# Search for Invisible Higgs Decays to muons+MET with CMS at the LHC

Nick Smith

Preliminary Exam

December 14, 2015

# Outline

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- Theoretical Motivation
- Large Hadron Collider
- Compact Muon Solenoid
- Event Reconstruction
- Previous Results
- Analysis Cut Flow
- Discussion of Systematics
- Final Result
- Future Plans

# The Standard Model

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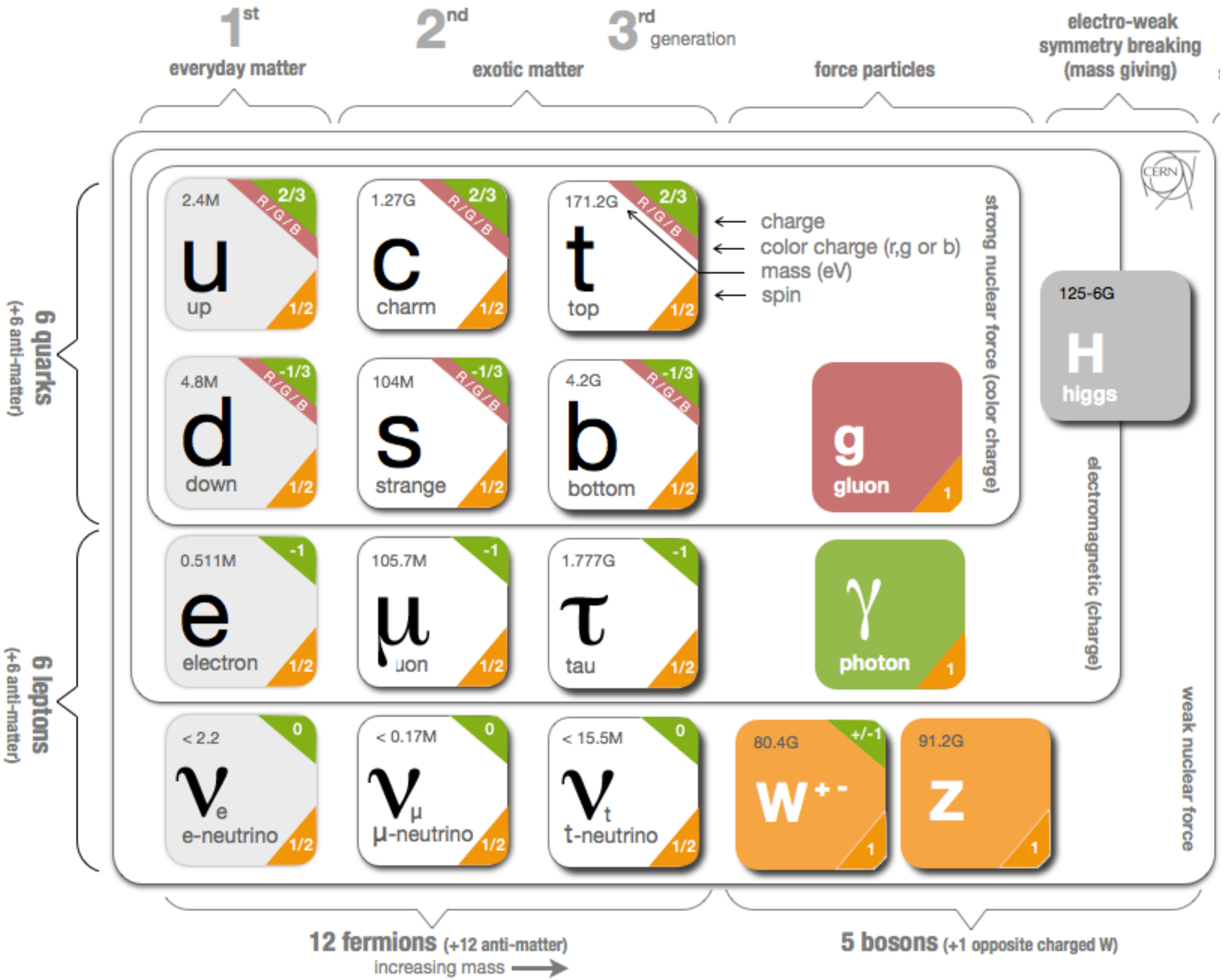

# Standard Model Interactions

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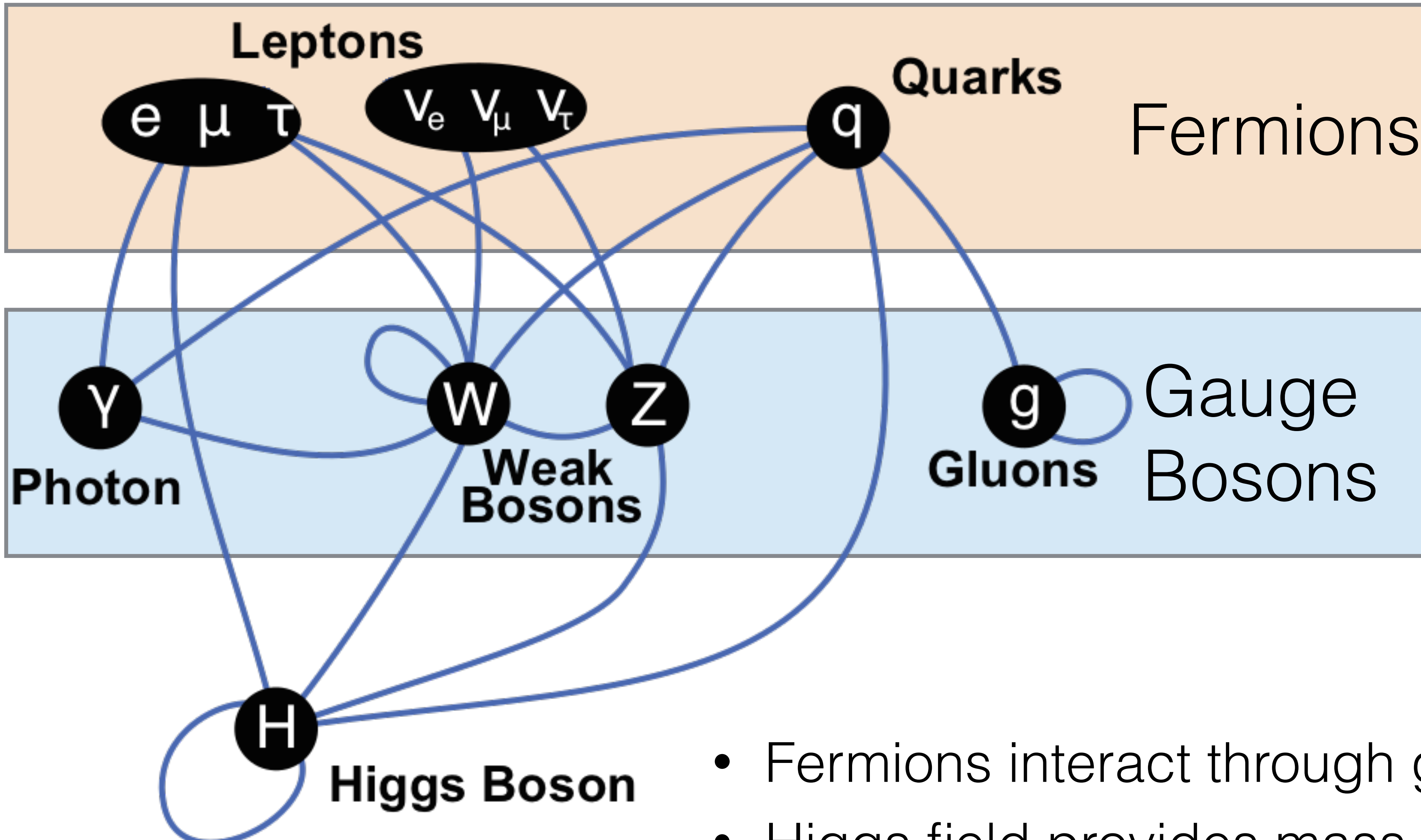


- Fermions interact through gauge bosons
- Higgs field provides mass for:
  - Weak bosons
  - Massive fermions

# SM Higgs Production

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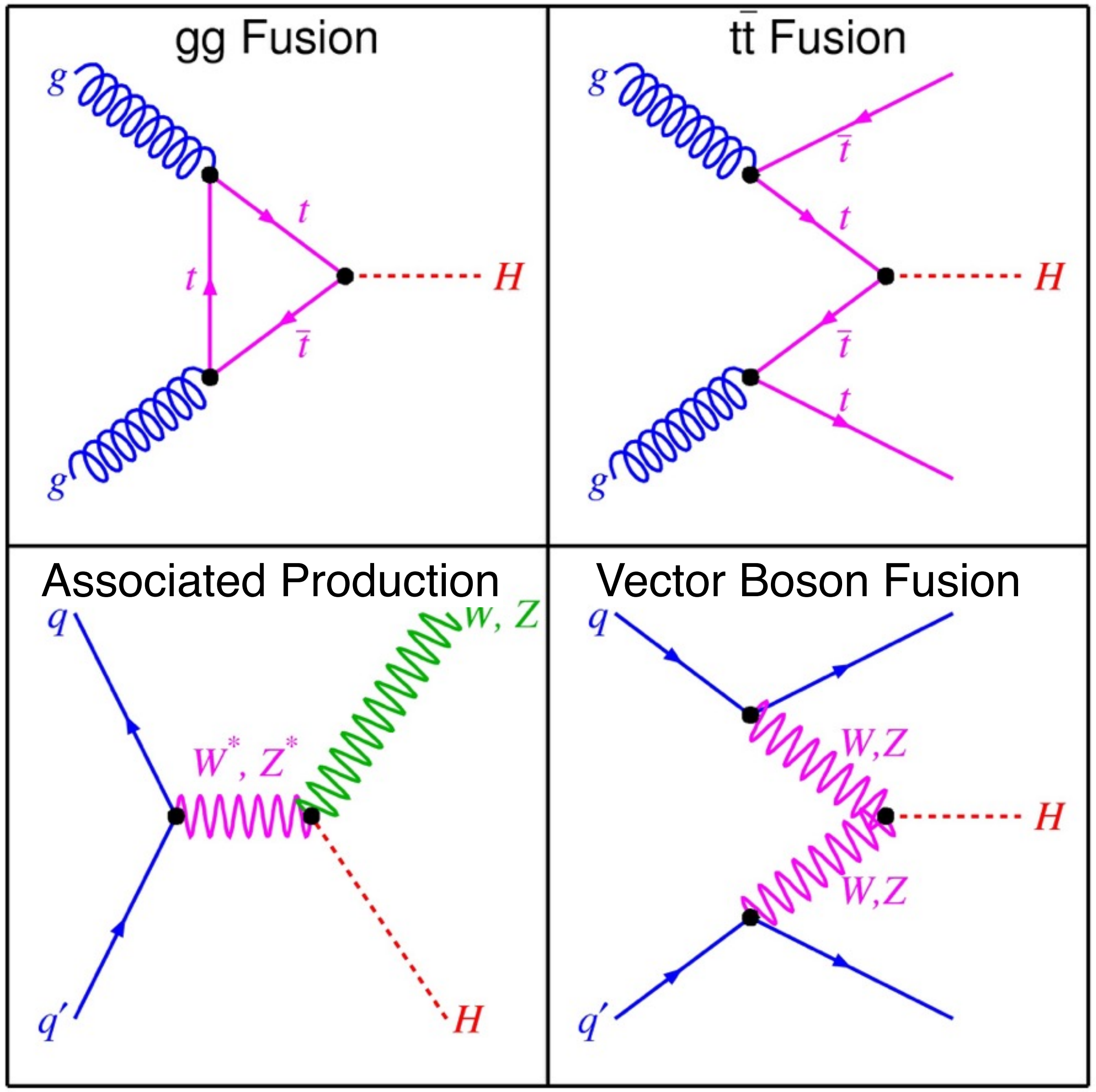


- Higgs interactions have implications for production mechanisms
- Most significant mechanisms at proton colliders shown here

| Major Channels | Cross section @ 13TeV ($m_h$=125GeV) |
|---|---|
| gg Fusion | 44pb |
| Vector Boson Fusion | 3.7pb |
| Wh Associated | 1.3pb |
| Others | < 1pb |

Note: eventual dataset for this analysis: 100fb$^{-1}$

# SM Higgs Decays

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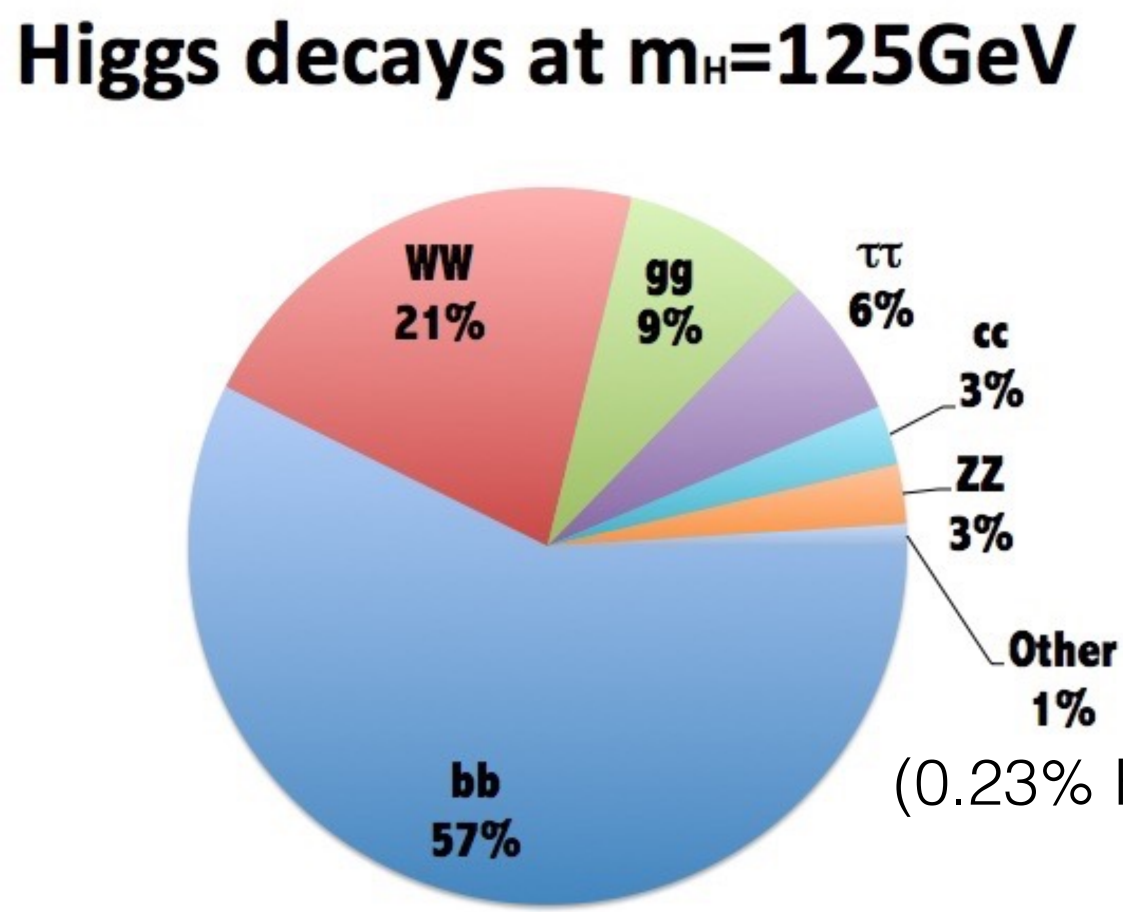
With 19.7fb$^{-1}$ at 8TeV and 5.1fb$^{-1}$ at 7TeV, CMS found the Standard Model Higgs

- Discovery channels (>5σ)
  - ZZ
  - γγ
- Evidence channels (>3σ)
  - WW
  - ττ
- Difficult channels
  - bb (~2σ)
  - μμ




(0.23% H→γγ)

# Invisible Higgs Decays

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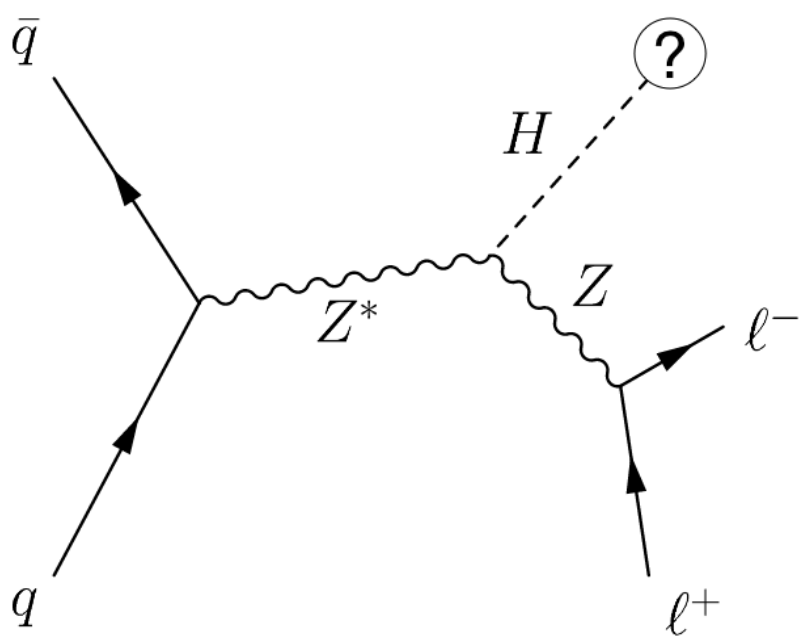
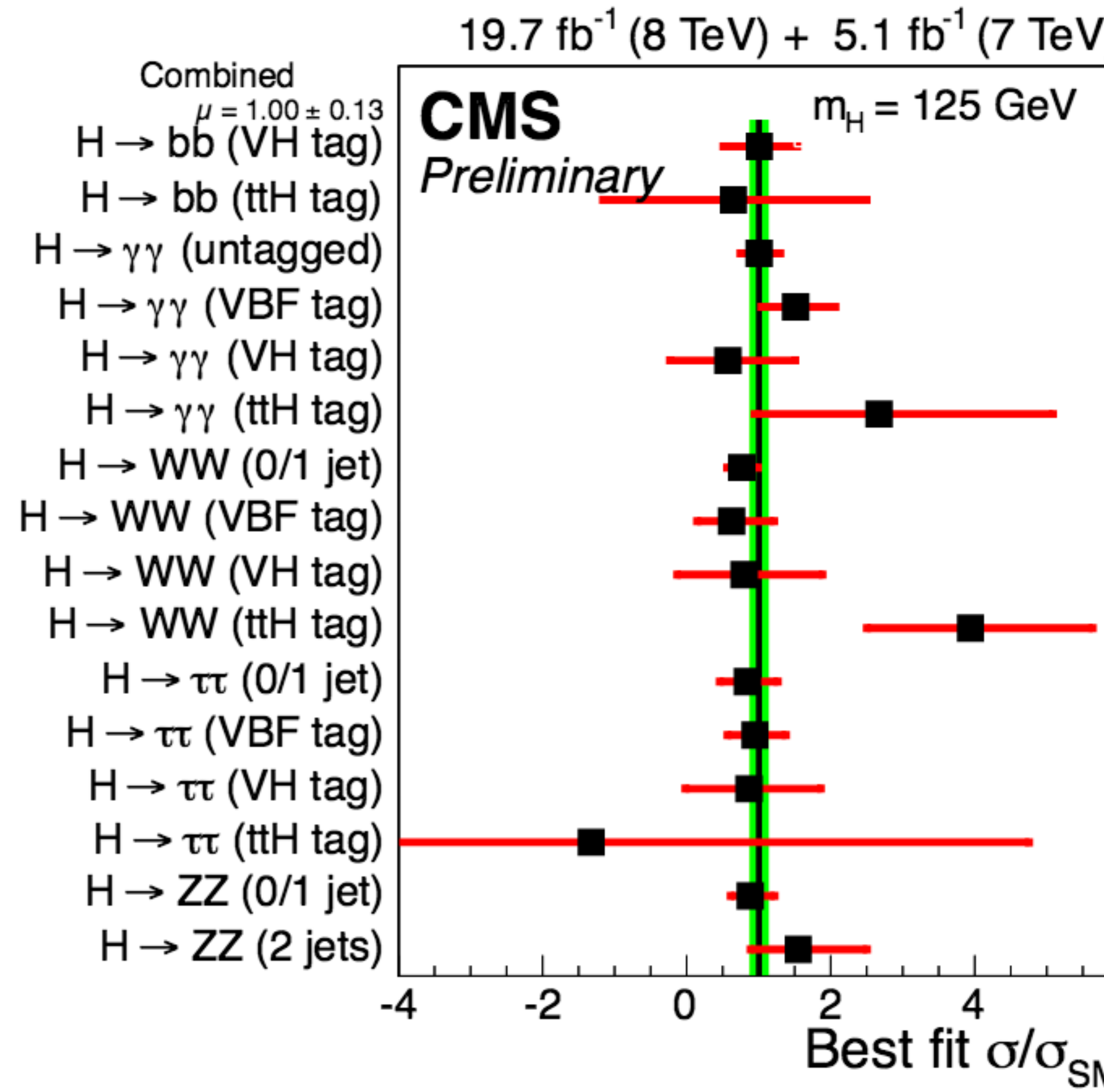
- All measured decay channels line up with SM expectation

- Of particular interest: *Invisible Higgs decays*
  - To particles impossible to directly detect at CMS
- In SM, only $H \rightarrow ZZ^* \rightarrow 4\nu$ (0.1%)

- Higgs is a newly observed particle…
- DM candidate couples to Higgs?

*How do we detect invisible particles?*
- In this analysis: ZH production channel
- Signature: two leptons, <u>missing energy</u>




(fit assumes $\Gamma_{BSM}$=0)

# The Large Hadron Collider

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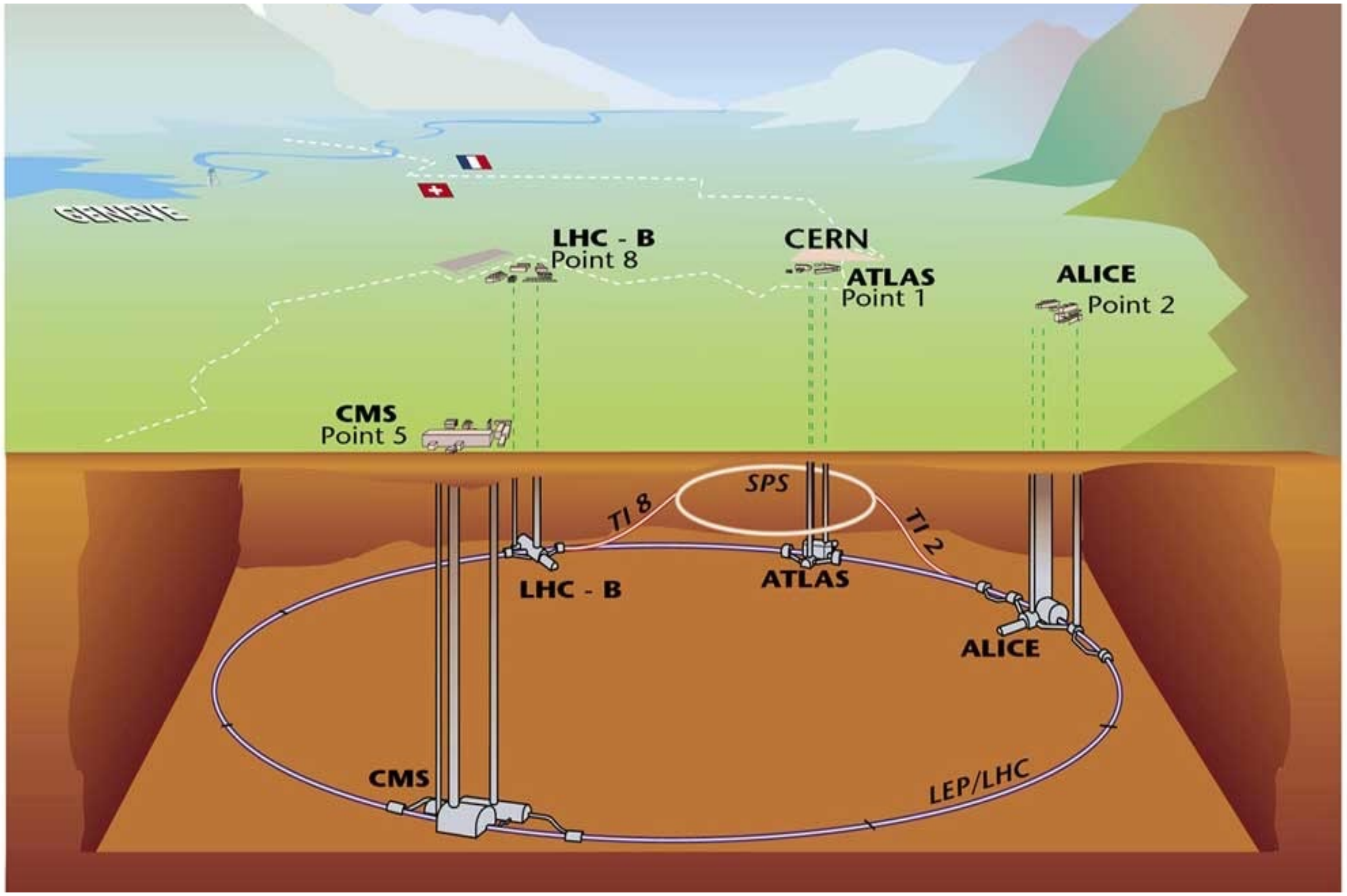
- 27km-circumference ring buried ~100m underground
- Collides both protons and heavy ions
- Two beams counter-rotate, interact at 4 points
- 4 Main Detectors
  - CMS, ATLAS: general purpose detectors
  - LHCb: Forward & b physics
  - ALICE: Heavy Ion physics




# Proton Beam & Luminosity

1 barn = $10^{-24}$ cm$^2$

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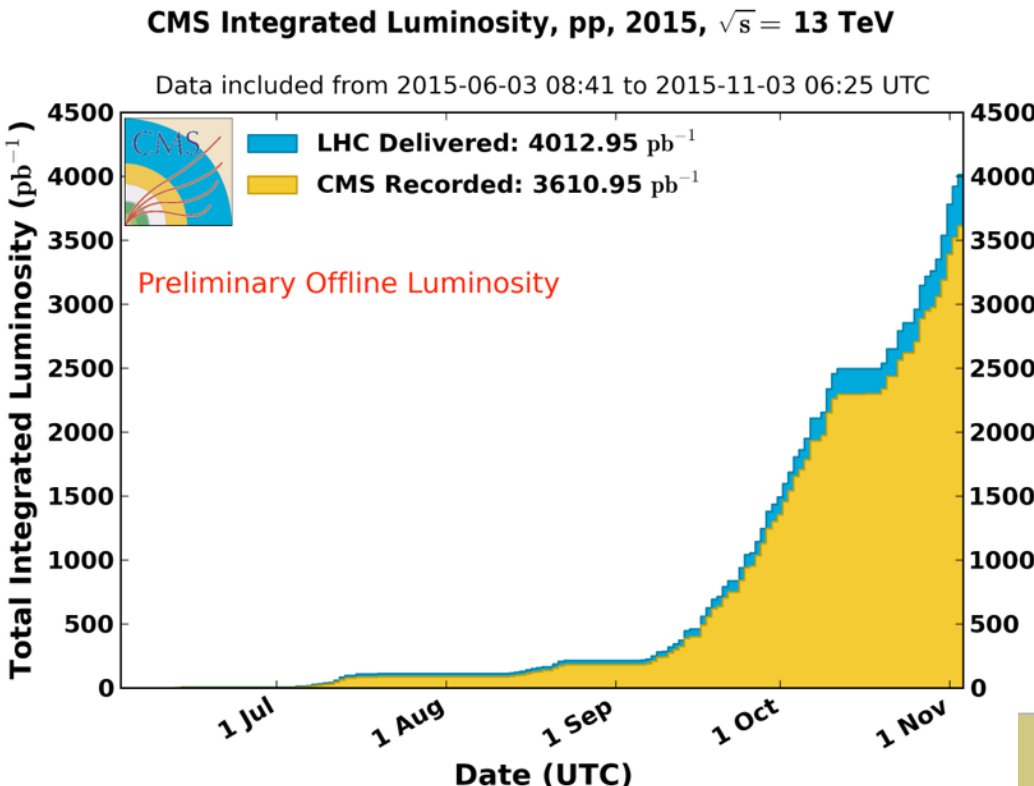
$$N = \sigma \int L \, dt$$




