Measuring the Drell-Yan the forward-backward asymmetry at the Large Hadron Collider

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CMS

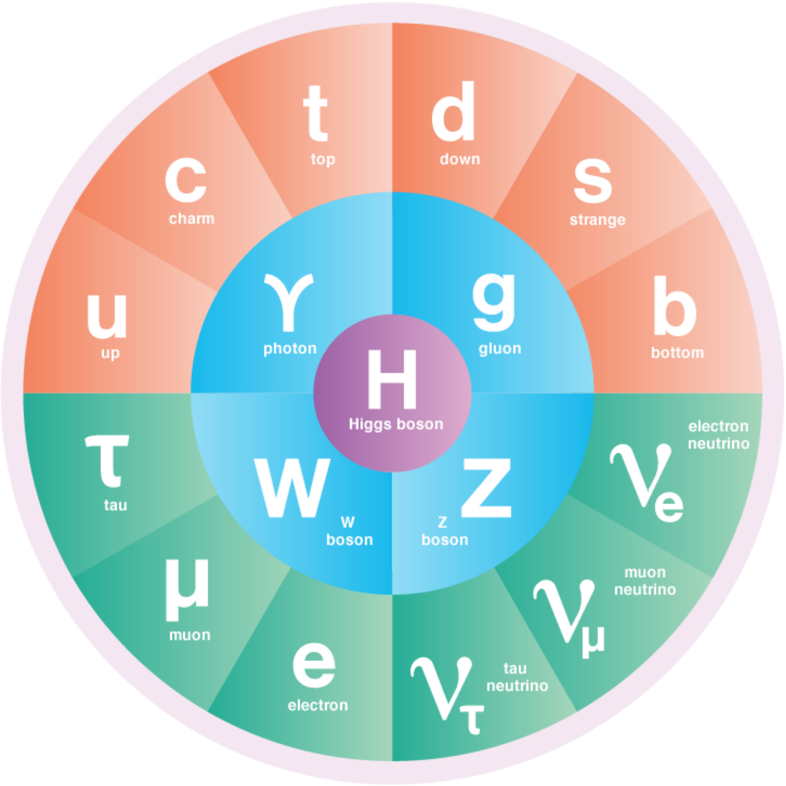
Outline

- Background: The Standard Model and the LHC
- My Analysis: Drell-Yan forward-backward asymmetry
- Techniques: Template Fitting
- Results

The Standard Model of Particle Physics

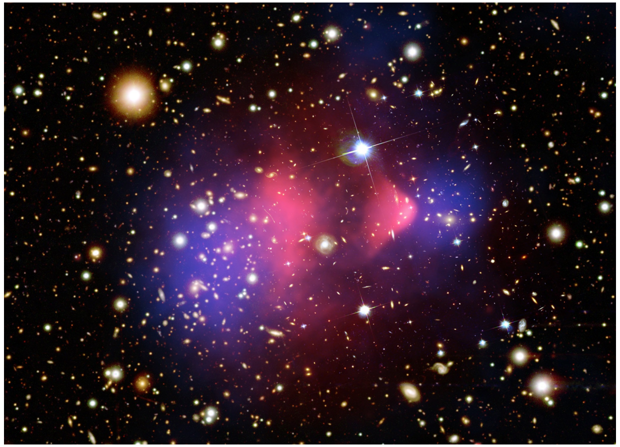
- Describes 3 of the 4 known forces of nature at a quantum level
- Quarks
  - Exist in protons and neutrons and other bound states
  - Interact with all three forces
- Leptons
  - Charged leptons experience weak and EM force, neutrinos only weak
- Gauge Bosons
  - Force carriers
- Higgs
  - Source of mass for all elementary particles

- **One of the most successful scientific theories of all time!**



Beyond the Standard Model

- Standard Model leaves many questions unanswered:
  - Dark Matter?
  - Why is the Higgs mass so small?
  - Why matter and not anti-matter?
  - And others...

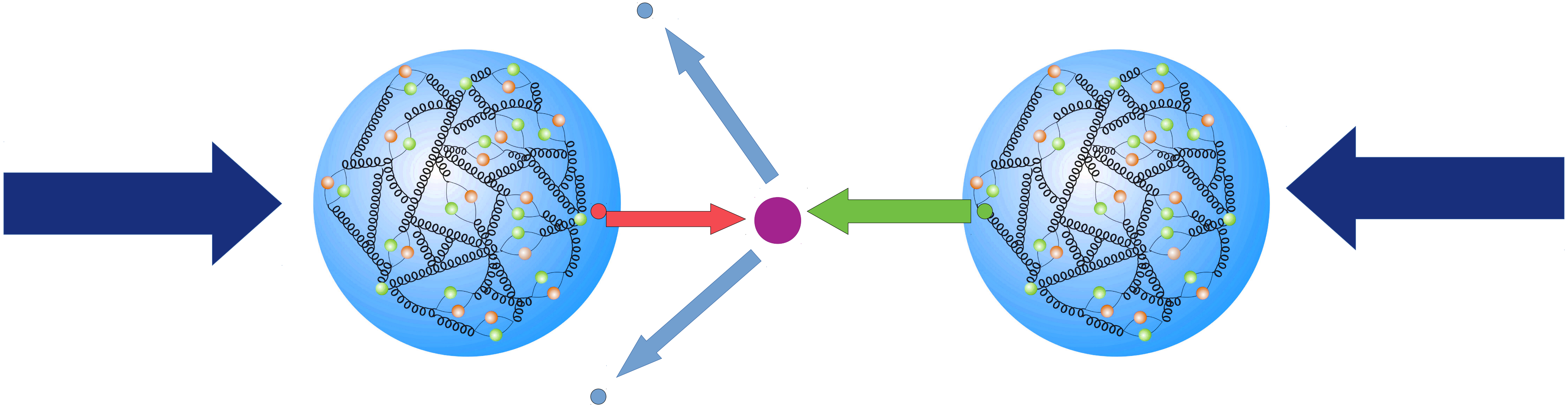


The Large Hadron Collider

- Use high energy collisions to look for new particles that would answer these questions

- 26 km long tunnel to accelerate protons, 150m underground
- Collides protons at 13 TeV center of mass energy
- 4 major experiments at interaction points

