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CMS

A measurement of $Wb\bar{b}$ production and a search for monophoton signals of dark matter using the CMS detector at the CERN LHC

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Thesis Endorsement Presentation
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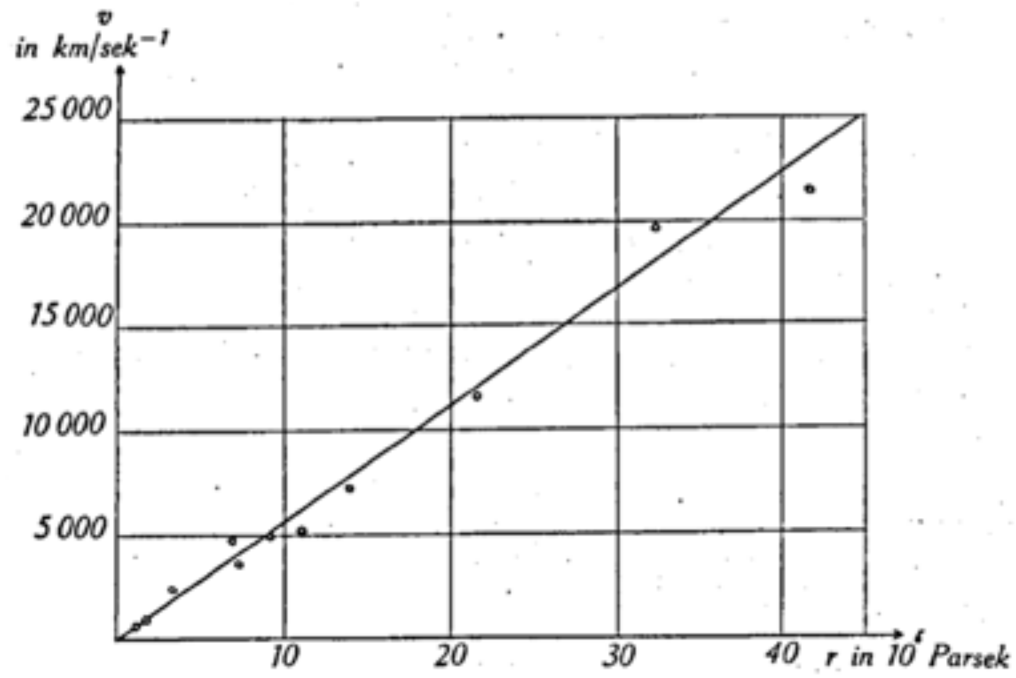
Overview

The Standard Model is a Local Quantum Field Theory

- Local Fields = Position dependent, obey Lorentz symmetry
- Quantum = Probabilities, number of particles not conserved
  - some particles don't interact via all forces

Dark matter is out there

- Overwhelming evidence for General Relativity to be correct
- 5/6 of all mass is not visible - particle dark matter (DM)



F. Zwicky - 1933
Die Rotverschiebung von extragalaktischen Nebeln

Wbb and monophoton measurements test the Standard Model
Monophoton is a search for dark matter

The Standard Model and dark matter

The LHC and CMS

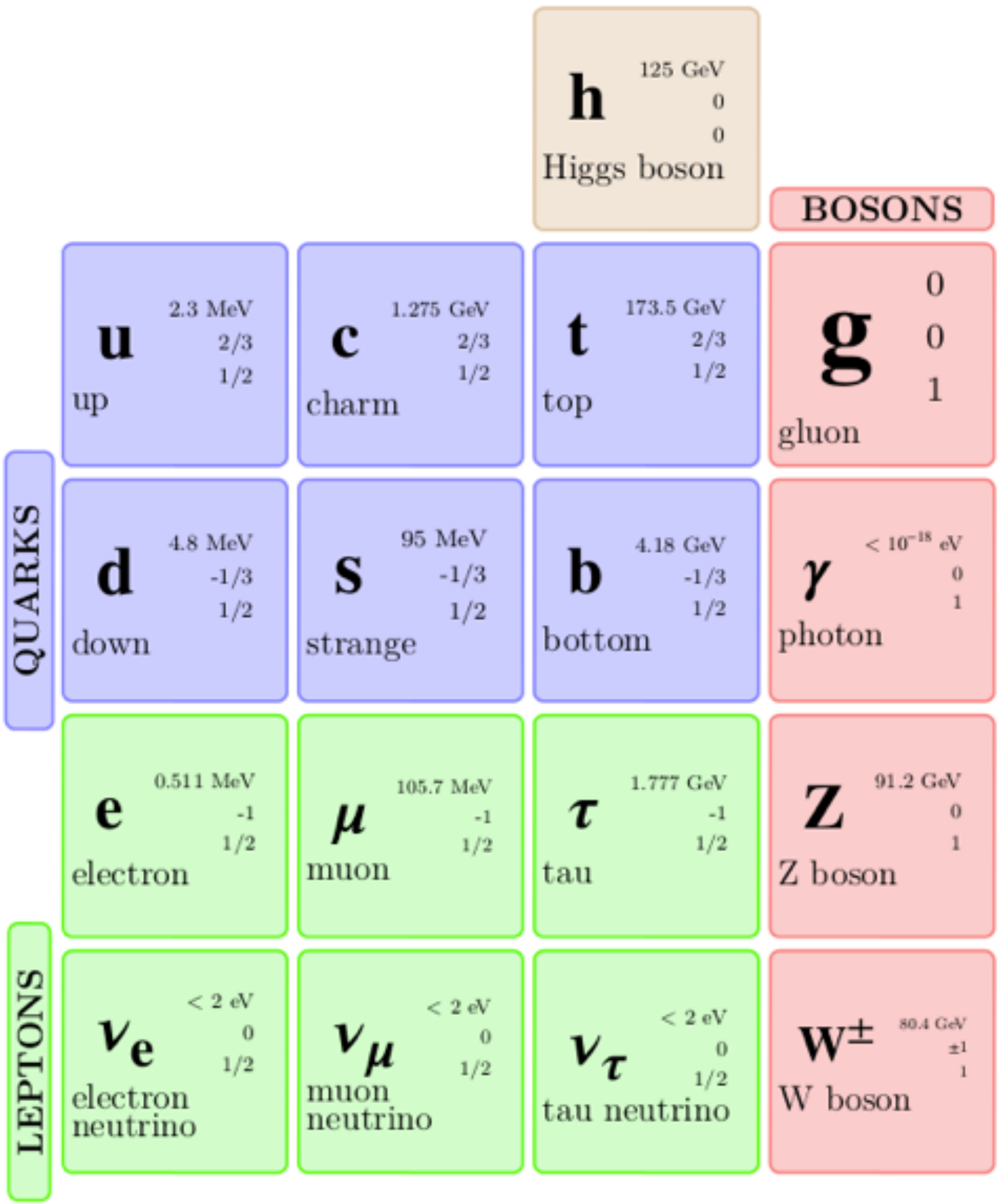
Simulation and reconstruction

Wbb cross section measurement

Monophoton analysis

Conclusions and future prospects

Standard Model Particles



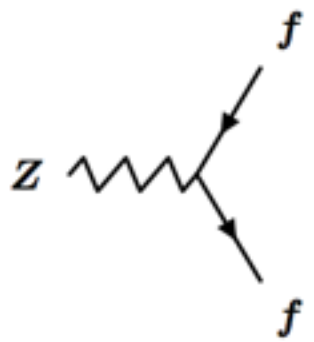
Fundamental Fermions (spin ½)
3 generations of SU(2) doublets
Quarks [u, d], [s, c], [b, t]
Leptons [e, ν_e], [μ, ν_μ], [τ, ν_τ]

Fundamental Bosons
Spin 1: Force Carriers
- Gluon: Strong Force
  - massless
  - color / anti-color
- Photon: Electroweak (EM)
  - massless
  - uncharged
- $W^\pm$, Z: Electroweak (Weak)
  - 80.4 GeV, 91.2 GeV
  - electric charge

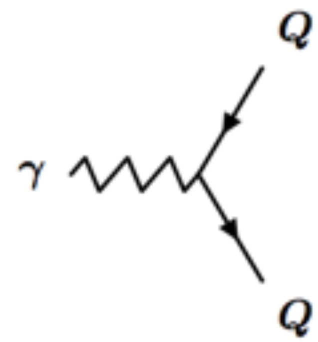
Spin 0: Higgs
- 125 GeV
- EWK Symmetry Breaking
- Mass to $W^\pm$, Z, quarks, leptons

Standard Model Couplings

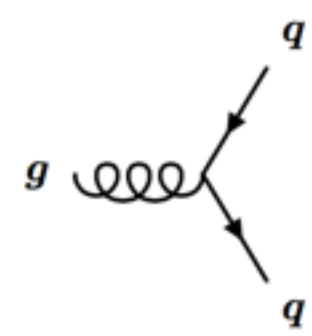
All interactions in the SM are built from these vertices



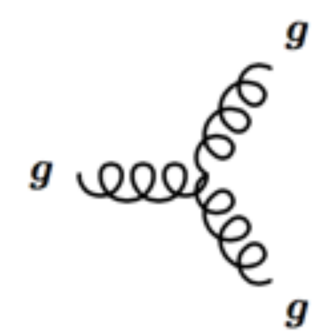
f is any fermion



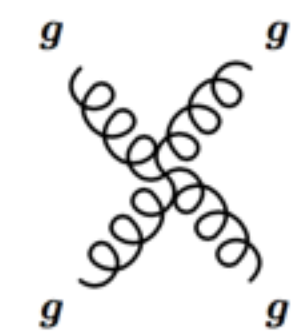
Q is electrically charged

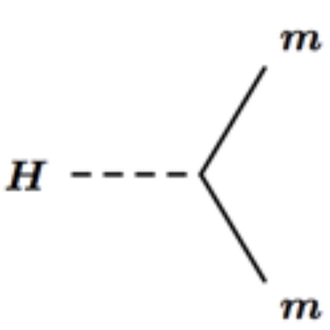


q is any quark

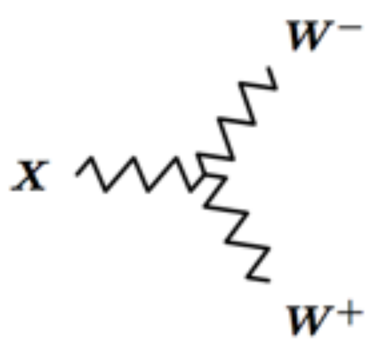


g is any gluon

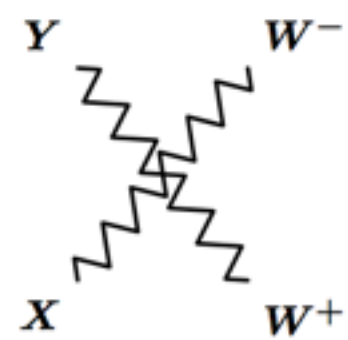




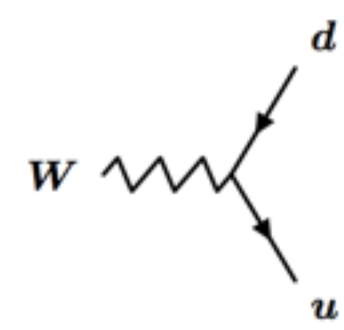
m is any massive particle



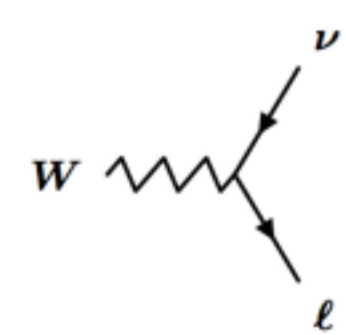
X is Z or γ



X and Y are EW bosons such that charge is conserved



u is an up-type quark and d is a down-type quark

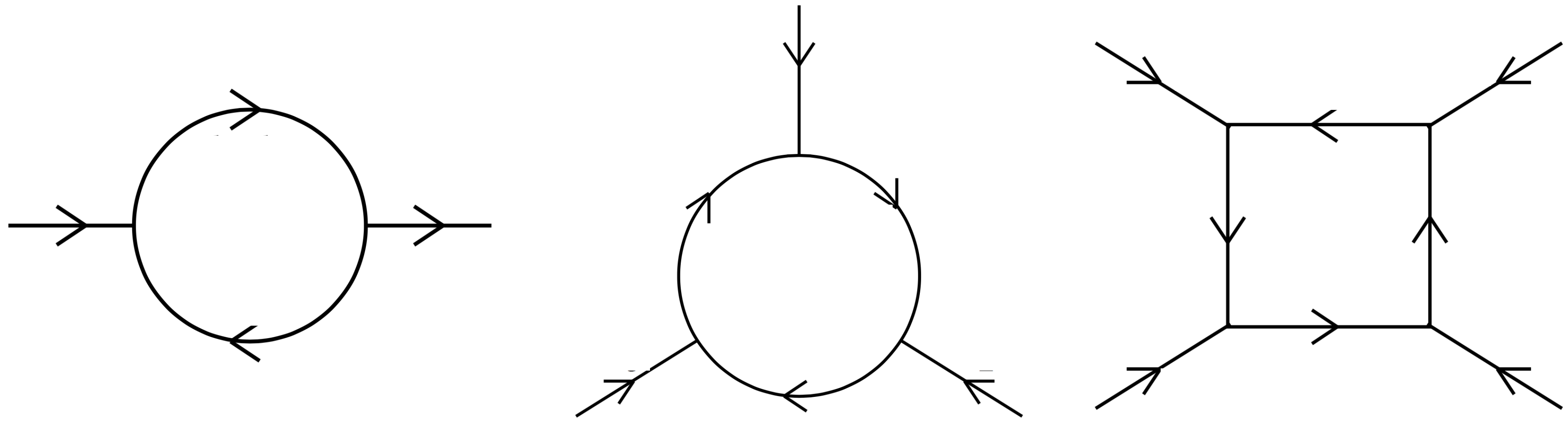


ℓ is a lepton and ν is the corresponding neutrino

Renormalization

Feynman diagrams containing the minimum number of vertices with desired initial and final state particles are Leading Order (LO)

Renormalization accounts for corrections to LO from virtual particles in closed loops



Diagrams with one line more than LO are next-to-LO (NLO)
Two more lines than LO are next-to-NLO (NNLO)

Primary and Secondary Vertices

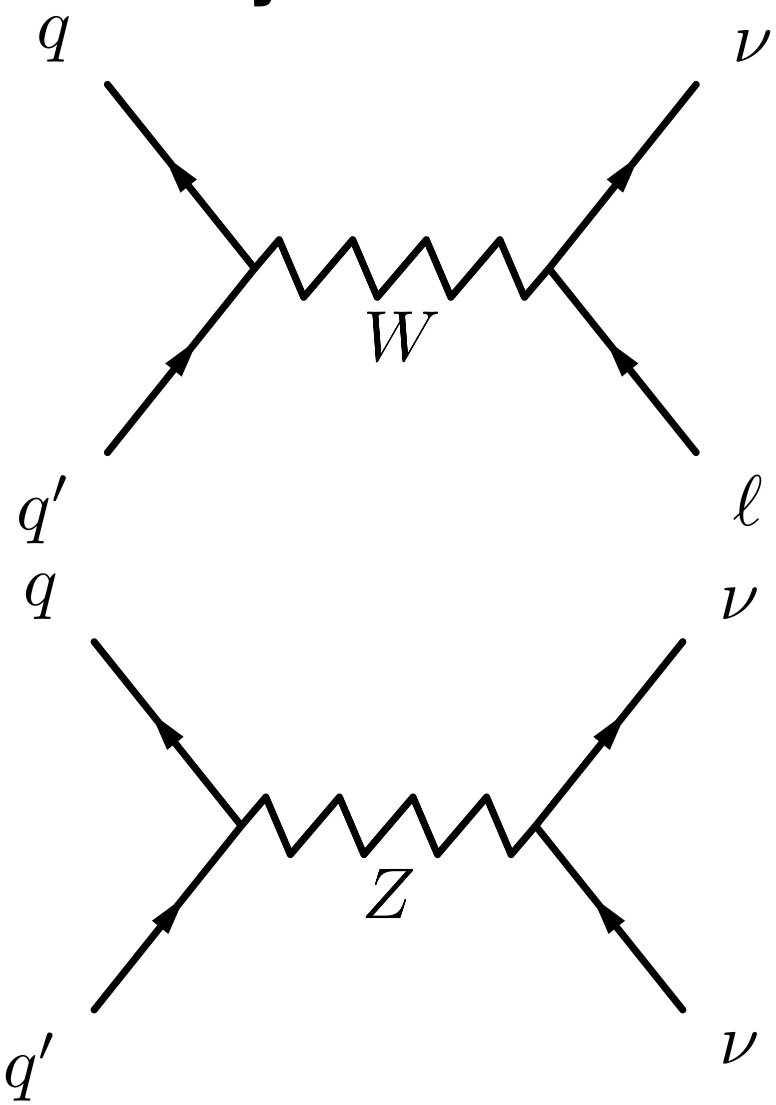
Primary vertex (PV)

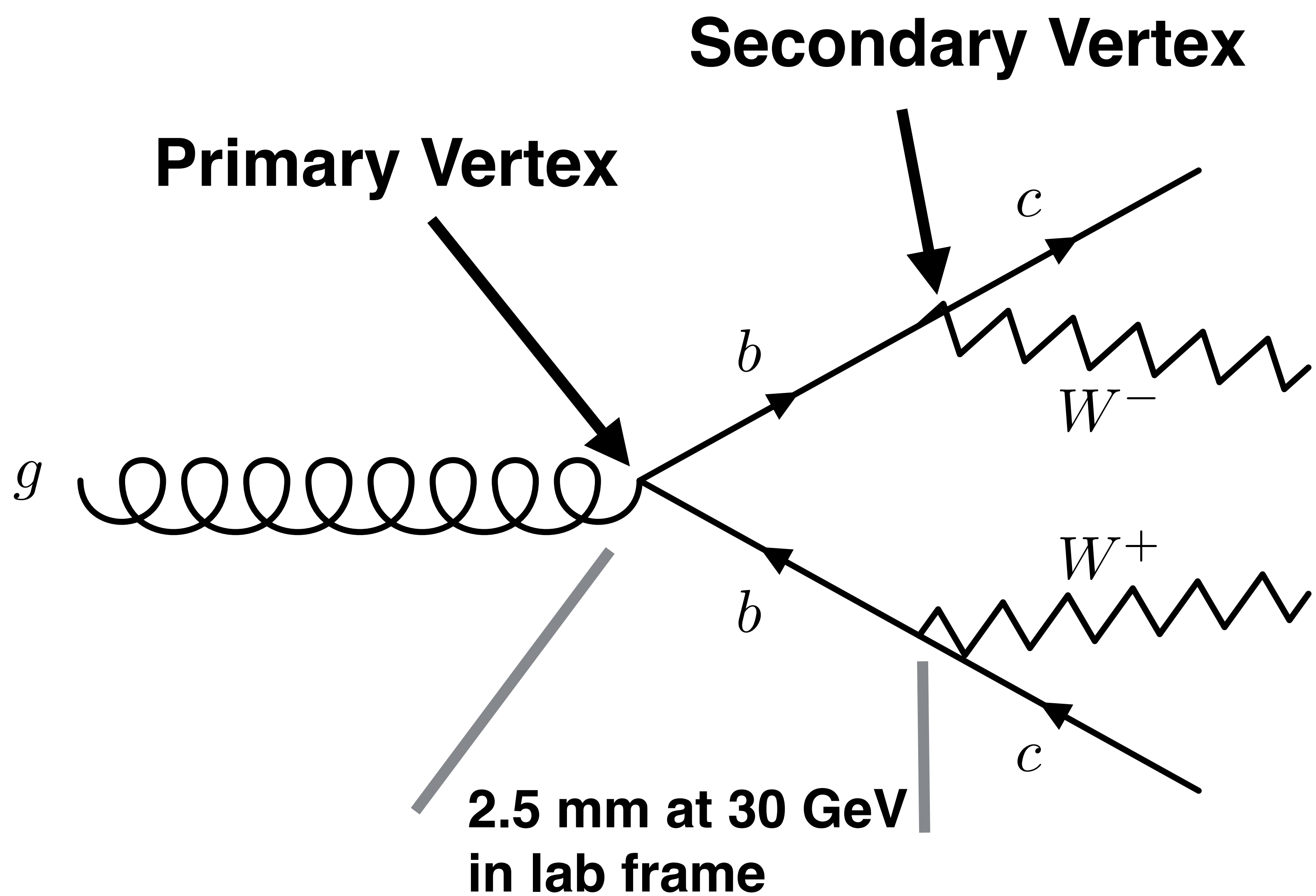
initial collision and decays within CMS resolution

Secondary vertex (SV)

vertex from a decay spatially resolved from PV

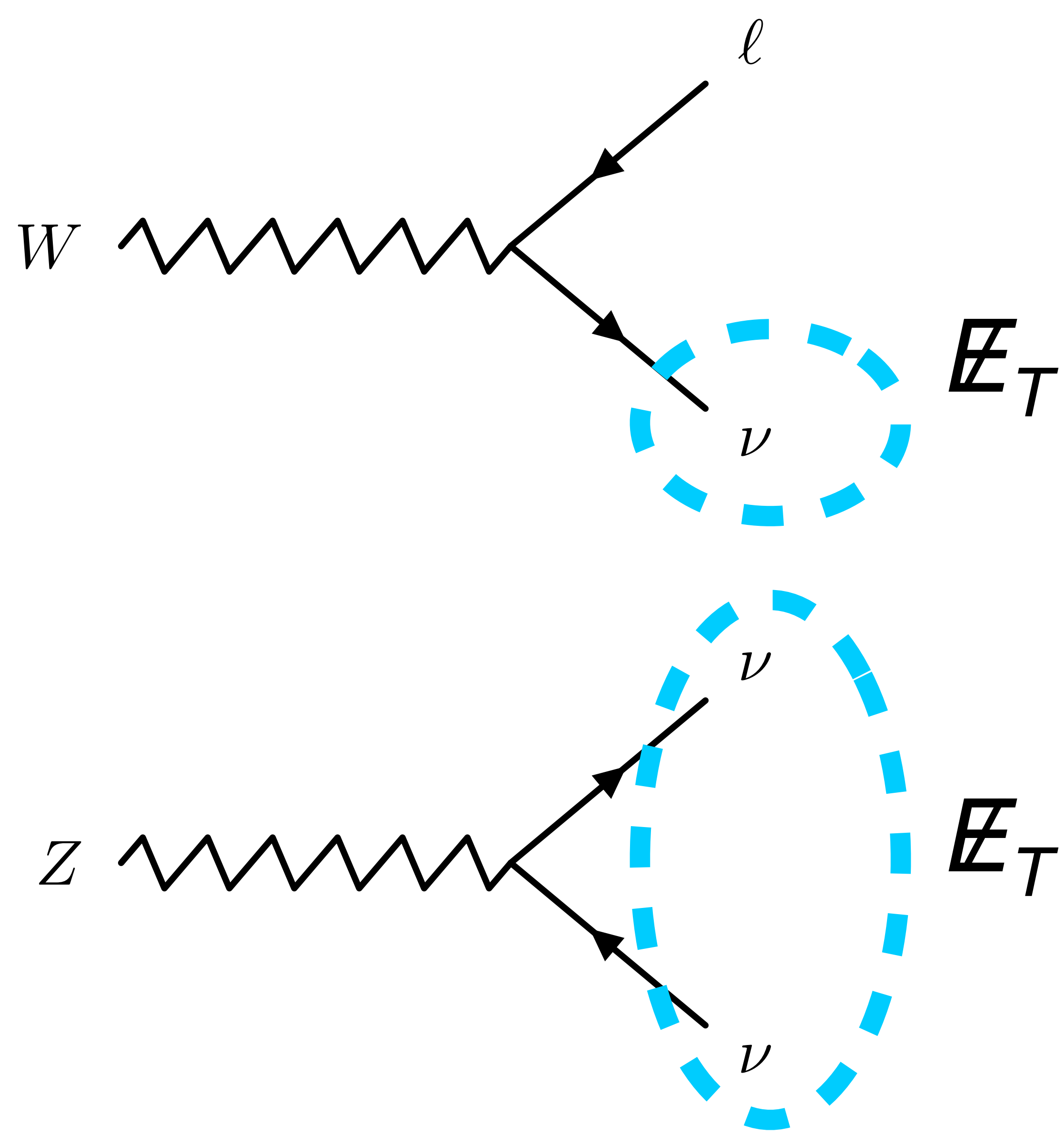
Primary Vertices

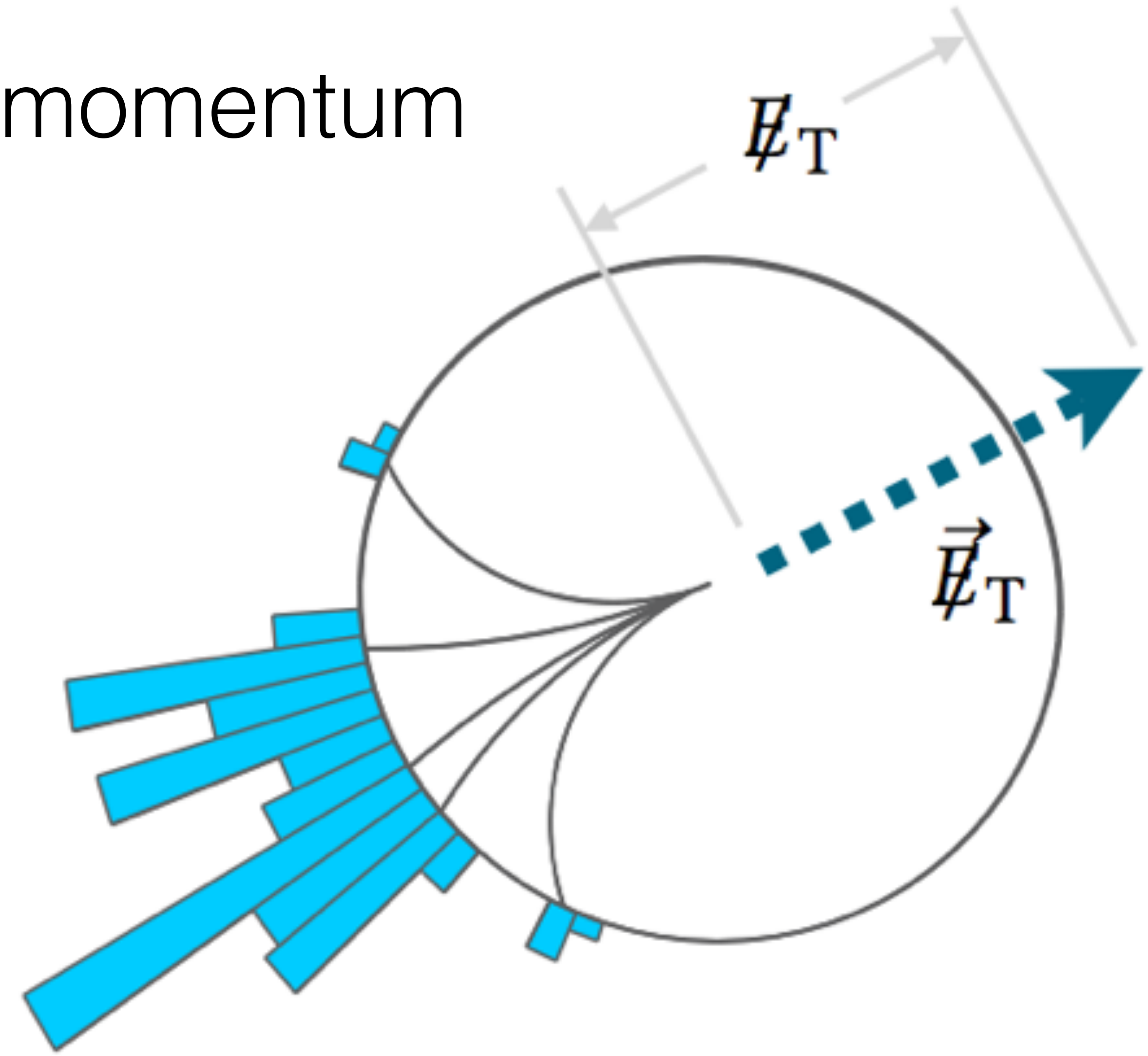




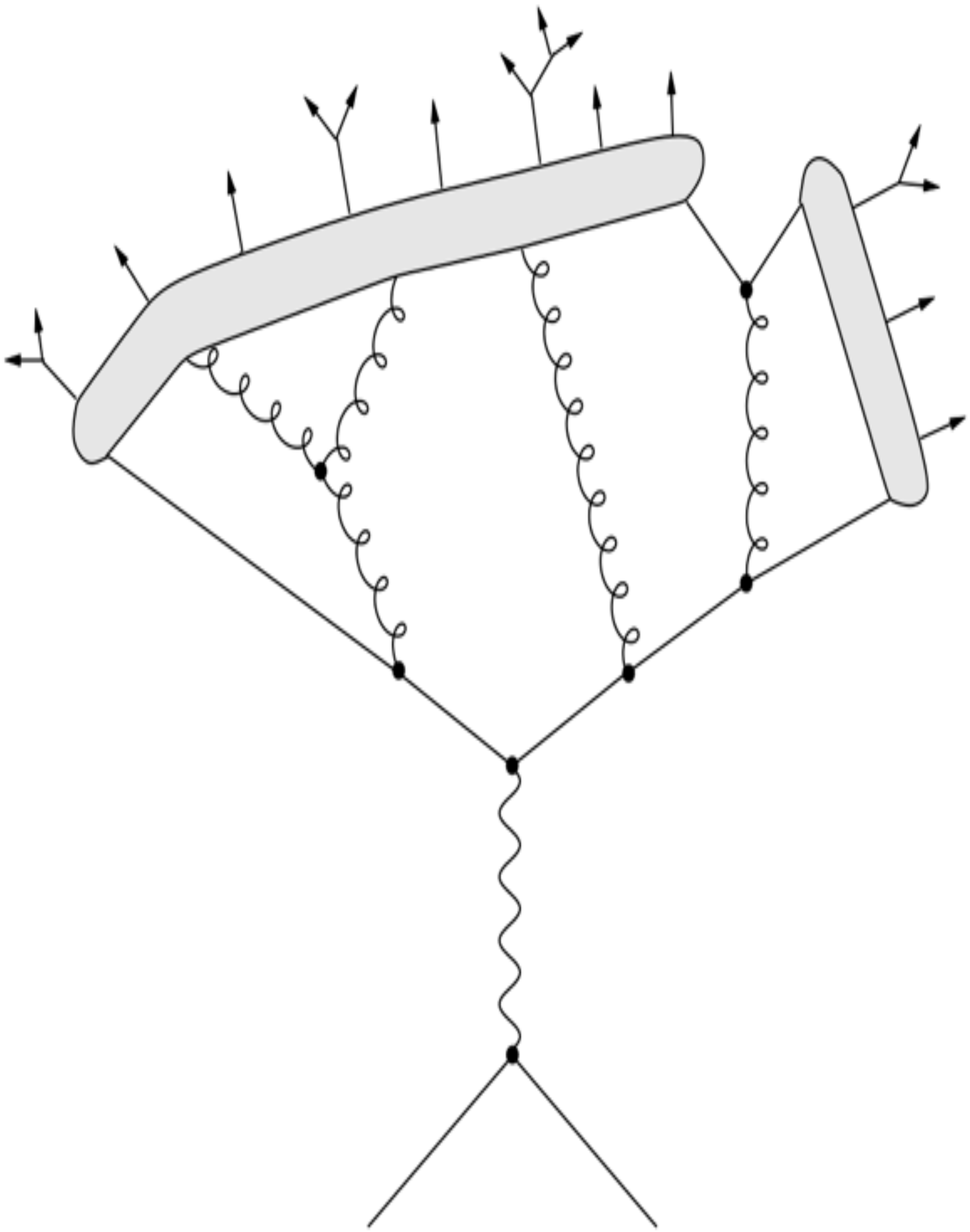
Neutrinos and $\not{E}_T$

Neutrinos interact only via weak force
Pass through CMS undetected
Signature is “missing" transverse momentum





