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Preliminary Exam

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MSSM Higgs Decays to Tau Leptons and Bottom Quarks using CMS at the LHC

Outline

Physics

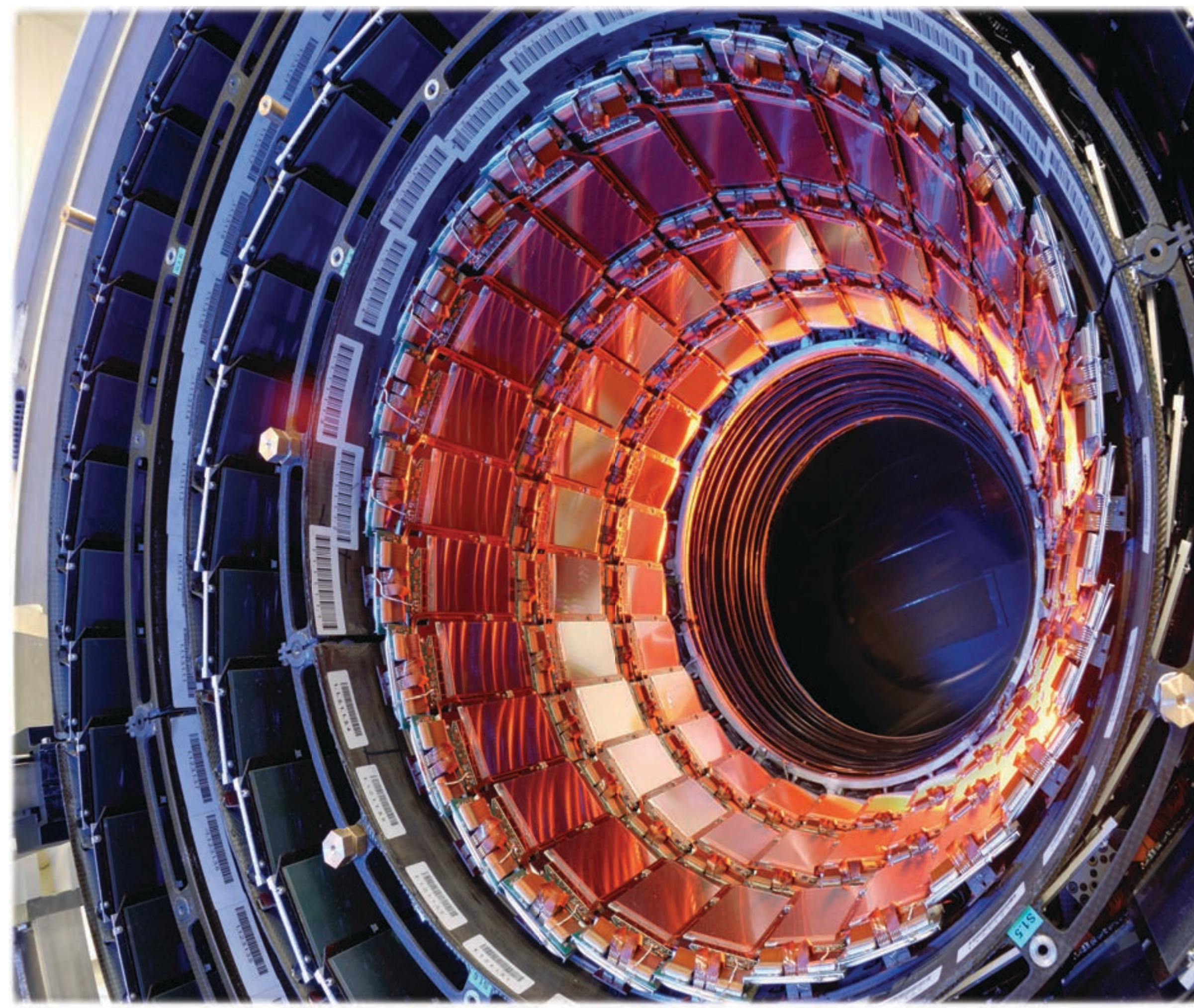
- Standard Model
- MSSM Higgs motivation
- Signature

Experiment

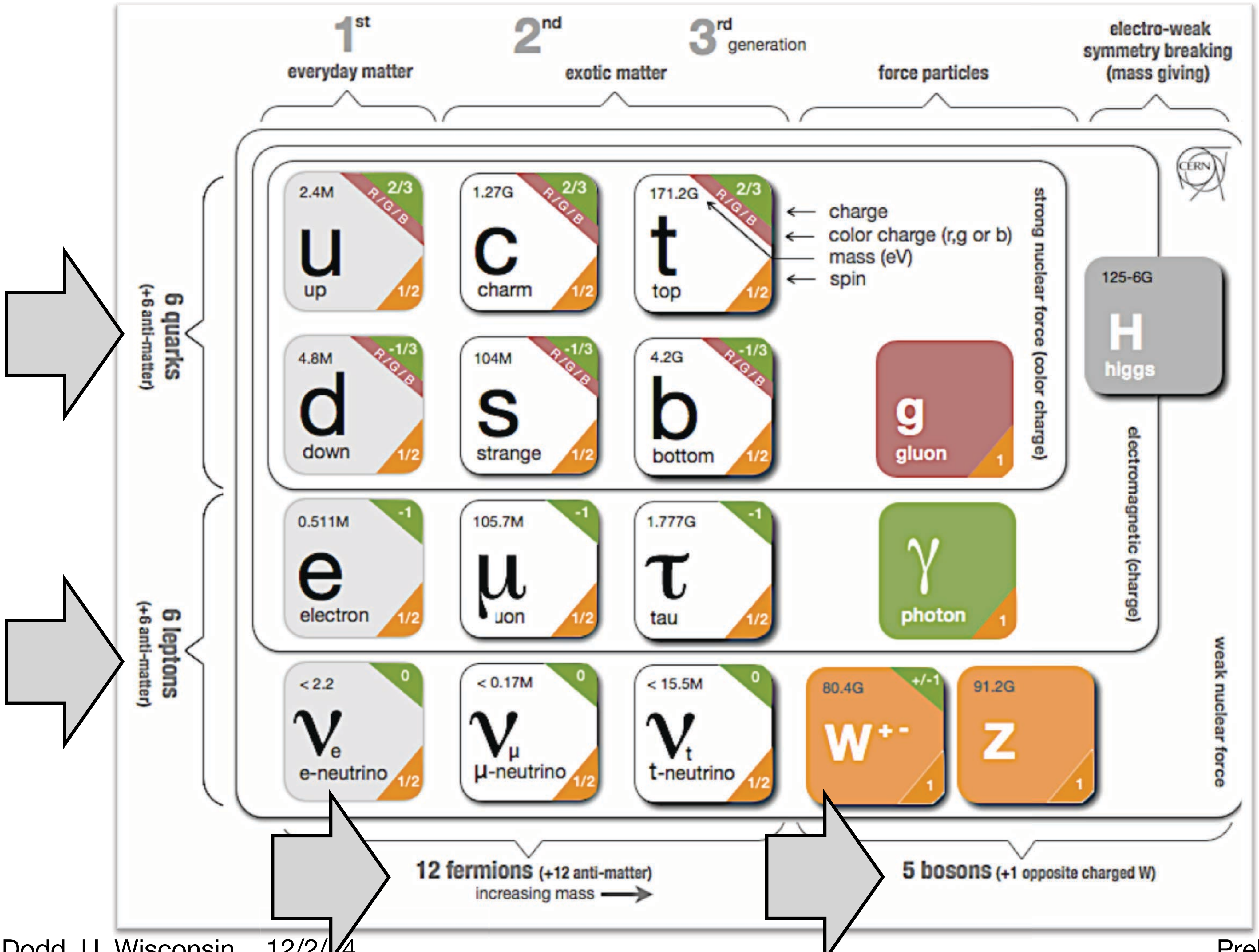
- Large Hadron Collider
- Compact Muon Solenoid

Analysis

- Backgrounds
- Expected Limit



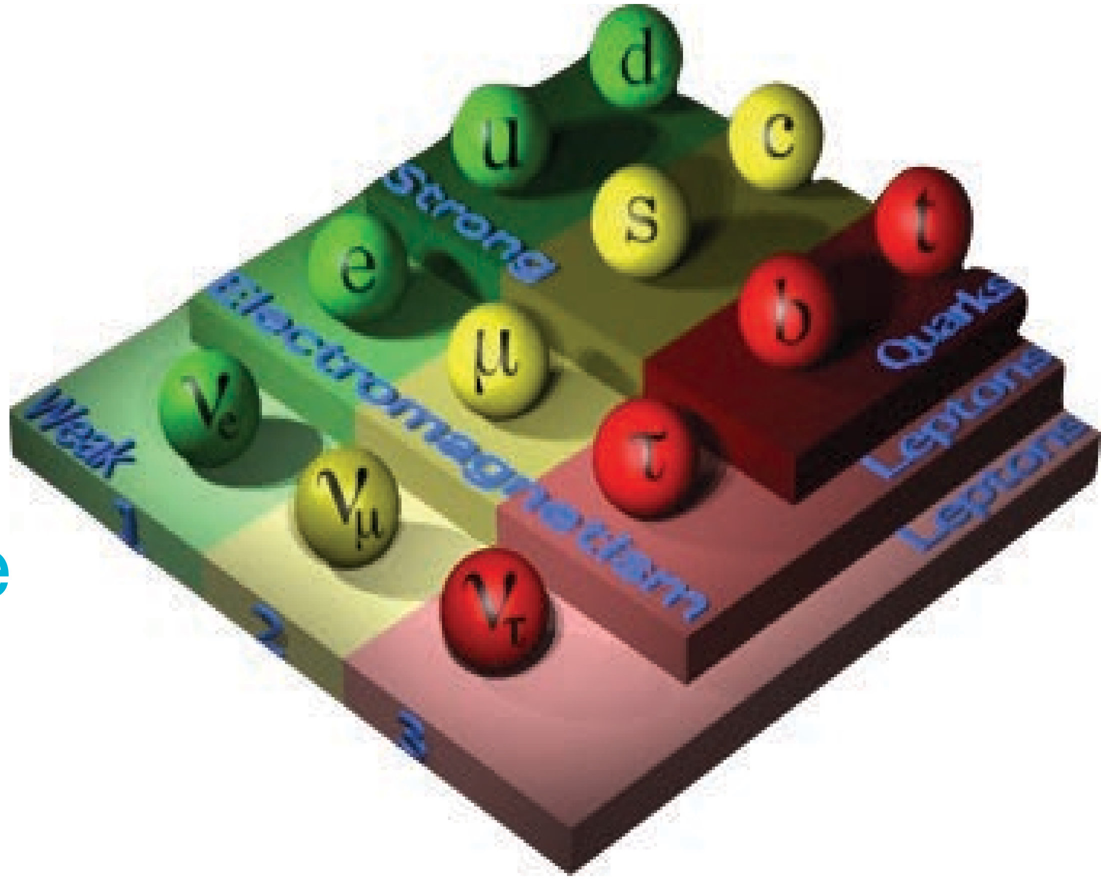
Standard Model Particles



Standard Model Bosons

Gauge Bosons

- Force carriers
  - Gluon (g): Strong Force
  - Photon (γ): Electromagnetic Force
  - $W^{+/-}$, Z^0: Weak Force



Standard Model Higgs

Higgs Mechanism

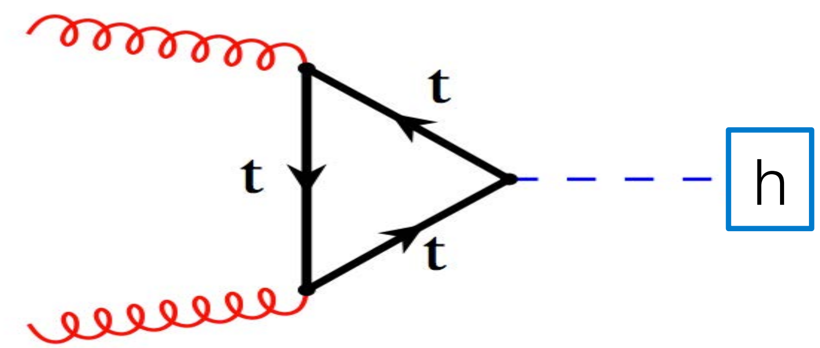
- Without the Higgs mechanism all the gauge bosons are massless in the Standard Model
  - Spontaneous symmetry breaking gives mass to $W^{+/-}$, Z^0
- Massive Higgs boson

Higgs boson

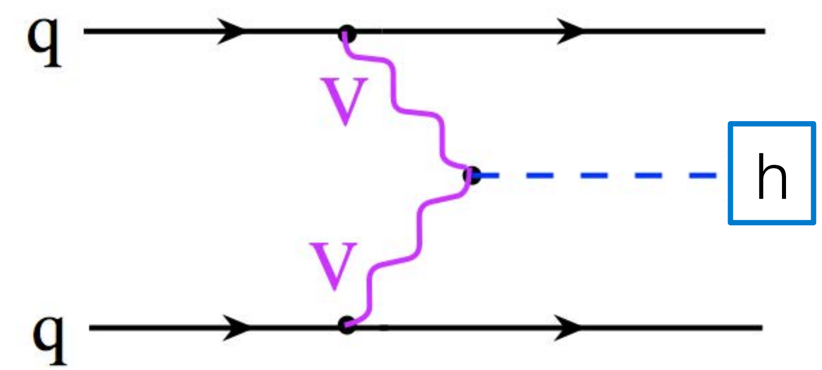
- In 2012 CMS and ATLAS announced the discovery of a particle at 125 GeV that is consistent with the SM Higgs

8 TeV SM Higgs Production (pp)

Gluon Fusion ~19.3 pb



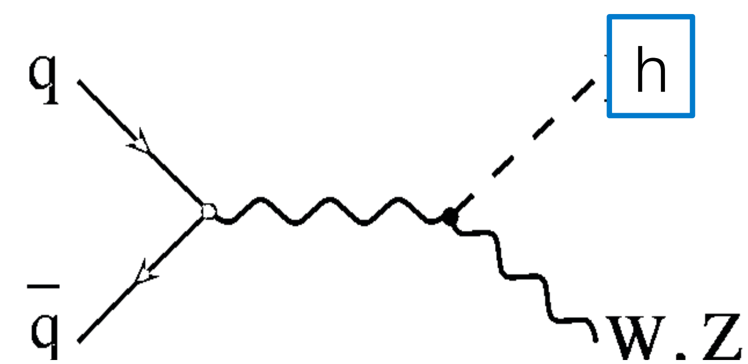
Vector boson fusion (VBF) ~1.58 pb



Wh, Zh associated production

Wh: ~0.7 pb

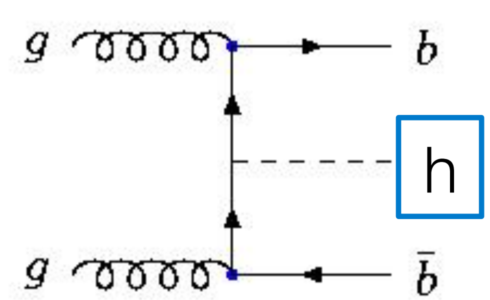
Zh: ~0.4 pb

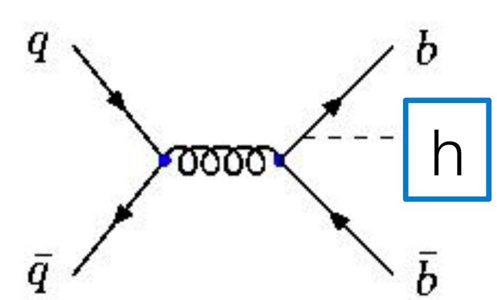


bbh, tth associated production

tth: ~0.13 pb

bbh: ~0.2 pb





SM Higgs Decays

At M_h=125 GeV: Main SM decay modes

- bb
  - largest branching ratio, but large QCD background
  - test Higgs coupling to quarks
- WW
  - final state lvlv make it difficult analysis
- ττ
  - large branching ratio
  - test Higgs coupling to fermions
- gg
  - very very small S/B!
- ZZ
  - small branching ratio but high S/B
  - very good resolution
- γγ
  - small branching ratio
  - very good resolution

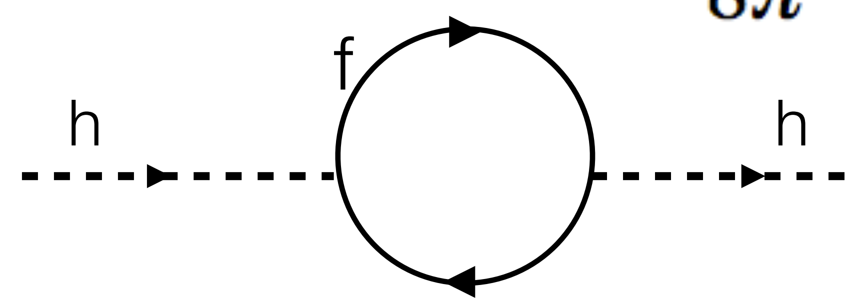
Decay channel	Branching ratio
$h \to \gamma\gamma$	2.28×10^{-3}
$h \to ZZ$	2.64×10^{-2}
$h \to W^+W^-$	2.15×10^{-1}
$h \to \tau^+\tau^-$	6.32×10^{-2}
$h \to b\bar{b}$	5.77×10^{-1}
$h \to Z\gamma$	1.54×10^{-3}
$h \to \mu^+\mu^-$	2.19×10^{-4}

Supersymmetry (SUSY)

SM problem

- Correction to the higgs mass is quadratically divergent
  - Excessive fine-tuning required to make the Higgs 125 GeV mass much lower than the Planck mass

$$-\frac{\lambda_f^2}{8\pi^2}\Lambda_{UV}^2$$



SUSY

- Particles have a superpartner whose spin differs by half-integer spin
  - Must be a broken symmetry

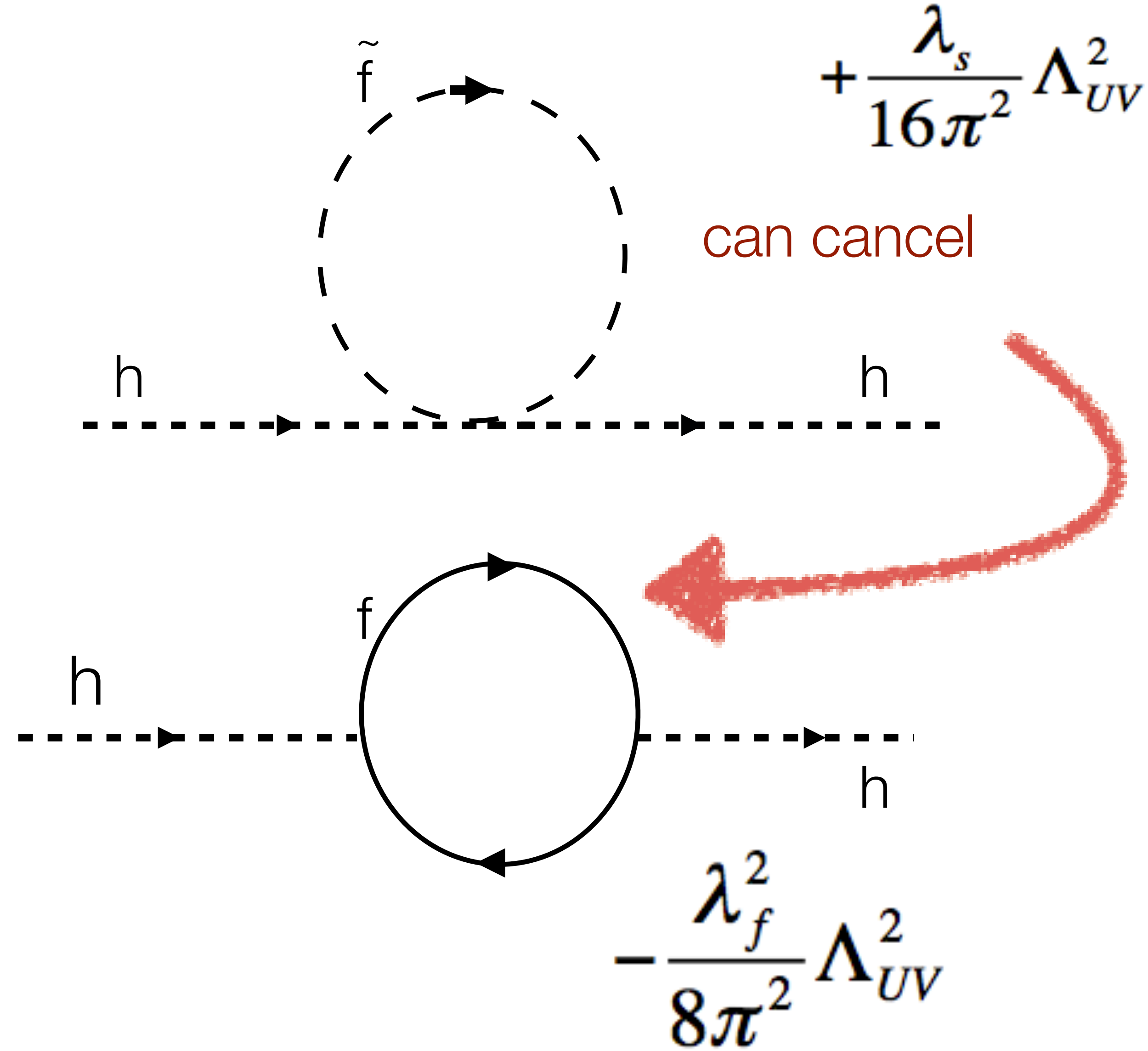
SUSY/MSSM

Minimal Supersymmetric Standard Model (MSSM)

- All SM particles have a superpartner
- Two Higgs doublets
  - 2 vacuum expectation values (v.e.v.)

Higgs self-energy corrections are quadratically divergent.

- Superpartner loop can cancel the divergent loop



MSSM Higgs Sector

Take discovered Higgs boson M_h=125 GeV as the MSSM h

5 Higgs

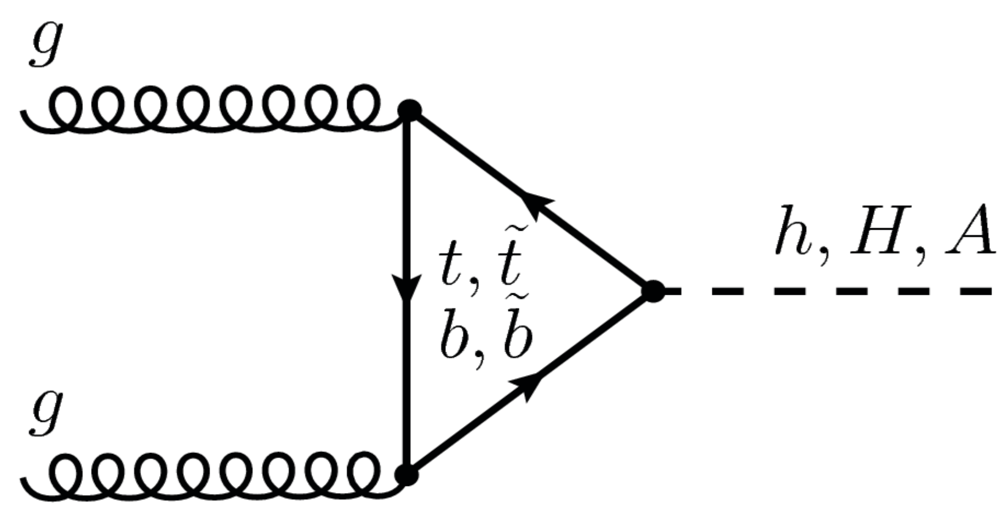
- h, H, A, $H^{+/-}$

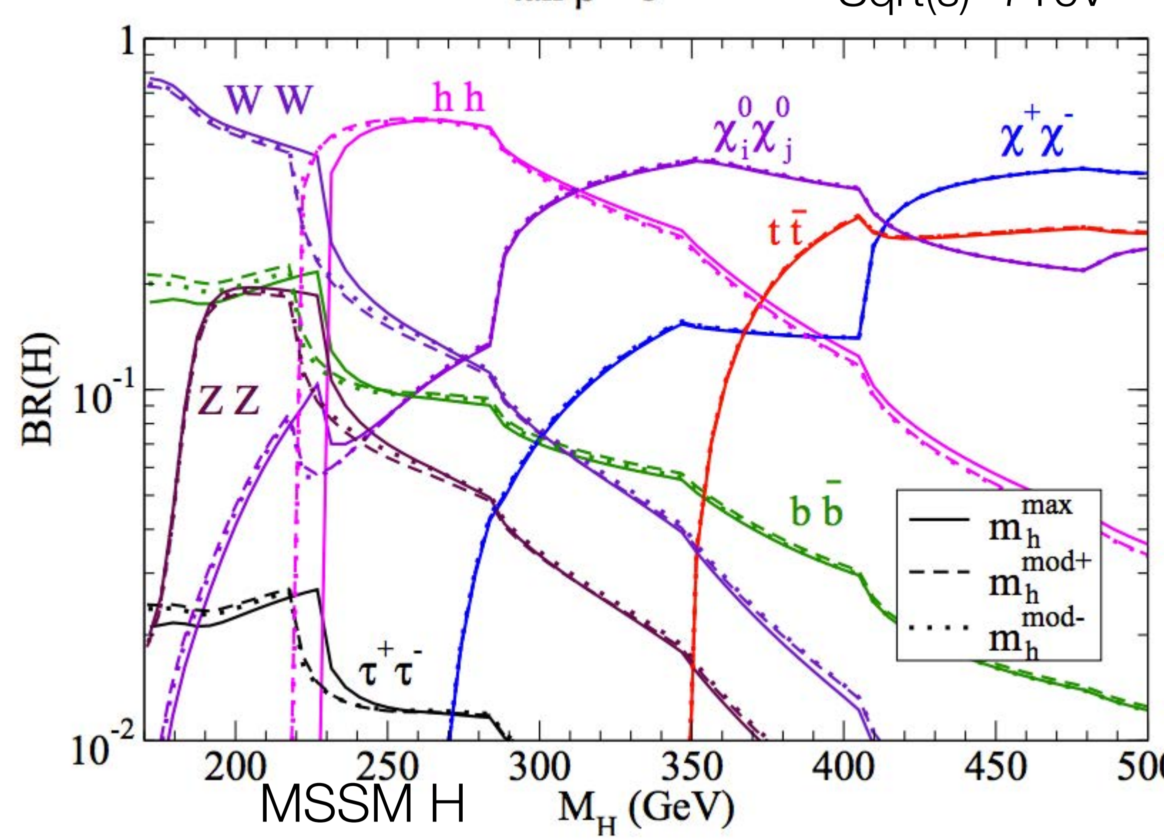
Two main parameters

- tanβ=ratio of the two v.e.v.'s
  - Two higgs doublets
- M_A, mass of the pseudoscalar A

Heavy Higgs, H

- Heavier than SM-like 125 GeV higgs h.
- Gluon-Gluon Fusion
- For tanβ=2 gg->H(300): 1.55 pb





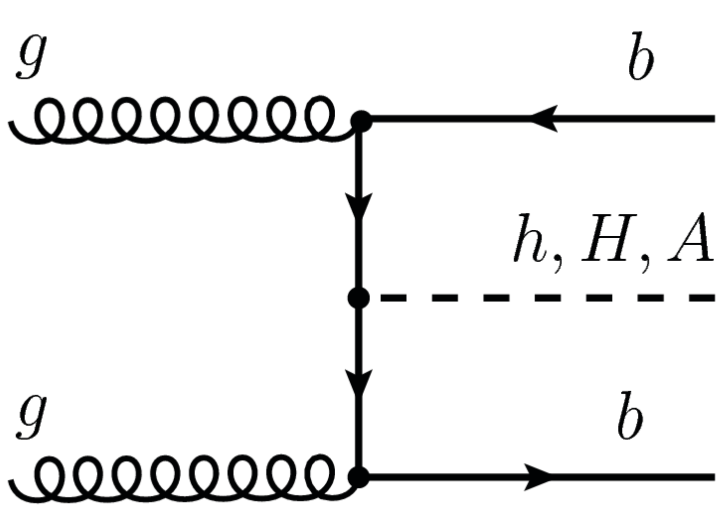
Previous Results MSSM Higgs

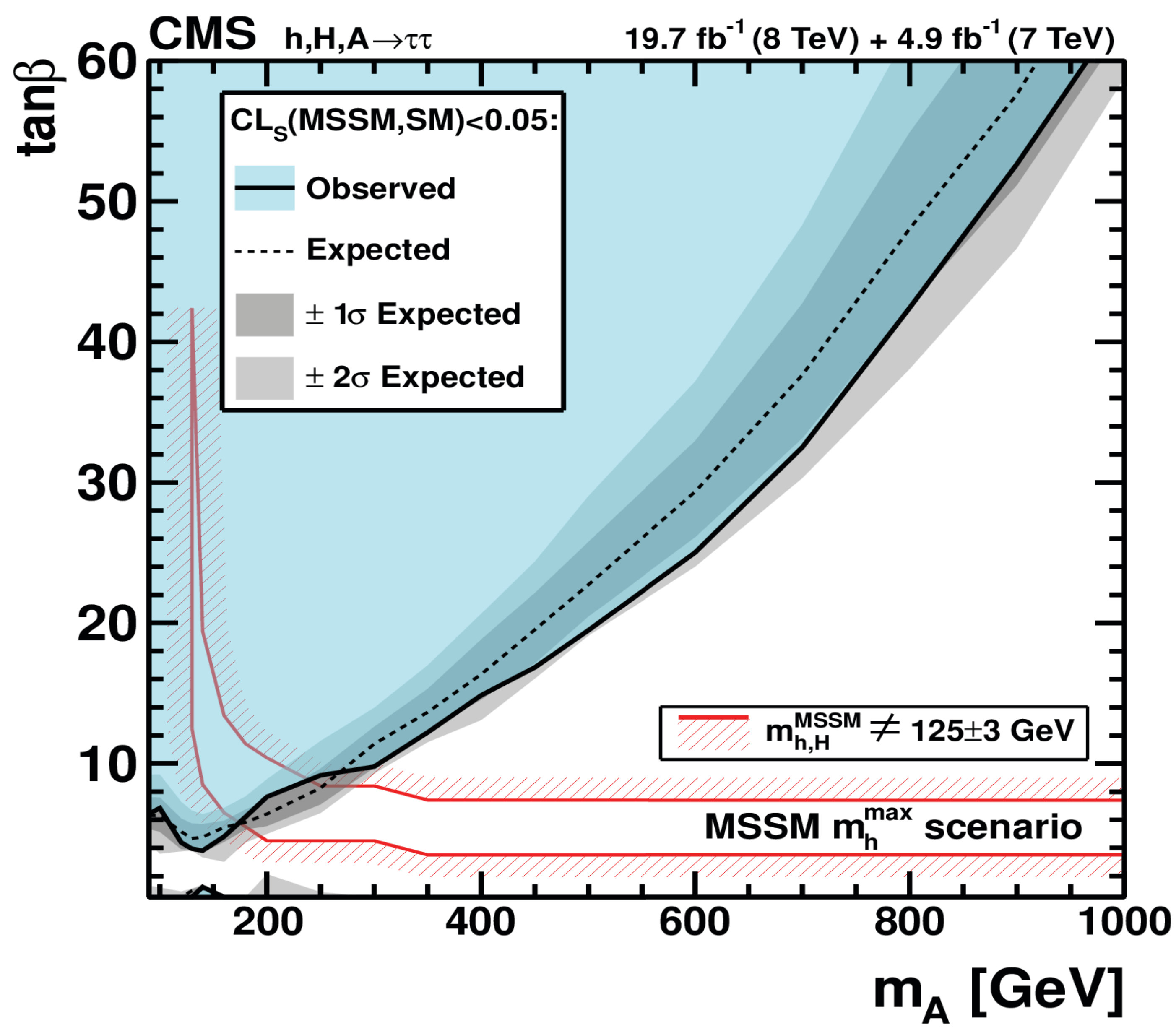
M_A-tanβ limits had been computed by LEP and TeVatron

CMS contributed to these limits in 2012

- h,H,A->ττ search
  - With and without associated b-jet production
  - Extended search to higher masses up to M_A=1000 GeV

Low tanβ regime still needs to be explored, to further narrow M_A-tanβ possibilities





Physics Signature

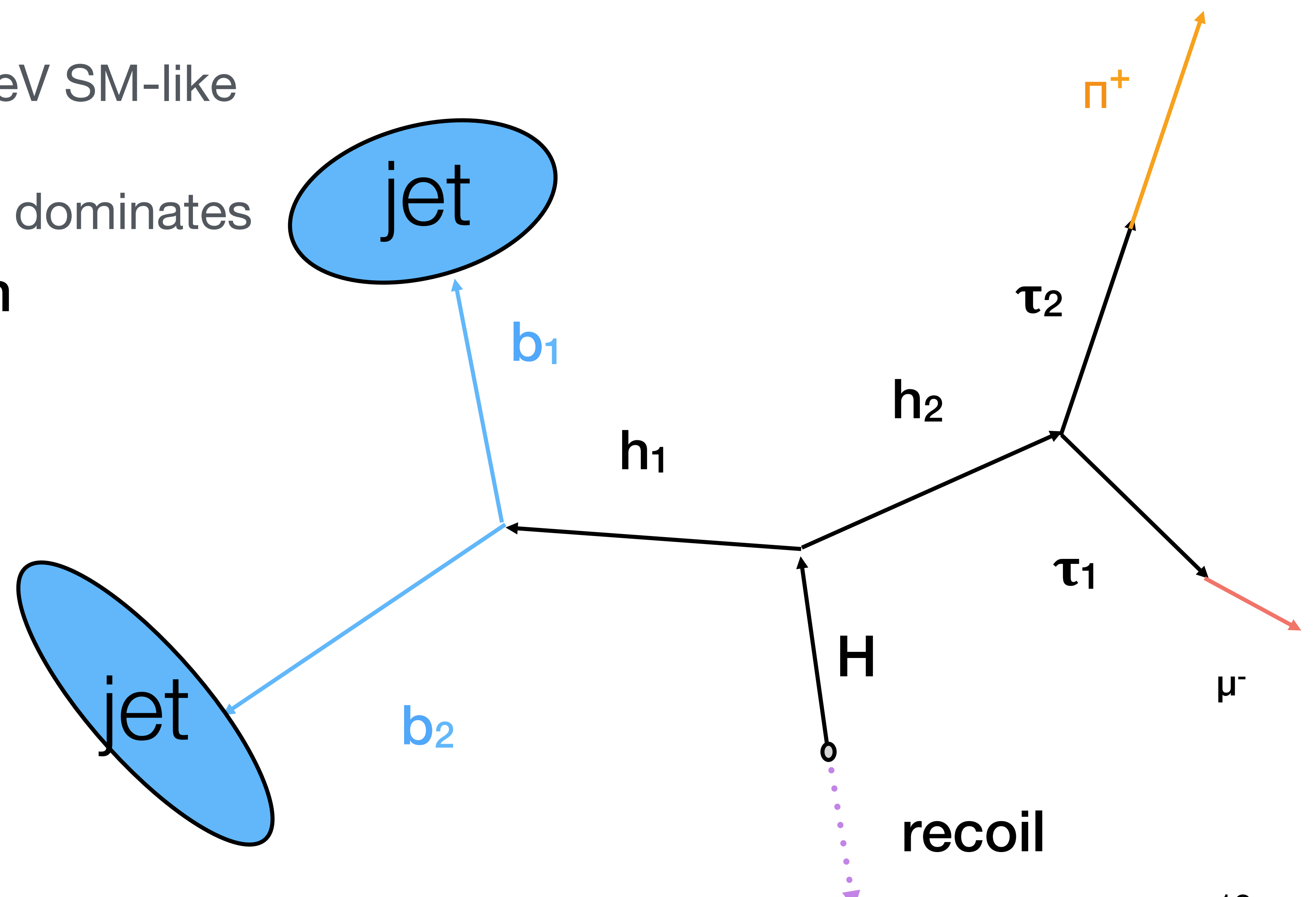
Interpret SM-like Higgs as light MSSM Higgs, h(125).

