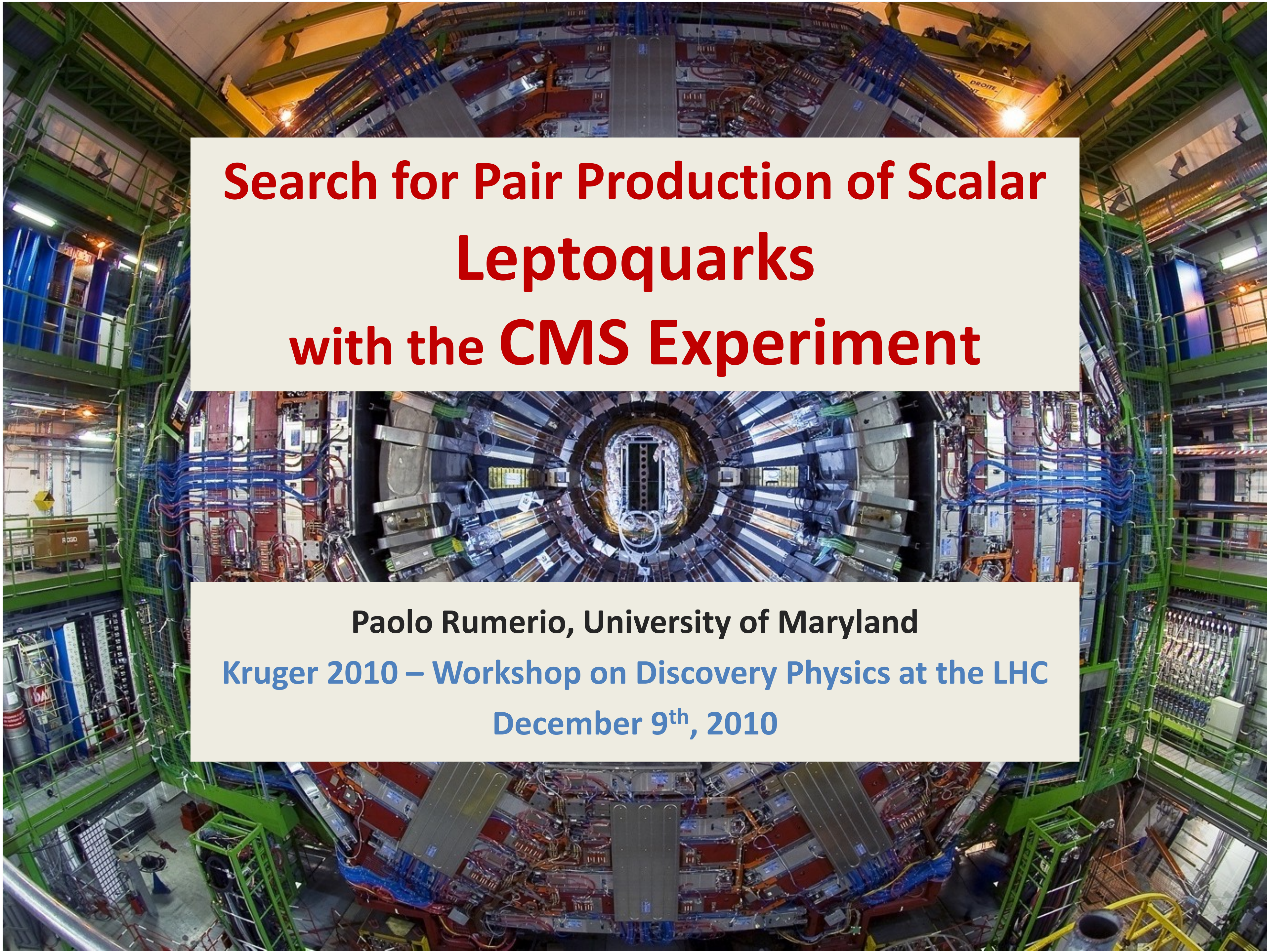

Search for Pair Production of Scalar Leptoquarks with the CMS Experiment

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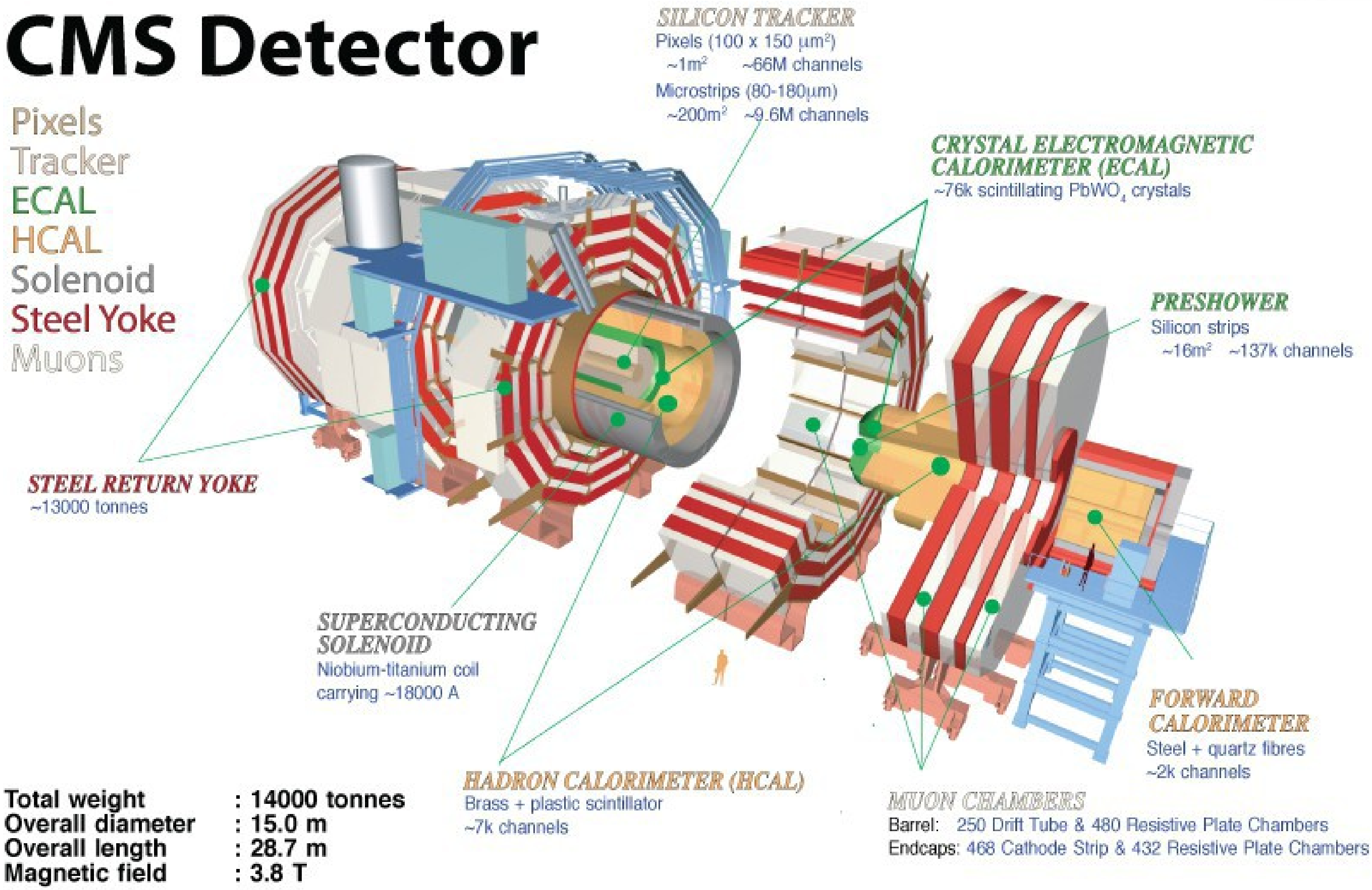
Kruger 2010 – Workshop on Discovery Physics at the LHC

December 9th, 2010

Overview

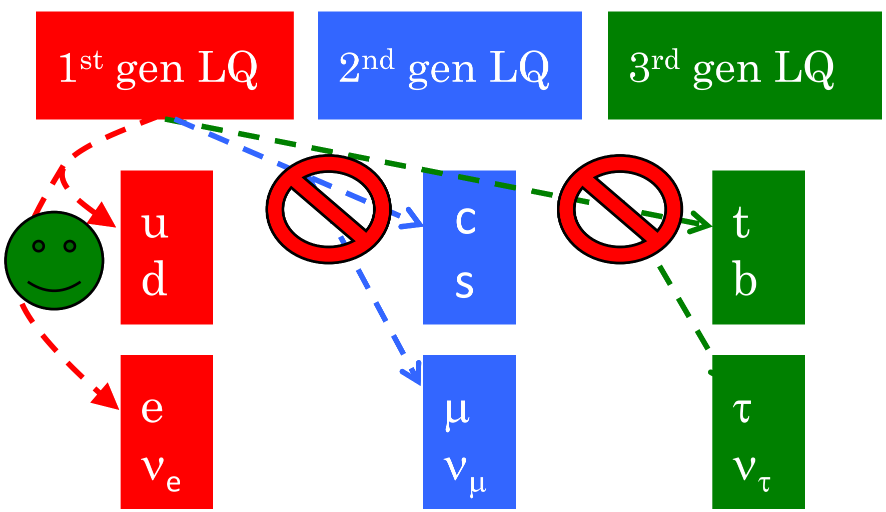
- The CMS detector in brief
- Introduction to leptoquarks (LQ)
- Search for pair production of 1st and 2nd generation LQs
  - In the final states eejj (33 pb^{-1}) and μμjj (34 pb^{-1})
  - Analysis strategy
  - Data vs. Monte Carlo at pre-selection level
  - Backgrounds
  - Final selection
  - Results
- Conclusions

The Detector



Introduction to Leptoquarks

- An apparent symmetry between quark and lepton generations of the Standard Model (SM) is unexplained within the SM itself. This symmetry may imply the existence of a more fundamental theory interrelating the SM quarks and leptons (GUT, Technicolor, Composite models, …)
  - Leptoquarks (LQs) naturally appear in such theories
- LQs are conjectured particles that couple to a lepton-quark pair and carry SU(3) color charge, fractional electric charge, baryon and lepton numbers
- LQs can be scalar or vector particles. Scalar LQs are considered in this talk.