Hadronization and Jets



Quarks / Gluons at high energy can separate

At ~10^{-15} m,
E(strong force) > $mc^2(q\bar{q})$

Quarks / Gluons
radiate / split,
dividing energy until strong force confinement stops process

result is “jets" - collimated collection of color singlets propagating in ~same direction

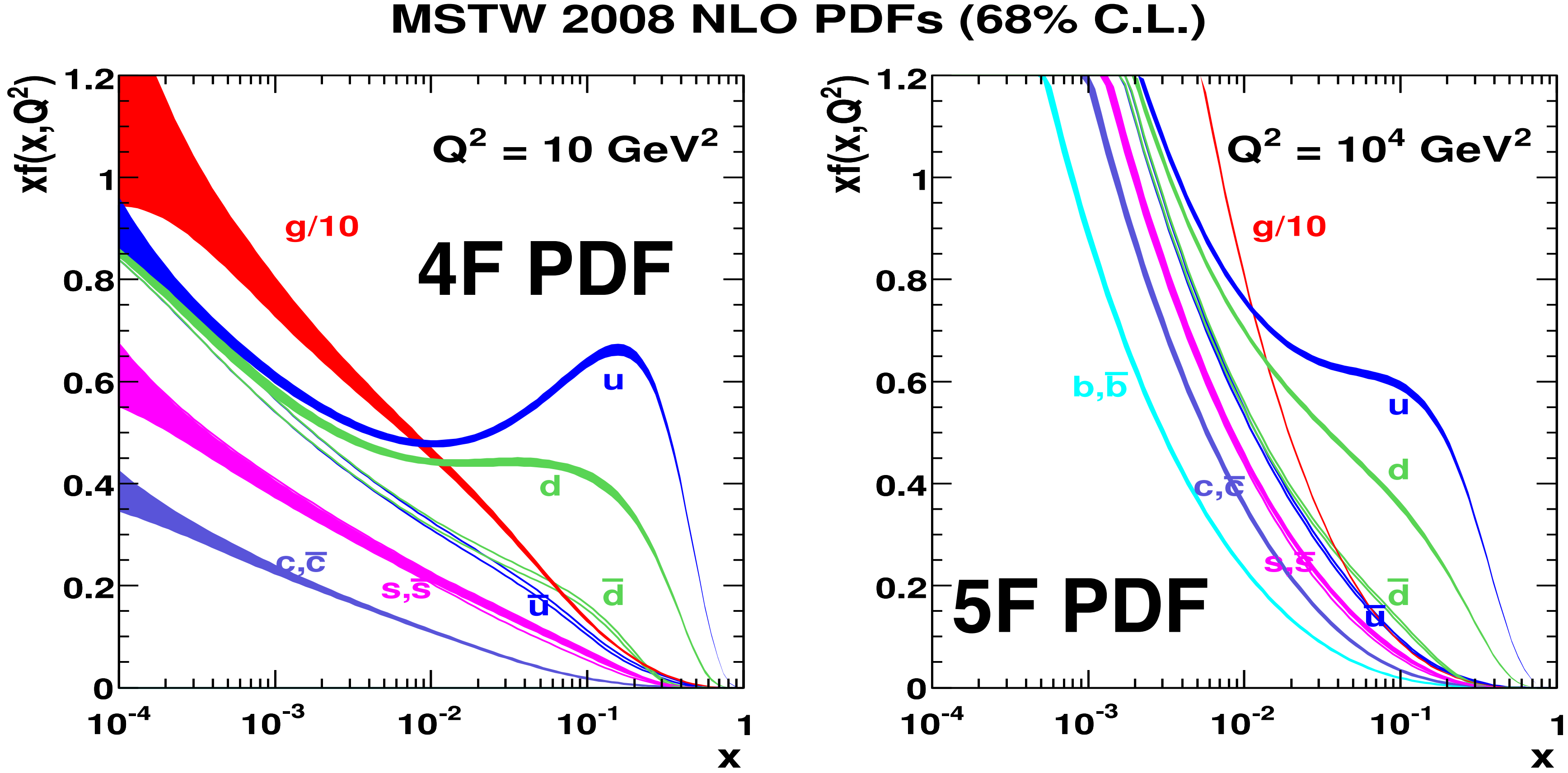
Protons

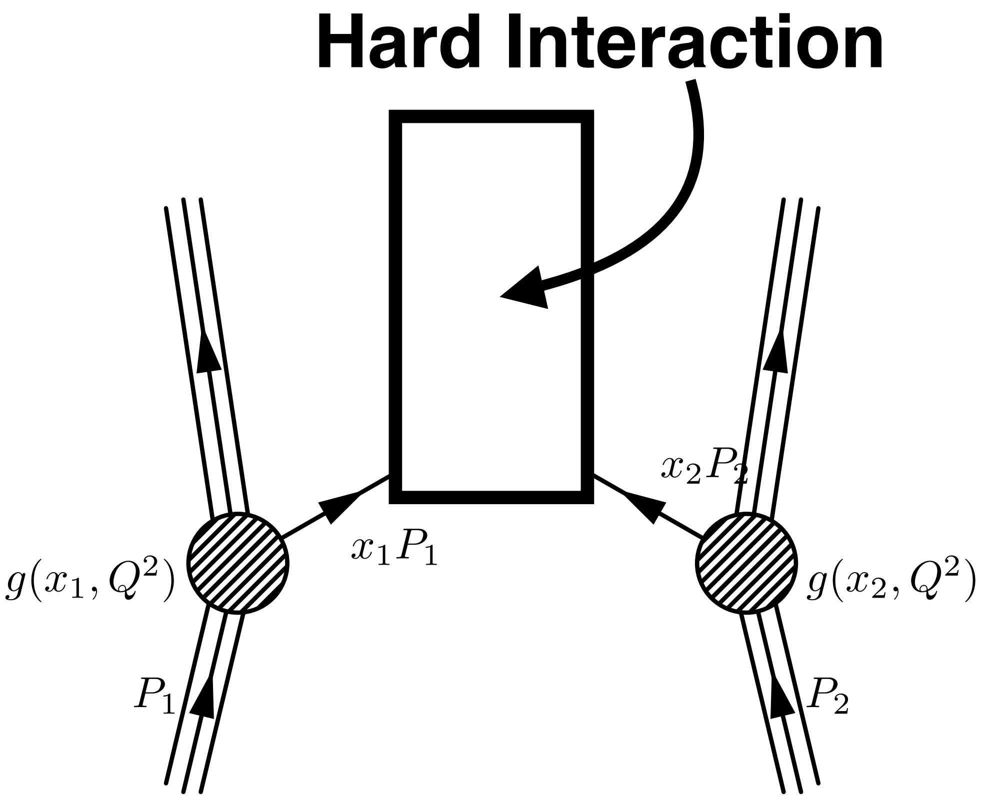
Protons are hadrons - a composite of quarks and gluons

- **u u d** quarks + gluons and sea of **q$\bar{\text{q}}$** pairs
- at high energy, more gluons

Parton Distribution Functions (PDF) provide the fraction of momentum carried by each parton (quarks and gluons)

- four-flavor (4F) includes u d c s in proton PDF
- five-flavor (5F) includes u d c s b in proton PDF





The Standard Model and dark matter

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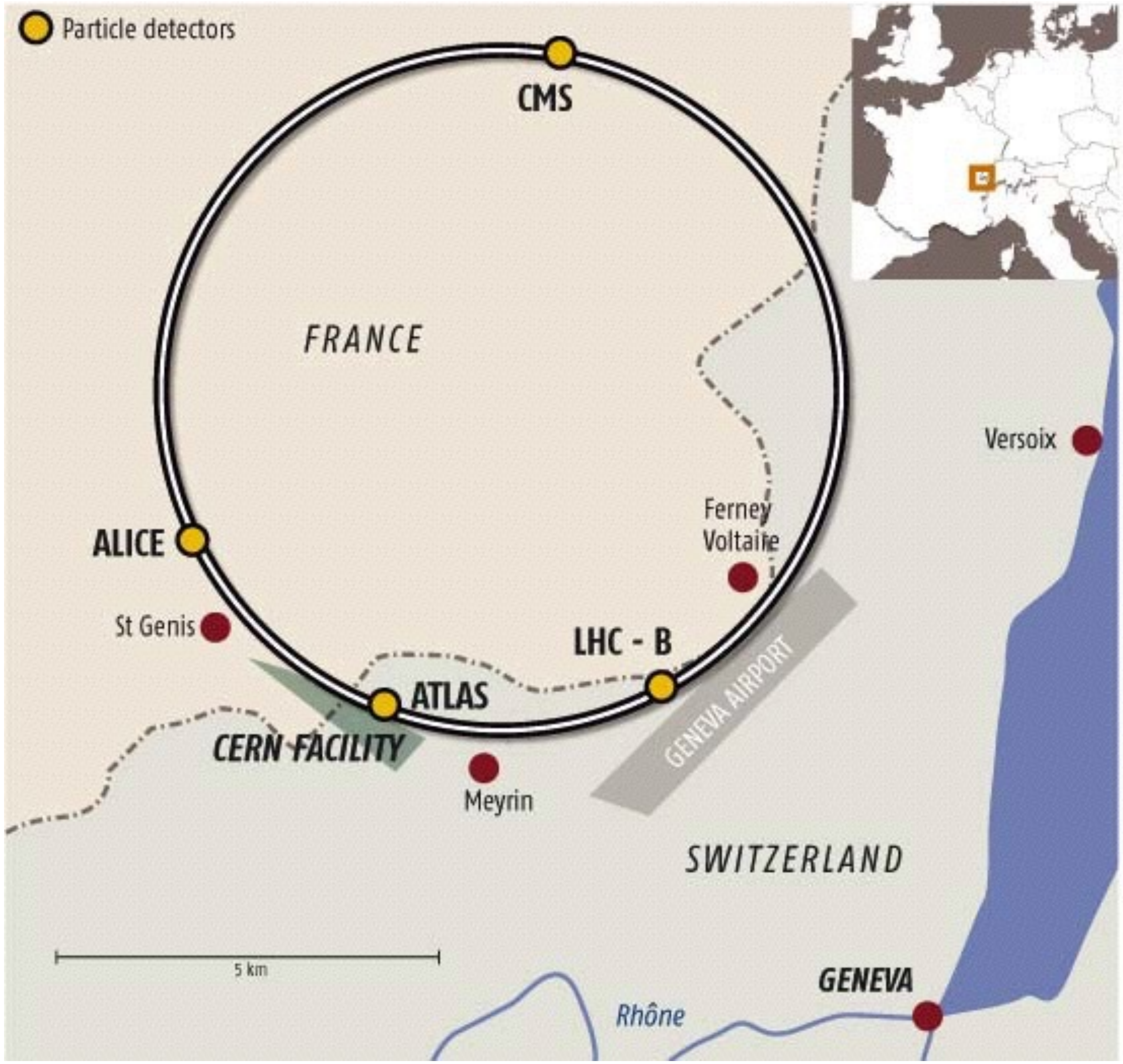
LHC General Information

At CERN : Located Near Geneva, Switzerland



Proton – Proton Collider

4.3 km radius

8 TeV CM Energy (2012)

13 TeV CM Energy (2015)

100 m underground

Four Detectors

CMS, ATLAS

General Purpose

ALICE

Heavy Ions

LHC-B

B Quark Physics

LHC Acceleration

Proton Source
90 keV energy, pulsed every 1.2 s

Radio Frequency Quadrupole
750 keV, pulsed every 1.2 s

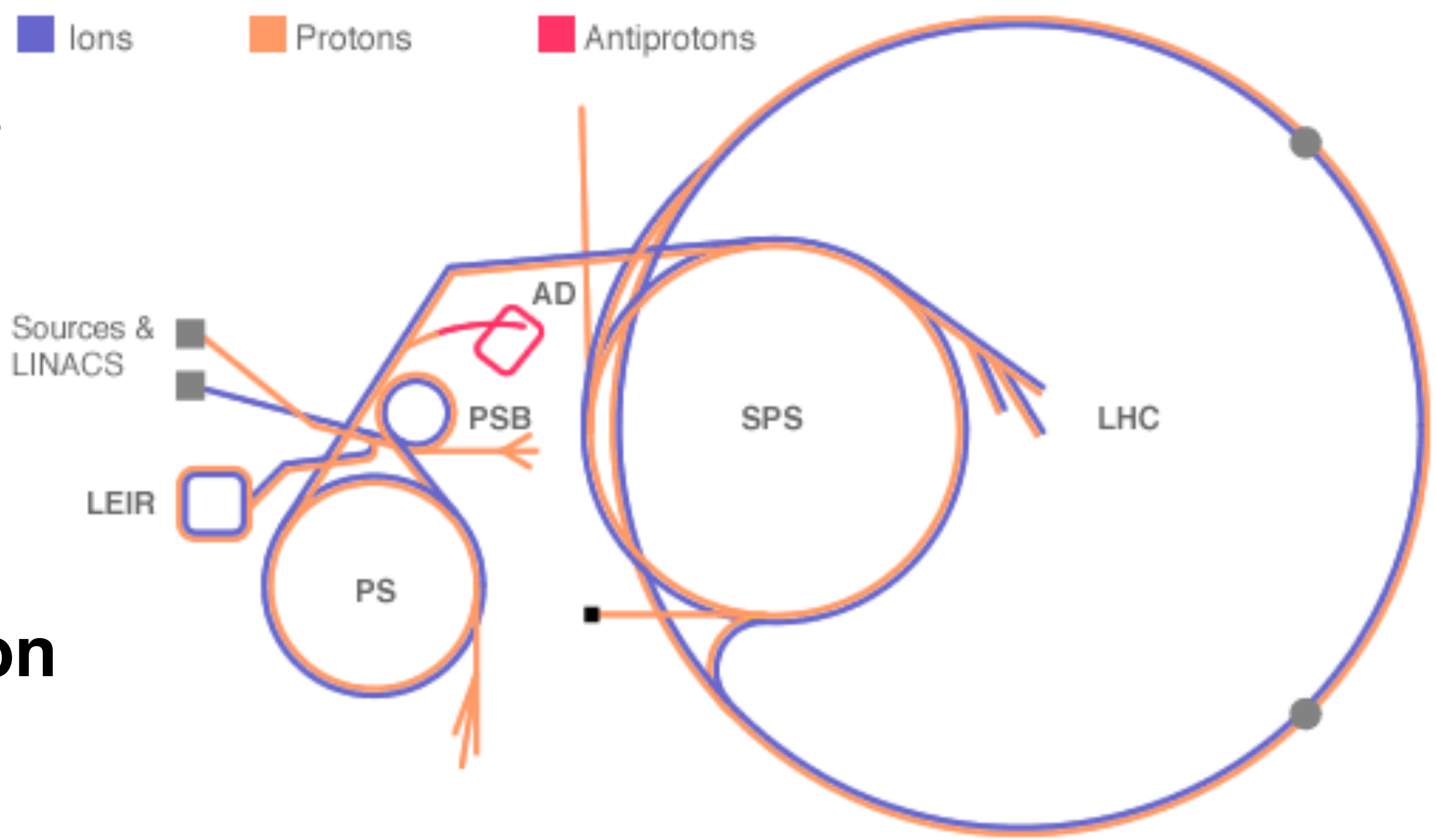
Linac 2
50 MeV, pulsed every 1.2s

PS Booster
1.4 GeV, 1.2s cycle time

Proton Synchrotron
25 GeV, 3.6 s cycle time

Super Proton Synchrotron
450 GeV, 200 MHz

Large Hadron Collider
8 (13) TeV, 89 μs orbit time
Collisions Every 50 (25) ns



Luminosity and Pileup

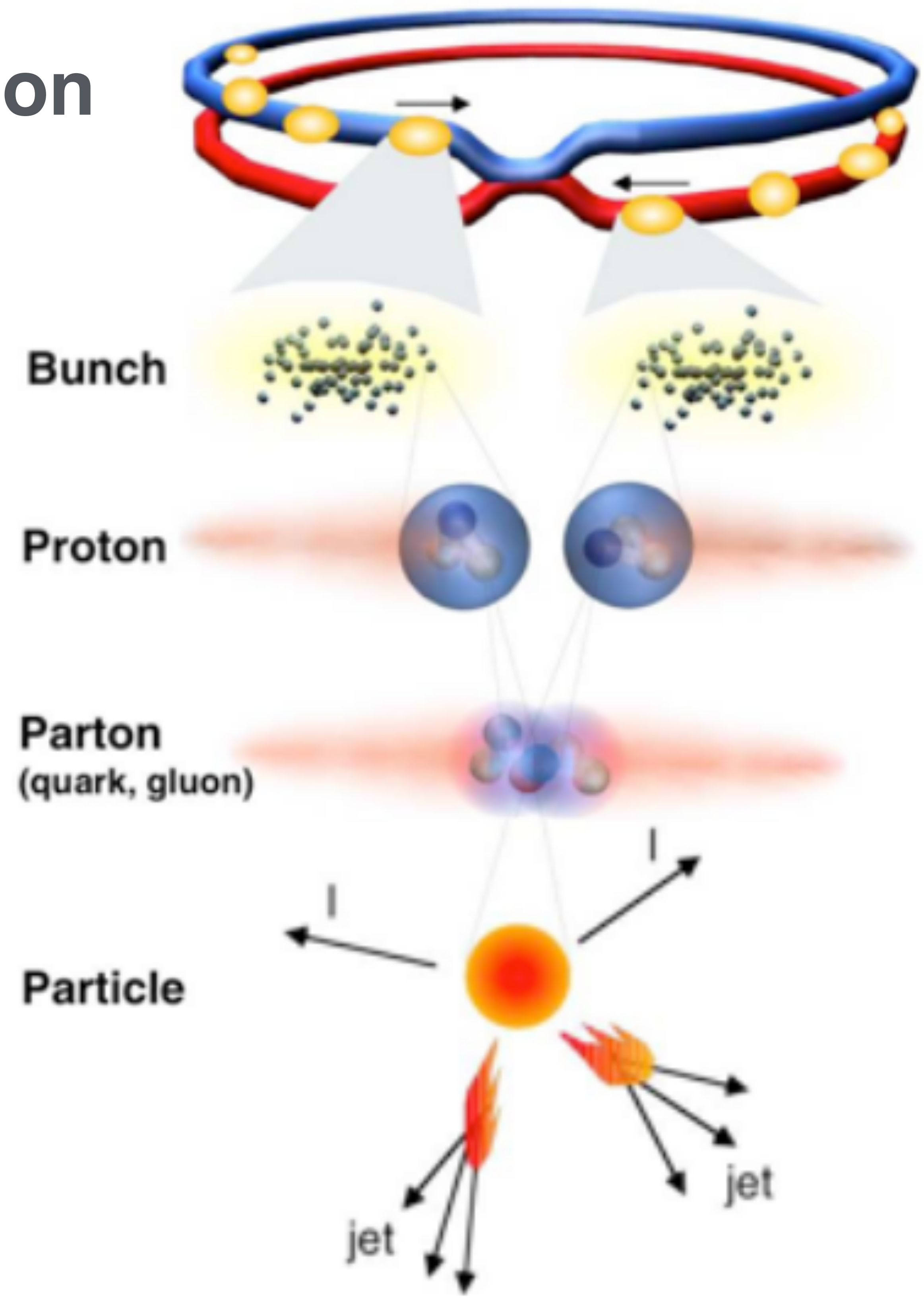
Number of events

Cross section

$$\frac{dN}{d\Omega} = \mathcal{L}\frac{d\sigma}{d\Omega}$$

Solid angle

Luminosity

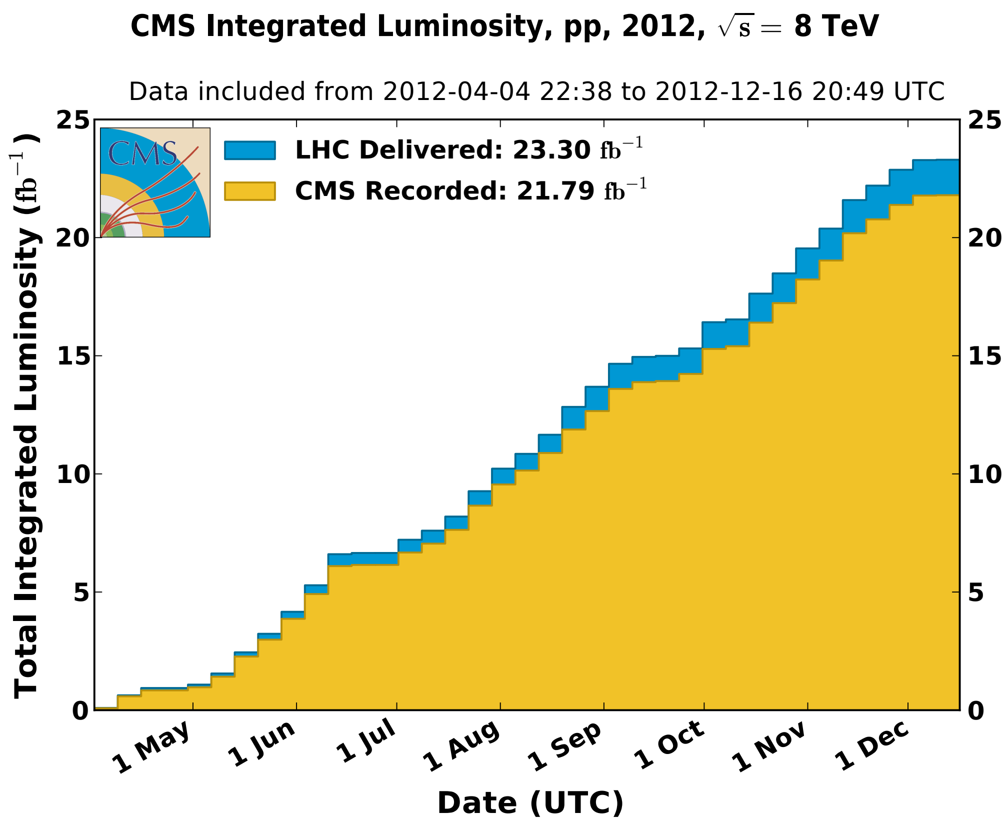


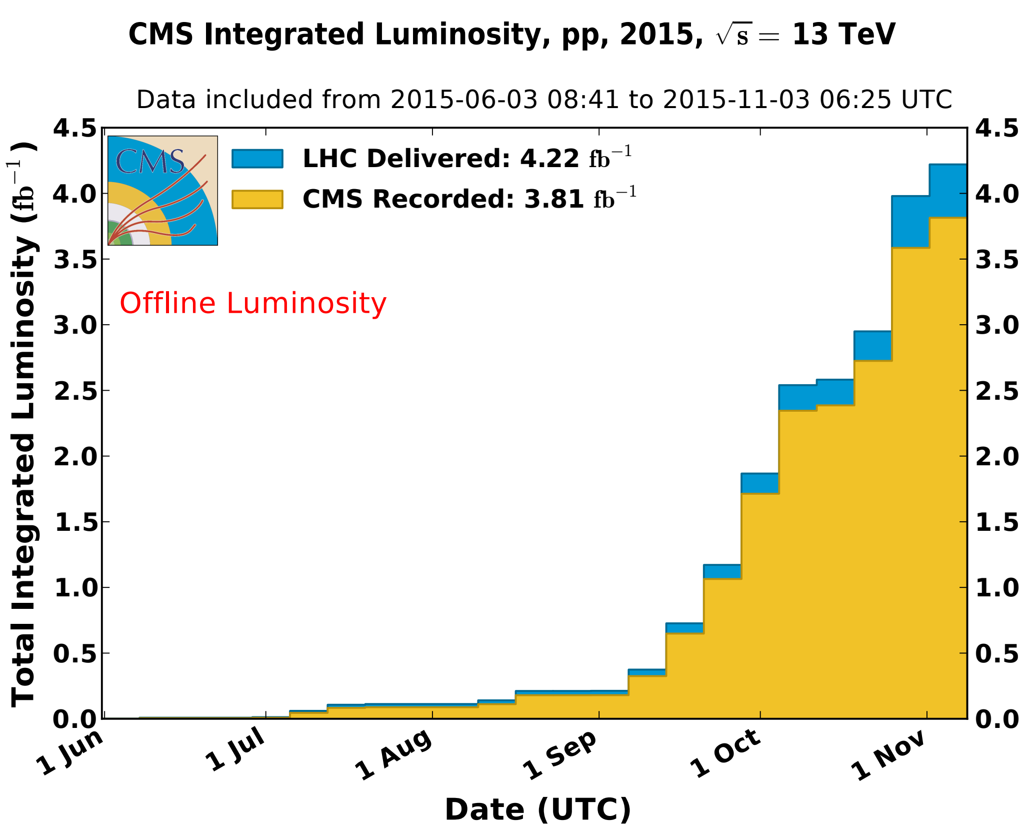
Luminosity is effectively the number of particles per unit area per unit time

