Physics Using Drell-Yan Events @ CMS

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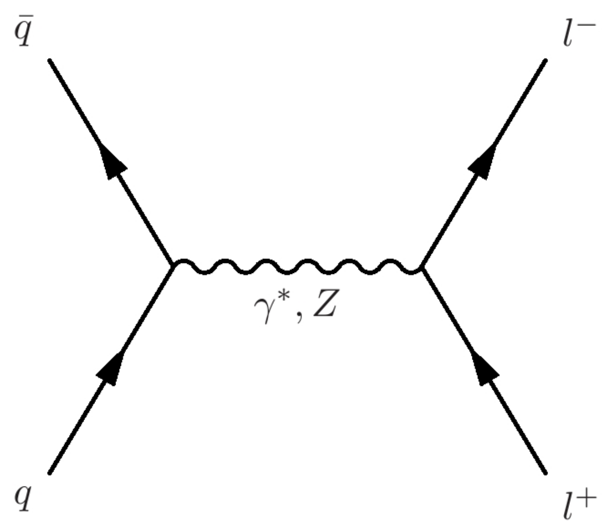
Outline

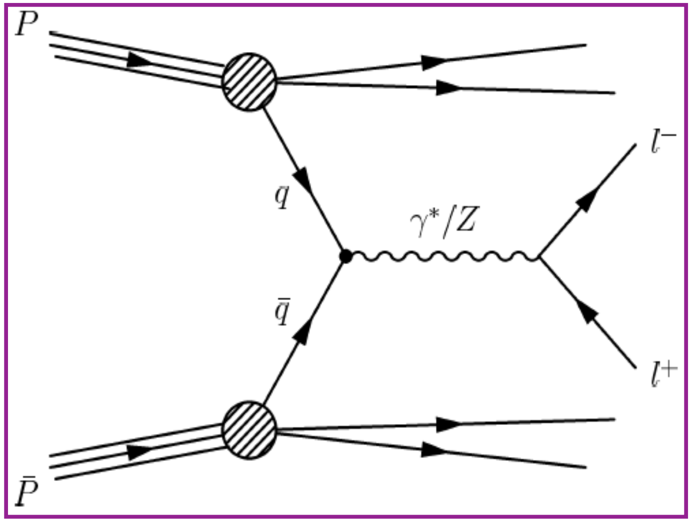
- **Drell-Yan cross section with muons**
  - Analysis Strategy and Procedure
  - Backgrounds
    - Comparisons with Simulation
    - Data based estimations
  - Acceptance and Efficiencies
  - Unfolding
  - Systematic Uncertainties
  - Results (+ combination with electron channel) and comparison to theory
- **Study of Final State Radiation in the Drell-Yan muon channel**
  - Event Selection
  - Generator level studies
  - Data/MC comparisons
  - $M_{\mu\mu\gamma}$
- **Multiple Parton Interactions in DY events**
  - Analysis strategy
  - Results and Prospects



Drell-Yan Differential Cross Section (dσ/dm)

Details of Measurement

The Drell-Yan Process:



- Analysis of entire 2010 data sample
  - $35.9 \pm 1.4\ pb^{-1}$
- Signal simulated using POWHEG + Pythia6
  - CT10 PDF
  - Z2 Tune
- Analysis performed for both muon and electron final state
  - Measurement completed and Final Reading today

- Our measurement is the differential cross-section: **$1/\sigma_Z\ (d\sigma/dm)$**

- We measure the normalized cross section per bin (R)
  - normalization to the cross-section in the Z peak region cancels some systematics (such as that on the Luminosity measurement)

Analysis

$$R_i = \frac{N_i^u}{A_i \cdot \varepsilon_i \cdot C_i} / \frac{N_{norm}^u}{A_{norm} \cdot \varepsilon_{norm} \cdot C_{norm}}$$

i: mass bin

N^u: background subtracted, unfolded yield

A: acceptance

ε: efficiency

C: Correction for efficiency, FSR

L_{int}: integrated luminosity

We take advantage of the CMS detector's capabilities to measure very low mass DY

Mass binning (GeV)

15 - 20
20 - 30
30 - 40
40 - 50
50 - 60
60 - 76
76 - 86
86 - 96
96 - 106
106 - 120
120 - 150
150 600

Analysis Strategy:

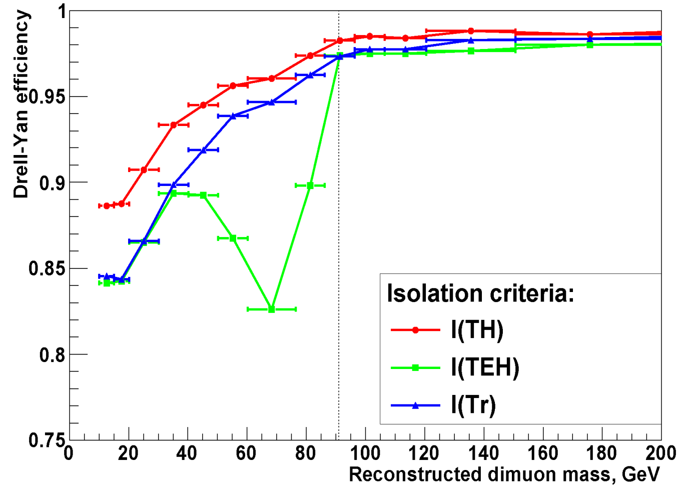
1. Select Events
2. Subtract Background
3. Unfold
4. Correct for Efficiencies and Acceptance
5. Correct for Final State Radiation effects
6. Normalize to the Z peak
7. Combine electron and muon results and compare to theoretical predictions

Event Selection

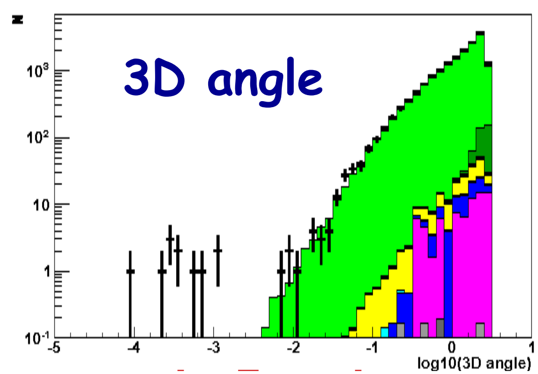
- Trigger Selection
  - Event must trigger a single muon HLT path
  - Analysis also performed with Double muon HLT trigger
- Kinematic Selection
  - 2 muons with opposite charge
  - 1 muon $p_T > 16$ GeV, $|\eta| < 2.1$
  - 1 muon $pT > 7$ GeV, $|\eta| < 2.4$
- Muon Identification
  - Both muons reconstructed as "Tracker Muons" (inside-out) and "Global Muons" (outside-in)
  - Minimum number of hits in Tracker/Pixel detector
  - Minimum number matched muon system hits
  - Global track fit must have $\chi^2/ndf < 10$
  - Di-muon vertex probability requirement
- Isolation
  - Relative Isolation not including ECAL

$$I_{rel} = (\sum p_T(tracks) + \sum E_T(HCAL)) / p_T(\mu) < 0.15$$

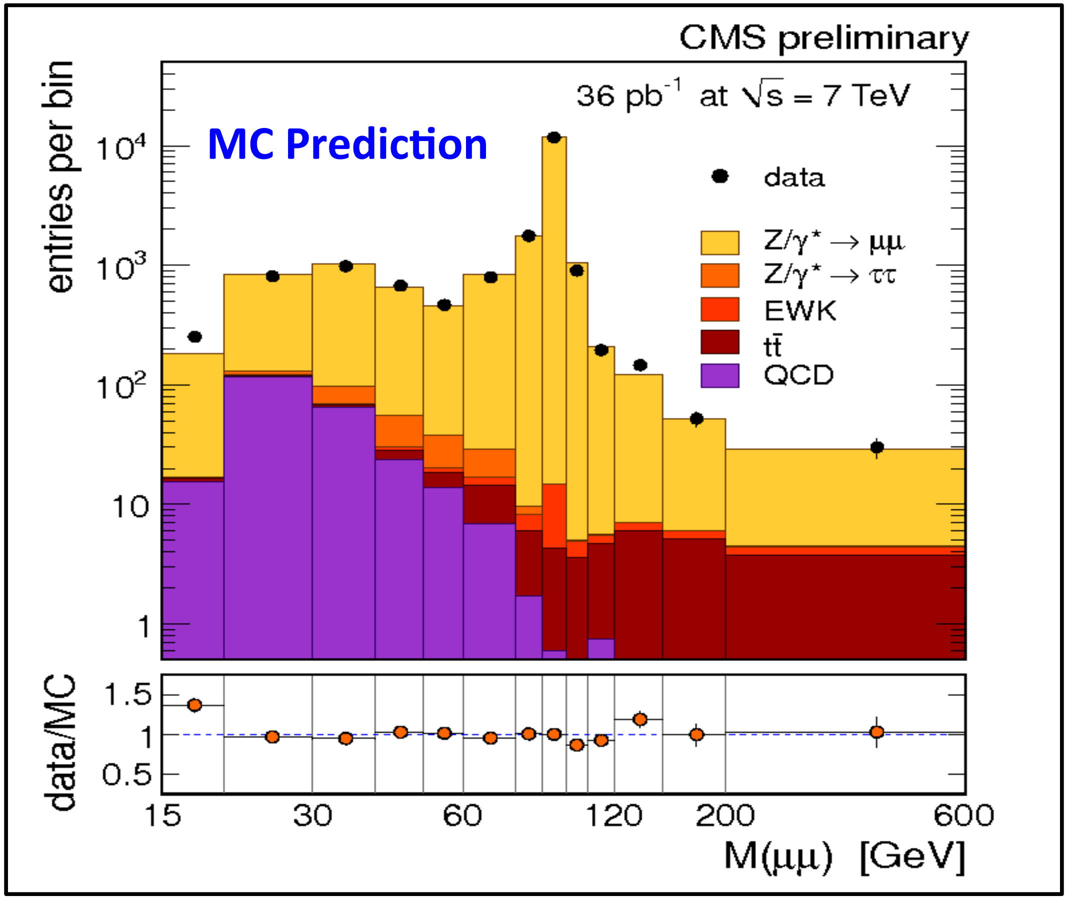
- Cosmic Ray Rejection
  - Track transverse impact parameter < 0.2 cm
  - 3D angle > 5 mrad (back-to-back rejection)



Electromagnetic Calorimeter not included in isolation requirement due to loss in efficiency below Z peak caused by Final State Radiation



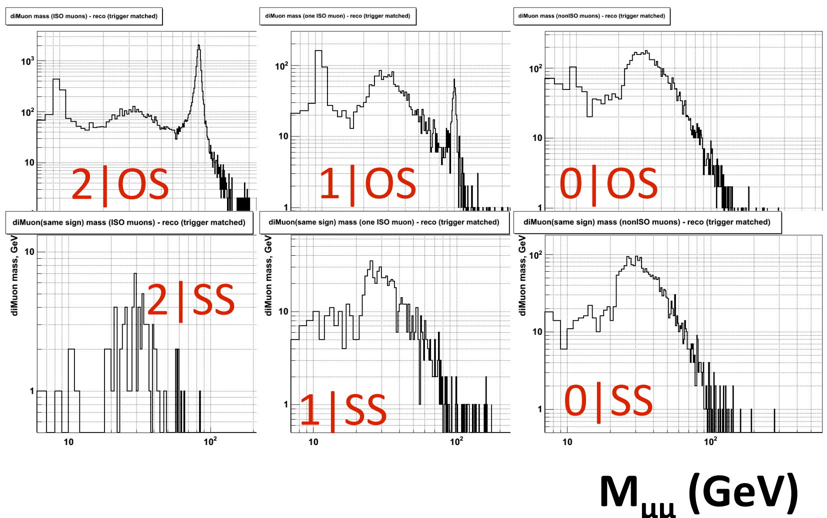
Background Estimations Techniques



- Muons:
  - QCD backgrounds estimated with data (OS/SS and template method)
  - All other backgrounds estimated from Simulation

- **QCD**
  - "punch through" or muons from heavy flavor decays
  - Dominant background in the low mass region
- **Top pair production**
  - Dominant background at high mass
- **Drell-Yan -> $\tau^+\tau^-$**
  - Dominant in "mid-range" masses
- **W -> lepton + neutrino + jet(s)**
- **Di-Boson production**
  - Small production cross section
- **Cosmic Rays**
  - removed by 3D angle and impact parameter cuts

Background Estimation

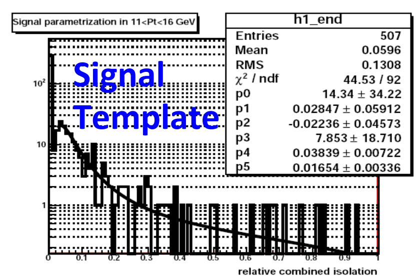


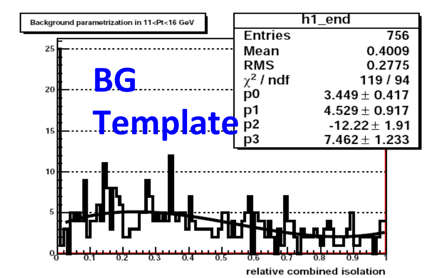
- Template method
  - Isolation variable has distinctive shape for signal and background
  - Create templates for shapes using data
    - Same sign events for background
    - Signal from opposite sign events in the Z peak region with one muon highly isolated (shape taken from second muon)
  - Extract estimate of background contamination in signal region using the fit results

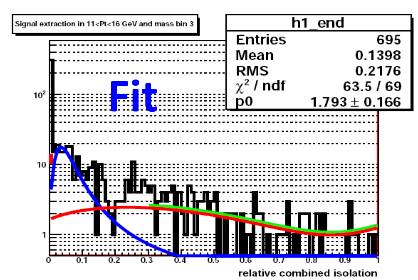
- Opposite Sign (OS) / Same Sign (SS) Method
  - Divide events into samples based on number of isolated muons and whether muons are OS or SS
  - Take ratio of OS/SS events for categories of 0, 1, or 2 isolated muons
  - Estimate background based on these ratios

$$N(2|OS) = N(2|SS)\frac{N(1|OS)}{N(1|SS)}$$

Relative Isolation







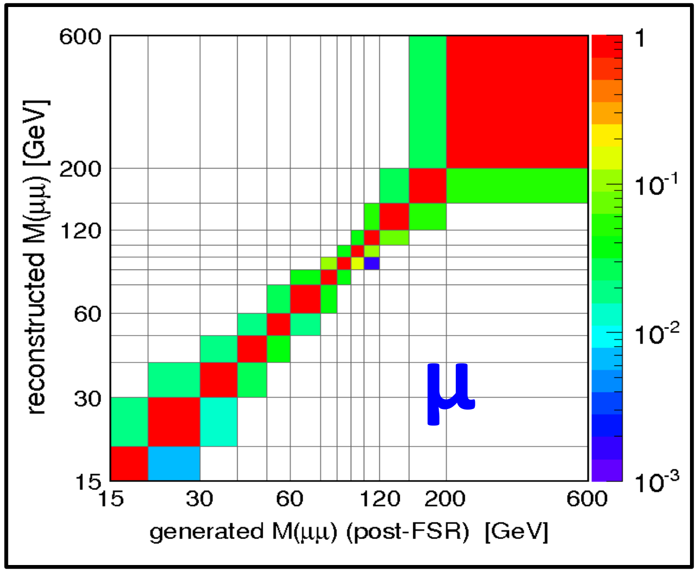
Data entries = 657
Data entries (I<0.15) = 470
Data entries (I<0.30) = 541
BG estimate (function) = 184.8 /ALT: 200.5/
BG estimate (function, I<0.15) = 41.4 /ALT: 44.9/
BG estimate (function, I<0.30) = 78.4 /ALT: 85.0/
Signal estimate (DATA-background) = 472.2
Signal estimate (DATA-background, I<0.15) = 428.6
Signal estimate (DATA-background, I<0.30) = 462.6

Unfolding

- The mass spectrum is corrected for resolution effects by using the response matrix unfolding technique
- The “true” spectrum is obtained by constructing the response matrix T where:

$$N_i^{obs} = \sum_k T_{ik} N_k^{true}$$

  - T_{ik} is the probability that an event belonging in mass bin k is reconstructed in mass bin I
  - T_{ik} is extracted from the Simulation
- By inverting T, the corrected spectrum can be obtained



