Tau Signals for Higgs Bosons in BSM theories at the CMS experiment

(experimentalist's view)

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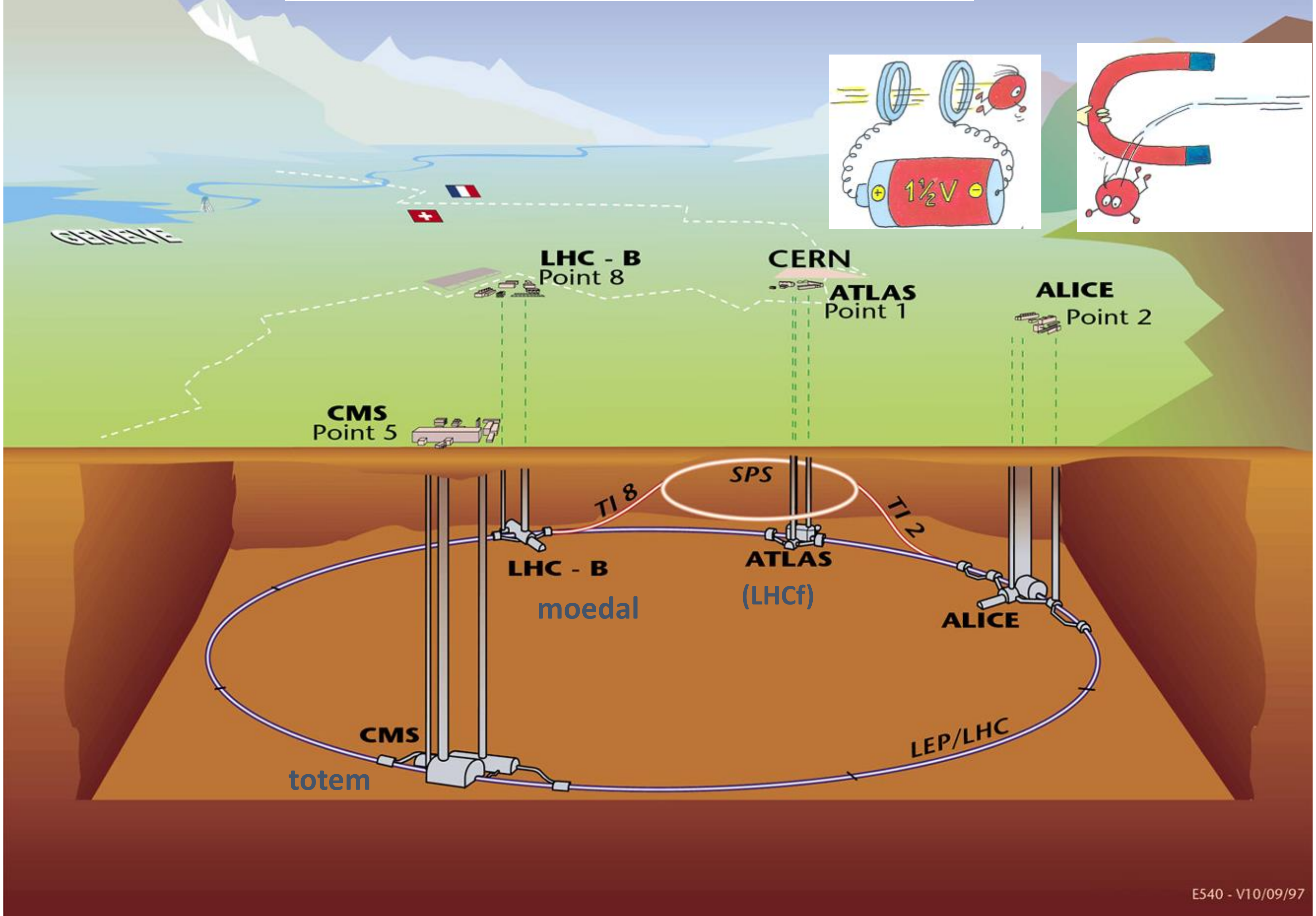
Candles of Darkness

June 5, 2017

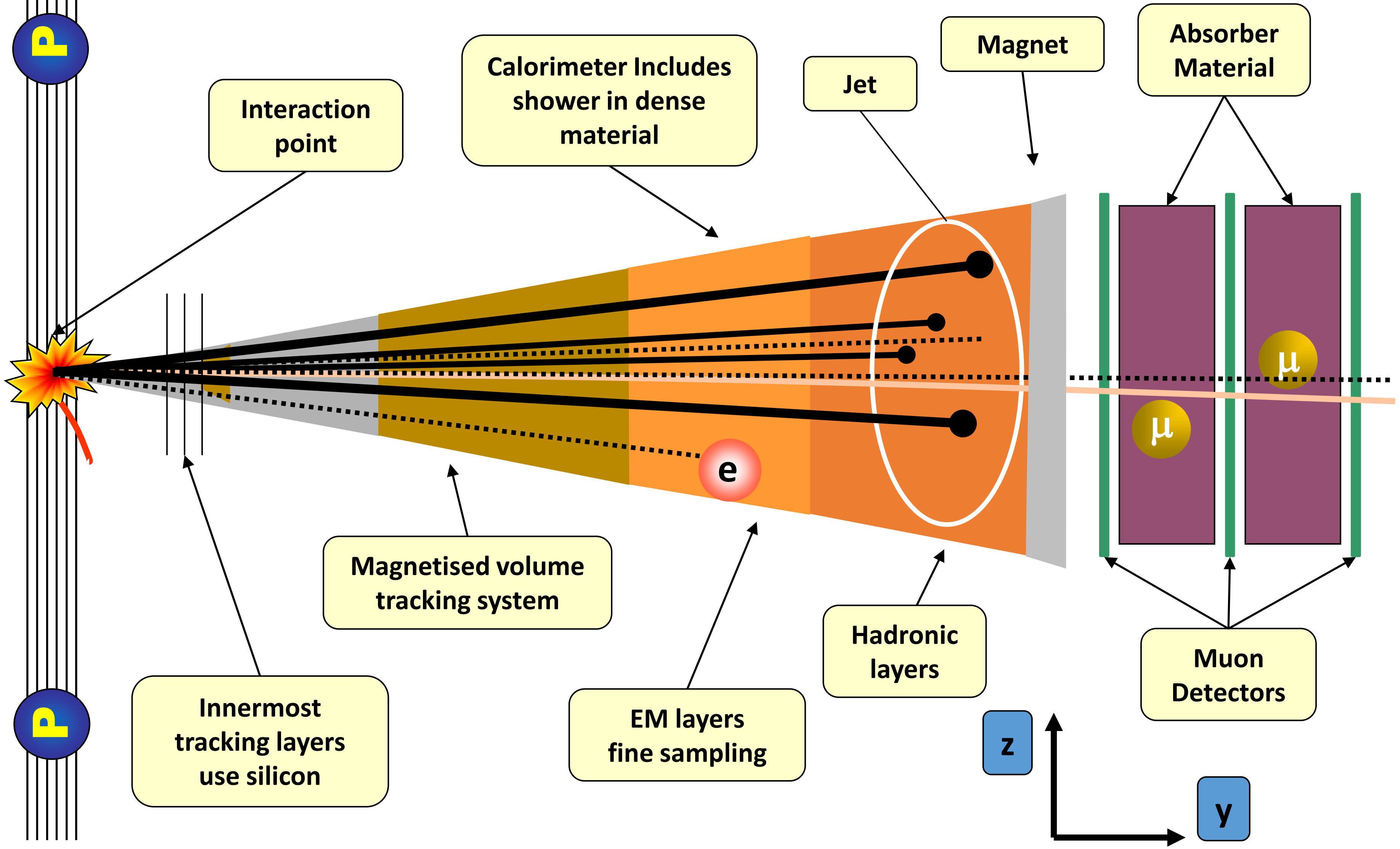
let us start at the begining

The LHC Machine and Experiments

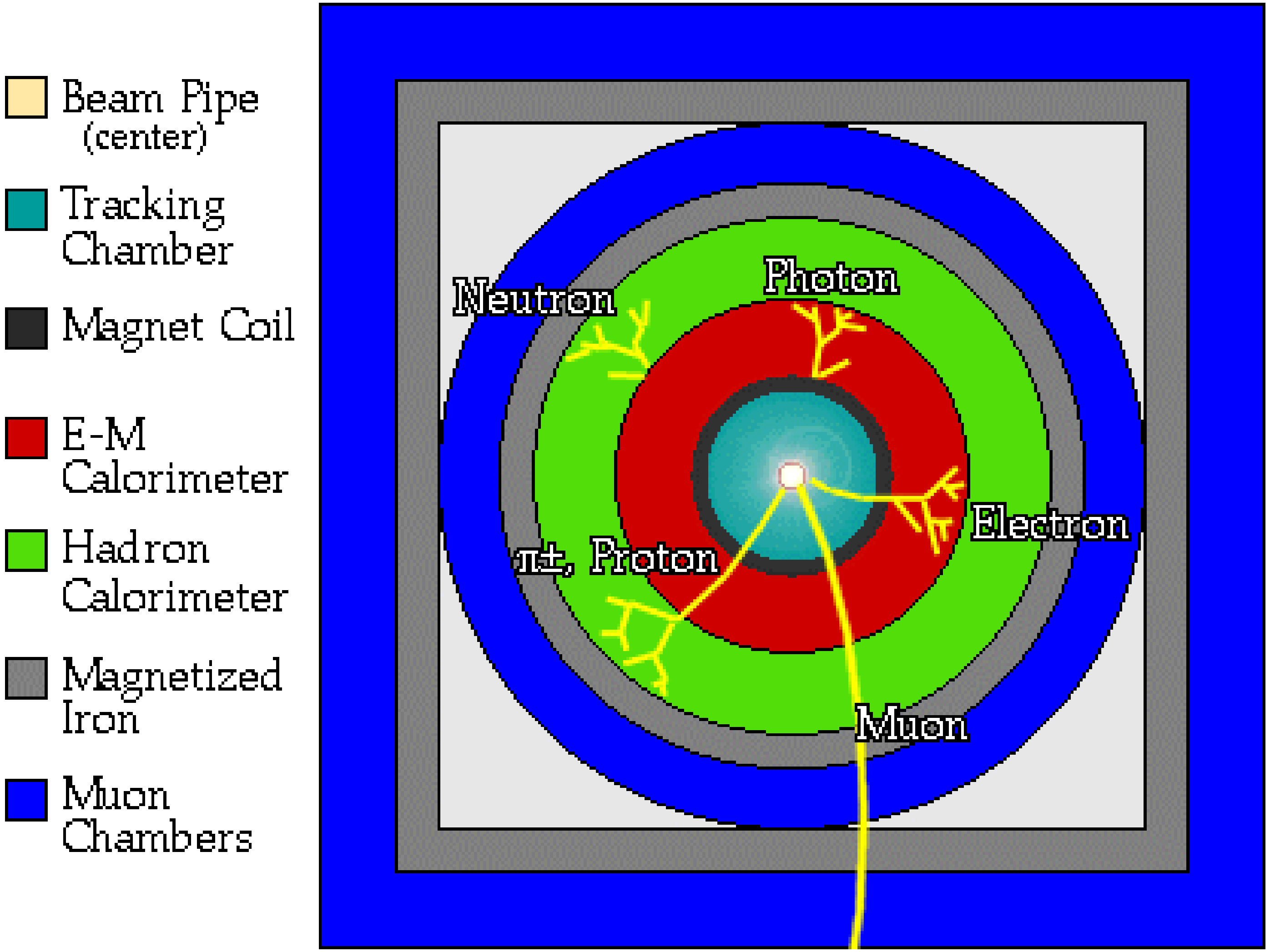


Typical Detector in a High Energy Physics Experiment

Electrons, Photons, Pions (mesons), Protons are identified by energy and momentum