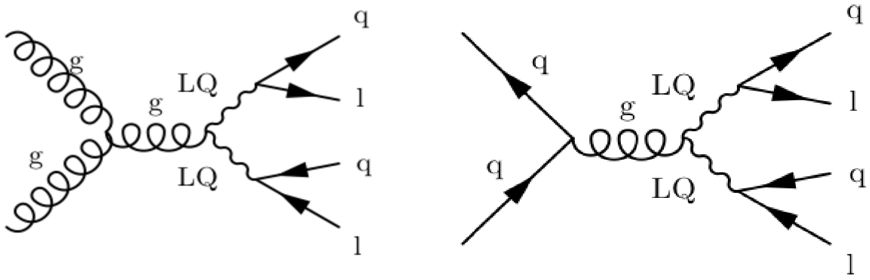


- Experimental limits on lepton number violation, flavor-changing neutral currents, and proton decay favor (for LQ masses directly accessible at the current colliders) three generations of LQs with no inter-generational mixing.
- In the model considered here, a LQ couples to a lepton and a quark from only one SM generation.

LQ Production at the LHC

- In hadron-hadron collisions, scalar LQs are pair-produced mainly through gluon-gluon fusion and quark-antiquark annihilation.

Scalar LQs are characterized by two free parameters	
M_{LQ}	LQ mass
λ	LQ-l-q coupling

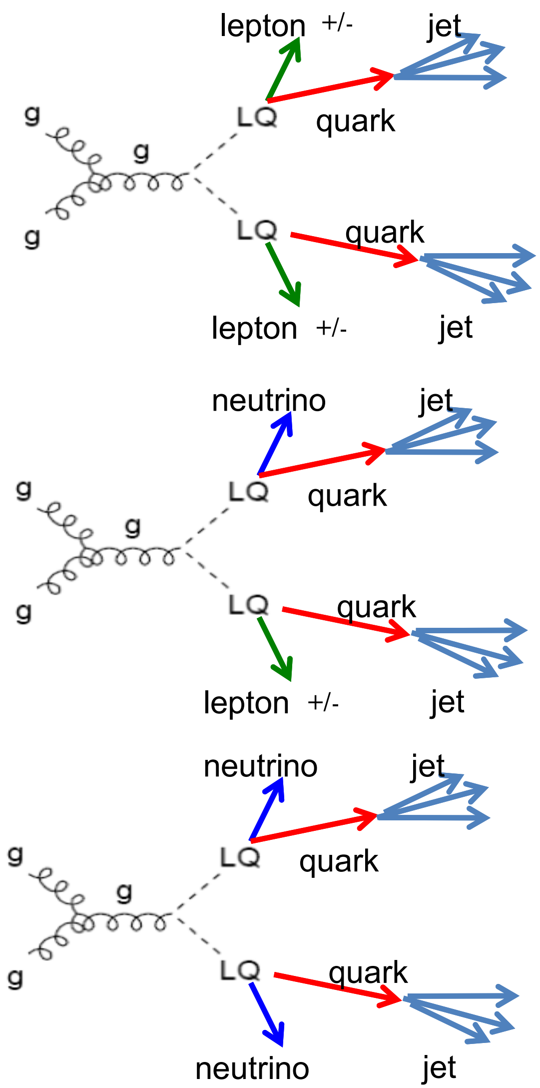


- At the LHC, gluon-gluon fusion is the dominant production mechanism, and is independent of the LQ-l-q coupling (λ)
  - Single LQ production becomes comparable at LQ masses above the reach with the 2010 data
- Results from low energy experiments and HERA collider restrict λ to be small ($\lambda <\approx \lambda_{EM} \approx 0.3$) for LQ masses currently accessible at the LHC
  - LQ relative width $\Gamma_{LQ}/M_{LQ} = \lambda^2/16\pi <\approx 0.2\%$, measurement dominated by detector resolution

Signature of LQ Decays

- Branching ratio for LQ $\rightarrow l^{+/-} + q$ is an unknown parameter
  - BR(LQ $\rightarrow l^{+/-} + q$) = β
  - BR(LQ $\rightarrow \nu + q$) = $1-\beta$
- 3 different signatures
  - **lljj**: 2 charged leptons + 2 jets
  - **lνjj**: 1 charged lepton + 2 jets + MET
  - **ννjj**: 2 jets + MET
- 3 LQ generations
  - 1^{st} generation: l=e
  - 2^{nd} generation: l=μ
  - 3^{rd} generation: l=τ

➢ **In this talk, results of a search for 1^{st} and 2^{nd} generation scalar LQs in the eejj and μμjj channels are presented**



lljj

β^2

lνjj

$2(1-\beta)\beta$

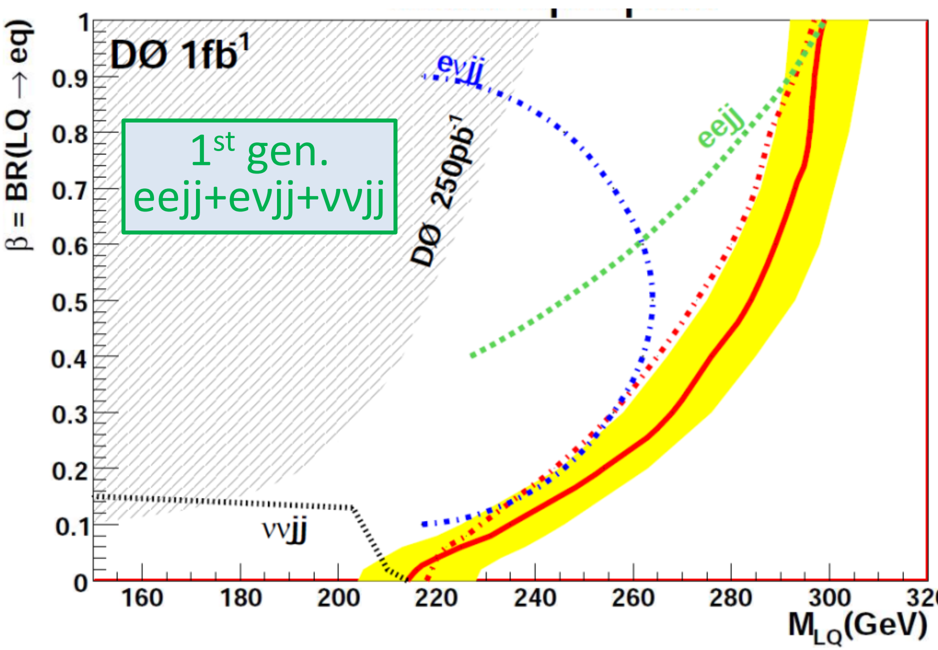
ννjj

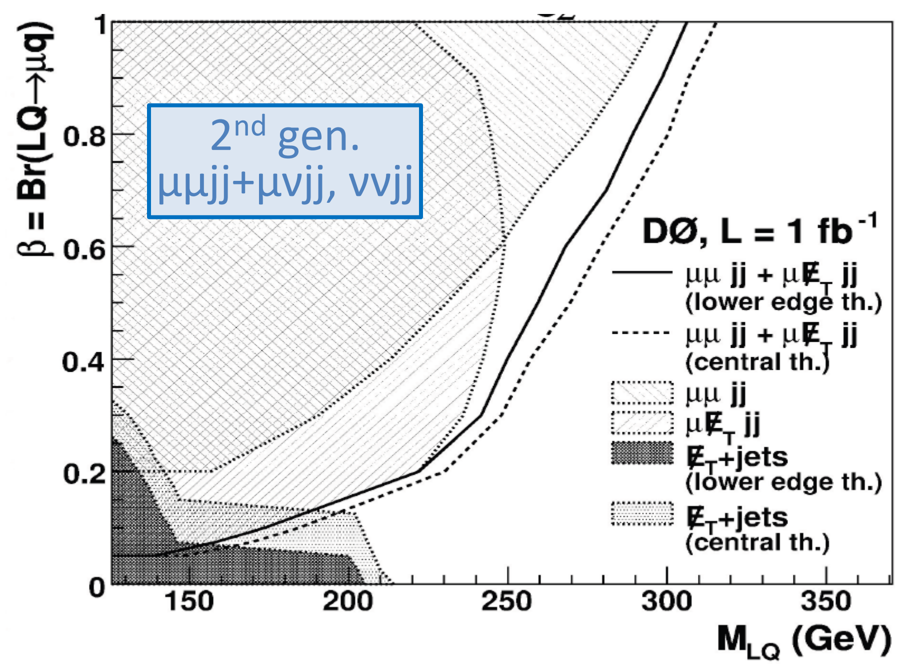
$(1-\beta)^2$

Limits from the Tevatron

- The Tevatron most stringent lower limits on the scalar LQ mass are set by D0 and based on 1 fb^{-1} of integrated luminosity. For β = 1:
  - $M_{LQ} > 299$ GeV for 1st generation
  - $M_{LQ} > 316$ GeV for 2nd generation

