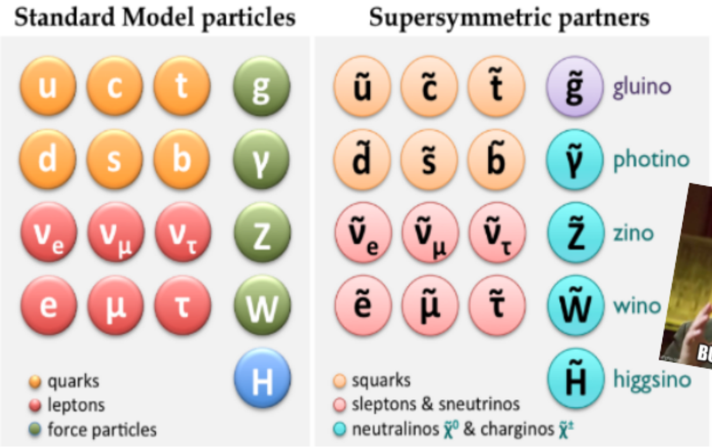
Outline

Compact Muon Solenoid Detector

Schematic view of the tracker of CMS based on the prefou technology



SuperSymmetry



SM particles => Superpartners + Neutralinos and charginos (mixing of photino, zino, wino and higgsino)

R-parity Violation

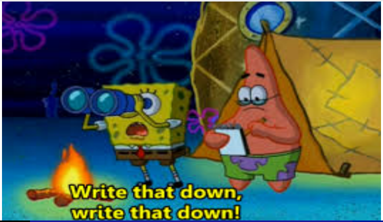
$P_R = (-1)^{3(B-L)+2s}$ where B and L are respectively the Baryonic and Leptonic numbers, s being the spin of the particle

P_R= +1 for SM particles

P_R= -1 for SUSY particles

R-parity Violation

- Non-conservation of the leptonic and/or the baryonic number
- Lightest-SUSY Particle (neutralino) has a lifetime
- Decay of the Lightest-SUSY Particle into SM Particles
- Displaced tracks can appear in the tracker from this decay

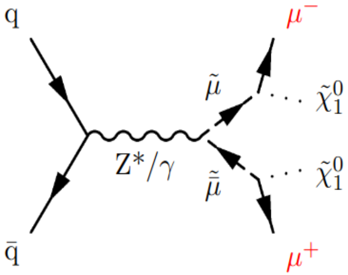


Looking for **displaced top quarks + prompt leptons**

Based on *a phenomenological study*[1] to look for displaced top quarks, we focus on the RPV process with a Bino-like neutralino production from slepton decay

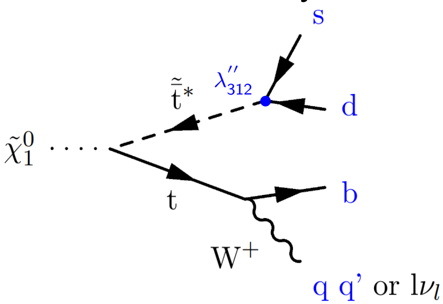
[1] : J.Andrea, D.Bloch, É.Conte, D.Darej, R.Ducrocq, E.Nibigira, arXiv:2212.06678 (2023)

smuon pair production



- $Br(\tilde{\mu} \rightarrow \mu\chi_1^0)$ =1
- 2 long-lived neutralinos
  - Two prompt muons
  - Trigger on muons

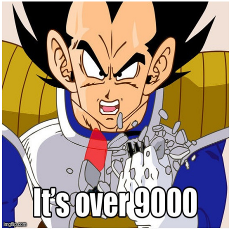
Neutralino decay



- λ''_{312} RPV Coupling
- displaced top and stop → 6 to 10 jets

Monte-Carlo samples

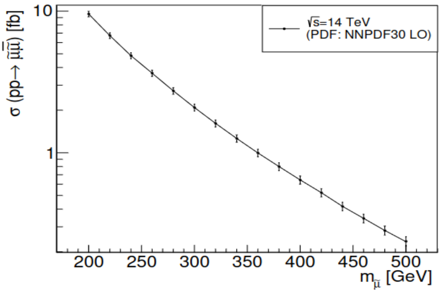
$\sim$240 Monte-Carlo samples of 10000 events each have been generated, simulated and reconstructed to cover part of the phase space :



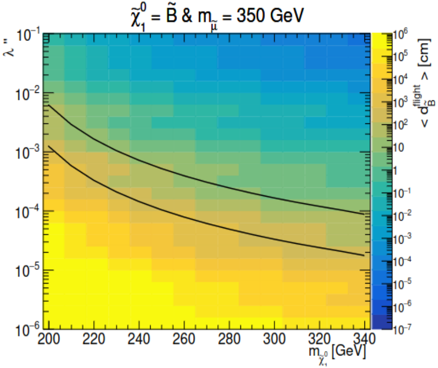
$\beta\gamma c\tau$(cm)	Mass $\tilde{\mu}$ (GeV)	Mass $\tilde{\chi}_1^0$ (GeV)	Mass $\tilde{t}$ (GeV)	Coupling λ''_{312}
0.1 to 100	**200 to 500**	**180 to 480**	$>$1000	10^{-3} to 10^{-1}

Table – SUSY particle masses and neutralino mean distance of flight $\beta\gamma c\tau$ and coupling λ''_{312}.