Examine heavy higgs mass range M_H=260-350 GeV

- 260 GeV: allow two 125 GeV SM-like higgs
- 350 GeV: top-quark decay dominates

Search for signature H->hh

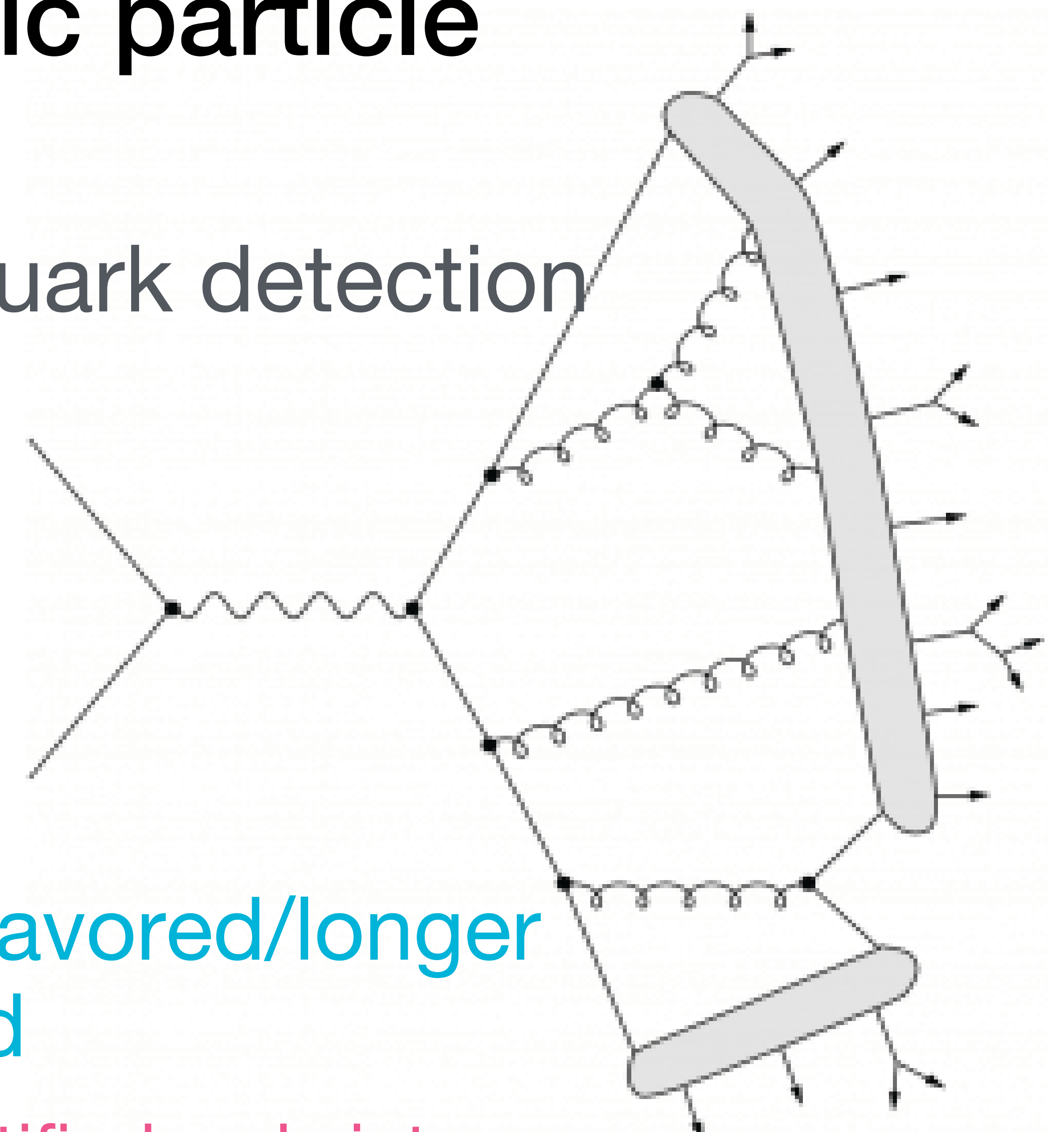
- 2 b-quarks
- 2 taus



Physics Signature: Jets

Quarks are detected as hadronic particle showers

- Confinement prevents single quark detection
  - Hadronic showers
    - Several models
      - E.g. String hadronization
- Called Jets
  - Jets originating from heavier flavored/longer lived particles can be identified
    - Jets from B hadrons can be identified as b-jets
      - B hadrons have a mean lifetime of 1.55×10^{-12} s



Physics Signature: Taus

Leptonic tau decay

- Denoted τ_e, τ_μ for plot labels
- Search for 1 lepton
  - 2 Channels: Electron/Muon
    - ~18% BR each

leptonic

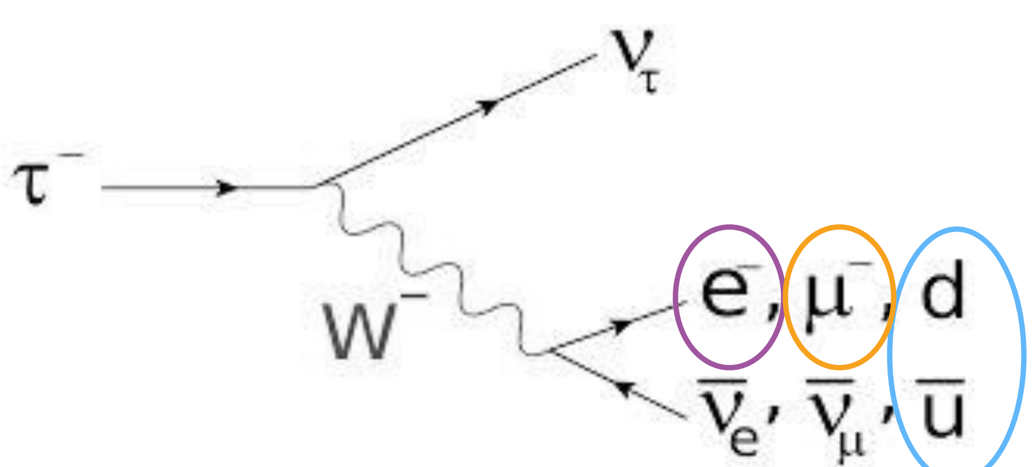
Hadronic tau decay

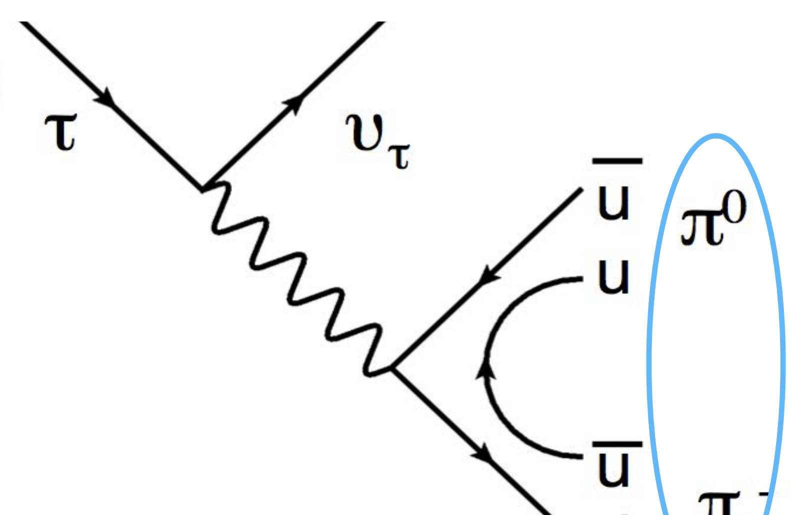
- Denoted τ_h for plot labels
- Search for 1 reconstructed tau decay to hadrons (τ_h)
  - 64% Branching Ratio

hadronic

Tau lepton mean lifetime 2.9 x 10^{-13} s

$\tau \to e\nu_e\,\nu_\tau$,	17.8 %
$\tau \to \mu\nu_\mu\,\nu_\tau$	17.4 %
$\tau \to \pi^{\pm}\nu_\tau$	11.1 %
$\tau \to \pi^0\pi^{\pm}\nu_\tau$	25.4 %
$\tau \to \pi^0\pi^0\pi^{\pm}\nu_\tau$	9.19 %
$\tau \to \pi^0\pi^0\pi^0\pi^{\pm}\nu_\tau$	1.08 %
$\tau \to \pi^{\pm}\pi^{\pm}\pi^{\pm}\nu_\tau$	8.98 %
$\tau \to \pi^0\pi^{\pm}\pi^{\pm}\pi^{\pm}\nu_\tau$	4.30 %
$\tau \to \pi^0\pi^0\pi^{\pm}\pi^{\pm}\pi^{\pm}\nu_\tau$	0.50 %
$\tau \to \pi^0\pi^0\pi^0\pi^{\pm}\pi^{\pm}\pi^{\pm}\nu_\tau$	0.11 %
$\tau \to K^{\pm}X\nu_\tau$	3.74 %
$\tau \to (\pi^0)\pi^{\pm}\pi^{\pm}\pi^{\pm}\pi^{\pm}\pi^{\pm}\nu_\tau$	0.10 %
others	0.03 %



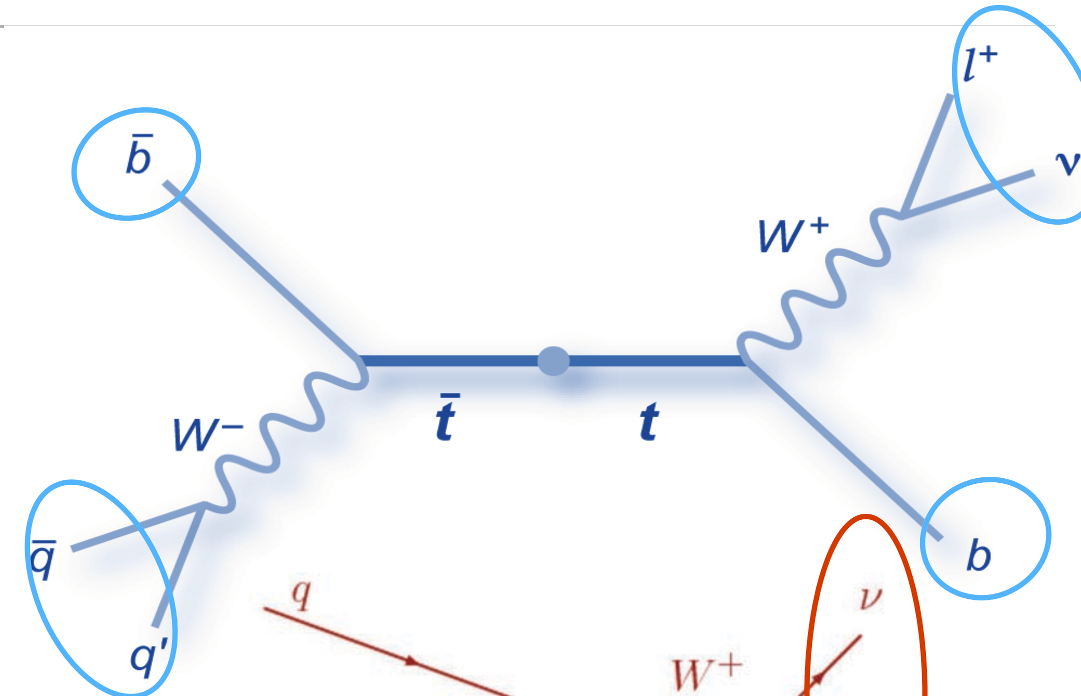


hadronic decay

Background Processes

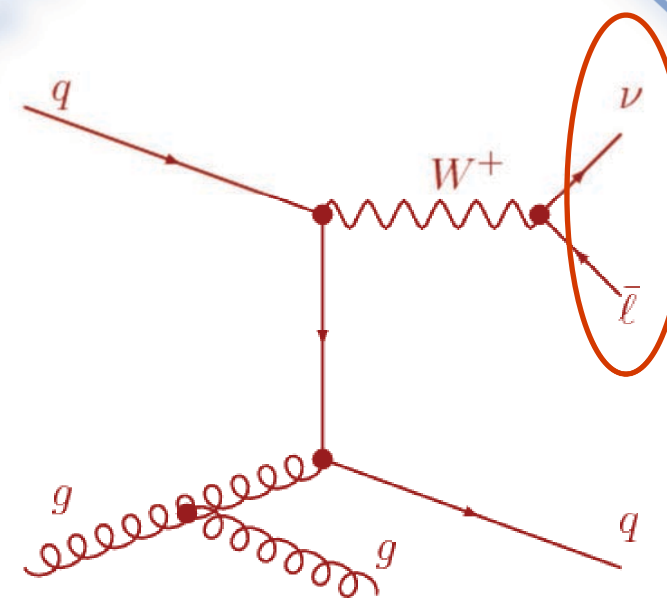
Top Quark and Anti-Top Quark

- Called TTBar
- Largest background



Electroweak Processes

- W+Jets



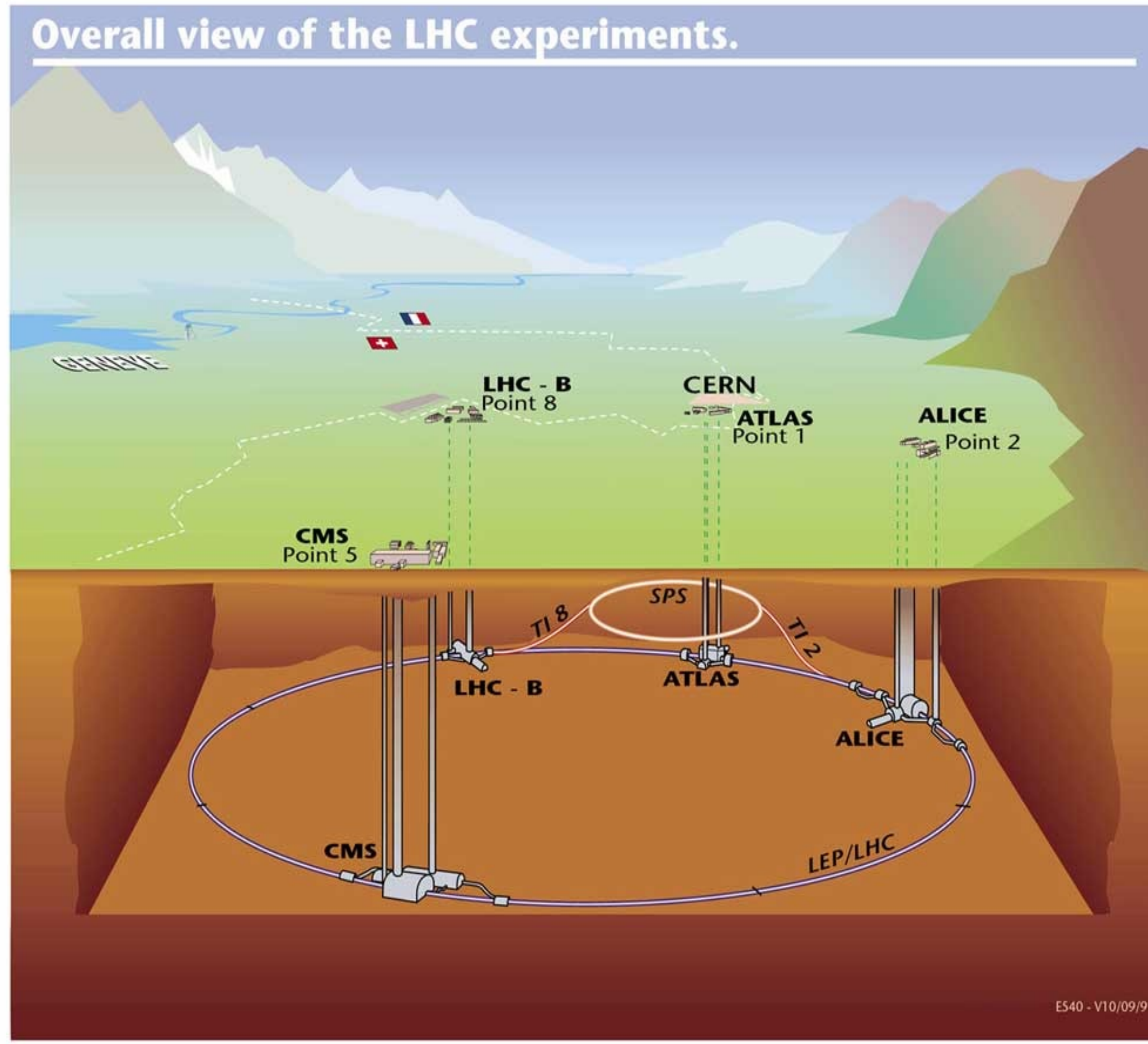
Drell Yan

- Treated separately from electroweak
- Z decay to tau pairs
- Z decay to fake tau pairs

Large Hadron Collider (LHC)

Proton-proton collider

- 27 km ring near Geneva, Switzerland
  - ~100-150 m underground
- Several detectors on LHC
  - ATLAS, CMS
    - General purpose hermetic detectors
  - Alice, LHCb
    - Heavy Ion, b-physics respectively
- Design Center of Mass energy 14 TeV
  - Before 2015: 7-8 TeV

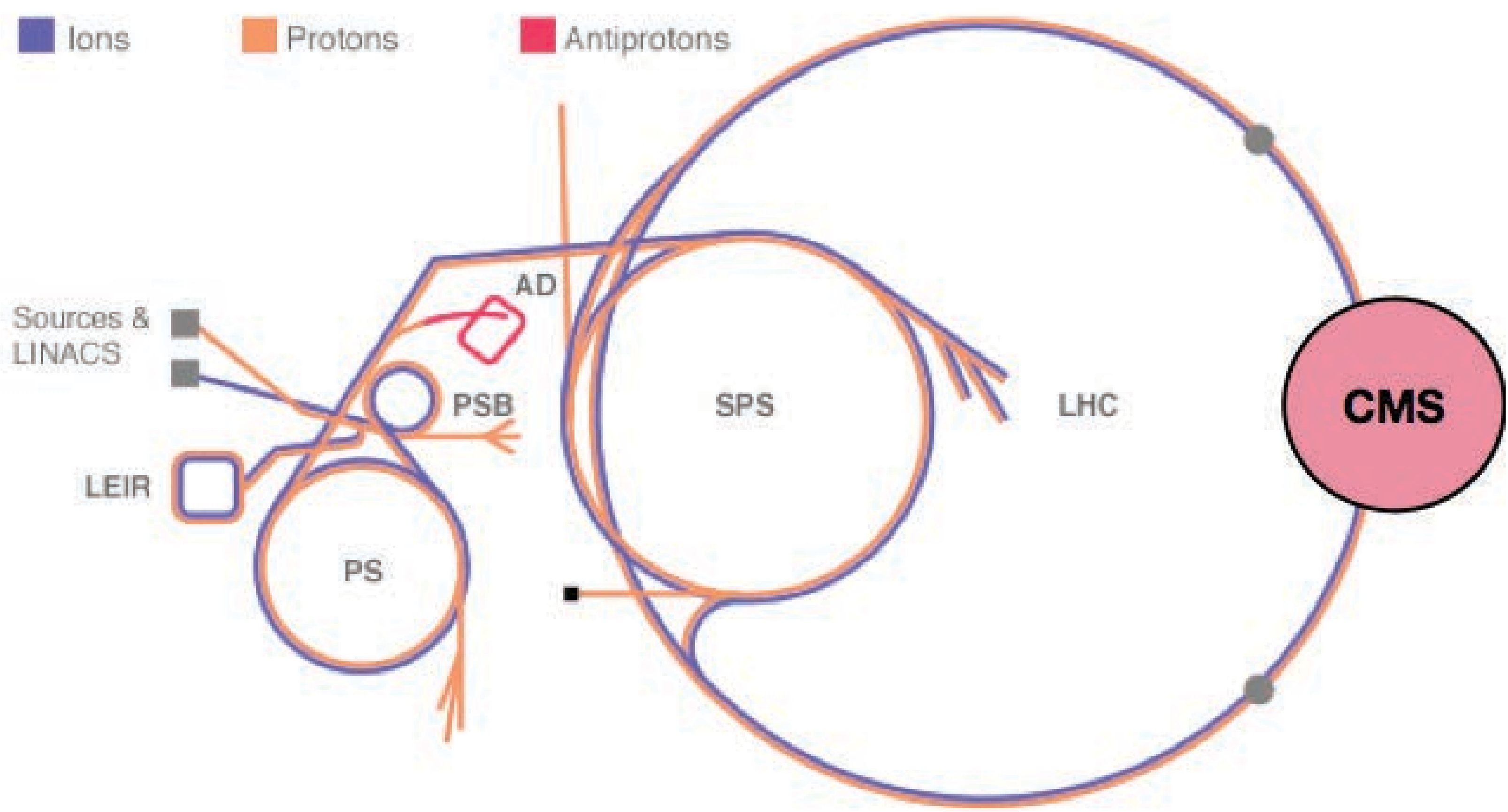


Large Hadron Collider

Acceleration process

- Start with hydrogen gas
  - Accelerate in successive steps
- LHC 8T superconducting magnets

2010-2012	Energy per Beam
Linac 2	50 MeV
Proton Synchrotron Booster	1.4 GeV
Proton Synchrotron	25 GeV
Super Proton Synchrotron	450 GeV
Large Hadron Collider	Upto 4 TeV



Beam & Luminosity

$$N = \sigma \int L \, dt$$

	2011	2012	2015	Design.
Beam Energy [TeV]	3.5	4	6.5	7
Bunch Spacing [ns]	50	50	25 (50)	25
Protons/ Bunch	1.45×10^{11}	1.48×10^{11}	$\sim 1.5 \times 10^{11}$	$< 1.3 \times 10^{11}$
Bunches/ Beam	~1380	~1380	~2800	~2800
Pileup PU (Max)	~20	35	40 (average)	~20
Peak Inst. L	3.7×10^{33}	7.7×10^{33}	1.4×10^{34}	10^{34}

Cross section

- Effective area, probability of interaction

Luminosity, L

- Relationship between rate and cross section

Maximize Luminosity

- Increase particle density of the two proton bunches colliding
  - Increase protons per bunch
  - Decrease cross sectional area of bunch
- Collide more bunches

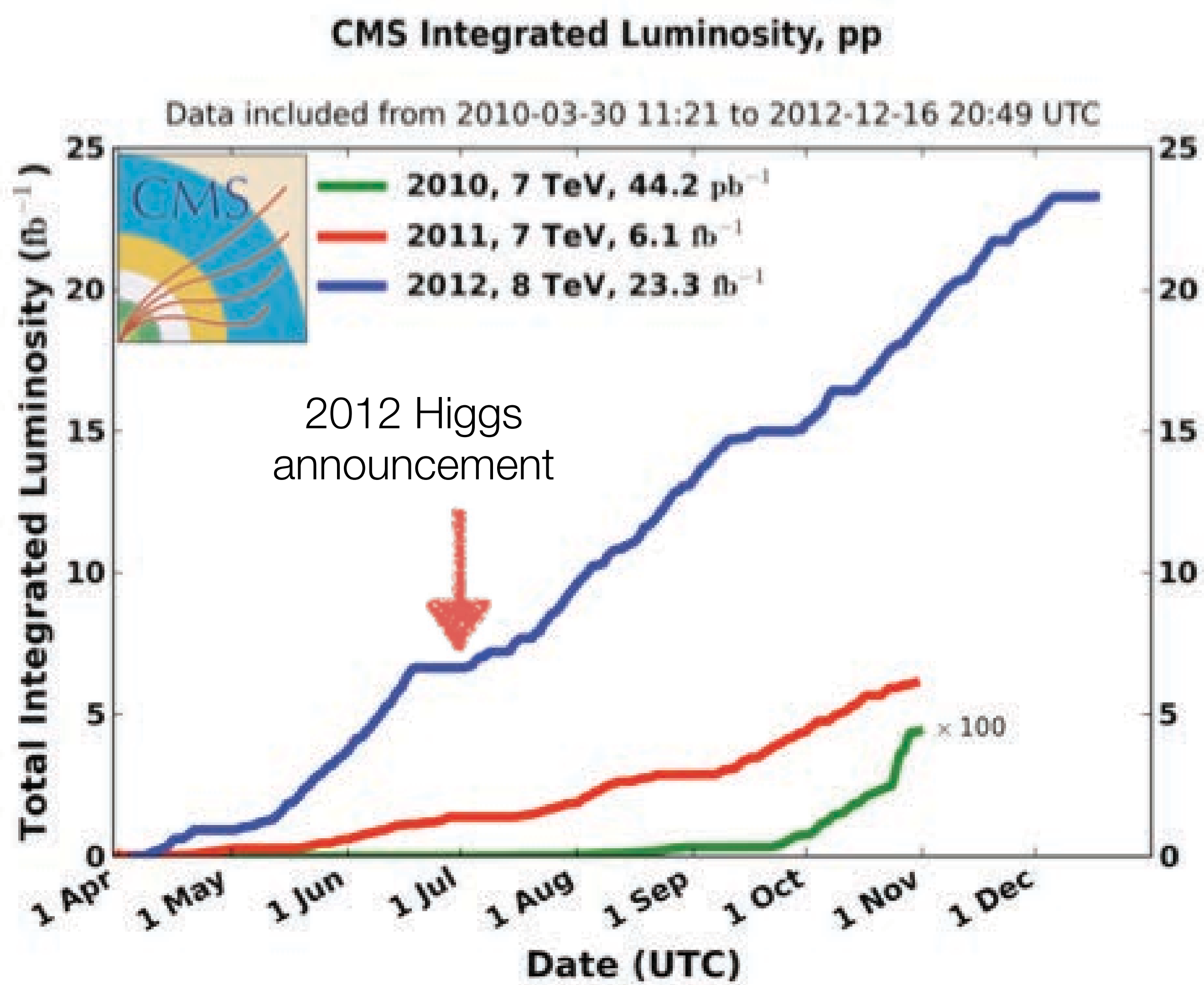
8 TeV Data

2012 Higgs Announcement

- Discovery made on about 10.4 fb^{-1}
  - On 7 TeV and partial 8 TeV dataset.
- ~16 additional fb^{-1} recorded since then

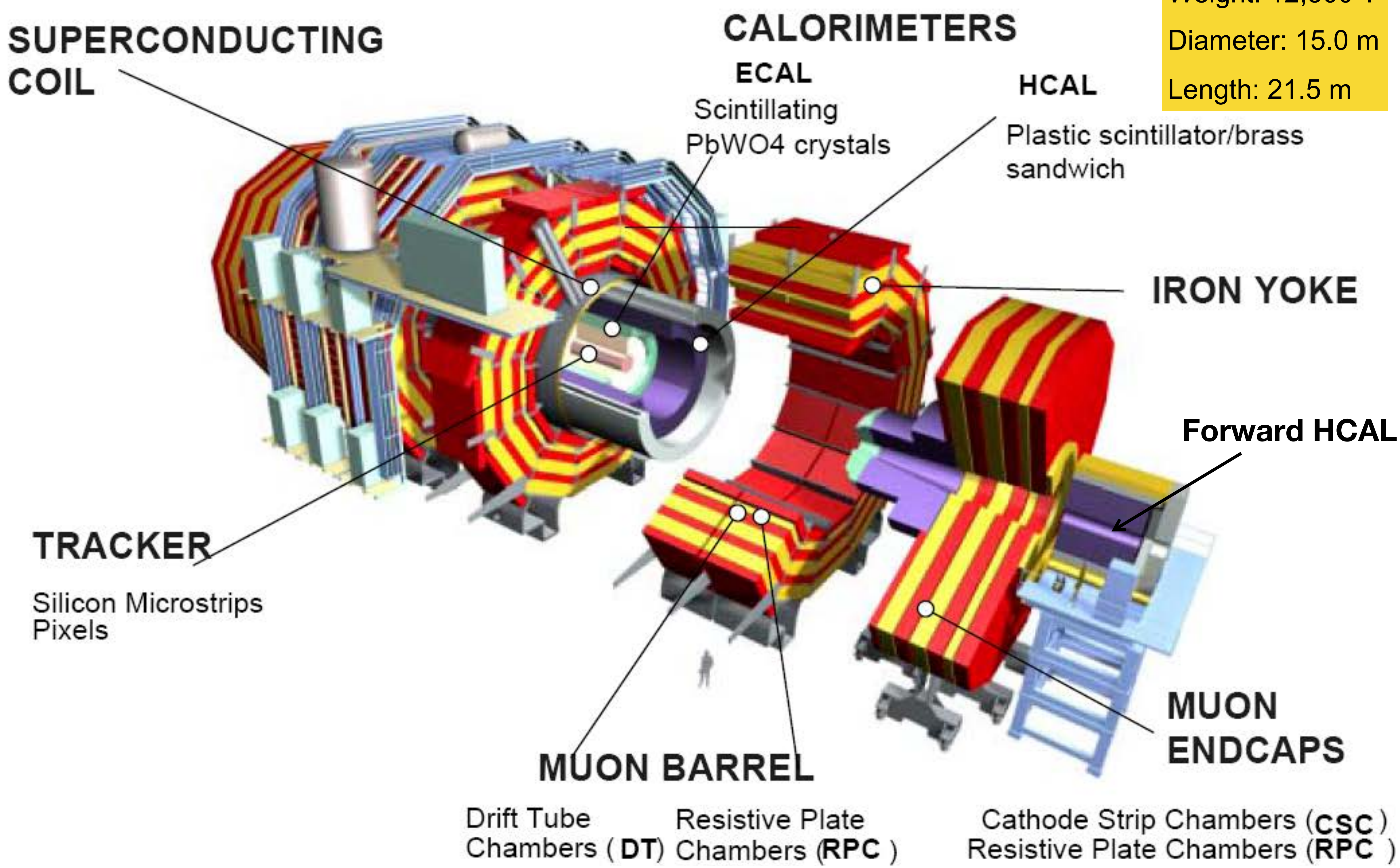
Analyzing the 8 TeV dataset

- 19.79 fb^{-1} recorded



CMS: Overview

Weight: 12,500 T
Diameter: 15.0 m
Length: 21.5 m



CMS: Features

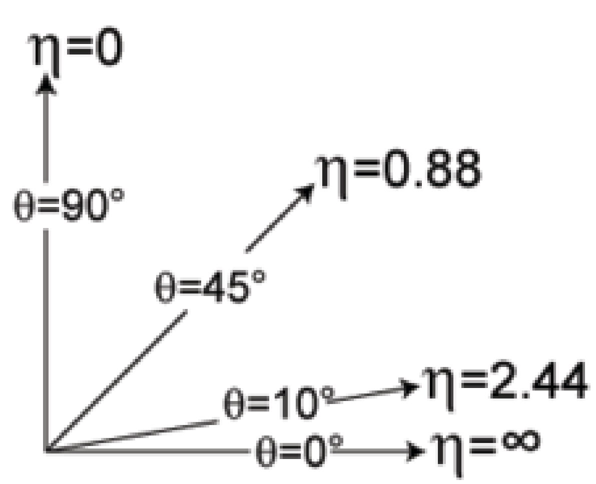
Calorimeters inside magnet

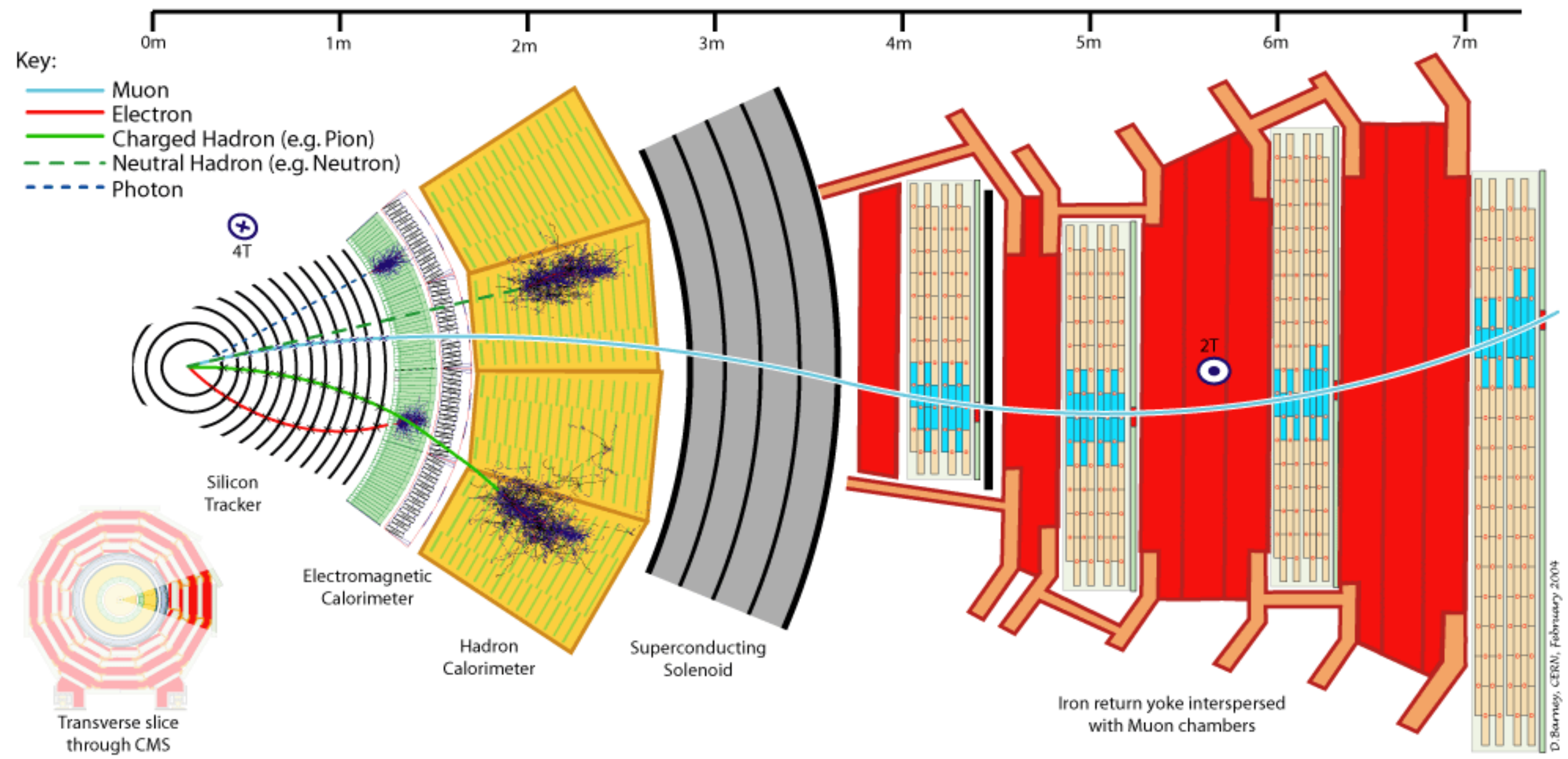
Hermetic design

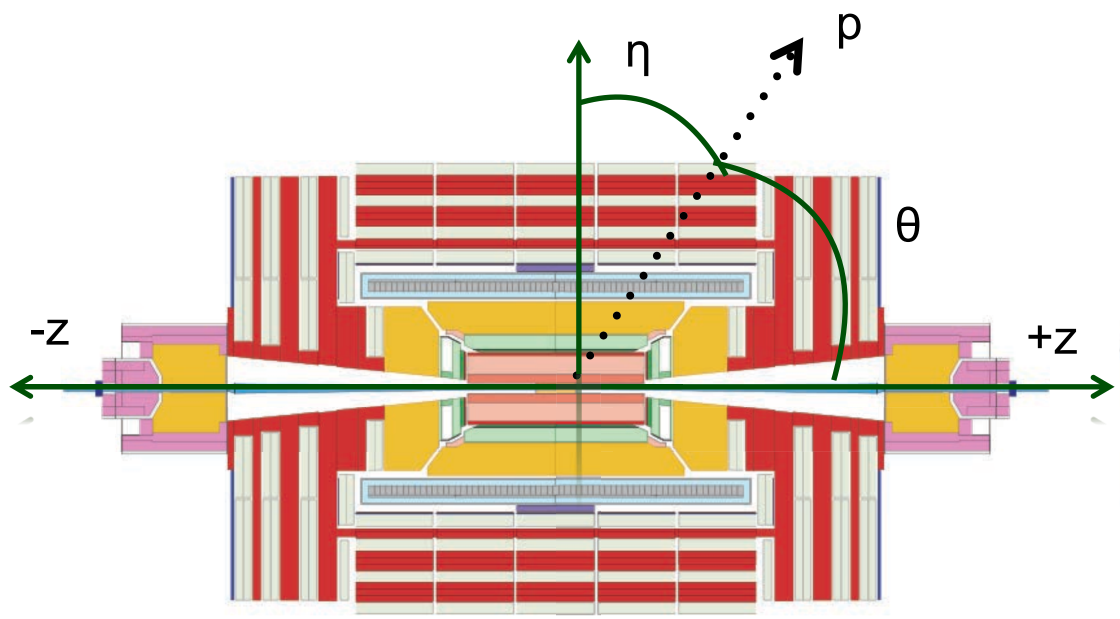
Geometry

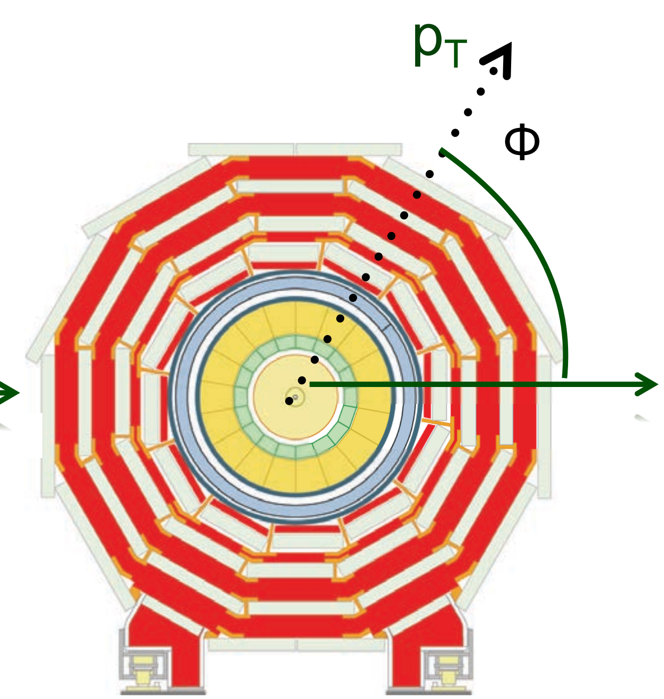
- Pseudorapidity, η

$$\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$









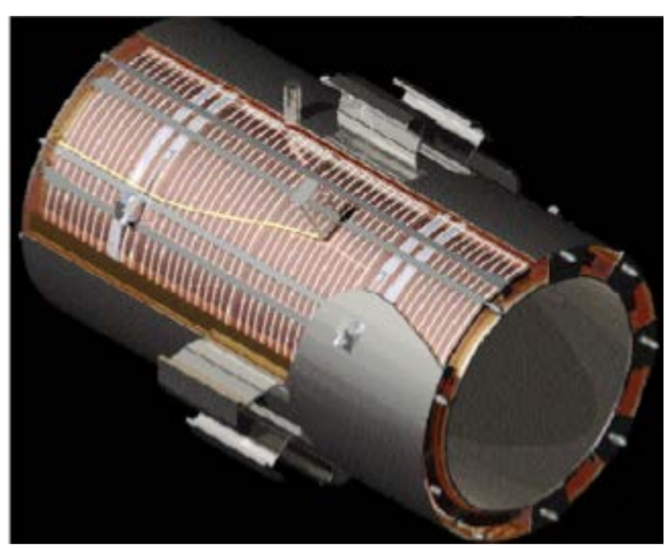
Solenoid and P_T Measurement

Solenoid is a fundamental part of CMS design

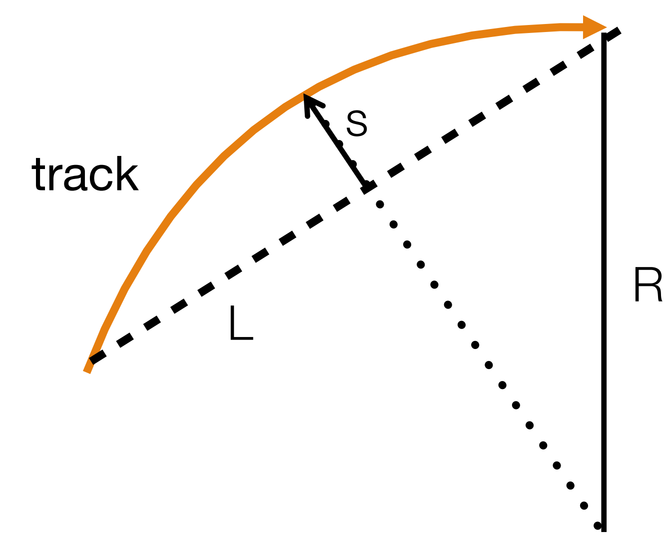
- P_T measurement of charged particles in Tracker and in Muon system.
    - ~4 T inside, ~2 T in return yoke

$$B = \mu_0 n I$$

6.3m diameter
12.5m length
Cooled to 4.7K
Largest Ever



- **P_T measurement**
    - Sagitta



for high P_T: $P_T \approx \frac{0.3 L^2 B}{8s}$

Silicon Tracker

~200 m^2 of silicon

Charged particle momentum measurement, "track" charged particles and secondary vertex identification.