Number of expected events depends on:

- Cross Section
    - Process-dependent
- Integrated luminosity
    - LHC tunes beam to optimize
    - CMS records data 24x7

| | Design | 2010-11 | 2012 | 2015 | 2016-18* |
|---|---|---|---|---|---|
| Beam Energy (TeV) | 7 | 3.5 | 4 | 6.5 | 6.5 |
| Inst. Luminosity (x$10^{33}$/cm$^2$/s) | 10 | ~3 | ~7 | ~4 | 14 |
| Bunches | 2808 | 1380 | 1380 | ~2200 | <2808 |
| Protons / Bunch | 130B | 145B | 148B | 150B | 150B |
| Bunch Spacing (ns) | 25 | 75/50 | 50 | 50/25 | 25 |
| Avg. Collisions / Bunch Crossing | 20 | ~20 | 35 | 40/20 | 20 |
| Integrated Lumi to CMS (fb$^{-1}$) | | ~5 | ~20 | 4 | 100 |

* Anticipated

# The Compact Muon Solenoid

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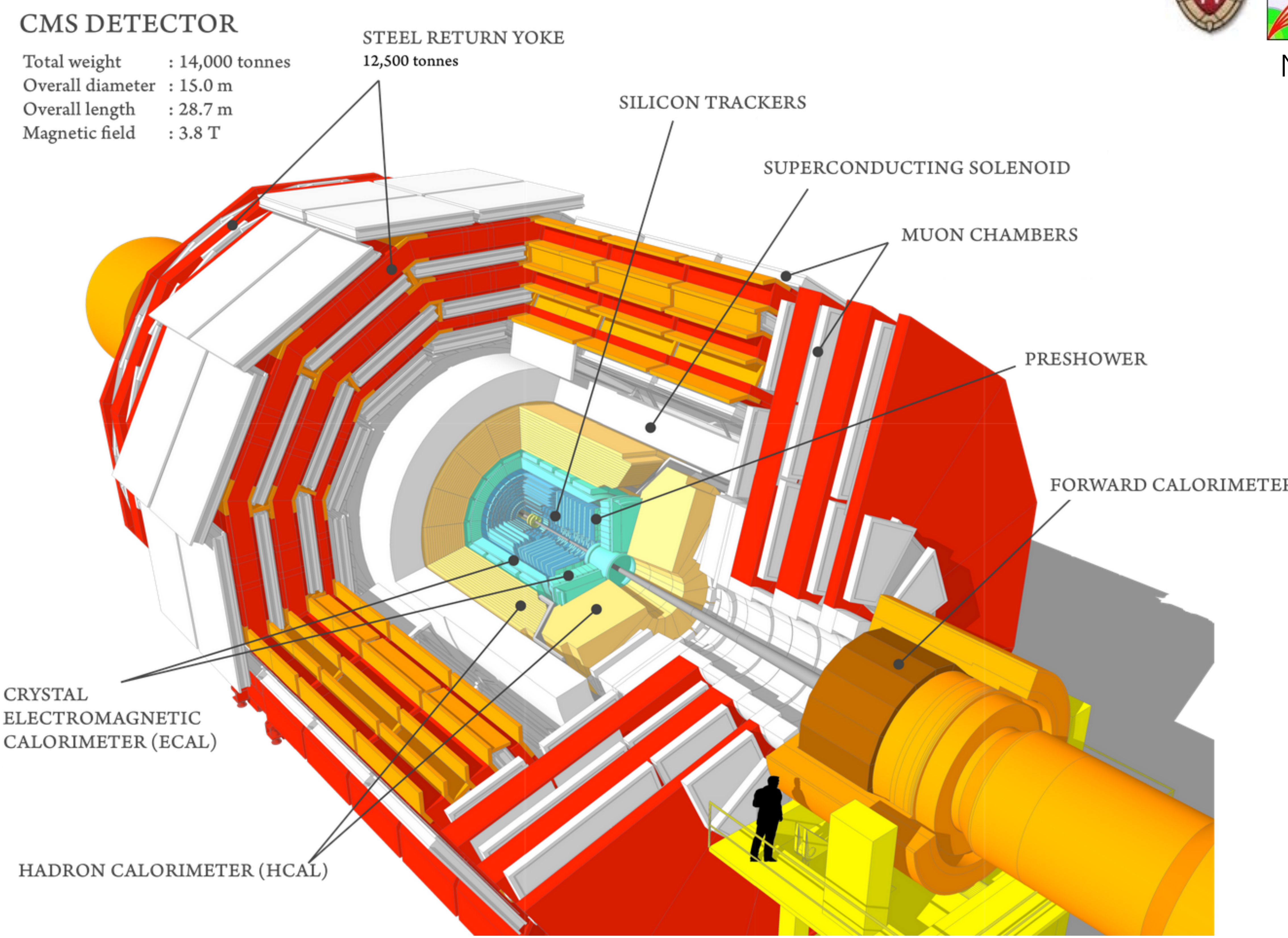

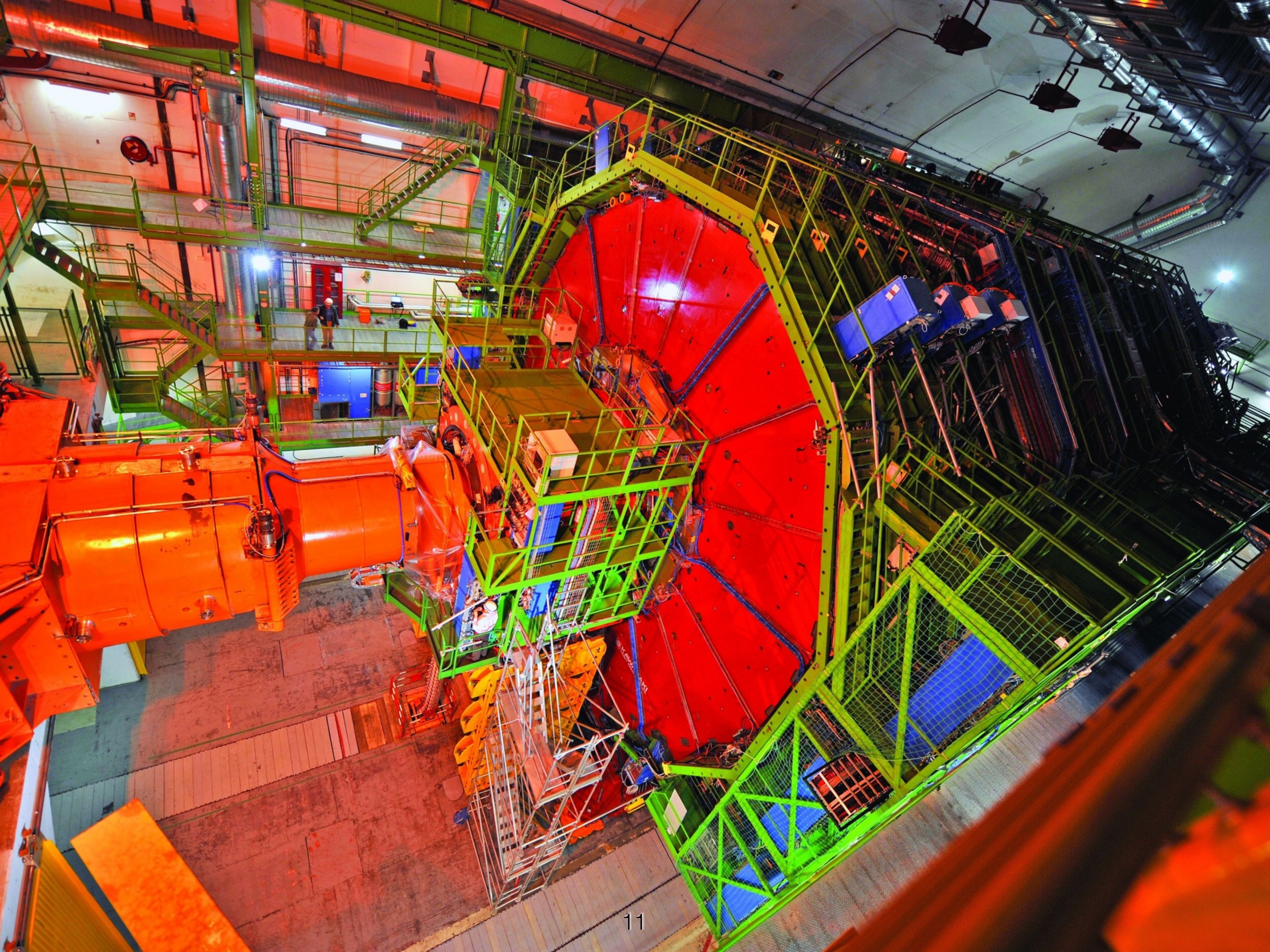

# Magnet

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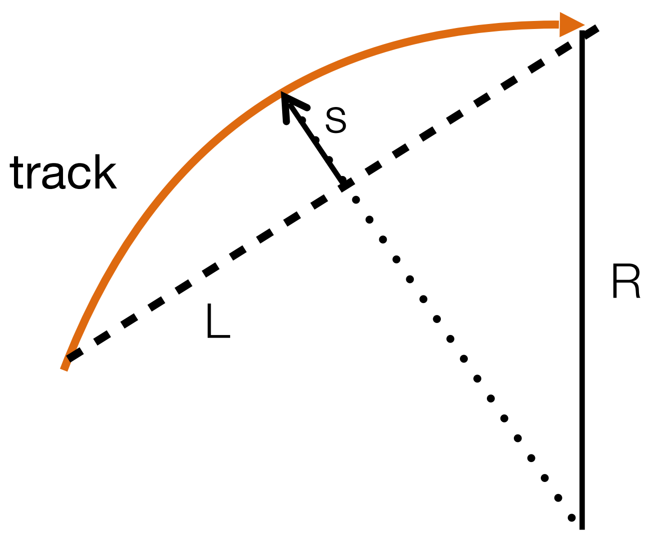
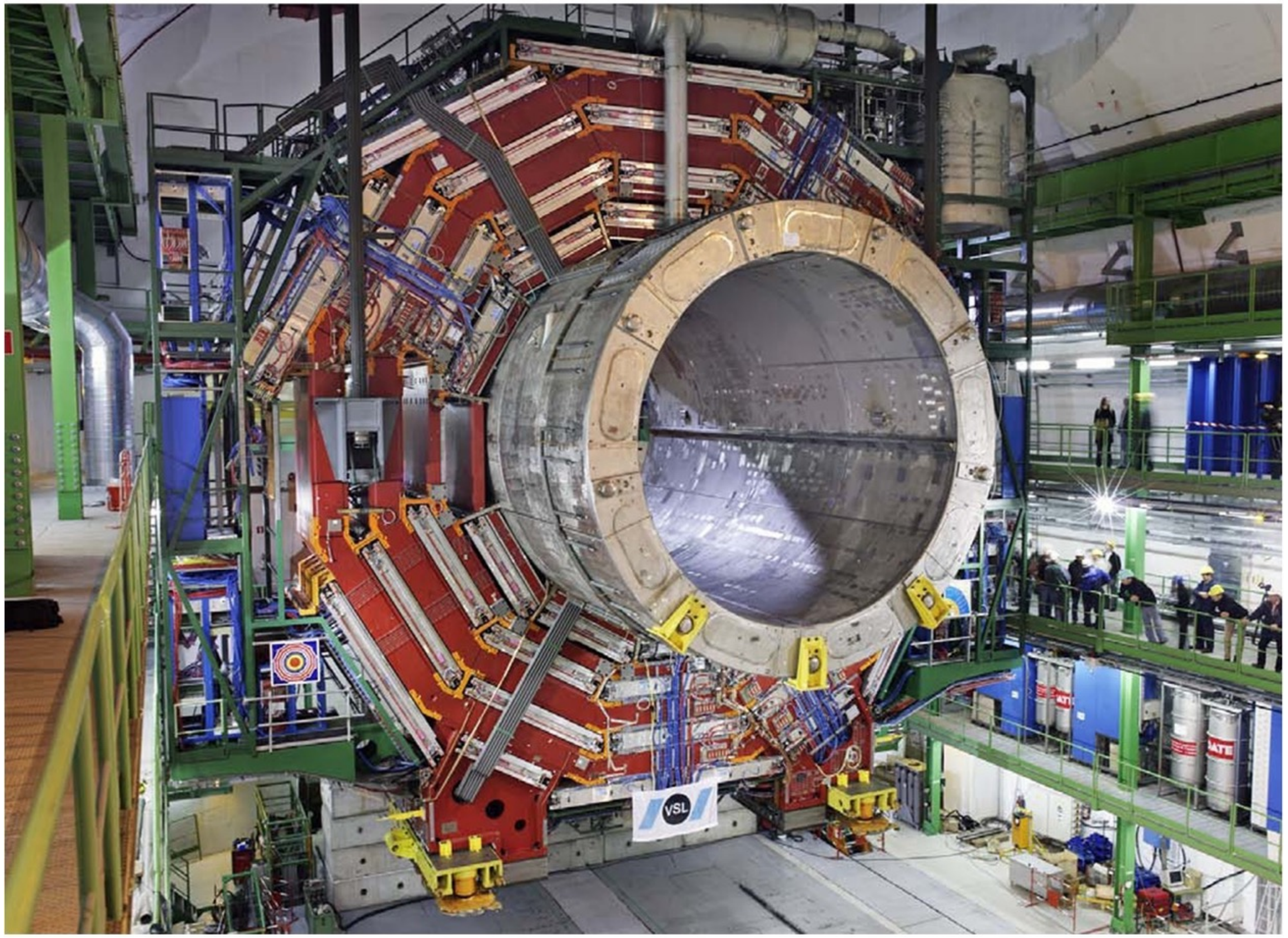
The CMS magnet is a central feature of the detector

- 12.5m Length, 6.3m inner diameter
- Superconducting coils produce 3.8T field
- Cooled by liquid Helium
- Iron return yoke concentrates flux → 2T field in iron outside solenoid
- Largest superconducting solenoid in the world
- 2.6GJ stored energy

The magnet bends charged particles, allowing the tracker to measure transverse momentum ($p_T$)




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



# Tracker

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CMS Tracker

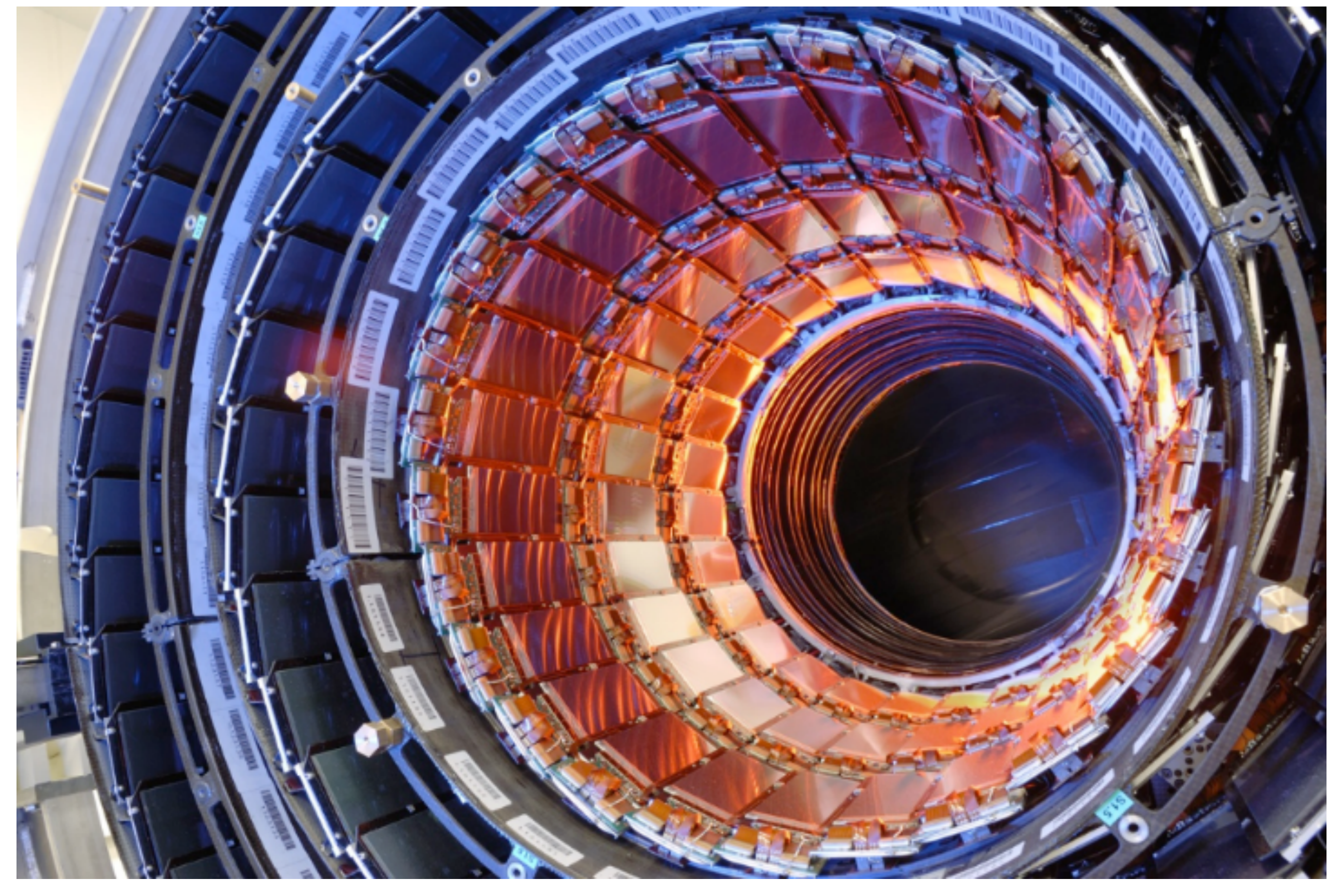
- Over 200m² Silicon
- Cooled to -10°C
- 66M channel pixel detector
  - 100x150μm pitch
- 9.6M channel strip detector
  - 80-180μm pitch, ~10cm long

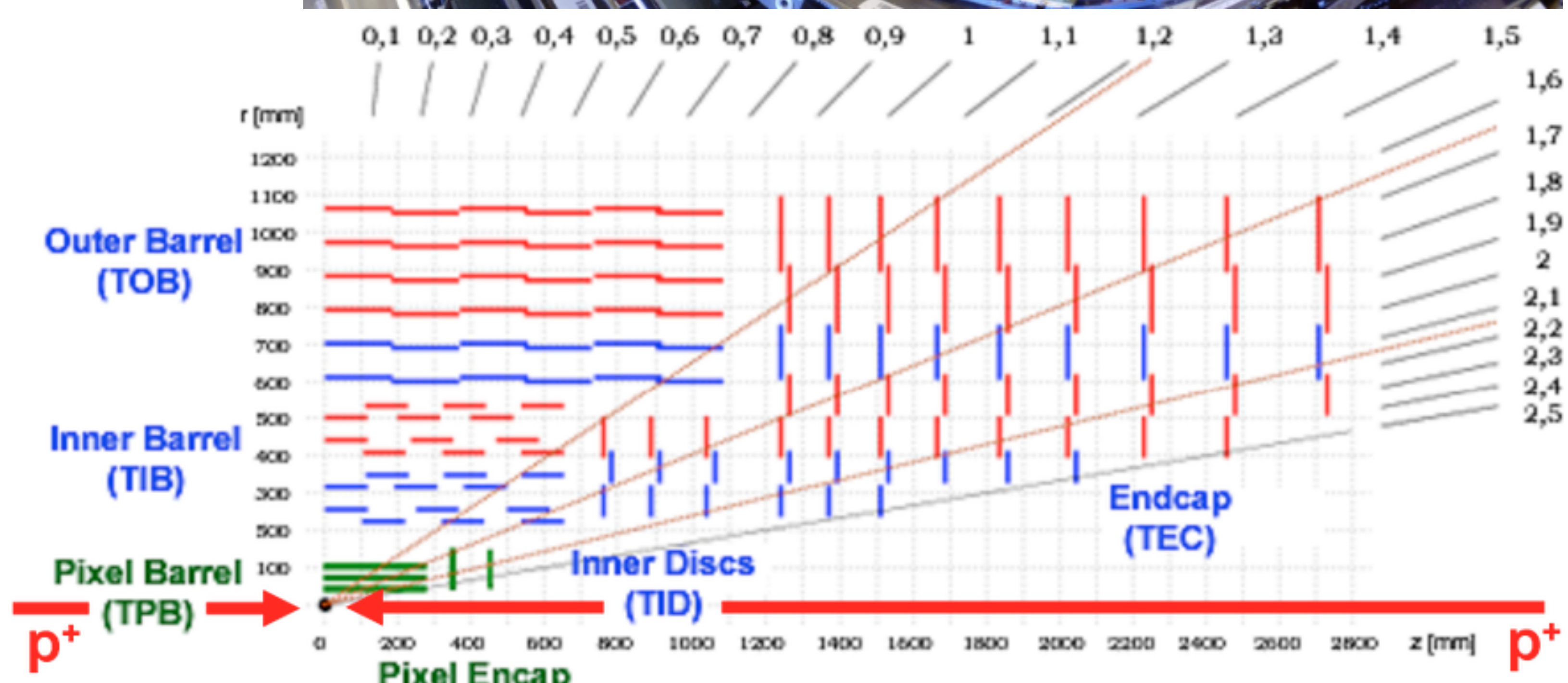
Resolution (barrel):

$$\frac{\delta p_T}{p_T} = (\frac{p_T}{1TeV}15\%) \oplus 0.5\%$$

Primary vertex resolution: O(10) μm

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





# Electromagnetic Calorimeter

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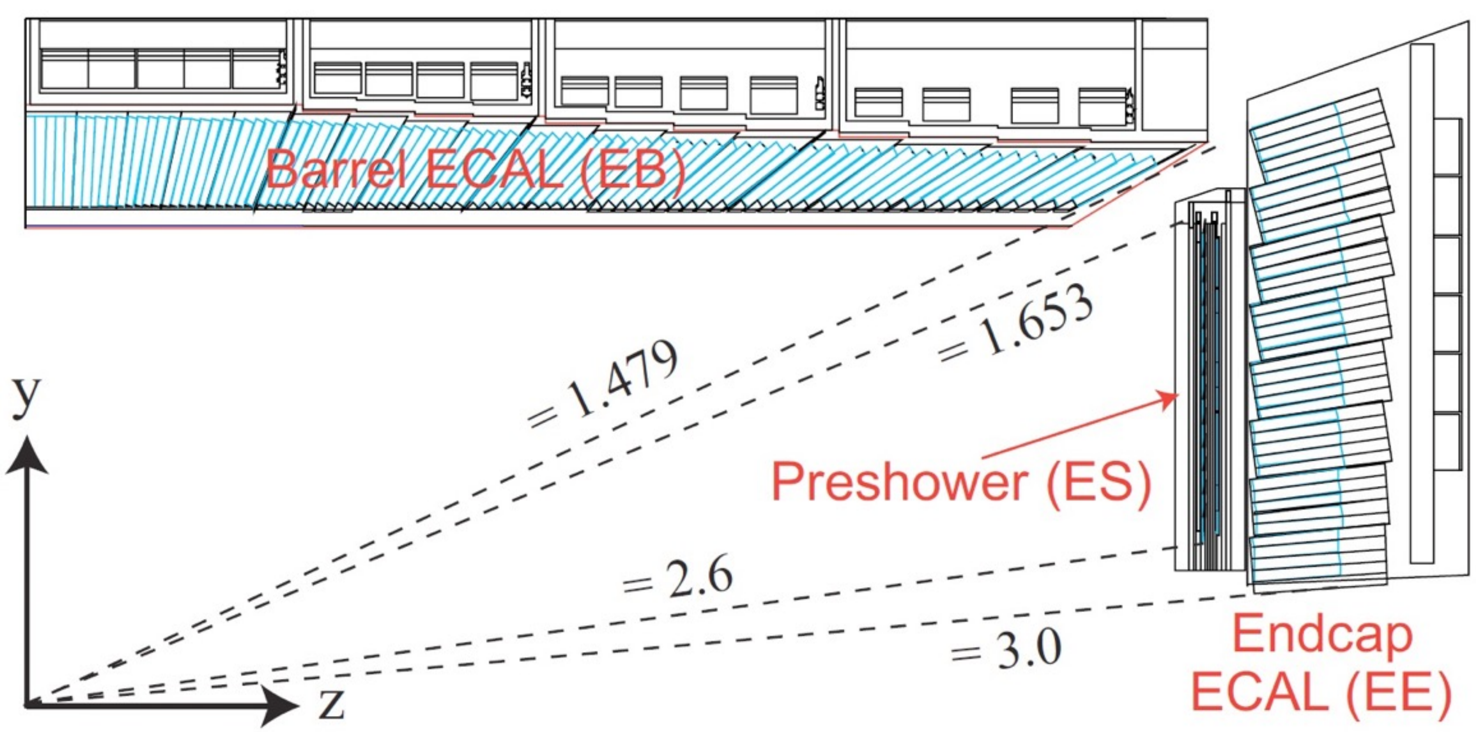
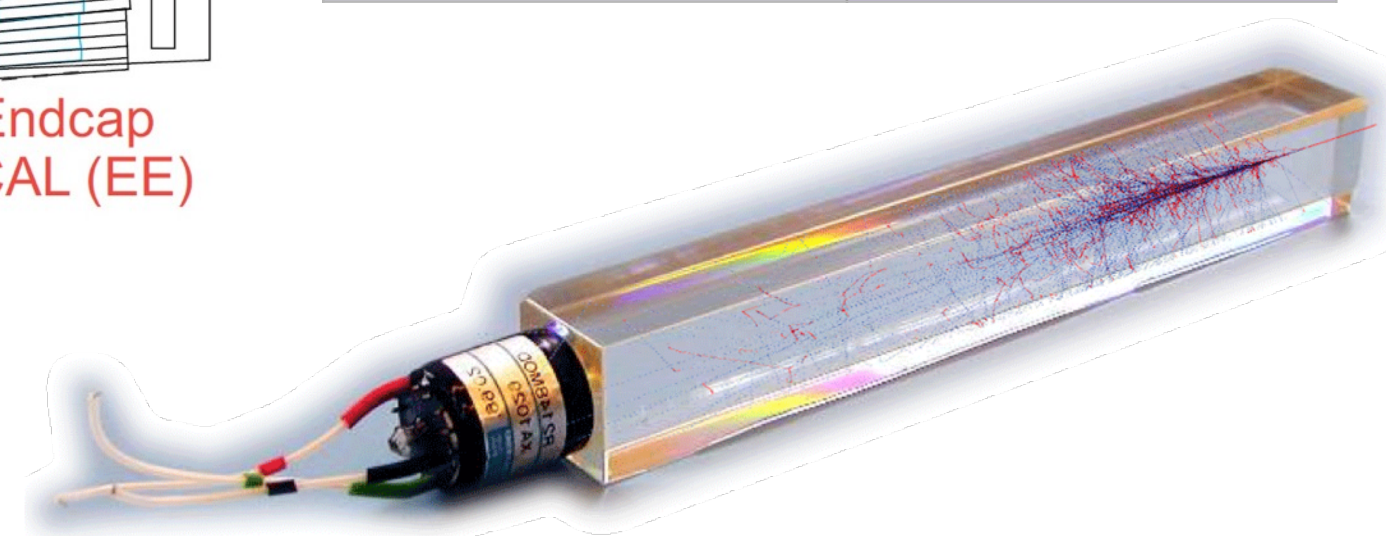
- Over 75k Lead Tungstate crystals, 61200 in Barrel
- Average crystal size: 2.2 x 2.2 x 22cm; weight:1.5kg
- Barrel crystal face $\Delta\eta \times \Delta\phi = 0.0175 \times 0.0175$
- Provides high resolution energy measurement for electrons and photons

| | Lead Tungstate ($PbWO_4$) |
|---|---|
| Density | 8.28 g/cm$^3$ |
| $X_0$ | 0.89cm |
| Molière radius | 2.19cm |
| Decay constant | 10ns |
| Peak Emission λ | ~430nm |
| Light Yield | ~100 γ/MeV |




Resolution (barrel):

$$\frac{\sigma}{E} = \frac{2.8\%}{\sqrt{E}} \oplus \frac{0.128}{E} \oplus 0.3\%$$



# Hadronic Calorimeter

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The CMS HCAL consists of 3 main regions:

Barrel (HB) and Endcap (HE) sampling calorimeters

- Over 1000 tons of brass plates interleaved with scintillator tiles
- WLS Fibers transfer scintillation light to readout electronics
- Covers $|\eta| < 3$, depth varies from 6-10 interaction lengths