Phase Space



- smuon pair-production has a cross section of the order of few fb
- Lower limit on $m_{\tilde{\mu}}$ due to previous experimental results
- Upper limit for the signal to be observable or to put limits on it



- λ''_{312} vs $m_{\chi^0_1}$ for a given $m_{\tilde{\mu}}$
- Constrain our search to the tracker volume (black lines)

Triggers + Muon selections

Focus on $\mu\mu$

Muon selections

Online selection of muons : Triggers : select one or two muons

Offline selection of muons : track parameters and kinematic cuts on muons

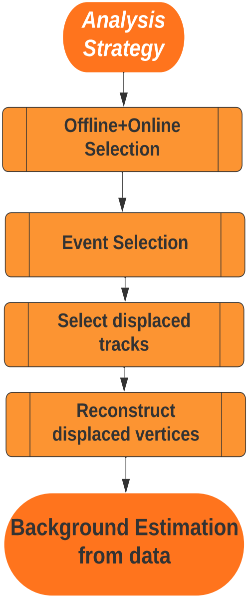
$\sim$65% of signal events pass through the triggers + offline selection

$\sim$12% of $t\bar{t} \rightarrow$ *ll*+jets events pass through the triggers + offline selection

Cross-section of $t\bar{t} \rightarrow \mu\mu + jets$ if of the order of 10000 fb

$\downarrow$

Aiming at reducing the background by a factor $\sim 10^4 - 10^5$


Analysis Strategy
Offline+Online Selection
Event Selection
Select displaced tracks
Reconstruct displaced vertices
Background Estimation from data

V^0 Candidates reconstruction

V^0 Candidates

1. $K_s^0 \rightarrow (\pi^+\pi^-)$
2. $\Lambda \rightarrow (p\pi^-)$ or $(\bar{p}\pi^+)$

"Displaced" vertices coming from these V^0 Candidates

Goal : Remove tracks coming from V^0 Candidates

V^0 Candidates : K_s^0 et Λ

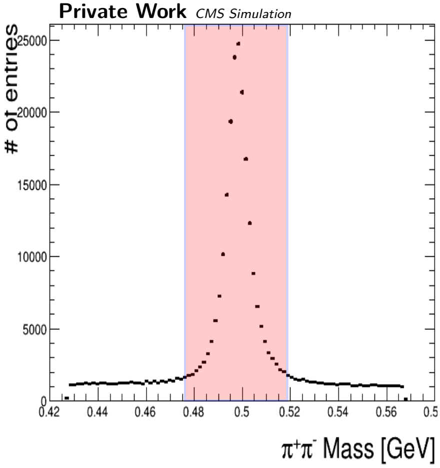
- Reconstruction of the V^0 Candidates vertices using pair of tracks
- Specific selection for K_s^0 and Λ

Impact on Signal and $t\bar{t}$

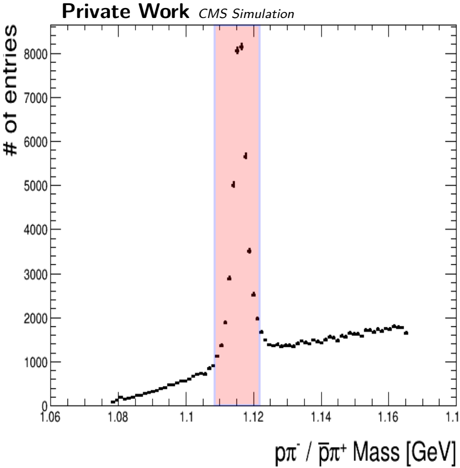
- $\sim$1.1 V^0 Candidates are reconstructed per event (both in signal and $t\bar{t}$)
- $\rightarrow$ Tracks from these V^0 Candidates are removed

V^0 Candidate reconstruction

K_s^0 Mass ± 0.022 GeV



Λ Mass ± 0.0060 GeV



$t\bar{t}$ sample

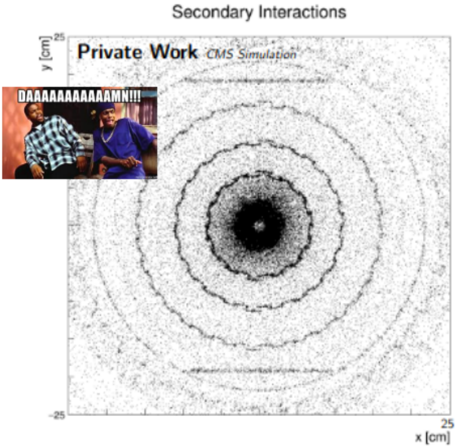
Secondary Interactions

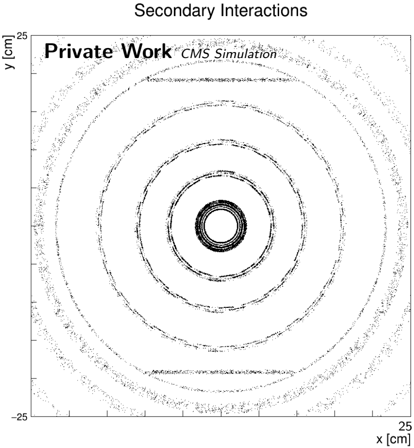
Goal : Remove tracks from secondary interactions (photon conversions and nuclear interactions) **occurring in the material of the tracker**

Reconstruction

- Slight modification of the V0 code to consider all kinds of pair of tracks and optimise the search for nuclear interactions and photon conversions
- Matching of the secondary interactions vertices with the material of the tracker is done using an approximate map of the tracker (see next slide)
- **Active layers** : Layers used for track reconstruction
- **Passive layers** : Adding Beam pipe, Pixels inner and outer support

Spatial Distribution of Secondary Interactions



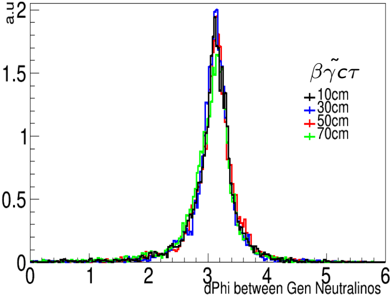


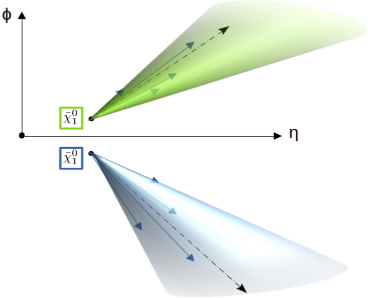
Note : We reject the tracks associated to the vertices of the plot on the right

- About 3.5 secondary interactions are matched with the material of the tracker in signal events while. . .
- 0.5 secondary interaction are matched with the material of the tracker per $t\bar{t}$ evt