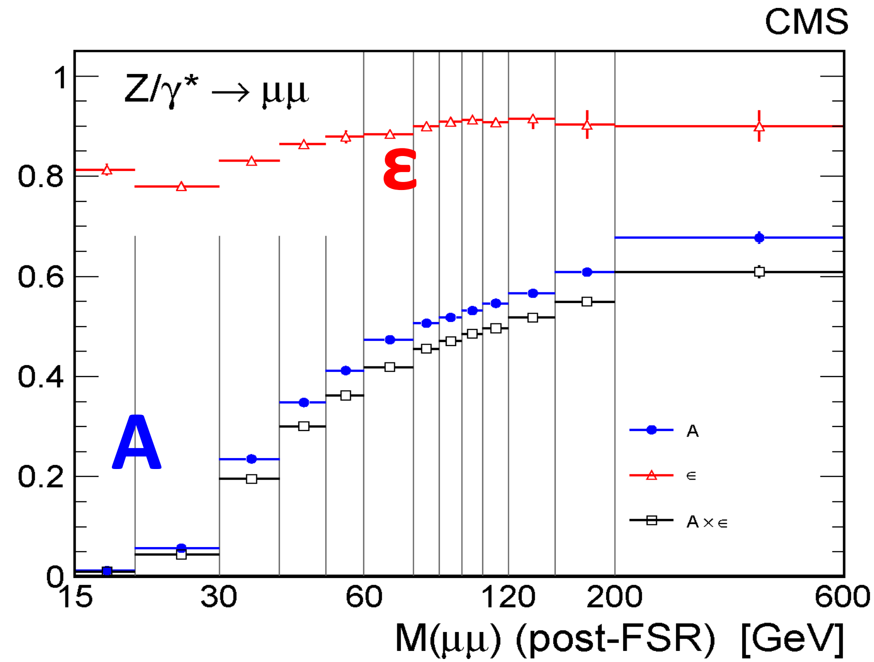
$$N_i^{true} = \sum_k (T_{ik})^{-1} N_k^{obs}$$

Acceptance and Efficiency

- In this definition:
  - Acceptance (A) accounts for p_T and η cuts
  - Efficiency (ε) reflects the full selection (lepton ID, reconstruction, isolation, trigger)
- **Acceptance*efficiency** is derived from the simulation

$$A*\epsilon = \frac{N_{ACC}}{N_{GEN}}\frac{N_{SEL}}{N_{ACC}} = \frac{N_{SEL}}{N_{GEN}} \quad (\leq 1)$$

GEN: generated; initially produced
ACC: accepted; within acceptance
SEL: selected; surviving selection cuts



- Efficiencies for leptons are measured using data driven techniques
  - **MC efficiencies are corrected to match data**
- For calculation of acceptance, we consider simulated leptons ***after*** Final State Radiation

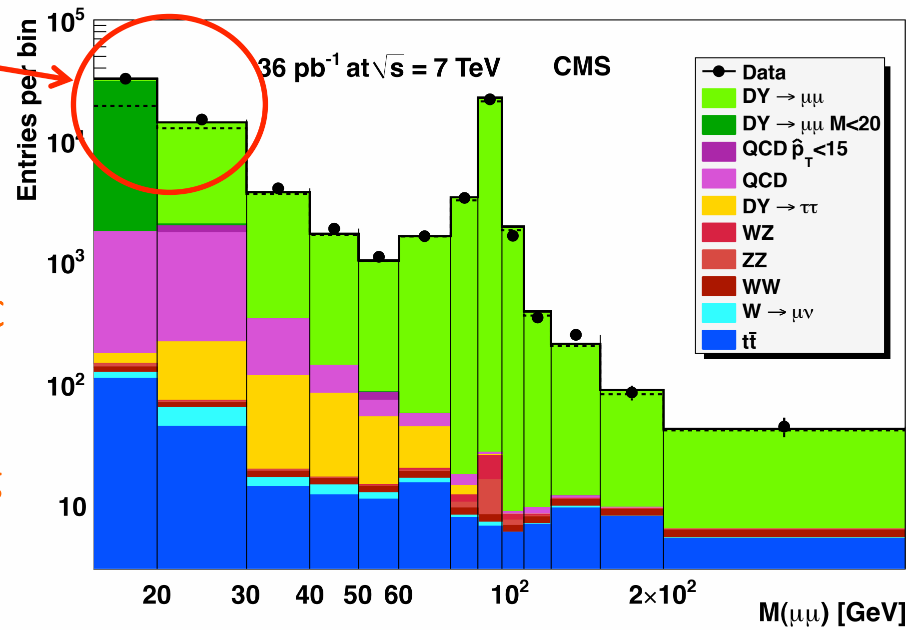
Acceptance

- Derived from the POWHEG (NLO) simulated samples
- Was seen to be in poor agreement with reality at low masses (< 40 GeV)
  – With our kinematic cuts, it is not possible to get an event in our acceptance in LO at low masses
  – POWHEG effectively becomes LO in this region
- Solution: Reweight POWHEG events based on NNLO FEWZ calculation
  – weight = $\sigma^{FEWZ}/\sigma^{Powheg}$

improvement

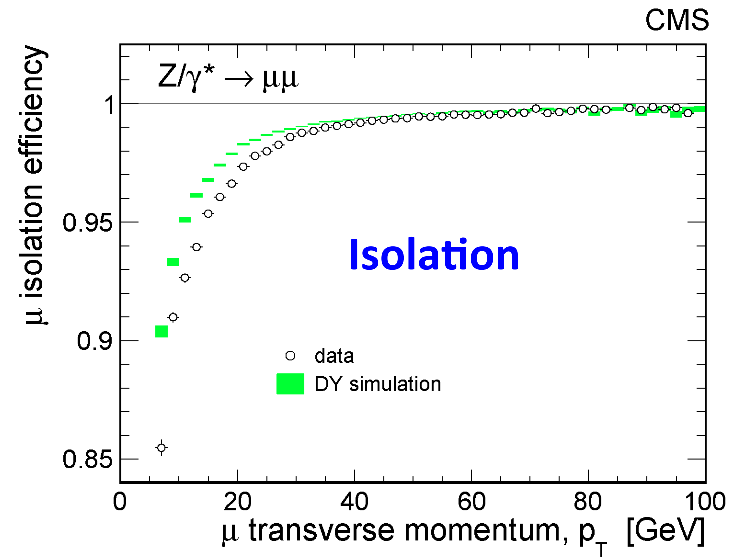
Solid hist: re-weighted MC

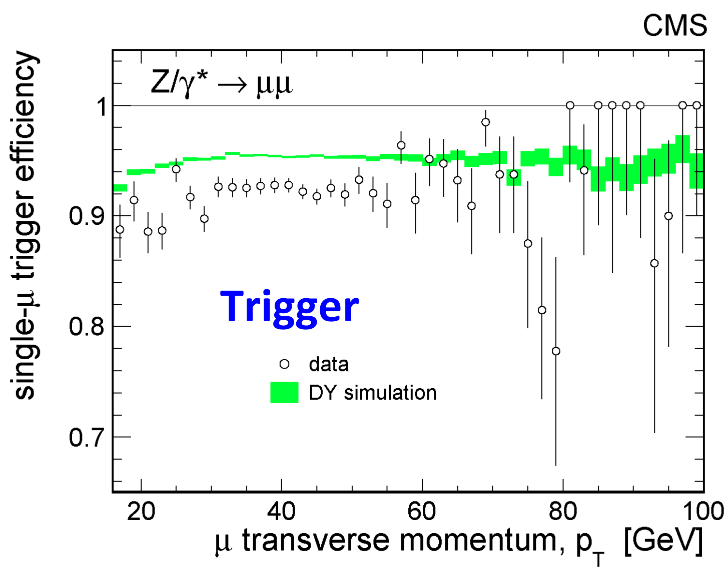
Dashed hist: original Powheg

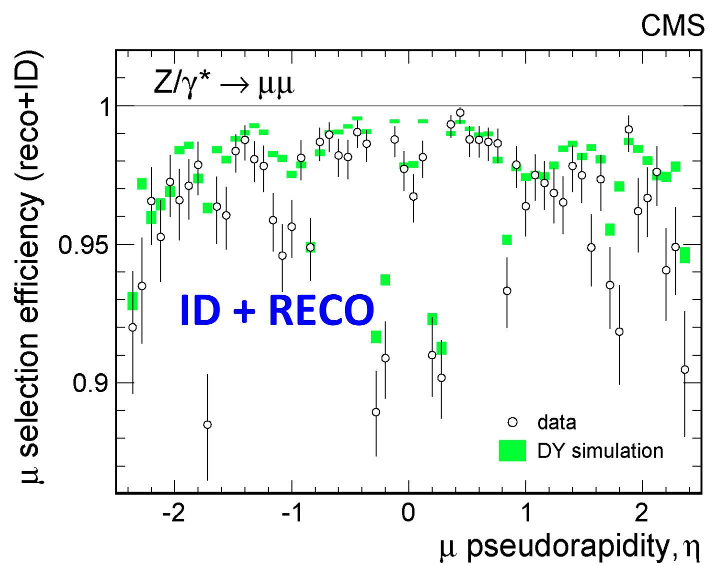


Efficiencies

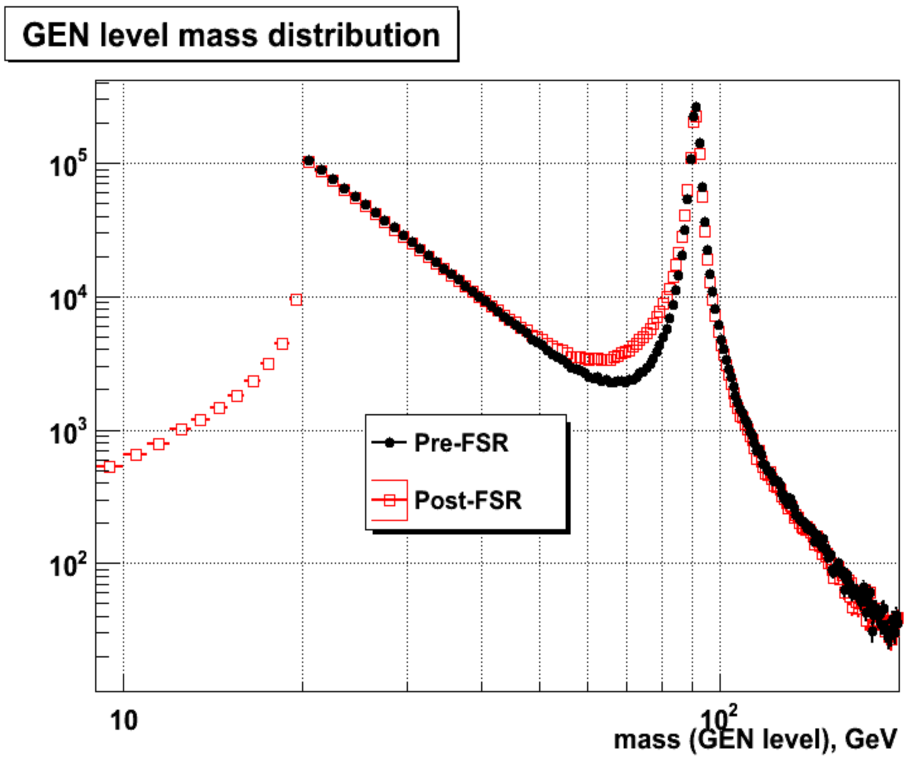
- Efficiencies are estimated using data driven techniques
  - Muon isolation efficiency by the "Random Cone" method
  - All others using Tag and Probe technique
  - Determined as function of (p_T,η)
- MC is corrected to match results from these measurements using weights







Final State Radiation (FSR) Correction

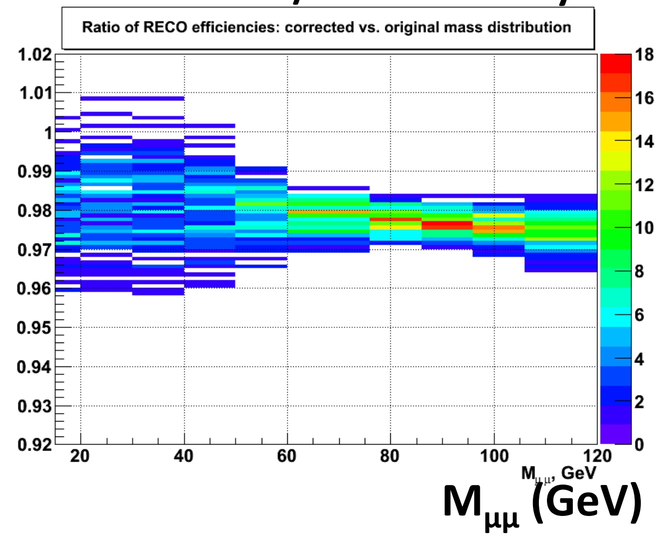


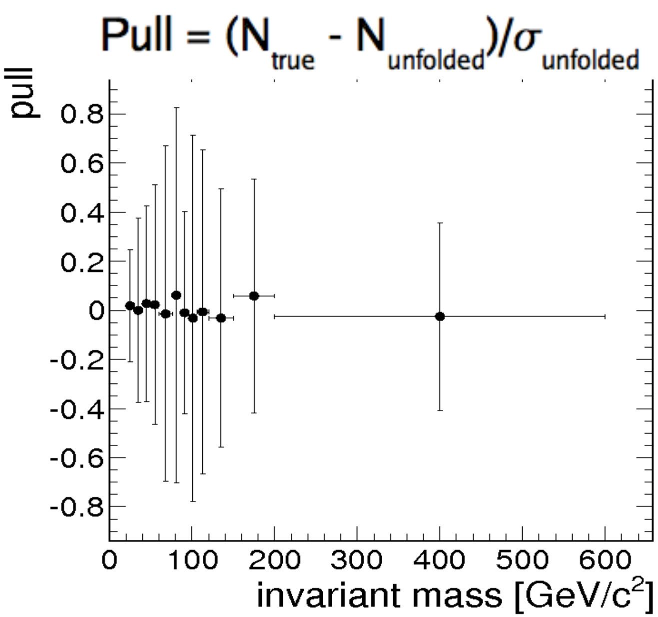
- Measurement in the acceptance is for post FSR muons/electrons (some FSR is unavoidably included with electron measurement)
- Correction made in order to compare to theoretical calculations which don't include FSR
  - Example: FEWZ
- The FSR modeling in the POWHEG signal sample is used to derive the corrections bin by bin

Systematic Uncertainties

- Efficiencies
  - Uncertainty per mass bin estimated by varying efficiency correction factors (assuming Gaussian behavior)
  - Example on right: Reconstruction ID efficiency

Ratio of mass before/after efficiency correction





Small Effect

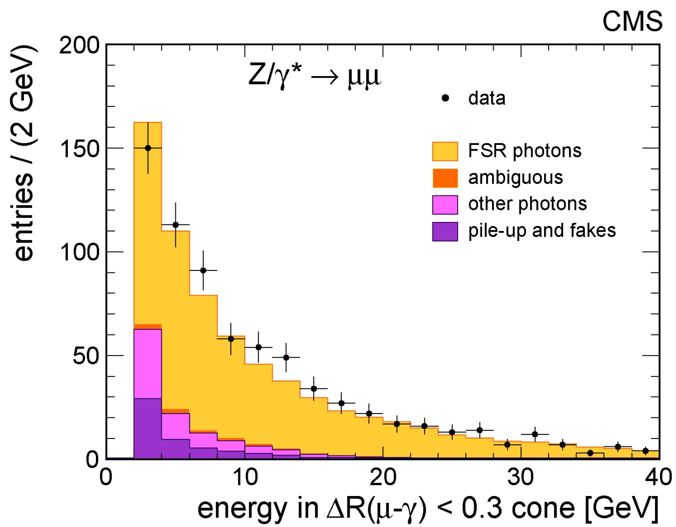
- Unfolding
  - Simulate bias in response matrix using pseudo-experiment ensembles but holding the response matrix fixed
  - Test uncertainty on possible distortion of mass spectrum by smearing of muon curvature and then unfolding

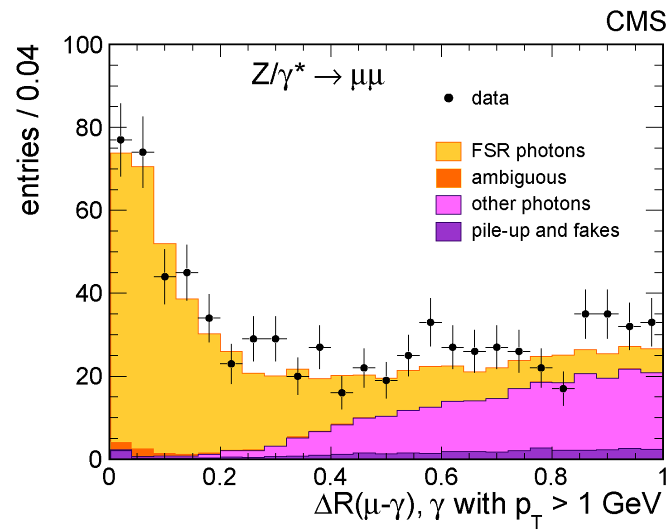
$$\frac{1}{p_T} + C = \frac{1}{p_T^{min}}; \quad \frac{1}{p_T^{min}} - C = \frac{1}{p_T^{max}}$$