Proton Collisions: $E = MC^2$

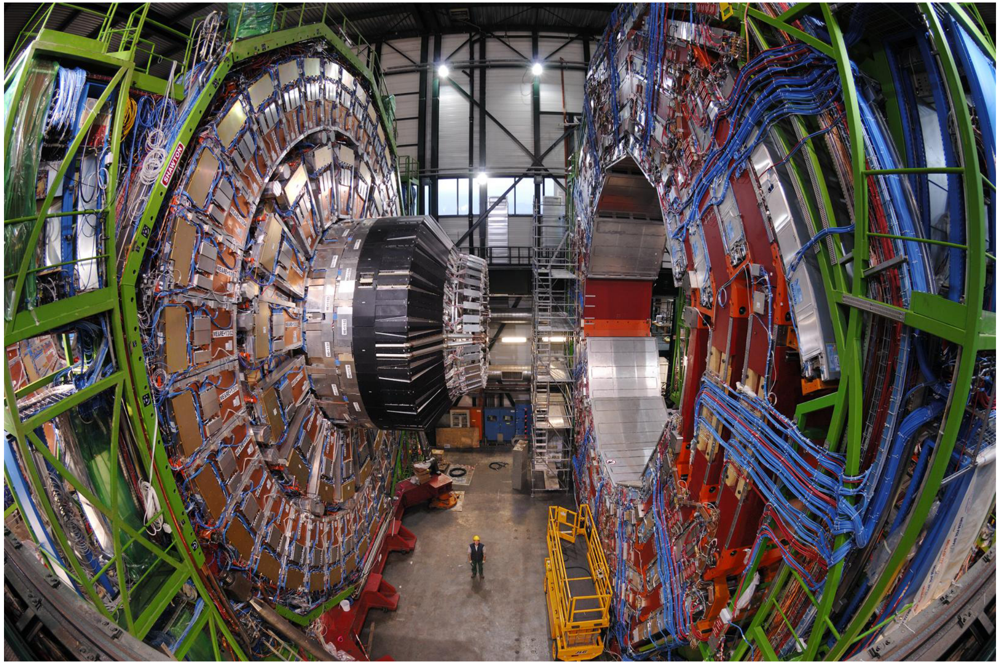


Proton Beams → **‘Partons’ collide** → **New Particle** → **Decay Products**

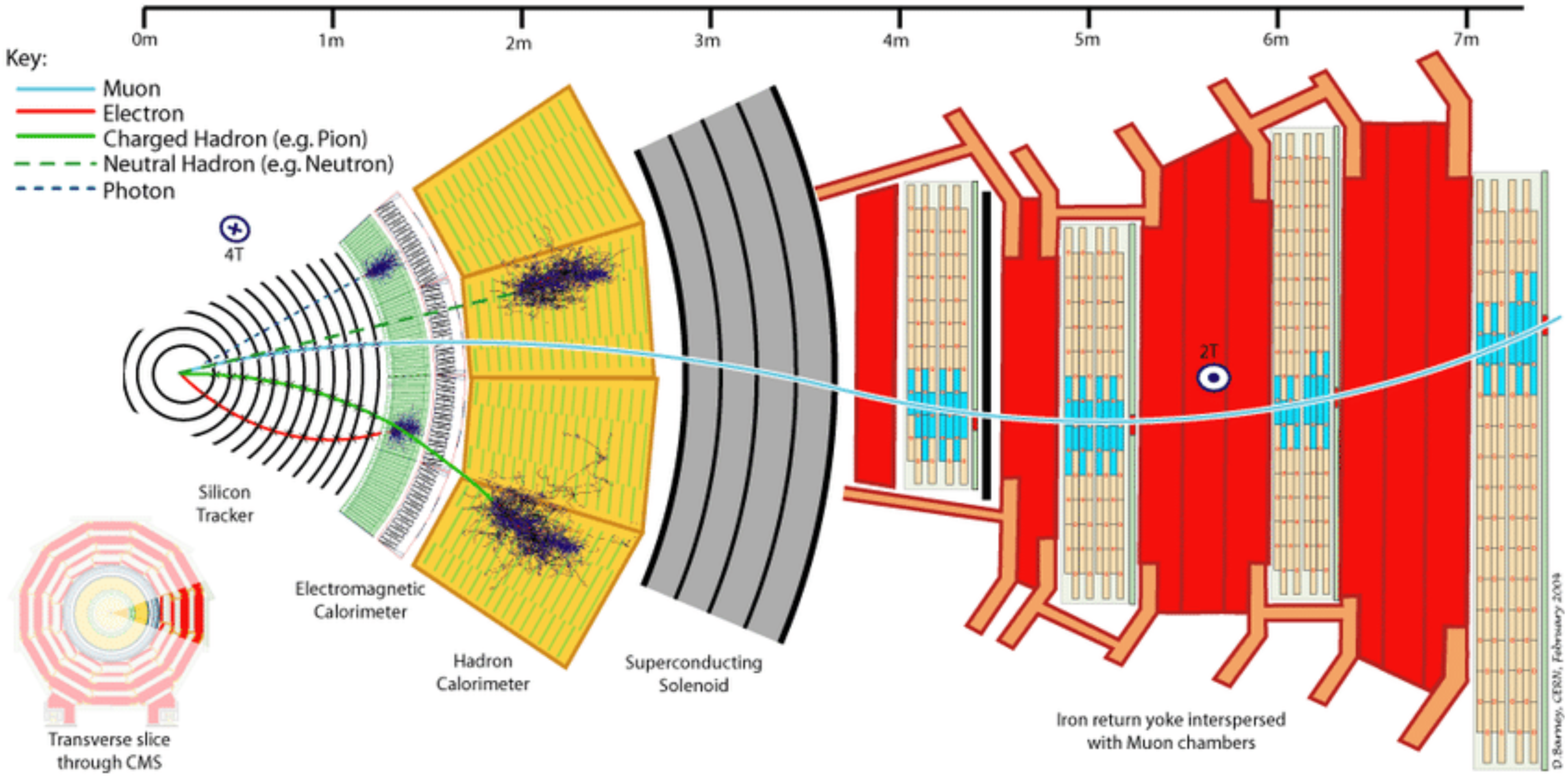
CMS: Compact Muon Solenoid

- 15m tall and 14,000 ton particle detector

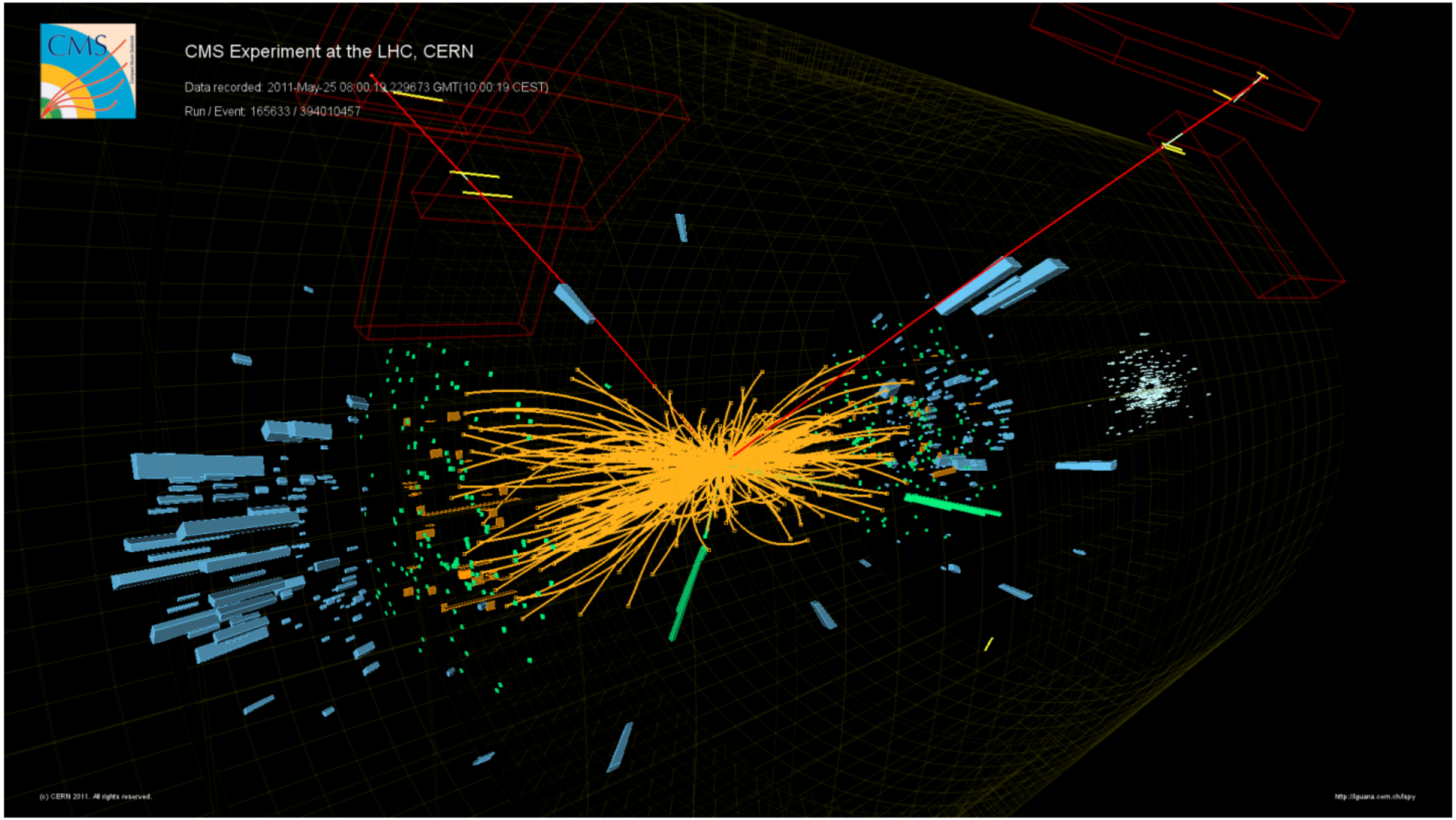
- 3,000 person international collaboration