Separation of the event into two cones

Goal : Reconstruct one vertex in each hemisphere



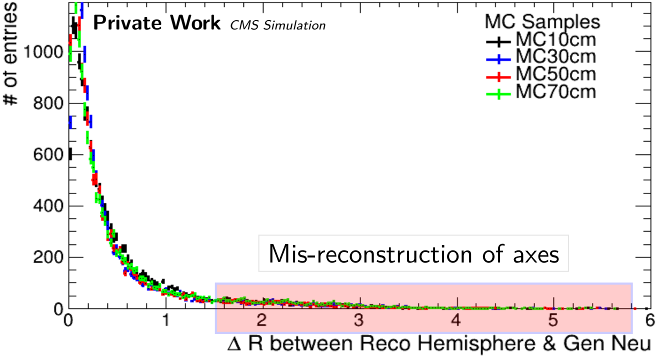


- Construct two axes from the jets ($p_t > 20$ GeV)
  - 1^{st} Hemisphere : Take the jet of highest p_t and we associate successively the nearest jets ($\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} < 1.5$)
  - 2^{nd} Hemisphere : jets non-associated with the 1^{st} hemisphere and associated within $\Delta R < 1.5$

Note : If a prompt muon belongs to a jet, its 4-vector is removed from the axis building procedure

Quality of the reconstructed axes

Check the ΔR between the reconstructed axis and the generated neutralino



ΔR between axes and neutralinos has long tail (10% of the reconstructed hemispheres have a $\Delta R > 1.5$ with the generated neutralino) $\Rightarrow$ Association criteria have been optimised but a gap is still observed $\Rightarrow$bad jets reconstruction, tracking efficiency, close neutralinos (both in η and ϕ)

Track pre-selections

kinematic and track parameters cuts

=> $\sim$95% of the tracks from generated neutralinos are kept
90% of the bkg tracks are removed (from primary vertex or pileup or fake tracks)

$\downarrow$

After preselection

<nbr of tracks from LLP> $\sim$15 & <nbr of tracks from bkg> $\sim$17

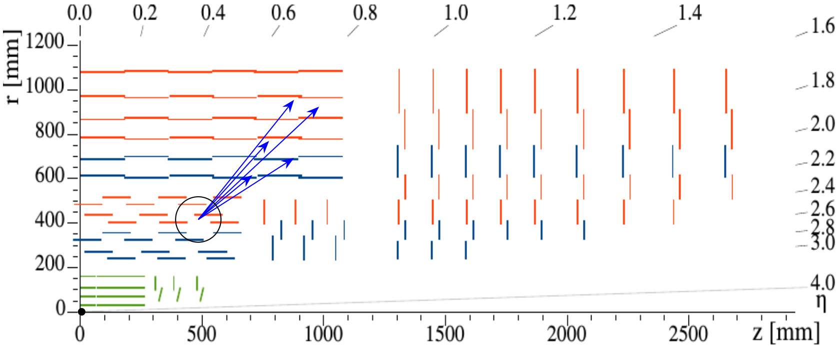
per signal event

$\sim$ 94% of the tracks from $t\bar{t}$ are rejected

Input for a Boosted Decision tree

$\rightarrow$ Distinguish tracks from a neutralino in a signal event and tracks from $t\bar{t}$

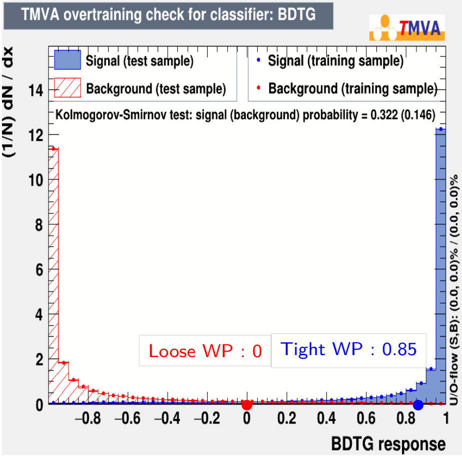
Track variables as input to the BDT

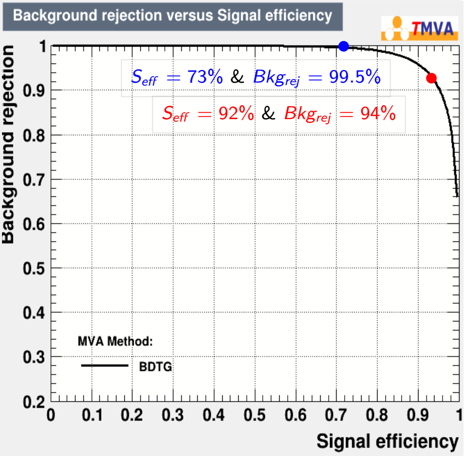


- For a given track with a firsthit (x1, y1, z1), we count the **number of tracks having their firsthit within** 10, 20, 30 up to 40cm
- **Impact parameters** : $|d_{xy}|$, $|d_z|$, $|\frac{d_{xy}}{\sigma_{xy}}|$, $|\frac{d_z}{\sigma_z}|$
- **Others** : p_t, η, χ^2/dof, n_{hits}, within a jet or not
- ΔR between the tracks and the two hemisphere axes

Signal (50 cm) 40k tracks & Bkg 200k tracks

- ROC Curve (Bkg rejection vs. Signal Efficiency)
- BDT working Points : depends on the level of bkg rejection needed for the search
- Tight : 10^3 rejection of background & Loose : reference working point

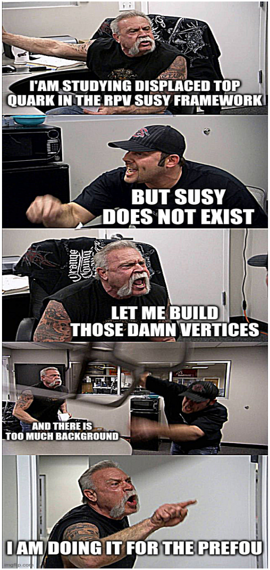




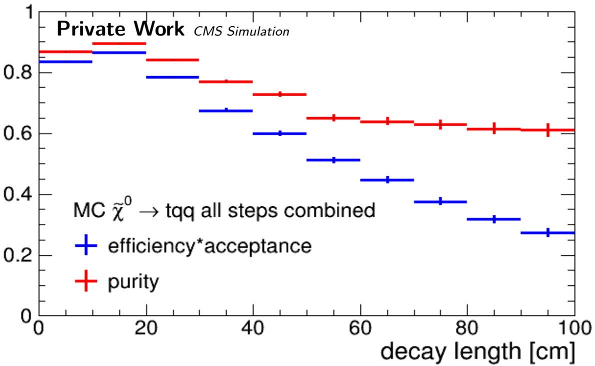
Vertexing

Goal : Multi-step vertexing using the Adaptive Vertex fitter to **reconstruct one vertex in each hemisphere**

