A Search for new physics in events with a leptonically decaying Z boson and a large transverse momentum imbalance with the CMS Detector at the LHC

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Thesis Defense
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Outline

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- Motivation & Theory
- The CMS Experiment
- Event Simulation
- Event Reconstruction
- Analysis Strategy
- Results
- Conclusions

The Standard Model

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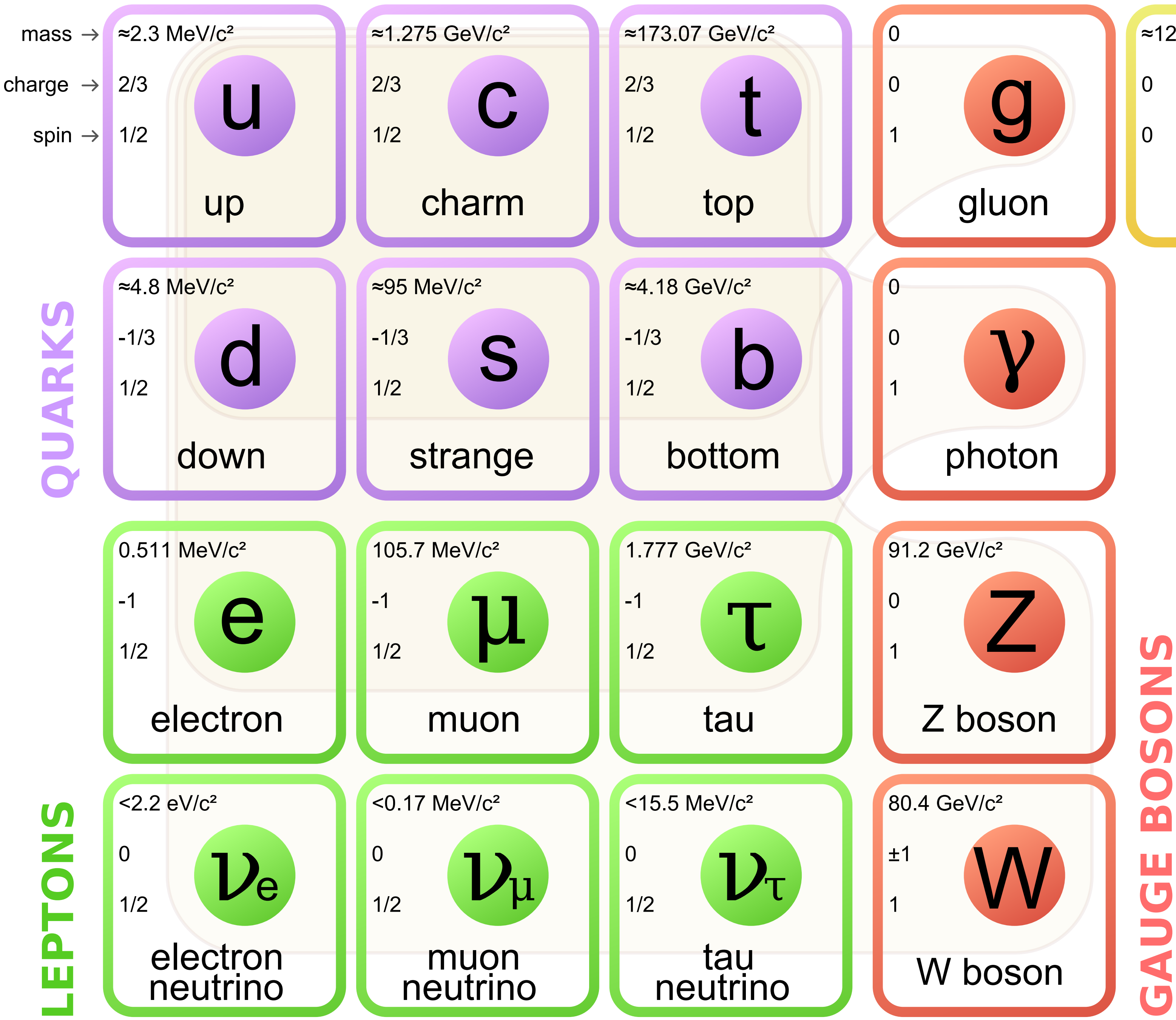

$$
\begin{aligned}
\mathscr{L} = &-\frac{1}{4}F_{\mu\nu}F^{\mu\nu} \\
&+ i\bar{\psi}\not{D}\psi \\
&+ \bar{\psi}_i y_{ij}\psi_j\phi + \text{h.c.} \\
&+ |D_\mu\phi|^2 - V(\phi).
\end{aligned}
$$

Standard Model Interactions

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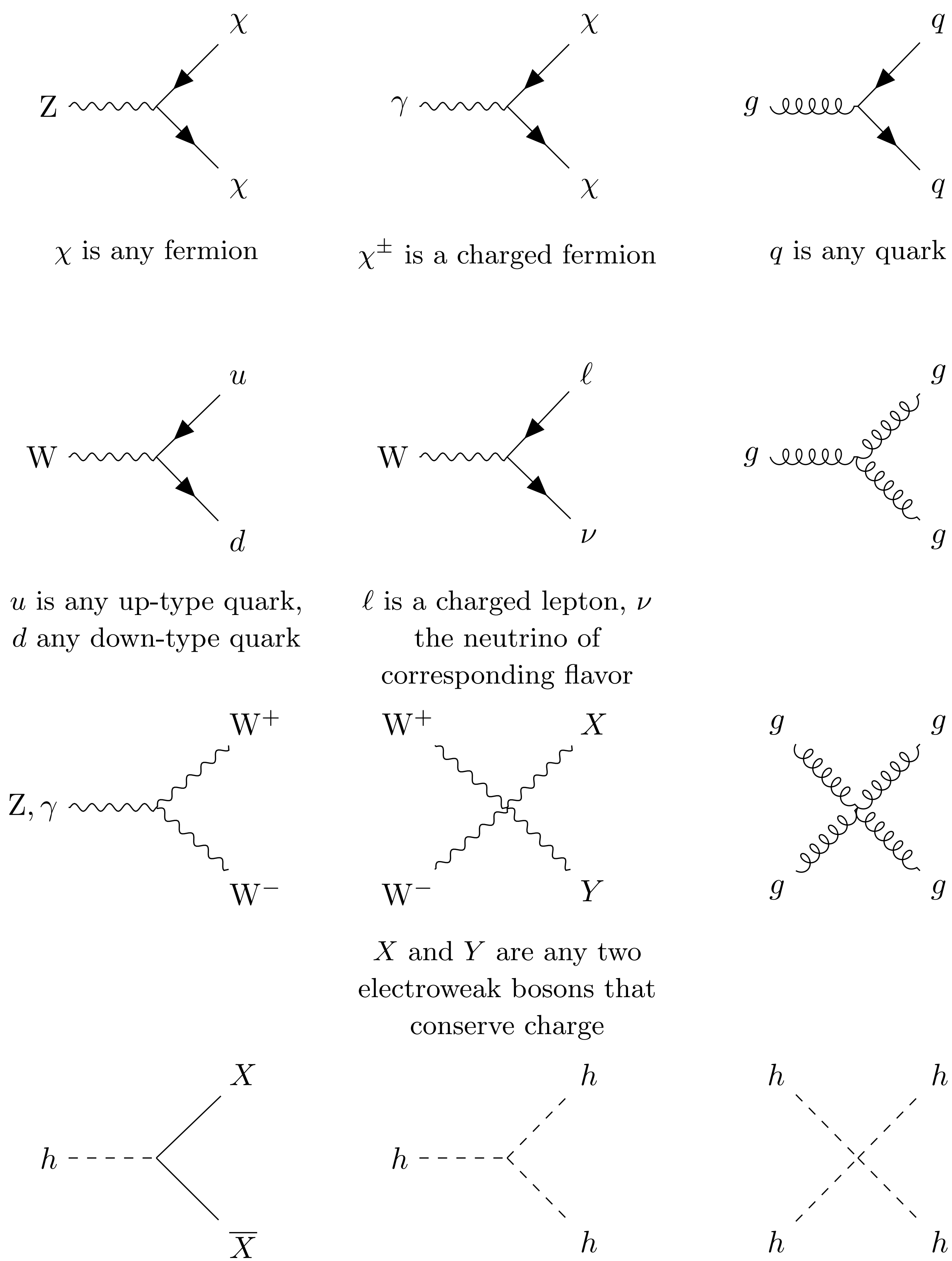

χ is any fermion

$\chi^{\pm}$ is a charged fermion

q is any quark

u is any up-type quark, d any down-type quark

ℓ is a charged lepton, ν the neutrino of corresponding flavor

X and Y are any two electroweak bosons that conserve charge

X is any massive SM particle

- Allowed interactions governed by SM symmetries*:

$$SU(3) \times SU(2)_L \times U(1)$$

* among others

- Feynman rules assign formulas to each vertex
- Cross section for a process: sum of amplitudes squared for contributing diagrams

The mono-Z final state

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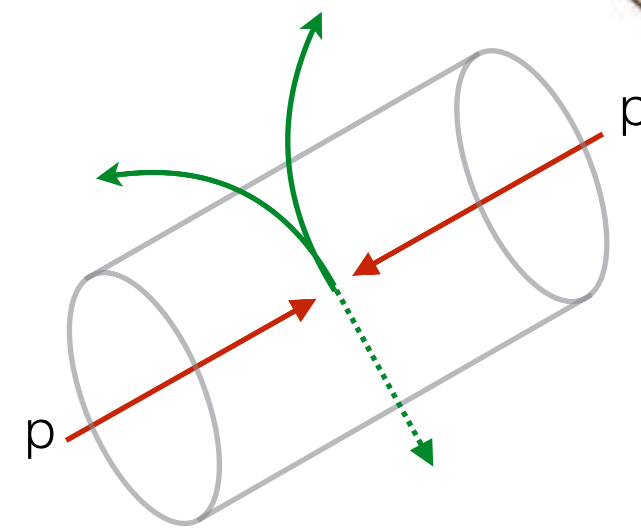
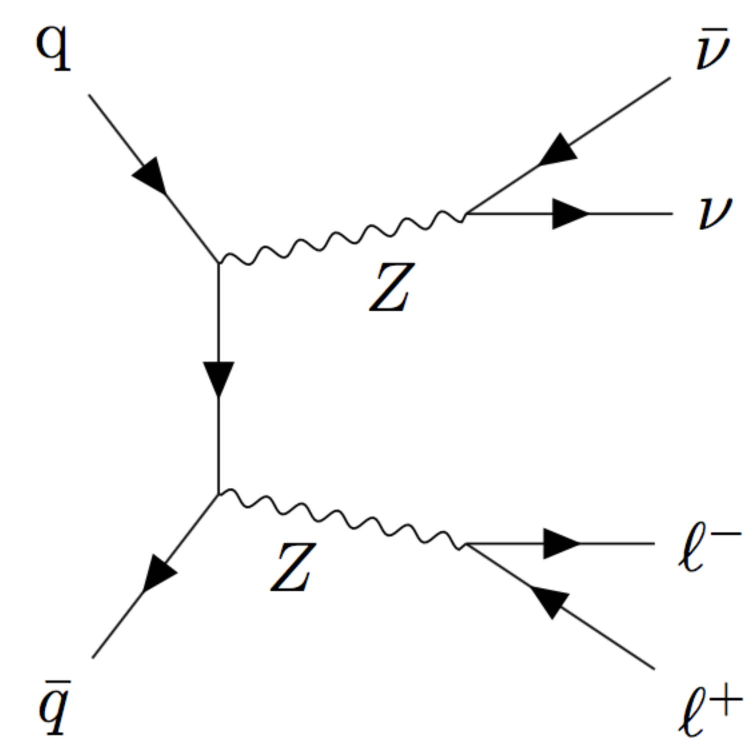
- Collide two proton beams at 13 TeV and look for a Z boson produced in association with a net imbalance in momentum transverse to the beamline
- SM example:
  - ZZ to 2 light leptons + 2 neutrinos
  - Light lepton = electron or muon
- Sensitive to new physics signatures containing undetectable particles
  - Dark matter production
  - Graviton production in a model of large extra dimensions
  - Unparticle production
  - Invisible decays of a Higgs boson
- These predictions are tested in this analysis





Dark Matter in the Universe

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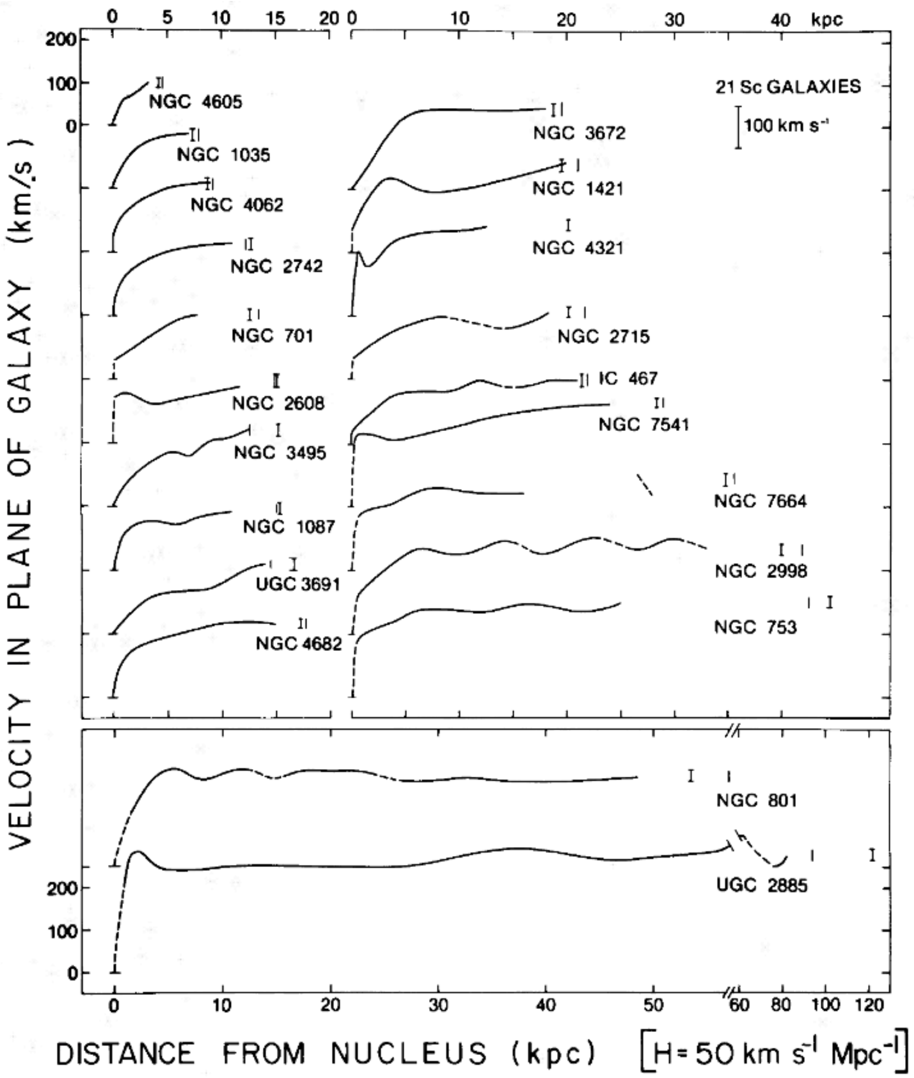
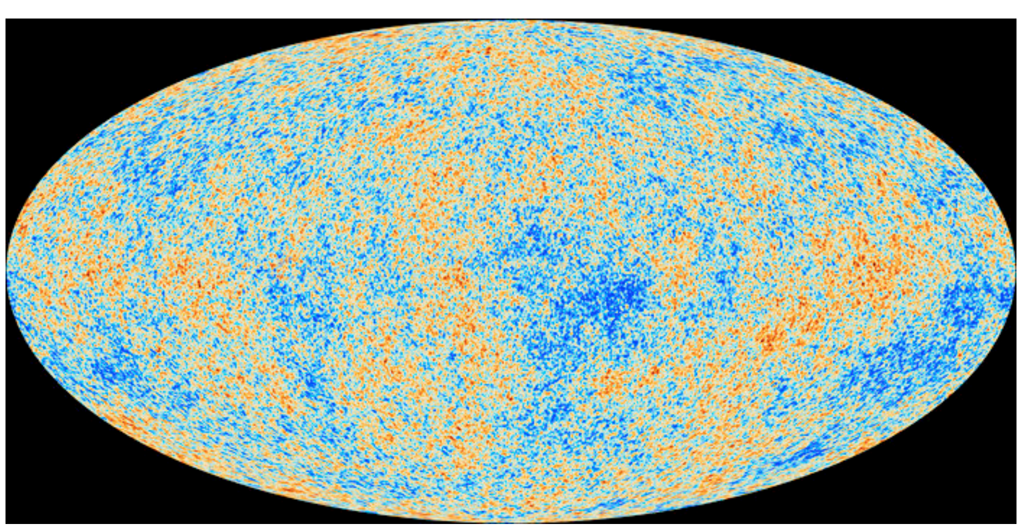
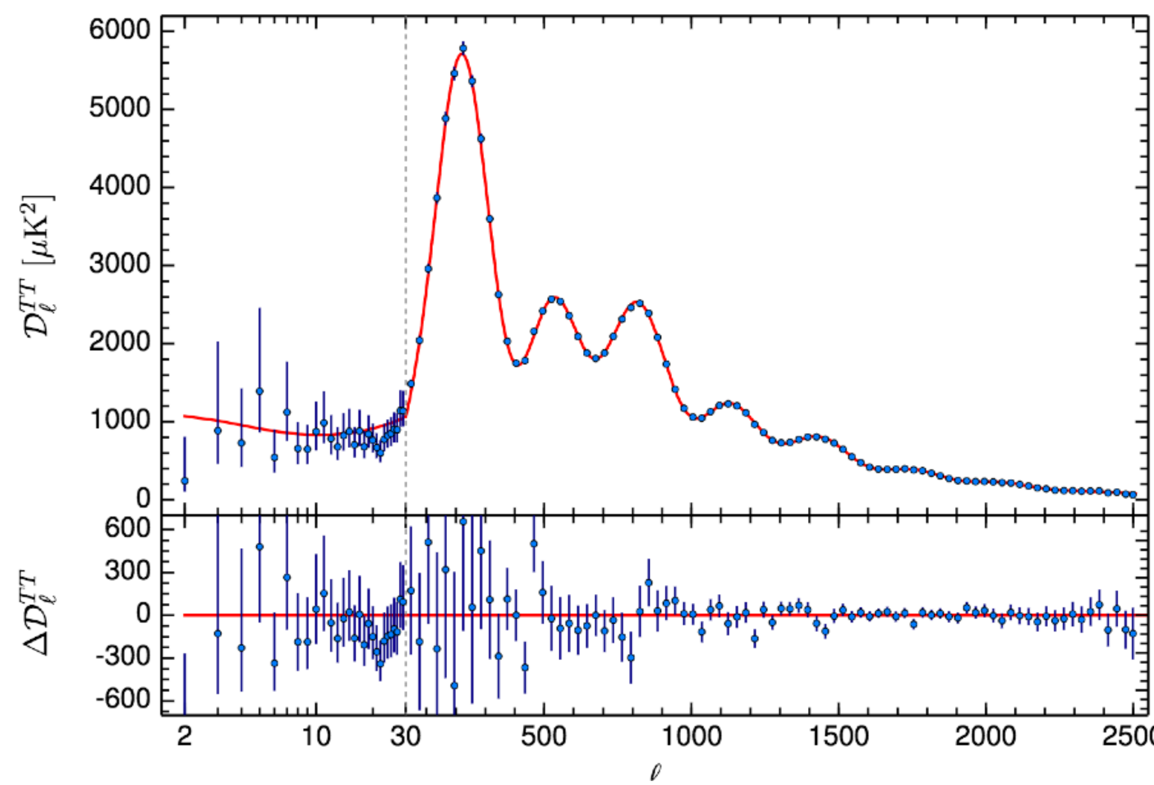


- Evidence for DM at $r \gtrsim r_{\text{galaxy}}$
  - Galactic rotation curves
  - Galaxy cluster velocity dispersion (M/L)
  - Cosmic Microwave Background
- Λ_{CDM} model: evolution of universe since big bang, predicts DM thermal decoupling

$$\Omega_c \approx 0.25 \rightarrow T_{\text{freeze-out}} \approx \text{TeV}$$

"WIMP miracle"





Dark Matter at Colliders

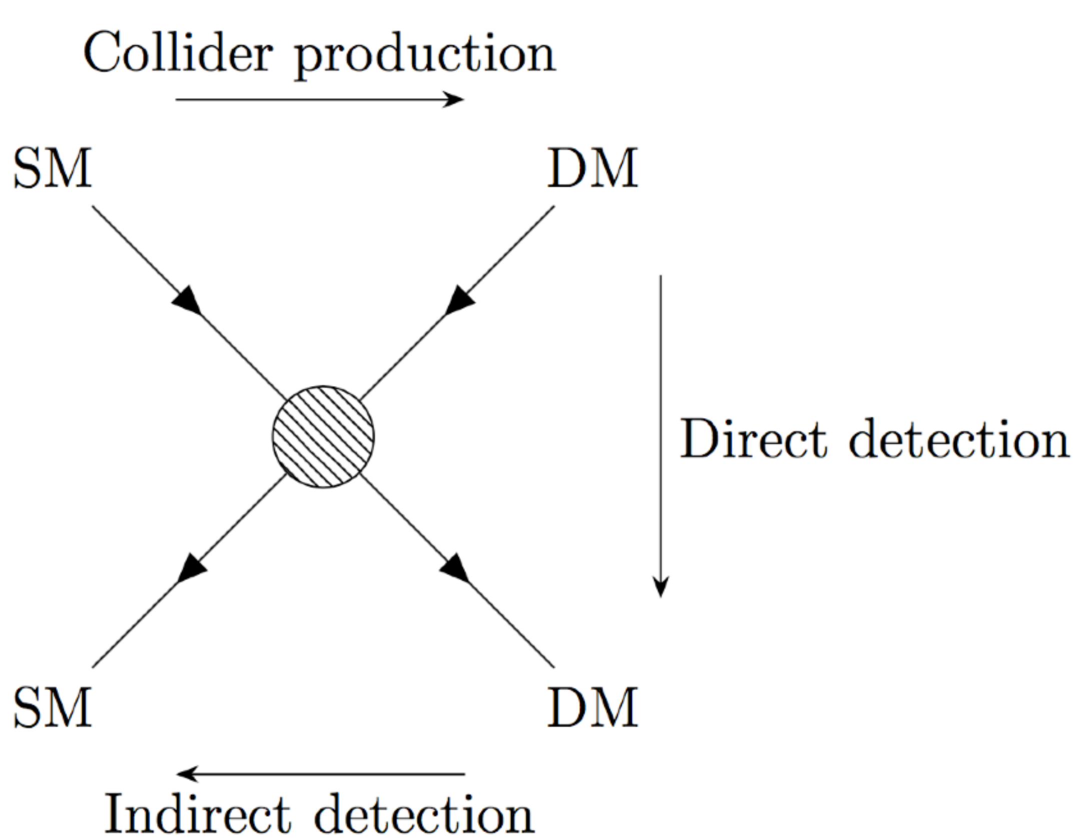
- LHC can probe DM interactions with SM at TeV scale
- Complementary to direct & indirect searches
  - Direct: nuclear recoil
  - Indirect: astronomy (γ,ν,p,...)
- For LHC, must define model
  - Construct simplified models with spin 0 or 1 mediators
  - Assume ~unity coupling
  - Probe mediator, DM mass

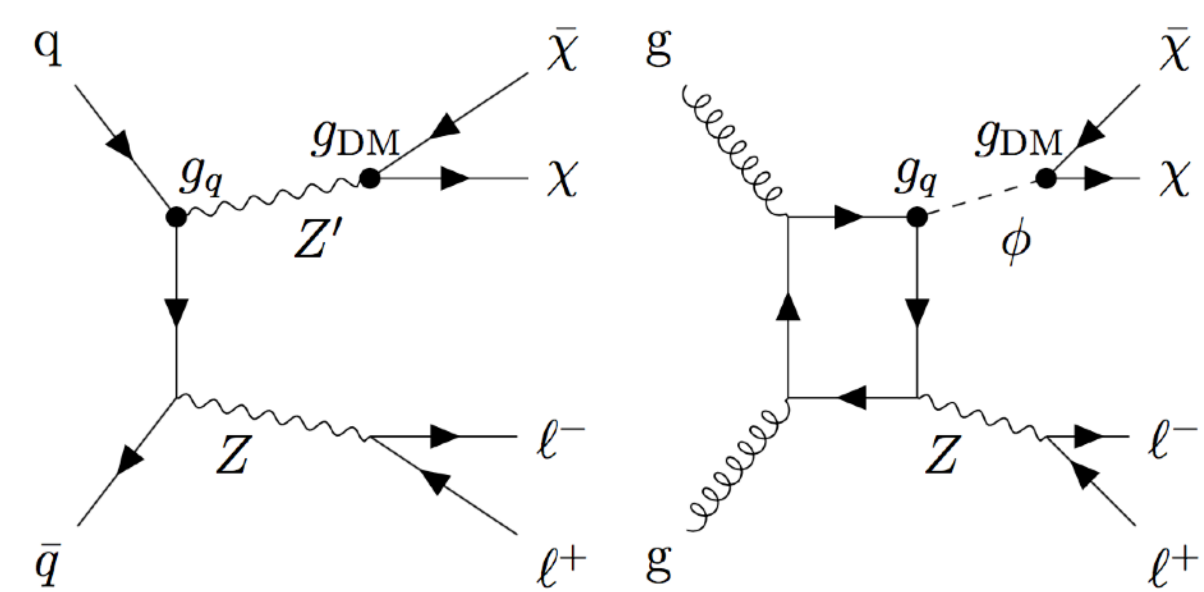
$$\mathcal{L}_{\text{vector}} = g_{\text{DM}} Z'_\mu \bar{\chi}\gamma^\mu\chi + g_q \sum_q Z'_\mu \bar{q}\gamma^\mu q,$$

$$\mathcal{L}_{\text{axial vector}} = g_{\text{DM}} Z'_\mu \bar{\chi}\gamma^5\gamma^\mu\chi + g_q \sum_q Z'_\mu \bar{q}\gamma^5\gamma^\mu q,$$

$$\mathcal{L}_{\text{scalar}} = g_{\text{DM}} \phi\bar{\chi}\chi + g_q \frac{\phi}{\sqrt{2}} \sum_q y_q \bar{q}q,$$

$$\mathcal{L}_{\text{pseudoscalar}} = i g_{\text{DM}} \phi\bar{\chi}\gamma^5\chi + g_q \frac{i\phi}{\sqrt{2}} \sum_q y_q \bar{q}\gamma^5 q.$$





Large Extra Dimensions & Unparticles

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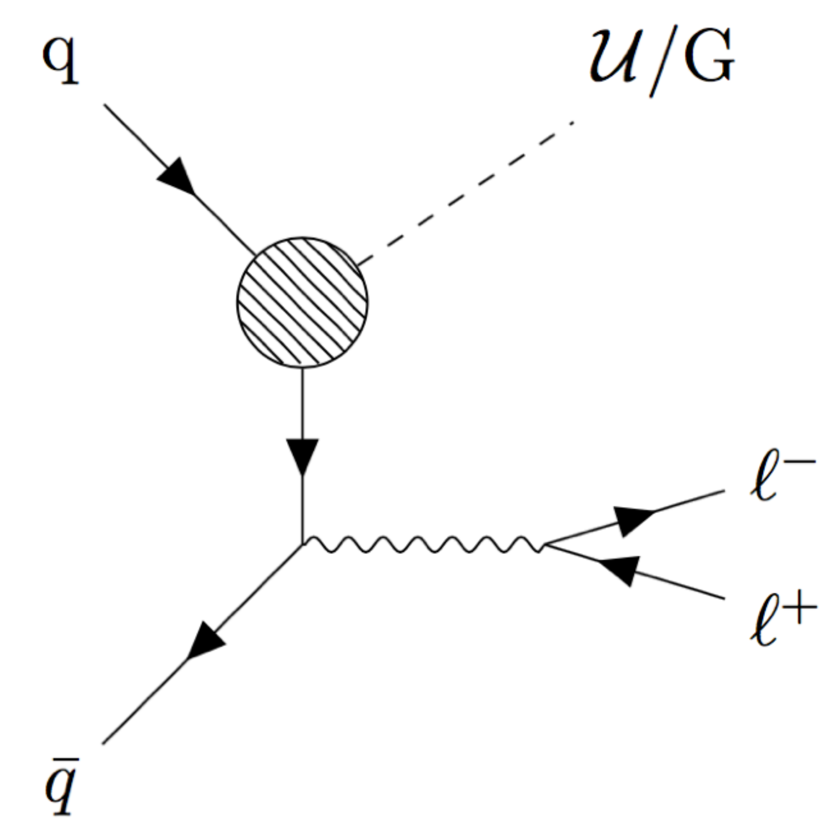
- Gravity not in SM, one challenge:
  $$m_{\mathrm{Pl}} \approx 10^{16}\,\mathrm{TeV} \gg m_{\mathrm{EW}} \approx 1\,\mathrm{TeV}$$
- Arkani-Hamed—Dimopoulos—Dvali (ADD) model (1998):
  - *n* compact extra dimensions
  - Gravity propagates in 4+*n* dimensions
  - True Planck scale (M_D) is then near EW scale
  - Pheno: effective field theory (EFT) predicts graviton emission with ~continuous mass spectrum, invisible

- Unparticle model (Georgi, 2007):
  - Scale invariance at low energy removes concept of free particle states with well-defined mass
  - Pheno: assume EFT interaction with quarks, predicts emission of invisible unparticles



- Both theories predict unusual phase space factors in integral over outgoing object states

Higgs Boson Properties

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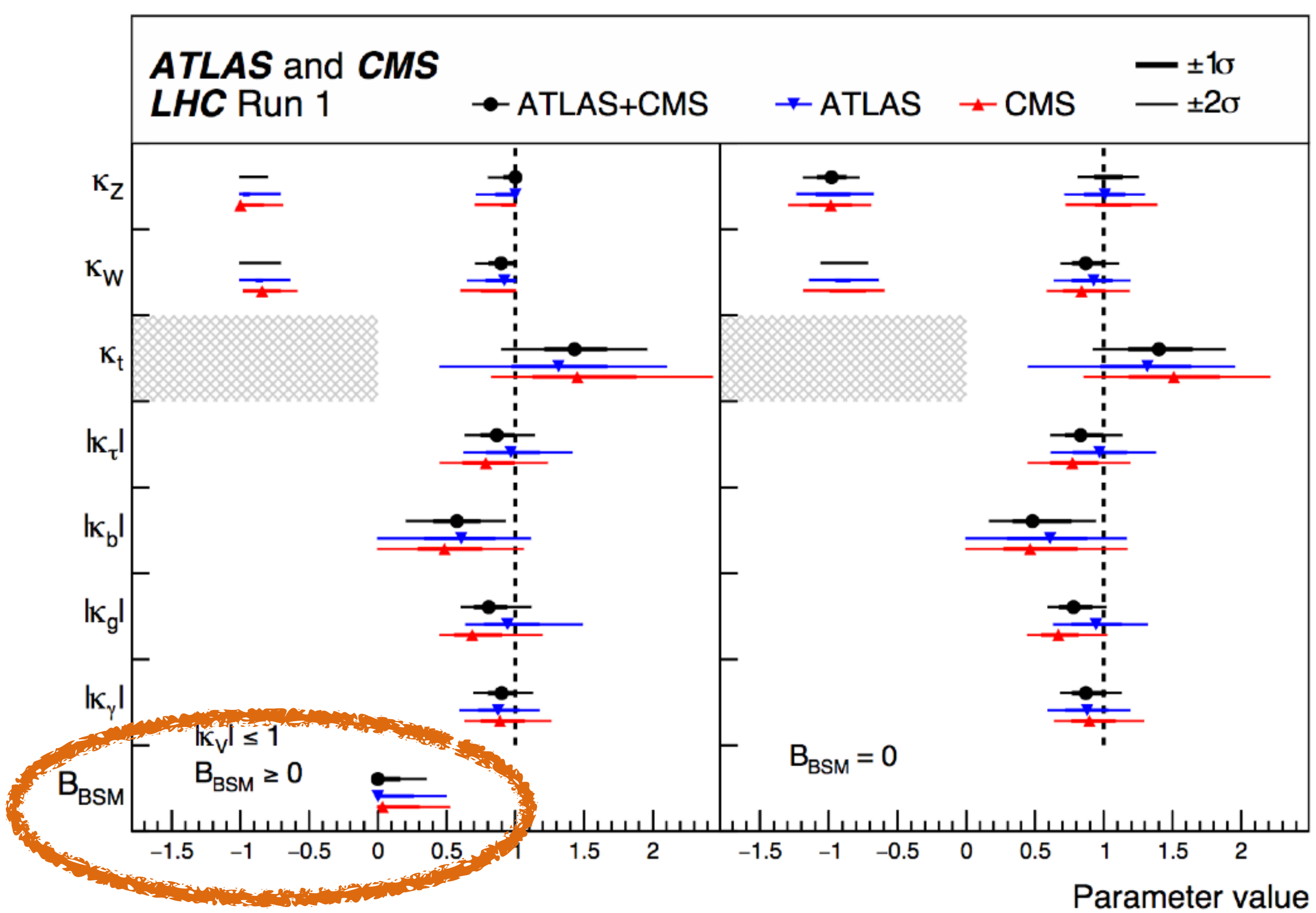
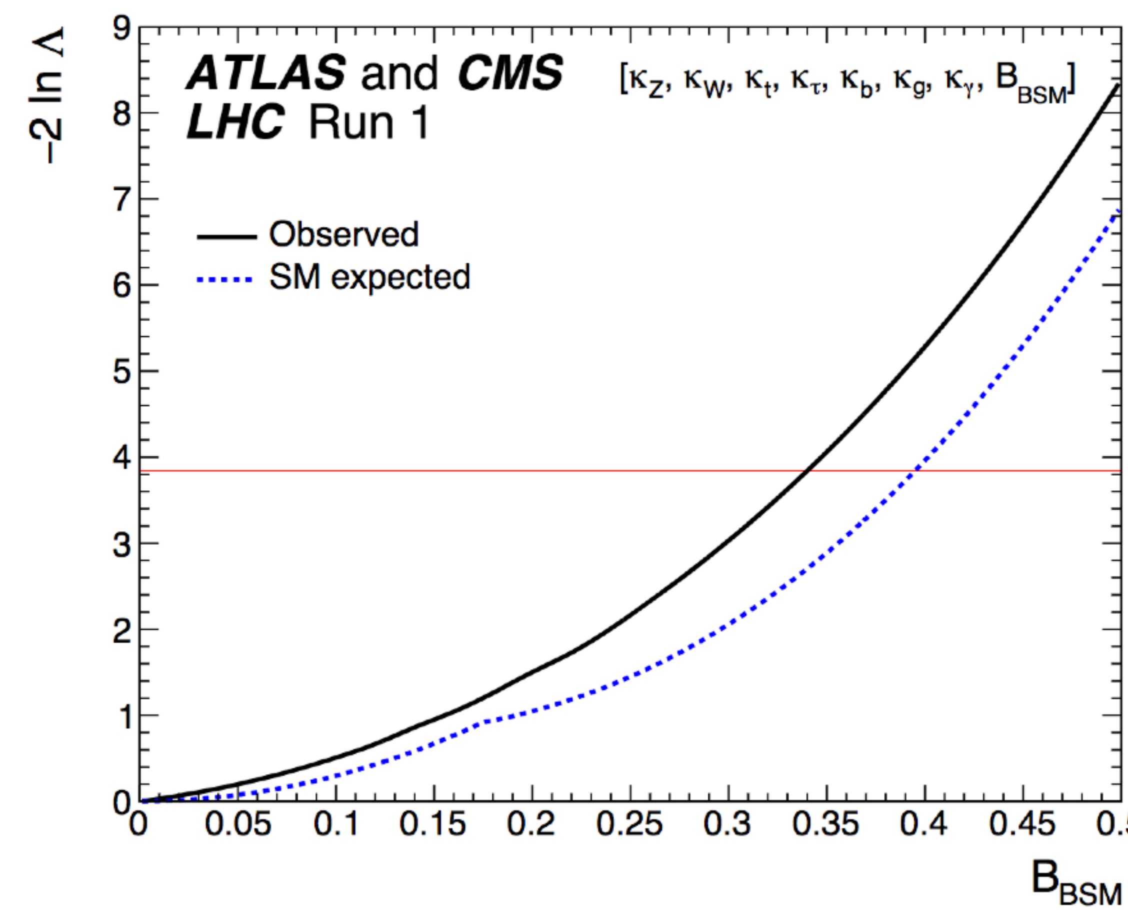
- The SM Higgs boson was discovered in 2012
- The task is now to measure couplings, both SM and beyond-SM
  - Left plot: best-fit Higgs couplings modifiers (w.r.t. SM)
  - Right plot: Indirect measurement of beyond-SM branching fraction
    - A portion of this could be a Higgs decay to DM particles, H(inv.)
- For H(inv.), direct measurement → better constraints

< 34% @ 95% CL





arXiv:1606.02266

The Higgs as a Dark Matter Portal

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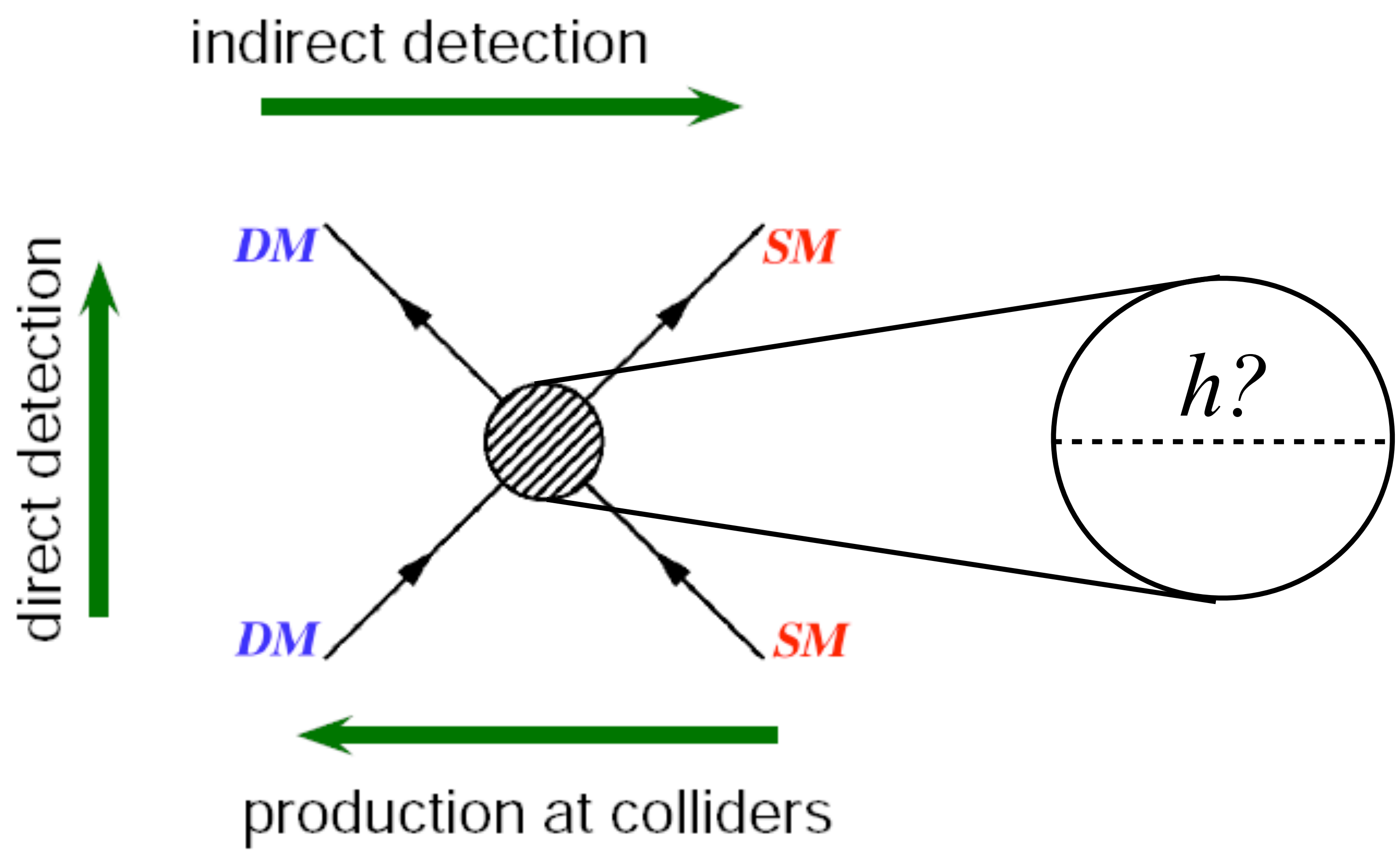
Does the Higgs connect the Standard Model to dark matter?

- For DM mass < Higgs mass / 2, H(inv.) decay possible
  - For scalar & fermion DM, Higgs coupling → nucleon coupling
  - Can compare to standard DM direct detection limits

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

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



Other BSM paradigms for H(inv.)

