Supersymmetry Searches with 2 Photons + Jets + Missing Energy and Photon + Lepton + Missing Energy Final States

Rachel Yohay
University of Virginia
Status of Higgs and BSM Searches at the LHC
April 13, 2011

on behalf of the CMS collaboration

Outline

- General gauge mediation (GGM) searches at the LHC
  - Production mechanisms
  - Next-to-lightest superpartner (NLSP) type → final state
- Bino NLSP: 2 photons + jets + missing transverse energy (ME_T)
  - Candidate event selection
  - Background estimation
  - Photon efficiency
  - Results
  - Interpretation in terms of simplified model spectra (SMS)
- Wino/bino co-NLSP: lepton + photon + jets + ME_T
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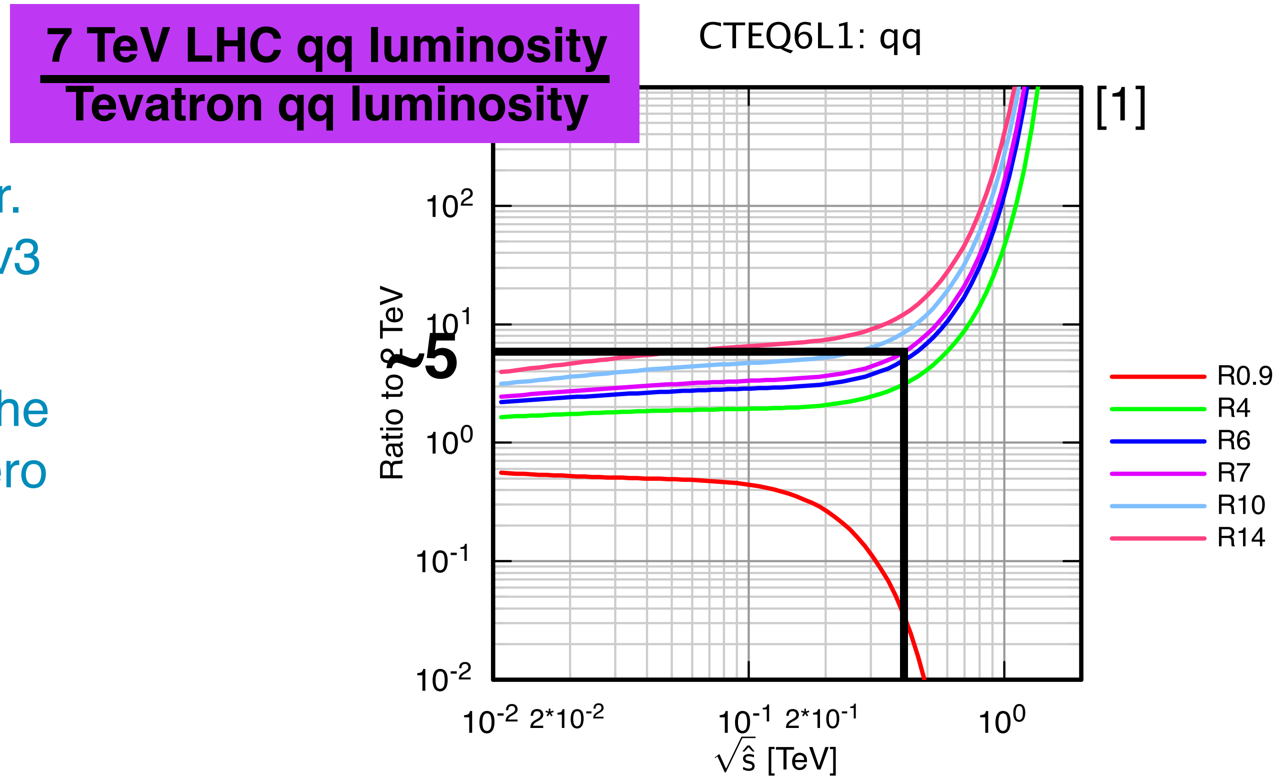
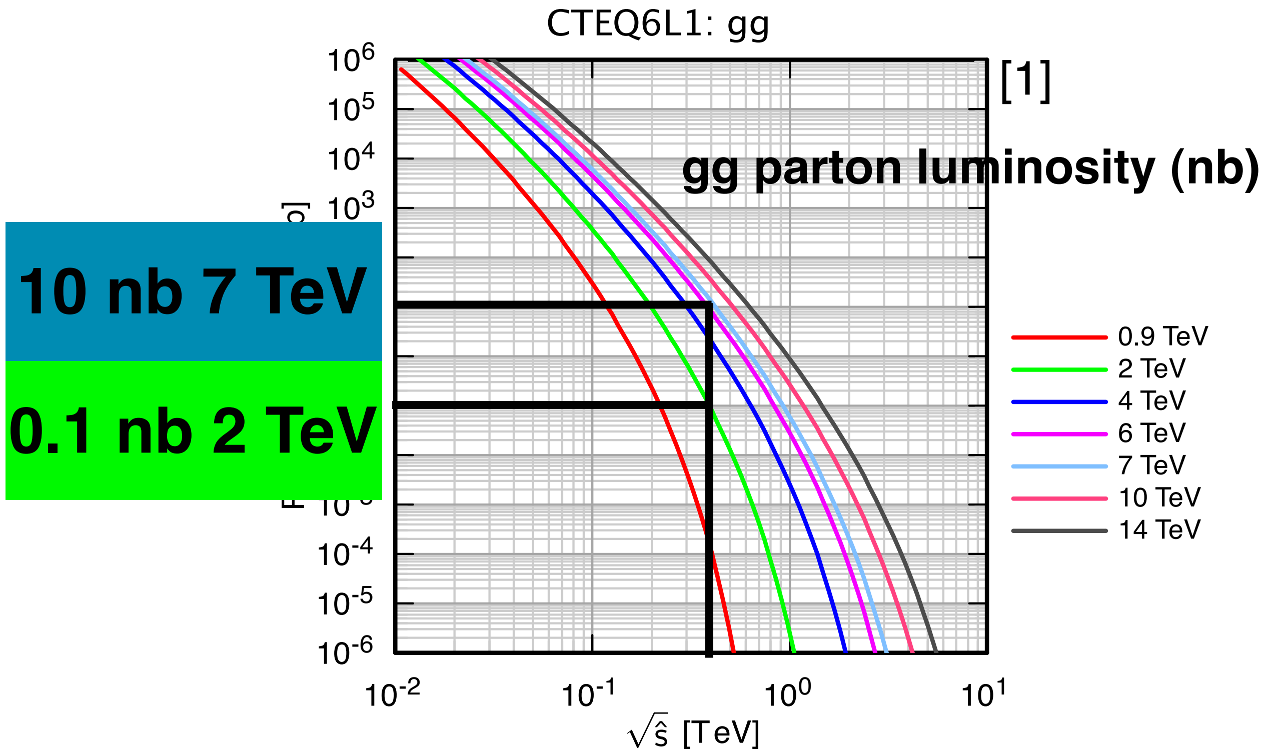
General gauge mediation at the LHC

- General gauge mediation (GGM)
  - P. Meade, N. Seiberg, and D. Shih, Prog. Theor. Phys. Suppl. **177** (2009) 143 (arXiv:0801.3278v3 [hep-ph])
  - Definition of gauge mediation: the MSSM and the SUSY-breaking sector are linked only by nonzero values of the MSSM gauge coupling constants
  - Different theories of gauge mediation can arise from the single general framework
  - Prescription provided for calculating the soft masses of the spectrum
  - SUSY-breaking sector leads to mass relations between the sfermions, constraining the allowed parameter space
- Consequences for phenomenology
  1. **Models with light squarks and gluinos not ruled out—ideal for LHC searches because of enhancement of gg PDF with respect to quark-antiquark**
  2. **Lightest neutralino NLSP can be bino, wino, or higgsino**



7 TeV LHC qq luminosity / Tevatron qq luminosity

~5



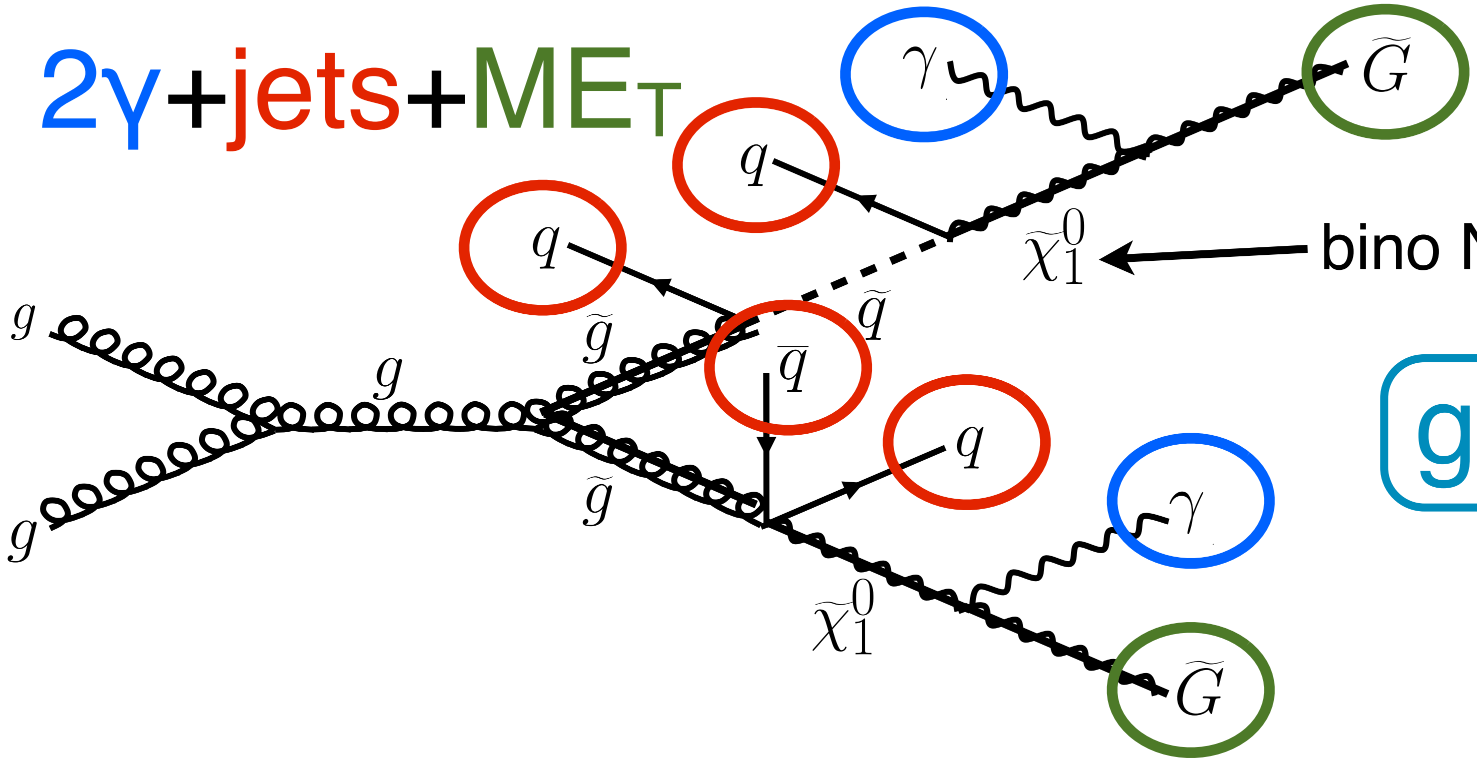
gg parton luminosity (nb)

10 nb 7 TeV

0.1 nb 2 TeV

GGM final states

2γ+jets+ME_T



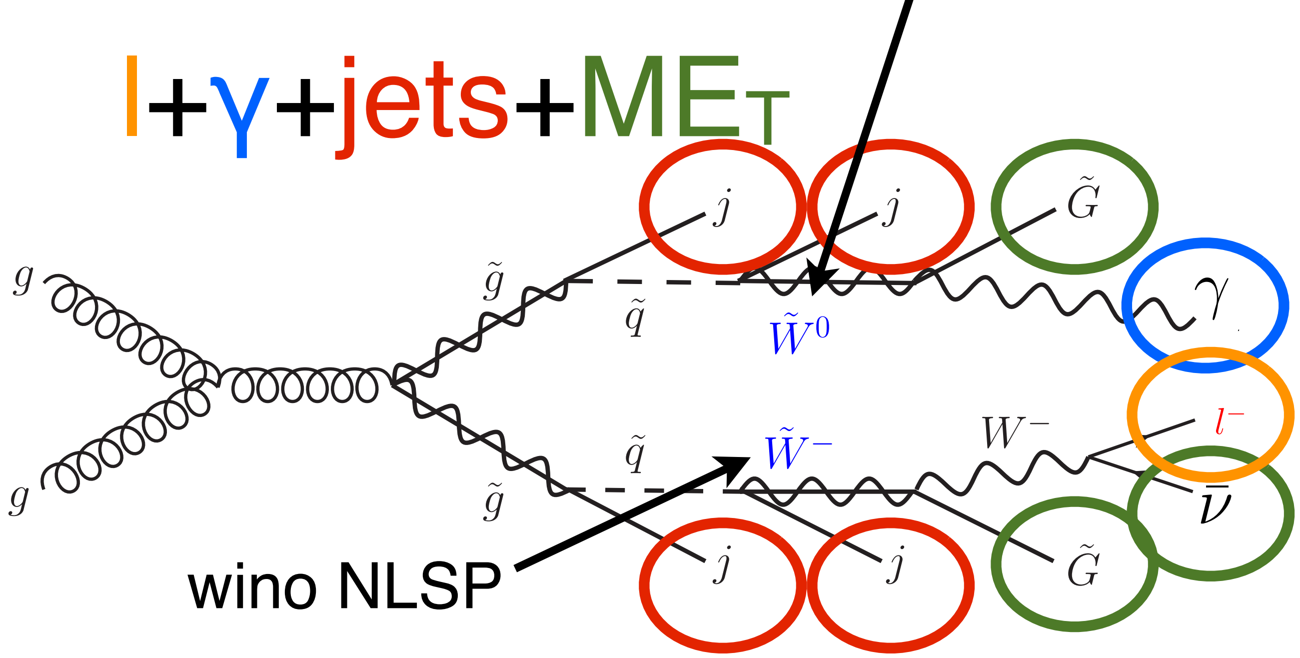
bino NLSP

gg production dominates

Bino NLSP: neutralino(bino)→**γ+gravitino**

bino NLSP

l+γ+jets+ME_T



wino NLSP

Wino/bino co-NLSP: neutralino(bino)→**γ+gravitino or** chargino(charged wino)→**l+gravitino**

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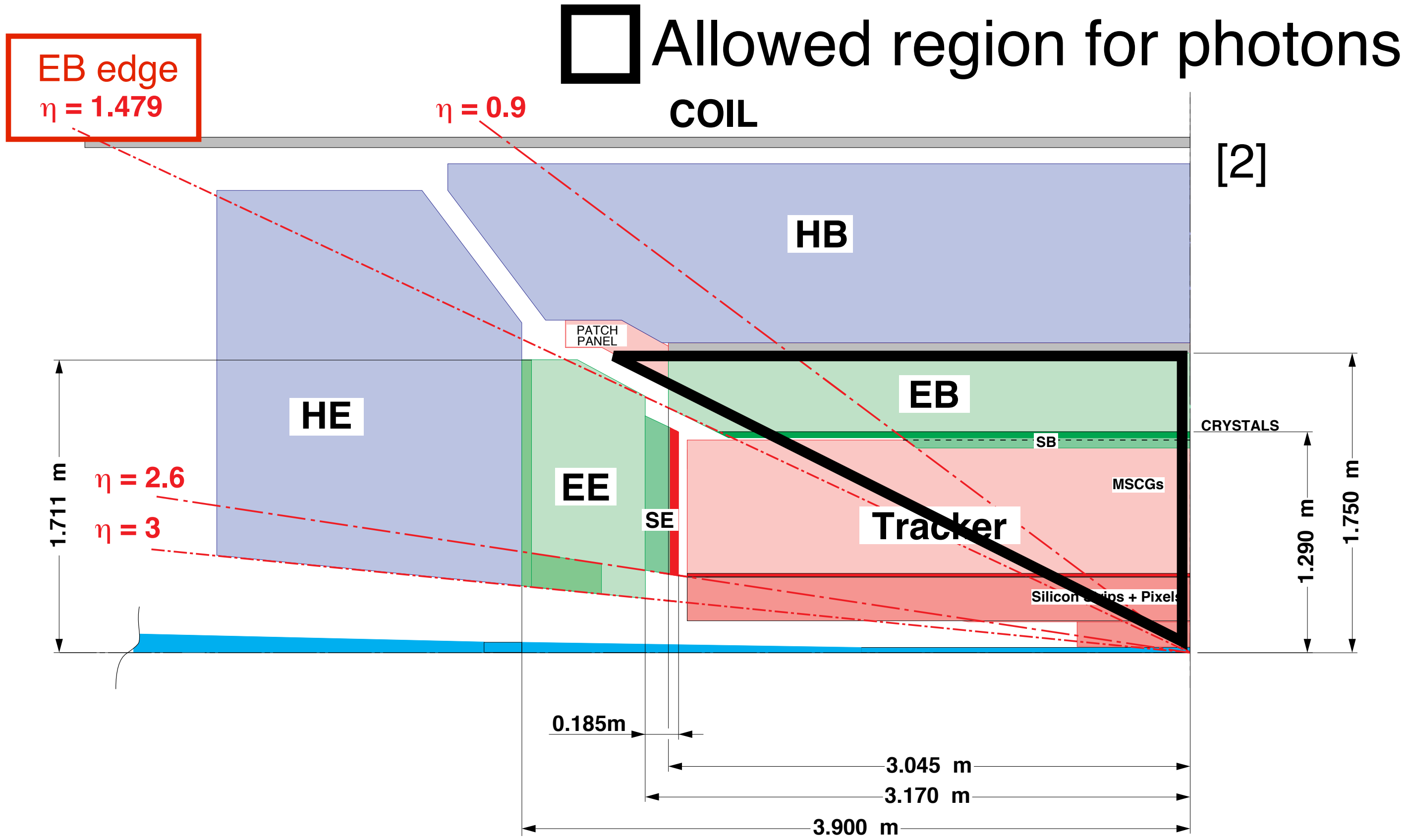
Photon selection