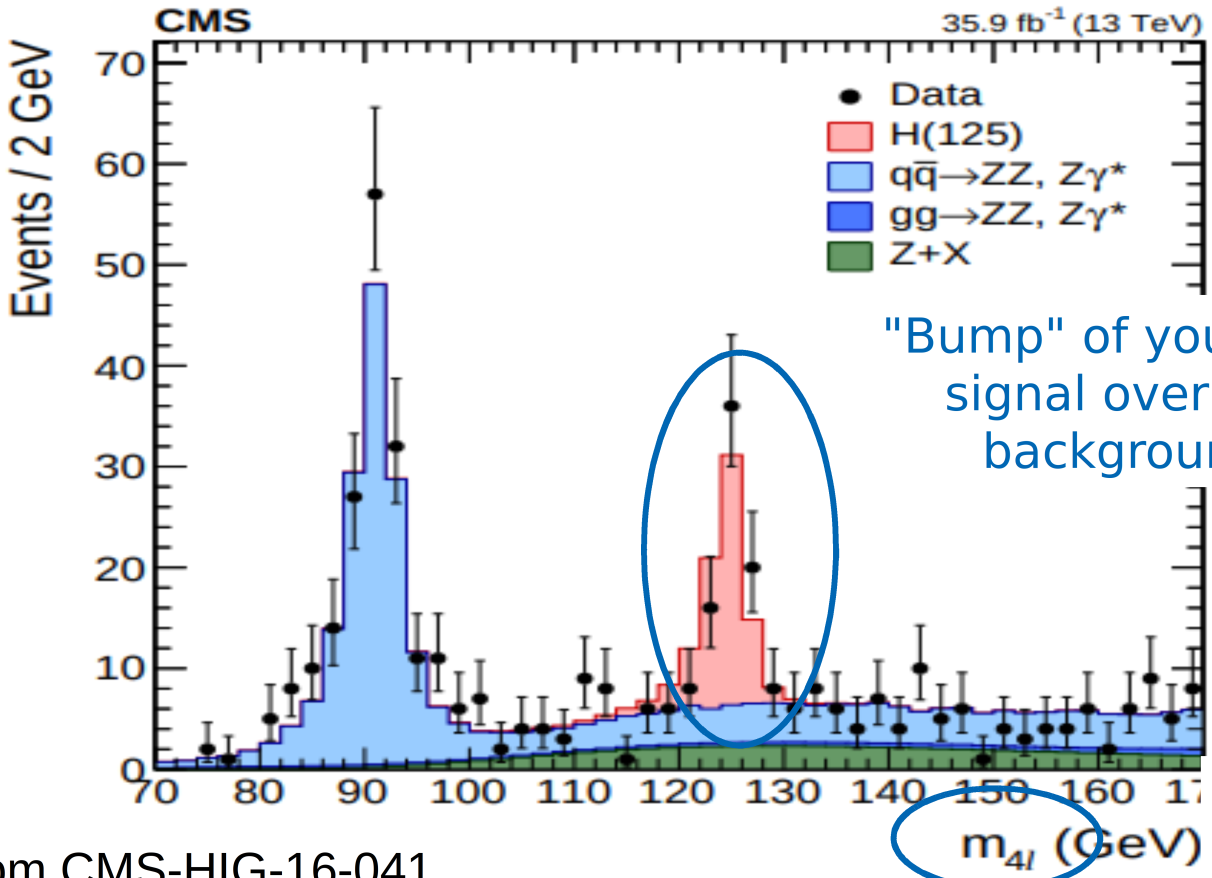
Particle Detection in CMS



Collisions


CMS Experiment at the LHC, CERN
Data recorded: 2011-May-25 08:00:19.229673 GMT(10:00:19 CEST)
Run / Event: 165633 / 394010457
(c) CERN 2011. All rights reserved.
http://iguana.cern.ch/ispy

The Traditional ‘Bump Hunt’ Search



"Bump" of your new signal over the background

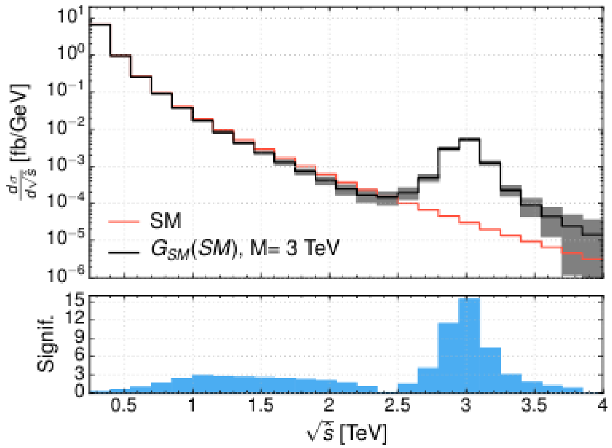
$$mc^2 = \sqrt{E^2 - p^2c^2}$$

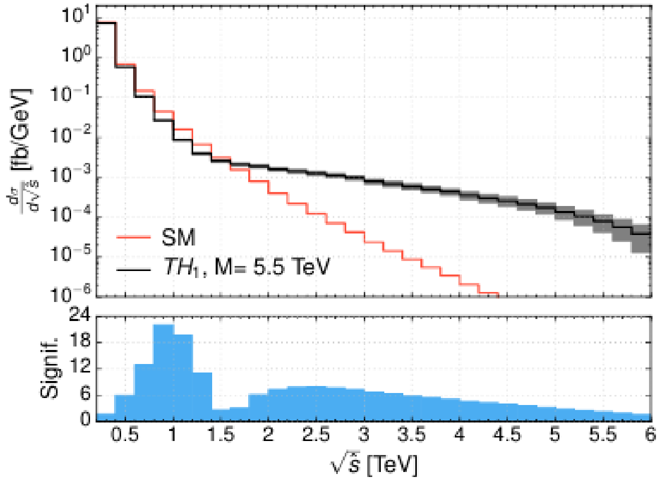
Invariant mass of final State Particles

Plot from CMS-HIG-16-041

Limitations of the Bump Hunt

- What if your bump gets very wide?





- Or you don't have enough energy?

Plots from arxiv:1503.02672v1

Indirect Searches

- Deviations from any Standard Model predictions would be evidence of new physics

- Precision measurements of the Standard Model:
  - Muon magnetic moment
    - Currently ~3 σ deviation
  - Decay rate of a particle
    - Currently a ~4 σ deviation across multiple experiments of B-meson decays

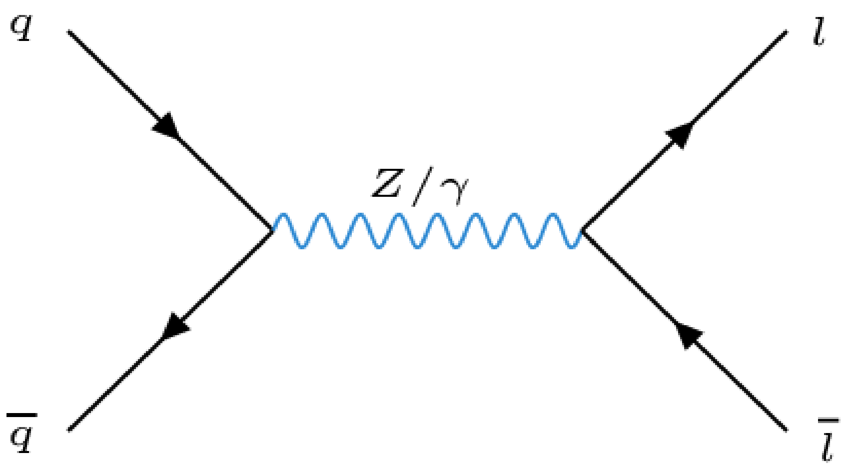
- <u>Asymmetries in the angular distribution of particles (my analysis)</u>