  - Also take into account small shift in the Z peak position between MC and data (momentum scale, very small effect)

Systematic Uncertainties

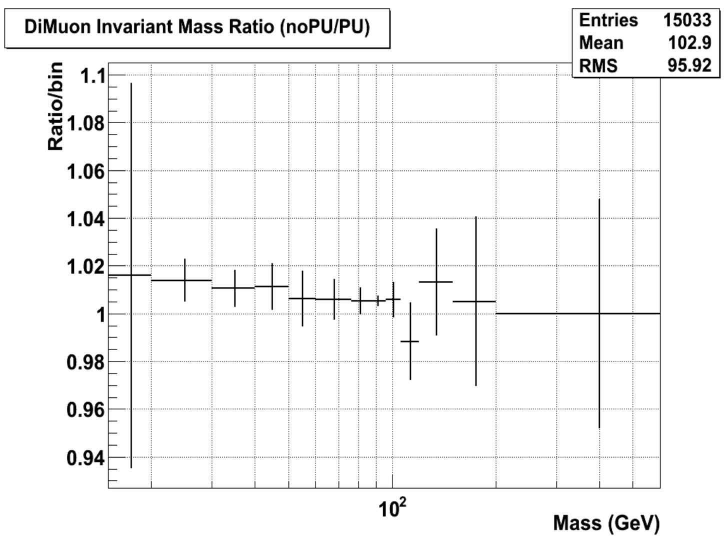
- Test modeling of Final State Radiation in the simulation
  - Take ratio of reconstructed photon spectrum in data and mc and determine allowable variation by fitting
    - In general they agree quite well, but large statistical errors lead to significant room for variation
    - **I'm going to talk about this in more detail later in this presentation**
  - Use variation to randomly remove events at generator level to modify shape of FSR distributions consistent with above
  - Recalculate the acceptance and check difference w.r.t. the nominal values





Systematic Uncertainties

- **Backgrounds**
  - Statistical uncertainties propagated as systematics
  - QCD estimation uncertainties at low masses added in quadrature
  - Uncertainty on yield at low masses < 4%
- **Pile-Up**
  - Analysis is based on simulated events without pile-up
  - Pile-up effects mostly the isolation efficiency
  - Comparisons between pile-up and no pile-up MCs show ~0.5% variation in each bin
- **Di-muon vertex selection**
  - No signs of data/MC differences
  - Efficiency of selection > 98% with < 0.3% variation per mass bin



- **PDFs**
  - Use standard re-weighting techniques, taking into account correlations between bins
  - Uncertainties are up to ~3%
- **QCD corrections**
  - Variations of the renormalization scale (current estimate < 1% effect excluding low mass region)
- **EWK corrections**
  - less than 1%, estimated using HORACE

Summary of Muon Systematics

Mass bin, GeV	Efficiency	Backgrounds	Unfolding	FSR	Others	Sum	Acceptance
15-20	1.1	3.6	0.4	1.5	1.0	4.2	$^{+2.2}_{-3.0}$
20-30	1.1	3.1	0.2	1.1	1.0	3.6	$^{+1.9}_{-3.2}$
30-40	1.2	1.9	0.1	0.7	1.0	2.6	$^{+1.7}_{-3.0}$
40-50	1.2	1.7	0.2	0.7	1.0	2.4	$^{+1.7}_{-2.9}$
50-60	0.8	2.1	0.2	0.5	0.5	2.4	$^{+1.7}_{-2.8}$
60-76	0.6	1.0	0.2	1.4	0.5	1.9	$^{+1.6}_{-2.6}$
76-86	0.4	0.2	1.7	2.0	0.5	2.7	$^{+1.5}_{-2.5}$
86-96	0.3	0.05	0.2	0.5	0.5	0.8	$^{+1.5}_{-2.4}$
96-106	0.3	0.4	3.8	0.5	0.5	3.9	$^{+1.5}_{-2.4}$
106-120	0.3	1.4	0.7	0.5	3.0	3.4	$^{+1.5}_{-2.3}$
120-150	1.1	2	0.4	0.5	1.0	2.6	$^{+1.5}_{-2.1}$
150-200	2.1	6	0.9	0.5	1.0	6.5	$^{+1.4}_{-1.8}$
200-600	2.1	10	0.1	0.5	1.0	10.3	$^{+1.2}_{-1.4}$

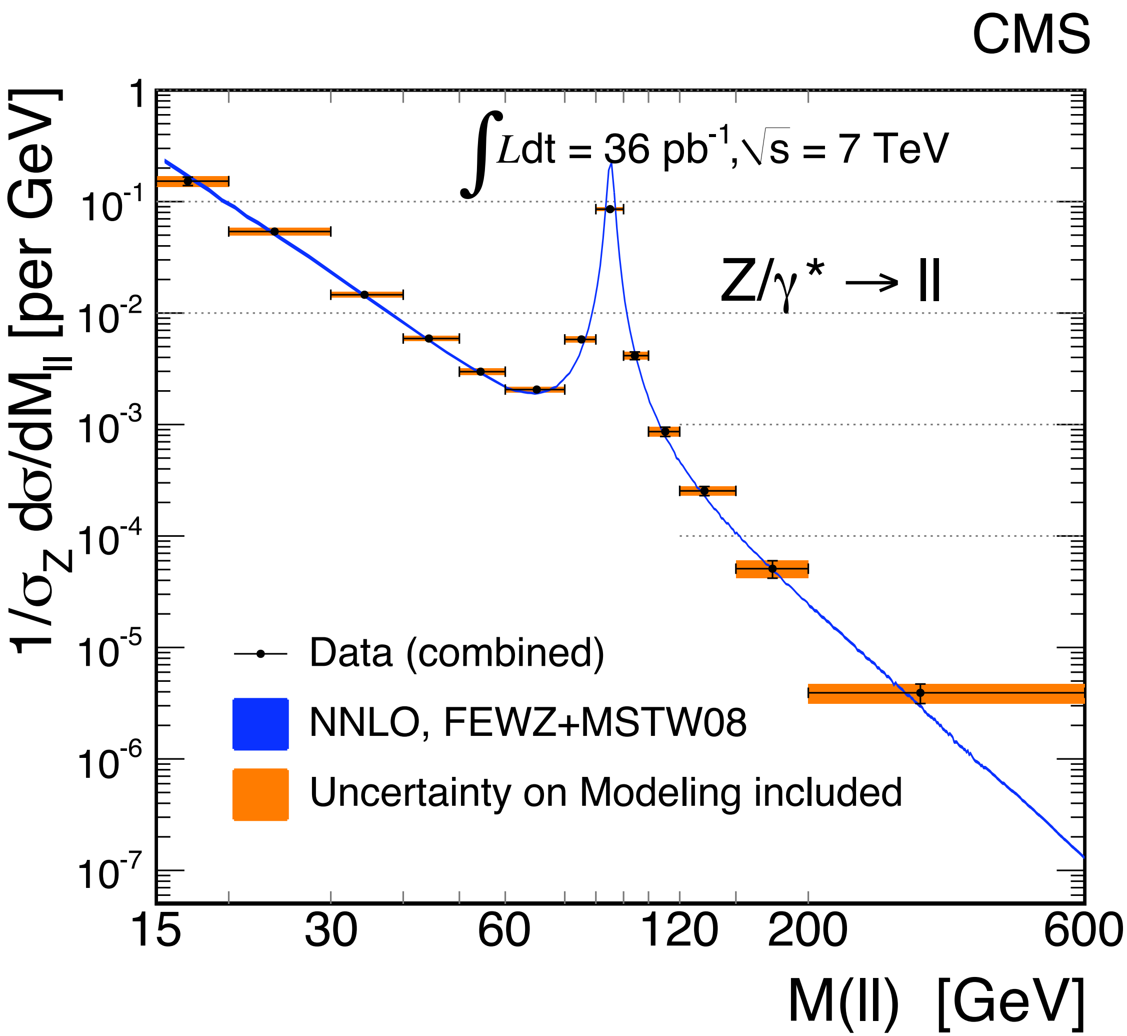
Results (I)

- The measurement is normalized to the Z peak Region

$$R = \frac{1}{\sigma_{ll}} \frac{d\sigma}{dM} = \frac{N_i^U}{A_i \, \varepsilon_i \, C_i} \left(\frac{A_{norm} \varepsilon_{norm} C_{norm}}{N_{norm}^U} \right)$$

  – 'norm' is mass range 60 GeV < M_{ll} < 120 GeV , as per the CMS Z cross section measurement
- Muon and Electron channels combined
  – Simple weighted average method employed, taking into account correlations of errors between the two channels
  – Measurement is driven by muon channel, due to smaller overall uncertainties
- Additionally, we give results with (see backup slides):
  - $R_{post\text{-}FSR}$ - no FSR corrections
  - R_{DET} - in kinematic acceptance, i.e. no acceptance corrections
  - $R_{DET,post\text{-}FSR}$ - in kinematic acceptance, no FSR corrections
  - This allows us (and theorists) to compare to a variety of theoretical tools

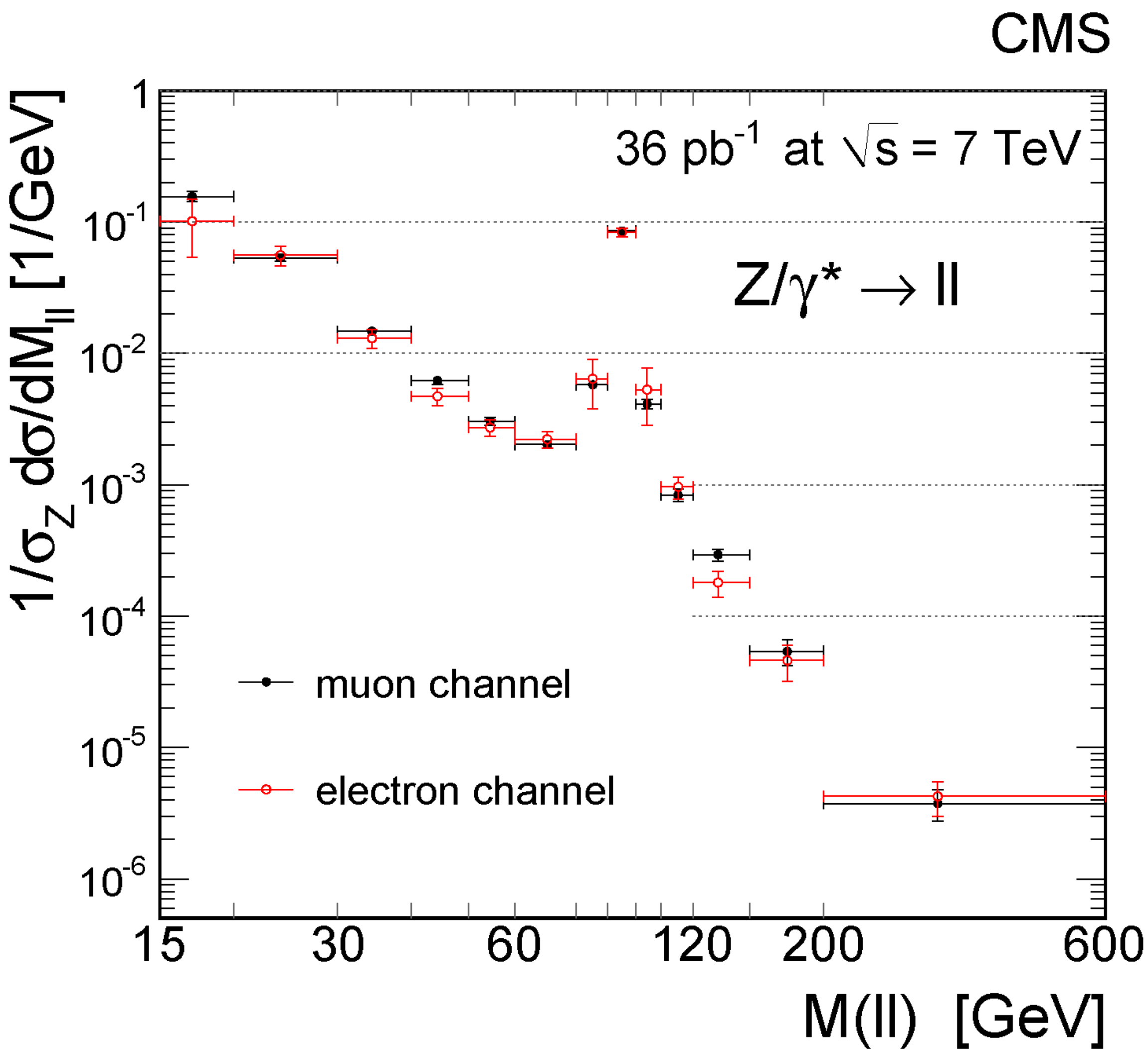
Results (II)

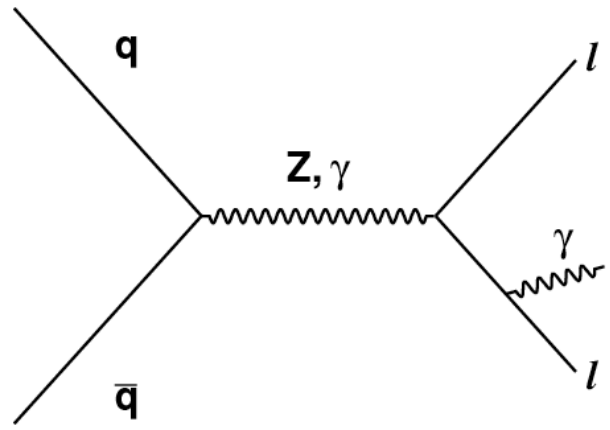


Good agreement for all bins!

Modeling uncertainty accounts for acceptance differences between FEWZ weighted POWHEG and FEWZ (NNLO)

Comparison of Electron and Muon Results

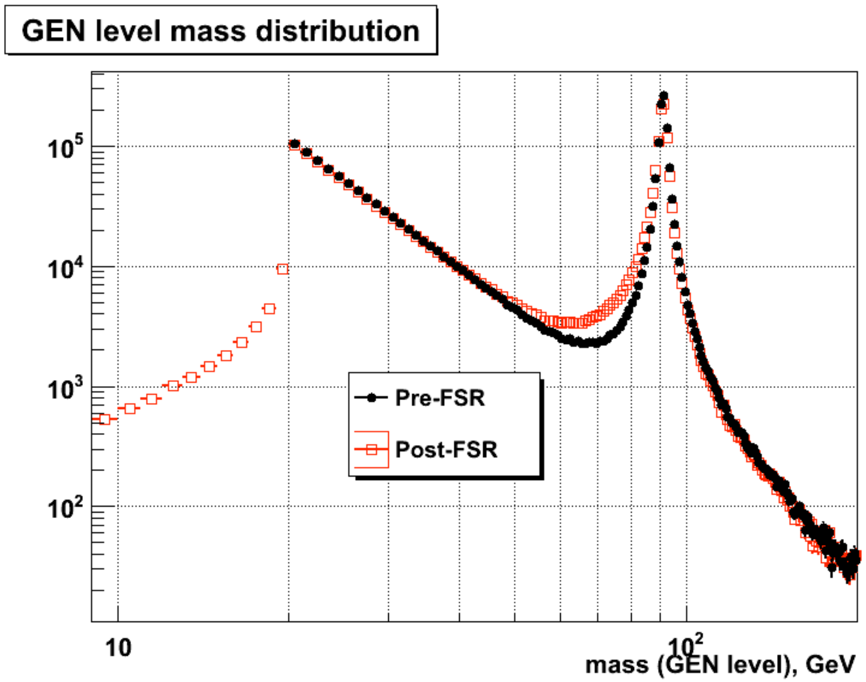




Final State Radiation in DY->μμ

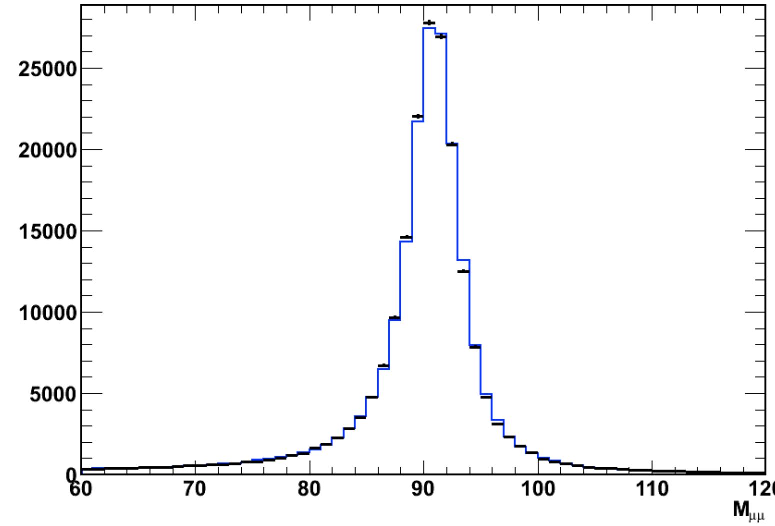
Motivation

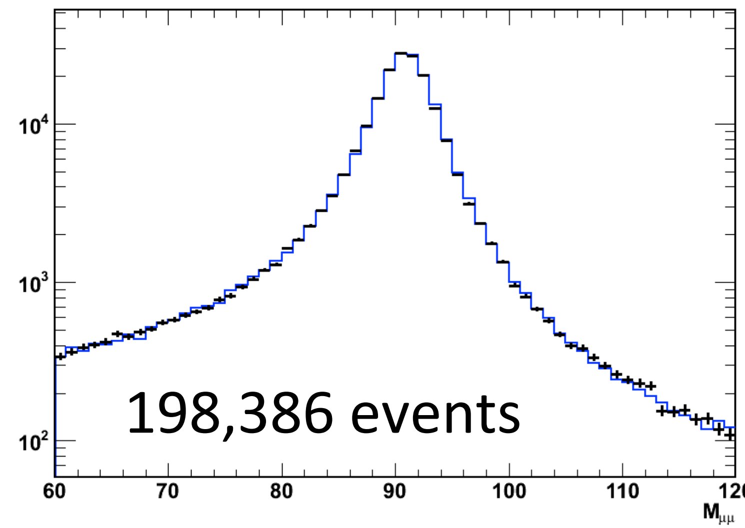
- As shown earlier, photon production via Final State Radiation (FSR) significantly alters the shape of the di-muon mass spectrum, as well as the signal acceptance
- The DY analysis relies on the modeling of FSR in the simulation to correct for this effect
  - Therefore it's important to verify the simulation using data if possible
- This analysis is an attempt to characterize FSR in the data
  - Is the simulation doing a good job?
  - How well can CMS identify and reconstruct FSR photons?