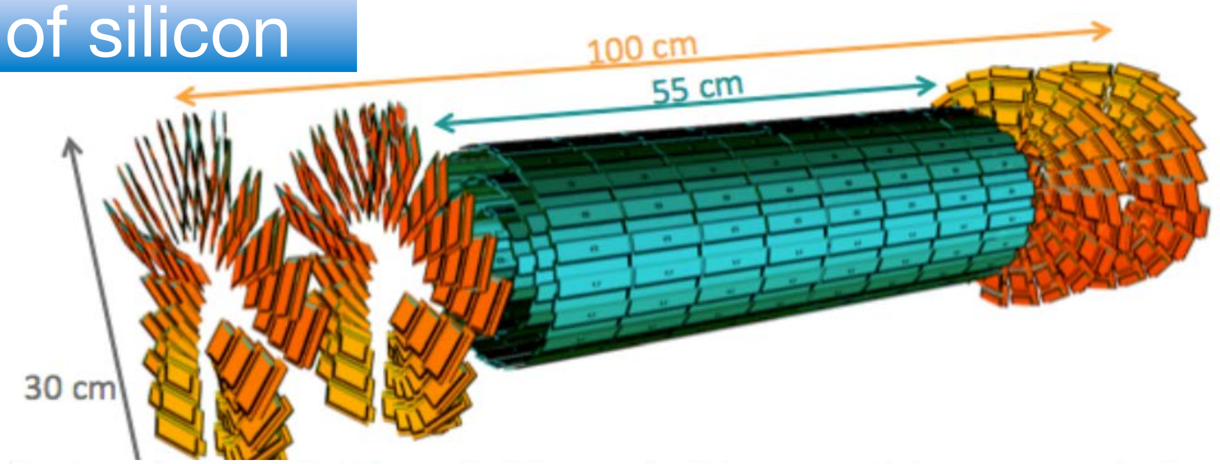
- Tracker highly dependent on magnetic field
- Cold: Below -10C

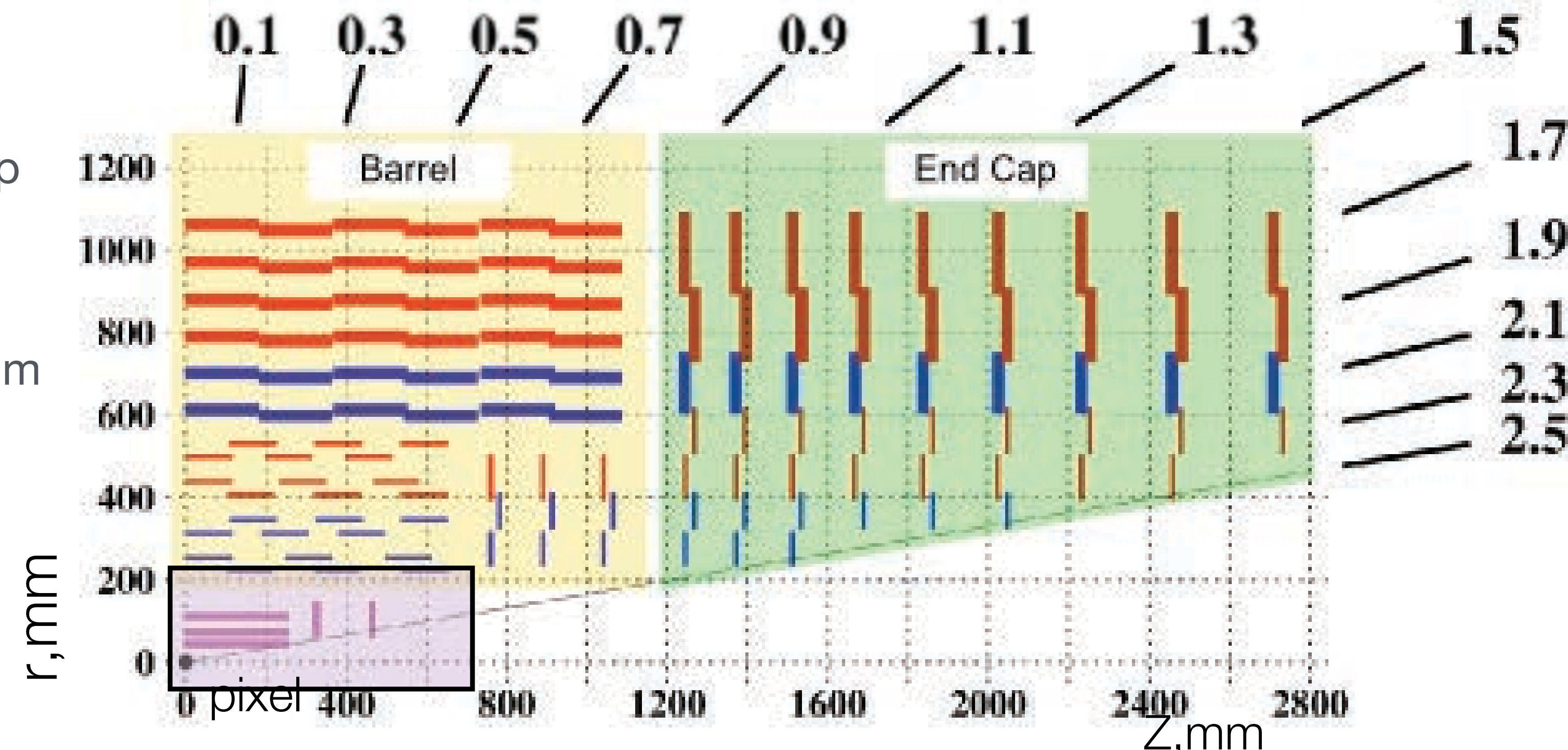
Silicon Pixel Detector : |η|<2.5

- Radius 4.3-11 cm with two endcap layers
- Long lived particle identification
- ~66 million pixels, 100 μm x 150 μm

Silicon Strip Tracker: |η|<2.5

- P_T measurement
- Silicon Strips outside of Pixel
    - Much larger than pixel detector
    - Size varies on placement in Tracker.
- ~10 million silicon strips

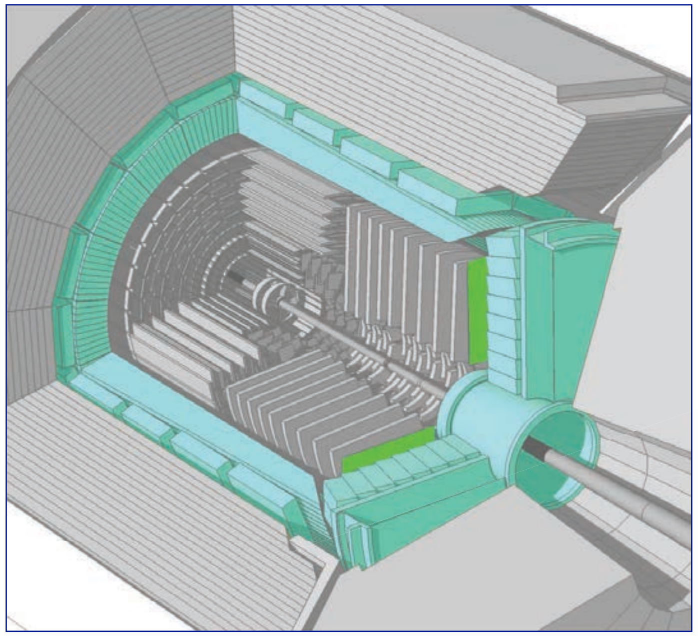




$$\frac{\delta p_t}{p_t} = \left(\frac{p_t}{TeV}15\%\right) \oplus 0.5\%$$

Electromagnetic Calorimeter

Electromagnetic Calo. (ECAL) measures electromagnetically interacting particle energies

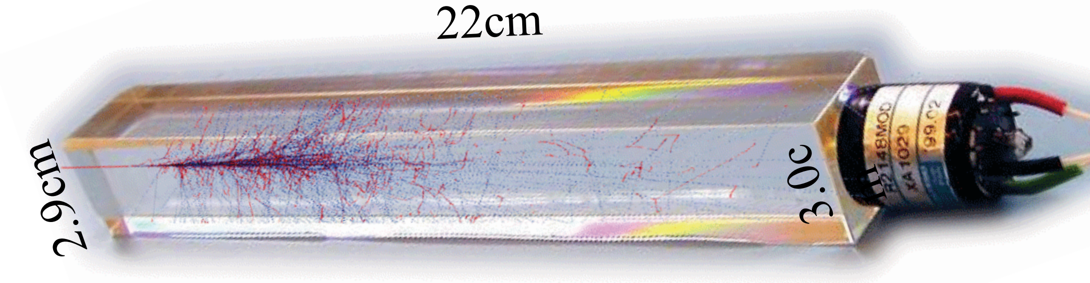


$PbWO_4$ Crystal Calorimeter

- ~26 Radiation lengths deep
- Barrel and endcap measure out to |η|<3.
  - Barrel (EB): |η| < 1.48
    - 61,200 crystals in the barrel
    - Crystal measures 2.2cm x 2.2cm x 23cm
  - Endcap (EE): 1.48< |η| <3
    - 7,324 crystals in each endcap
  - Resolution

Stochastic, Noise, Intrinsic

$$\frac{\sigma_E}{E} = \frac{2.8\%}{\sqrt{E\,(\mathrm{GeV})}} \oplus \frac{0.128}{E\,(\mathrm{GeV})} \oplus 0.3\%$$



$PbWO_4$ QUALITIES
Density: 8.28 g cm^-3
X_0: .85 cm, R_M: 2.19 cm
λ: 19.5 cm
Wavelength peak: ~430 nm
Light Yield: ~100 γ/MeV

Hadron Calorimeter

Hadronic Calorimeter denoted (HCAL) measures charged and neutral hadron energies

- Hermetic and dense, for good MET measurement
  - Hermetic to $|\eta|<5$
- Brass/Plastic Scintillator
  - Sampling fraction: ~7%

HCAL Barrel $|\eta|<1.3$

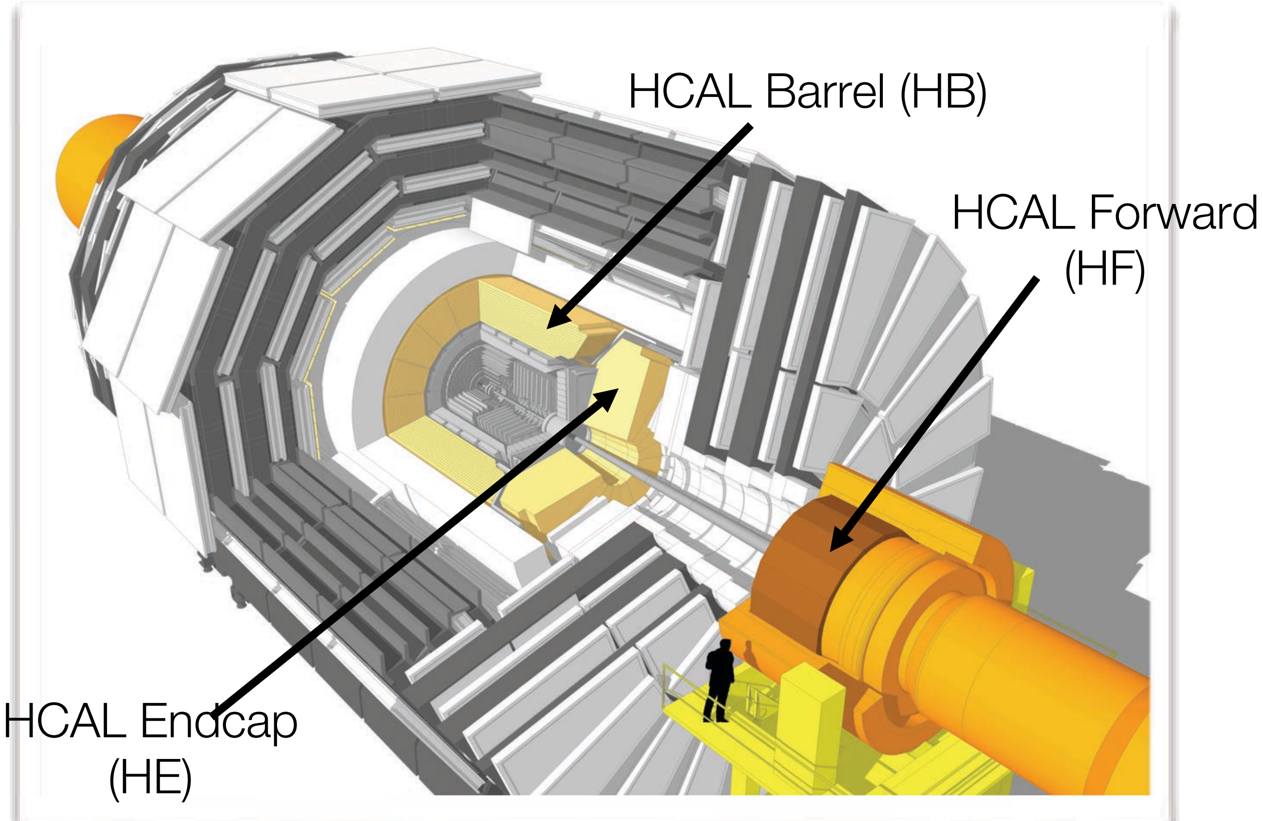
- Resolution $$\left(\frac{\sigma}{E}\right)^2 = \left(\frac{115\%}{\sqrt{E}}\right)^2 + (5.5\%)^2$$

HCAL Endcap $1.3< |\eta|<3$

- Resolution $$\left(\frac{\sigma}{E}\right)^2 = \left(\frac{280\%}{\sqrt{E}}\right)^2 + (11\%)^2$$

HCAL Forward $3<|\eta|<5$

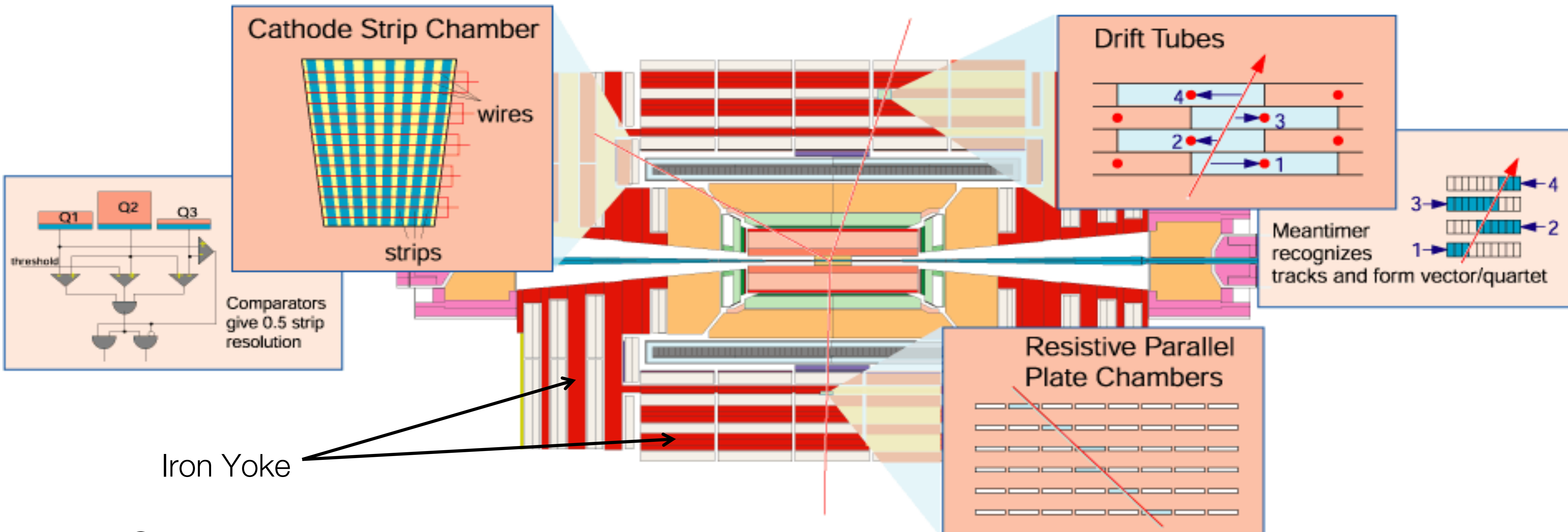
- Steel absorbers and quartz fibers
  - Radiation-hard components



Brass Properties
density: 8.53 g cm^-3
radiation length: 1.49 cm
interaction length: 16.42 cm
Non-ferromagnetic

Tower size: $\Delta\eta \times \Delta\varphi = 0.087 \times 0.087$

Muon System



Muon Goals: Identification, P_T measurement, triggering

Return Yoke, ~2T field

Drift Tubes(DT):

- 0<|η|<1.2

Resistive Plate Chambers (RPC):

- 0<|η|<2.4
- Fast output used for triggering

In forward region Cathode Strip Chambers(CSC):

- 0.9<|η|<2.4

Level-1 Trigger

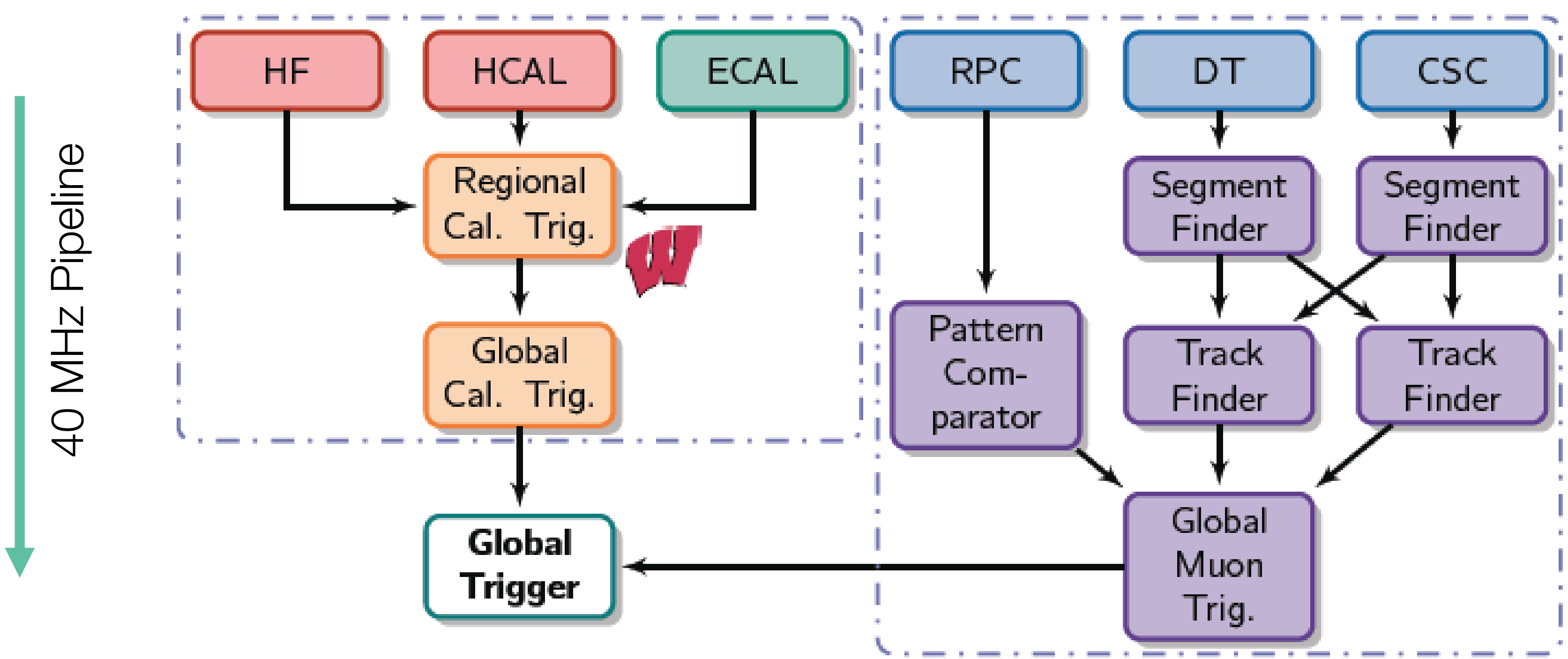
Reduce 40 MHz collision rate to 100 kHz L1 output rate

- ~4 μs latency

Level-1 (L1) Calorimeter Trigger outputs leading candidates from reduced ECAL and HCAL(incl. HF) information

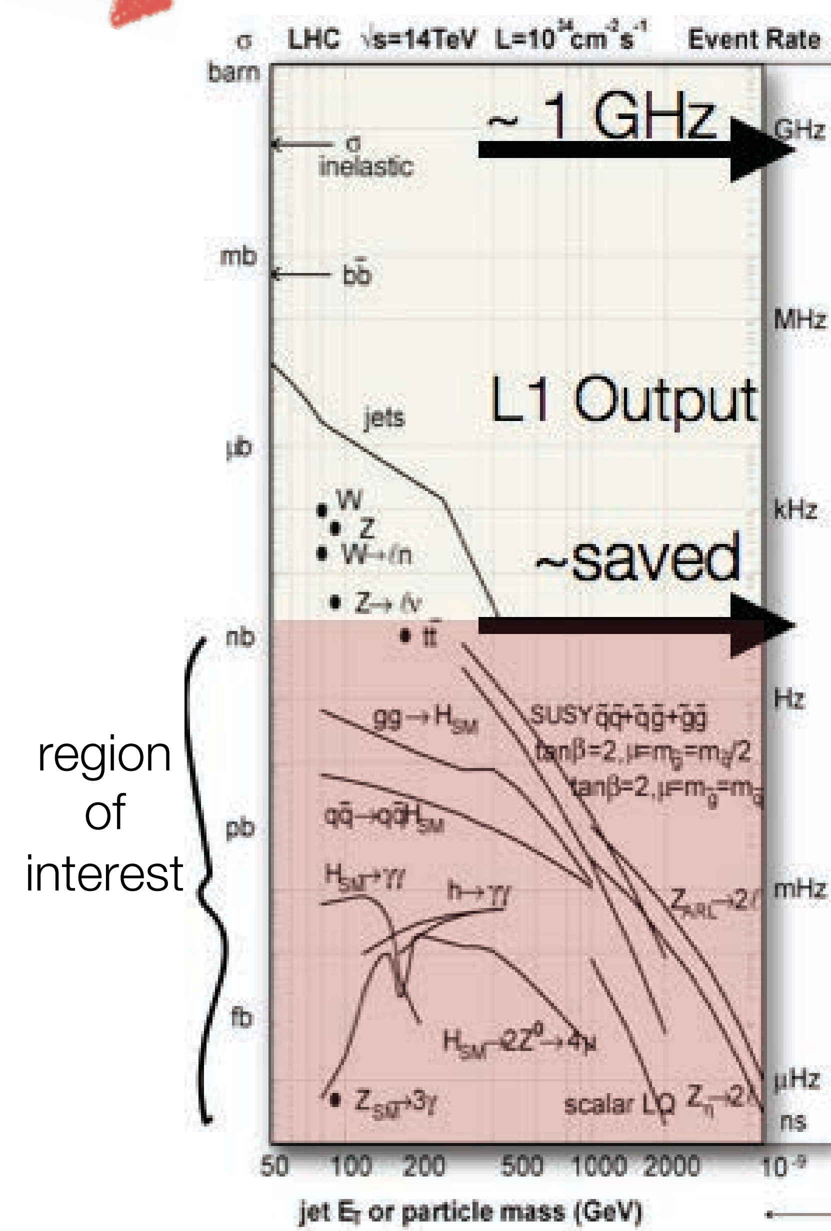
- Jets
- Electrons/γ, isolated and non-isolated
- ET, HT, MET

L1 Muon Trigger outputs 4 leading muon candidates from Muon system.

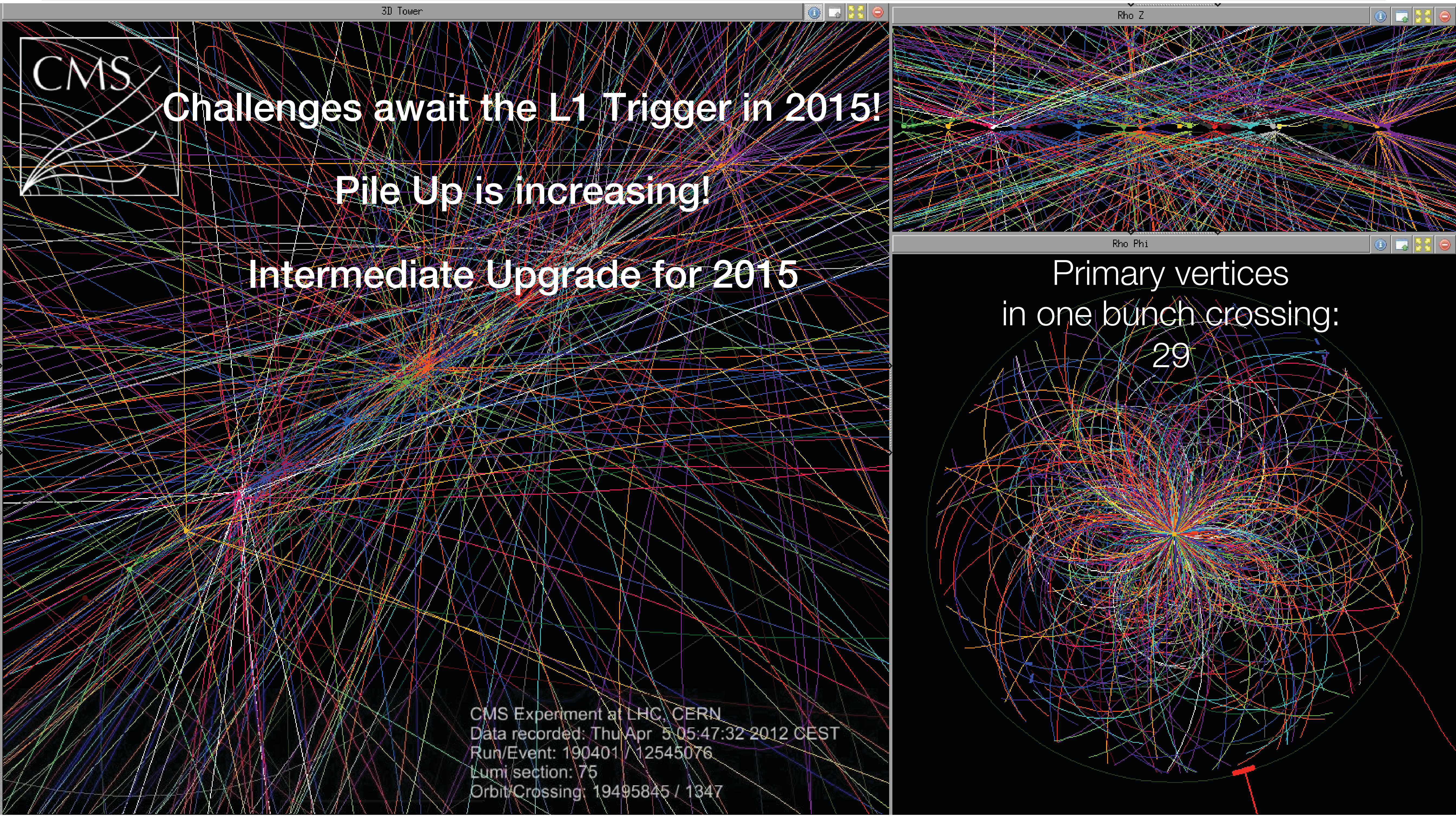


To High Level Trigger

14 TeV Example



Pile Up!


3D Tower
CMS
Challenges await the L1 Trigger in 2015!
Pile Up is increasing!
Intermediate Upgrade for 2015
CMS Experiment at LHC, CERN
Data recorded: Thu Apr 5 05:47:32 2012 CEST
Run/Event: 190401 / 12545076
Lumi section: 75
Orbit/Crossing: 19495845 / 1347
Rho Z
Rho Phi
Primary vertices
in one bunch crossing:
29

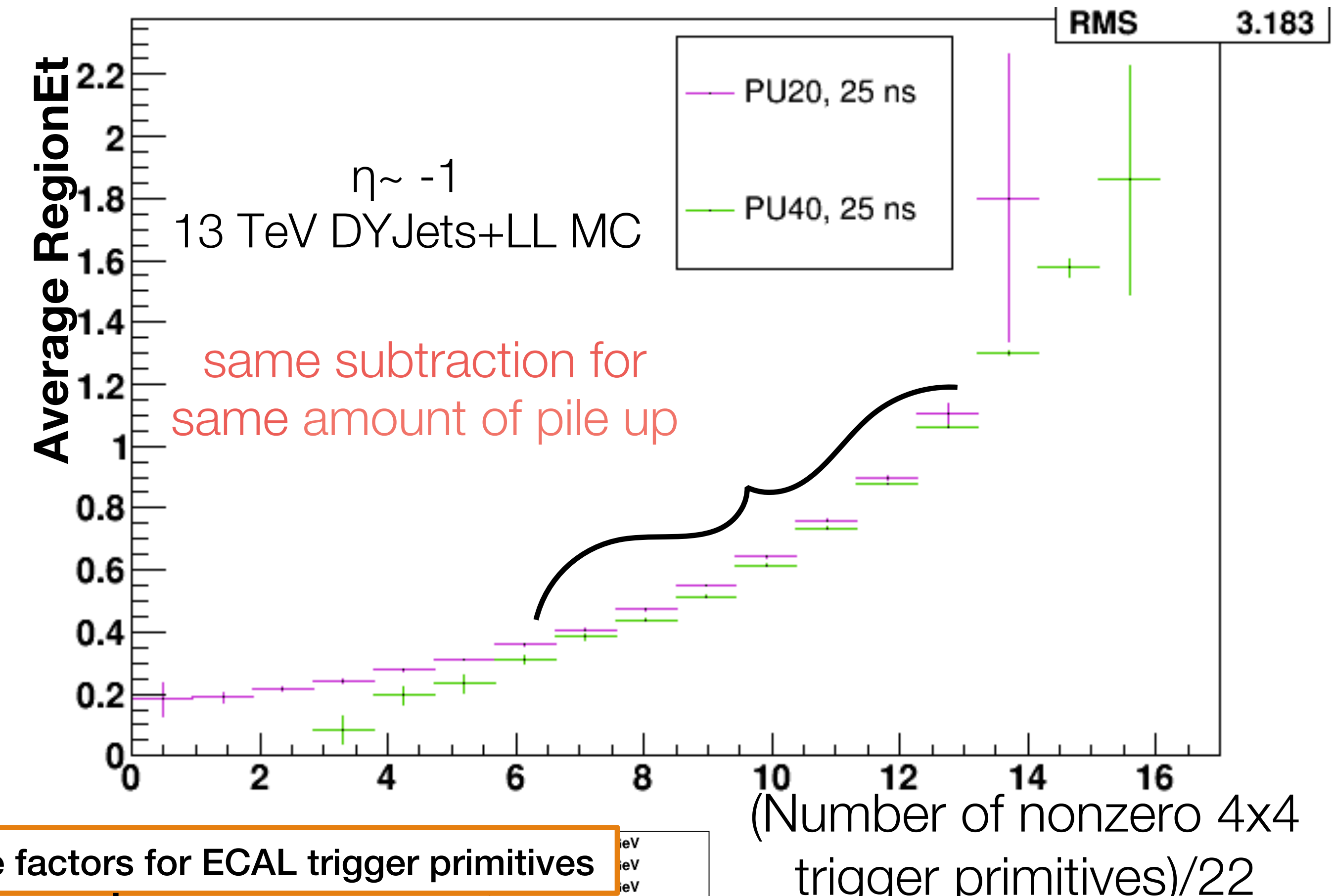
My Work on Regional Calorimeter Trigger

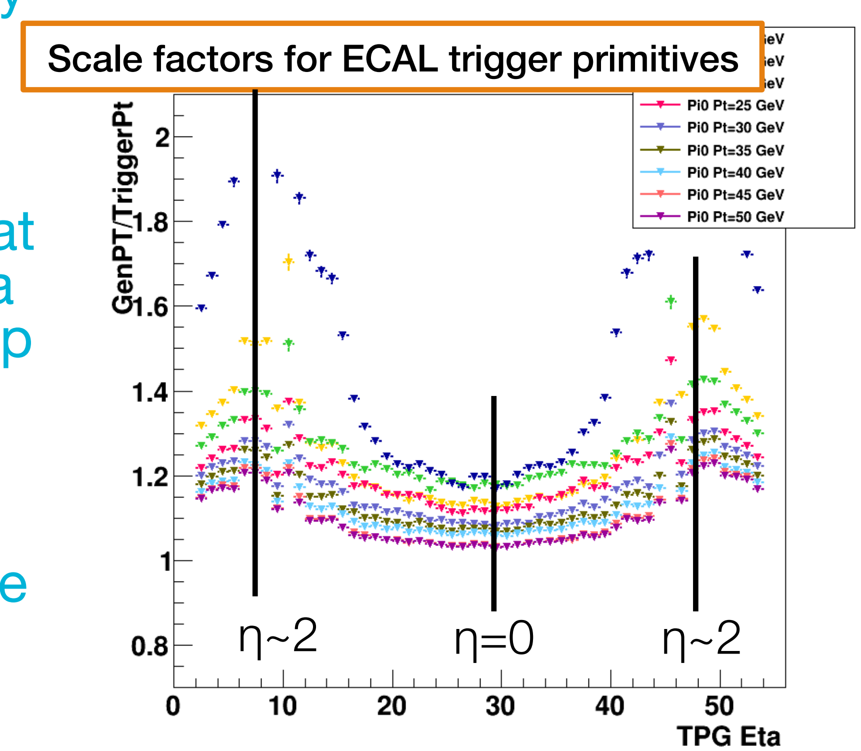
Pile Up is increasing

- At 13 TeV, 25 ns between bunch crossings and average 40 primary vertices per bunch crossing
- Improve trigger as much as possible in interim before larger trigger upgrade in 2017

2015 Intermediate Calorimeter Trigger Upgrade

- Emulator development
  - Used to test new algorithms and verify performance
- Pile Up Subtraction Algorithms
  - Found a proxy for primary vertices that can be used at trigger level, used as a handle to subtract approximate pile up energy density quickly.
- Trigger Energy Calibrations
  - Used single π Monte Carlo to calibrate Calo Trigger in P_T and η.





High Level Trigger

High level trigger (HLT)

- Software based with access to full event information
- Output rate to ~300 Hz of data we can analyze!