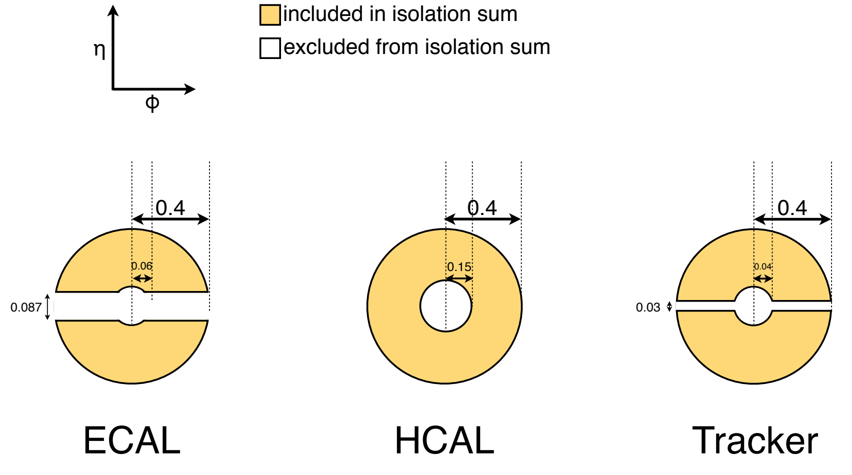


- Candidate events must pass a photon high level trigger
  - First 27.5 pb^{-1}: unprescaled 30 GeV single photon trigger
  - Last 8.0 pb^{-1}: unprescaled 22 GeV diphoton trigger
  - Both triggers seeded by single 8 GeV electromagnetic calorimeter (ECAL) energy deposit

- Each candidate event contains at least 2 isolated photons
  - **$E_T > 30$ GeV**
  - Inconsistent with electromagnetic calorimeter (ECAL) noise
  - No matching hit in the silicon pixel detector

- $|\eta| < 1.379$
  - Within the ECAL barrel (EB) excluding the edges, and within the silicon tracker coverage
  - Less background from jets
  - Photons from neutralino decay tend to be produced centrally

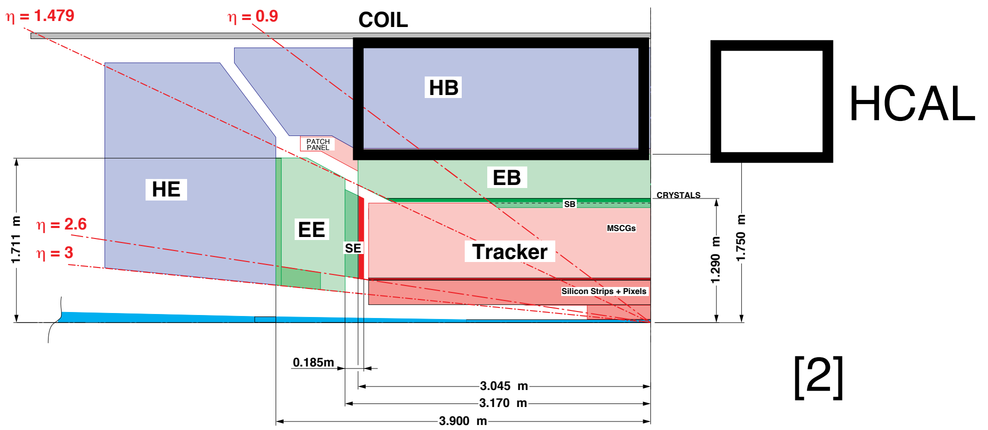
Photon isolation criteria



not to scale

- ECAL isolation energy $< 0.006E_T + 4.2$ GeV
- HCAL isolation energy $< 0.0025E_T + 2.2$ GeV
- Tracker isolation energy $< 0.001E_T + 2.0$ GeV

$$\frac{\text{HCAL energy in } R < 0.15 \text{ cone around photon candidate}}{\text{ECAL energy of photon candidate}} < 0.05$$



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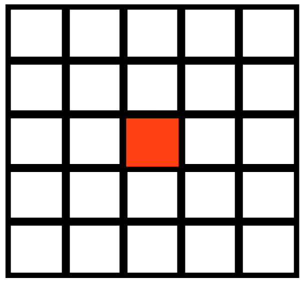


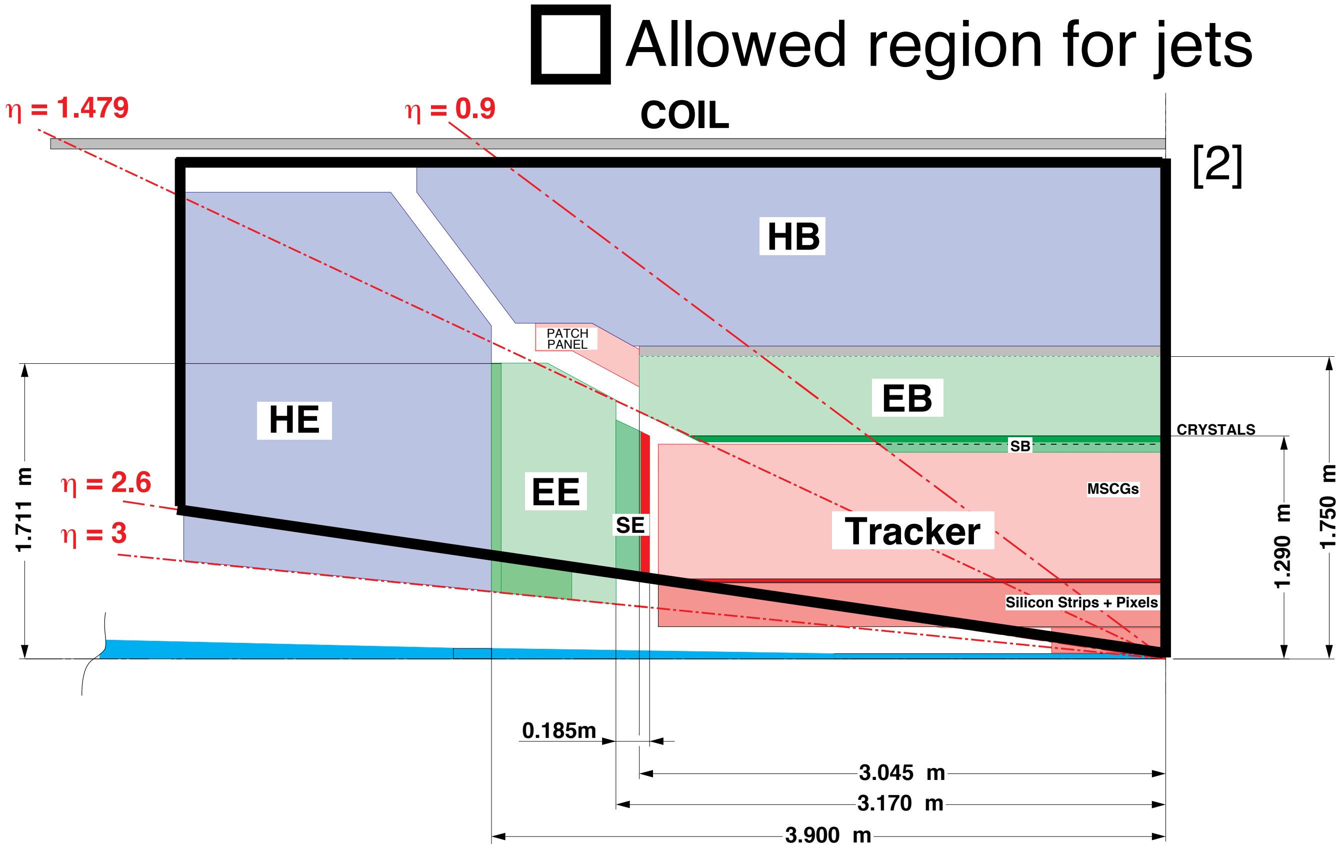
🟥 Highest energy (photon seed) crystal

$$\sigma_{\eta\eta}^2 = \sum_{i=1}^{25} w_i(\eta_i - \bar{\eta})^2 \Big/ \sum_{i=1}^{25} w_i, \qquad < 0.013$$

where $w_i = \max(0, 4.7 + \ln(E_i/E))$, E_i is the energy of the i^{th} crystal in a group of 5×5 centred on the one with the highest energy, and $\eta_i = \hat{\eta}_i \times \delta\eta$, where $\hat{\eta}_i$ is the η index of the ith crystal and $\delta\eta = 0.0174$; E is the total energy of the group and $\bar{\eta}$ the average η weighted by w_i in the same group [20]. [3]

Jet selection

- Strong production guarantees that most events contain at least one hard jet
- Presence of jet activity suppresses fake ME$_T$ backgrounds from beam halo and cosmic muon bremsstrahlung (equivalent to requiring a good vertex)



- Each candidate event contains at least 1 track-corrected jet (anti-k$_T$ algorithm with R = 0.5)
  - **E$_T$ ≥ 30 GeV**
  - **|η| ≤ 2.6**
  - Inconsistent with hadronic calorimeter (HCAL) noise
  - At least ΔR = 0.9 away from both photon candidates

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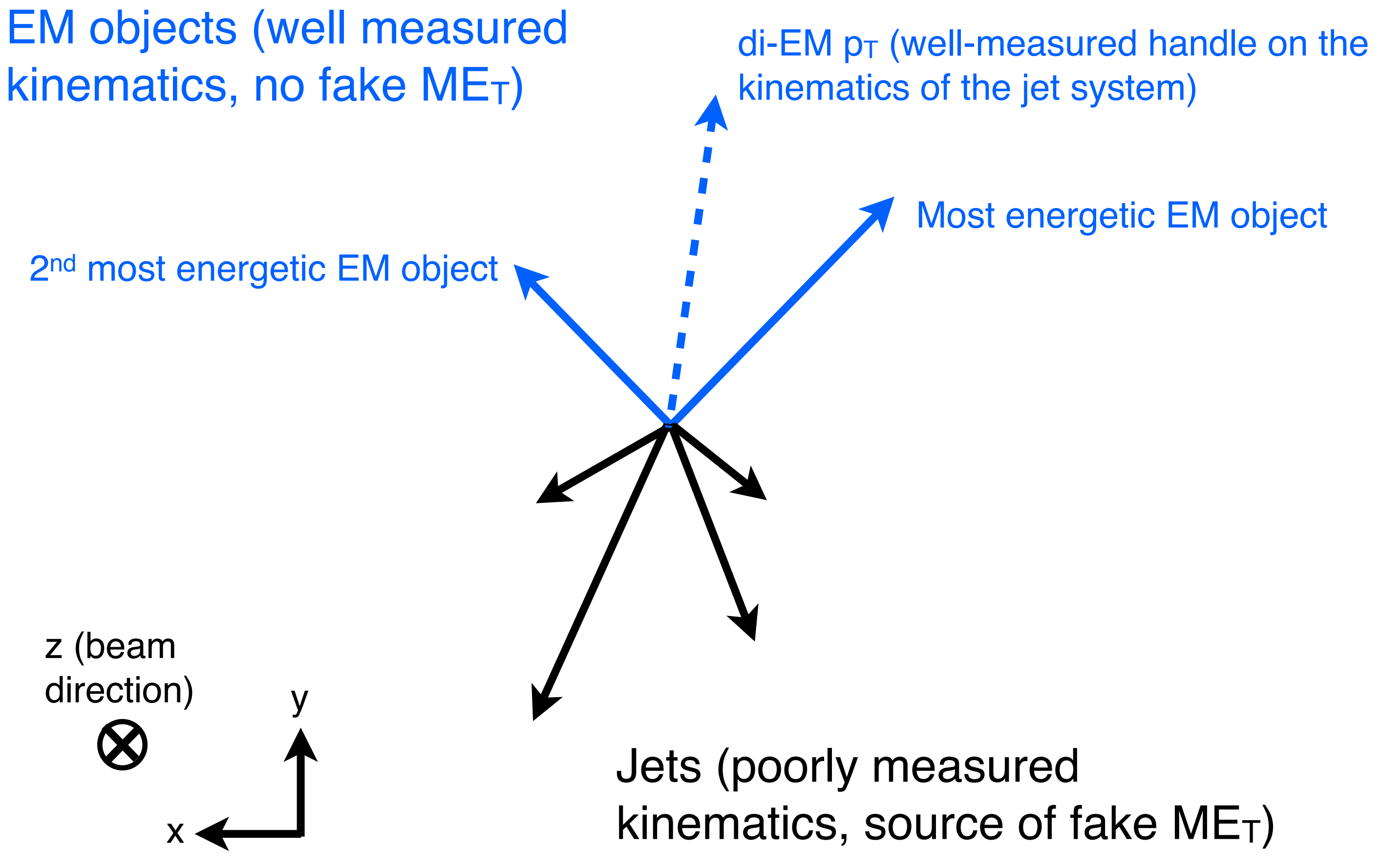
Relevant backgrounds

- Dominant: **QCD with fake ME_T**
  - Multijet: at least 2 jets misidentified as photons
  - γ+jet: 1 jet misidentified as a photon
  - QCD diphoton
- Subdominant: **electroweak processes with real ME_T**
  - $W(\rightarrow e\nu)\gamma$: electron misidentified as a photon
  - $W(\rightarrow e\nu)$+jet: electron and jet misidentified as photons
- Negligible: irreducible backgrounds
  - $W\gamma\gamma$ (total cross section ~7 fb at 14 TeV LHC) [4]
  - $Z\gamma\gamma$

Estimating the QCD background



EM objects (well measured kinematics, no fake ME_T)

di-EM p_T (well-measured handle on the kinematics of the jet system)

Most energetic EM object

2^{nd} most energetic EM object

z (beam direction)

Jets (poorly measured kinematics, source of fake ME_T)

QCD control sample	Identical to photon except...
EM object = fake	•Fake MUST fail $\sigma_{\eta\eta}$ OR track isolation cut on slide 8 •Fake MAY fail the pixel match veto •Fake MUST pass $\lvert t \rvert \leq 3$ ns and $\Delta\phi$(fake, fake) $\geq$ 0.05 (to fight beam halo)
EM object = electron	•Electron MUST fail the pixel match veto (i.e. it must have a pixel match) •Electron MUST pass $\lvert t \rvert \leq 3$ ns and $\Delta\phi$(electron, electron) $\geq$ 0.05 (to fight beam halo)

- Use the fact that the electromagnetic (EM) energy resolution is much better than the hadronic energy resolution, so fake ME_T is wholly determined by the hadronic jets

- Find a **data control sample** with 2 well-measured EM objects, just like the candidate sample, to model the QCD fake ME_T spectrum