1. Using collections of Tight+Loose WP of the tracks
2. By applying a χ^2 requirement during the building procedure of the vertex
3. Mutli-step : using the two working points with different selection criteria and algorithms



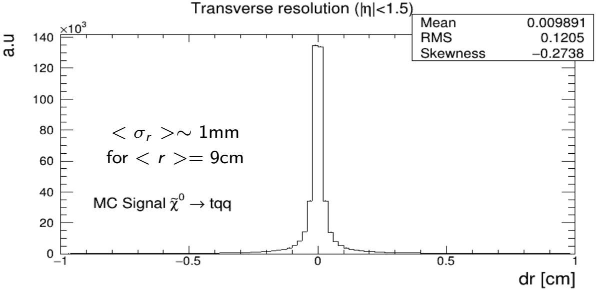
Efficiency for Tight+Loose WP

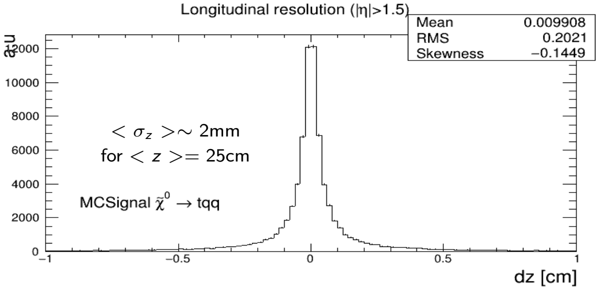


Efficiency : ratio of the number of matched vertices (with gen vertices) with the number of vertices that should be reconstructed

Purity : ratio of matched vertices (with gen vertices) with the number of vertices having a good χ^2 $(0 < \frac{\chi_2}{Dof} < 10)$

Resolution





- $\beta\tilde{\gamma}c\tau_{\tilde{\chi}_0^1} = 50$ cm
- Look for the spatial resolution between generated LLP vertices and reconstructed secondary interactions vertices

Conclusion

Beginning of a new analysis

Search for displaced top-quarks in the tracker of CMS

Vertexing :

1. Current Workflow : Multi-steps Vertexing using the AVF
2. Rejection of backgrounds by a factor 10^3 with the Tight WP

Future :

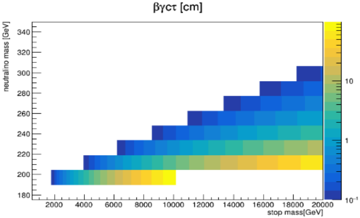
1. Check for data/simulation agreement with Run2 data
2. Implement a method to estimate the background from data $\Rightarrow$ need discriminating variables at event and vertex level (ABCD Method)

Thanks a lot !!

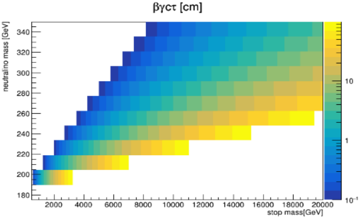
Back-up

Back-up

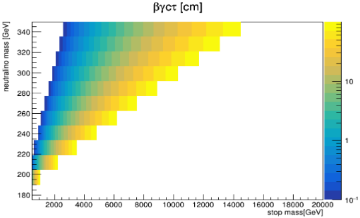
Phase Space



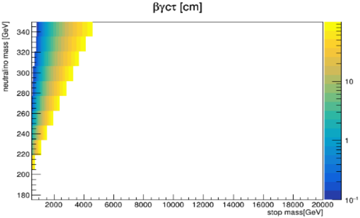
(a) $\lambda'' = 10^{-1}$



(b) $\lambda'' = 10^{-2}$



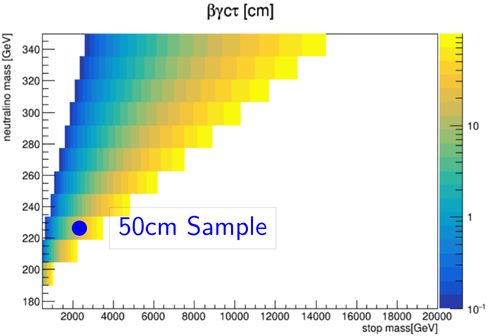
(c) $\lambda'' = 10^{-3}$



(d) $\lambda'' = 10^{-4}$

Mean decay length of the neutralino in the lab frame as a function of the neutralino and squark mass, and according to different values of λ''_{312}

Phase Space



Mean decay length of the neutralino in the lab frame as a function of the neutralino and squark mass for a value of 10^{-3} for λ''_{312}

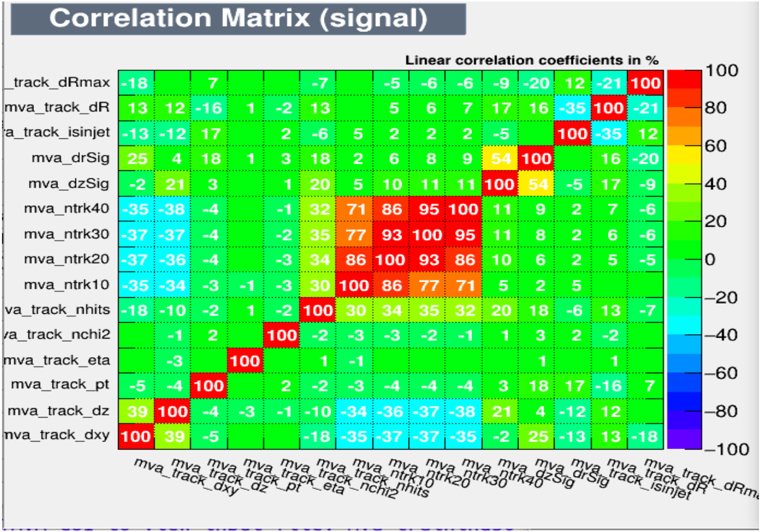
Generator :