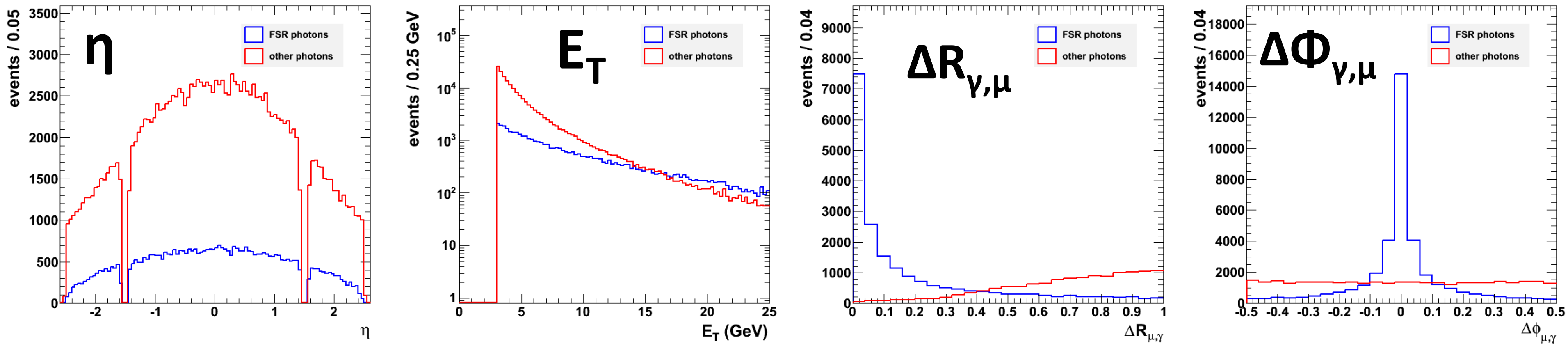
Datasets, etc.

- **Data:**
  - **Approximately 500 pb^{-1} from 2011**
- **MC:**
  - Pythia 8 Drell-Yan sample
  - Backgrounds from other processes are very small and not considered in data/MC comparisons
- Selection Identical to DY analysis with following exceptions:
  - HLT_Mu30 (Single Muon with $p_T > 30$ GeV/c): the lowest consistently non-prescaled single muon trigger in considered datasets
  - At least one muon with $p_T > 31$ GeV
- In all cases, the MC is normalized to the data using the Z-peak
  - $60 < M_{\mu\mu} < 120$ GeV/c^2





Generator Studies



- Start by looking at generator level info ($E_T(\gamma) > 3$ GeV)
  - This will give a general idea of what to expect
  - **RED**: Background photons from underlying event, **BLUE**: FSR photons
  - Eta distributions are similar (holes are just due to rejection of ECAL barrel/endcap transition region)
  - Much more BKG photons at low energy, FSR overtakes them at around 15 GeV
  - **FSR photons tend to be emitted nearly collinear with the muon**

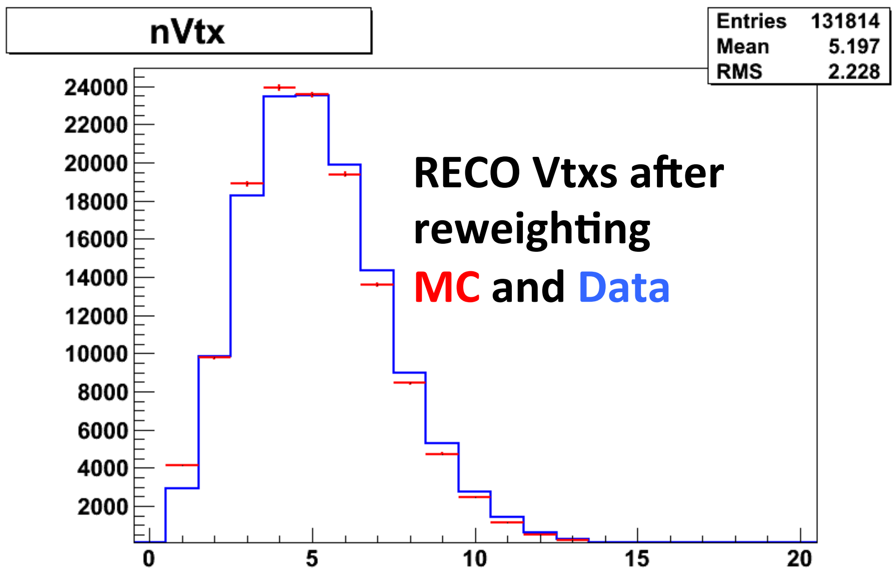
$$\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$$

Photons in Data

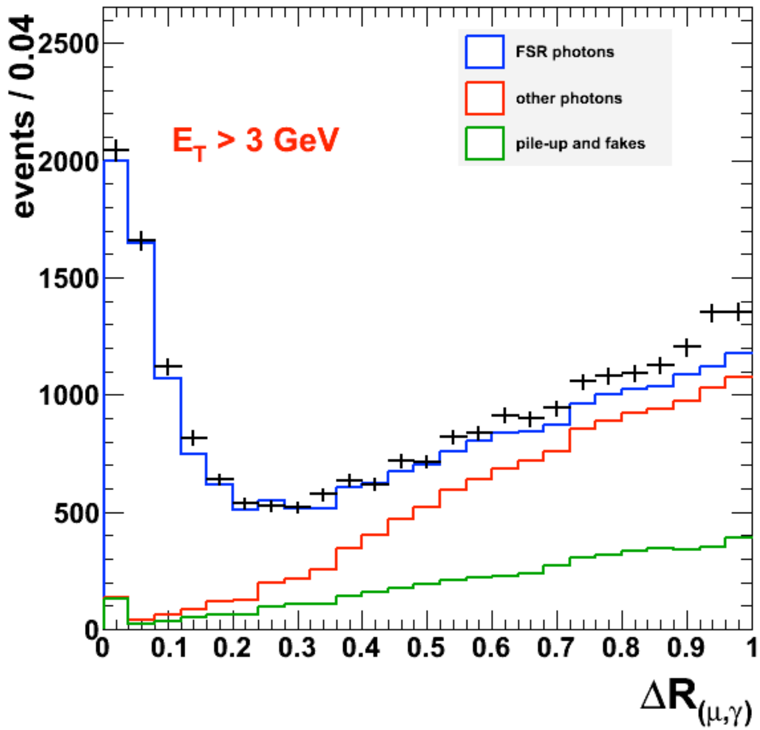
- Particle flow based photons are used in this analysis
  - Inclusive nature of PF allows for reconstruction of photons < 10 GeV
- All PF photons with:
  - $E_T > 2$ GeV
  - $|\eta| < 2.5$ (excluding $1.44 < |\eta| < 1.57$)
- Potential backgrounds include (but not limited to):
  - **Underlying event**: mostly neutral pion decays
  - **Pile-up**: similar to underlying event only from secondary interactions
  - **Other**: Brehm in tracker, jets faking photons, misreconstructions
  - **ISR/Zgamma**: Photons from interesting physics but not FSR
- Take two approaches to identifying FSR photons in the data
  - Look for photons near the final state muon within some ΔR cone
  - Look for photons away from muon but impose isolation requirement

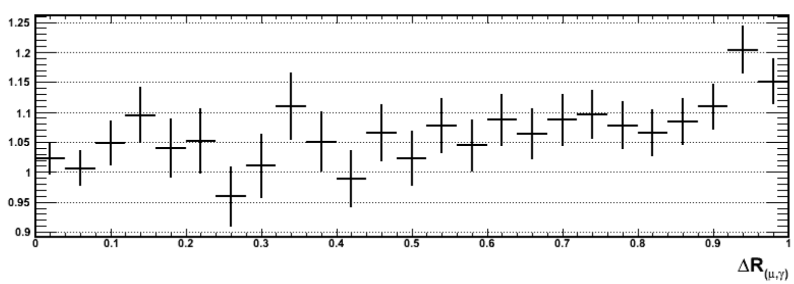
Treatment of Pile-up

- Proper treatment of PU is crucial since it is a significant background
- Simulated events are weighted based on expected pile-up in data and simulated pile-up distributions
  - Reconstructed vertices show good agreement in data and MC after this procedure
  - small difference due to difference in reconstruction efficiencies in data/MC



First Case: Photons near Muon

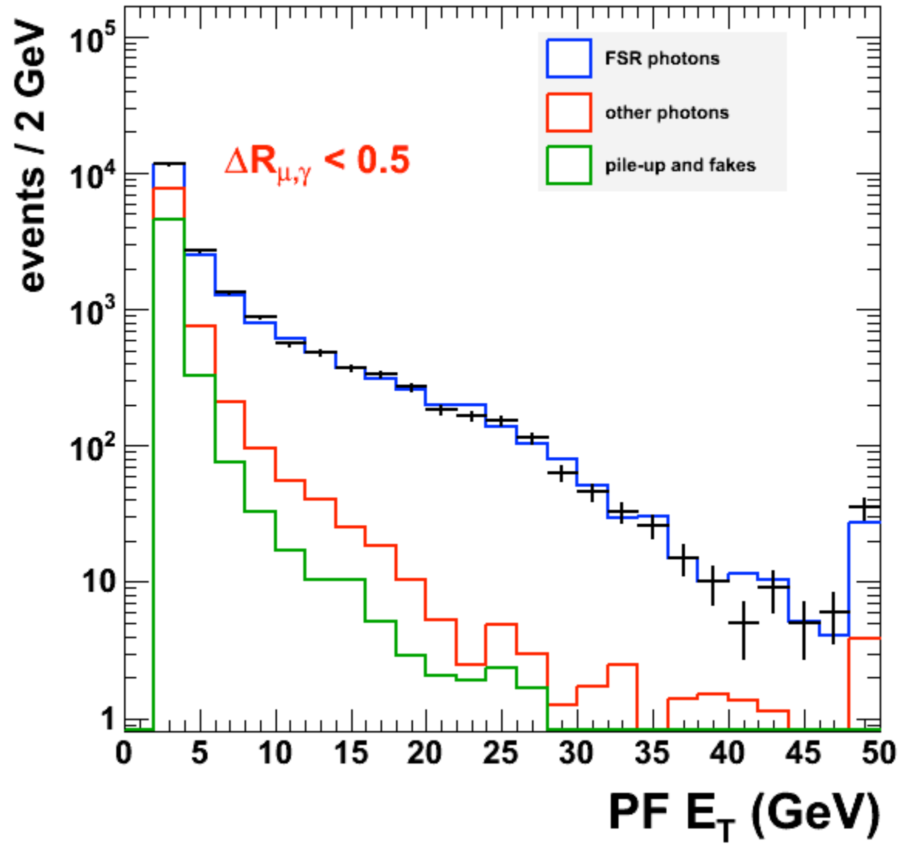


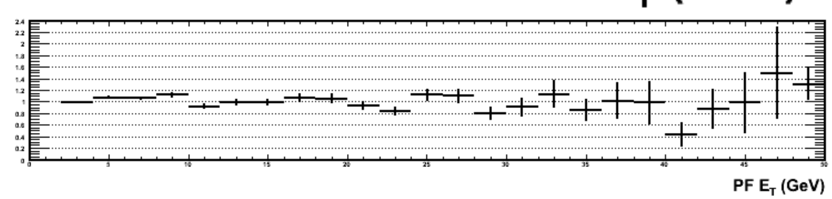


- Compare the reconstructed PF photon distributions for data and MC
- In the following plots, the MC distributions are represented by a stacked histogram color coded by photon origin
  - Origin determined by ΔR matching to generator truth
- Color code:
  - BLUE: matched to FSR
  - RED: matched to background
  - GREEN: Unmatched (pileup and fakes)
  - BLACK: Data
- Plot: ΔR between photon and muon for all photons with E_T > 3 GeV
  - Error bars are statistical errors only

First Case: Photons near Muon

- Also compare the photon Energy distributions
- Plot: Sum of photon energy within cone of ΔR < 0.5 around muon
- Color code is the same as previous
  - Error bars statistical only
  - Color code:
    - BLUE: matched to FSR
    - RED: matched to background
    - GREEN: Unmatched
    - BLACK: Data



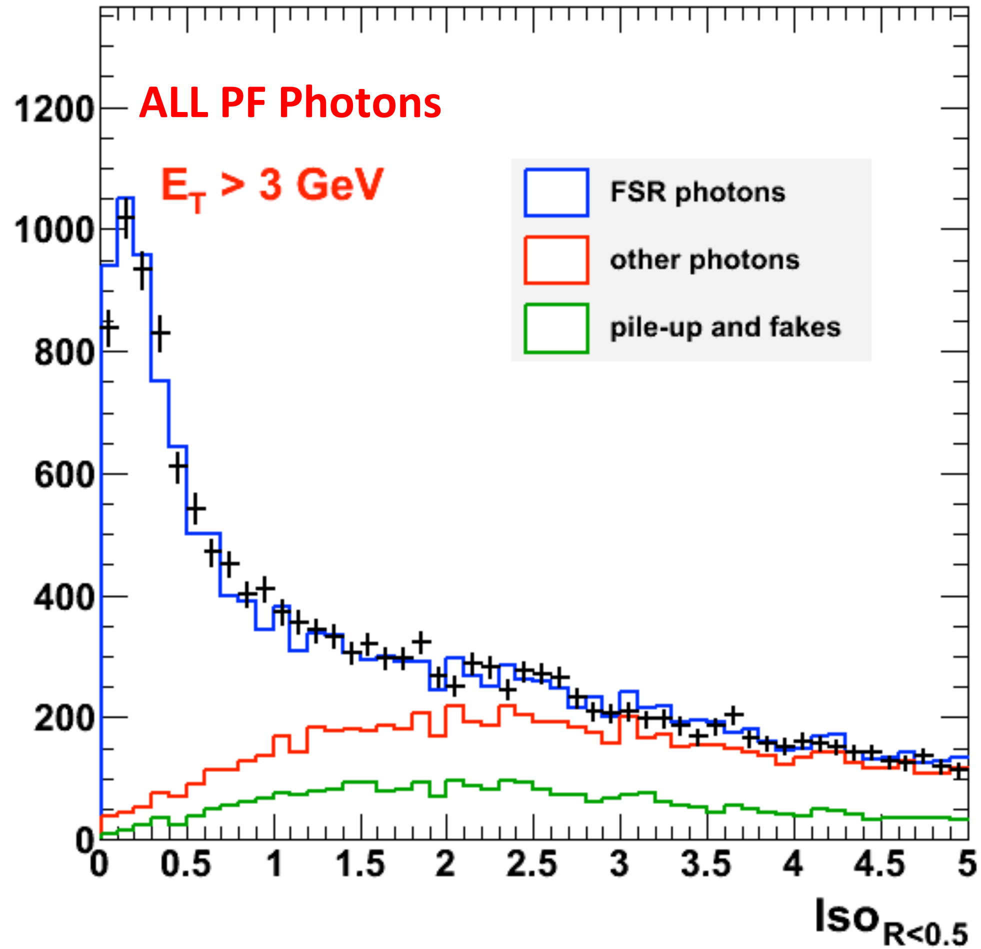


Photon Isolation

- Non-negligible amount of FSR photons are emitted at wide angle w.r.t. the muon
  - In general, these photons should be isolated
- Define a Particle Flow based Isolation as:

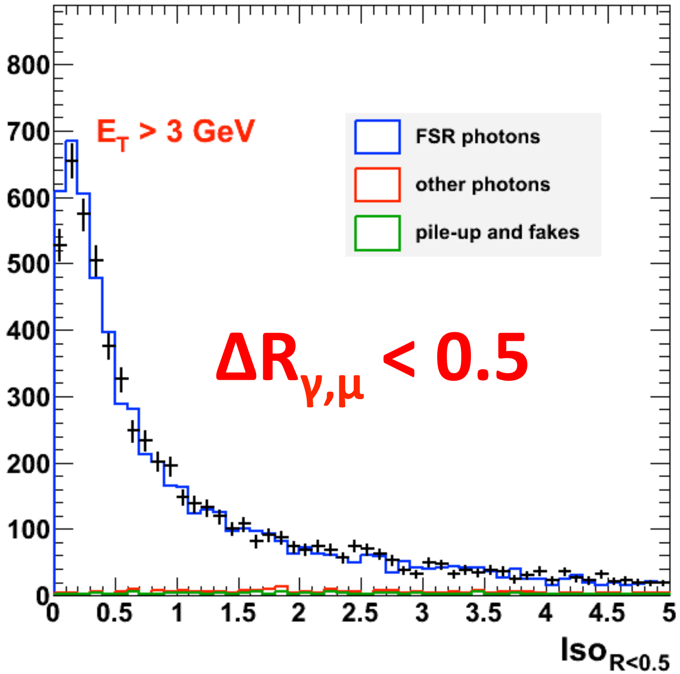
  I^{rel} = (Σp_T (Charged Hadrons) + ΣE_T(Neutral Hadrons) + ΣE_T(Photons)) / E_T(Photon)

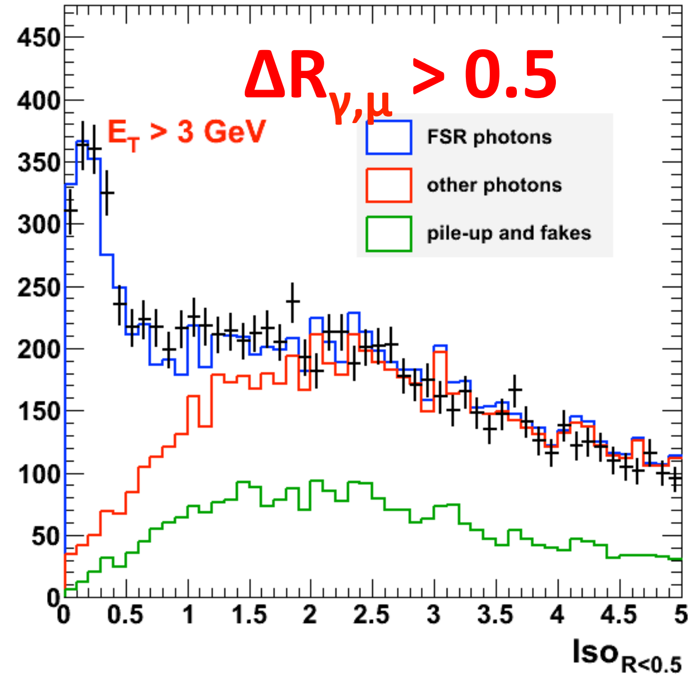
  - use cone size $\Delta R < 0.5$
- Plot this variable, again dissecting MC plots based on matched SIM photon origin and compare to data
  - Only $50 < M_{\mu\mu} < 85$ considered in following plots



Photon Isolation (II)

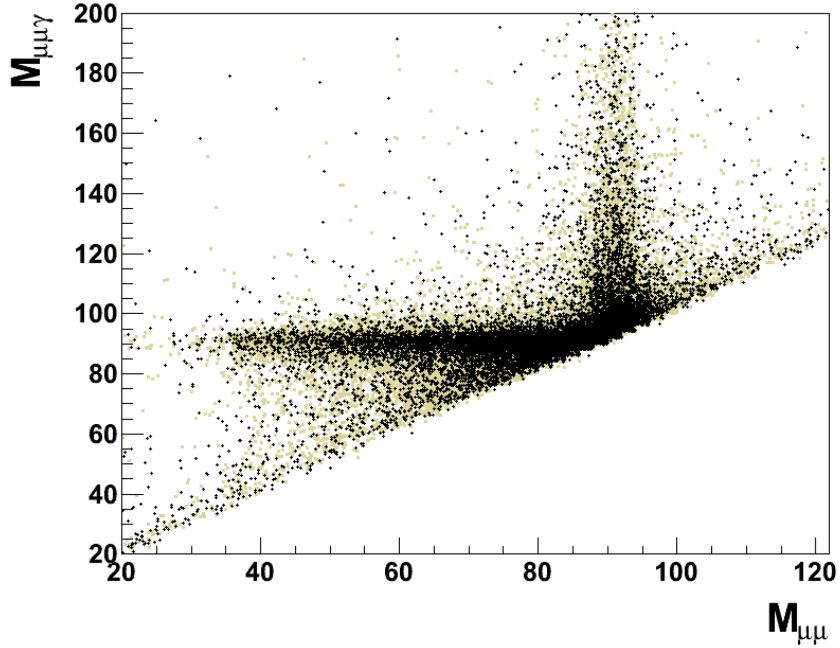
- Now separate PF photons by proximity to muons

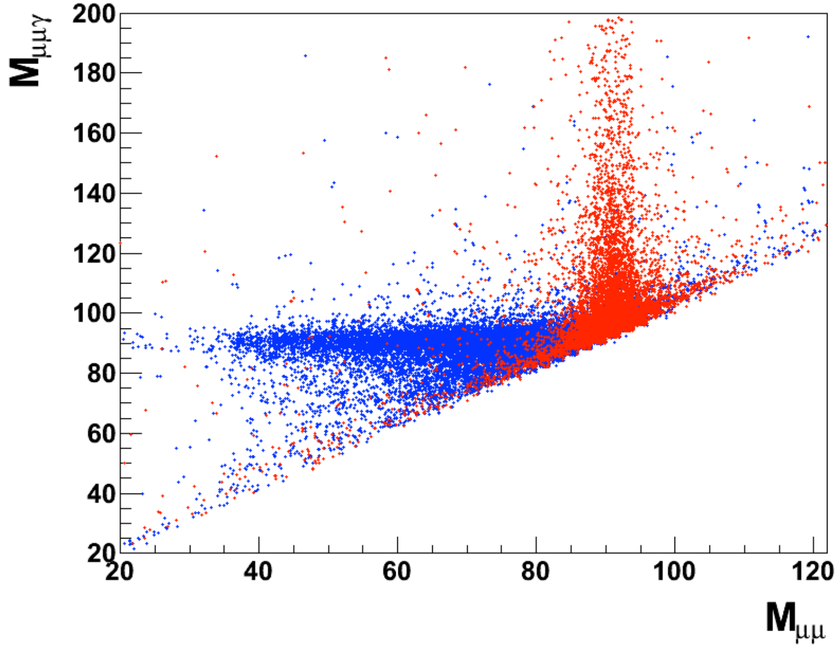




- Based on the these and previous studies, photon selection is as follows
  - **"Close" Photons:** $\Delta R_{\gamma,\mu} < 0.5$, $E_T > 3$ GeV
  - **"Wide" Photons:** $\Delta R_{\gamma,\mu} > 0.5$, $E_T > 3$ GeV, PF Iso < 0.5

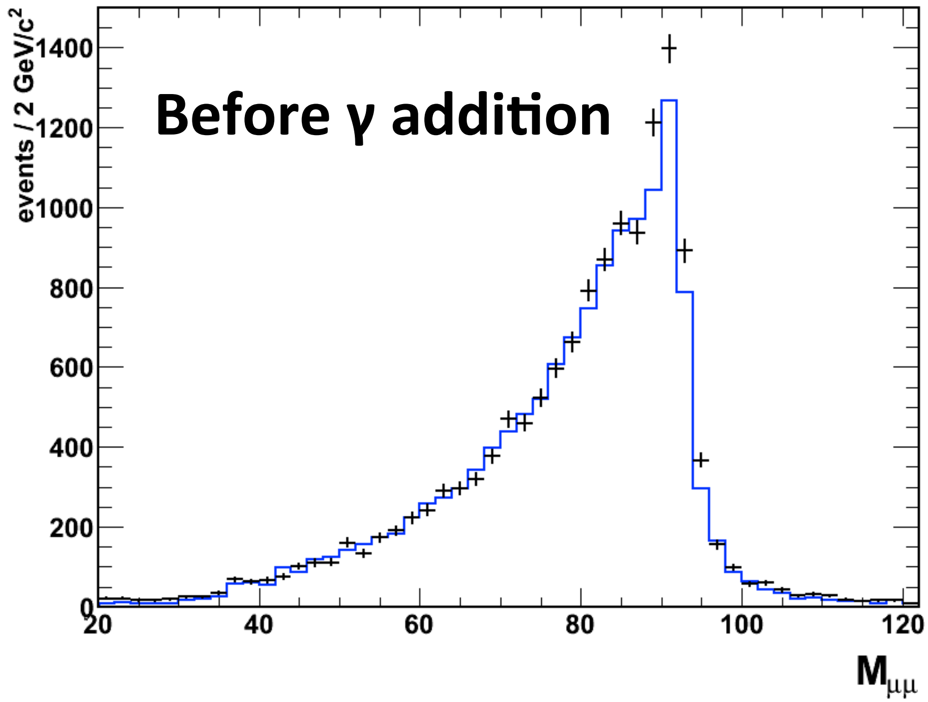
$M_{\mu\mu\gamma}$ vs $M_{\mu\mu}$

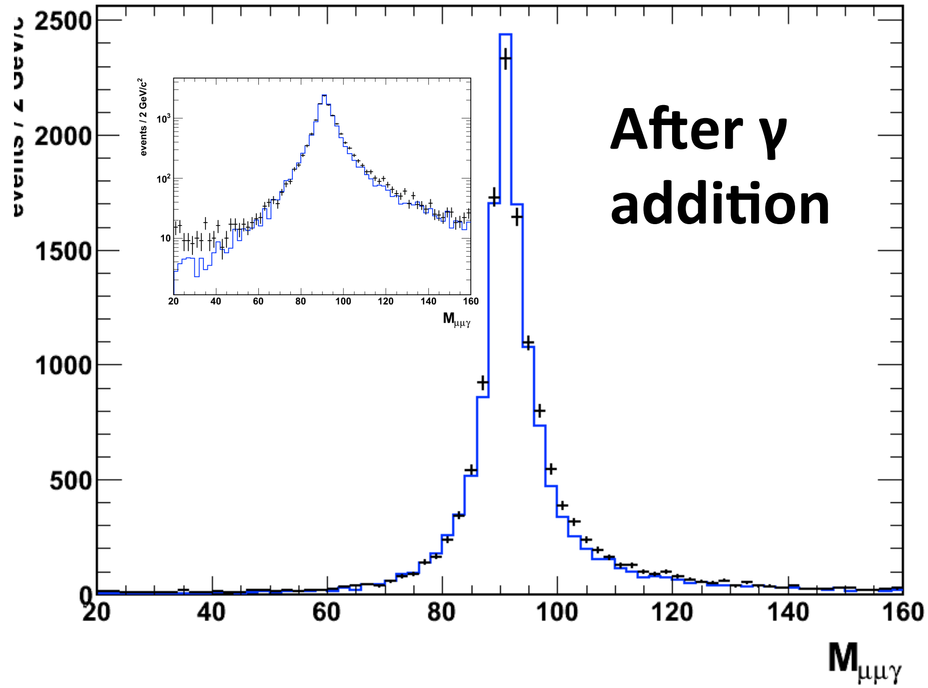




- Take any photon passing selection
- Combine with di-muon system and re-compute the invariant mass
- Plot the three (or more) body mass versus the nominal di-muon mass for events with a selected photon only
  - Left: MC gold shaded, data superimposed as **black** points
  - Right: MC only, separated by photon origin (**FSR** and **BKG**)

1D Projections

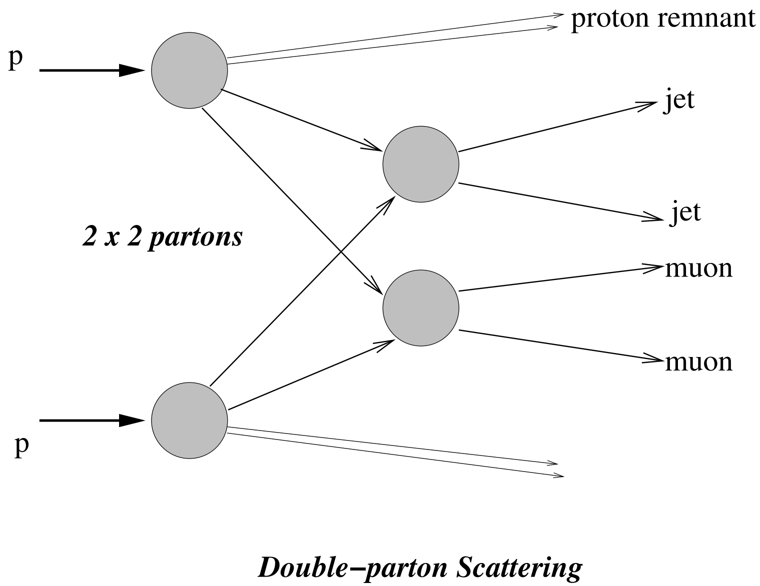




- Plot the $M_{\mu\mu}$ and $M_{\mu\mu\gamma}$ in 1-D the check how the normalization is doing
  - again, only events with a selected photon are plotted
- Small excess in data in Z-peak region
  - slightly more background in data at low E due to pile-up
- Tails agree quite well

Summary

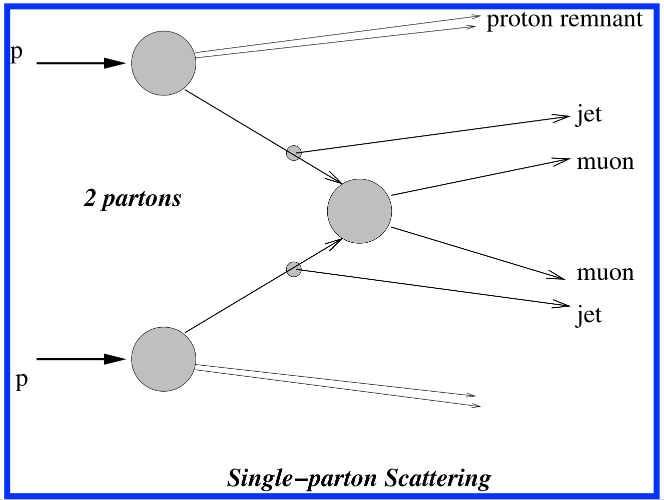
- Study of FSR photons in DY->μμ events is performed
- Data and MC show very nice agreement
  - some small discrepancies where background composition is large
- Efficiency for reconstruction is fairly high, even for low E_T photons
- Publication of these results is planned (with 2011 data)
- This study was also carried out on 2010 data
  - The results were used to estimate the systematic uncertainties for the FSR correction in the DY muon analysis as described earlier

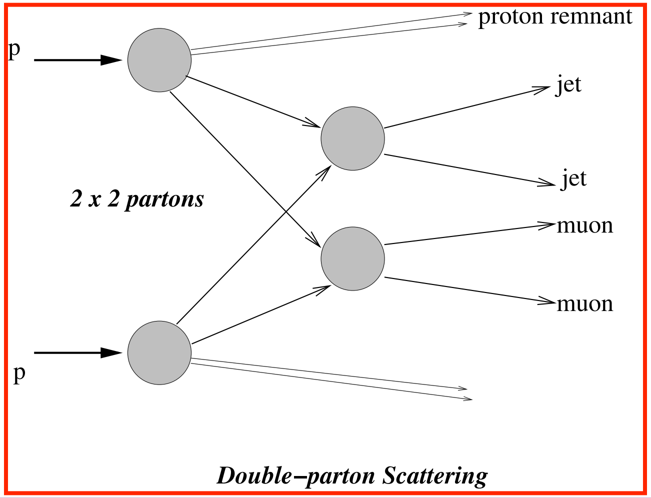


Double Parton Scattering in Z->μμ and Z->ee Events

Motivation

- Most LHC proton-proton interactions involve one parton from each oncoming proton
- A fraction of events will have two such interactions from two sets of partons in the same colliding proton pair
- It's difficult to model this theoretically
  - Pythia (6 and 8) has multiple parton interaction modeling built in
  - We should try to measure/verify it
- Exploit kinematics to identify events with multiple parton interactions
  - Look at Z + jets events, clean and easy to identify in the data
  - Z events with jets from single parton-parton interactions will tend to have high Z transverse momentum (q_T) due to recoil against the initial state jets
  - Events with a second hard scattering assumed to be uncorrelated with the Z and therefore independent of the Z q_T