Forward (HF) Cherenkov detector

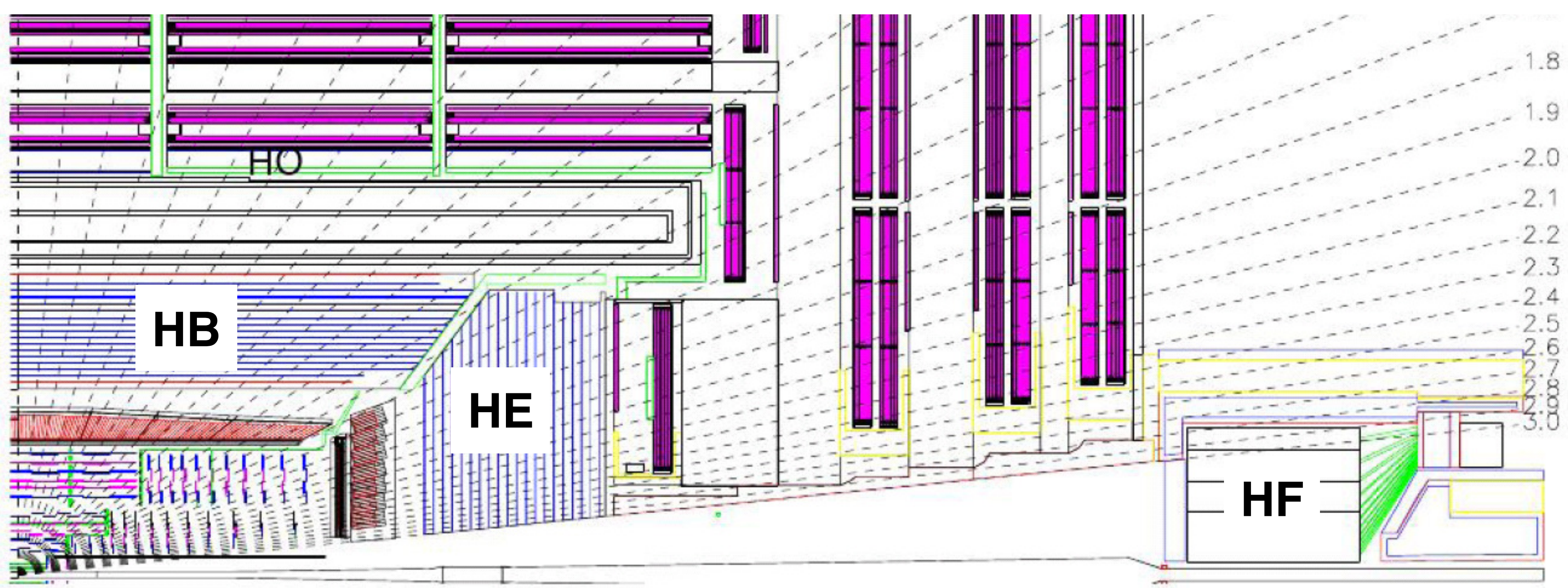
- Steel plates embedded with quartz fibers
- Covers $3 < |\eta| < 5$

Resolution (HB/HE):

$$\frac{\sigma}{E} = \frac{115\%}{\sqrt{E}} \oplus 5.5\%$$

Resolution (HF):

$$\frac{\sigma}{E} = \frac{280\%}{\sqrt{E}} \oplus 11\%$$



# Muon Systems

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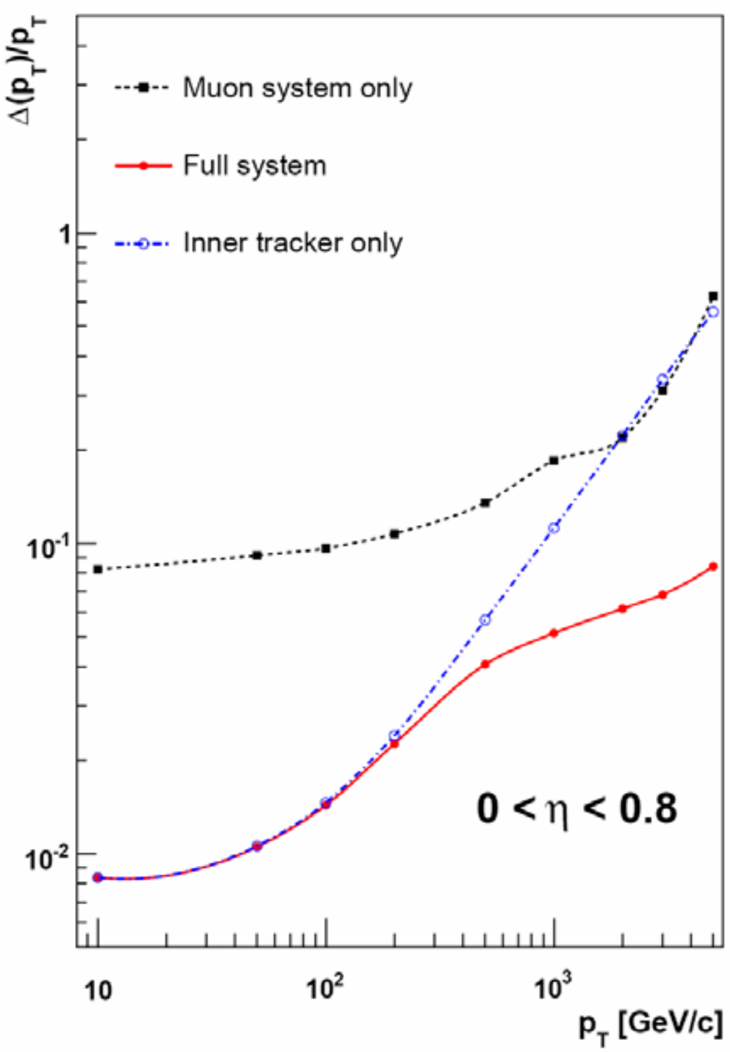
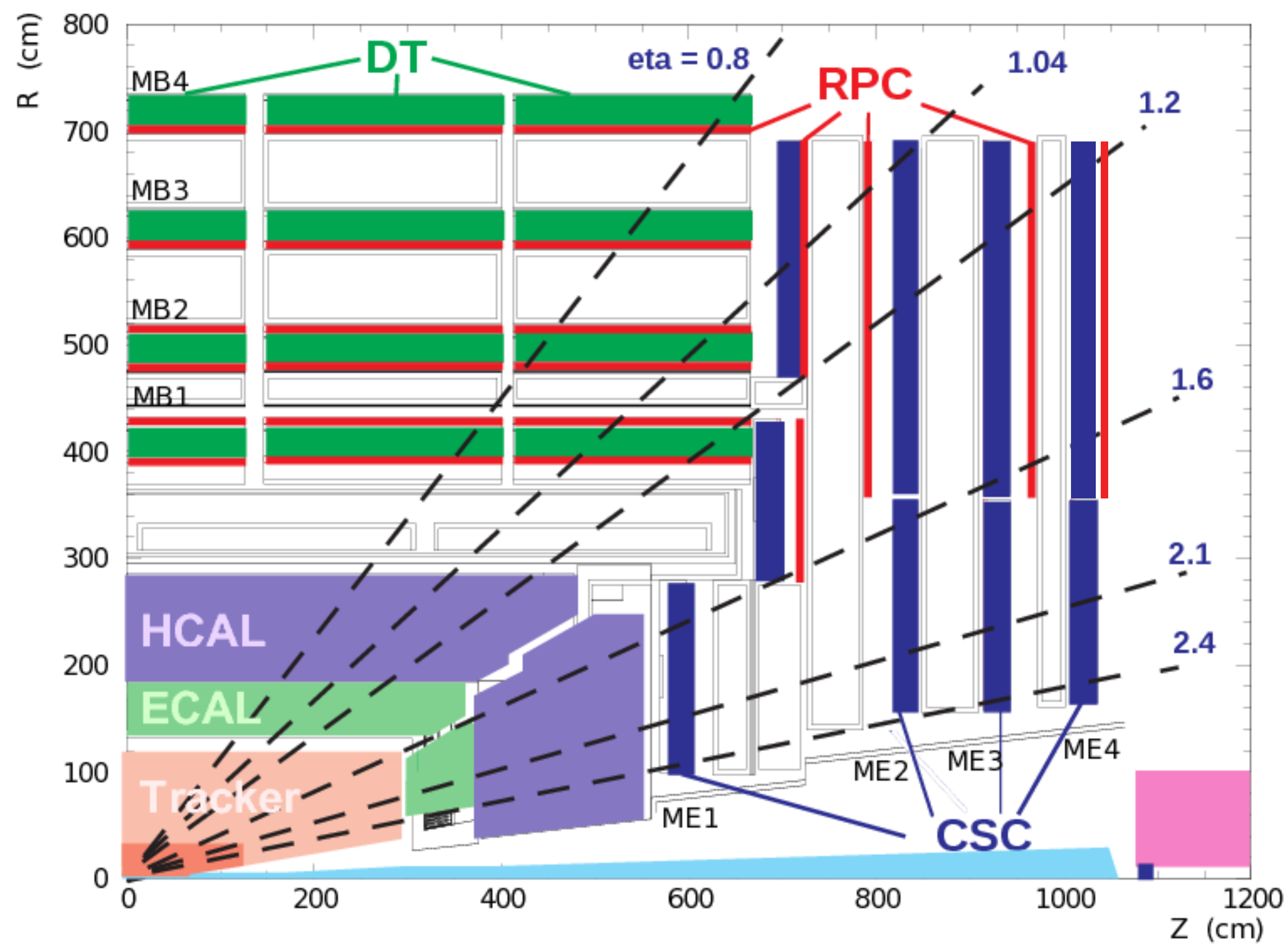
3 muon detection systems embedded in the iron return yoke:

- Drift Tubes (DT) in barrel |η| < 1.2
- Cathode Strip Chambers (CSC) in endcaps 0.9 < |η| < 2.4
- Resistive Plate Chambers (RPC) in |η| < 1.6

Three main tasks: triggering, identification, and assisting inner tracker in measuring high-$p_T$ muons




Muon $p_T$ Resolution



# Trigger System

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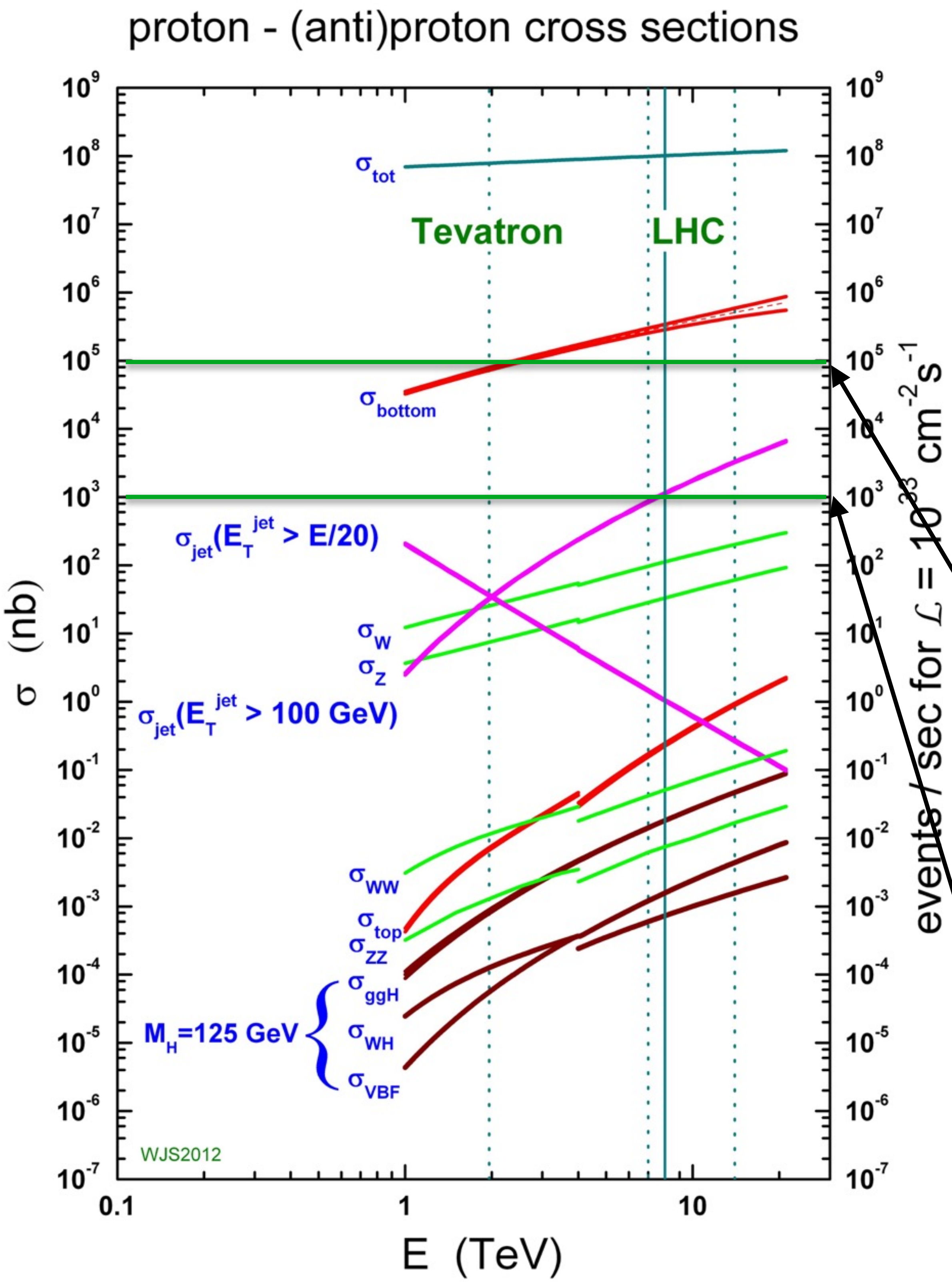


LHC collides bunches of protons at 40MHz

~25 collisions per bunch → GHz rate

At a Mb per event, CMS can record ~1kHz

Trigger System decides what to keep

Rate reduction in two steps:

- Level-1 Trigger
  - Custom hardware
  - Subset of detector information
  - Reduces rate to ~100kHz
- High-Level Trigger
  - Software, CPU-limited
  - Full detector information
  - Reduces rate to ~1kHz

# Level 1 Trigger

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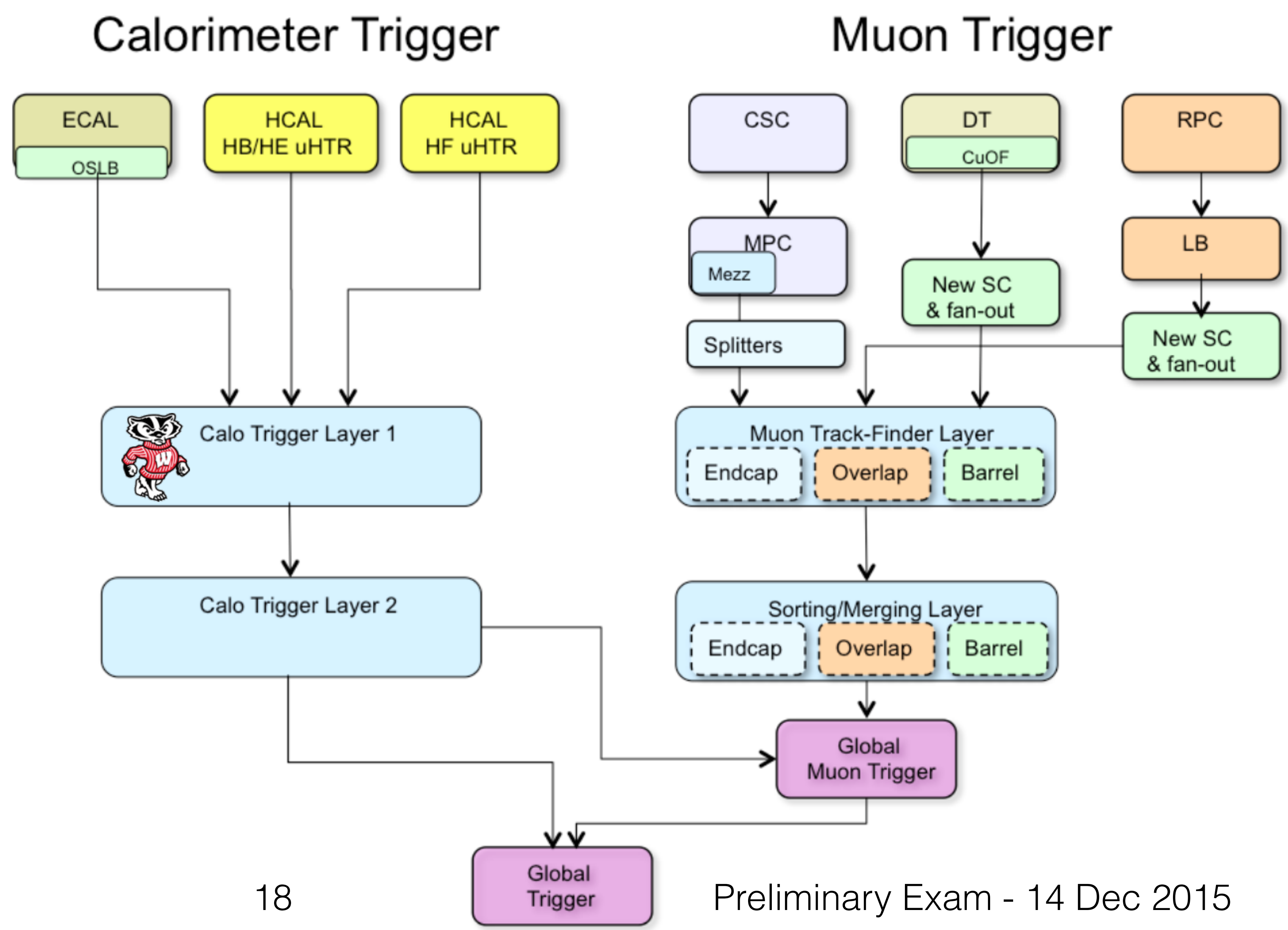
L1 Trigger receives simplified detector information from calorimeters and muon systems, and forms

- EG Candidates (electrons/photons)
- Jet Candidates
- Missing Energy estimate
- Muon Candidates

L1 accept if objects pass

- Energy thresholds
- Coincidence
- Object topology

- Defined in ‘trigger menu’
- Once every 25ns
- Pipeline ~4μs long



# High Level Trigger

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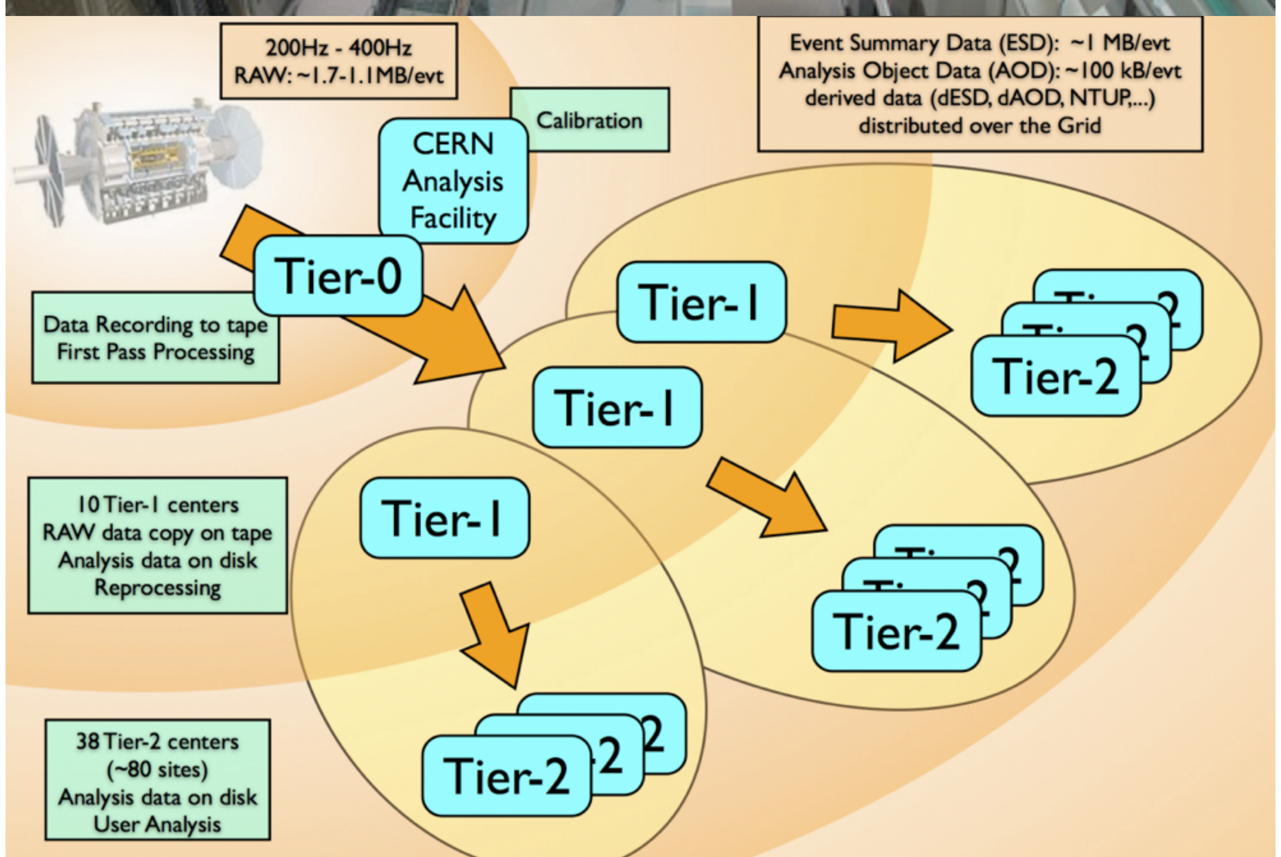


- Dedicated compute farm
- Commodity hardware
- Receives full detector readout
- Subset of reconstruction algorithms
- Over 450 trigger paths in HLT menu

- For HLT accepts, raw data is processed, compressed and calibrations are applied
- Some raw data can be ‘parked’

# Event Simulation - Hard Scatter

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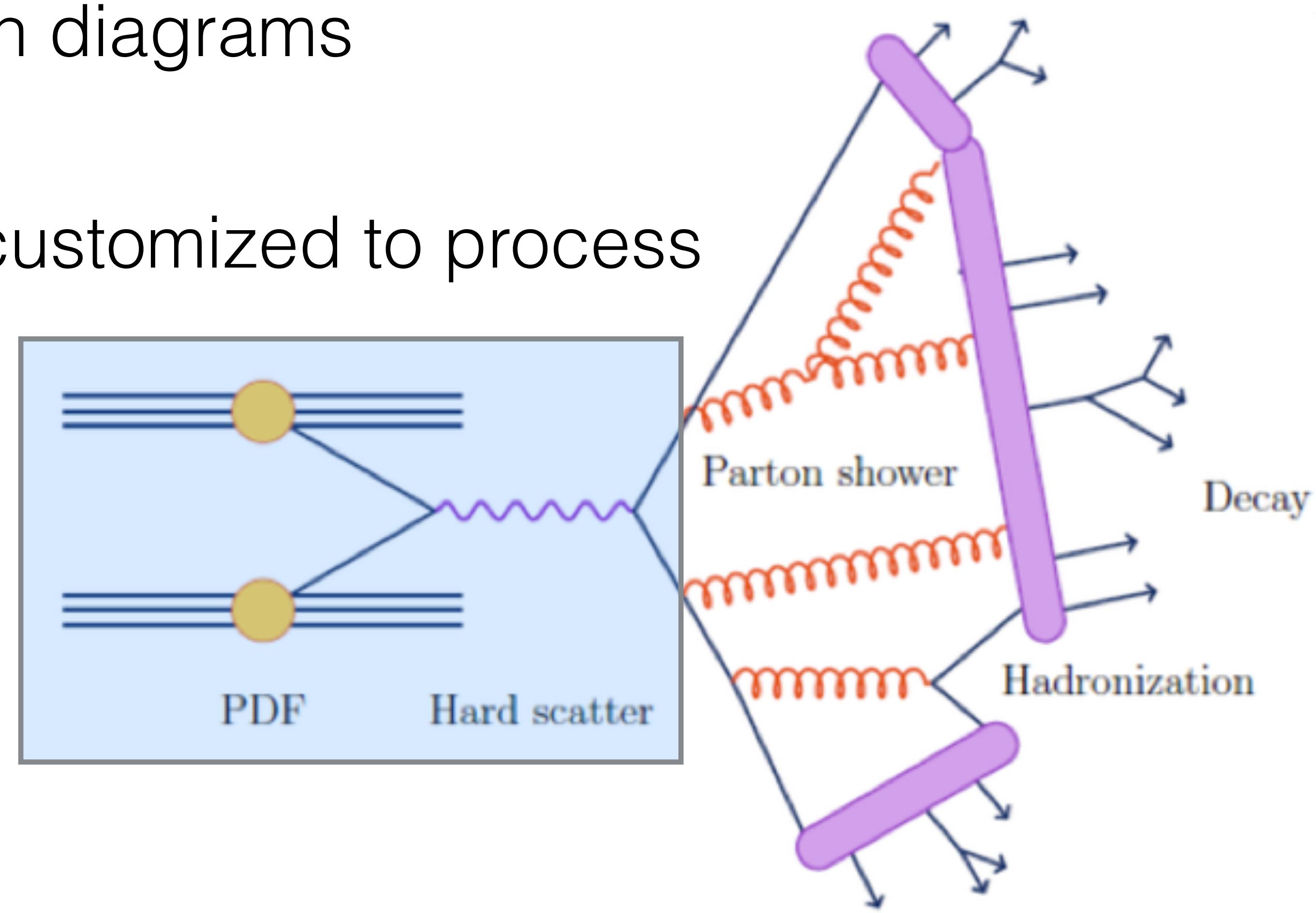
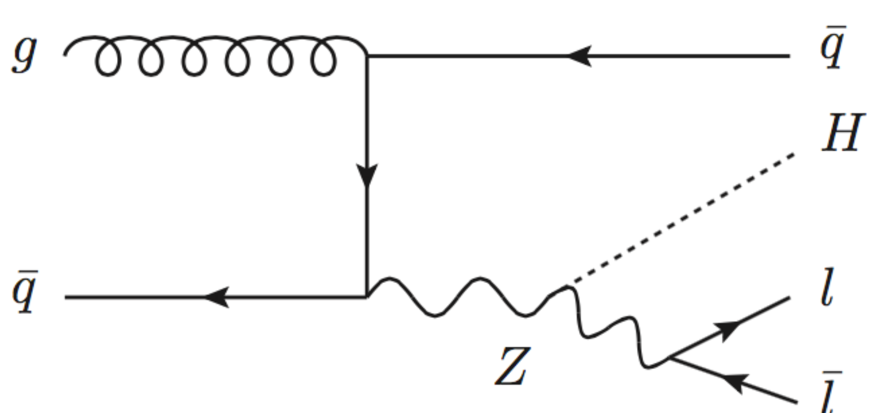
Two common programs for hard scatter simulation:

- MadGraph / aMC@NLO
  - Automated calculation of Feynman diagrams
- POWHEG
  - Library of tools plus calculations customized to process

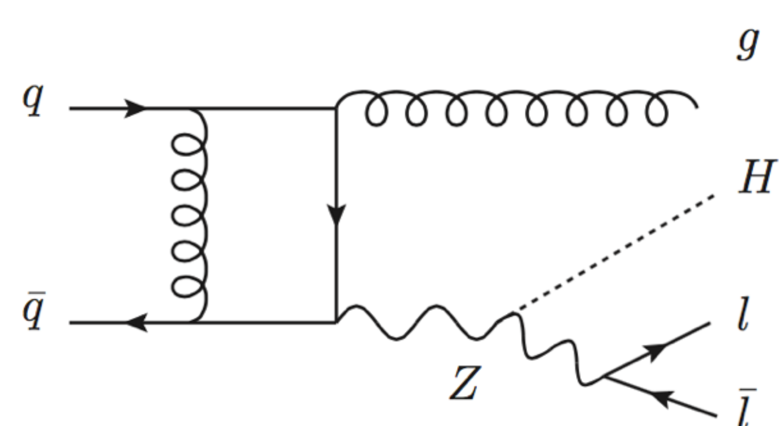



Both now* provide predictions at Next-to Leading Order (NLO)

e.g.