Many (~10^{11}) protons per bunch

Pileup is the number of collisions per bunch crossing

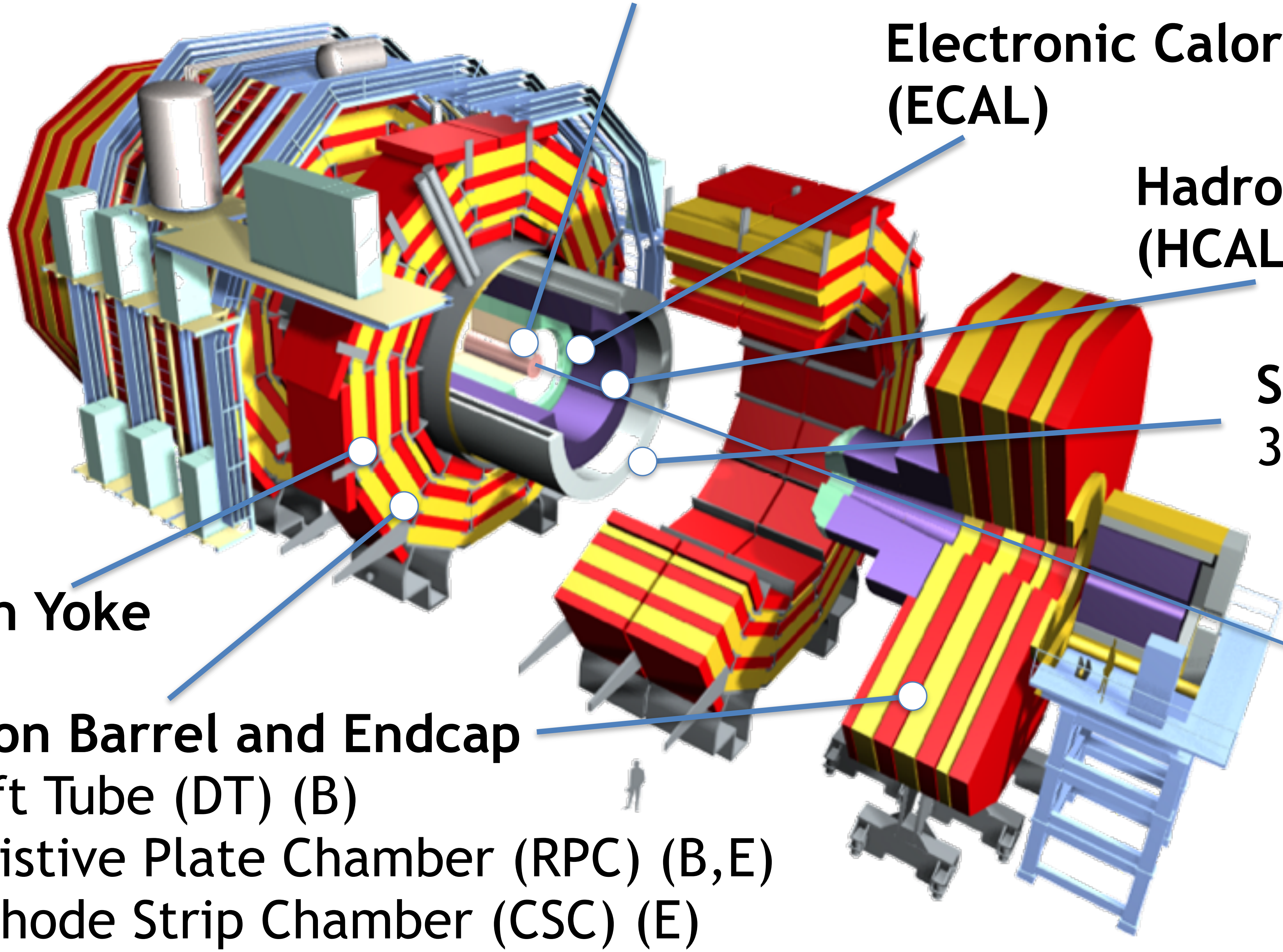
LHC Operating Conditions



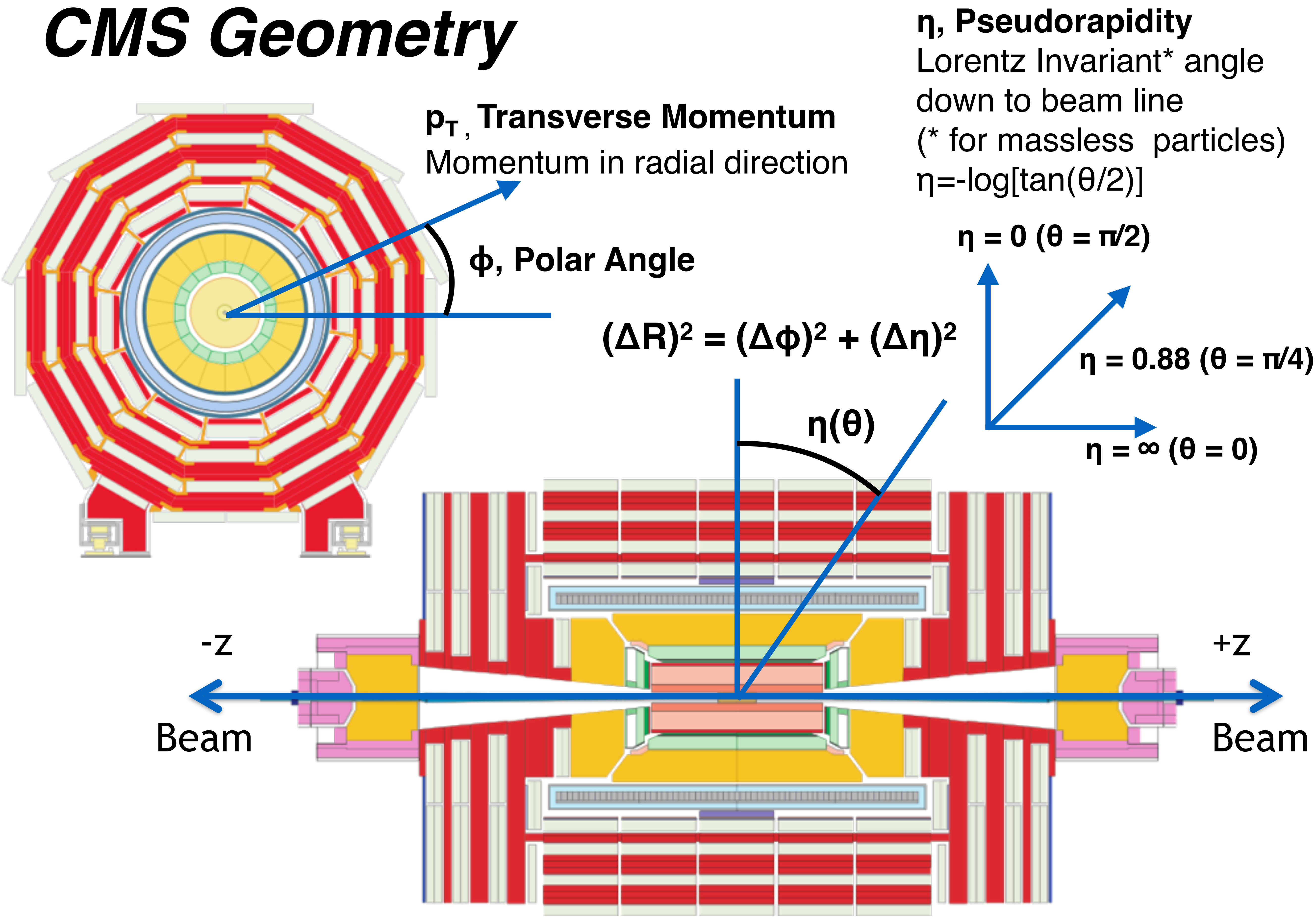


	2012	2015	2016+
Beam Energy (TeV)	4	6.5	6.5
Bunches / Beam	1380	~2200	2000+
Protons / Bunch (10^{11})	1.3	1.5	1.5
Peak Luminosity (10^{32} cm^{-2} s^{-1})	77	51	120+
Integrated Luminosity (/fb)	21.8	3.8	~30-40
Nr. $Wb\bar{b}$ Interactions	15000	-	-
Nr. Monophoton Interactions	630	77	1000-1400

CMS Overview



CMS Geometry



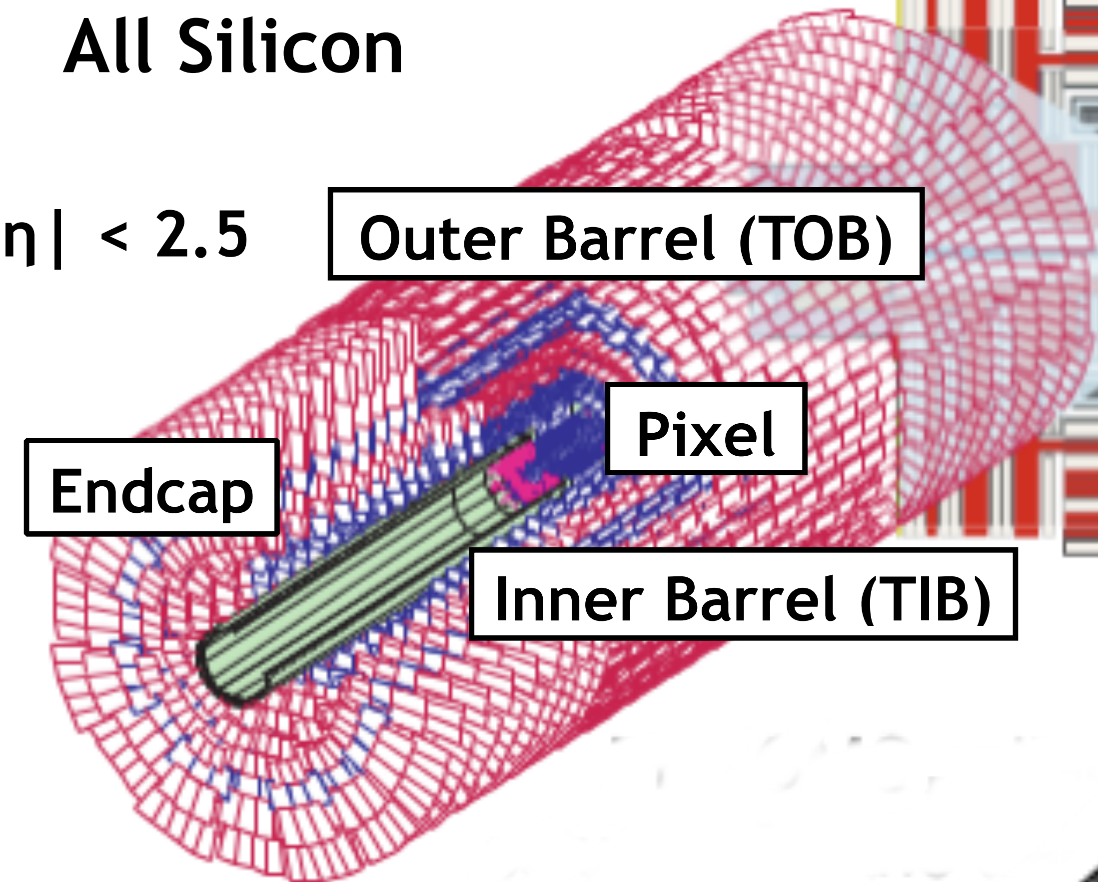
CMS Tracker

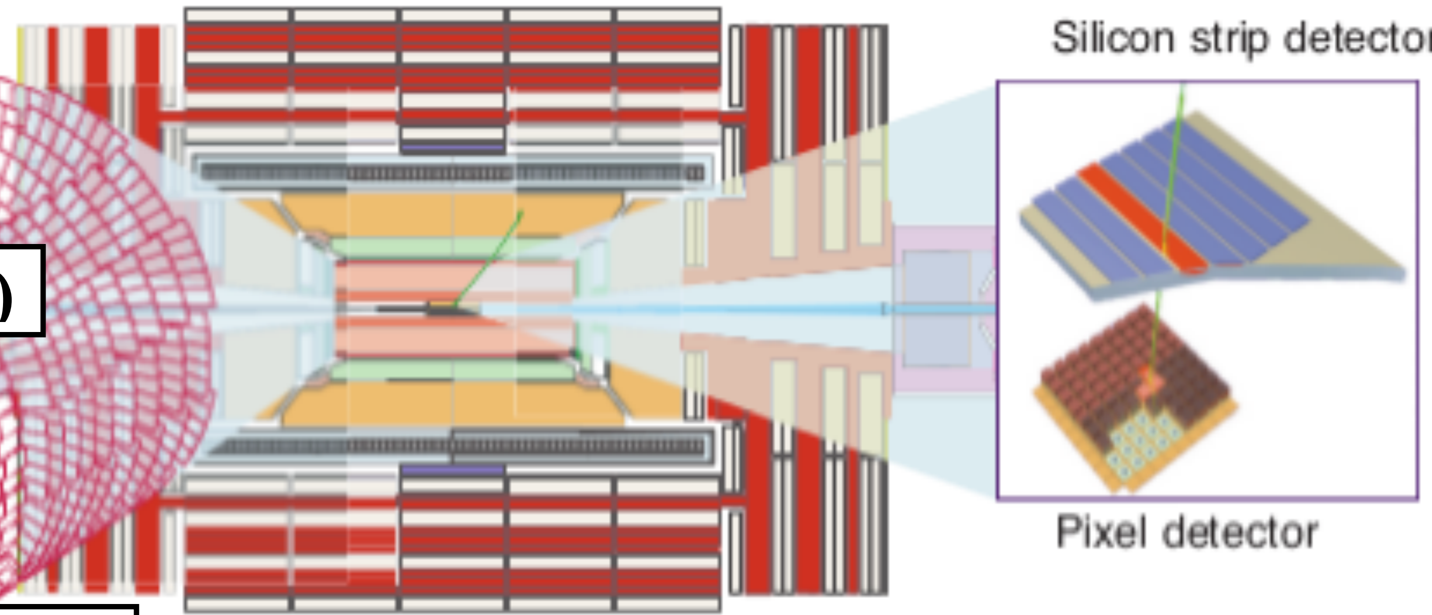
$\delta p_T / p_T \approx (15 \times p_T[\text{TeV}] + 0.5)\ \%$

Radius: 1.2 m Length: 5.4 m

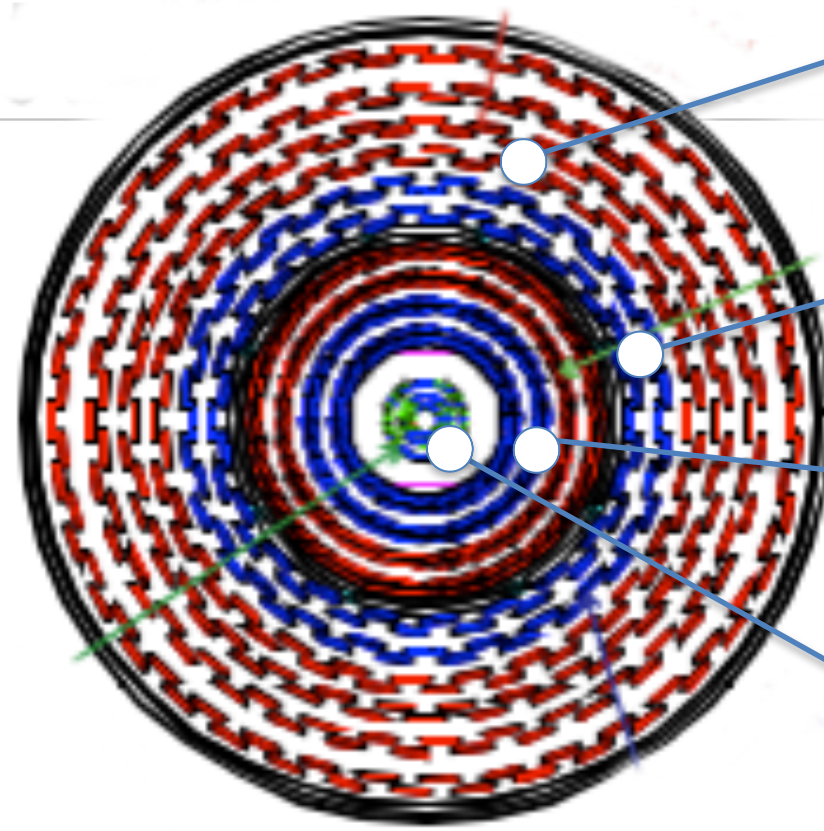
All Silicon

|η| < 2.5





Closest detector component to PV ~4cm



Used for detecting

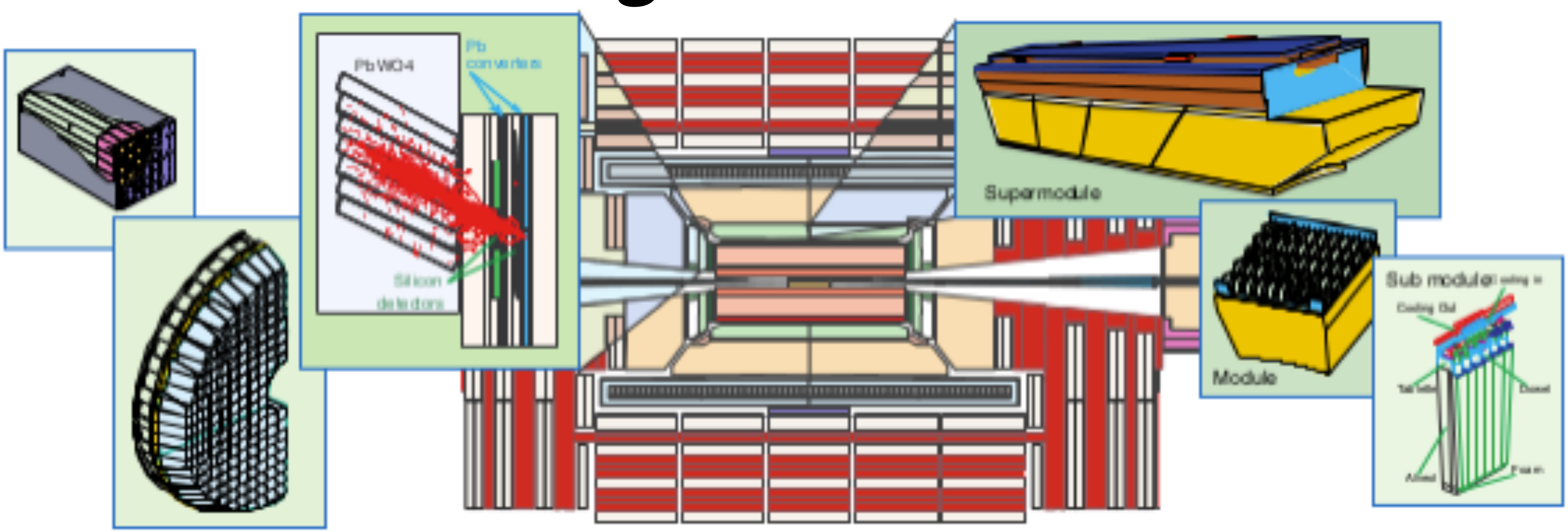
High p_T Muons

Hadrons with high momentum resolution

Isolated Electrons

Secondary Vertices

CMS: Electromagnetic Calorimeter



80,000 Lead-Tungstate Crystals
attached to avalanche photodiodes (barrel)
phototriodes (endcap)

$\sigma/E[\mathrm{GeV}] \approx ((2.83/\sqrt{E}) + (0.124/E) + 0.3)$ %

Crystals
Radiation Length = 0.89 cm
Length: 26 RL = 23 cm
Molière Radius = 22 mm
Cross Section: 22 mm x 22 mm
$\Delta\eta \times \Delta\phi = 0.0175 \times 0.0175$

Used for detecting
- EM Interacting Particles
- Electrons, Photons

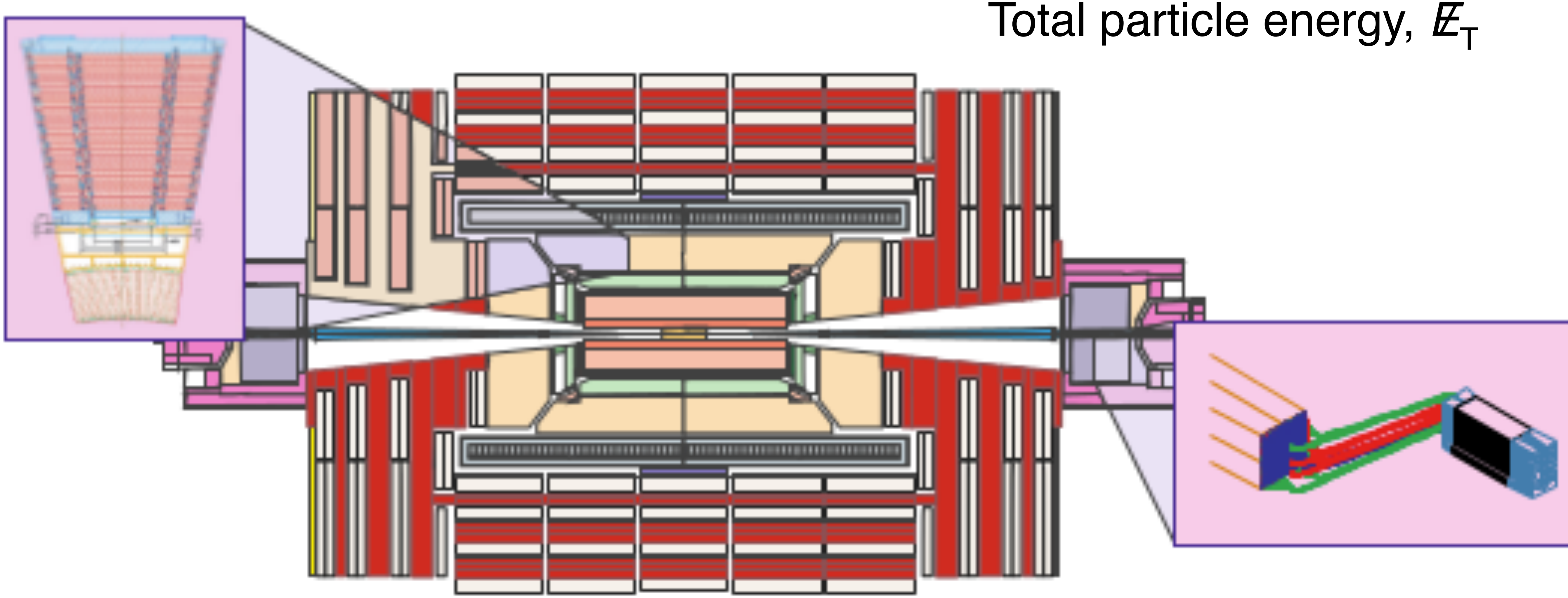
CMS: Hadronic Calorimeter

Barrel (HB): $|\eta| < 1.4$
Endcap (HE): $1.3 < |\eta| < 3.0$
- 50 mm brass plates
- 4 mm scintillator sheets
- Tiles: $\Delta\eta \times \Delta\phi = 0.87 \times 0.87$

Forward (HF): $3.0 < |\eta| < 5.0$
- Steel + Quartz Fibers

HB + HE ($|\eta| < 3$) : $\sigma/E[\text{GeV}] \approx ((115/\sqrt{E}) + 5.5)$ %
HF ($3 < |\eta| < 5$): $\sigma/E[\text{GeV}] \approx ((280/\sqrt{E}) + 11)$ %

Used for detecting
- Neutral hadrons
- Jets
- Total particle energy, $\not{E}_T$



CMS: Muon Spectrometer

Barrel

DT, RPC: $|\eta| < 1.3$

Endcap

CSC: $0.9 < |\eta| < 2.4$

RPC: $|\eta| < 1.6$

All Components are used in triggering

Cathode Strip Chambers

Crossed Wires (r)

Cathode Strips (ϕ)

Drift Tubes

40 mm x 11 mm

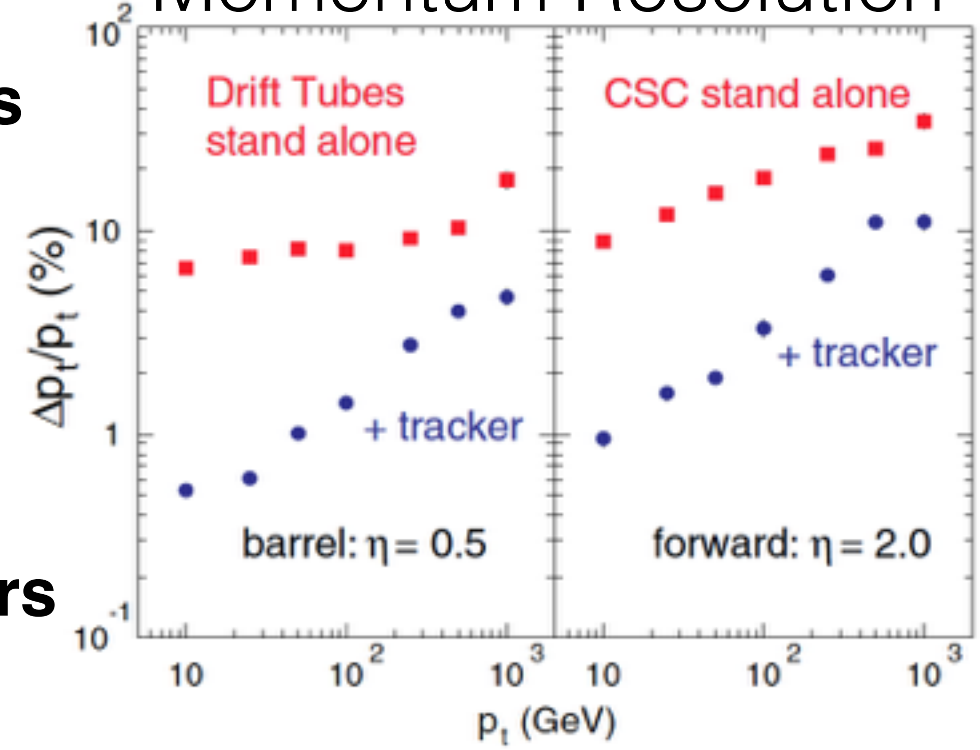
Ar/CO_2 Mixture

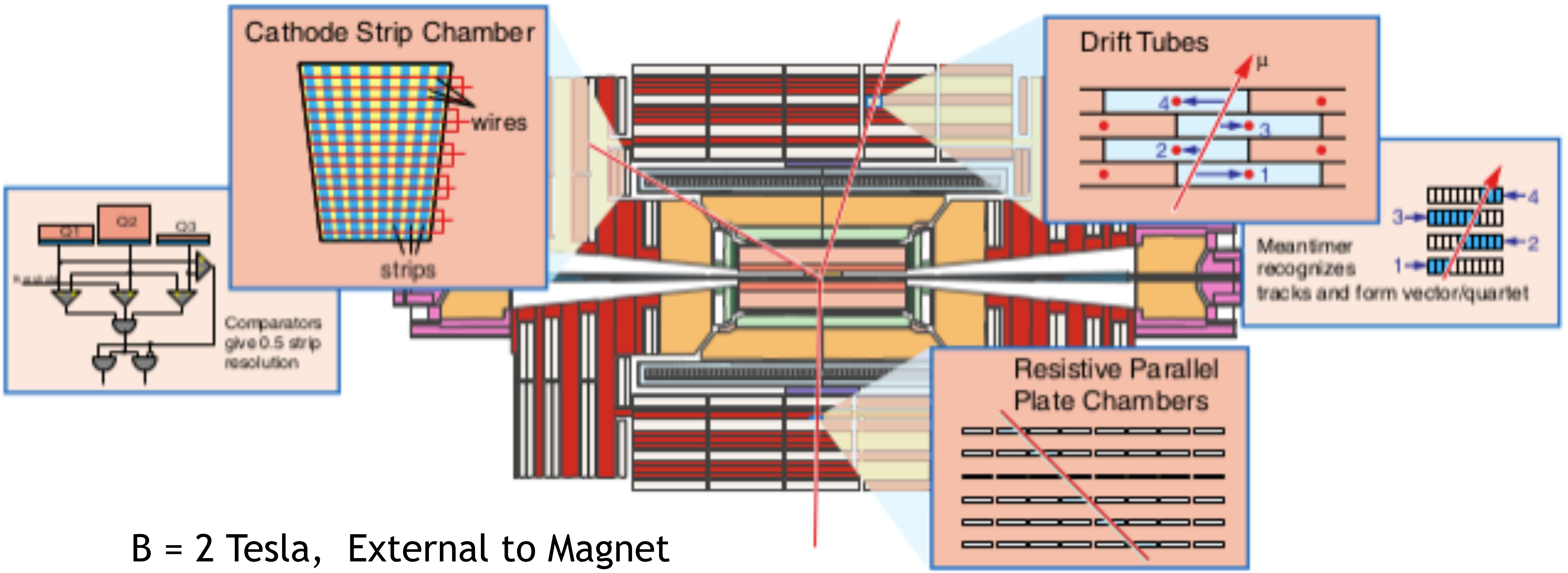
Resistive Plate Chambers

Gasious Parallel Plate

Plastic Anode + Cathode

Momentum Resolution





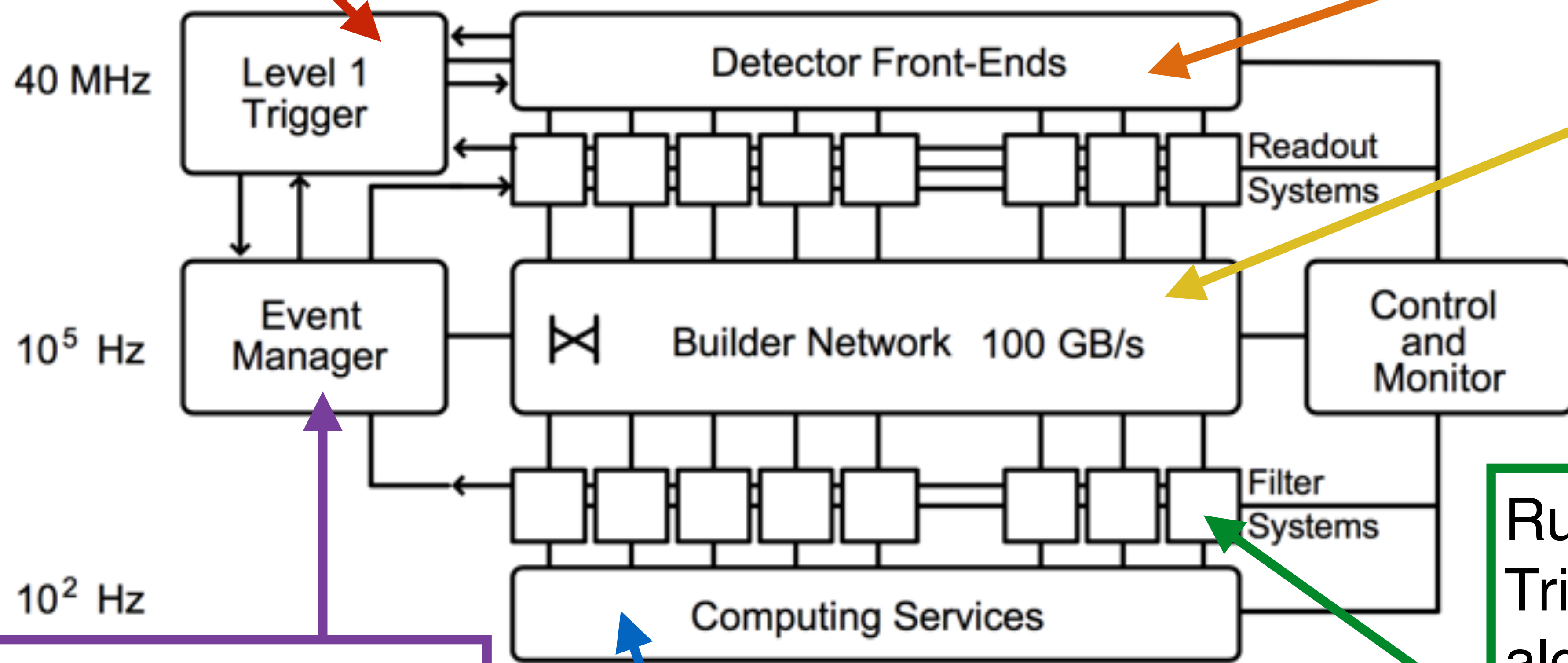
B = 2 Tesla, External to Magnet

Data Acquisition

Bunch crossing rate 20/40 MHz
- more data produced than can be stored
Reduce rate, keeping "interesting" events