The Drell-Yan Process

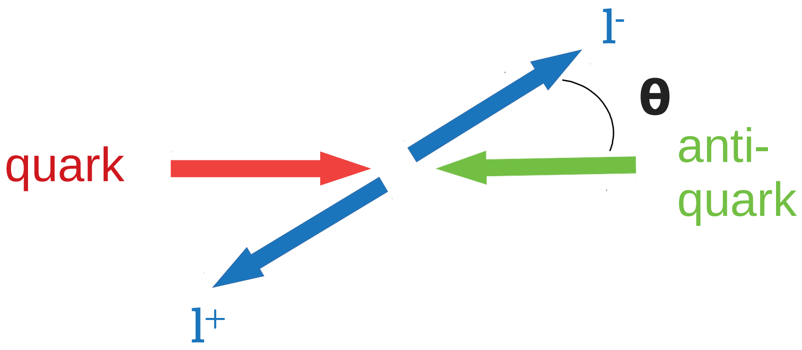
- Very well studied

- Final state leptons are easy to reconstruct with great precision

- Sensitive to interference from new force carriers



The Forward-Backward Asymmetry



Measure the angle between final state **lepton** and initial **quark**

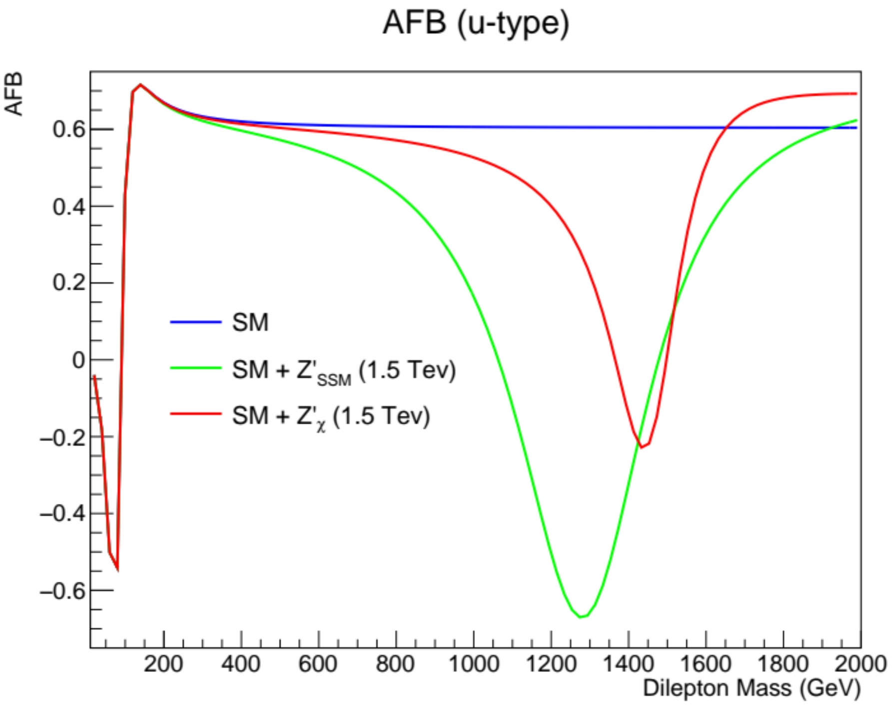
N_F= number of events with cos(θ) > 0
N_B = number of events with cos(θ) < 0

$$A_{FB} = \frac{N_F - N_B}{N_F + N_B}$$

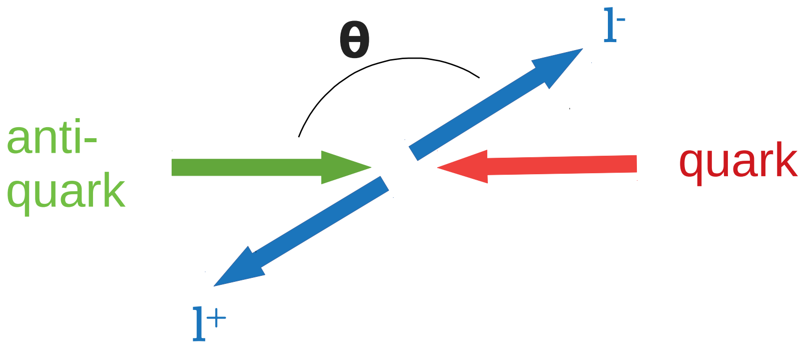
Sensitivity to New Force Carriers

- SM value of AFB becomes roughly constant (0.6) at high mass

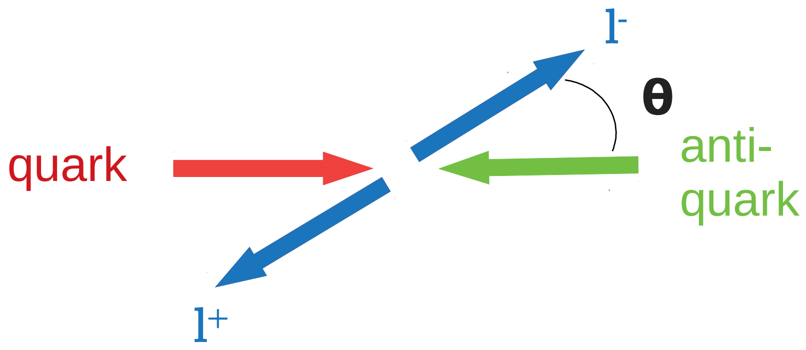
- New force carriers could produce interference effects



Challenge of measuring this at the LHC: What is the direction of the initial quark?

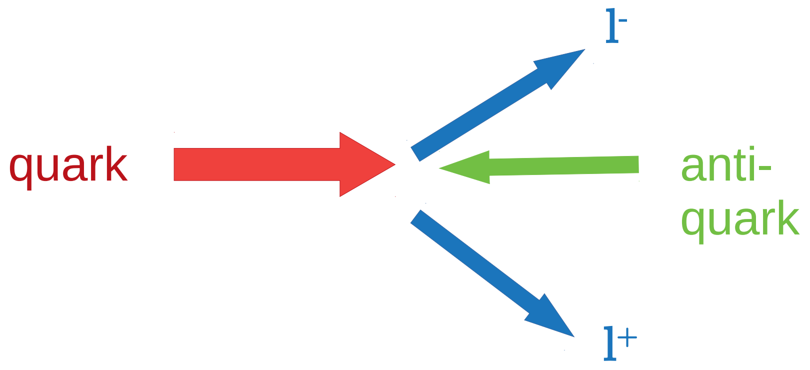


OR



We can use our knowledge of proton structure to make an educated guess

Guessing the Quark Direction



- **Anti-quarks** must come from the 'sea', **quarks** can be valence
- On average the **quark** will carry more momentum than the **anti-quark**
- We guess that final direction of the **lepton pair** is the direction of the initial **quark**
- The higher the lepton pair momentum (boost), the more likely the guess is correct
- Incorrect guesses will dilute the true asymmetry

Extracting AFB

$c_* = \text{Cos}(\theta)$

- Our approach is to fit for the **anti-symmetric** part of the angular distribution

$$f_{parton}(c_*) \approx K \left(\underline{f_s(c_*^2)} + \underline{A_{FB}\, c_*} \right)$$

- Observed distribution is convolution of cross section and detector resolution + efficiency
- Linearity of **c_* odd term (AFB)** is undisturbed
- Construct 2D templates of **symmetrized** and **anti-symmetrized** Monte Carlo events binned in c_* and x_F (measures boost of the event)
- Fit data to MC and background templates to extract **AFB** in different mass bins
- Fully utilizes each event’s information and automatically accounts for dilution and detector effects!