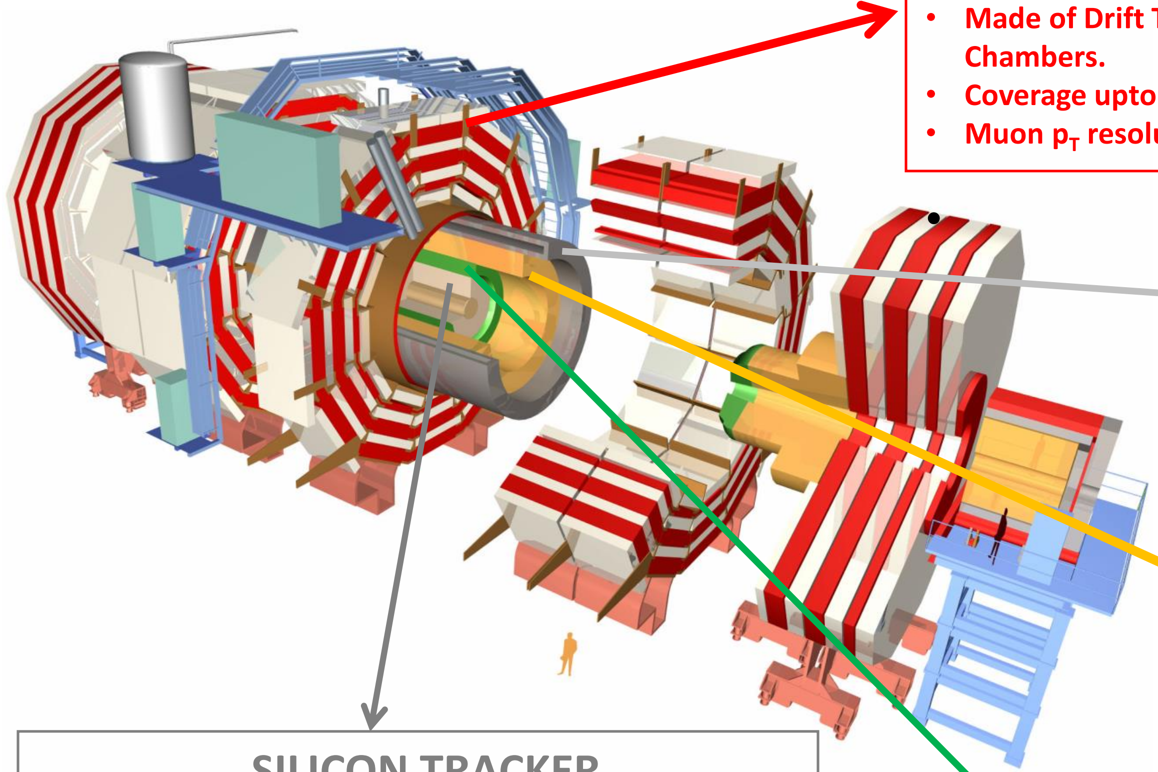


Cross Section of a Particle Detector



Particle Data Group, Lawrence Berkeley National Laboratory

CMS DETECTOR



MUON CHAMBERS

- Made of Drift Tubes, Cathode Strip Chambers and Resistive Plate Chambers.
- Coverage upto $|\eta| < 2.4$
- Muon p_T resolution 1-1.5% upto $p_T^{\mu} = 1$ TeV

MAGNET

- Superconducting Nb-Ti coil , 12m long and 6m diameter.
- Design Magnetic field : 4 Tesla

HADRON CALORIMETER

- Sampling calorimeter made of alternating layers of Brass and plastic scintillator.
- WLS fibres used for collection of signal. measured by HPDs.
- Energy resolution 10% for 100 GeV pion.

SILICON TRACKER

- Inner most 3/2 layers in the Barrel/Endcap comprising 100 x 150 μm^2 pixels (66 million channels)
- Outermost 10/12 layers in the Barrel/Endcap made of strip detectors.
- p_T resolution 0.5% for 10 GeV charged track.

ELECTROMAGNETIC CALORIMETER

- Homogeneous calorimeter made of $PbWO_4$ crystals .
- Signal measured by Avalanche Photo diodes.
- Energy resolution of 1% for 30 GeV e/γ.

Reconstructing Physics

Energy momentum Particle ID Missing Energy

difficult ↓

Electron Muon Photon Missing Energy

pion kaon Lambda ………

τ

J/psi D^0 $D^{\pm}$…………

Mass

B^0 $B^{\pm}$……………………

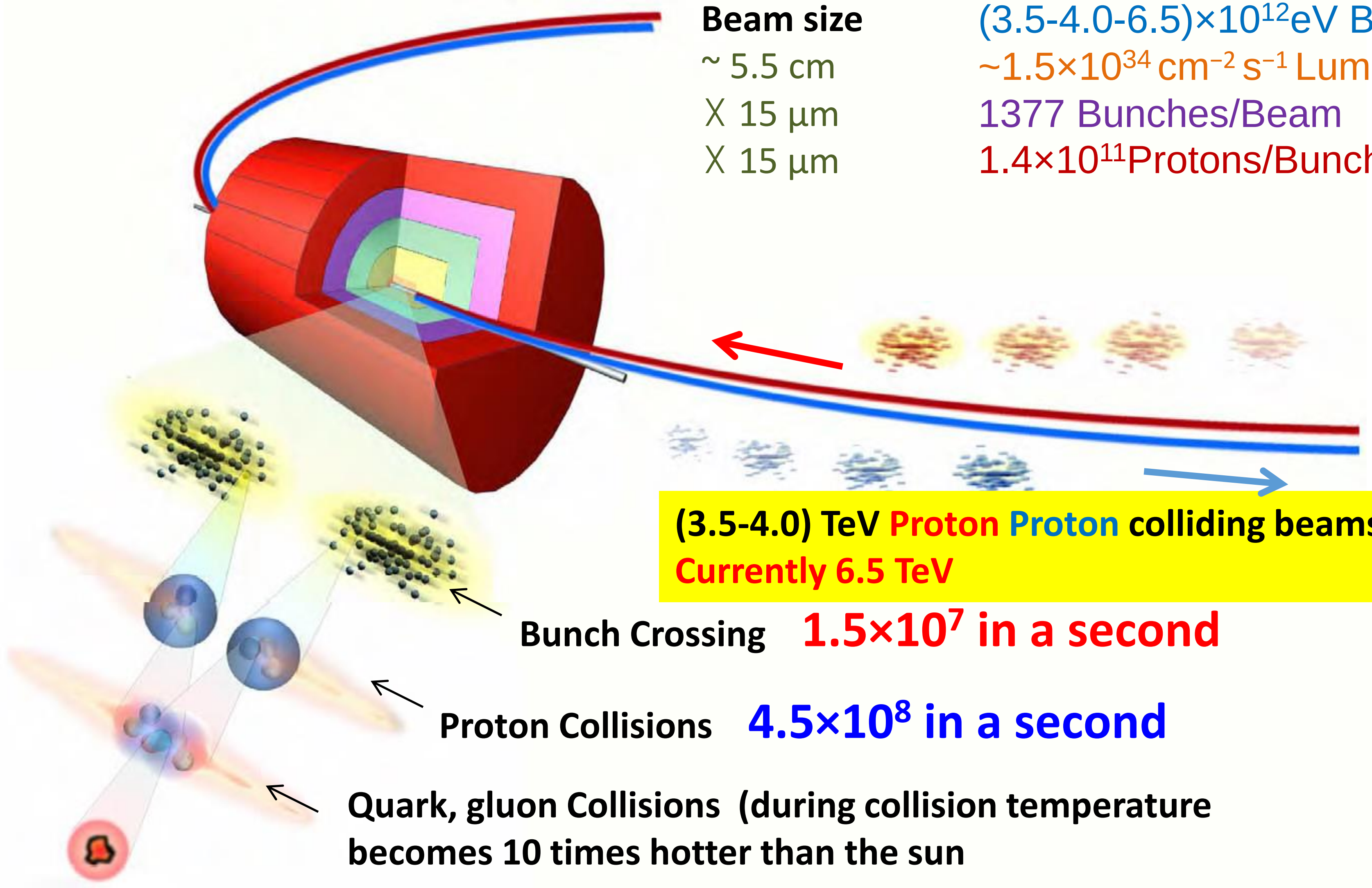
t $\bar{t}$

Supersymmetric particles Higgs

(SUSY)

Same particles make signal and background

Rates:



Beam size
~ 5.5 cm
X 15 μm
X 15 μm

$(3.5\text{-}4.0\text{-}6.5)\times10^{12}$ eV Beam Energy
$\sim1.5\times10^{34}\ cm^{-2}\ s^{-1}$ Luminosity
1377 Bunches/Beam
1.4×10^{11} Protons/Bunch

(3.5-4.0) TeV Proton Proton colliding beams
Currently 6.5 TeV

Bunch Crossing **1.5×10^{7} in a second**

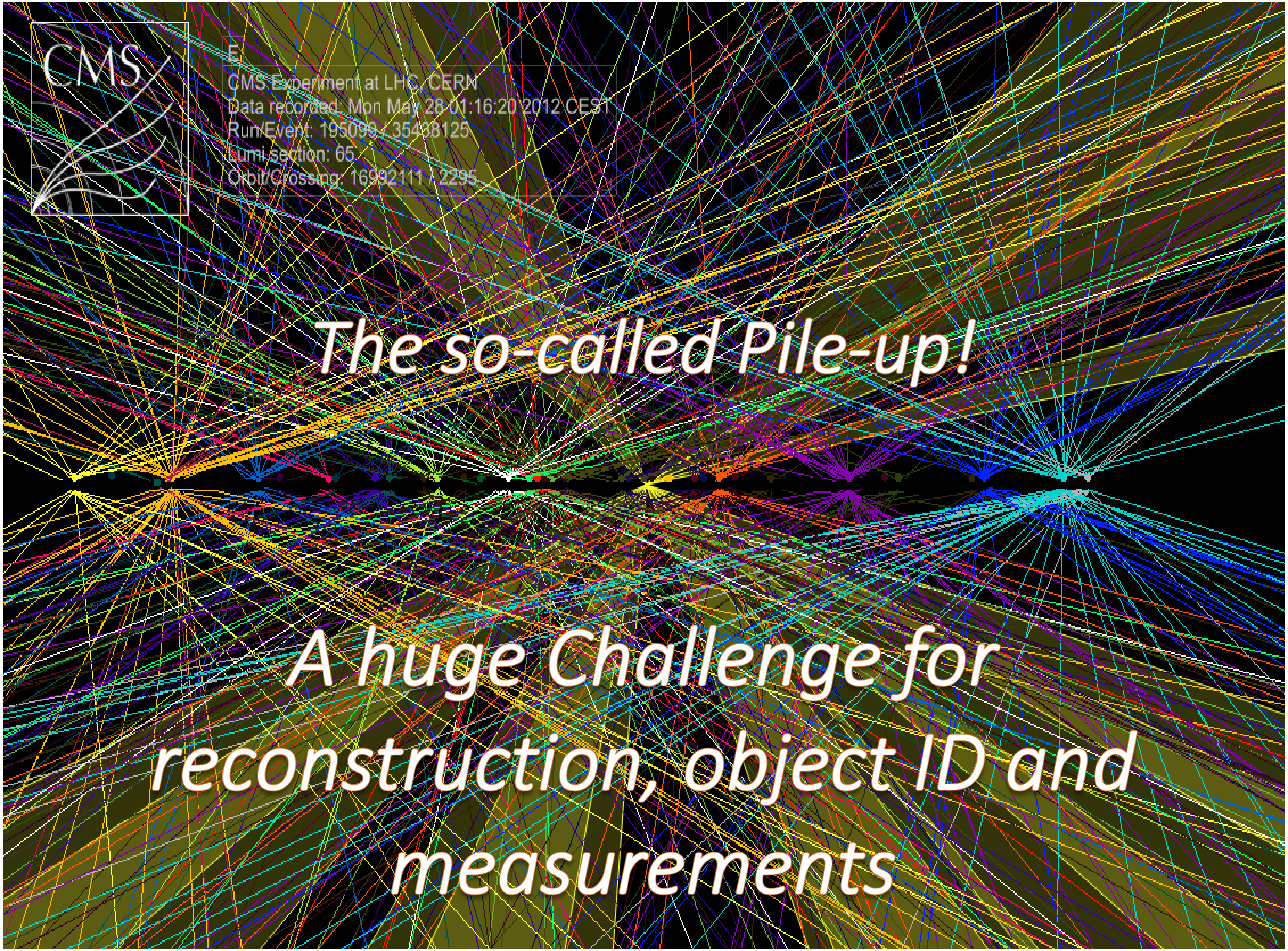
Proton Collisions **4.5×10^{8} in a second**