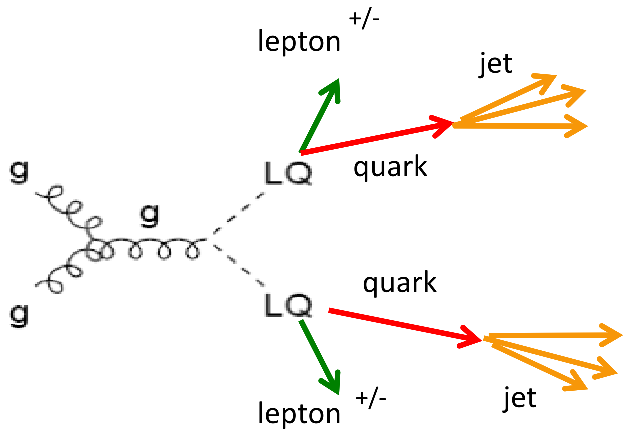
  (Results for β < 1 are improved by combining the lljj, lνjj and ννjj limits)





CMS Analysis Strategy

- Look for a striking experimental signature: two high-p_T charged leptons and two high-p_T jets



- Trigger: robust and efficient lepton triggers
- Event selection:
  - At least 2 isolated high-p_T leptons, at least 2 high-p_T jets
  - A lower cut on M_{ll} to remove Z+jets bkg
  - $S_T = p_T(l1) + p_T(l2) + p_T(j1) + p_T(j2) > f(M_{LQ})$
- Background estimate:
  - Backgrounds containing vector bosons are estimated using MC samples
    - Z+jets and ttbar are the dominant backgrounds
    - MC normalization and systematic uncertainty on the background estimate are assessed by comparing data and MC
  - The small QCD background is determined from data

Electron, Muons and Jets

- Electrons:
  - Electromagnetic clusters with consistent shower shape
  - Spatially matched to a reconstructed track in η and ϕ
  - Isolated in calorimeter and tracker
- Muons:
  - Tracks in muon system matched to tracks in inner tracking system
  - Isolated in tracking system and calorimeter
  - More than 10 hits in silicon tracker
  - transverse impact parameter < 2mm
- Jets:
  - Reconstructed using calorimeter information
  - Anti-kT algorithm with distance parameter R=0.5
  - Jet energy corrections derived from MC are applied
  - Applied residual data-based energy corrections (p_T balance in di-jet events)

Pre-Selection

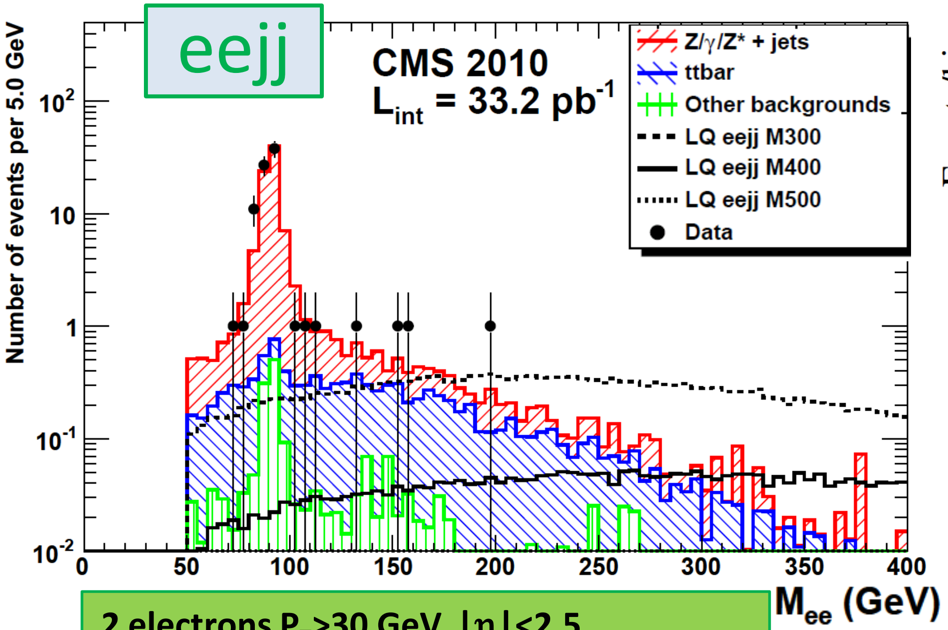
eejj

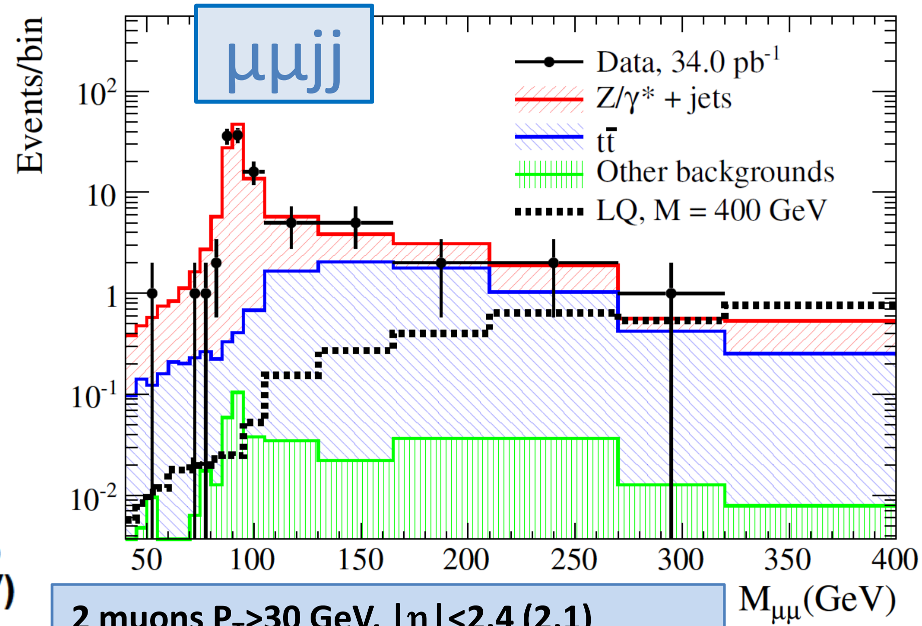
- Select the 2 leading (in p_T) electrons p_T>30 GeV, $|\eta|<2.5$
- Select the 2 leading (in p_T) jets p_T>30 GeV , $|\eta|<3$
- $\Delta R(e,j) > 0.7$
- M_{ee}> 50 GeV
- S_T (scalar sum of pT of selected electrons and jets) >250 GeV

μμjj

- Select the 2 leading (in p_T) muons p_T>30 GeV, $|\eta|<2.4$ (2.1)
- Select the 2 leading (in p_T) jets p_T>30 GeV , $|\eta|<3$
- $\Delta R(\mu, \mu) > 0.3$
- $M_{\mu\mu}$>50 GeV
- S_T (scalar sum of pT of selected muons and jets) >250 GeV

M_{ee} and $M_{\mu\mu}$ after pre-selection





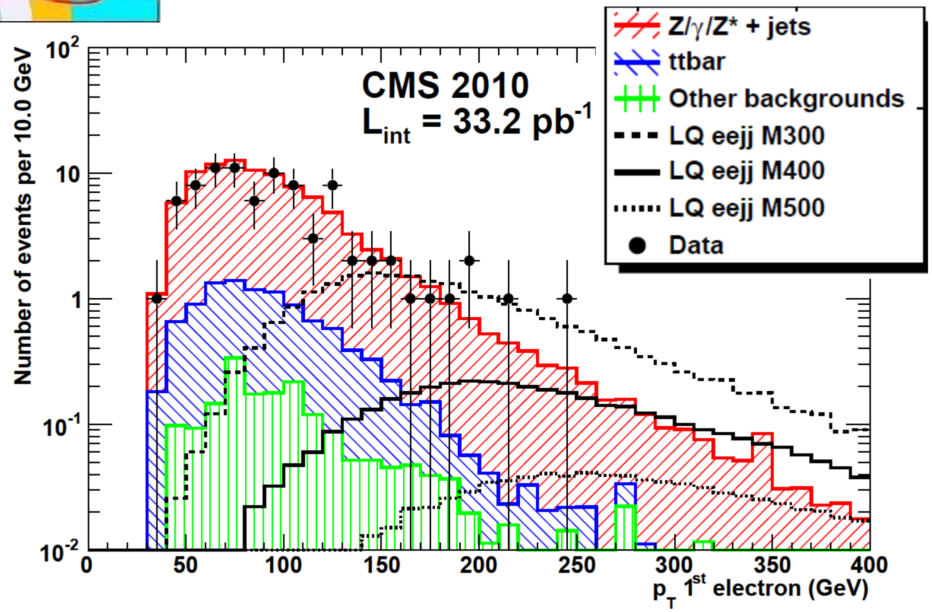
2 electrons P_T>30 GeV, |η|<2.5
2 jets P_T>30 GeV , |η|<3
ΔR(e,j) > 0.7, M_{ee}> 50 GeV, S_T>250 GeV

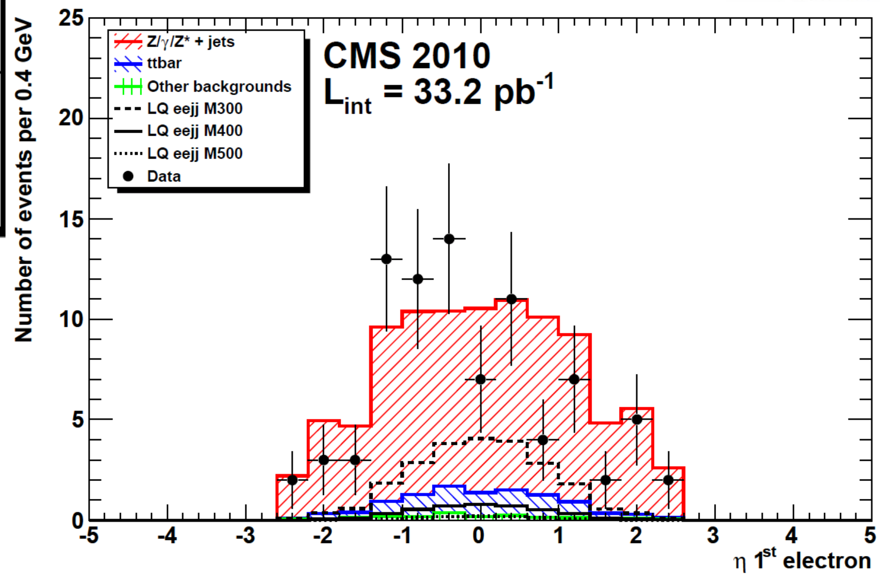
2 muons P_T>30 GeV, |η|<2.4 (2.1)
2 jets P_T>30 GeV , |η|<3
ΔR(μ, μ) > 0.3, S_T>250 GeV