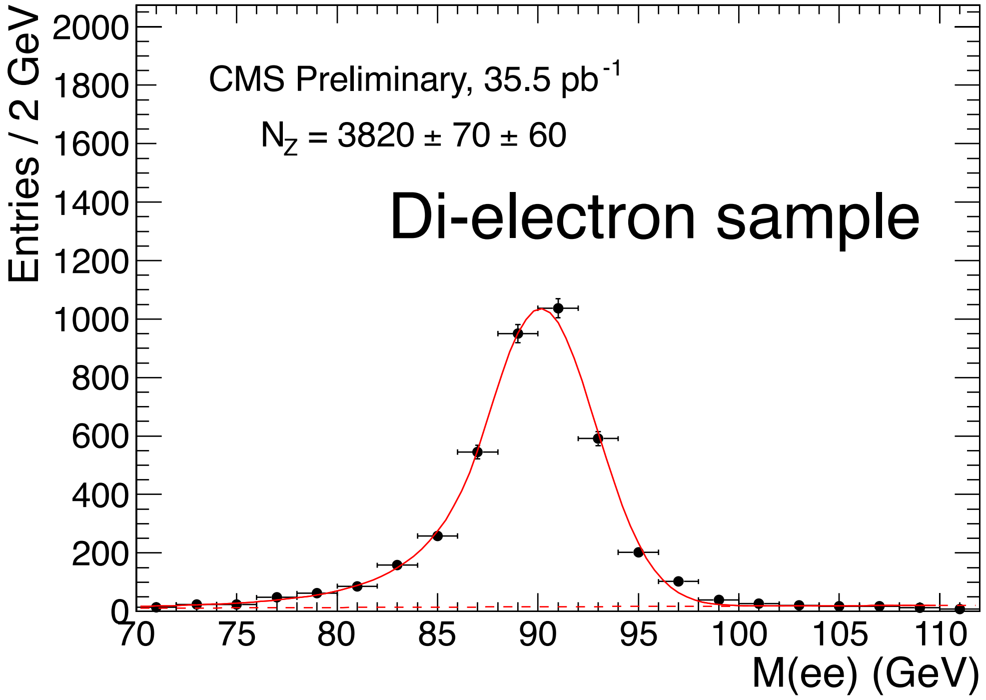
- Adjust for kinematic differences between the control and candidate samples by reweighting the ME_T spectrum of the control sample such that such that the p_T spectrum of its di-EM system matches that of the candidate sample

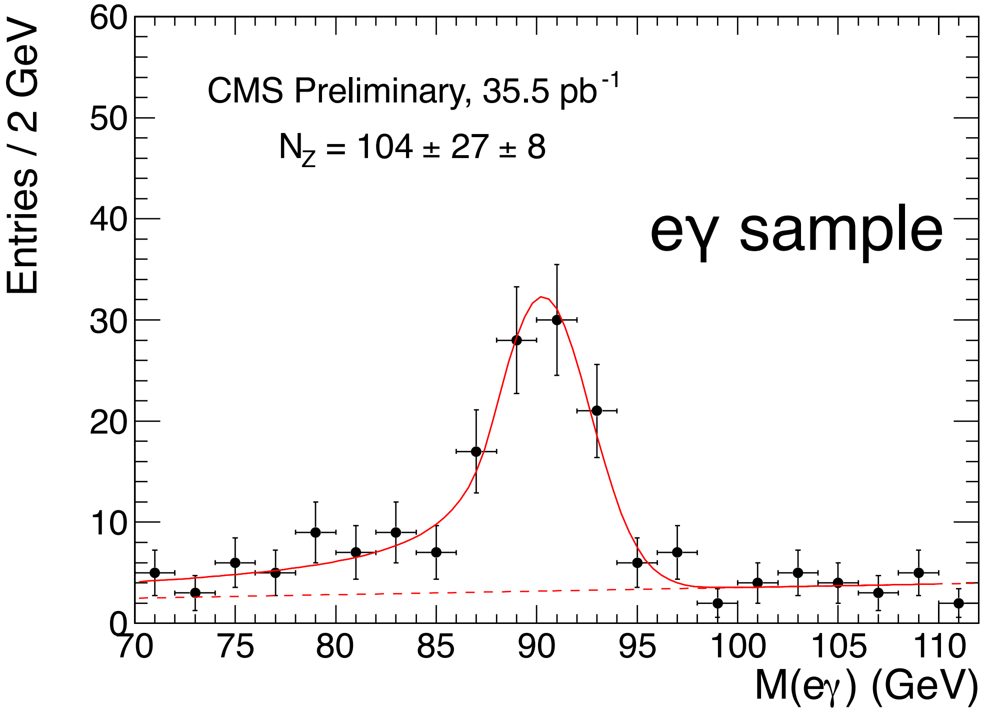
- Normalize the predicted QCD fake ME_T spectrum to the $ME_T < 20$ GeV region in the candidate sample, assuming negligible signal contamination there

“electron”: passes tight ID cuts + pixel match
“photon”: passes same tight ID cuts + pixel match *veto*

Estimating the electroweak background

- Wγ and W+jet can enter the candidate sample if the W decay electron is sometimes misidentified as a photon
- Use the eγ **data control sample**
    - Events with 1 object passing the electron criteria on slide 12 and 1 object passing the photon criteria on slides 7-8
    - Short version: e and γ differ ONLY in the presence/absence of a pixel match
- Scale the ME_T distribution of eγ events by $f_{e\to\gamma}/(1-f_{e\to\gamma})$ to get the predicted electroweak background, where $f_{e\to\gamma}$ is the electron→photon mis-ID rate
- Estimate $f_{e\to\gamma}$ by fitting the di-EM invariant mass spectra in the di-electron (slide 12) and eγ samples



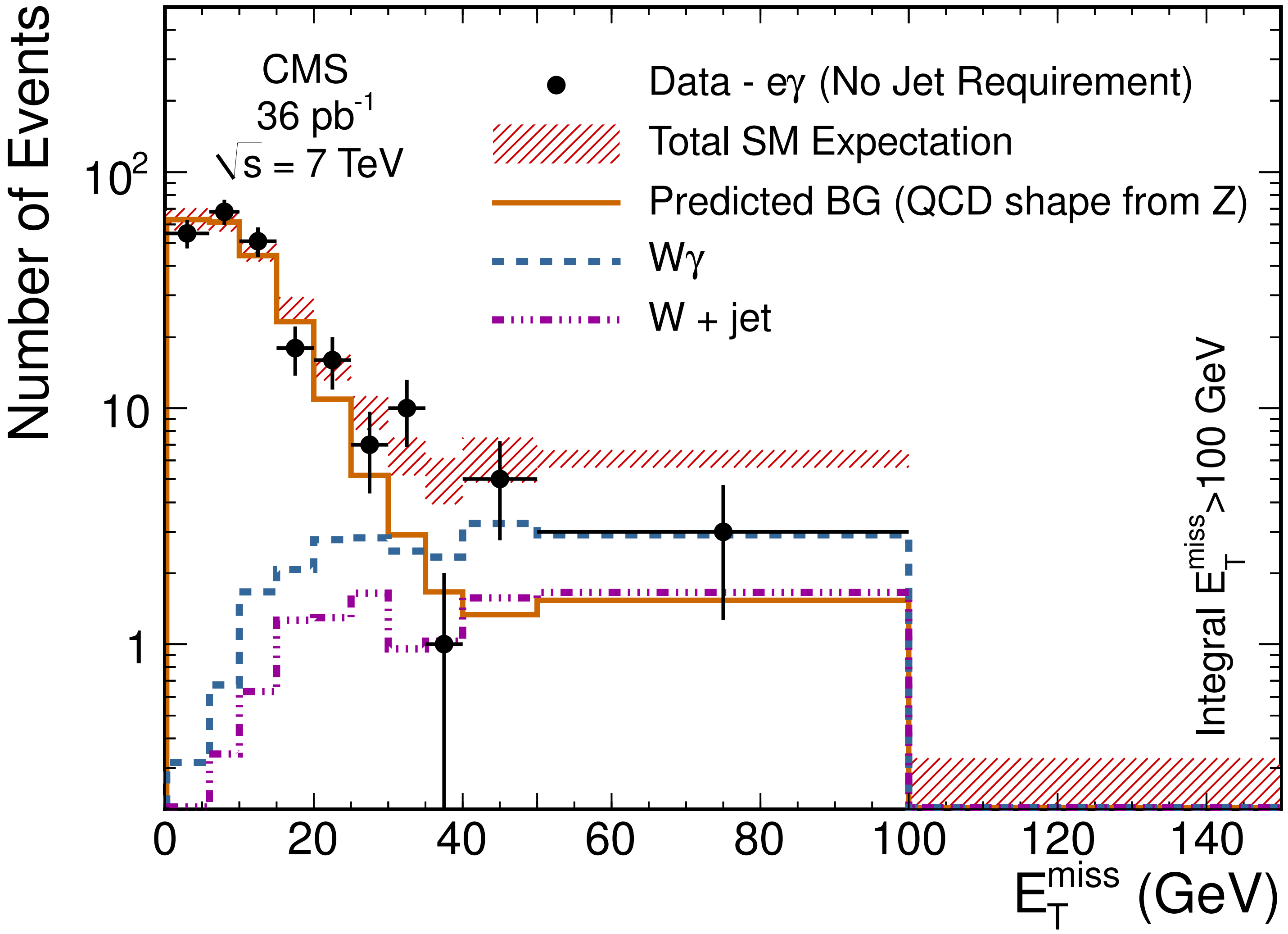


Stat. ⊕ fit ⊕ syst.(background shape linear→quadratic)

$$\boxed{f_{e\to\gamma} = 0.014 \pm 0.004}$$

Check of the background estimation

- Question: Can the QCD background prediction method described on slide 12 correctly predict the QCD contribution to the eγ (W-like) sample?
- Answer: Yes
  - Reweight the di-electron ME_T spectrum such that the di-electron p_T spectrum matches the eγ di-EM p_T spectrum (i.e. use the method described on slide 12 to get a prediction for the QCD component of the eγ sample)
  - Observe an excess (esp. for $ME_T > 30$ GeV) of eγ events over the predicted QCD background
  - Excess is consistent with expected yield of Wγ and W+jet Monte Carlo (MC)



[5]

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Photon ID efficiency

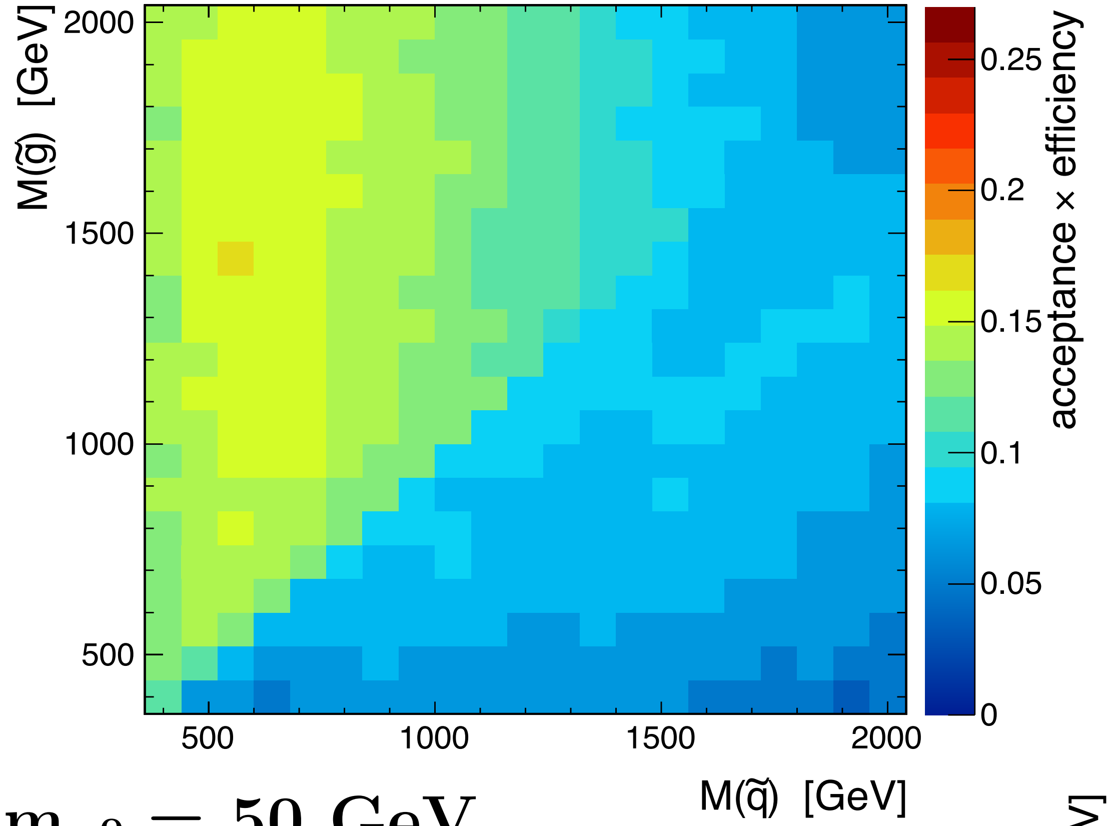
- Photon ID cuts (ECAL/HCAL/track isolation, H/E, and $\sigma_{\eta\eta}$) designed to behave similarly for electrons and photons
  - Our definition of “electron” only differs from our definition of “photon” by the presence of a pixel match
- Lacking a large, clean source of photons in the data, take **photon ID efficiency from MC**
- Use Z→ee events in data and MC to measure the efficiency of the photon ID cuts on electrons
- Scale the signal MC acceptance × efficiency by the ratio of electron efficiencies in data and MC to get a **data-driven correction**
- Data/MC scale factor: 0.967 ± 0.016

Stat. ⊕
Syst.(Z signal and background shape variation) ⊕
Syst.(Electron energy scale) ⊕
Syst.(pileup effects) ⊕
Syst.(MC electron/photon difference)

Stat. ⊕
Syst.(tracker material budget variation)

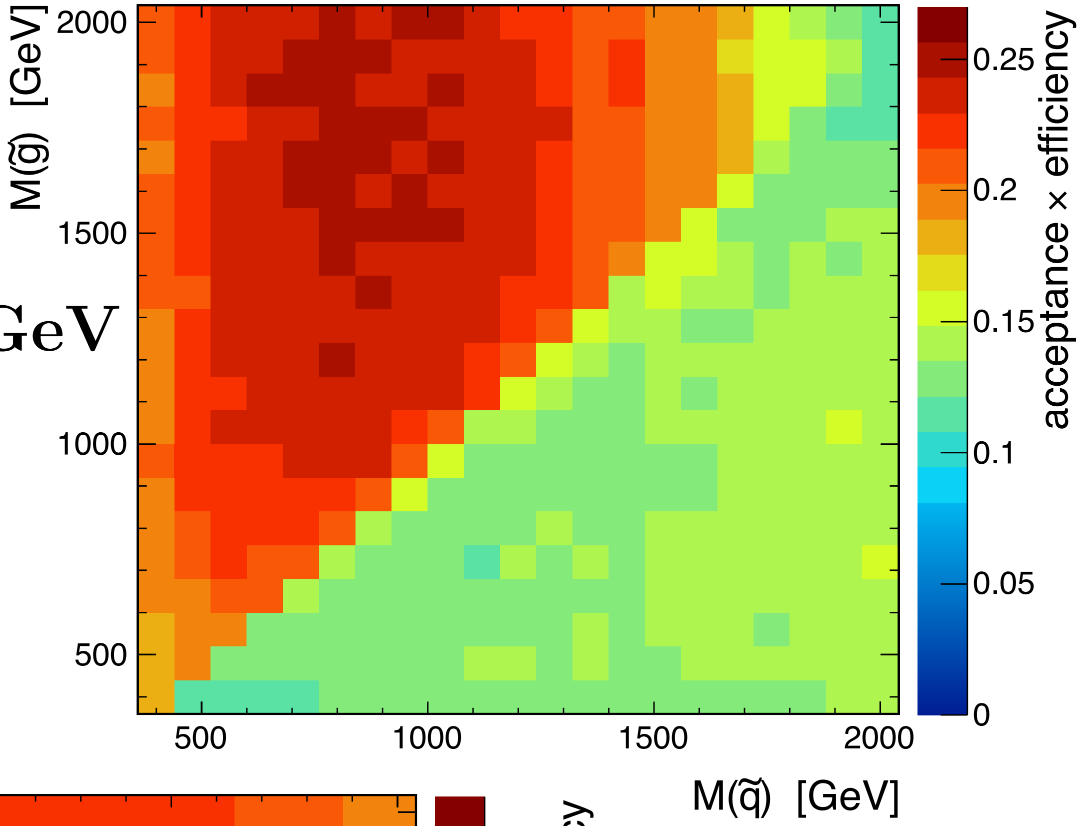
- Pixel veto efficiency **estimated from MC**: (96.4 ± 0.5)%