Triggers Used in analysis

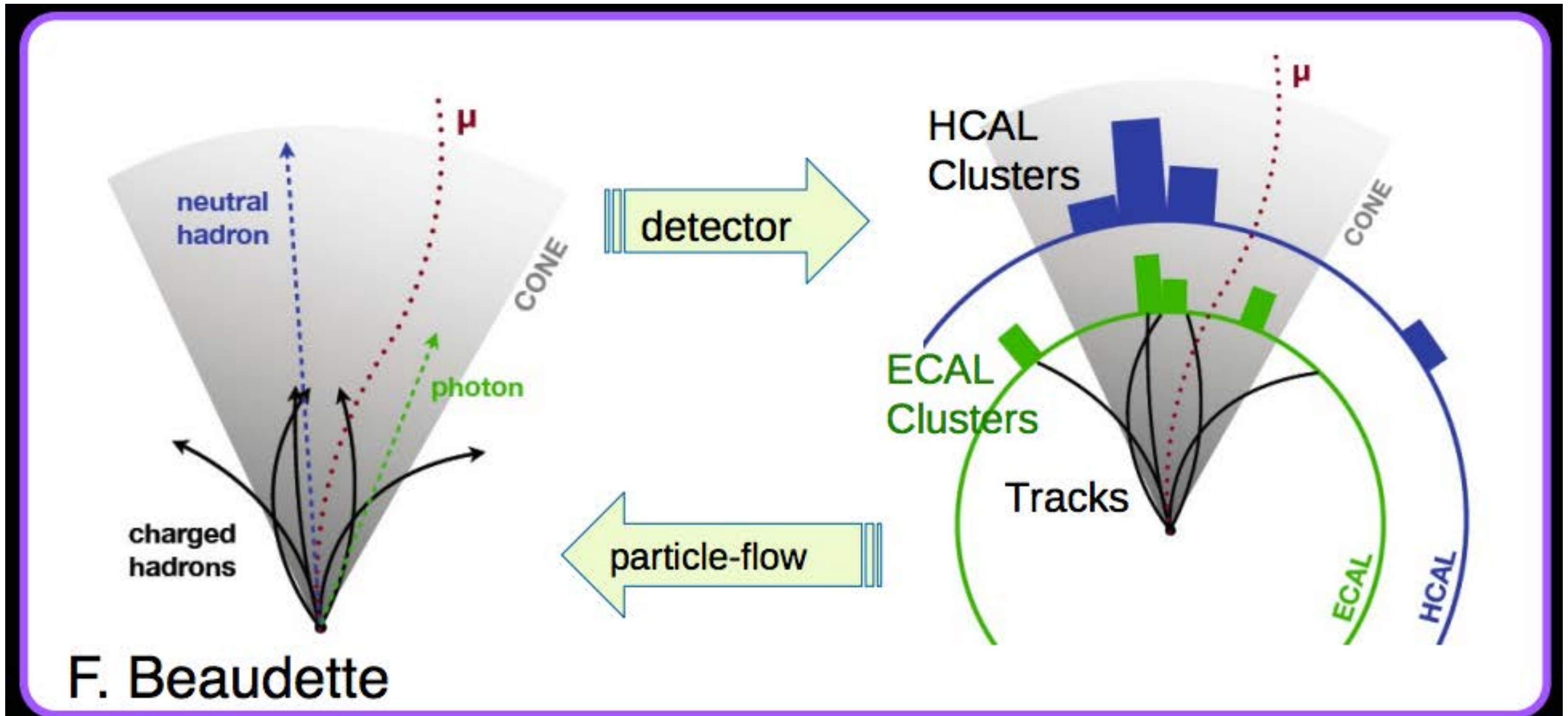
- Di-Muon for background estimation
- Muons with P_T>17 GeV (muon channel)
- Electrons with P_T>17 GeV (electron channel)
- And Taus with P_T>20 GeV

Particle Reconstruction

To improve energy resolution: Particle flow (PF)

- Combine signals from all relevant detectors to optimize energy resolution and particle identification.
- Types
  - photon, charged/neutral hadron, muon, electron
- Processes
  - clustering, tracking, muons, electrons, secondaries

PF Jet
65% charged particles
25% photons
10% neutral hadrons



Electron ID/Reconstruction

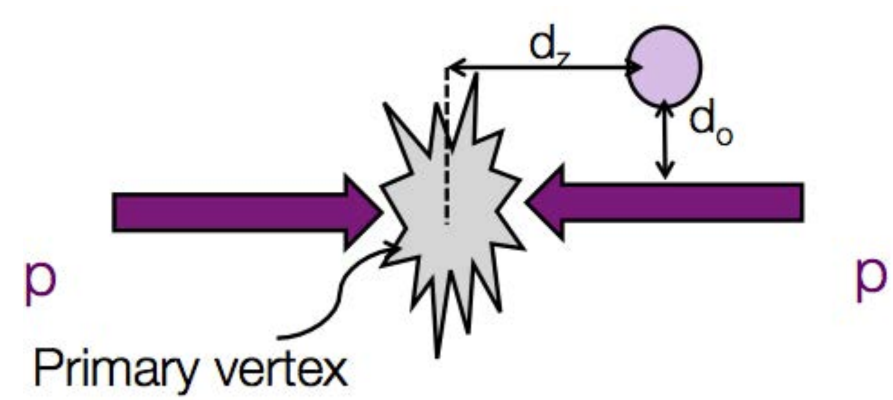
Electrons

- Charged; expect curvature
  - Can reconstruct from track in silicon tracker or from cluster in ECAL
- Additionally for τ_e we require
  - Photon conversion rejection by reconstructing OS pairs to vertex where photon pair produced and requiring no missing inner hits in tracker
  - Close to primary vertex
    - d_0 and d_Z
  - Chi squared of track fit, number of tracks, HCAL/ECAL energy fraction

Calo. Region	Electron likelihood Identifier Cut
$\eta<0.8$	0.925
$0.8<\eta<1.479$	0.975
$\eta>1.479$	0.985

To do this

- We do a Multivariate Analysis (MVA) utilizing a Boosted Decision Tree (BDT) to combine into one likelihood Identifier (ID) and calculate for $P_T>20$, and in 3 bins of η
  - Require a "tight" MVA ID for a pure sample of electrons, at the cost of efficiency

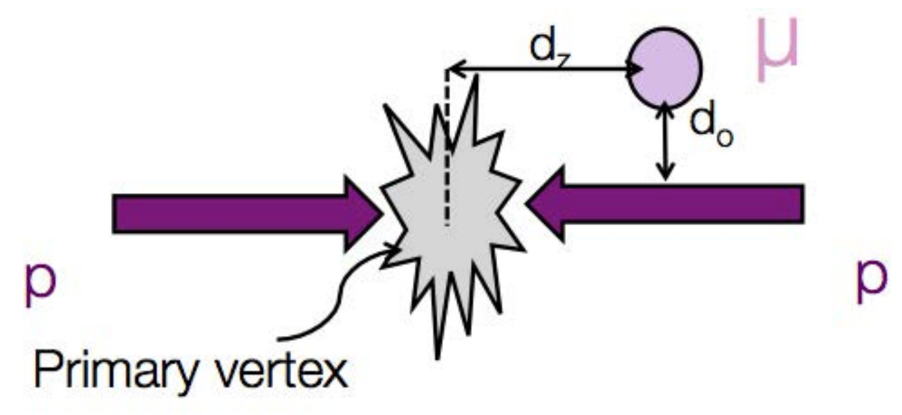


Muon ID/Reconstruction

Can use tracker, muon system, or tracker and muon system

For τ_μ require

- Use both tracker and muon system
- "Tight" muon for a pure sample of muons
  - Close to primary vertex
  - Require inner tracker hits and no missing inner hits
  - Various cuts to suppress hadronic punch through to Muon system
    - Example: Small chi squared of track
    - Well matched in muon system



Electron/Muon Isolation

Signal Leptons are isolated

- Standard Isolation
  - ~sum energy deposited by particles around a lepton
  - Gets worse as pileup increases
- PF Isolation
  - Utilize particle flow candidates to offset pile up
  - Require Relative Isolation <.1 for muon and electron

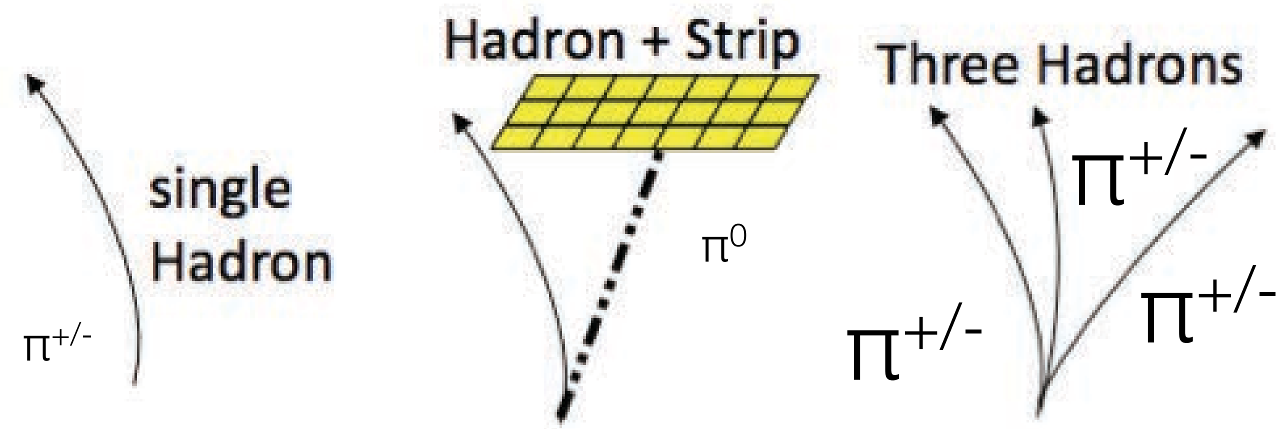
$$I_{rel} = \frac{\sum P_T(\text{charged}) + \max[\sum E_T(\text{neutral}) + \sum E_T(\text{photon}) - \Delta\beta, 0]}{P_T(\mu \text{ or } e)}$$

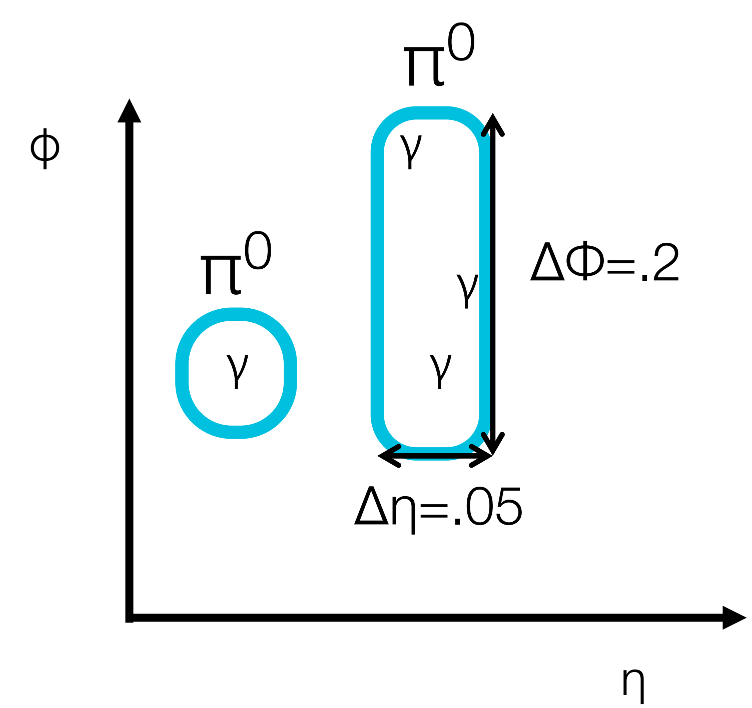
energy estimate of neutral particles from pileup calculated per event

Hadronic Tau Reconstruction

Hadron Plus Strips(HPS) algorithm

- Particle Flow based
  - γ, Charged Hadrons
- τ decays to hadrons
  - Isolation discriminators applied
- Does not reconstruct leptonic modes
- About 60% efficient
  - Sometimes ID a particle as a tau when it is not
    - “Fake” is usually an electron
    - ~1% fake rate for 60% efficiency





Jet Reconstruction

Anti-Kt jets

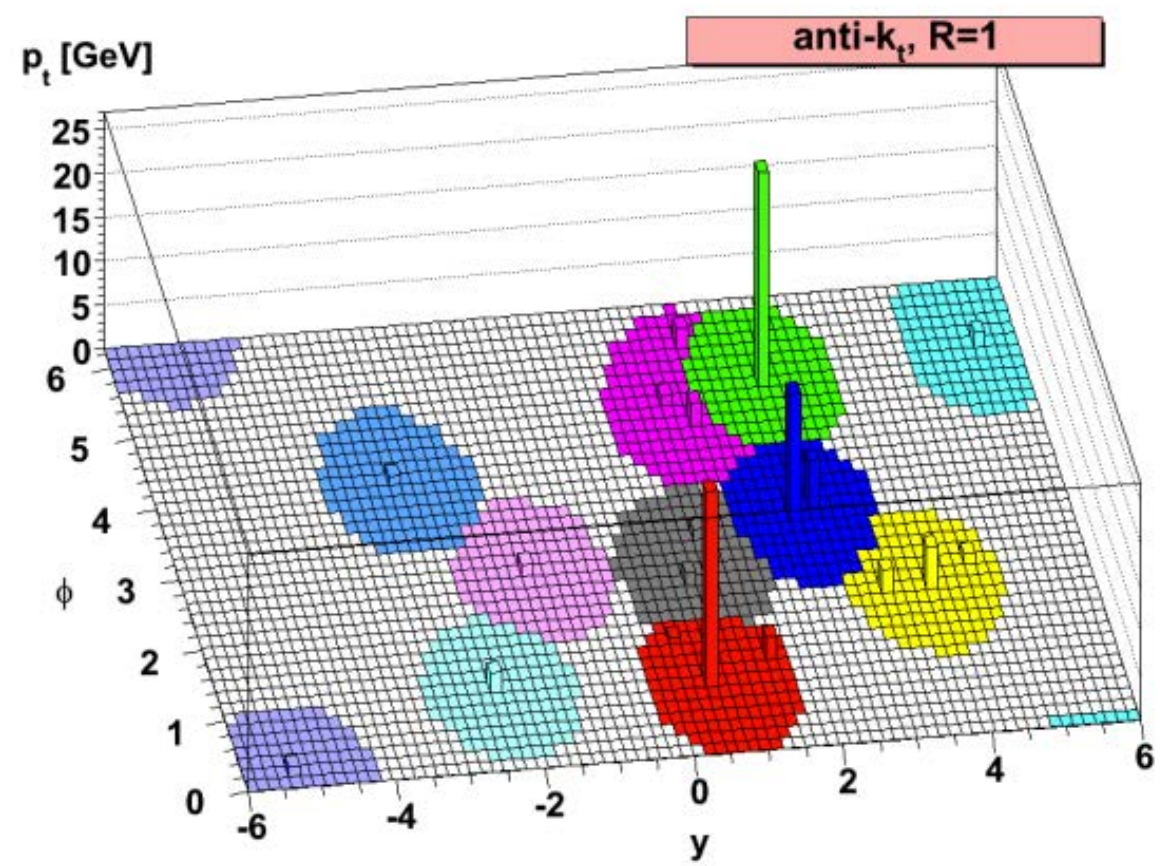
- Infrared and Collinear Safe
- Circular and centered around harder energy deposits, instead of soft deposits
- 2012 default R =.5

$$d_{ij} = \min(\frac{1}{k_{ti}^2}, \frac{1}{k_{tj}^2})\frac{\Delta_{ij}^2}{R^2}$$

$$\Delta_{ij}^2 = (\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2$$

Jet Energy Corrections applied

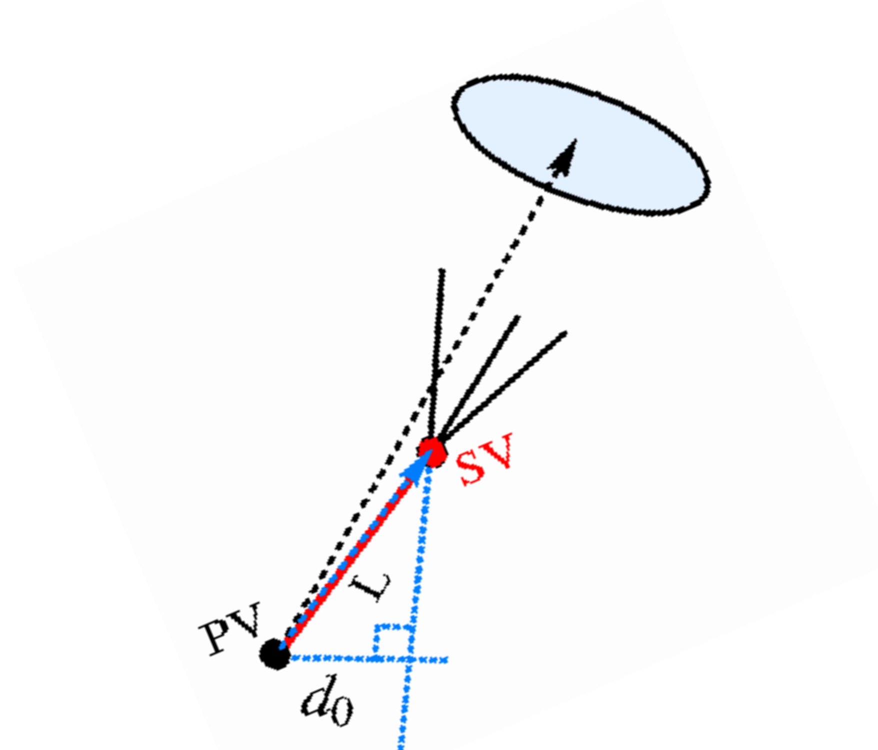
- Improve Jet P_T accuracy
  - Flatten Jet P_T response as function of η and P_T



b-Jet Identification

Combined Secondary Vertex algorithm used to identify jets originating from heavy quarks

- Several variables combined into one tagging variable
  - e.g. Distance from interaction point



Likelihood for being b-jet

- Values range from 0-1
  - Medium working point used

CSV	Likelihood value for being b-jet	mis-identification probability for light-flavored jets as b-jets	B-tagging Efficiency*
Medium	0.679	~1%	~70%

* arXiv:1211.4462 [hep-ex]

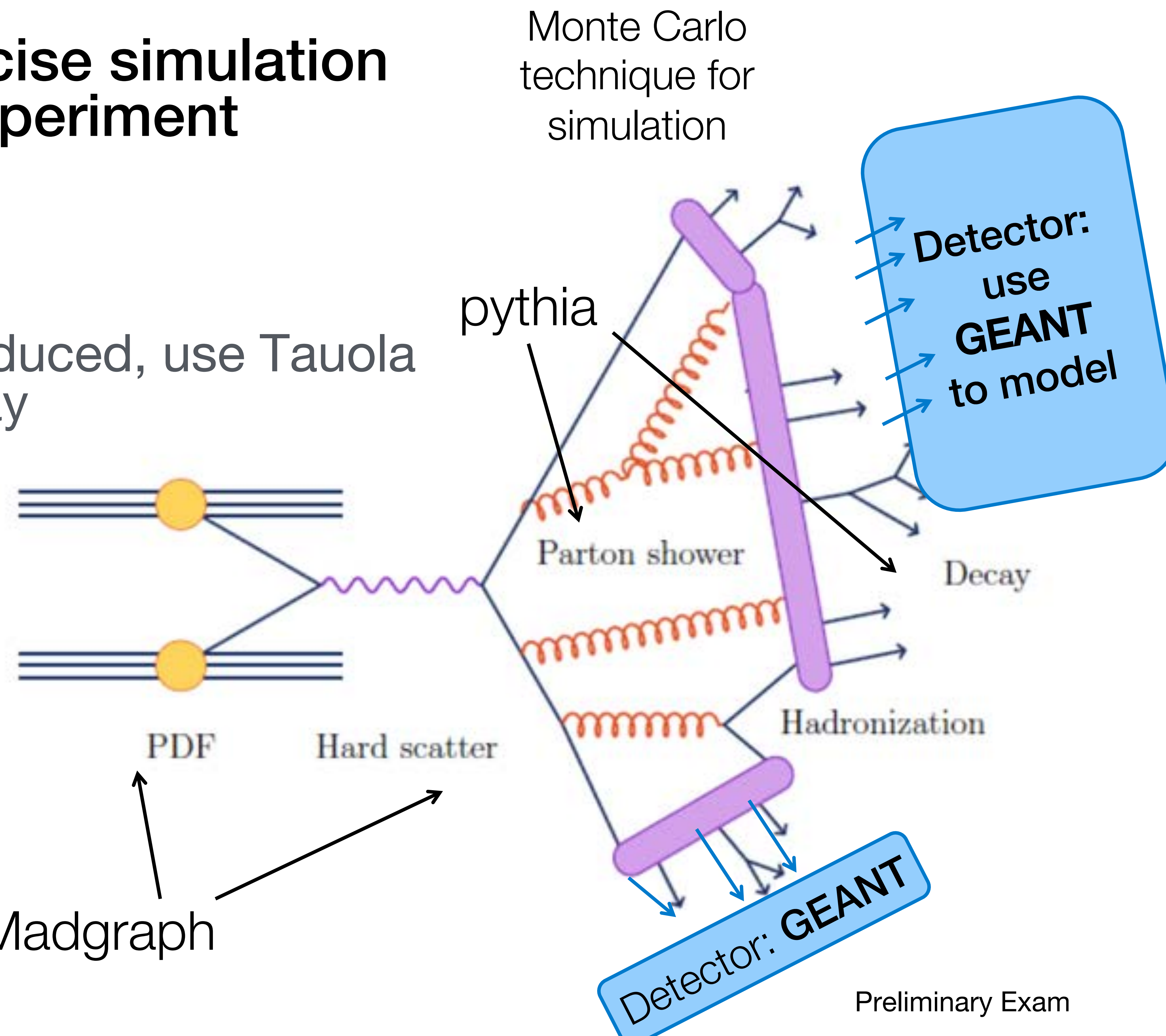
Monte Carlo Production

Require very precise simulation to compare to experiment

- Validation

Production

- If tau lepton produced, use Tauola to simulate decay



MSSM H->ττbb backgrounds

MSSM H->hh production cross section*BR is ~1 pb

TTBar 257 pb

- Largest background because of 2-jet requirement in our category selections. Dominates 2 Jet, 2 B-Jets category
  - Production cross section*BR: ~13 pb

W+jets 36257 pb

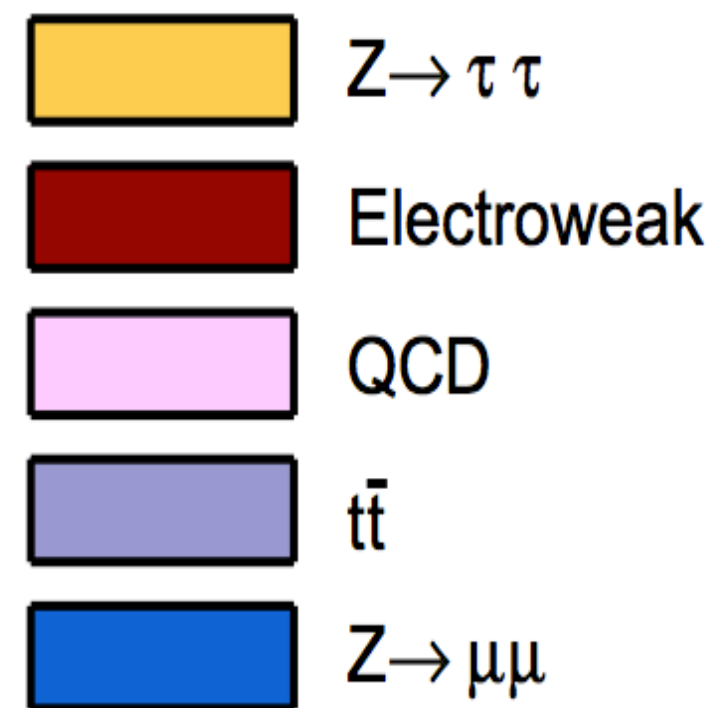
- W+3 Jet production cross section drops to 519 pb
  - Production cross section*BR: ~50 pb
- Other cuts further reduce yield

Drell Yan 3504 pb

- DY+2 Jet production cross section drops to 181 pb
- Zττ peak is distinct from signature peak, and small 2 lepton BR
  - Production cross section*BR: ~6 pb

QCD Processes

- Inclusive selection rejects a large portion of QCD background

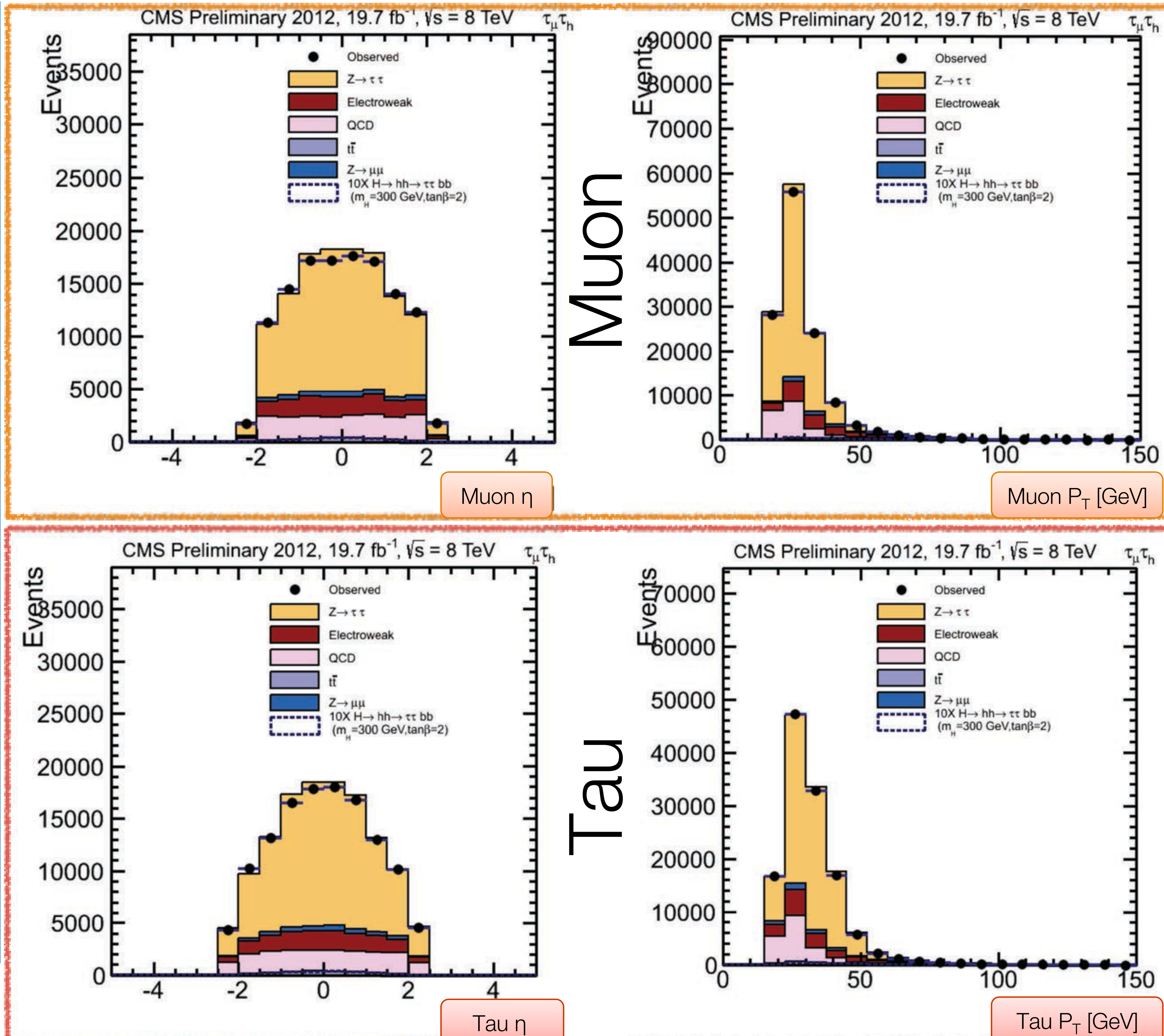


Hadronic tau fake rate reduces much further for dimuon decays

$\tau_\mu \tau_h$ Inclusive Selection

- **Trigger: Isolated Muon of P_T > 17 GeV (at least) with a Tau with P_T >20 GeV**
- Isolated Muon P_T>20 GeV and |η| <2.1
- Isolated Tau P_T>20 GeV and |η| <2.3
- No extra OS di-Leptons
- Signal Selection
  - M_T<30 GeV

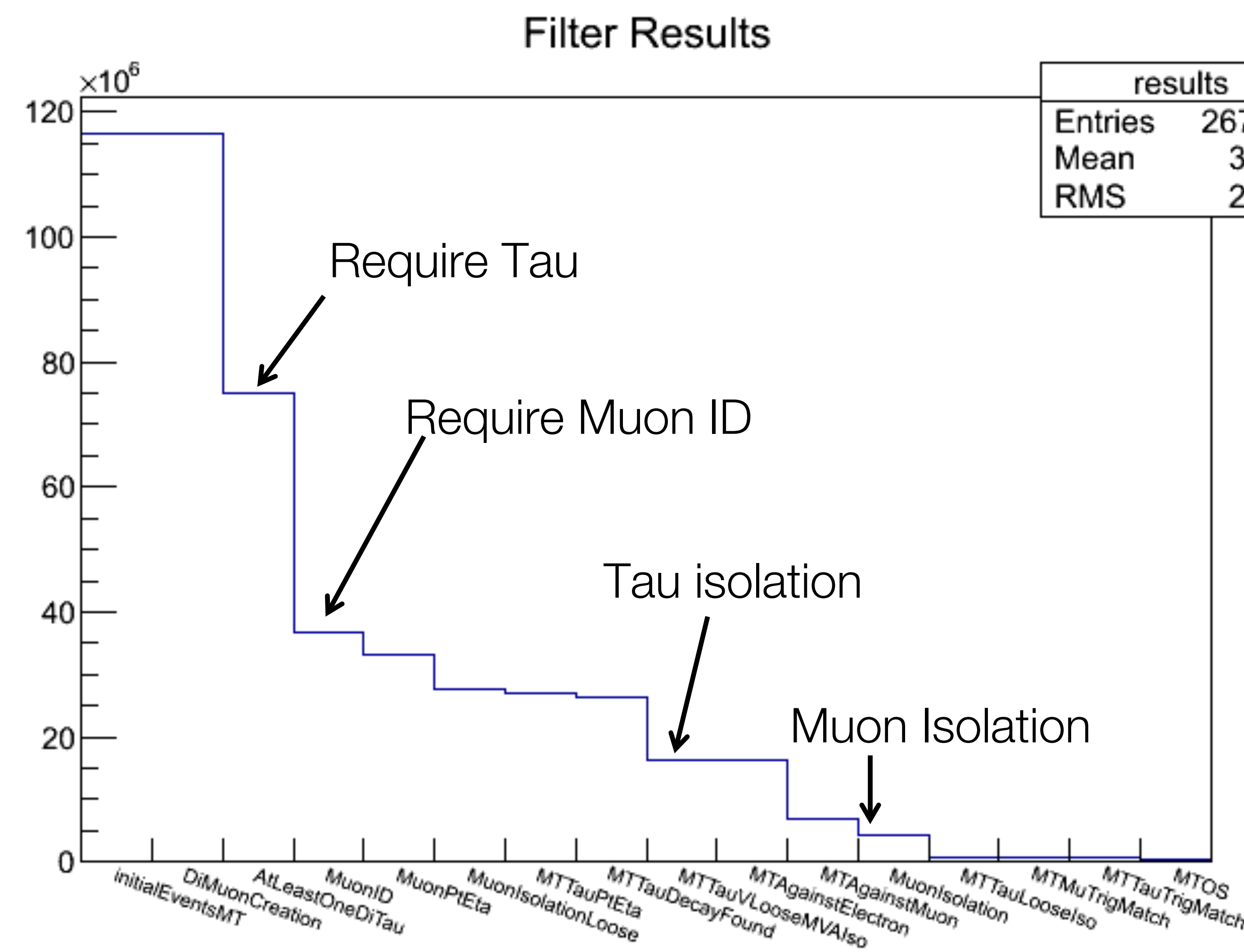
$$M_T = \sqrt{2 p_T{}^{\ell} E_T^{\text{miss}} \left(1 - \cos \Delta\phi\right)}$$



Selection and Yields

Number of events passing selections

Inclusive yields shown



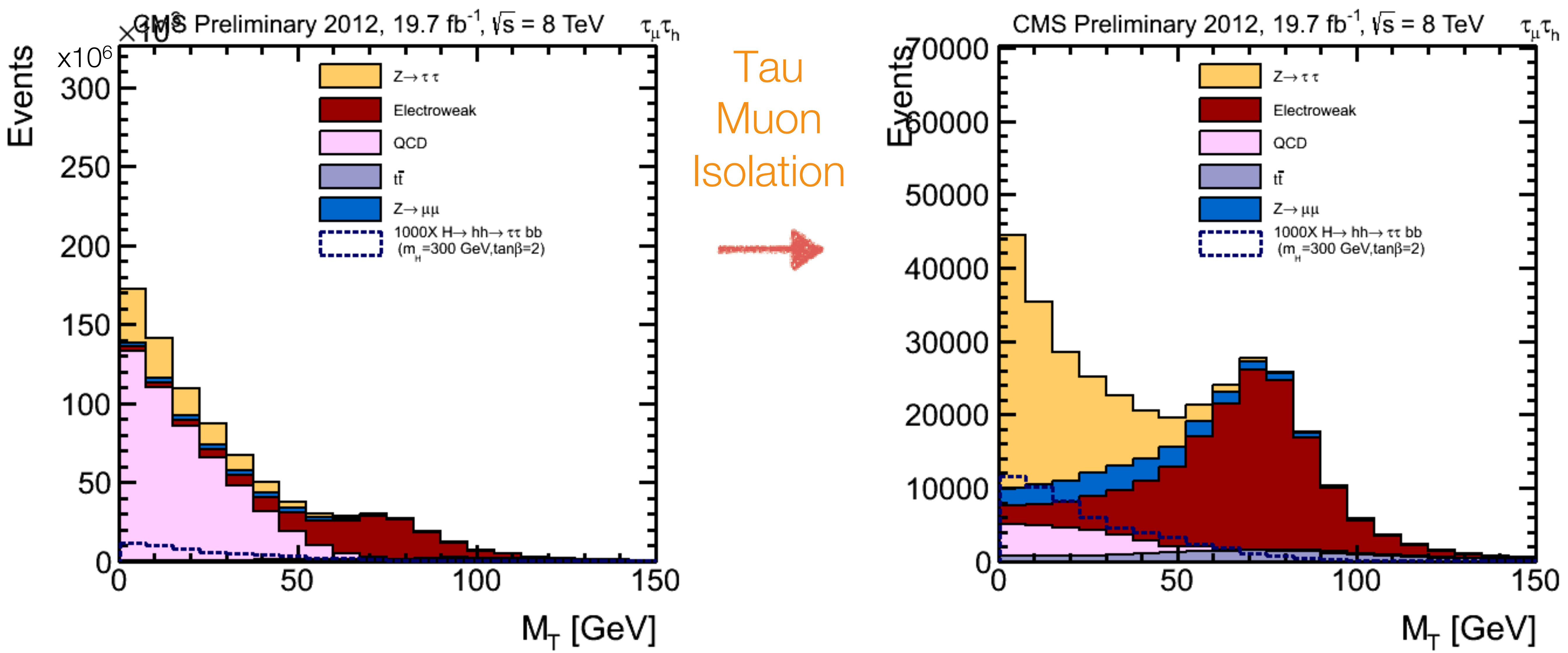
Sample	Inclusive Yield
Data:	***128K***
TOTAL Background =	***129K***
+ QCD	**19K**
+ W+Jets	**13K**
+ Top	**2K**
+ VV	**.7K**
+ ZLFT	**.2K**
+ ZJFT	**.2K**
+ ZTT	**90K**

Isolation in Selection

Offline Primary Vertices>0
Data used to estimate Electroweak, QCD, Z yields
Tau P_T>20, Muon P_T>20

Isolation dramatically reduces QCD.

M_T Transverse mass: MET+Lepton



Di-tau Mass & MVA MET Recoil Energy

Di-Tau Mass reconstructed

Maximum likelihood technique

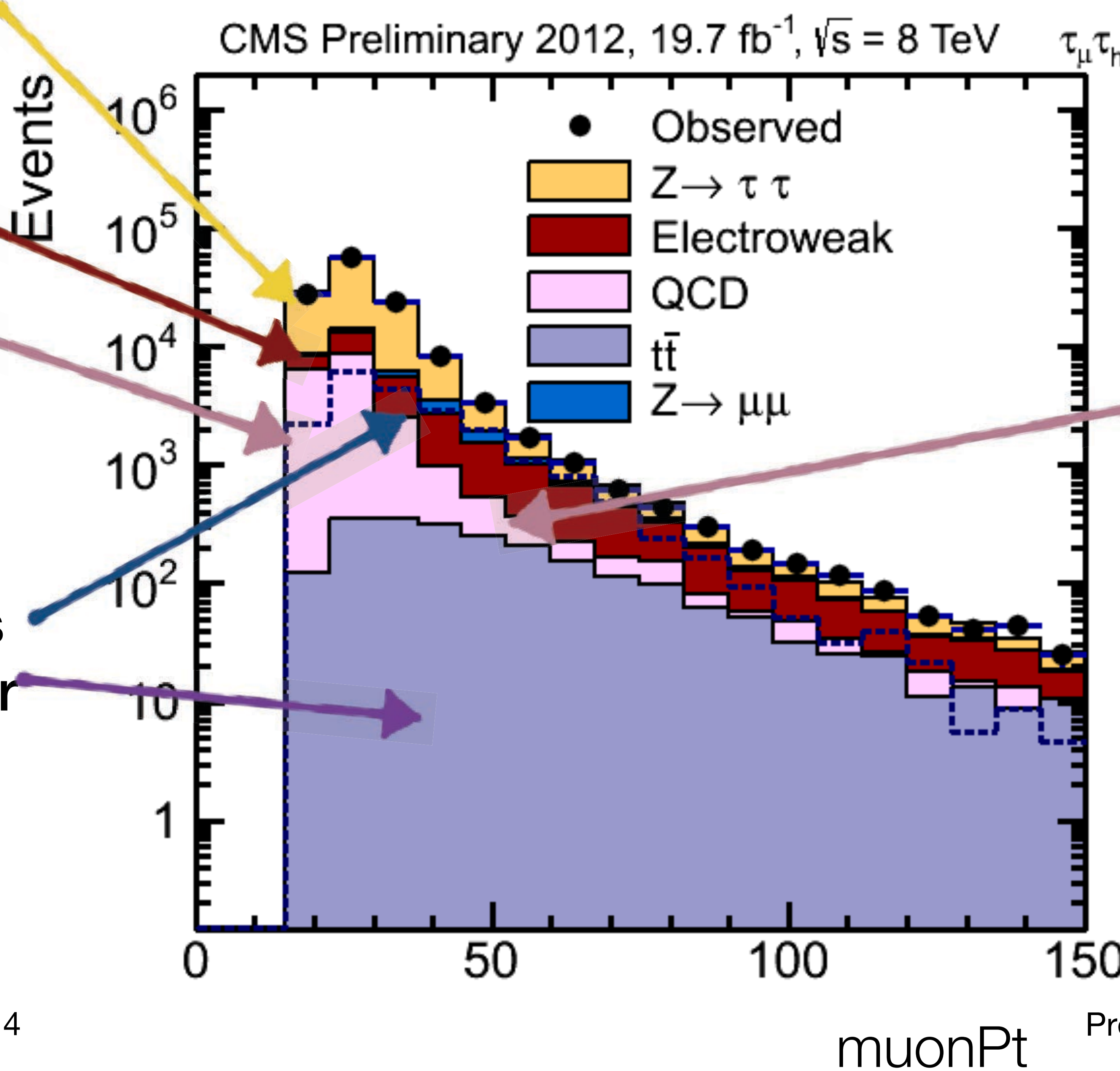
- Visible tau decay products
- Missing energy in the event to help determine neutrinos energy
  - Neutrino energy still kinematically constrained.