LO




NLO

* 8TeV simulations are not all NLO

# Event Simulation - Decay & Detection

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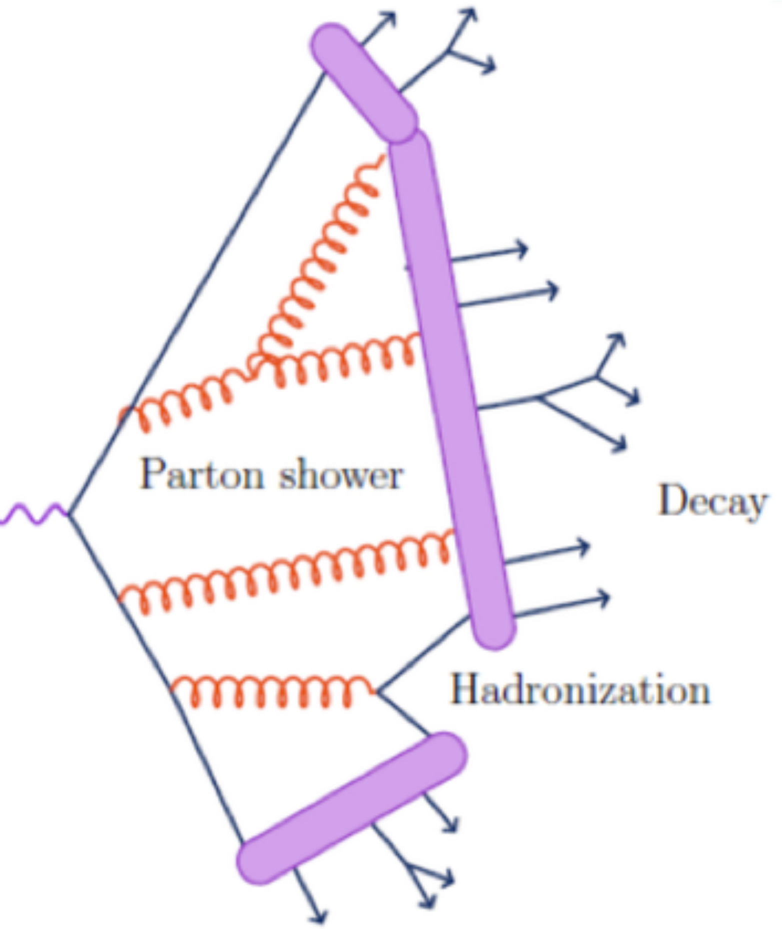
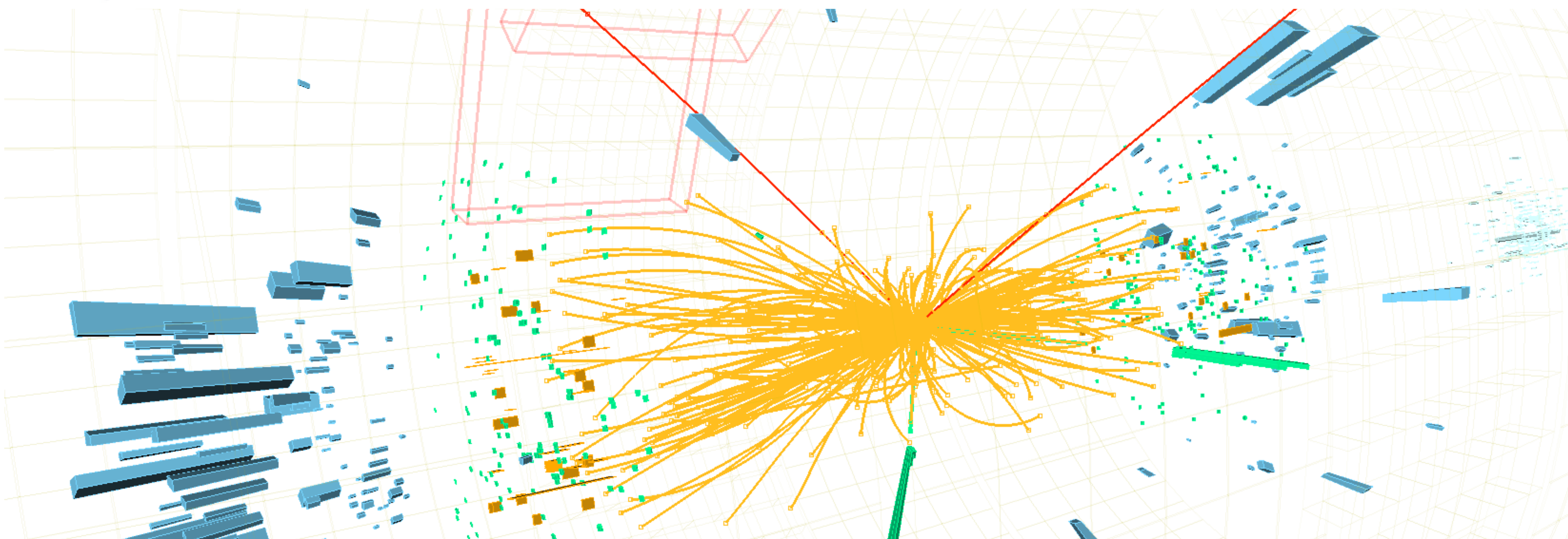



After the hard scatter simulation:

- Pythia simulates
  - Parton Shower
  - Hadronization
  - Decay to stable particles
- GEANT4
  - Passage of stable particles through detector



# Event Reconstruction

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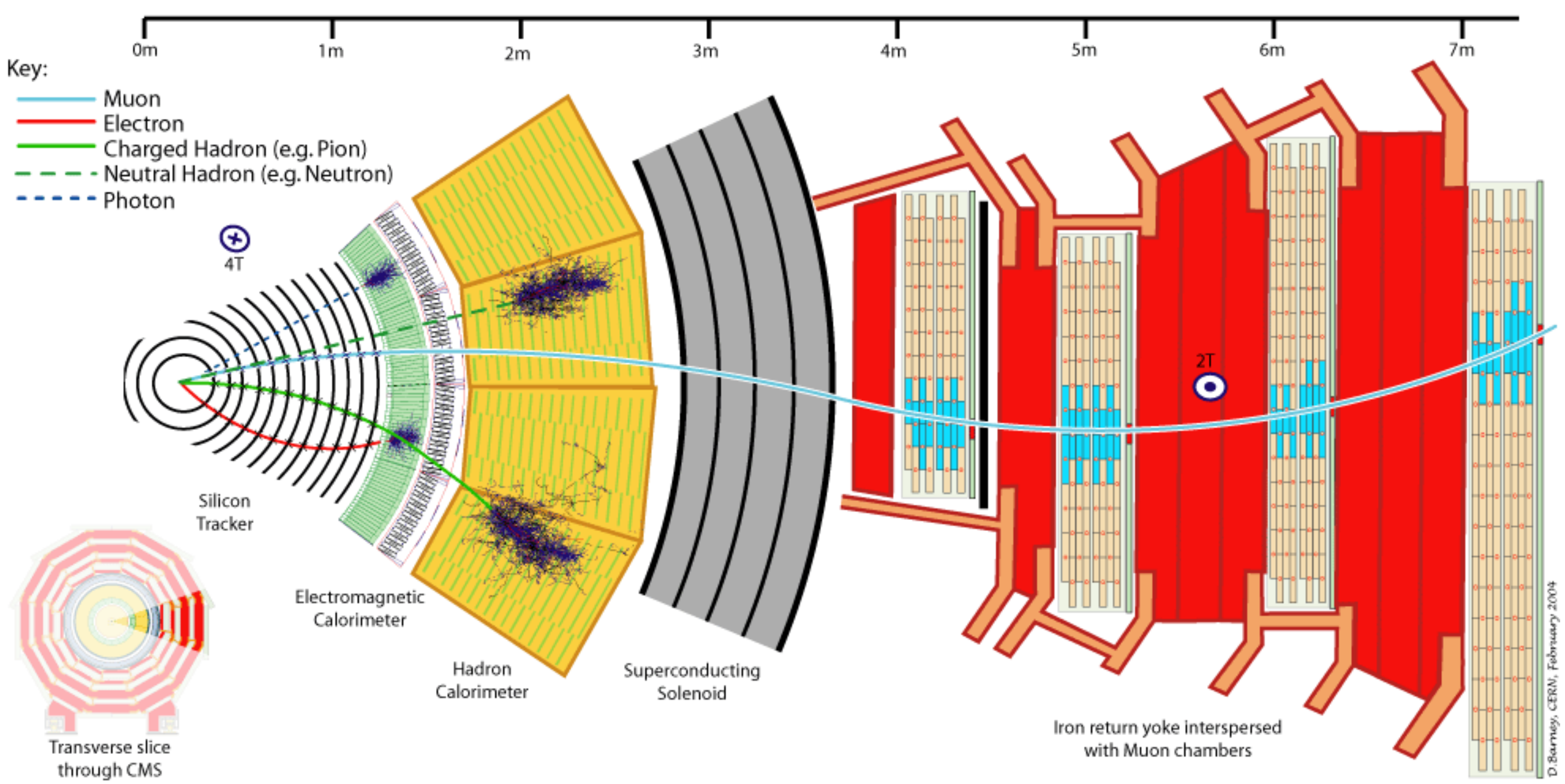
Particle Flow (PF) Reconstruction combines information from all detector components, building candidates in order of purity

- Muon system tracks are combined with inner tracker to make muon candidates
- ECAL & HCAL deposits are matched to tracker tracks to make electron & charged hadron candidates
- Remaining calorimeter energy is clustered to form photon candidates (ECAL) & neutral hadron candidates (HCAL)



# Muon Reconstruction

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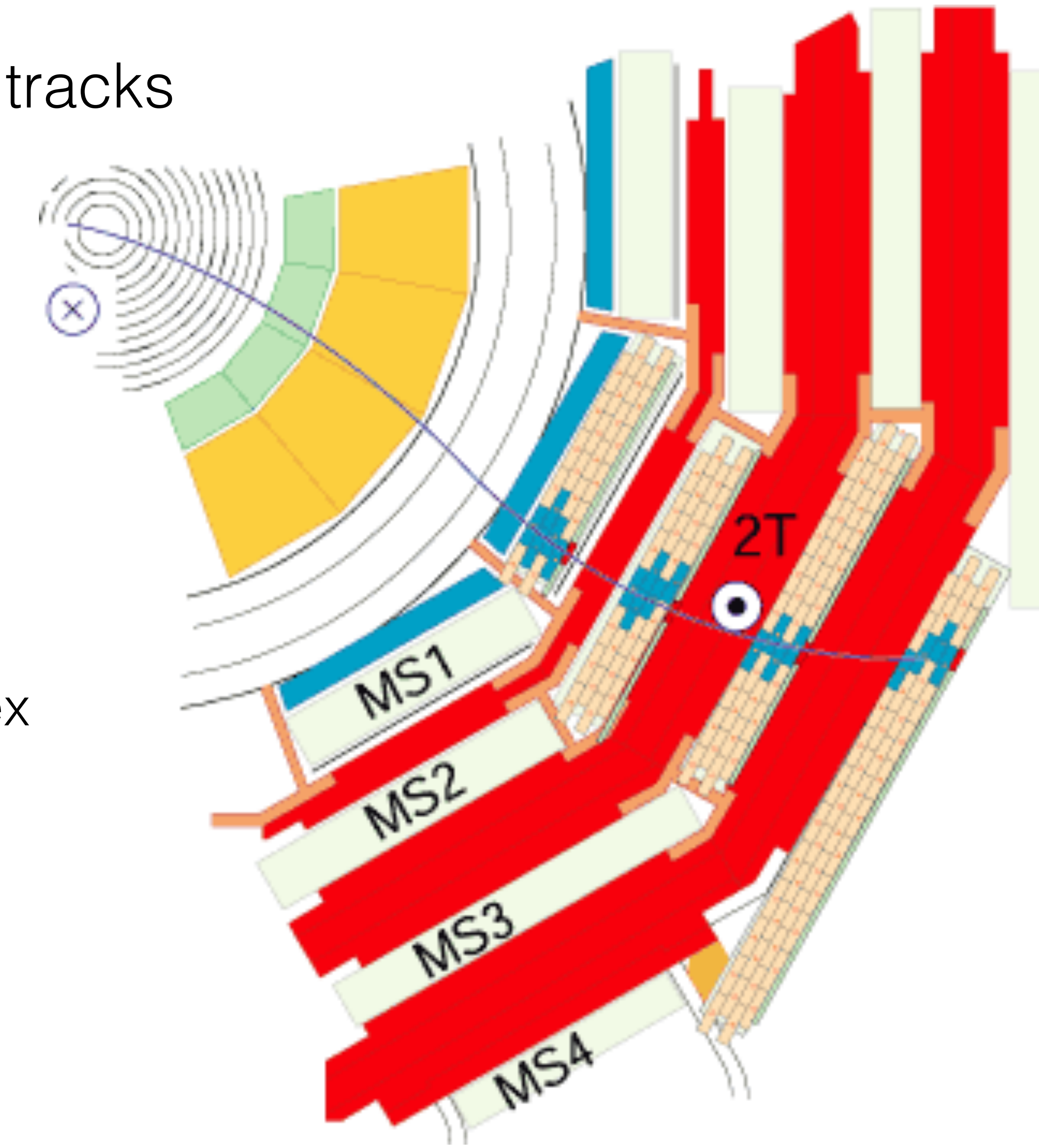
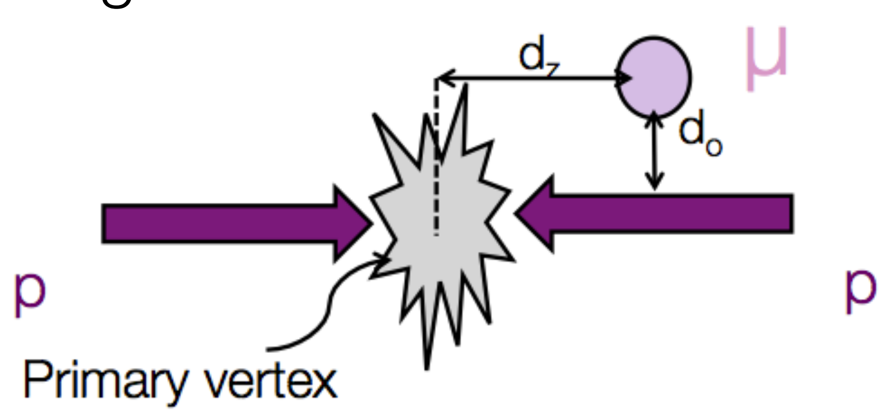
Categories of reconstructed muons:

- *Standalone* - tracks from segments in muon systems
  - 1% exclusive rate, very high cosmic muon acceptance
- *Tracker* - match inner detector tracks with one segment in muon system
  - High efficiency for low $p_T$ muons
- *Global* - match standalone muons with tracks
  - More information available
  - High purity




Requirements in this analysis:

- Global reconstruction
- Require segments in at least 2 muon stations
- >5 tracker layers for $p_T$ measurement
- Distance of closest approach to primary vertex
  - Transverse < 0.2cm
  - Longitudinal < 0.5cm



# Electron Reconstruction

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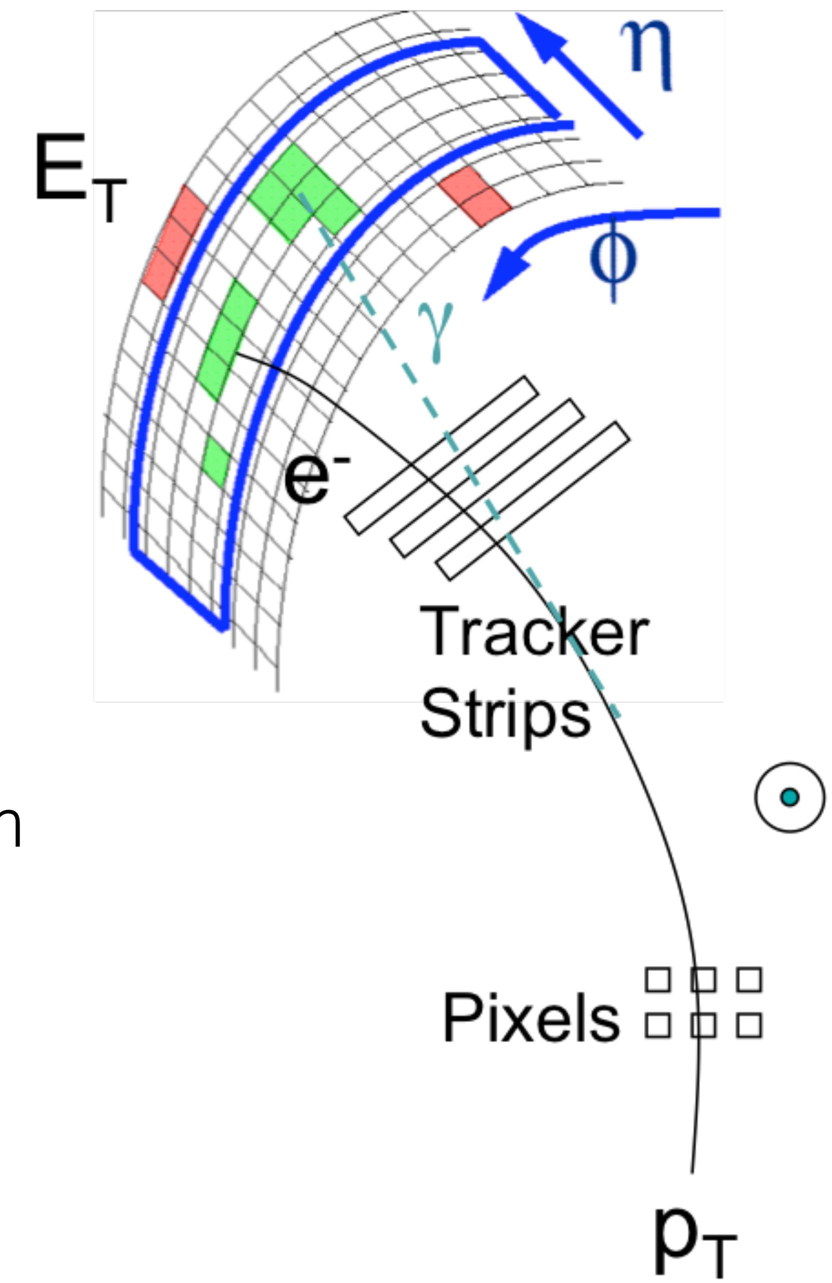
- Electrons identified by combination of detectors
- Basic object called 'GSF electron'
  - ECAL supercluster
  - Gaussian-Sum Filter track reconstruction

Requirements in this analysis:

- Pixel hits
  - <2 missing hits, for photon conversion veto
- Tracker
  - Photon conversion vertex veto
  - Distance of closest approach to primary vertex ~ 1mm
- ECAL
  - Distance between cluster and track
  - Shower shape requirement
- HCAL
  - H/E cut for rejection of hadrons
- Distance to nearest PF muon > 0.1




ECAL Barrel: $|\eta| < 1.479$

# Jet Reconstruction

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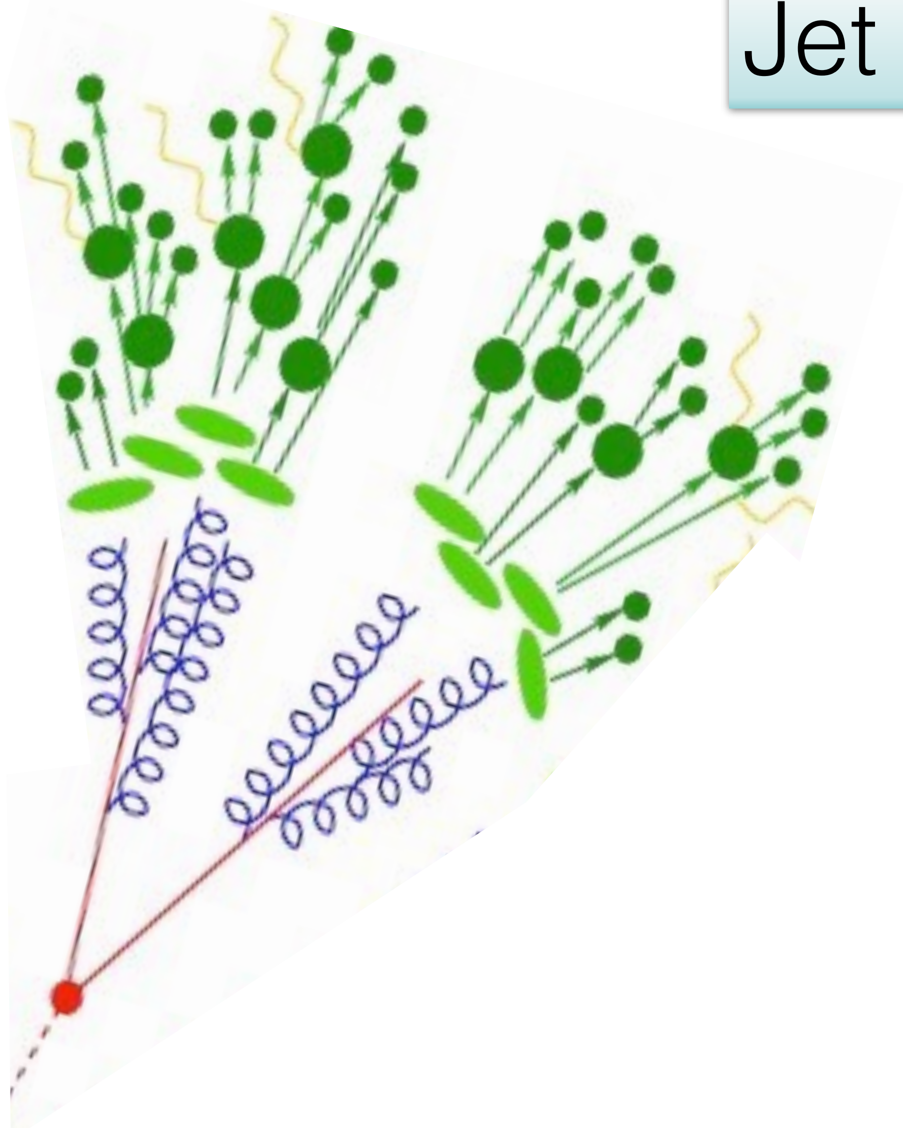
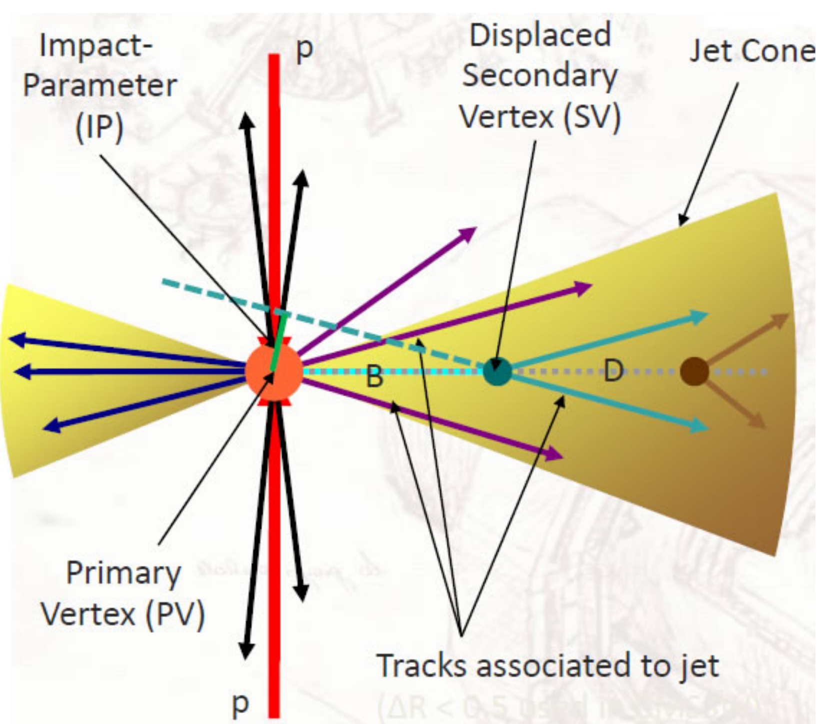
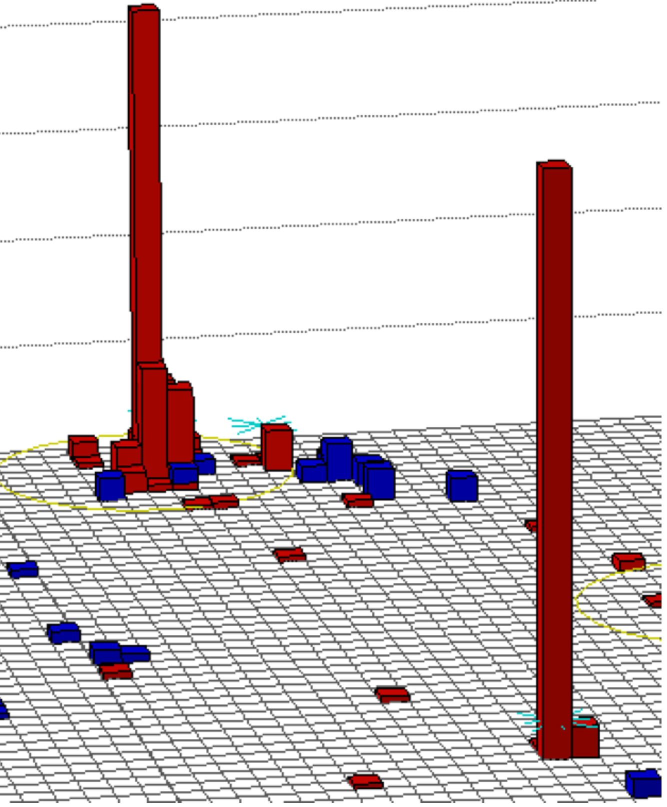


- Quarks and gluons hadronize
- Showers of many particles formed
- Jet reconstruction algorithms:
  - Iteratively cluster nearby particles
  - Form macroscopic objects
  - Preserve ability to compare to theory
- In this analysis, Anti-$k_T$ distance metric:

$$d_{ij} = \min\left(\frac{1}{k_{ti}^2}, \frac{1}{k_{tj}^2}\right)\frac{\Delta_{ij}^2}{R^2}, \quad R = 0.5$$




- In this analysis, veto b quarks
- Jets from b quarks are distinctive
- Long-lived b hadrons form displaced vertex
- B-tagging identifies jets with displaced tracks



# Lepton Isolation

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- Leptons from hard process typically isolated
- Jets can produce real leptons
- Jet fragments can fake leptons
- Isolation cuts help distinguish leptons of interest

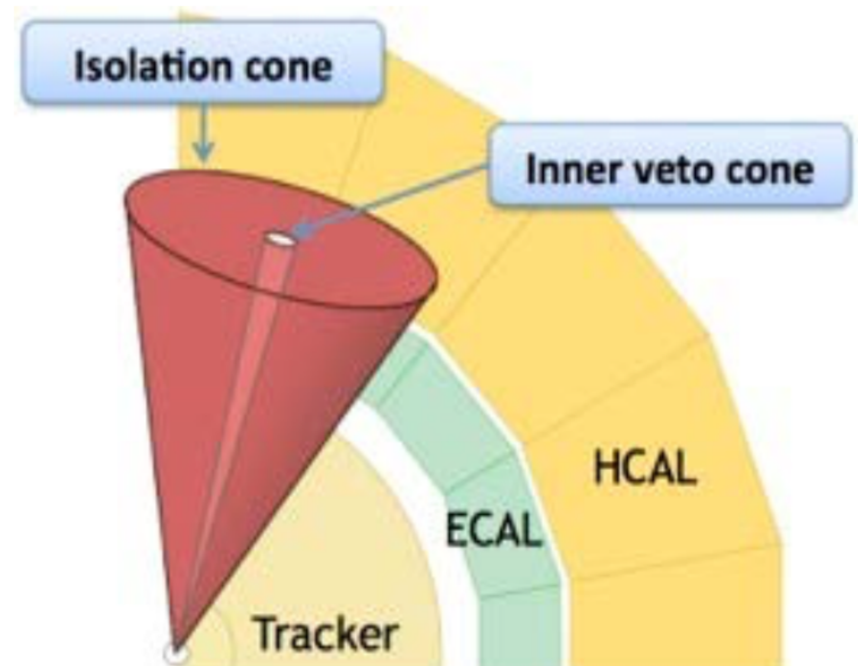
Electron isolation: $$I^{e}_{rel} = \frac{\sum p_T^{charged} + max[\sum E_T^{neutral} + \sum E_T^{photon} - \Delta\rho \cdot E.A., 0.0]}{p_T}$$