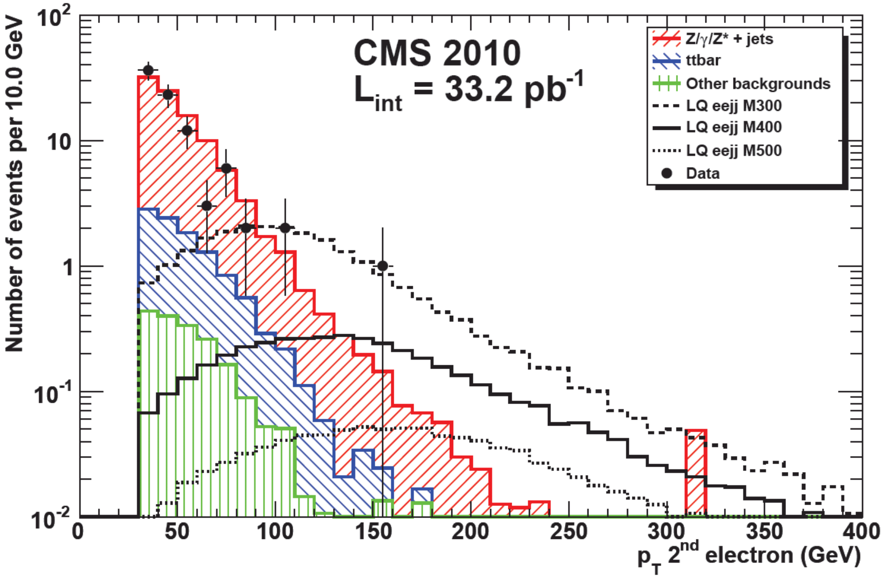
- Data/MC at Z boson peak (80<M_{ll}<100 GeV) after pre-selection is
  - 1.20 ± 0.14 for eejj and 1.28 ± 0.14 for μμjj
- Given the good agreement in the shape of the kinematic distributions of data and MC (see next slides), the Z+jets MC has been rescaled by such amounts (in all plots and tables in this talk)

eejj

Electrons after pre-selection



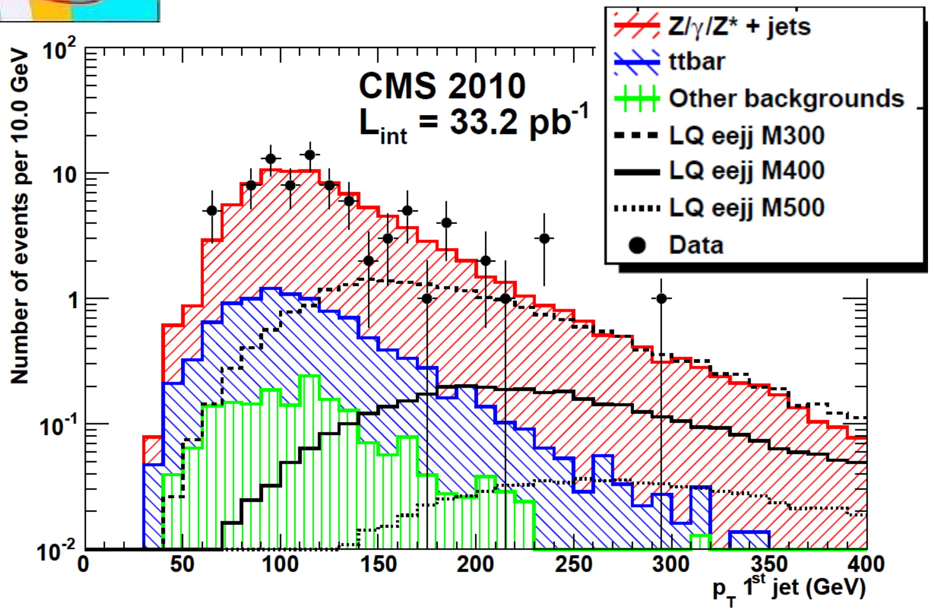


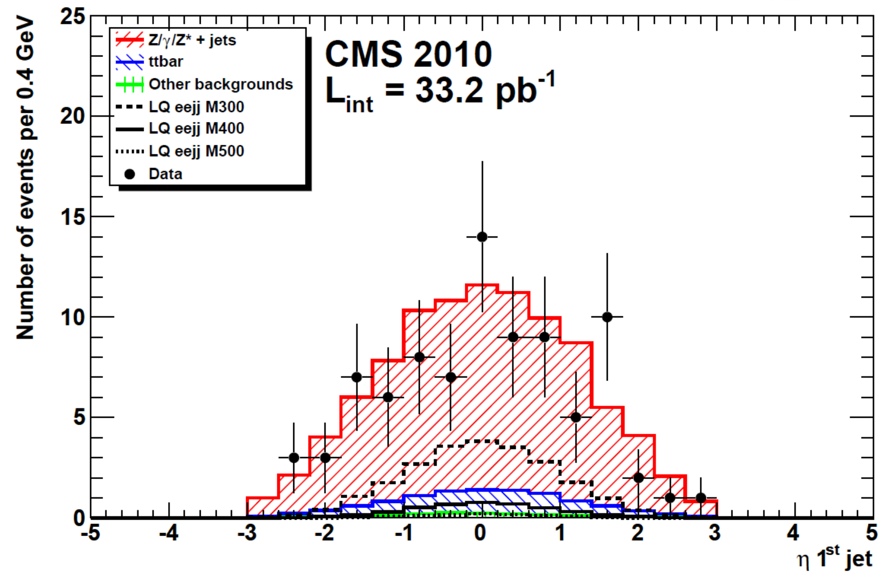


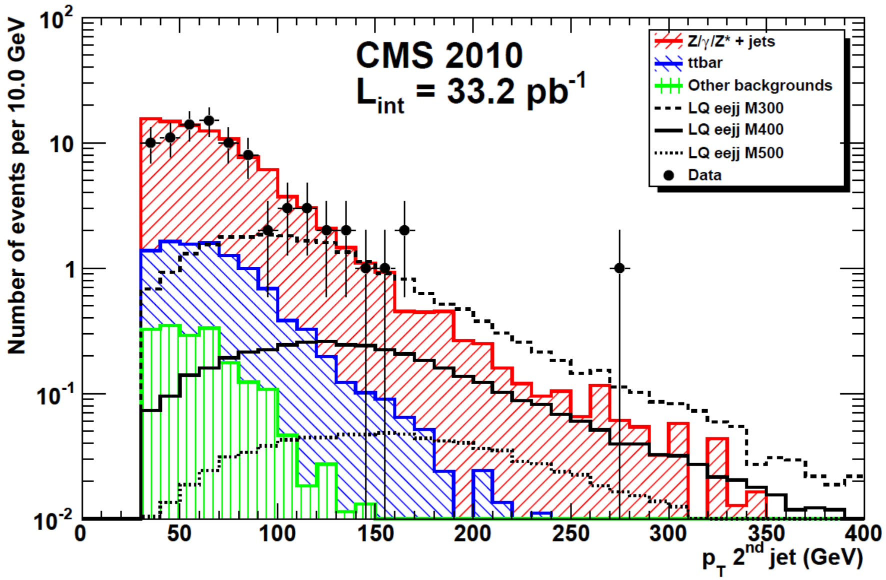
2 electrons P_T>30 GeV, |η|<2.5
2 jets P_T>30 GeV , |η|<3
ΔR(e,j) > 0.7, M_{ee}> 50 GeV,
S_T>250 GeV