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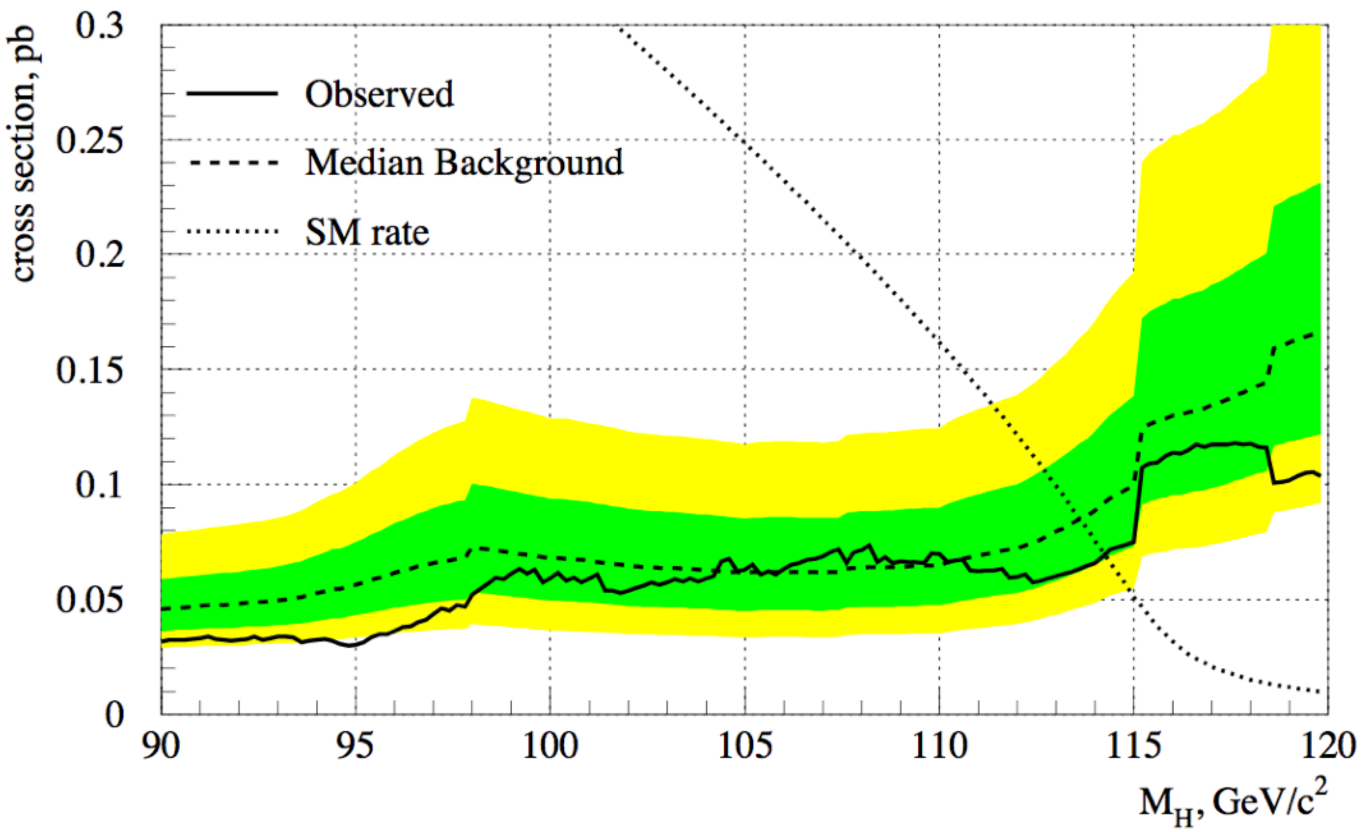
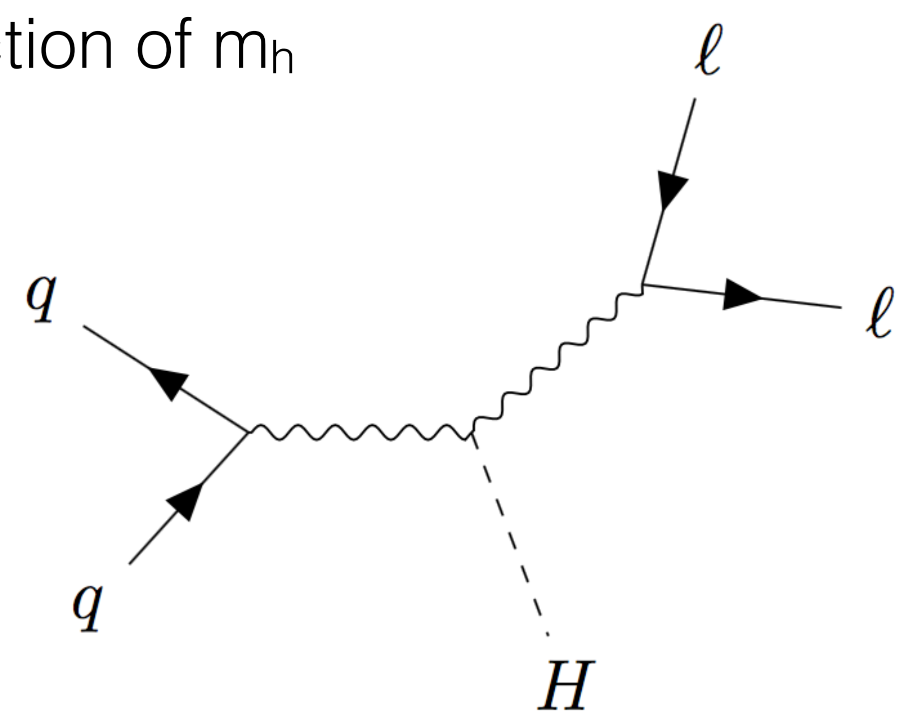
H(inv.) provides generic and flexible limits on new physics:

- Supersymmetry, 2 Higgs doublet models, extra dimensions, etc.
- Easy to add coupling to scalar Higgs doublet
- Not just SM 125GeV Higgs!
    - H(inv.) searches parametrized in m_h since LEP
    - Another scalar boson might decay mostly invisibly
    - We can set cross section limits as function of m_h



arXiv:hep-ex/0107032



The Large Hadron Collider

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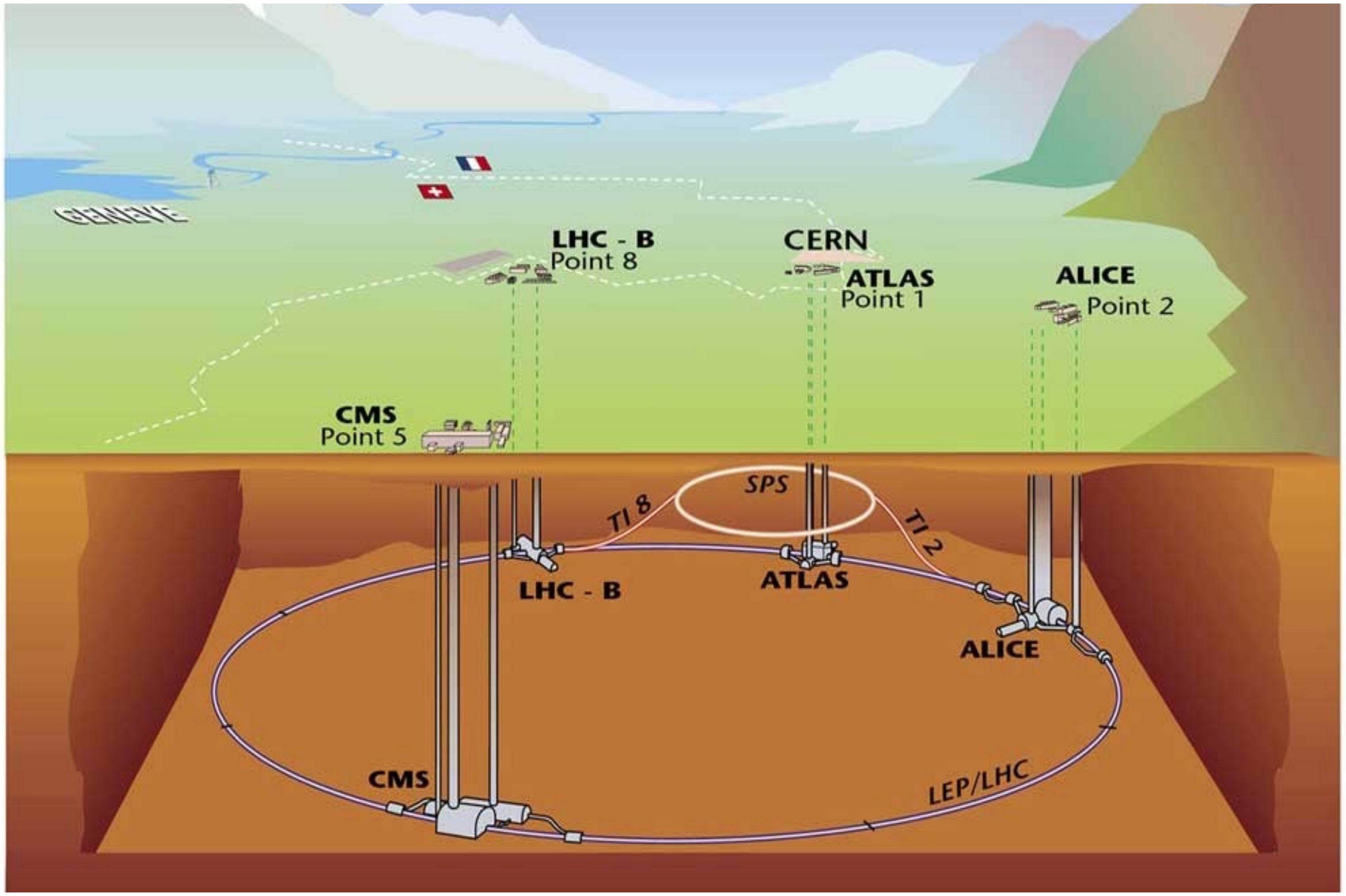
- 27km-circumference ring buried ~100m underground
- Collides both protons and heavy ions
- Two beams counter-rotate, interact at 4 points
- 4 Main Detectors
  - CMS, ATLAS: general purpose detectors
  - LHCb: Forward & b physics
  - ALICE: Heavy Ion physics



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

Proton Beam & Luminosity

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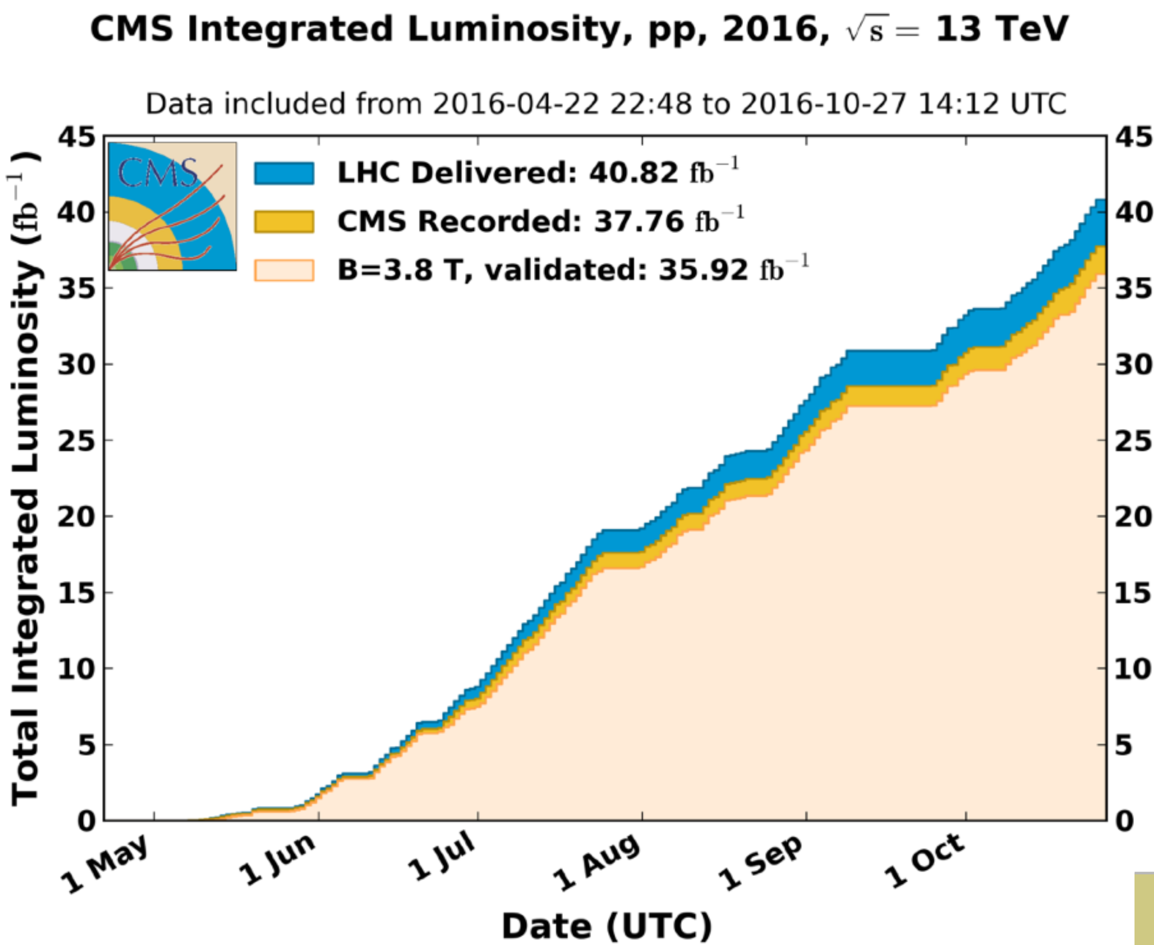

Number of expected events depends on:

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

	Design	2016	Now
Beam Energy (TeV)	7	6.5	6.5
Inst. Luminosity (x10^{34}/cm^2/s)	1.1	1.3	2.0
Bunches	2808	2076	2544
Protons / Bunch	115B	125B	110B
Bunch Spacing (ns)	25	25	25
Avg. Collisions / Bunch Crossing	20	23	38
Integrated Lumi to CMS (fb^{-1})		35.9	>120

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

The Compact Muon Solenoid

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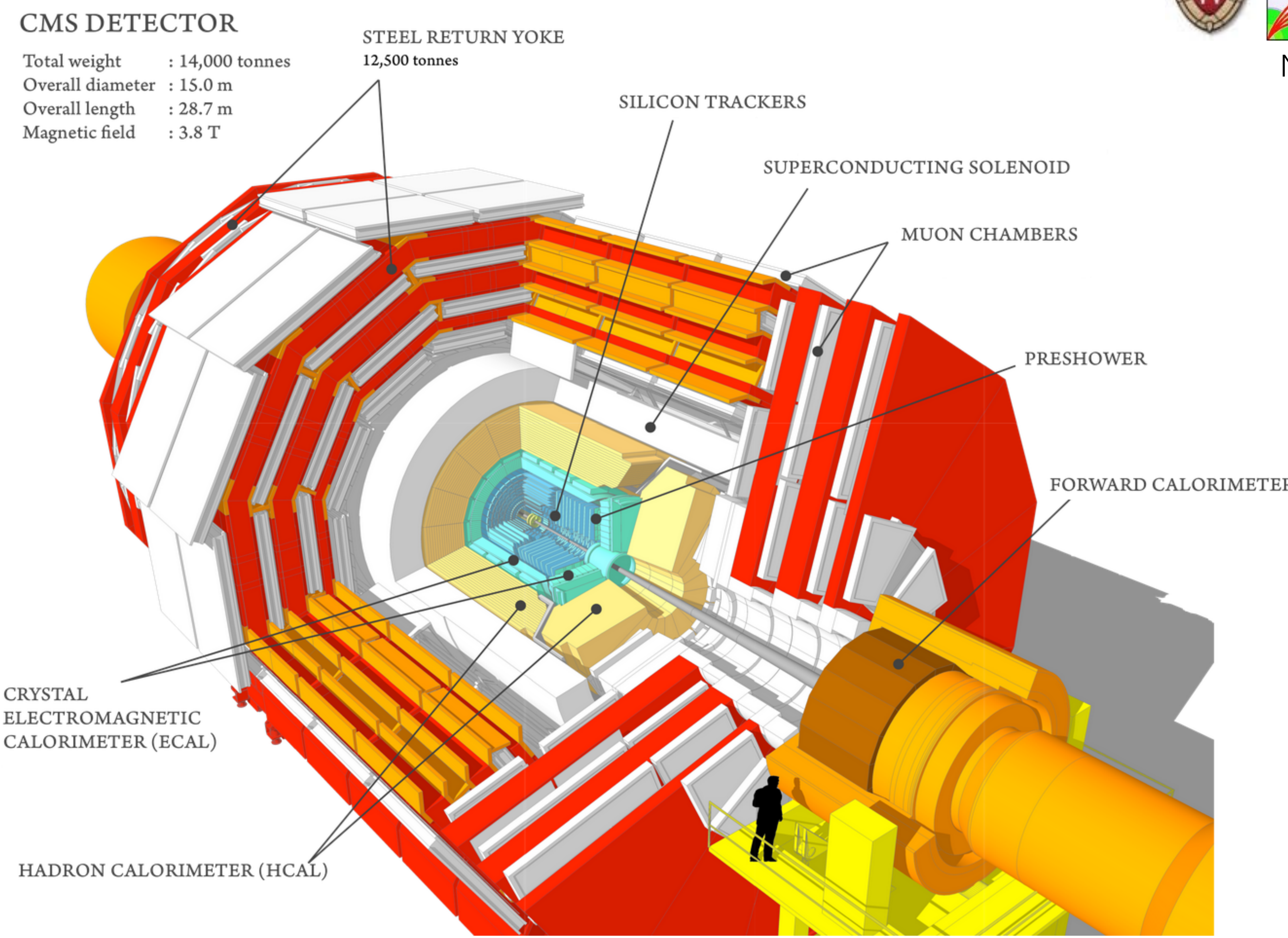

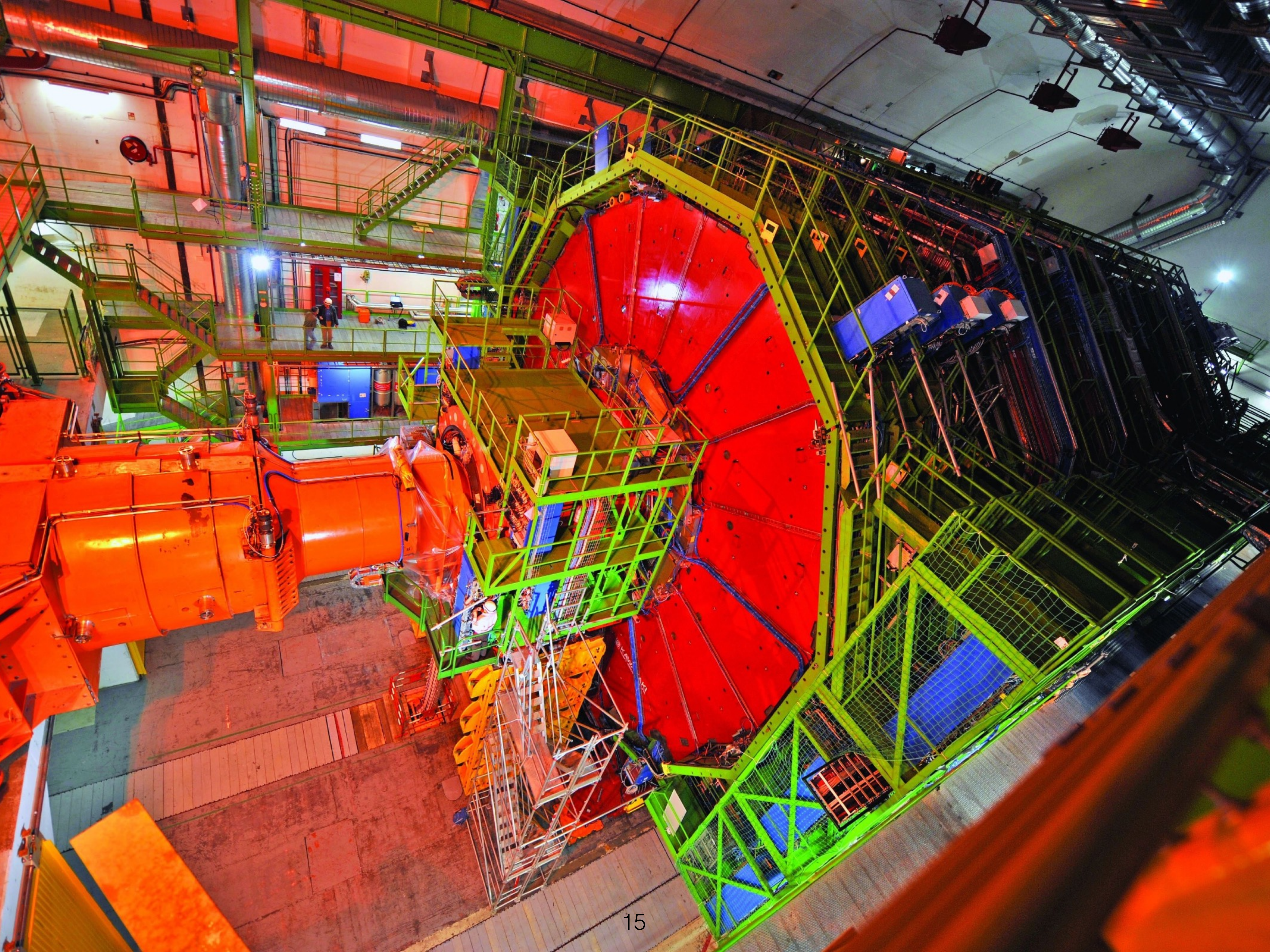

Magnet

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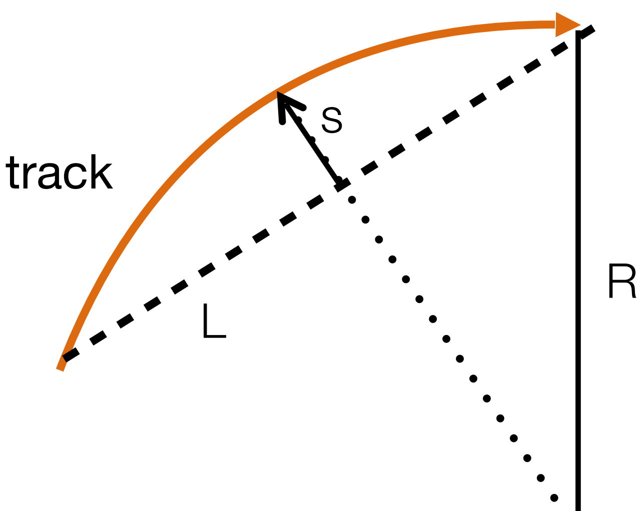
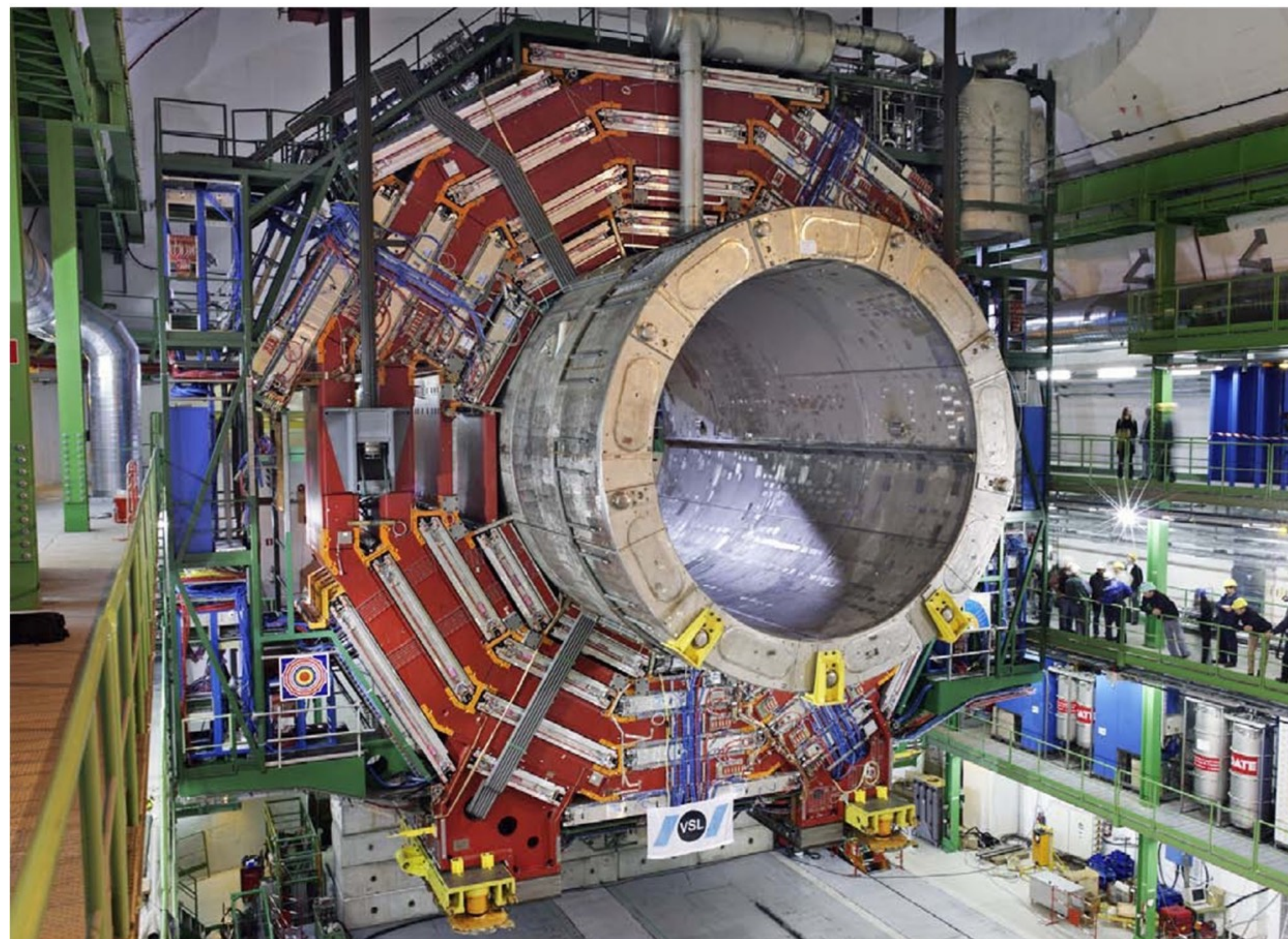
The CMS magnet is a central feature of the detector

- 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)



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



Tracker

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CMS Tracker

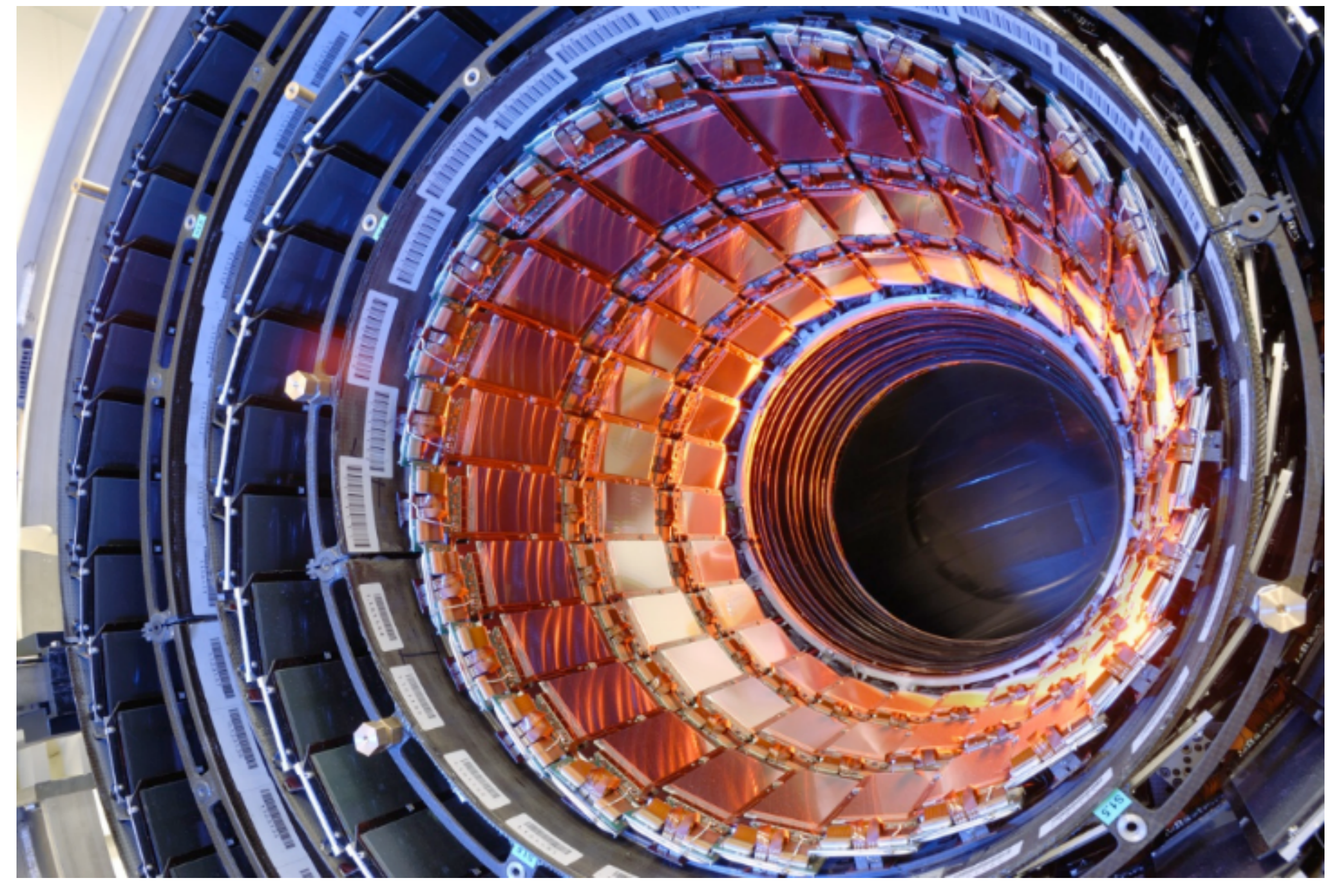
- Over 200m² Silicon
- Cooled to -10°C
- 66M channel pixel detector
  - 100x150μm pitch
- 9.6M channel strip detector
  - 80-180μm pitch, ~10cm long

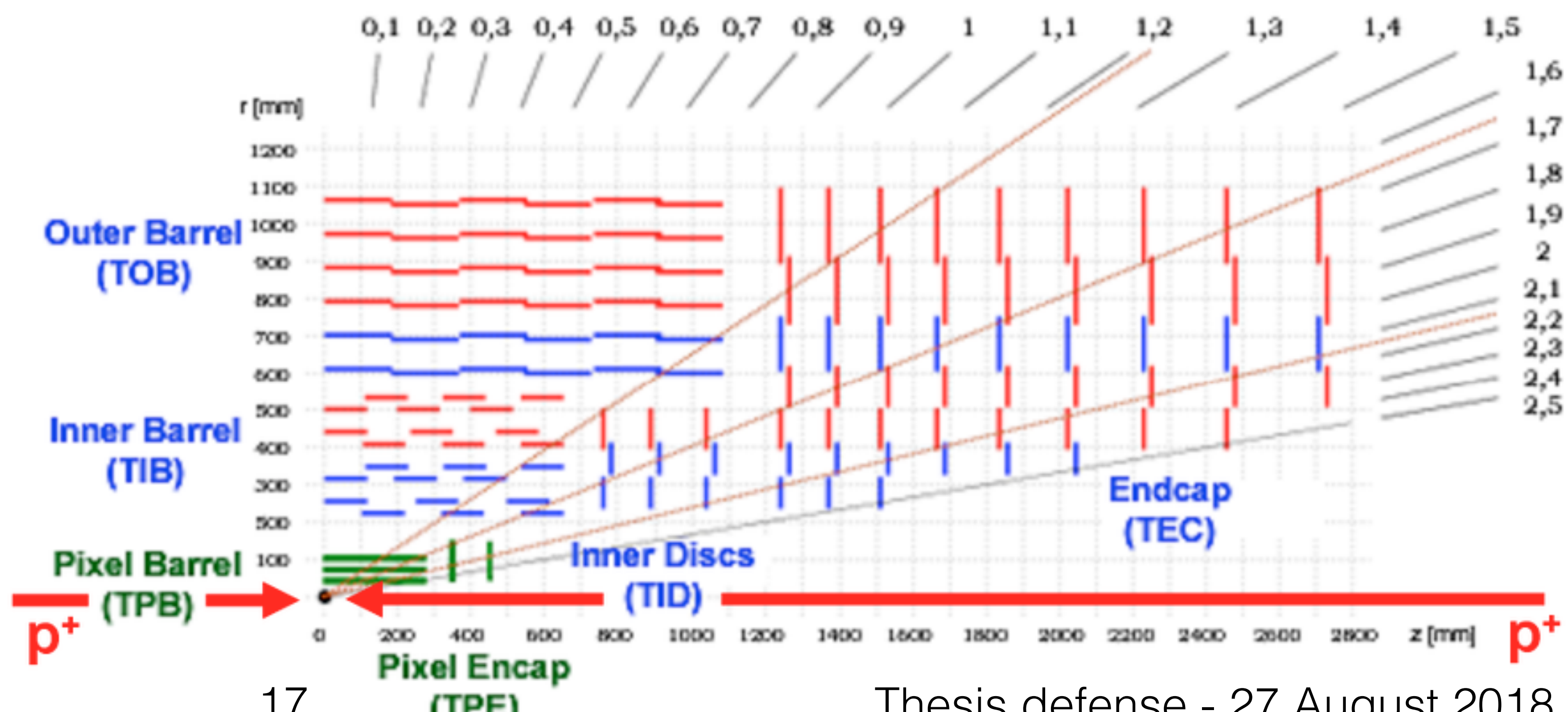
Resolution (barrel):

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

Primary vertex resolution: O(10) μm

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





Electromagnetic Calorimeter

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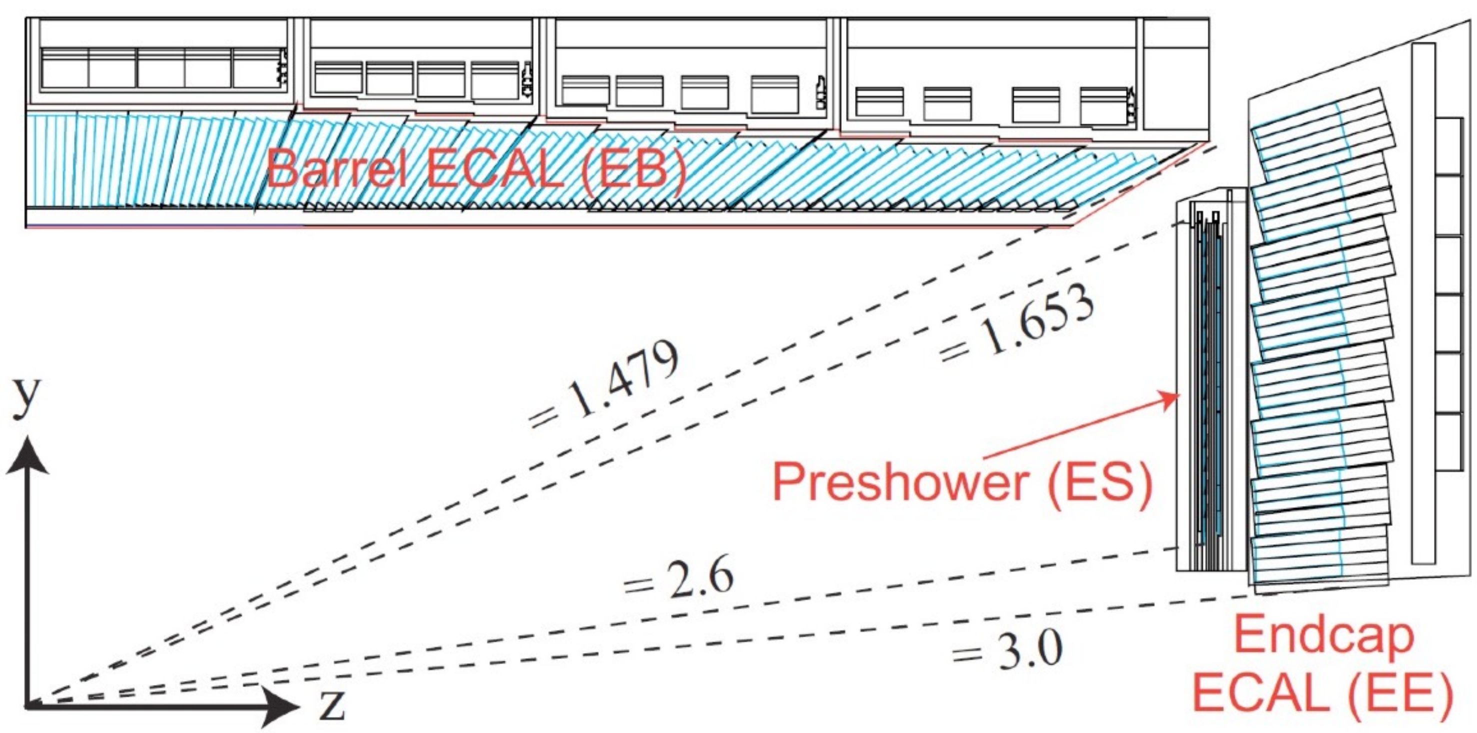
- Over 75k Lead Tungstate crystals, 61200 in Barrel
- Average crystal size: 2.2 x 2.2 x 22cm; weight:1.5kg
- Barrel crystal face $\Delta\eta \times \Delta\phi = 0.0175 \times 0.0175$
- Provides high resolution energy measurement for electrons and photons

	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:

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

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

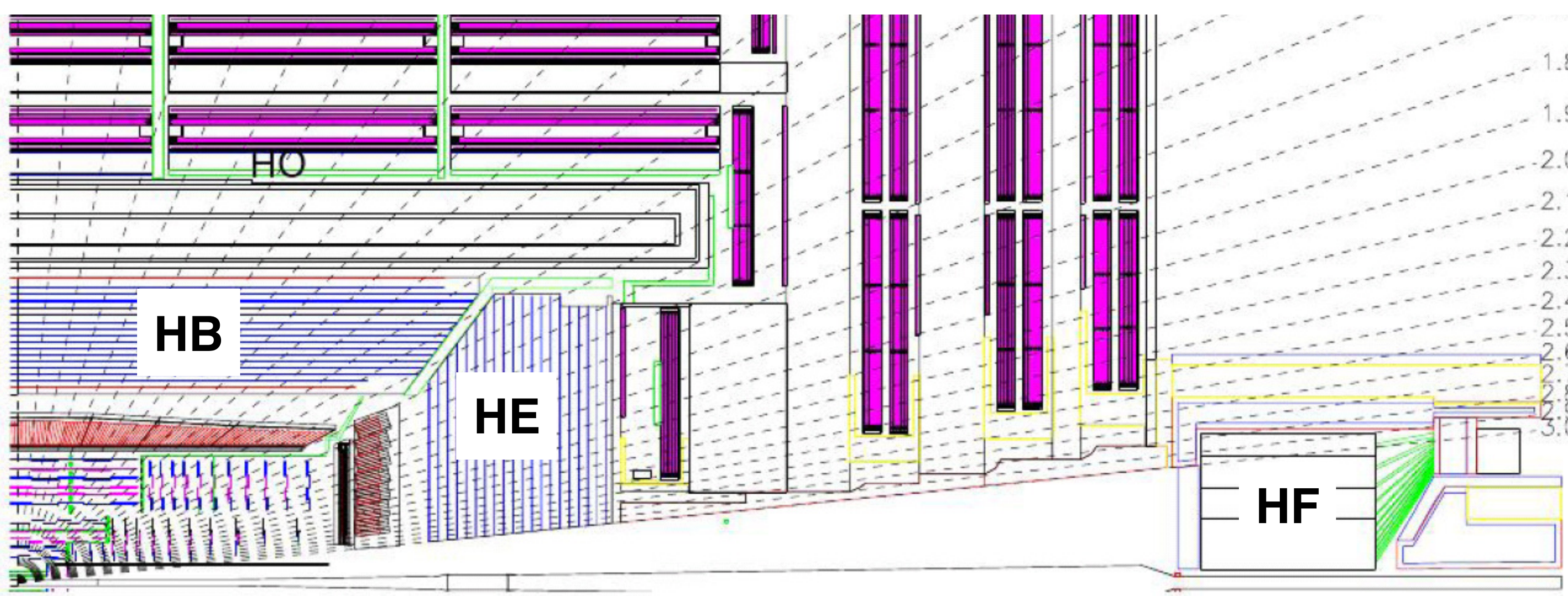
- Steel plates embedded with quartz fibers
- Covers $3 < |\eta| < 5$

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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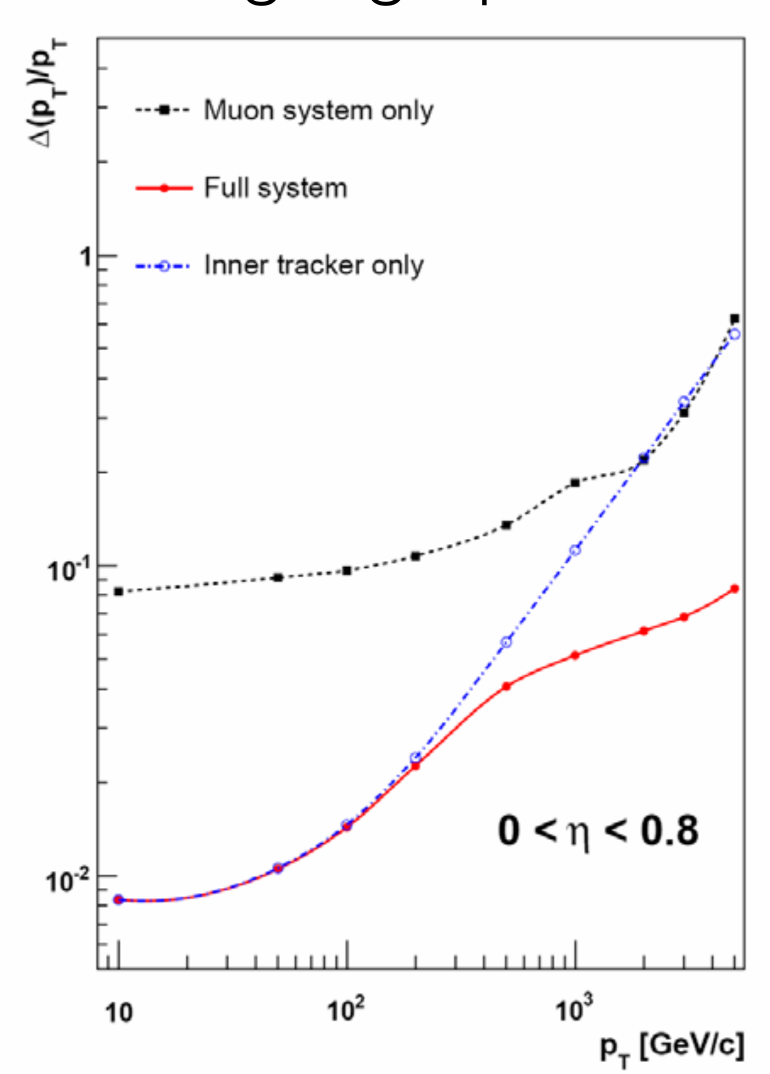
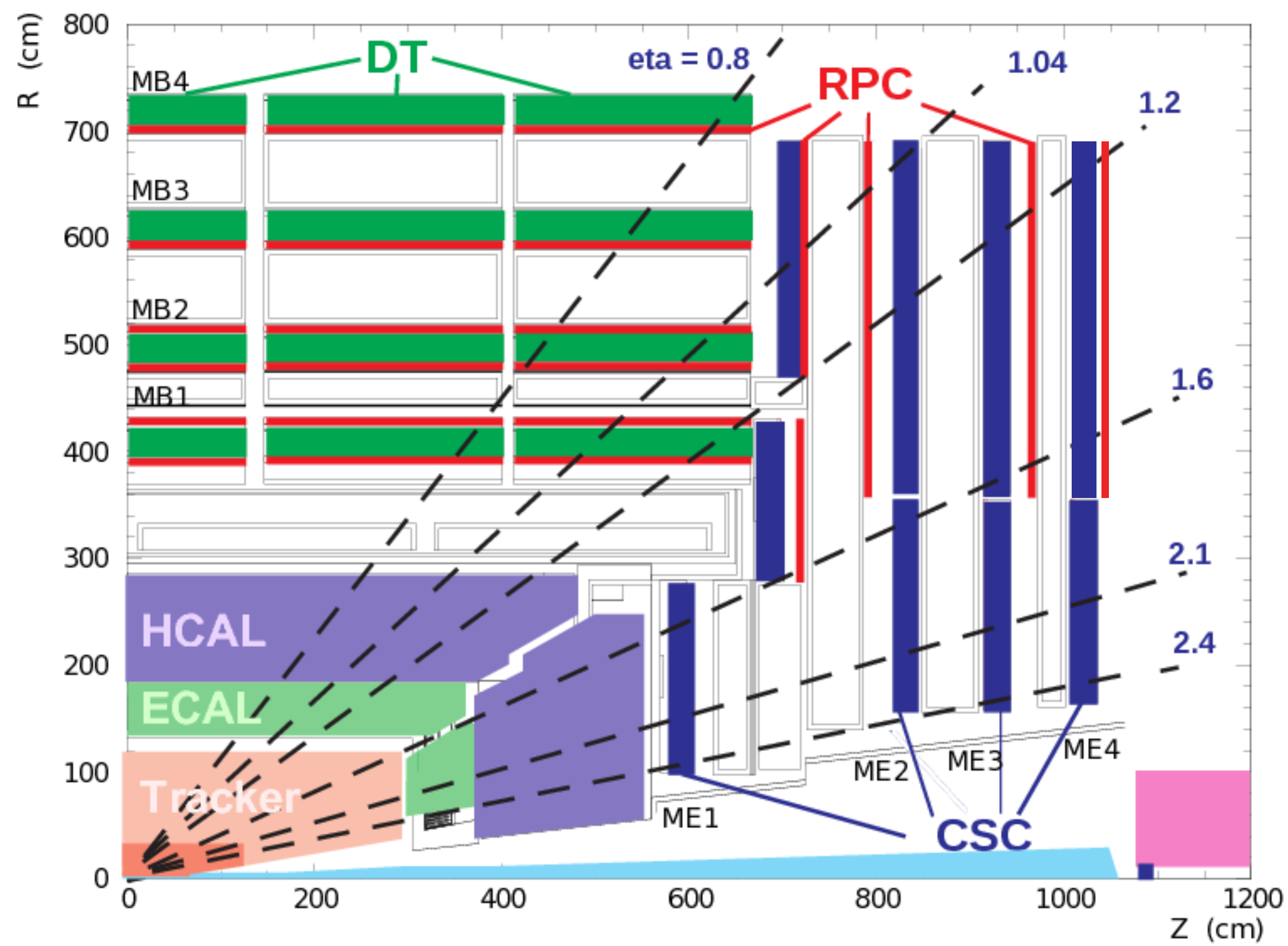
3 muon detection systems embedded in the iron return yoke:

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

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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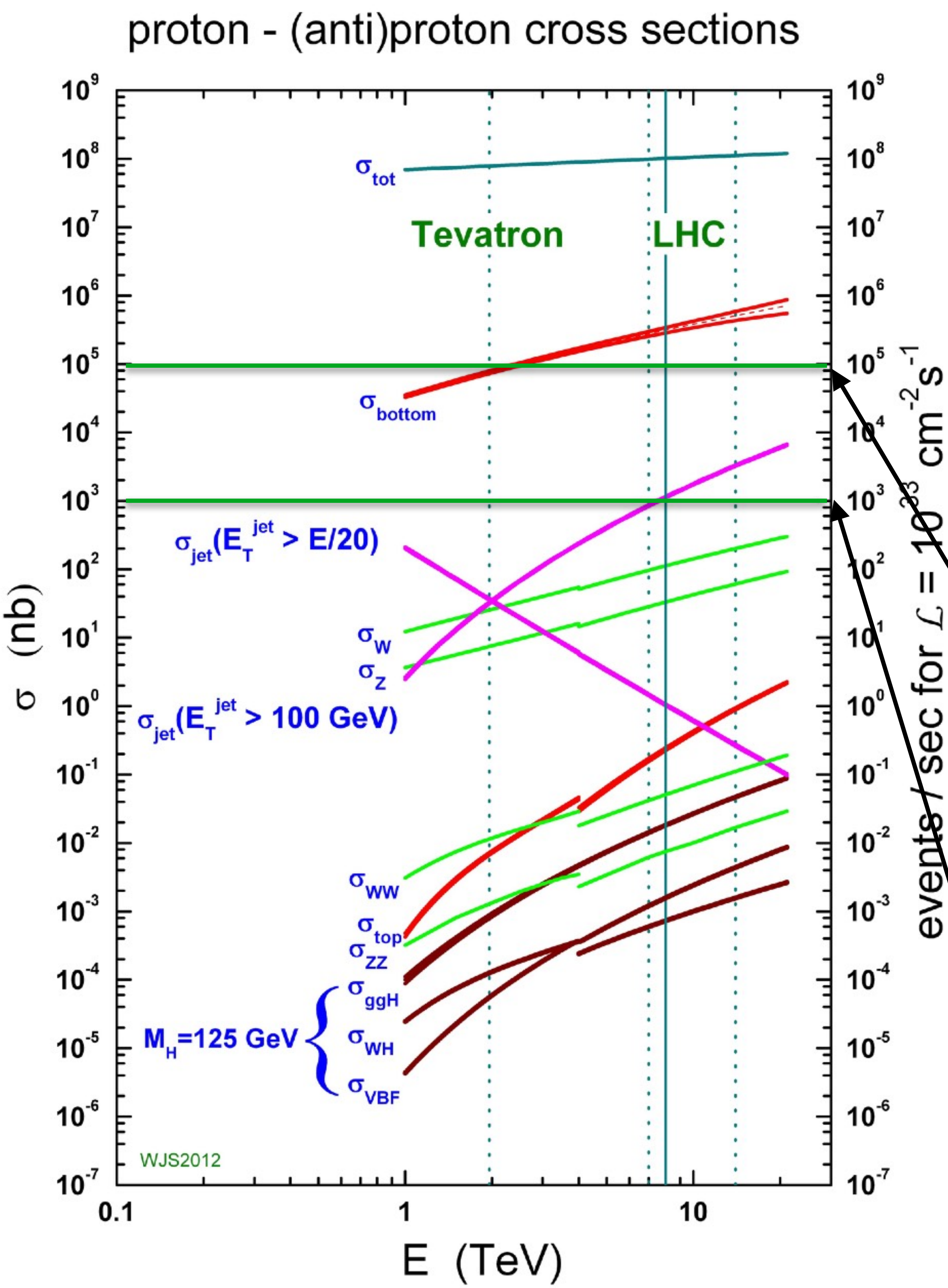