Signal acceptance

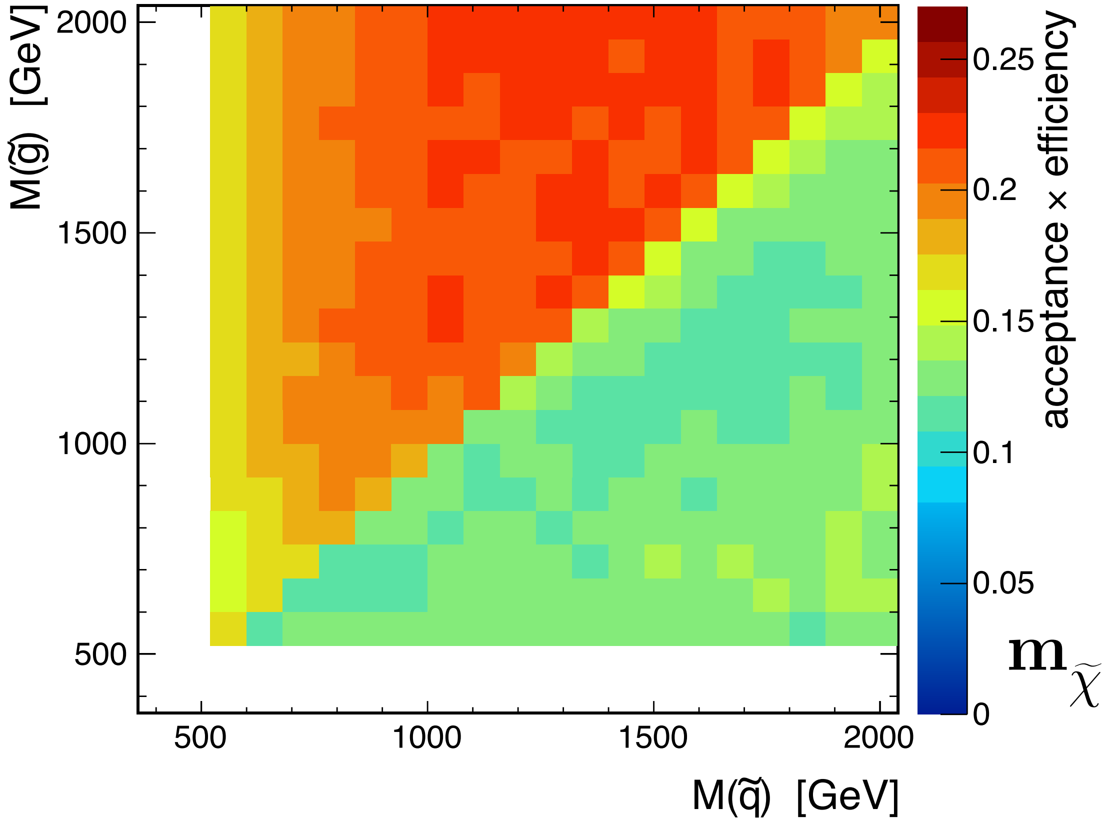


$\mathbf{m}_{\tilde{\chi}_1^0} = \mathbf{50\ GeV}$

$\mathbf{m}_{\tilde{\chi}_1^0} = \mathbf{150\ GeV}$



Stat. ⊕ syst.(11% luminosity) ⊕
syst.(photon ID efficiency) ⊕
syst.(pixel veto efficiency) ⊕
syst.(<2% jet energy scale variation) ⊕
syst.(10%-40% PDF uncertainty [6]) ⊕
syst.(10%-20% renormalization scale)



$\mathbf{m}_{\tilde{\chi}_1^0} = \mathbf{500\ GeV}$

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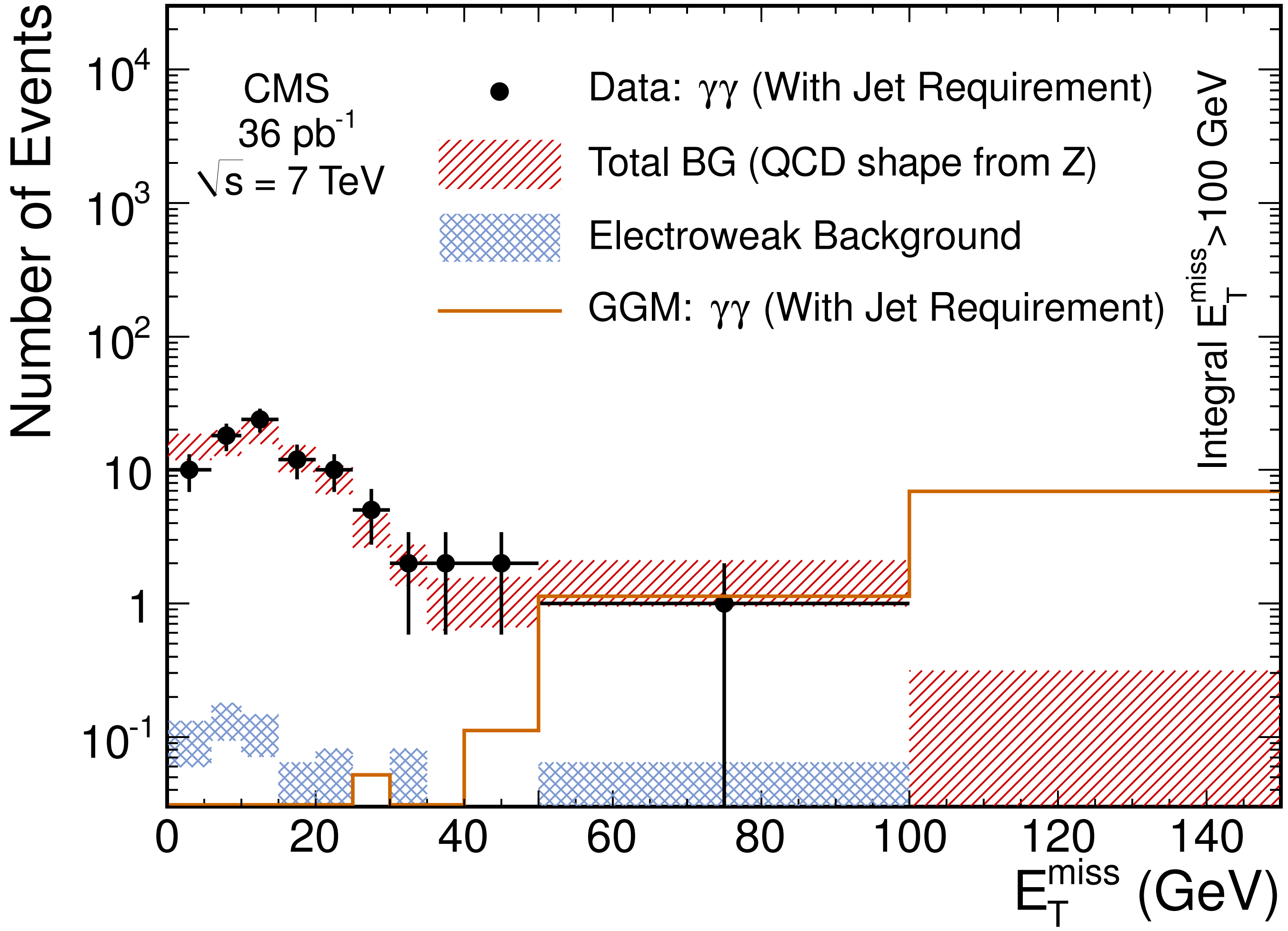
Candidate ME$_T$ spectrum



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Observed events consistent with predicted background

Example GGM model:
$\mathbf{m_{\tilde{g}} = 720\ GeV,\ m_{\tilde{q}} = 720\ GeV,\ m_{\tilde{\chi}_1^0} = 150\ GeV}$

Type	Number of events	Stat error	Reweight error	Normalization error
$\gamma\gamma$ events	1			
Electroweak background estimate	0.04 ± 0.03	± 0.02	± 0.0	± 0.01
QCD background estimate (*ff*)	0.49 ± 0.37	± 0.36	± 0.06	± 0.07
QCD background estimate (*ee*)	1.67 ± 0.64	± 0.46	± 0.38	± 0.23
Total background (using *ff*)	0.53 ± 0.37			
Total background (using *ee*)	1.71 ± 0.64			
Combined total background	1.2 ± 0.8			
Expected from GGM sample point	8.0 ± 1.7			

[5]

weighted average (with log-normal PDFs of the uncorrelated errors) of the 2 background estimates, + common EW component, ⊕ correlated errors

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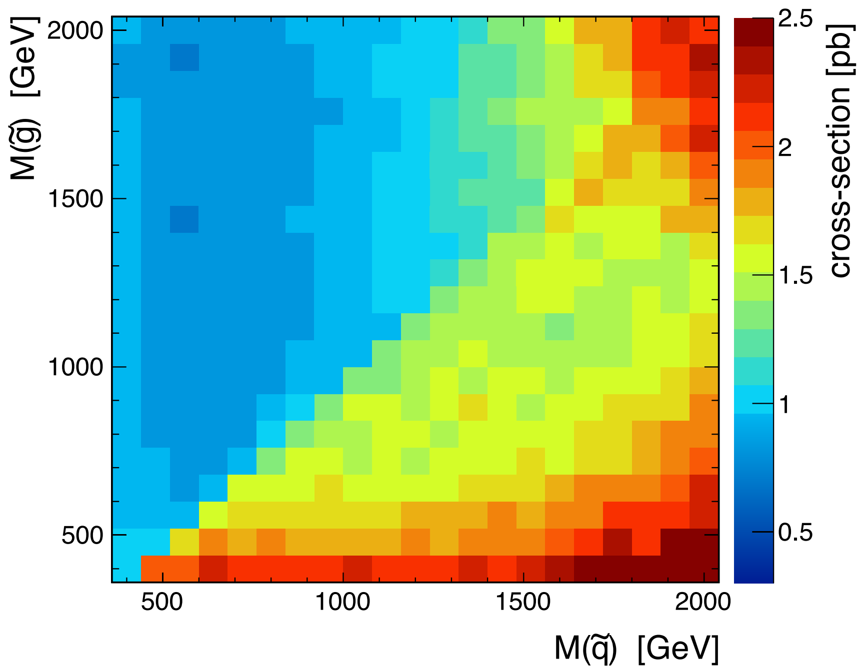
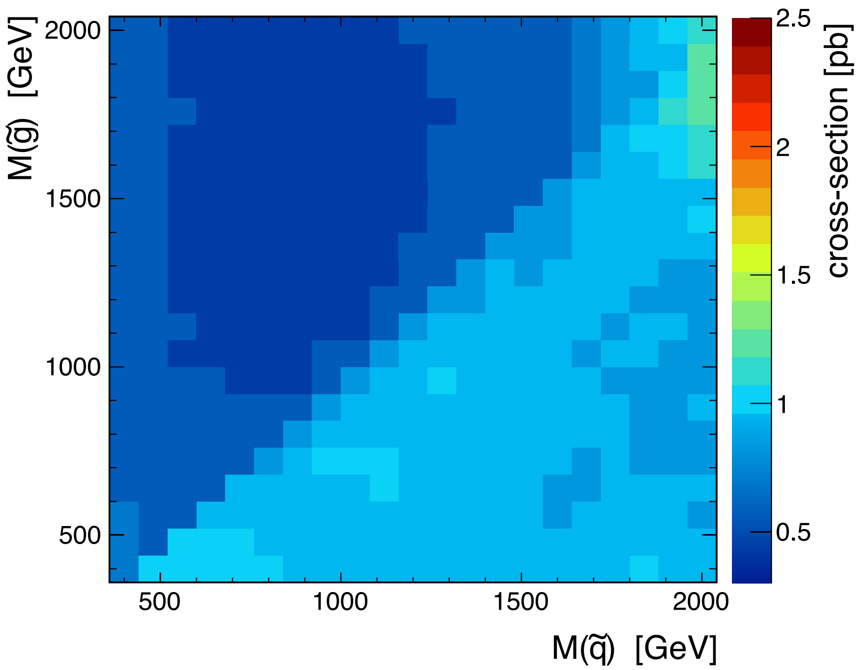
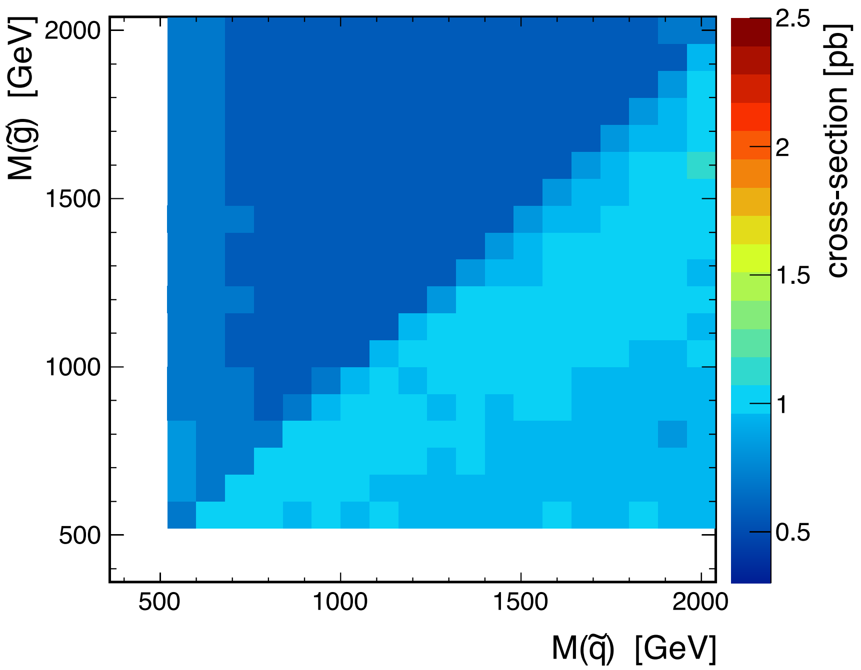
Upper limit on GGM with bino-like neutralino



$$m_{\tilde{\chi}_1^0} = 50\ \mathrm{GeV}$$



$$m_{\tilde{\chi}_1^0} = 150\ \mathrm{GeV}$$

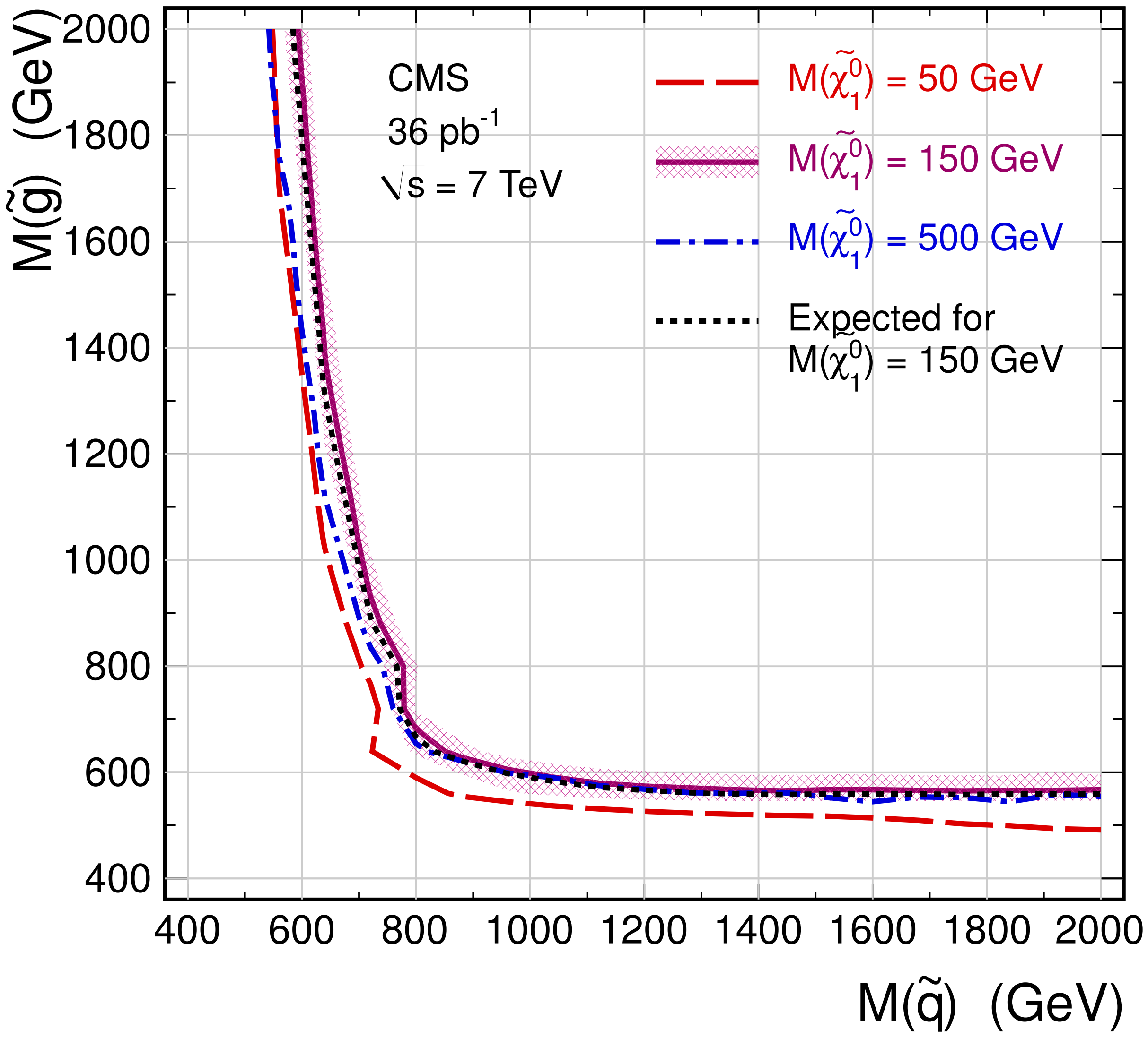


$$m_{\tilde{\chi}_1^0} = 500\ \mathrm{GeV}$$

- Generation of “simplified model” GGM signal
  - Pythia 6.422 for hadronization and decay
  - Full CMS detector simulation based on GEANT
  - Production cross-section calculated with PROSPINO 2.1
  - PROSPINO for K-factors (1.4 on average with 20% variation depending on the model parameters)
  - Soft masses of squarks degenerate
  - Sleptons and all gauginos except the lightest neutralino have mass 1.5 TeV
- Bayesian upper limit calculation with flat prior à la PDG [7]
- Repeat for 3 different nuisance parameter PDFs: Gaussian, log-normal, and gamma; results are very similar (used log-normal in published calculation)