eejj

Jets after pre-selection



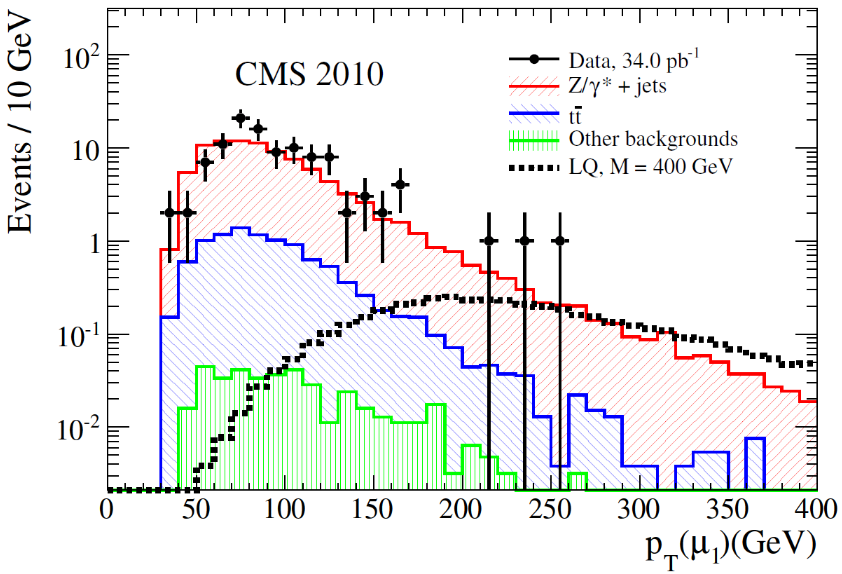


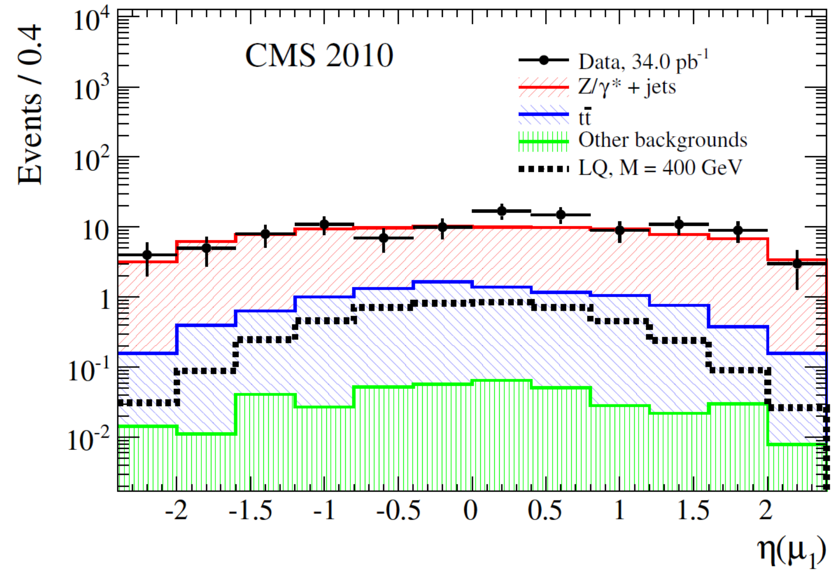


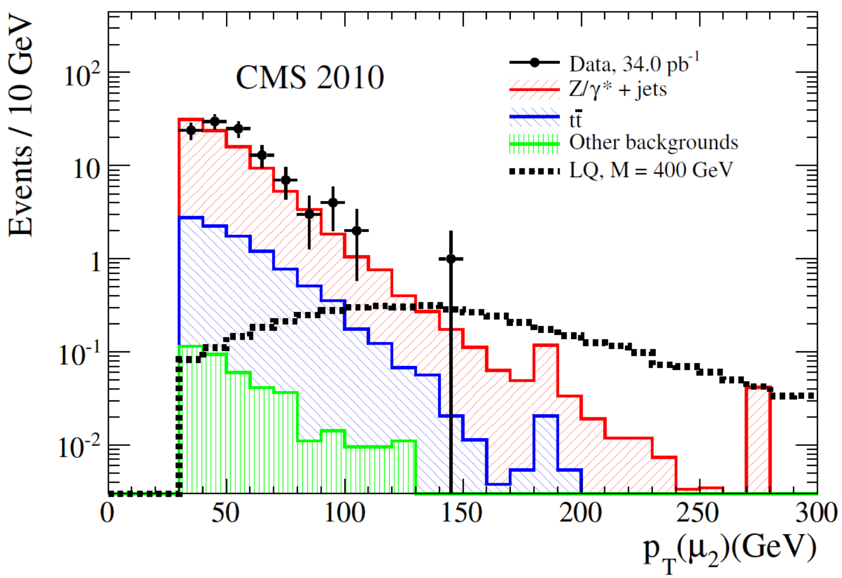
2 electrons P_T>30 GeV, |η|<2.5
2 jets P_T>30 GeV , |η|<3
ΔR(e,j) > 0.7, M_{ee}> 50 GeV,
S_T>250 GeV

μμjj

Muons after Pre-selection



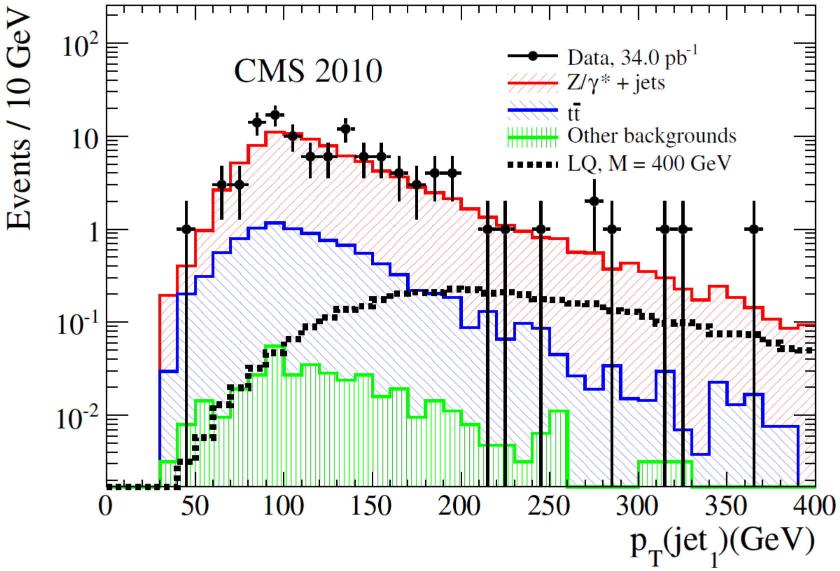


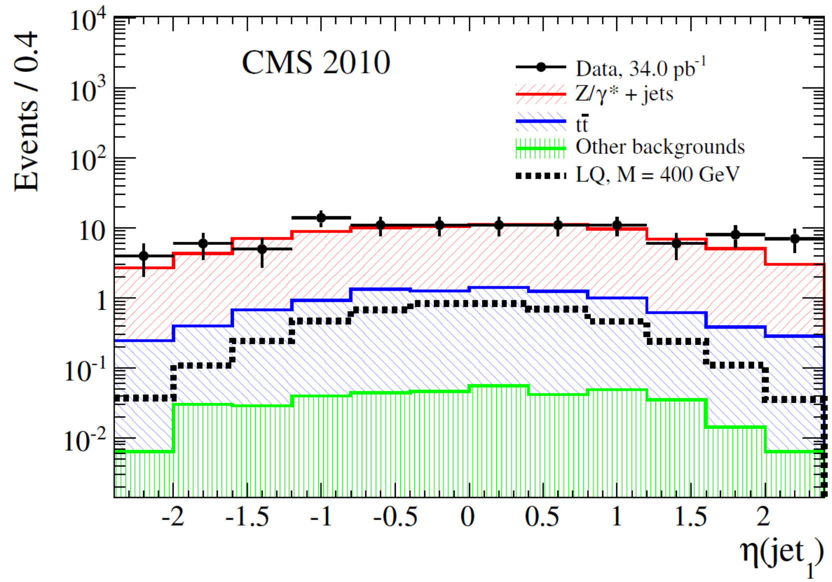


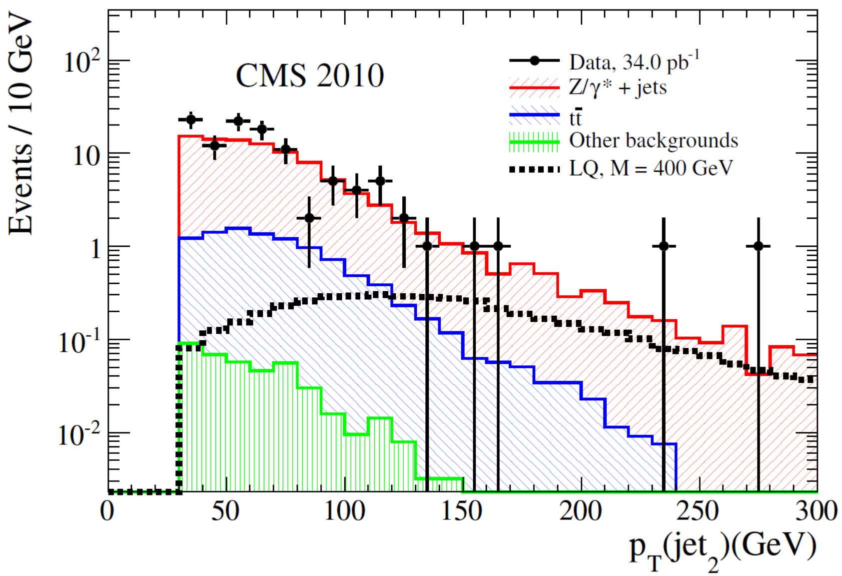
2 muons P_T>30 GeV, |η|<2.4 (2.1)
2 jets P_T>30 GeV , |η|<3
ΔR(μ, μ) > 0.3 , $M_{\mu\mu}$>50 GeV,
S_T>250 GeV