- MADGRAPH AMC@NLO v.2.7.0, at LO QCD
- PDF : NNPDF30 (LHAPDF package)
- Shower Program : PYTHIA 8.306

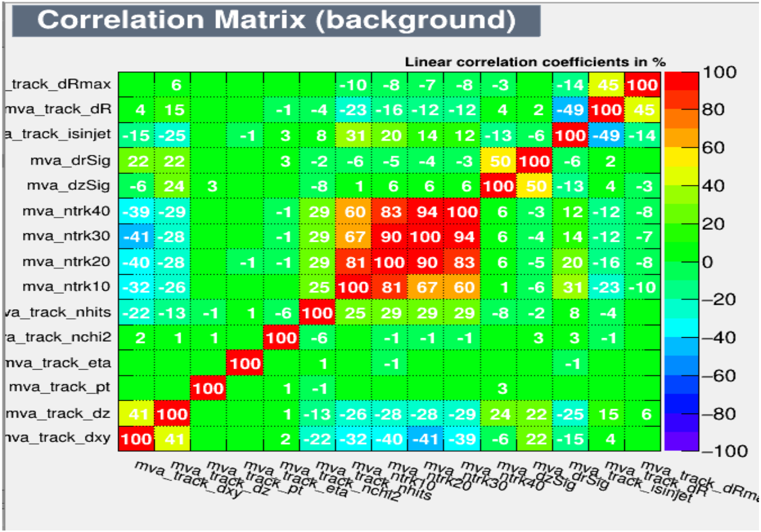
Background Samples

- /TTJets_DiLept_TuneCP5_13TeV-madgraphMLM-pythia8
- /TTTo2L2Nu_TuneCP5_13TeV-powheg-pythia8
- /ST_tW_top_5f_NoFullyHadronicDecays_TuneCP5_13TeV-powheg-pythia8
- /ST_tW_antitop_5f_NoFullyHadronicDecays_TuneCP5_13TeV-powheg-pythia8
- /DYJetsToLL_M-10to50_TuneCP5_13TeV-madgraphMLM-pythia8
- /DYJetsToLL_M-50_TuneCP5_13TeV-madgraphMLM-pythia8/
- /WWTo2L2Nu_TuneCP5_13TeV-powheg-pythia8/
- /WWTo2L2Nu_MLL_200To600_TuneCP5_13TeV-powheg-pythia8/
- /WWTo2L2Nu_MLL_600To1200_TuneCP5_13TeV-powheg-pythia8/
- /WZTo2Q2L_mllmin4p0_TuneCP5_13TeV-amcatnloFXFX-pythia8/
- /ZZTo2Q2L_mllmin4p0_TuneCP5_13TeV-amcatnloFXFX-pythia8/
- /ttWJetsToLNu_5f_EWK_TuneCP5_13TeV_amcatnlo-pythia8/
- /TTZToLL_5f_TuneCP5_13TeV-madgraphMLM-pythia8/
- /TTToHadronic_TuneCP5CR1_13TeV-powheg-pythia8/
- /TTWW_TuneCP5_13TeV-madgraph-pythia8/

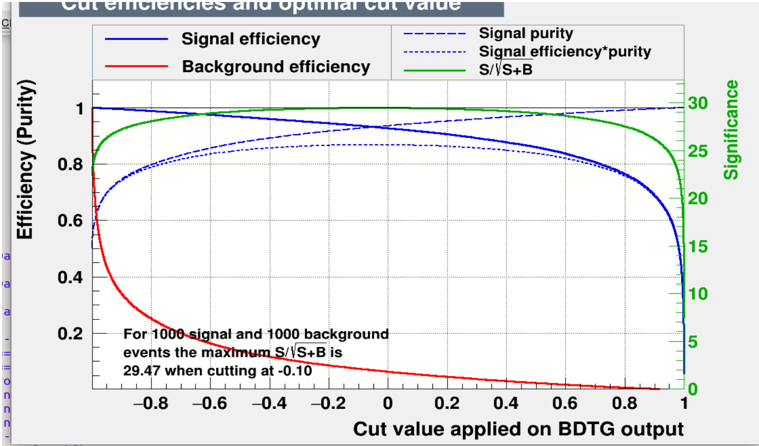
Correlation Matrix between the 15 initial variables for the signal