Cut: 0.15

Muon isolation: $$I^{\mu}_{rel} = \frac{\sum p_T^{charged} + max[\sum E_T^{neutral} + \sum E_T^{photon} - 0.5 \cdot \sum p_T^{charged,PU}, 0.0]}{p_T}$$

Cut: 0.2

- Isolation cone defines components in sum
  - 0.3 for electrons
  - 0.4 for muons
- Electron veto cone in endcaps only



# Missing Transverse Energy

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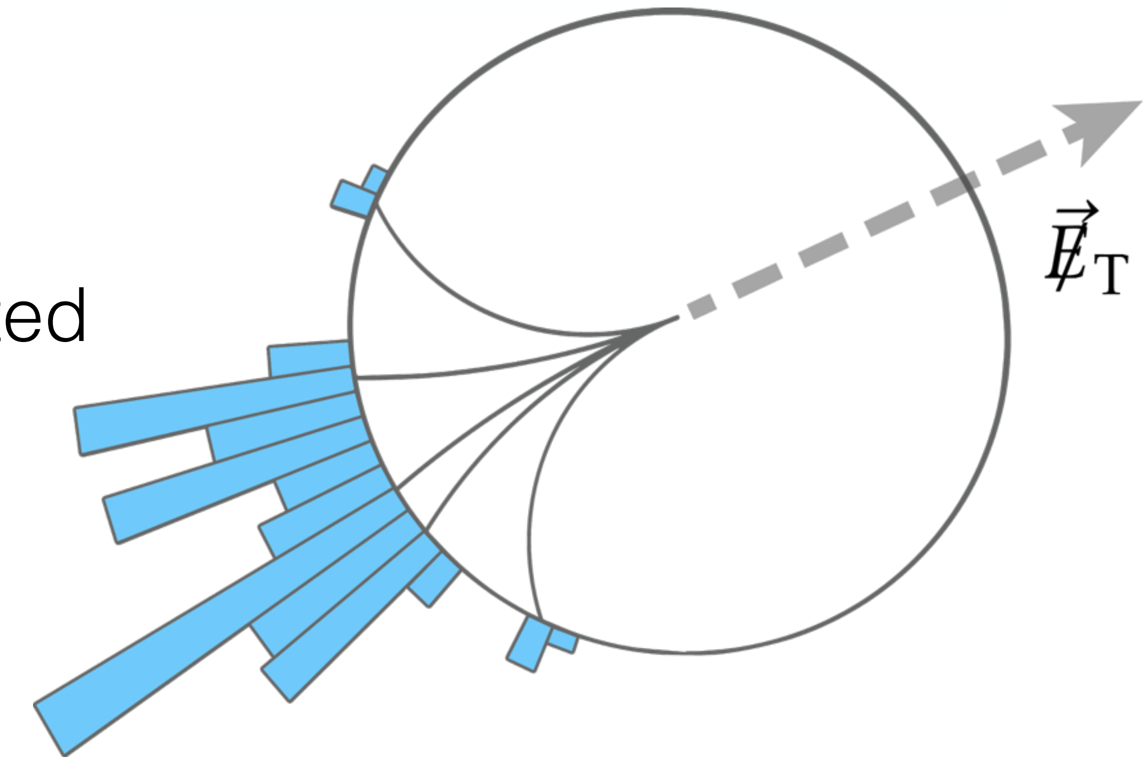
Missing Transverse Energy (MET):
Negative vector sum of transverse momentum from all reconstructed particles.

$$\vec{\not{E}}_T = -\sum_{i \in \text{vis.}} \vec{p}_{Ti}$$




In this analysis,

- All particle-flow candidates summed
- Jet energy corrections to particles associated with a jet are applied
- Correction for systematic ϕ modulation observed in both data & MC, due to
    - Beam spot x-y shift
    - Noise, gain variation in ECAL/HCAL readout

# Existing Limits

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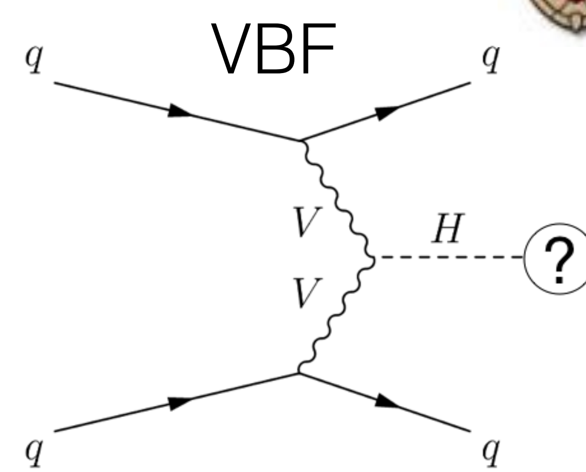
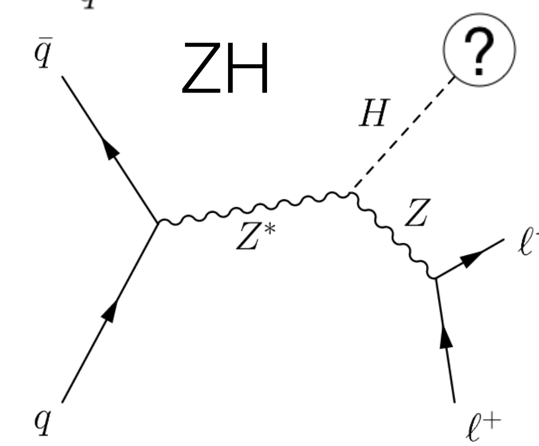



Approaches to searching for BSM Invisible Higgs decays:

Look for deficit in sum of visible decays
- Must extrapolate from accessible decay channels
- Requires accurate knowledge of production rate




Look for missing energy in the detector
- MET measurement becomes easier when there is a recoil topology
  - Vector Boson Fusion
  - Associated Production

Selection of 95% CL observed (expected) upper limits on BR(H→inv.) for ~25fb$^{-1}$ collected at 7,8TeV with CMS and ATLAS

| Channel | CMS Limit | ATLAS Limit |
|---|---|---|
| Deficit in sum visible | 0.32 (0.43) | 0.49 (0.48) |
| ZH production (Z→ll) | 0.83 (0.86) | 0.75 (0.62) |
| VBF production | 0.65 (0.49) | 0.28 (0.31) |

# Dark Matter Interpretation

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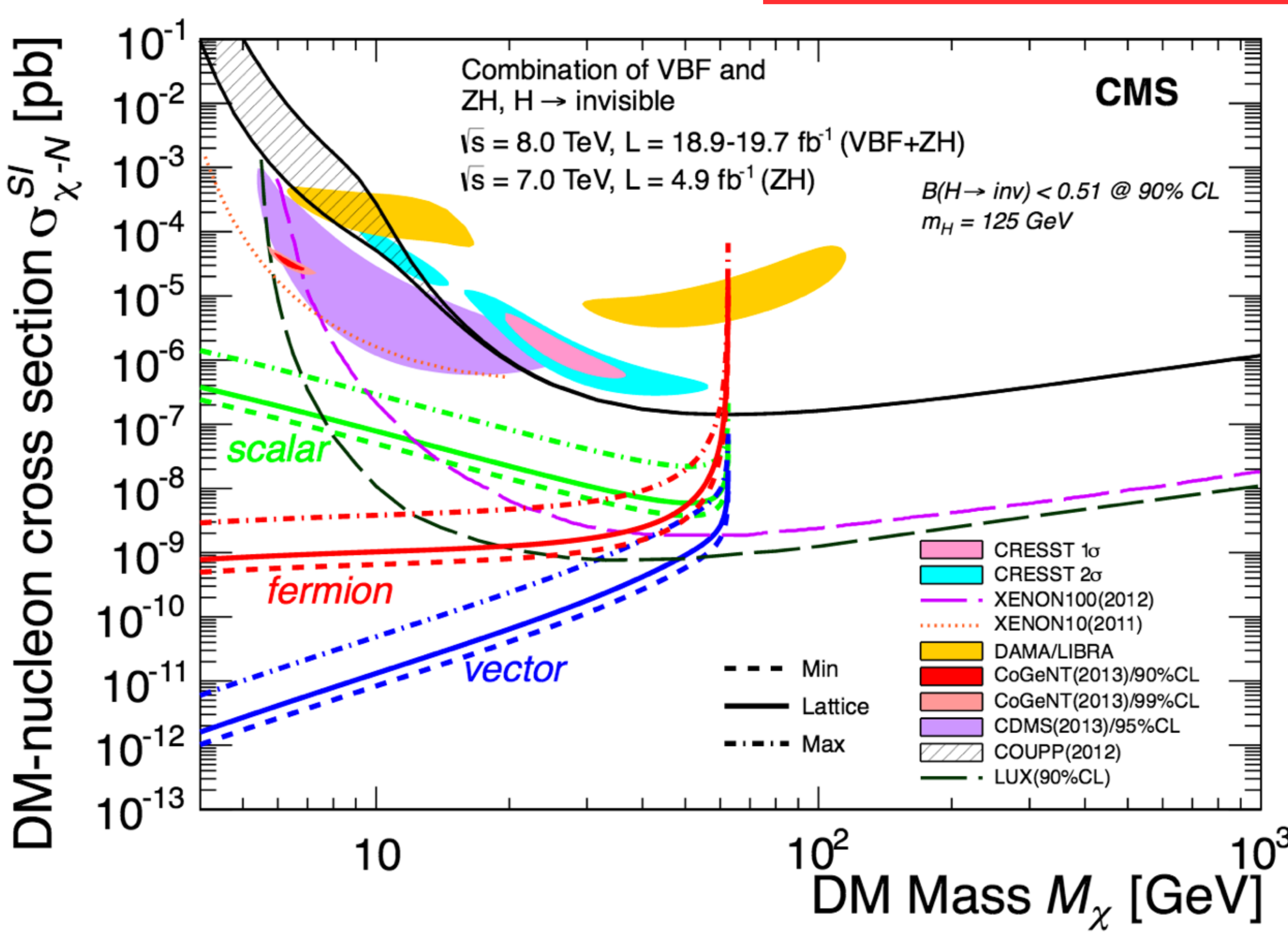
- Limits on invisible Higgs decays → limits on DM-Nucleon σ
- Assume stable DM coupling directly to Higgs
- DM mass < Higgs mass / 2
- Comparison to direct-detection
- Complementary phase space

$$\Delta\mathcal{L}_S = -\frac{1}{2}m_S^2 S^2 - \frac{1}{4}\lambda_S S^4 - \frac{1}{4}\lambda_{hSS} H^\dagger H S^2,$$

$$\Delta\mathcal{L}_V = \frac{1}{2}m_V^2 V_\mu V^\mu + \frac{1}{4}\lambda_V (V_\mu V^\mu)^2 + \frac{1}{4}\lambda_{hVV} H^\dagger H V_\mu V^\mu$$

$$\Delta\mathcal{L}_f = -\frac{1}{2}m_f \bar{\chi}\chi - \frac{1}{4}\frac{\lambda_{hff}}{\Lambda} H^\dagger H \bar{\chi}\chi.$$



# Signature & Dominant Backgrounds

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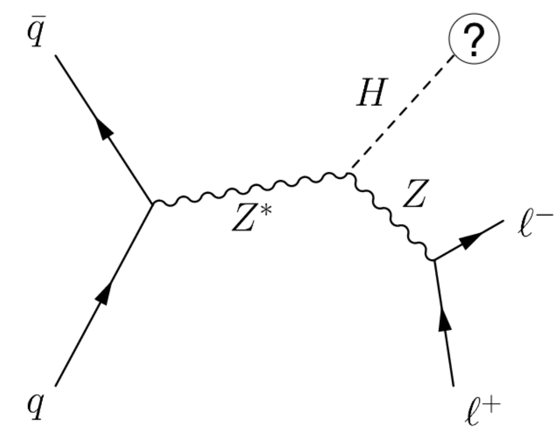
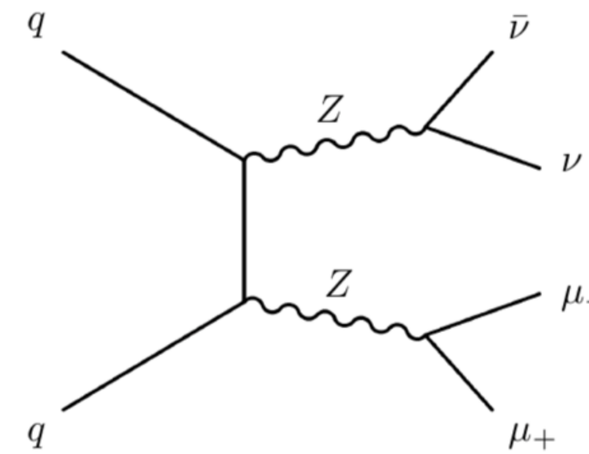
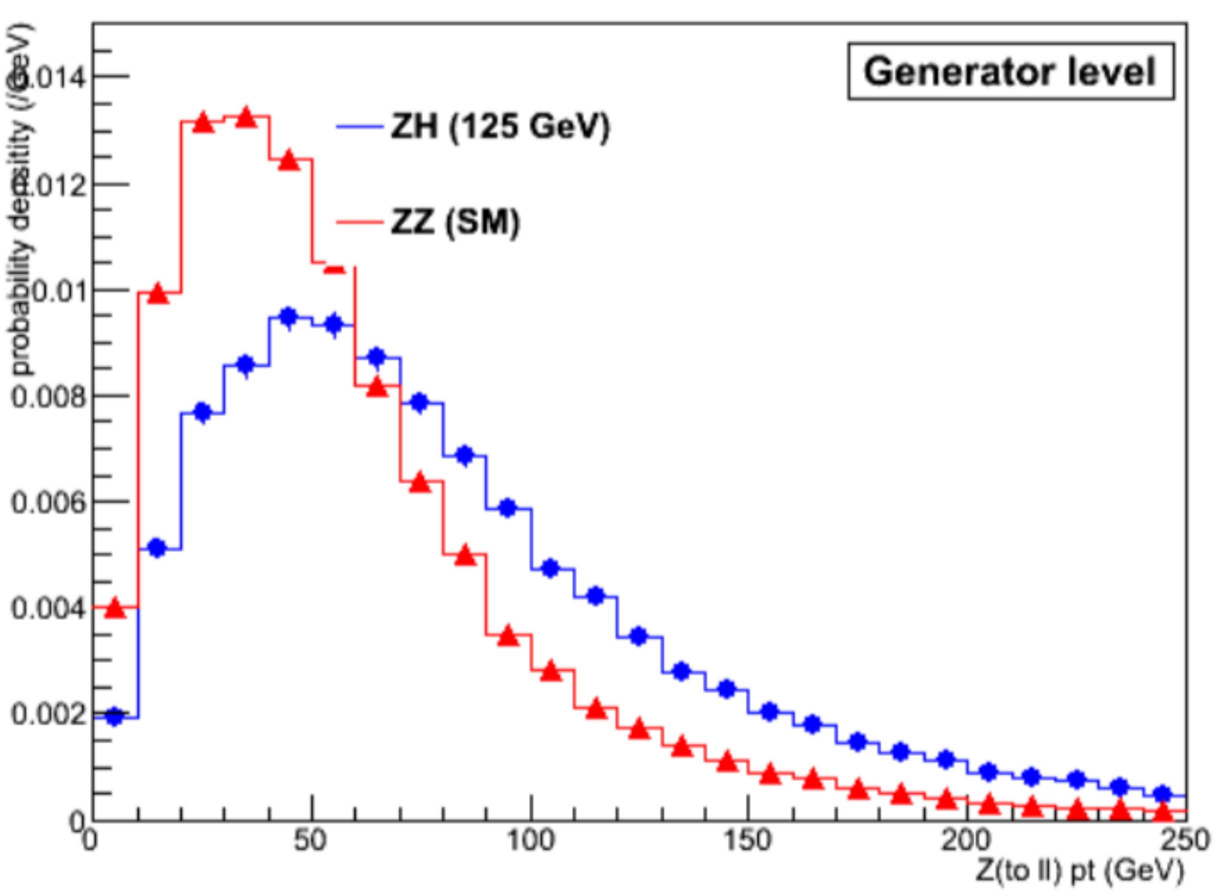
Physics signature: ZH Associated Production
- Z boson decaying to two electrons or muons
- Higgs decay products escape detection
  - Significant Missing Transverse Energy (MET)




Irreducible background: ZZ
- One Z decays as in signal
- Other Z to neutrinos
- Slightly different kinematics: visible Z less boosted (lower transverse momentum)




Other backgrounds due to:
- Fakes
- Detector Acceptances
- Rejection Efficiencies

All significant backgrounds on next slide

# 8 TeV Datasets

N. Smith

All significant background MC processes are plotted along with the data, here is a summary:

| | |
|---|---|
| $ZZ \to 2l2\nu$ | Primary Irreducible Background |
| $WW \to 2l2\nu$ | Can contribute two same-flavor leptons, but non-resonant |
| $WZ \to 3l\nu$ | Can contribute if one lepton is lost (esp. the W lepton) |
| $t\bar{t}$ | Top decays predominantly to Wb, two Ws give two leptons |
| Single top | One lepton from top, another fake |
| $W \to l\nu$ | One lepton from W, another fake |
| $Z \to ll\gamma$ | No photon veto + fake MET |
| $Z \to ll$ | Fake MET |
| Data | |
| Z(ll)H(inv) | Signal simulation, with Higgs decay set 100% invisible |

# Cut Flow Overview

N. Smith

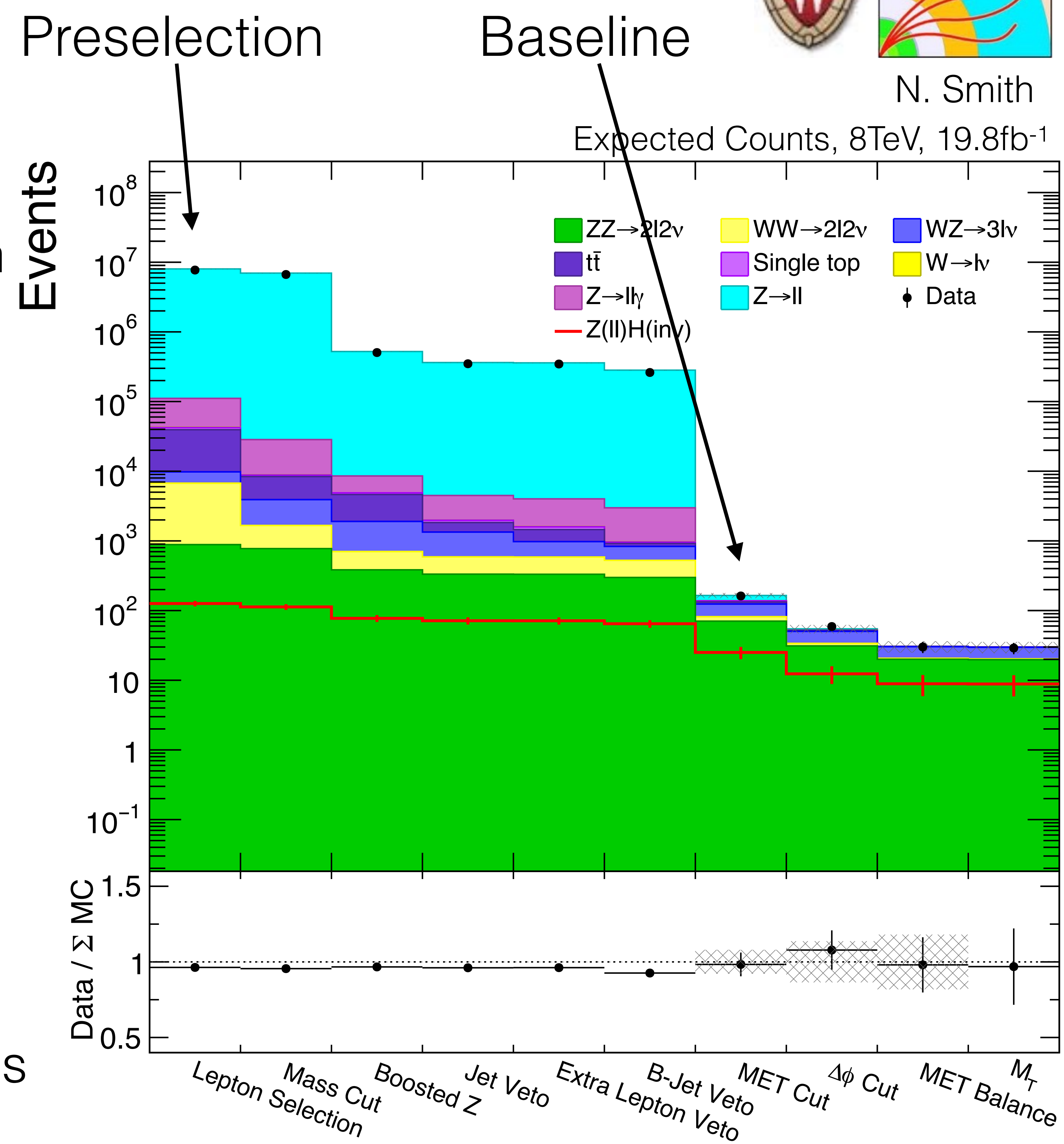
Over 1 quadrillion collisions contribute to this plot, preselection reduces to ~10 million.

Preselection:

- Require 2 muons with ID, Isolation as defined earlier
- Require HLT paths with
    - One muon >17GeV
    - One muon >8GeV

Baseline:

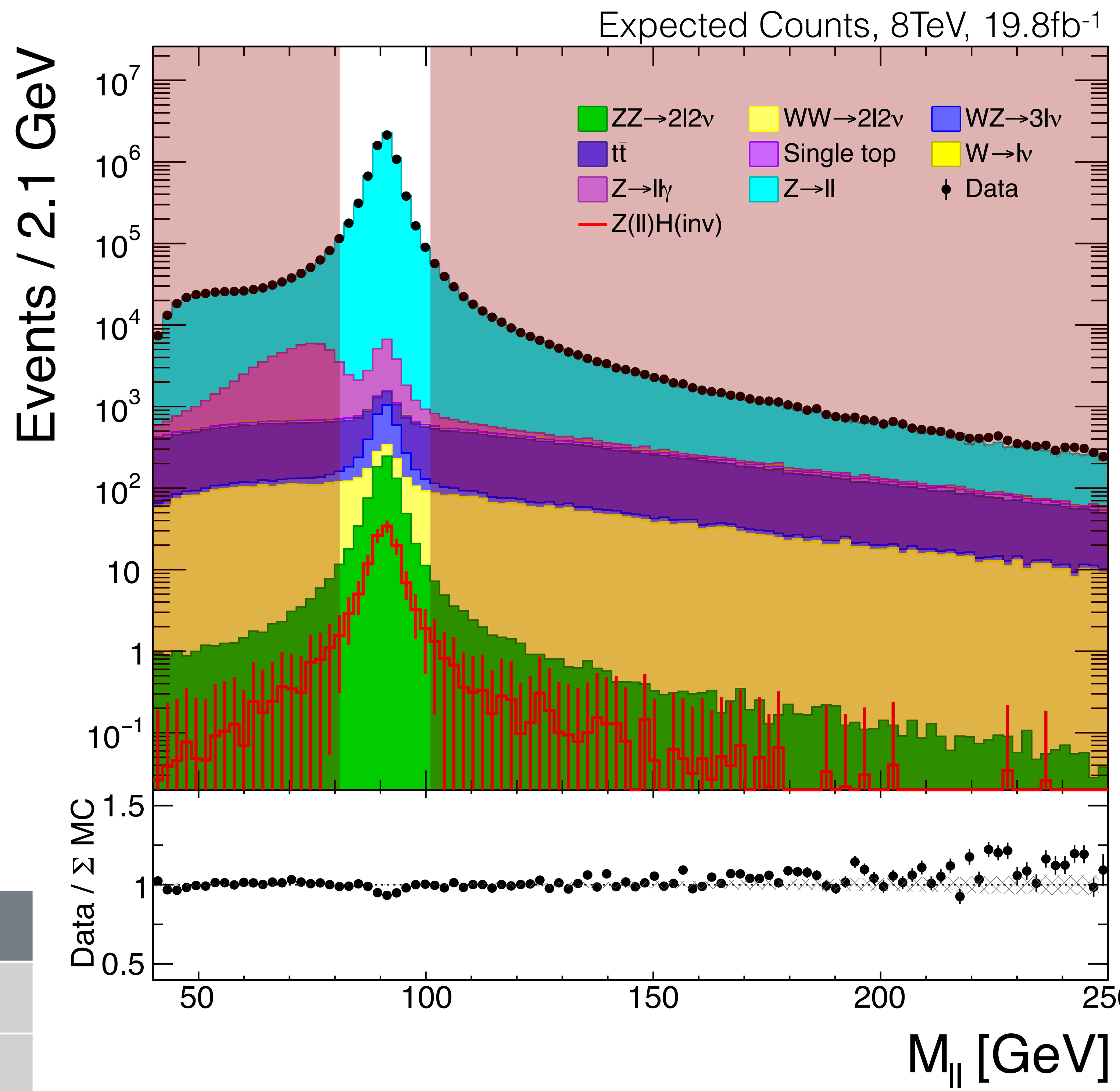
- Cuts motivated in following slides



# Cut Flow - M(μμ)

N. Smith

- Signal events contain a Z boson
- Cut on dimuon invariant mass
- 10GeV window around Z mass



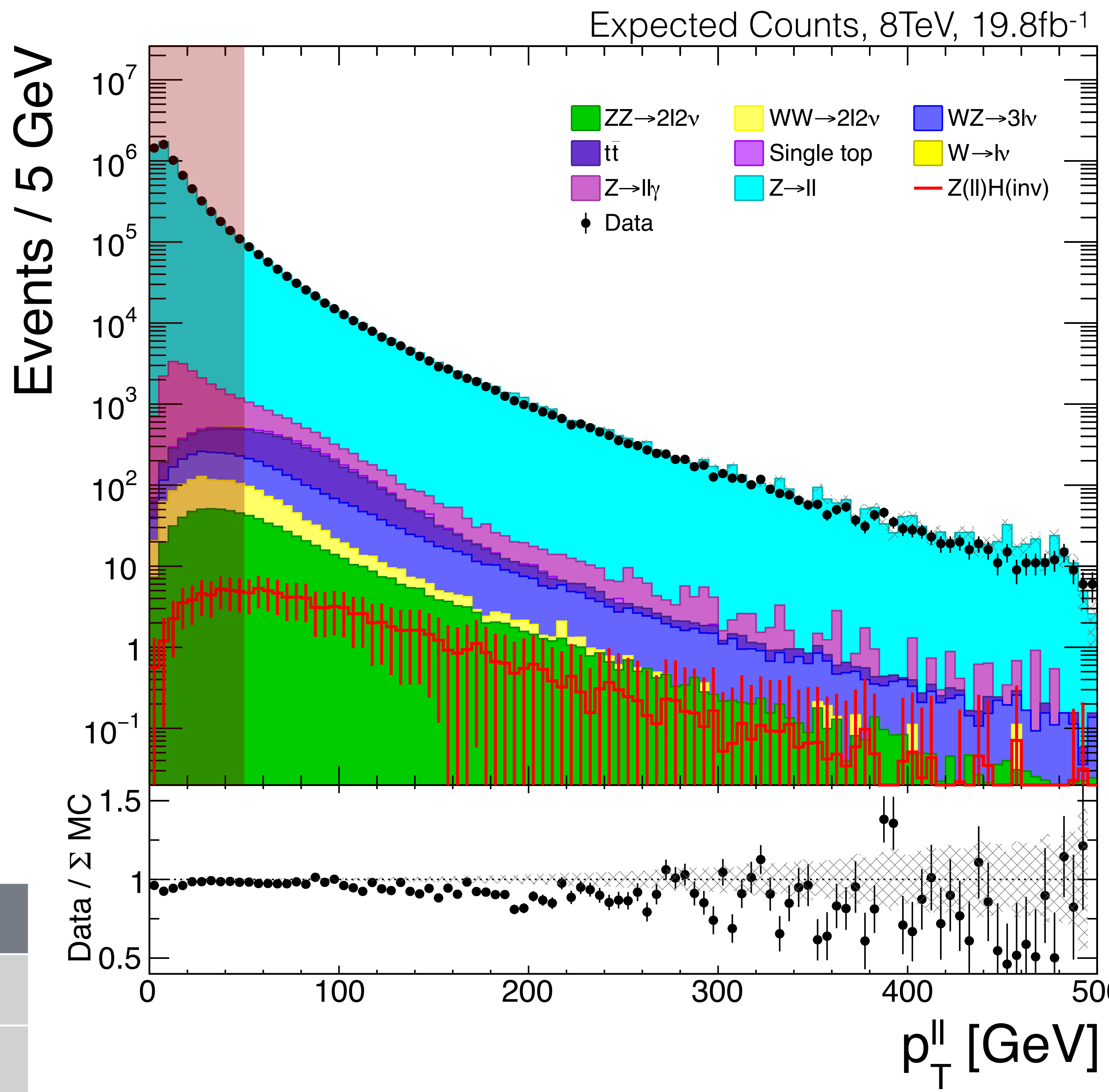

Expected Counts

| | Before Cut | After Cut |
|---|---|---|
| **Signal** | 126 | 113 |
| **Background** | 8008716 | 6972250 |
| **Ratio** | $\sim 10^{-5}$ | $\sim 10^{-5}$ |