Makes initial decision to further analyze event

Stores data from detector electronics after Level 1 Trigger accepts event



Provides interconnections between readout and filter systems

Manages flow of data and synchronization

Processors and networks which receive filtered events

Runs High Level Trigger (HLT) algorithms to select events for final offline processing

Four Stages:

Detector Readout - store event data after Level 1 Trigger accepts event
Event Building - data from subdetectors is merged into a single event
Selection - HLT algorithms select events to be saved and analyzed
Storage/Analysis - Selected events are forwarded for storage and analysis

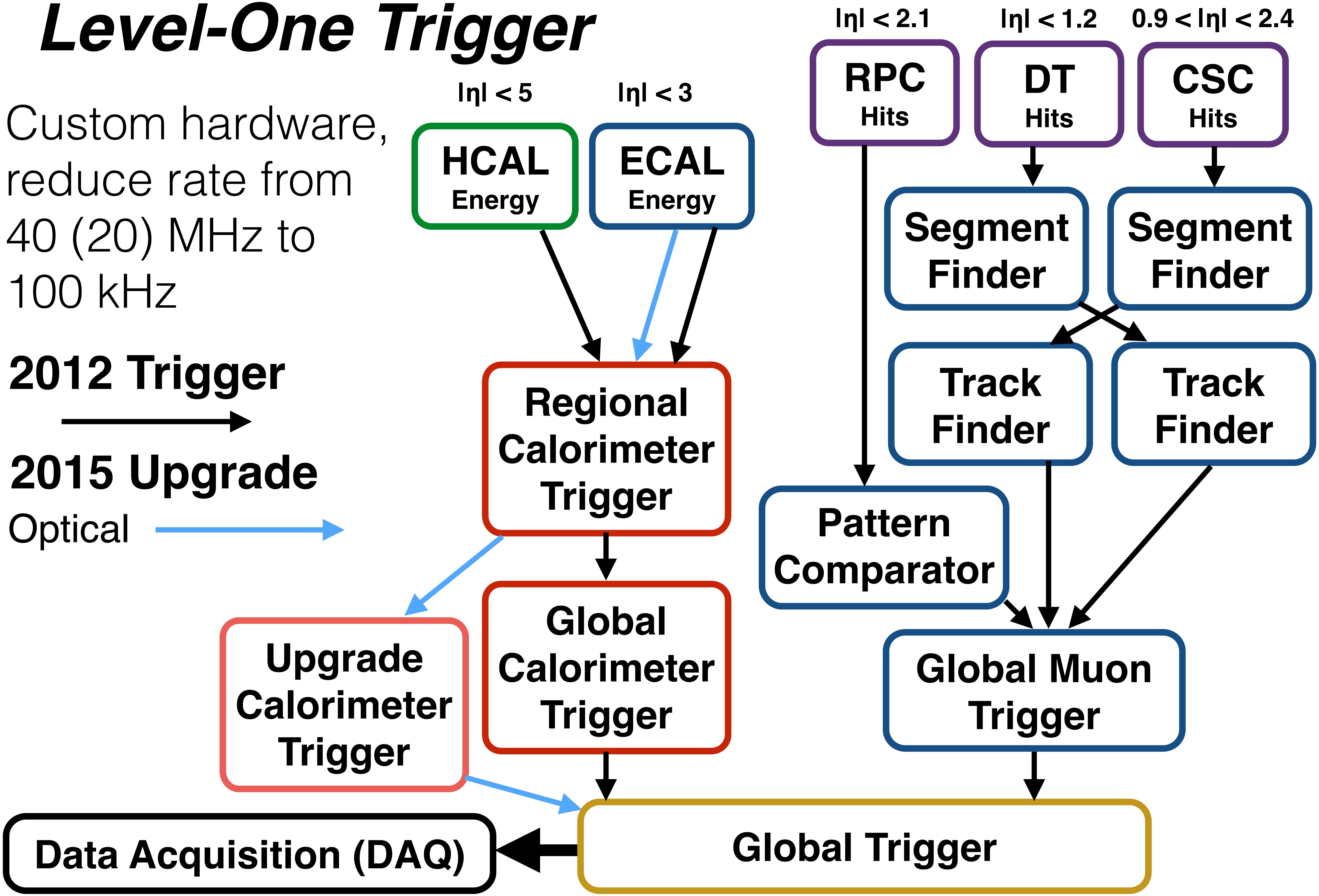
Level-One Trigger

Custom hardware, reduce rate from 40 (20) MHz to 100 kHz

2012 Trigger

2015 Upgrade

Optical



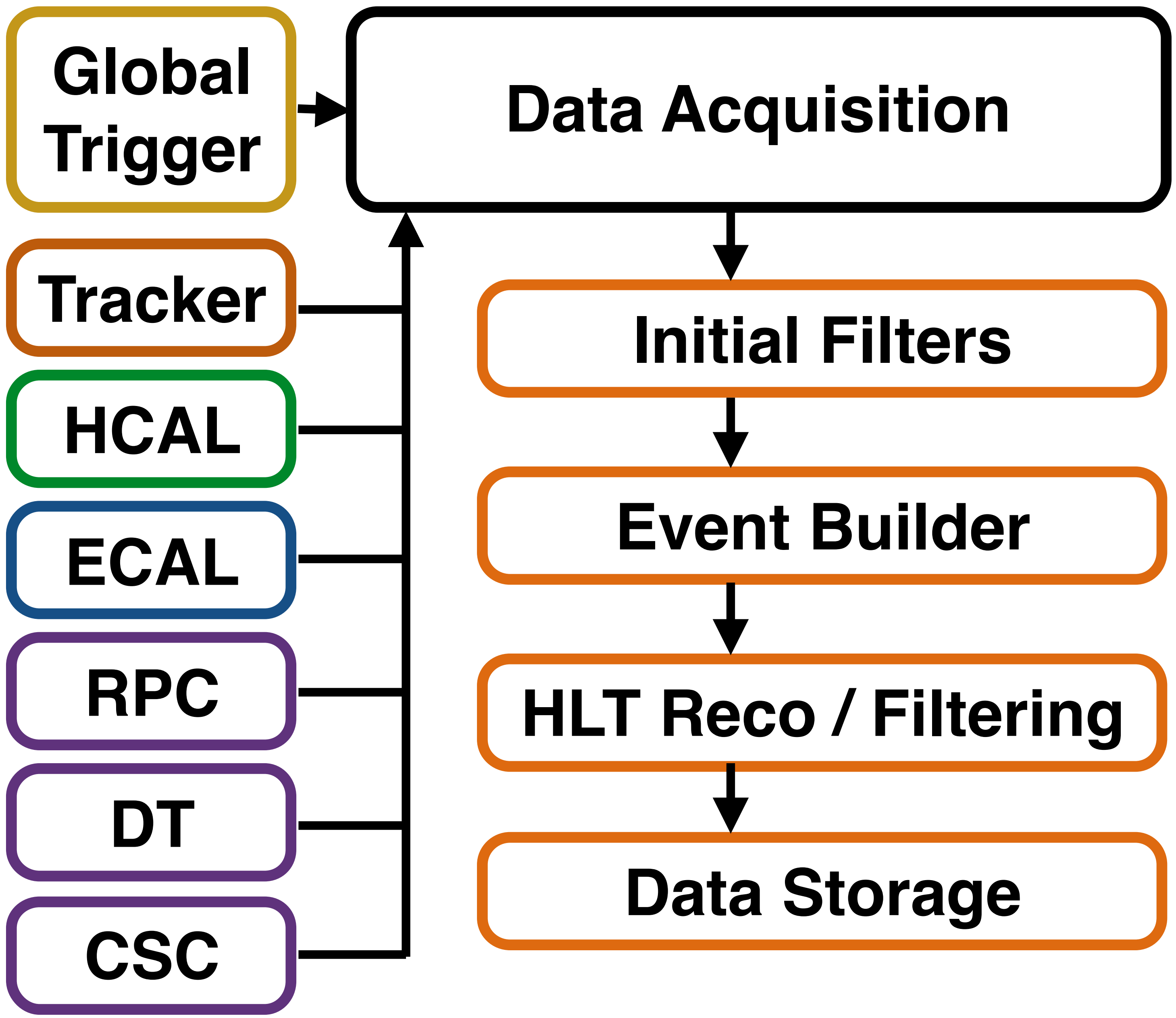
High Level Trigger

100 kHz Level One Output Rate to 1 kHz for Permanent Storage

Custom Software on Commercial Processor Farm

Algorithms Similar to Offline Reconstructions

Uses Full Event Data



HLT Triggers used:

Single Isolated Muon

$p_T > 24$ GeV

Single Isolated Electron

$p_T > 27$ GeV

Single Isolated Photon

$p_T > 165$ GeV

$E_{ECAL}/E_{HCAL} > 90\%$

The Standard Model and dark matter

The LHC and CMS

Simulation and reconstruction

$Wb\bar{b}$ cross section measurement

Monophoton analysis

Conclusions and future prospects

Event Simulation

Ultimately data are compared to simulation

Simulation of collision events use Monte Carlo techniques

- Calculate scattering amplitude (Matrix Element)
- Decay, hadronization, radiation, higher order corrections
- Other collision products (underlying event)

GEANT4: Simulation of energy deposits in CMS detector

- detailed model of CMS (detector, inert material, electronics)
- passage of particles through matter, background noise

CMSSW: CMS particle reconstruction / analysis software

- Number of generated MC events scaled to match data luminosity
- Pileup distribution reweighted in MC to match data
- Real and simulated data are processed in the same way

Monte Carlo Generators

Matrix Element Generators

MADGRAPH / MADEVENT Version 5.1
Matrix element at fixed order (LO + fixed number of jets)

A Monte Carlo for FeMtobarn (MCFM) Version 7.0
Matrix element at NLO, parton level (hadronization needed)

Fully Exclusive W,Z Production (FEWZ) Version 3.1
Matrix element at NNLO

Secondary Effects (Hadronization, NLO effects, Underlying Event)

PYTHIA Version 6.4 (Fortran) / 8.2 (C++)
Radiation/Hadronization, Lund string model, underlying event

Positive Weight Hardest Emission Generator (POWHEG) Version 2.0
Replace leading jet from other generator with NLO prediction

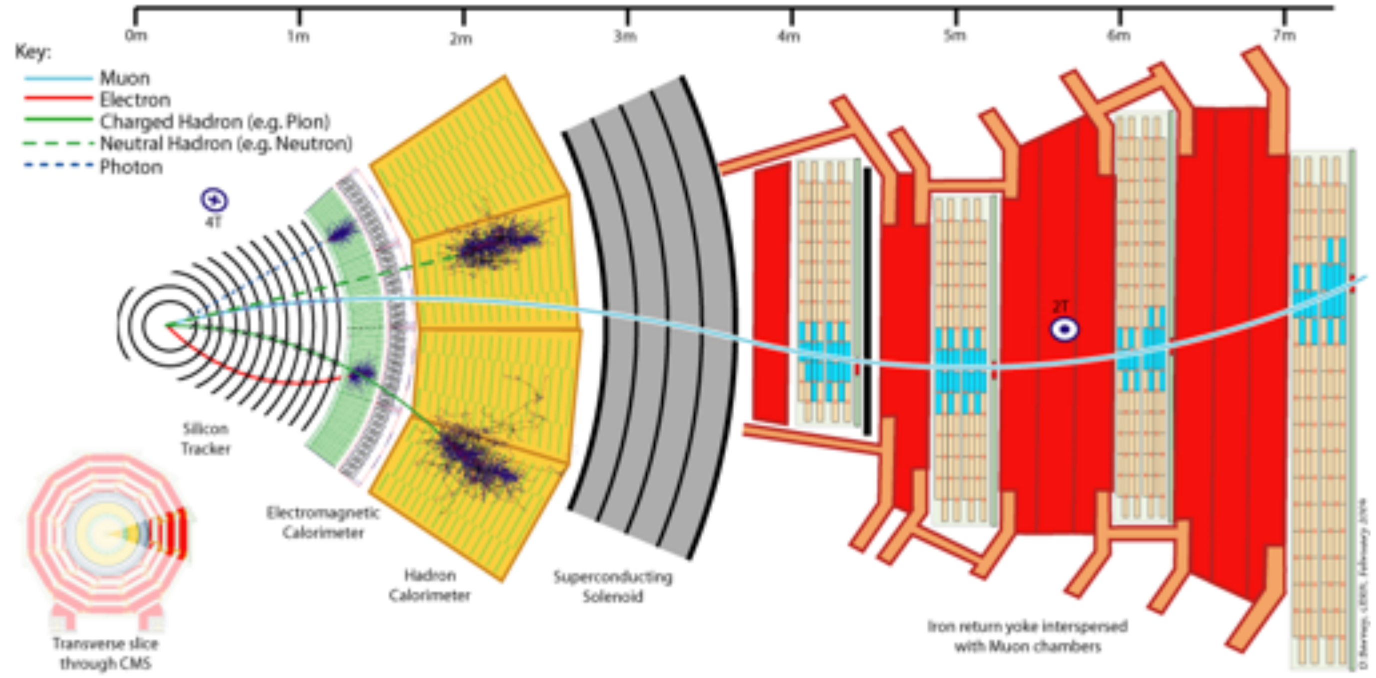
aMC@NLO Version 2.2
like POWHEG, but designed to be interfaced with Madgraph in 2015

Particle Flow

combines information from subdetectors to reconstruct particles with better resolution

Three Basic Elements:

Charged Particle Tracks
Calorimeter Clusters
Muon Tracks



Reconstruction Steps:

Iterative Track Finding

- ID Tracks in Tracker, Direction of Particle at PV

Calorimeter Clustering

- Energy/Direction of Hadrons, Separate Neutral/Charged Deposits
- ID Electrons/Bremsstrahlung Photons

Linking

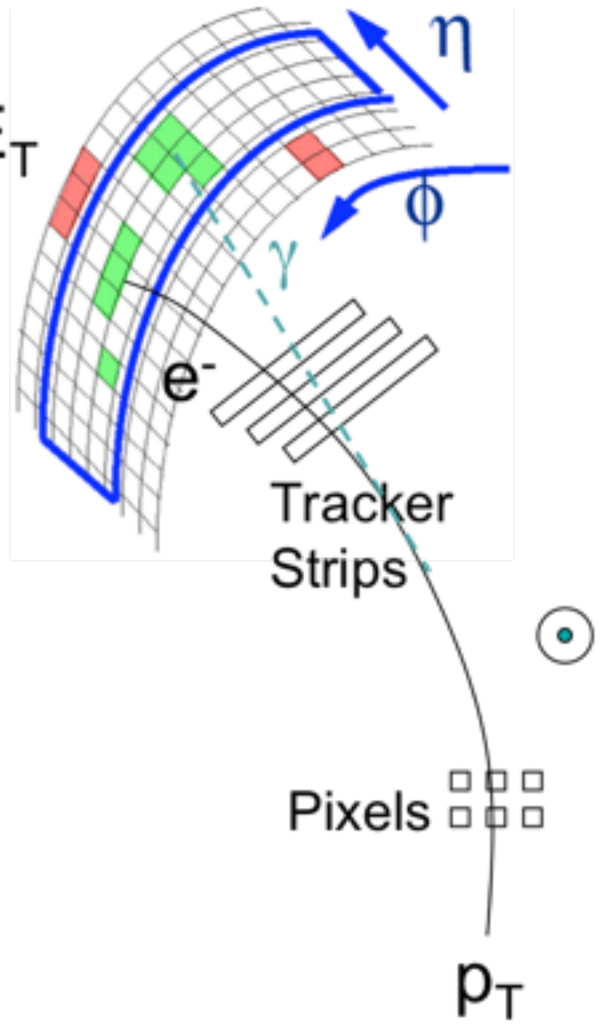
- Match Elements to form 'blocks' and avoid double counting

Reconstructed Particles:

Photons, Charged/Neutral Hadrons, Muons, Electrons, $\not{E}_T = -\sum(p_T \text{ PF cands})$

Serves as an input for higher level reconstruction algorithms

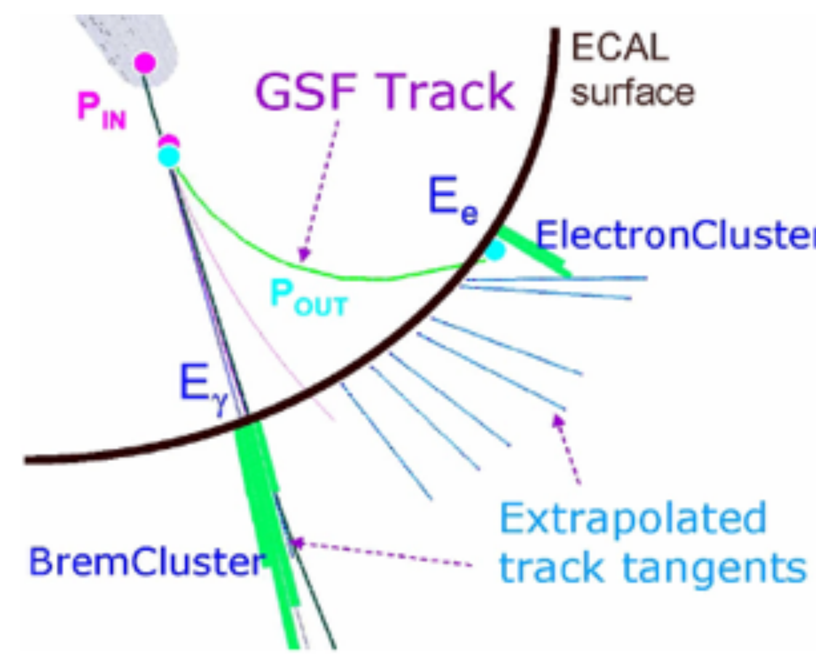
Electron/Photon Reconstruction



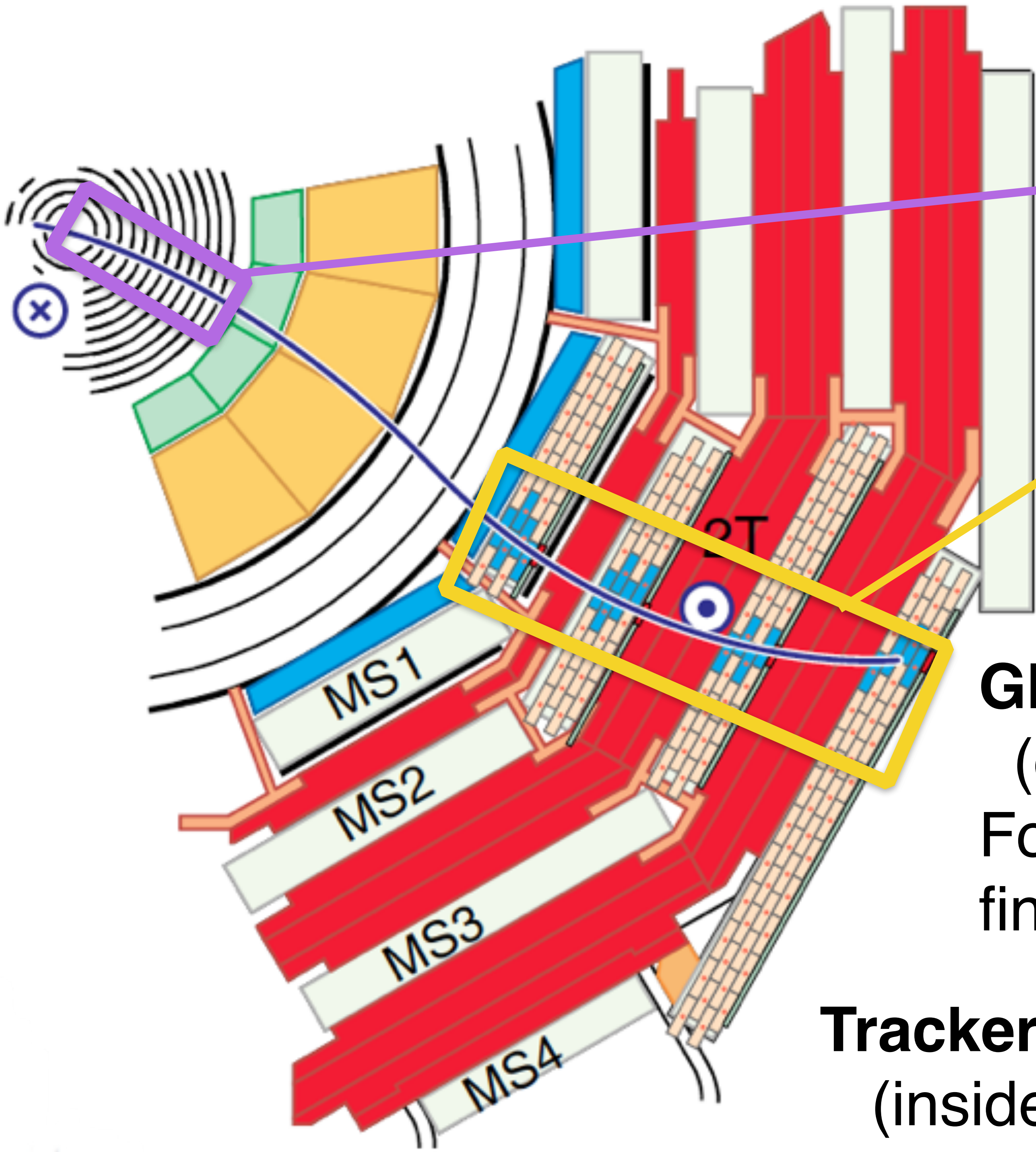
Electron: match superclusters to track seeds
Photon: superclusters unmatched to track seeds

Supercluster:
Group of clusters of ECAL energy deposits
Uses Strip in ϕ to Account for
  Bremsstrahlung Radiation
Loose cut on HCAL / ECAL energy deposit ratio

Track Seed:
Iteratively ID hits in tracker
Expect helical path if no Bremsstrahlung radiation
Kinks indicate emission of Bremsstrahlung Photons
  Search a straight line tangent to track for ECAL hit



Muon Reconstruction



Tracker Muon Track
Reconstructed from inner tracker

Standalone Muon Track
Using muon stations

Global-Muon Reconstruction
(outside-in: high p_T muons)
For each standalone-muon track
find matching tracker track + reconstruct

Tracker-Muon Reconstruction
(inside-out: low p_T muons)
For tracker track ($p_T > 0.5$ GeV, $p > 2.5$ GeV)
find standalone-muon track + reconstruct

Isolation

Muons, electrons from W decay and ISR photons leave collimated energy deposits in the detector

Require only minimal energy deposits nearby (isolated) reduces incorrect identification

Leptons: I < 0.12 (0.10) for muon (electron) in ΔR < 0.4 (0.3)

$$I = \frac{\sum p_T^{\mathrm{charged}} + \max(0, \sum p_T^{\gamma} + \sum E_T^{\mathrm{neutral}} - 0.5 \cdot p_T^{\mathrm{PU}})}{p_T^{\ell}}$$

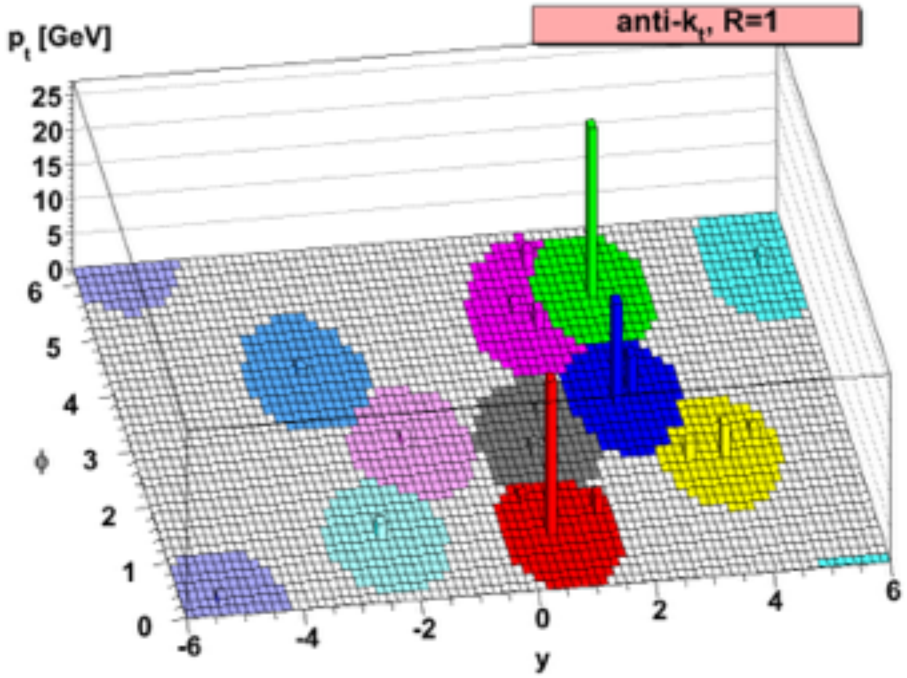
Photon: sums within ΔR < 0.3

$\sum (p_T \text{ photons}) < 0.28 + 0.0053\, p_T$

$\sum (p_T \text{ neutral hadrons}) < 1.06 + 0.014\, p_T + 0.000019\, p_T^2$

$\sum (p_T \text{ charged hadrons}) < 1.37$

Jets Clustering and SV Identification



Energetic colored particles hadronize to into "jets"

Anti-k_T Algorithm for Jet Clustering

$$d_{ij} = \min\left(1/p_{T,i}^2 ,\ 1/p_{T,j}^2 \right) \frac{\Delta R_{ij}^2}{R^2}$$

$$d_{iB} = 1/p_{T,i}^2$$

Highest p_T track, *i*, called a jet

For Subsequent Tracks, *j*:

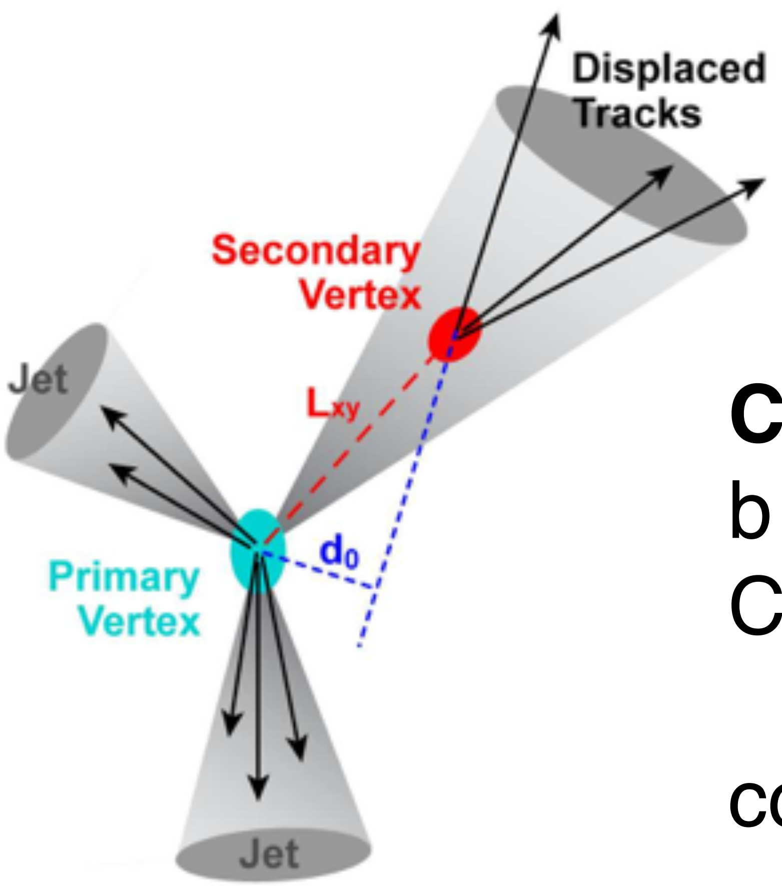
If $d_{ij} < d_{iB}$: combine with *i*

Else *j* is a jet

Soft particles cluster around hard ones

Hard shape is circular, clips from soft particles

Collinear and Infrared Safe



Combined Secondary Vertex (CSV) Algorithm

b hadrons have long life (travel mm)