LHC collides bunches of protons at 40MHz

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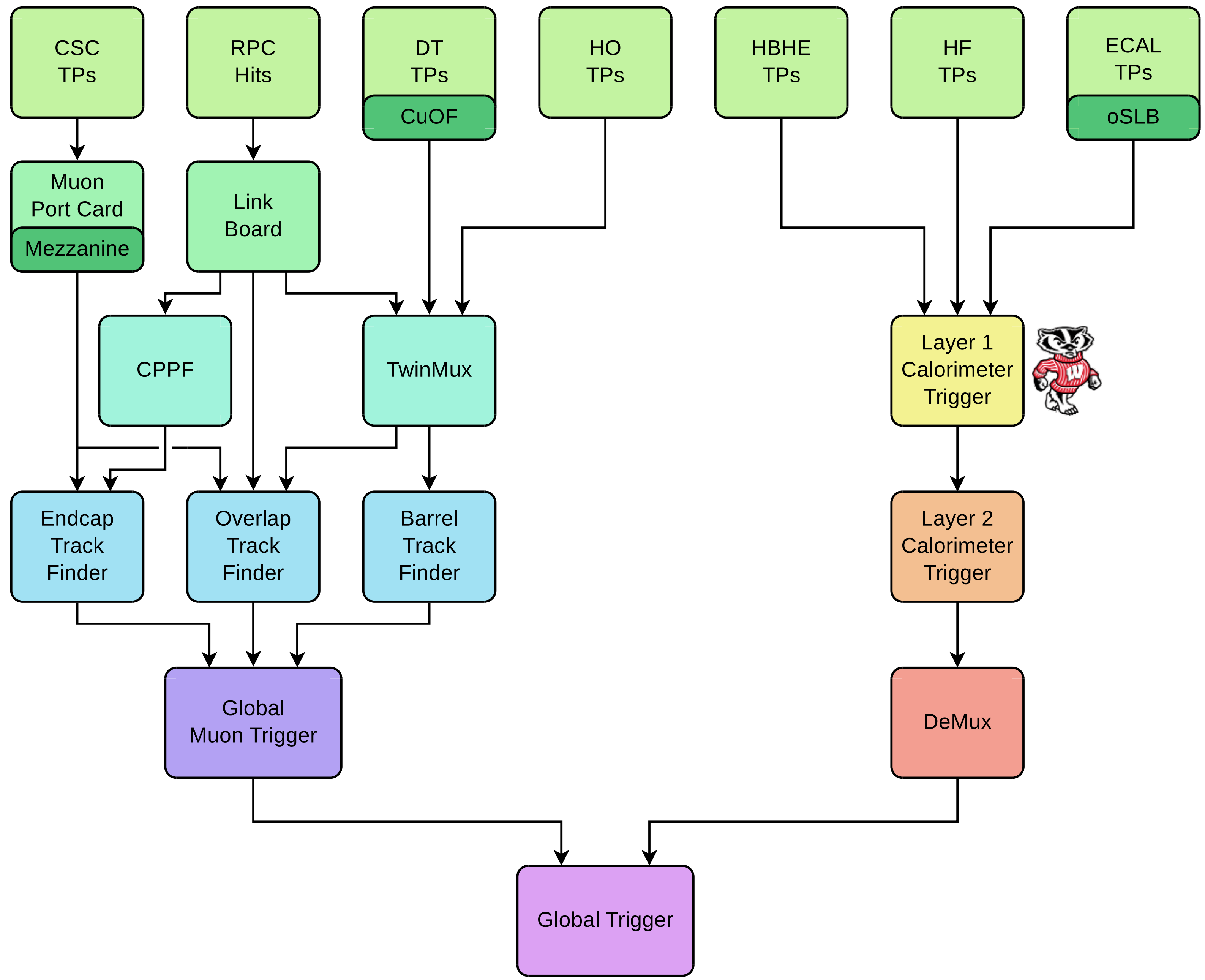
L1 Trigger receives simplified detector information from calorimeters and muon systems, and forms

- 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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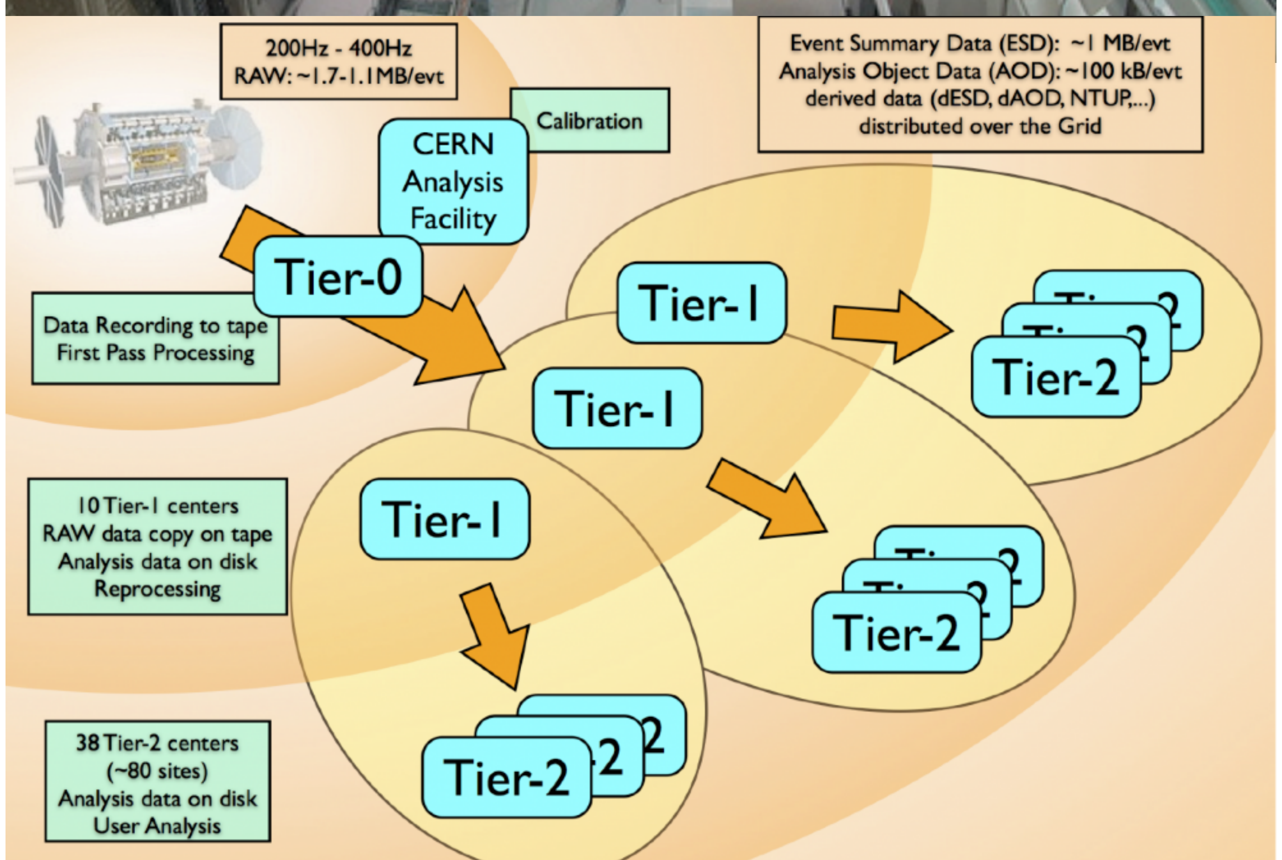

- Dedicated compute farm
- Commodity hardware
- Receives full detector readout
- Subset of reconstruction algorithms
- Over 450 trigger paths in HLT menu

- For HLT accepts, raw data is compressed and saved to tape
- Data is queued for reconstruction

Event Simulation - Proton Collision

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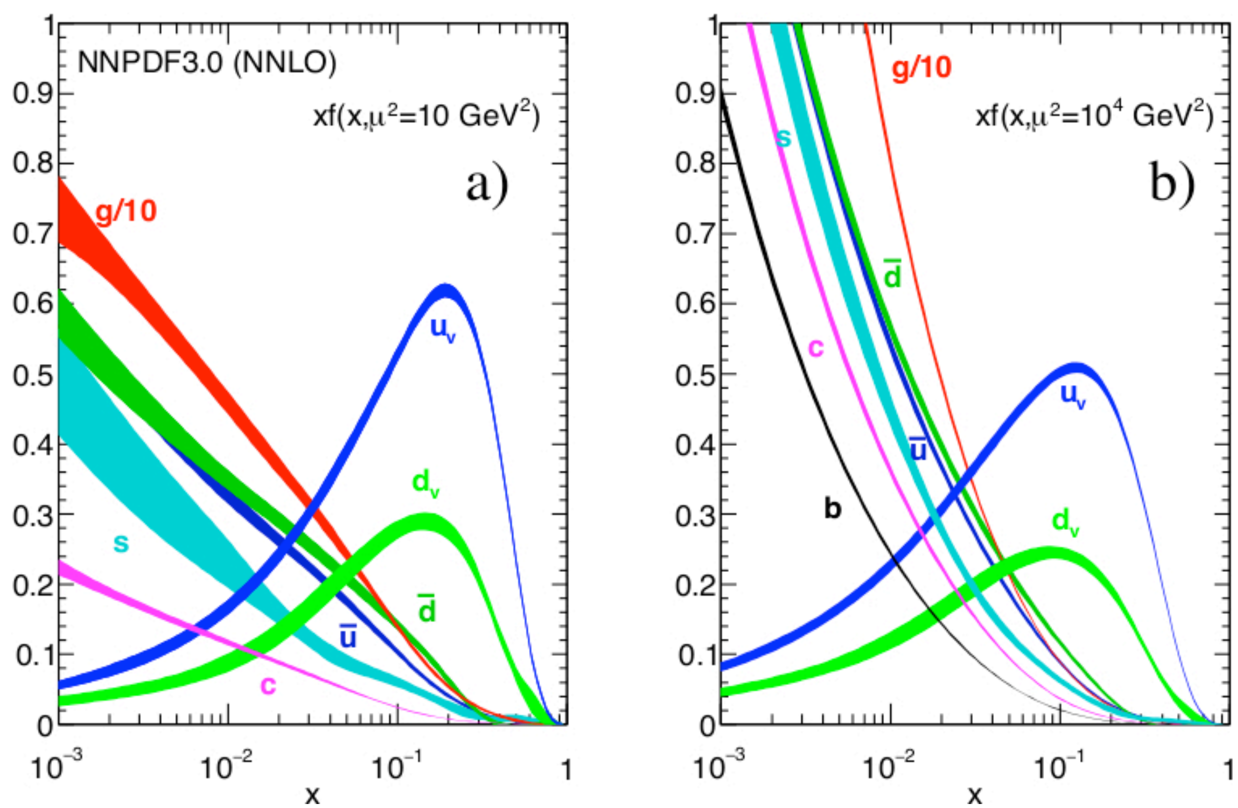
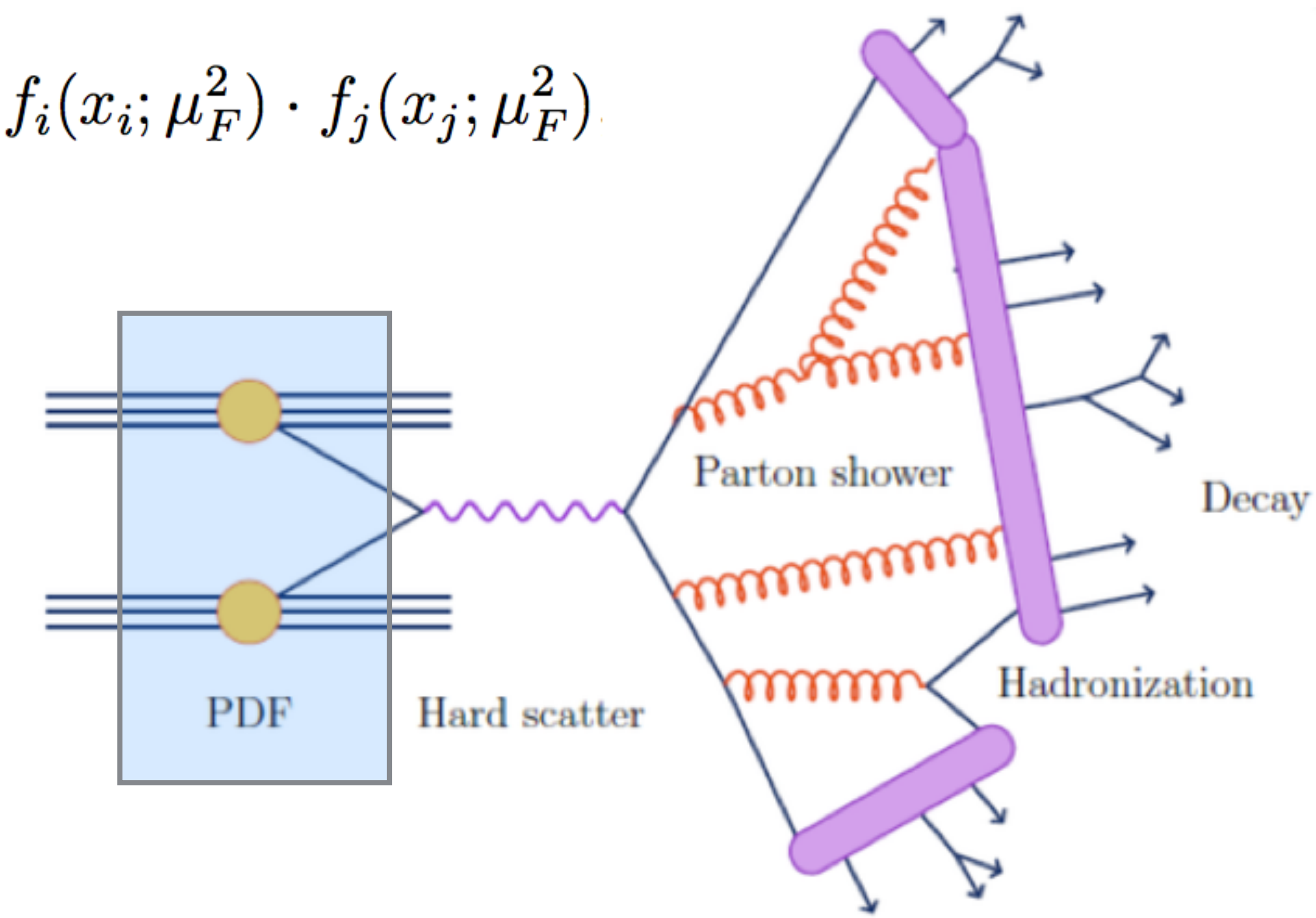
- Factorization theorem: proton collision consists of
  - Hard scatter (high-energy)
  - Underlying event (low-energy)
- Modern picture of a proton:
  - Each parton (quark/gluon) contributes momentum fraction x with probability f, as resolved at factorization scale μ
- Cross section:

$$\sigma_{pp\to X} = \sum_{i,j} \int dx_i dx_j \, \sigma_{ij\to X}(x_i, x_j) \cdot f_i(x_i; \mu_F^2) \cdot f_j(x_j; \mu_F^2)$$





Hard Scatter Simulation

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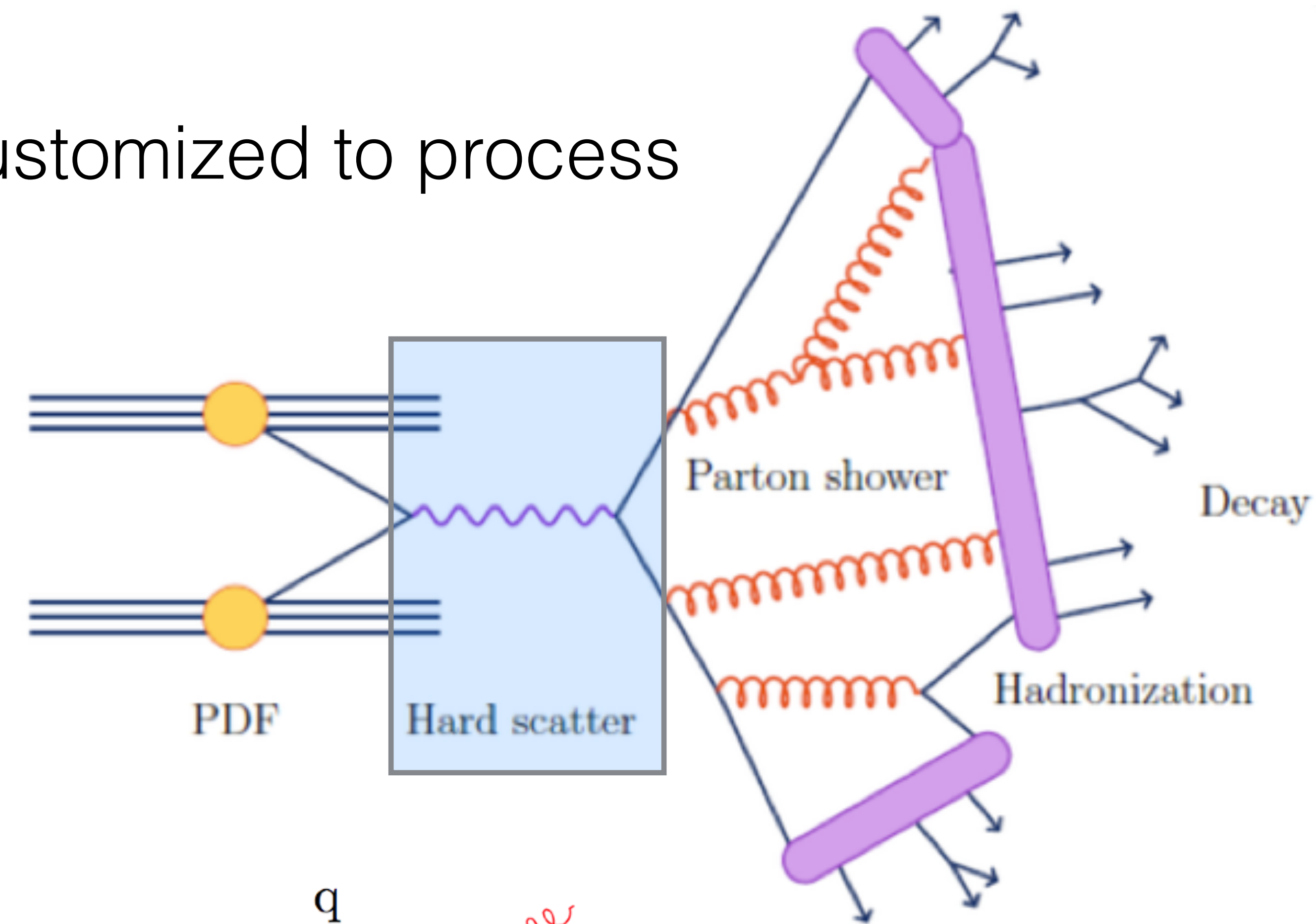
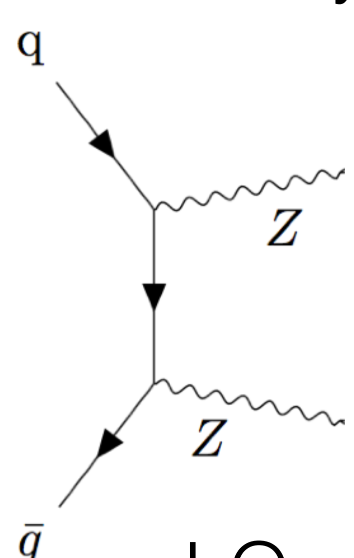
Programs for hard scatter simulation:

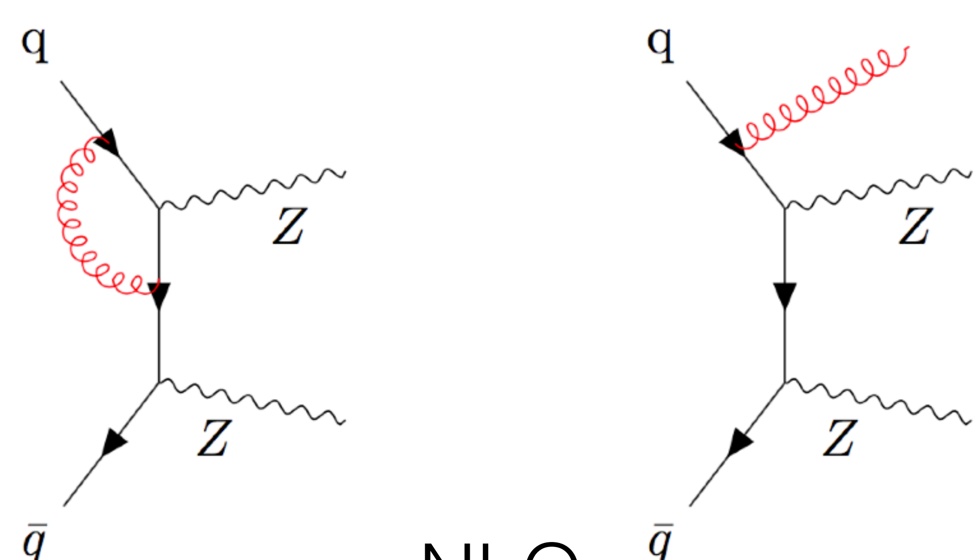
- MadGraph / aMC@NLO
  - Automated calculation of Feynman diagrams
- POWHEG
  - Library of tools plus calculations customized to process
- MCFM, PYTHIA, etc.



These (mostly) provide predictions at Next-to Leading Order (NLO) in quantum chromodynamics (QCD) perturbation theory, e.g.



LO



NLO

Hadronization & Detector Effects

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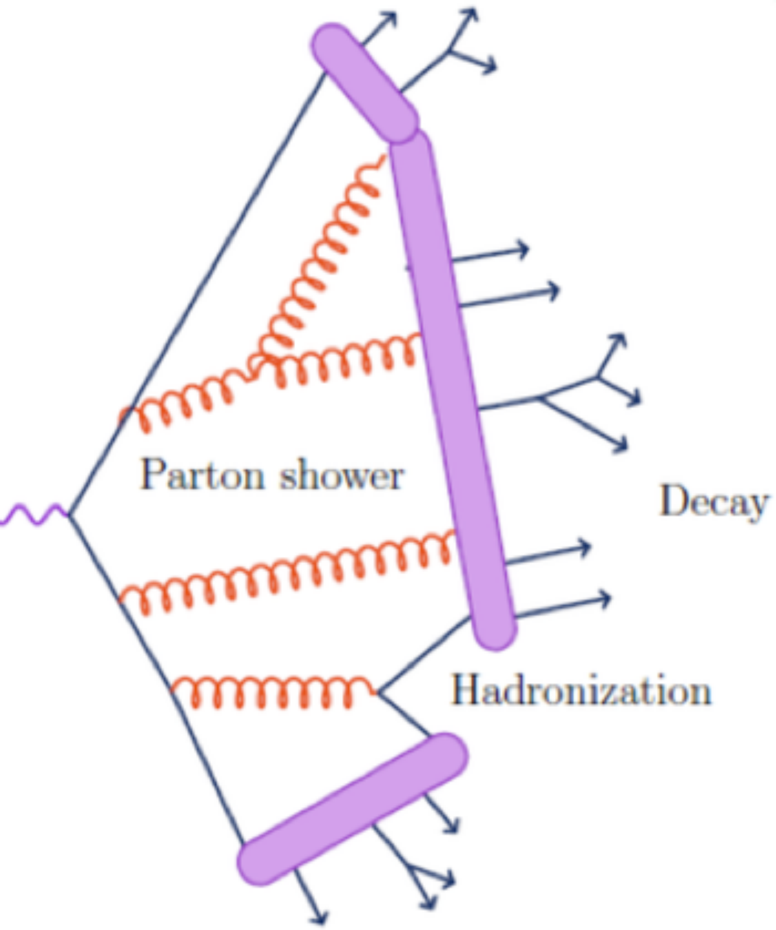
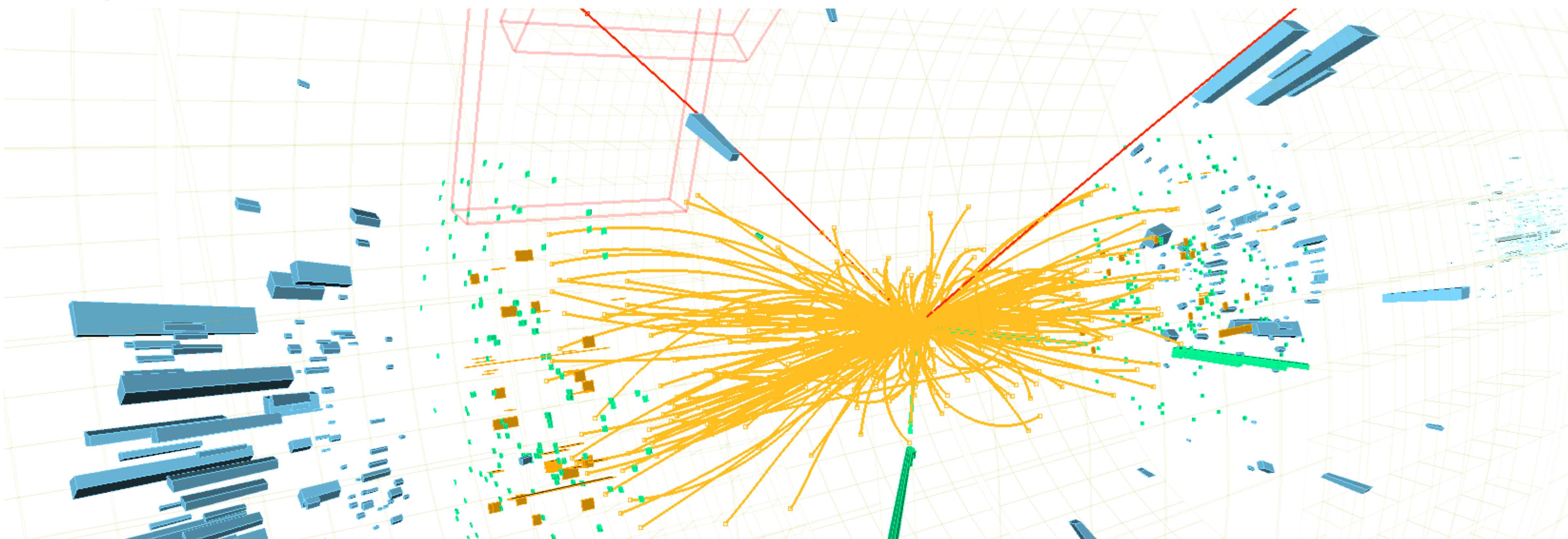


After the hard scatter simulation:

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



Event Reconstruction

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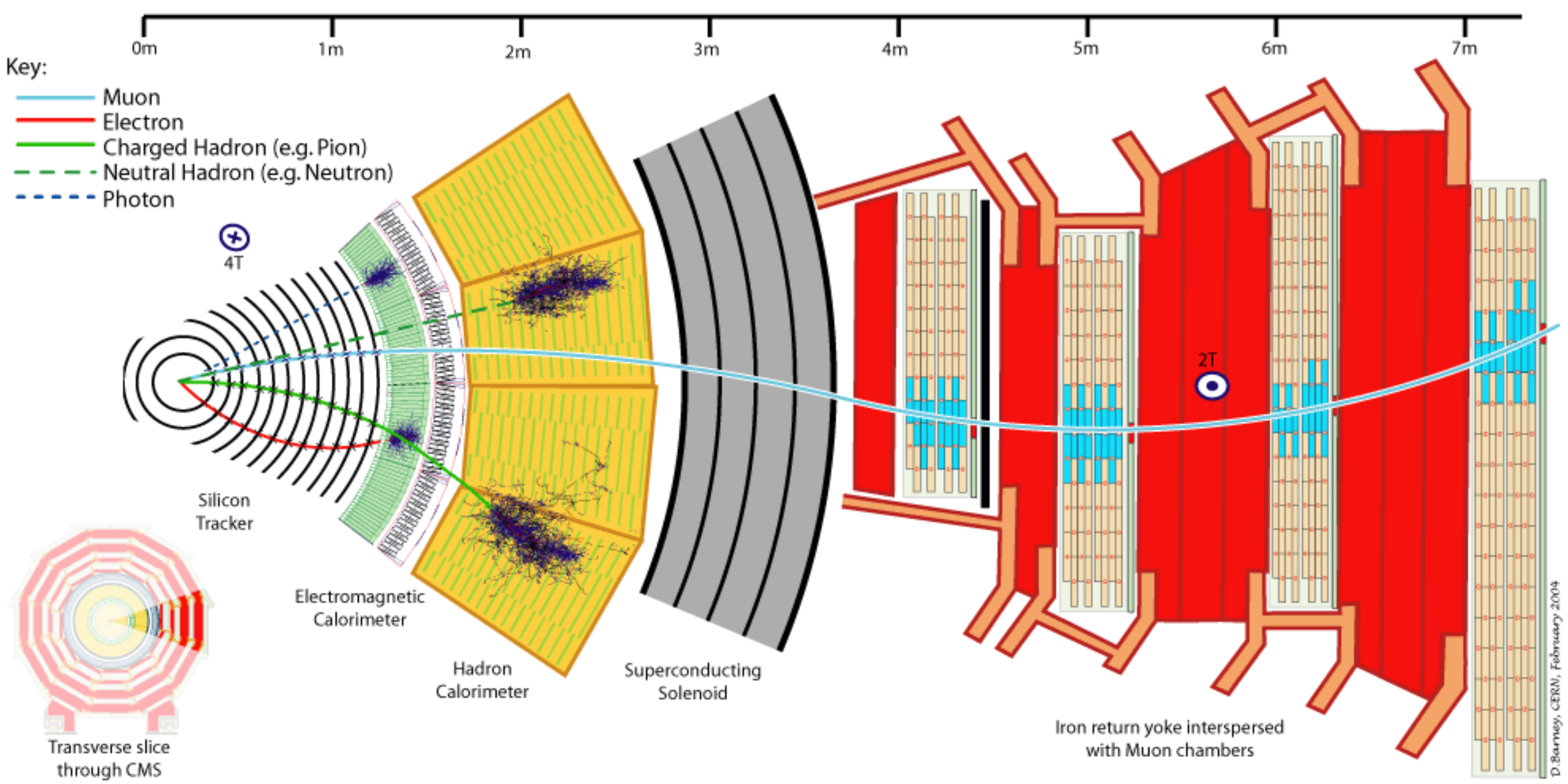
Particle Flow (PF) Reconstruction combines information from all detector components, building candidates in order of purity

- 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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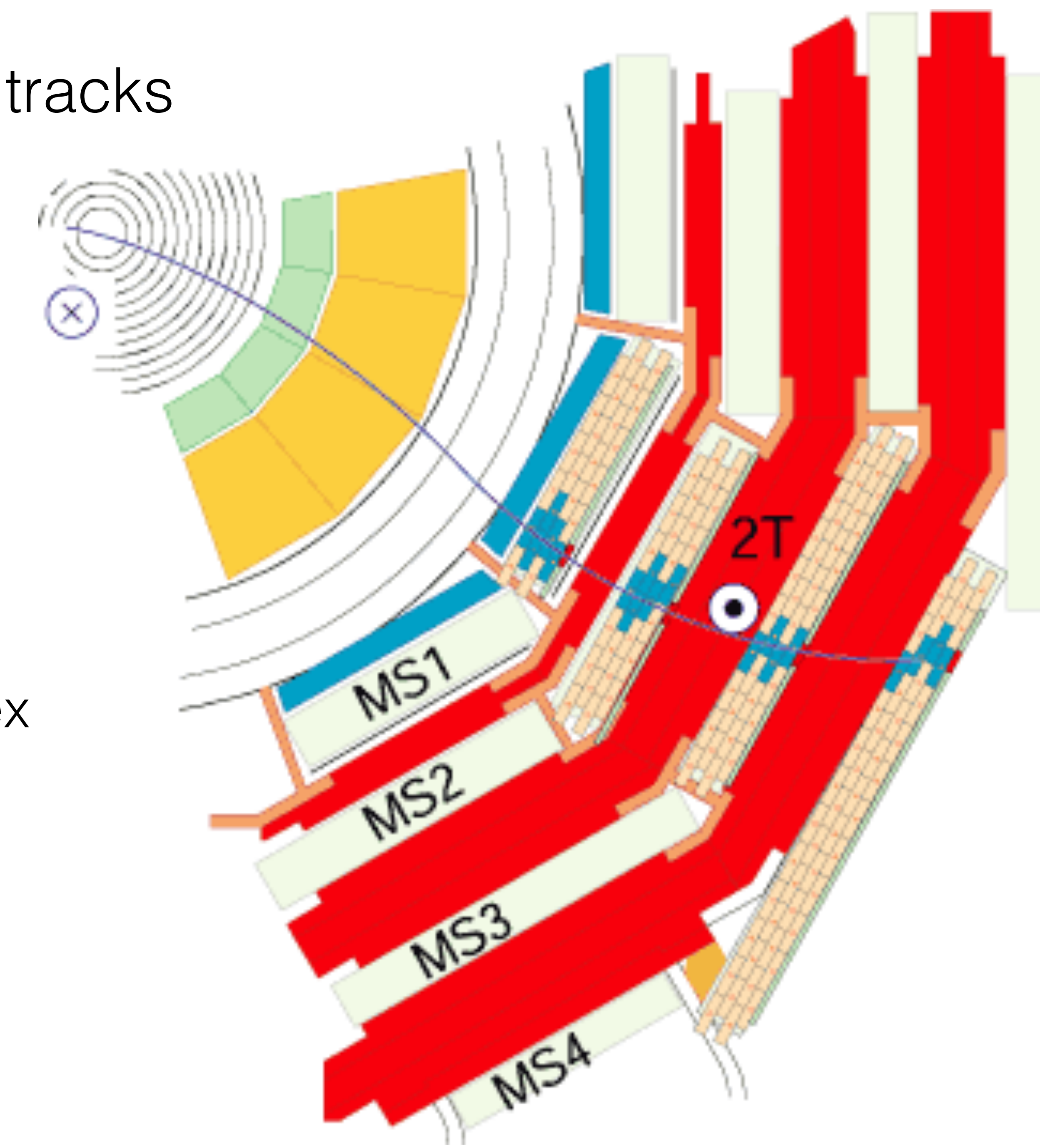
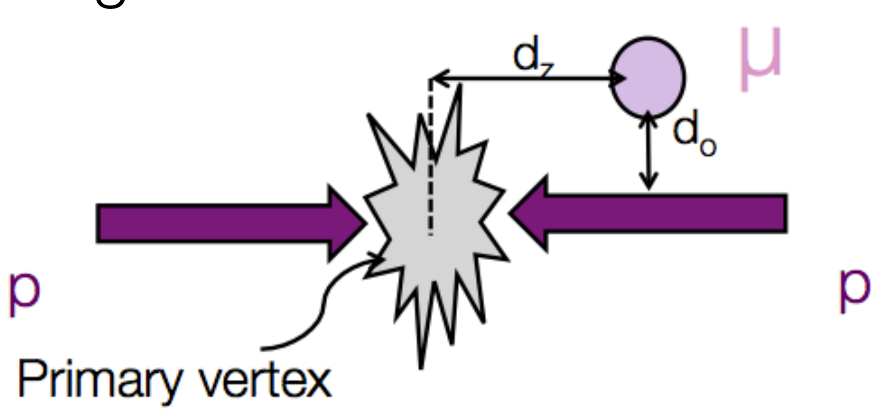
Categories of reconstructed muons:

- *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 < 0.2 mm
  - Longitudinal < 1 mm



Electron Reconstruction

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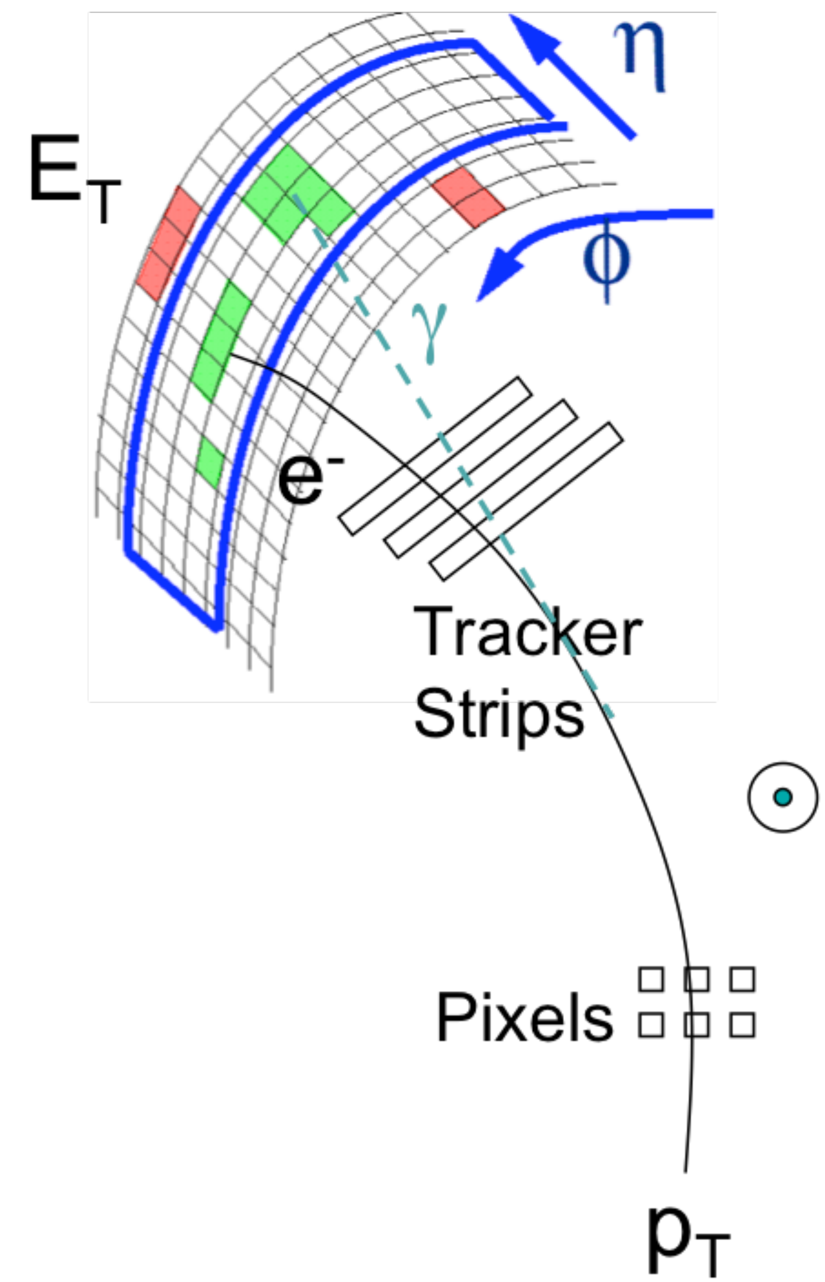
- Electrons identified by combination of detectors
- Basic object called ‘GSF electron’
  - ECAL supercluster
  - Gaussian-Sum Filter track reconstruction



Requirements in this analysis:

- Tracker
  - <2 missing track hits
  - Photon conversion vertex veto
- ECAL
  - Distance between cluster and track
  - ECAL energy to track momentum compatibility
  - Shower shape compatibility requirement
- HCAL
  - H/E cut for rejection of hadrons

ECAL Barrel: $|\eta| < 1.479$

Jet Reconstruction

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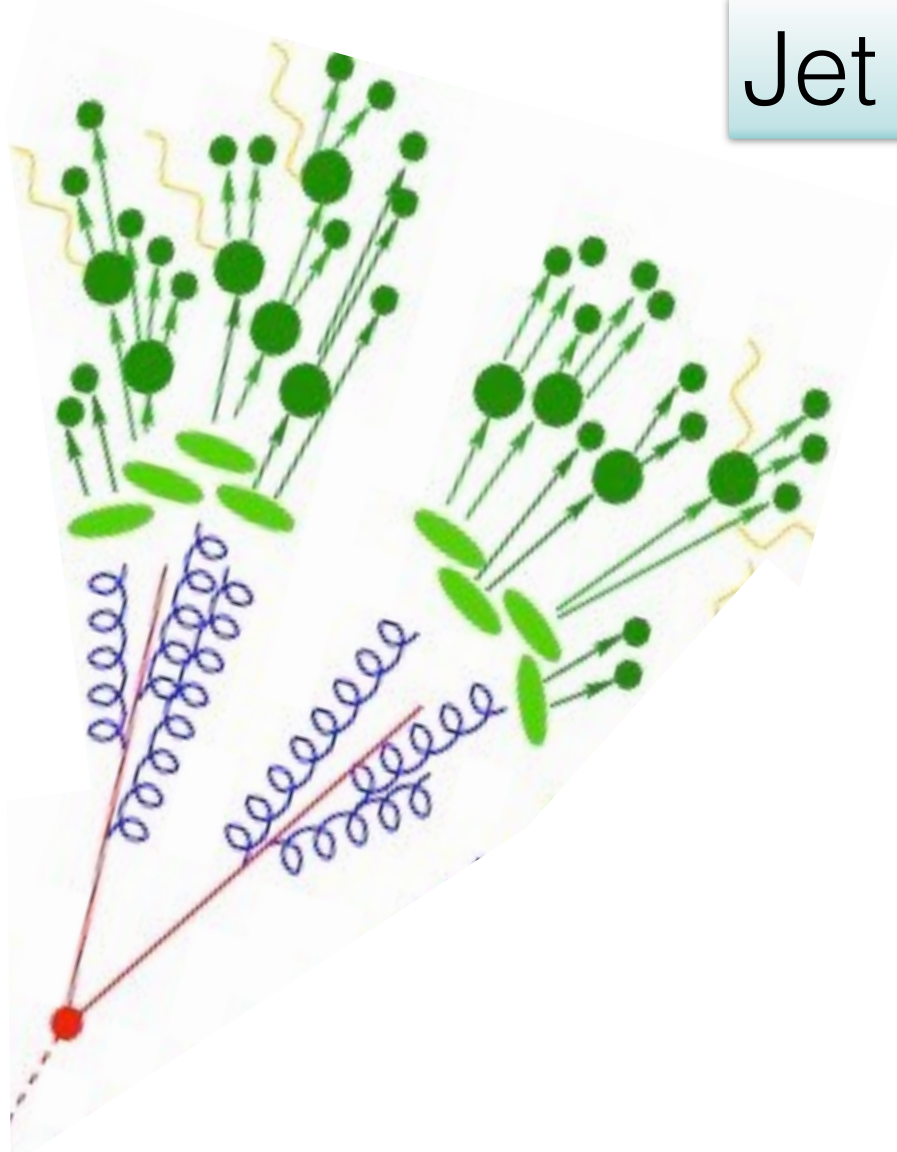
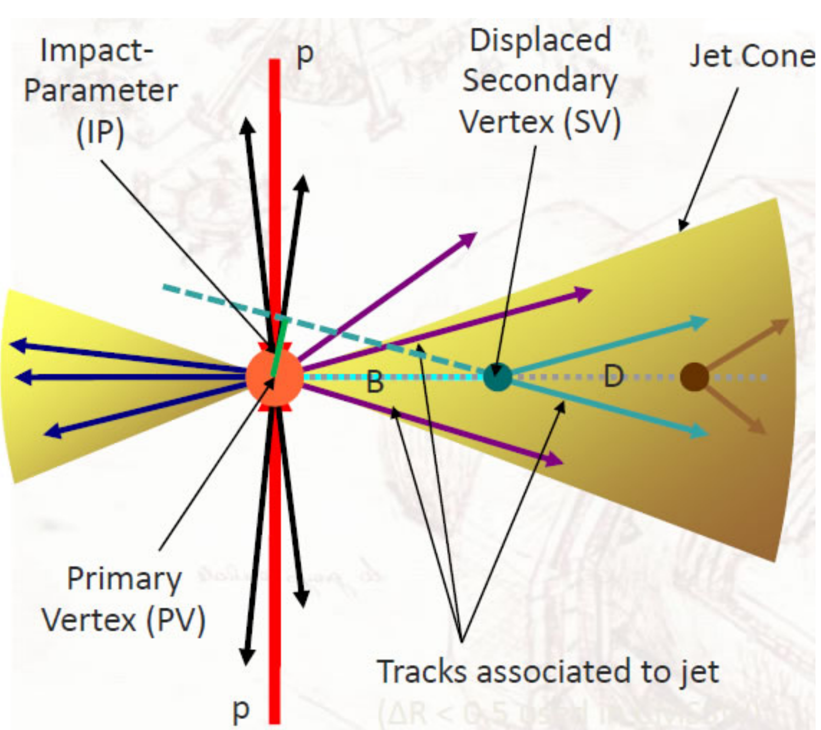
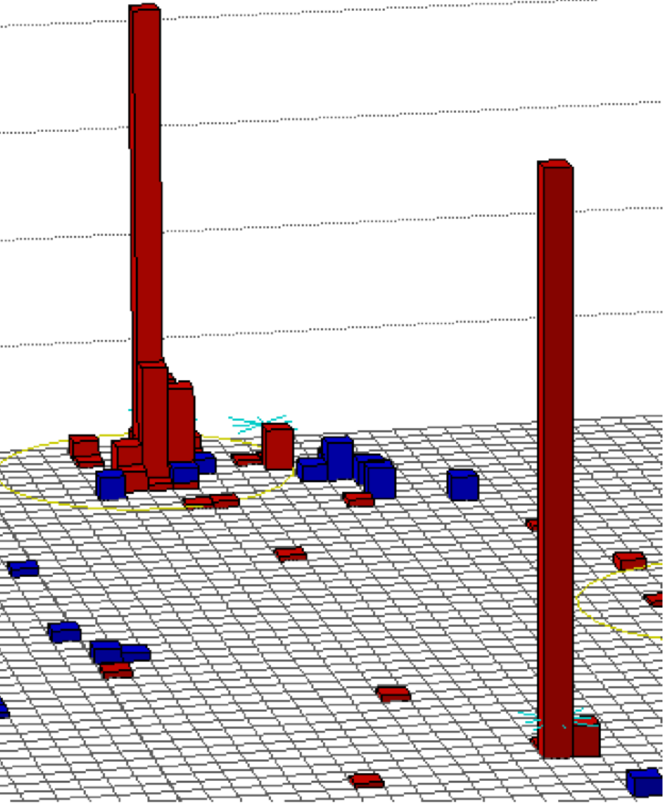