# Cut Flow - Boosted Z

N. Smith

- Z recoils against Higgs
- Significant transverse momentum
- Decay products will appear Lorentz boosted
- Cut on dimuon $p_T$ > 50GeV



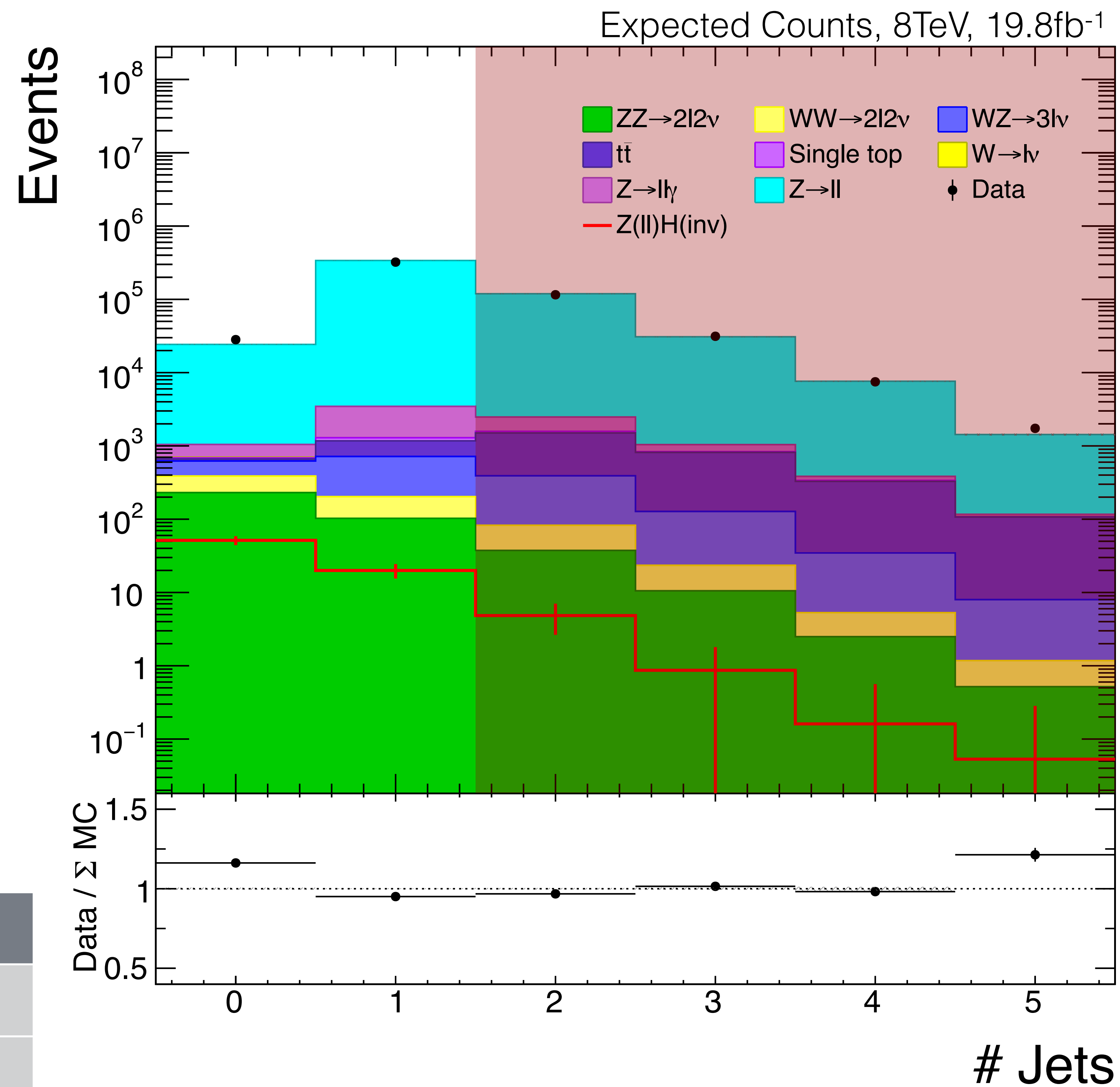

Expected Counts

| | Before Cut | After Cut |
|---|---|---|
| **Signal** | 113 | 77 |
| **Background** | 6972250 | 522363 |
| **Ratio** | $\sim 10^{-5}$ | $\sim 10^{-4}$ |

# Cut Flow - Jet Veto

N. Smith

- MET sensitive to jet energy uncertainty
- Vetoing large jet multiplicity reduces this effect
- Bin final yields in 0,1 jets
- Jet counted if $p_T$>30GeV




Expected Counts

| | Before Cut | After Cut |
|---|---|---|
| Signal | 77 | 71 |
| Background | 522363 | 362910 |
| Ratio | $1.4 \times 10^{-4}$ | $2 \times 10^{-4}$ |

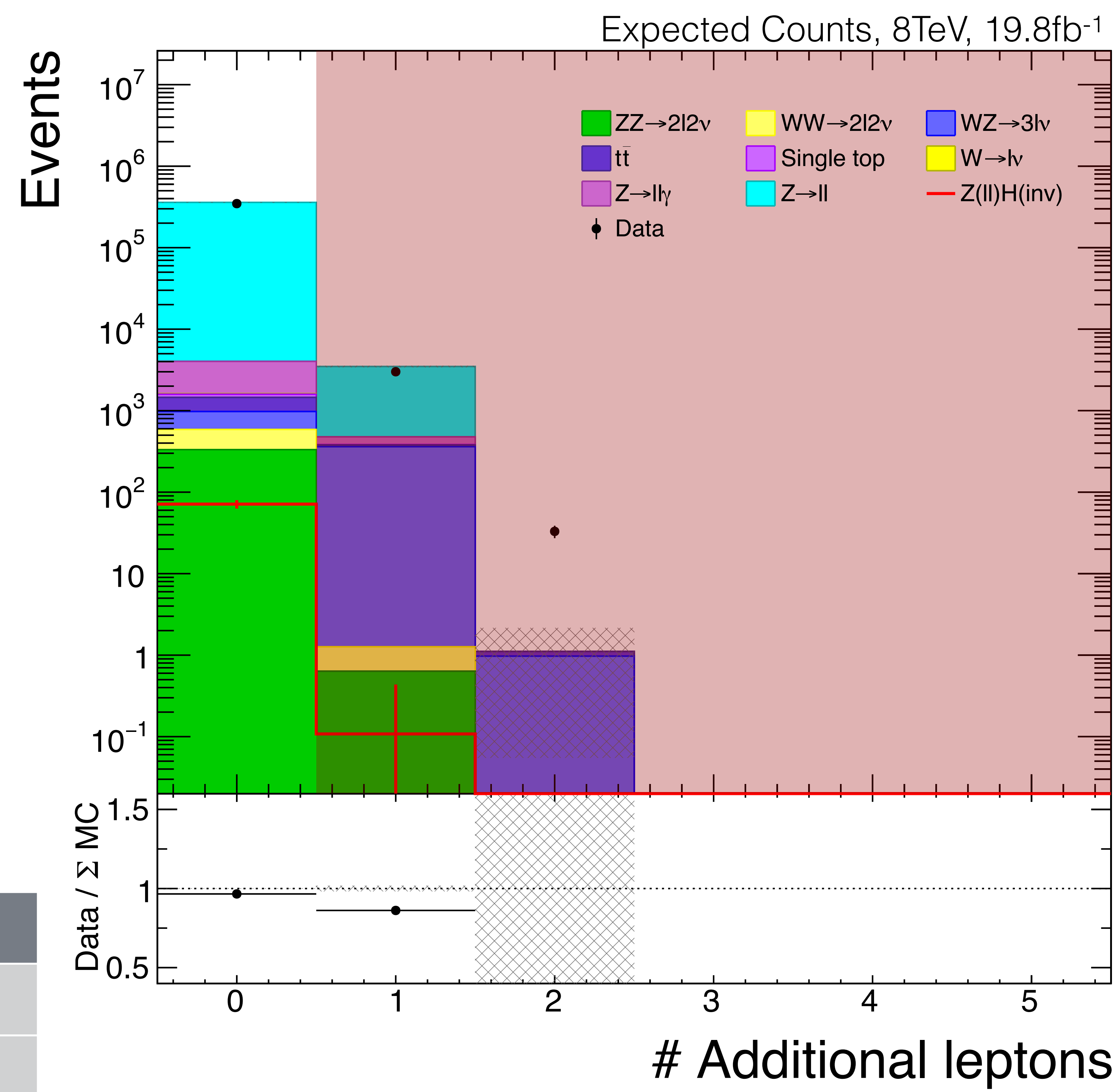
# Cut Flow - Extra Lepton Veto

N. Smith

- Expect exactly 2 muons
- Remove events with extra e/μ

NB: No ZZ*→4l simulation

- Would contribute ~200 events in 2 extra lepton bin



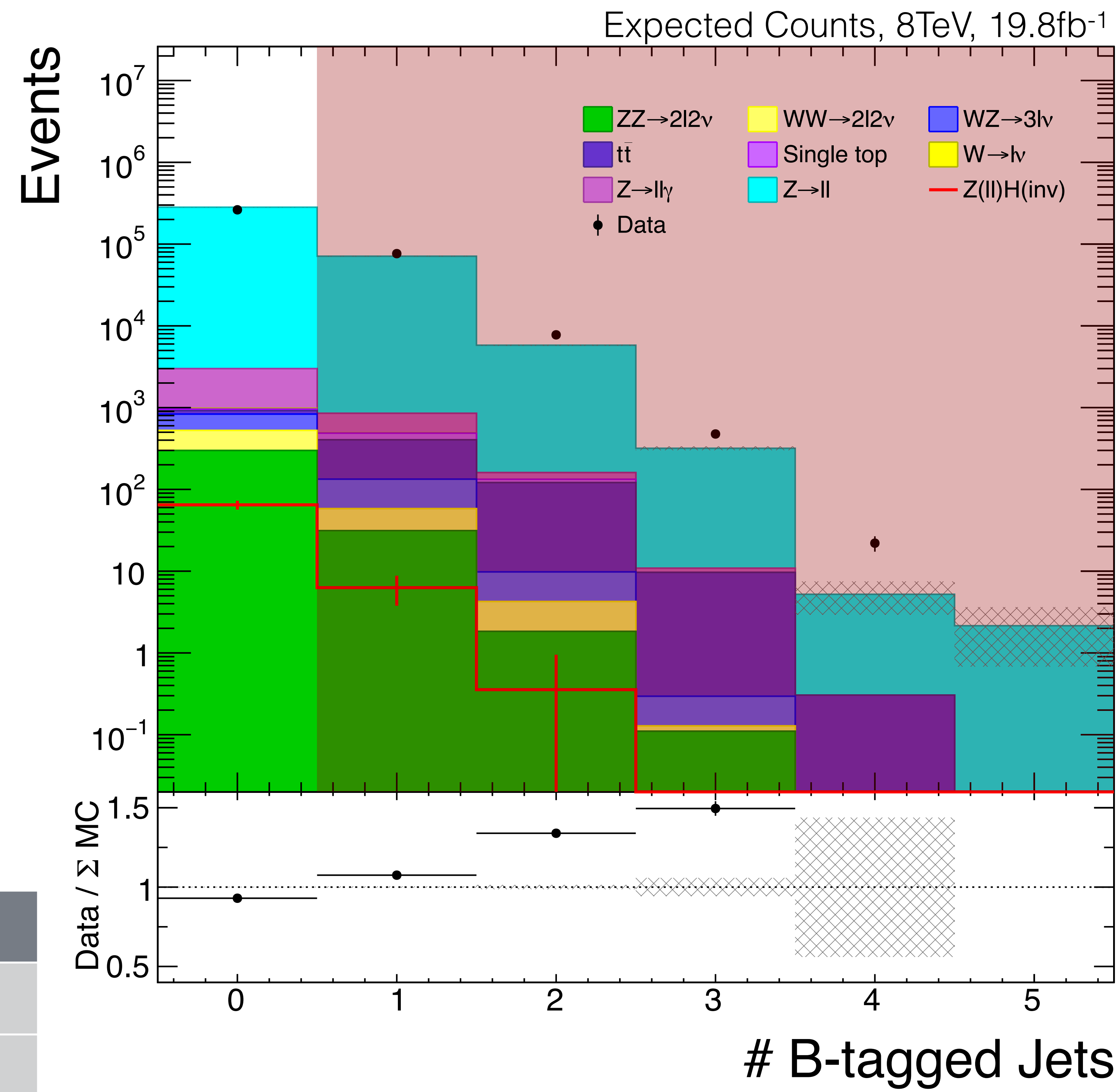

Expected Counts

| | Before Cut | After Cut |
|---|---|---|
| **Signal** | 71 | 71 |
| **Background** | 362910 | 359426 |
| **Ratio** | $2x10^{-4}$ | $2x10^{-4}$ |

# Cut Flow - B-Jet Veto

N. Smith

- ~100% top to W+b
- Veto of b-tagged jets lowers top background
- B-tagging has non-negligible fake rate



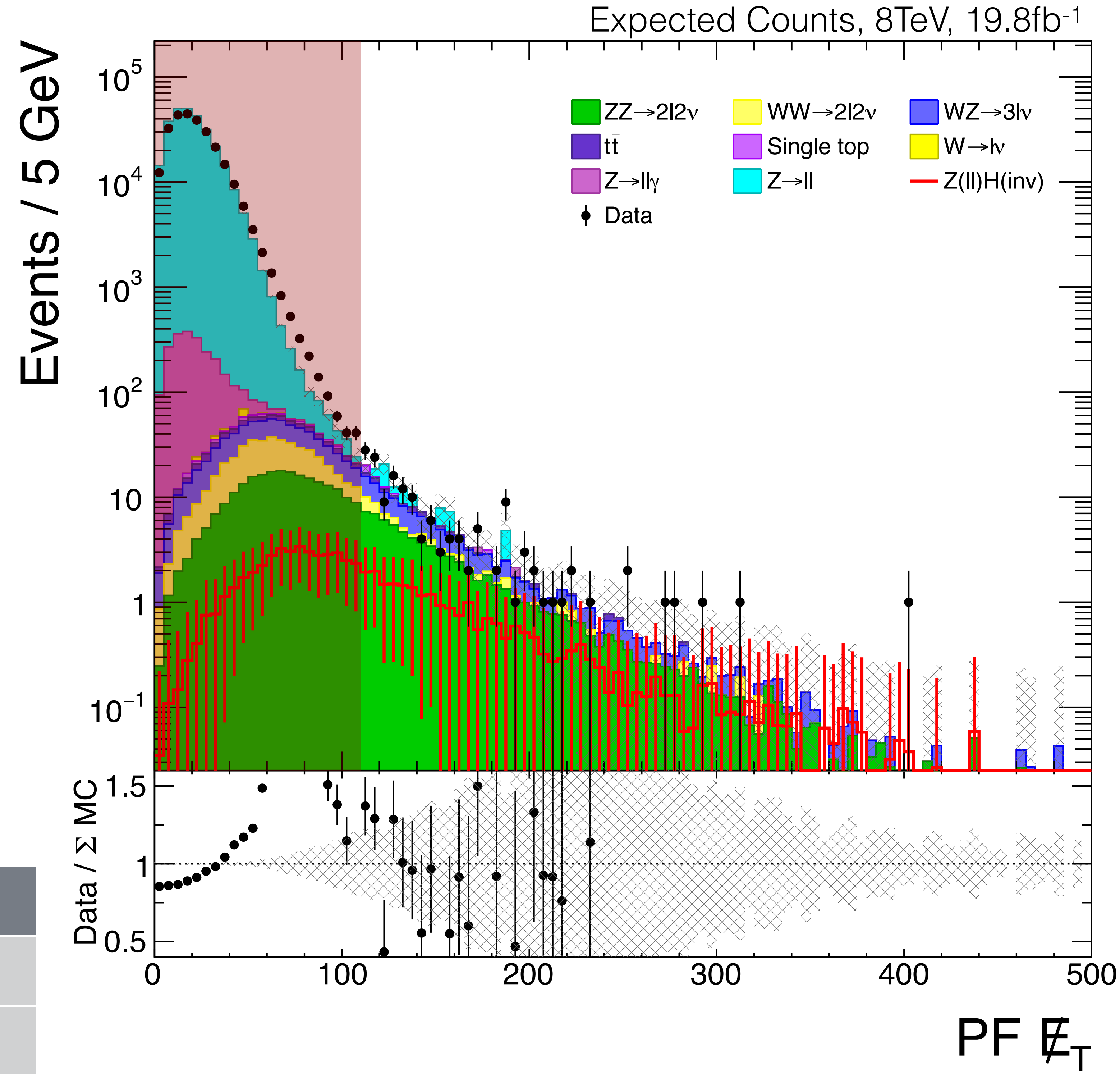

Expected Counts

| | Before Cut | After Cut |
|---|---|---|
| Signal | 71 | 65 |
| Background | 359426 | 282192 |
| Ratio | $2\times10^{-4}$ | $2.3\times10^{-4}$ |

# Cut Flow - High MET

N. Smith

- Expect significant MET
- MET very sensitive to jet energy measurement
- Z+Jets has large σ and no real MET
- High threshold necessary due to poor data/MC agreement
- Cut MET > 110GeV




Expected Counts

| | Before Cut | After Cut |
|---|---|---|
| **Signal** | 65 | 25 |
| **Background** | 282192 | 164 |
| **Ratio** | $2.3 \times 10^{-4}$ | 0.15 |

# M(μμ) at Baseline

N. Smith

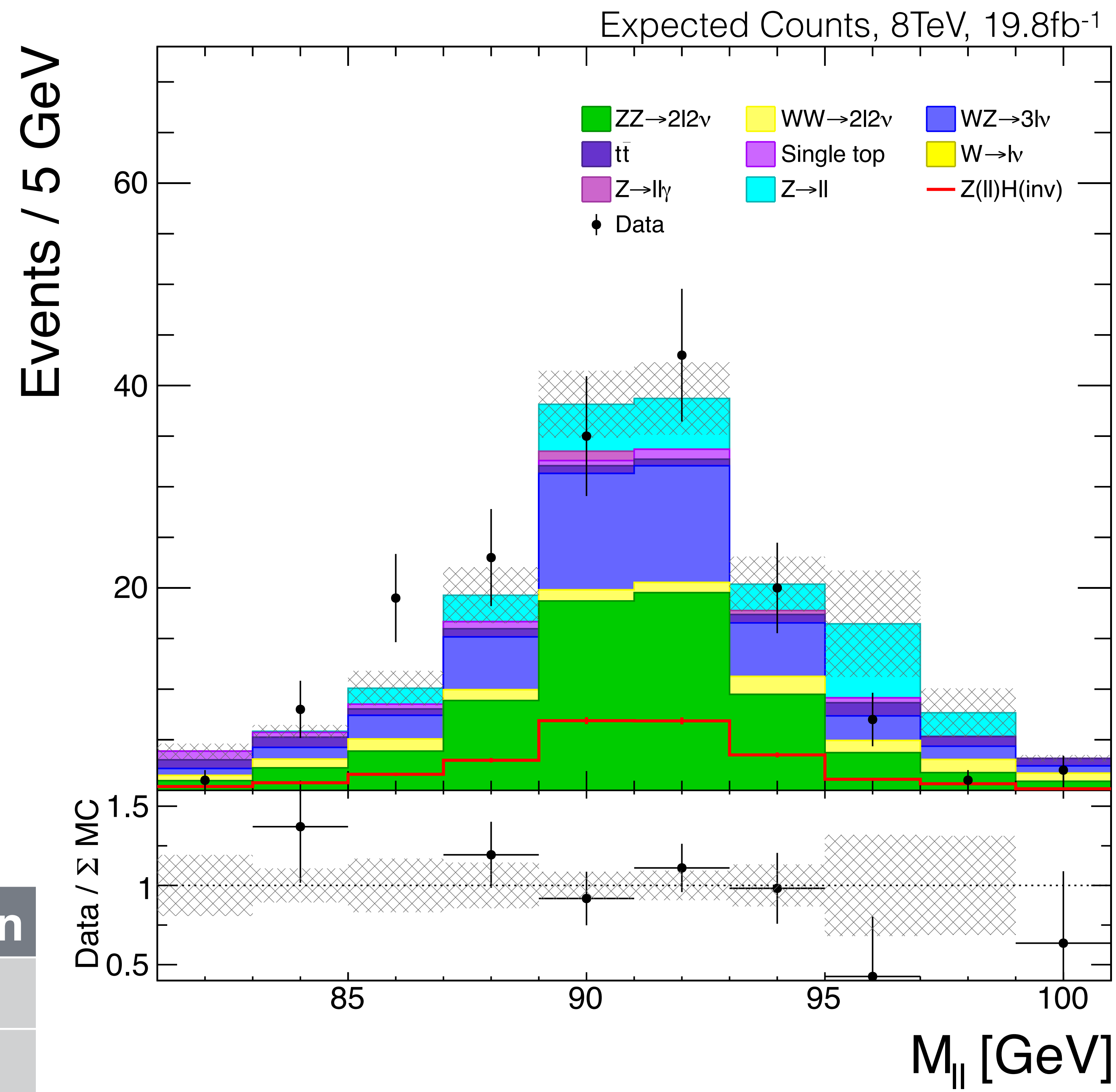
Baseline selection:

All previous cuts applied

Dominant backgrounds now:

ZZ*→2l2ν and WZ→3lν

- ZZ* background irreducible (same final state)
- WZ background due to lost W lepton (detector acceptance)



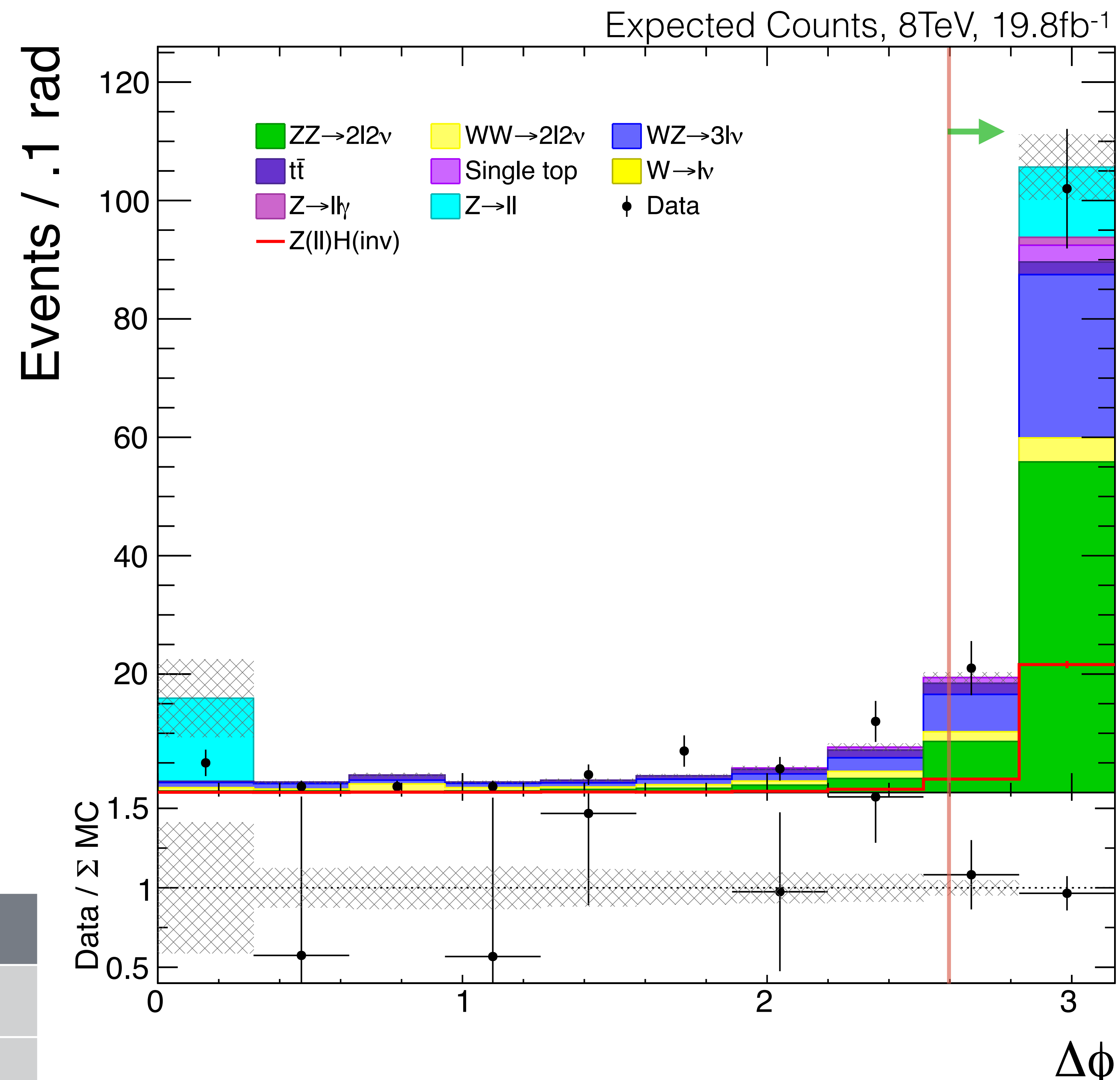

Expected Counts

| | Baseline Selection |
|---|---|
| **Signal** | 25 |
| **Background** | 164 |
| **Ratio** | 0.15 |

# Z-MET Δϕ at Baseline

N. Smith

- Kinematics of the Z and MET considered together
- Most events 'back-to-back'
- Cut on angle between Z decay products and MET in transverse plane > 2.6



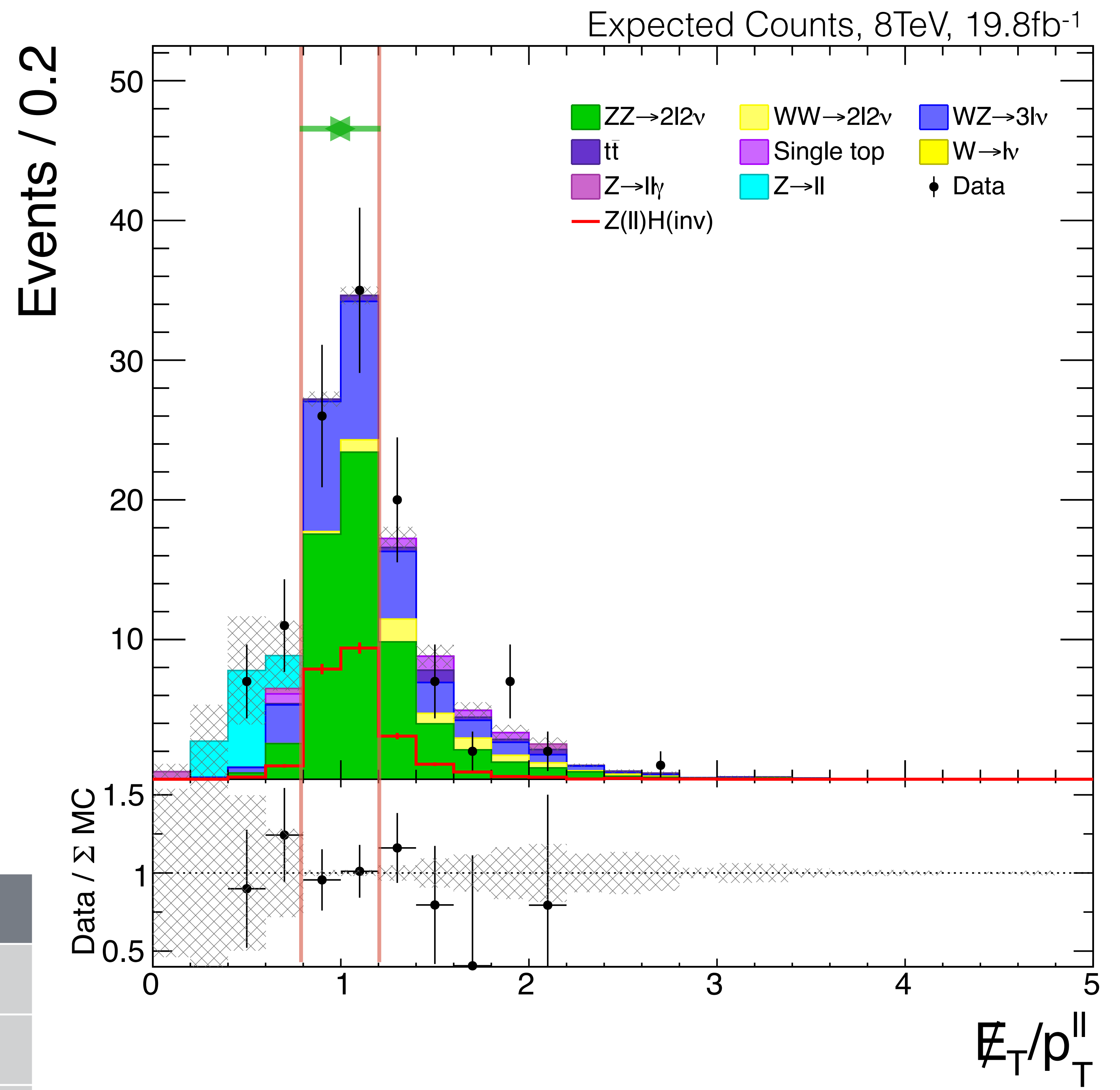

Expected Counts

| | Before Cut | After Cut |
|---|---|---|
| **Signal** | 25 | 24 |
| **Background** | 164 | 121 |
| **Ratio** | 0.15 | 0.19 |