Correlation Matrix between the 15 initial variables for the background

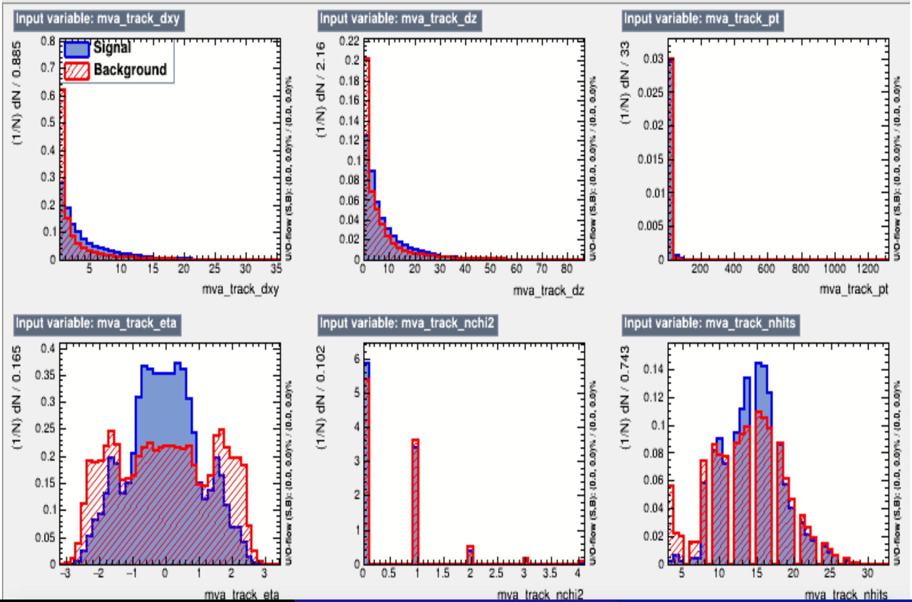


Efficiency vs BDT response

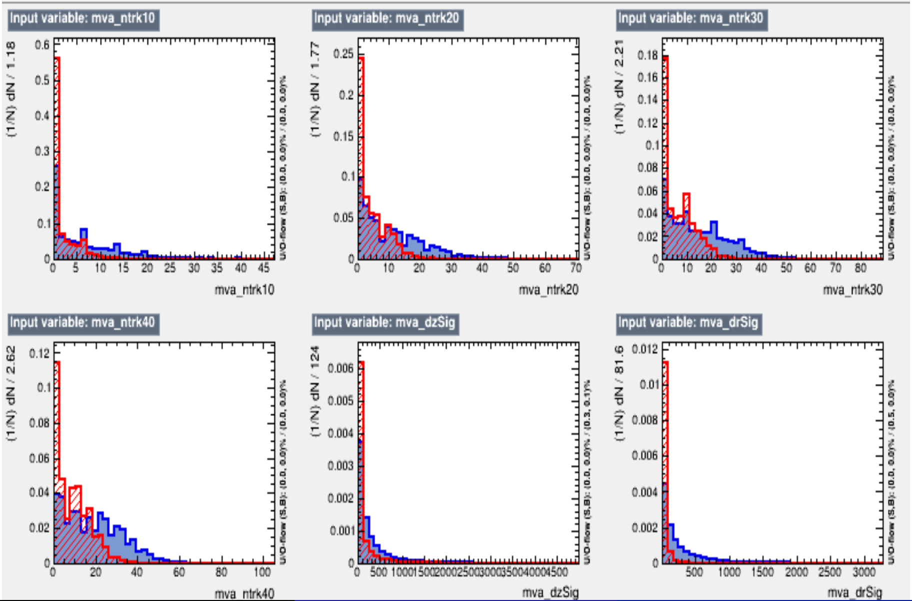



```
-- Classifier: BDTG
-- ==========================================================================================
-- Classifier   ( #signal, #backgr.)  Optimal-cut  S/sqrt(S+B)      NSig      NBkg   EffSig   EffBkg
-- ------------------------------------------------------------------------------------------
--       BDTG:  (     1000,      1000)      -0.0977      29.4737  937.055  73.73334   0.9371  0.07373
-- ------------------------------------------------------------------------------------------
```