- Quarks and gluons hadronize
- Showers of many particles formed
- Jet reconstruction algorithms:
  - Iteratively cluster nearby particles
  - Form macroscopic objects
  - Preserve ability to compare to theory
- In this analysis, Anti-k_T distance metric:

$$d_{ij} = \min\left(\frac{1}{k_{t,i}^2}, \frac{1}{k_{t,j}^2}\right)\frac{\Delta_{ij}^2}{R^2}, \quad R = 0.4$$



- 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: $I^e = \sum_{\Delta R<0.3} p_{\mathrm{T}}^{h^\pm} + \max\left(\sum_{\Delta R<0.3} p_{\mathrm{T}}^{h^0} + \sum_{\Delta R<0.3} p_{\mathrm{T}}^{\gamma} - \rho \cdot A_{eff}(|\eta_{\mathrm{SC}}|), 0\right)$

Muon isolation: $I^\mu = \sum_{\Delta R<0.4} p_{\mathrm{T}}^{h^\pm} + \max\left(\sum_{\Delta R<0.4} p_{\mathrm{T}}^{h^0} + \sum_{\Delta R<0.4} p_{\mathrm{T}}^{\gamma} - \frac{1}{2}\sum_{\Delta R<0.4} p_{\mathrm{T}}^{h^{\pm,PU}}, 0\right)$

- Require relative isolation less than
  - 6.9% (8.2%) of p_T for electrons in barrel (endcaps)
  - 15% of p_T for muons

Missing Transverse Momentum

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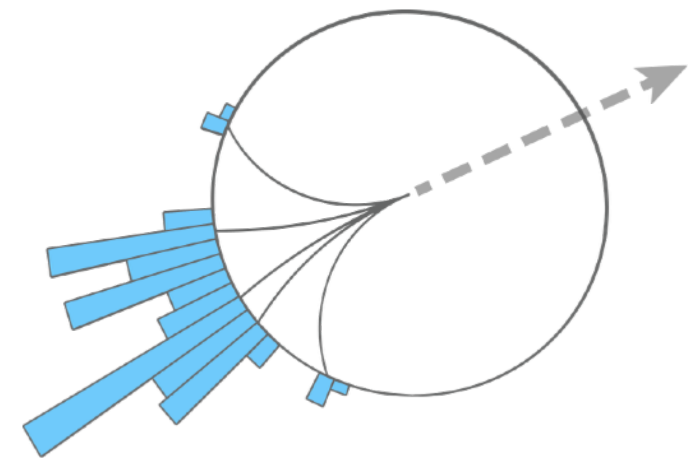
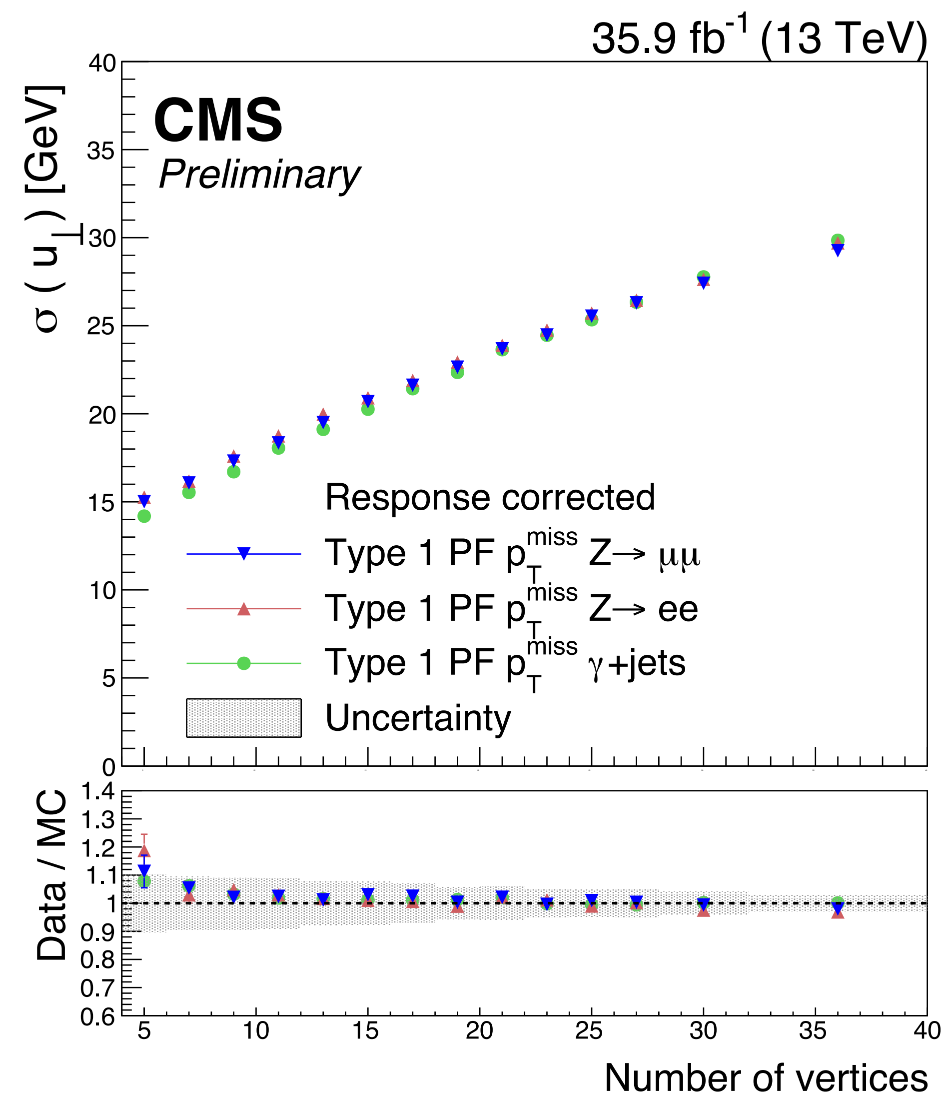
Missing Transverse Momentum (pTmiss):
Negative vector sum of transverse momentum from all reconstructed particles,

$$\vec{p}_T^{\,\text{miss}} = -\sum_{i \in \text{PF}} \vec{p}_{T,i}$$



In this analysis,

- All particle-flow candidates summed, jet energy corrections are propagated
- Events with anomalous pTmiss removed:
  - Noise in HCAL
  - Beam halo muons
  - Pathologies in reconstruction
  - ECAL crystal saturation
- Resolution: ~30 GeV



Signal Extraction

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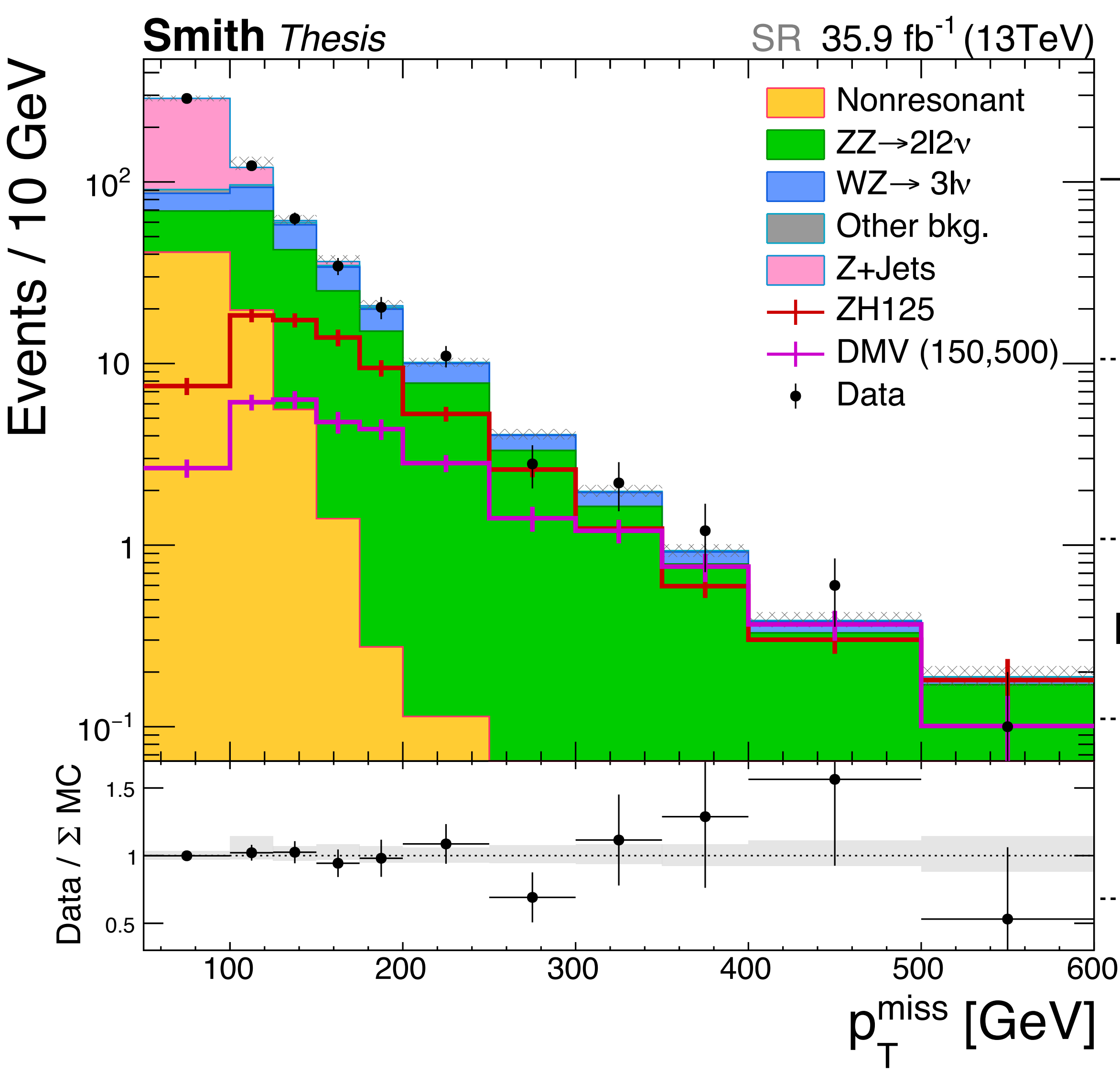
- Signal region (SR):
  - Select boosted ee/μμ pair compatible with Z mass
  - Remove events with extra leptons, b jets
  - Optimize for back-to-back Z+pTmiss topology
- Complementary selections defining data control regions (CRs) validate and improve estimates of significant backgrounds
- A binned likelihood model parameterized by signal strength, uncertainties in signal & background predictions is fit to the observation to extract results



Background	Source	% Signal region	Legend
ZZ(2ℓ2ν)	Main background, same final state as signals	56%	
WZ(3ℓν)	Light lepton from W boson lost due to detector acceptance or reconstruction inefficiencies	22%	
Nonresonant	Top-antitop production, WW production, Drell-Yan decays to τ pairs. No Z boson mass resonance	10%	
Drell-Yan	Z boson plus jets production. pTmiss due to detector acceptance or jet energy mismeasurement	10%	
Other	Other diboson processes, processes with misreconstruction of final state, triboson processes.	2%	

Diboson Background Estimation I

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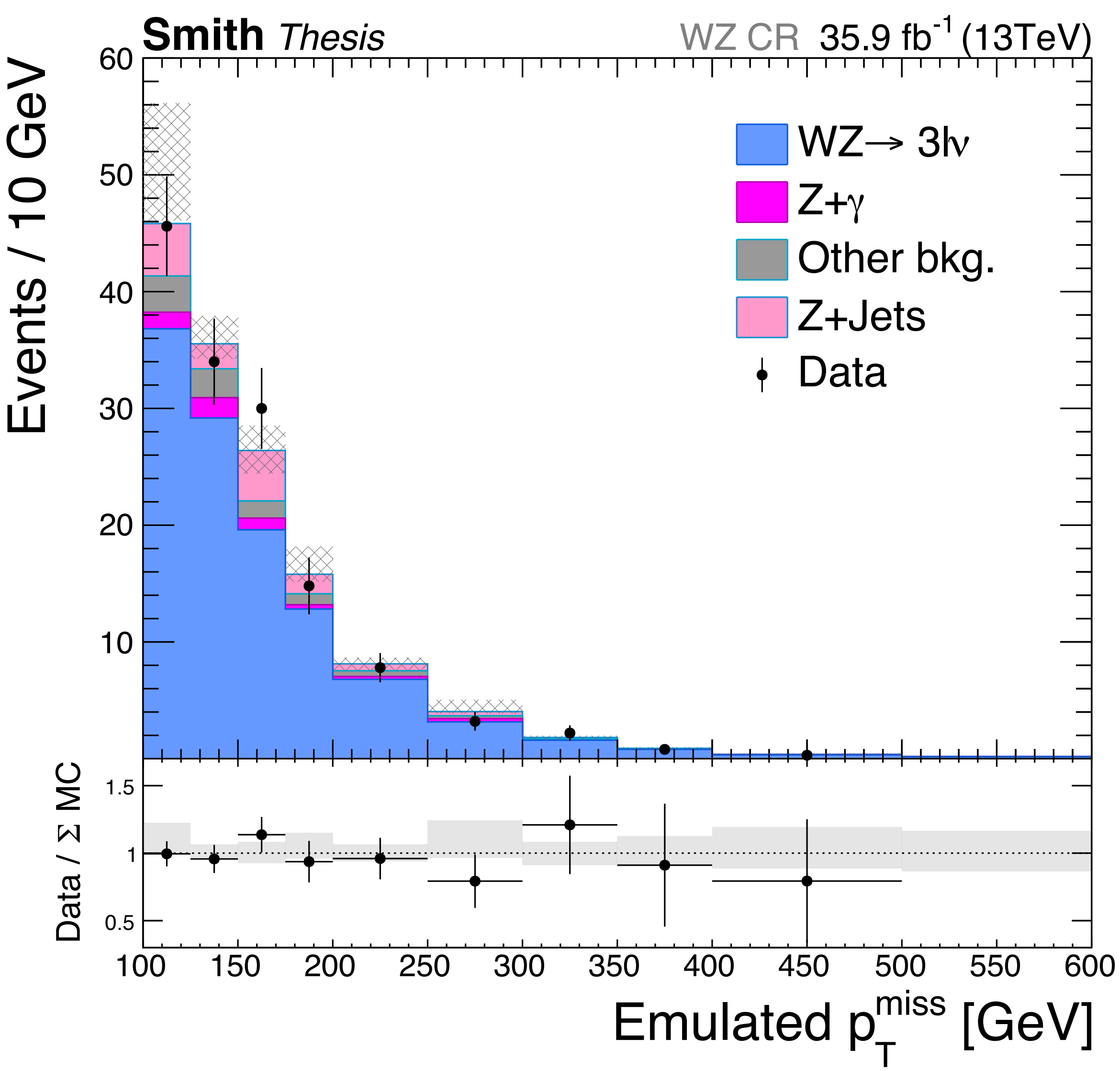
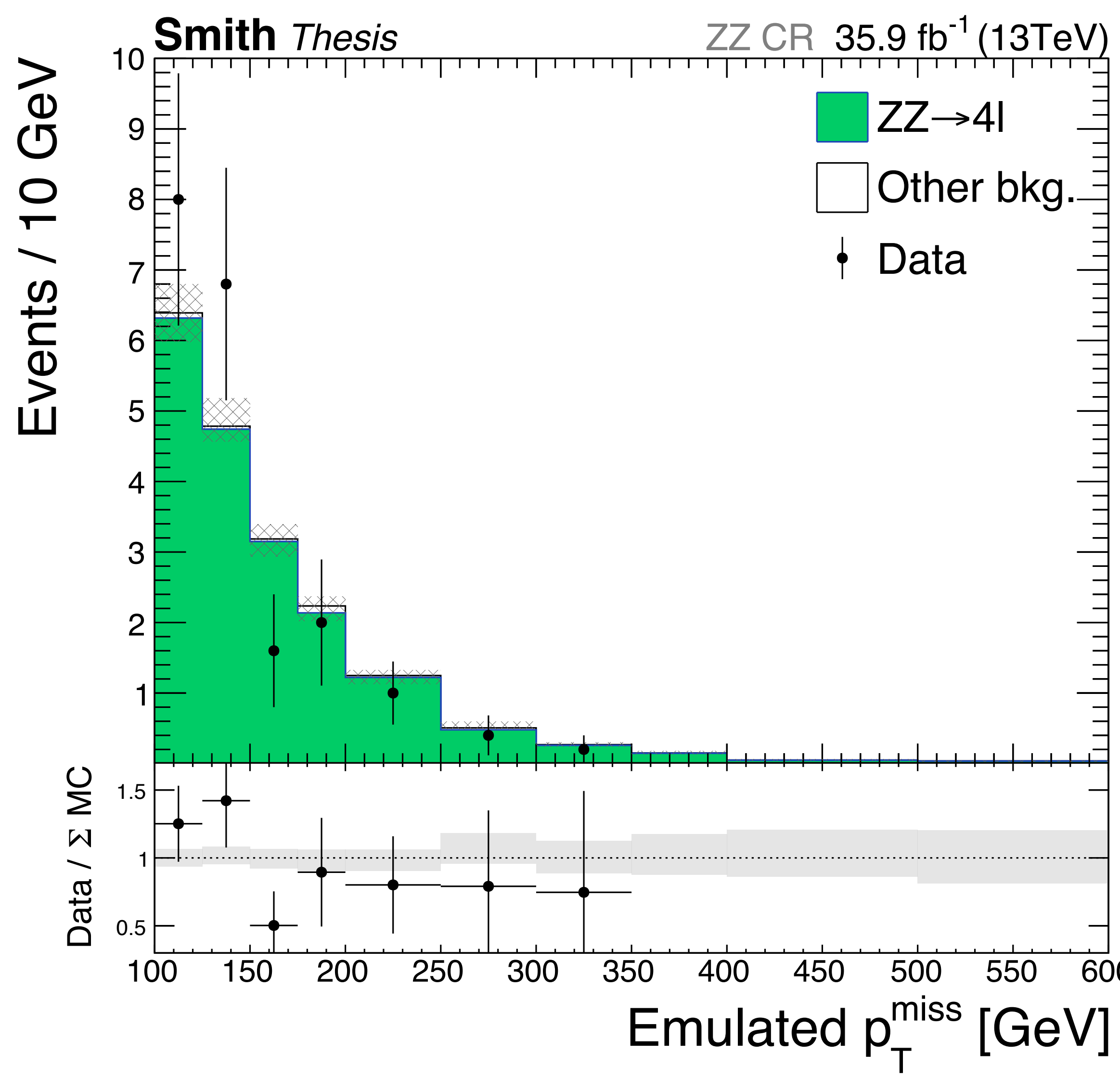
- Main backgrounds at high pTmiss are ZZ(2ℓ2ν) and WZ(3ℓν)
  - pTmiss represents boson p_T
- Select control regions for each
  - WZ: 3 leptons with selections to enhance WZ purity
  - ZZ: 4 leptons compatible with two Z production
- Form 'Emulated pTmiss' = pTmiss + extra lepton(s) momentum
- Apply signal selection using Emulated pTmiss





Diboson Background Estimation II

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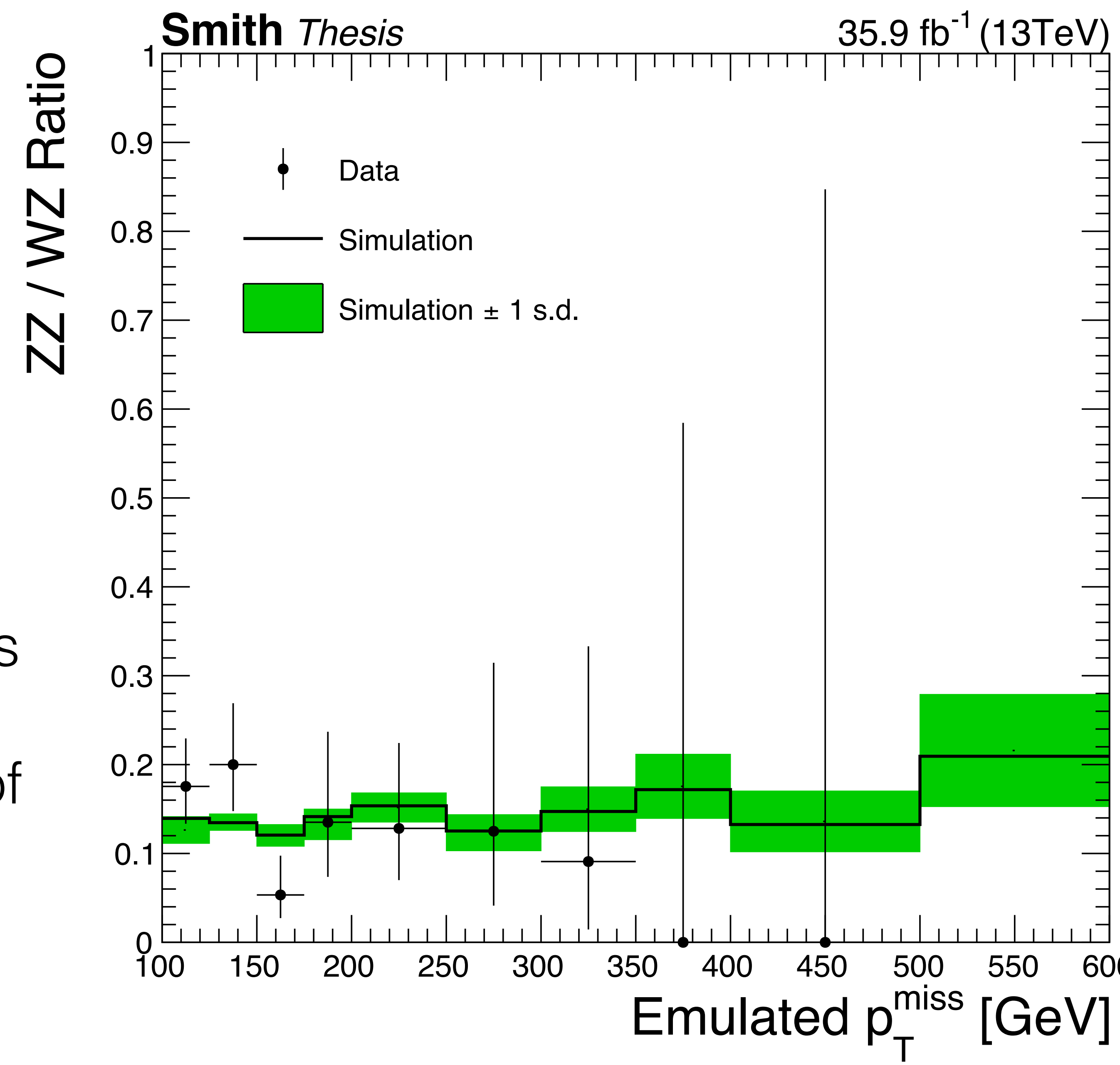
- Single floating normalization parameter in maximum likelihood fit for processes:
  - ZZ(4ℓ) yields in ZZ CR
  - WZ(3ℓν) yields in WZ CR
  - ZZ(2ℓ2ν) yields in SR
  - WZ(3ℓν) yields in SR
- Differential distribution predicted by simulation
  - NNLO QCD + NLO electroweak corrections applied to improve prediction for ZZ and WZ
  - Uncertainty on differential predictions anti-correlated between ZZ and WZ
- Validation of prediction: compare ratio of ZZ and WZ CR observed data



Nonresonant Background Estimation

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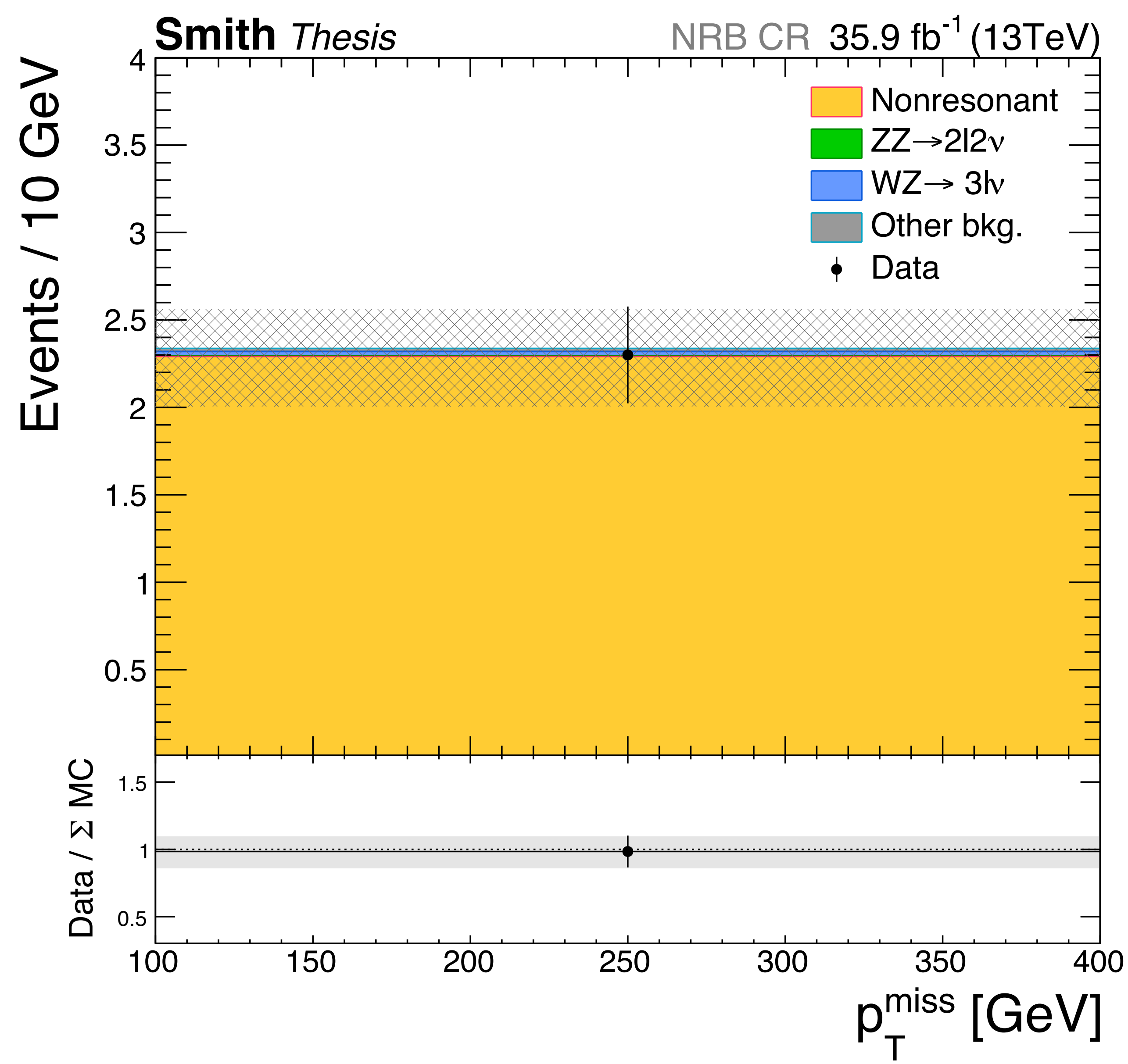
NRB includes ttbar, WW, single-top, Drell-Yan($\tau\tau$)
In all cases, leptons from W/τ decay have ee:μμ:eμ ratio of 1:1:2
Account for lepton efficiency differences with:

$$k_{ee} = \frac{\epsilon_e}{\epsilon_\mu} = \sqrt{\frac{N_{\mathrm{NRB}}^{ee}}{N_{\mathrm{NRB}}^{\mu\mu}}}$$

Then the NRB estimate in signal region:

$$N_{\mathrm{NRB}}^{\ell\ell} = \frac{1}{2}\left(k_{ee} + \frac{1}{k_{ee}}\right) N_{\mathrm{NRB}}^{e\mu}$$

- pTmiss spectrum identical in CR and SR, simulation models data well
  - Use single bin CR to define SR normalization, according to above formula
  - Conservative 20% uncertainty on transfer factor, gives <1% impact on result



Drell-Yan Background Estimation

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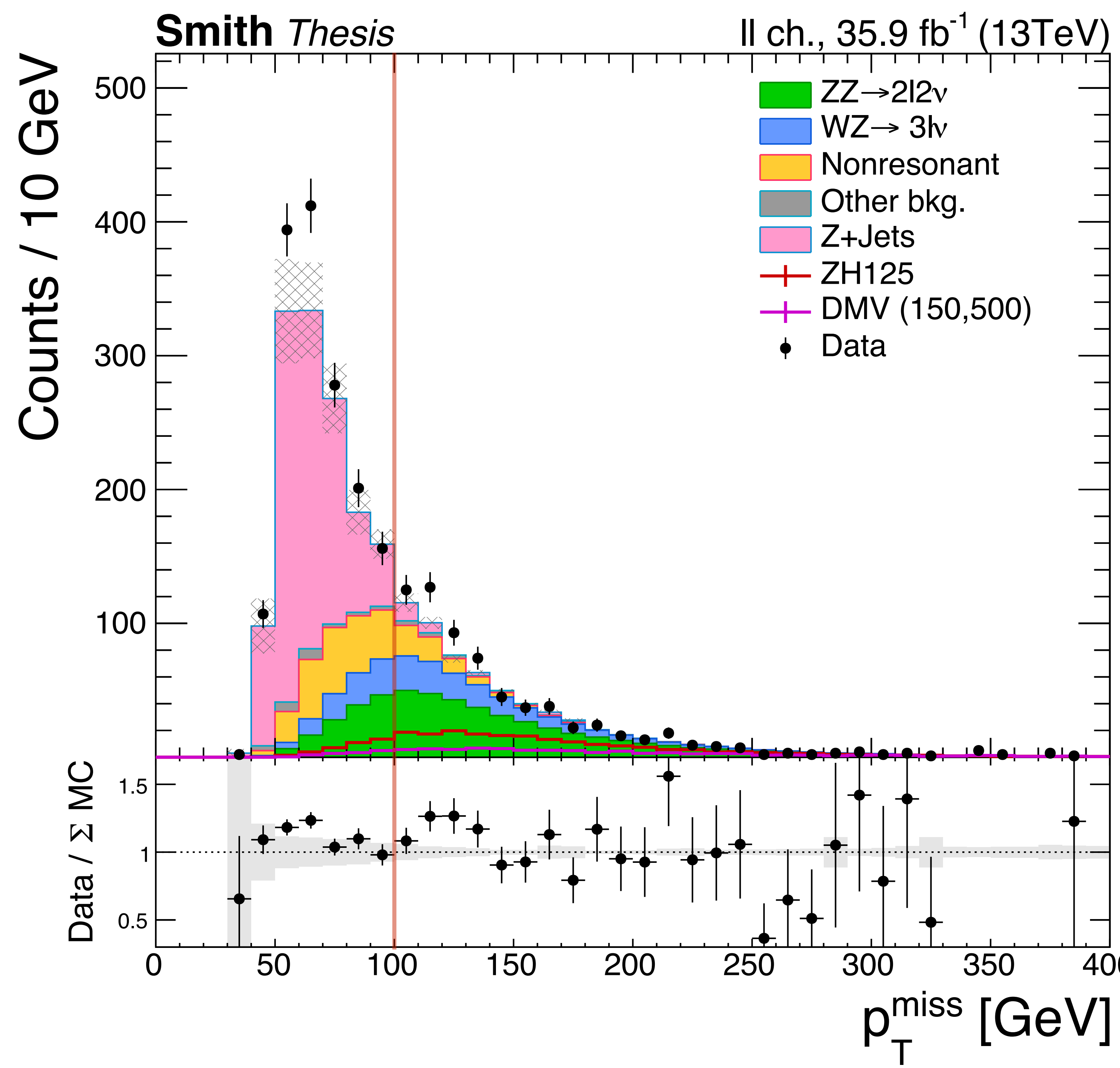
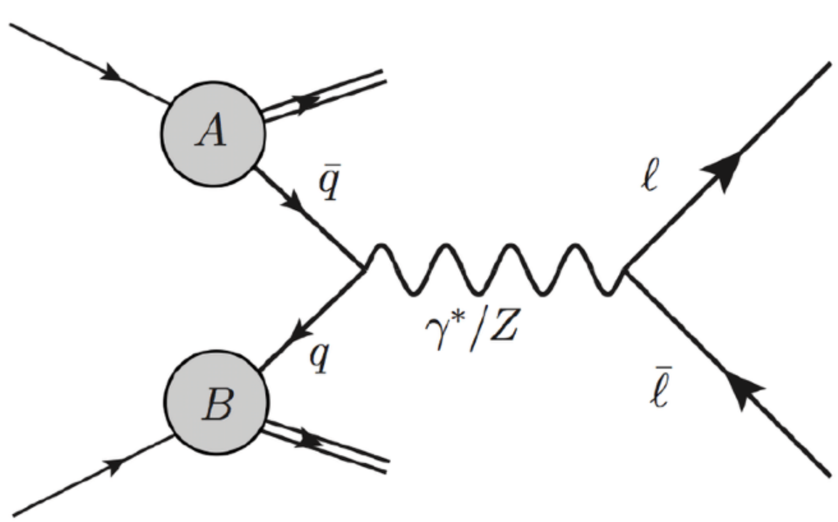
- pTmiss > 100 GeV cut removes vast majority of DY
- Use [50,100] as control region for normalization
  - Observed (ML fit) normalization: 0.98 +/- 0.1
  - This plot prior to ML fit
- Simulation models data well
- Assign 100% extrapolation uncertainty to normalization in SR
- As DY is only 10% of yield, and negligible at high pTmiss, it has little effect on the final results





Results

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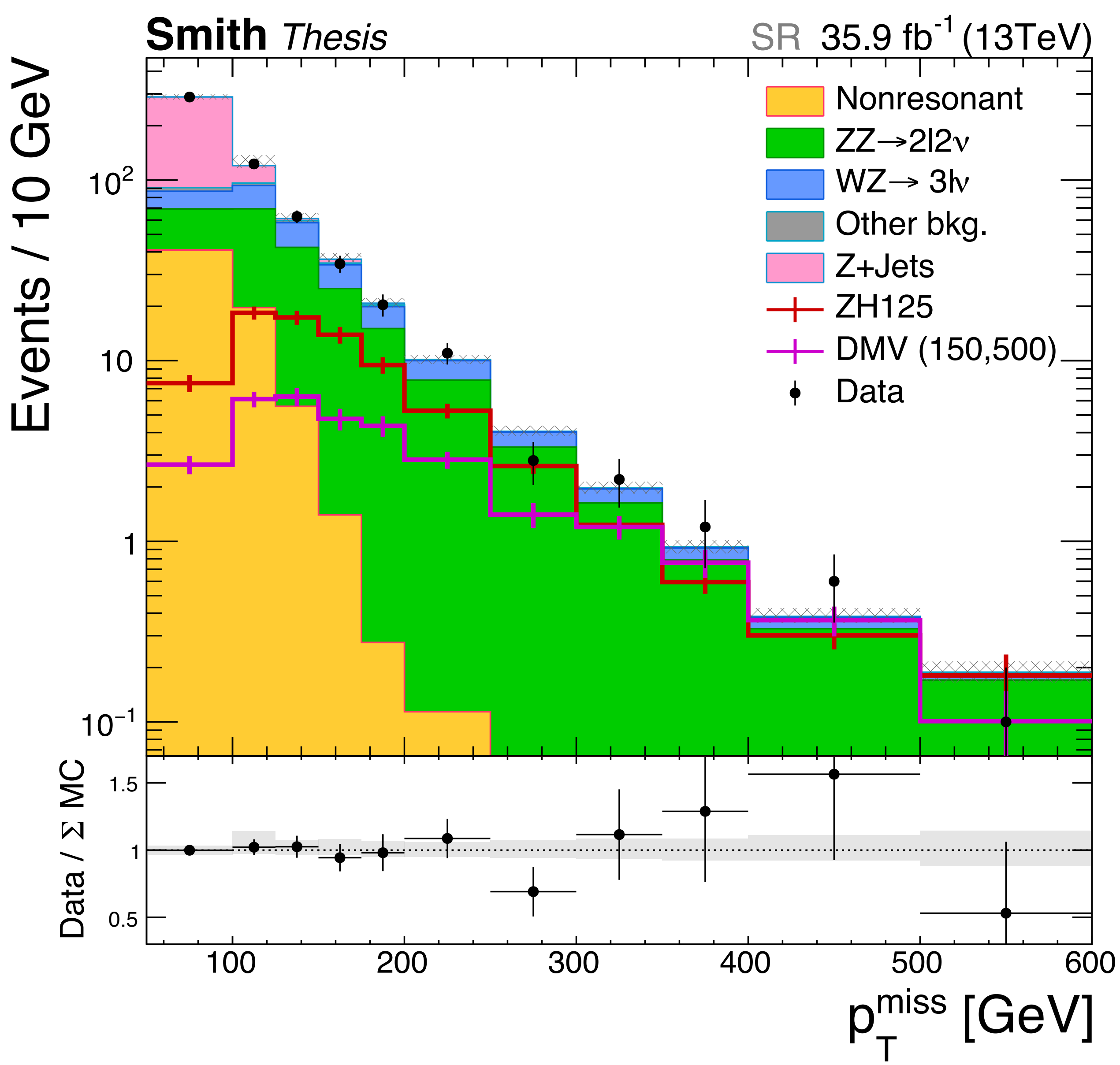
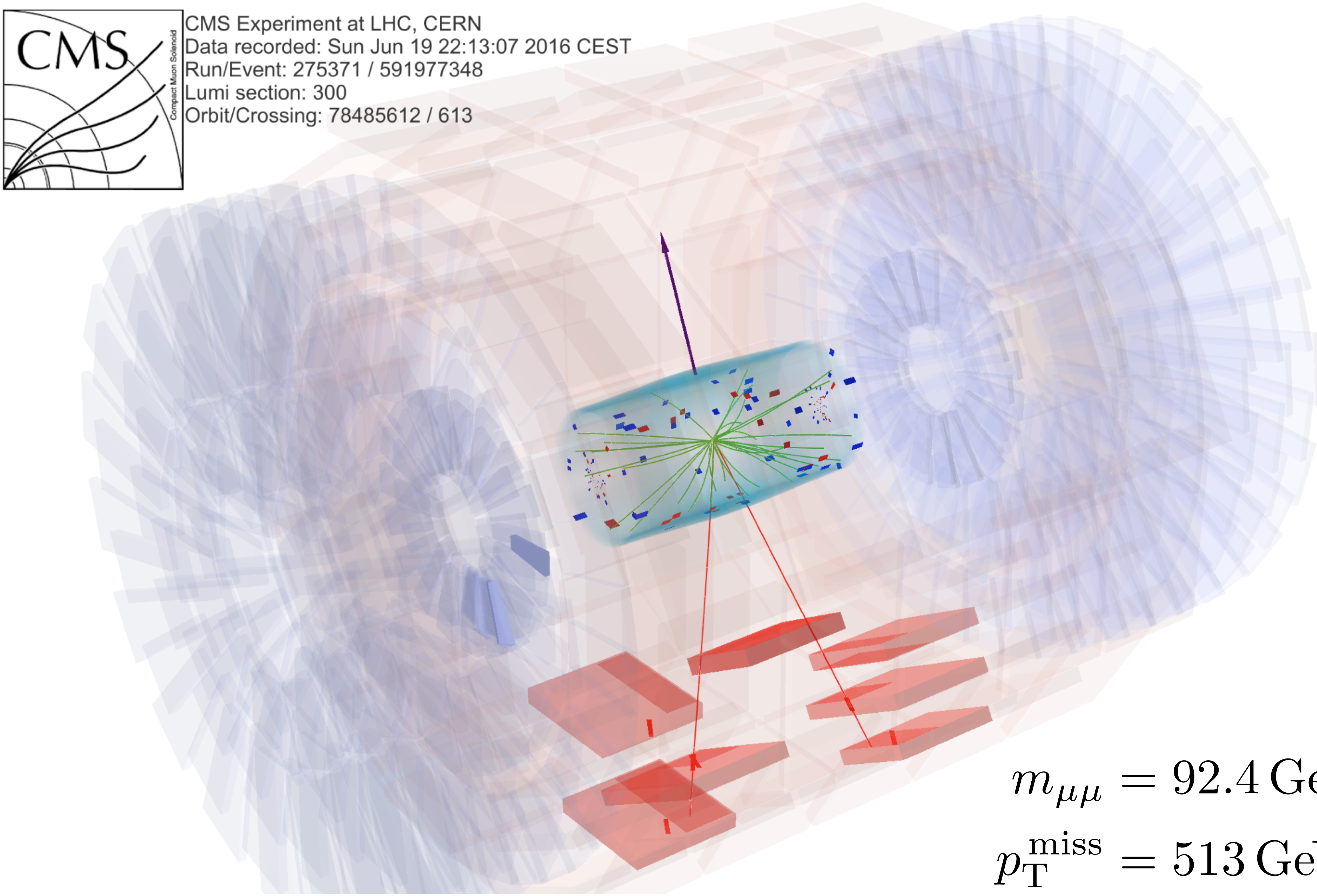
- Data fits Standard Model expectation
- We therefore:
  - Set exclusion limits on model parameters
  - Compare these exclusions to those of other experimental results