Quark, gluon Collisions (during collision temperature becomes 10 times hotter than the sun

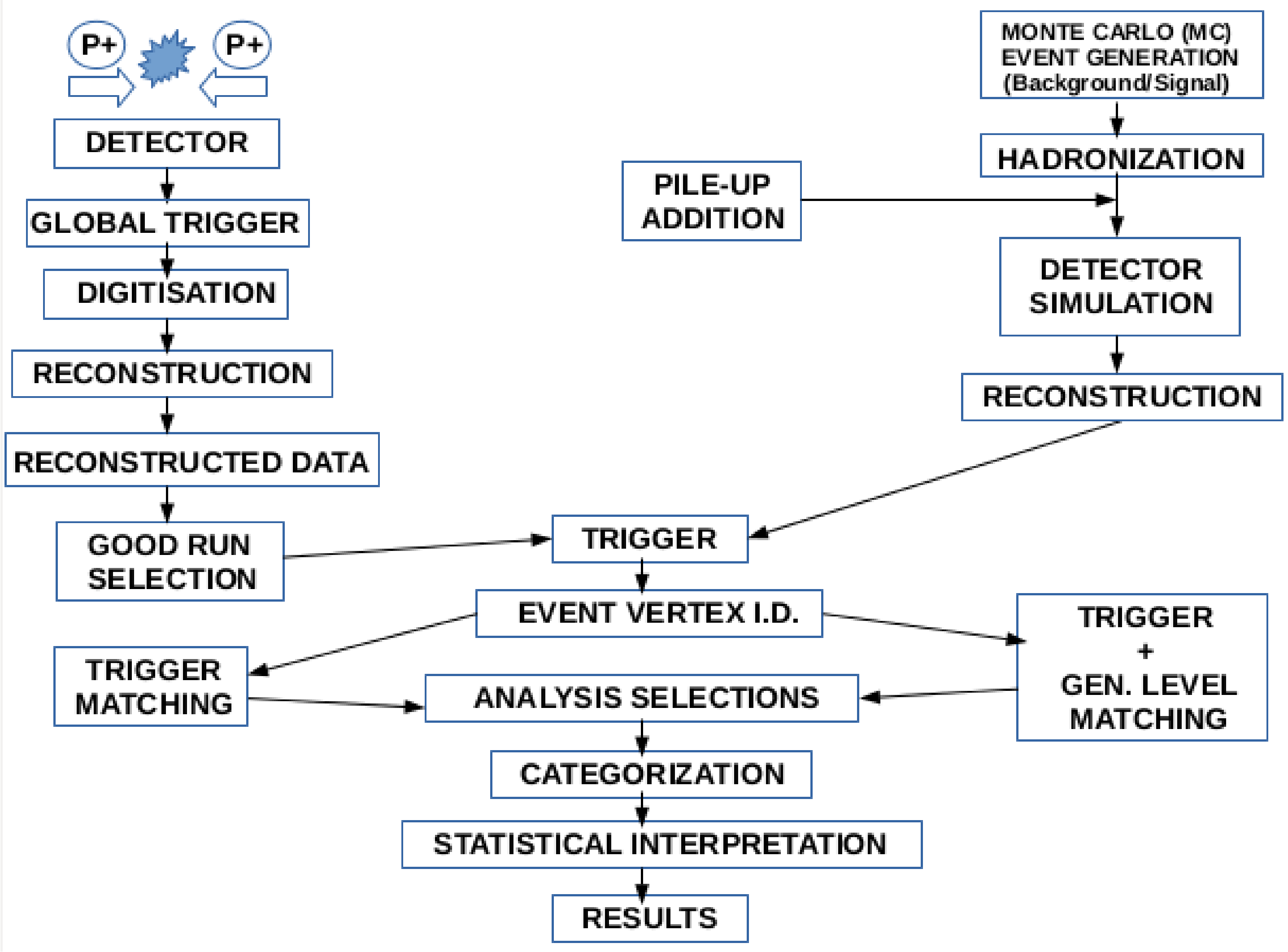
New Particle Production (Higgs, SUSY, ...)

1 in 10 seconds

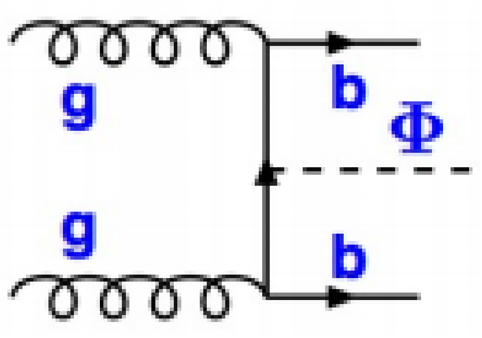
Luminosity = no. of collisions per unit area per unit time
Integrated luminosity over a period of time is expressed in picobarn^{-1} (1/area)
[1 barn = $10^{-24}\ cm^{2}$]

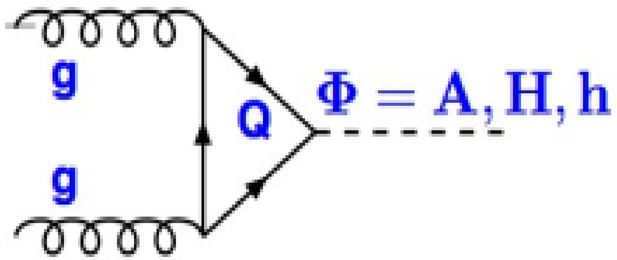

CMS
CMS Experiment at LHC, CERN
Data recorded: Mon May 28 01:16:20 2012 CEST
Run/Event: 195099 / 35438125
Lumi section: 65
Orbit/Crossing: 16992111 / 2295
The so-called Pile-up!
A huge Challenge for reconstruction, object ID and measurements

ANALYSIS STRATEGY



Production of MSSM Higgs bosons





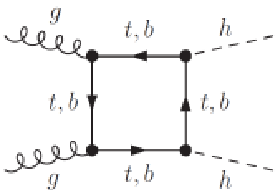
Production of two Higgs bosons

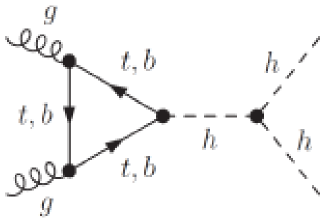
H→bb

H→ττ

MOTIVATION: HH→ $bb\tau_h\tau_h$ SEARCH

- Di-higgs production important → probe tri-linear higgs coupling.
- Low mass (125 GeV) SM Higgs gives small (Non Resonant) SM di-higgs cross section (10.16 fb @ 8TeV computed to NNLO).

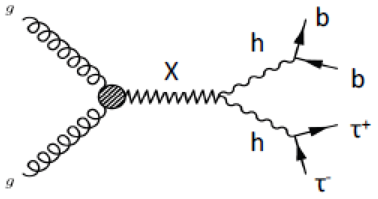




PRL 111 (2013) 201801

Leading Order Feynman Diagrams for SM (Non Resonant) Di-Higgs production

- Many BSM theories predict enhancement of di-higgs cross section (upto 1 pb) due to decay of exotic particles (e.g. Spin-0 [Radion] or Spin-2[Graviton]) to SM higgs boson pair.



Phy. Rev. Lett. 83, 4926 (1999)
arXiv:0705.3844v1

Leading Order Feynman Diagrams for BSM (Resonant) Di-Higgs production

- We searched for both Resonant and SM (Non Resonant) di-higgs production in the $bb\tau_h\tau_h$ channel (where τ_h denotes hadronic tau decay).

BACKGROUNDS

SAME FOR MSSM & DI-HIGGS ANALYSIS

$Z \rightarrow \tau\bar{\tau}$

Estimated in shape from Embedded sample comprising of $Z \rightarrow \mu\bar{\mu}$ data events in which muons are replaced by taus from simulation

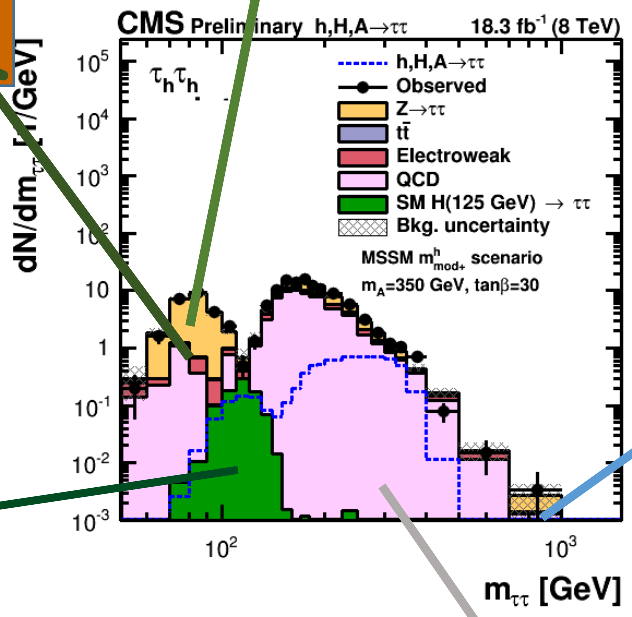
Yield is derived from $Z \rightarrow \tau\bar{\tau}$ simulation

Electroweak

This comprises of the following:

. W+Jets: Shape from simulation, yield from high m_T region in data

. Di-Boson: Estimated from simulation



$t\bar{t}$

Estimated in shape and yield from simulation which are validated in high purity regions in data from the eμ channel.

SM 125

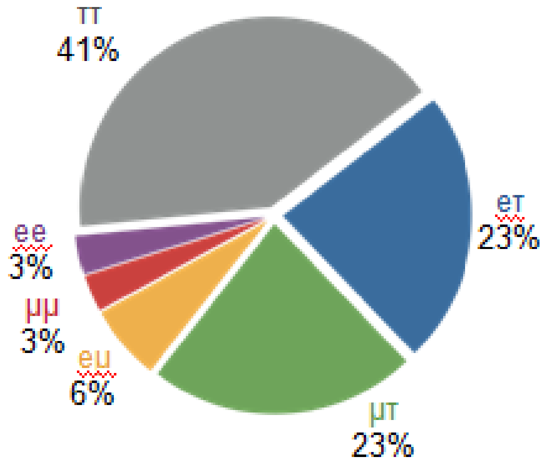
Estimated from MC, it is the sum of SM Higgs (m_H =125 GeV) backgrounds:

$ZH(H \rightarrow b\bar{b})$, $WH(H \rightarrow b\bar{b})$, $VH(H \rightarrow \tau\bar{\tau})$, $qqH(H \rightarrow \tau\bar{\tau})$, $ggH(H \rightarrow \tau\bar{\tau})$ and $H \rightarrow b\bar{b}$.