MVA Missing ET and Recoil energy

- MVA MET uses a BDT to improve MET resolution
- $E_T^{\text{miss}} = -\sum_i p_T(\text{PFlow}) \longrightarrow p_{\text{recoil},T} = \sum_i p_T - q_{T,H}$

Backgrounds Overview

W+jets, Z+jets, Zττ, QCD use data-driven methods



QCD is additionally scaled based on prior MSSM h->ττ studies*

*arXiv:1408.3316 [hep-ex]

Zμμ, TTbar yields are based on prior MSSM h->ττ studies*. Shape from Drell Yan Monte Carlo.

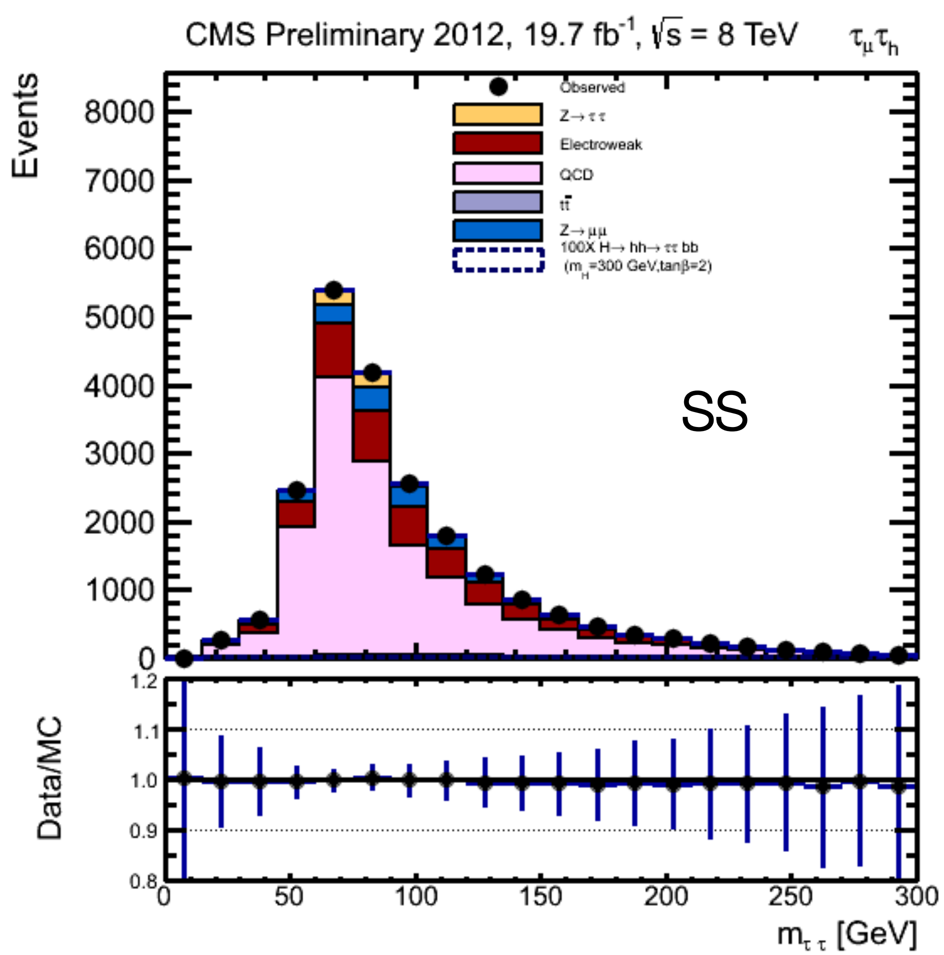
Details in next slides

QCD Background Method

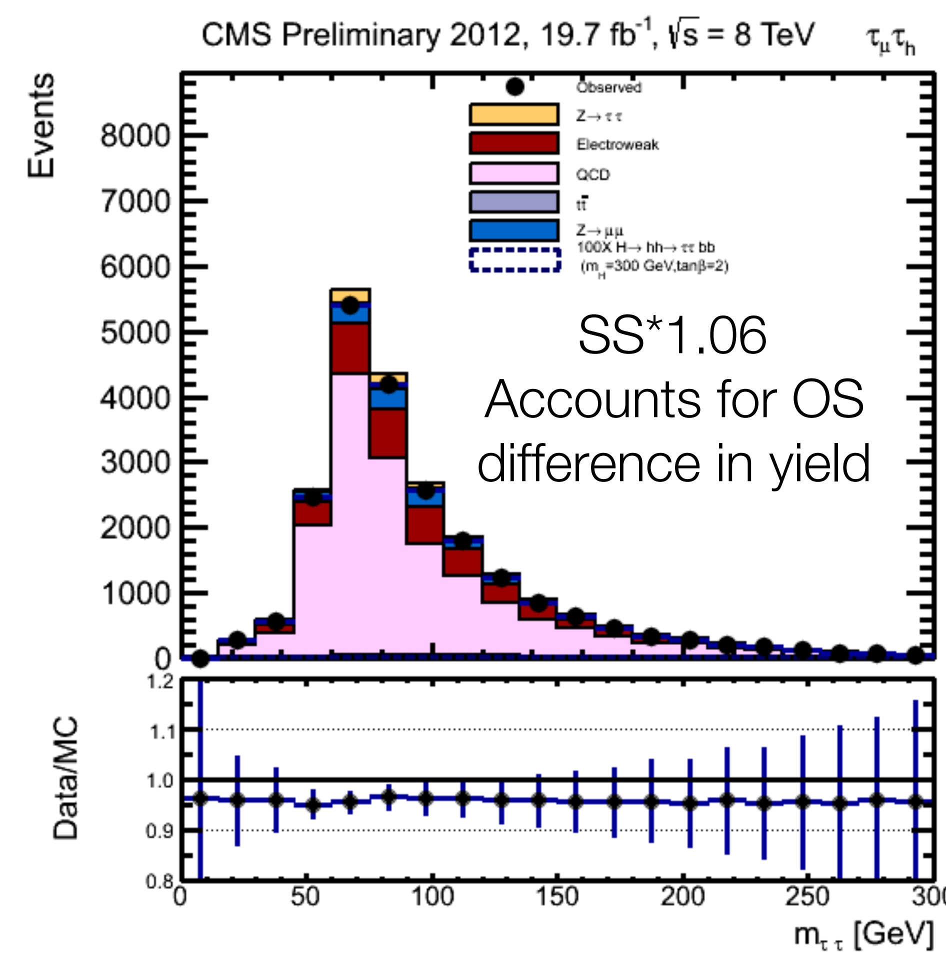
QCD background estimation

- Same sign (SS) (e.g. $\tau^+ \tau^+$) region, M_T <30 GeV cut
  - QCD = Data- Other backgrounds

QCD factor =1.06
Applied to go from SS to OS.
Computed for MSSM h->ττ paper
arXiv:1408.3316 [hep-ex]



SF = 1.06



W+Jets Background Method

Select signal and reduce W +Jets by using a selection

- M_T <30 GeV

W+Jets normalization procedure

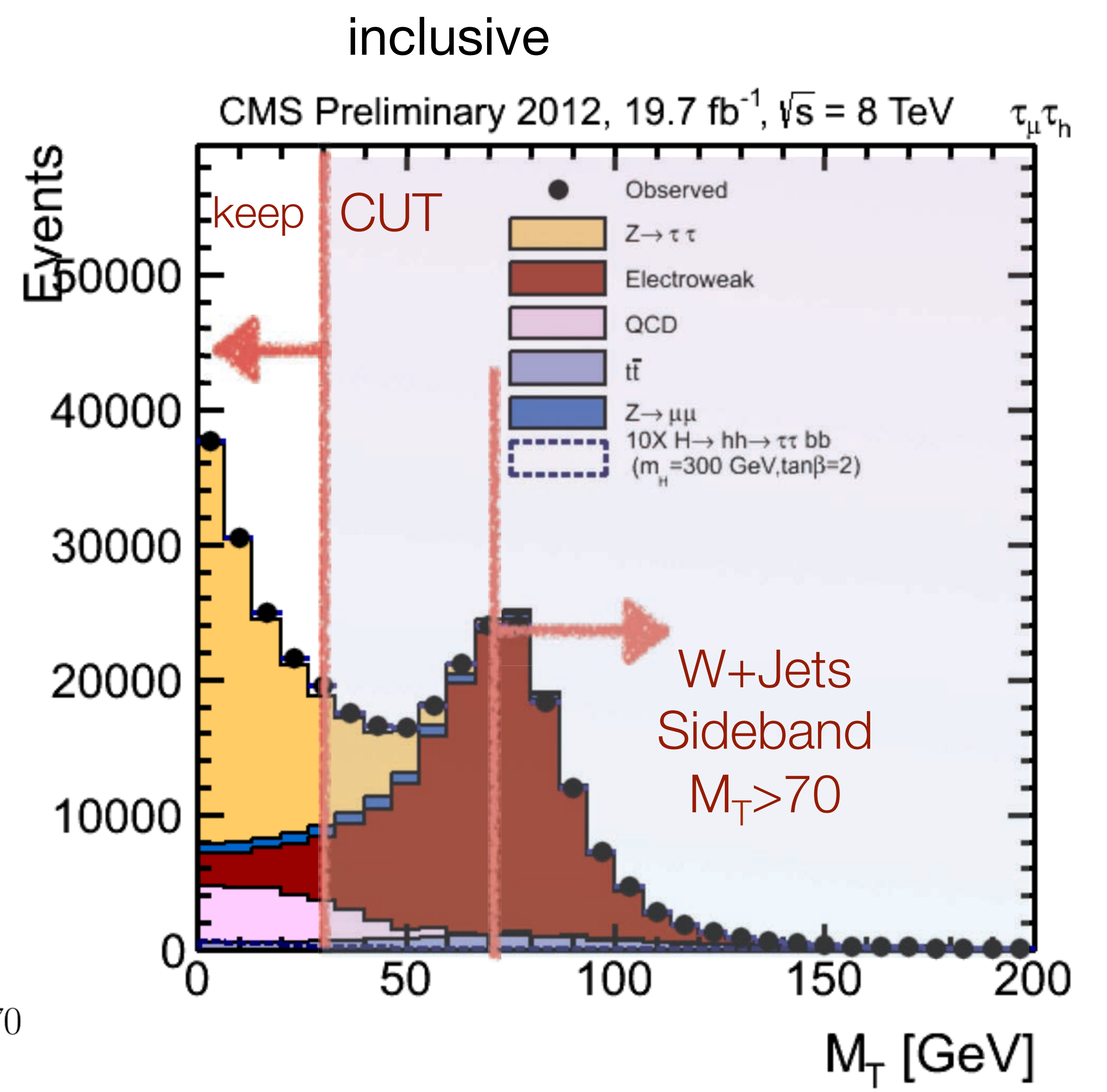
- W+Jets yield is normalized using data in M_T>70 GeV region

$$\text{W+Jets}_{M_T>70} = (\text{data-backgrounds})_{>70GeV}$$

- This is then used to scale the M_T<30 GeV W+Jets MC.

$$\text{W+Jets}_{M_T<30} = \frac{\text{W+Jets MC}_{M_T<30}}{\text{W+Jets MC}_{M_T>70}} \text{W+Jets}_{M_T>70}$$

- The shape of W+Jets is taken directly from W+Jets MC.



TTbar Background Method

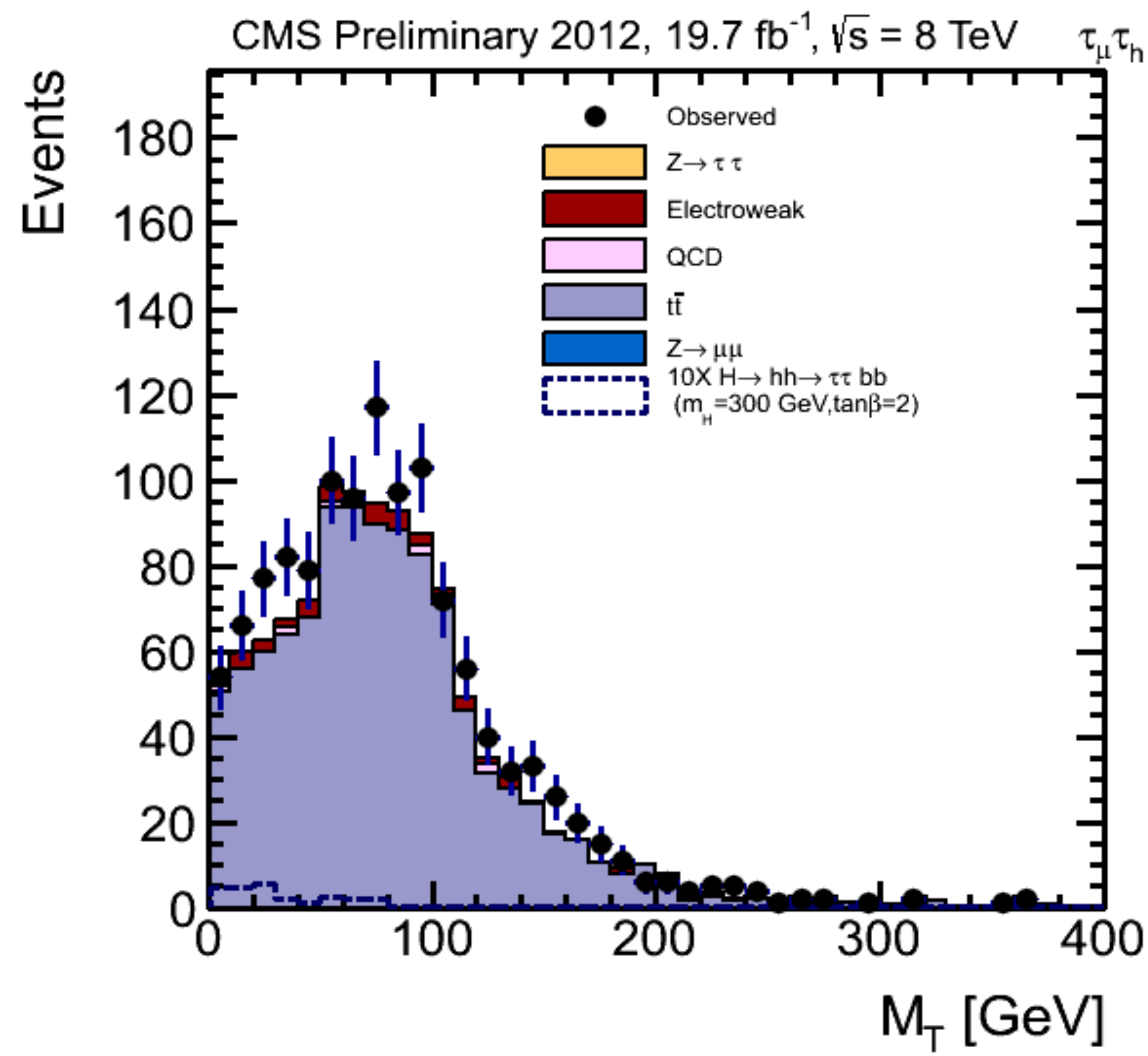
TTbar shape taken directly from TTBar Simulation.

Use scale factor found from a TTbar control region in data to extrapolate TTBar MC yields to data

$$t\bar{t}\ \text{yield} = t\bar{t}_{MC} * .96$$

TTbar selection for control plots:
τ P_T>20 Gev and τ Isolation
At least one tight μ Pt>20 Gev
At least one tight electron
At least 2 P_T>20 GeV jets
At least 1 Medium CSV B-tag Jet
mt1>0

Agrees within uncertainty



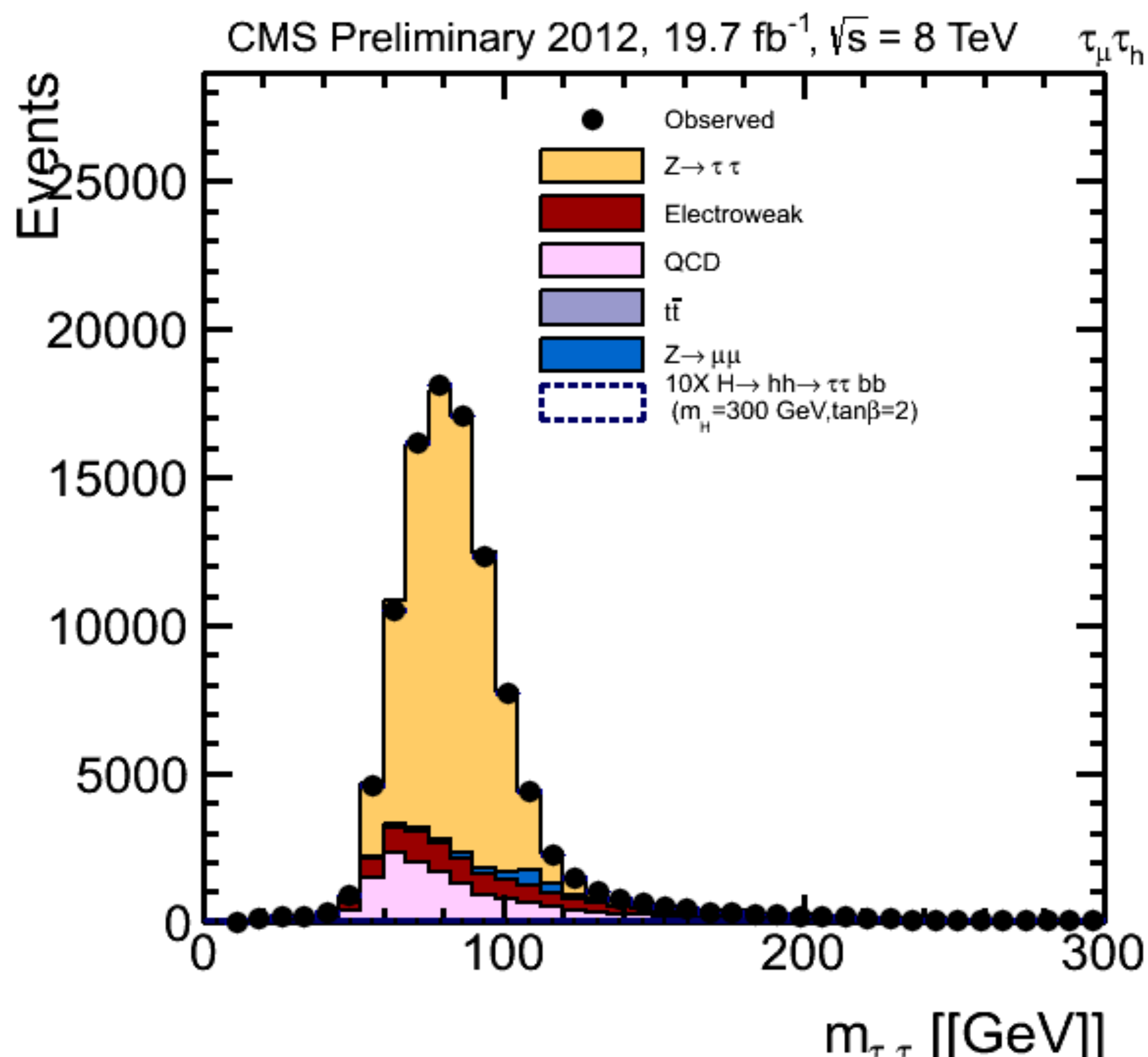
Z$\tau\tau$ Background Method

Z—>$\tau\tau$ Embedding

- Embedding
  - Use a di-muon data sample
  - Keep the kinematics of the muons but model muons as taus and simulate the tau decay.
- Shape
  - Shape is taken from embedded sample with category selections
- Normalization
  - Yield is taken from DY+Jets Monte Carlo with inclusive selections
  - Scaled by efficiency from embedded sample to go from inclusive to category selection.

Z—>$\tau\tau$ Selection:
Tau P_T>20 Gev+Isolation
Inclusive Selection
M_T <30 GeV
No medium bjets, <2 Jets pt20

Z-peak clearly visible
And well modeled



Zμμ Background Method

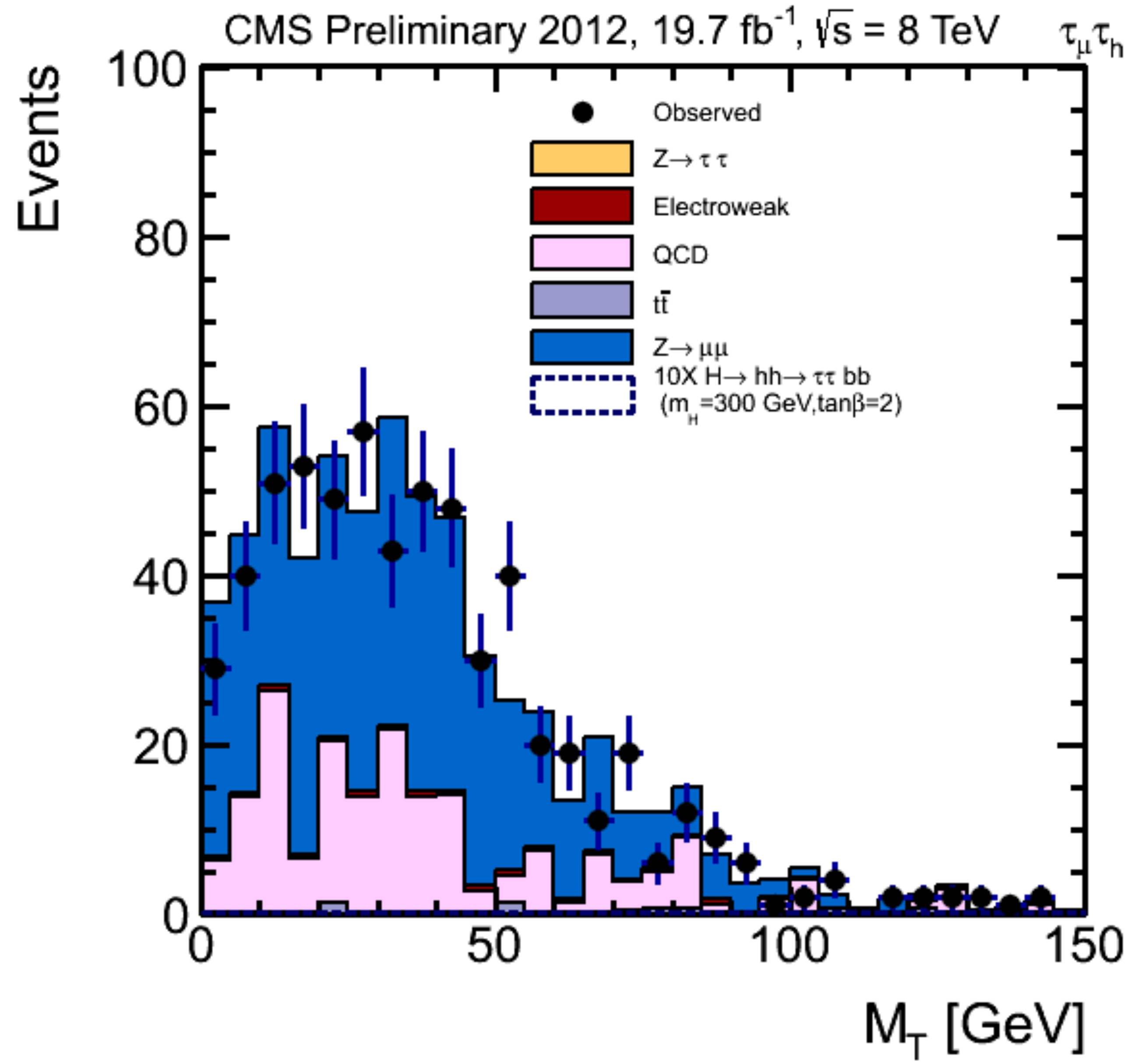
Z->μμ

- Shape from Drell Yan+Jets Monte Carlo
  - Generator-level selections applied to get Z->μμ sample
- Normalization factor used is 1
  - Calculated from Tag and Probe method
    - Relies on Z peak, one muon tagged, the other probed for efficiencies.

For $\tau_e\tau_h$ channel, generator level selections provide Z->ee sample from same DY+Jets simulation.

Zμμ Selection:
Inclusive Selection
with M_T >0 GeV
(undoing M_T >30)
dLeptons>0
(reversing no extra OS diLeptons)

Good Agreement

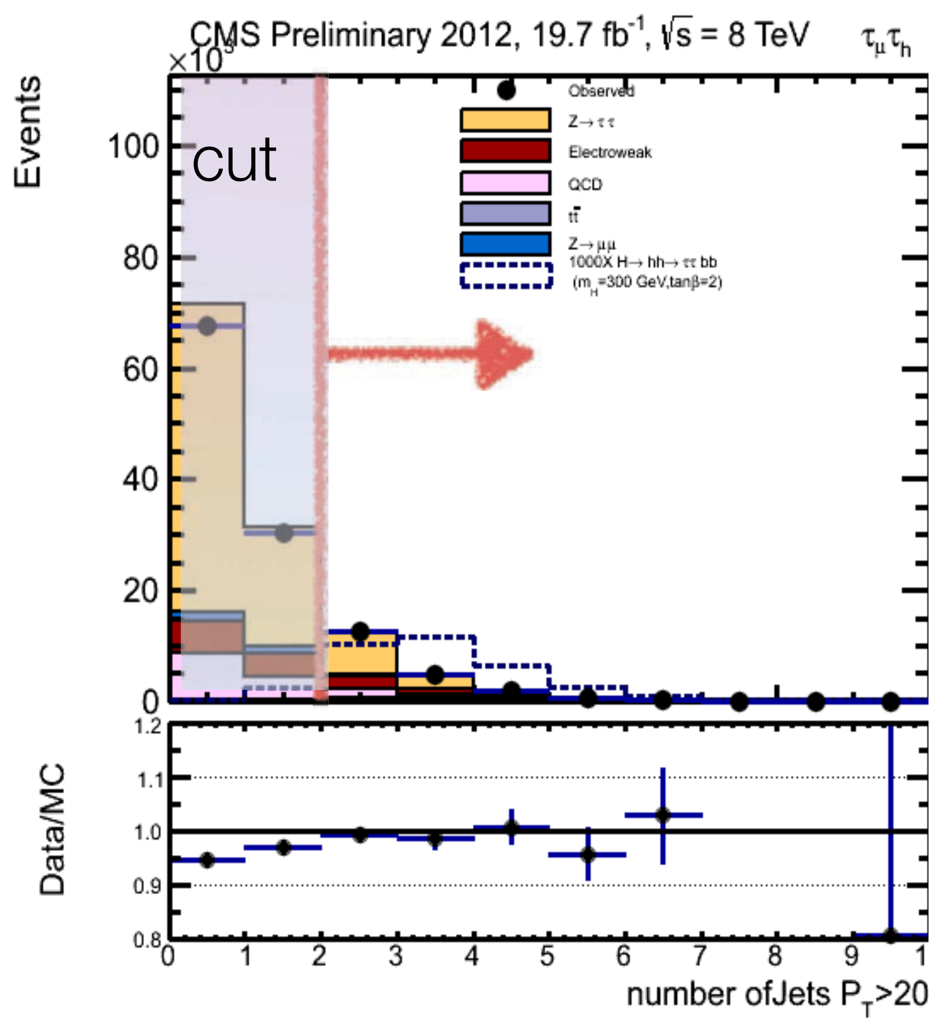


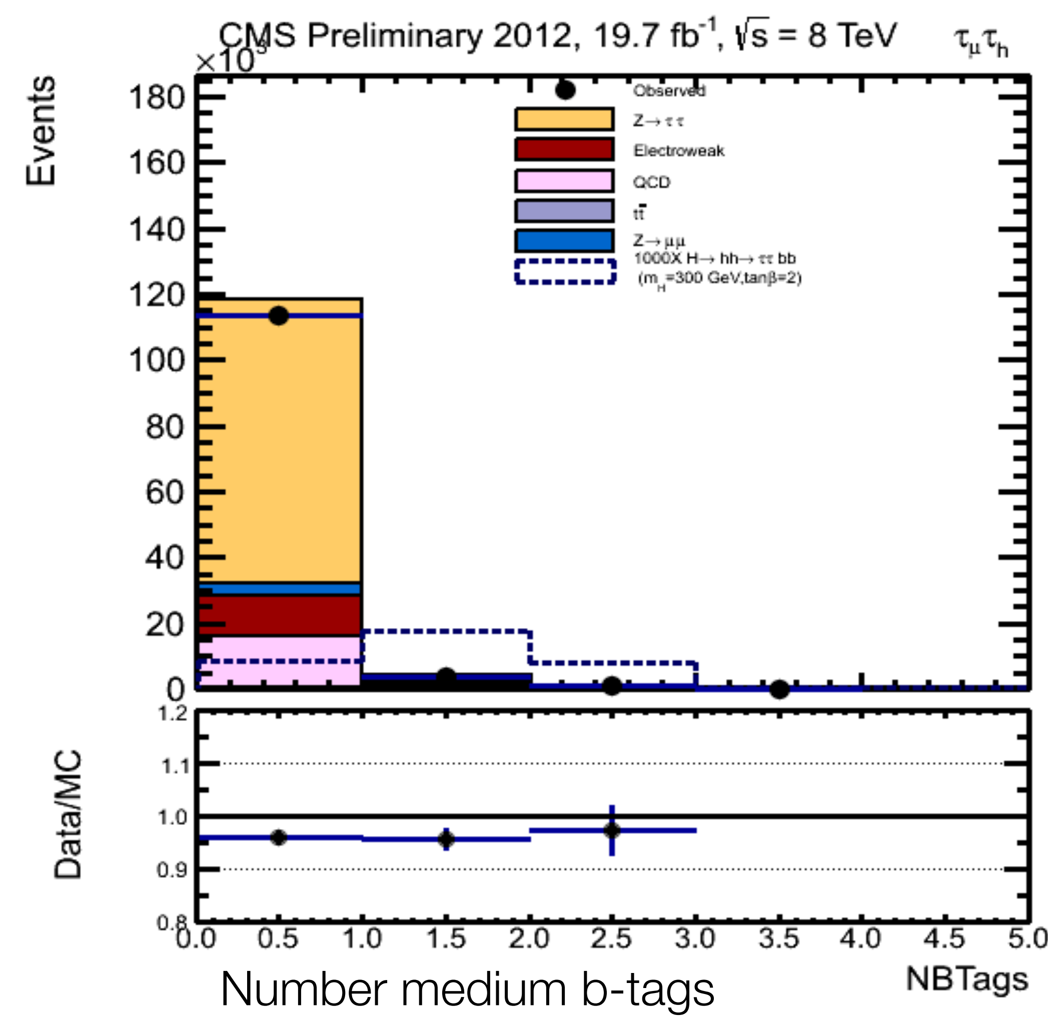
Jet Selection: 3 Categories

Well understood backgrounds

No reduction Signal/ Background ratio in categories

Category	# Jets: Pt>20 |Eta| <2.4	# Medium CSV tag
2jet, 0btag	>=2	0
2jet, 1btag	>=2	1
2jet, 2btag	>=2	>=2





3 Categories of jets should be exclusive

When expected limits calculated the same event only appears once.