# MET Balance at Baseline

N. Smith

- Transverse Z $p_T$ should balance MET
- Restrict ratio of MET and dimuon $p_T$ between 0.8 and 1.2




Expected Counts

| | Before Cut | After Cut |
|---|---|---|
| **Signal** | 24 | 17 |
| **Background** | 121 | 62 |
| **Ratio** | 0.19 | 0.28 |

# Transverse Mass at Baseline

N. Smith

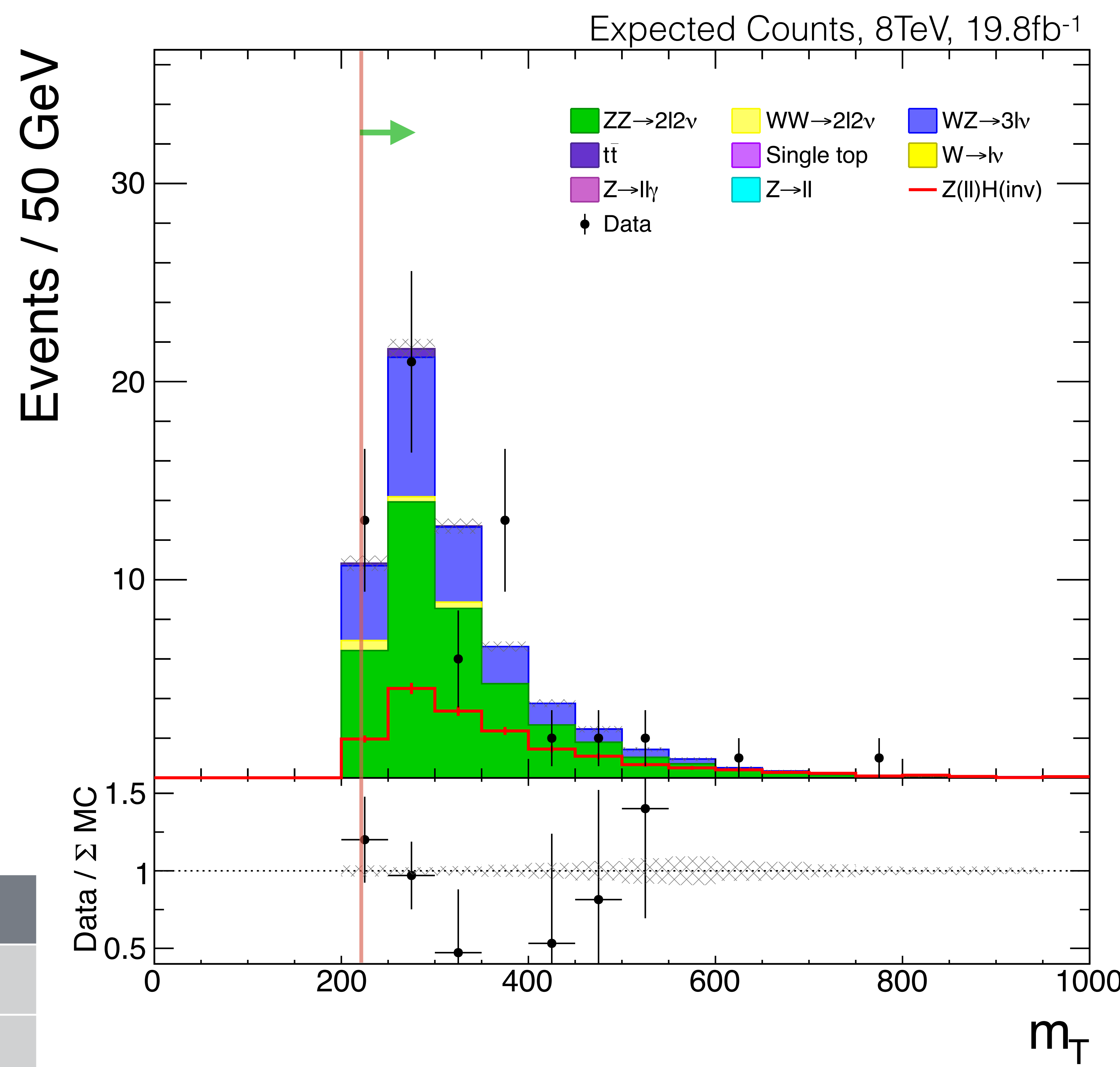
- Associated production implies large $m_T$
- Cut >220 GeV

Transverse Mass definition:

$$M_T^2 = (E_{T,1} + E_{T,2})^2 - (\vec{p}_{T,1} + \vec{p}_{T,2})^2$$
$$E_T^2 = m^2 + (\vec{p}_T)^2$$

Expected Counts

| | Before Cut | After Cut |
|---|---|---|
| Signal | 17 | 17 |
| Background | 62 | 61 |
| Ratio | 0.28 | 0.28 |



# Muon Efficiency

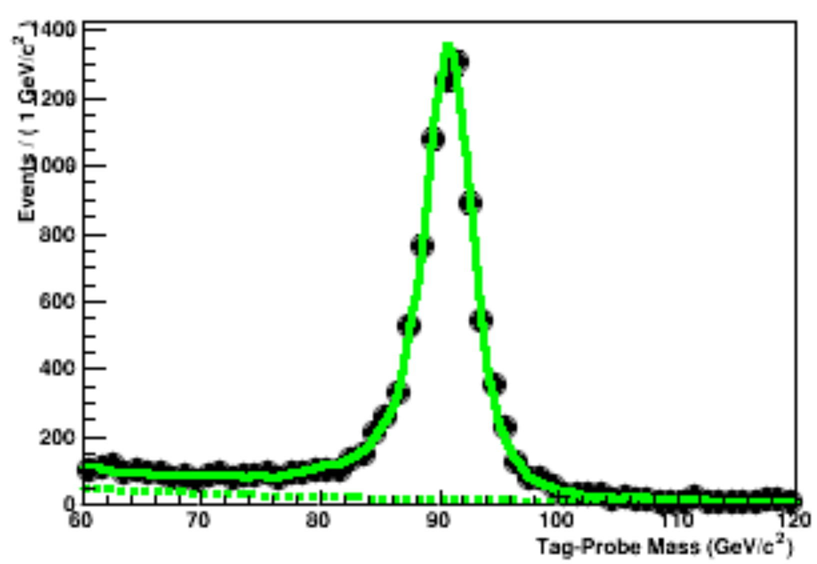
N. Smith

To measure efficiency of muon identification, use *Tag and Probe Method*

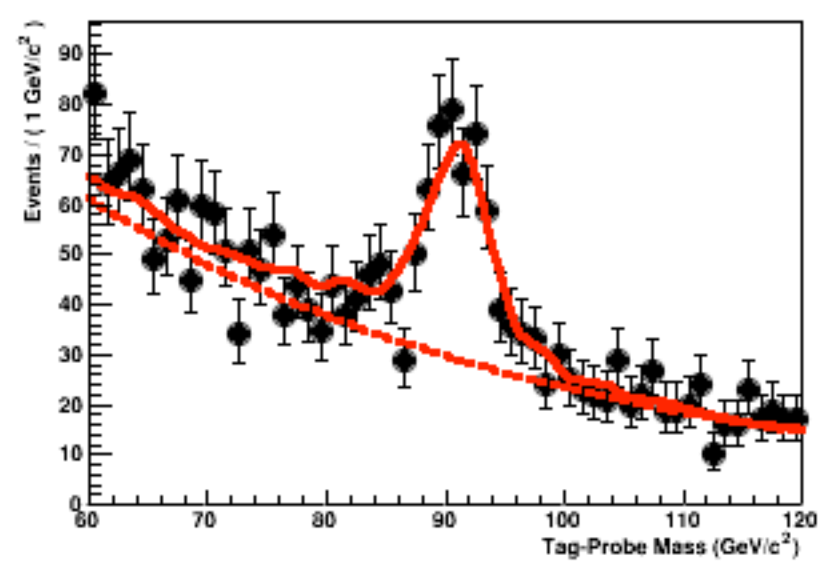
- Find one well-reconstructed muon (*tag*)
- Look for other tracks (*probes*), form pairs
- Probes forming pairs with mass close to known resonance (e.g. Z) are likely true muons
- Fit mass distribution to find efficiency

$$\epsilon = \frac{N_{pass}}{N_{pass} + N_{fail}}$$

Pass




Fail



# Systematics

N. Smith

Significant Sources of Systematic Uncertainty

| Source | Uncertainty | Comments |
|---|---|---|
| Luminosity | 2.6%* | CMS Luminosity Uncertainty @ 8TeV |
| Lepton ID/Iso Efficiency | 3%* | Efficiencies calculated using Tag & Probe |
| B-tag efficiency | 0.2%* | B tag efficiency Data/MC difference |
| PDF & QCD Scale | ~8%* | Varies between samples<br>Use largest value as conservative estimate |
| Pileup Corrections | 0.3% | Vary PU correction factor by 8% |
| Lepton Momentum Scale | 0.5% | Muon momentum scale corrections |
| Jet Energy Scale/Resolution | 3%* | Shift jet energy up/down by corresponding uncertainties |
| MC Statistics | 1-5% | Varies between samples |

* c/o AN2012-123

# Final Yields & Limits

N. Smith

Final Event Yields for 19.8/fb at 8TeV

| | μμ+0 jets | μμ+1 jet |
|---|---|---|
| ZZ | 34.1±0.5 | 6.3±0.2 |
| WZ | 13.7±0.4 | 5.2±0.3 |
| WW/Top/W | 1.3±0.3 | 0.3±0.1 |
| DY+Jets | 0+.5 | 0+.5 |
| **Sum Backgrounds** | **49.1±0.7 (±4.9)** | **11.8±0.4 (±1.2)** |
| **ZH Signal (100%)** | **14.7±0.5 (±1.5)** | **2.5±0.2 (±0.2)** |
| **Data** | **47** | **12** |

Format: Value±stat (±est. systematic)

- Event yields in two-bin counting experiment with 4 backgrounds
- Asymptotic CL$_S$ upper limit on signal strength relative to predicted signal

- Observed (Expected) 95% CL Upper Limit on BR(ZH→μμ+MET):
  1.15 (1.25)

# Conclusion & Future Plans

N. Smith

- Completed 8TeV analysis
- Results compatible with existing existing CMS & ATLAS published results
- Many possible improvements, e.g.
  - Data-driven Drell-Yan background prediction
  - Electron channel
  - **Most important: 13TeV data!**

At 13TeV:

- Expecting 100 $fb^{-1}$ before Long Shutdown 2 in 2018
- ZH associated production $\sigma$ increases by factor ~2
  - Expect ~300 dimuon events @ 100% BR
- VV background $\sigma$ also factor ~2
  - Expect ~700 dimuon events for ZZ
- Assuming similar detector performance, expect factor ~3 improvement

# Backup

# Higgs significance by channel

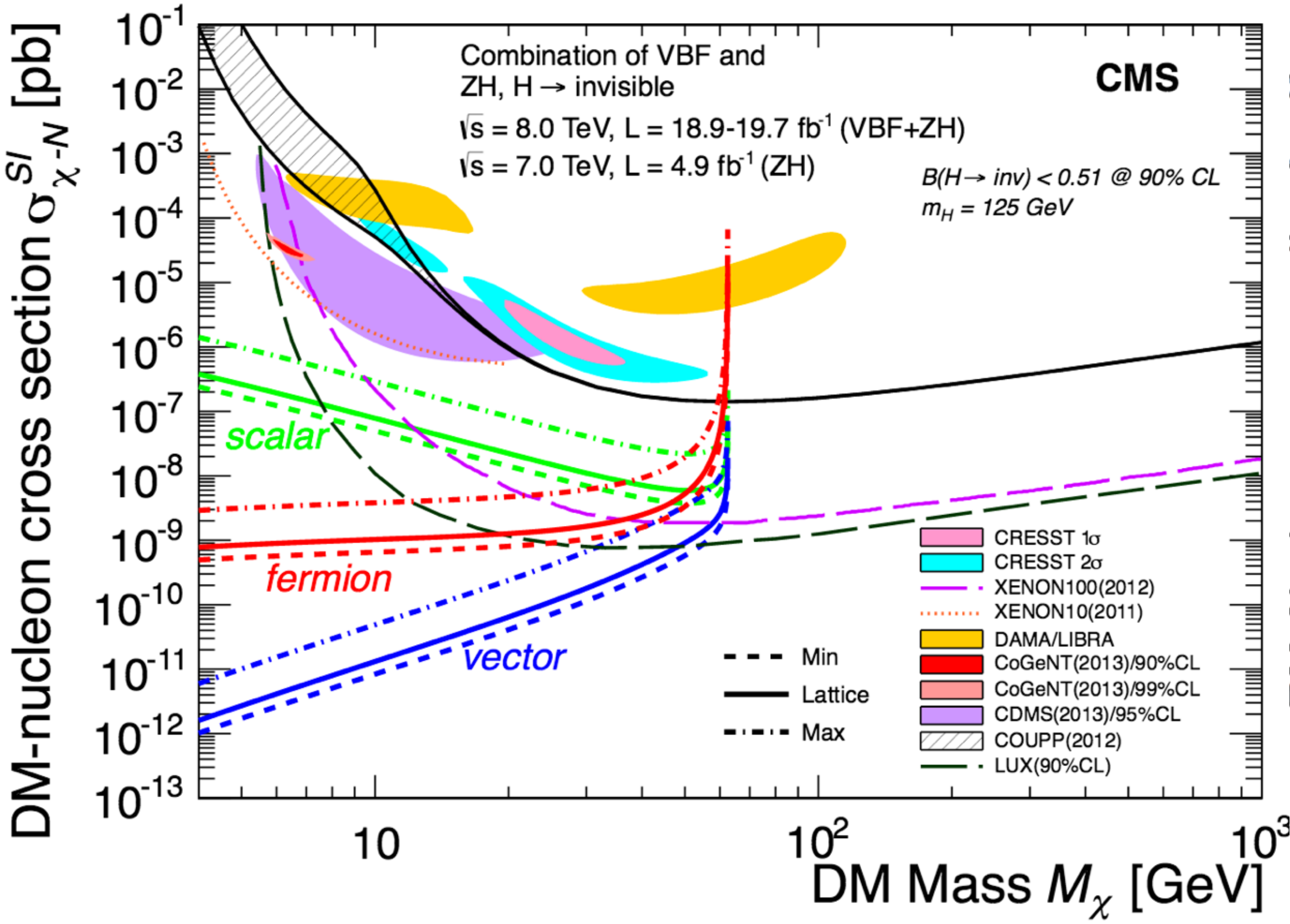
N. Smith

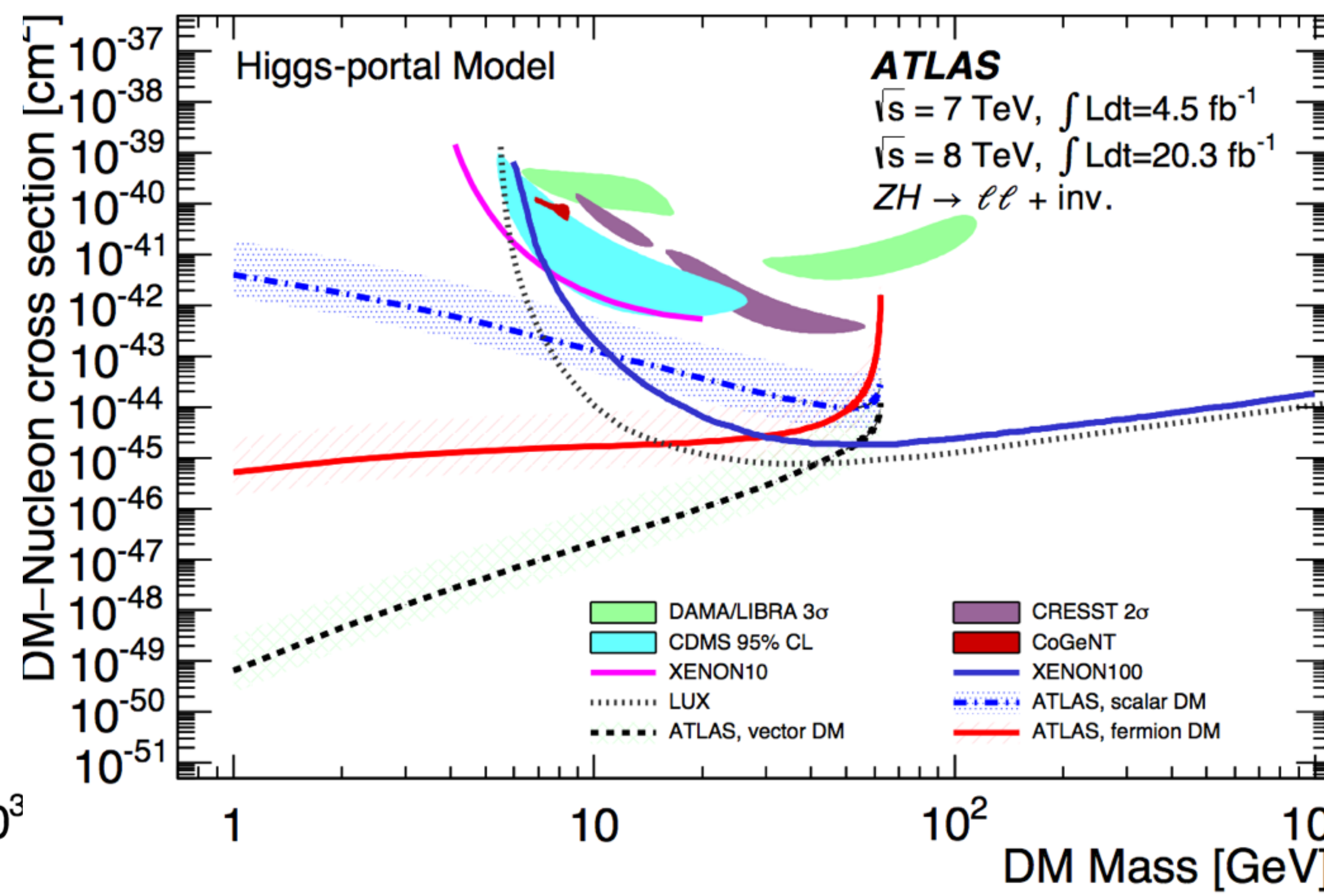
| Channel grouping | Significance ($\sigma$) Observed | Significance ($\sigma$) Expected |
|---|---|---|
| $H \to ZZ$ tagged | 6.5 | 6.3 |
| $H \to \gamma\gamma$ tagged | 5.6 | 5.3 |
| $H \to WW$ tagged | 4.7 | 5.4 |
| *Grouped as in Ref. [17]* | *4.3* | *5.4* |
| $H \to \tau\tau$ tagged | 3.8 | 3.9 |
| *Grouped as in Ref. [19]* | *3.9* | *3.9* |
| $H \to bb$ tagged | 2.0 | 2.3 |
| *Grouped as in Ref. [16]* | *2.1* | *2.3* |

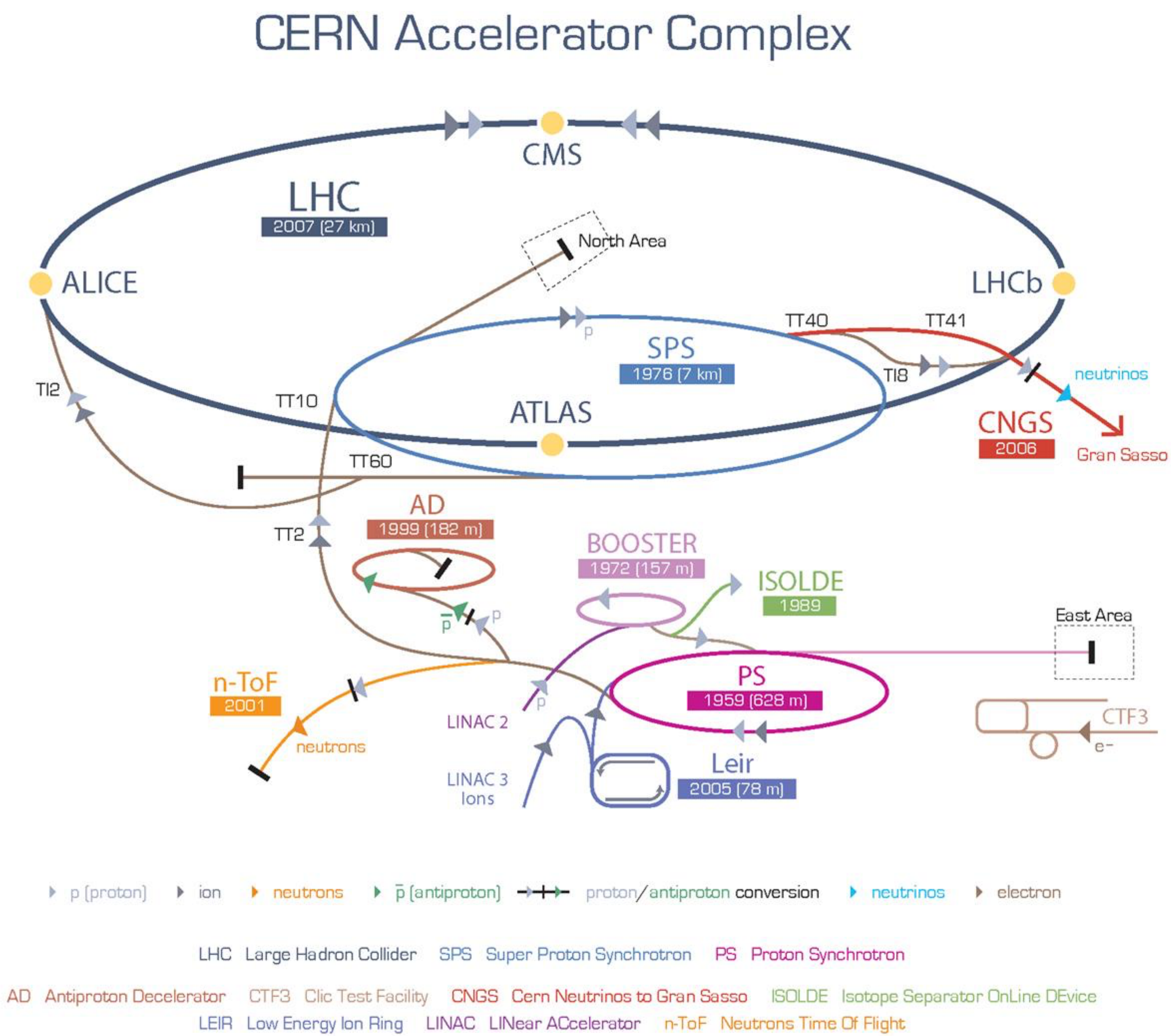
CMS 7+8TeV Higgs combination PAS (19.7+5.1/fb)

# CMS & ATLAS Higgs-portal DM limits

N. Smith



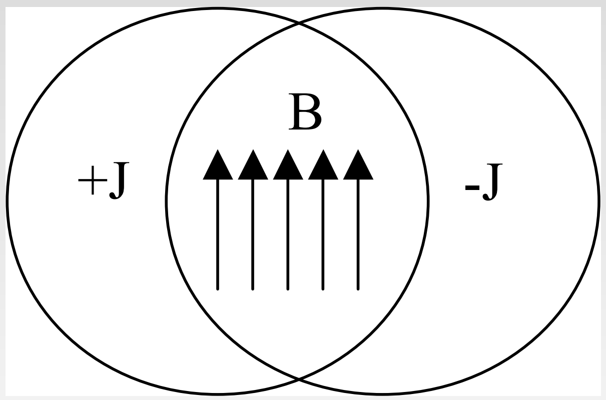

CERN Accelerator Complex
CMS
LHC
2007 (27 km)
North Area
ALICE
LHCb
TT40
TT41
SPS
1976 (7 km)
TI8
neutrinos
TI2
TT10
ATLAS
CNGS
2006
Gran Sasso
TT60
AD
1999 (182 m)
TT2
BOOSTER
1972 (157 m)
ISOLDE
1989
East Area
n-ToF
2001
PS
1959 (628 m)
CTF3
e–
LINAC 2
neutrons
LINAC 3
Ions
Leir
2005 (78 m)
p (proton)
ion
neutrons
p̄ (antiproton)
proton/antiproton conversion
neutrinos
electron
LHC Large Hadron Collider
SPS Super Proton Synchrotron
PS Proton Synchrotron
AD Antiproton Decelerator
CTF3 Clic Test Facility
CNGS Cern Neutrinos to Gran Sasso
ISOLDE Isotope Separator OnLine DEvice
LEIR Low Energy Ion Ring
LINAC LINear ACcelerator
n-ToF Neutrons Time Of Flight