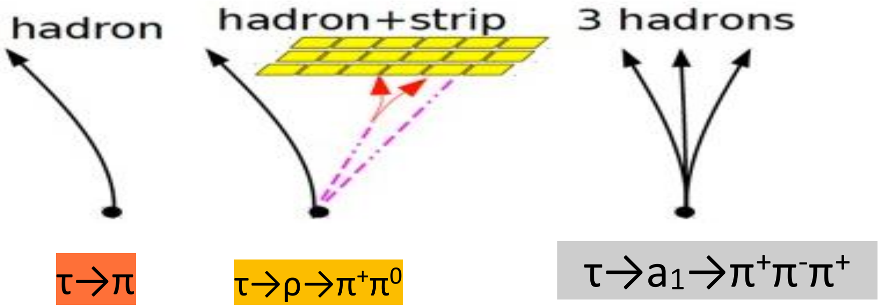
QCD

Estimated from data using sidebands defined by di-tau charge and isolation (after subtracting all other non QCD backgrounds)

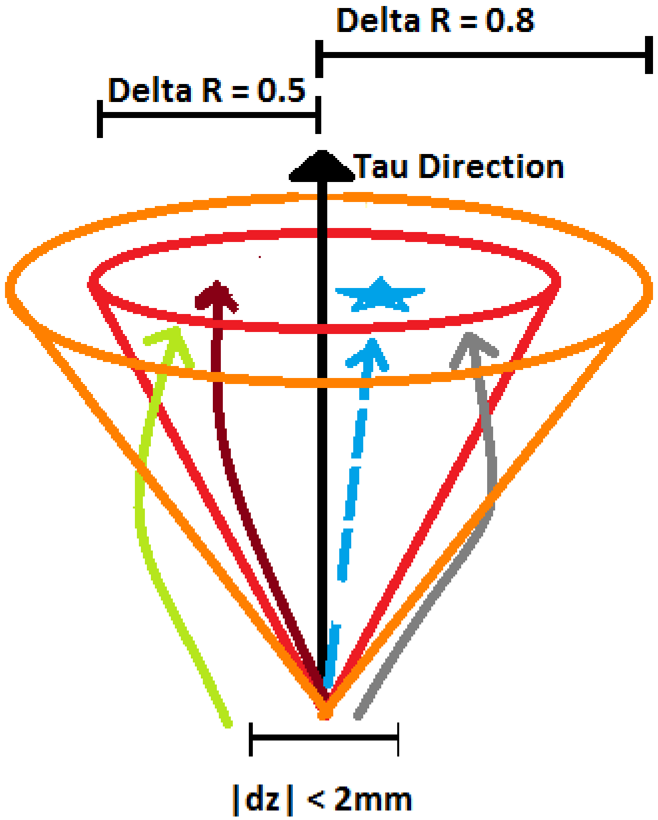
HADRONIC TAUS: IDENTIFICATION & RECONSTRUCTION



- **Tau leptons : High probability of hadronic decays (~41%).**
- **Hadronic Tau decays: 1 Prong 0π_0 , 1 Prong 1π_0 , 1 Prong 2π_0 and 3 Prong.** Prong - charged track (π^+)
- **Hadron Plus Strips Algorithm (HPS) : reconstructs and distinguishes decay modes, reduces Jet →τ_h fake rate.**
- **Tau ID efficiency at CMS ~ 60% (for Tau p_T 20 GeV - 2 TeV) and Jet → τ_h, e → τ_h and μ → τ_h fake rates around 0.1% .**
- **Taus are also required to satisfy isolation criteria (absence of hadronic activity in their immediate vicinity).**



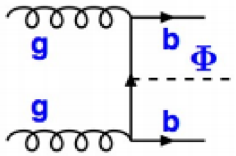
HADRONIC TAU ISOLATION: OLD

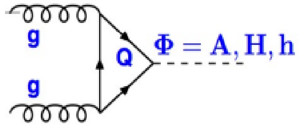


- Tau Isolation P_T Sum Input: PFCharged Hadrons (P_T > 0.5 GeV) and PFPhotons (E_T > 0.5 GeV) within dZ < 2mm from production vertex within a cone of ΔR < 0.5 .
- Production vertex: Has highest probability of association with the leading (Highest P_T) track of the Tau candidate.
- PFCharged Hadrons and Photons forming the Tau candidate, excluded from the sum.
- Pile Up contribution have to be accounted for.
- Working Points: Loose (< 2GeV), Medium (< 1GeV) and Tight (< 0.8 GeV).

MSSM $\phi \rightarrow \tau\tau$ SEARCH: CATEGORIES

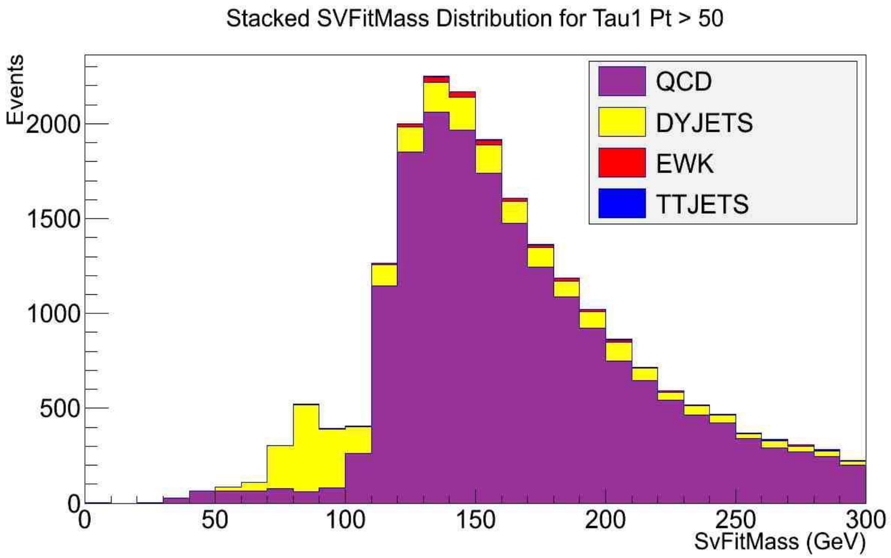
$p_T(\tau_h) > 45$ GeV, $|\eta|<2.1$ (Both Taus) Opposite Sign	b-Tag Category	No b-Tag Category
	≥ 1 b-Tagged Jets ($p_T > 20$ GeV), < 2 Jets ($p_T > 30$ GeV)	No b-Tag Jets with $p_T > 20$ GeV

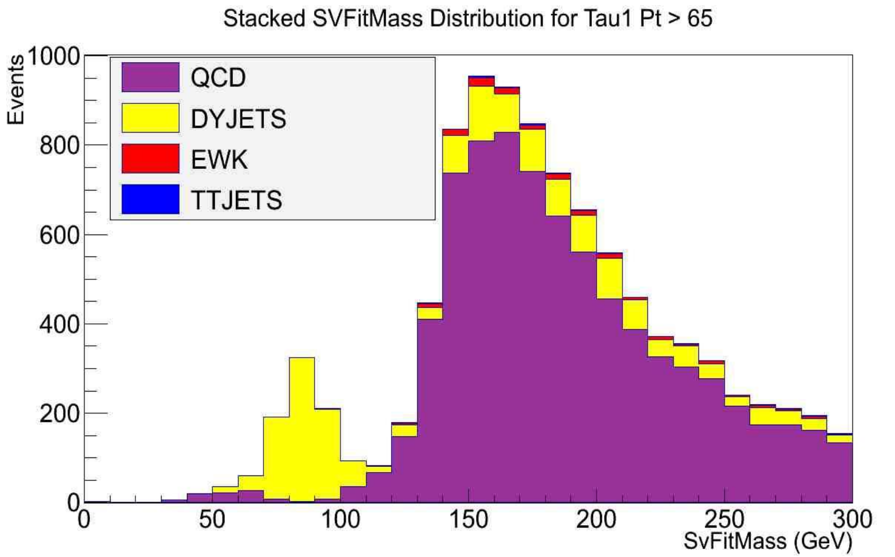


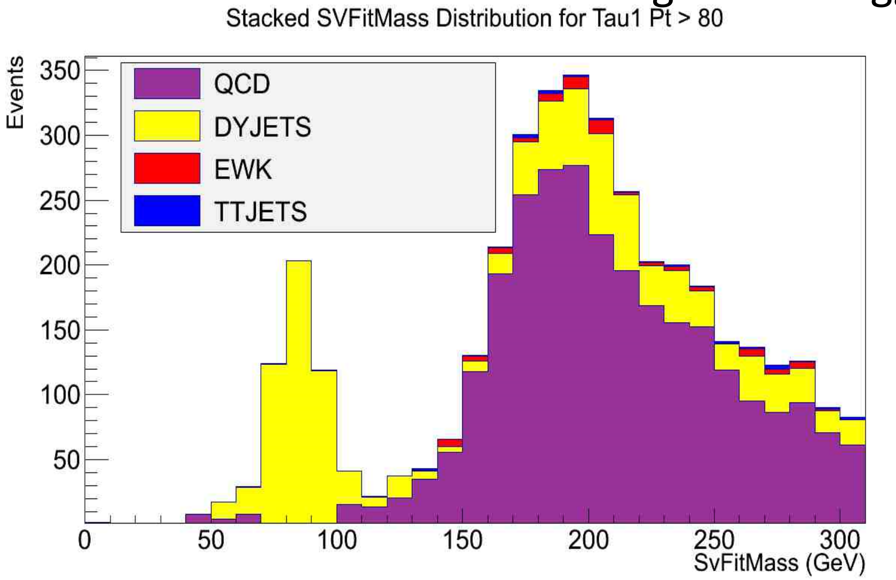


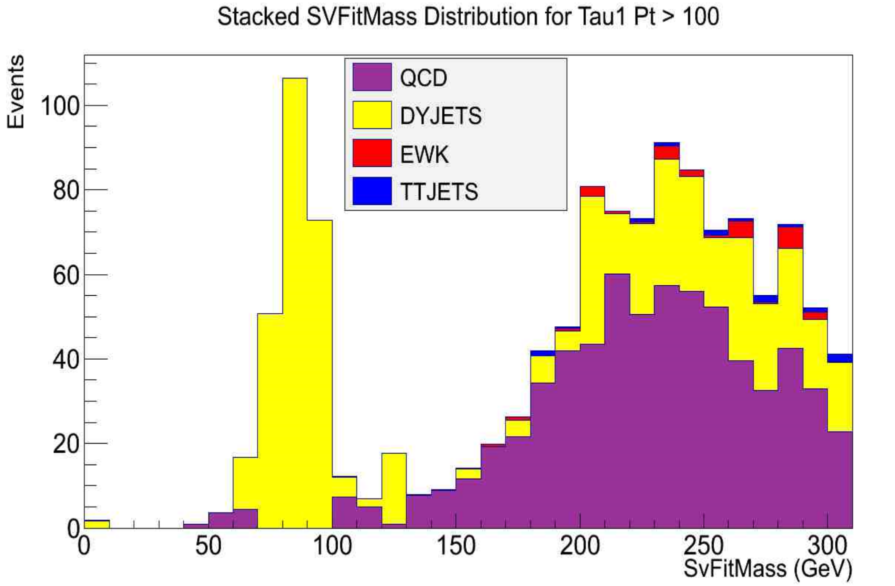
- To enhance analysis sensitivity, the dominant QCD multijets background must be reduced.
- To achieve this, scanned Tau p_T for both leading (Tau1) and sub-leading (Tau2) taus to see the effect on sensitivity (Signal/√Background) in both b-tag and no b-tag categories.