Exclusion contours

CMS limit



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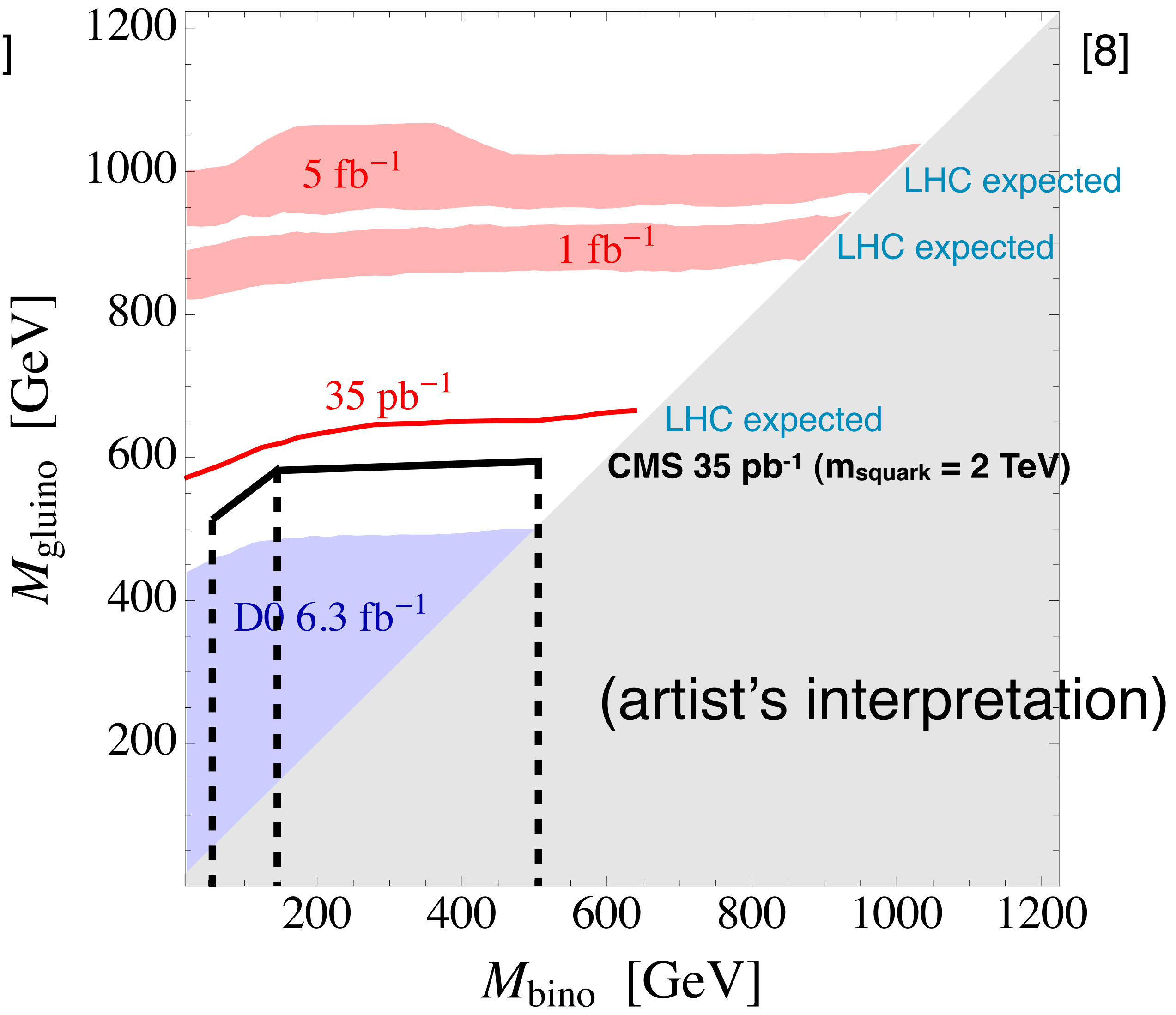
Tevatron limit



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(artist's interpretation)

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Event selection

- e+γ or μ+γ, ΔR(l,γ) > 0.4
- ≥1 good quality vertex (no jet requirement)
- Triggers
    - e+γ: unprescaled single electron trigger with 15 or 17 GeV E_T threshold
    - μ+γ: unprescaled single muon trigger with 9, 11, or 15 GeV E_T threshold
- Photon selection defined on slides 7-8
- Trigger and selection efficiencies in data estimated with Z events; signal MC acceptance × efficiency corrected by data/MC efficiency scale factor as described on slide 16

Lepton selection	Efficiency scale factor
Electron	0.928 ± 0.015
Muon	0.990 ± 0.001

Electron selection

Cut	Value		Notes
	EB	EE	EB = ECAL barrel, EE = ECAL endcap
p_T	**>20 GeV**	**>20 GeV**	
$\lvert\eta\rvert$	**<1.444**	**1.566-2.1**	1.444-1.566 is the crack between EB and EE
ECAL isolation	$<0.07E_T$	$<0.05E_T$	Same cones as on slide 8
HCAL isolation	$<0.01E_T$	$<0.025E_T$	Same cones as on slide 8
Track isolation	$<0.09E_T$	$<0.04E_T$	Same cones as on slide 8
Missing track hits	≤ 0	≤ 0	Conversion rejection cut—(expected - actual) number of hits on track
$\Delta(\cot\theta)$	<0.02	<0.02	Conversion rejection cut—θ is the polar angle between the 2 conversion clusters
Dist	<0.02	<0.02	Conversion rejection cut—distance between the 2 conversion tracks when they are parallel
$\sigma_{\eta\eta}$	<0.01	<0.03	
$\Delta\phi_{in}$	<0.06	<0.03	Between the track momentum at the primary vertex and the cluster position
$\Delta\eta_{in}$	<0.004	<0.007	Between the track momentum at the primary vertex and the cluster position
H/E	<0.04	<0.025	

NB. This electron selection uses a dedicated track reconstruction and cluster matching.
The “electron” on slide 12 is just an ECAL cluster with a matching pixel hit.

Muon selection

Cut	Value	Notes
p_T	**>20 GeV**	
$\|\eta\|$	**<2.1**	Geometrical acceptance of the muon high level trigger
Combined isolation	<0.15	Combined isolation = (ECAL isolation + HCAL isolation + track isolation)/(muon p_T), cone size R = 0.3, muon track p_T and calorimeter energy subtracted
Reconstruction algorithm	Global and tracker	Tracker muon = reconstructed from tracker hits only; global muon = reconstructed from tracker and muon station hits
Muon chamber hits	≥1	
Tracker muon match	≥2 muon chambers	
Tracker hits	>10	
Pixel hits	≥1	
χ^2/ndof	<10	Global muon track fit
$\|d_{xy}\|$	<2 mm	Transverse impact parameter
High level trigger match	Yes	

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Relevant backgrounds

- Dominant: **$W(\to e\nu)\gamma$, $W(\to \mu\nu)\gamma$**
    - Modeled with **MadGraph MC**, tune D6T
    - K-factors estimated from BAUR NLO generator using CTEQ66 NLO PDF sets
    - K-factors range from ~1.5-6, depending on photon E_T
    - Leading order photon E_T spectrum modified by K-factors, but ME_T and M_T distributions are much more stable with respect to NLO effects

Syst.(10% from halving/doubling factorization and renormalization scale) ⊕ syst.(<2% PDF uncertainty [6]) ⊕ syst.(4% luminosity)

- Subdominant: **jets faking photons in events with real ME_T**
    - $W(\to e\nu)$+jet, $W(\to \mu\nu)$+jet
- Subdominant: **electrons faking photons**
    - $Z\to ee$
    - ttbar with at least 1 W decaying to an electron
- Subdominant: **QCD with fake ME_T**
- Negligible: ttbar+γ

Estimating the jet→γ backgrounds

- Jet→γ fake rate determination
  - Muon-, jet-, and photon-triggered datasets to determine the fake rate
  - Fake rate = (# of tight photons)/(# of fakeable objects)
    - “Tight photon” same as defined on slides 7-8
  - Real photon component in tight photon sample extracted from fit to MC $\sigma_{\eta\eta}$ template and subtracted
  - Strong dependence on p_T, no dependence on $|\eta|$ in EB
- ME_T spectrum of lepton + fakeable object **data control sample** weighted by E_T-dependent fake rate

$$\boxed{\text{fake rate} = 0.0159 + \frac{2431}{p_T^{\gamma\ 2.67}} \pm 20\%}$$

Stat. ⊕ syst.(isolation template) ⊕ syst.(fit residuals)

Fakeable object definition:

Cut	Value
p_T	>20 GeV
$\lvert\eta\rvert$	<1.4
ECAL isolation	<min(5 × (0.006E_T + 4.2 GeV), 0.2E_T)
HCAL isolation	<min(5 × (0.0025E_T + 2.2 GeV), 0.2E_T)
Track isolation	<min(5 × (0.001E_T + 3.5 GeV), 0.2E_T)

and

Cut	Value
ECAL isolation	>(0.006E_T + 4.2 GeV)
or	
HCAL isolation	>(0.0025E_T + 2.2 GeV)
or	
Track isolation	>(0.001E_T + 3.5 GeV)
or	
$\sigma_{\eta\eta}$	>0.013

Estimating the e→γ backgrounds

QCD control sample	Identical to photon except...
EM object = fake	•Fake MUST fail $\sigma_{\eta\eta}$ OR track isolation cut on slide 8 •Fake MAY fail the pixel match veto •Fake MUST pass $|t| \leq 3$ ns and $\Delta\phi$(fake, fake) $\geq$ 0.05 (to fight beam halo)
EM object = electron	•Electron MUST fail the pixel match veto (i.e. it must have a pixel match) •Electron MUST pass $|t| \leq 3$ ns and $\Delta\phi$(electron, electron) $\geq$ 0.05 (to fight beam halo)

fakeable object

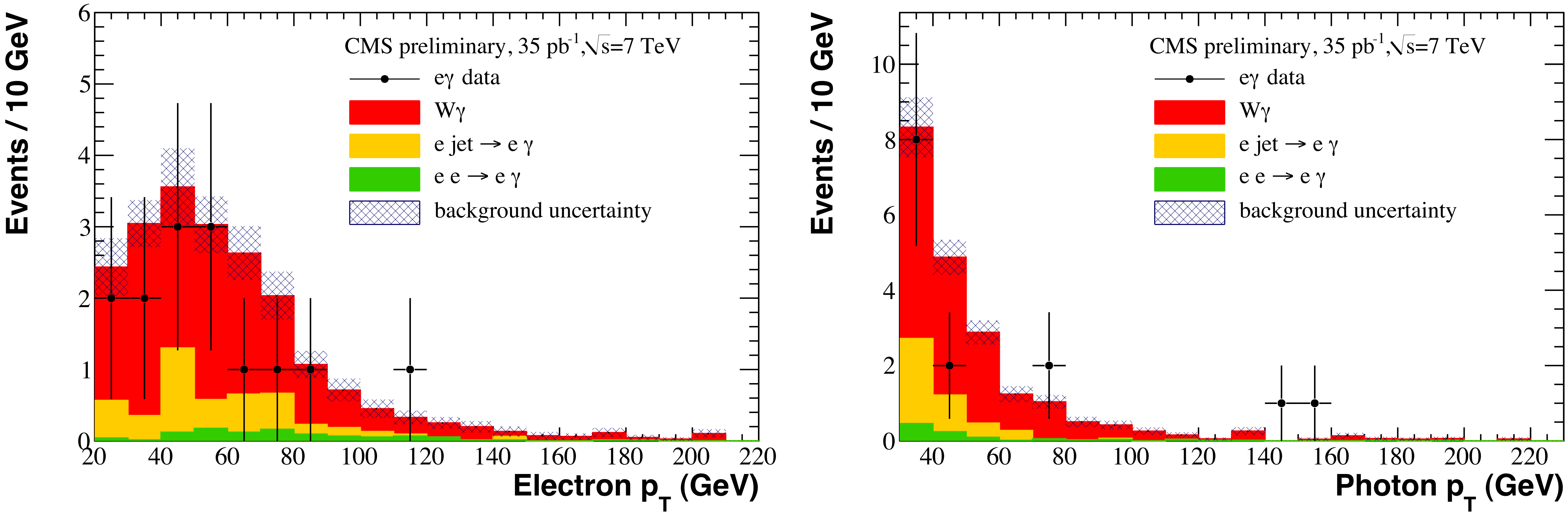
- Use $f_{e\rightarrow\gamma}$ from slide 16
- Fakeable object is the "electron" defined on slide 12
- ME_T spectrum of lepton + fakeable object **data control sample** weighted by $f_{e\rightarrow\gamma}$
  - If lepton is an electron (as on slide 25) in EB with $p_T > 30$ GeV, event weighted by $2f_{e\rightarrow\gamma}$ (in CMS photon reconstruction, the fakeable object could also be reconstructed as a good electron)

Estimating the QCD background

Identical to photon except:
- Electron MUST fail the pixel match veto (i.e. it must have a pixel match)
- Electron MUST pass $|t| \leq 3$ ns and $\Delta\phi$ (electron, electron) ≥ 0.05 (to fight beam halo)