Invariant Mass Variables: Signal

$M_{\tau\tau}$

- Mass of light higgs
  - Invariant mass of two taus

M_{bb}

- Mass of light higgs
  - Di-jet invariant mass from 2 highest CSV valued jets

$M_{\tau\tau bb}$

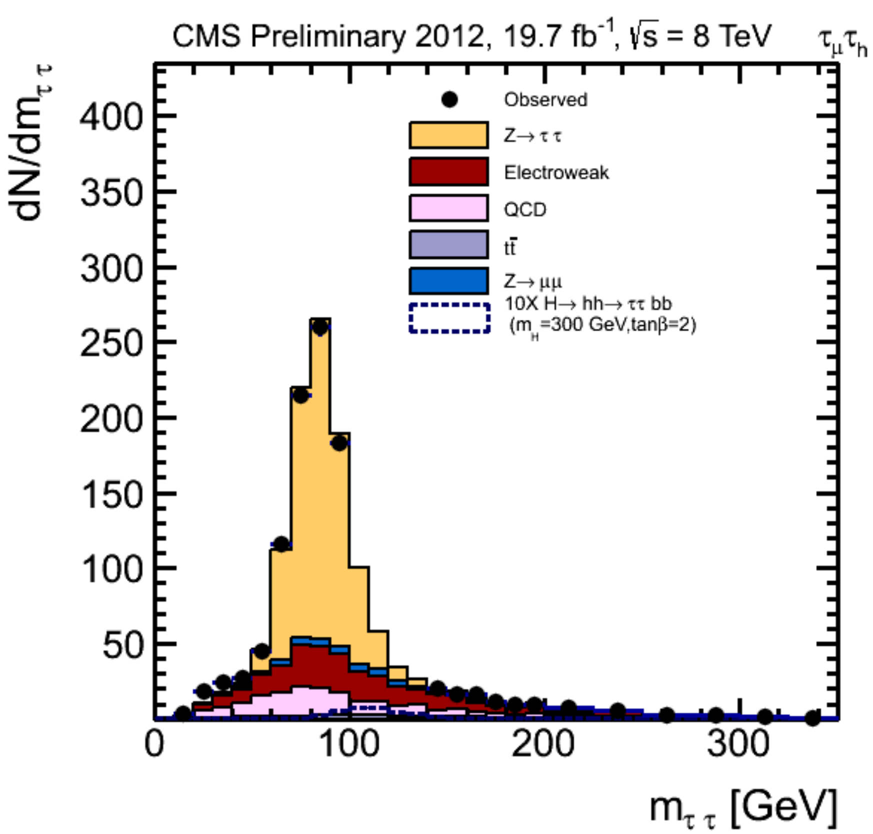
- Mass of Heavy Higgs
- $M_{bb} + M_{\tau\tau}$

$M_{\tau\tau}$ in 3 categories

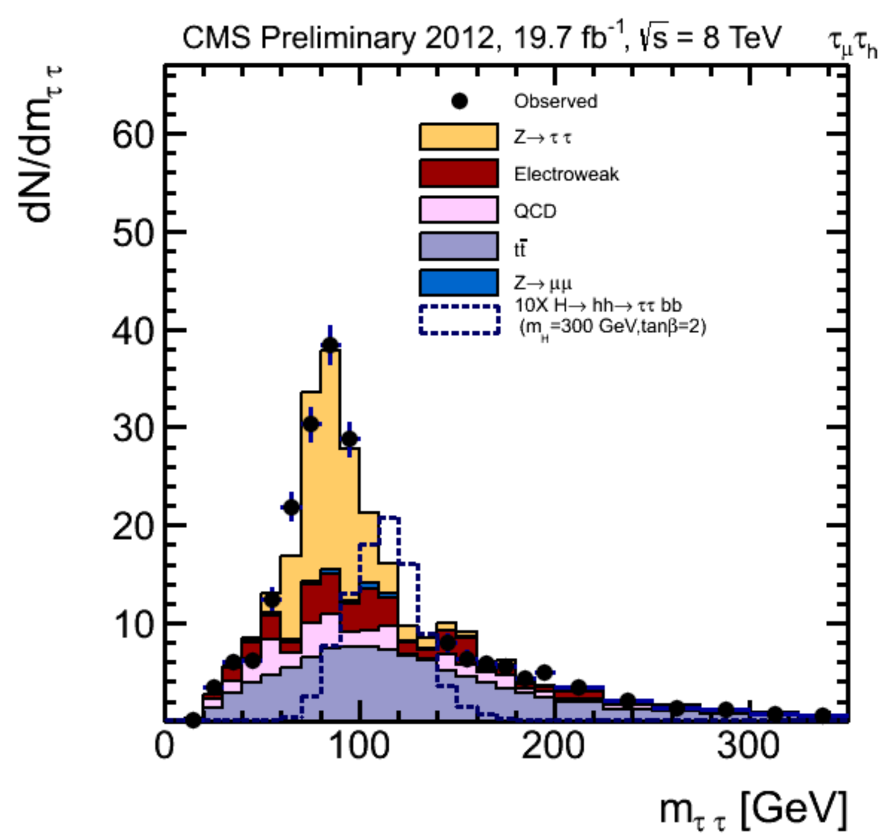
Invariant Mass of h->ττ final state

Very Good Data/MC agreement outside of blinded region

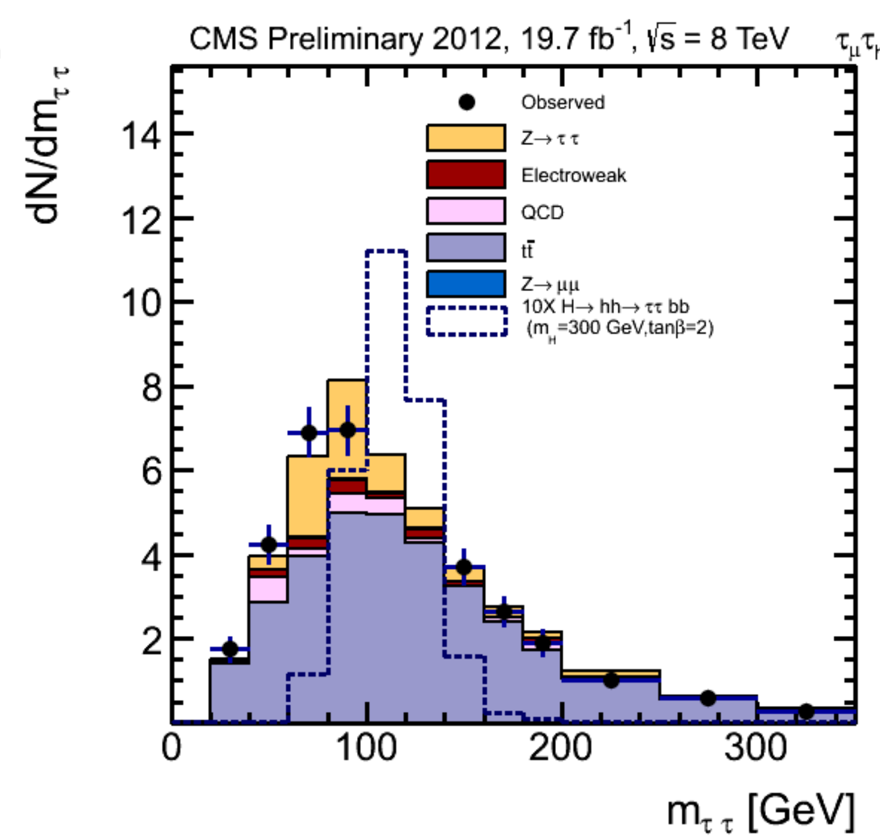
2 jet 0 tag



2 jet 1 tag



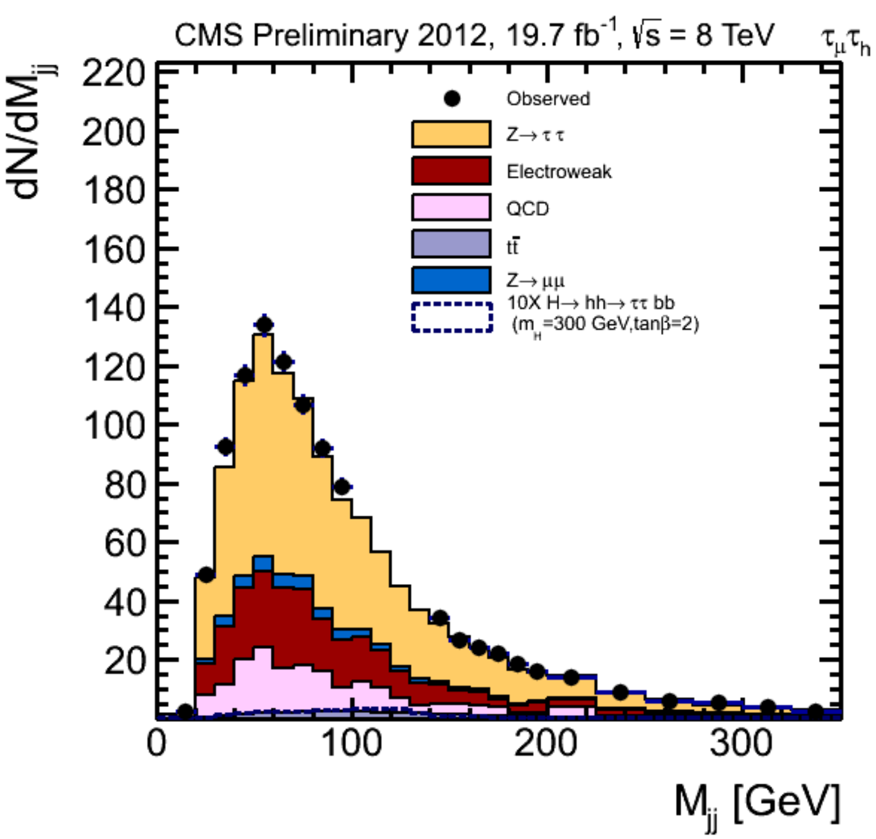
2 jet 2 tag



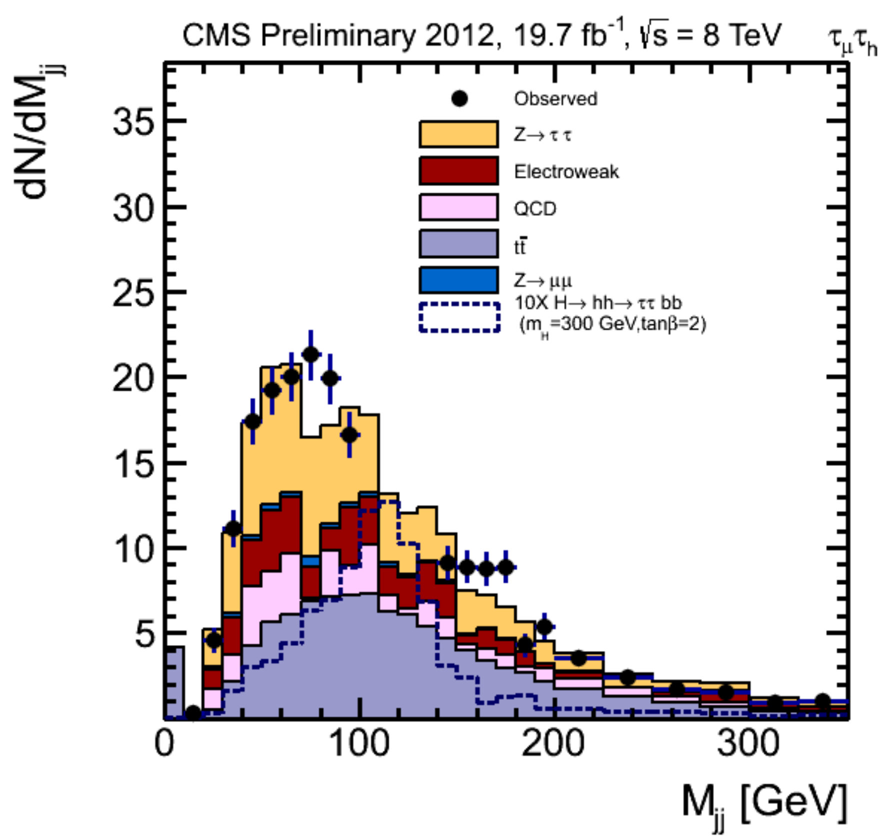
M_{bb} in 3 categories

Invariant Mass of h->bb final state
Acceptable Data/MC agreement outside of blinded region

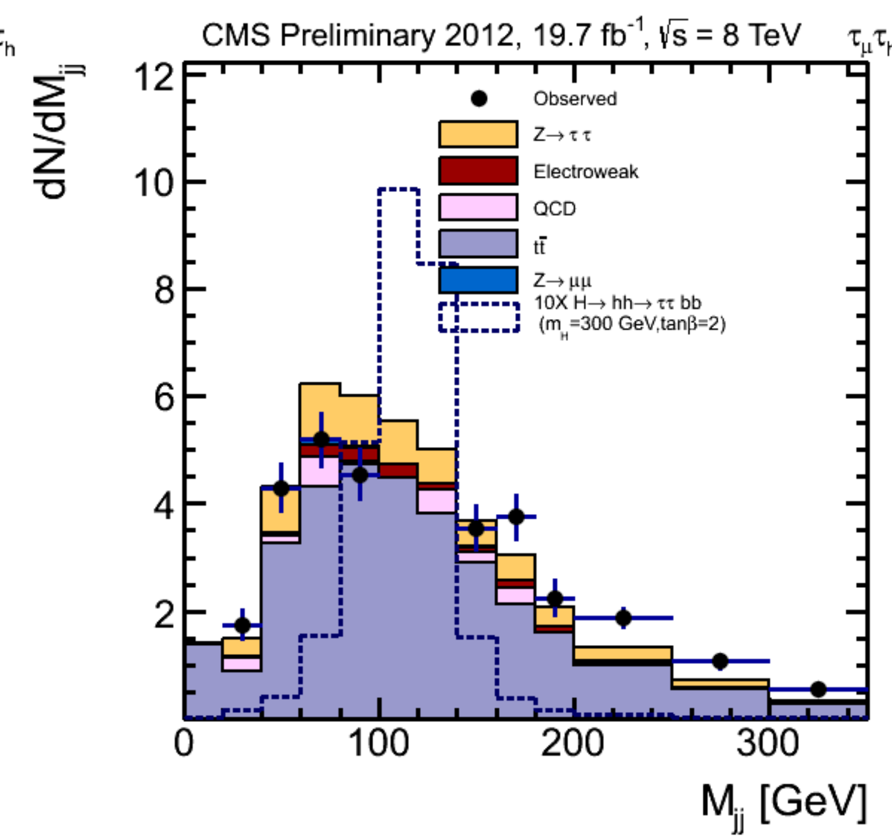
2 jet 0 tag



2 jet 1 tag



2 jet 2 tag

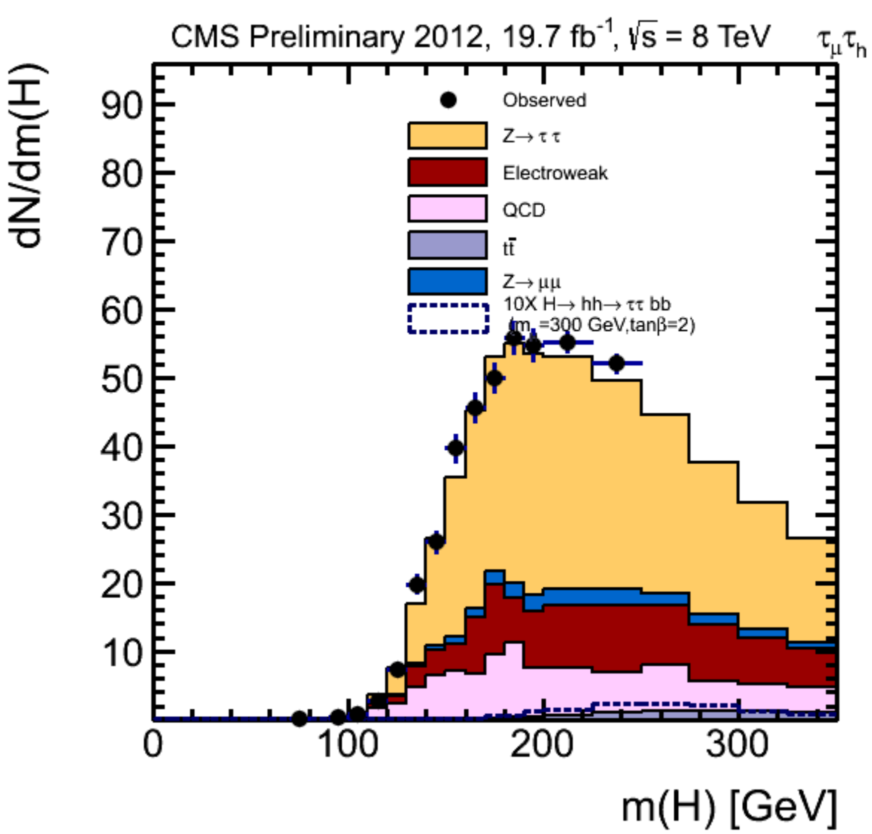


M_H in 3 categories

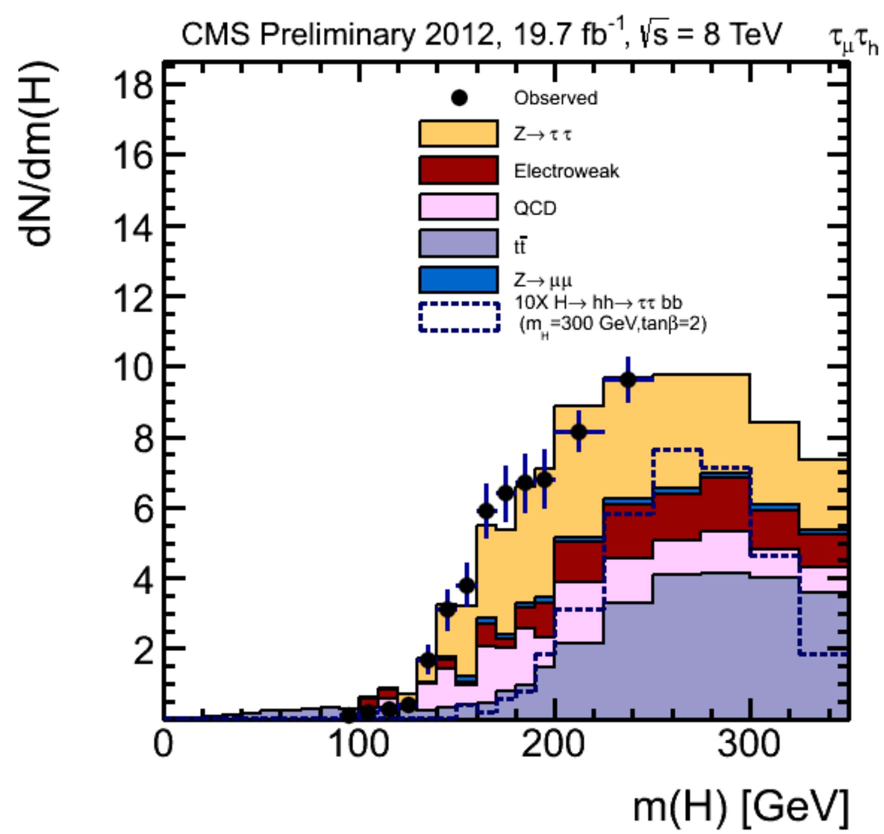
Invariant Mass of H->hh final state

Good Data/MC agreement outside of blinded region

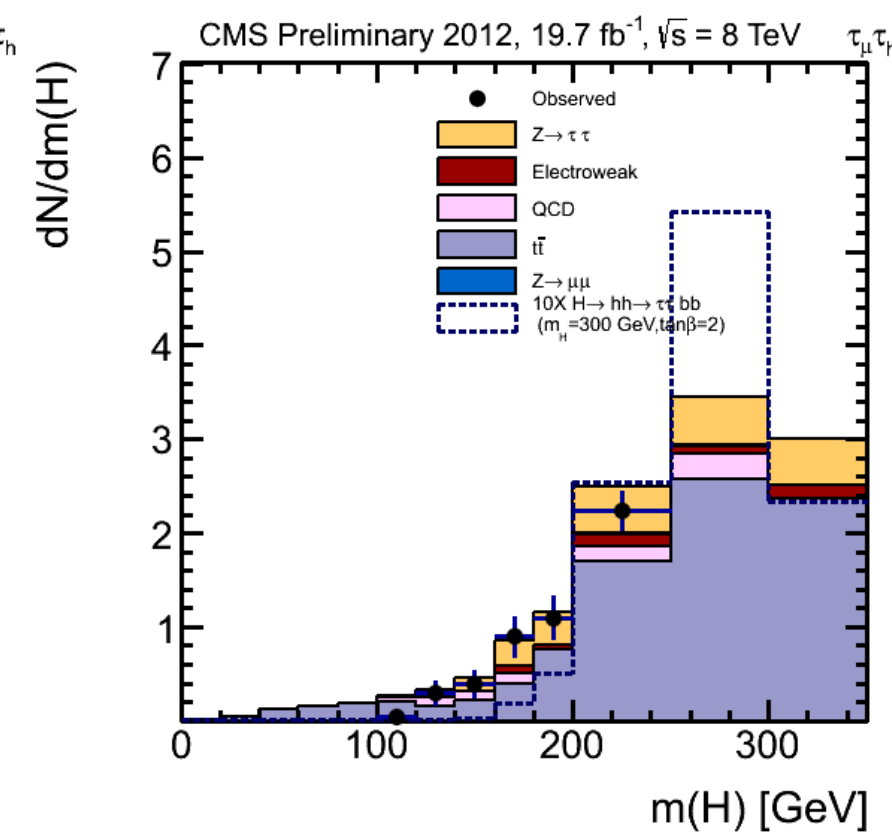
2 jet 0 tag



2 jet 1 tag

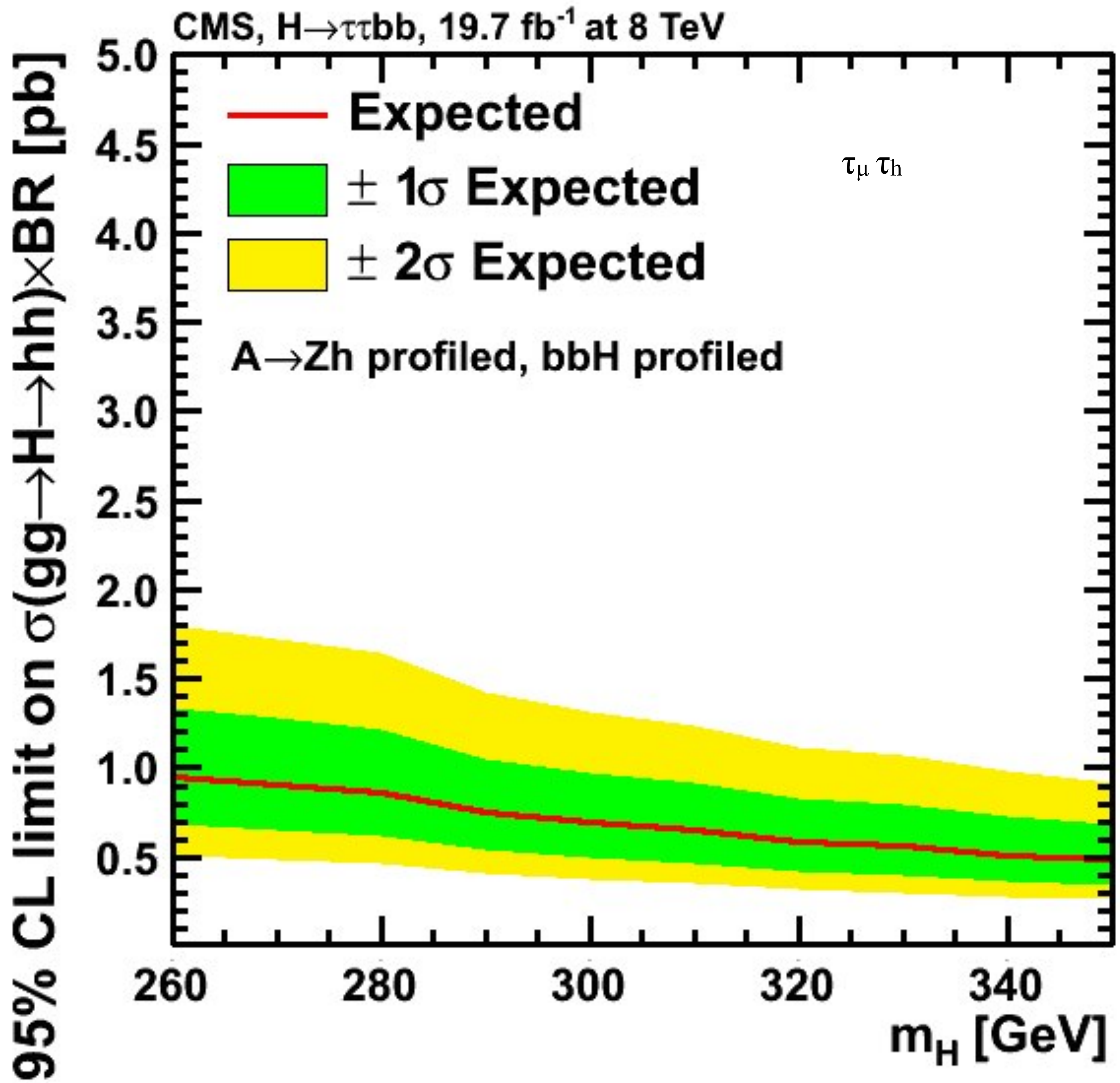


2 jet 2 tag



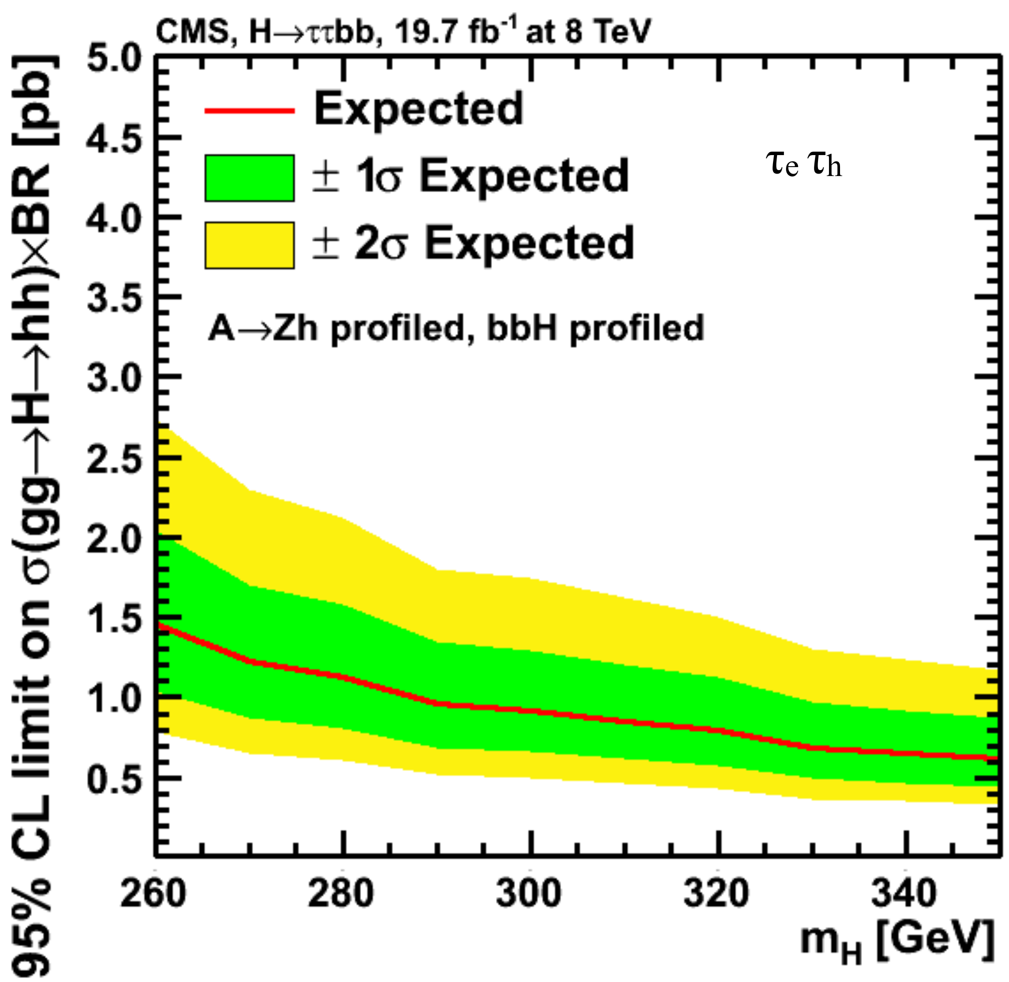
Expected Limits: $\tau_\mu \, \tau_h$

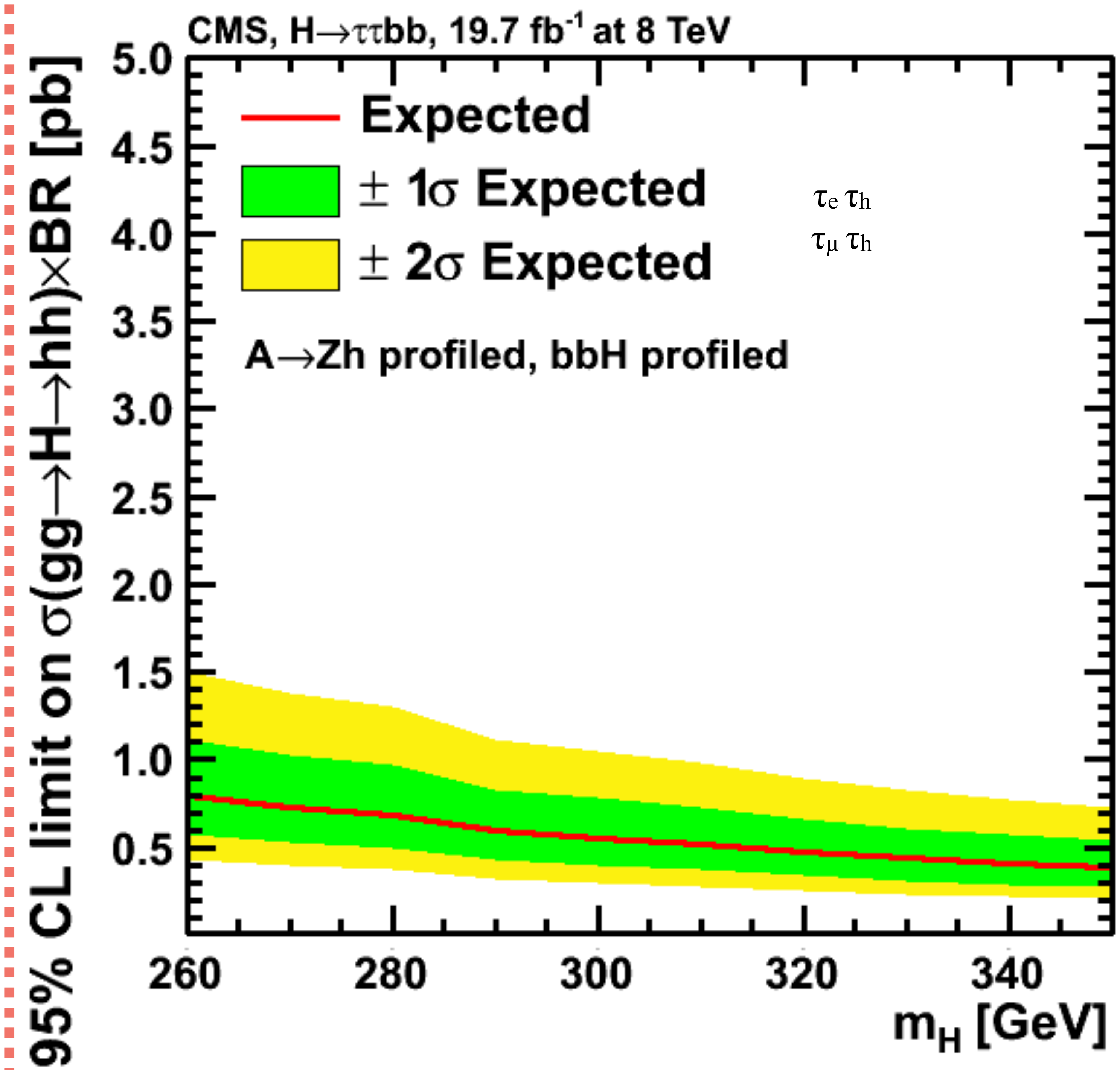
- Minimized expected limit means maximal experimental sensitivity
- $\tau_\mu \tau_h$ expected limit for model independent scenario
- Expected limit on σ*BR is similar to other di-higgs seaches



Expected Limits: $\tau_e \tau_h$+Combined

Combined model-independent expected limit in the two channels for MSSM H





13 TeV Outlook

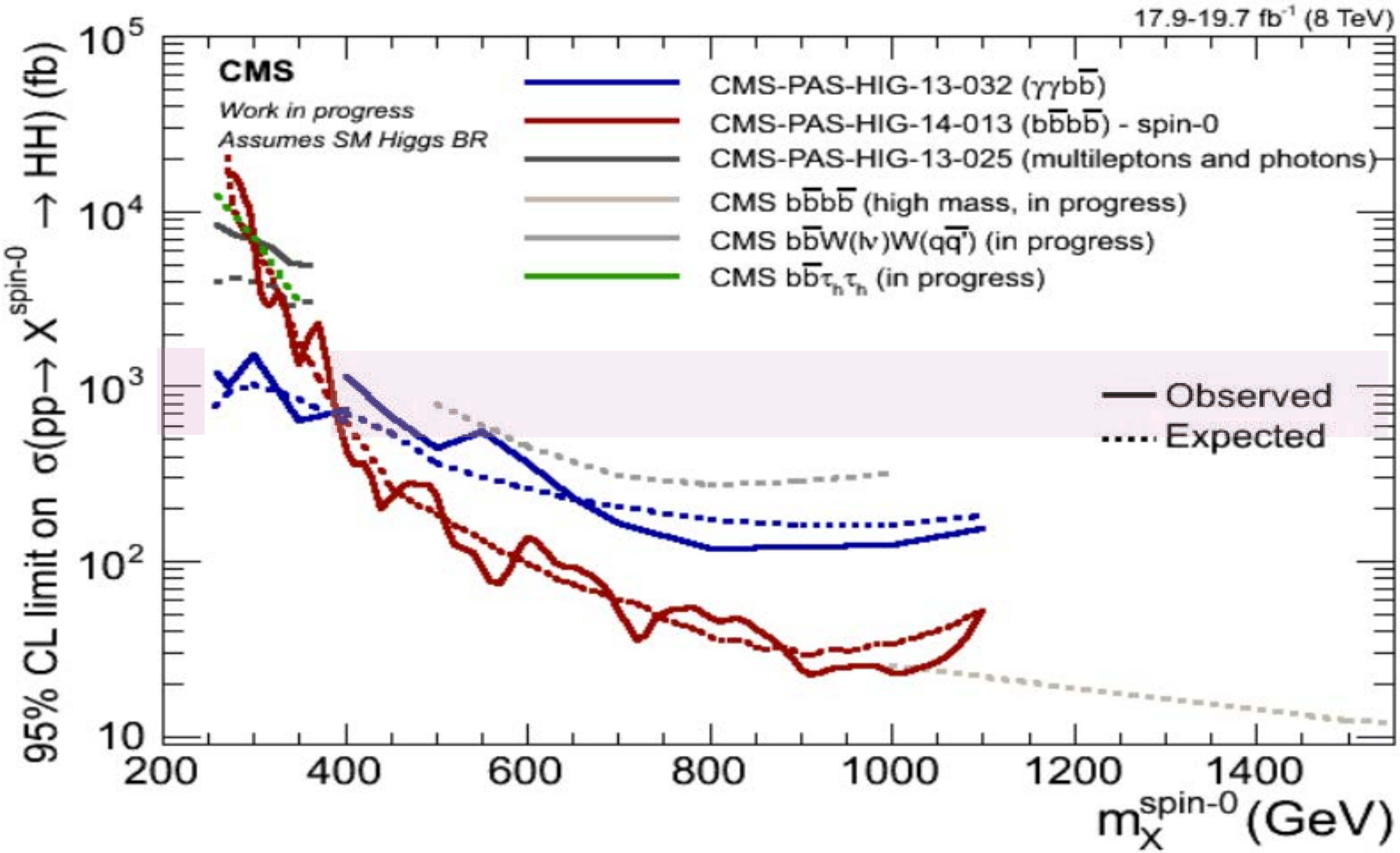
13 TeV Outlook

- Increased Higgs production and more data
  - However TTBar production cross section is predicted ~830 pb at 13 TeV
    - 330% increase
- Precision 125 GeV Higgs measurements
- Reevaluation of methods will be necessary

I will continue help with the L1 calorimeter trigger in 2015 and will be involved with the Higgs to Tau Tau CMS Group.

Backup

Compare to other cms di-higgs



Cross section

- Effective area, probability of interaction

Luminosity, L

- Relationship between rate and cross section

	2011	2012	2015	Design.
Beam Energy [TeV]	3.5	4	6.5	7
Bunch Spacing [ns]	50	50	25 (50)	25
Protons/ Bunch	1.45×10^{11}	1.48×10^{11}	$\sim 1.5 \times 10^{11}$	$< 1.3 \times 10^{11}$
Bunches/ Beam	~1380	~1380	~2800	~2800
ε [μm]	~2.4	~2.6	~2.5	3.75
β* [m]	1.0	0.6	0.4	0.55
Pileup (Max)	~20	35	40 (average)	~20
Peak Inst. L	3.7×10^{33}	7.7×10^{33}	(.5*)1.4 10^34	10^{34}

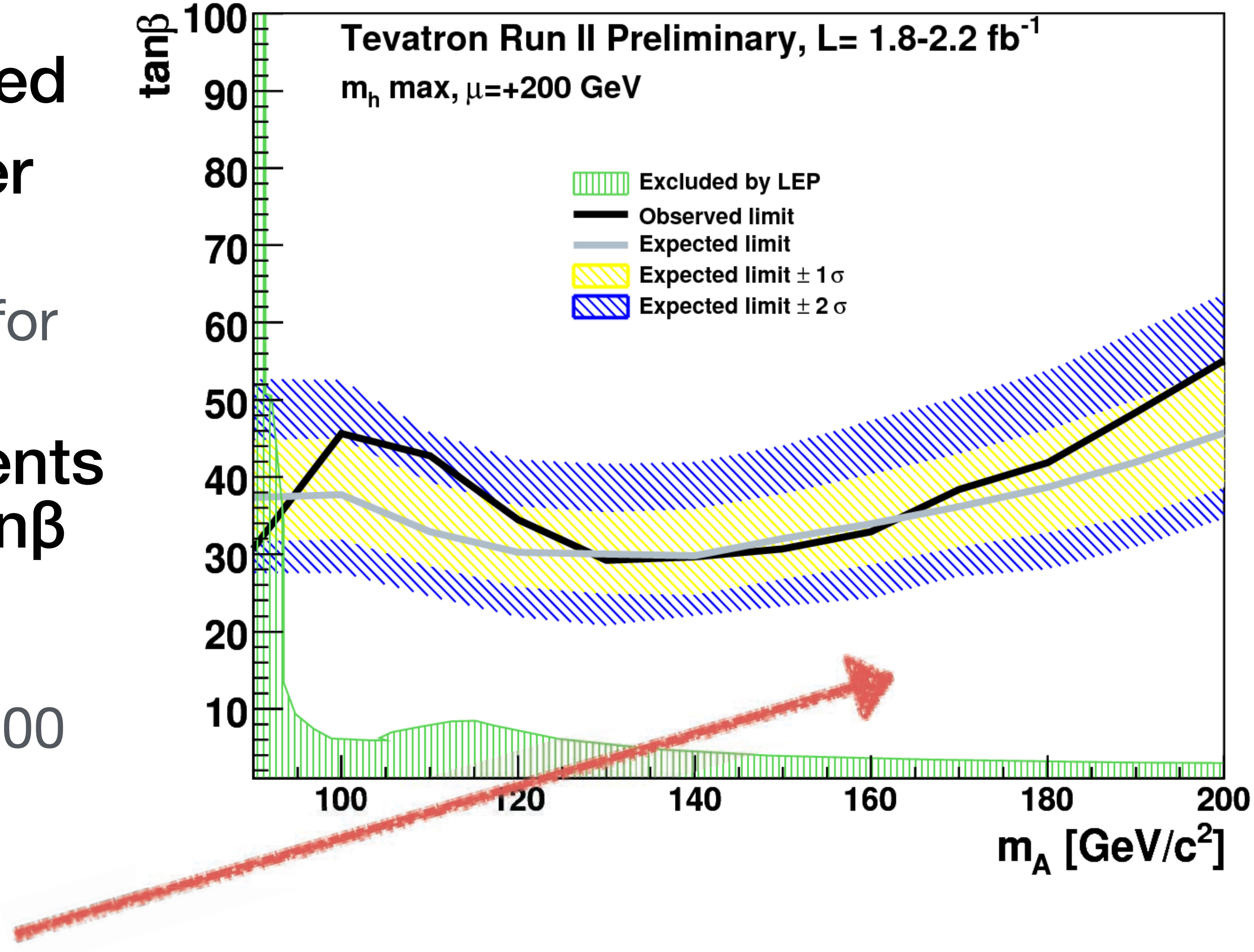
Symbol	Quantity
N_b	particles per bunch
n_b	number of bunches
f_r	revolution frequency
γ	lorentz factor
ε_n	normalized emittance
$\beta^\star$	lattice parameter
F	geometric eduction factor

$$N = \sigma \int L \, dt$$

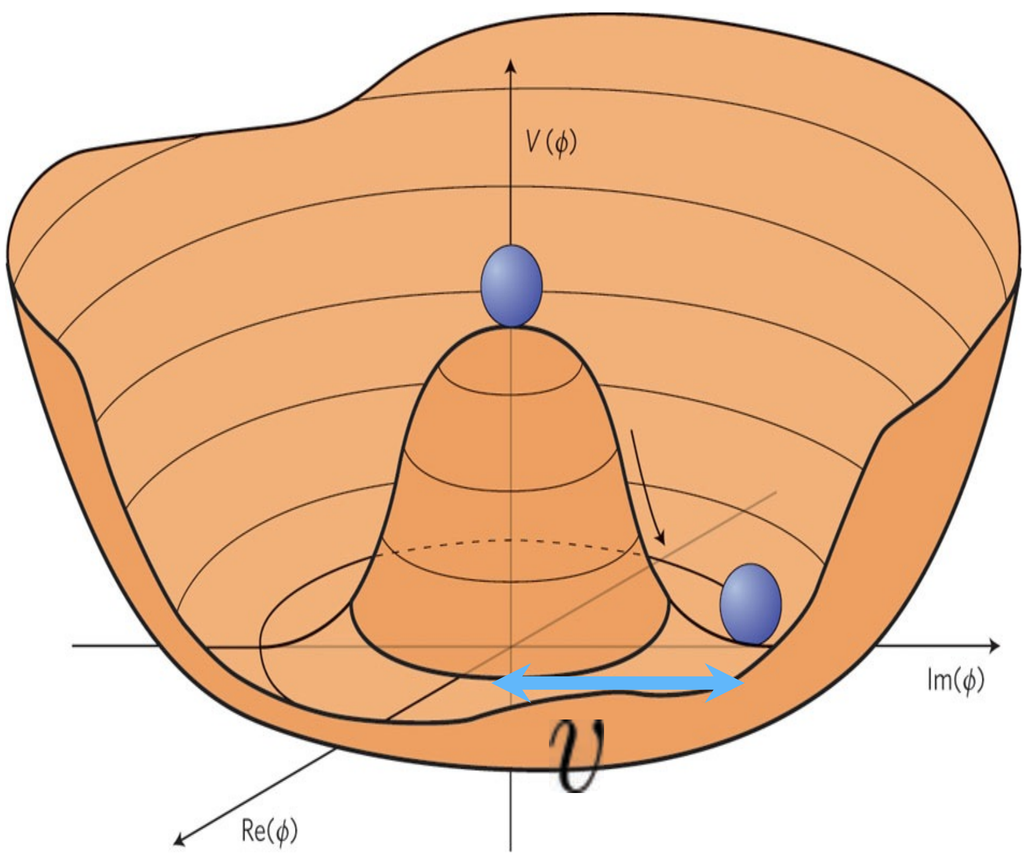
$$L = \frac{N_b^2 n_b f_r \gamma}{4\pi \varepsilon_n \beta^\star} F$$