Data and MC Samples

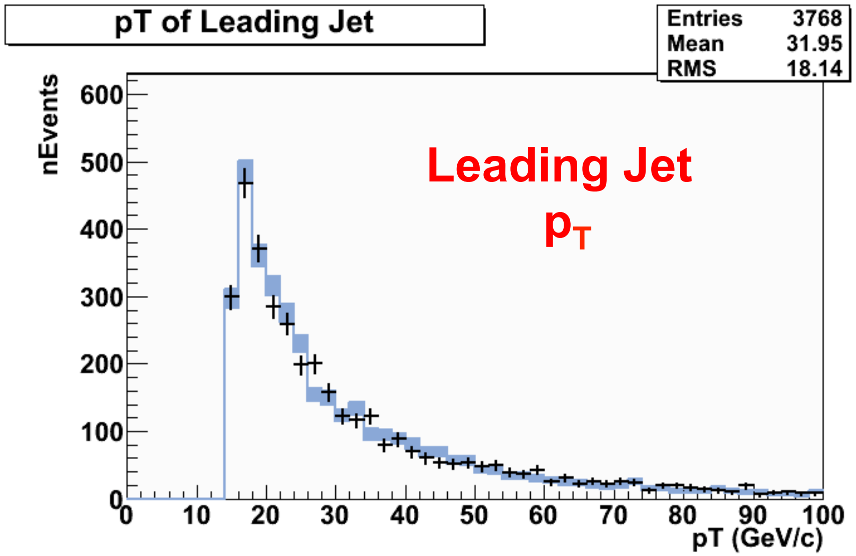
Data:

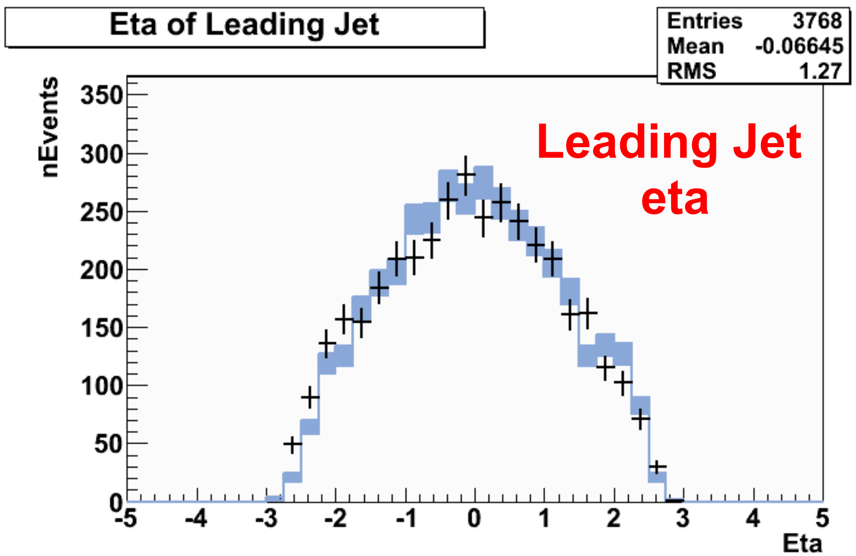
- 2010 data ($35.9 \pm 1.4\ pb^{-1}$)
- Event selection also same as DY except:
  - $60 < M_{ll} < 120\ GeV/c^2$

MC:

- Three privately generated Pythia 8 samples (with and without pileup)
  - Zmumu + Zee, multiple parton interactions (MPI) forced off
  - Zmumu + Zee, default MPI model
  - Zmumu + Zee, MPI forced ON ("enriched" sample)
    - SecondHard:generate = on
    - SecondHard:TwoJets = on
    - p_T-hat for second interaction > 15 GeV
- Madgraph Z+jets sample with pileup + pythia6 parton showering and MPI modeling
  - Serves as a cross-check, Pythia is not necessarily giving the correct: number of jets, jet kinematics, etc…
- **Normalize to selected data events**

Jet Selection

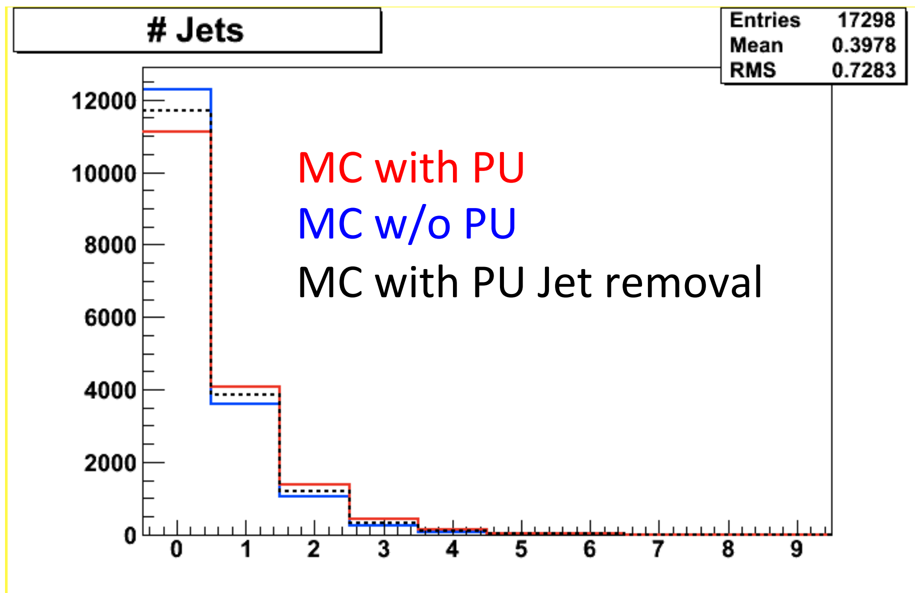




- Particle Flow jets
  - $p_T > 15$ GeV
  - at least 4 charged tracks
- Jets must be well separated from the muons
  - $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} > \mathbf{0.1}$

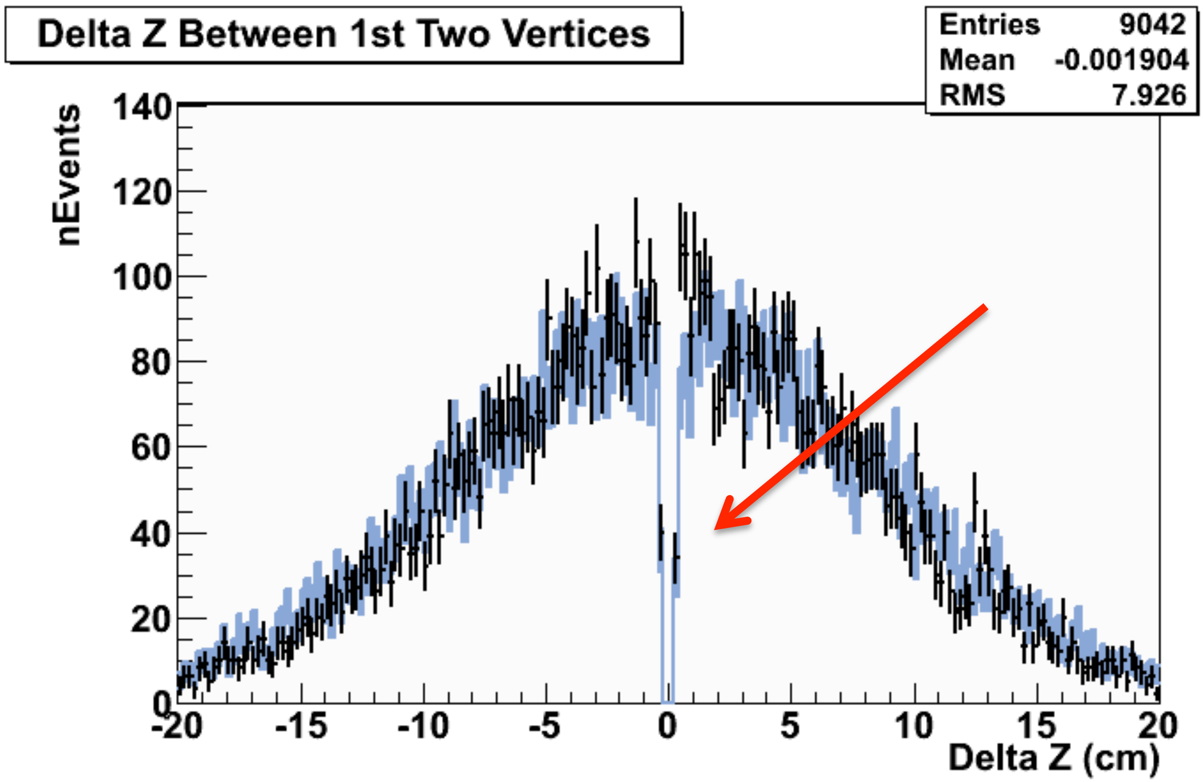
Pile-up

- Jet activity from a second collision will mimic our signal
  - We must reduce this contribution if possible or simulate it well (or both)
- One possible way to reduce the effect of pileup is to only look at activity which can be associated to the same primary vertex
  - Take advantage of the excellent primary vertex reconstruction in CMS
  - Associate jets to a vertex based on any charged tracks clustered as part of the jet
  - We use a "democratic" method (the vtx with the most associated tracks gets associated to the jet)
  - Only count jets which associated to the same vertex as the leptons

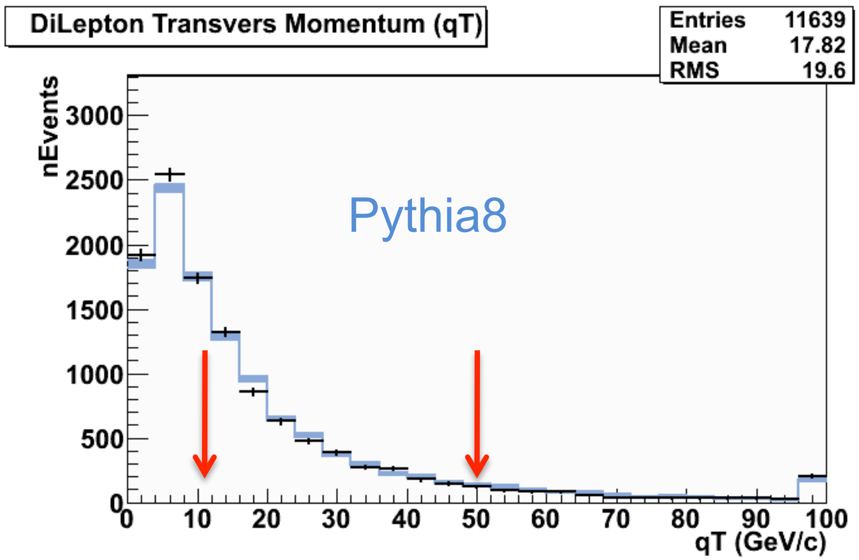


Pile-up (II)

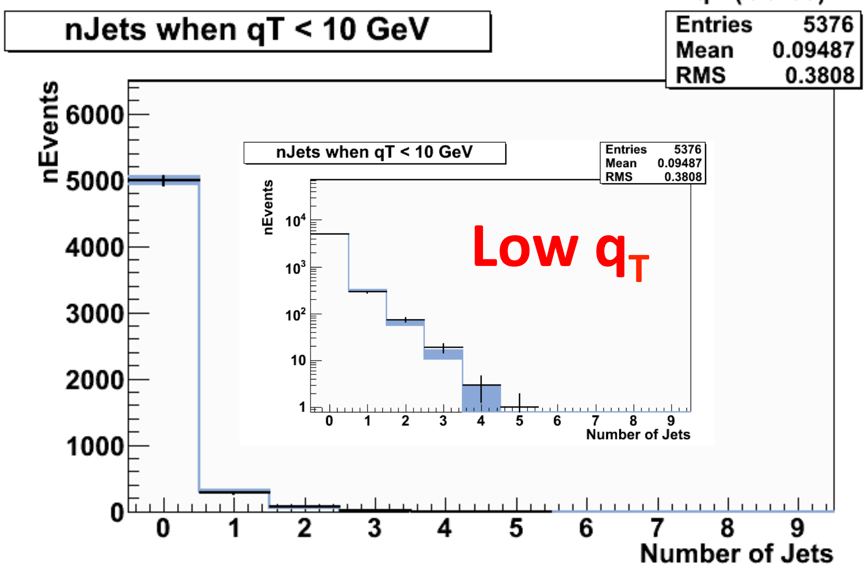
- The CMS vertex reconstruction is very good, but there is still a small but significant amount of contribution from two proton-proton collisions which are too close to distinguish from each other
  - We plan to use this to help estimate the background from remaining Pileup

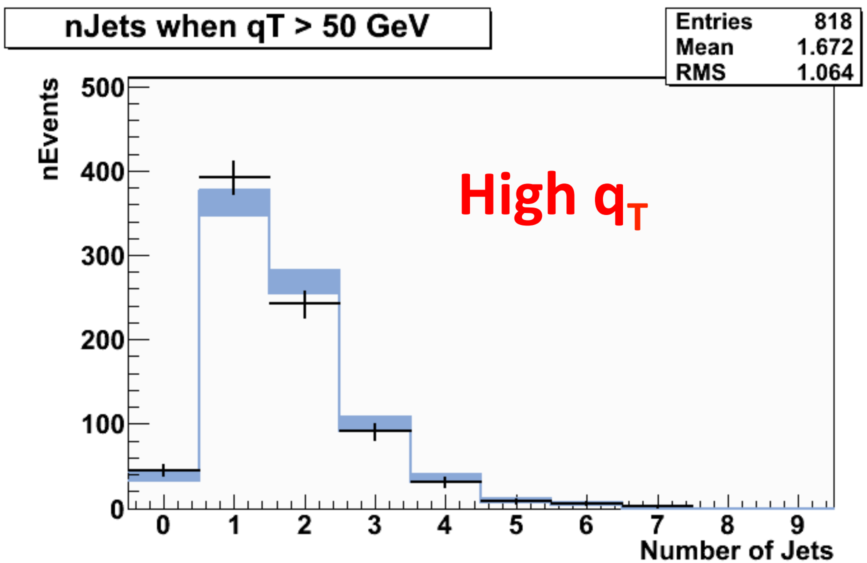


High and Low qT Regions



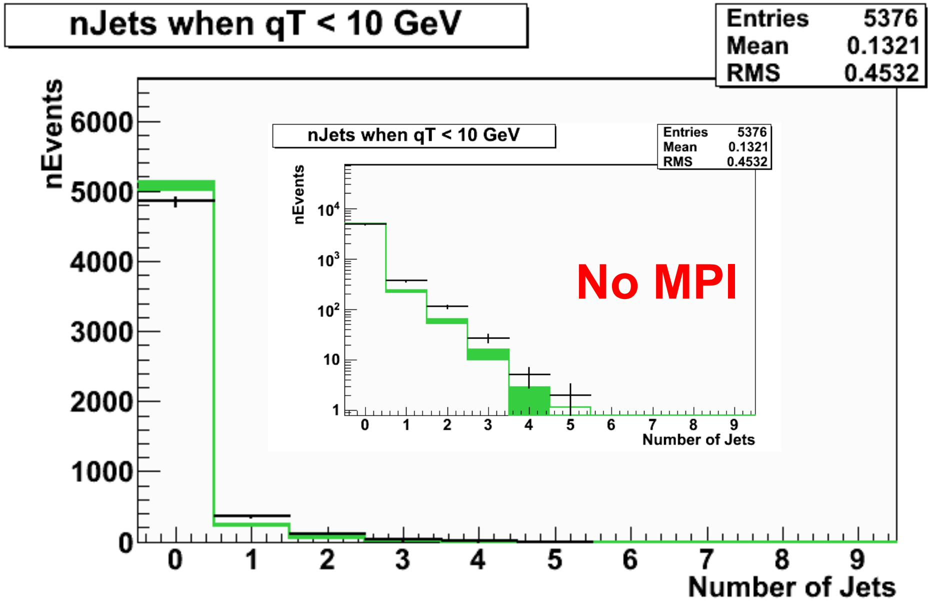
- Events are categorized based on the di-lepton q_T spectrum
- Low and High q_T regions defined as…
  - Low: $q_T < 10$ GeV
  - High: $q_T > 50$ GeV