CSV is a multivariate analysis / neural network

displaced tracks, secondary vertices, soft leptons

combine information into single variable to “b-tag” jets

The Standard Model and dark matter

The LHC and CMS

Simulation and reconstruction

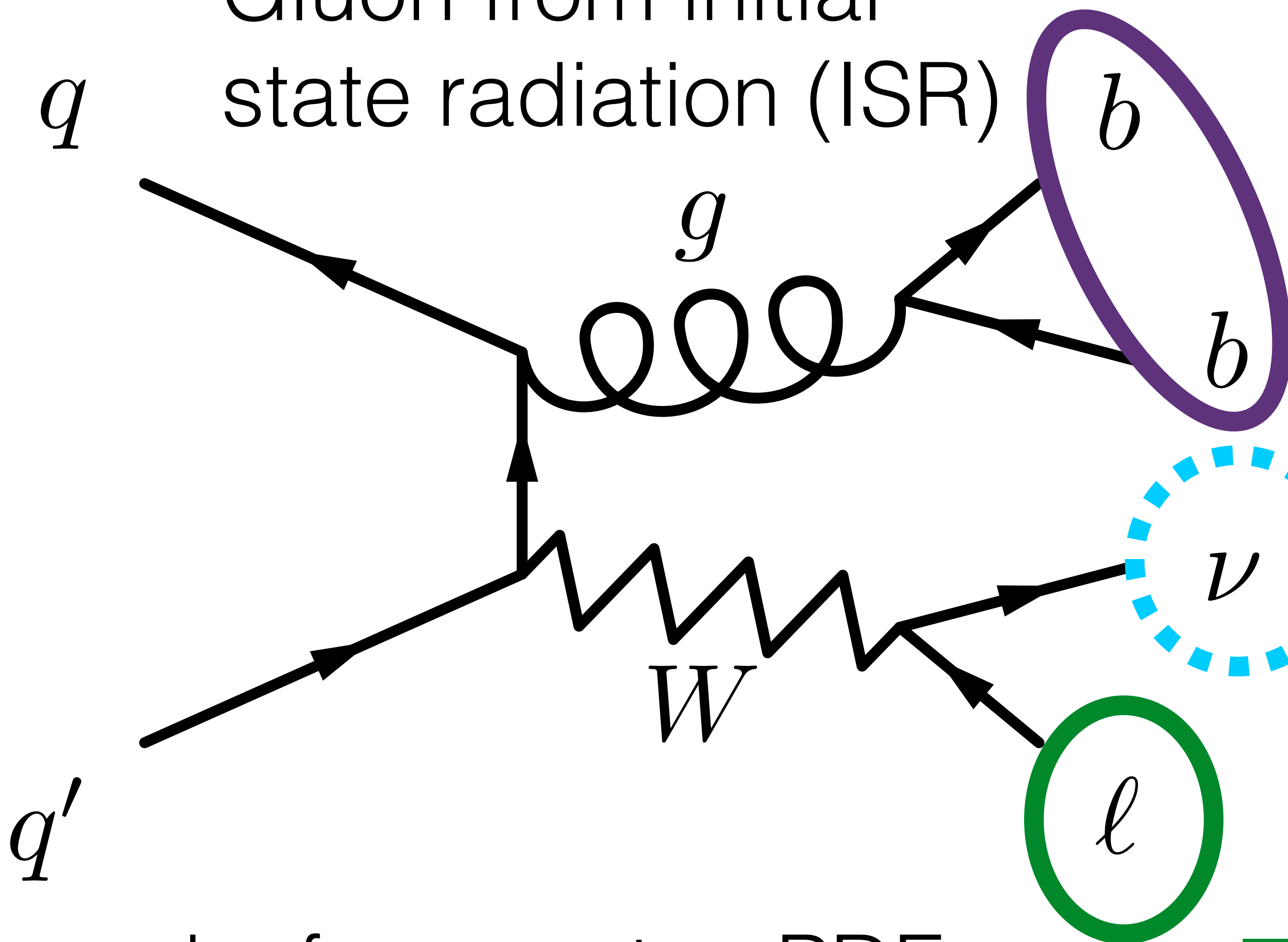
$Wb\bar{b}$ cross section measurement

Monophoton analysis

Conclusions and future prospects

$Wb\bar{b}$ Phenomenology

Gluon from initial state radiation (ISR)



quarks from proton PDF

$b\bar{b}$ signature is two hadron showers (jets), each from a SV

Neutrinos leave $\not{E}_T$ in the detector

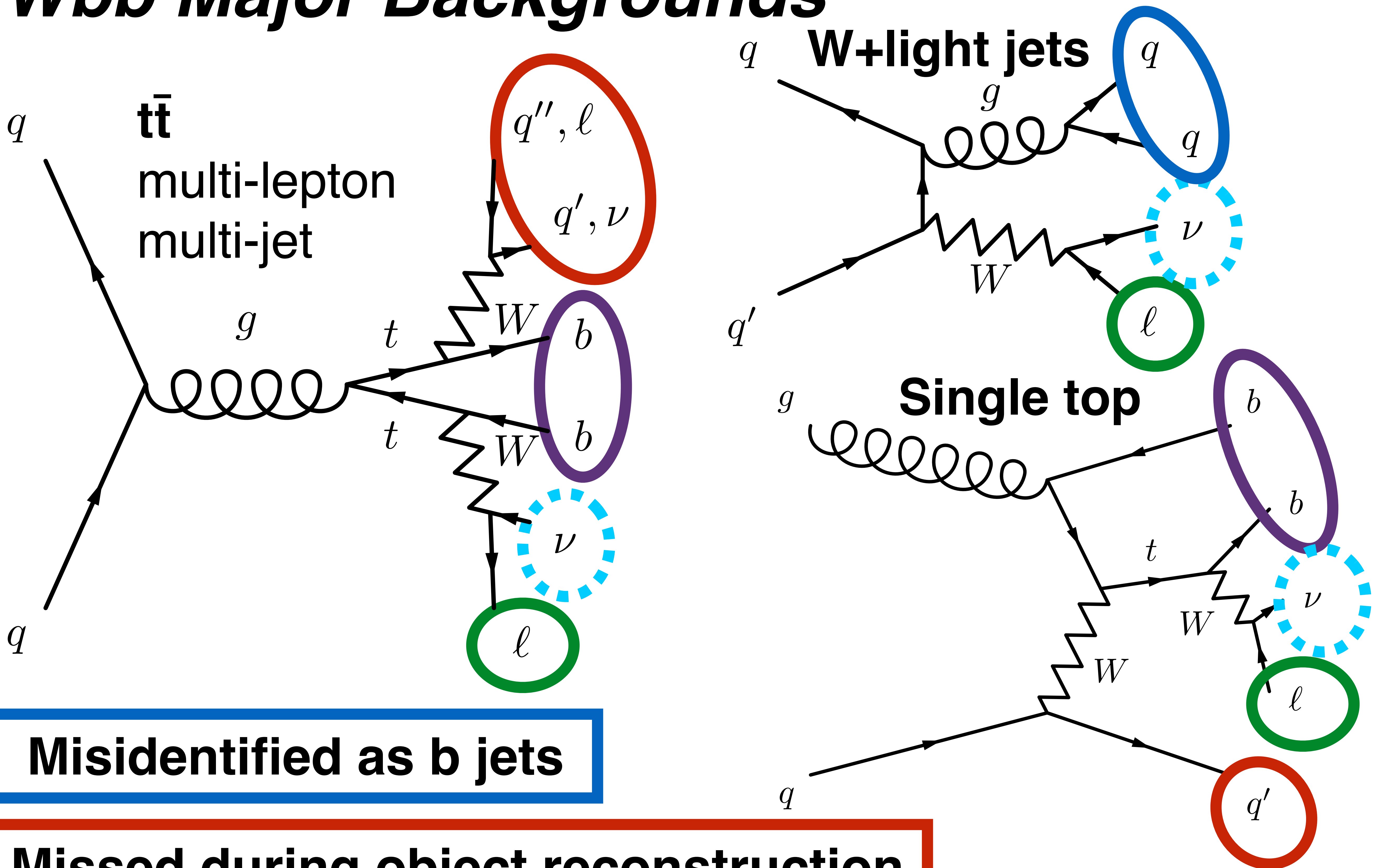
Leptons (electron or muon) leave isolated energy deposits

Transverse mass of W boson:

$m_T{}^2 = 2\, p_T{}^{lep}\, \not{E}_T\, (1 - \cos\phi)$

ϕ = angle btw lepton and $\not{E}_T$

$Wb\bar{b}$ Major Backgrounds



Misidentified as b jets

Missed during object reconstruction

Previous Wb($\bar{b}$) measurements

Fermilab (Tevatron) at 1.96 TeV

$p\bar{p} \rightarrow Wbj \rightarrow \ell\nu bj$ (j is a jet, b is a b jet)

CDF Collaboration measured cross section twice as high as best NLO prediction at the time

DØ Collaboration measured cross section 20%-40% higher than various NLO predictions

CERN (LHC) at 7 TeV

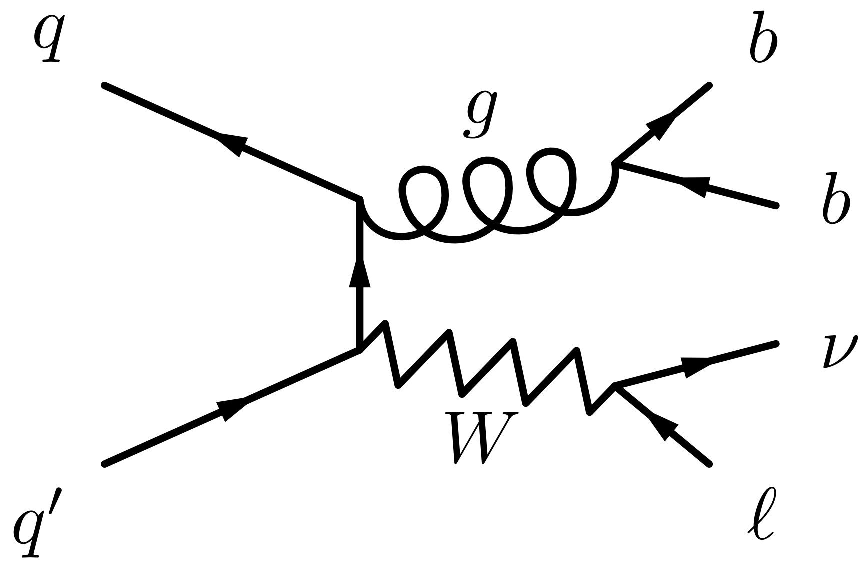
Atlas Collaboration: $pp \rightarrow Wbj \rightarrow \ell\nu bj$

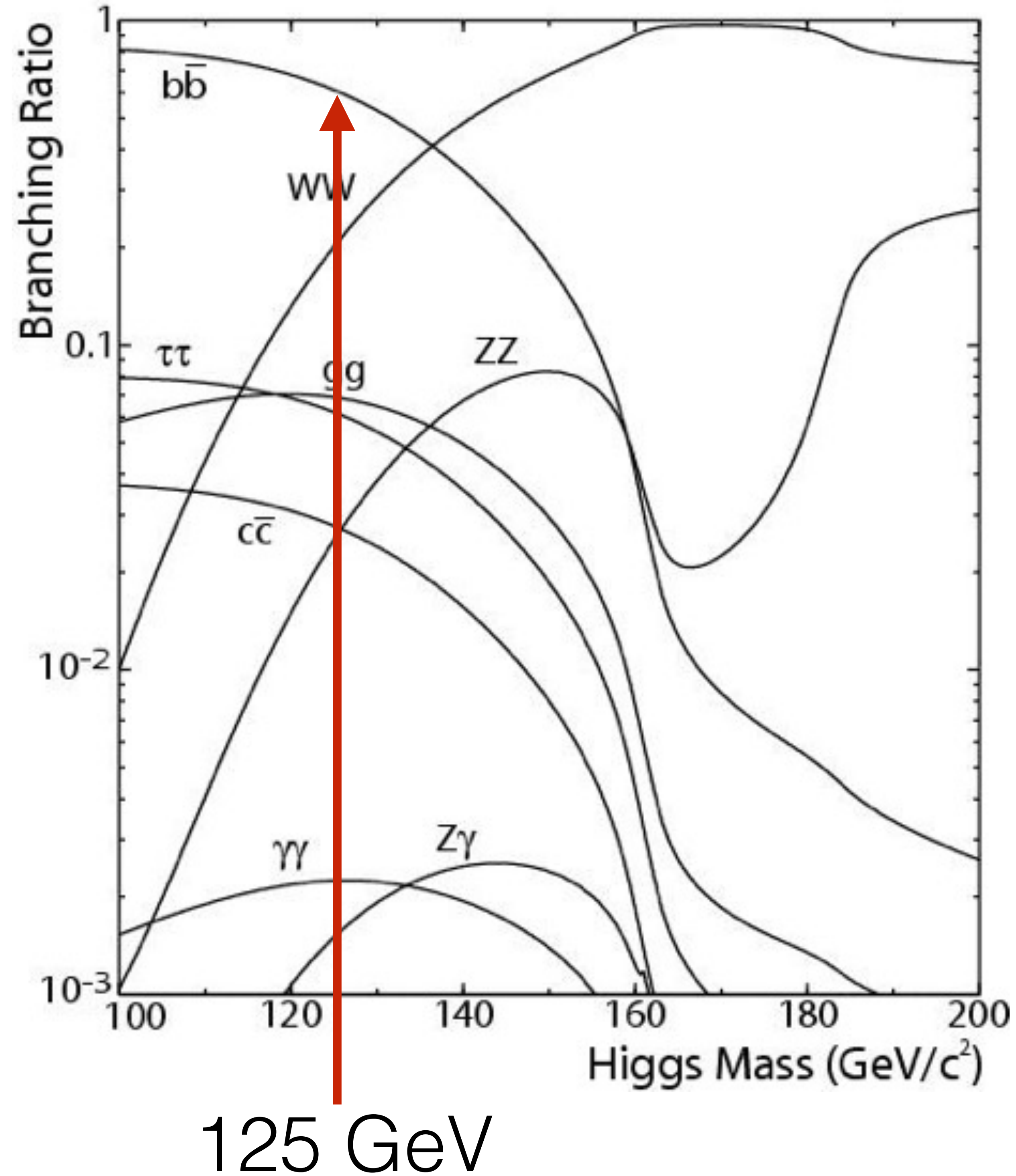
1 jet: 70% high, 2 jets: 30% high

CMS Collaboration: $pp \rightarrow Wb\bar{b} \rightarrow \ell\nu b\bar{b}$

Agreement within 4% (I also worked on this)

$Wb\bar{b}$ in the Standard Model





Atlas, CDF, DØ Collaborations see tension between simulation and observation for W+b($\bar{b}$)

Important for Searches

H($b\bar{b}$) has highest branching ratio

E_T^{miss} + lepton + heavy quark predicted in non-SM models

This is the only cross section measurement in this phase space and energy

$Wb\bar{b}$: Selections

Exactly two jets
- $p_T > 25$ GeV, $|\eta| < 2.4$
- ΔR(jet, lepton) > 0.5
- both b-tagged with CSV

Jet veto
- reject events with 3rd jet
- $p_T > 25$ GeV, $|\eta| < 4.7$

Exactly one isolated lepton
- muon or electron
- passed HLT path (slide 25)
- $p_T > 30$ GeV, $|\eta| < 2.1$

Lepton veto
- reject events with 2nd lepton
- $p_T > 10$ GeV, $|\eta| < 2.1$

Require two b jets not merged

Light / Charm background rejection

TTbar background rejection

W identification

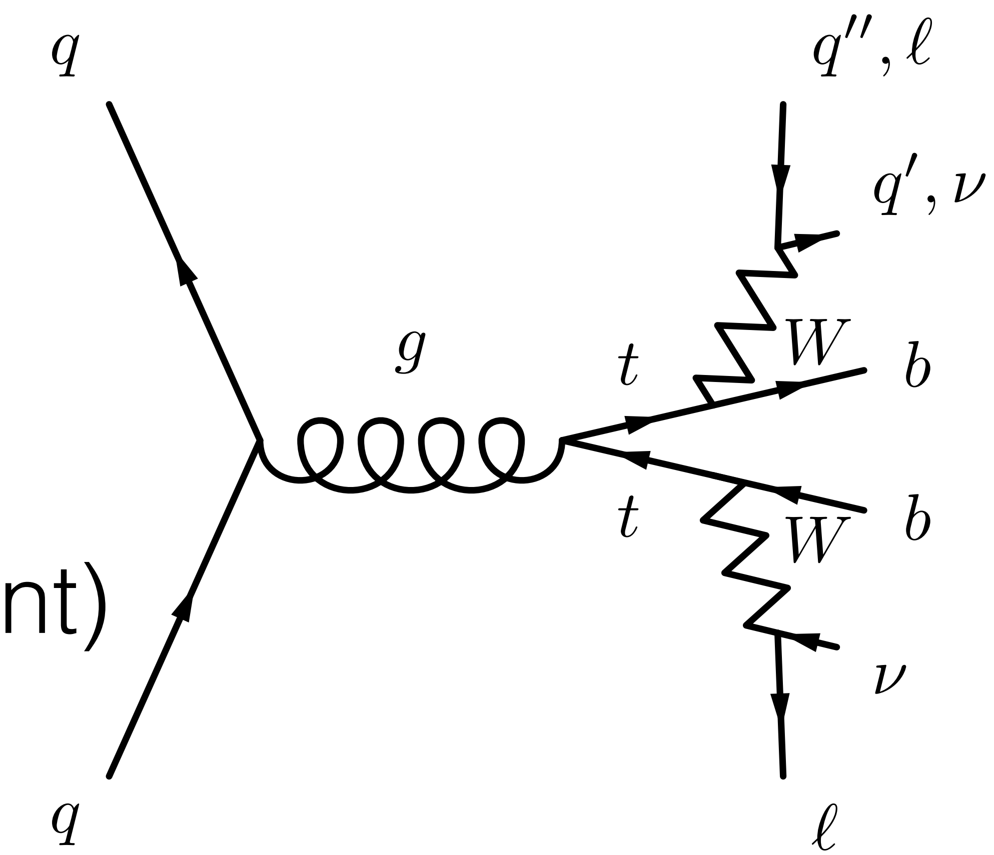
Background rejection for TTbar and Drell-Yan (Z+qq)

$Wb\bar{b}$: Pre-Fitting Procedure

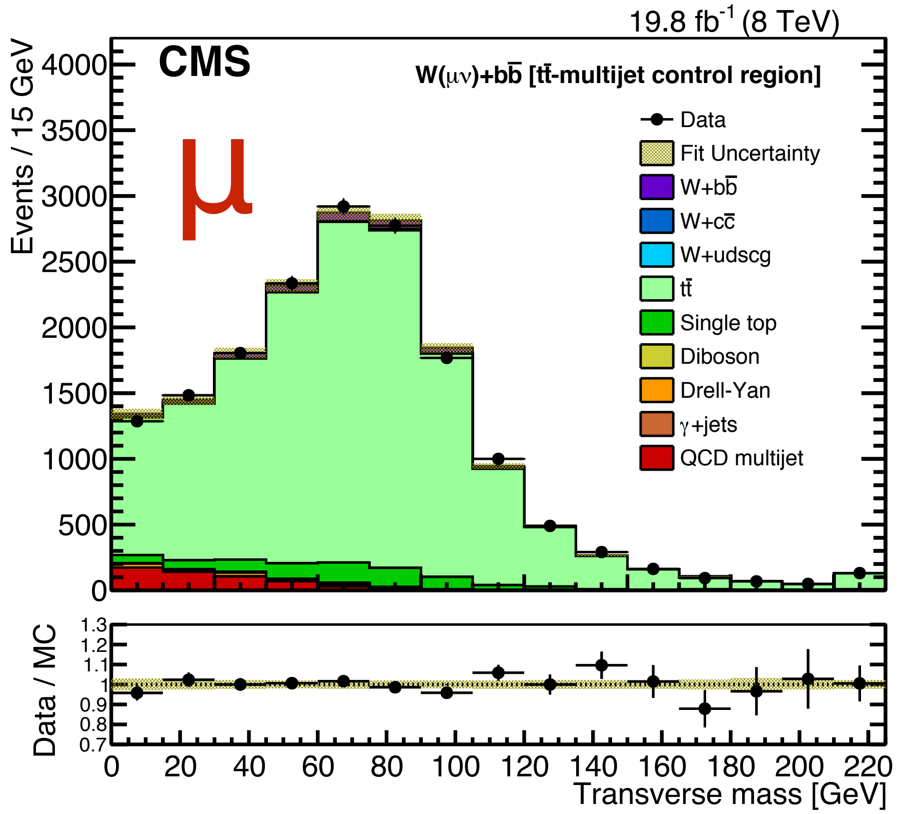
Use two ttbar control regions very similar to signal region
isolate b-tagging efficiency and jet energy scale (JES) uncertainties

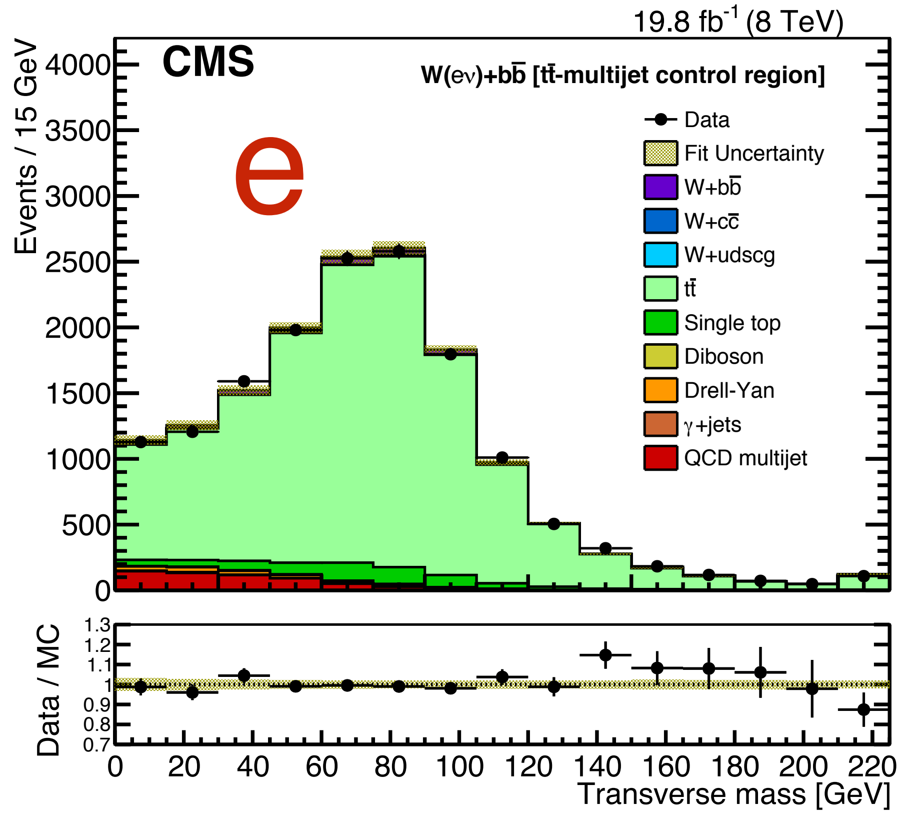
TTbar-multijet region:
Drop veto on events with 3rd jet, require at least three jets
No jet veto = not sensitive to JES
rescale simulation by 14% (b-tagging efficiency)

TTbar-multilepton region:
Drop veto on events with 2nd lepton
require two leptons, opposite flavor
Sensitive to JES and b-tag efficiency
Rescale by ~3.4% (process-dependent)

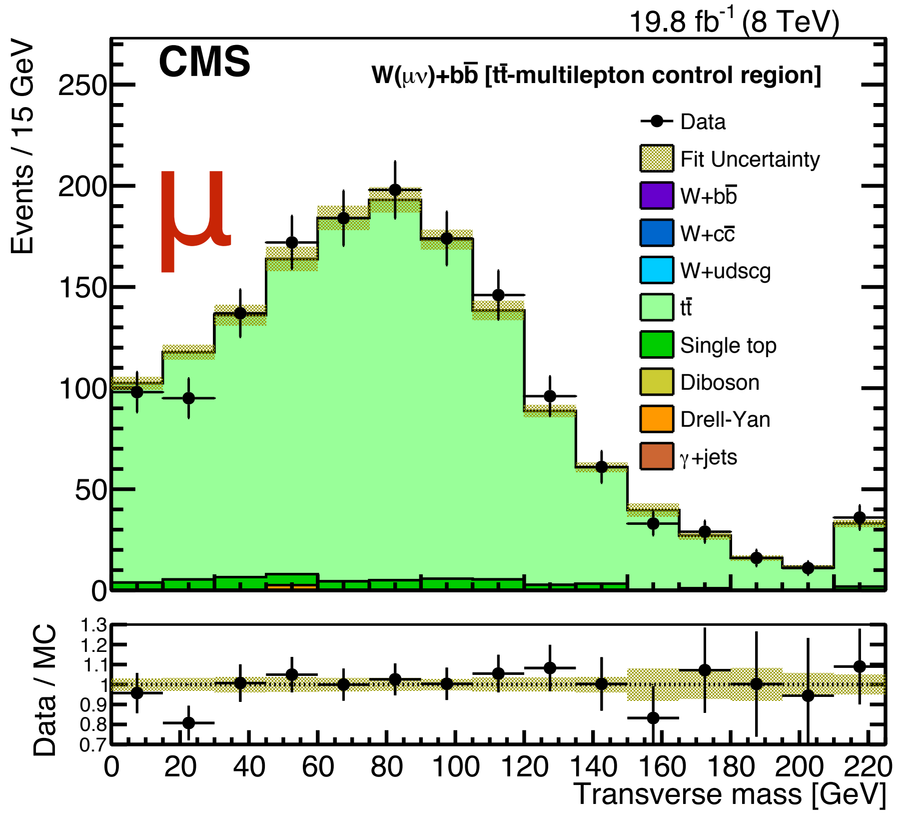


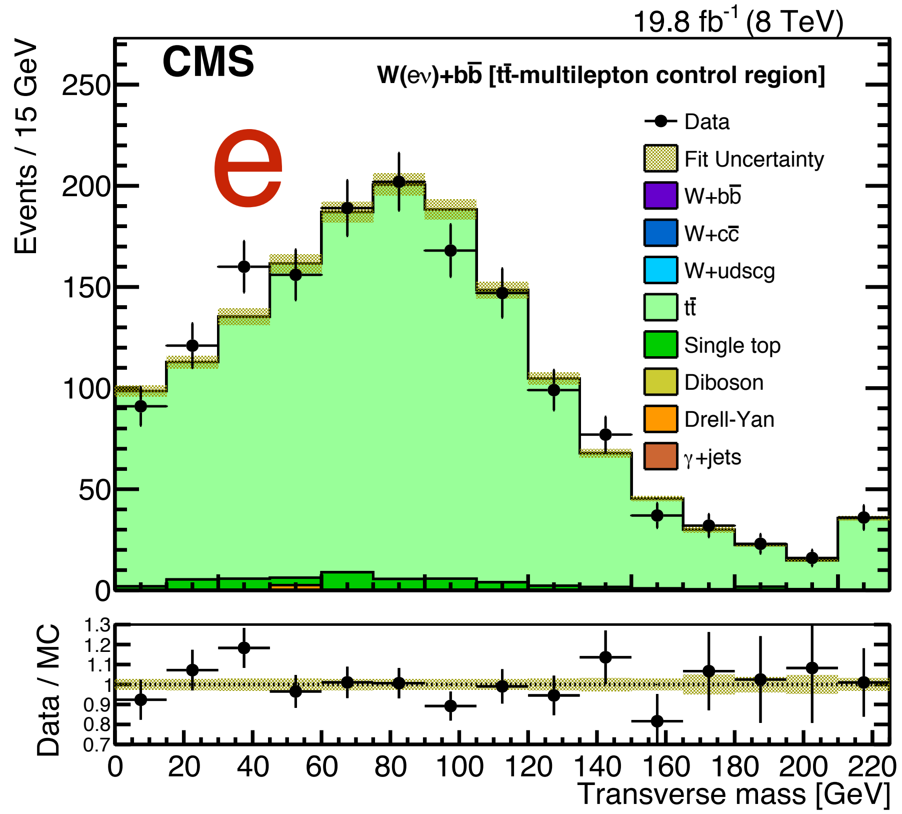
$Wb\bar{b}$: TTbar Fits





TTbar Multijet Control Region Fit Result





TTbar Multilepton Control Region Fit Result

$Wb\bar{b}$: Systematic Uncertainties

Source of Uncertainty	Effect on Measured Cross Section
TTbar cross section	3.8 %
Single top cross section	2.5 %
QCD rate	2-3 %
Other SM cross sections	< 2 %
b-tag efficiency rescaling	9.2 %
Jet Energy Scale rescaling	3.8 %
Lepton Energy Scales	< 2 %
Lepton ID / Isolation / Trigger efficiencies	<2 %
Luminosity	2.6 %
Theoretical on Simulation	10 %