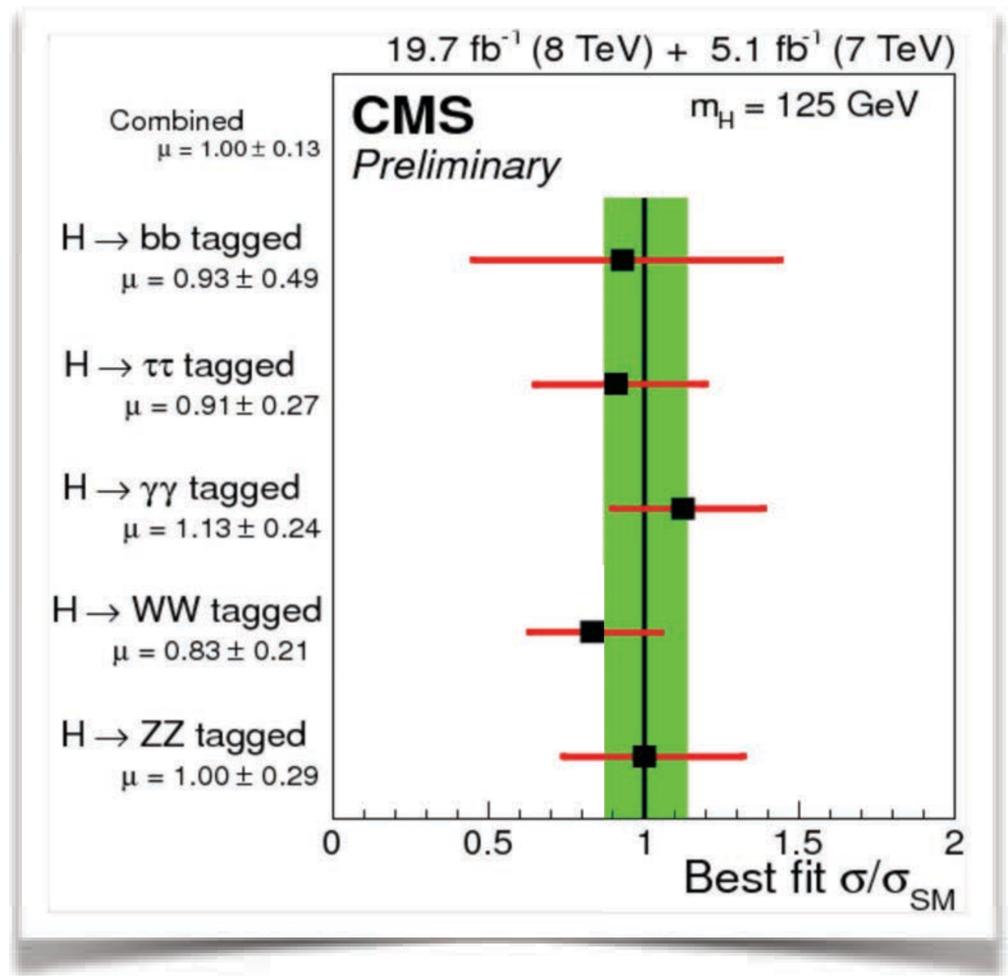
Previous Results MSSM Higgs

- M_h^{max} scenario commonly examined
- LEP provided lower tanβ bounds
  - Excluded tanβ<3 for 150<M_A<450
- TeVatron experiments provided higher tanβ bounds
  - Excluded about tanβ>40 for M_A <200
- Close the wedge

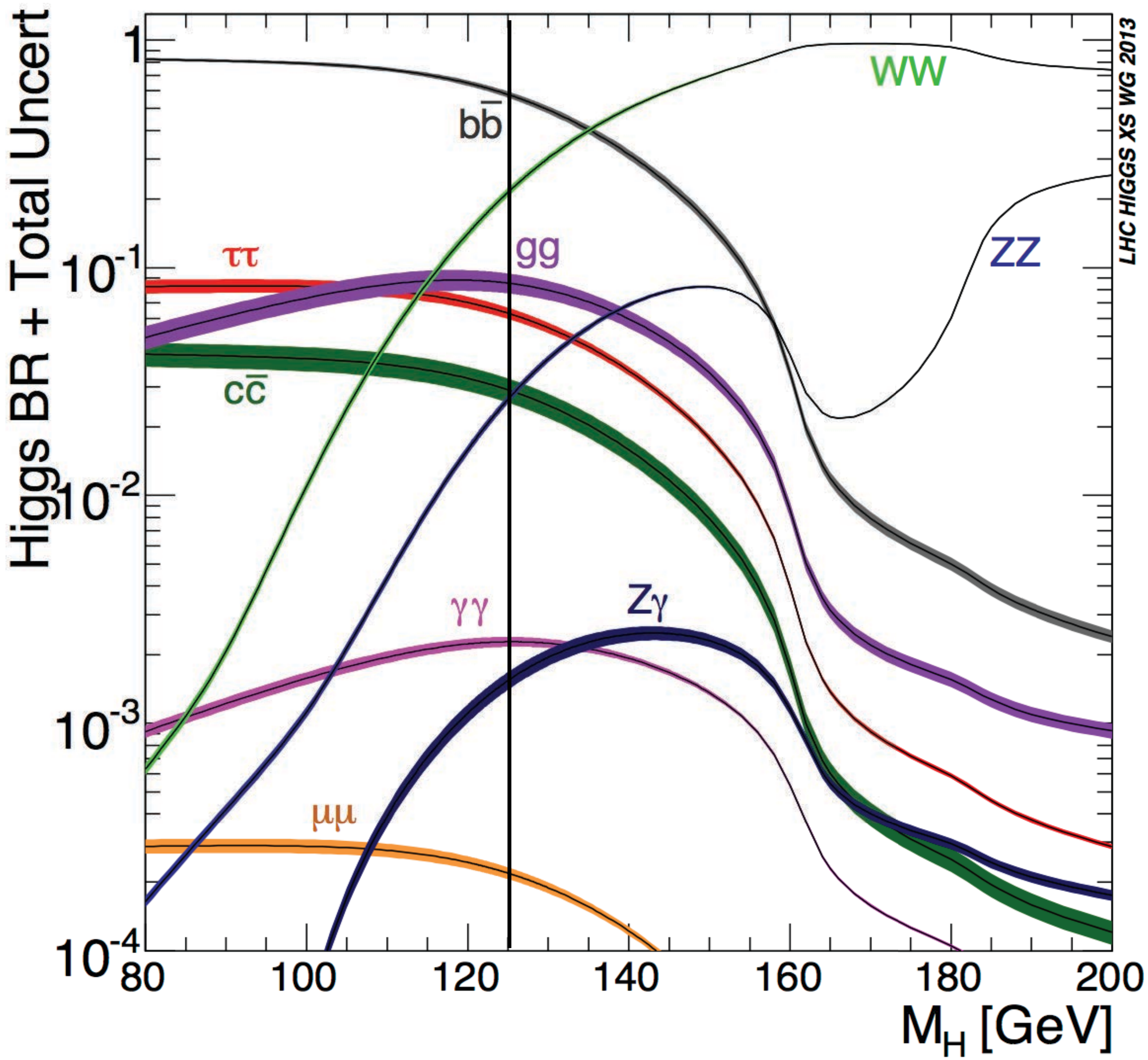


Standard Model (SM) Higgs





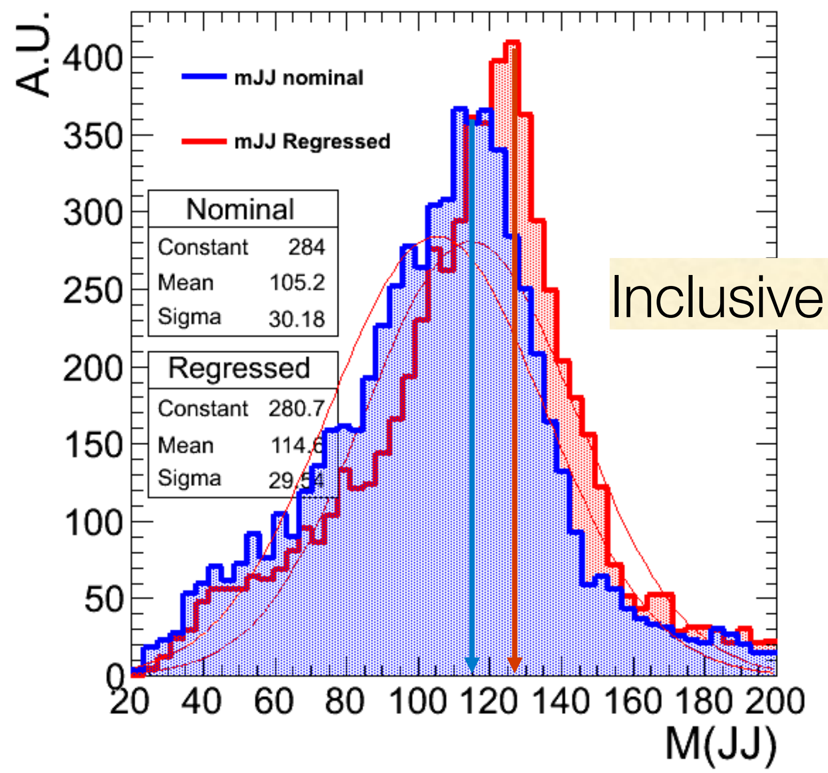
SM Higgs Decays

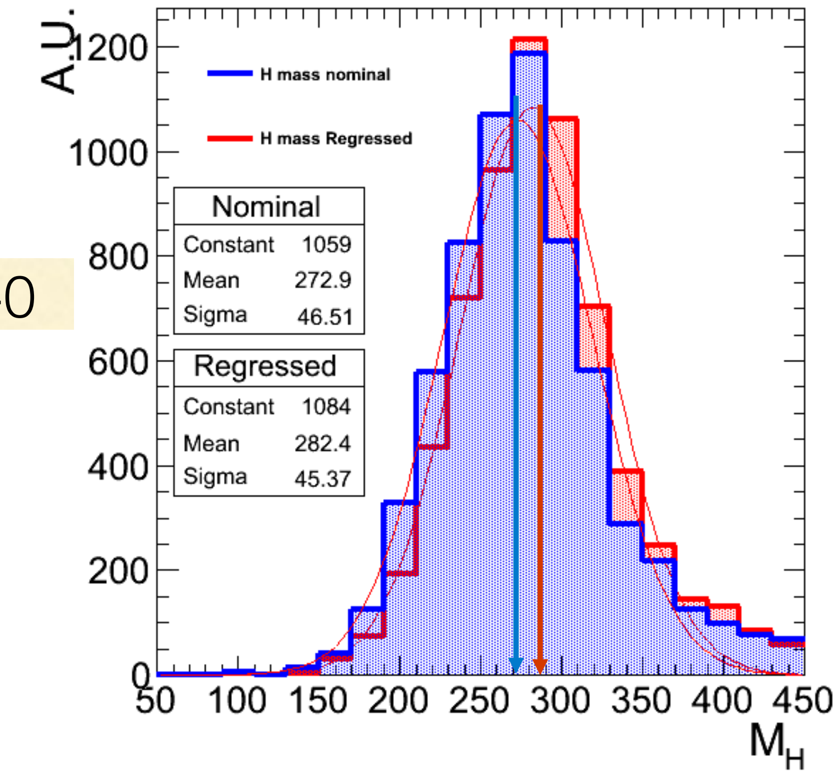


B-Jet Regression: Hhh

Improved M_{JJ} and M_H resolution

Narrower width and improved peak value





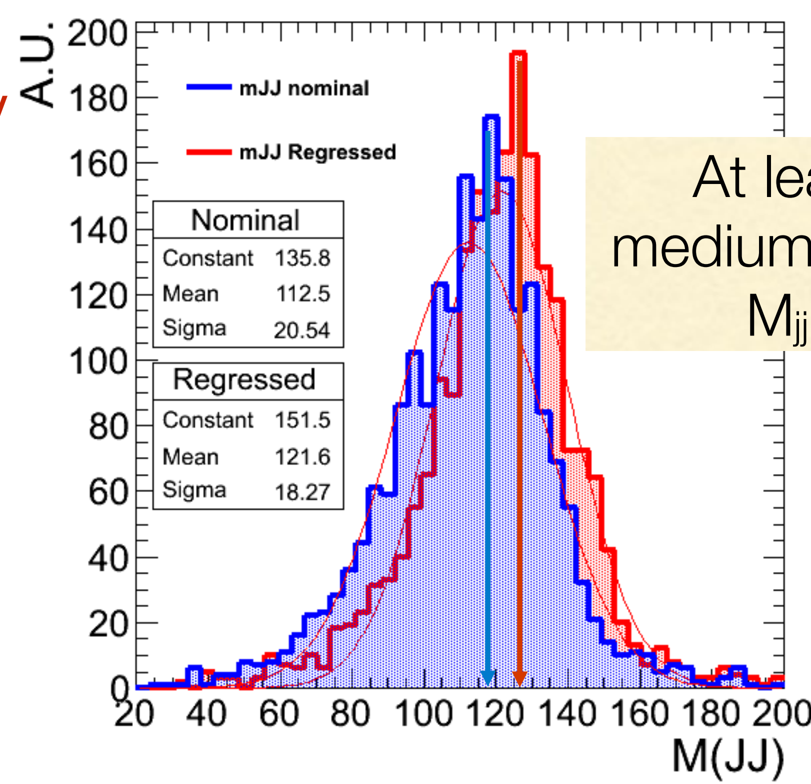
Inclusive, $M_{jj}>0$

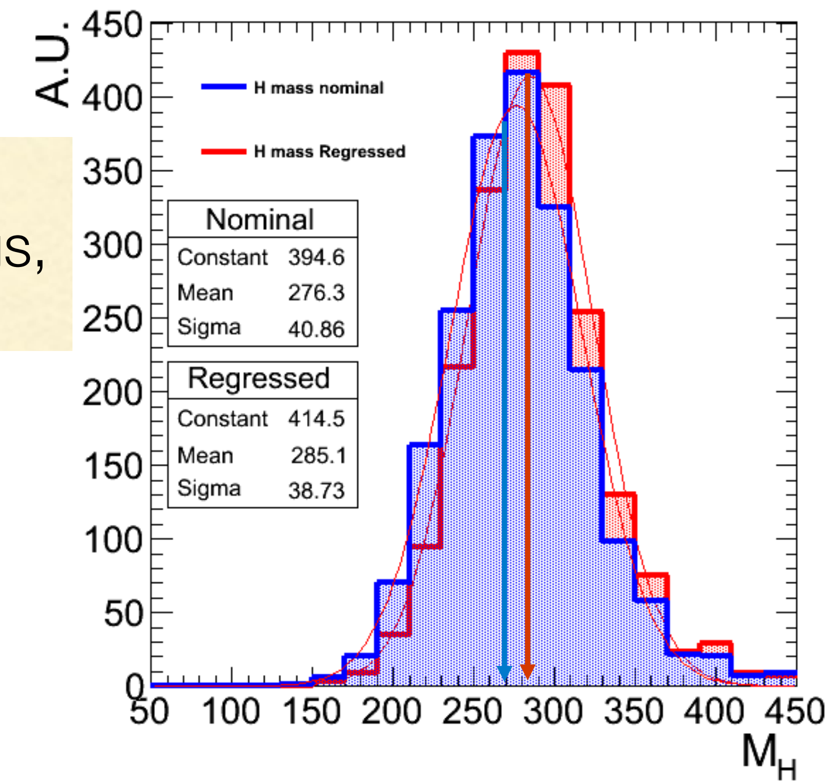
MEAN:

mJJ Nominal = 112 GeV

BDT

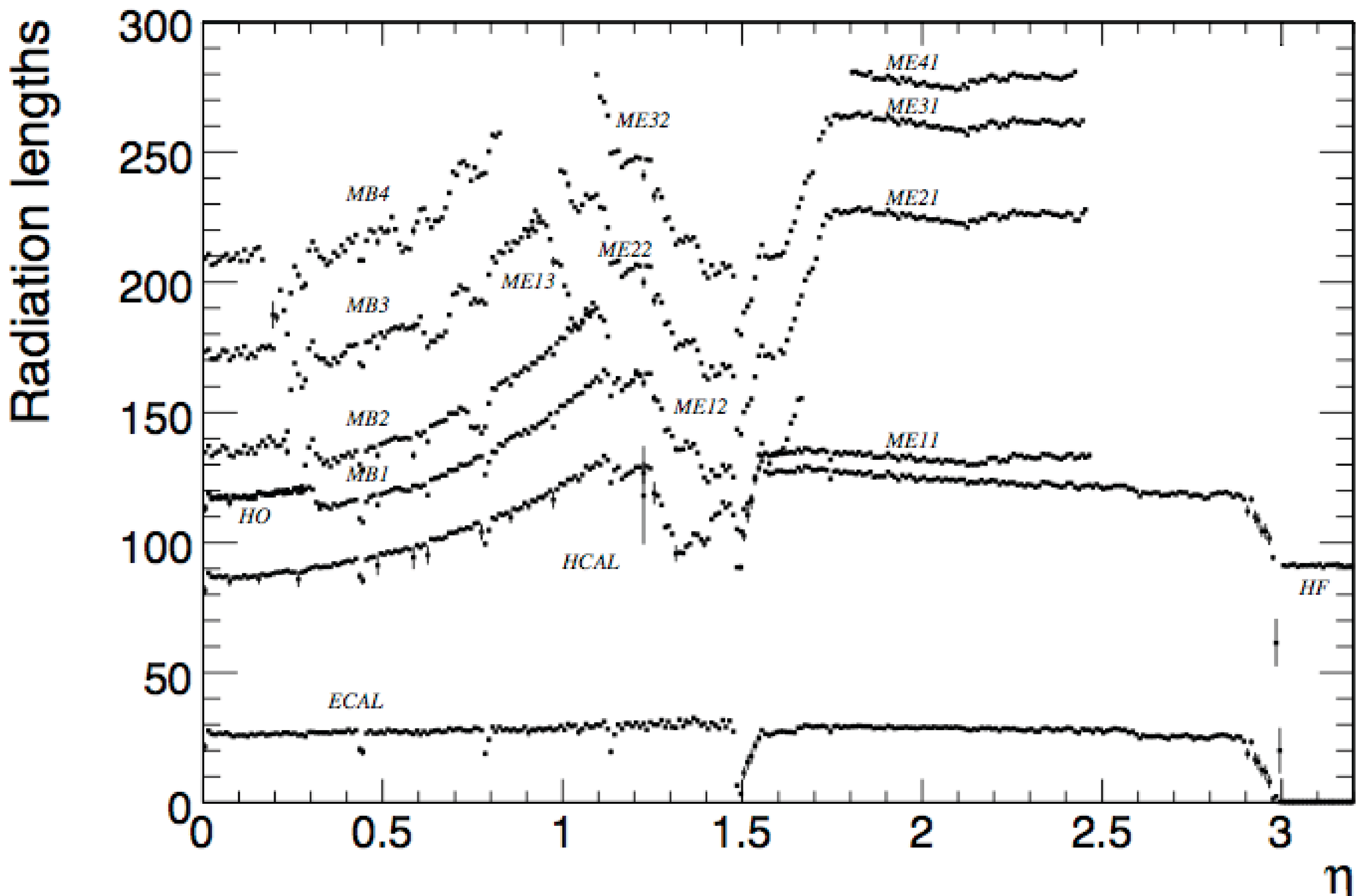
mJJ Regressed = 121 GeV



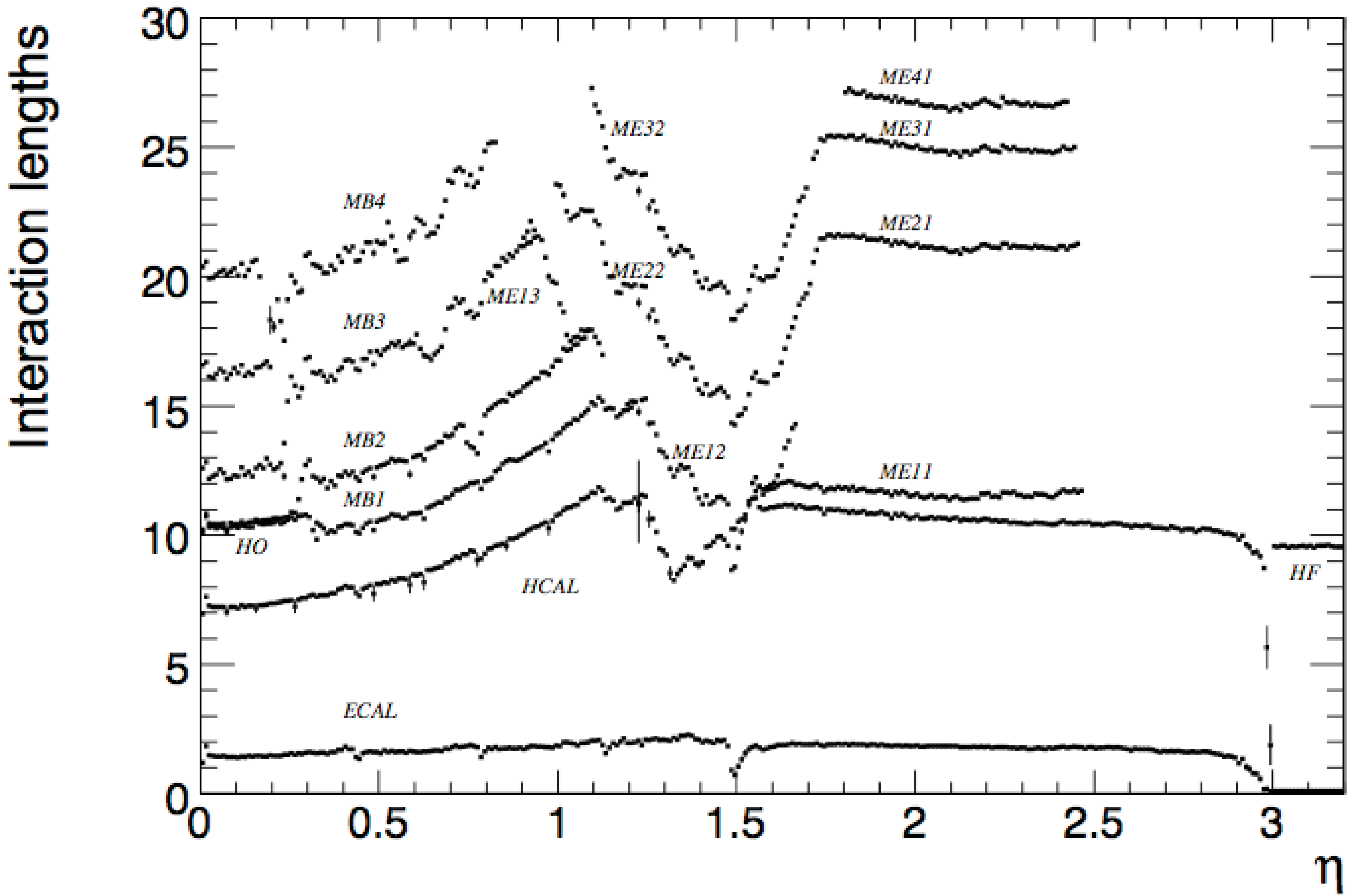


At least 2 medium b-tags, $M_{jj}>0$

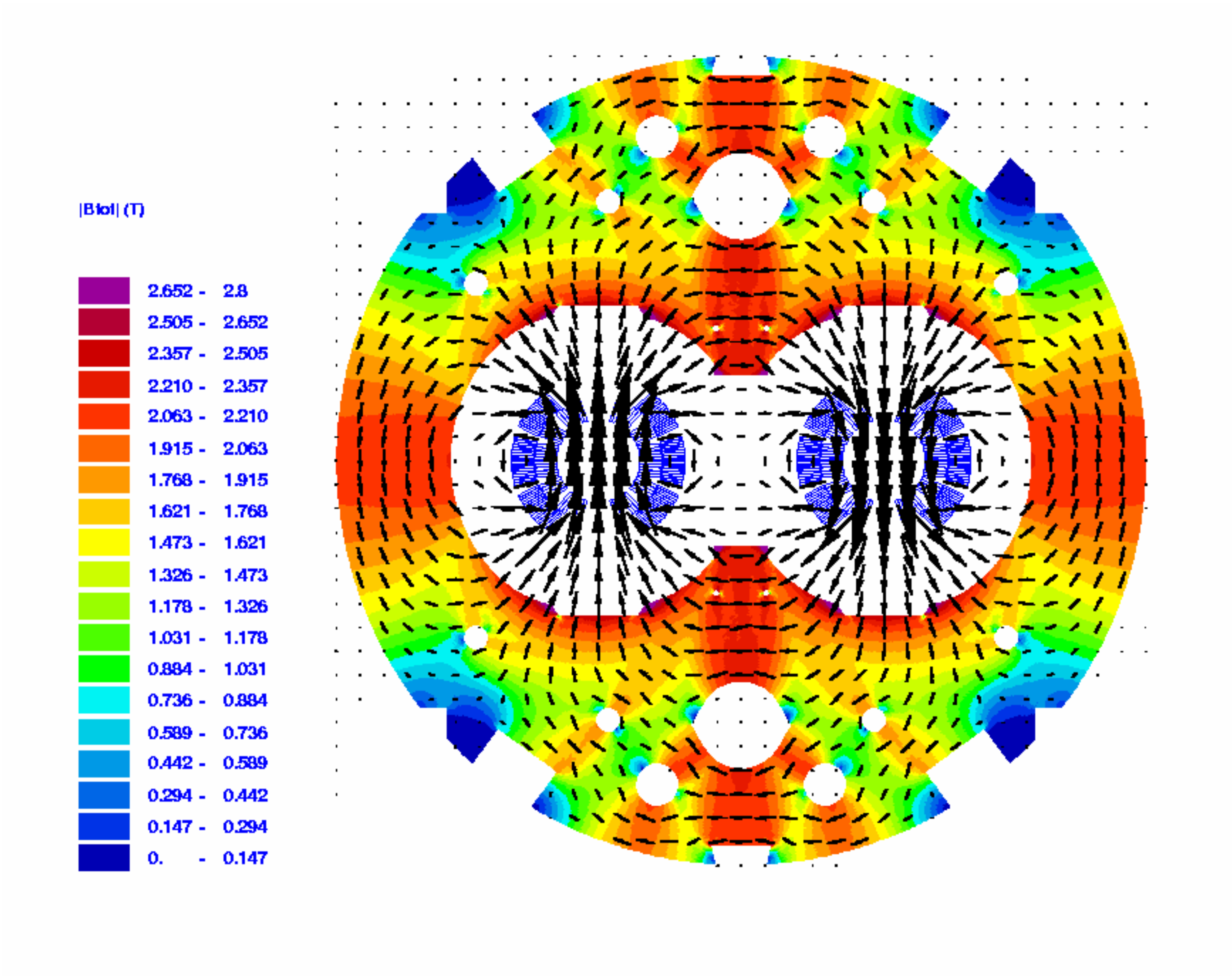
Radiation lengths



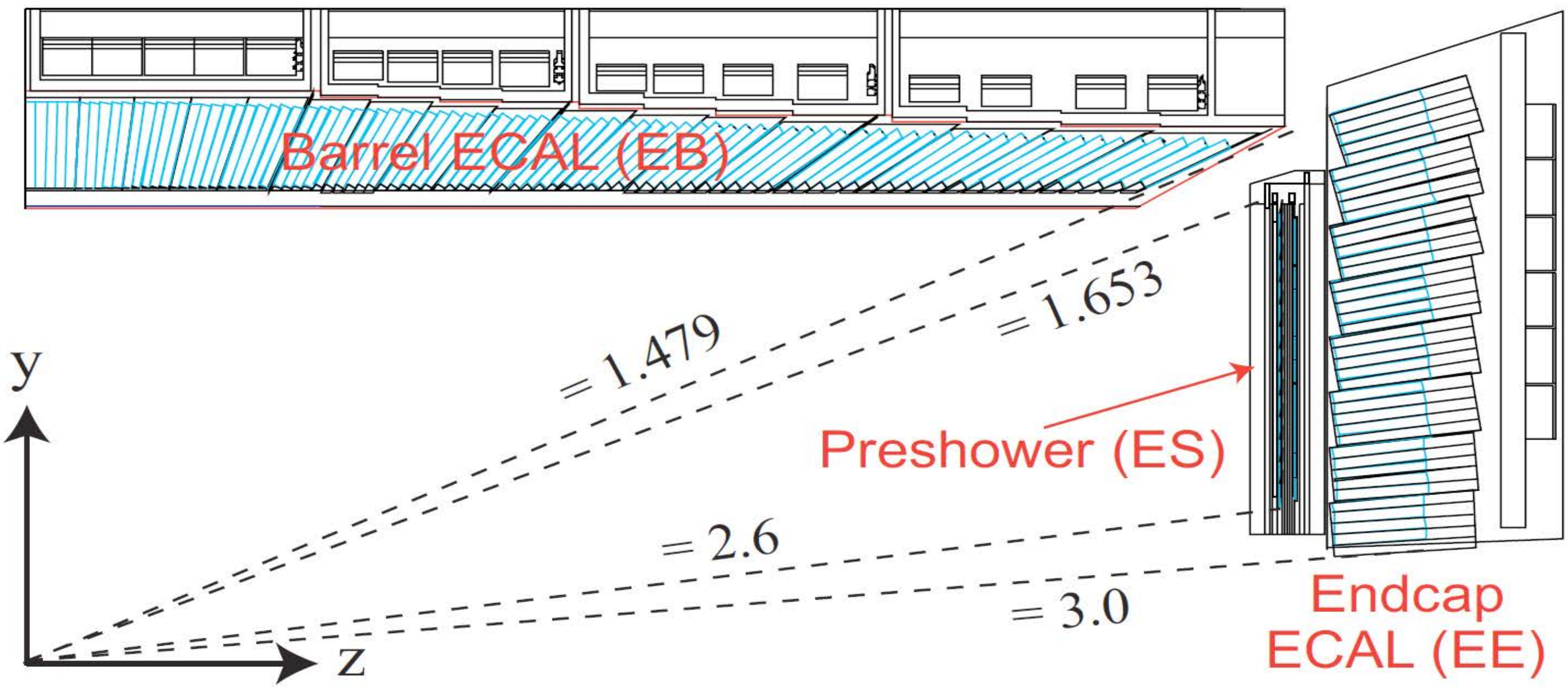
Interaction lengths



Dipole magnetic fields



ECAL Gap

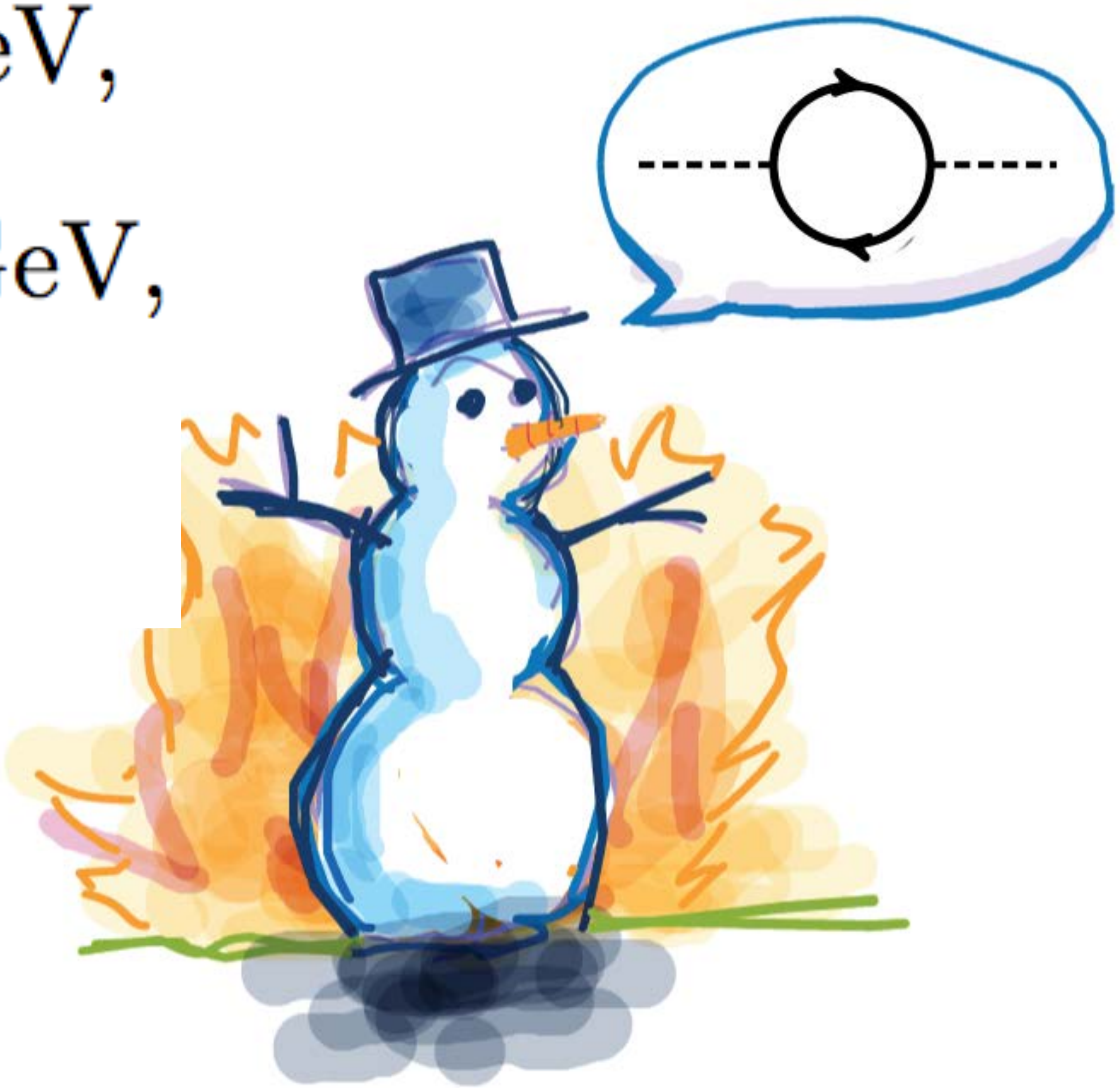


M_h^{max}

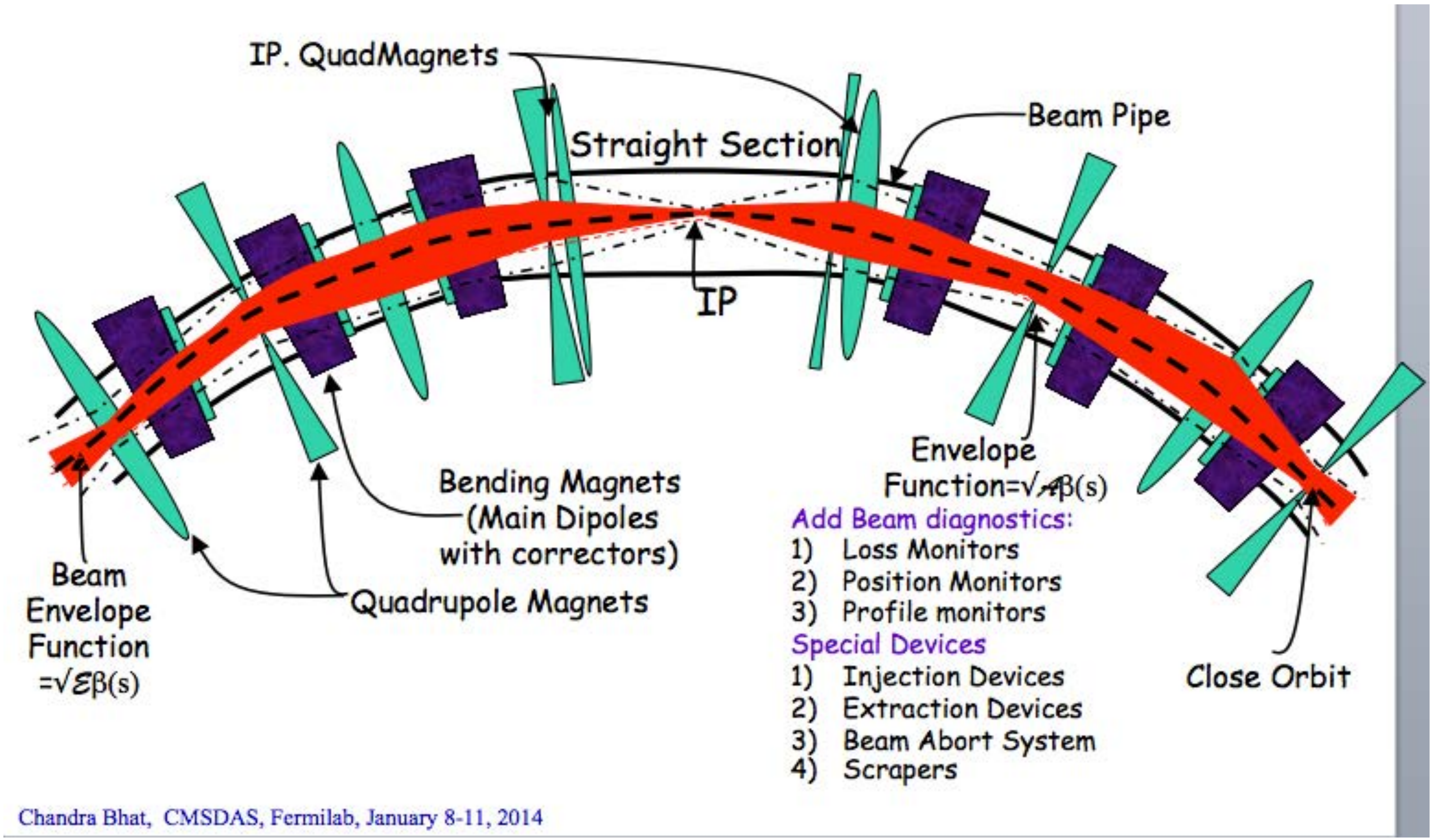
$$M_{SUSY} = 1\text{TeV}, \mu = -200\text{GeV},$$