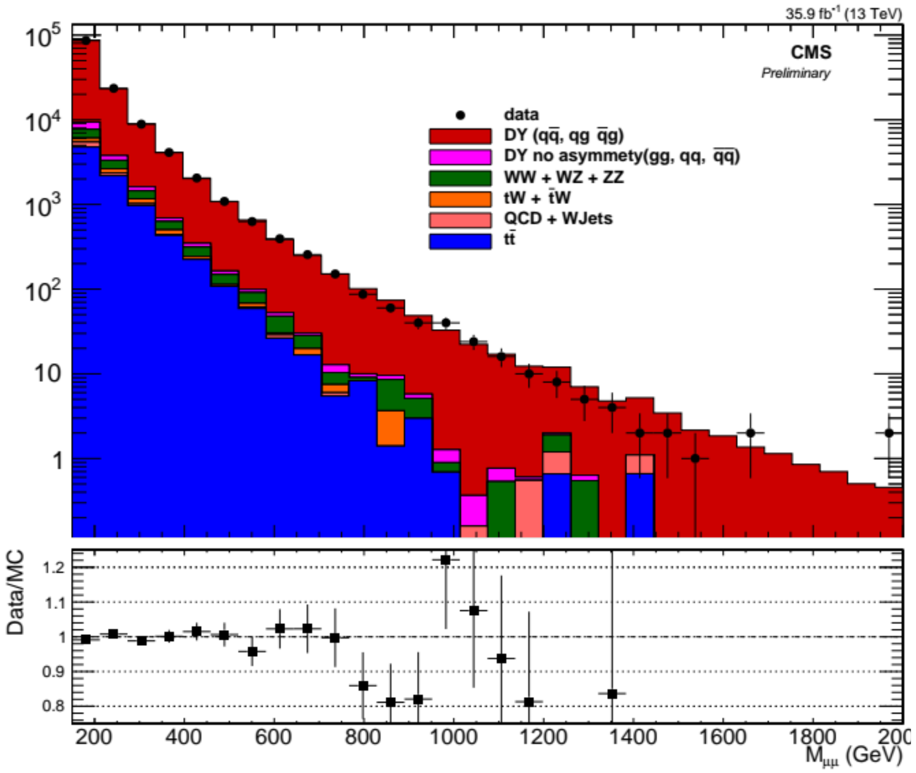
Event Selection

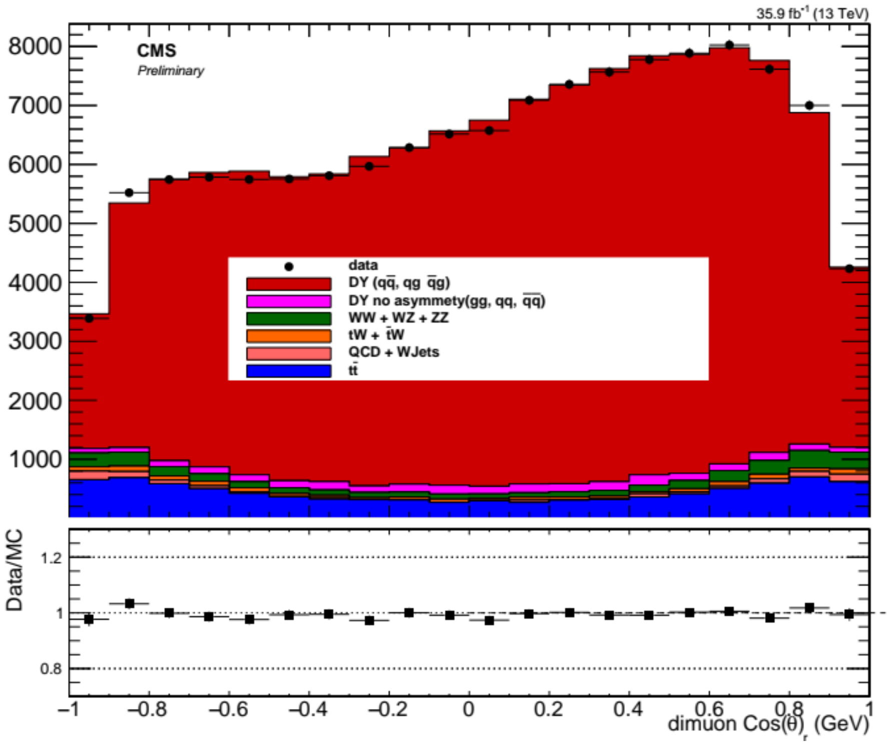
- One high momentum lepton to set off the trigger
- Two leptons of same type and opposite charge passing CMS identification criteria
- Isolated from other particles in the same event
  - Reduce leptons from hadronic decays
- Low ‘missing transverse energy’ (from neutrinos) and no objects that look like b-quarks
  - reduce backgrounds from top quark decays

Backgrounds

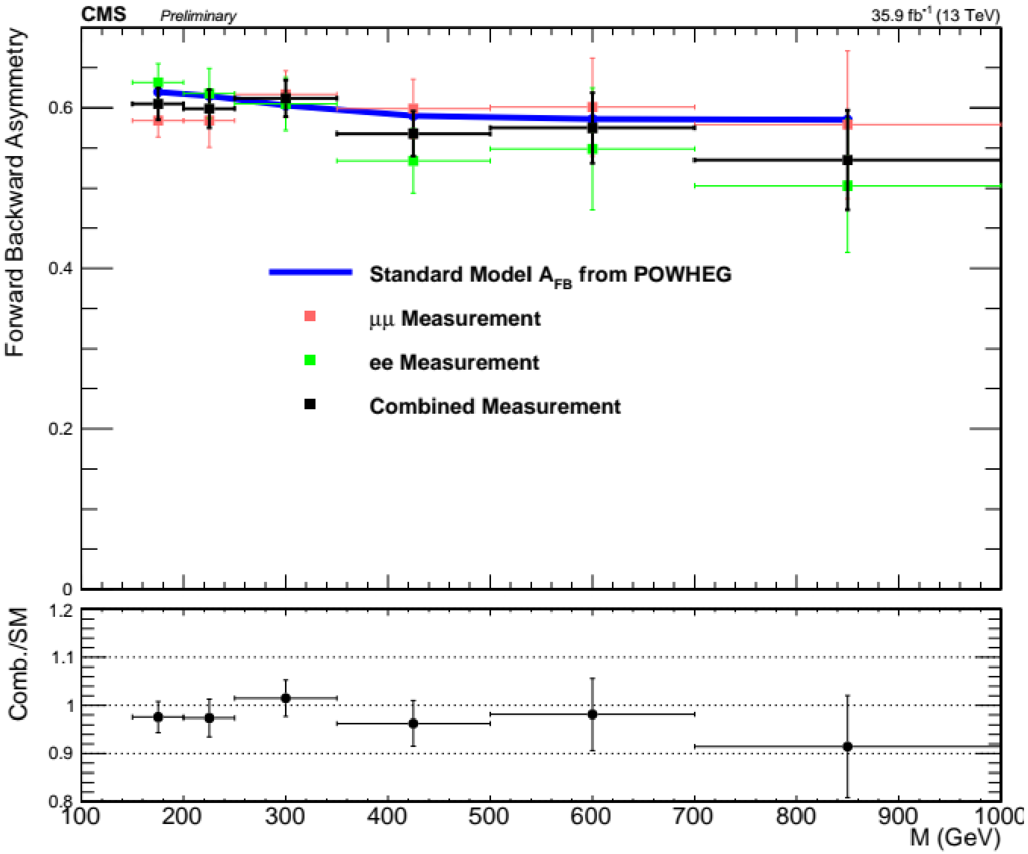
- Backgrounds from decaying top quarks and dibosons also produce electron + muon events
- Normalize our MC to data measurements of these events
- Hadronic backgrounds are estimated using a data-driven fakerate method
  - Use leptons failing isolation and measured rate of leptons from hadronic decays passing isolation requirements

Data vs. Signal + Background





Results: Good Agreement With SM



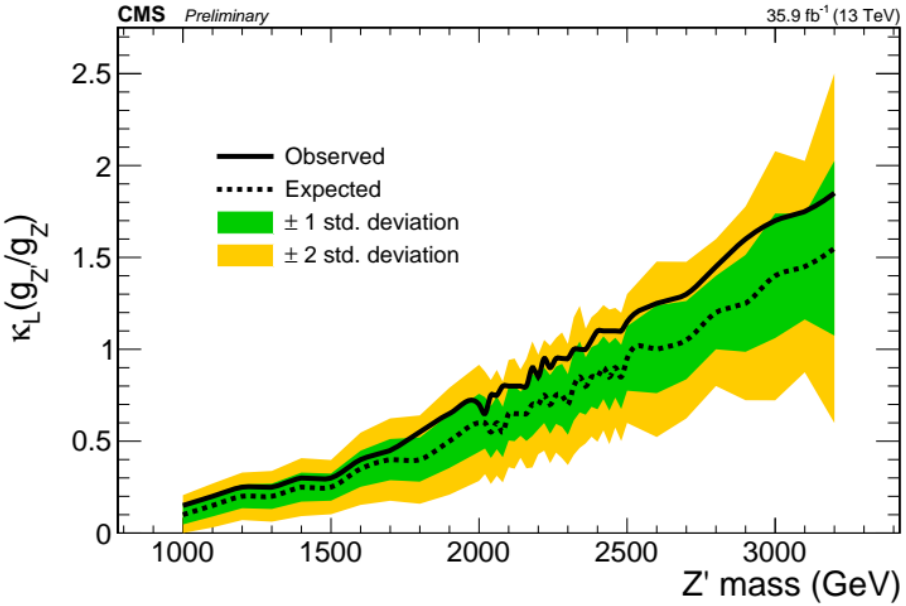
Slight downward fluctuation in last mass bin

Limits on Z’ Models

- Set limits on existence of heavier version of SM Z

- For exactly the SM couplings
  - $M_{Z'}$ > 2.3 TeV

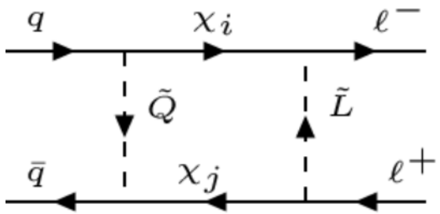
- We expect to get better limits on other models
  - Better for models with negative AFB on peak
  - Insensitive to width of Z’