Theoretical uncertainty on cross section of specific process (published measured uncertainty for TTbar)

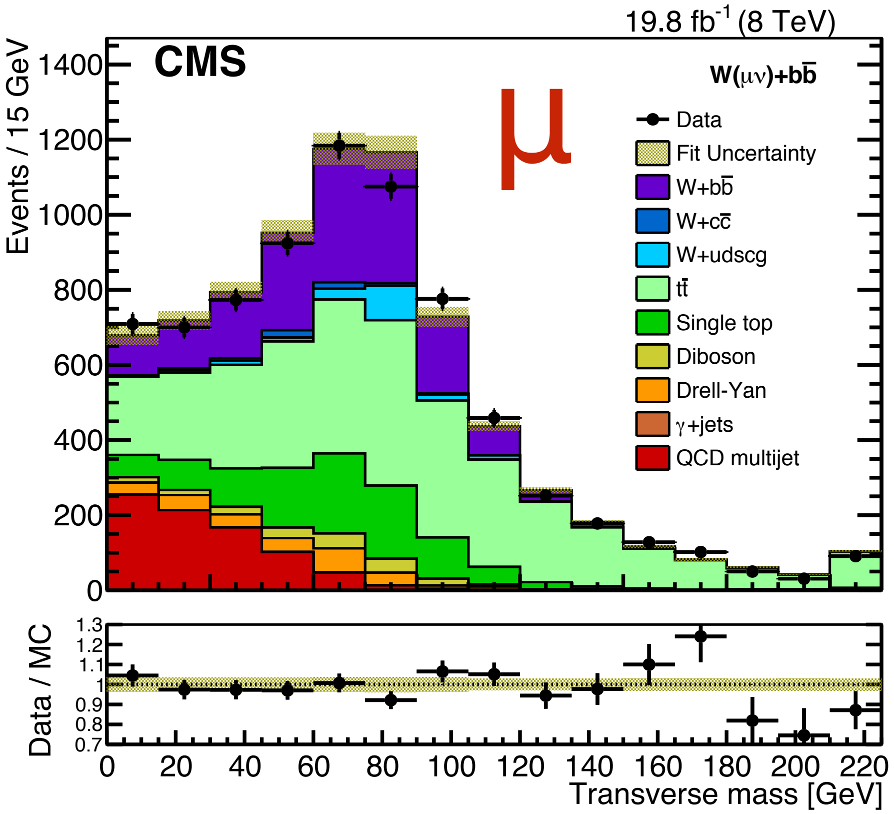
Uncertainties from fitting procedures

Uncertainty on reconstruction of particles

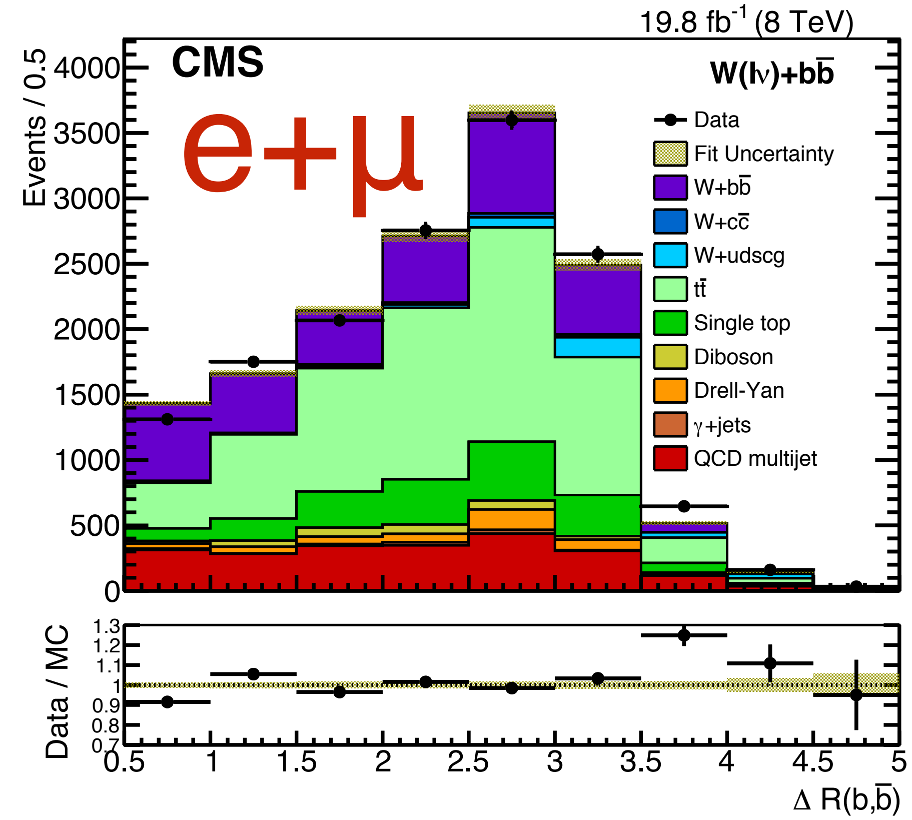
Measured centrally by CMS

Theoretical uncertainty on simulation

$Wb\bar{b}$: Fitted Distributions

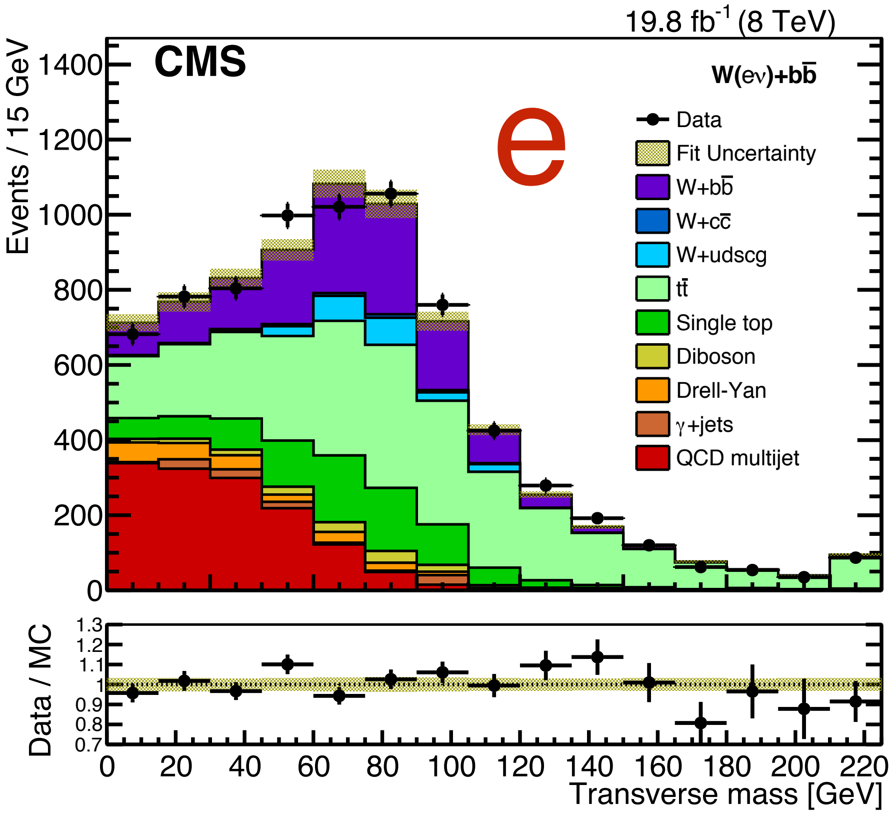


After fitting, good agreement between data and simulation



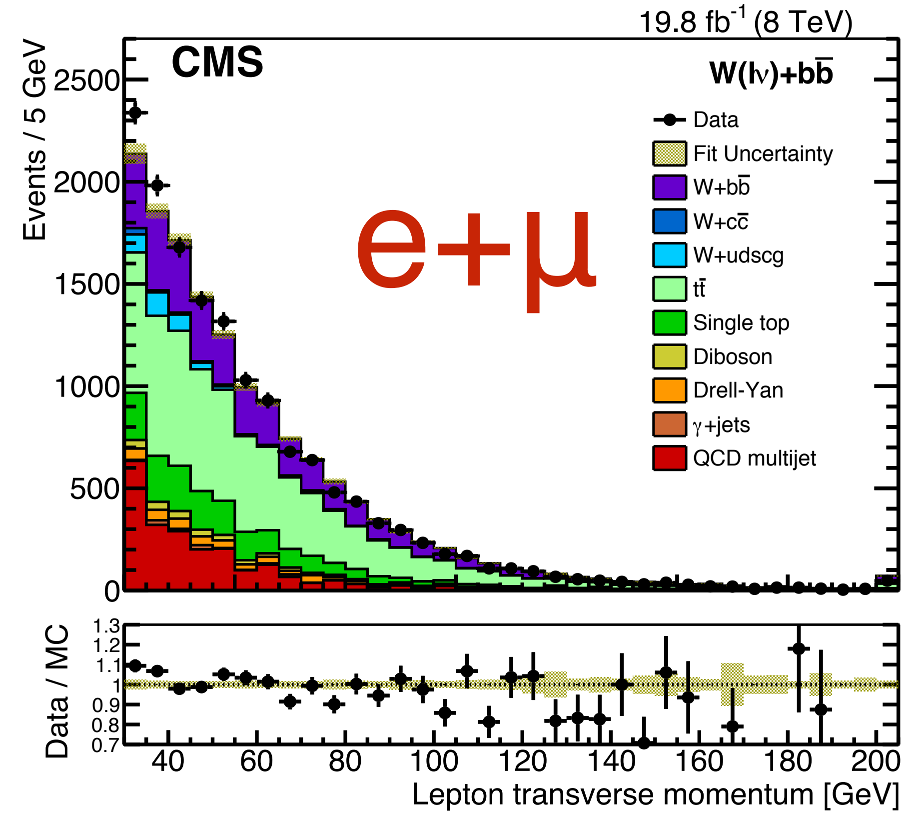
Left:

m_T distributions used in fit



Right:

separation between b jets and lepton p_T



$Wb\bar{b}$: Cross Section

Yields in data and simulation before and after fitting in the signal region

Signal strength from fit factors systematic effects from cross section

	Muon		Electron	
	Initial	Fitted	Initial	Fitted
Data	7432		7357	
$Wb\bar{b}$	1323	1712	1121	1456
$Wc\bar{c}$	60	61	36	37
$Wusdcg$	182	179	220	217
$t\bar{t}$	3049	3296	2640	2864
Single top	958	1008	820	865
Drell-Yan	261	265	220	224
Diboson	175	181	139	144
γ+jets	-	-	98	105
QCD	1109	803	1654	1373
Total MC	7116	7505	6948	7284
Signal strength	1.21 ± 0.19		1.37 ± 0.23	
Combined	1.26 ± 0.17			

$$\sigma(pp \to Wb\bar{b} \to \ell\nu b\bar{b}) = \frac{N^{\mathrm{Data}}_{\mathrm{signal}}}{A \cdot \epsilon \cdot \mathcal{L}} = \frac{N^{\mathrm{Data}}_{\mathrm{signal}}}{(N^{\mathrm{MC}}_{\mathrm{signal}}/N^{\mathrm{MC}}_{\mathrm{generated}}) \cdot \mathcal{L}} = \alpha\sigma_{\mathrm{gen}}$$

$Wb\bar{b}$: Cross Section Comparisons

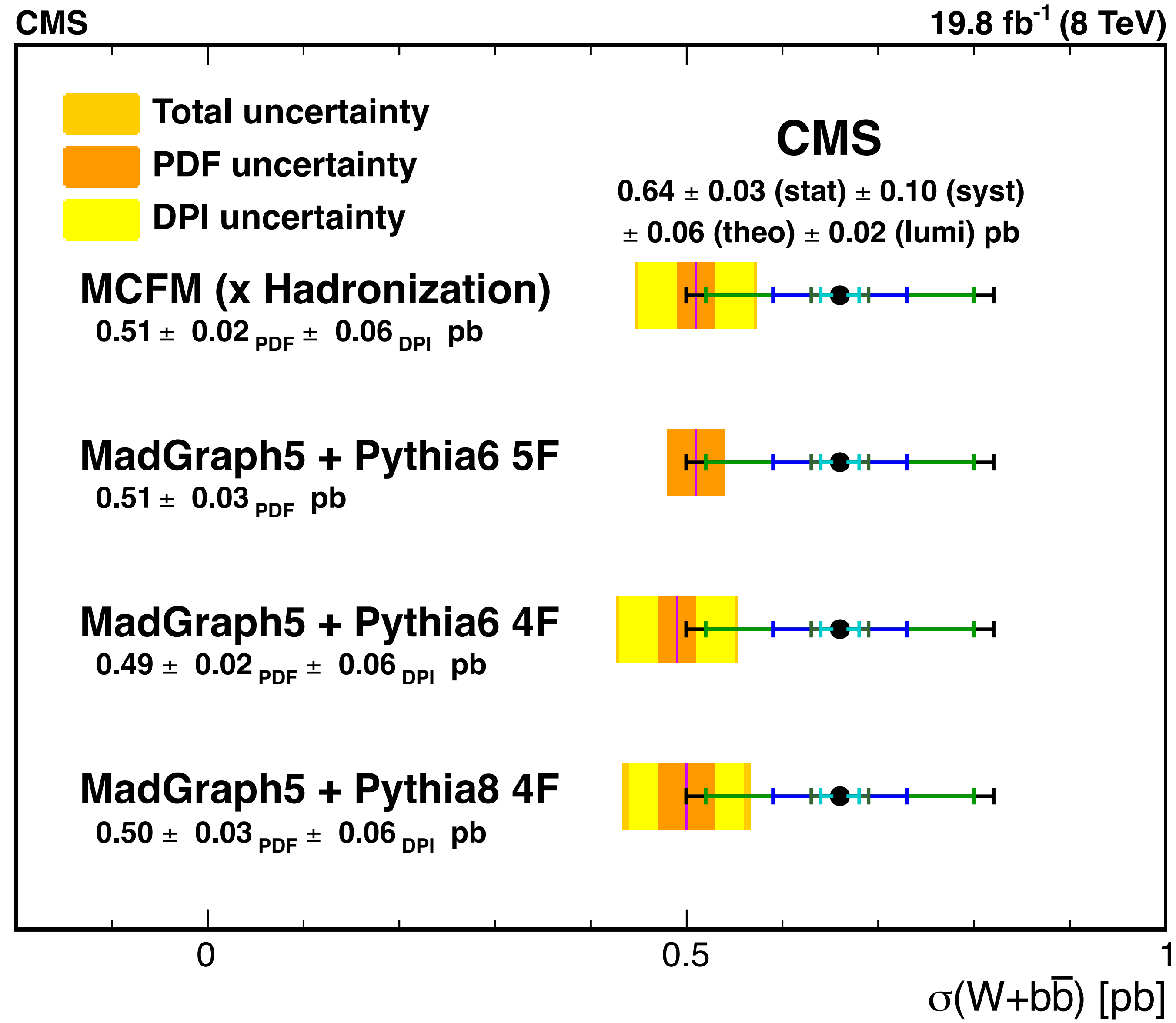
Measured cross section is within one standard deviation of predictions
- systematically high

MCFM (NLO)

Parton level calculation (81% correction factor for parton→hadron)

MCFM / 4F MADGRAPH samples

Don't include effects of multiple partons scattering - additive correction calculated at 0.06 ± 0.06 fb
Double Parton Interaction = DPI



Channel	$\sigma(pp \to Wb\bar{b} \to \ell\nu b\bar{b})$ pb
Combined	$0.64 \pm 0.03(\text{stat}) \pm 0.10(\text{syst}) \pm 0.06(\text{theo}) \pm 0.02(\text{lumi})$
Muon	$0.62 \pm 0.04(\text{stat}) \pm 0.11(\text{syst}) \pm 0.06(\text{theo}) \pm 0.02(\text{lumi})$
Electron	$0.70 \pm 0.05(\text{stat}) \pm 0.15(\text{syst}) \pm 0.07(\text{theo}) \pm 0.02(\text{lumi})$

The Standard Model and dark matter

The LHC and CMS

Simulation and reconstruction

$Wb\bar{b}$ cross section measurement

Monophoton analysis

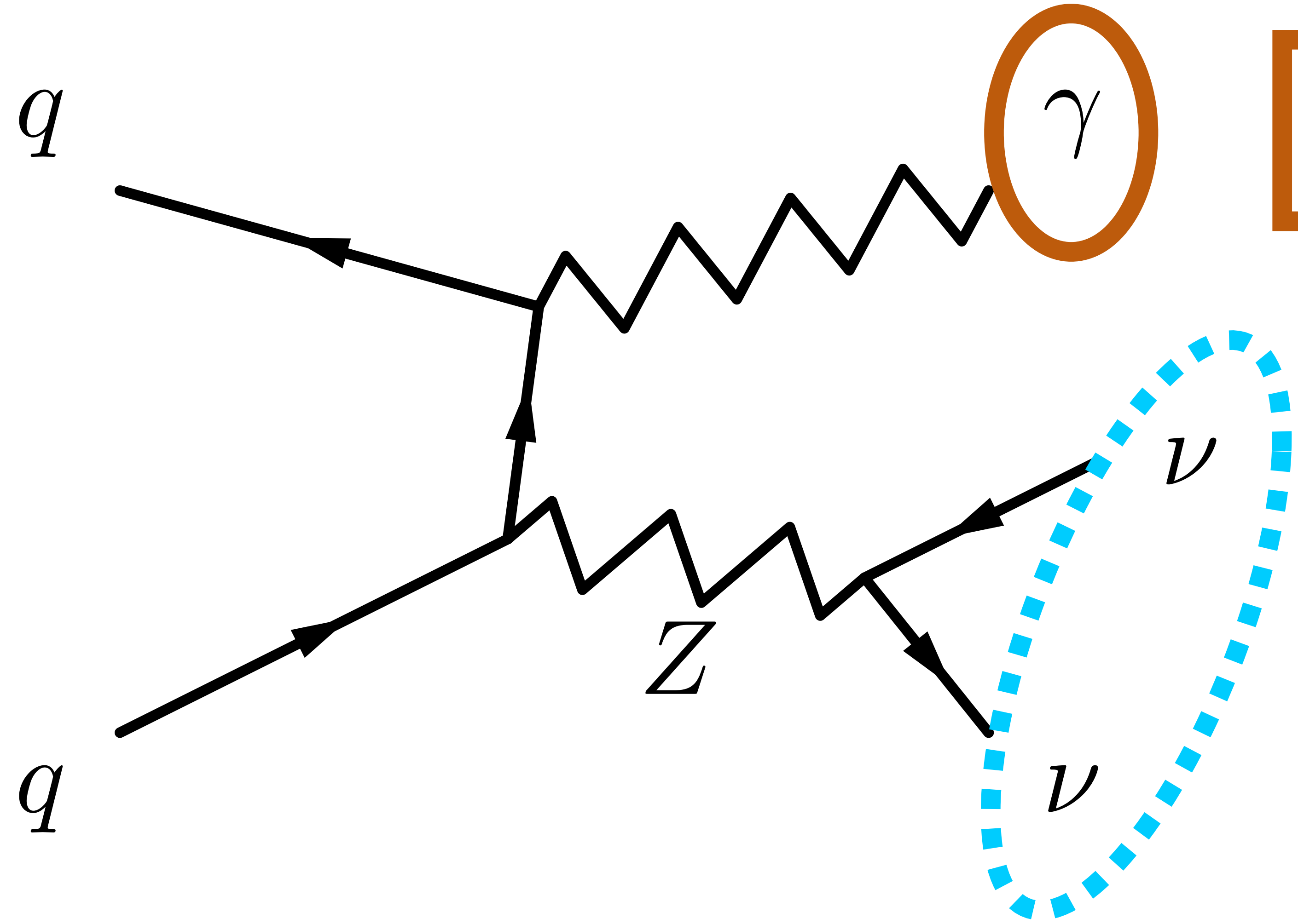
Conclusions and future prospects

SM Monophoton Phenomenology

An ISR photon recoils against a Z boson

Z decays to neutrinos

The photon and missing energy are back-to-back



the monophoton

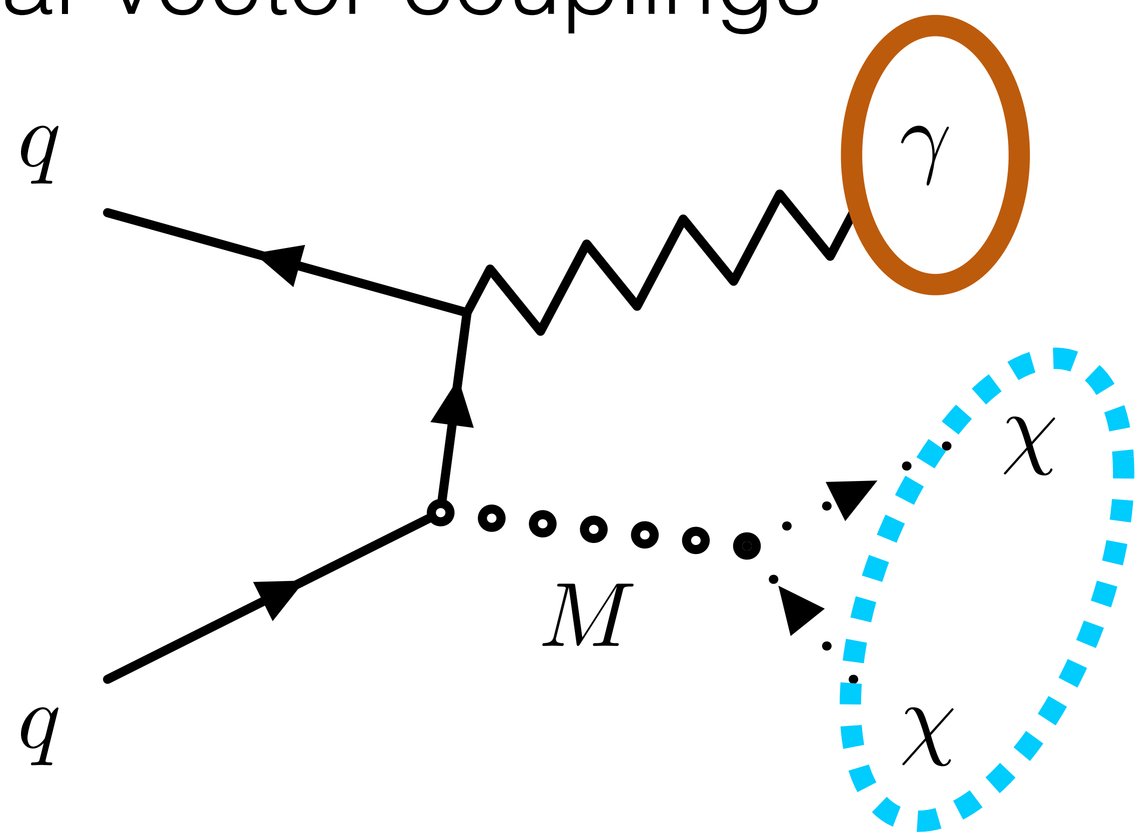
the entire Z boson goes to $\not\!\!E_T$

DM Monophoton Phenomenology

An ISR photon is emitted by $q\bar{q}$ pair

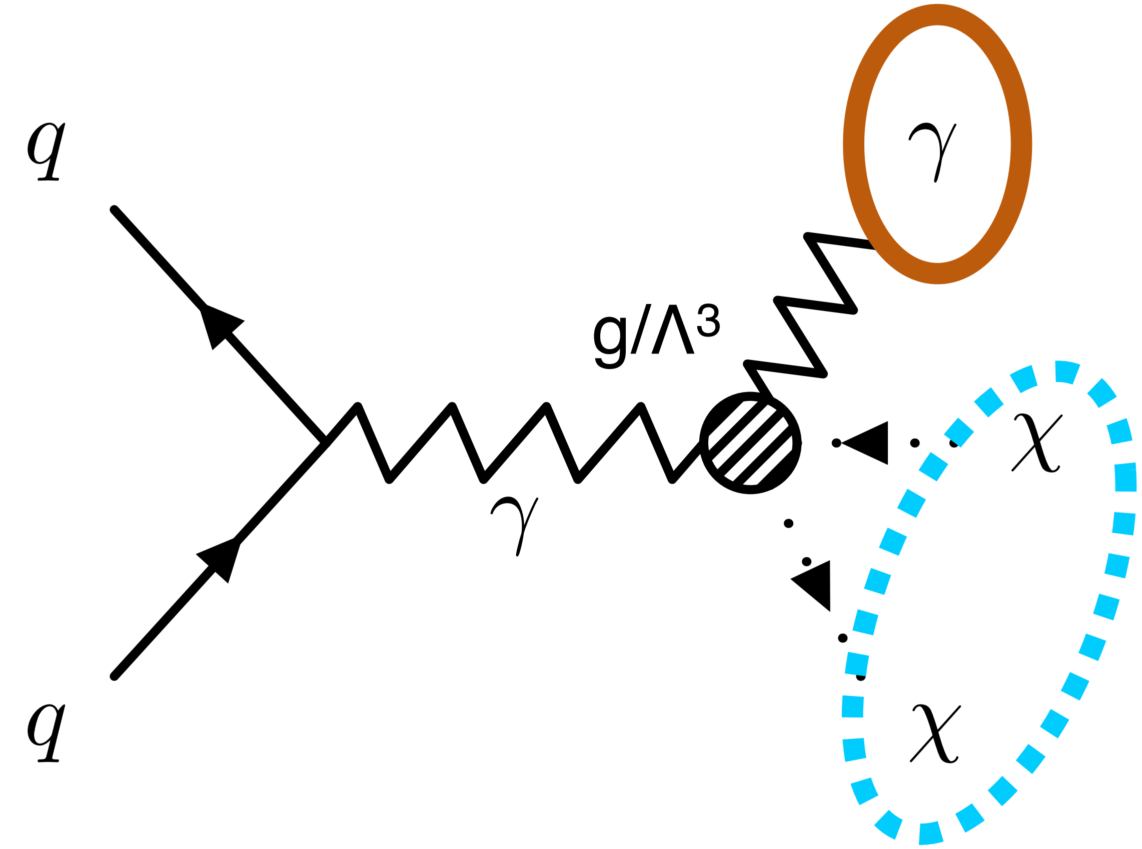
The photon recoils off a mediator M, that decays to dark matter, χ

Mediator can have vector or axial-vector couplings

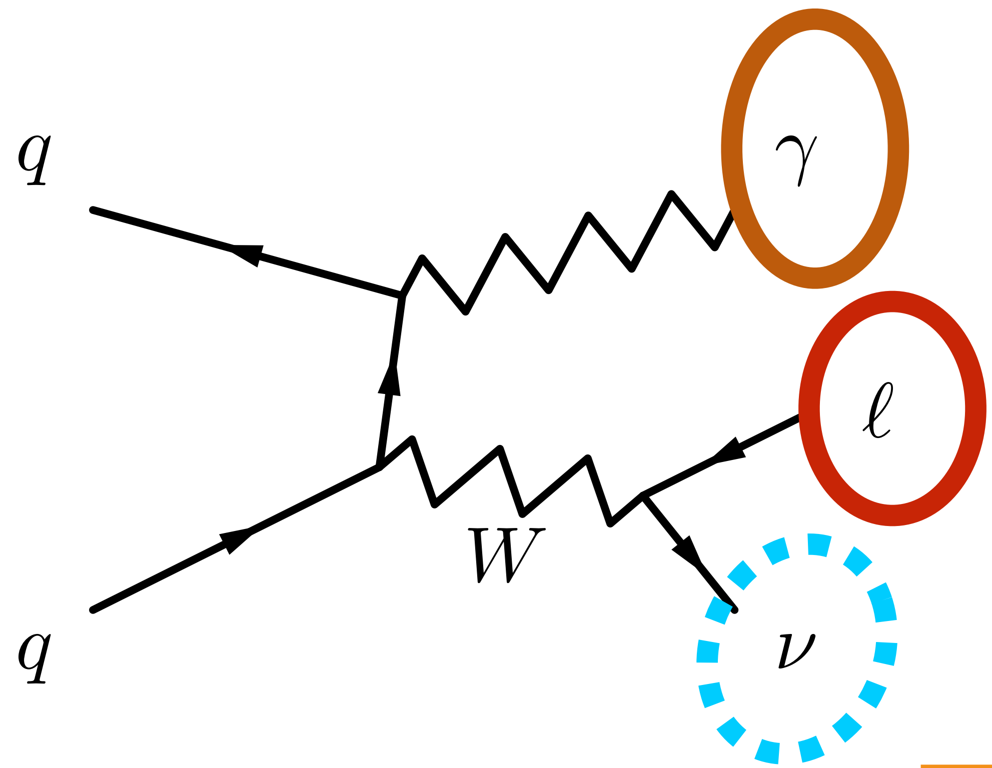


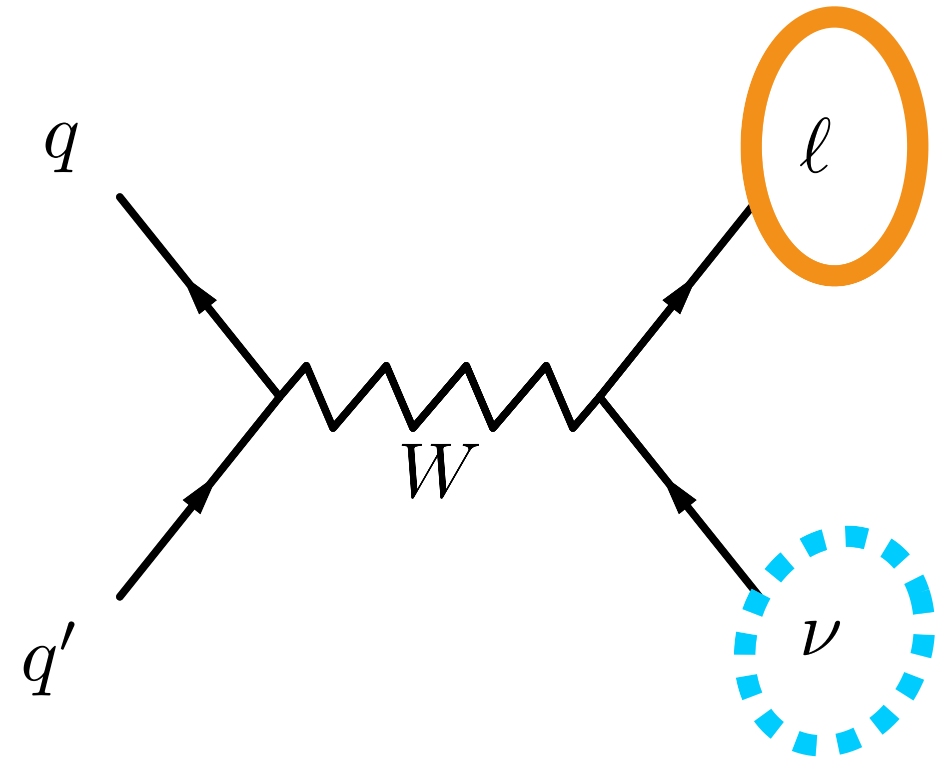
The photon directly couples with DM in an effective field theory (EFT)