Process	Signal region yield
qqZH(inv.) $m_{\mathrm{H}} = 125\,\mathrm{GeV}$, $\mathcal{B}(\mathrm{H} \to \mathrm{inv.}) = 1$	159 ± 13
ggZH(inv.) $m_{\mathrm{H}} = 125\,\mathrm{GeV}$, $\mathcal{B}(\mathrm{H} \to \mathrm{inv.}) = 1$	43 ± 11
DM, vector mediator $m_{\mathrm{med}} = 500\,\mathrm{GeV}$, $m_{\mathrm{DM}} = 150\,\mathrm{GeV}$	89.6 ± 6.3
ZZ	384 ± 22
WZ	151.3 ± 9.4
Nonresonant bkg.	68 ± 17
Drell–Yan	70 ± 45
Other bkg.	14.7 ± 1.6
Total bkg.	688 ± 38
Data	694



$$m_{\mu\mu} = 92.4\,\mathrm{GeV}$$

$$p_{\mathrm{T}}^{\mathrm{miss}} = 513\,\mathrm{GeV}$$

Vector DM interpretation

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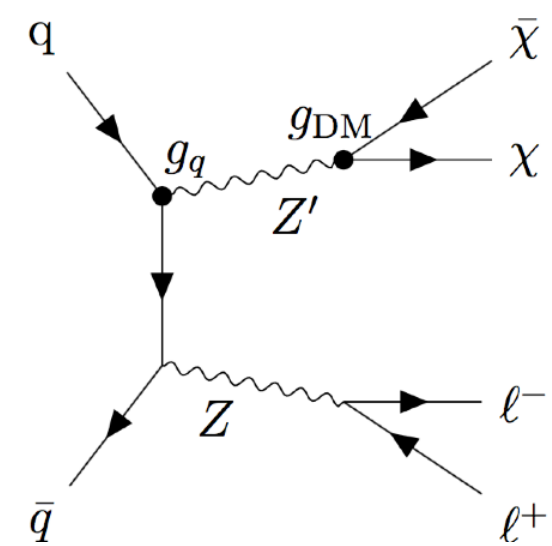
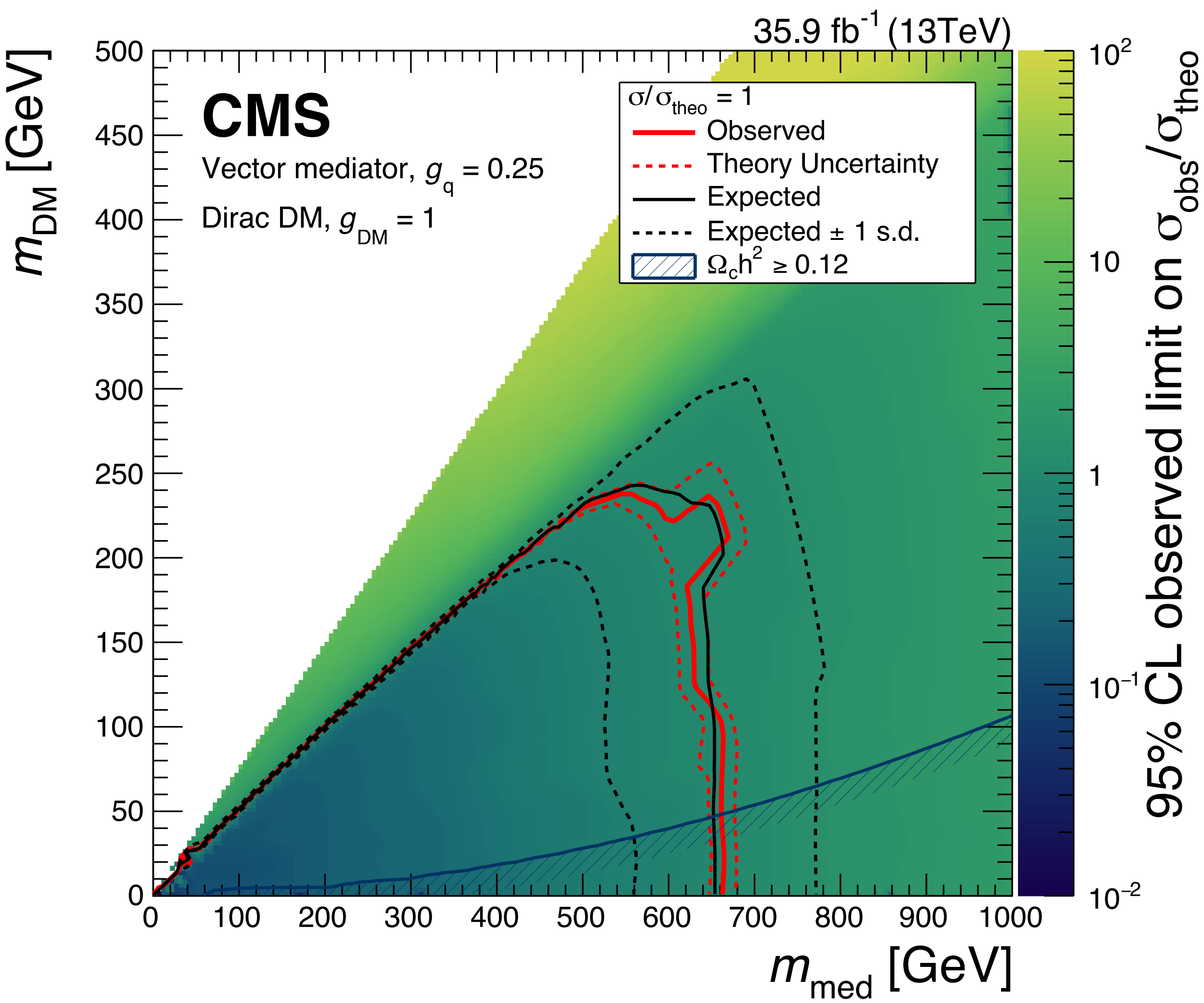
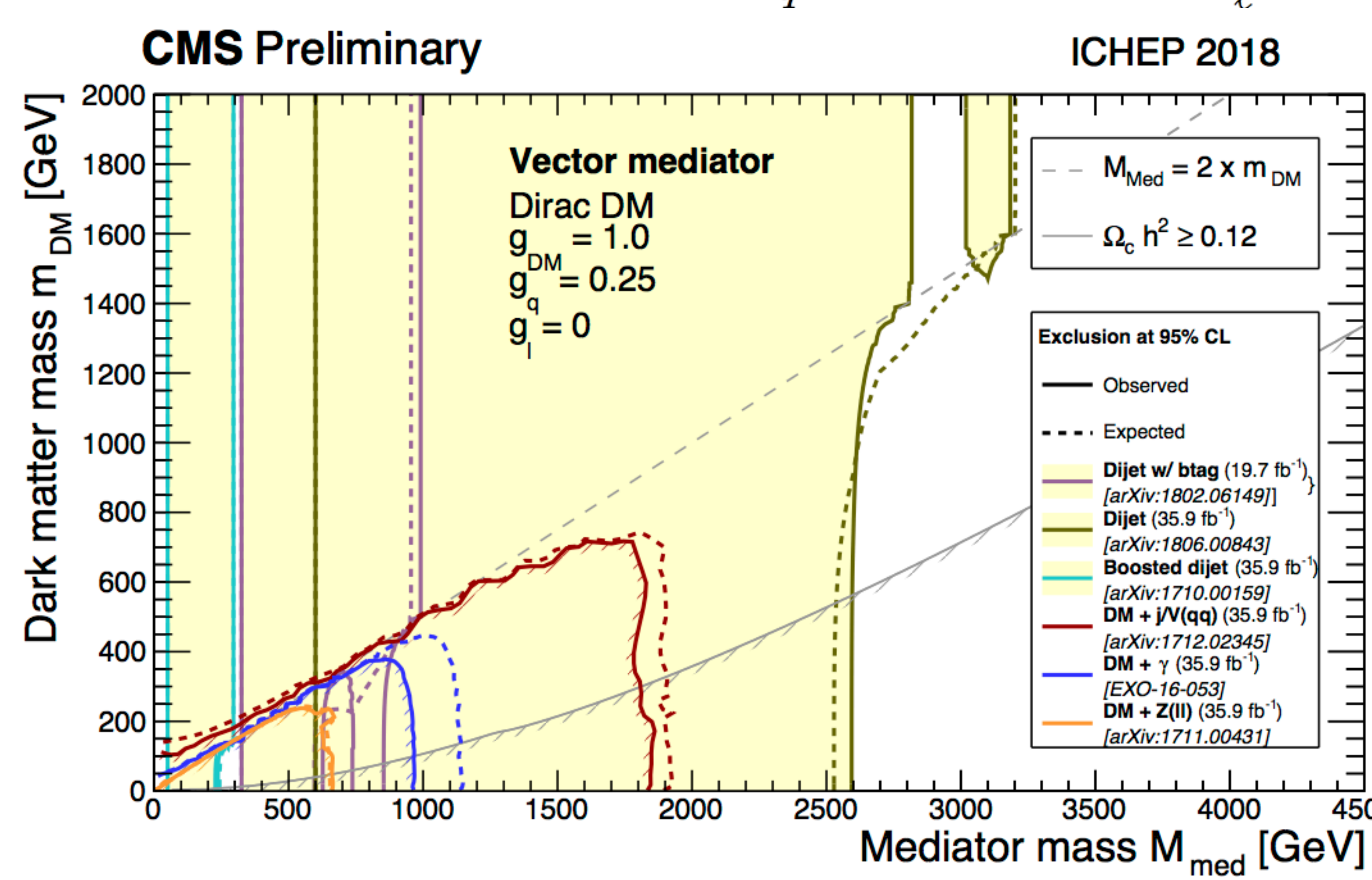
- In simplified model with chosen couplings (g_{DM}=1, g_q=0.25):
  - This analysis excludes vector mediator masses up to 650 GeV
  - Other CMS searches exclude larger phase space
- Choice of couplings governs relative sensitivity of channels
  - e.g. if mediator-gauge boson coupling nonzero, mono-Z would be more sensitive w.r.t. mono-Jet



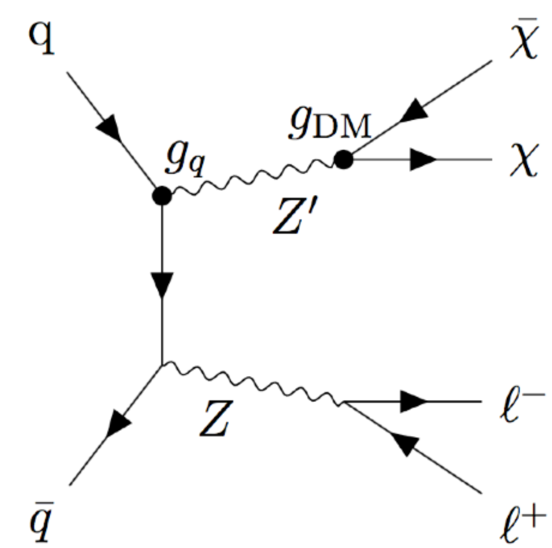


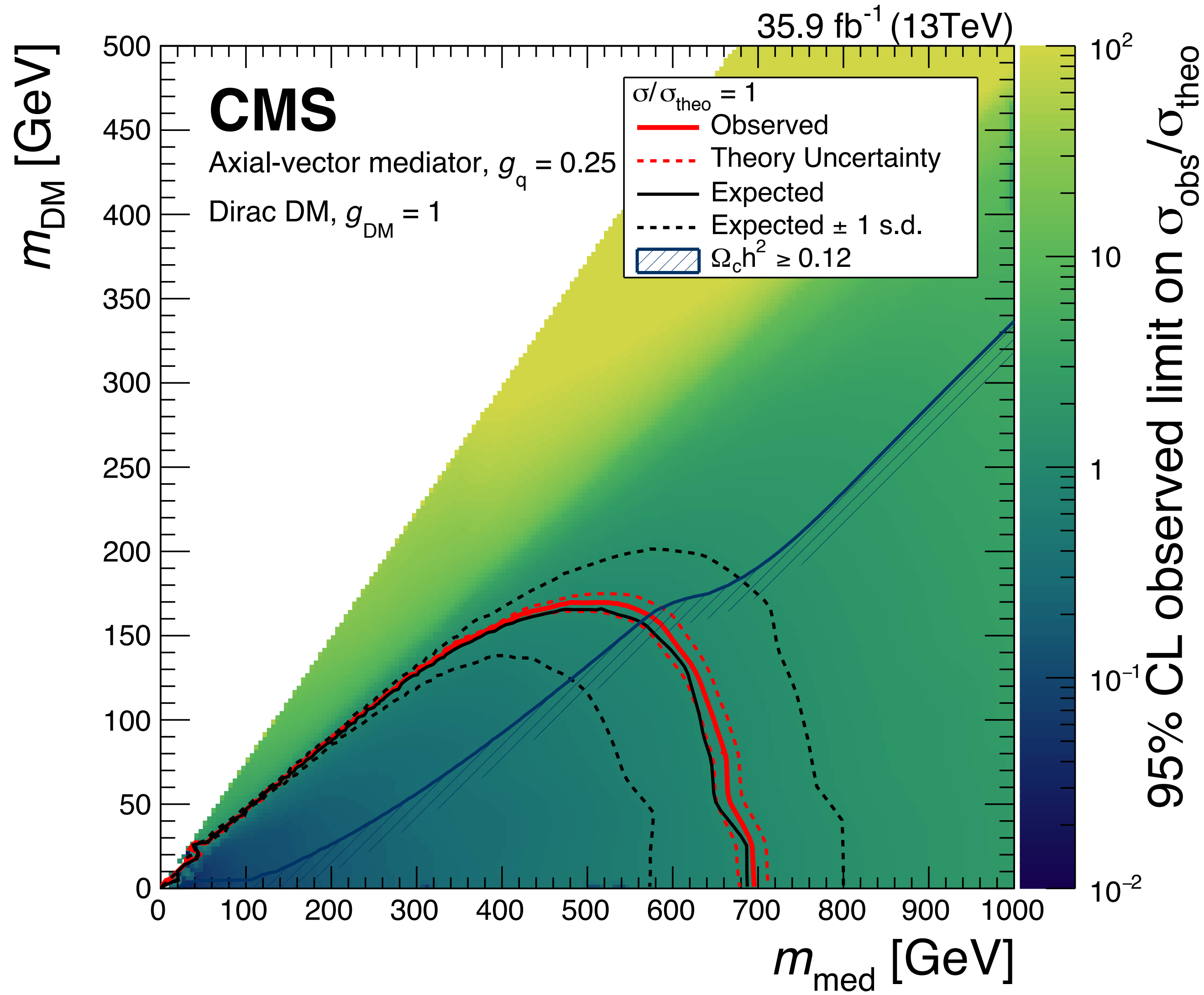


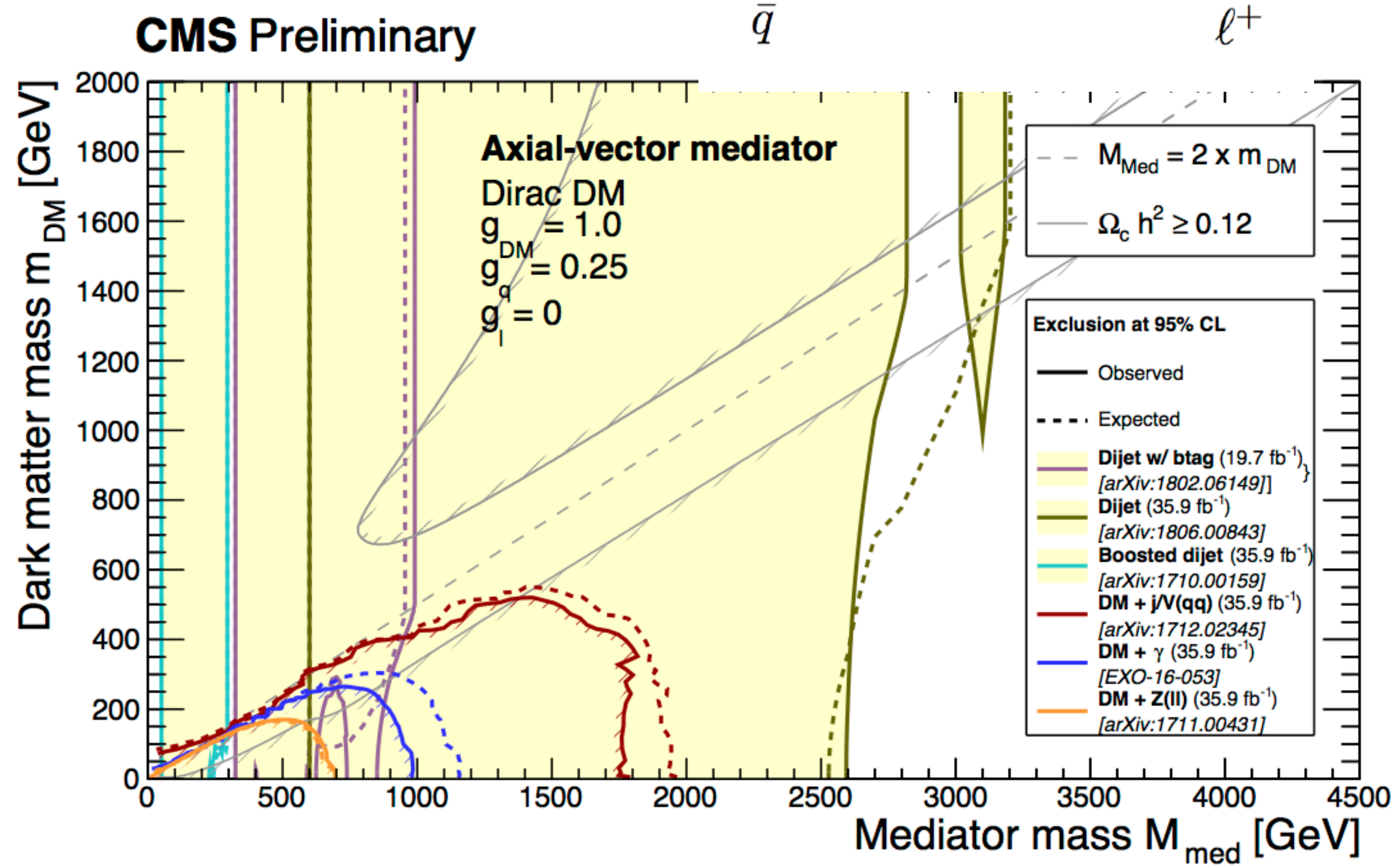
Axial Vector DM interpretation

N. Smith

- In simplified model with chosen couplings (g_{DM}=1, g_q=0.25):
  - This analysis excludes axial vector mediator masses up to 700 GeV
  - Other CMS searches exclude larger phase space
- Choice of couplings governs relative sensitivity of channels







The Competition

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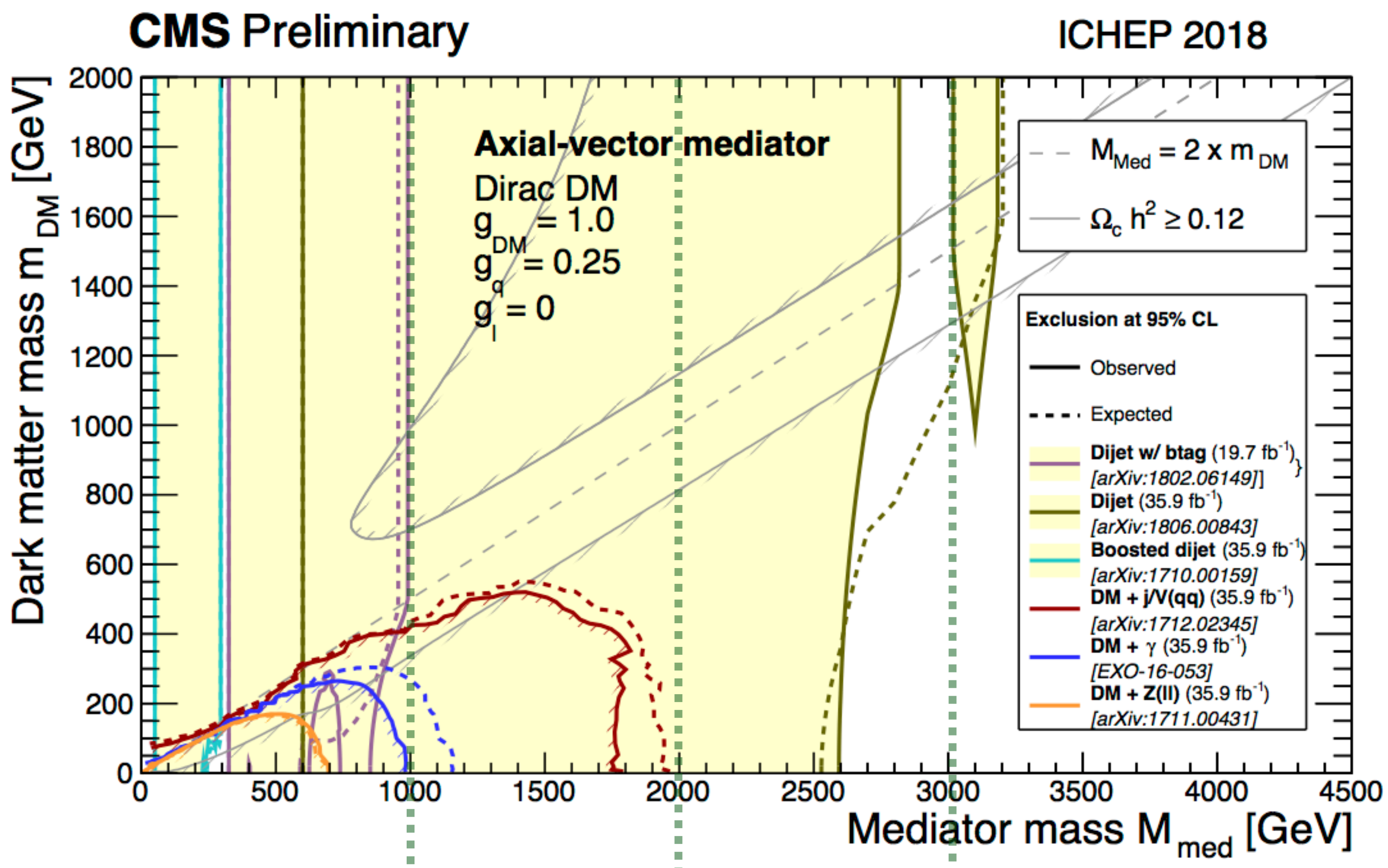
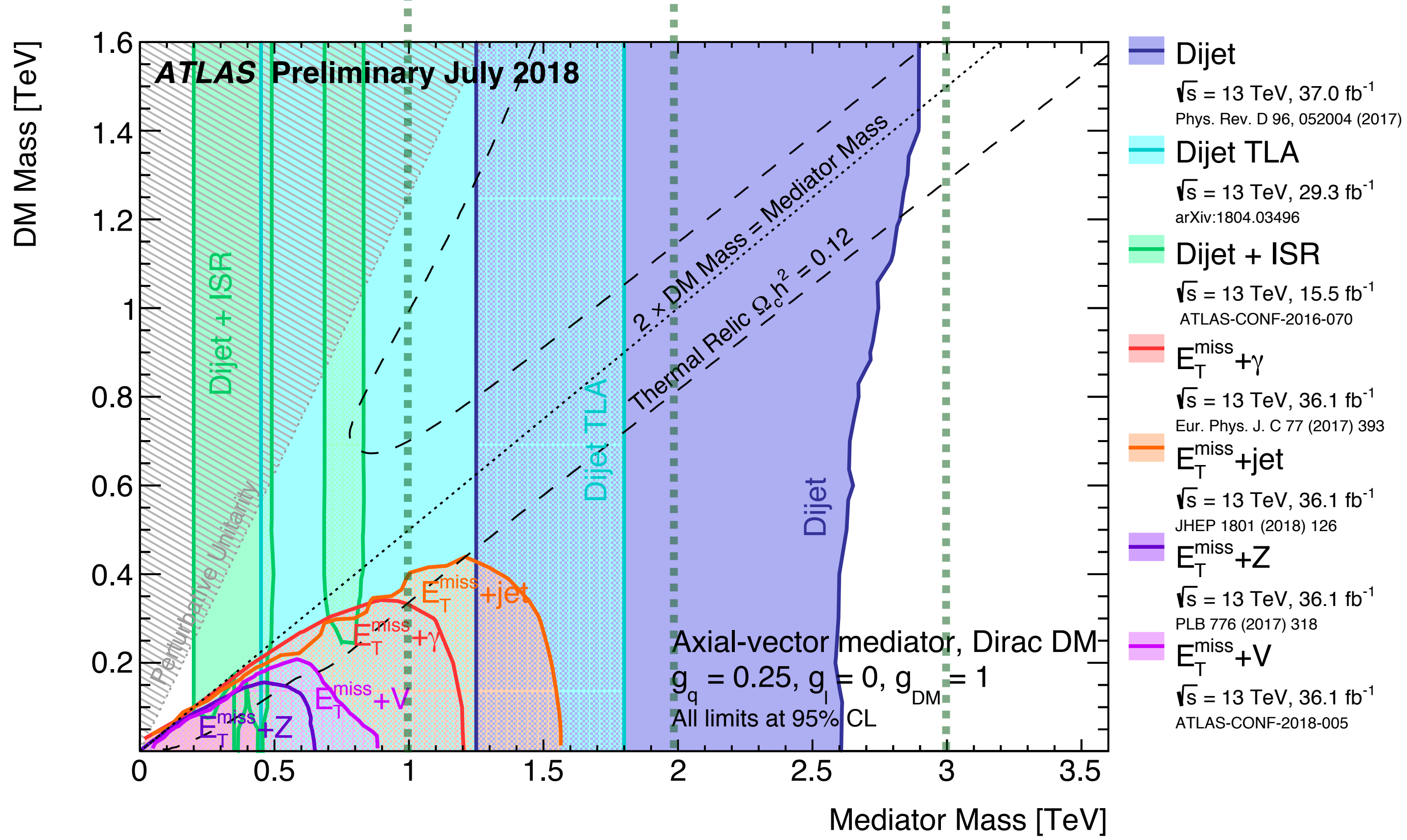
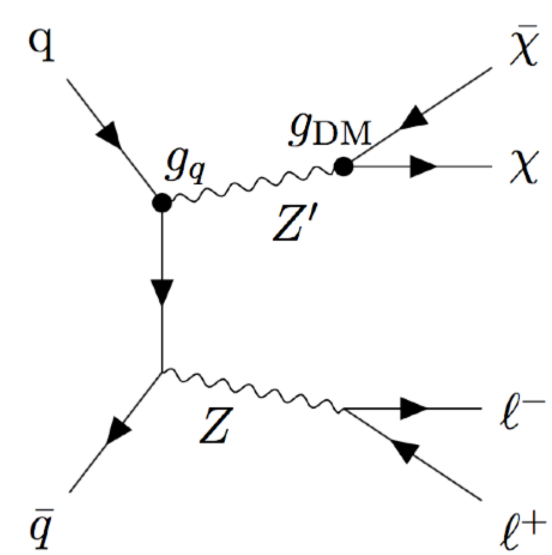




- ATLAS and CMS present results for the same DM model with the same choice of couplings (g_{DM}=1, g_q=0.25)
- Both experiments are excluding very similar parameter space for all channels
  - We do slightly better here for mono-Z axial vector mediated DM (650 vs. 560 GeV)



DM-Nucleon Cross Section

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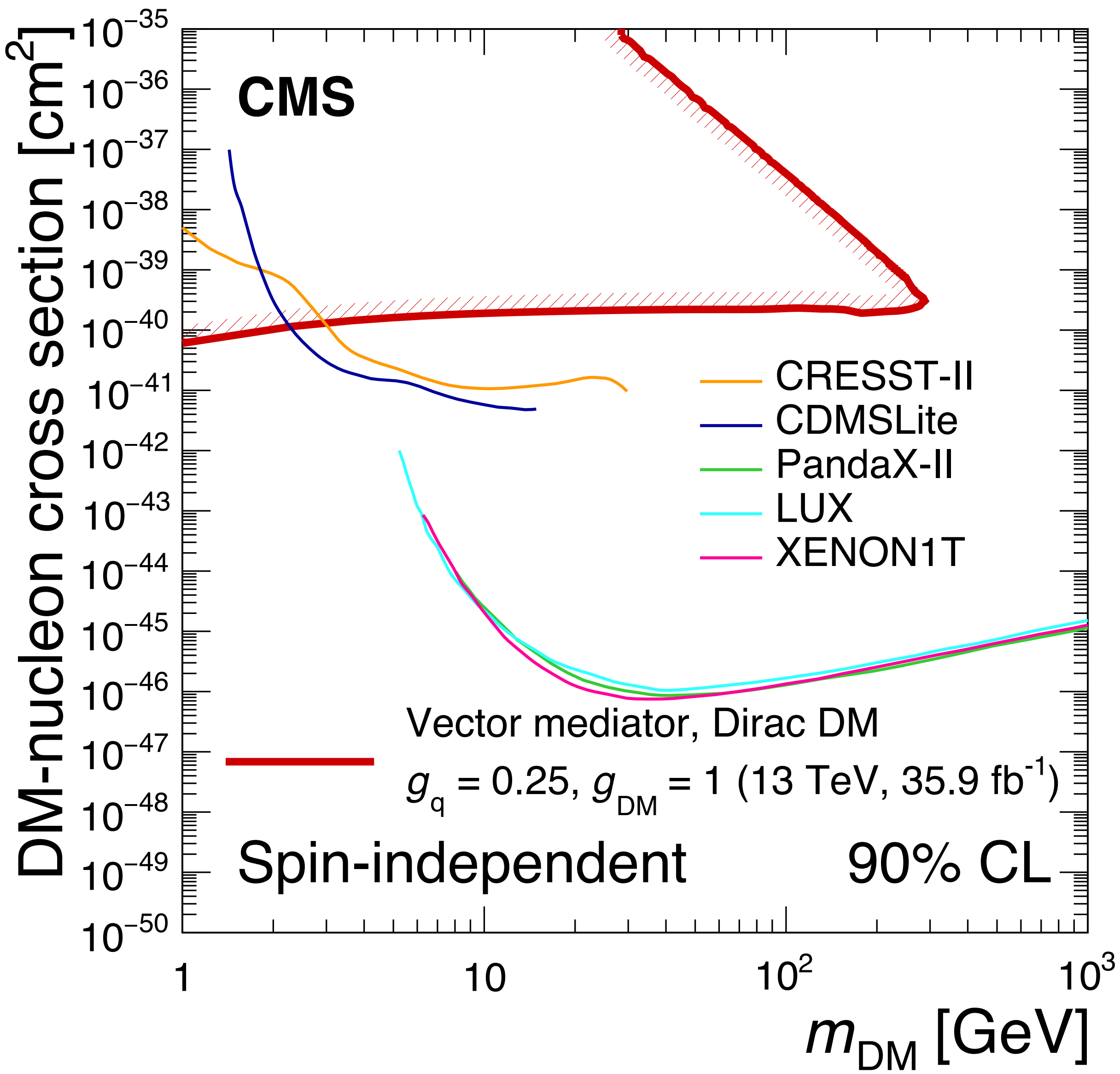
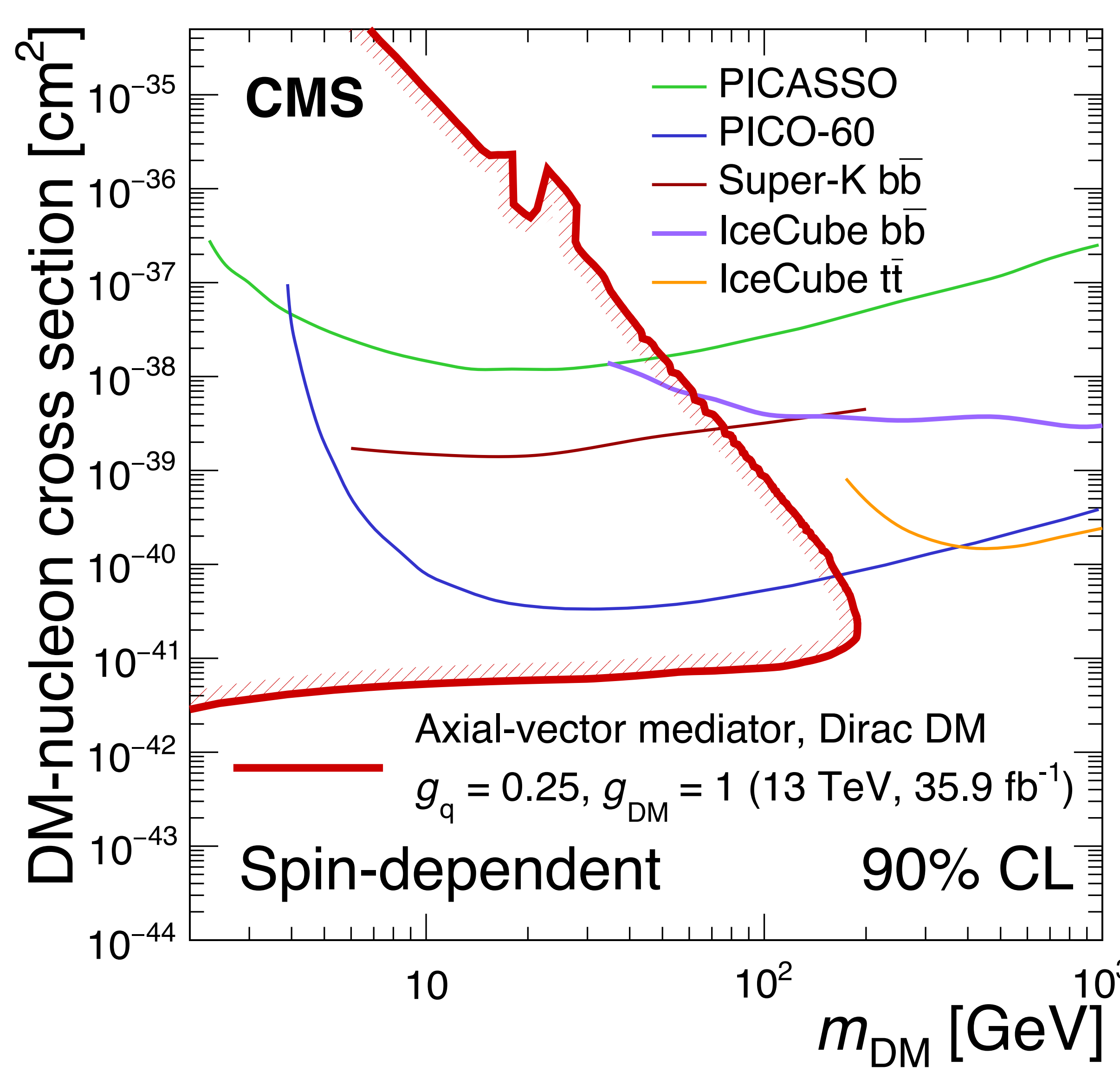
- The mass-plane DM limits are interpretable as DM-nucleon XS limits
  - LHC more sensitive to spin-dependent couplings than direct detection nucleon scattering limits
- LHC limits assume a particular model and couplings
- Direct & indirect limits assume one species of thermal relic DM
  - Large uncertainty on local DM density, relative velocity

$$\sigma \propto \frac{g_q^2 g_{\mathrm{DM}}^2}{m_{\mathrm{med}}^4}$$





(Pseudo)Scalar DM interpretation

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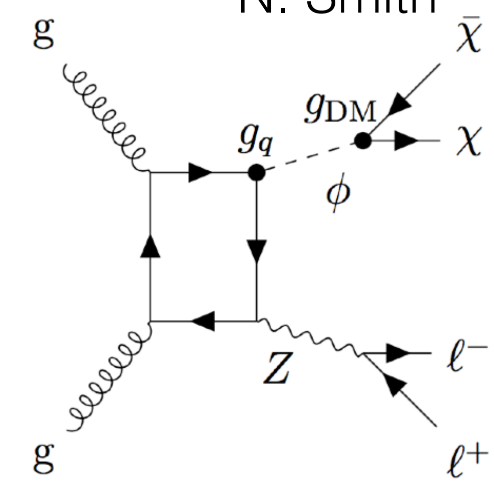
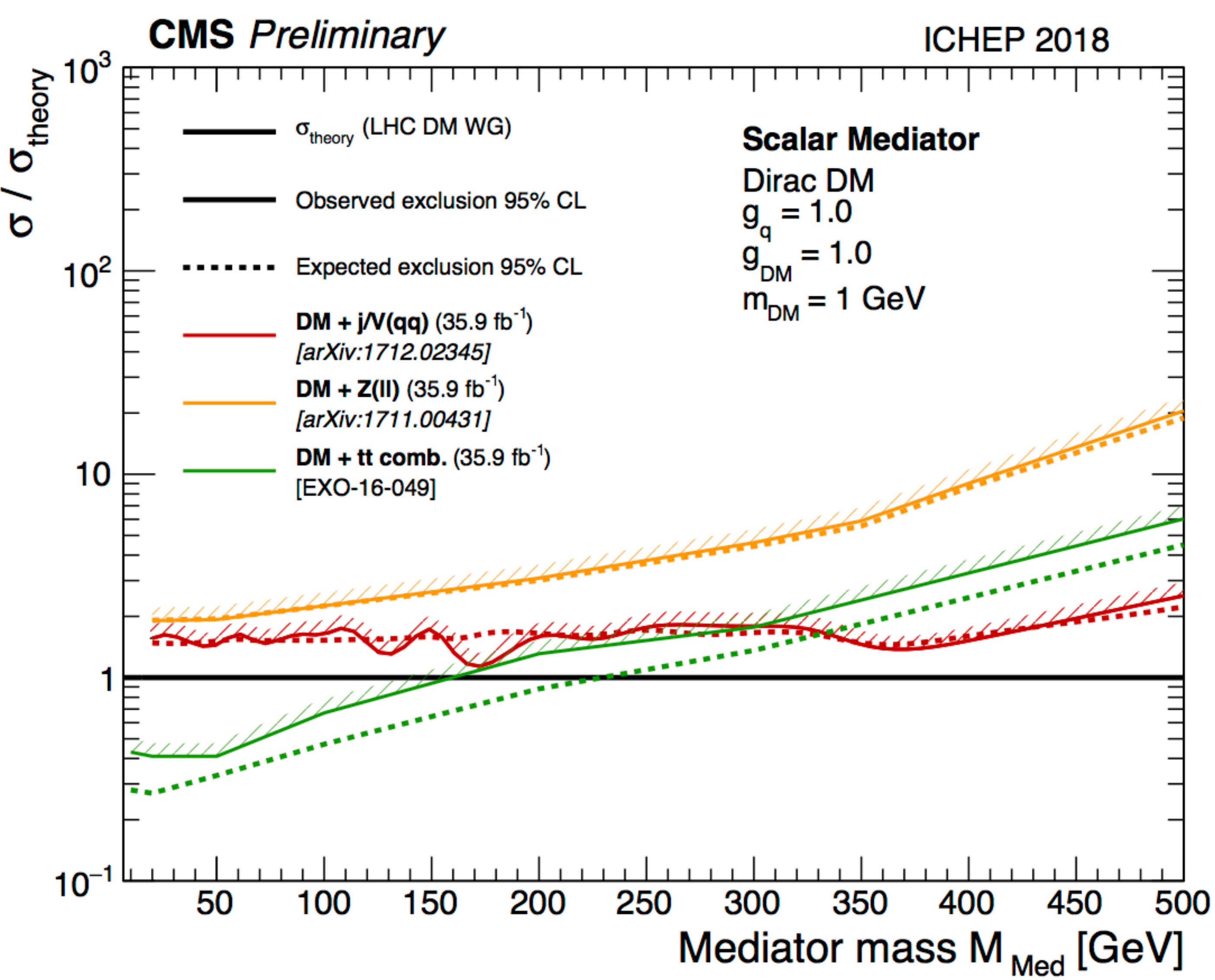
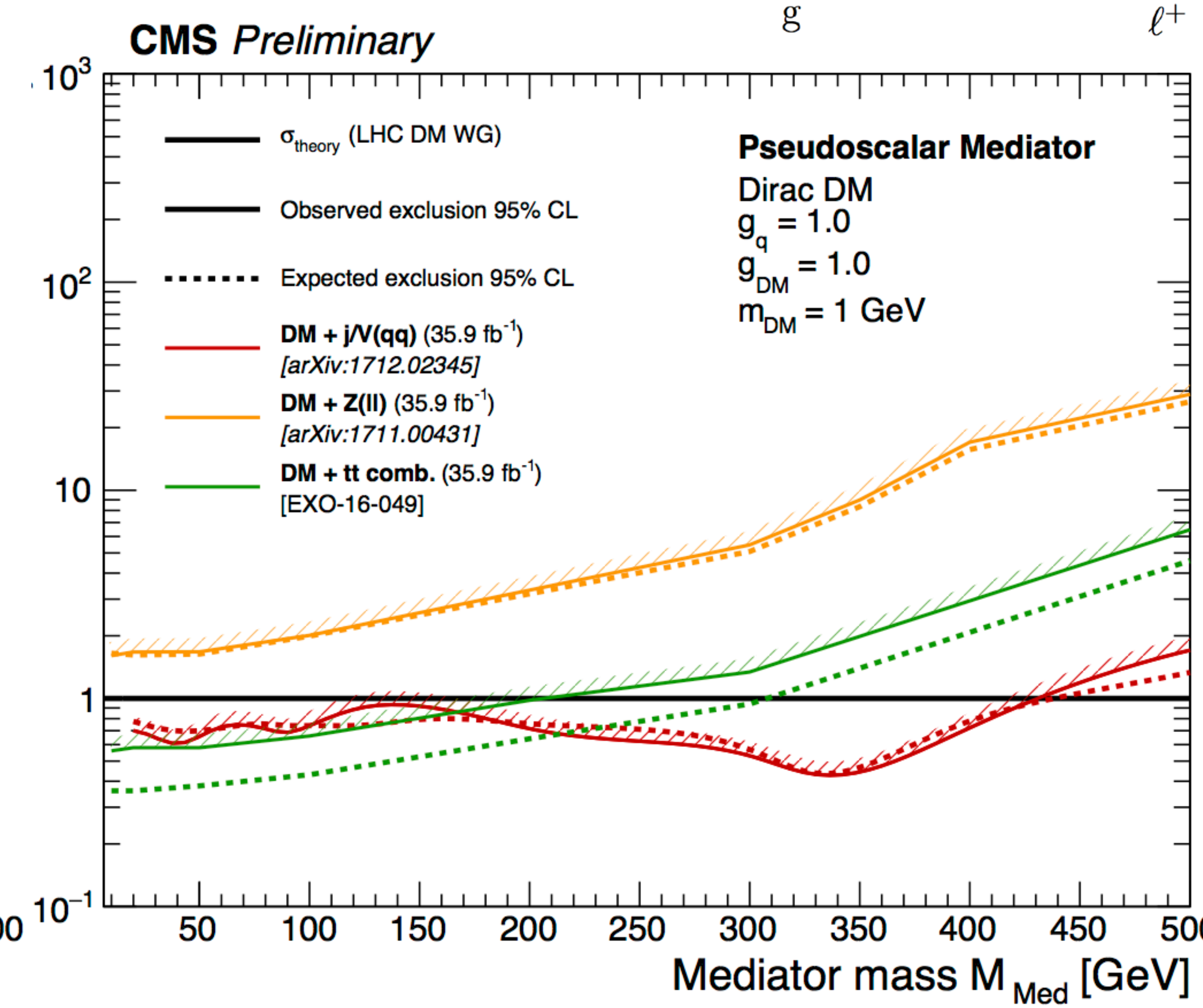
- In simplified model with chosen couplings (g_{DM}=1, g_q=1):
  - This analysis does not yet exclude any mass parameter space
  - Other CMS searches exclude small mediator masses
- For scalar models, mono-Z limits closer to mono-Jet, and top-antitop + pTmiss channel is most sensitive





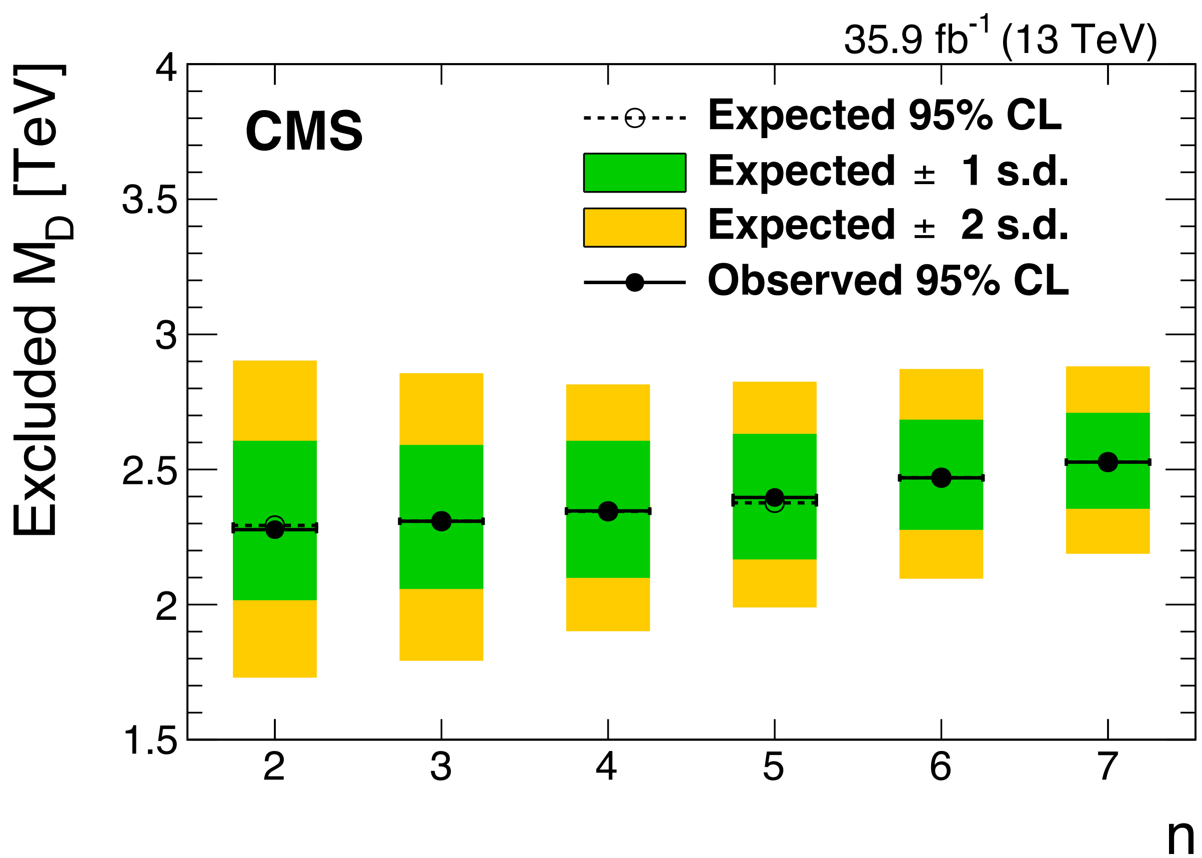


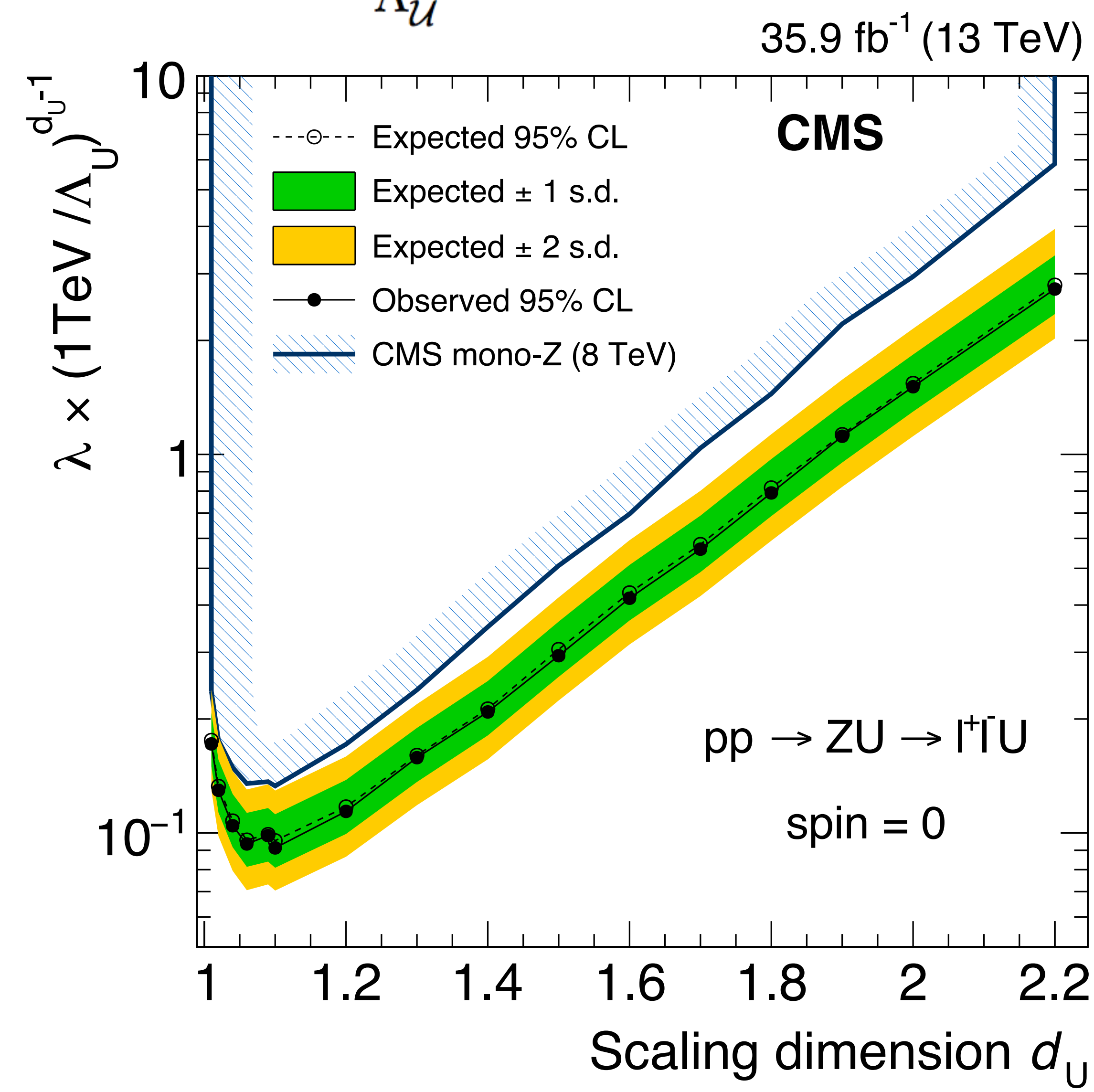
ADD & unparticle interpretations

N. Smith

- Left: Arkani-Hamed–Dimopoulos–Dvali (ADD) model
  - Set limit on Planck scale M_D for *n* discrete extra dimensions
  - Limits not as competitive as some earlier mono-Jet results
    - e.g. CMS 8 TeV mono-Jet excludes M_D < 3-5 TeV for *n* = 6 to 3
- Right: unparticle model
  - We double the exclusion on the EFT operator's Wilson coefficient compared to 8 TeV CMS mono-Z analysis

$$\mathcal{L}_{\mathcal{U}} = \frac{\lambda}{\Lambda_{\mathcal{U}}^{d_{\mathcal{U}}-1}} q\bar{q} O_{\mathcal{U}}$$