$$m_{\tilde{g}} = 0.8 M_{SUSY}, M_A \leq 1000\text{GeV},$$

$$X_t = 2M_{SUSY}, A_b = A_t$$

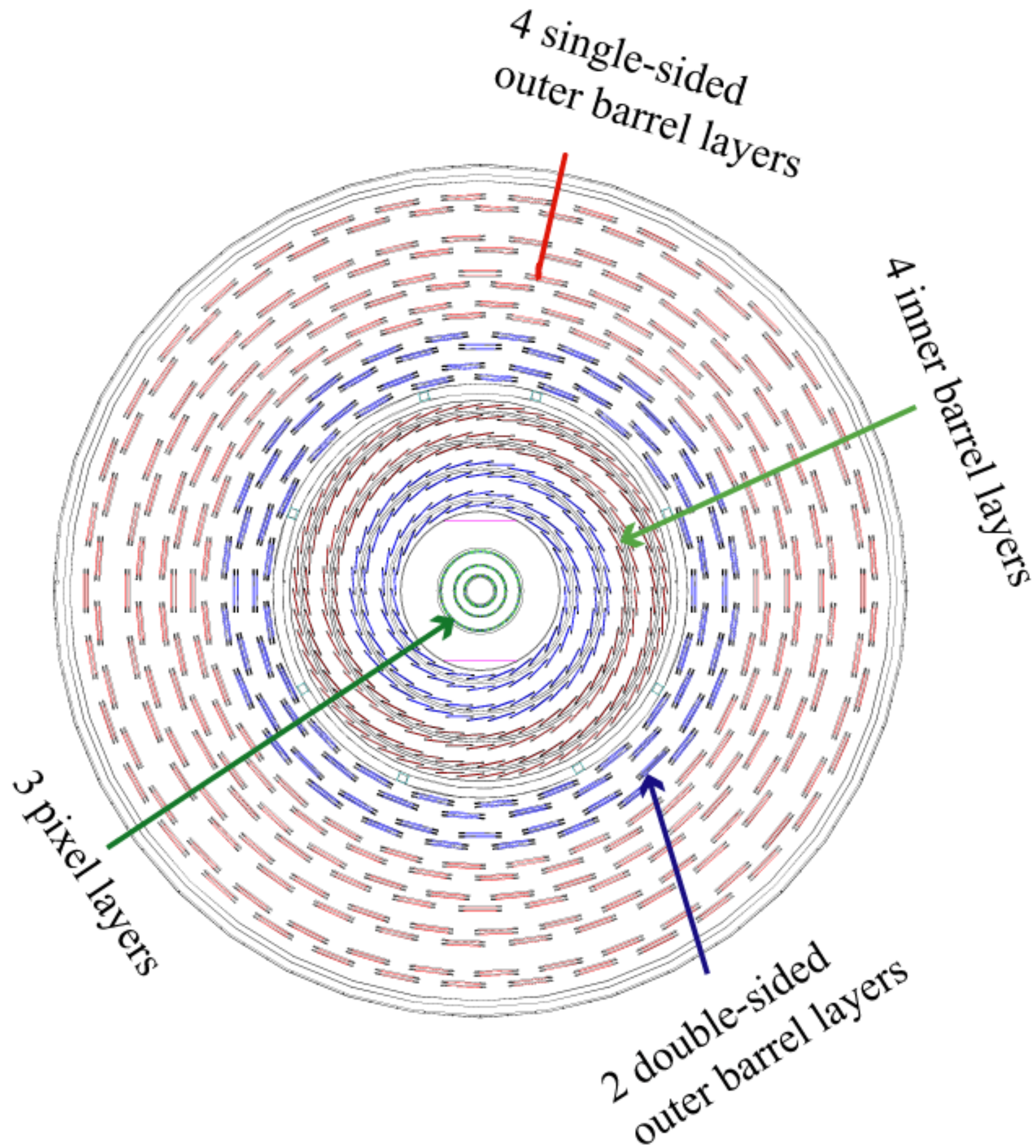


IP diagram



IP. QuadMagnets
Straight Section
Beam Pipe
IP
Envelope
Function=√εβ(s)
Add Beam diagnostics:
1) Loss Monitors
2) Position Monitors
3) Profile monitors
Special Devices
1) Injection Devices
2) Extraction Devices
3) Beam Abort System
4) Scrapers
Close Orbit
Bending Magnets
(Main Dipoles
with correctors)
Quadrupole Magnets
Beam
Envelope
Function
=√εβ(s)
Chandra Bhat, CMSDAS, Fermilab, January 8-11, 2014

Side view tracker/Materials



	Sampling	Homogeneous scintillators		
Property	***Pb/plastic Shashlik***	***Liquid Xenon***	***CeF_3 crystals***	***$PbWO_4$ crystals***
Density (g cm^{-3})	***4.5***	***3.06***	***6.16***	***8.28***
Radiation length X_0 (cm)	***1.7***	***2.77***	***1.68***	***0.85***
Molière radius R_M (cm)	***3.4***	***4.1***	***3.39***	***2.19***
Wavelength peak (nm)	***500***	***175***	***300***	***440***
Fast decay constant (ns)	***<10***	***2.2***	***5***	***<10***
Light yield (γ per MeV)	***13***	***~5 x 10^4***	***4000***	***100***

B-filed mapping

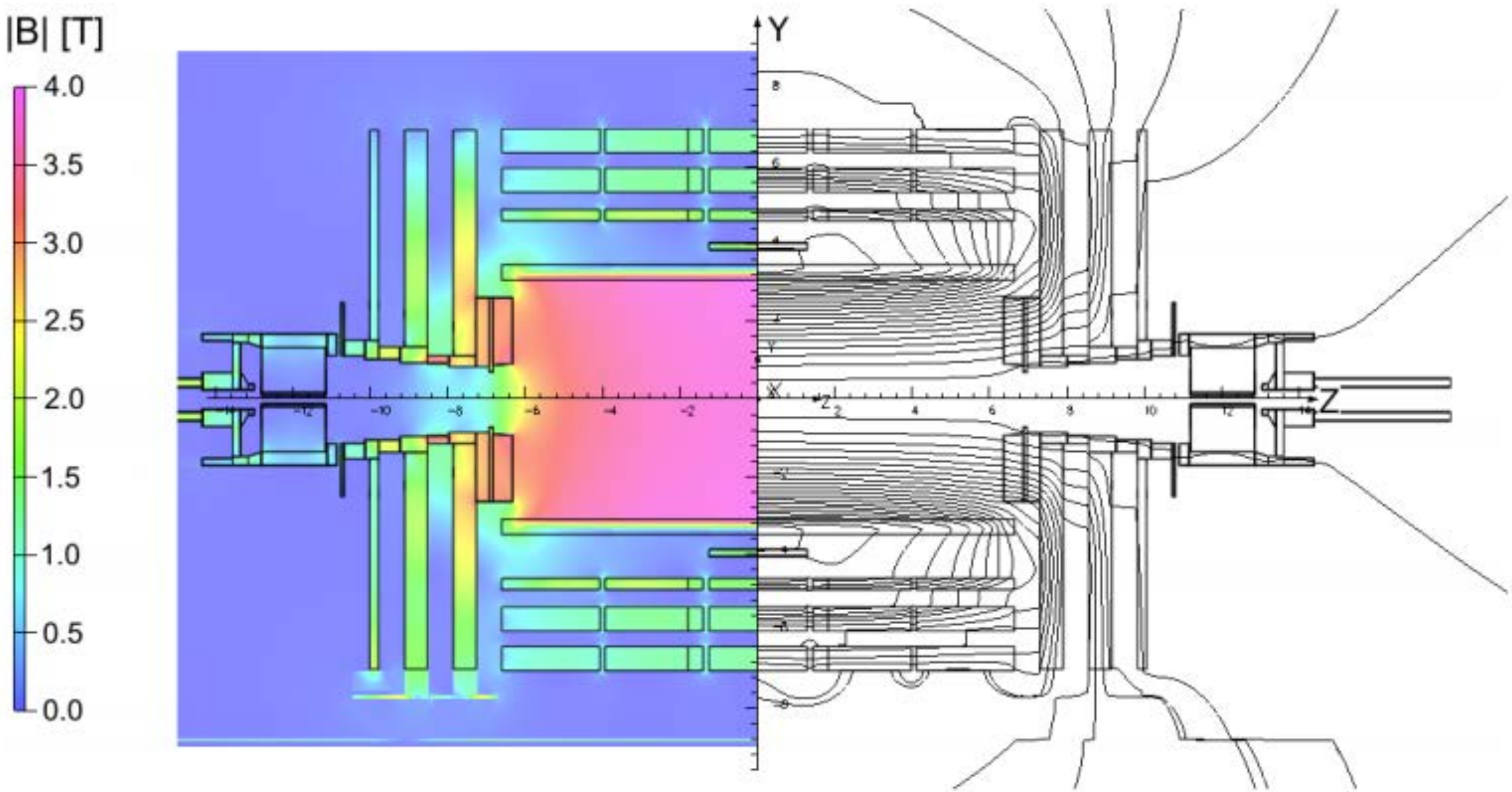
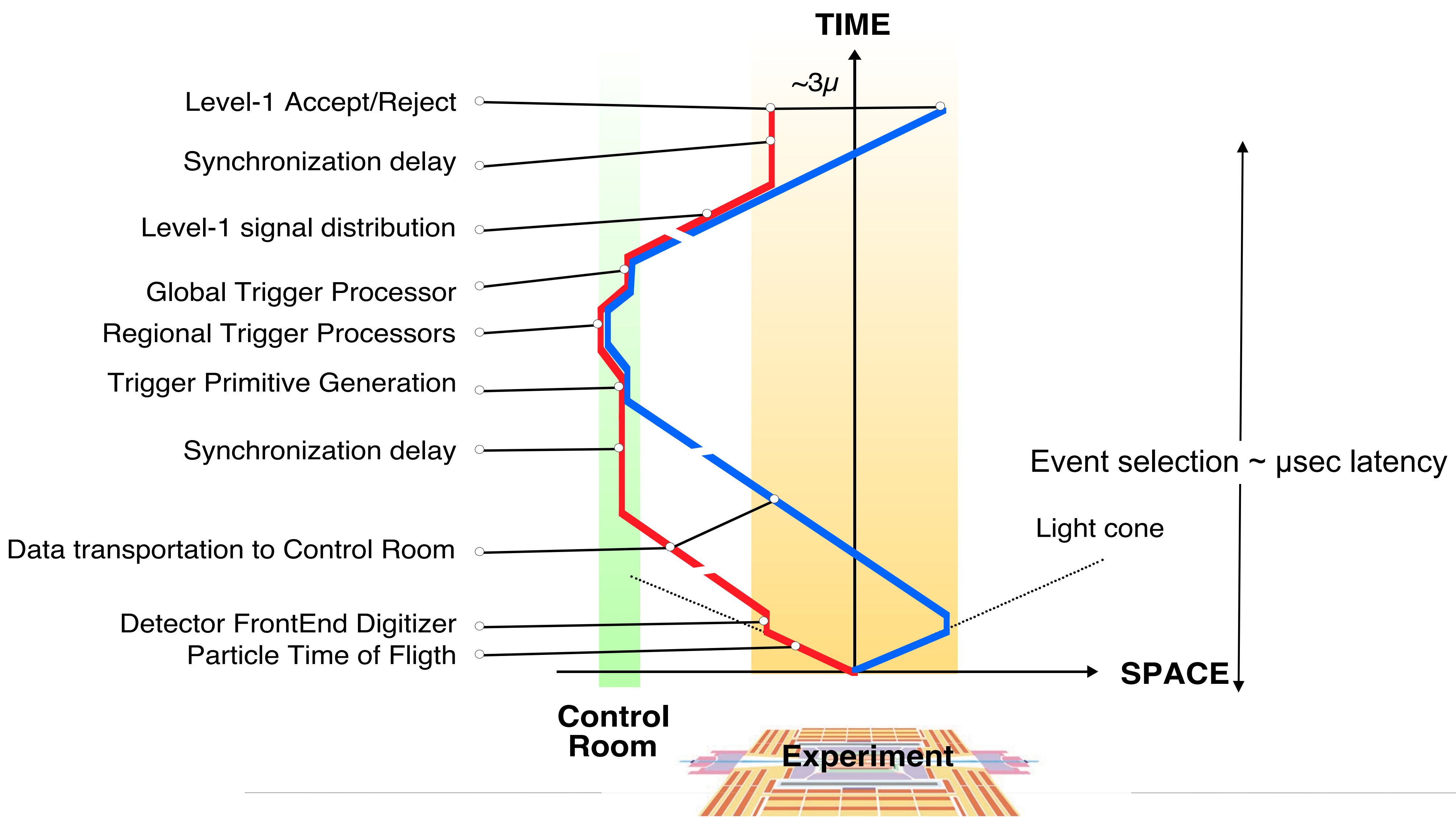


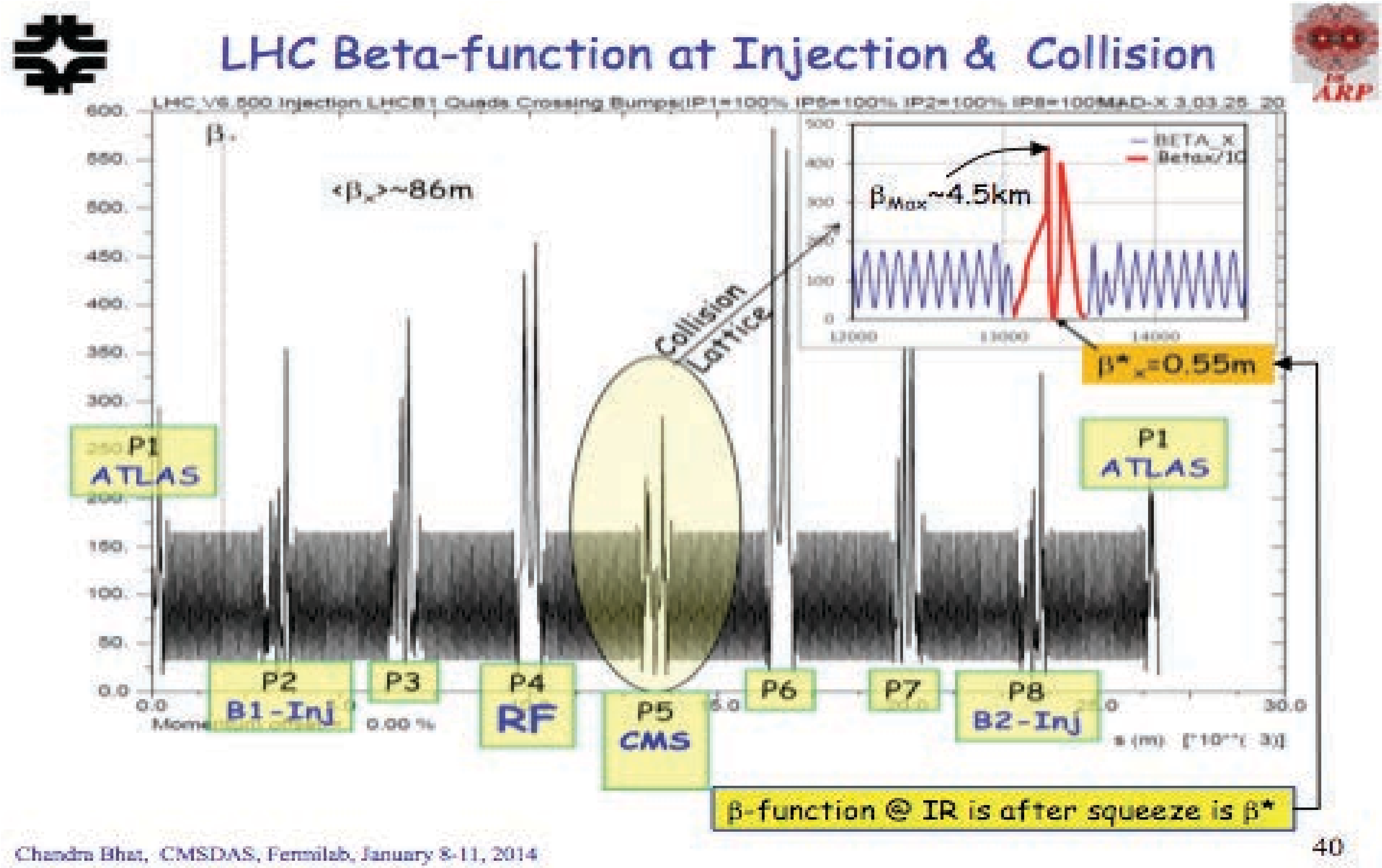
Figure 5: Value of $|B|$ (left) and field lines (right) predicted on a longitudinal section of the CMS detector, for the underground model at a central magnetic flux density of 3.8 T. Each field line represents a magnetic flux increment of 6 Wb.

arXiv:0910.5530v2 [physics.ins-det] 4 Jan 2010

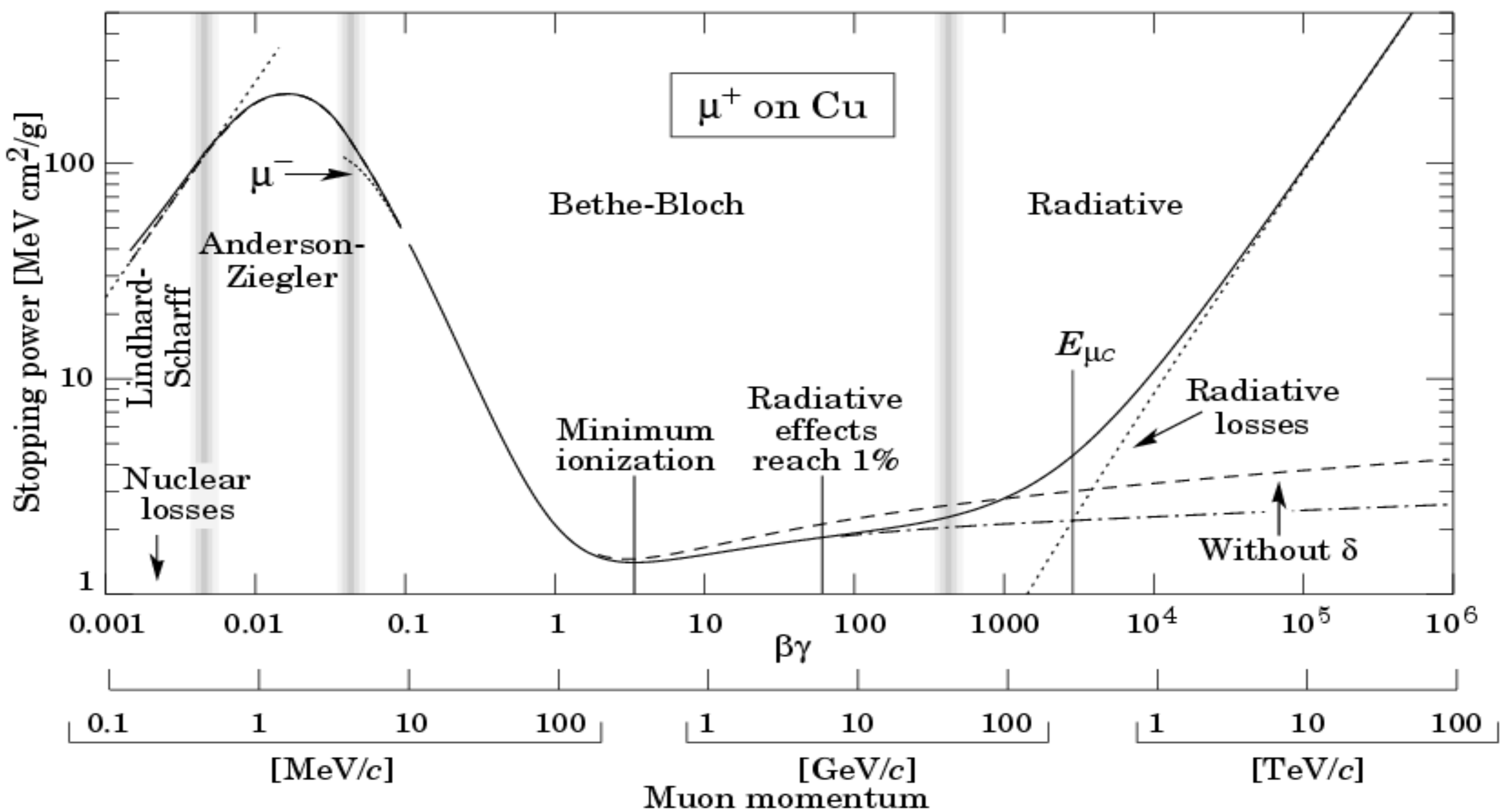
Trigger Latency



Beta function



Bethe-Bloch

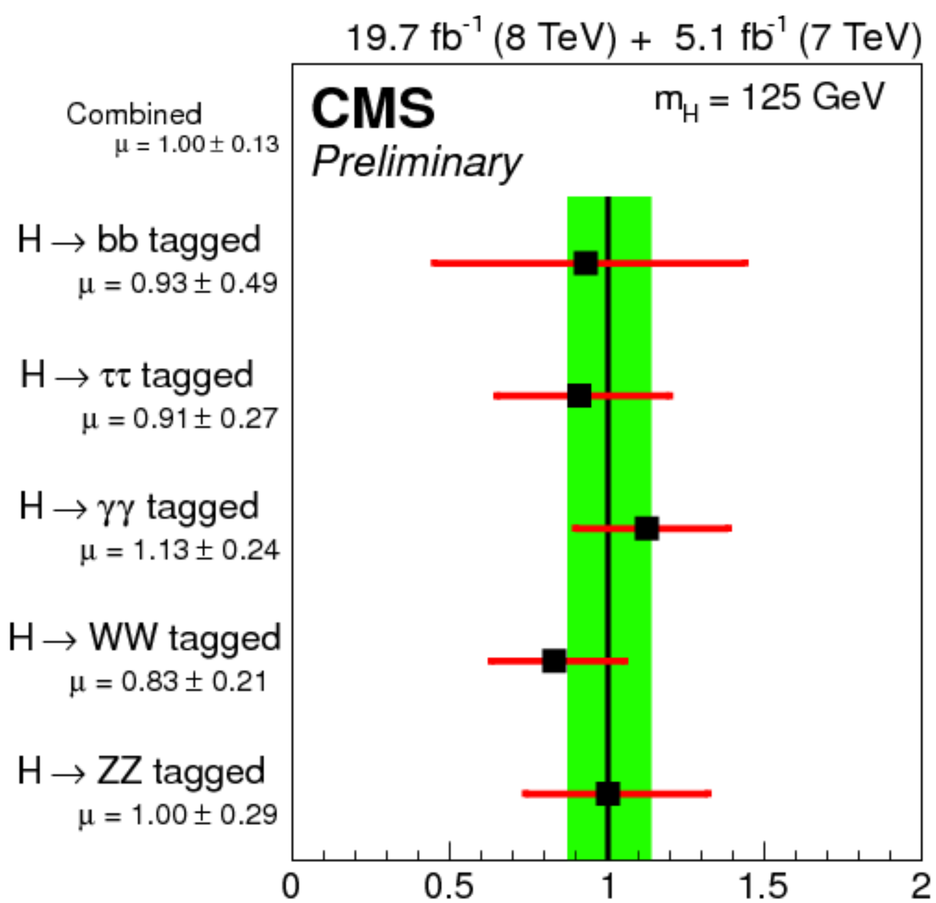

μ+ on Cu
Stopping power [MeV cm2/g]
Bethe-Bloch
Radiative
μ−
Anderson-
Ziegler
Lindhard-
Scharff
Nuclear
losses
Minimum
ionization
Radiative
effects
reach 1%
Eμc
Radiative
losses
Without δ
0.001
0.01
0.1
1
10
100
1000
10^4
10^5
10^6
βγ
0.1
1
10
100
[MeV/c]
1
10
100
[GeV/c]
1
10
100
[TeV/c]
Muon momentum

HIG-14-009

Higgs news: Legacy Combination

With the completion of the 5 main channels we have produced a preliminary combination of all results (HIG-14-009), and work continues on the final publication

- ➡ The combination was made public concurrently to $H\rightarrow\gamma\gamma$ paper submission and presented for the first time in ICHEP.
- ➡ Detailed schedule/timeline for submission of the legacy paper (see below)
- ➡ Work on a 'Grand Combination' with ATLAS ongoing in the reformed Higgs Combination Group (HCG), with first target to produce a combined mass measurement.



Best fit σ/σ_{SM}

$$\mu = 1.00 \pm 0.13$$

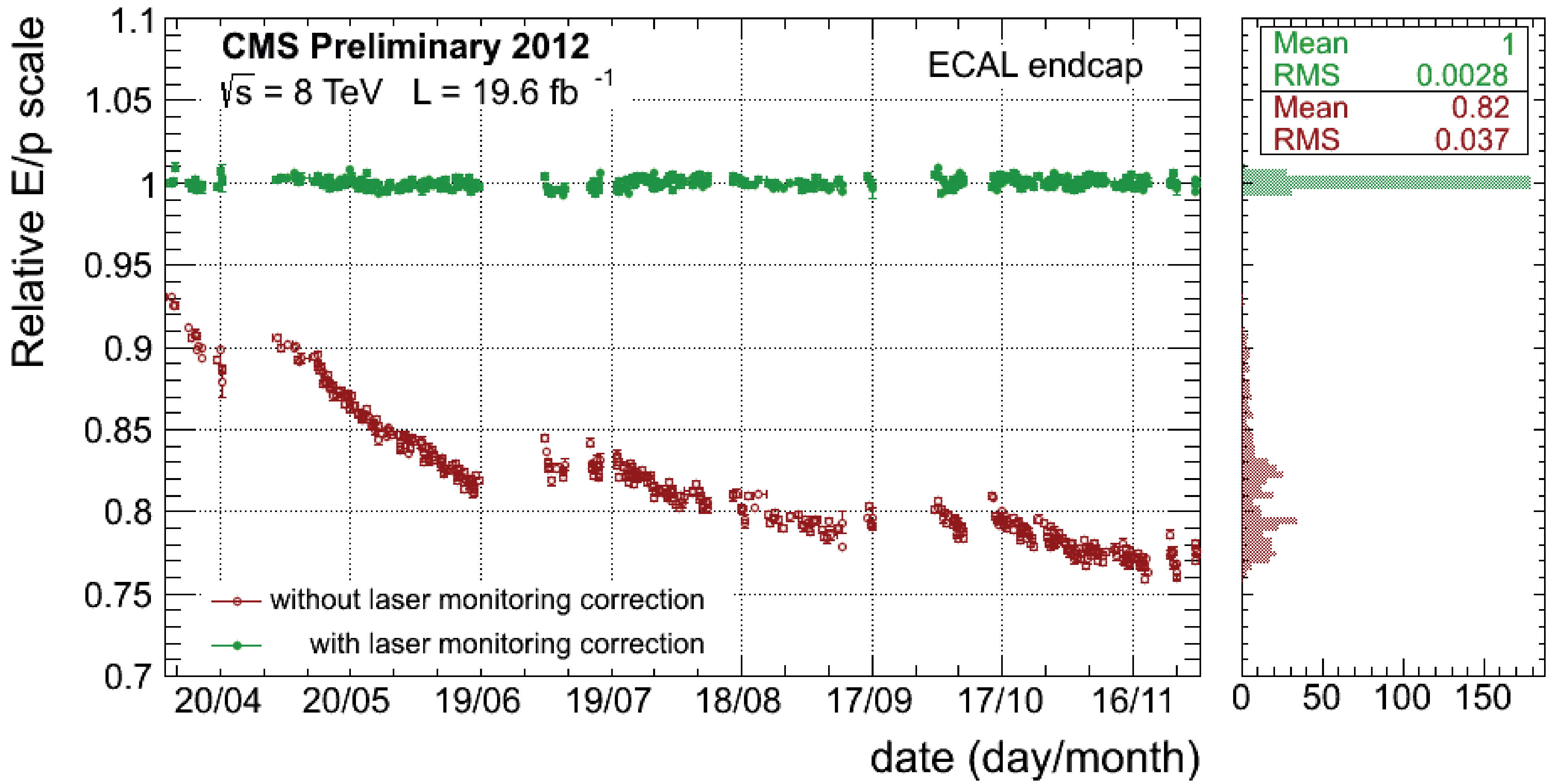
$$m_H = 125.03 \ ^{+0.26}_{-0.27}\,(\text{stat})\ ^{+0.13}_{-0.15}\,(\text{syst})$$

Timeline:

- 13 Oct: Draft ready for review by HIG and ARC
- 29 Oct: Pre-approval in the Higgs group
- 3 Nov: Aim at beginning of CWR
- 5 or 12 Nov: Approval Meeting
- 17 Nov: End of CWR

Goal: submission by mid-Dec

Laser monitoring



arXiv:0910.5530v2 [physics.ins-det] 4 Jan 2010

MSSM Higgs Cross Sections

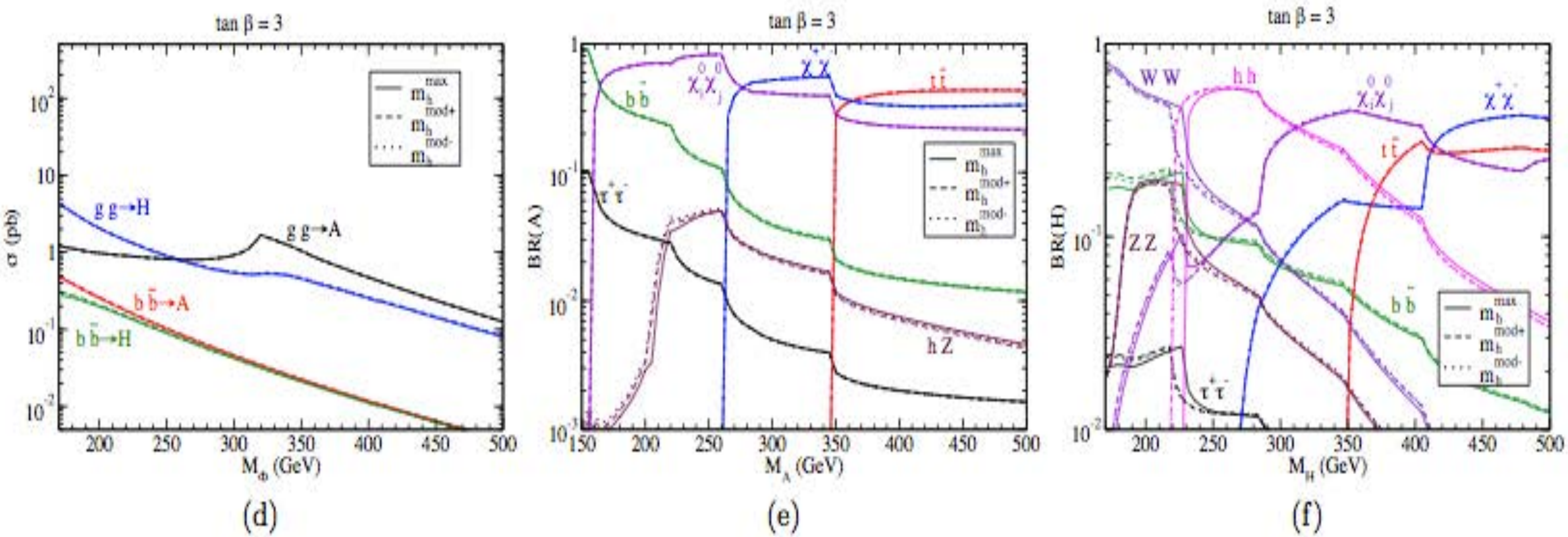
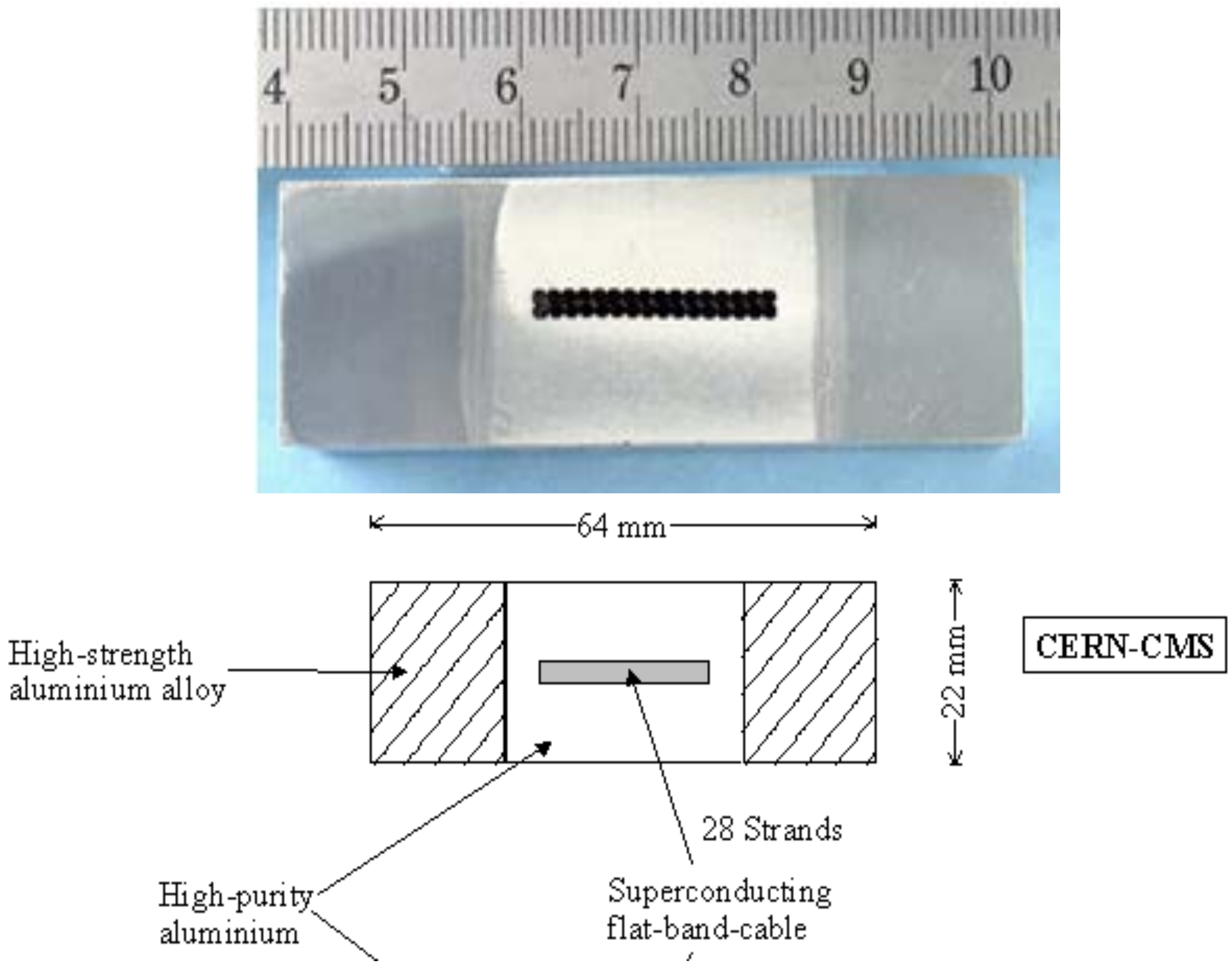


FIG. 1: (a,d) Production rates at $\sqrt{S} = 7$ TeV and (b,c,e,f) branching ratios of heavy neutral Higgs, H and A, as a function of $M_{A,H}$ for (a-c) $\tan\beta = 30$ and (d-f) $\tan\beta = 3$.

Solenoid winding



Brem