This coupling takes a scale Λ



Monophoton Major Backgrounds





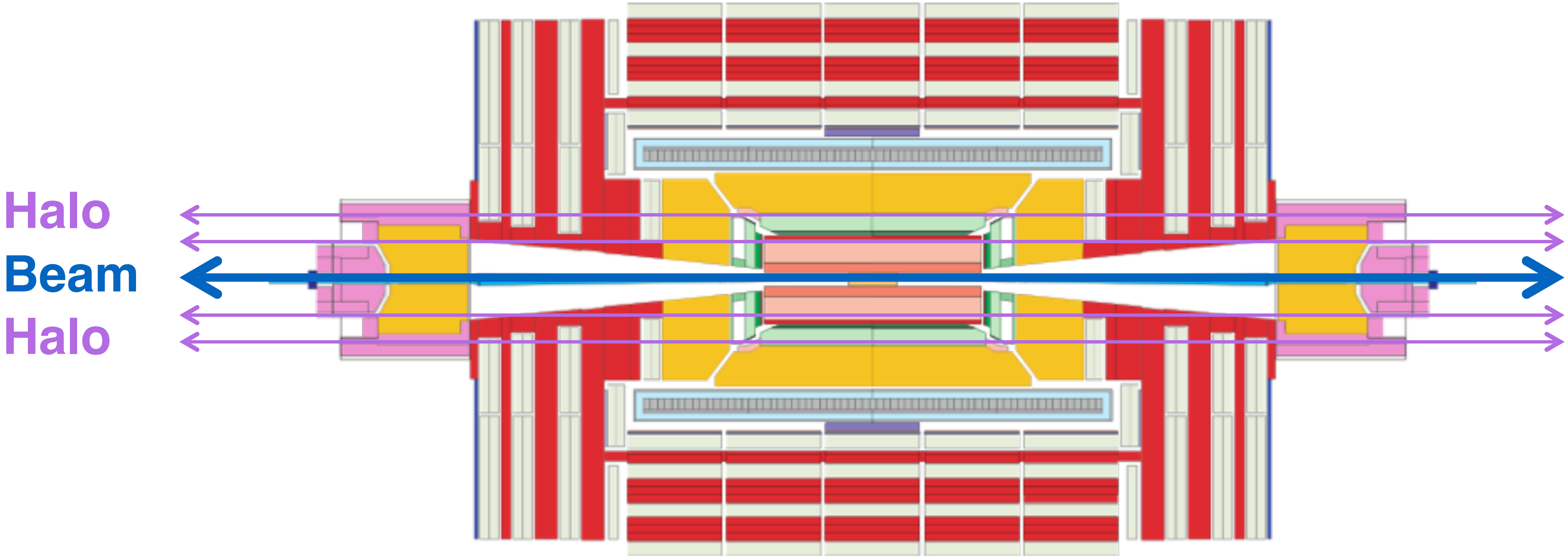
Lepton misidentified as photon

Missed during object reconstruction

Also important are noncollision backgrounds

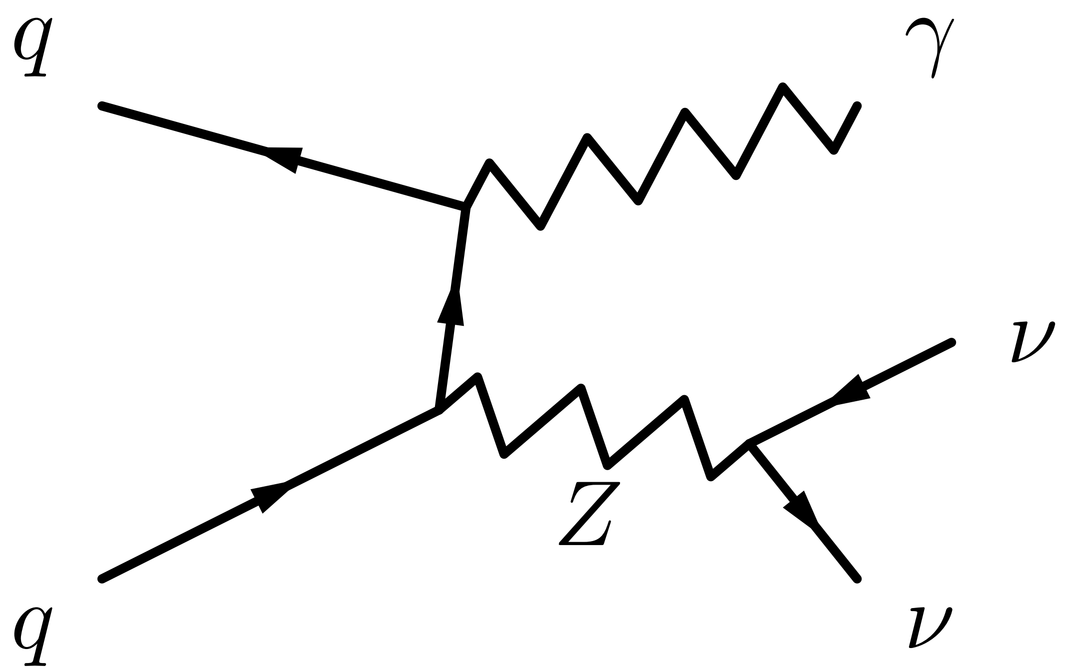
- beam halo - particles (muons) collinear with beam
- spikes - random fluctuations in ECAL

Beam Halo Identification

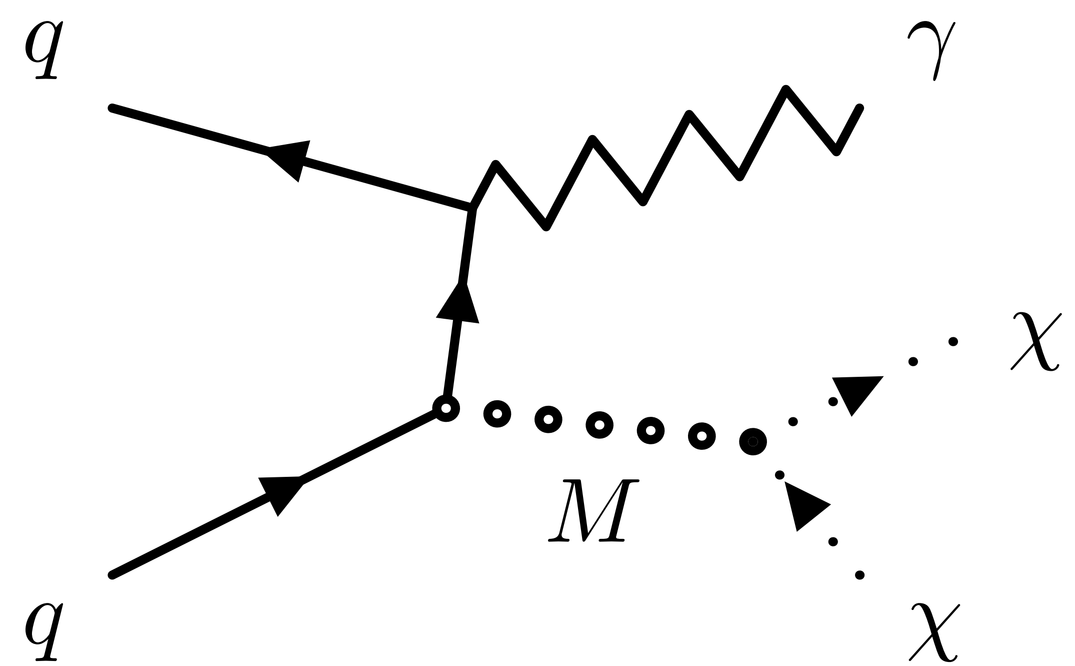


Particles (muons) collinear with beam are called beam halo
Can interact with detector and leave energy in ECAL
Monophoton has no tracks so halo can fake signal
ID halo by performing linear fit on ECAL hits
- add all energy deposits along line
- identified as halo if E > 4.9 GeV
- this technique can only work in the barrel

Monophoton Measurements



Standard Model

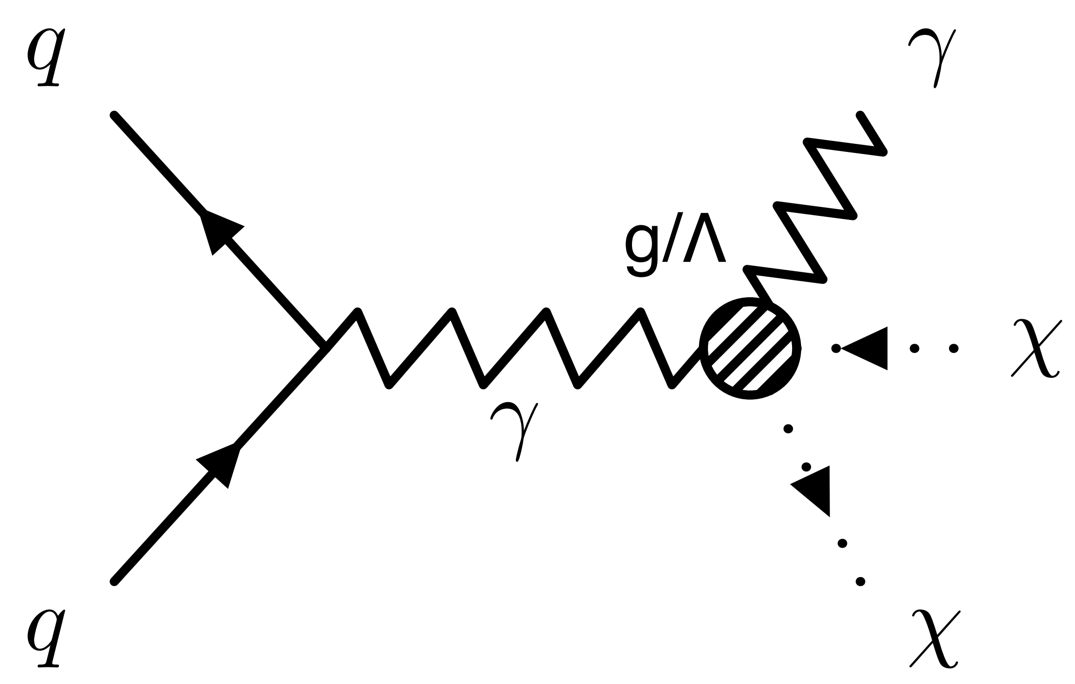


Dark Matter with Mediator

Standard Model
Measure Cross Section

DM with Mediator
Limits on mediator mass

DM with EFT
Limit on coupling scale, Λ



Dark Matter with EFT

Monophoton Selections

Photon passes HLT path

$p_T > 165$ GeV, $E_{ECAL}/E_{HCAL} > 90\%$

Well-reconstructed (mono)photon at high energy

Photon ID, Isolation (calculated wrt. all vertices)

$p_T > 175$ GeV, $|\eta| < 1.44$

beam halo rejection, spike cleaning

Beam halo is difficult to model in endcaps, so restrict to barrel

Lepton Veto (mu, ele)

$p_T^{lep} > 10$ GeV

Monophoton has no extra leptons

PF $\not{E}_T > 170$ GeV

$\Delta\phi$(photon, $\not{E}_T$) > 2

Photon and $\not{E}_T$ should be equal and opposite

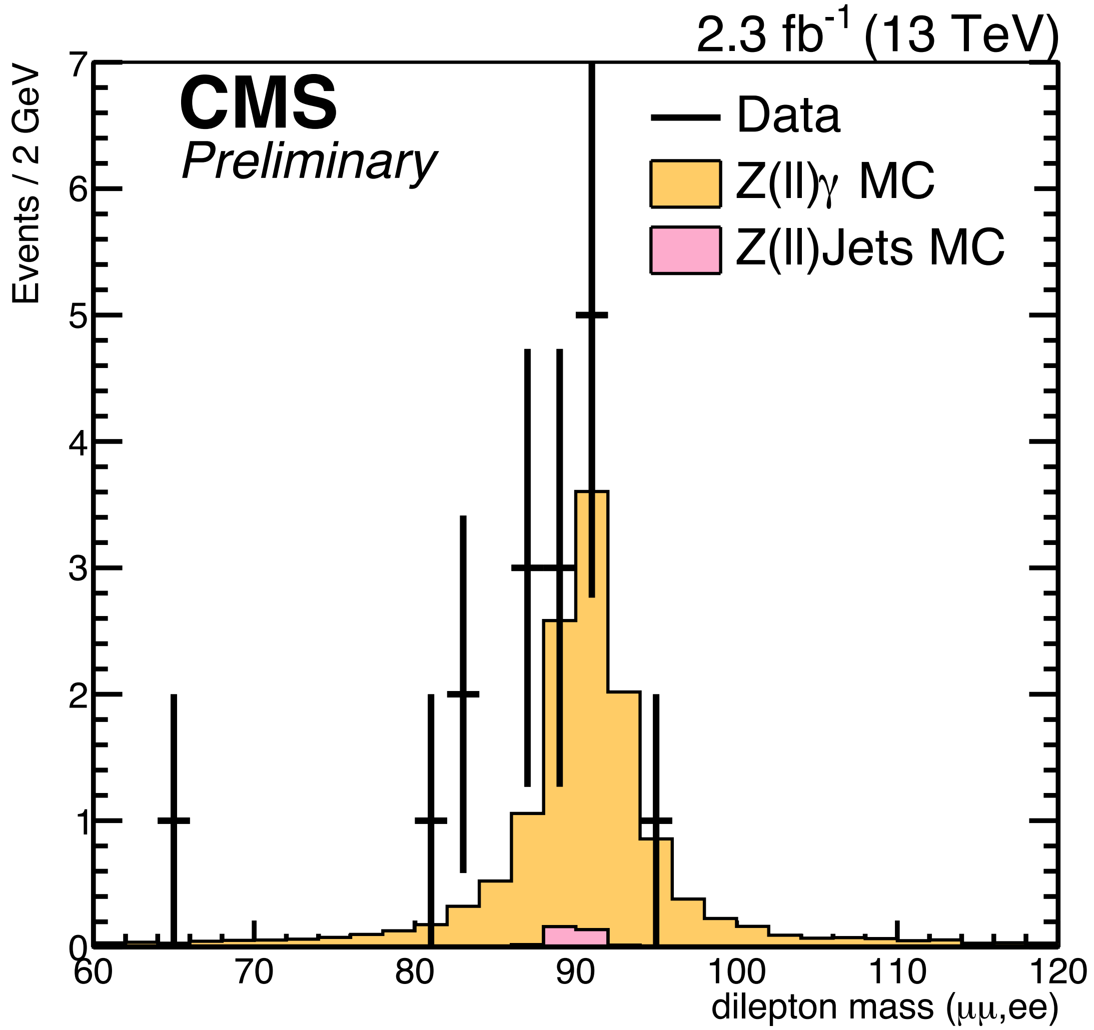
min $\Delta\phi$(jet, $\not{E}_T$) > 0.5

Avoid jet mismeasurement as source of $\not{E}_T$

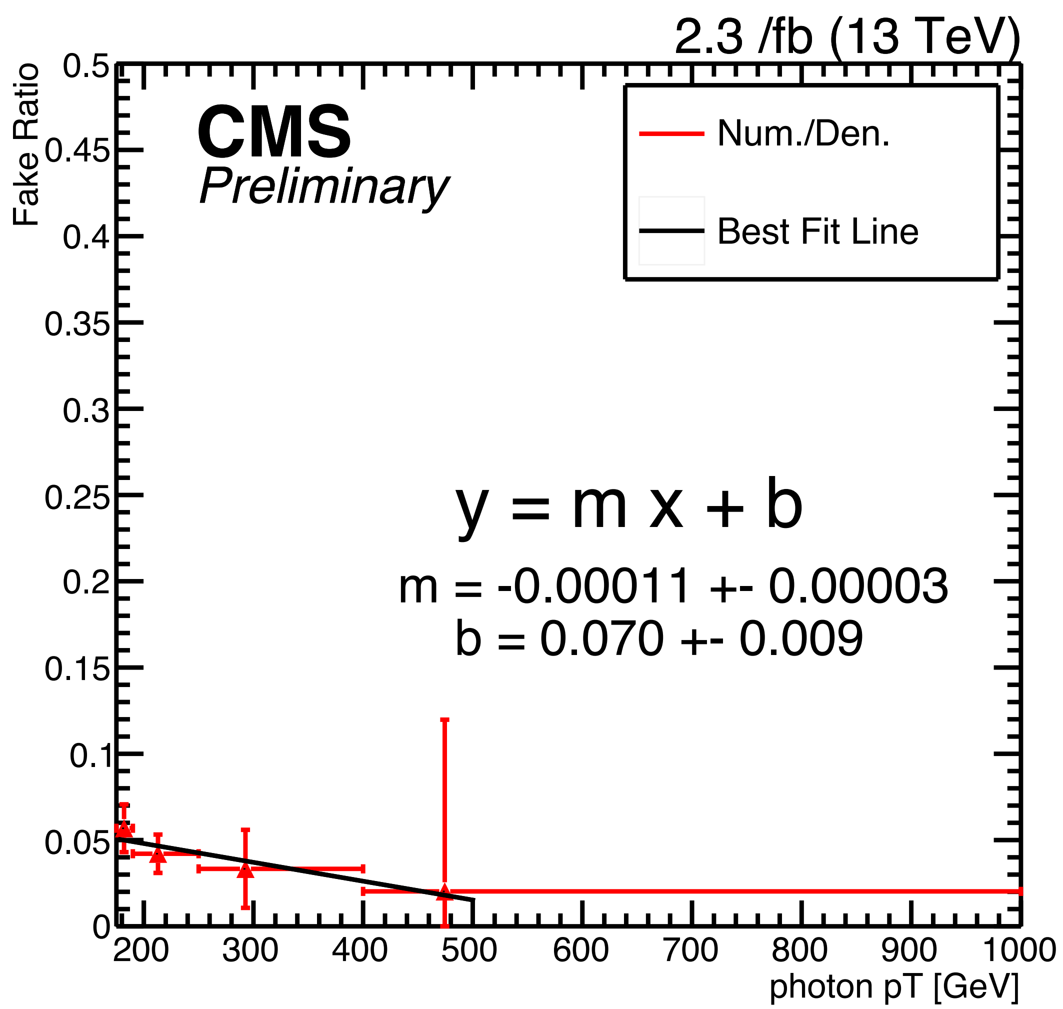
SM Monophoton Processes

The main SM processes with apparent monophoton signatures are **$Z(\nu\bar{\nu})\gamma$** (54%), **$W(l\nu)\gamma$** (14%), **$W(e\nu)$** (10%), **QCD** (4%)

$Z(\nu\bar{\nu})\gamma$ estimate using $\not{E}_T = \not{E}_T$ + dilepton



QCD fake rate estimate



Monophoton Systematic Uncertainties

Source of Uncertainty	Effect on Measured Cross Section	
Luminosity	3.3 %	Measured and published by CMS
Theoretical on Simulation	3.5 %	Theoretical uncertainty on choice of parameters used in simulation
Electroweak corrections	7.2 %	$Z\gamma$ and $W\gamma$ use LO→NNLO scaling, theoretical uncertainty on factor
JET,MET, Photon energy scale	3.9 %	Use Z boson mass to calibrate
Data/MC efficiency scale factors	5.2 %	Charged hadron isolation, beam halo, and lepton veto have different efficiencies in data and MC

Uncertainty on Data driven estimates

Jet faking photon: 35% — Vary the parameters used in fake rate estimation, largest bound

Electron faking photon: 8% — Compare $Z \to e\bar{e}$ with $Z \to e\gamma$ yields

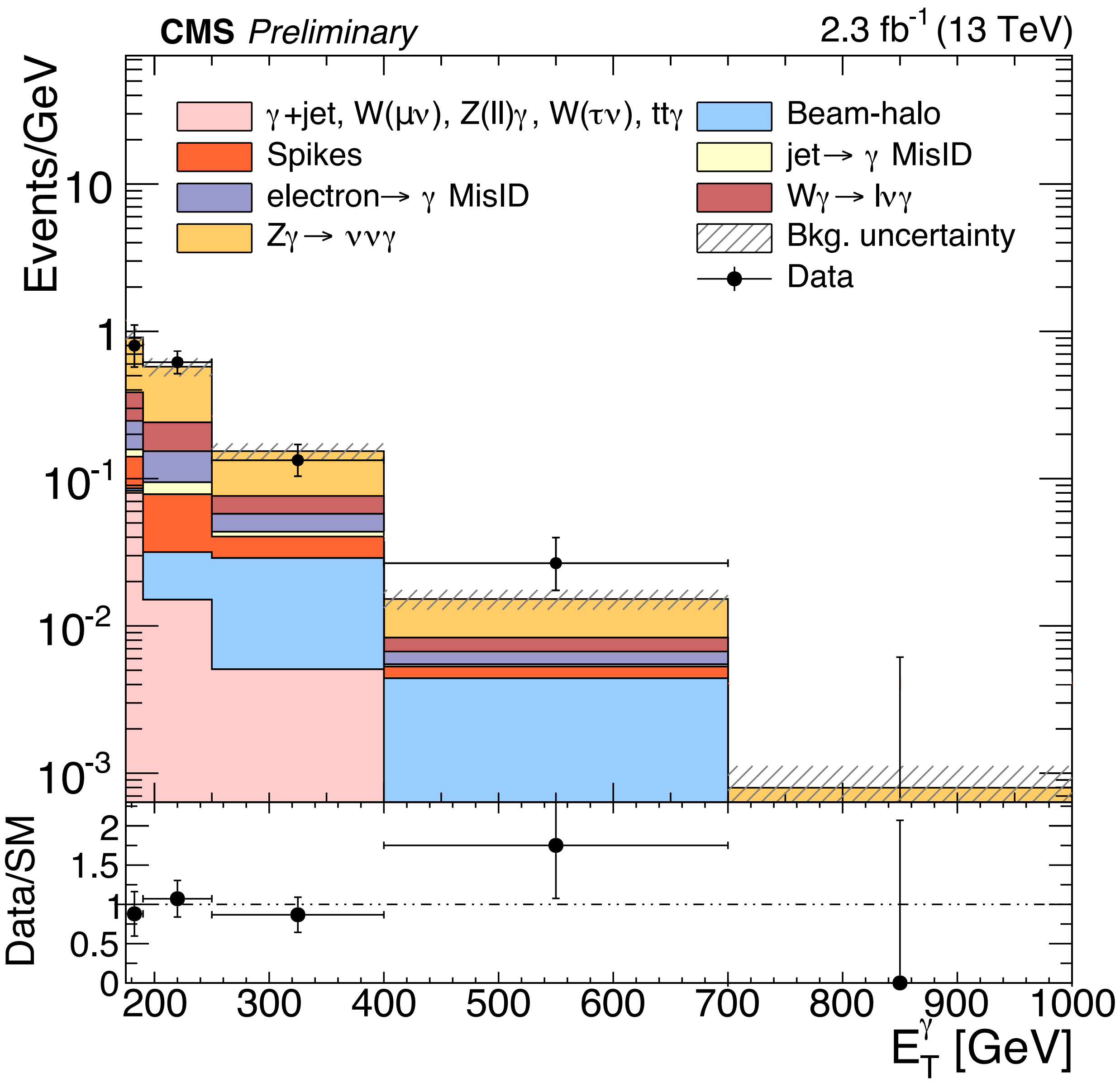
$Z(\nu\bar{\nu})\gamma$ Cross Section

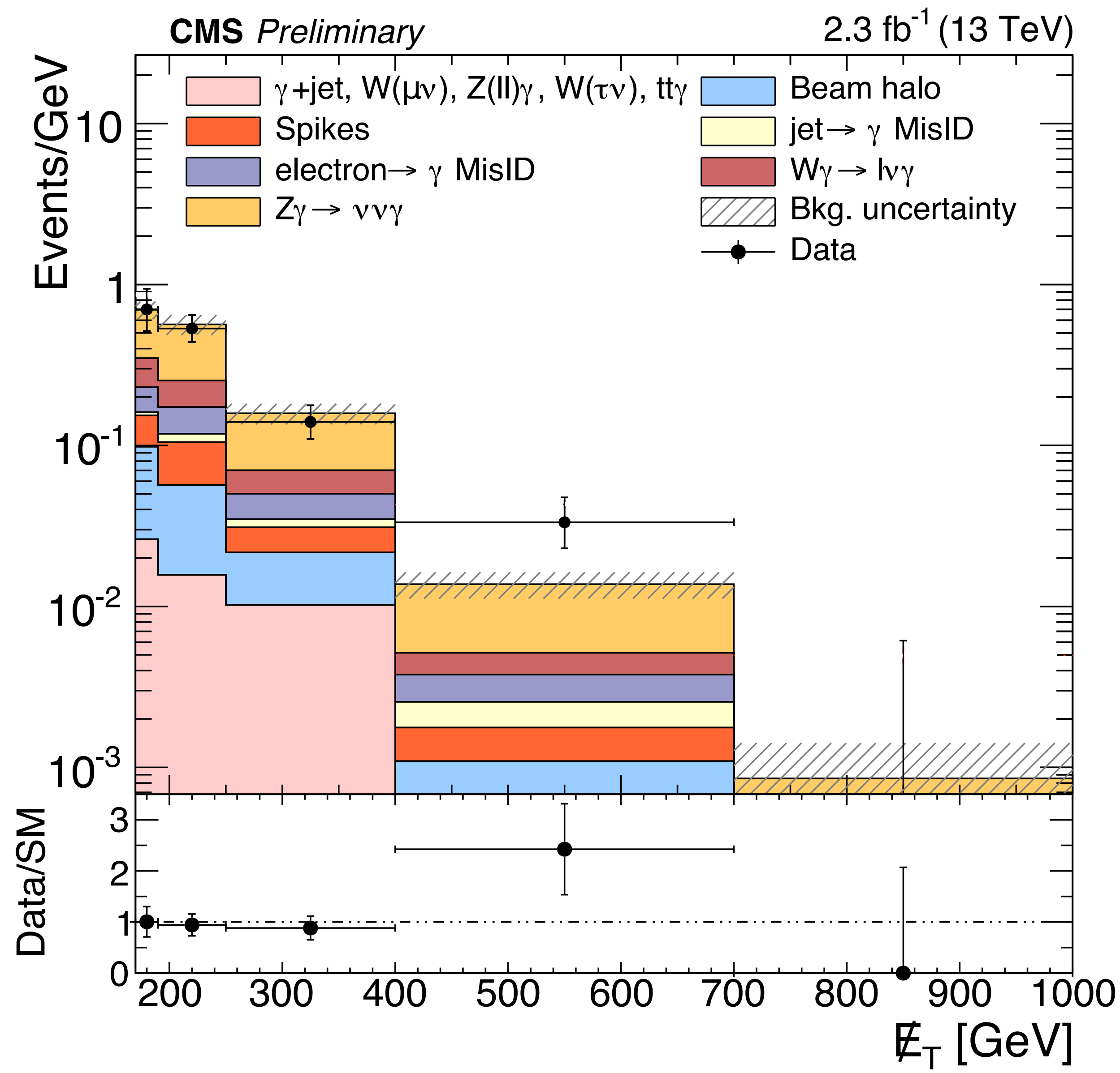
Final distributions with the monophoton signature