μμjj

Jets after Pre-selection



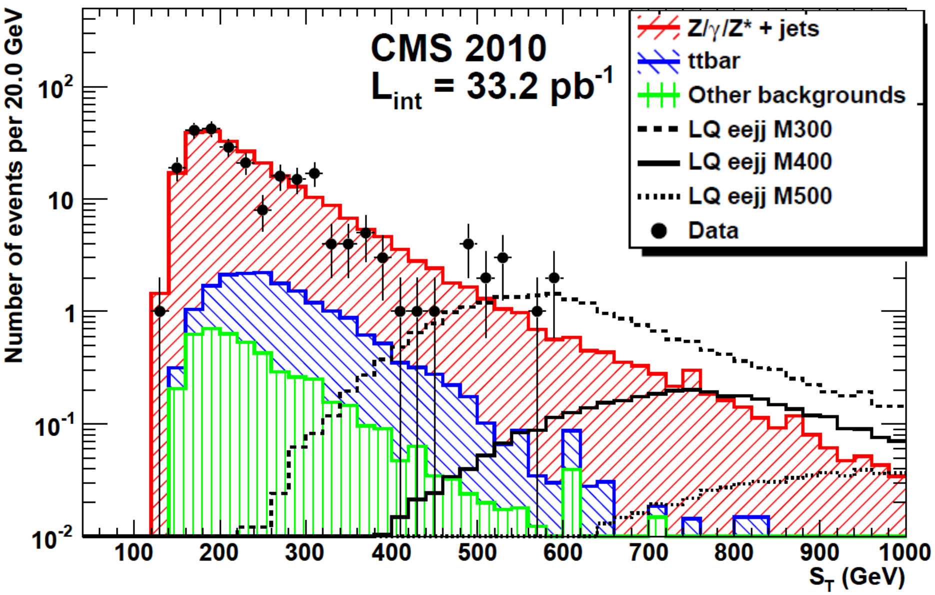




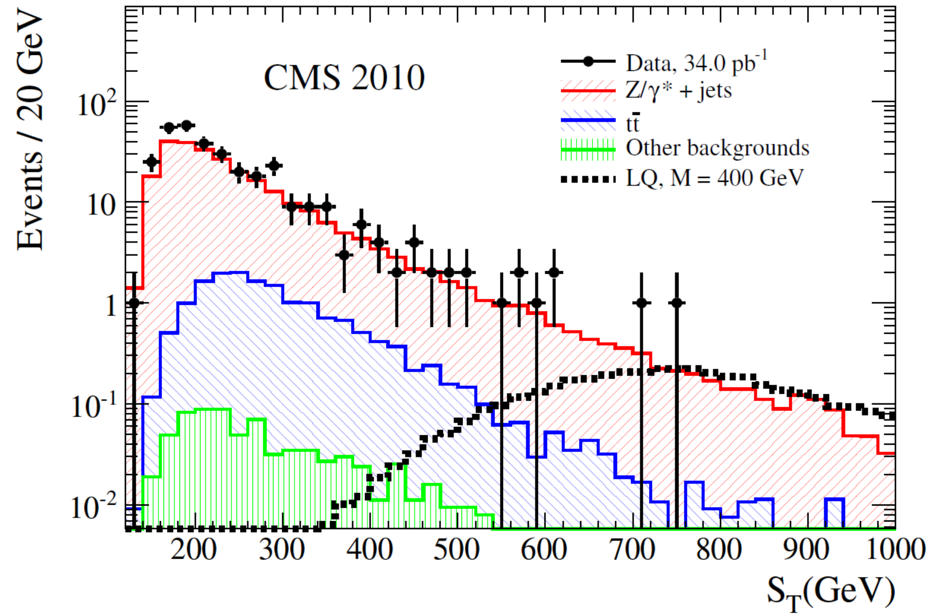
2 muons P_T>30 GeV, |η|<2.4 (2.1)
2 jets P_T>30 GeV , |η|<3
ΔR(μ, μ) > 0.3 , $M_{\mu\mu}$>50 GeV,
S_T>250 GeV

S_T after pre-selection

eejj



μμjj



2 electrons P_T>30 GeV, |η|<2.5
2 jets P_T>30 GeV , |η|<3
ΔR(e,j) > 0.7, M_{ee}> 50 GeV,
S_T>250 GeV (but not applied in this plot)

2 muons P_T>30 GeV, |η|<2.4 (2.1)
2 jets P_T>30 GeV , |η|<3
ΔR(μ, μ) > 0.3, $M_{\mu\mu}$>50 GeV
S_T>250 GeV (but not applied in this plot)

S_T = scalar sum of the pT of the 2 selected leptons and 2 selected jets

Backgrounds

- Z+jets
  - Determined from MC rescaled by the data/MC ratio at the Z peak at pre-selection
  - A systematic uncertainty is derived from the uncertainty on the above ratio (dominated by the statistics on the data → slide 11)
- ttbar
  - The CMS measurement σ(ttbar) = 194 ± 72 (stat.) ± 24 (syst.) ± 21 (lumin.) is fully consistent with next-to-leading order predictions
  - The ttbar background is determined from MC without any rescaling
  - The sum in quadrature of the above uncertainties (41%) is used as a systematic uncertainty on the MC estimate of this background
- Small contribution from other backgrounds containing vector bosons is determined from MC (W+jets, di-boson, single-top)
- QCD background is determined from data and found to be negligible
  - eejj: fake rate method applied to data sample with 2 isolated electromagnetic clusters and 2 jets
  - μμjj: using control data sample of same-sign di-muon events

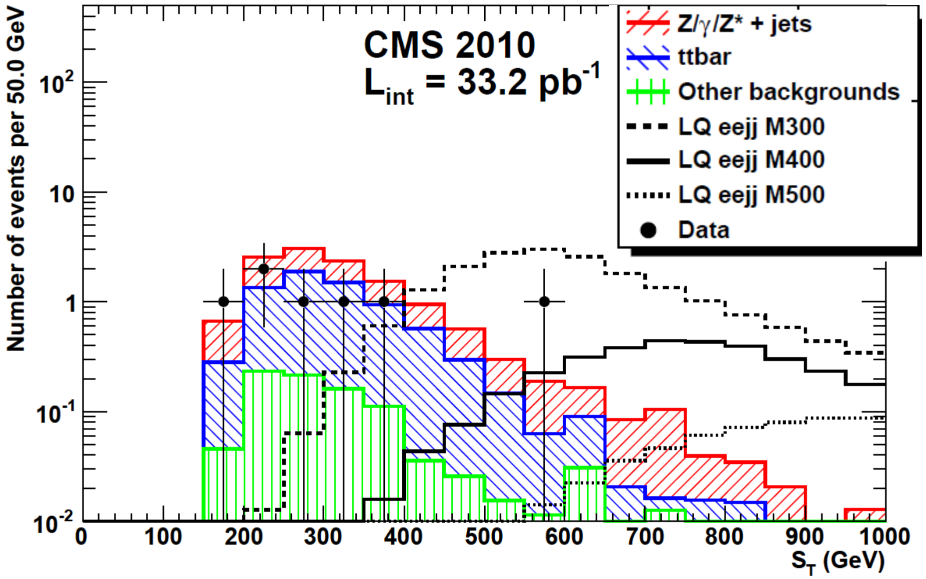
Final Selection

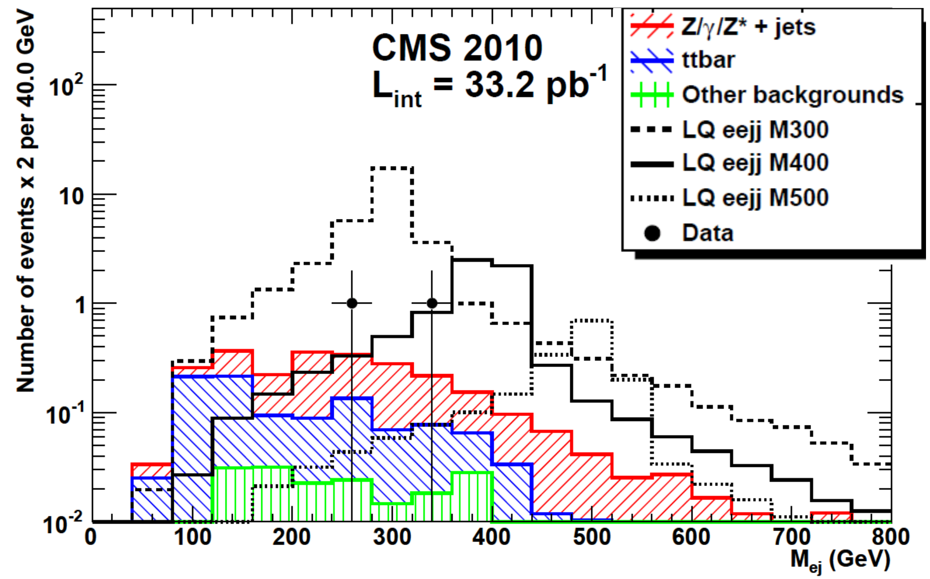
- M_{ll} (di-lepton invariant mass) and S_T (scalar sum of pT of the 2 selected leptons and 2 selected jets) are the two most powerful variables in discriminating signal and background
- M_{ll} and S_T have been optimized using a Bayesian approach to minimize upper limit (*) (systematic uncertainties treated as nuisance parameters) in a 35 pb^{-1} scenario
  - M_{ee} > 125 GeV and $M_{\mu\mu}$ > 115 GeV
  - $S_T > f(M_{LQ})$ – see tables in next two slides

(*) Optimization for discovery produces similar results

eejj

S_T and M_{ej} after Final Selection





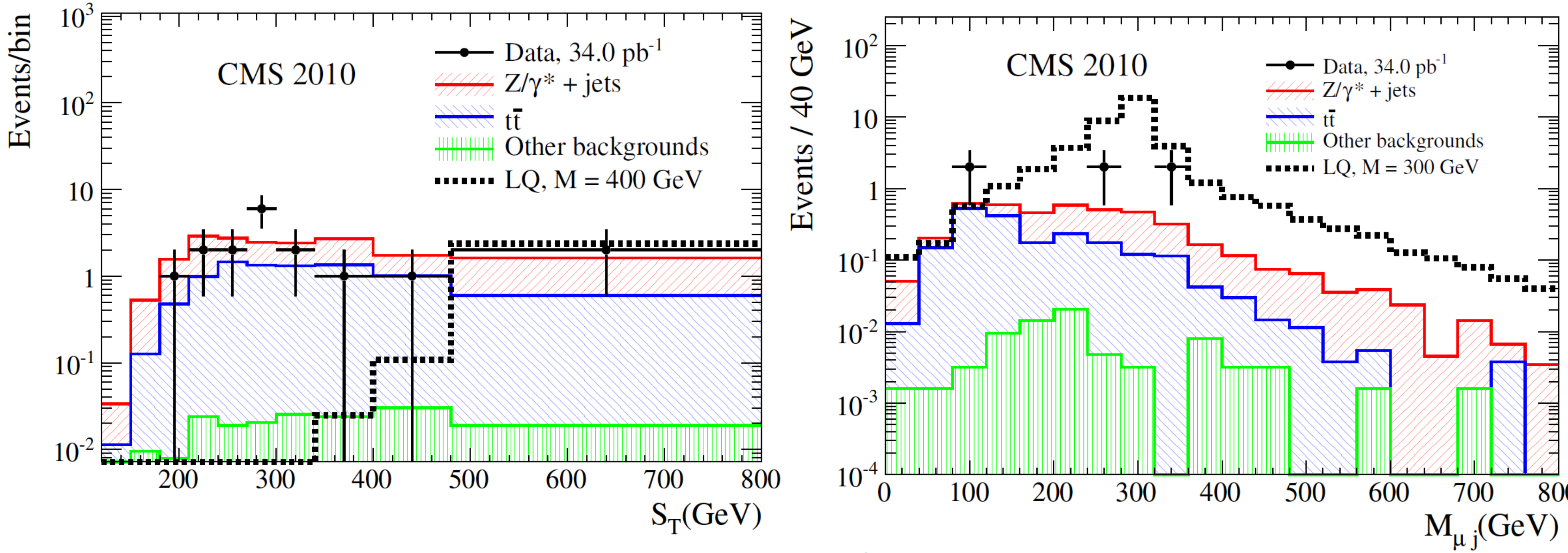
M_{ej} = electron-jet inv. mass (2 entries/event). Of the 2 ways to combine 2 electron and 2 jets – the combination with minimum mass difference is chosen