Invisible Higgs interpretation

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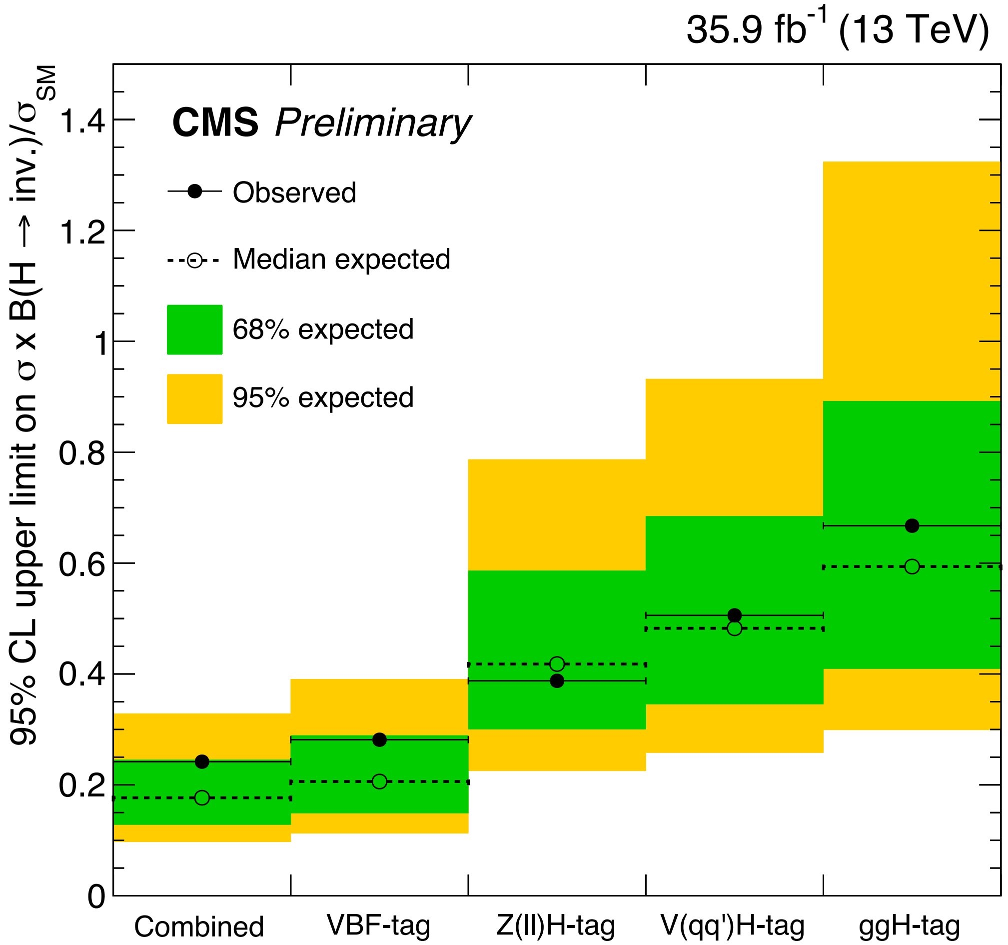
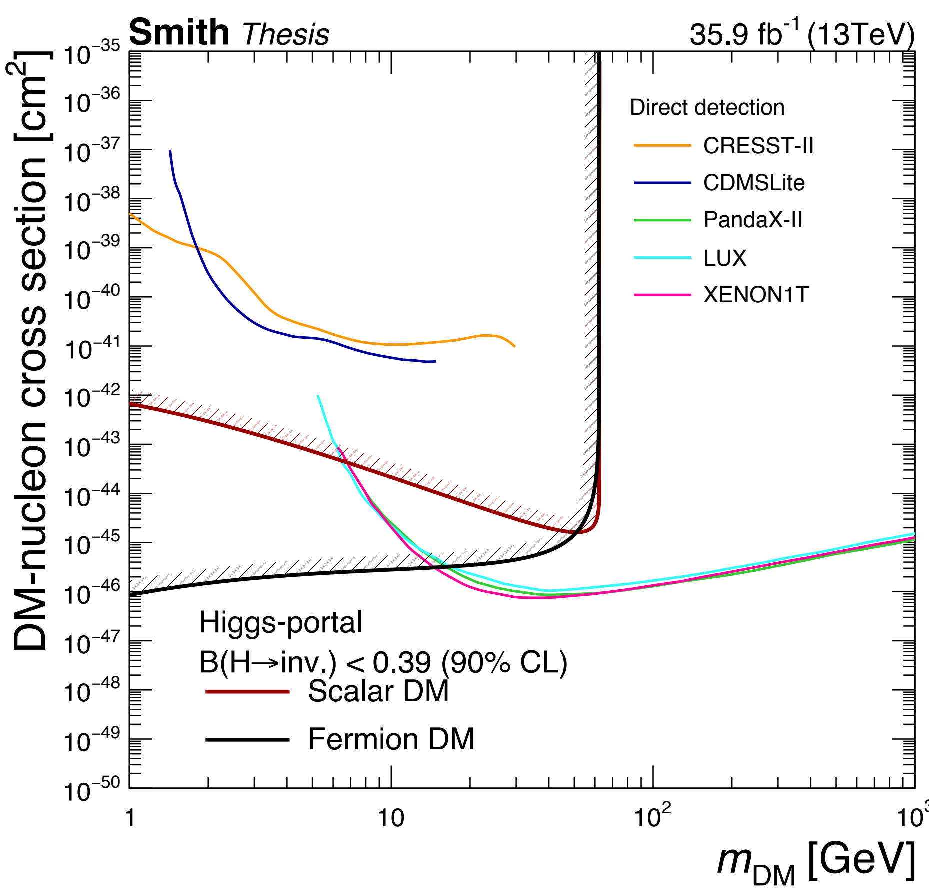
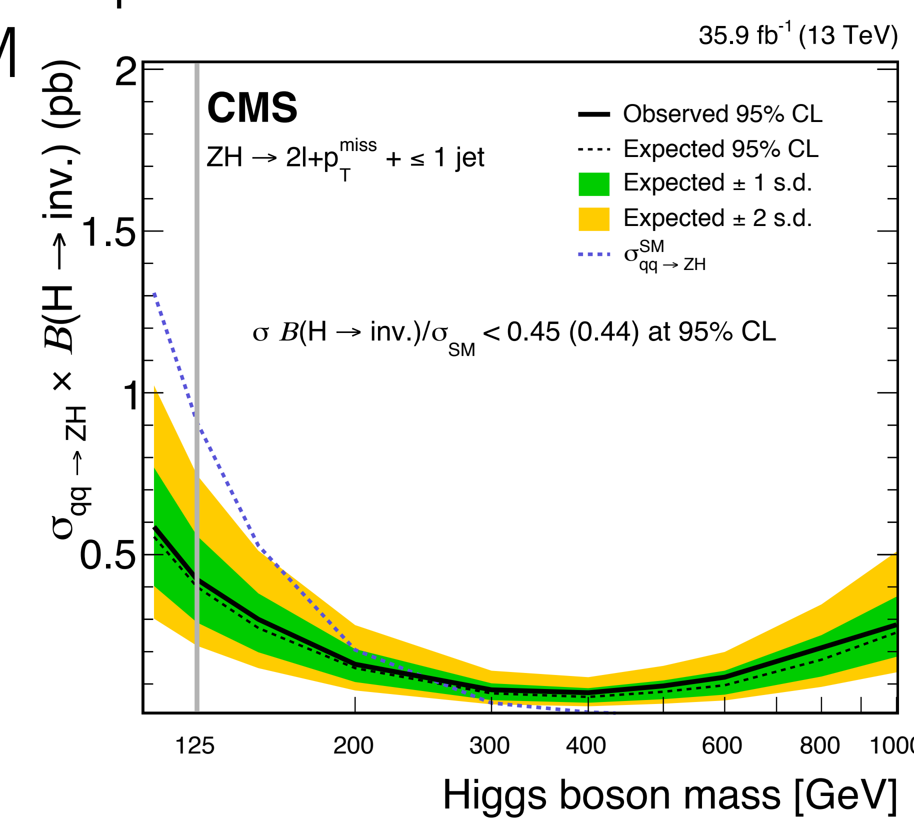


- For SM Higgs, assuming SM production, interpret signal strength limit as H(inv.) branching fraction limit
  - This analysis: H(inv.) < **0.45 (0.44)** (95% CL)
  - 8 TeV CMS Z(ℓℓ)H(inv.) limit: 0.75 (0.91)
    - 8 TeV ATLAS: 0.75 (0.62)
- This result is combined with other channels
  - CMS combined limit: 0.24 (0.18)
- Higgs-portal DM-nucleon XS complements direct detection phase space
- Limits for beyond-SM Higgs boson production cross sections exclude SM-like production rates with purely invisible decay up to m(H) < 250 GeV





Simplified Likelihood

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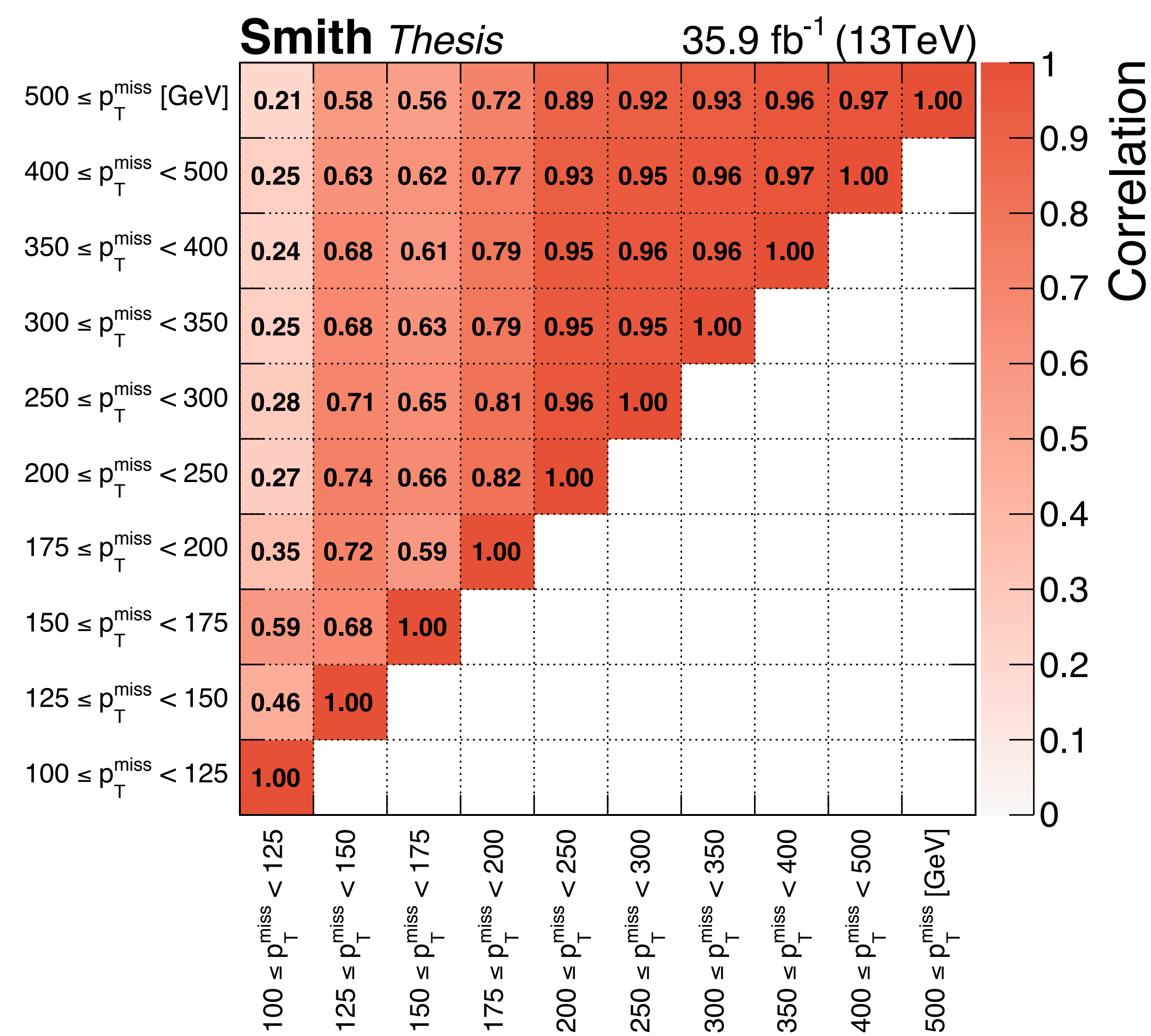
- The models probed here are not the only mono-Z signatures
- Include information to re-interpret observation in context of alternative models
  - Reconstruct an approximate likelihood function for other signal models with knowledge of background expectations and their correlation in each pTmiss bin of SR
- Allows high-fidelity re-interpretation of the results despite low signal-background separation of pTmiss variable

p_T^{miss} bin (GeV)	Observed events	Total background prediction SR+CR fit	CR-only fit
$100 \leq p_T^{miss} < 125$	307	301 ± 33	259 ± 56
$125 \leq p_T^{miss} < 150$	157	153 ± 14	147 ± 14
$150 \leq p_T^{miss} < 175$	86	91.1 ± 6.2	88 ± 10
$175 \leq p_T^{miss} < 200$	51	52.0 ± 3.6	50.3 ± 5.8
$200 \leq p_T^{miss} < 250$	55	50.6 ± 2.8	49.8 ± 5.0
$250 \leq p_T^{miss} < 300$	14	20.2 ± 1.3	19.8 ± 2.4
$300 \leq p_T^{miss} < 350$	11	9.86 ± 0.74	9.7 ± 1.2
$350 \leq p_T^{miss} < 400$	6	4.66 ± 0.37	4.55 ± 0.64
$400 \leq p_T^{miss} < 500$	6	3.84 ± 0.38	3.75 ± 0.60
$p_T^{miss} \geq 500$	1	1.88 ± 0.25	1.84 ± 0.38



Conclusions

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- Presented a search for several models of new physics
- No evidence for new physics, limits are set on relevant model parameters
  - Simplified models of dark matter production
    - Vector & Axial-vector mediators up to 650 GeV excluded at 95% CL
    - Doubles the exclusion of previous mono-Z searches
  - First exclusions for a model of large extra dimensions in the mono-Z final state
  - Unparticle model exclusions improved over previous mono-Z results
  - Invisible branching fraction of the SM Higgs boson < 44% at 95% CL

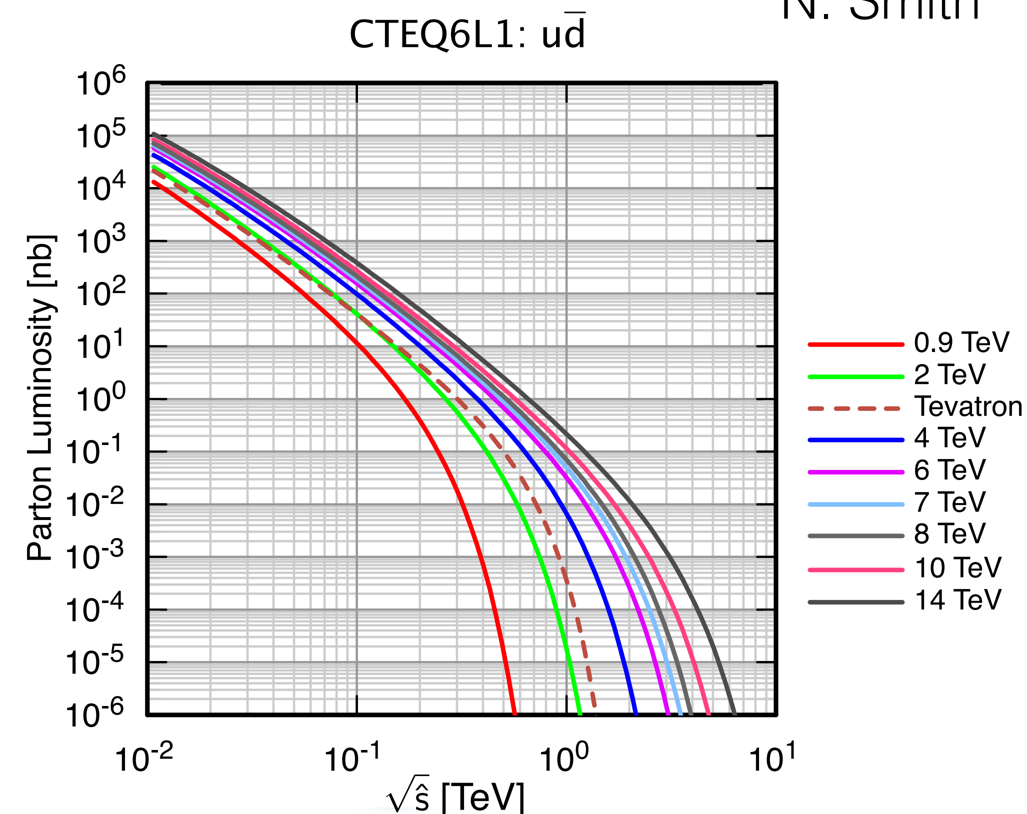
- This analysis utilizes novel background estimation methods to improve sensitivity to new physics, analyzes the largest CMS dataset available thus far, and interprets the observed result in the largest set of new physics models to date for the mono-Z final state

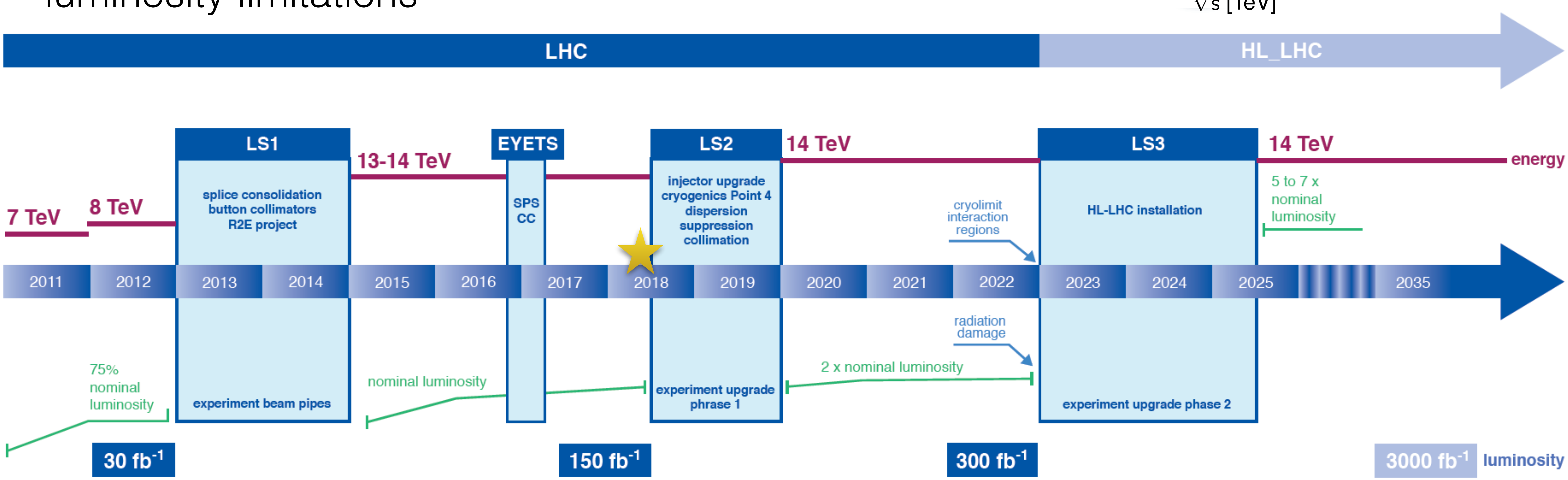
- ATLAS published a contemporaneous mono-Z result with similar-size dataset:
  - Axial-vector mediators up to 560 GeV excluded at 95% CL
  - Invisible branching fraction of the SM Higgs boson < 67% at 95% CL

Outlook

N. Smith

- LHC Run 3 will increase integrated luminosity 10x
- Unlike other X+pTmiss searches, mono-Z is still statistically limited
- With increased data statistics, the control regions in this analysis will better constrain SM background predictions
- In long term, new physics discovery/exclusion limits governed by energy limitations rather than luminosity limitations





Backup

SI WIMP limits

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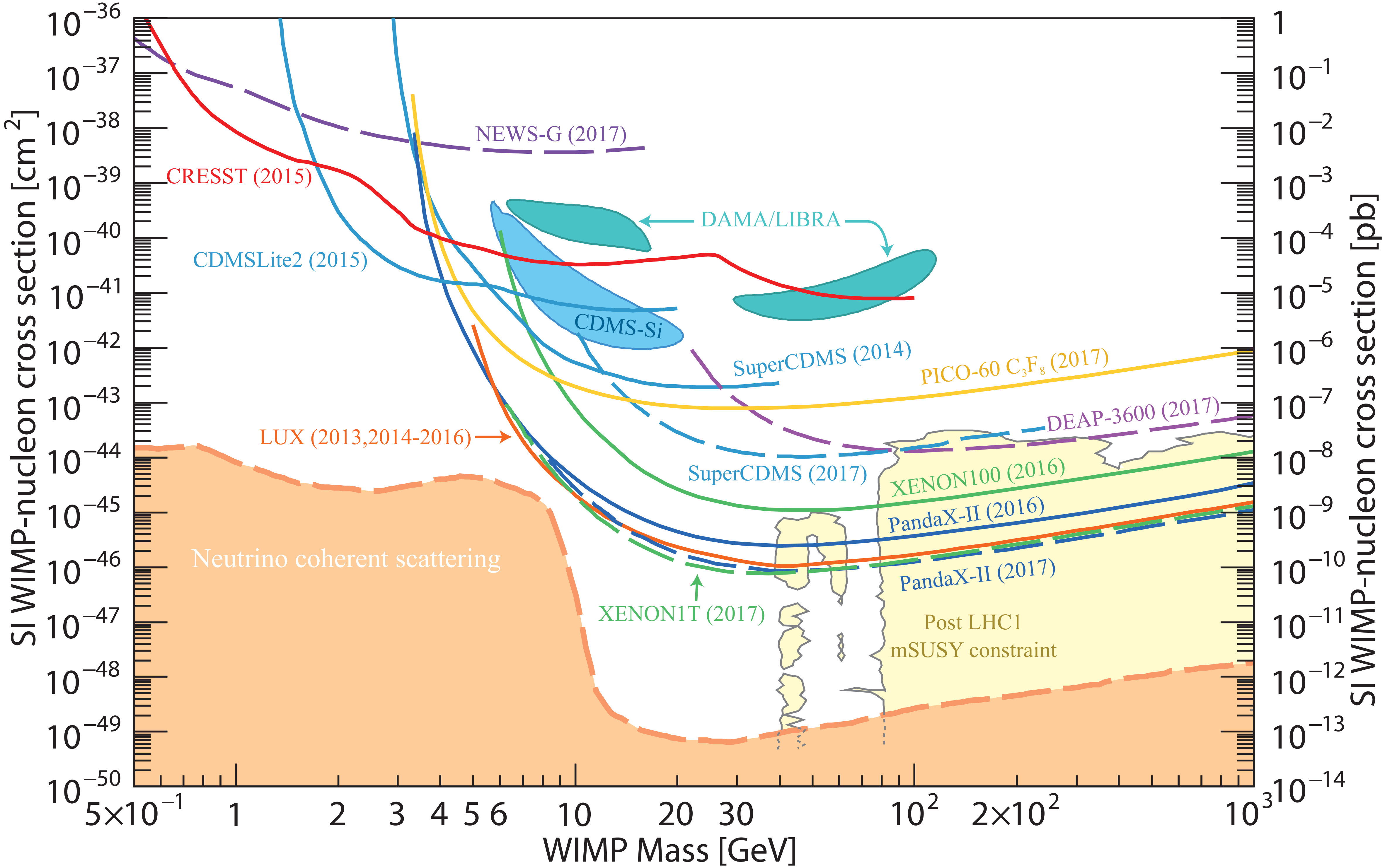

Higgs significance by channel

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Channel grouping	Significance (σ)	
	Observed	Expected
$H \rightarrow ZZ$ tagged	6.5	6.3
$H \rightarrow \gamma\gamma$ tagged	5.6	5.3
$H \rightarrow WW$ tagged	4.7	5.4
Grouped as in Ref. [17]	*4.3*	*5.4*
$H \rightarrow \tau\tau$ tagged	3.8	3.9
Grouped as in Ref. [19]	*3.9*	*3.9*
$H \rightarrow bb$ 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

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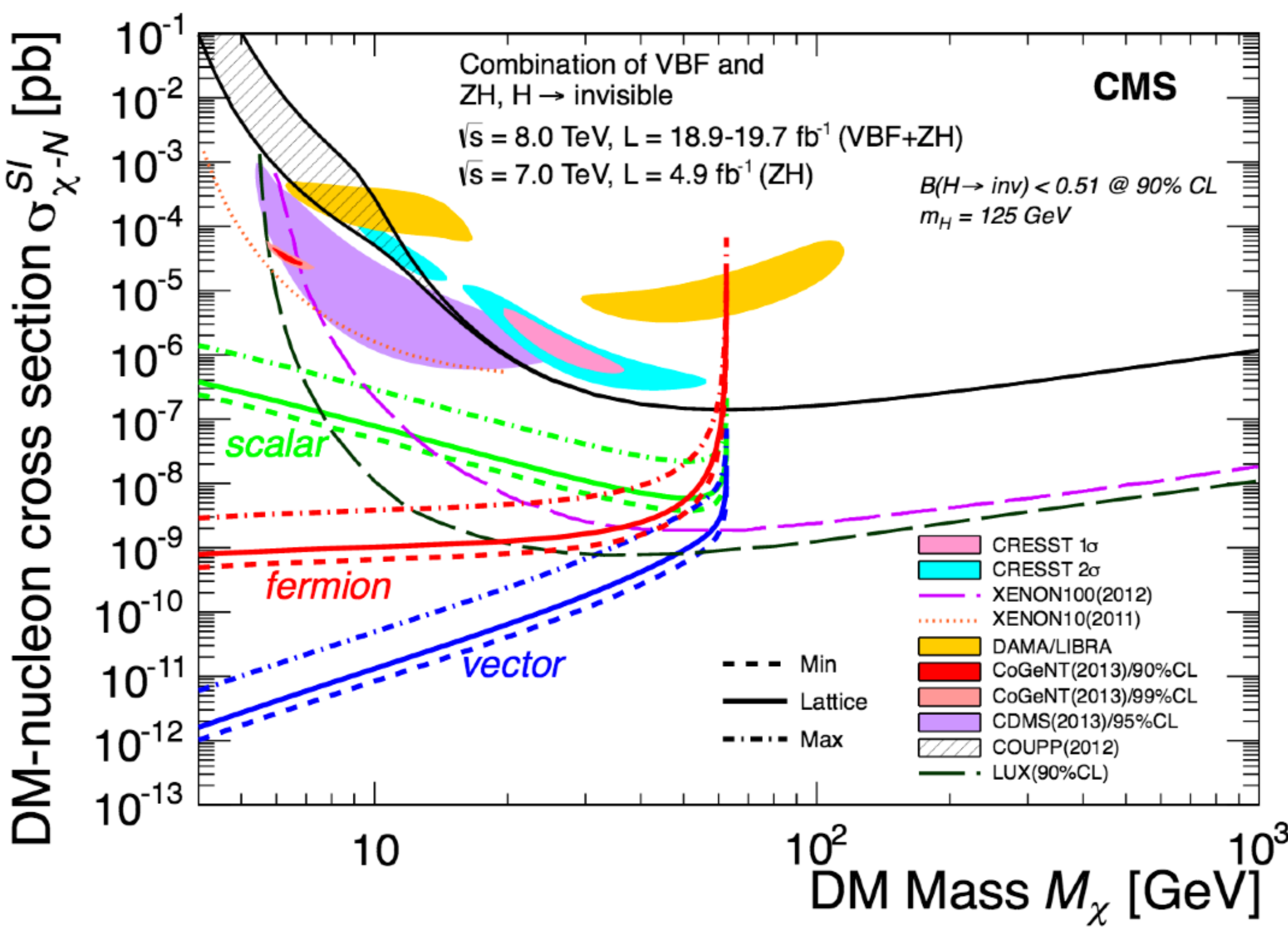
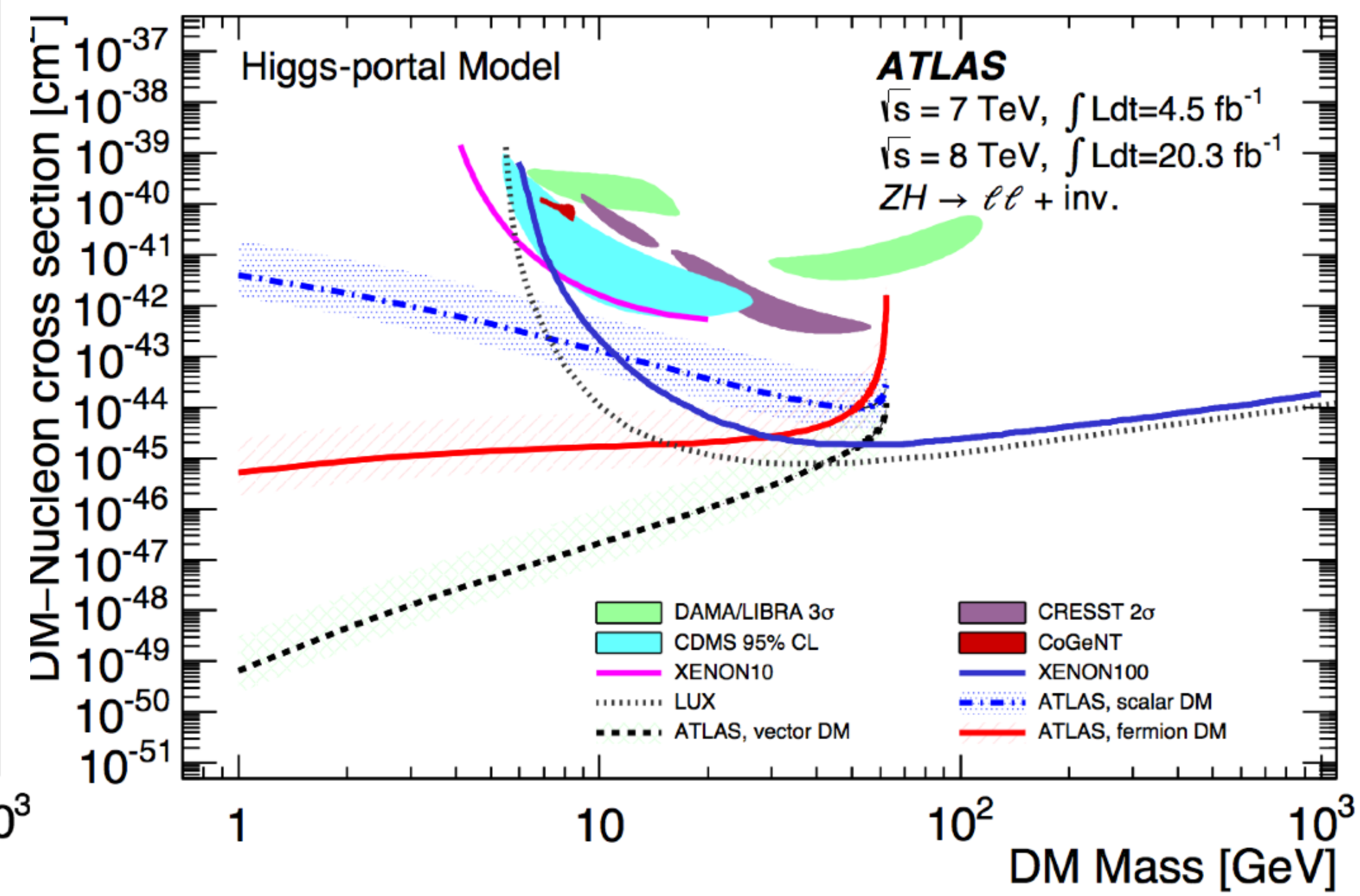
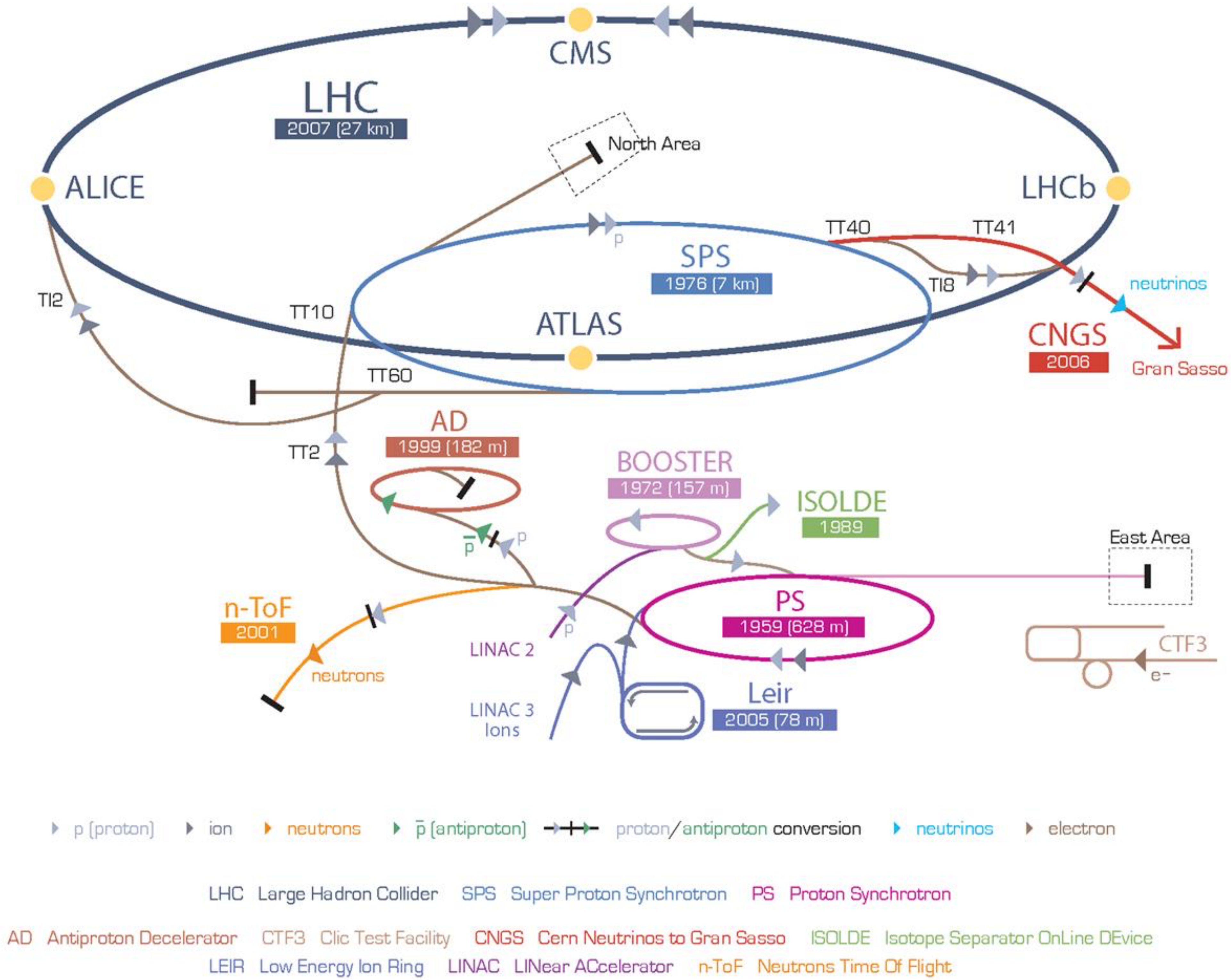




CERN Accelerator Complex



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LHC Dipole

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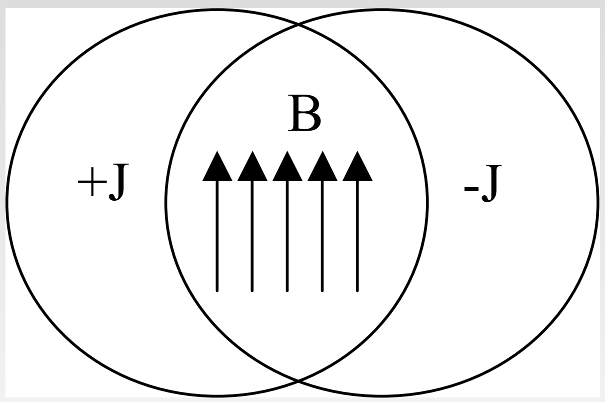
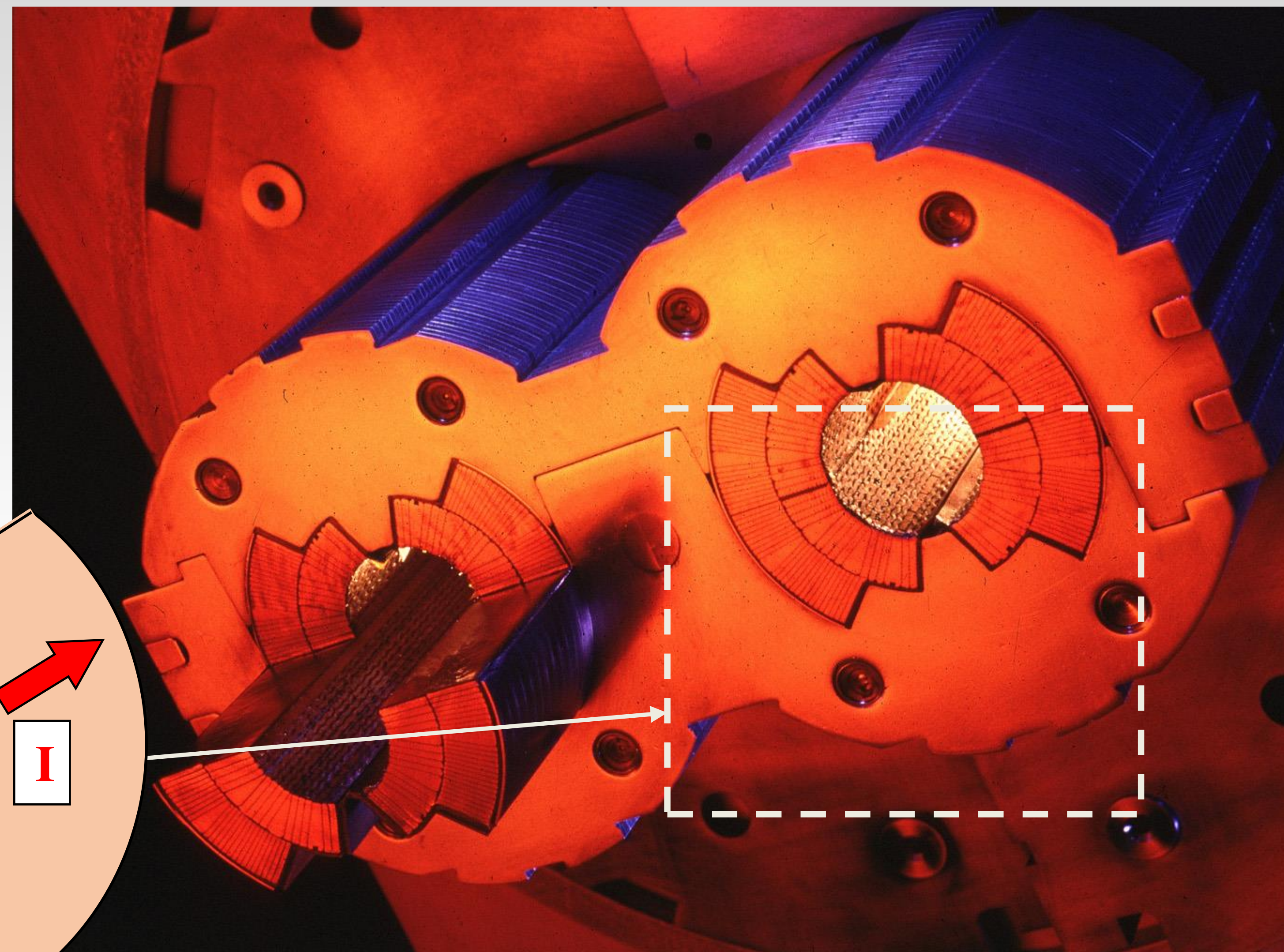
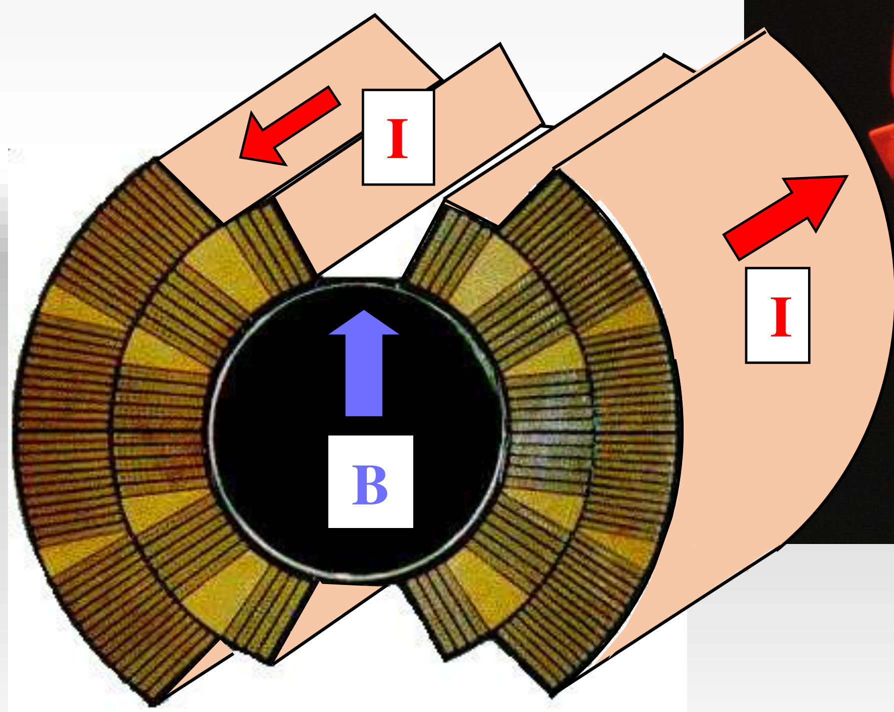
Main components – dipole magnets