Good agreement is seen between data and MC

Measured cross section = 66.5 ± 13.6 (stat) ± 14.3 (syst) ± 2.2 (lumi) fb

NNLO Predicted cross section = 65.6 ± 3.3 fb





Previous Dark Matter Limits

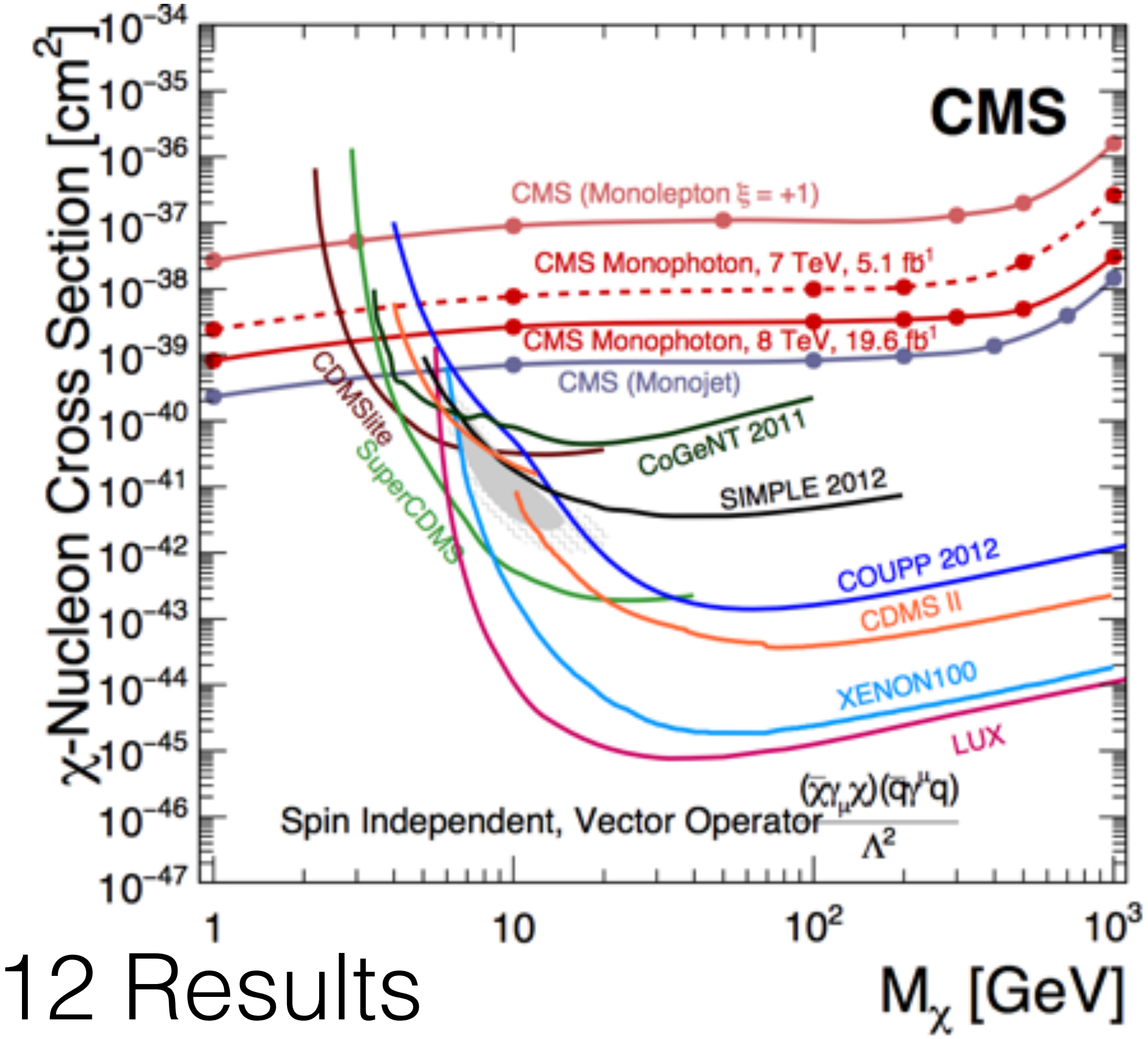
Limits can be translated between cross sections and coupling scale μ = reduced mass (proton / DM)

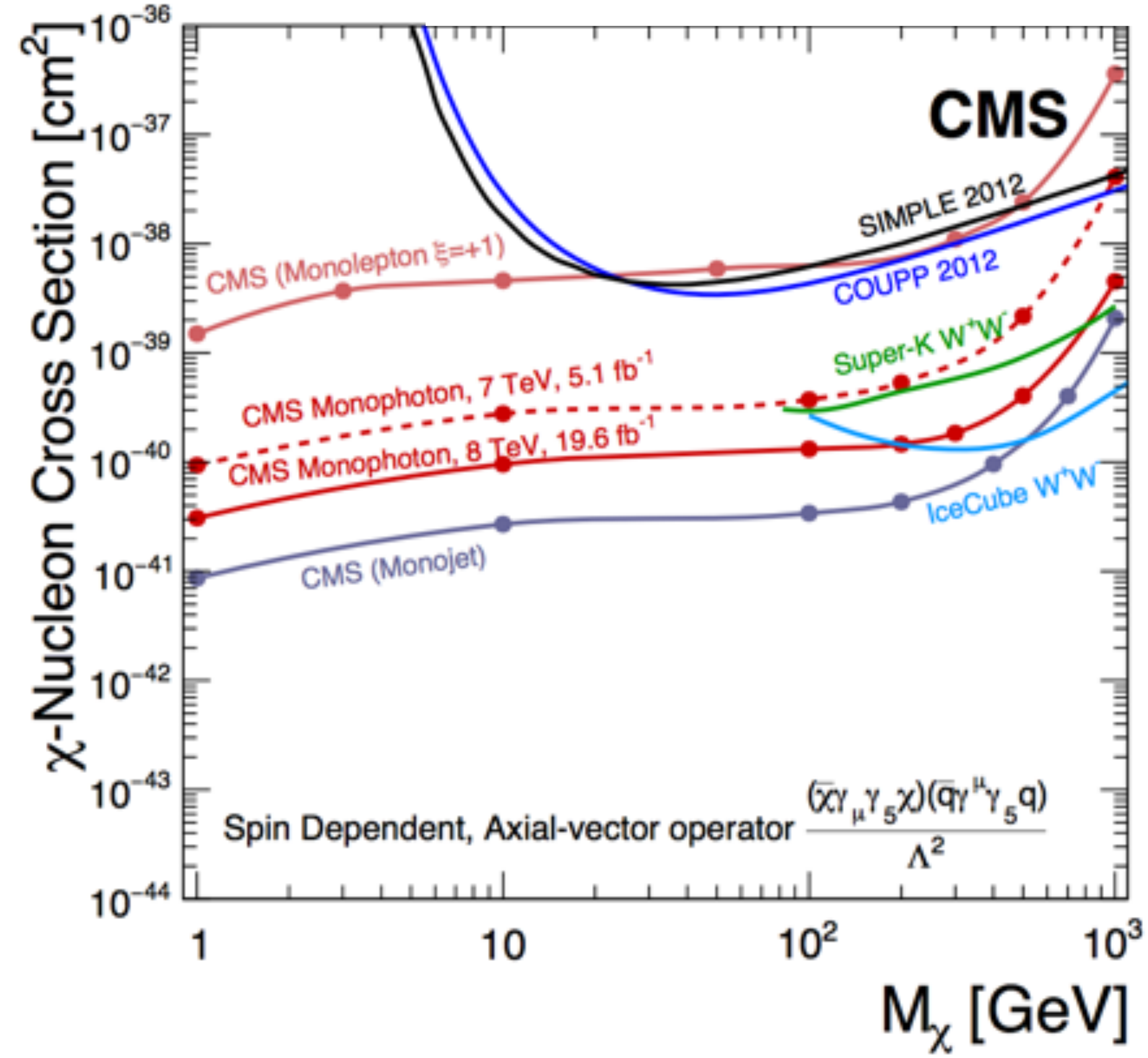
Spin Independent

$$\sigma_{SI} = \frac{9}{\pi}\left(\frac{\mu}{\Lambda^2}\right)^2$$

Spin Dependent

$$\sigma_{SD} = \frac{0.33}{\pi}\left(\frac{\mu}{\Lambda^2}\right)^2$$





2012 Results

Monophoton DM Interpretation

New limits are set on parameters in DM models

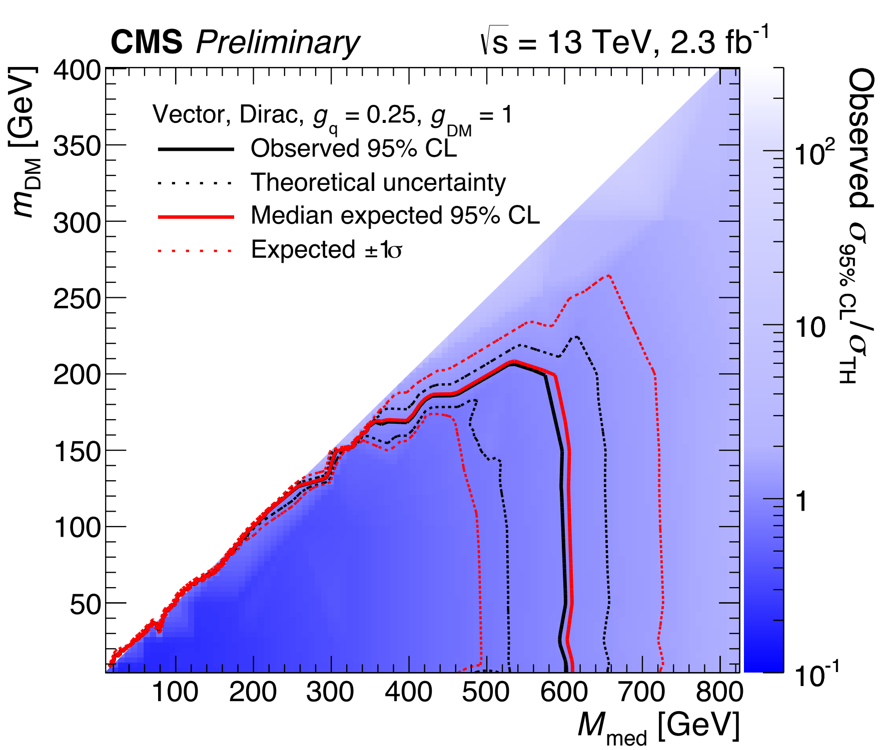
Mediator model (vector or axial vector couplings)
limits set on mediator mass

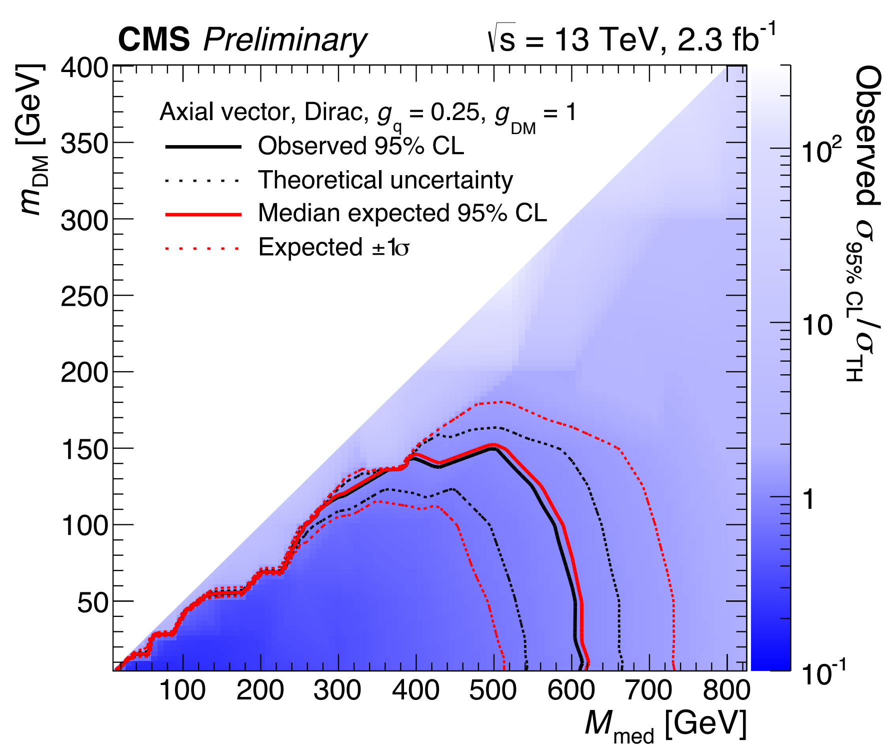
Mediator Mass > 600 GeV for DM Mass < 10 GeV

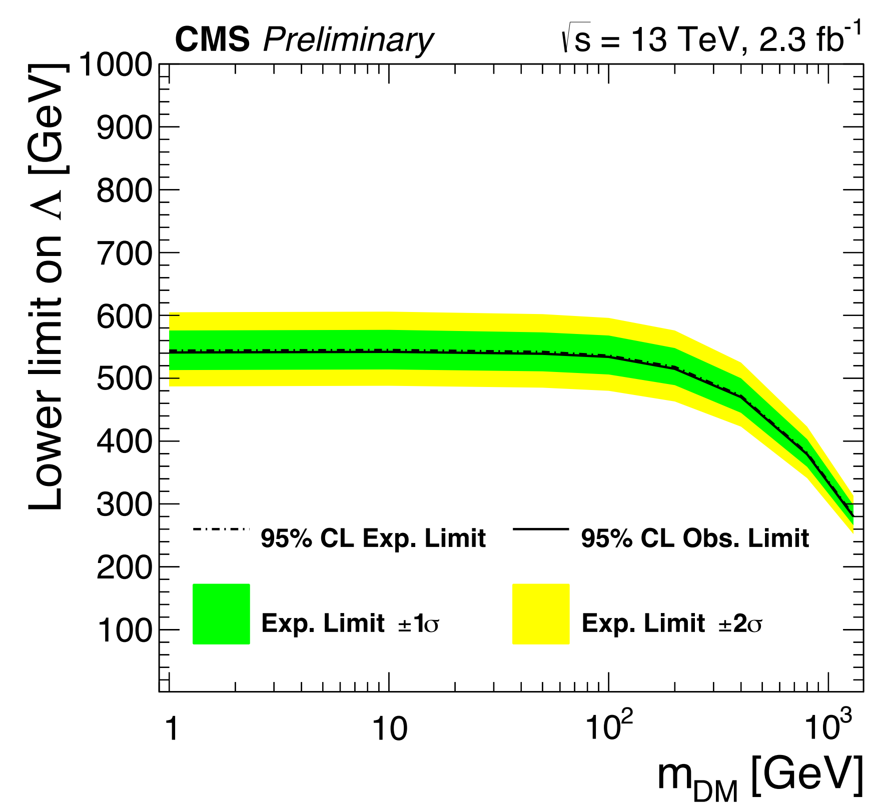
(translates into cross section : 10^{-40}, 10^{-41} cm^2 for vector / axial-vector)

EFT model, limits set on coupling scale, Λ

Λ > 540 GeV







Conclusions

Measurements were performed at the LHC using proton-proton collisions at 8 and 13 TeV

Wbb at 8 TeV ($pp \to Wb\bar{b} \to \ell \nu b\bar{b}$):

Three consecutive fits in closely related regions

Agreement with SM within one standard deviation

Only measurement of W boson with two identified b jets at 8 TeV

Monophoton at 13 TeV:

SM process $pp \to Z\gamma \to \nu\bar{\nu}\gamma$ cross section agrees with prediction

Dark Matter searches set new limits on

- Vector / Axial Vector mediator masses
- EFT coupling strength

Outlook

Some 2016 data is already here and more comes in daily

Wbb

Higher energy - more gluons in PDF - even more TTbar background
Higher energy - more boosted - jets less separated

Monophoton

With 30-40 \fb predicted, can put limits (or discover!) DM with mediator mass up to ~1 TeV

The SM predicts no direct coupling ZZγ - this can also be tested via the monophoton signature ($pp \rightarrow Z \rightarrow Z\gamma \rightarrow \nu\bar{\nu}\gamma$)

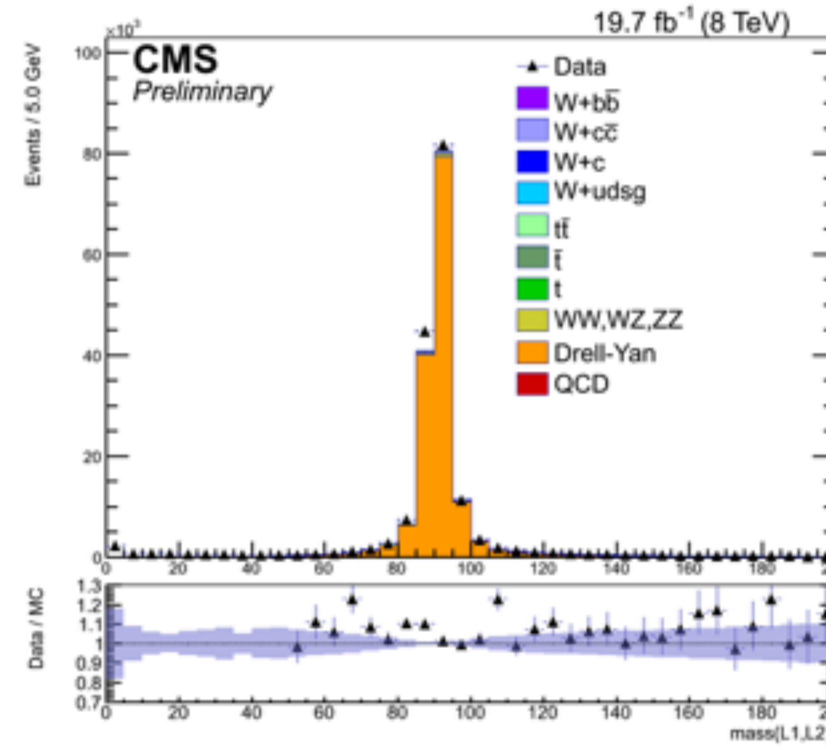
The future is ~~bright~~ Dark

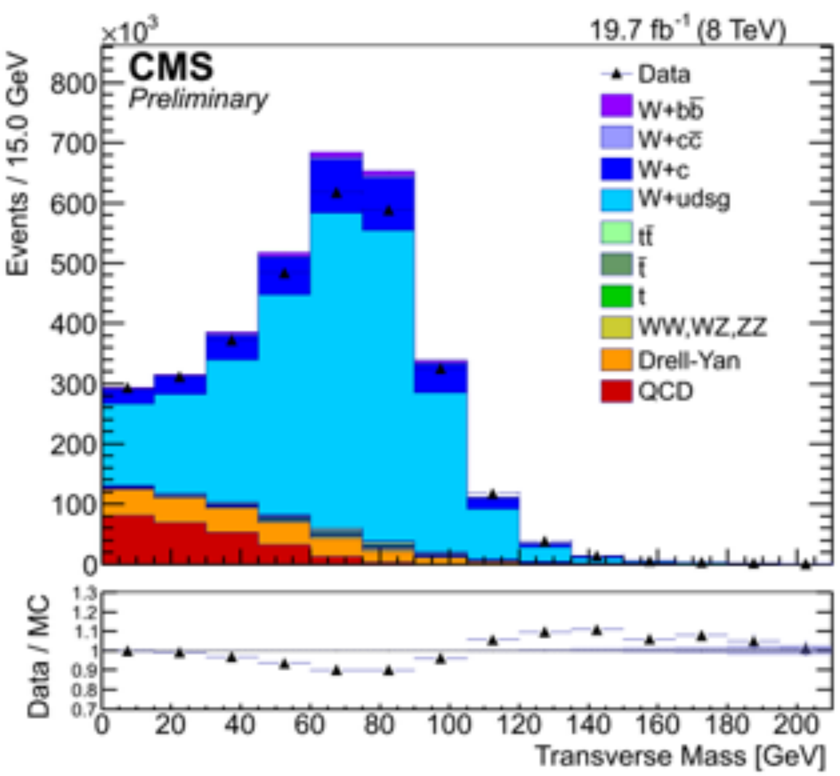
Bonus Slides

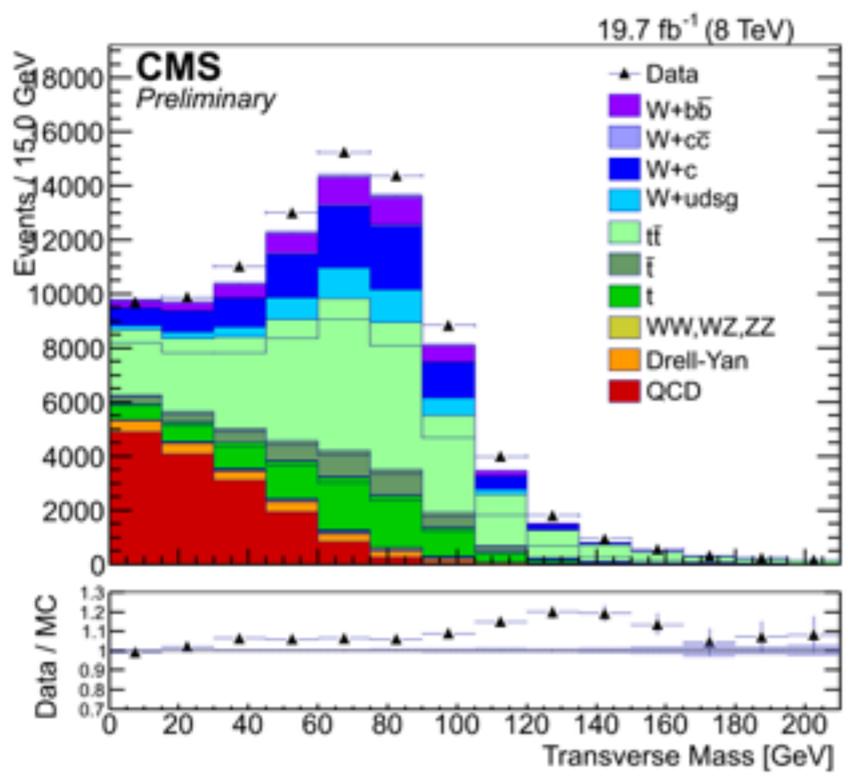
Wbb Control Regions

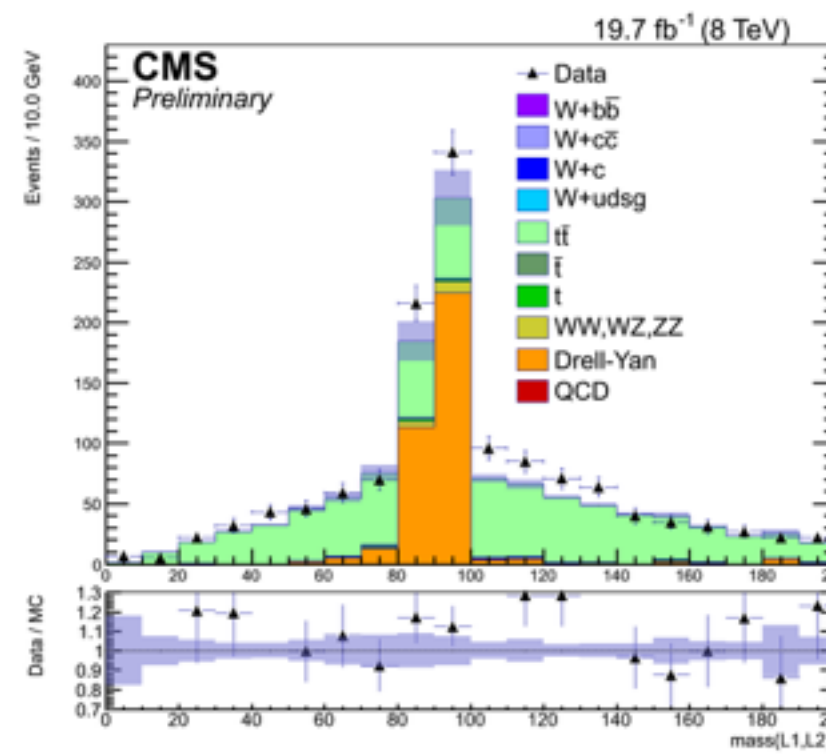
Selections listed counter clockwise as difference w.r.t. signal region

W+jj:
Remove b-tag requirement on jets
Single top:
one central jet b-tagged, one forward jet no tag
Drell-Yan+bb:
Drop lepton veto, require same sign lepton
Drell-Yan:
Same as Drell-Yan+bb but no b-tag requirement









Wbb QCD estimation

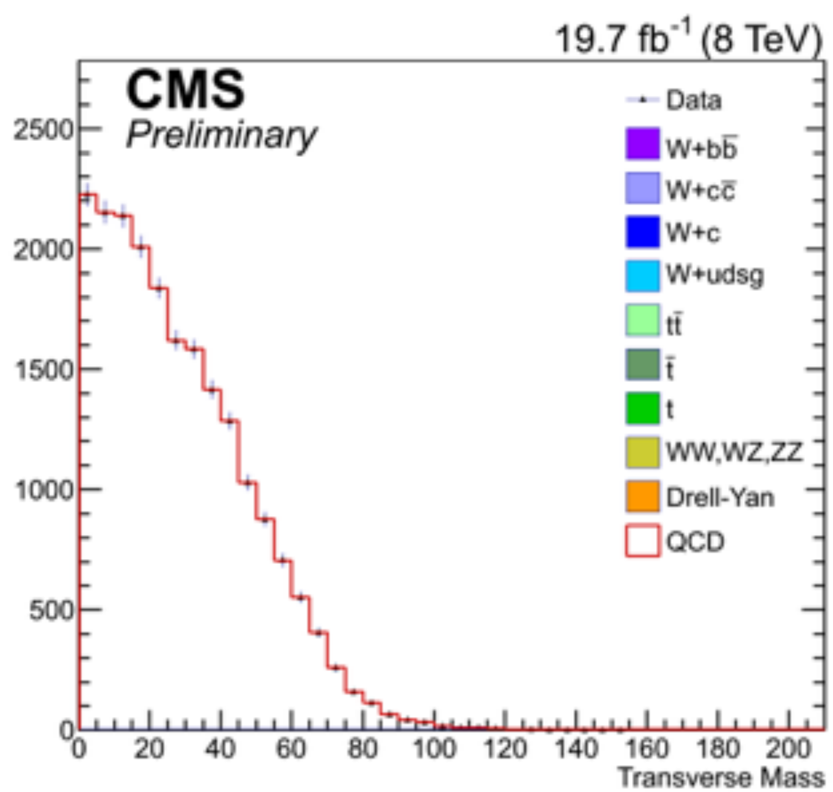
All backgrounds in signal region are taken from simulation except QCD - use a data-driven method

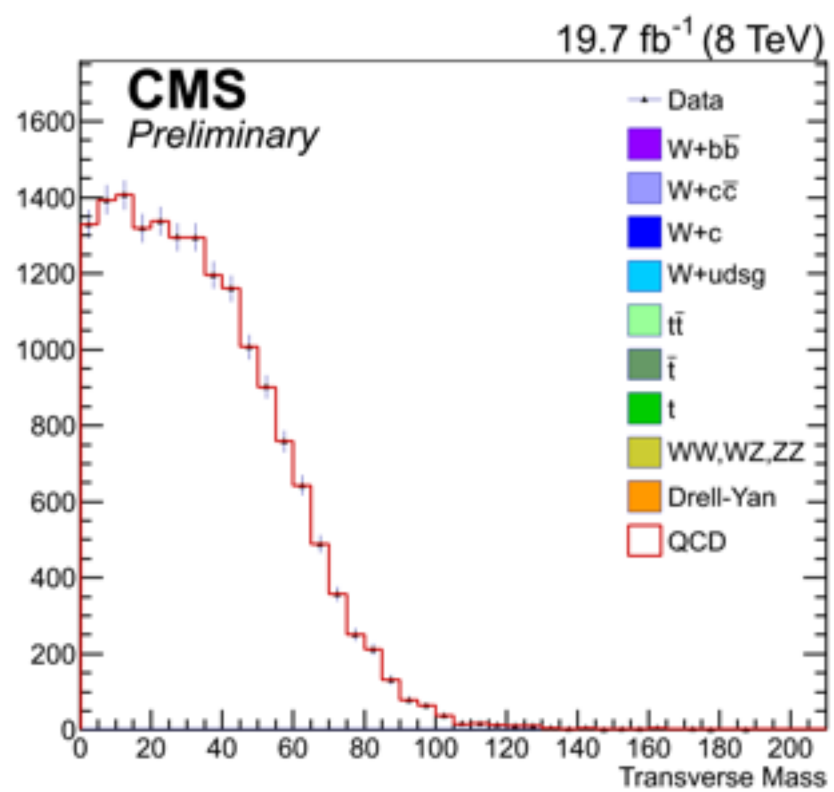
For m_T, invert lepton isolation, I > 0.20 (0.15) for mu (e)

For other variables, require $\not{E}_T$ < 30 GeV

Subtract (Data - All MC) to get QCD shape

Fit for final normalization





Monophoton Yields

Process	Estimate
$Z\gamma \to \nu\bar{\nu}\gamma$	41.74 ± 6.67
$W\gamma \to \ell\nu\gamma$	10.60 ± 1.58
$W \to e\nu$	7.80 ± 1.78
Jet $\to \gamma$ misidentified	1.75 ± 0.61
Beam halo	5.90 ± 4.70
Spurious ECAL signals	5.63 ± 2.20
Rare backgrounds	3.03 ± 0.69
Total Expectation	76.45 ± 8.82
Data	77