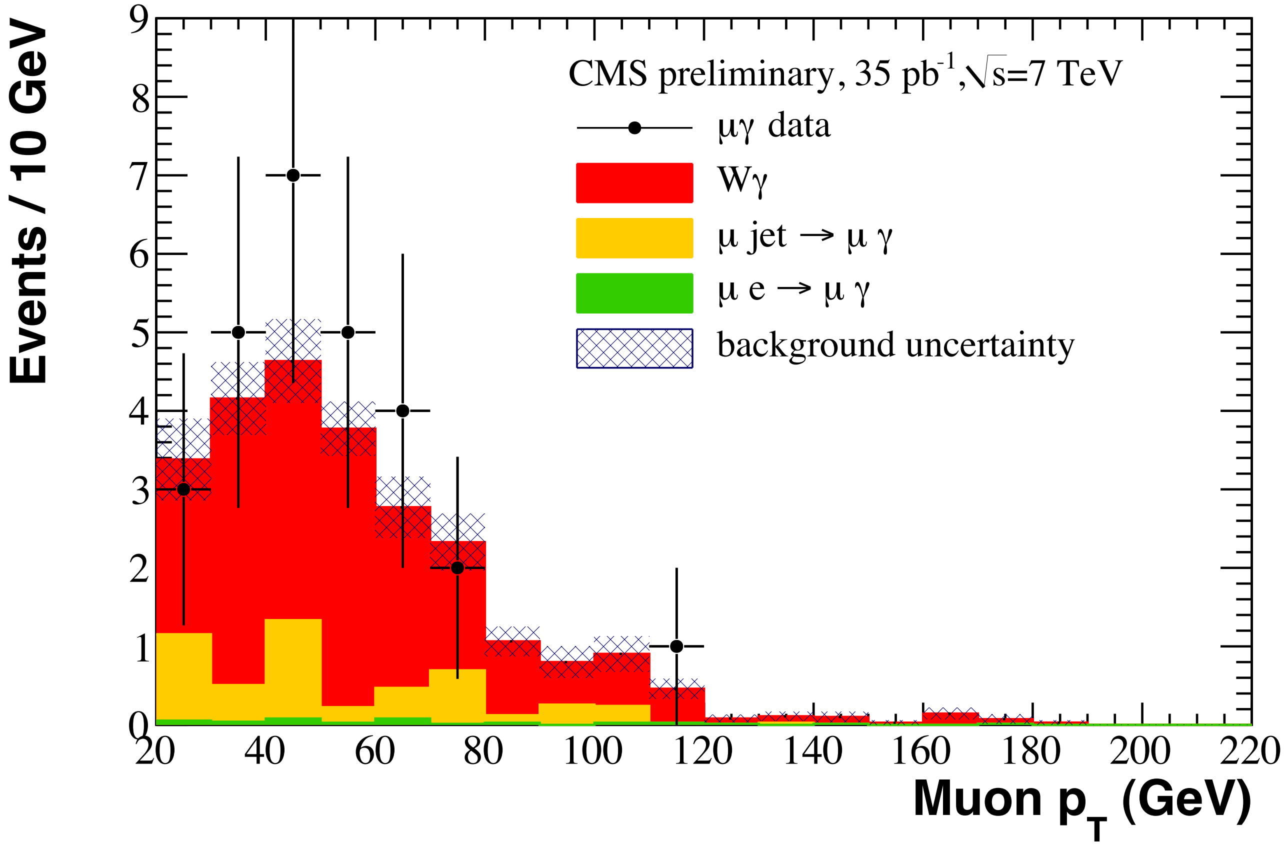
- Di-EM p_T reweighting method employed by 2-photon analysis (slide 12)
- 2 independent **data control samples**
  1. Primary: **di-electron** (electron as defined on slide 12; high statistics)
  2. Cross-check: **fake lepton** (lepton with loosened isolation or shower shape) **+ EM object** (photon with loosened track isolation and no $\sigma_{\eta\eta}$ requirement)
- 2 weights to apply to each control sample
  1. Di-EM p_T weight: reweight the ME_T spectra of the control samples such that the p_T spectrum of the di-electron or (fake lepton)-(EM object) system matches that of the candidate lepton-photon system
  2. p_T^l weight to account for significantly different lepton kinematics between the candidate and control samples: reweight the ME_T spectra of the control samples such that the p_T spectrum of the electron (e.g. the electron fakeable object in the primary control sample) or fake lepton matches that of the candidate selected lepton
- Normalization to the $ME_T < 30$ GeV region, assuming negligible signal contamination there

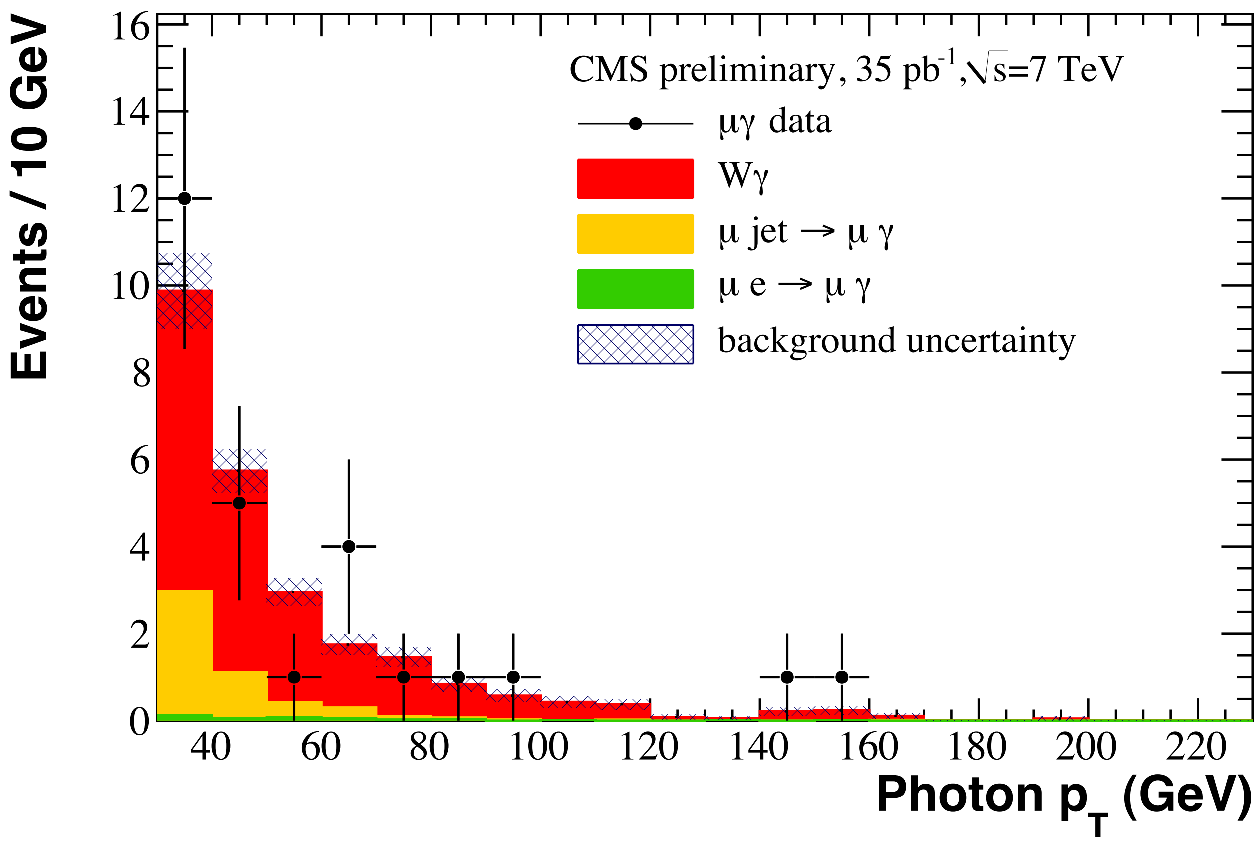
e+γ object p_T



- $M_T > 70$ GeV
- Wγ MC plus jet→γ and e→γ data-derived background estimates shown
- Good agreement between data and predicted background

μ+γ object p_T





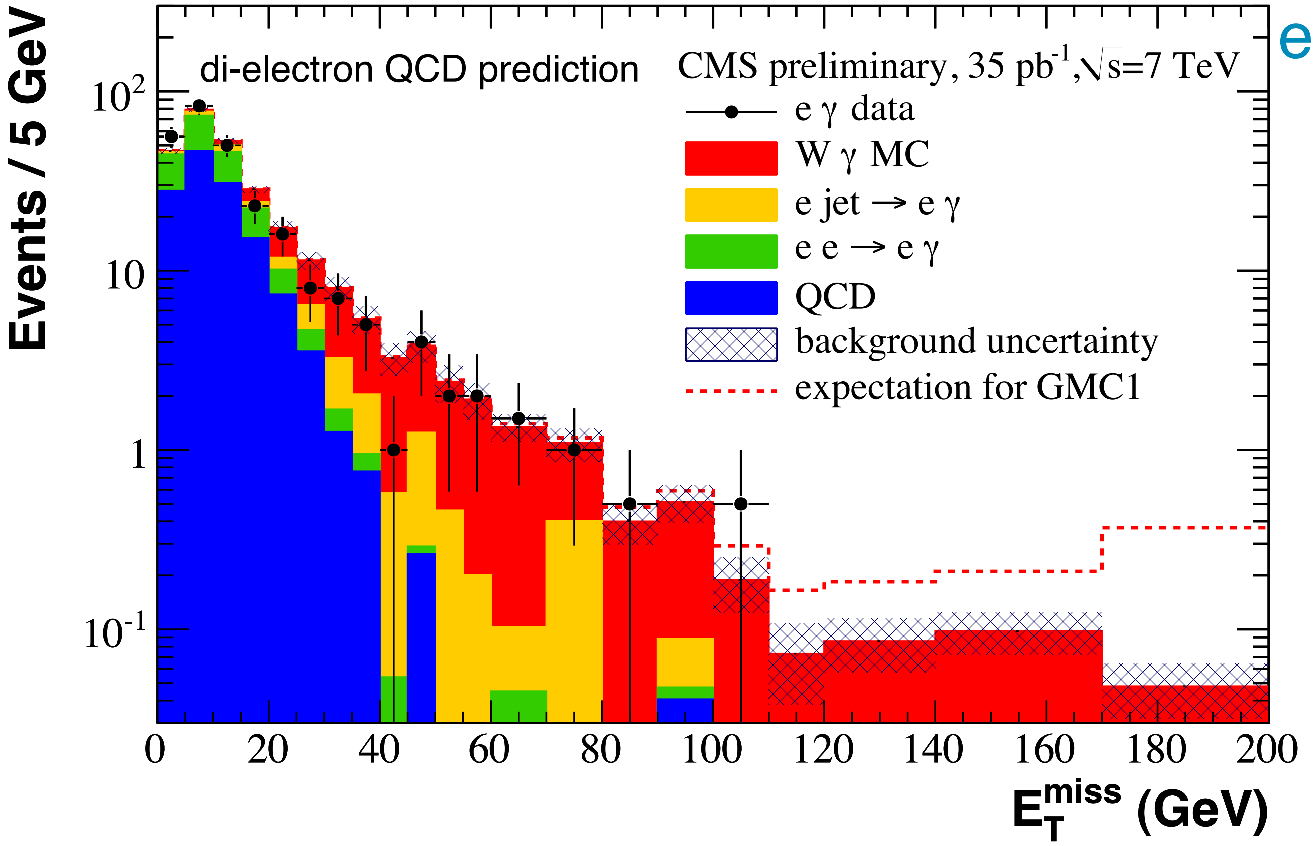
- $M_T > 70$ GeV
- Wγ MC plus jet→γ and e→γ data-derived background estimates shown
- Good agreement between data and predicted background

Outline

- General gauge mediation (GGM) searches at the LHC
    - Production mechanisms
    - Next-to-lightest superpartner (NLSP) type → final state
- Bino NLSP: 2 photons + jets + missing transverse energy (ME_T)
    - Candidate event selection
    - Background estimation
    - Photon efficiency
    - Results
    - Interpretation in terms of simplified model spectra (SMS)
- **Wino/bino co-NLSP: lepton + photon + jets + ME_T**
    - Candidate event selection
    - Background estimation
    - **Results**
    - Interpretation in terms of SMS

Candidate ME$_T$ spectra

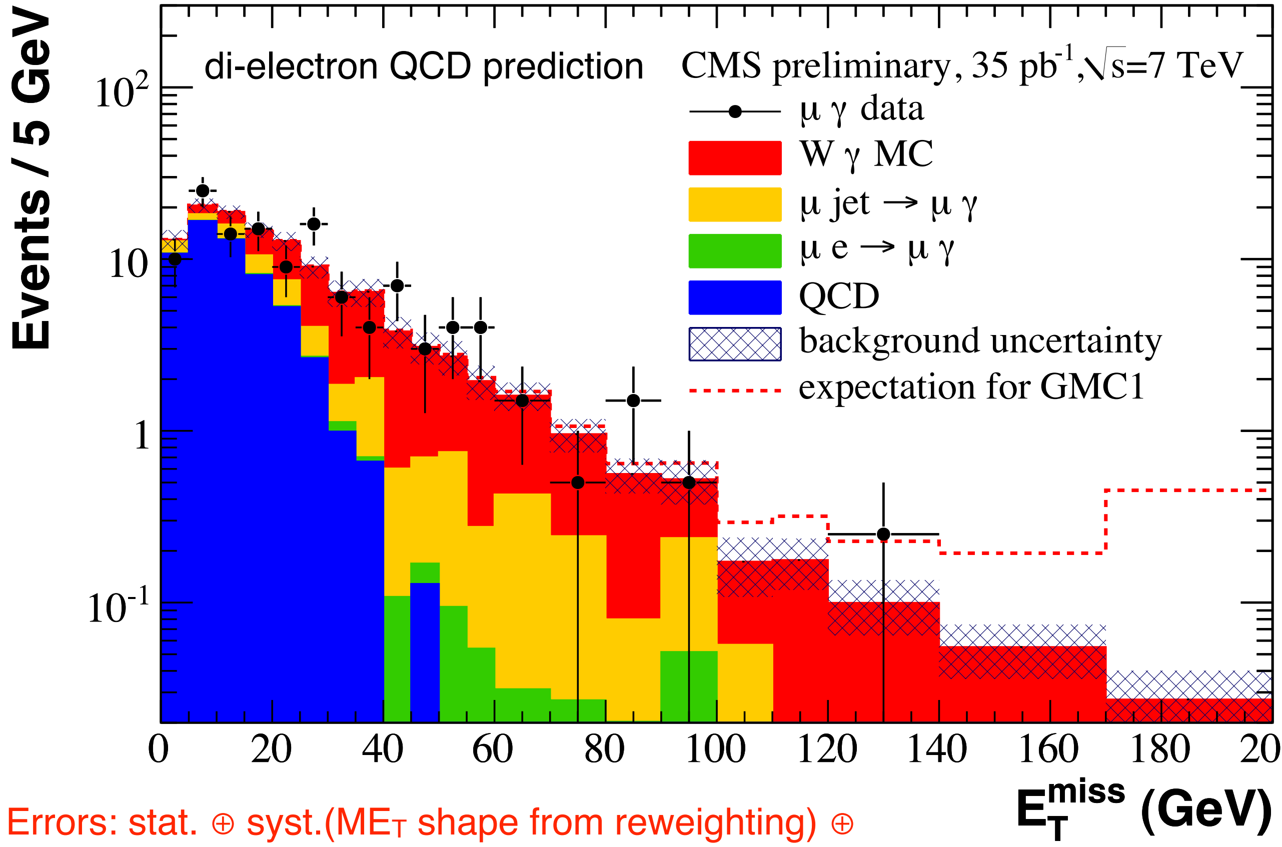
e+γ+ME$_T$



Example GGM model:
$m_{\tilde{g}} = m_{\tilde{q}} = 450$ GeV, $m_{\tilde{\chi}_1^0} \approx m_{\tilde{\chi}_1^+} = 195$ GeV

Observed events consistent with predicted background

μ+γ+ME$_T$



e+γ+ME$_T$	
Sample	ME$_T$ > 100 GeV
Wγ (MC)	1.68 ± 0.42
jet→γ	0.02 ± 0.02
e→γ	0.04 ± 0.03
QCD (di-e pred.)	0.00 ± 0.00
Total background	**1.74 ± 0.43**
Data	**1**
GGM prediction	**3.38 ± 0.68**

μ+γ+ME$_T$	
Sample	ME$_T$ > 100 GeV
Wγ (MC)	1.40 ± 0.37
jet→γ	0.10 ± 0.09
e→γ	0.09 ± 0.04
QCD (di-e pred.)	0.00 ± 0.00
Total background	**1.59 ± 0.39**
Data	**1**
GGM prediction	**4.41 ± 0.88**

Errors: stat. ⊕ syst.(ME$_T$ shape from reweighting) ⊕ syst.(normalization)