EFFECT OF TAU1 p_T CUT ON BACKGROUNDS

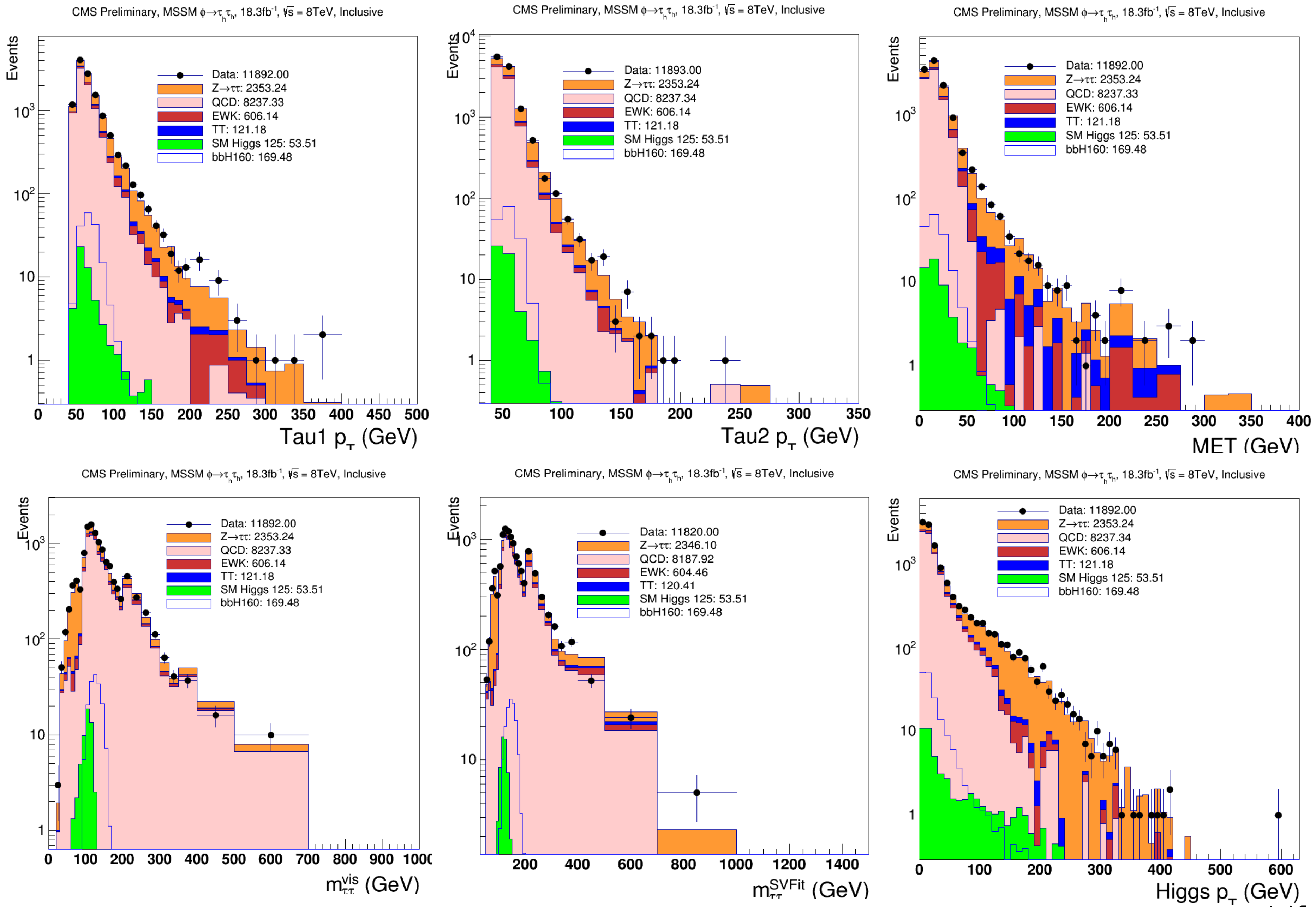








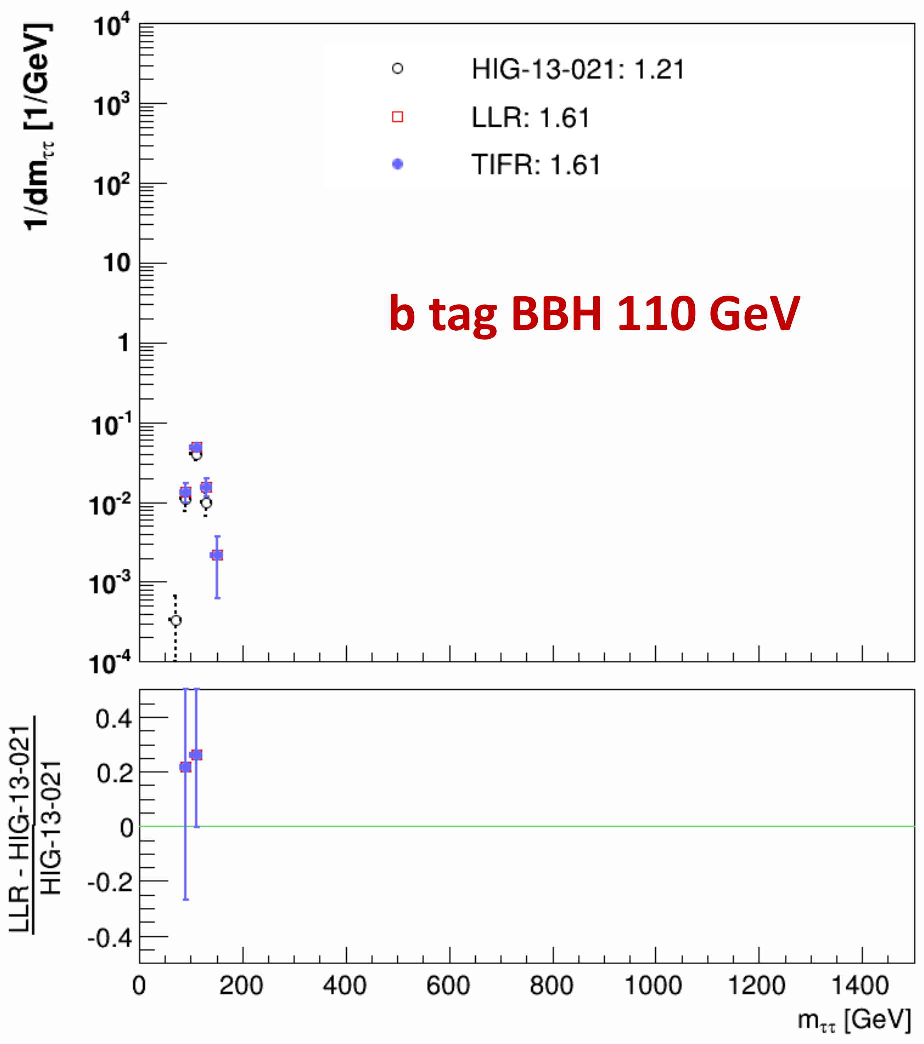
CONTROL PLOTS

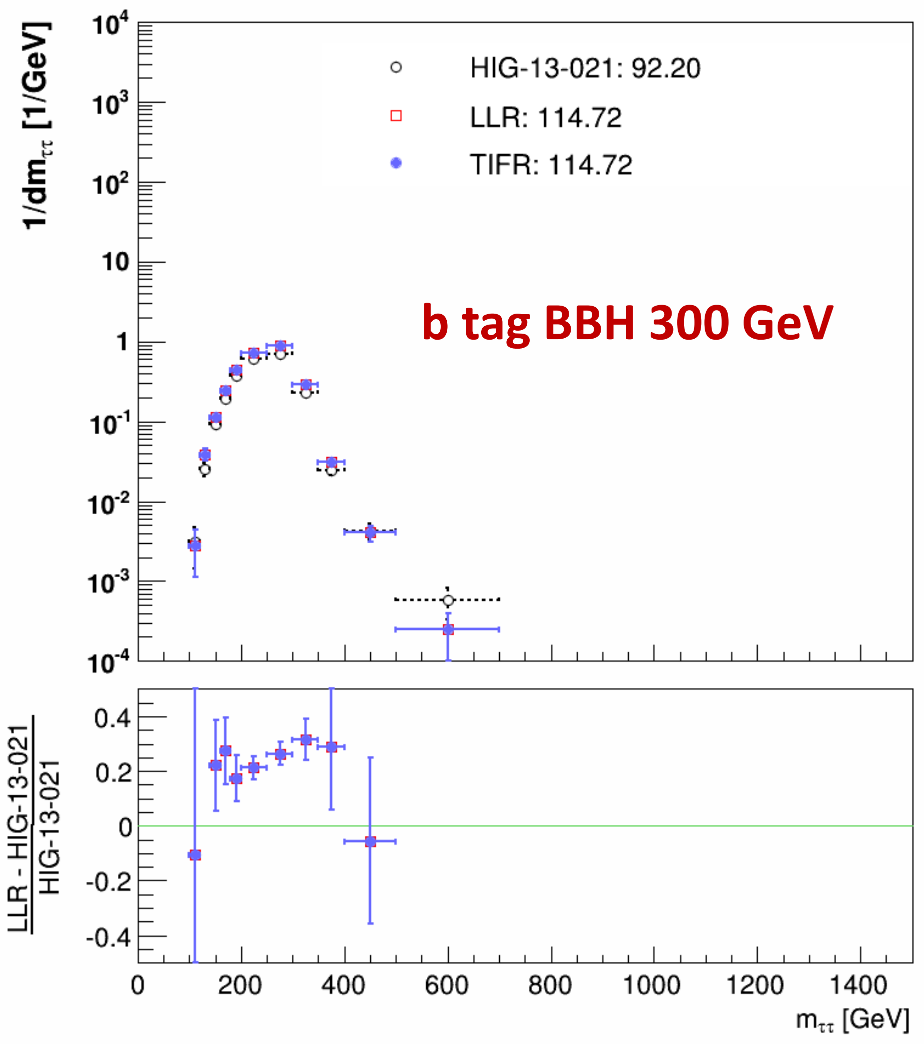


$$* \text{Higgs } p_T = |\vec{p}_t^{\,\tau_1} + \vec{p}_t^{\,\tau_2} + \text{MET}|$$