11

CMS Primary Vertex Resolution

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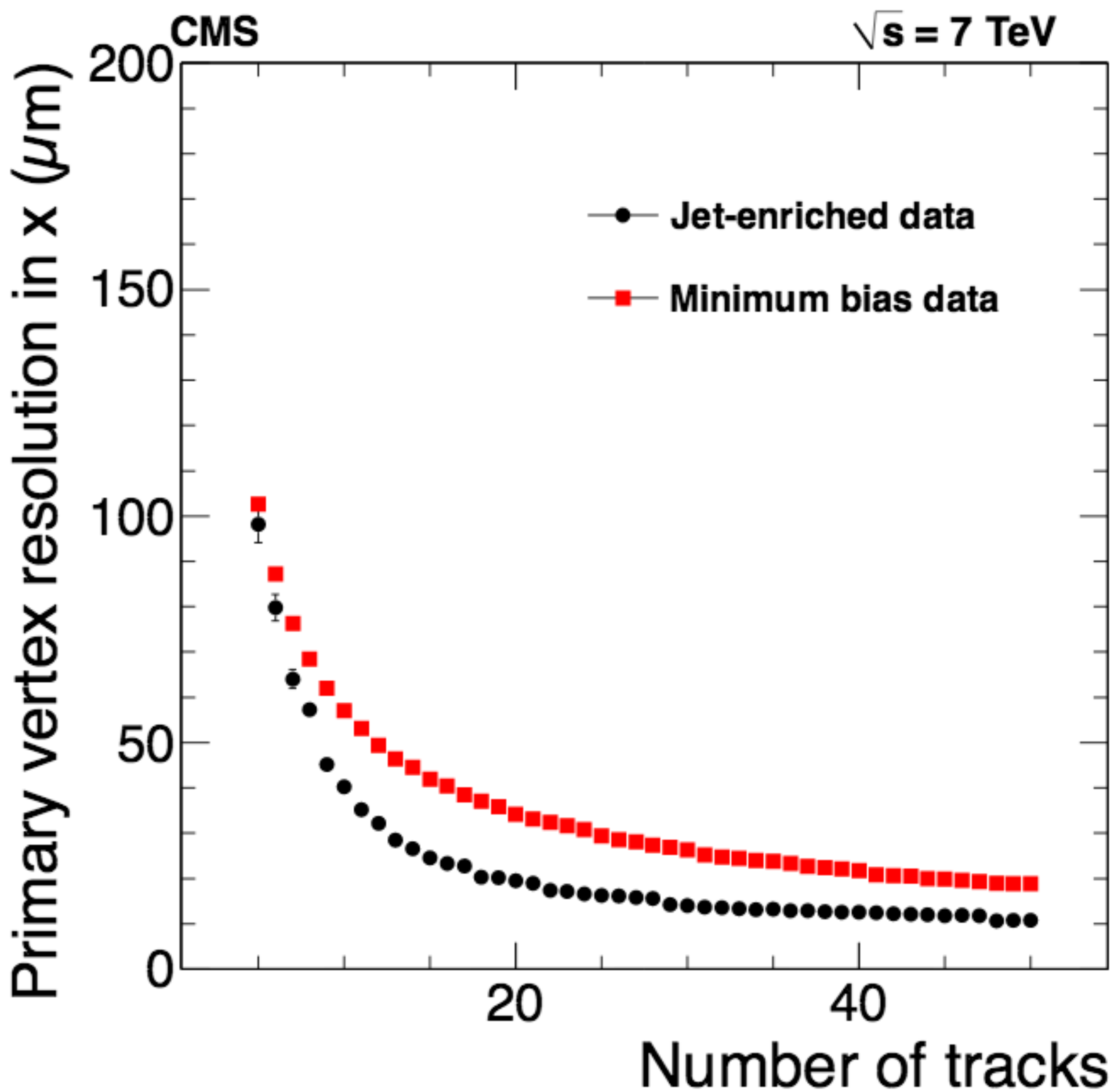
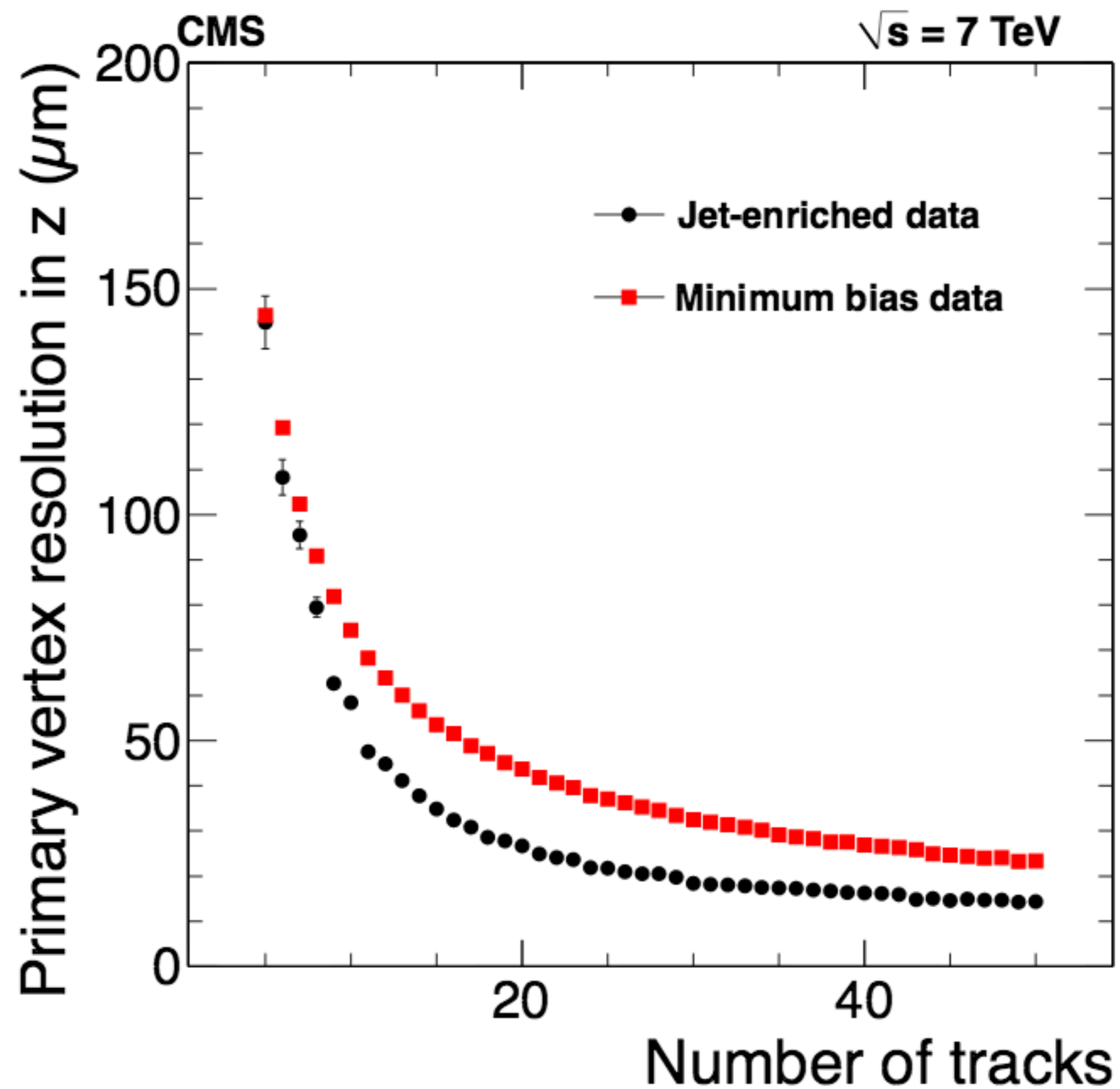
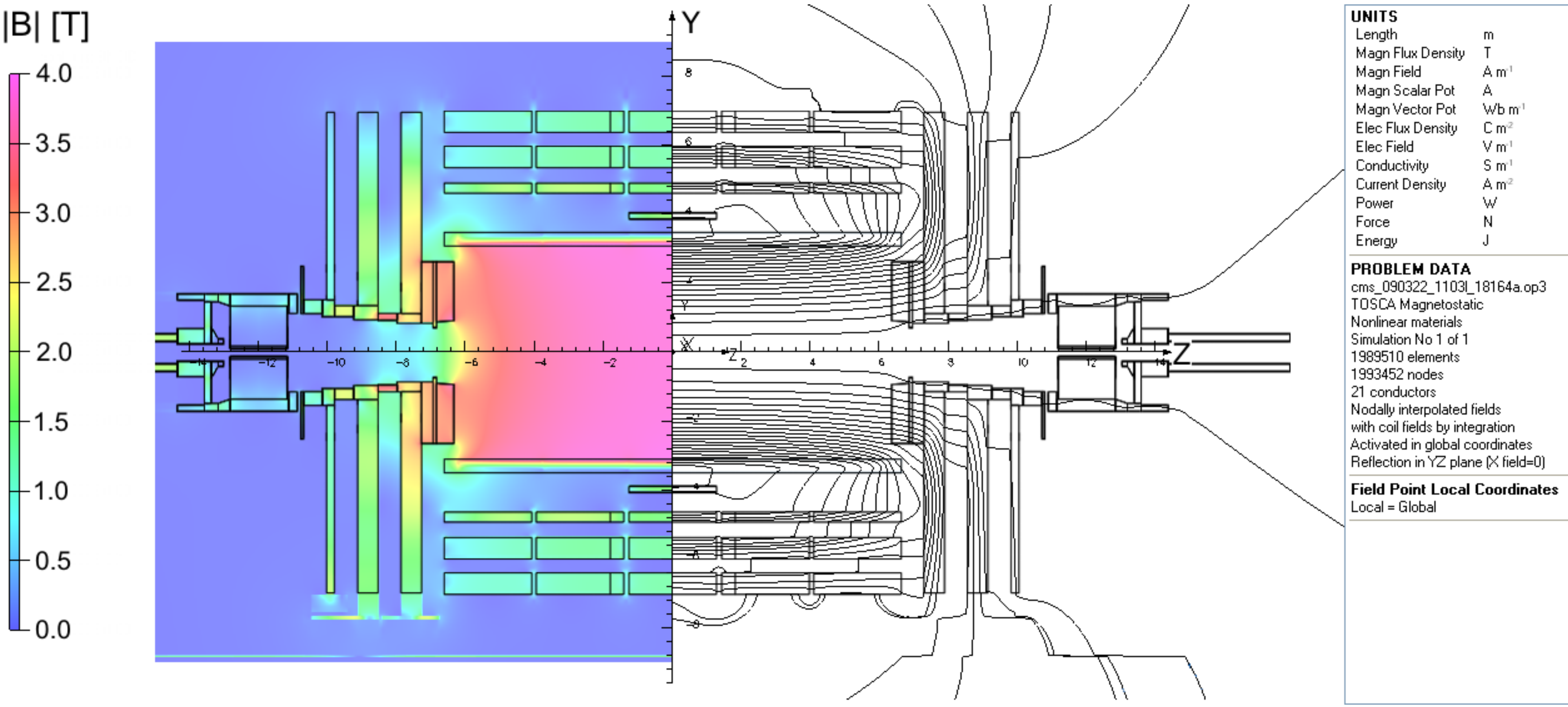




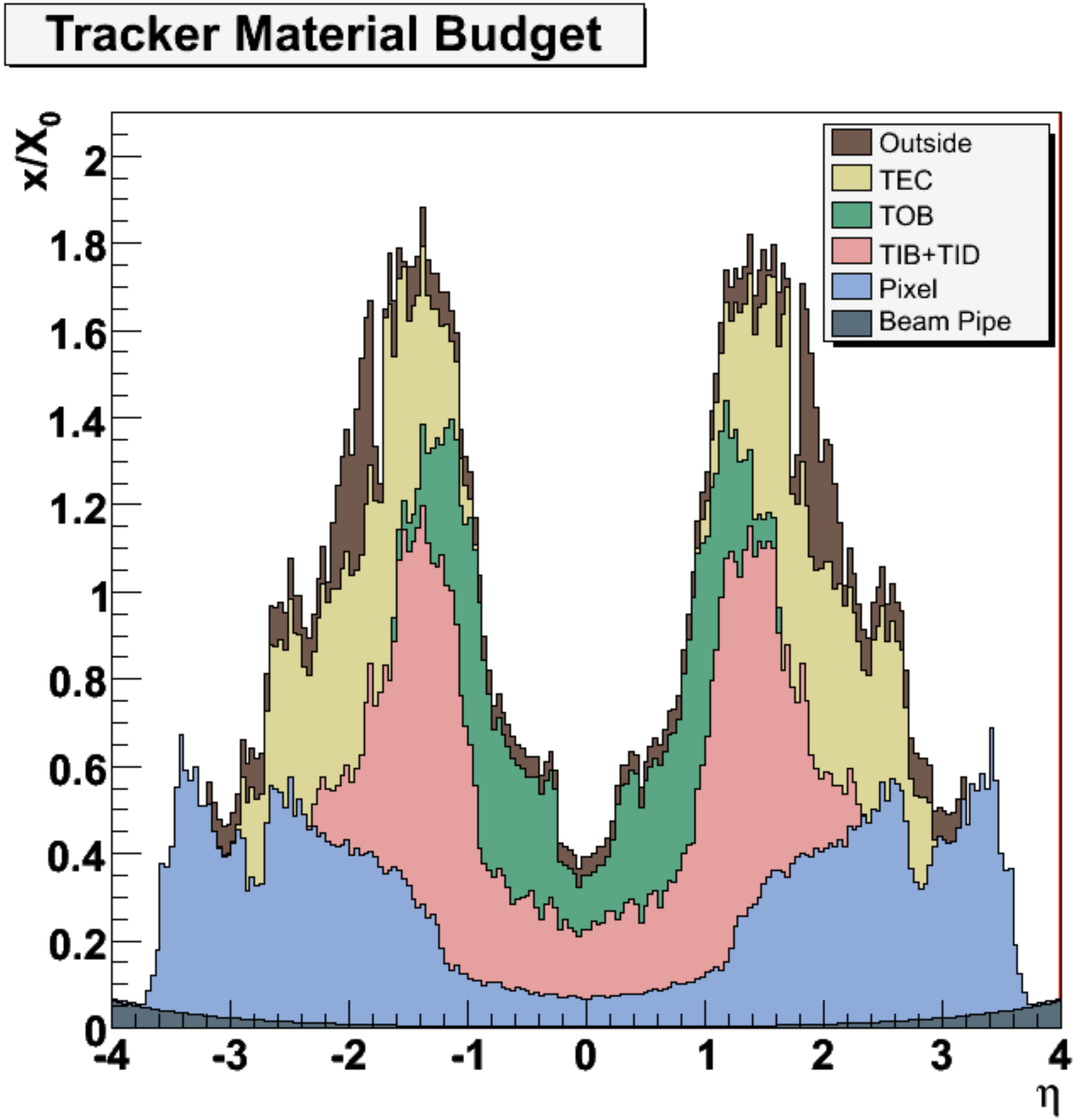
CMS Magnetic Field

N. Smith



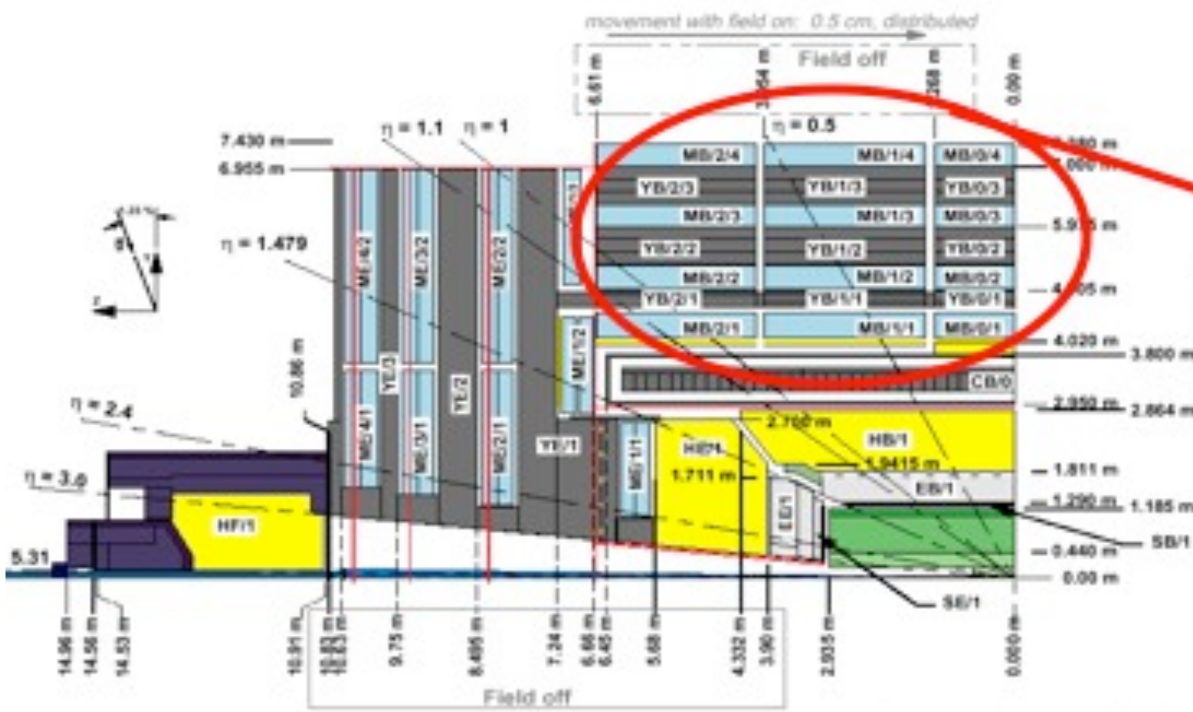
CMS Tracker Material

N. Smith

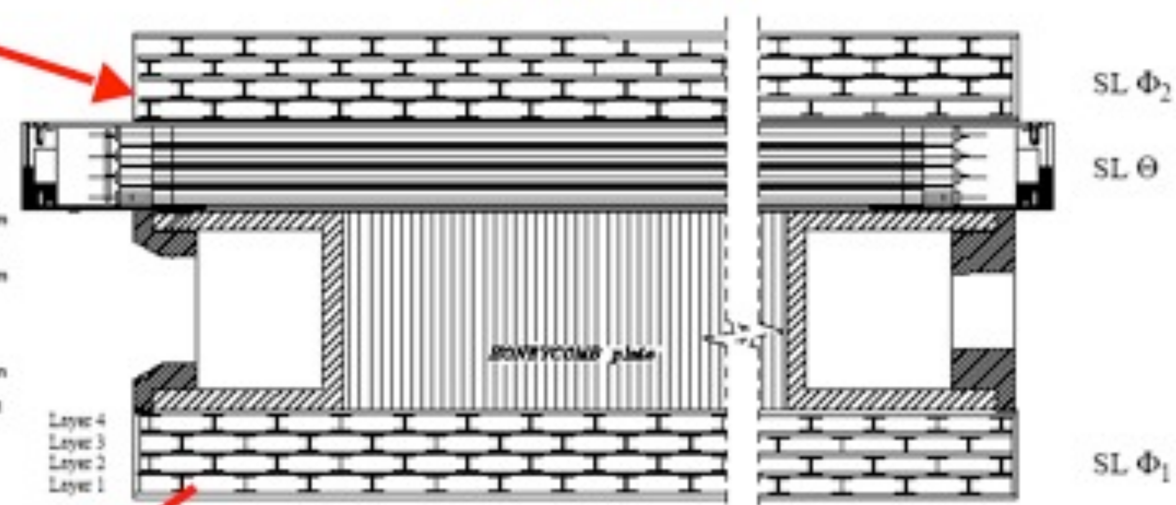


CMS Drift Tubes

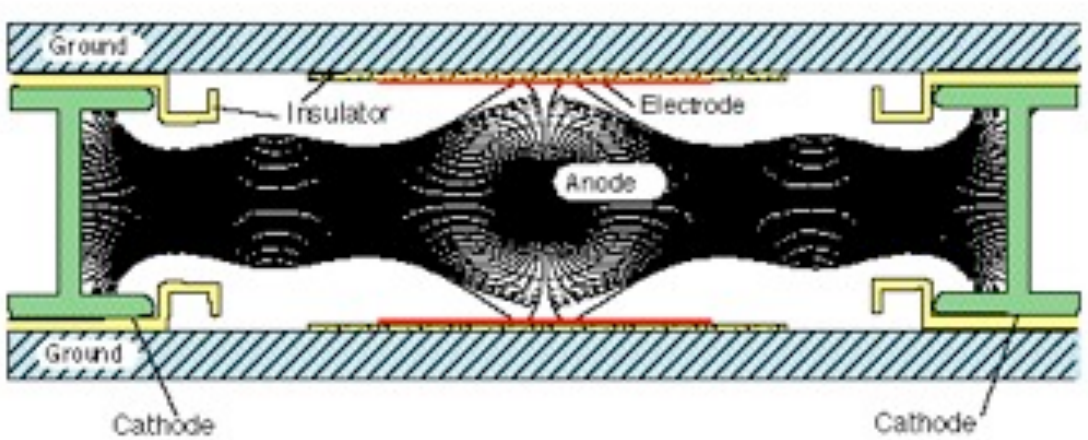
N. Smith



Chamber



Drift Tube Cell



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

Trigger Efficiency

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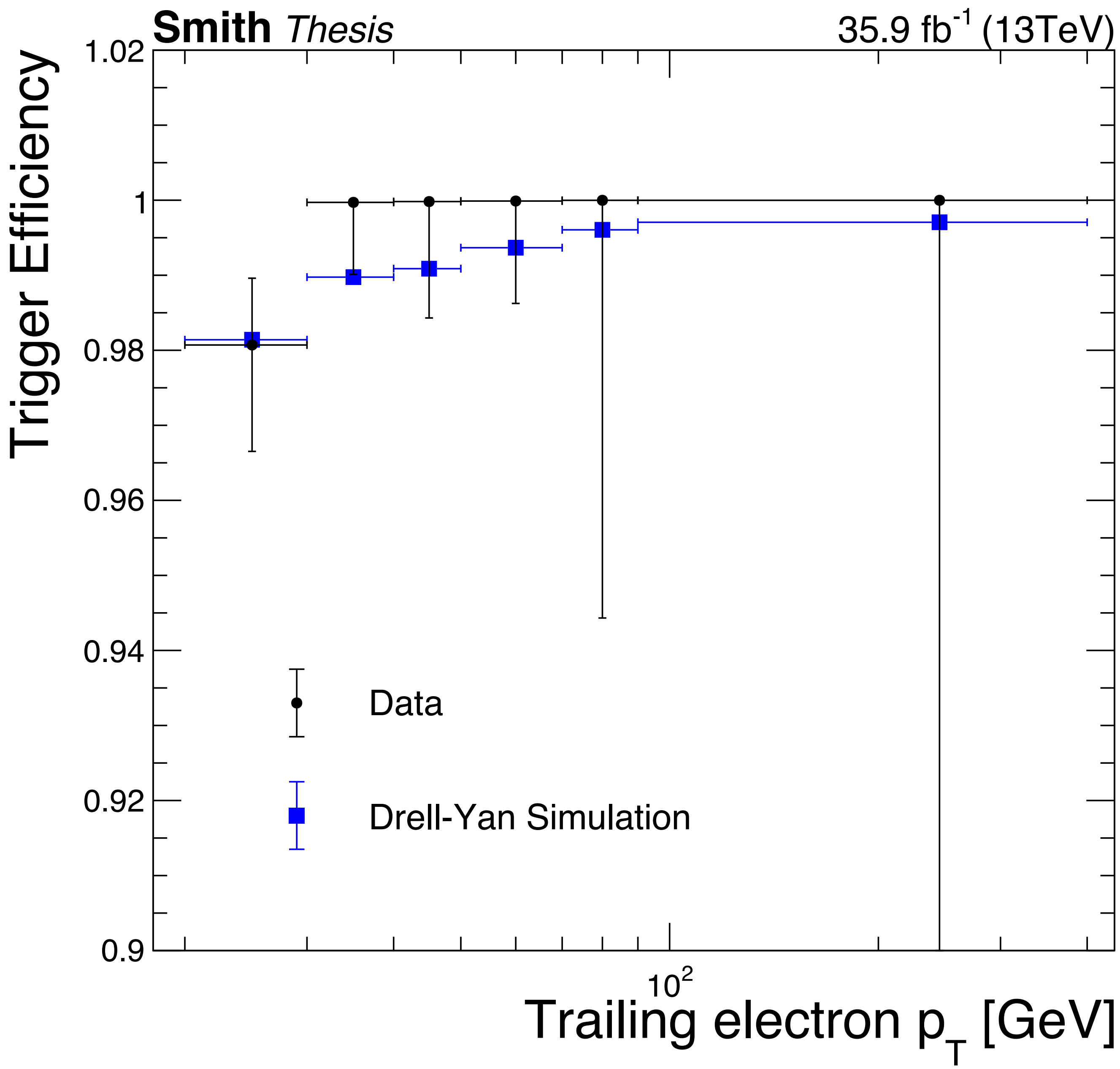

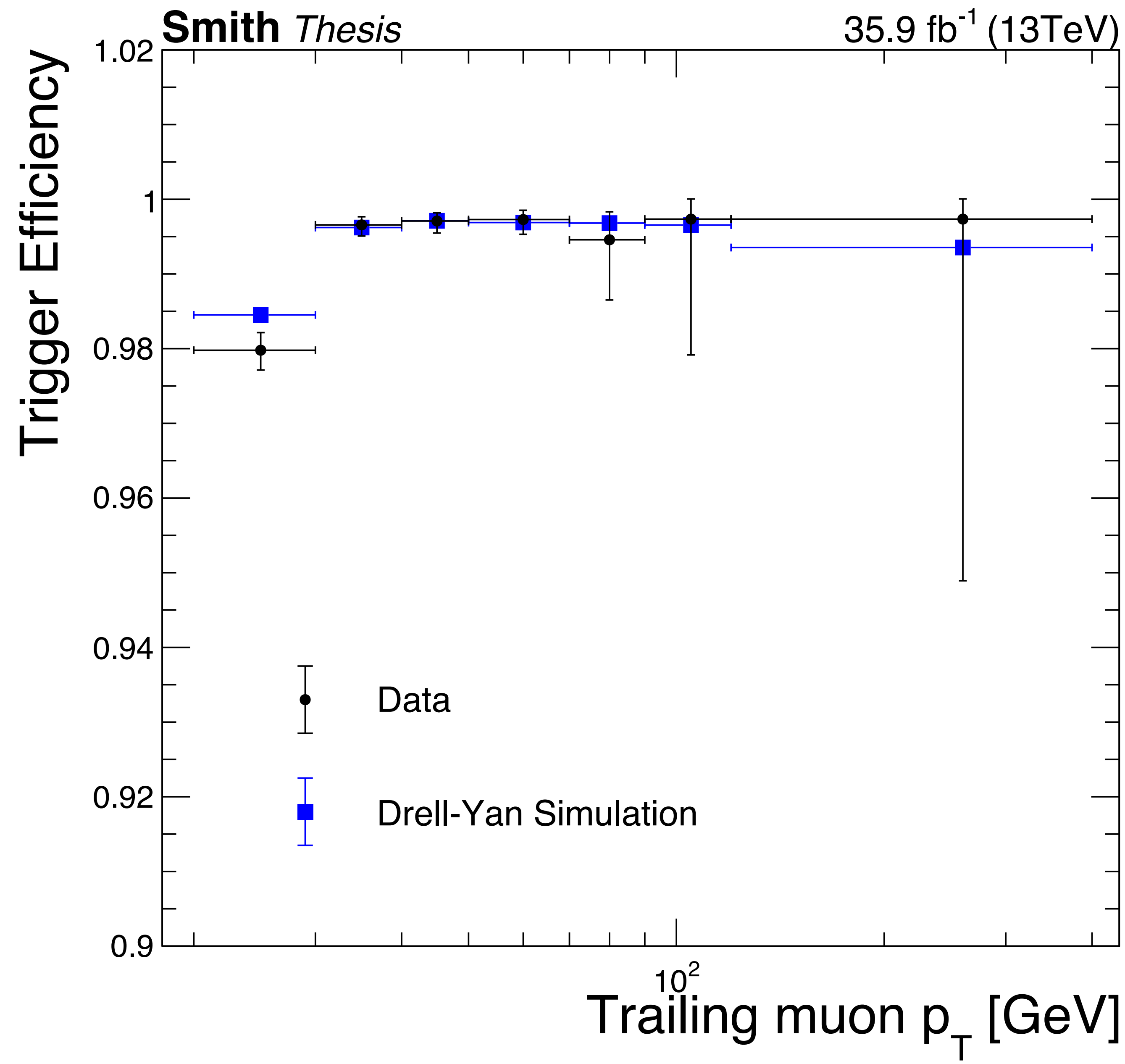

Selections

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Selection	Requirement	Reject
N_ℓ	=2	WZ, triboson
p_T^ℓ	>25/20 GeV for electrons >20 GeV for muons	QCD
Z boson mass	$\lvert m_{\ell\ell} - m_Z \rvert < 15\,\text{GeV}$	WW, top quark
$p_T^{\ell\ell}$	>60 GeV	DY
Jet counting	$\leq$1 jet with $p_T^j > 30\,\text{GeV}$	DY, top quark, triboson
b tagging veto	0 b-tagged jets with $p_T^j > 20\,\text{GeV}$	Top quark, triboson
τ lepton veto	0 τ_h cand. with $p_T^\tau > 18\,\text{GeV}$	WZ
p_T^{miss}	>100 GeV	DY, WW, top quark
$\Delta\phi(\vec{p}_T^{\ell\ell}, \vec{p}_T^{miss})$	>2.6 rad	DY
$\lvert p_T^{miss} - p_T^{\ell\ell} \rvert / p_T^{\ell\ell}$	<0.4	DY
$\Delta\phi(\vec{p}_T^{j}, \vec{p}_T^{miss})$	>0.5 rad	DY, WZ
$\Delta R_{\ell\ell}$	<1.8	WW, top quark

Selection	Event yield								
	ZZ	WZ	NRB	Other	DY	Total bkg.	ZH(inv.)	Vector DM	Data
e^+e^- or $\mu^+\mu^-$	5269.5 ± 1.6	7663.2 ± 8.4	430700 ± 330	307240 ± 340	37017000 ± 13000	37768000 ± 13000	861.3 ± 3.9	295.3 ± 5.4	38879200 ± 6200
Z boson mass	4868.0 ± 1.5	5904.2 ± 7.4	78210 ± 100	172090 ± 250	33941000 ± 12000	34202000 ± 12000	816.9 ± 3.8	281.8 ± 5.3	34788900 ± 5900
$p_T^{\ell\ell}$	1968.39 ± 0.97	2569.6 ± 4.9	35866 ± 53	48520 ± 130	2321900 ± 3300	2410800 ± 3300	580.9 ± 3.1	229.8 ± 4.8	2430800 ± 1600
Jet counting	1620.02 ± 0.88	1466.5 ± 3.7	8514 ± 32	19590 ± 90	1376500 ± 2500	1407700 ± 2500	453.7 ± 2.8	184.4 ± 4.2	1446100 ± 1200
b tagging veto	1591.33 ± 0.87	1433.1 ± 3.6	4544 ± 27	18255 ± 87	1290500 ± 2400	1316300 ± 2400	446.8 ± 2.8	182.5 ± 4.2	1361400 ± 1200
τ lepton veto	1572.97 ± 0.87	1258.5 ± 3.4	4463 ± 27	17648 ± 86	1261600 ± 2400	1286500 ± 2400	442.0 ± 2.8	180.4 ± 4.1	1328100 ± 1200
p_T^{miss}	624.67 ± 0.54	332.5 ± 1.7	727.1 ± 9.5	44.2 ± 3.3	771 ± 51	2499 ± 52	278.4 ± 2.2	126.7 ± 3.5	2473 ± 50
$\Delta\phi(\vec{p}_T^{\ell\ell}, \vec{p}_T^{miss})$	553.42 ± 0.51	252.5 ± 1.5	348.6 ± 6.6	31.6 ± 2.6	318 ± 30	1504 ± 31	252.2 ± 2.1	114.3 ± 3.4	1602 ± 40
$\lvert p_T^{miss} - p_T^{\ell\ell} \rvert / p_T^{\ell\ell}$	448.58 ± 0.46	196.9 ± 1.3	176.9 ± 4.7	20.3 ± 2.2	173 ± 21	1015 ± 22	223.0 ± 2.0	100.0 ± 3.2	1107 ± 33
$\Delta\phi(\vec{p}_T^{j}, \vec{p}_T^{miss})$	431.80 ± 0.45	179.8 ± 1.3	166.2 ± 4.6	16.5 ± 1.7	38 ± 11	833 ± 12	215.1 ± 1.9	96.0 ± 3.1	910 ± 30
$\Delta R_{\ell\ell}$	370.79 ± 0.42	153.5 ± 1.2	66.6 ± 2.8	15.3 ± 1.6	23.8 ± 8.3	629.9 ± 9.0	202.2 ± 1.9	90.4 ± 3.0	694 ± 26

Diboson kinematics

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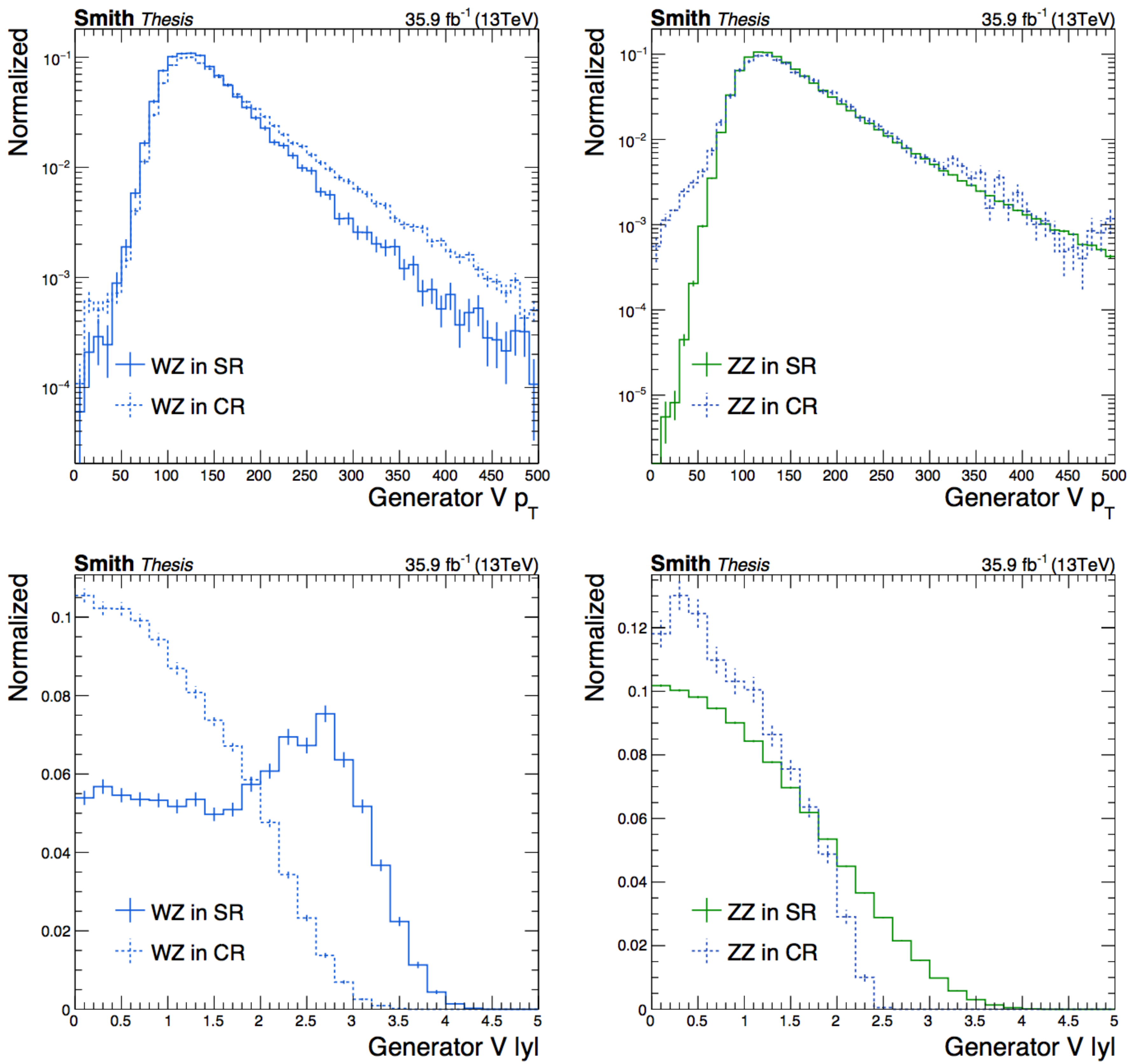

Diboson kinematics

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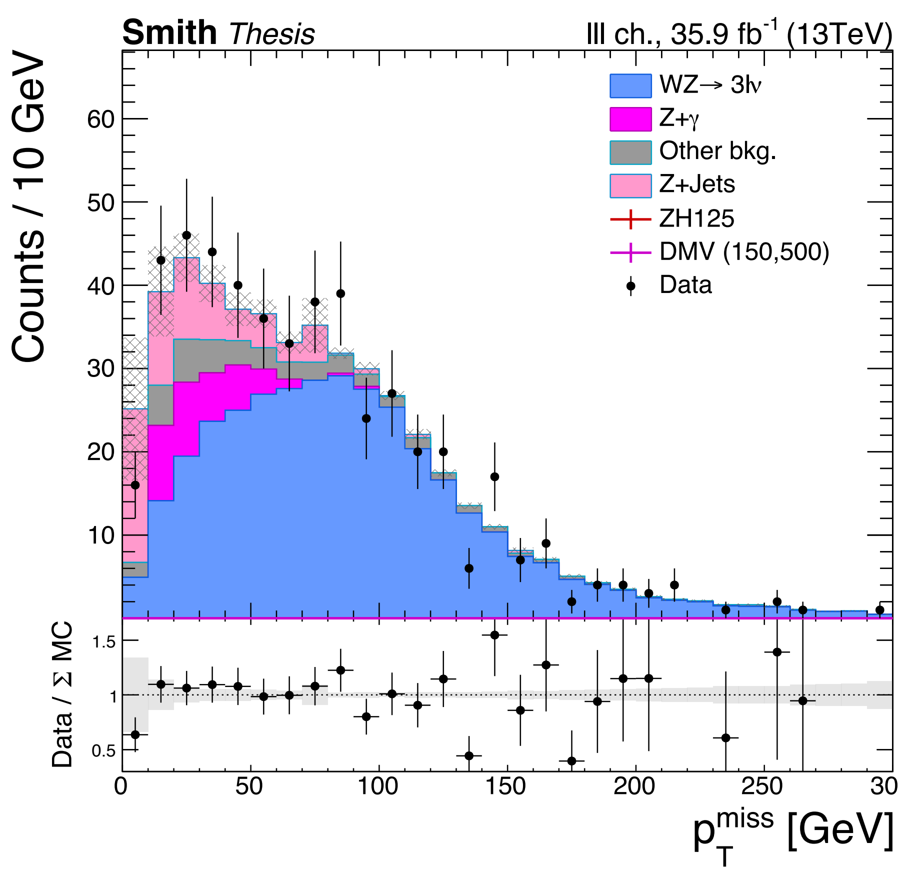
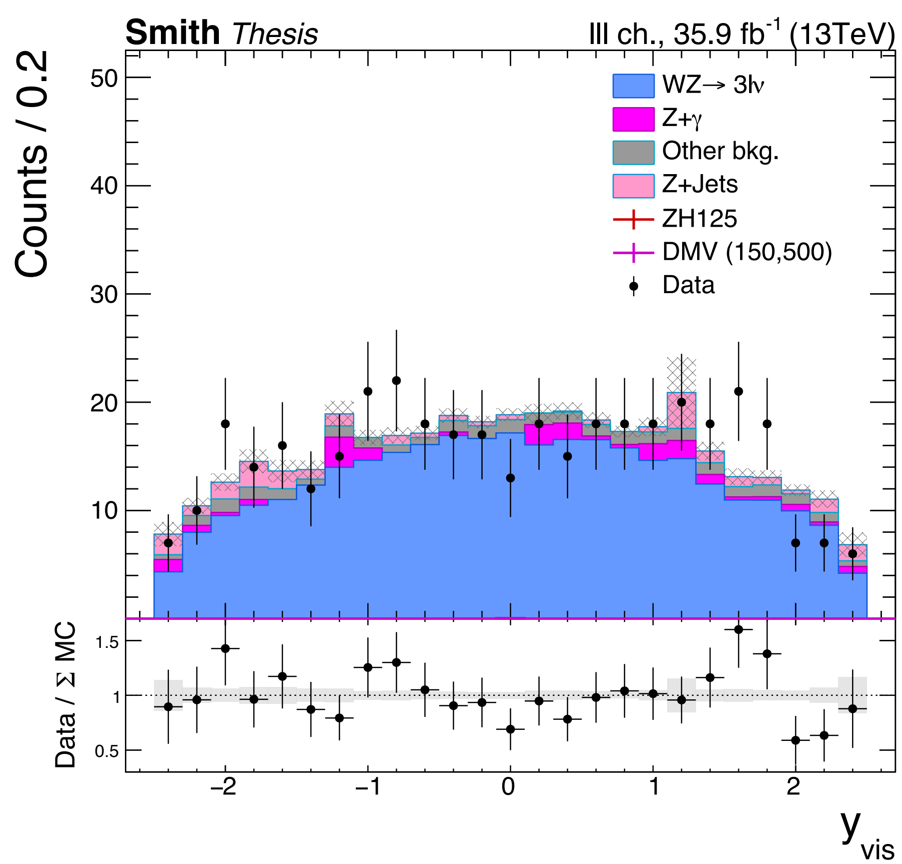
WZ CR

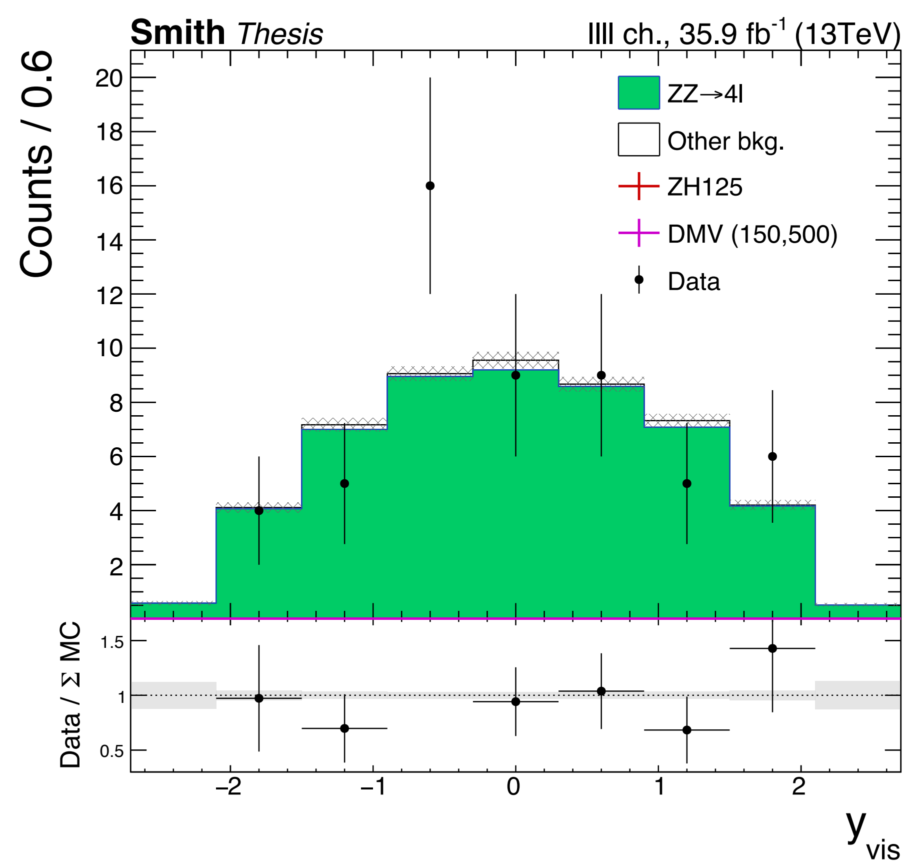
$$p_{\mathrm{T}}^{\mathrm{miss}} > 30\,\mathrm{GeV}$$

$$m_{3\ell} > 100\,\mathrm{GeV}$$

$$m_{\ell^+\ell^-} > 4\,\mathrm{GeV}$$







DY + fake pTmiss

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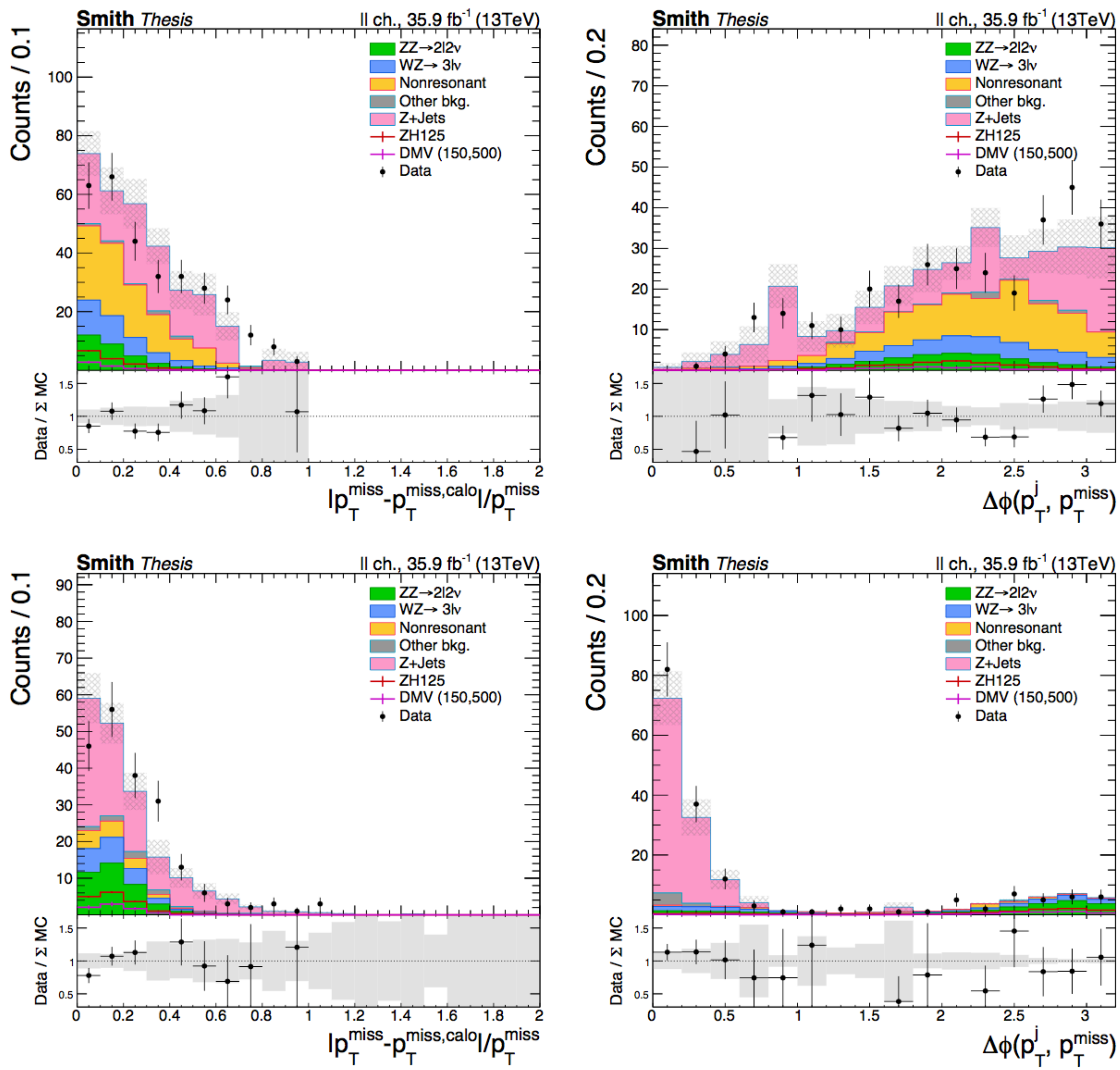