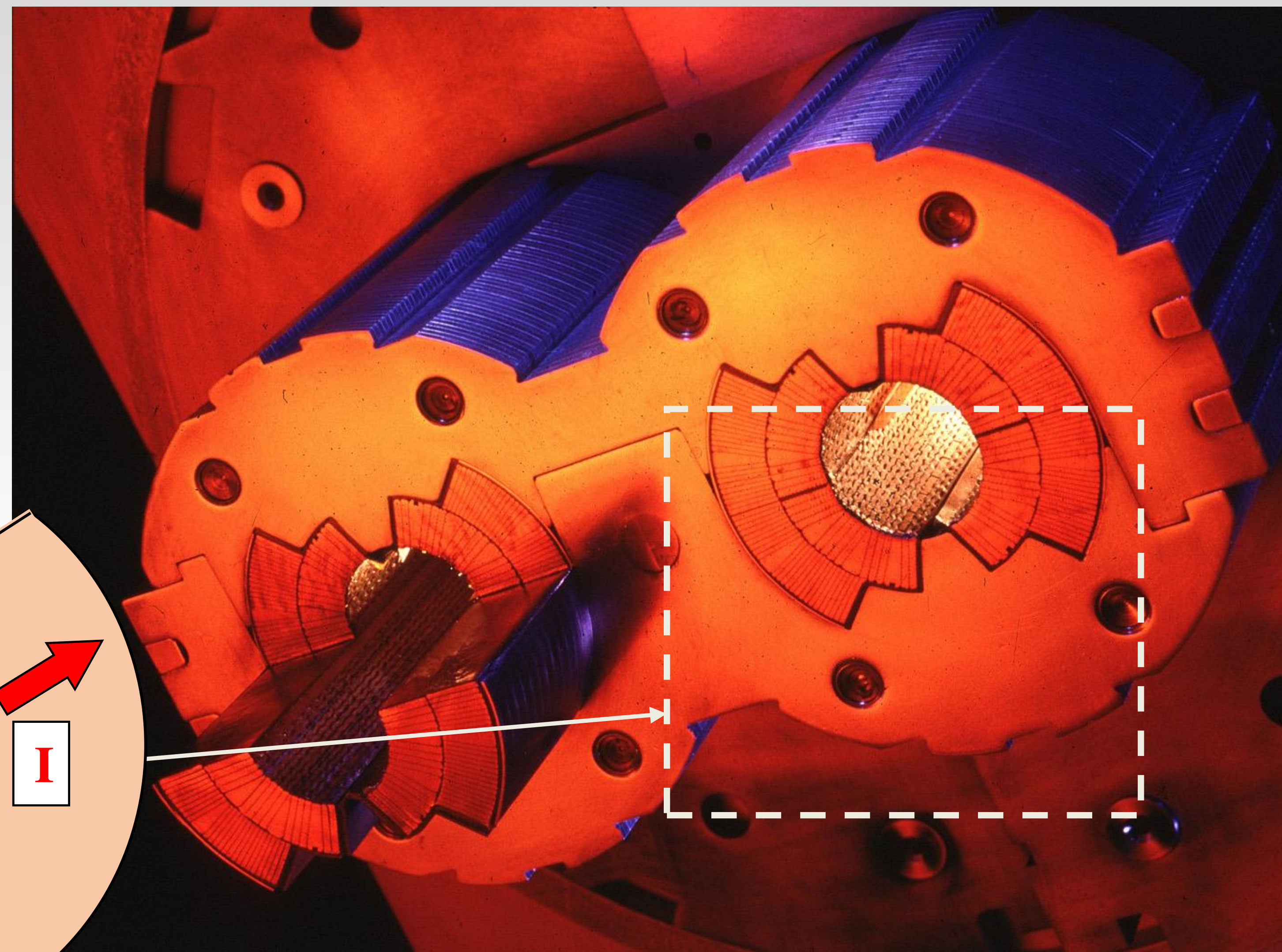
N. Smith

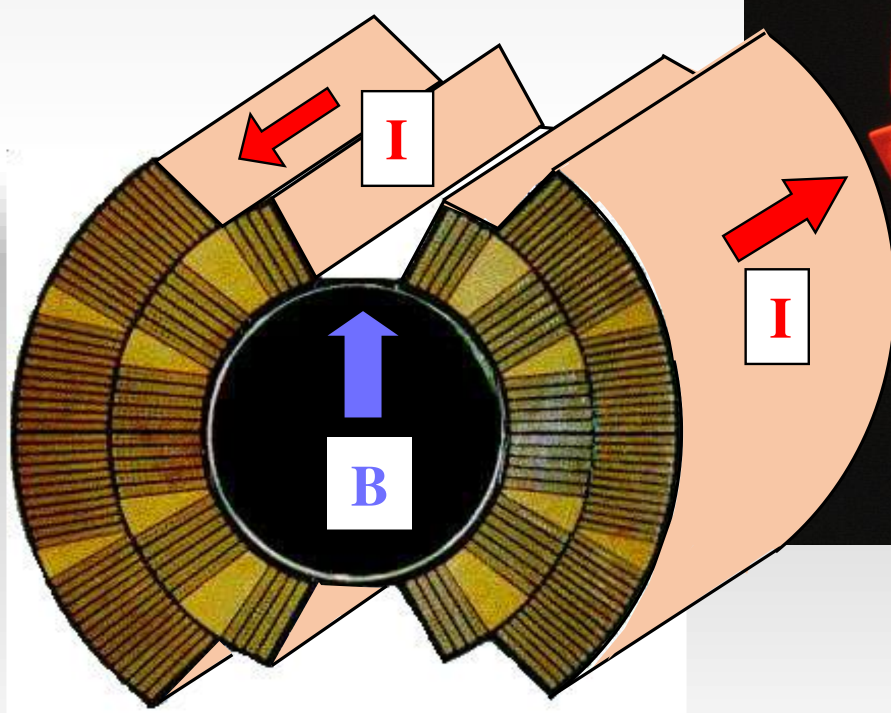
# LHC Dipole

N. Smith

## Main components – dipole magnets

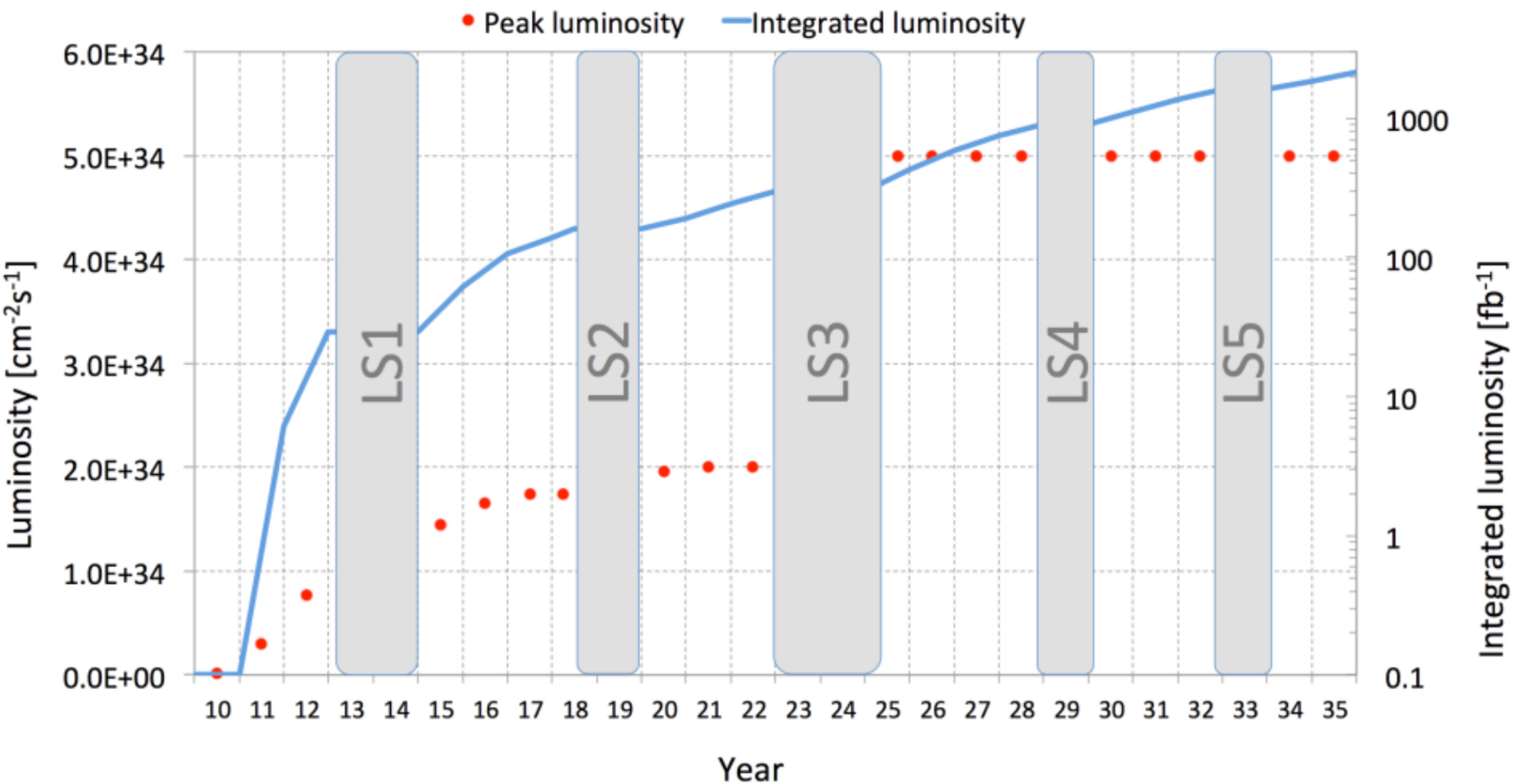




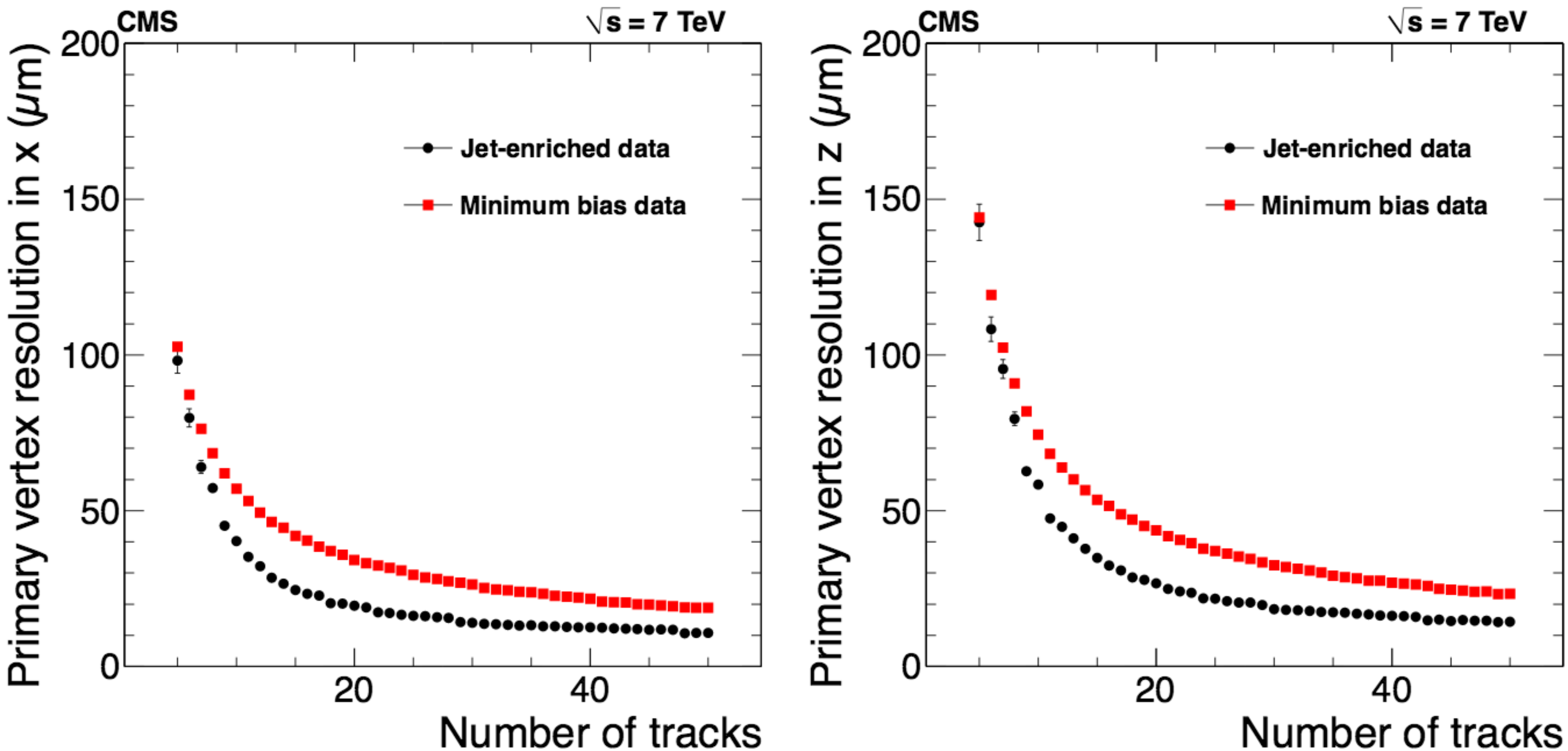
# Long-term LHC Luminosity Estimates

## 2010 - 2035



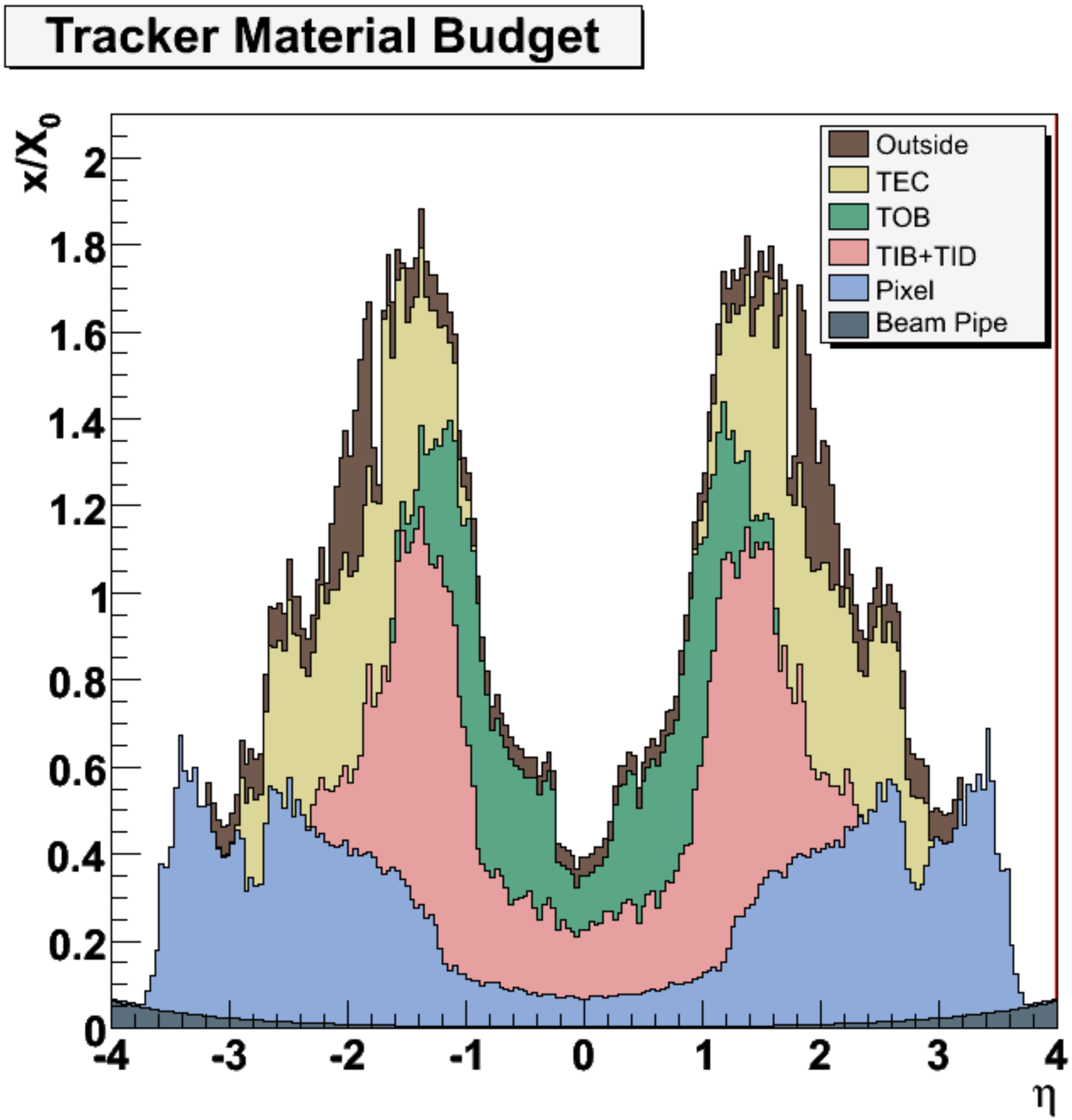
# CMS Primary Vertex Resolution

N. Smith



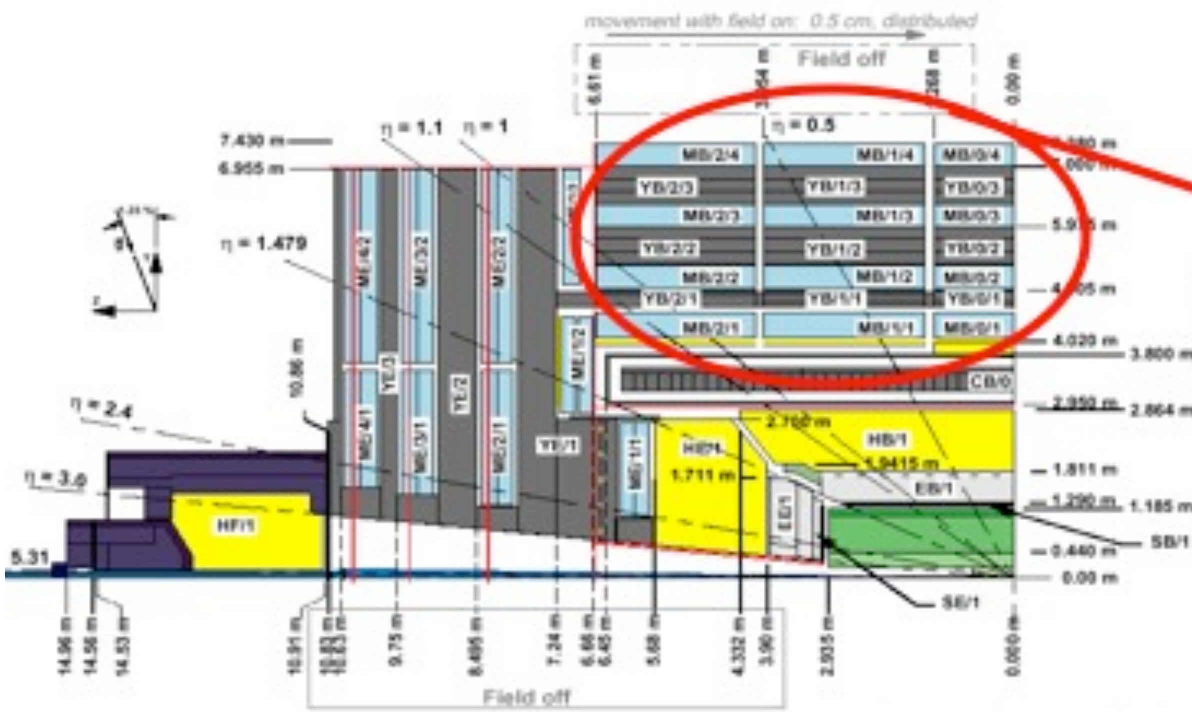
N. Smith

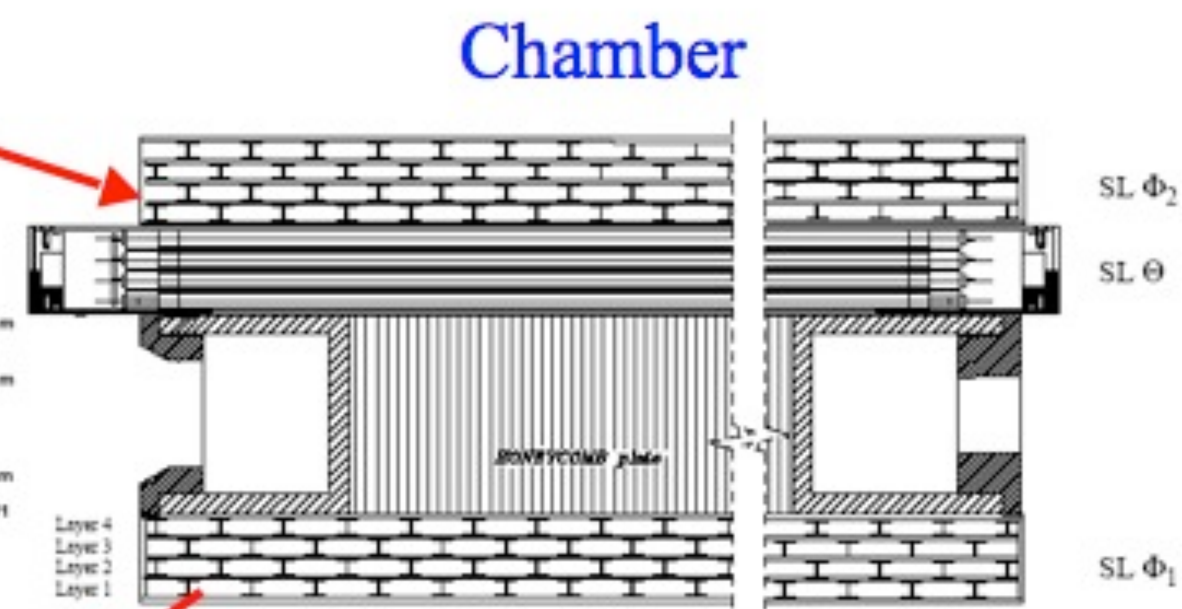
# CMS Tracker Material



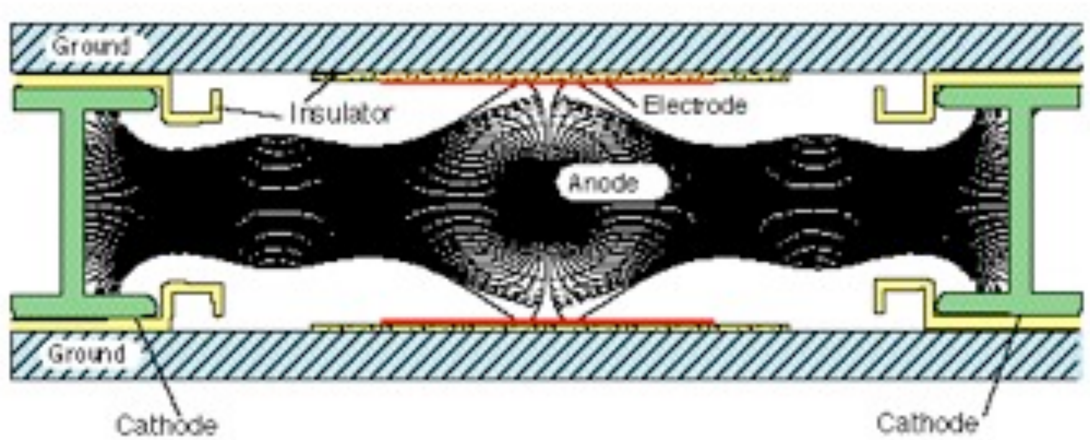
# CMS Drift Tubes

N. Smith



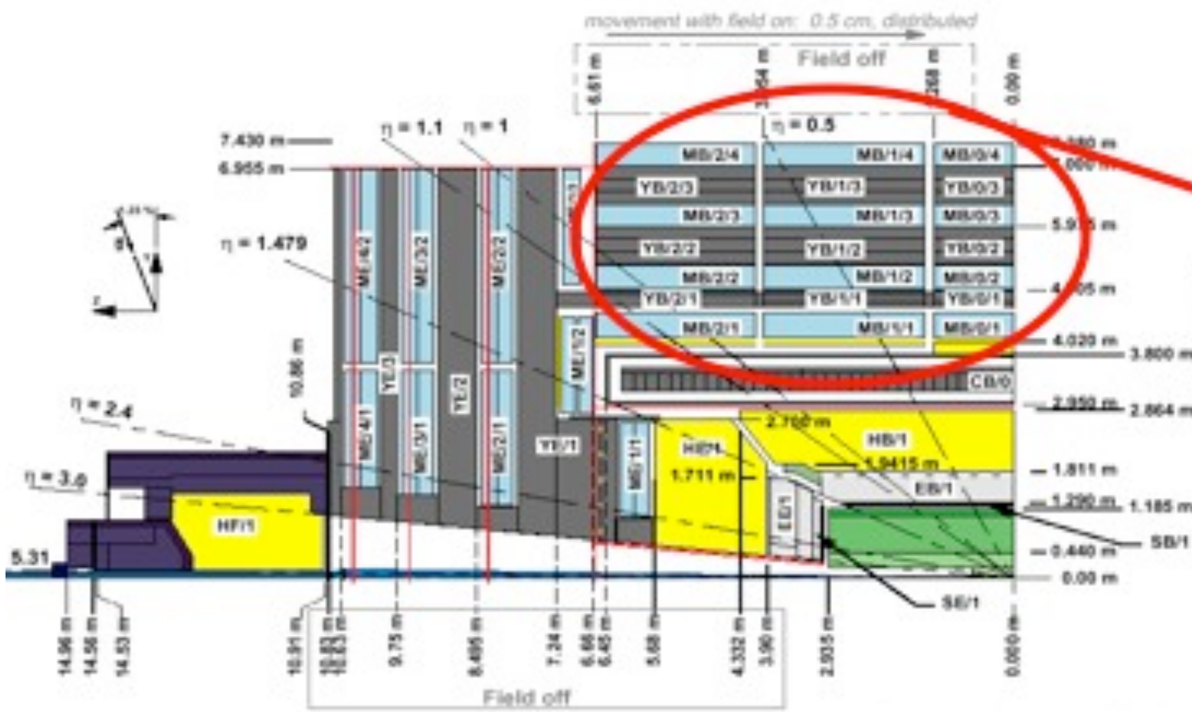

## Drift Tube Cell



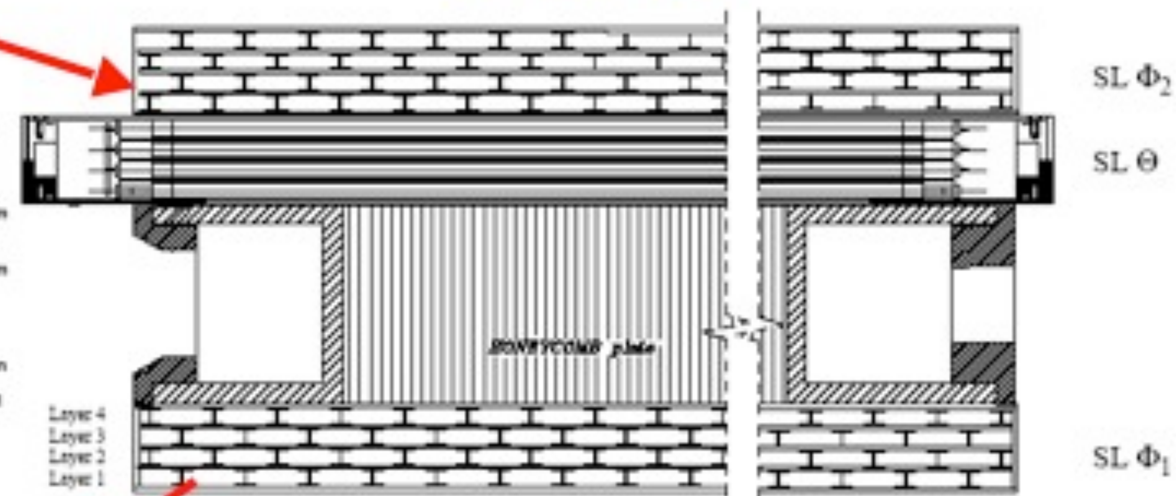

- Three types of electrodes
  - wires: 3600 V
  - cathodes: -1200 V
  - strips: 1800 V

# CMS Drift Tubes

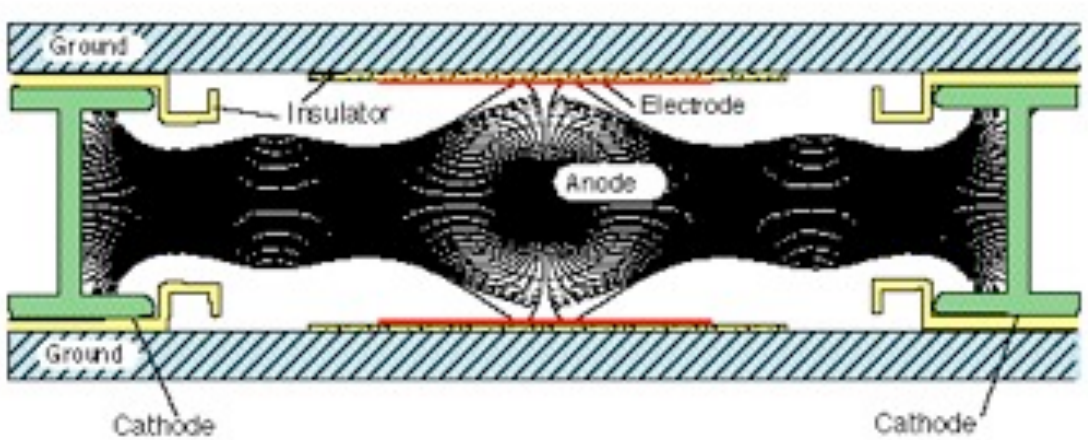
N. Smith




Chamber




Drift Tube Cell




- Three types of electrodes
  - wires: 3600 V
  - cathodes: -1200 V
  - strips: 1800 V

# Drell-Yan Expected Events

N. Smith

```
B-Jet Veto : 279213.8
#Delta#phi Cut : 23994.6
MET Balance : 495.1
M_{T} : 0.0
MET Cut : 0.0
```

```
B-Jet Veto : 279476.8
MET Cut : 25.9
#Delta#phi Cut : 2.3
MET Balance : 0.0
M_{T} : 0.0
```

```
B-Jet Veto : 279213.8
MET Balance : 4941.2
M_{T} : 0.2
MET Cut : 0.0
#Delta#phi Cut : 0.0
```

```
B-Jet Veto : 279213.8
M_{T} : 218.3
MET Cut : 11.9
#Delta#phi Cut : 2.3
MET Balance : 0.0
```