Synchronization: Higgs boson signal

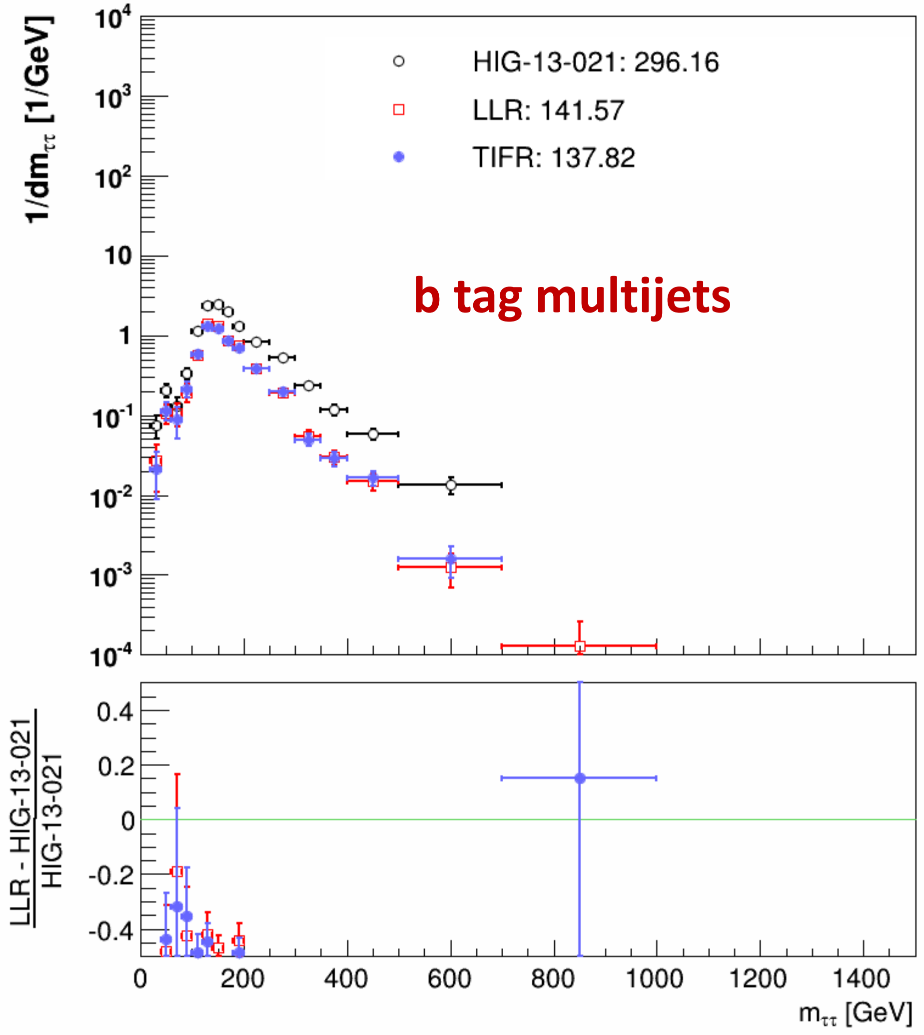
Tau1 PT > 45 && Tau2 PT > 45

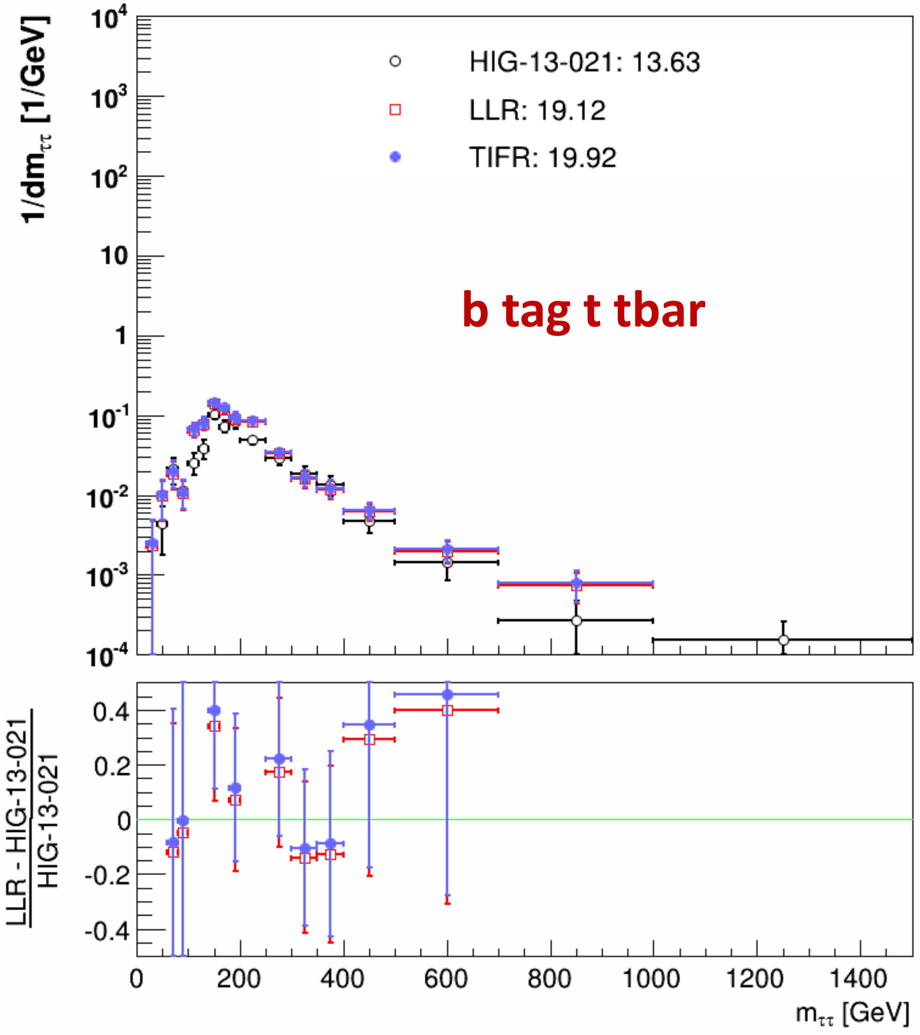




Synchronization: Background events

Tau1 PT > 45 && Tau2 PT > 45





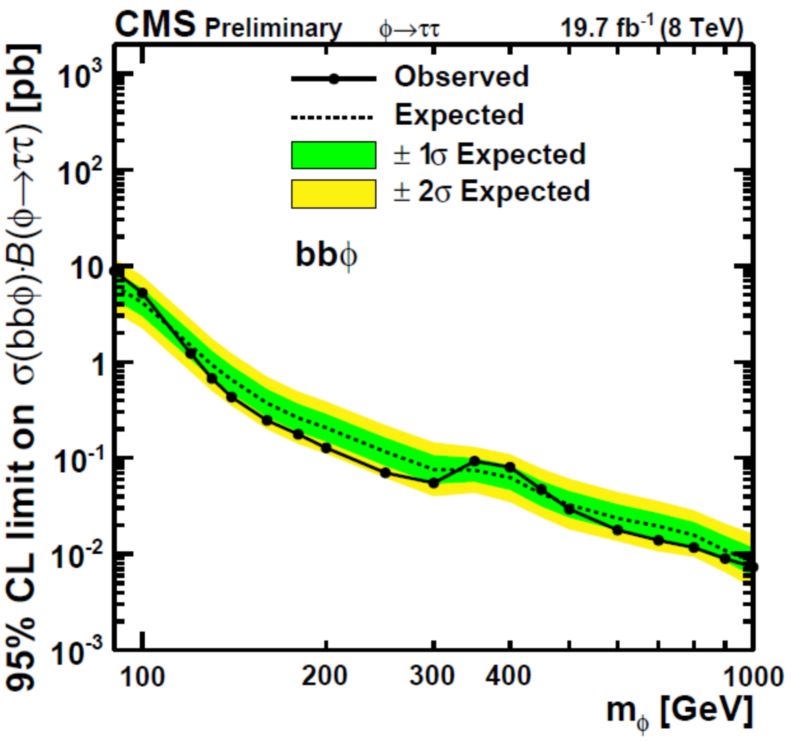
MSSM Higgs search EVENT YIELDS

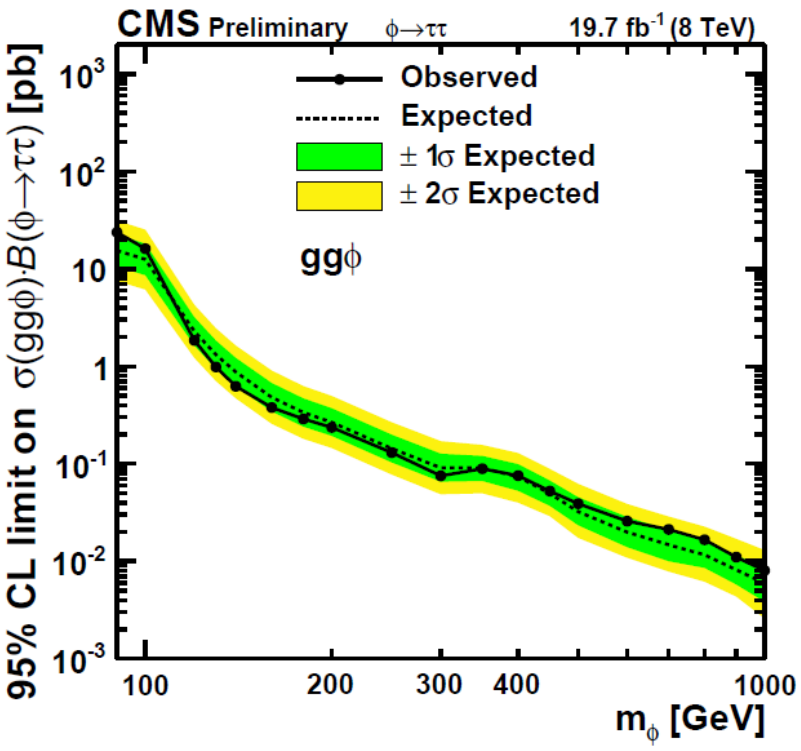
$\tau_h\tau_h$ channel $\sqrt{s} = 8$ TeV			
Process	no-b-tag		
	low	*medium*	*high*
$gg \to \phi, \phi \to \tau\tau$	66 ± 8	23 ± 5	28 ± 3
$gg \to \phi b, \phi \to \tau\tau$	82 ± 8	108 ± 10	174 ± 18
$Z \to \tau\tau$	1645 ± 73	542 ± 34	193 ± 13
QCD	6982 ± 144	942 ± 52	147 ± 21
W+jets	428 ± 116	122 ± 38	28 ± 9
Z+jets (e, μ or jet faking τ)	65 ± 10	23 ± 3	5 ± 0.9
$t\bar{t}$	23 ± 3	8 ± 1	2 ± 0.4
Di-bosons + single top	37 ± 8	16 ± 3	6 ± 1
SM Higgs	48 ± 16	8 ± 2	2 ± 0.6
Total expected	9228 ± 98	1659 ± 44	382 ± 22
Observed data	9259	1695	400

Process	b-tag	
	low	*high*
$gg \to \phi, \phi \to \tau\tau$	1 ± 0.3	1 ± 0.1
$gg \to \phi b, \phi \to \tau\tau$	18 ± 2	58 ± 8
$Z \to \tau\tau$	35 ± 3	14 ± 2
QCD	118 ± 11	21 ± 4
W+jets	6 ± 2	2 ± 1
Z+jets (e, μ or jet faking τ)	1 ± 0.2	0 ± 0.1
$t\bar{t}$	9 ± 2	5 ± 0.9
Di-bosons + single top	2 ± 0.5	3 ± 0.6
SM Higgs	1 ± 0.3	0 ± 0.1
Total expected	172 ± 11	45 ± 5
Observed data	172	41

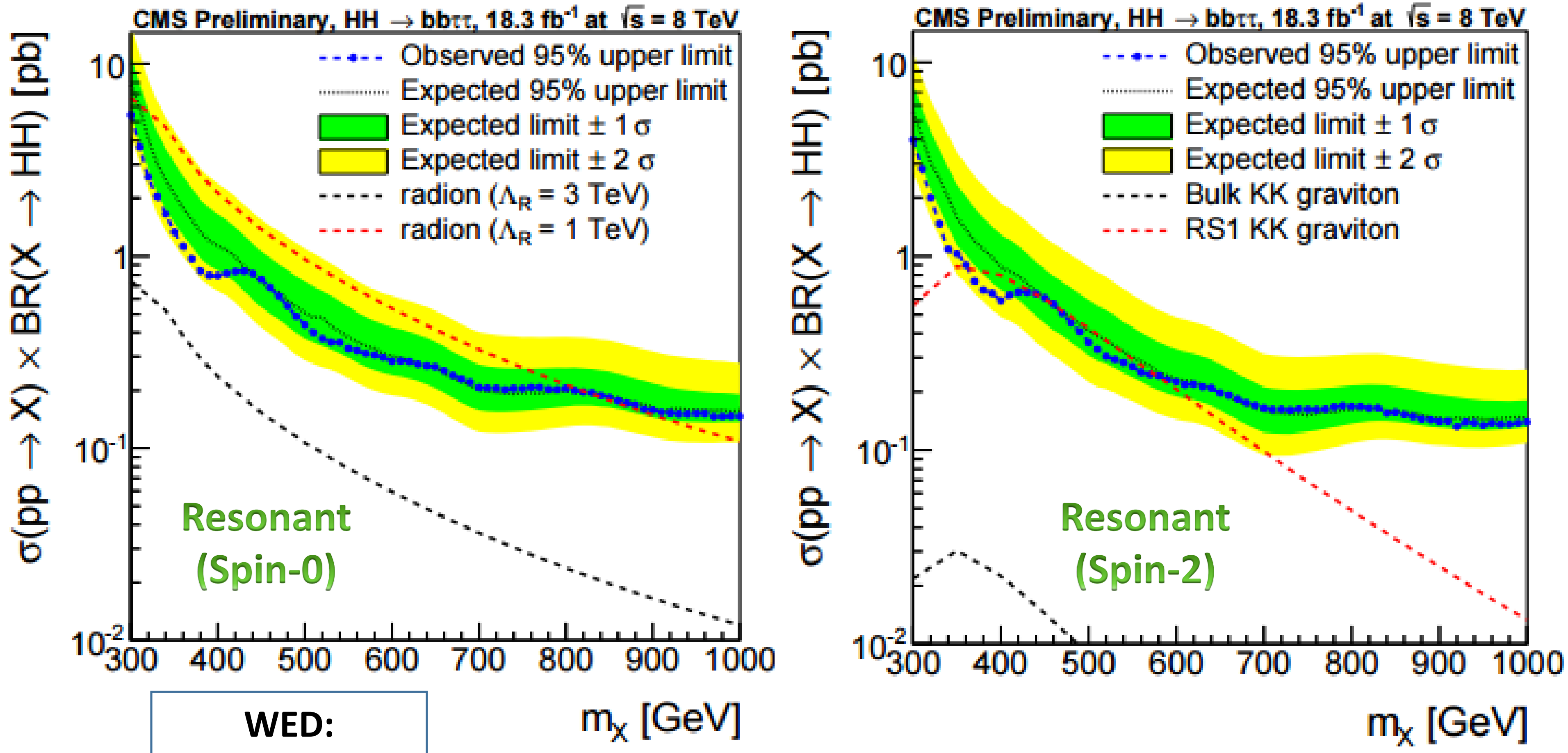
MSSM Higgs (8 TeV)

- SM 125 GeV higgs treated as background and exclusion limits are set at 95% CL for Gluon Fusion (b - assoc. production) while treating b - assoc. production (Gluon Fusion) as nuisance parameter in the Max. Likelihood fit (Profiling).