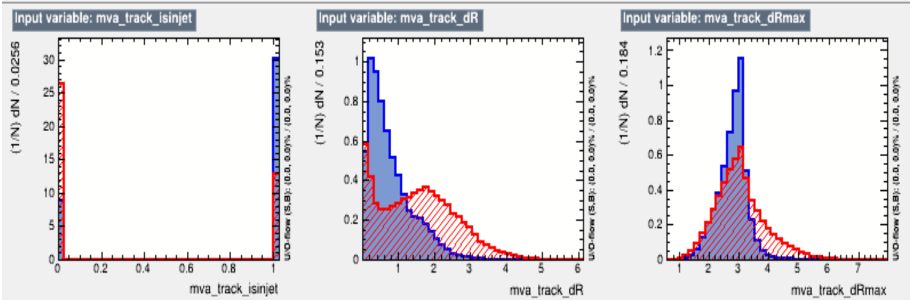
Input Variables



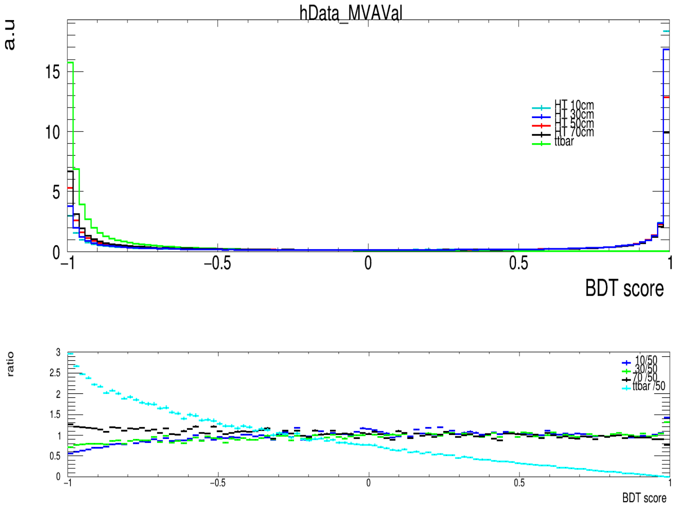
Input Variables



Input Variables

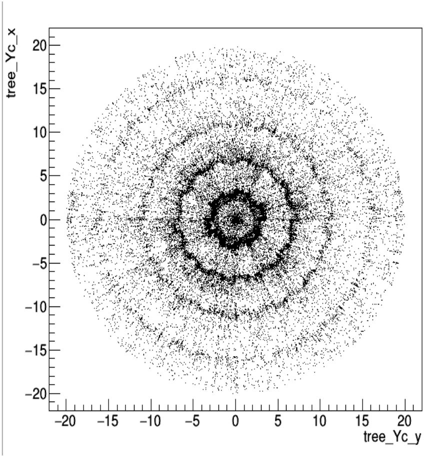


MVA Output for the 4 samples of Signal

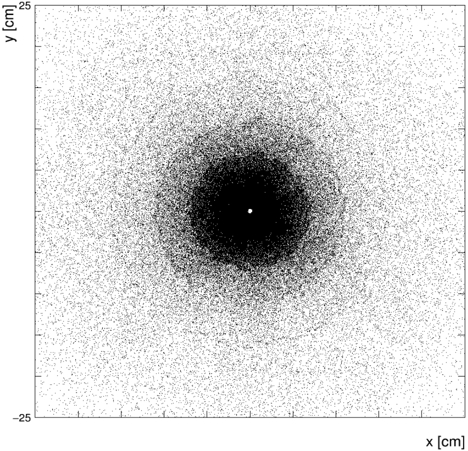


Transverse distribution of Photon Conversion and V^0 candidates

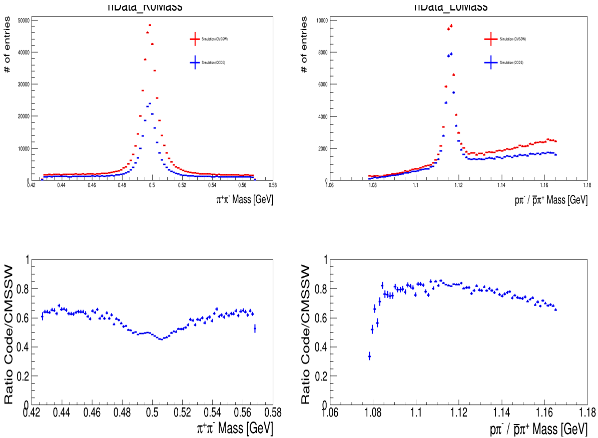
Photon Conversions



V^0 candidates

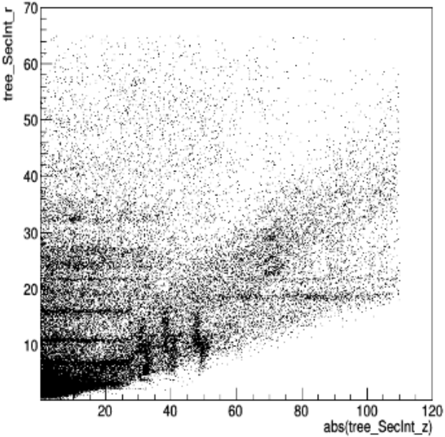


Comparison of V^0 candidates : reconstructed and CMSSW collection

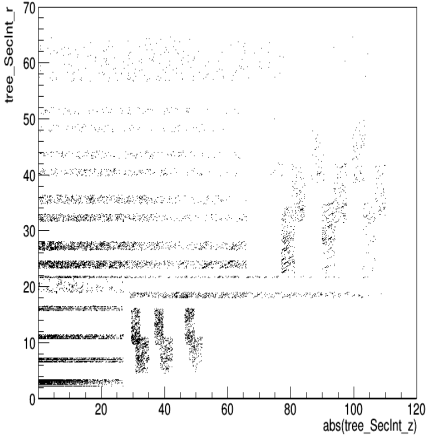


Spatial disitrbution of secondary interactions

Vertex Secondaires



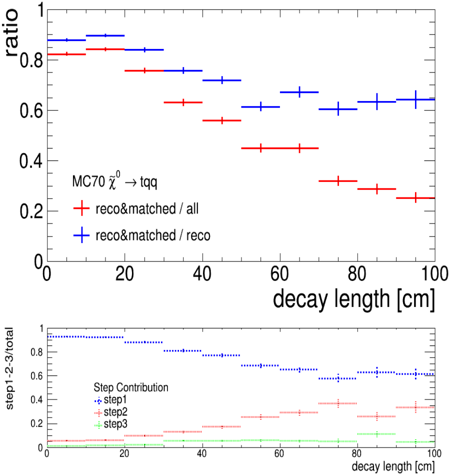
Veto appliqué ⇒vertex rejetés



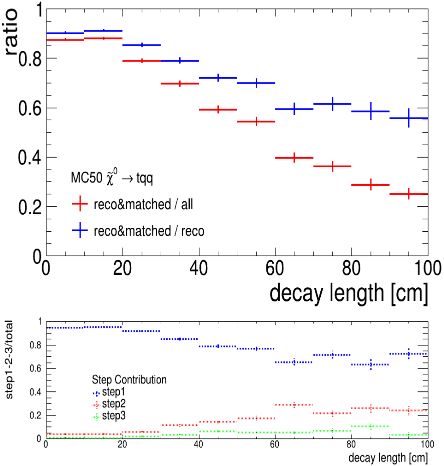
Note : Identification de la position des layers ainsi que du beam pipe, du support des pixels et du TID grâce aux premiers hits des tracks pour appliquer le veto

Vertexing details

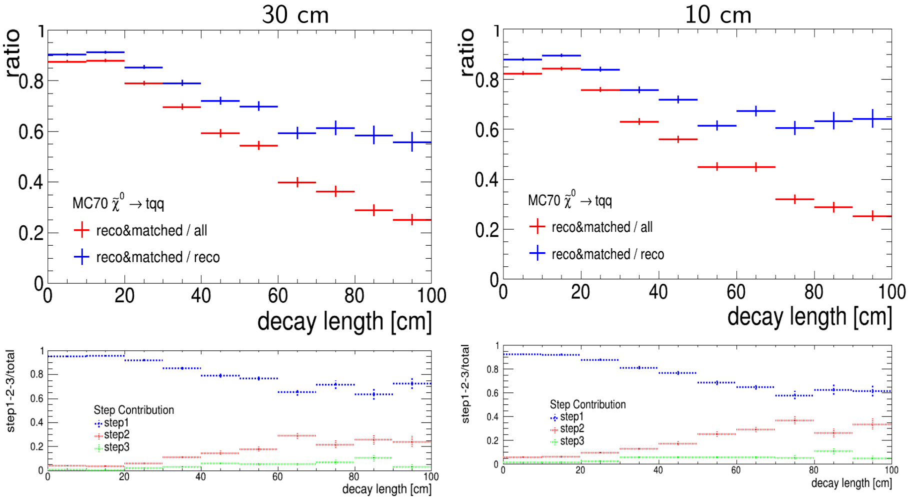
70 cm



50 cm



Vertexing details



Reconstruction efficiency

Sample	Events Selec. by Triggers + Offline	Nb of Hemi (2*nb of events selected)	Vtx with $0 < \frac{\chi^2}{DoF} < 10$	$\Delta d < 0.1$ (relative distance between Gen and Reco Vtx $< 10\%$)	Eff	Eff step1	<Dist> (cm)
10 (cm)	74.5%	14.9k	13.7k	11.6k	78%	68%	9
30 (cm)	78.2%	15.6k	13.7k	11.8k	76%	66%	19
50 (cm)	75%	14.9k	11k	9k	61%	52%	22
70 (cm)	75.3%	15k	8.9k	7.5k	50%	41%	25
ttbar	12%	15k	118	XXX	0.8%	0.2%	42