Limits all ~1 sigma up due to downward fluctuation in last mass bin

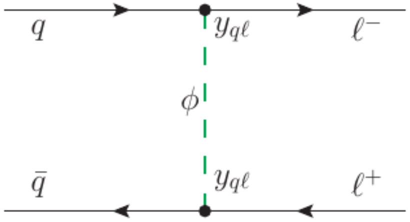
Constraints on Other Types of Particles

- Dark matter



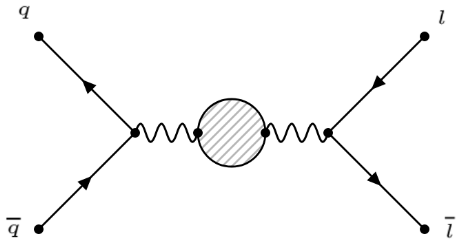
from arxiv:1709.00439

- Leptoquarks



from arxiv:1610.03795

- Additional (vector-like) fermions



arxiv:1602.03877

Conclusions

- We have measured AFB at high energy with better precision than ever before
- We set constraints on the existence of new gauge bosons using our measurements
  - Working on other Z’ models and possibly leptoquarks as well
- We hope to go through the CMS review process and publish our results soon

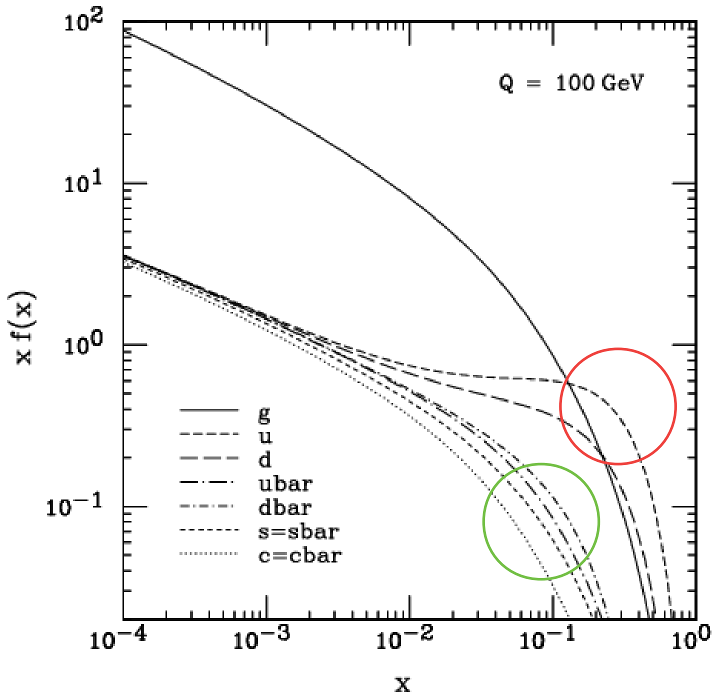
Backup Slides

CMS Detector

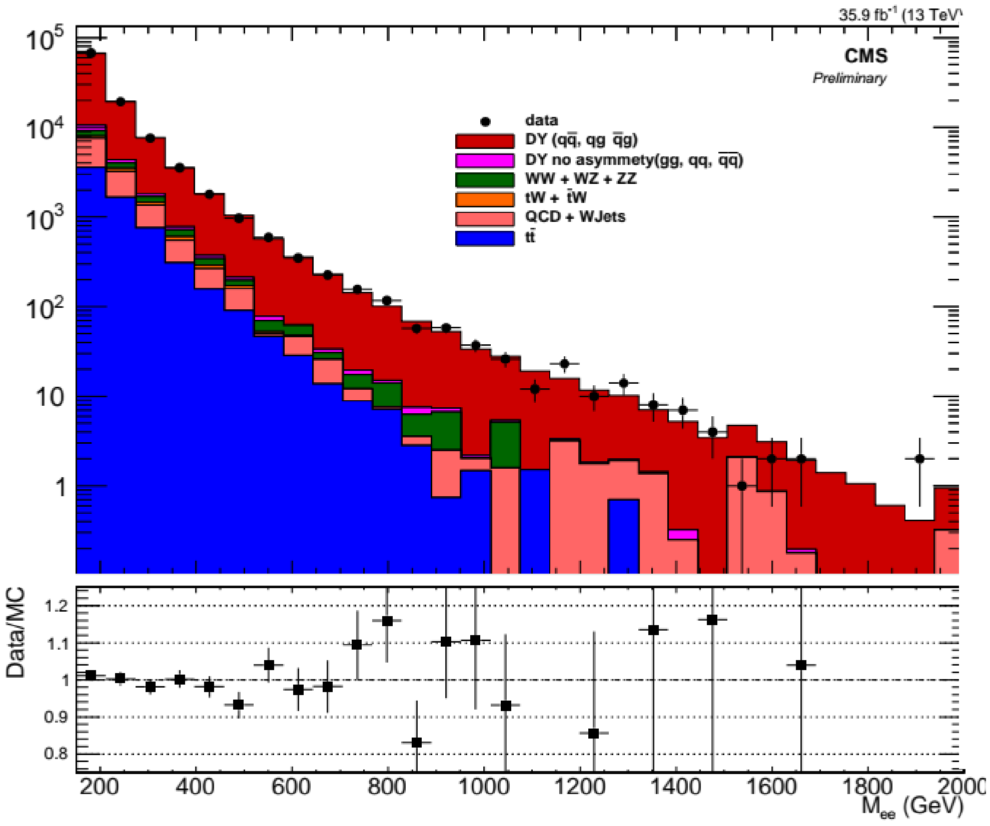
- Tracker
  - 4 layers of silicon ‘pixels’
  - 10 layers of silicon strips
- ECAL
  - Lead tungstate crystals and avalanche photodiodes
- HCAL
  - Alternating layers of brass and scintillators
- Magnet
  - 3.8 T, bends tracks of particles
- Muon system
  - Drift tubes (barrel), cathode strip chambers (endcap) and resistive plate chambers

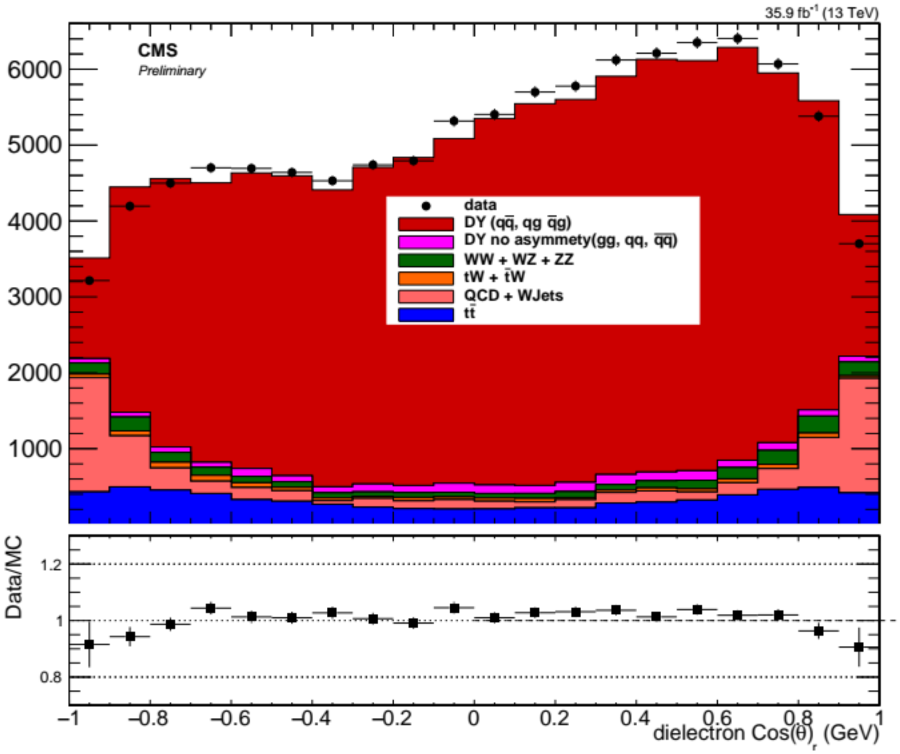
Protons Structure

- The naive picture is that protons are made of two up quarks and a down quark
- Up Up Down (valence) quarks are there, but so are gluons, anti-up, anti-down, strange, … (sea)
- We can't compute what's going on so we have to measure it
  - Parton Distribution Functions
- On average, valence quarks carry more momentum than sea quarks