LIMITS ($X \rightarrow hh \rightarrow bb\tau_h\tau_h$) (8 TeV)



WED:
kl =35,
k/Mpl = 0.1,
No R/H mixing

CMS-PAS-HIG-15-013

CMS Collaboration and the LHC Computing Grid

The CMS collaboration

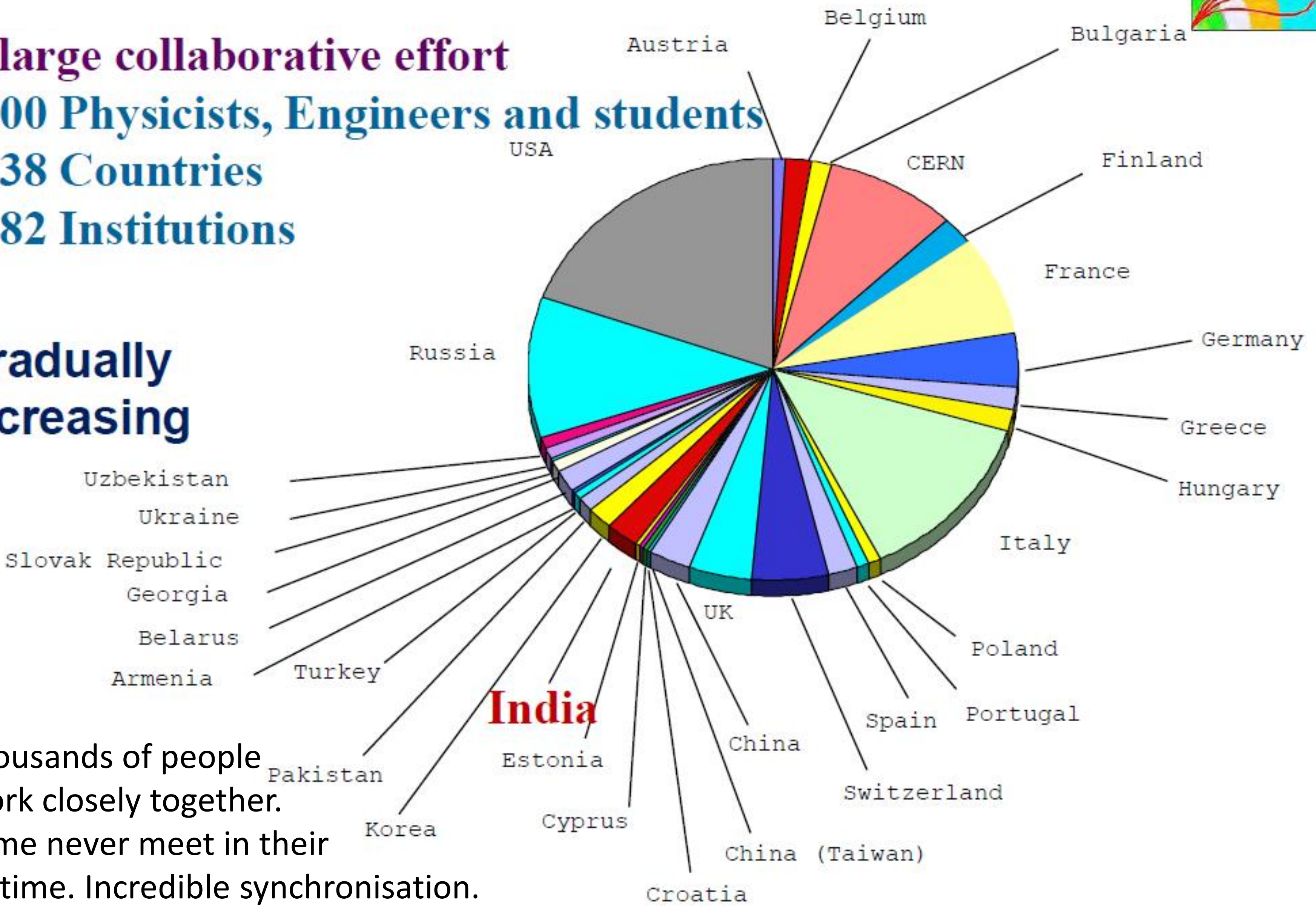
A large collaborative effort

3600 Physicists, Engineers and students

38 Countries

182 Institutions

Gradually increasing



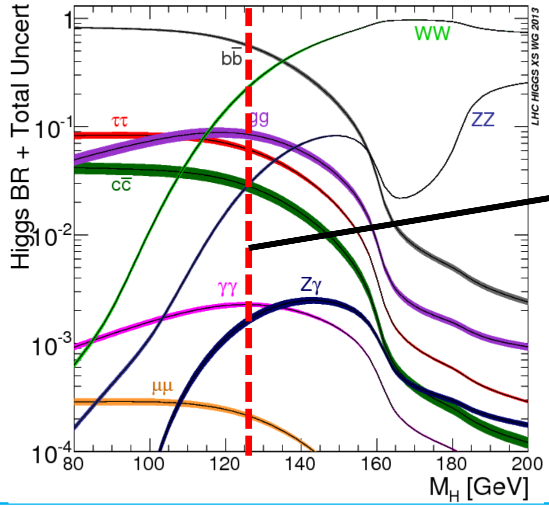
Thousands of people
Work closely together.
Some never meet in their
lifetime. Incredible synchronisation.

Outlook

- The search for HH production in the bbττ channel has been combined with bbϒϒ and bbbb channel to produce more stringent limits at 8 TeV
- The searches for H→ ττ and HH→ bbττ have been carried out at 13 TeV with 35.9 fb^{-1} . Results will soon be more public.

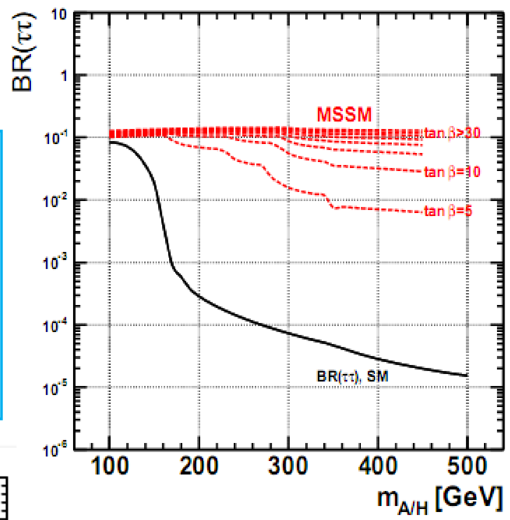
BACKUP

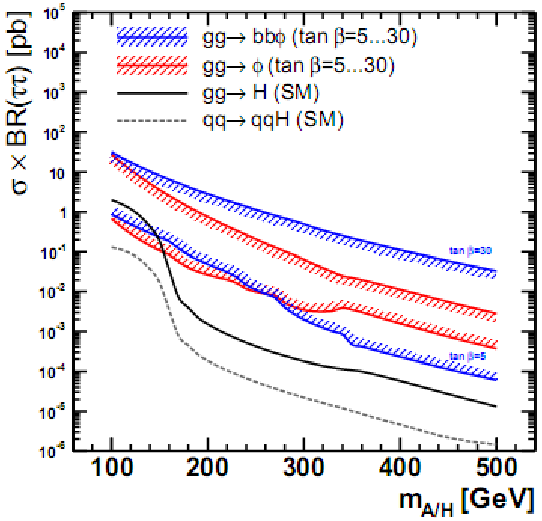
MOTIVATION-2

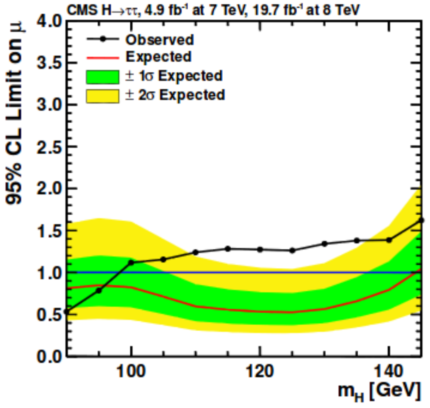


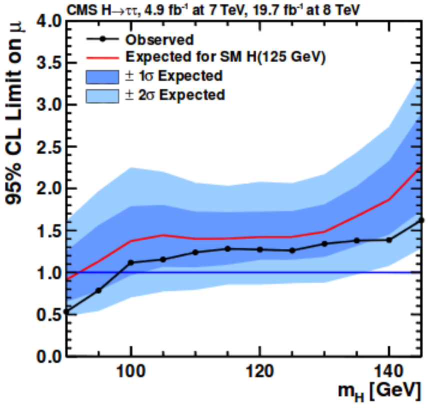
- Di-Tau final state is an important channel in Higgs searches.
- H→ττ in SM has 3rd highest Branching Ratio (~6.3% next only to bb̄ and WW) at 125 GeV.
- Only channel that constrains well Higgs couplings to fermions (Over whelming background in H→bb̄).

- H→ττ : Important in MSSM.
- σ x BR(ττ) is enhanced w.r.t SM values for large Tanβ due to enhanced bottom Yukawa coupling.



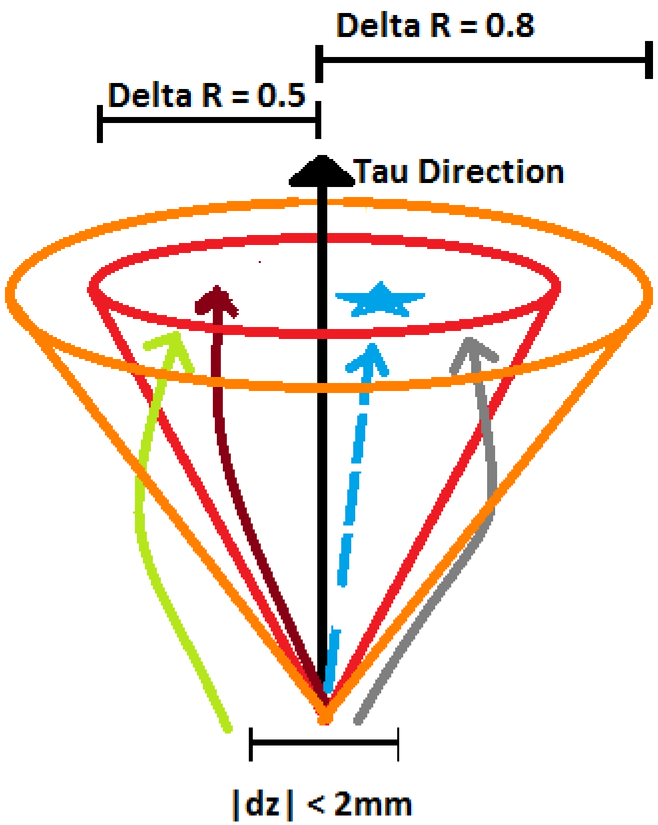






- > 3σ observation of SM Higgs decay to Taus
  http://dx.doi.org/10.1007/JHEP(2014)104
- Triggered interest in interpreting this particle in context of BSM physics scenarios (esp. SUSY).