Outline

- General gauge mediation (GGM) searches at the LHC
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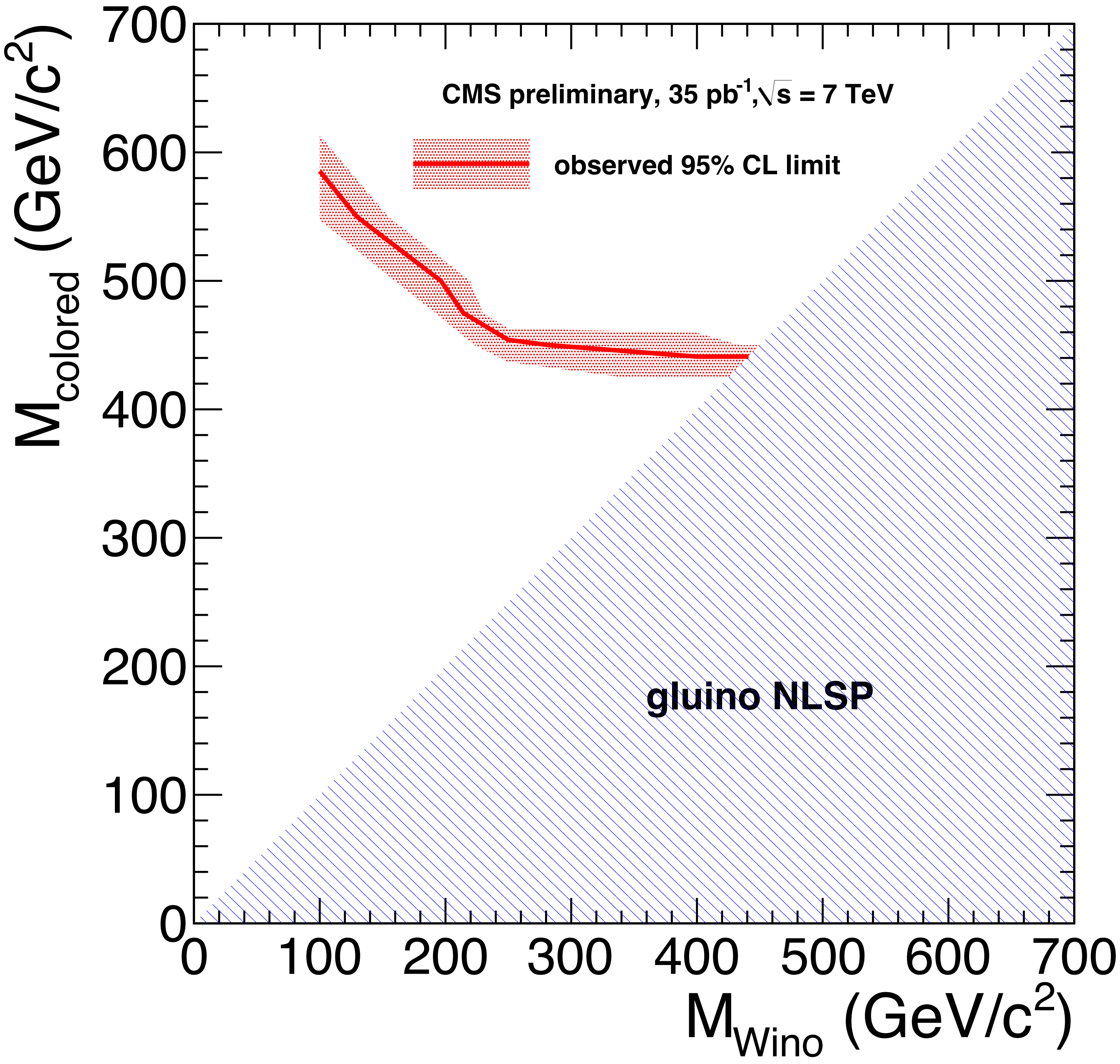
- **Wino/bino co-NLSP: lepton + photon + jets + ME_T**
  - Candidate event selection
  - Background estimation
  - Results
  - **Interpretation in terms of SMS**

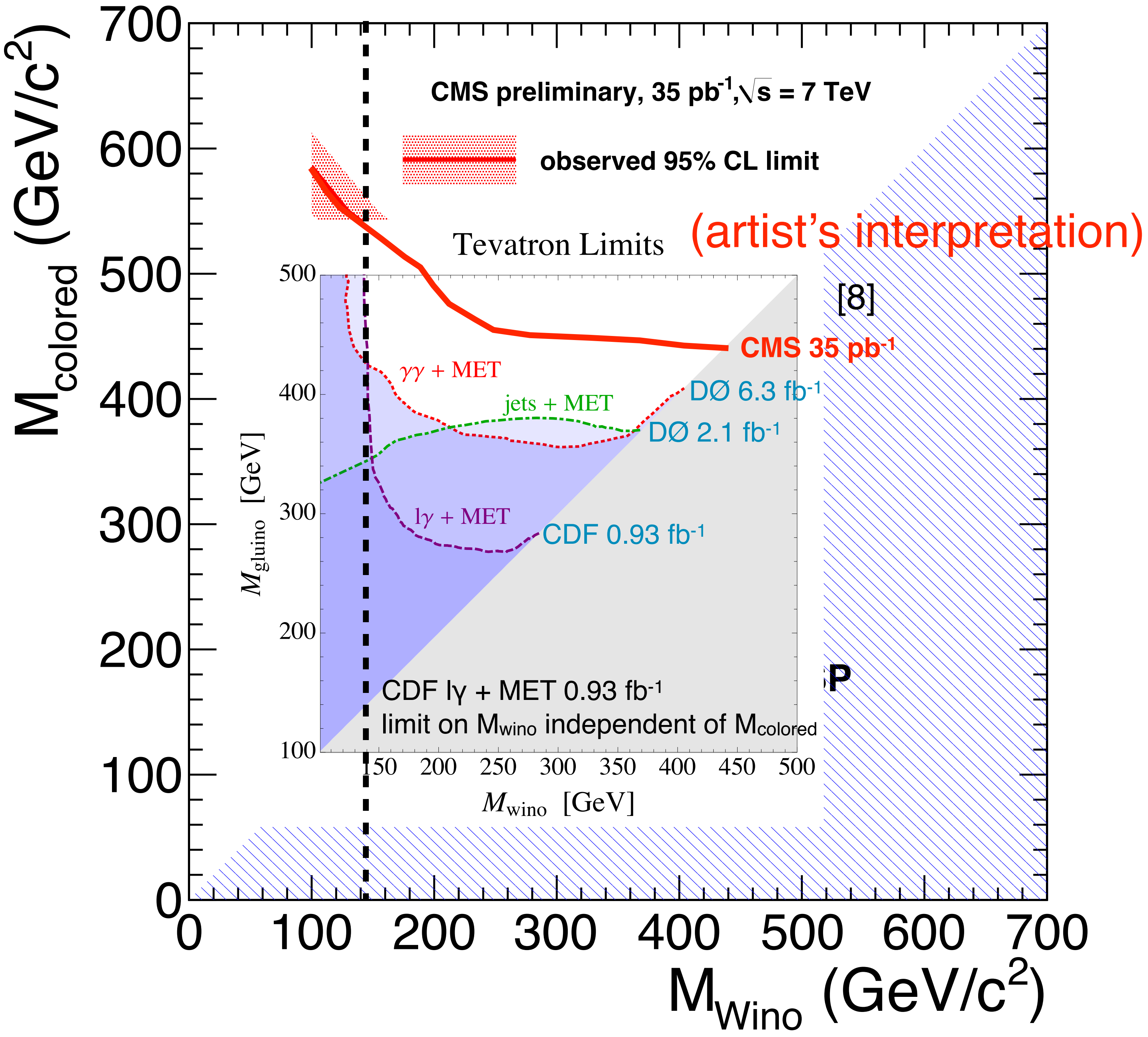
Upper limit on GGM with wino/bino co-NLSP

- Generation of “simplified model” GGM signal
  - Squark and gluino masses approximately equal
  - tan β = 2
  - NLSP mass > 100 GeV
  - Pythia 6.422 for hadronization and decay
  - Full CMS detector simulation based on GEANT
  - PROSPINO for K-factors (1.4 on average with 20% variation depending on the model parameters)
- Bayesian upper limit calculation with flat prior à la PDG [7]
  - Electron and muon channels combined
  - Gaussian shape for nuisance parameters



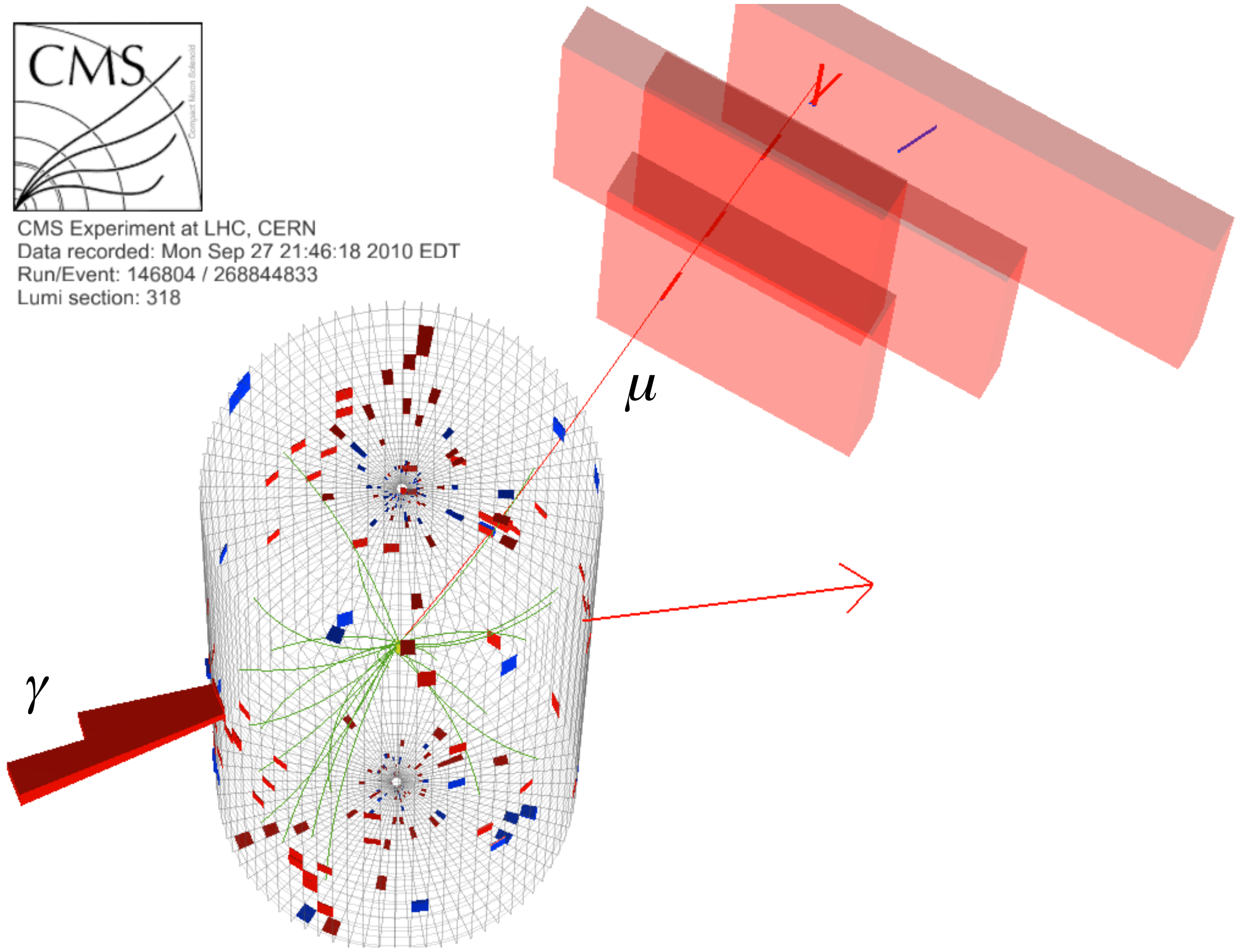
Upper limit on GGM with wino/bino co-NLSP

- Tevatron limits significantly extended



Conclusions

Highest ME_T $\mu+\gamma$ event

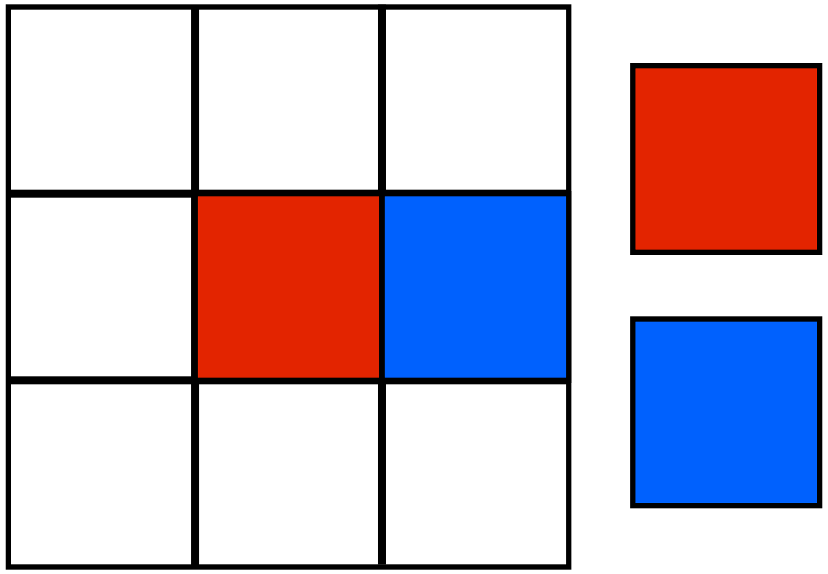


- Searches in di-photon and photon+lepton final states are powerful tools for observing SUSY
  - Clean trigger objects
  - Manageable backgrounds that can mostly be estimated from data
- CMS is beginning to explore the full GGM parameter space
  - Results presented in terms of simplified models to ease interpretation
- No SUSY so far, but where haven't we looked yet?
  - Higgsino-like neutralino decaying to Z+gravitino
  - Long-lived neutralinos
  - ...

Stay tuned in 2011!

Backup

ECAL noise cleaning



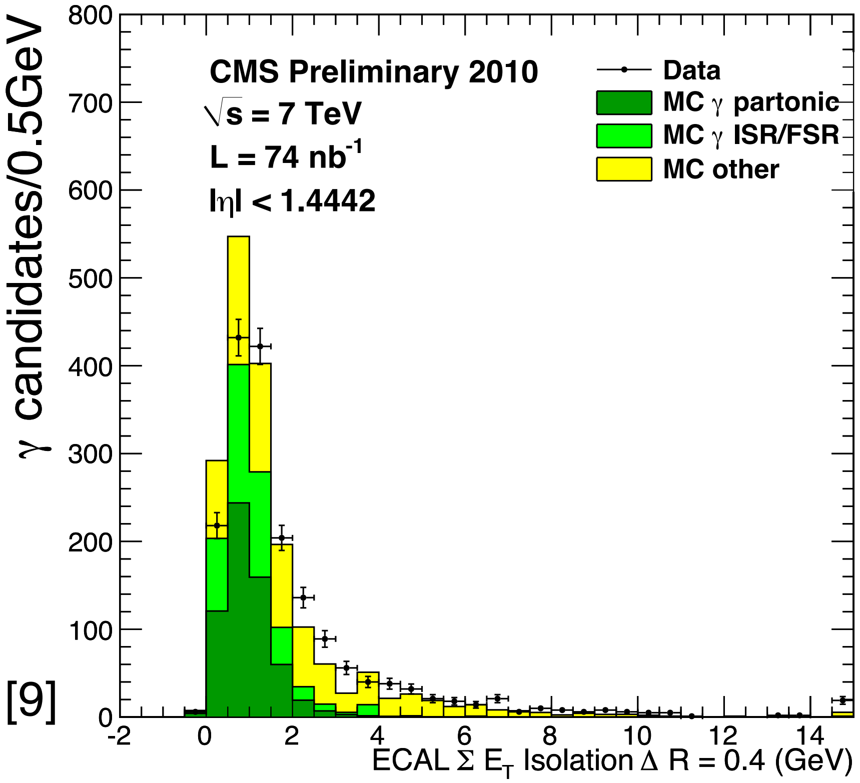
Highest energy crystal

2^{nd} highest energy crystal

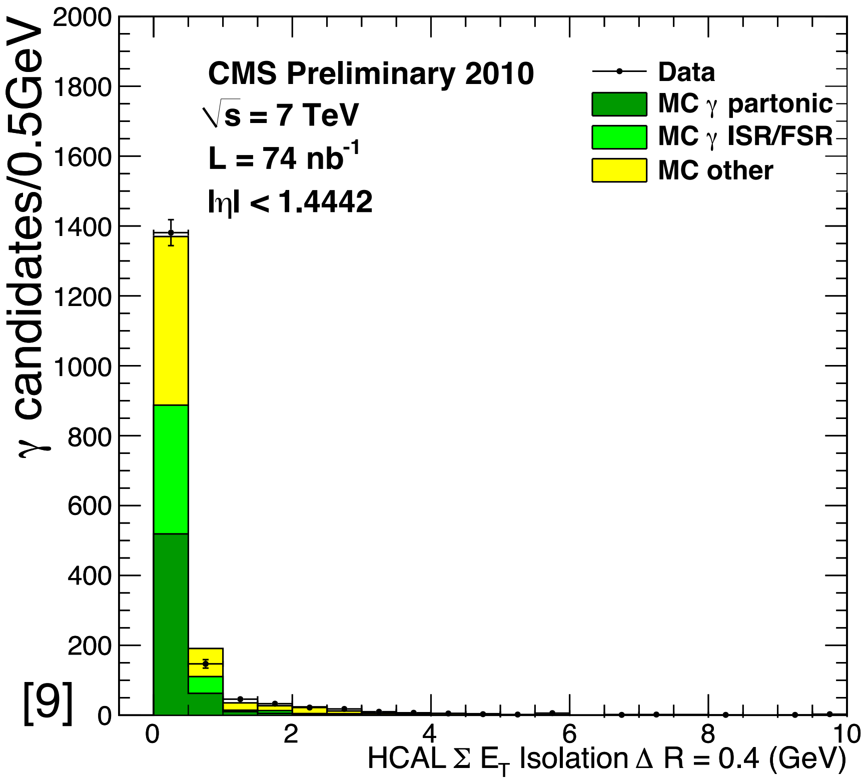
$$\frac{E_{\text{🟥}} + E_{\text{🟦}}}{E_{3\times3}} > 0.95 \Rightarrow \text{reject}$$