2 electrons P_T>30 GeV, |η|<2.5; 2 jets P_T>30 GeV, |η|<3; ΔR(e,j)>0.7; M_{ee}> 125 GeV; S_T>f(M_{LQ})

M_{LQ} (S_T Request) [GeV]	MC Signal Samples Selected Events	Acceptance ×Efficiency	Monte Carlo Background Samples Selected Events in $t\bar{t}$ + jets	Z/γ + jets	Others	All	Events in Data
250 (S_T >400)	43.8±0.2	0.380±0.002	1.1 ±0.06	1.3 ±0.1	0.14±0.02	2.5 ±0.1	1
300 (S_T >470)	17.3±0.1	0.430±0.002	0.44±0.04	0.75±0.07	0.10±0.02	1.3 ±0.1	1
340 (S_T >510)	8.88±0.04	0.469±0.002	0.27±0.03	0.56±0.06	0.08±0.02	0.91±0.08	1
400 (S_T >560)	3.55±0.02	0.522±0.002	0.17±0.02	0.41±0.05	0.06±0.02	0.63±0.06	1
450 (S_T >620)	1.70±0.01	0.539±0.002	0.10±0.02	0.28±0.05	0.02±0.01	0.41±0.06	0

μμjj

S_T and $M_{\mu j}$ after Full Selection



$M_{\mu j}$ = muon-jet inv. mass (2 entries/event). Of the 2 ways to combine 2 muons and 2 jets – the combination with minimum mass difference is chosen

2 muons P_T>30 GeV, |η|<2.4(2.1); ΔR(μ, μ)>0.3; 2 jets P_T>30 GeV, |η|<3; $M_{\mu\mu}$>115 GeV; S_T>f(M_{LQ}) GeV

M_{LQ}	S_T	Z/γ^*+jets	$t\bar{t}$	Other Bkg	All Bkg	Data	S	ϵ_S
250	400	1.92 ± 0.03	1.60 ± 0.08	0.05 ± 0.01	3.57 ± 0.09	3	51.5 ± 5.2	0.437 ± 0.003
300	449	1.53 ± 0.03	0.98 ± 0.06	0.04 ± 0.01	2.54 ± 0.07	3	21.3 ± 2.1	0.518 ± 0.004
340	530	0.79 ± 0.01	0.34 ± 0.04	0.01 ± 0.00	1.14 ± 0.04	1	9.8 ± 1.0	0.508 ± 0.003
400	560	0.67 ± 0.01	0.27 ± 0.03	0.01 ± 0.00	0.94 ± 0.03	1	4.0 ± 0.4	0.578 ± 0.004
450	620	0.49 ± 0.01	0.16 ± 0.02	0.01 ± 0.00	0.66 ± 0.03	0	1.9 ± 0.2	0.600 ± 0.004

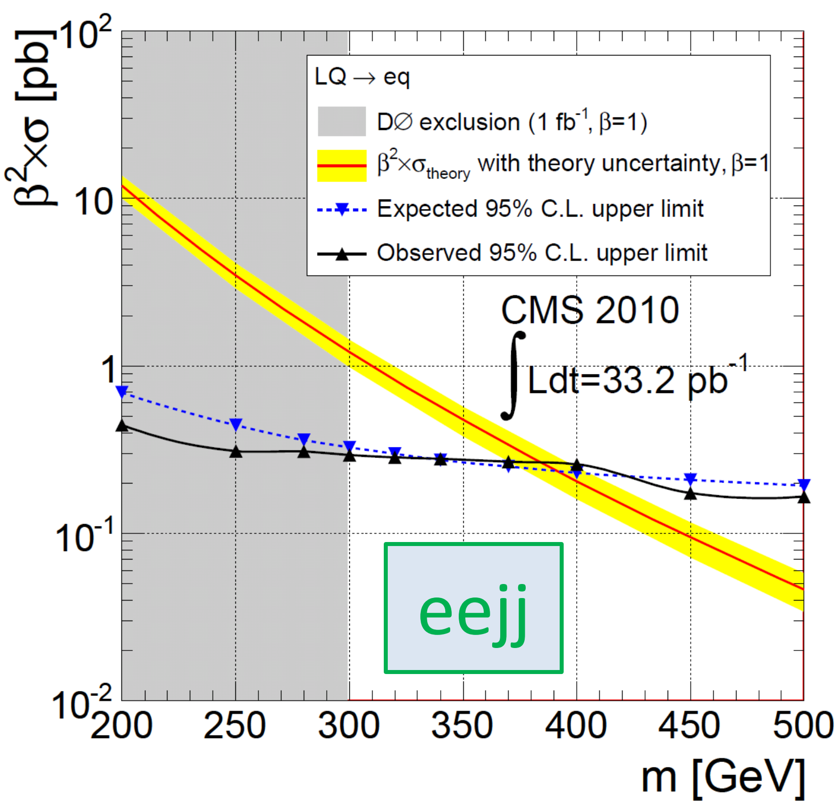
Systematic Uncertainties

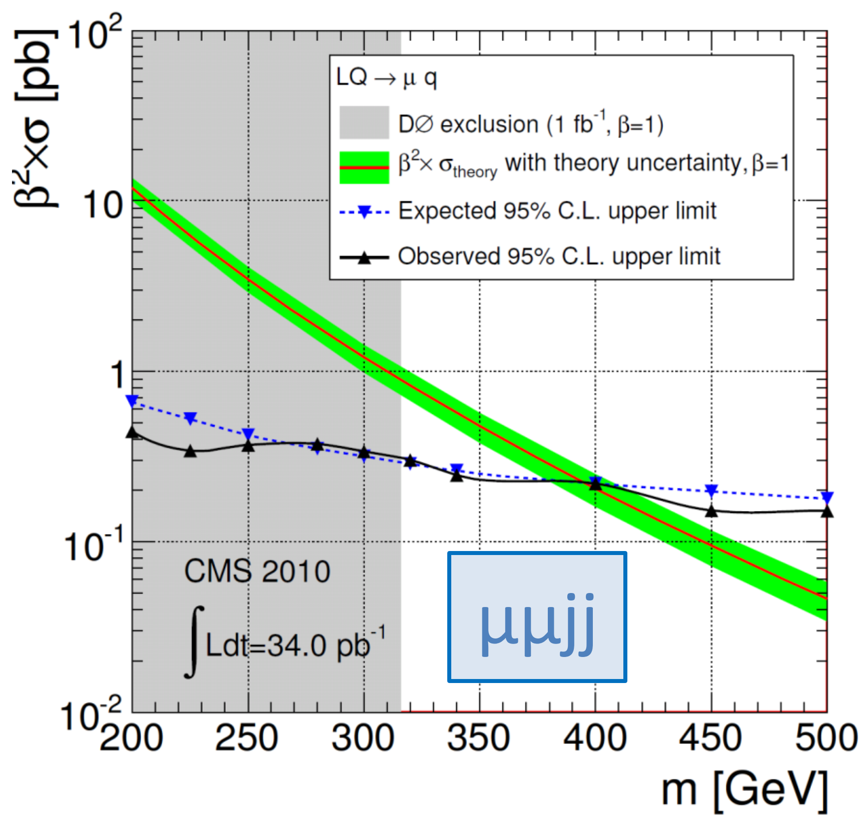
- Dominant systematic uncertainties:
  - Luminosity: 11%
  - Di-lepton selection/recostruction efficiencies: 10% for both channels
  - Jet energy scale: 5%
  - Electron energy scale: 1% (3%) in barrel (endcaps)
  - Muon momentum scale: 1%
- Their effect on signal and background is shown in the table
- Some do not apply to the background estimate
  - Because of the systematic error determined from data-MC comparison (21% for eejj and 25% for μμjj)

Channel	Effect on N_{signal}	Effect on $N_{background}$
eejj	15%	25%
μμjj	15%	25%