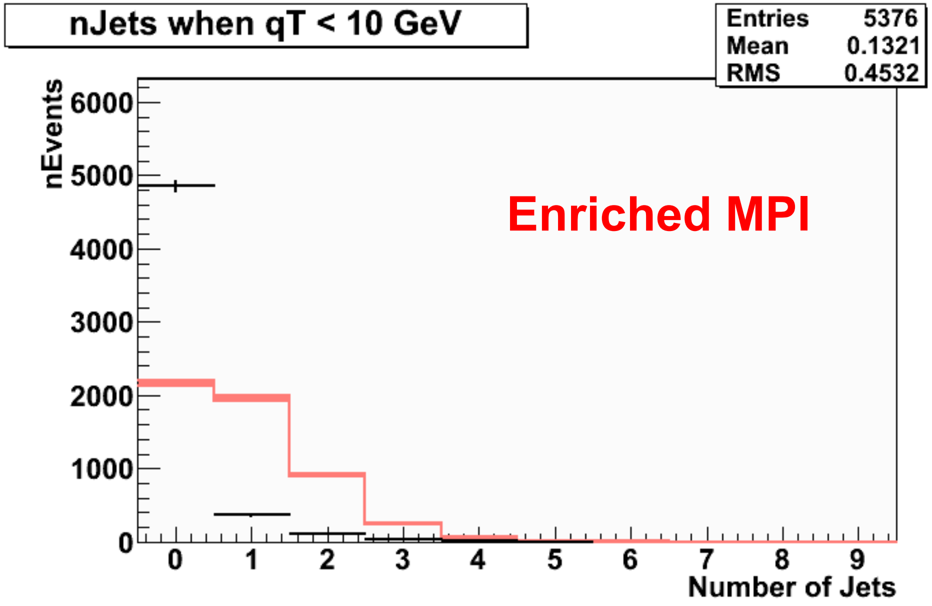




of Jets at High and Low q_T

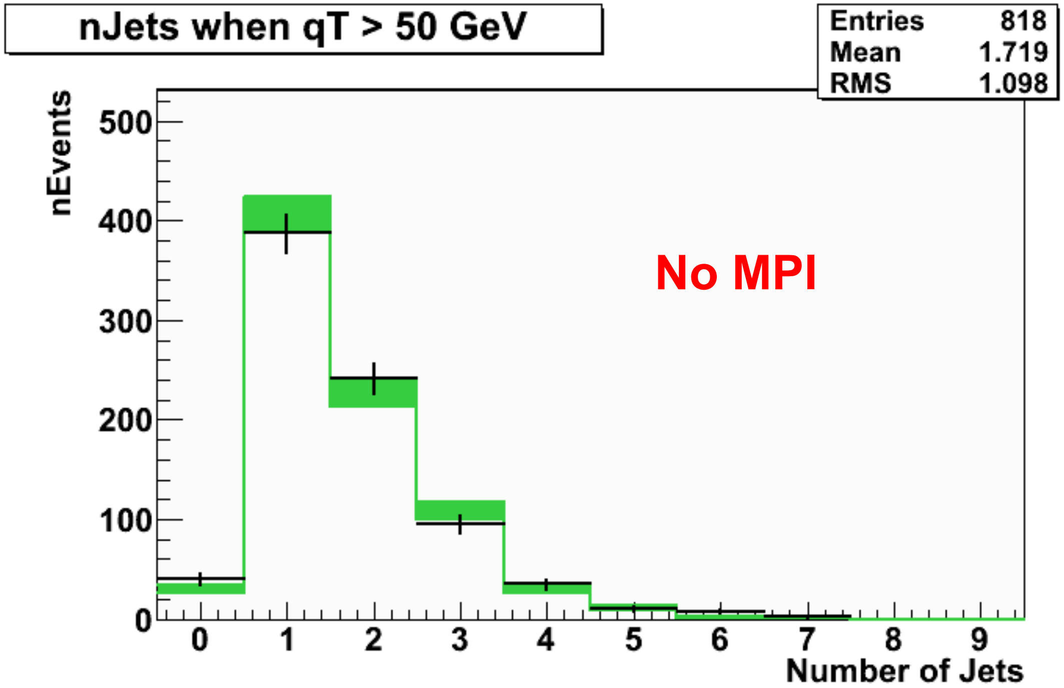
- What might you expect if there were excess MPI?
  - Green: nJets at low q_T when MPI is turned completely off
  - Pink: nJets at low q_T when MPI is enhanced as described earlier





of Jets at High and Low q_T

- In our high q_T control region, the shape of number of jets distribution is fairly insensitive to MPI as expected



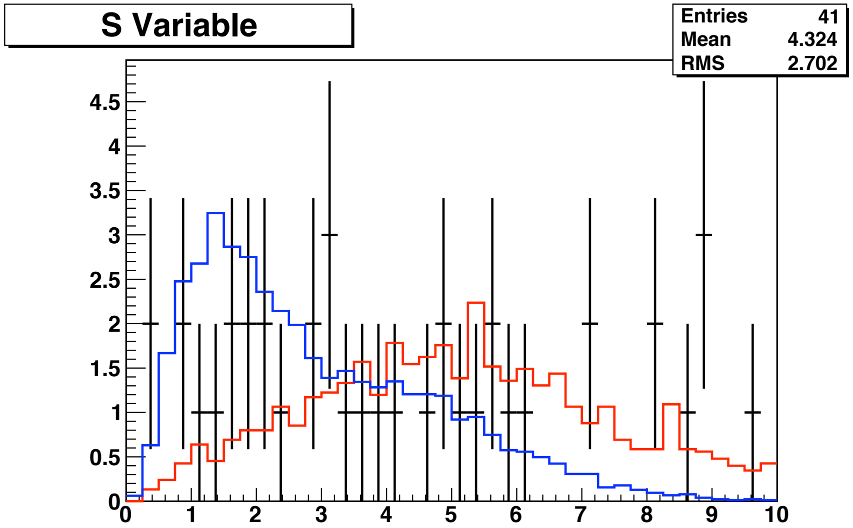
Fitting nJets

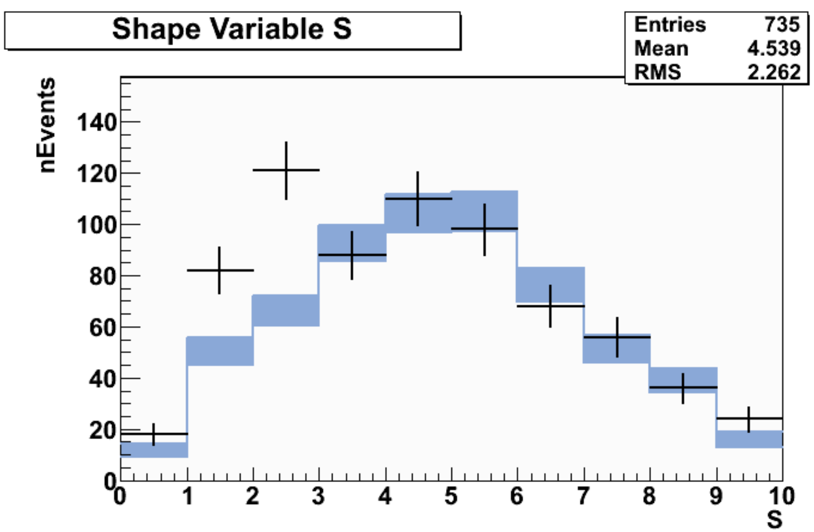
- Assume that our enriched sample with MPI forced on is "signal" and the standard pythia8 (or madgraph) is the background
- Try fitting to data based on template of the two histograms
- Results are consistent with zero, as expected by eye

Fit for a fraction of DPS events:
f = 0.014 ± 0.023 (muons)
f = 0.020 ± 0.023 (electrons)

upper limit
$f < 0.045$
at 95% CL

Exploiting Kinematics





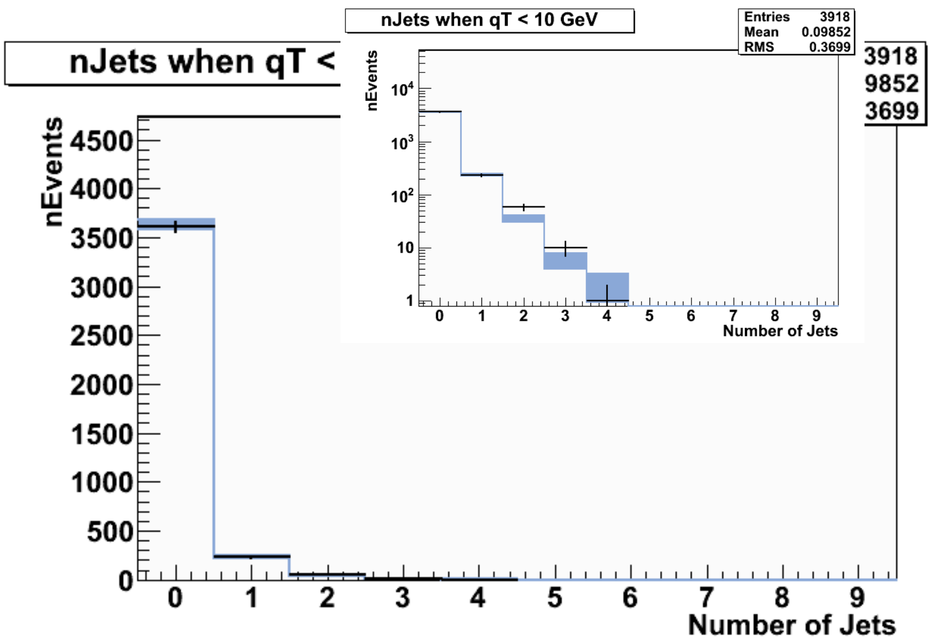
$$S = \frac{1}{\sqrt{2}}\sqrt{\left(\frac{|\mathbf{p}_{T,1}+\mathbf{p}_{T,2}|}{\sqrt{p_{T,1}+p_{T,2}}}\right)^2 + \left(\frac{|\mathbf{p}_{T,3}+\mathbf{p}_{T,4}|}{\sqrt{p_{T,3}+p_{T,4}}}\right)^2}.$$

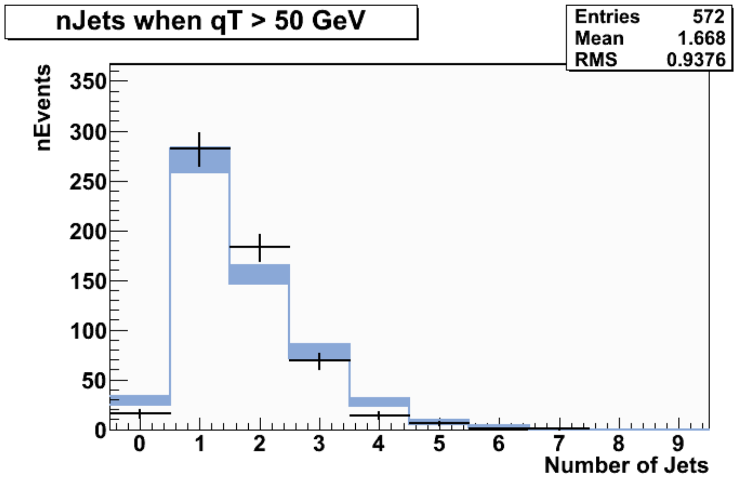
- Similar to variable used in CDF MPI analysis using 4 jet events (and also being used in a similar analysis at NWU using 4 jets)
- p_1 and p_2 are the muon p_T, p_3 and p_4 are the p_T of the jets
- Looks promising as a discriminating variable in the simulation
  - Even with full 2010 dataset there are large statistical error on data (one needs a Z event with 2+ jets to construct the variable)

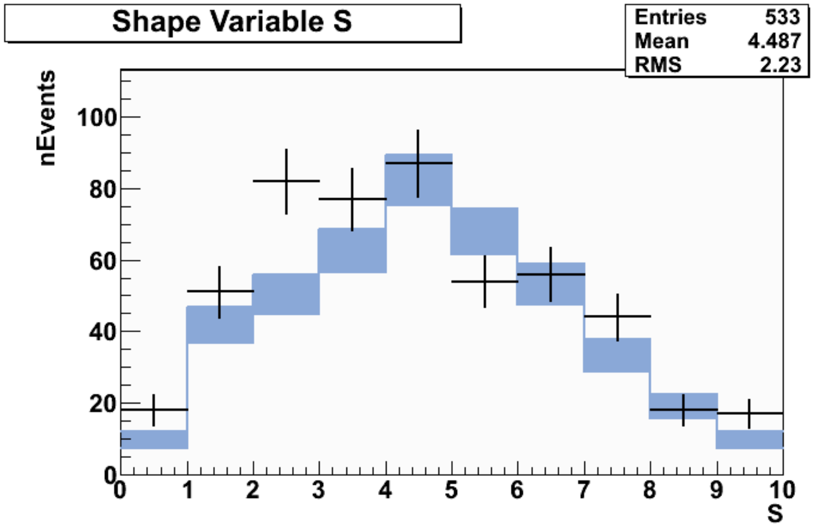
- Top: **MPI Forced ON** and **Default MPI** with early data. The distributions have clearly different shapes
- Bottom: Full 2010 dataset for muon events, possible excess at low S needs further study (maybe left over pileup). The excess is less pronounced in the electron data (see next slide)

Electron Channel

- Consistent with muons, so I'll just flash some plots here







Conclusion

- A new approach for measuring and verifying MPI in data and MC is presented, and it seems promising
- Enhancements in MPI can effect both jet multiplicity and kinematics in ways which can be exploited
- 36 pb^{-1} have been analyzed and no strong evidence for MPI enhancement over current Pythia models is seen
  - Clear evidence in favor of MPI, and that the current pythia6/8 MPI models are doing a decent job
- Analysis being repeated with 2011 data now
  - much better statistics, but also much trickier due to large increase in pileup
  - Publication planned

BACKUP

Mass bin, GeV	Acceptance, %	Acc * Eff, %	FSR correction,%	FSR correction in the acceptance, %
15-20	1.23±0.01	1.00±0.01	97.28±0.02	96.30±0.02
20-30	5.69±0.03	4.44±0.03	97.28±0.02	97.99±0.02
30-40	23.53±0.10	19.56±0.10	98.43±0.03	98.77±0.03
40-50	34.79±0.18	30.06±0.17	104.01±0.08	105.87±0.09
50-60	41.19±0.24	36.20±0.23	120.19±0.26	125.06±0.30
60-76	47.35±0.19	41.87±0.19	166.42±0.52	175.11±0.57
76-86	50.62±0.14	45.54±0.14	167.07±0.39	169.84±0.40
86-96	51.78±0.05	47.05±0.05	91.63±0.03	91.62±0.03
96-106	53.14±0.21	48.50±0.21	88.01±0.13	88.14±0.13
106-120	54.61±0.41	49.61±0.42	91.31±0.22	91.23±0.22
120-150	56.60±0.55	51.77±0.56	93.15±0.27	93.10±0.27
150-200	60.83±0.87	54.95±0.89	94.32±0.40	94.95±0.38
200-600	67.69±1.21	60.91±1.27	92.76±0.65	93.10±0.63

Table 1: DY acceptance and acceptance times efficiency per invariant mass bin for DY $\rightarrow \mu^+\mu^-$. In addition, the correction factors from the pre-FSR to post-FSR mass distributions are given.

Mass bin, GeV	combined efficiency correction	
	muon channel	electron channel
15-20	0.917 ± 0.010	1.098 ± 0.087
20-30	0.915 ± 0.010	1.089 ± 0.091
30-40	0.919 ± 0.011	1.107 ± 0.103
40-50	0.933 ± 0.011	1.076 ± 0.081
50-60	0.946 ± 0.008	1.034 ± 0.053
60-76	0.955 ± 0.006	1.008 ± 0.033
76-86	0.961 ± 0.004	0.995 ± 0.024
86-96	0.963 ± 0.003	0.979 ± 0.019
96-106	0.964 ± 0.003	0.973 ± 0.018
106-120	0.964 ± 0.003	0.960 ± 0.018
120-150	0.959 ± 0.010	0.953 ± 0.019
150-200	0.960 ± 0.021	0.945 ± 0.020
200-600	0.960 ± 0.021	0.940 ± 0.020

le 3: Combined efficiency corrections for the muon and electron channels per mass
y account for the data/MC differences in reconstruction, identification, isolation and trig
ciencies.

ss bin, GeV	N_{obs}	Backgrounds		$N_{obs} - N_{bg}$	N_{unf}
		EWK and $t\bar{t}$	QCD		
5-20	253 ± 16	1	$11 \pm 8(syst)$	$241 \pm 16 \pm 8(syst)$	243 ± 1
0-30	809 ± 28	15	$59 \pm 21(syst)$	$735 \pm 28 \pm 22(syst)$	736 ± 2
0-40	986 ± 31	30	$46 \pm 15(syst)$	$910 \pm 32 \pm 16(syst)$	907 ± 3
0-50	684 ± 26	30	$22 \pm 8(syst)$	$632 \pm 27 \pm 10(syst)$	631 ± 2
0-60	471 ± 22	25	$11 \pm 7(syst)$	$435 \pm 22 \pm 9(syst)$	436 ± 2
0-76	797 ± 28	22	$7 \pm 6(syst)$	$768 \pm 28 \pm 8(syst)$	752 ± 3
6-86	1761 ± 42	6	–	1755 ± 42	$1471 \pm$
6-96	11786 ± 109	25	–	11761 ± 109	$12389 \pm$
6-106	909 ± 30	5	–	904 ± 30	591 ± 3
6-120	194 ± 14	3	–	191 ± 14	178 ± 1
0-150	145 ± 12	4	–	141 ± 12	142 ± 1
0-200	53 ± 7	4	–	49 ± 8	47 ± 9
0-600	30 ± 6	3	–	27 ± 6	28 ± 6

4: Observed data yields, estimated backgrounds, and background-corrected and
d signal yields for DY $\rightarrow \mu^+\mu^-$.