1. Form 3 × 3 matrix of crystals around the photon seed crystal
2. Find the 2 highest energy crystals within the matrix
3. If the sum of the energies of the 2 highest energy crystals divided by the sum of the energies of all 9 crystals within the matrix exceeds 0.95, reject the photon as ECAL noise

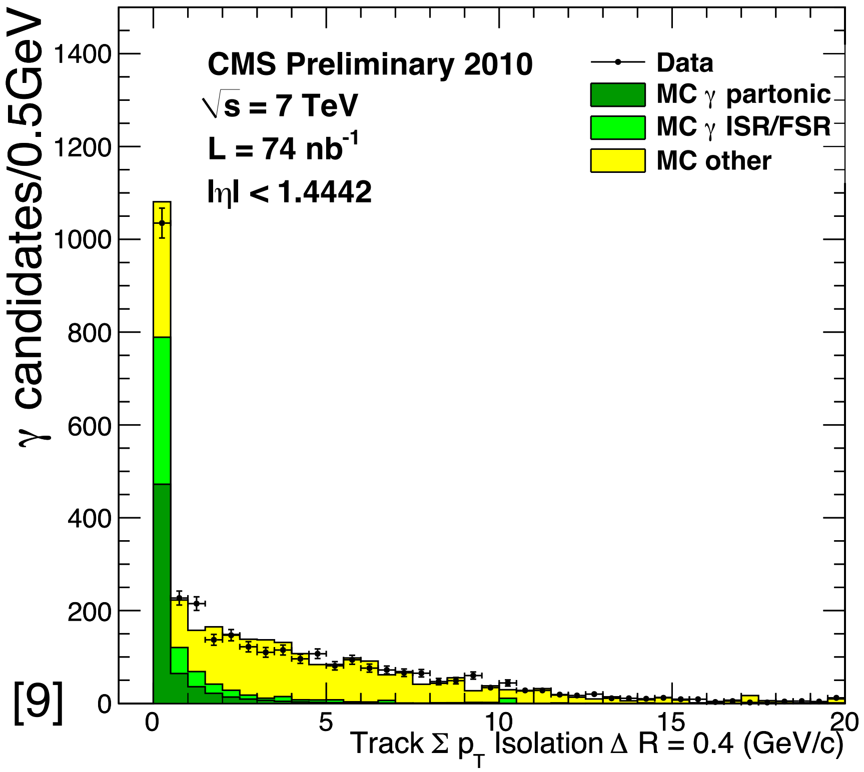
Photon ID variables



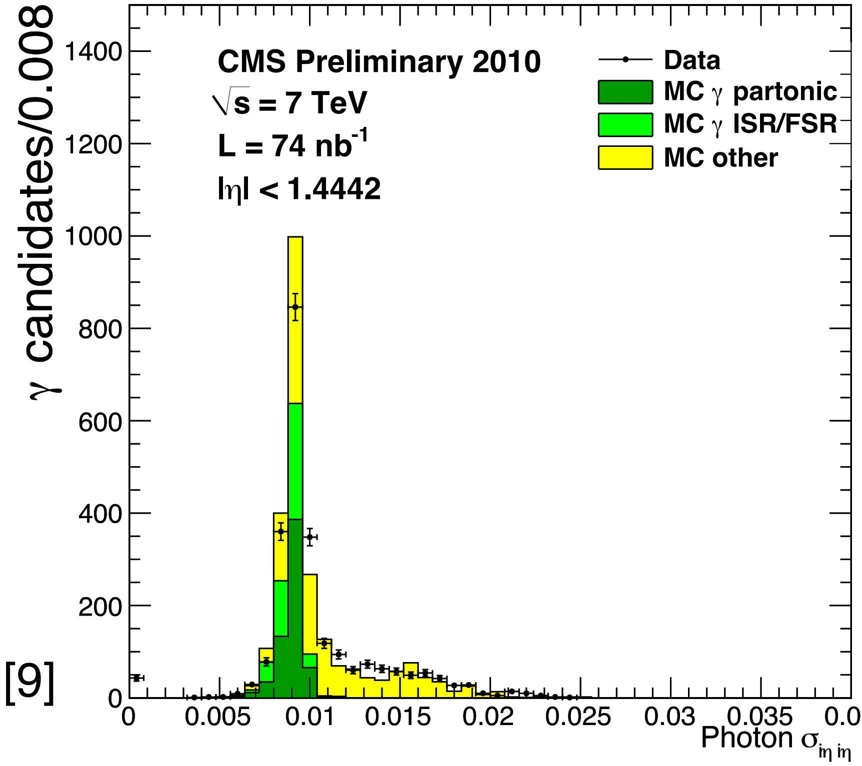
[9]



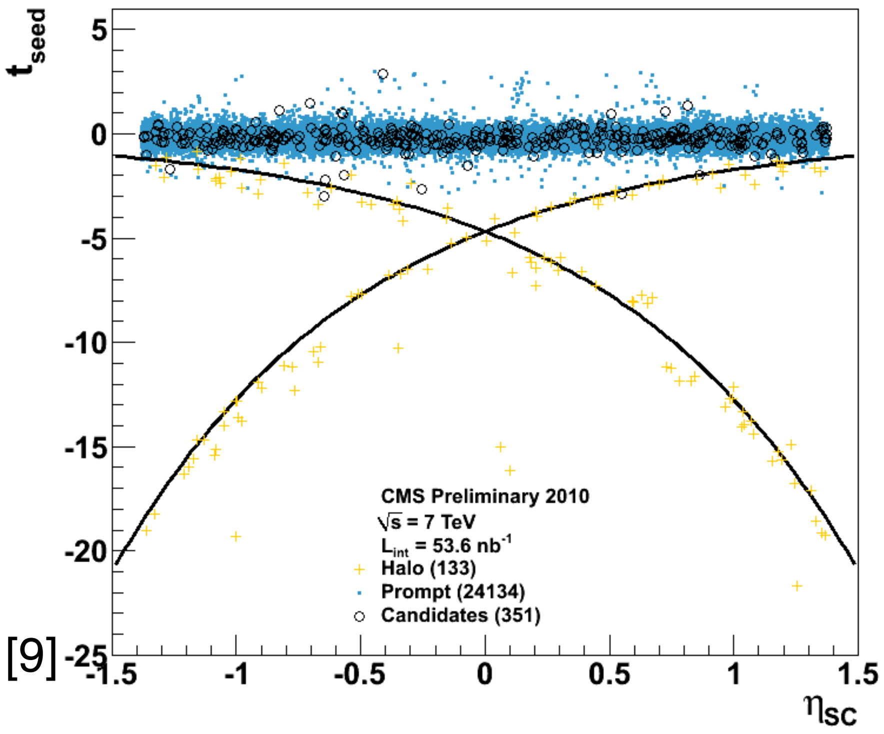
[9]



[9]



[9]



[9]

HCAL noise cleaning

1. $f_{HPD} \leq 0.98$, where f_{HPD} is the fraction of the jet's energy contributed by the highest energy hybrid photodetector
2. n90Hits > 1, where n90Hits is the minimum number of HCAL channels containing 90% of the jet's energy
3. EMF ≥ 0.01, where EMF is the electromagnetic fraction of the jet's energy

See [10]

Jet-plus-tracks (JPT) algorithm

- Main idea: replace poorly measured charged hadron energies in calorimeter with well-measured charged hadron momenta in tracker to improve the overall jet energy resolution

1. Correct the calorimeter jet for zero suppression (i.e. effect of small, positive calorimeter cell readout threshold)
2. Subtract the expected average energy of charged particles inside the jet cone from the jet total energy, and add in the measured momenta of the tracks in the cone
3. Add to the jet energy the momenta of tracks that originate inside the jet cone but bend outside of it at the calorimeter surface
4. Correct for track-finding inefficiency
5. Subtract the average muon calorimeter deposit from the jet energy and add in the measured muon momentum

- See [11] for details and performance in LHC data

$f_{e\to\gamma}$ calculation

The number of events in the di-electron sample is given by

$$N_{ee} = f_{e\to e}^2 N_{Z\to ee}$$

where $f_{e\to e}$ is the efficiency to correctly identify an electron via pixel match and $N_{Z\to ee}$ is the true number of Z→ee events. The number of events in the eγ sample due to misidentification of 1 Z electron as a photon is given by

$$N_{e\gamma}^Z = 2f_{e\to e}(1 - f_{e\to e})N_{Z\to ee}$$

Solving for $f_{e\to e}$,

$$f_{e\to e} = \frac{1}{1+\frac{1}{2}\frac{N_{e\gamma}^Z}{N_{ee}}}$$

The number of events in the eγ sample due to correctly identifying a W electron is given by

$$N_{e\gamma}^W = f_{e\to e}N_W$$

where N_W is the number of true W→eν events. The number of $\gamma\gamma$ events from W electron misidentification is given by

$$N_{\gamma\gamma}^{EW} = (1 - f_{e\to e})N_W$$

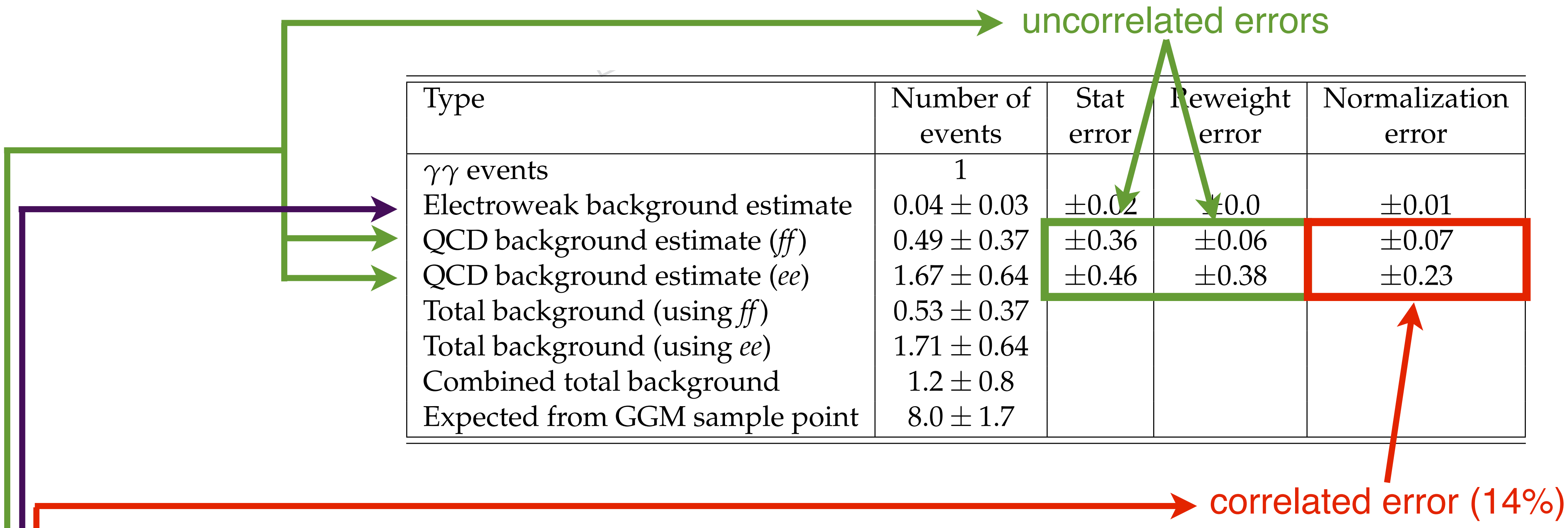
where we have neglected the contribution from Z electron misidentification since it is small (i.e., $f_{e\to\gamma}$ is small and the Z contribution involves $f_{e\to\gamma}^2$, since both electrons have to be misidentified). Since

$$f_{e\to e} = 1 - f_{e\to\gamma}$$

solving for $N_{\gamma\gamma}^{EW}$

$$N_{\gamma\gamma}^{EW} = \frac{f_{e\to\gamma}}{1-f_{e\to\gamma}}N_{e\to\gamma}$$

Background averaging



uncorrelated errors

Type	Number of events	Stat error	Reweight error	Normalization error
$\gamma\gamma$ events	1			
Electroweak background estimate	0.04 ± 0.03	± 0.02	± 0.0	± 0.01
QCD background estimate (*ff*)	0.49 ± 0.37	± 0.36	± 0.06	± 0.07
QCD background estimate (*ee*)	1.67 ± 0.64	± 0.46	± 0.38	± 0.23
Total background (using *ff*)	0.53 ± 0.37			
Total background (using *ee*)	1.71 ± 0.64			
Combined total background	1.2 ± 0.8			
Expected from GGM sample point	8.0 ± 1.7			

correlated error (14%)

weighted average assuming uncorrelated backgrounds and Gaussian nuisance parameter PDFs: 0.83 ± 0.34

weighted average assuming uncorrelated backgrounds and log-normal nuisance parameter PDFs: 1.17 ± 0.36

1. Find the weighted average of the di-electron and di-fake QCD background estimates, assuming log-normal PDFs with widths given by the uncorrelated errors
2. Add in quadrature the common error of 14% due to normalization in the low-ME$_T$ region to the error from step 1
3. Add the electroweak background estimate to the average from step 1, and add its error in quadrature to the error from step 2
4. Add in quadrature, as a systematic error, the difference between the combined background estimate and the di-fake estimate to the error from step 3

Good vertex criteria

Cut	Value	Notes
ndof	>4	
|z|	<24 cm	Reconstructed z position of vertex
r	<2 cm	Reconstructed x-y position of vertex

Fake lepton and EM object selection

Fake electron		
Cut	Value	
	EB	EE
p_T	>20 GeV	>20 GeV
$\lvert\eta\rvert$	<1.444	1.566-2.1
ECAL isolation	$<0.07E_T$	$<0.05E_T$
HCAL isolation	$<0.01E_T$	$<0.025E_T$
Track isolation	$<0.09E_T$	$<0.04E_T$
Missing track hits	≤0	≤0
$\Delta(\cot\theta)$	<0.02	<0.02
Dist	<0.02	<0.02
$\Delta\phi_{in}$	<0.06	<0.03
$\Delta\eta_{in}$	<0.004	<0.007

EM object	
Cut	Value
p_T	>30 GeV
$\lvert\eta\rvert$	<1.4
ECAL isolation	$<(0.006E_T + 4.2\text{ GeV})$
HCAL isolation	$<(0.0025E_T + 2.2\text{ GeV})$
Track isolation	<10 GeV
H/E	<0.05
Noise-cleaned	Yes
Pixel match	No

Fake muon	
Cut	Value
p_T	>20 GeV
$\lvert\eta\rvert$	<2.1
Combined isolation	0.15-0.25
Reconstruction algorithm	Global and tracker
Muon chamber hits	≥1
Tracker muon match	≥2 muon chambers
Tracker hits	>10
Pixel hits	≥1
χ^2/ndof	<10
$\lvert d_{xy}\rvert$	<2 mm
High level trigger match	Yes

Fake electron: electron with only isolation requirements

Fake muon: muon with relaxed isolation requirement

EM object: photon with relaxed track isolation and no shower shape requirement

High photon E_T events

Channel	Expected background with $E_T^\gamma > 120$ GeV	Observed events with $E_T^\gamma > 120$ GeV	Probability to observe ≥2 events with $E_T^\gamma > 120$ GeV in each channel at the same time
e+γ	0.76 ± 0.18	2	>10%
μ+γ	0.93 ± 0.21	2	

- Good agreement between background predictions in electron and muon channels

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