Likelihood functions

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Full

$$\mathcal{L} = \prod_i \mathcal{P}\left(N^{2\ell}_{obs,i} \middle| \mu_{DY} N^{2\ell}_{DY,i}(\boldsymbol{\theta}) + \mu_{NRB} N^{2\ell}_{NRB,i}(\theta) + N^{2\ell}_{other,i}(\boldsymbol{\theta}) + \mu_{VV}(N^{2\ell}_{ZZ,i}(\boldsymbol{\theta}) + N^{2\ell}_{WZ,i}(\boldsymbol{\theta})) + \mu N^{2\ell}_{Sig,i}(\boldsymbol{\theta})\right)$$

$$\times \prod_i \mathcal{P}\left(N^{3\ell}_{obs,i} \middle| N^{3\ell}_{other,i}(\boldsymbol{\theta}) + \mu_{VV} N^{3\ell}_{WZ,i}(\boldsymbol{\theta})\right)$$

$$\times \prod_i \mathcal{P}\left(N^{4\ell}_{obs,i} \middle| N^{4\ell}_{other,i}(\boldsymbol{\theta}) + \mu_{VV} N^{4\ell}_{ZZ,i}(\boldsymbol{\theta})\right)$$

$$\times \mathcal{P}\left(N^{e\mu}_{obs} \middle| \mu_{NRB} N^{e\mu}_{NRB}(\boldsymbol{\theta}) + N^{e\mu}_{other}(\boldsymbol{\theta})\right)$$

$$\times \mathcal{P}\left(N^{DY\,sb}_{obs} \middle| \mu_{DY} N^{DY\,sb}_{DY}(\boldsymbol{\theta}) + \mu_{NRB} N^{DY\,sb}_{NRB}(\boldsymbol{\theta}) + N^{DY\,sb}_{other}(\boldsymbol{\theta}) + \mu_{VV}(N^{DY\,sb}_{ZZ}(\boldsymbol{\theta}) + N^{DY\,sb}_{WZ}(\boldsymbol{\theta})) + \mu N^{DY\,sb}_{Sig}(\boldsymbol{\theta})\right)$$

$$\times e^{-|\boldsymbol{\theta}|^2/2},$$

Simplified

$$\mathcal{L} = \prod_i \mathcal{P}\left(N_{obs,i} \middle| \mu N_{exp,i} + N_{bkg,i} + \theta_i\right) \cdot \exp\left(-\frac{1}{2}\vec{\theta}^T \left(\vec{\sigma}\mathbf{C}\vec{\sigma}^T\right)^{-1} \vec{\theta}\right)$$

Systematics

N. Smith

Source of uncertainty	Effect (%)					Impact on the exp. limit (%)
	Signal	ZZ	WZ	NRB	DY	
* VV EW corrections	–	10	−4	–	–	14
* Renorm./fact. scales, VV	–	9	4	–	–	2
* Renorm./fact. scales, ZH	3.5	–	–	–	–	
* Renorm./fact. scales, DM	5	–	–	–	–	
* PDF, WZ background	–	–	1.5	–	–	
* PDF, ZZ background	–	1.5	–	–	–	
* PDF, Higgs boson signal	1.5	–	–	–	–	
* PDF, DM signal	1–2	–	–	–	–	
* MC sample size, NRB	–	–	–	5	–	1
* MC sample size, DY	–	–	–	–	30	
* MC sample size, ZZ	–	0.1	–	–	–	
* MC sample size, WZ	–	–	2	–	–	
* MC sample size, ZH	1	–	–	–	–	
* MC sample size, DM	3	–	–	–	–	
NRB extrapolation to the SR	–	–	–	20	–	<1
DY extrapolation to the SR	–	–	–	–	100	<1
Lepton efficiency (WZ CR)	–	–	3	–	–	<1
Nonprompt bkg. (WZ CR)	–	–	–	–	30	<1
Integrated luminosity	2.5					<1
* Electron efficiency	1.5					1
* Muon efficiency	1					
* Electron energy scale	1–2					
* Muon energy scale	1–2					
* Jet energy scale	1–3 (typically anticorrelated w/ yield)					
* Jet energy resolution	1 (typically anticorr.)					
* Unclustered energy (p_T^{miss})	1–4 (typically anticorr.), strong in DY					
* Pileup	1 (typically anticorrelated)					
* b tagging eff. & mistag rate	1					

ADD Limits 2012

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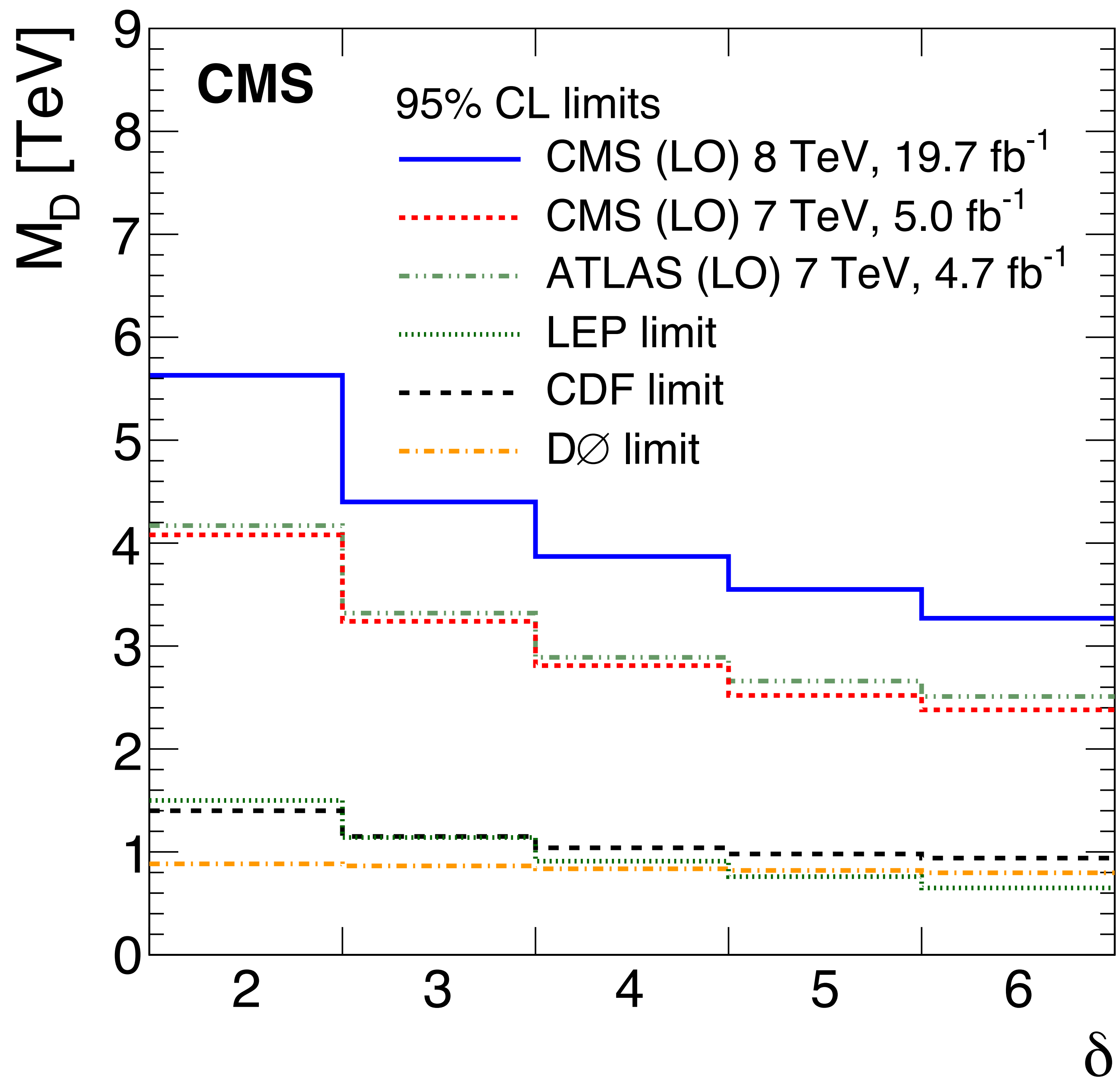

Parton Luminosity

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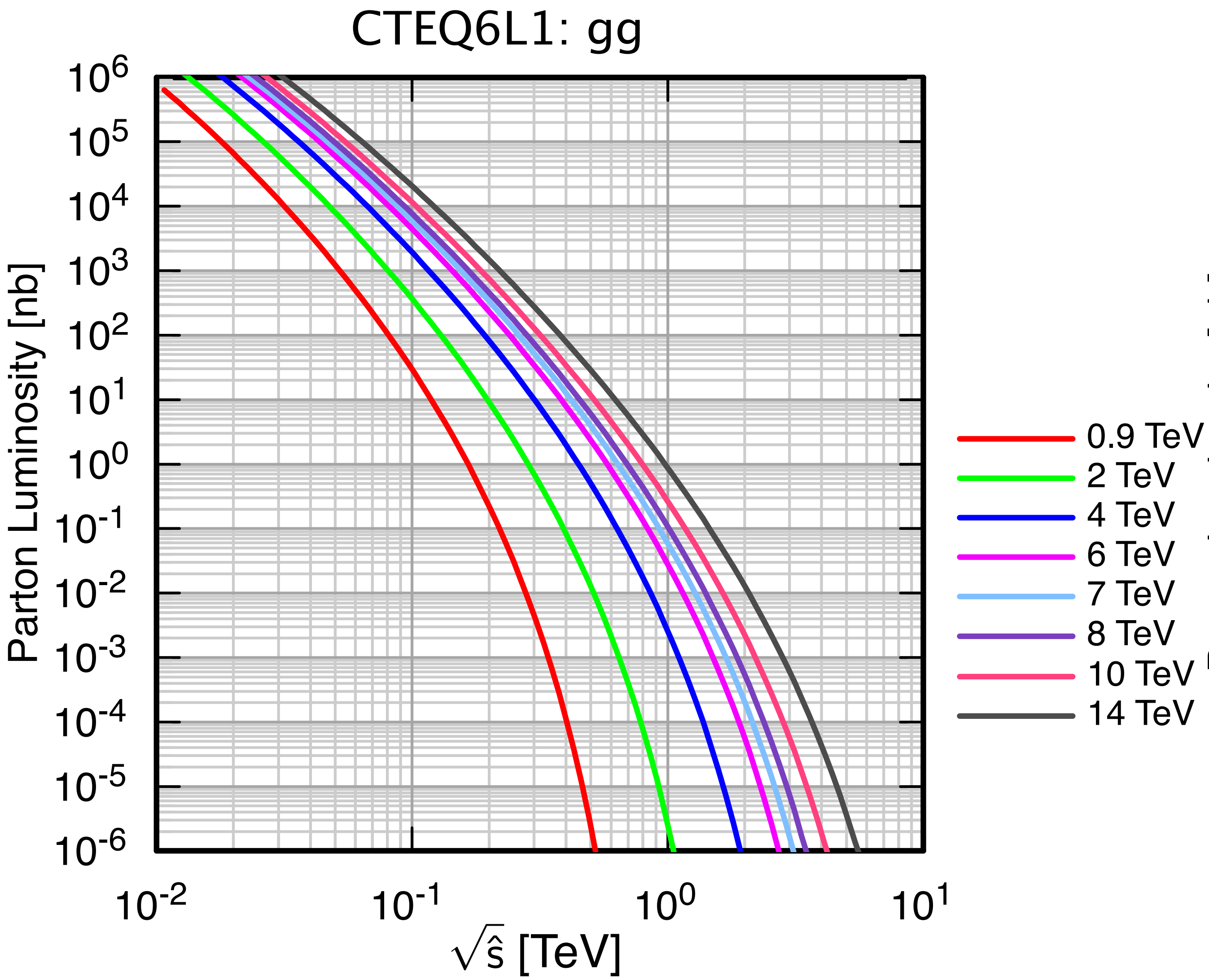
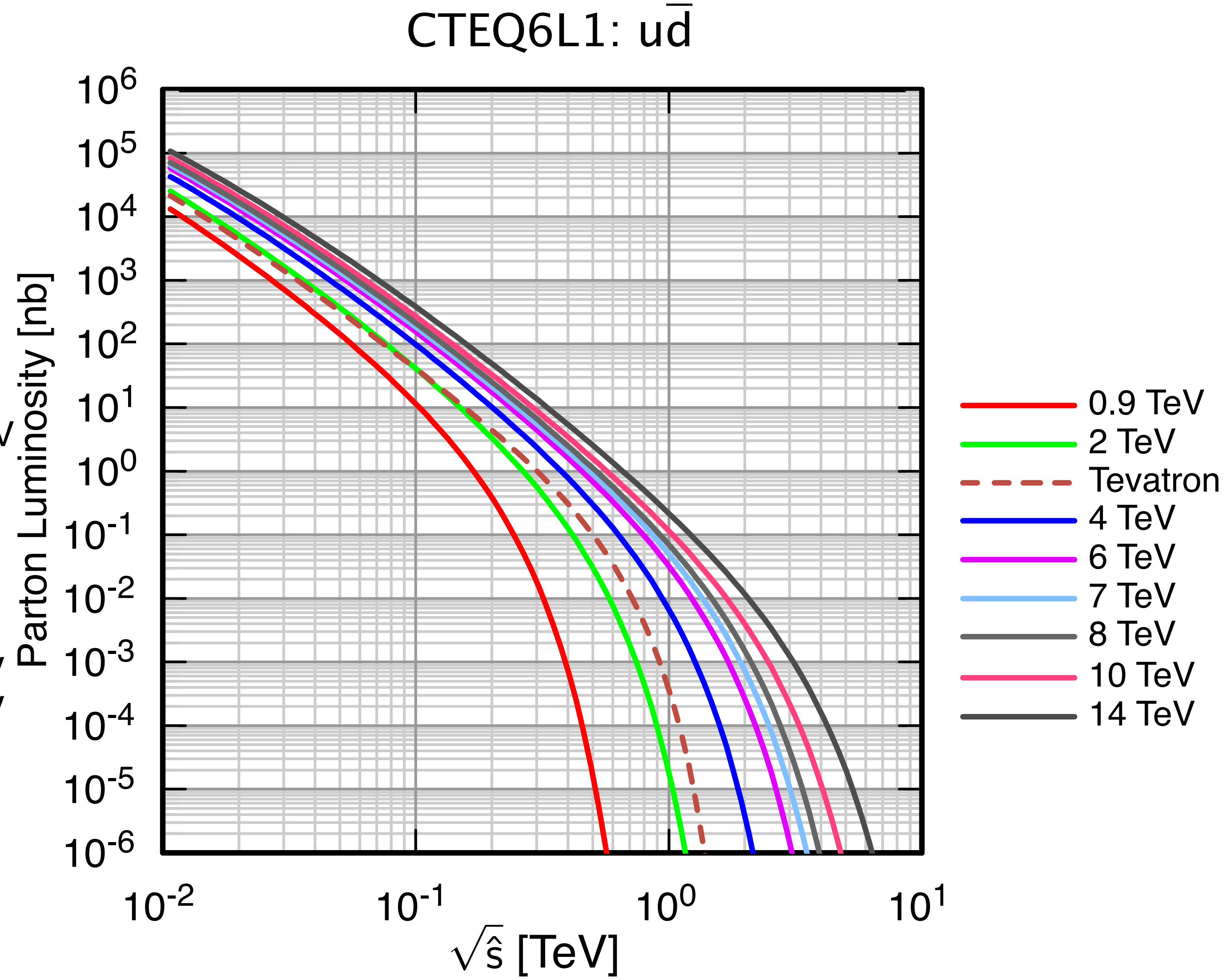
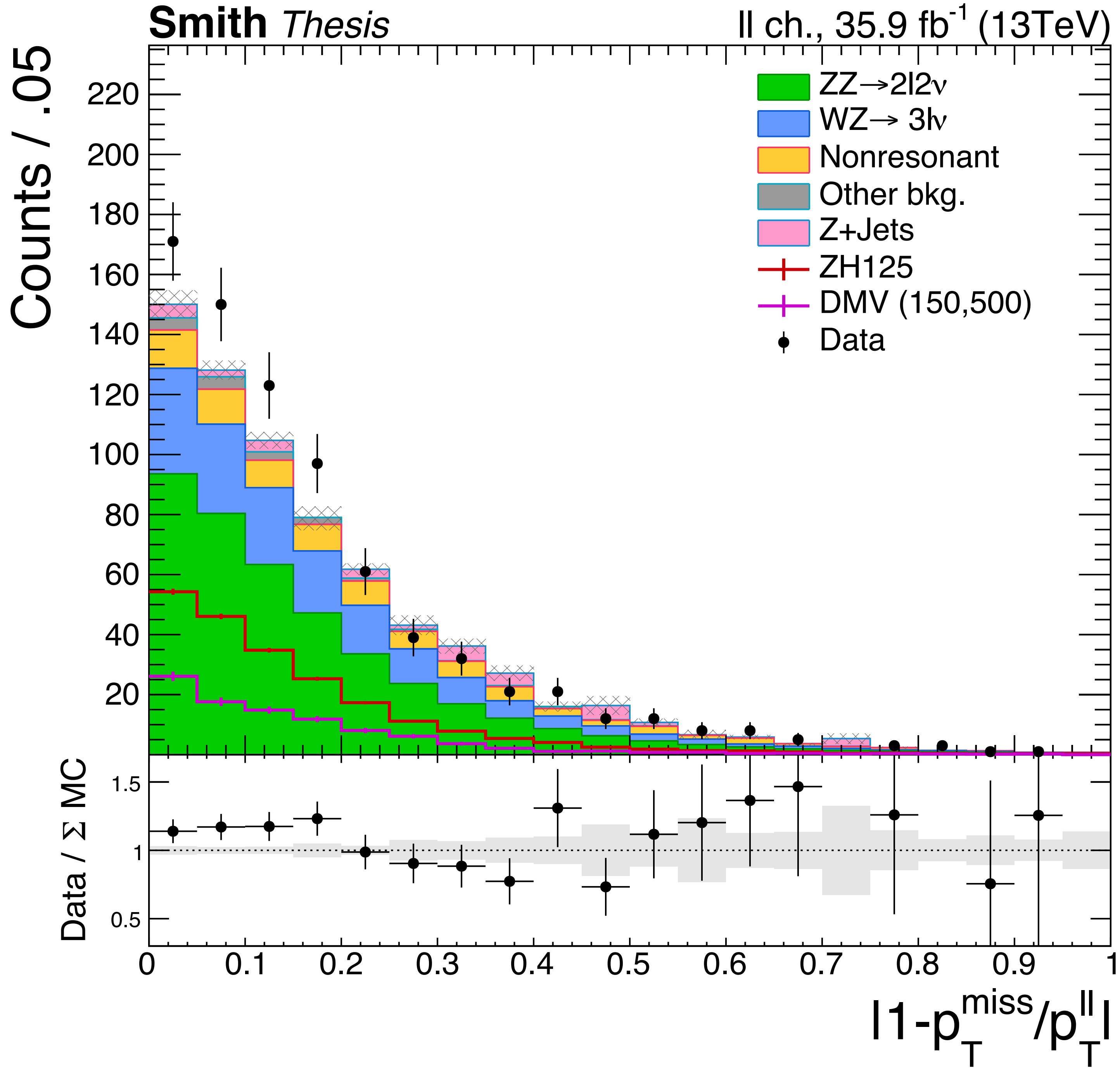




Backup

N. Smith



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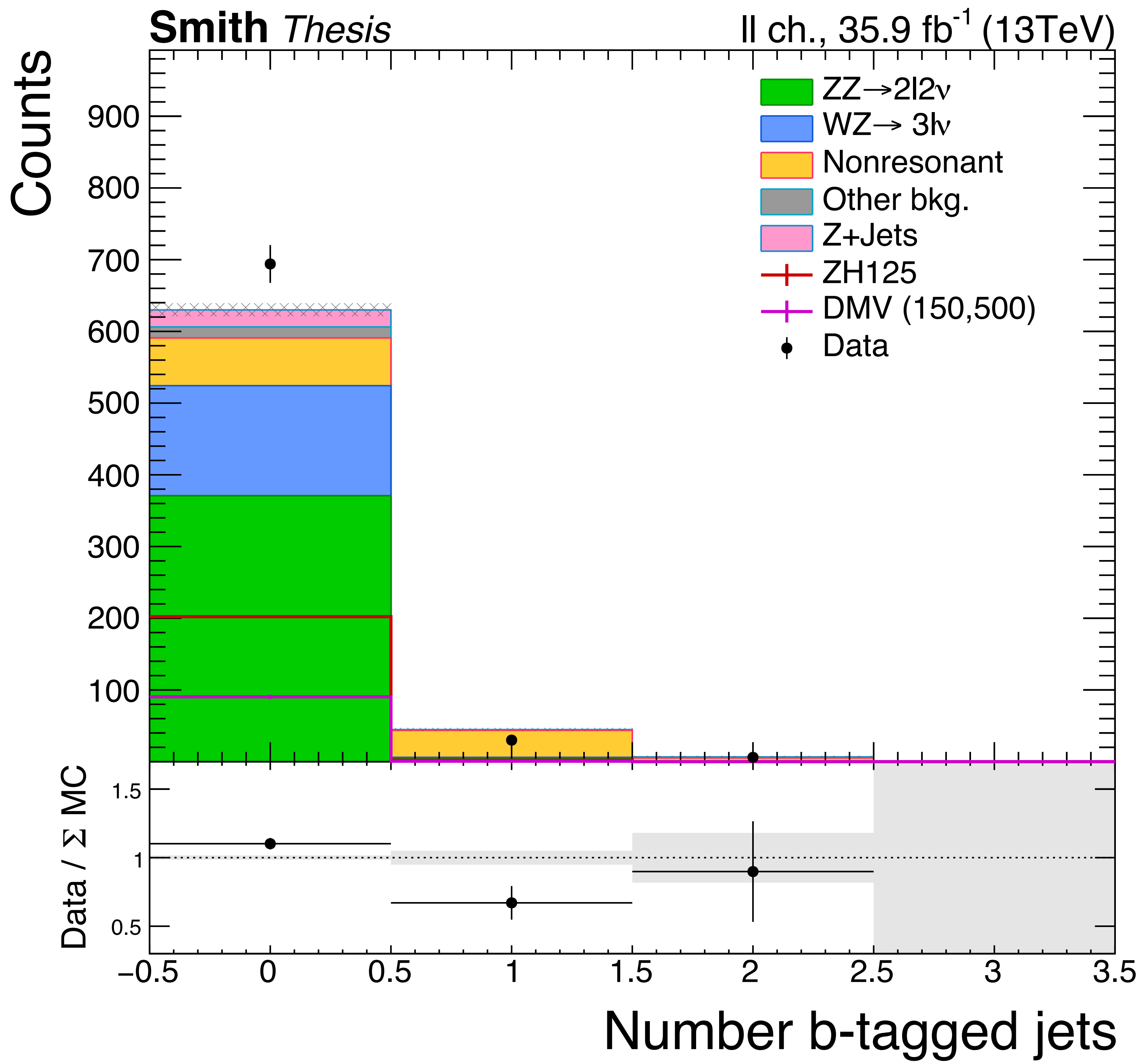

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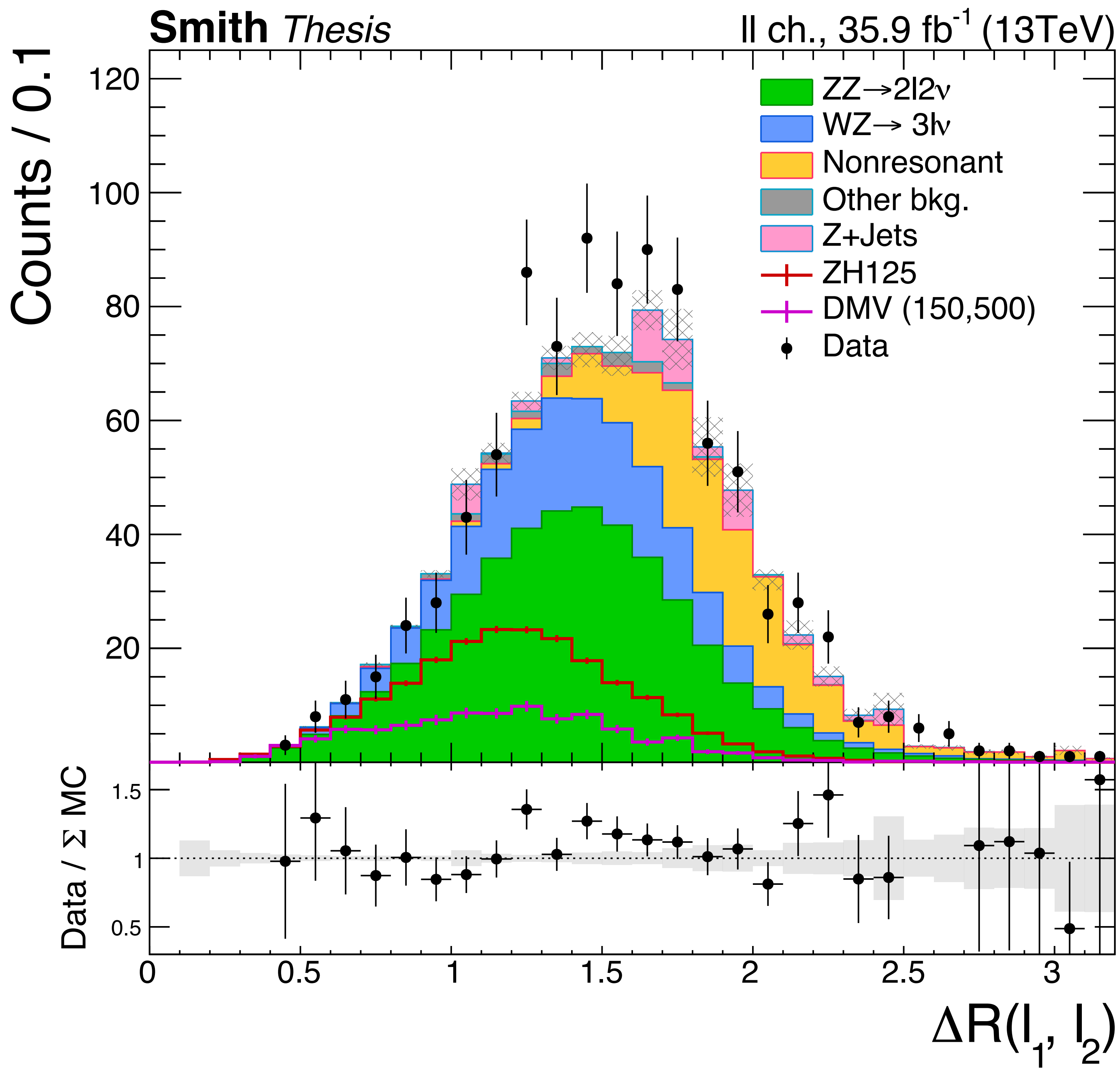

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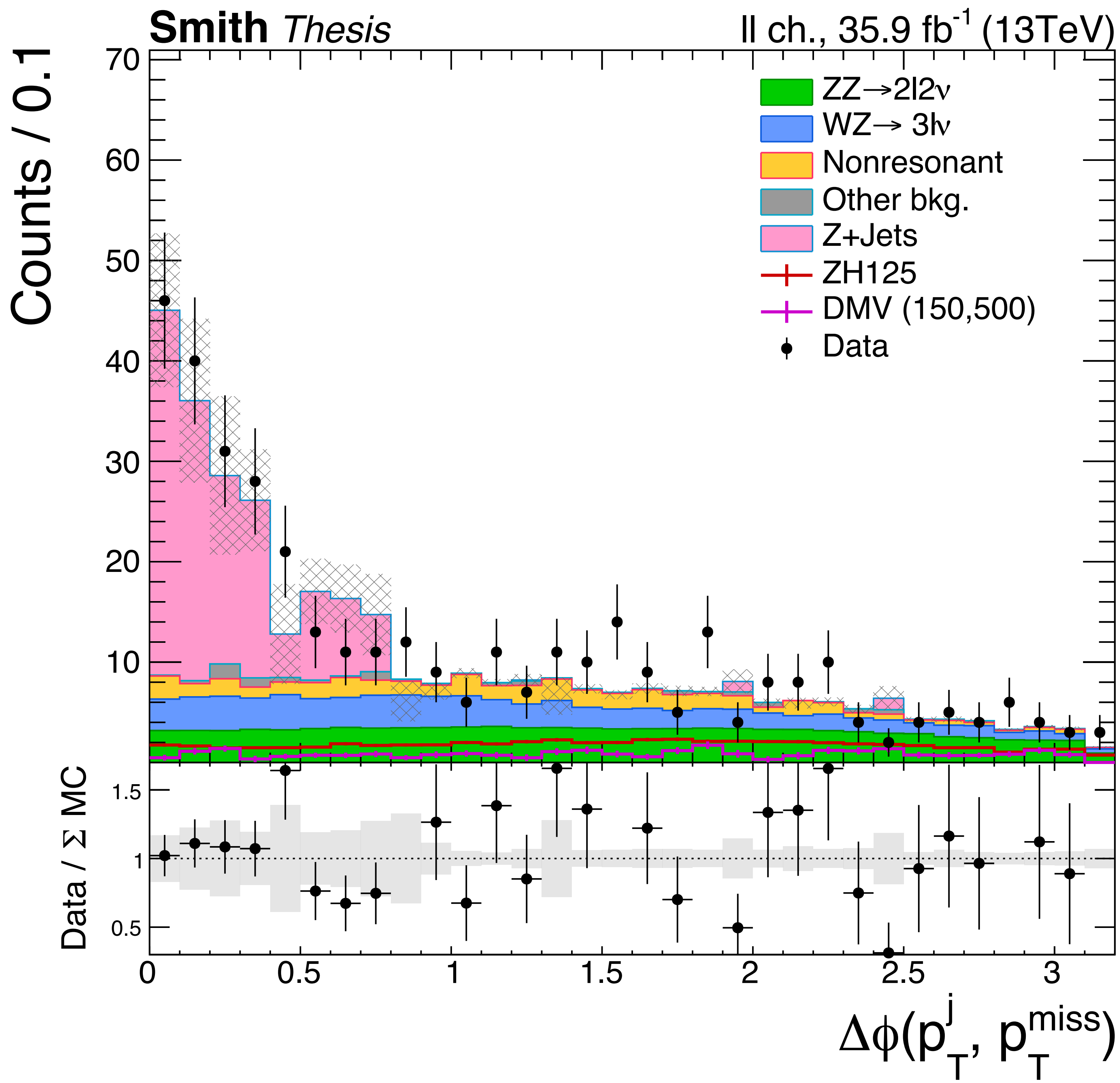

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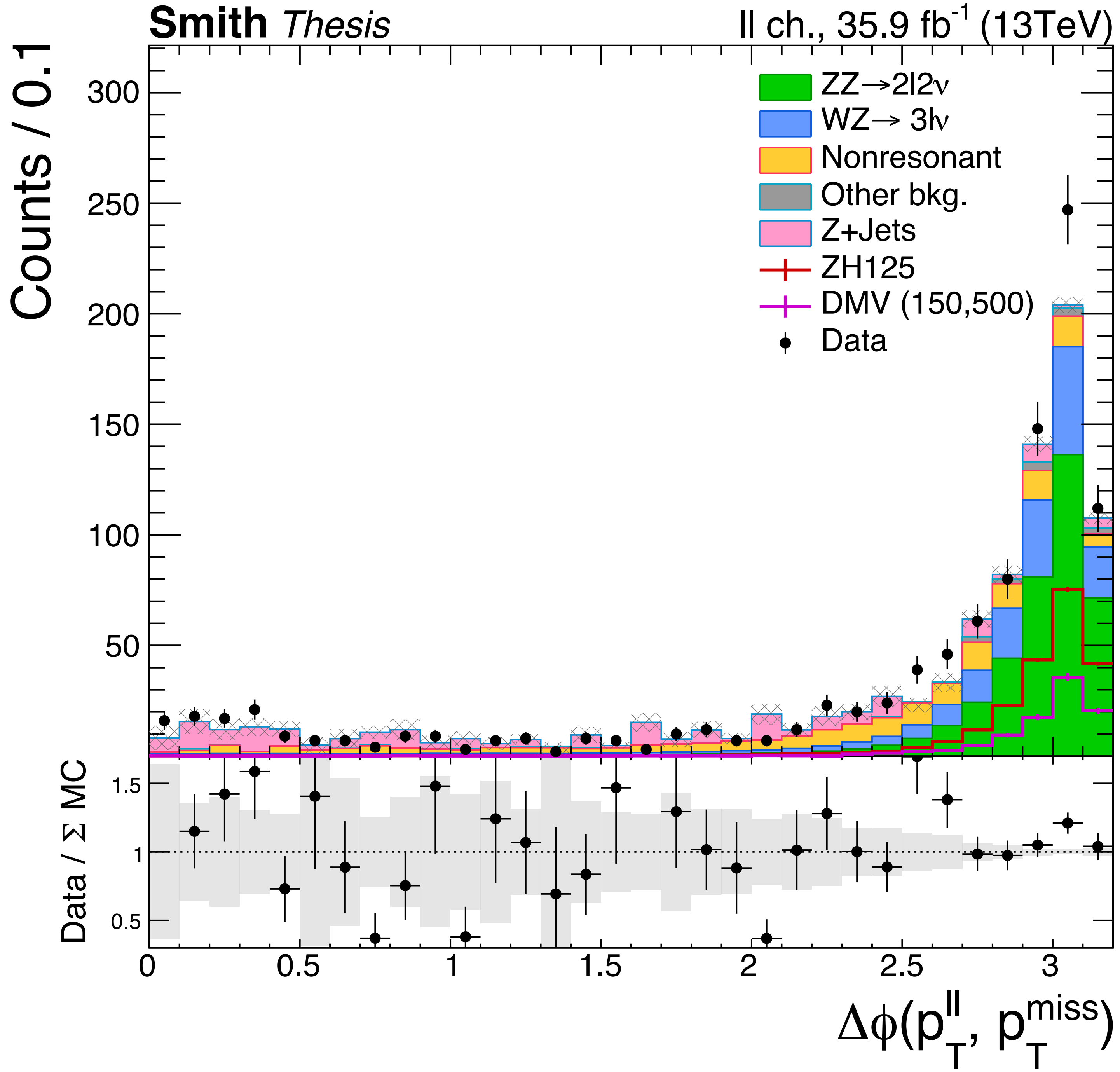

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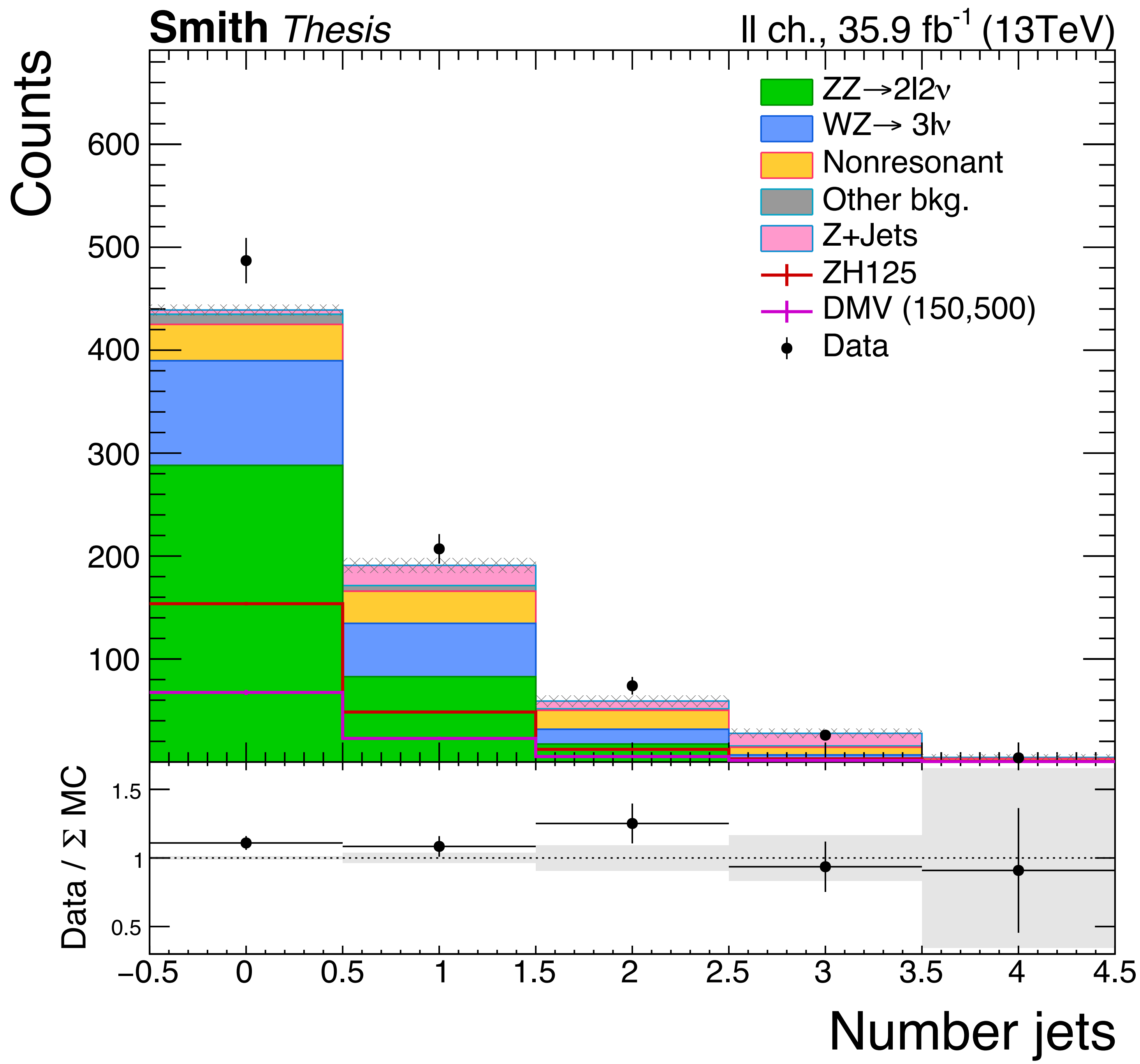

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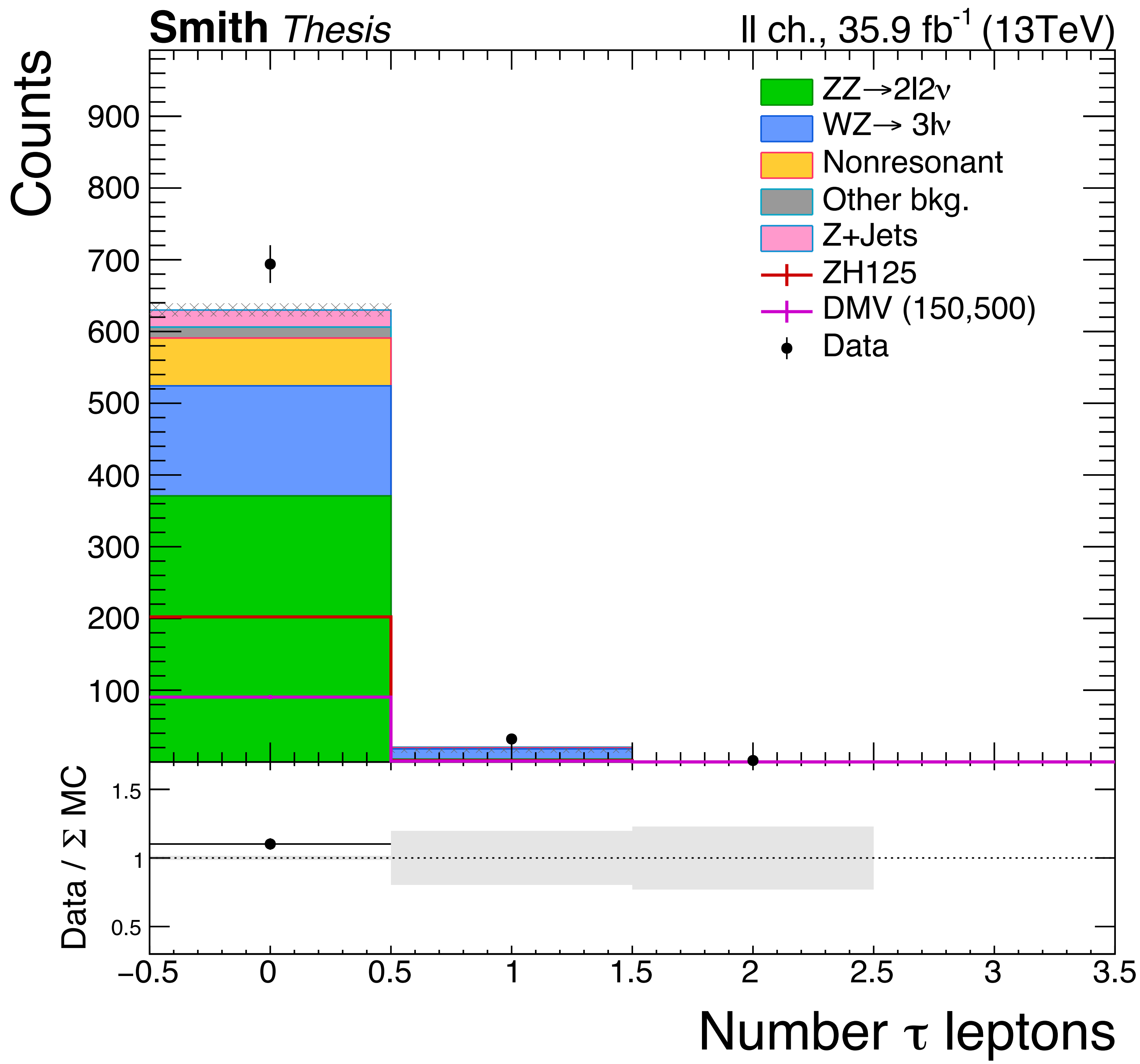

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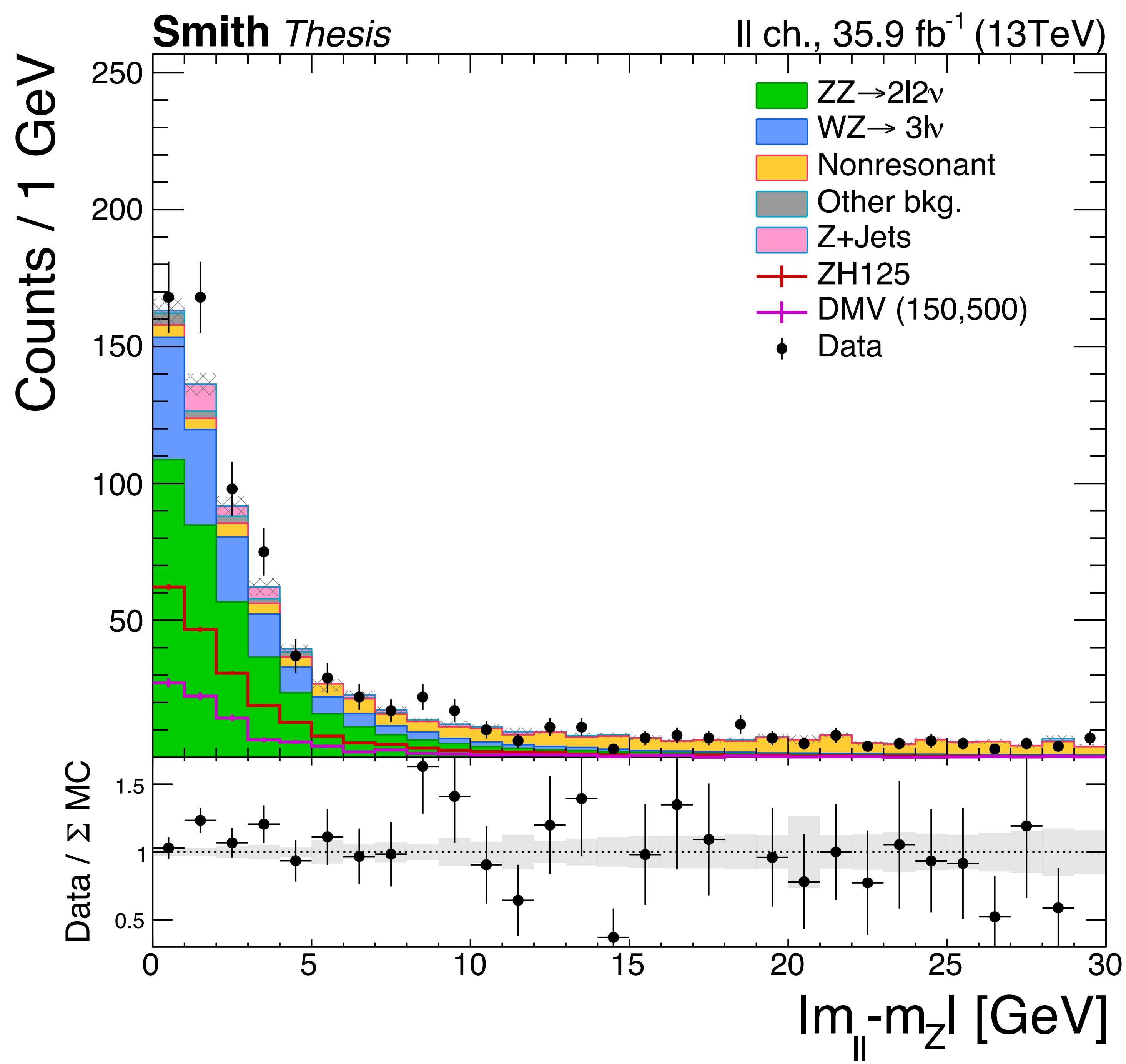

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N. Smith