Upper Limits on LQ Pair Production Cross Section

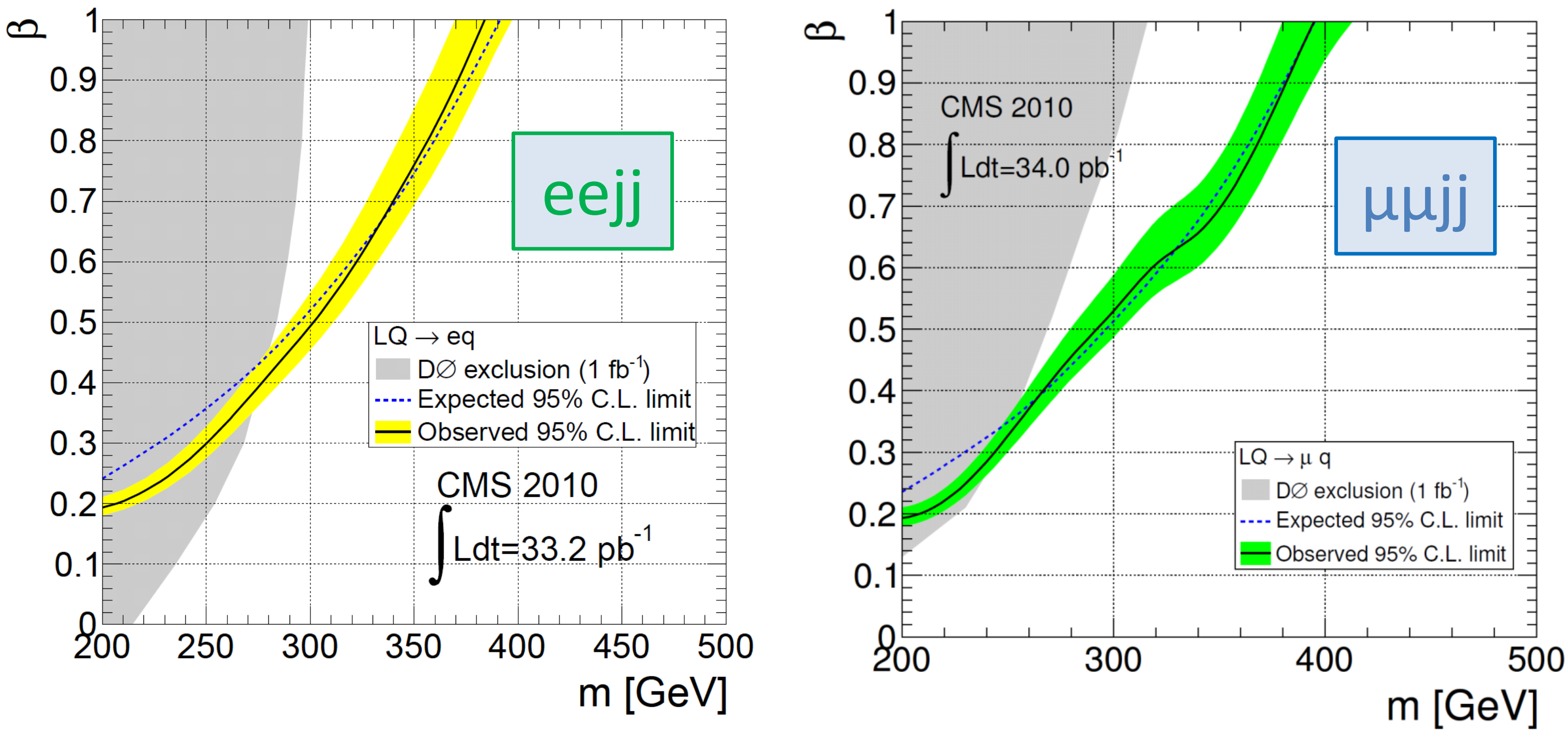
- The data are consistent with SM background expectation
  - upper limits on the LQ cross section are set using a Bayesian approach (systematic uncertainties included in the calculation)





Lower Limits on M_{LQ}

- By comparing the upper limits to a theoretical calculation of the LQ cross section, the existence of first- and second-generation LQs with mass below 384 and 394 GeV, respectively, are excluded for β=1:



  - D0 results combine the limits obtained using the lljj and lvjj (and vvjj in left plot)
    - For β = 1, D0 sets M_{LQ} > 299 and 316 GeV for first- and second-gen.

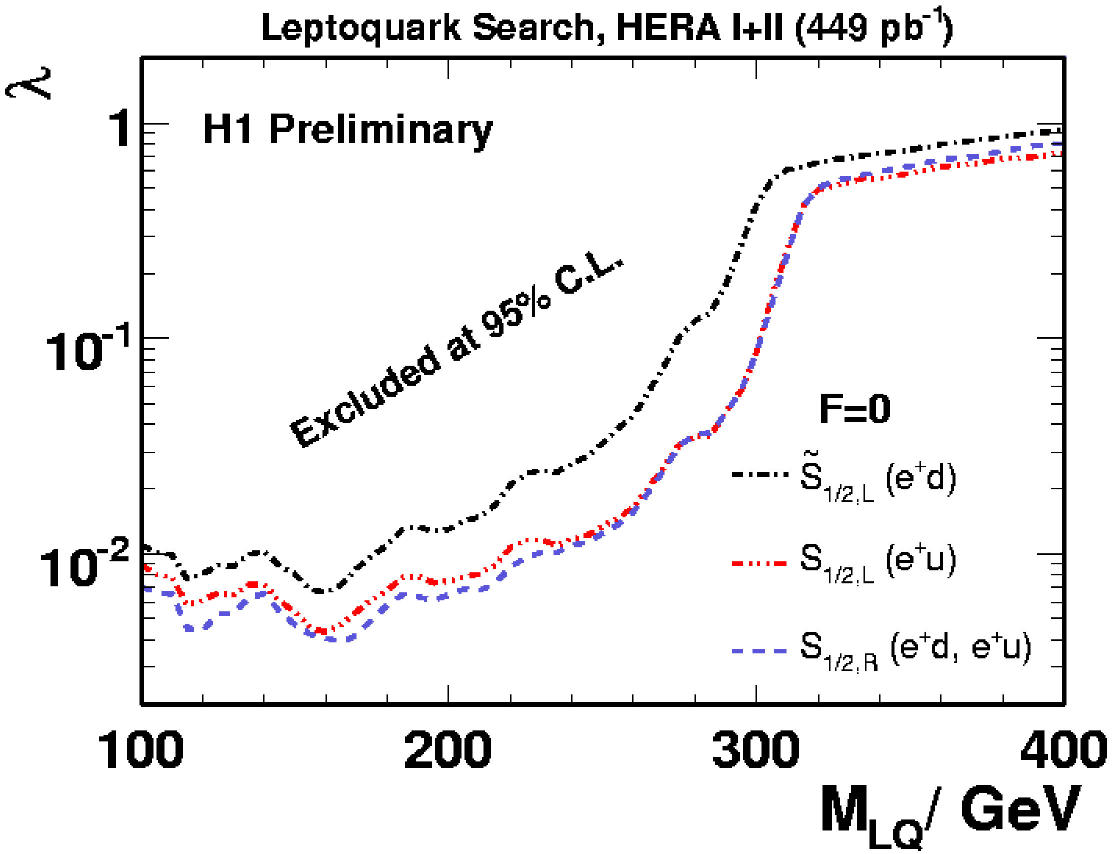
Conclusions

- Searches for pair production of first- and second-generation leptoquarks at CMS have been performed
  - in the channels with 2 charged leptons and 2 jets
- The full 2010 dataset has been used: just short of 35 pb^{-1}
- We set lower limits on the LQ mass that significantly improve the Tevatron (D0) results over a large range of β values (> 0.4)
- For β=1, we exclude
  - First-generation LQ with masses below 384 GeV
  - Second-generation LQ with masses below 394 GeV
- Publication drafts for the eejj and μμjj channels are being finalized
- The analyses of the eνjj and μνjj channels are being pursued

BACKUP SLIDES

Limits from HERA

(electron-proton)



Systematic Uncertainties

eejj

Systematic Uncertainty	Magnitude [%]	Effect on N_{signal} [%]	Effect on N_{AllBkg} [%]
Data-Driven Uncertainty	-	-	21
Jet Energy Scale	5	3	11
Elec. Energy Scale Barrel/Endcap	1/3	1	5
Electron Pair Reco/ID/Iso	10	10	-
MC Statistics	See Table 1	1	6
Integrated Luminosity	11	11	-
Total	-	15	25

μμjj

Systematic Uncertainty	Magnitude	Effect on Signal	Effect on N_{AllBkg}
JES	$\pm 5\%$	$\pm 2\%$	—
JES and Data Background Est.	—	—	$\pm 25\%$
Muon Momentum Scale	$\pm 1\%$	$\pm 1\%$	$\pm < 0.5\%$
Muon Pair Reco/ID/Iso	$\pm 10\%$	$\pm 10\%$	$\pm < 0.05\%$
Integrated Luminosity	$\pm 11\%$	$\pm 11\%$	—
Total		$\pm 15\%$	$\pm 25\%$

Bayesian Upper Limit

- 95% C.L. upper limit on the LQ pair production cross section *σ* is calculated using a Bayesian approach

$$\int_{-\infty}^{\sigma_{\rm up}(n)} p(\sigma|n, A, \mathcal{L}, b)\,{\rm d}\sigma = \frac{\int_{-\infty}^{\sigma_{\rm up}(n)} L'(n|\sigma, A, \mathcal{L}, b)\pi(\sigma){\rm d}\sigma}{\int_{-\infty}^{+\infty} L'(n|\sigma, A, \mathcal{L}, b)\pi(\sigma){\rm d}\sigma} = 0.95$$

$$L'(n|\sigma, A, \mathcal{L}, b) = \int_0^{+\infty}\int_0^{+\infty}\int_0^{+\infty} L(n|\sigma, A', \mathcal{L}', b')\,\underbrace{g(A')h(\mathcal{L}')f(b')}\,{\rm d}A'{\rm d}\mathcal{L}'{\rm d}b'$$

Flat prior

$$\pi(\sigma) = \begin{cases} 0 & \sigma < 0 \\ 1 & \sigma \geq 0 \end{cases}$$

$$g(A'),\ h(\mathcal{L}'),\ f(b')$$

Log-normal distributions describing uncertainties in *A*', $\mathcal{L}$', *b*'

Poisson distribution

$$L(n|\sigma, A', \mathcal{L}', b') = \frac{(\sigma A'\mathcal{L}' + b')^n}{n!} e^{-(\sigma A'\mathcal{L}' + b')}$$

Expected upper limit

$$<\sigma_{\rm up}> = \sum_{n=0}^{+\infty} \sigma_{\rm up}(n) L(n|\sigma = 0, A, \mathcal{L}, b)$$

n = number of observed events
A = acceptance×efficiency
$\mathcal{L}$ = integrated luminosity
b = expected number of background events