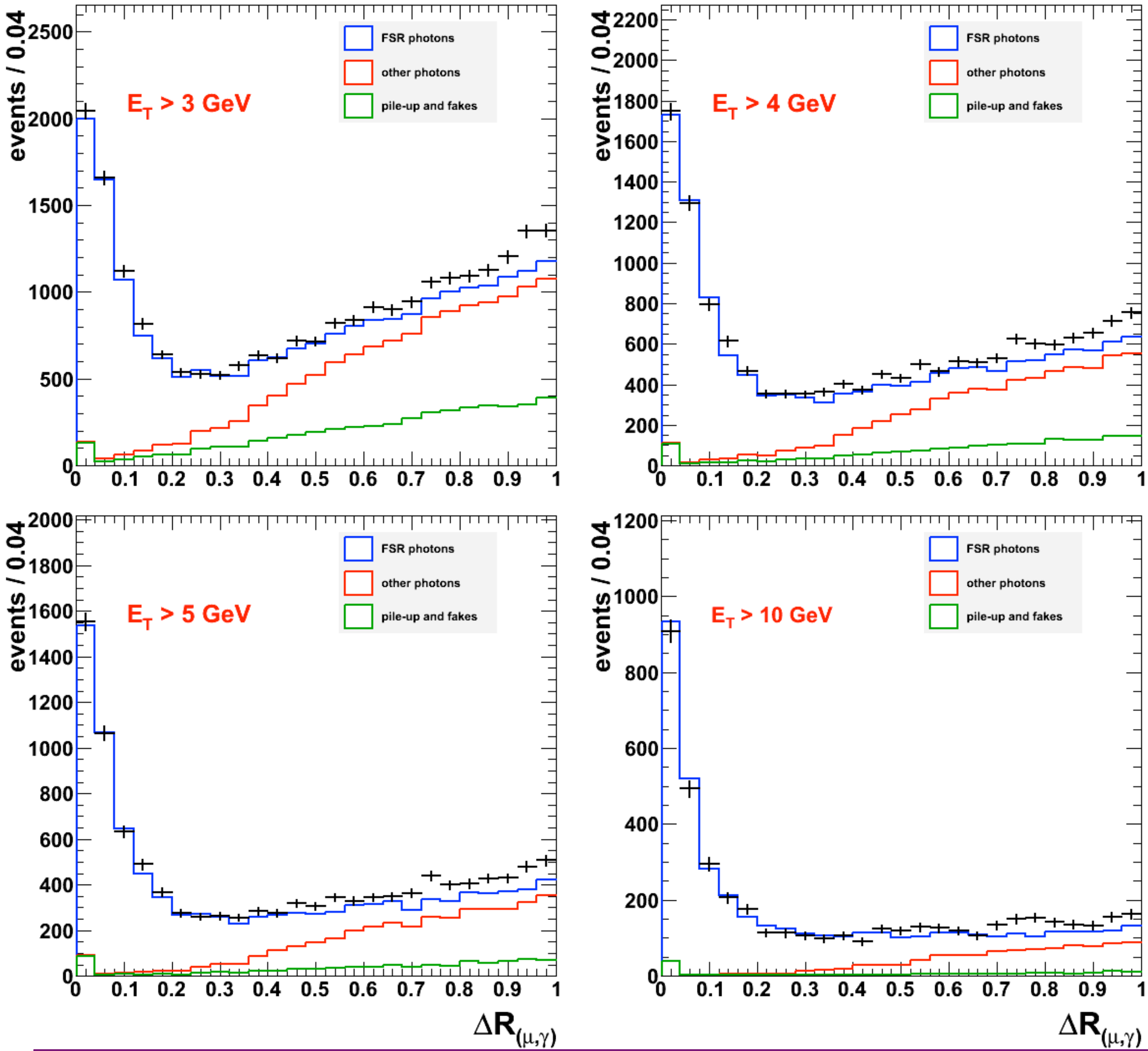
	Cross section (pb)			R	Uncertainties on R (%	
lass bin, GeV	CT10	CTEQ66	MSTW2008	MSTW2008	PDF	Other
5–20	786.6	810.5	819.1	0.812	+4.3/−3.3	+2.5/−2.
0–30	476.4	482.5	498.8	0.494	+3.6/−2.8	+1.9/−3.
0–40	134.5	136.7	142.1	0.141	+2.7/−2.3	+3.1/−2.
0–50	53.4	54.0	55.8	0.0553	+2.1/−1.9	+2.4/−2.
0–60	27.4	27.3	28.5	0.0282	+1.6/−1.5	+2.6/−2.
0–76	32.1	32.2	33.3	0.0330	+0.9/−0.9	+2.0/−2.
6–86	56.4	57.1	58.4	0.0579	+0.2/−0.2	+2.1/−2.
6–96	822.4	825.3	851.7	0.8441	+0.1/−0.1	+1.8/−2.
6–106	51.4	50.5	52.9	0.0524	+0.2/−0.2	+2.8/−2.
06–120	12.4	12.4	12.9	0.0127	+0.5/−0.5	+2.6/−2.
20–150	6.71	6.71	7.00	0.00694	+0.9/−0.9	+2.5/−1.
50–200	2.64	2.61	2.71	0.00269	+1.5/−1.6	+2.0/−1.
00–600	1.28	1.26	1.32	0.00131	+2.8/−2.9	+1.8/−2.

le 8: Theoretical predictions at NNLO with FEWZ and three sets of PDFs. The cross secti
ıis table are calculated in the full phase space. The theoretical predictions of the ratio R
ıncertainties are also given. "Other" contains uncertainties from EWK correction, s
endence and α_S.

mass bin, GeV	$R_{\text{DET,post-FSR}}, 10^{-3}$	$R_{\text{DET}}, 10^{-3}$	$R_{\text{post-FSR}}, 10^{-3}$	$R, 10^{-3}$
15–20	18.5 ± 1.5	18.9 ± 1.6	774.4 ± 67.4	782.2 ± 69.2
20–30	58.5 ± 3.2	58.6 ± 3.3	529.4 ± 33.4	534.7 ± 34.4
30–40	67.4 ± 3.1	67.0 ± 3.1	147.4 ± 8.1	147.4 ± 8.2
40–50	44.4 ± 2.3	41.2 ± 2.2	65.7 ± 3.9	62.1 ± 3.8
50–60	29.8 ± 1.8	23.4 ± 1.5	37.2 ± 2.5	30.4 ± 2.1
60–76	50.5 ± 2.3	28.3 ± 1.3	55.0 ± 2.9	32.4 ± 1.7
76–86	96.5 ± 4.3	55.8 ± 2.5	98.2 ± 5.0	57.8 ± 3.0
86–96	803.3 ± 13.5	861.0 ± 14.7	799.0 ± 23.4	856.8 ± 25.5
96–106	38.1 ± 2.9	42.5 ± 3.3	36.9 ± 2.9	41.2 ± 3.3
106–120	11.5 ± 1.2	12.4 ± 1.3	10.9 ± 1.2	11.7 ± 1.3
120–150	9.2 ± 0.9	9.7 ± 1.0	8.4 ± 0.8	8.8 ± 0.9
150–200	3.1 ± 0.6	3.2 ± 0.7	2.6 ± 0.5	2.7 ± 0.6
200–600	1.8 ± 0.4	1.9 ± 0.5	1.4 ± 0.3	1.5 ± 0.4

9: Results for the DY spectrum normalized to the Z peak in the dimuon channel. ical and systematic uncertainties are summed in quadrature. $R_{\text{post-FSR}}$ and $R_{\text{DET,pos}}$ lculated using Eqs. 9 and Eq. 10, respectively. R_{DET} and R are calculated using the tions given in Table 1.

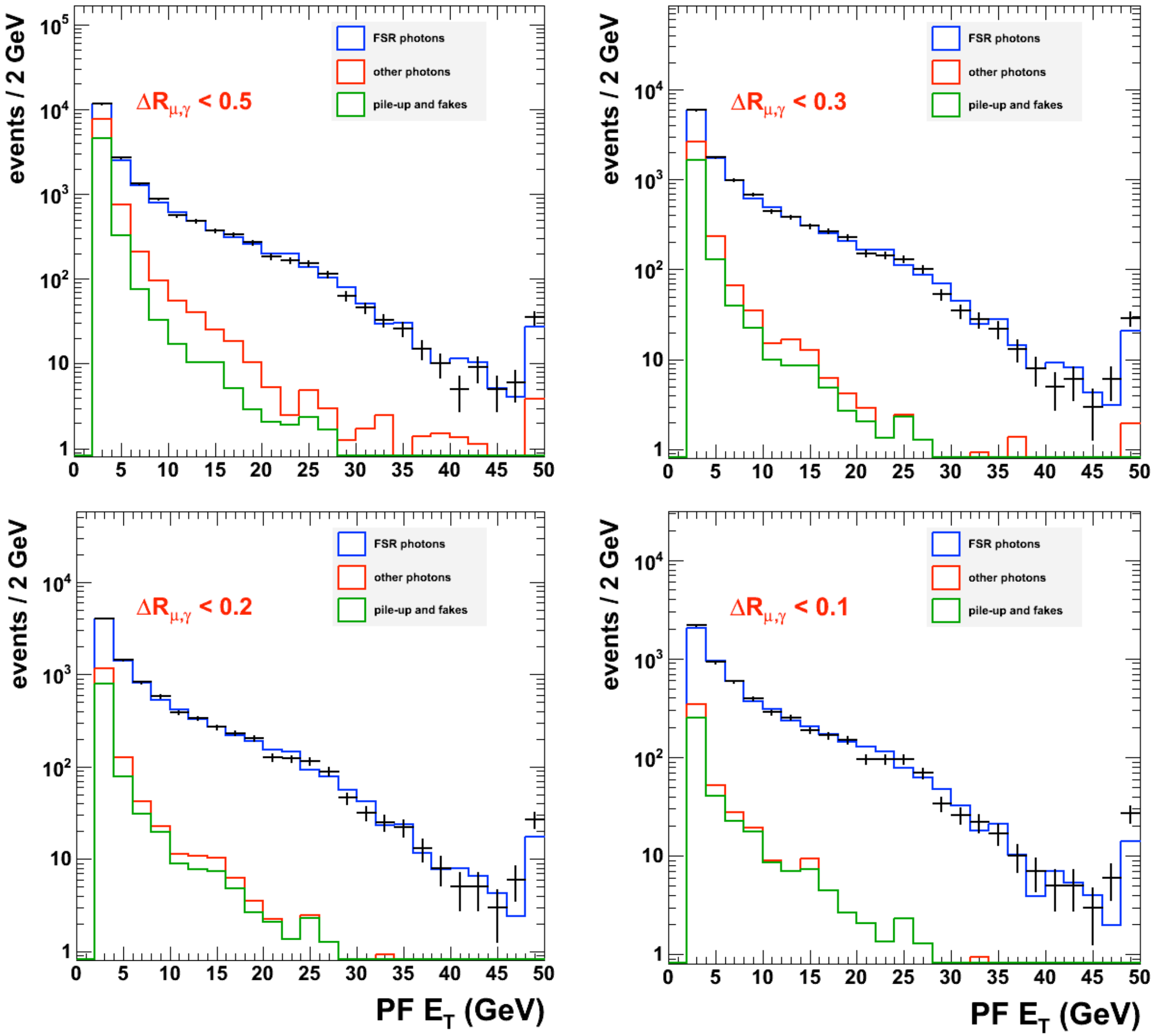
First Case: Photons near Muon



- The same ΔR plots for varying cuts on photon E_T

- Color code:
  - BLUE: matched to FSR
  - RED: matched to background
  - GREEN: Unmatched
  - BLACK: Data

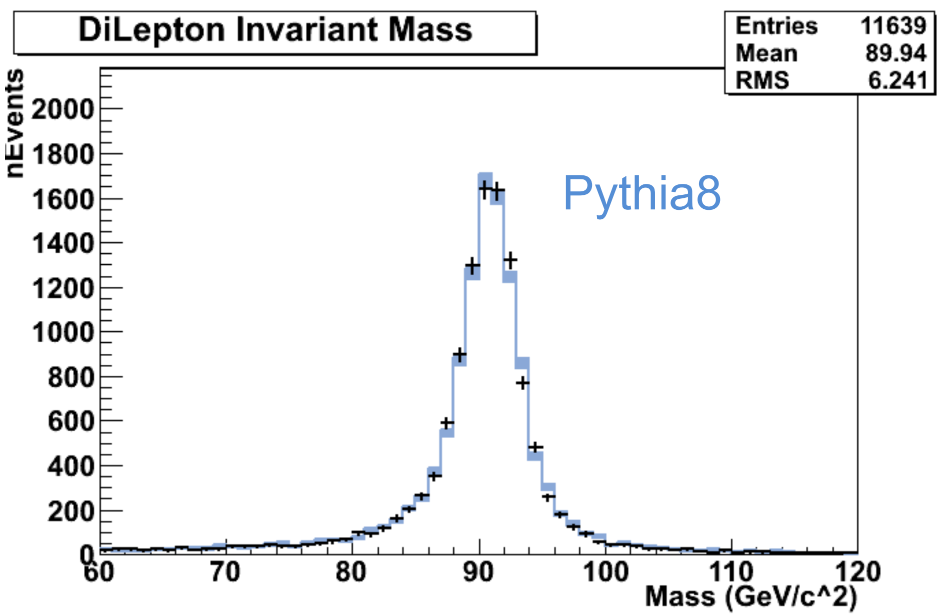
Data/MC Comparisons (IV)

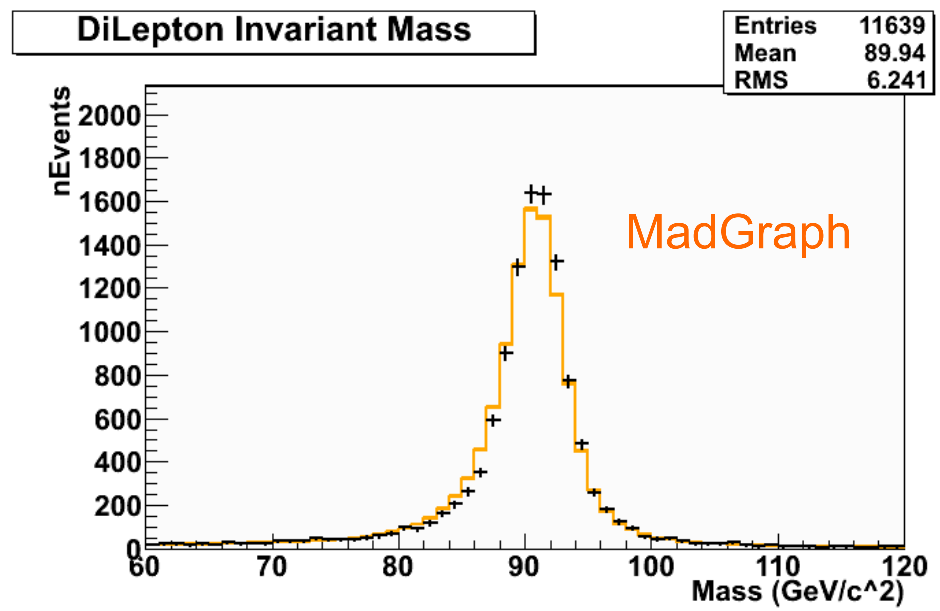


- Plot the energy distribution for various cuts on ΔR
- As ΔR becomes tighter, background is much reduced
- Color code:
  - BLUE: matched to FSR
  - RED: matched to background
  - GREEN: Unmatched
  - BLACK: Data

$\mu^+ \mu^-$ Mass

Both the pythia8 and Madgraph samples reproduce the Z mass distribution well





Verifying jet multiplicities with Madgraph

- We've also carried out the analysis with an official madgraph Z+jets sample (including pileup and Z2 tune)
- Results are consistent