HADRONIC TAU ISOLATION: OLD



$$I_\tau = \sum p_T^{charged}(\Delta z < 2mm) + max(p_T^\gamma - \Delta\beta, 0)$$

$$\Delta\beta = 0.4576 \cdot \sum p_T^{charged}(\Delta z > 2mm)$$

- Tau Isolation P_T Sum Input: PFCharged Hadrons (P_T > 0.5 GeV) and PFPhotons (E_T > 0.5 GeV) within dZ < 2mm from production vertex within a cone of ΔR < 0.5 .
- Production vertex: Has highest probability of association with the leading (Highest P_T) track of the Tau candidate.
- PFCharged Hadrons and Photons forming the Tau candidate, excluded from the sum.
- Pile Up contribution accounted for by applying Δβ corrections.
- Δβ corrections: Computed by summing the P_T of PFCharged Hadrons having dZ > 2mm from production vertex within a cone of ΔR < 0.8.
- They are scaled by a factor (0.4576) to make them insensitive to Pile Up.
- Working Points: Loose (< 2GeV), Medium (< 1GeV) and Tight (< 0.8 GeV).

HADRONIC TAU ISOLATION: NEW

- **BDT based Isolation uses the following input variables :**
  1. **P_T and η of the reconstructed τ_h candidate and the reconstructed decay mode.**
  2. **Charged Particle Isolation P_T sum :**

     $$\sum P_T^{Charged} (\Delta z < 2\,\mathrm{mm})$$

  3. **Neutral Particle Isolation P_T sum :**

     $$\sum P_T^{\gamma}$$

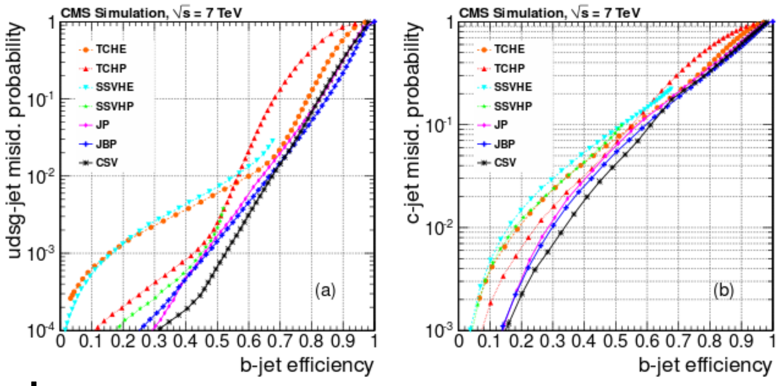
  4. **Δβ corrections.**
  5. **Transverse Impact parameter (d_0) of the leading track of the τ_h candidate and its significance (d_0/σ_{d0}) for 1Prong0π0 and 1Prong1π0 decay modes.**

  6. **Distance b/w τ_h production and decay vertex and its significance for 3Prong0π0 decay mode :**

     $$\left| \vec{r}_{PV} - \vec{r}_{SV} \right| \,, \quad \left| \vec{r}_{PV} - \vec{r}_{SV} \right| \Big/ \sigma_{\left| \vec{r}_{PV} - \vec{r}_{SV} \right|}$$

- **MVA trained on simulated Φ→ττ, Z→ττ, Z'→ττ and W'→τν "Signal" samples (~ 10^6 events each) and QCD multijets, WJets and Z→ll (l = e/μ) "background " samples covering 20 GeV to 2000 GeV in Gen Tau P_T.**

b-TAGGING



Sec. Vtx. Candidate selection

- 100 μm < $|d_{(Prim.Vtx-Sec.Vtx)}|$ < 2.5 cm
- $|d_{(Prim.Vtx-Sec.Vtx)}/\sigma_{d(Prim.Vtx-Sec.Vtx)}| > 3$
- Invariant mass of charged particles assoc. to Sec. Vtx < 6.5 GeV
- Sec. Vtx incompatible with K^0_s decay (having 2 OS charge tracks having inv. Mass within □ 50 MeV around K^0_s mass[497 MeV]).

Sec. Vtx. Candidate events divided into 3 categories

Reco. Vtx. (>1 Sec. Vtx)

- Invariant mass of charged particles of Sec. Vtx.
- Charged particle multiplicity
- $|d_{(Prim.Vtx-Sec.Vtx)}/\sigma_{d(Prim.Vtx-Sec.Vtx)}|$
- $E_{Sec.Vtx\ Chg\ partcles}/E_{Jet\ Chg\ particles}$
- Charged particle rapidity

Pseudo Vtx. (0 Sec. Vtx)

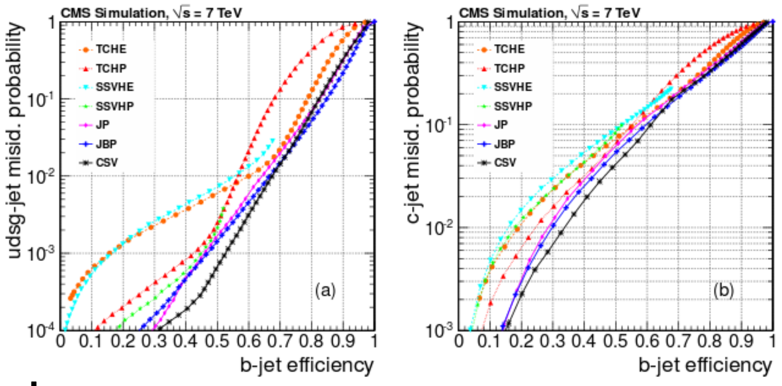
- Charged hadron tracks incompatible with Prim. Vtx.

No Vtx.

- Complement of other 2 categories.

All these variables are combined into 1 single discriminator using likelihood ratio

b-TAGGING



Sec. Vtx. Candidate selection

- 100 μm < $|d_{(Prim.Vtx-Sec.Vtx)}|$ < 2.5 cm
- $|d_{(Prim.Vtx-Sec.Vtx)}/\sigma_{d(Prim.Vtx-Sec.Vtx)}| > 3$
- Invariant mass of charged particles assoc. to Sec. Vtx < 6.5 GeV
- Sec. Vtx incompatible with K^0_s decay (having 2 OS charge tracks having inv. Mass within □ 50 MeV around K^0_s mass[497 MeV]).

Sec. Vtx. Candidate events divided into 3 categories

Reco. Vtx. (>1 Sec. Vtx)

- Invariant mass of charged particles of Sec. Vtx.
- Charged particle multiplicity
- $|d_{(Prim.Vtx-Sec.Vtx)}/\sigma_{d(Prim.Vtx-Sec.Vtx)}|$
- $E_{Sec.Vtx\ Chg\ partcles}/E_{Jet\ Chg\ particles}$
- Charged particle rapidity

Pseudo Vtx. (0 Sec. Vtx)

- Charged hadron tracks incompatible with Prim. Vtx.

No Vtx.

- Complement of other 2 categories.

All these variables are combined into 1 single discriminator using likelihood ratio

"sTransverse Mass" (m_{T2}): new variable for Non Resonant Di-Higgs search

- **Unlike the resonant case, search for SM non resonant di-higgs search suffers from large $t\bar{t}$ background.**

- **For better signal to background discrimination we use a new variable, m_{T2} called 'sTranverse mass' (arXiv:1309.6318v1) .**

- **Consider an event where 2 equal mass particles A and A' decay as:**

$$\mathrm{A} \rightarrow \mathrm{B} + \mathrm{C} \ \ (\text{e.g. } \ \mathrm{t} \rightarrow \mathrm{b} + W^{+} \rightarrow \mathrm{b} + \tau^{+} + \upsilon_{\tau})$$

$$\mathrm{A'} \rightarrow \mathrm{B'} + \mathrm{C'} \ \ (\text{e.g. } \ \bar{\mathrm{t}} \rightarrow \bar{\mathrm{b}} + W^{-} \rightarrow \bar{\mathrm{b}} + \tau^{-} + \bar{\upsilon}_{\tau})$$

where B, B' correspond to visible and C, C' correspond to invisible particles of the decays. Then m_{T2} is given by:

$$m_{\mathrm{T2}}(m_B, m_{B'}, \vec{b}_T, \vec{b}_T^{'}, m_C, m_C^{'}) \equiv \min_{\vec{c}_T + \vec{c}_T^{'} = \sum \vec{p}_T = -MET} \{\max(m_T, m_T^{'})\}$$

Here, m_T is defined as,

$$m_{\mathrm{T}}(\vec{b}_{\mathrm{T}}, \vec{c}_{\mathrm{T}}, m_b, m_c) \equiv \sqrt{m_{\mathrm{b}}^2 + m_{\mathrm{c}}^2 + 2(E_b E_c - \vec{b}_T . \vec{c}_T)} \quad \text{where,} \mathrm{E}_{\mathrm{b/c}} = \sqrt{m_{\mathrm{b/c}}^2 + \vec{p}_T^2}$$

For $t\bar{t}$ events, m_{T2} is bounded above by top mass (in the narrow width approx. and in absence of detector related effects) but for genuine hh signal, it can be higher.

MSSM $\phi \rightarrow \tau\tau$ SEARCH: NEW CATEGORIES

Categories in the MSSM Higgs search

CATEGORY NAME	TAU2 P_T BINS (TAU1 P_T > 45 GeV)
NON B-TAG LOW	45 GeV < TAU2 P_T ≤ 60GeV
NON B-TAG MEDIUM	60 GeV < TAU2 P_T ≤ 80GeV
NON B-TAG HIGH	80 GeV < TAU2 P_T
B-TAG LOW	45 GeV < TAU2 P_T ≤ 60GeV
B-TAG HIGH	60 GeV < TAU2 P_T

LIMITED BY STATISTICS

POST FIT EVENT YIELDS

HH Production

Non-resonant analysis			
Process	2jet0tag	2jet1tag	2jet2tag
Non-resonant HH production	1 ± 0.1	5 ± 0.5	4 ± 0.5
$Z \rightarrow \tau\tau$	120 ± 12	18 ± 3	2 ± 0.8
QCD	28 ± 3	5 ± 0.9	1 ± 0.2
W+jets	4 ± 0.9	–	–
Z+jets (e, μ or jet faking τ)	1 ± 0.2	–	–
$t\bar{t}$	1 ± 0.2	3 ± 0.5	1 ± 0.2
Di-bosons + single top	6 ± 1	1 ± 0.2	0 ± 0.1
SM Higgs	4 ± 1	1 ± 0.2	0 ± 0.1
Total expected	164 ± 11	28 ± 3	5 ± 1
Observed data	165	26	1

m_X=500 GeV →

Resonant analysis			
Process	2jet0tag	2jet1tag	2jet2tag
Radion → HH	2 ± 0.2	6 ± 0.7	6 ± 0.8
Graviton → HH	2 ± 0.4	8 ± 0.9	8 ± 0.9
$Z \rightarrow \tau\tau$	131 ± 13	20 ± 3	3 ± 1
QCD	92 ± 8	13 ± 2	2 ± 0.6
W+jets	8 ± 2	1 ± 0.3	–
Z+jets (e, μ or jet faking τ)	2 ± 0.5	–	–
$t\bar{t}$	2 ± 0.4	5 ± 0.7	3 ± 0.45
Di-bosons + single top	6 ± 1	2 ± 0.4	0.0 ± 0.1
SM Higgs	5 ± 2	1 ± 0.2	0.0 ± 0.1
Total expected	247 ± 14	41 ± 4	8 ± 1
Observed data	268	39	4

No evidence for signal

LIMITS ($gg \rightarrow hh \rightarrow bb\tau_h\tau_h$)

LIMIT	VALUE (pb)
+2σ	2.289 (225 x SM)
+1σ	1.439 (141 x SM)
Expected	0.876 (86 x SM)
-1σ	0.548 (54 x SM)
-2σ	0.362 (36 x SM)
Observed	0.502 (50 x SM)

Best Run-1 Non Reso. bbττ Result (by a factor of 2)

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