Step1 : factor ∼1000 for the reduction of background

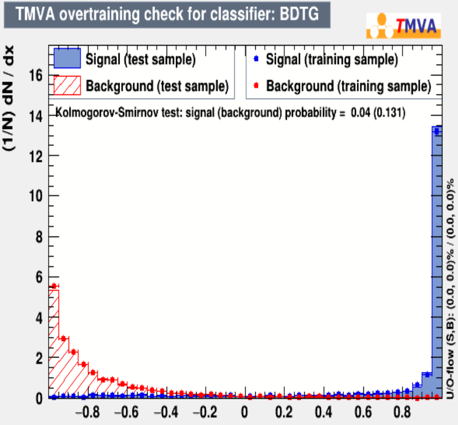
Going Forward

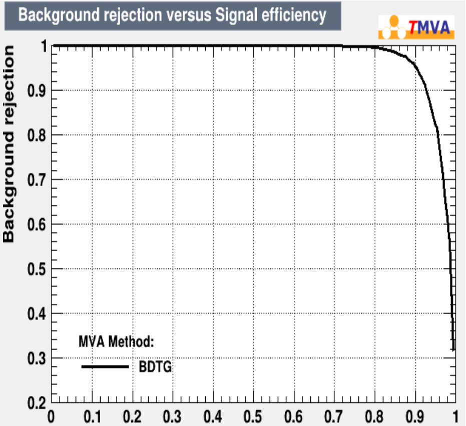
Going Forward

- Implement the ABCD Method $\Rightarrow$ need discriminating variables at event level
  1. nbr of tracks
  2. pt of leading and sub-leading leptons
  3. pt of leading and sub-leading jets,
  4. $\Delta\phi$ between leading letpons, leading-jets and between leptons and jets.
- We are also thinking about discriminating variables at the vertex level
  1. Invariant Mass of the hemisphere
  2. Nbr of tracks associated to a vertex
  3. Mean Weight of the tracks associated to a vertex
  4. $\frac{\chi^2}{DoF}$ of the vertex
  5. DCA of the tracks w.r.t the associated vertex
  6. Step of reconstruction of the vertex (i.e : Tight WP)

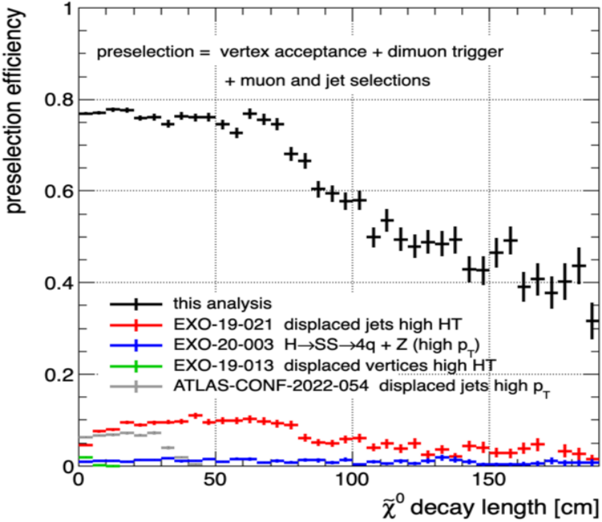
Vertex Selection

- Invariant Mass of the Vtx
- Quantities related to track multiplicity of the vertex
- $\frac{\chi^2}{DoF}$ of the vertex
- DCA of the tracks w.r.t the associated vertex
- Step of reconstruction of the vertex (i.e : Tight WP)





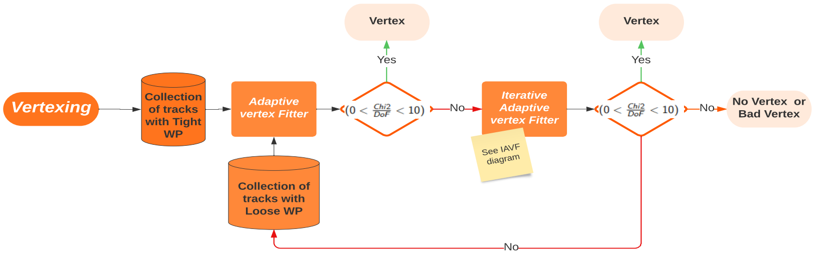
Analyses Overlap

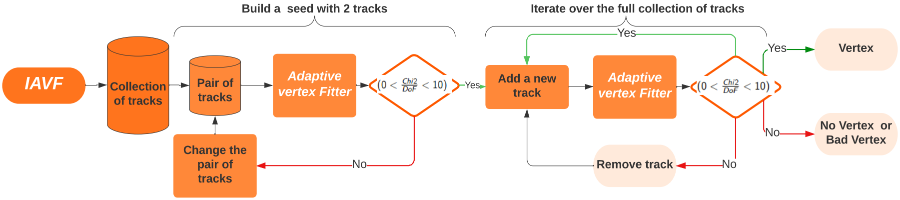


Using the preselections on events from other analyses, we check that other analyses do mostly reject our signal

Vertexing

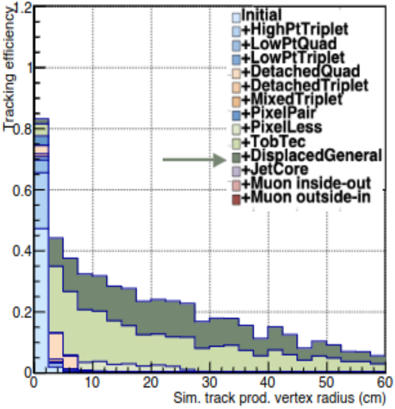
Goal : Multi-step vertexing using the Adaptive Vertex fitter to **reconstruct one vertex in each hemisphere**





Tracking

In transverse plane



Along beam axis