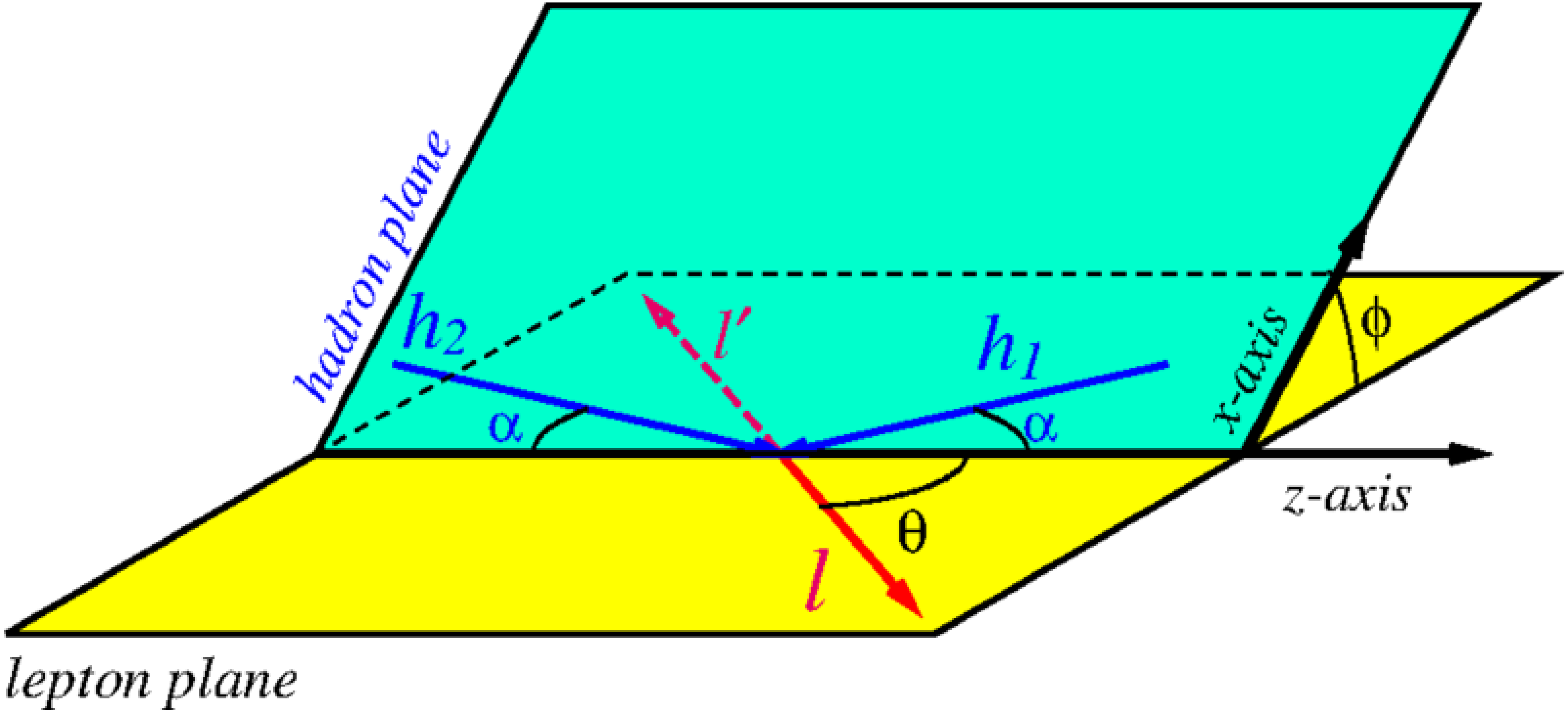


Electrons Distributions





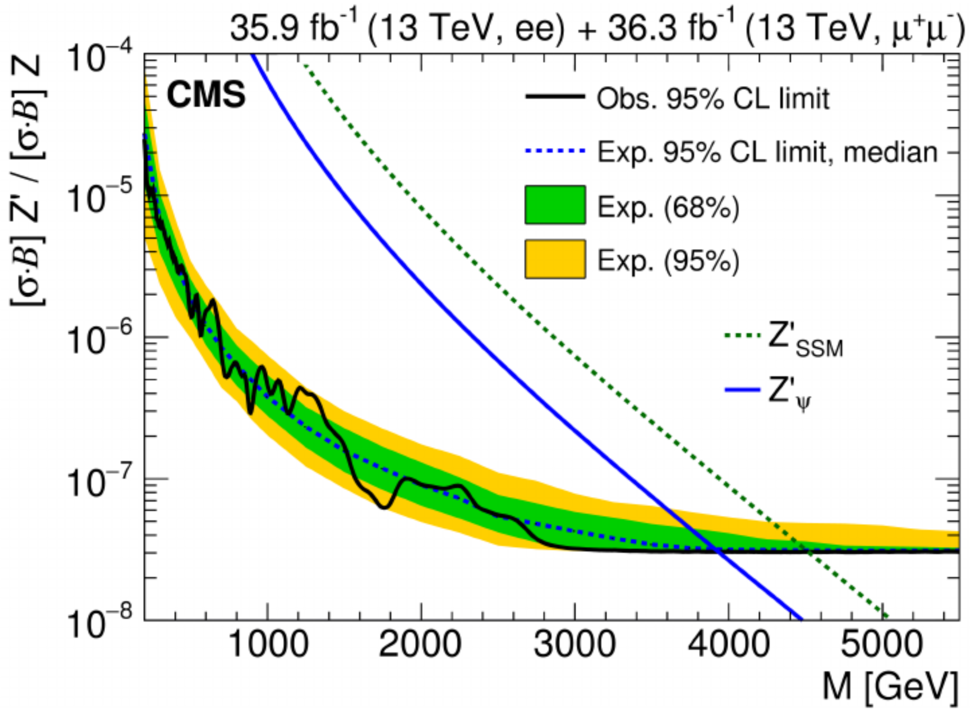
The Colins-Soper Frame

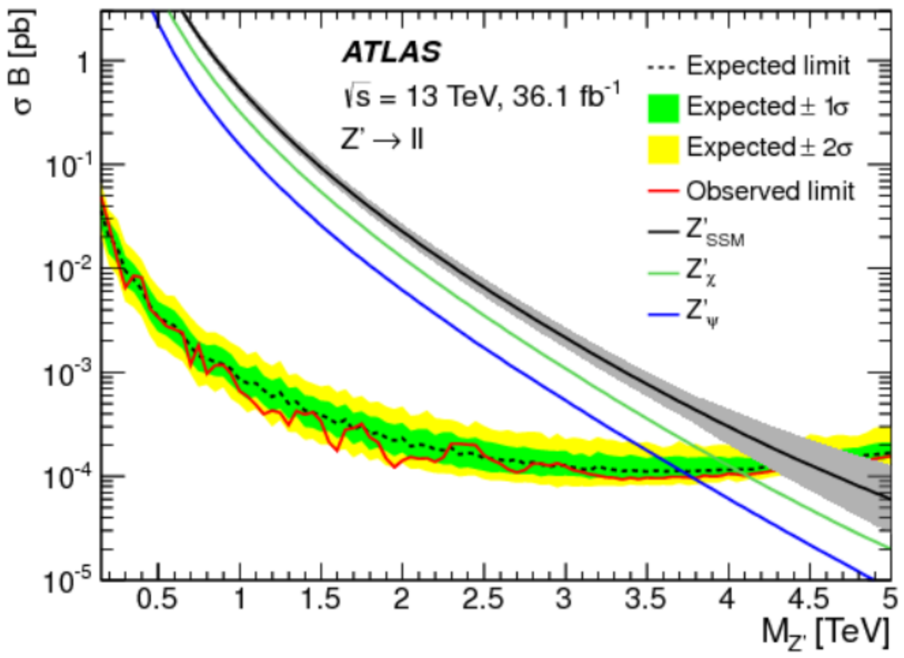


Event Selection

- Trigger: HLT_IsoMu24 OR HLT_IsoTkMu24
- Kinematics:
  - Leading muon (electron) $P_t > 26$ GeV (29 GeV), subleading muon $P_t > 10$ GeV, $|\eta| < 2.4$, opposite charge
- ID's:
  - HighPt Muon ID and tracker based loose isolation
  - Medium ID electrons
- tt background rejection: MET < 50 GeV and anti-b-tag (CMVAv2) on highest two P_t jets

Direct Z' Searches





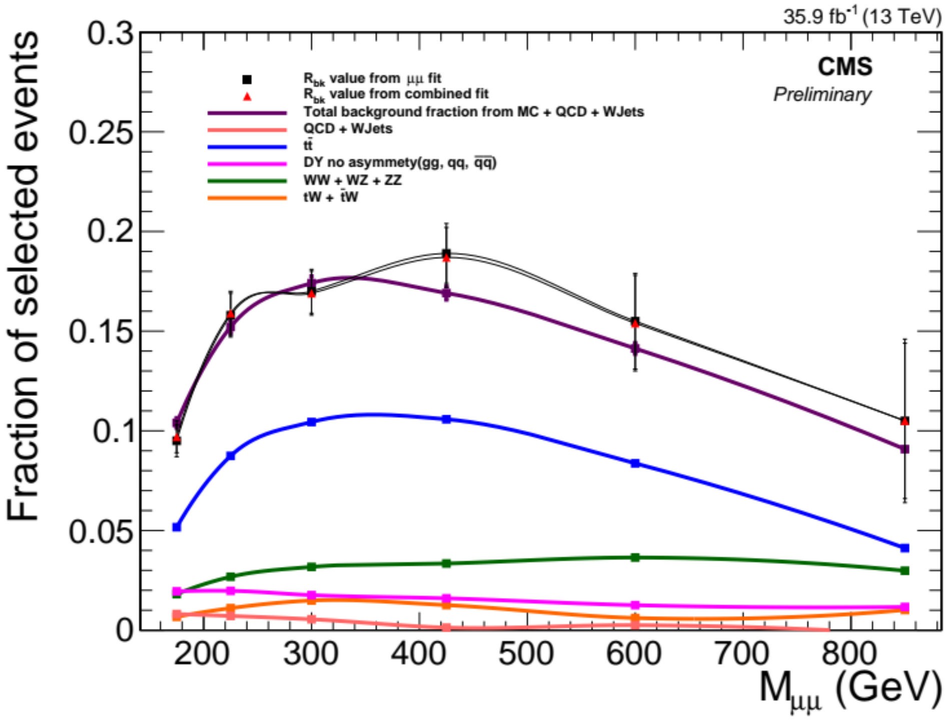
From CMS-EXO-16-047 and JHEP10(2017) 182 respectively

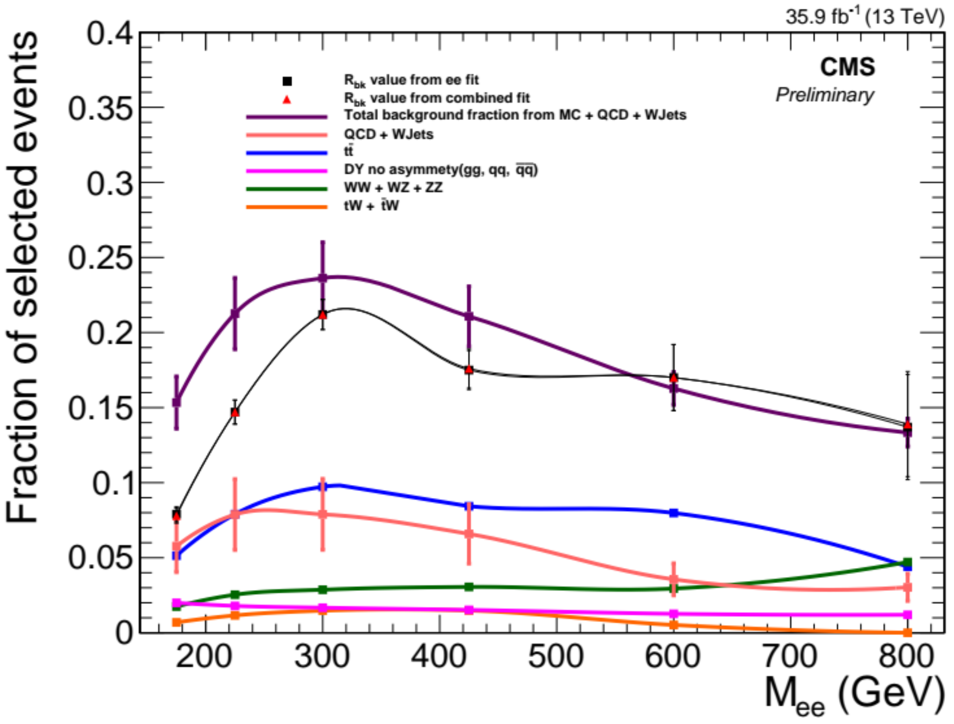
Full Differential Cross Section

$c_* = \mathrm{Cos}(\theta)$

$$\frac{d\sigma}{dc_*}(q\bar{q}; M^2) = \frac{\pi\alpha(M^2)^2}{2M^2} K(M^2) \left\{ \underline{1 + c_*^2 + \alpha(M^2)\left(1 - c_*^2\right)} + \frac{4}{3}\left[2 + \alpha\right] \underline{A_{\mathrm{FB}}(M^2) c_*} \right\}$$

Backgrounds From Fit Crosscheck





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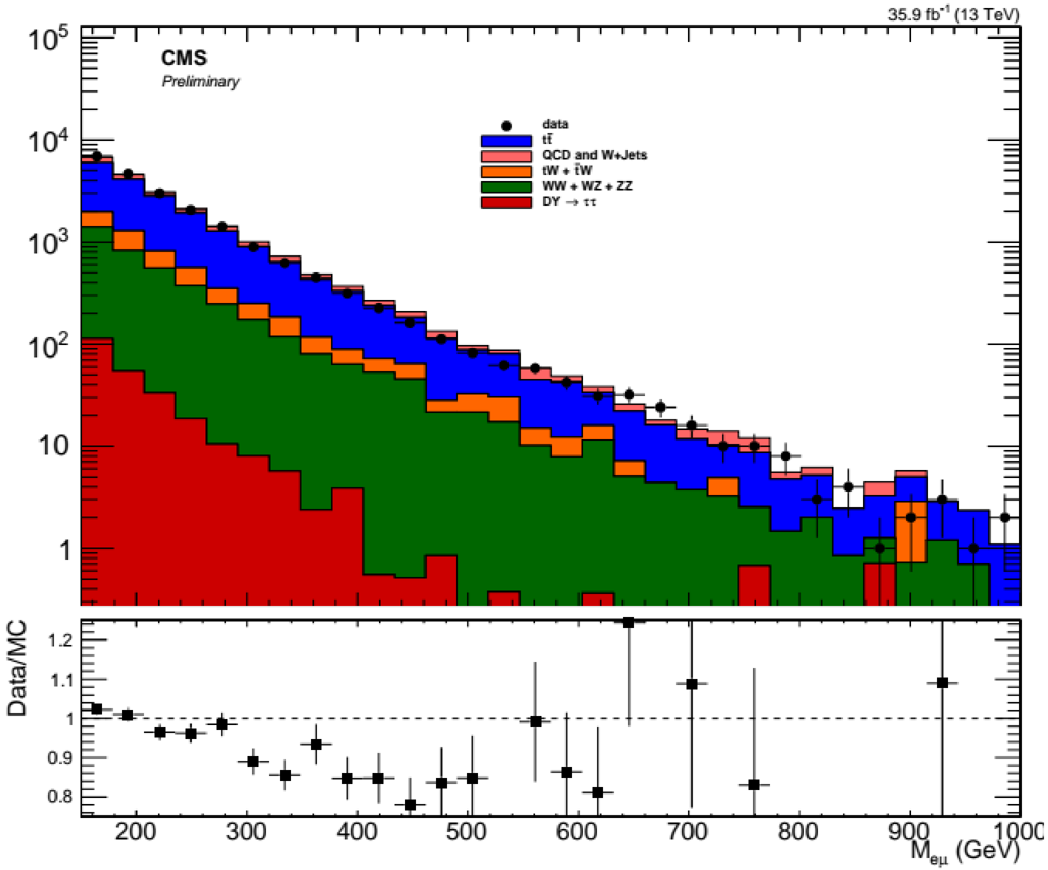

35.9 fb^{-1} (13 TeV)
CMS
Preliminary
data
$t\bar{t}$
QCD and W+Jets
tW + $\bar{t}$W
WW + WZ + ZZ
DY → ττ
10^5
10^4
10^3
10^2
10
1
Data/MC
1.2
1.1
1
0.9
0.8
200
300
400
500
600
700
800
900
1000
$M_{e\mu}$ (GeV)

Systematics

Source of Systematic Error	Maximal Bin	Maxmimum Value	Fraction of total unc.
pdf's	150-200	0.0012	0.39
Fakerate Estimates	150-200	0.006	0.09
Template Binning	$\geq$700	0.016	0.06
Lepton SFs	200-250	0.005	0.05
Renormalization and Factorization Scales	150-200	0.004	0.04
Pileup	150-200	0.004	0.04
Z polarization (α)	250-350	0.001	0.001
$e\mu$ scaling	250-350	0.01	0.001
Btagging	150-200	< 0.0005	< 0.001

Muon momentum corrections and electron scale corrections uncertainties to be added