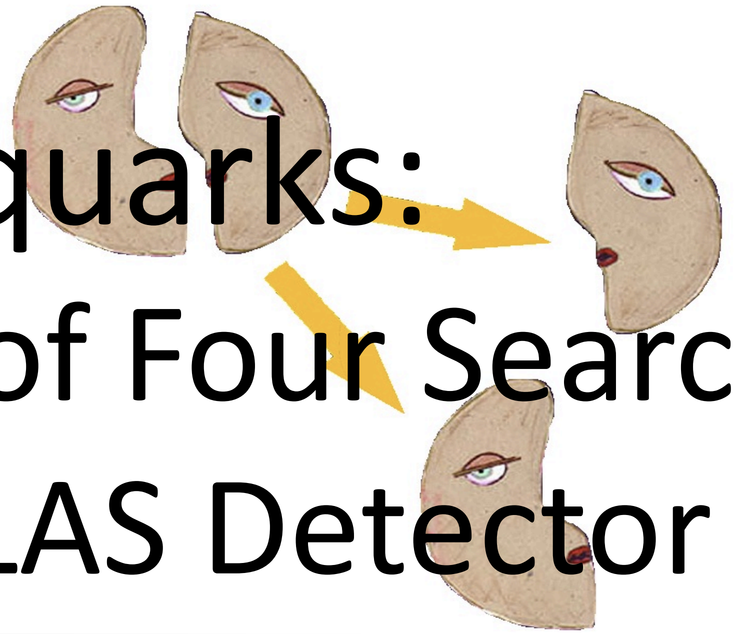
Leptoquarks: A Tale of Four Searches at the ATLAS Detector



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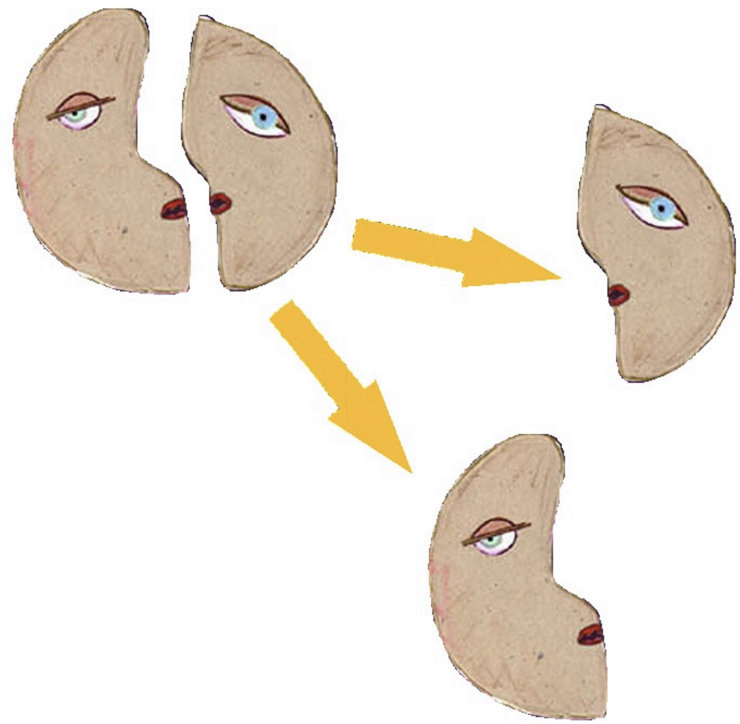
BNL Seminar

April 28, 2011

On Behalf of the ATLAS Collaboration

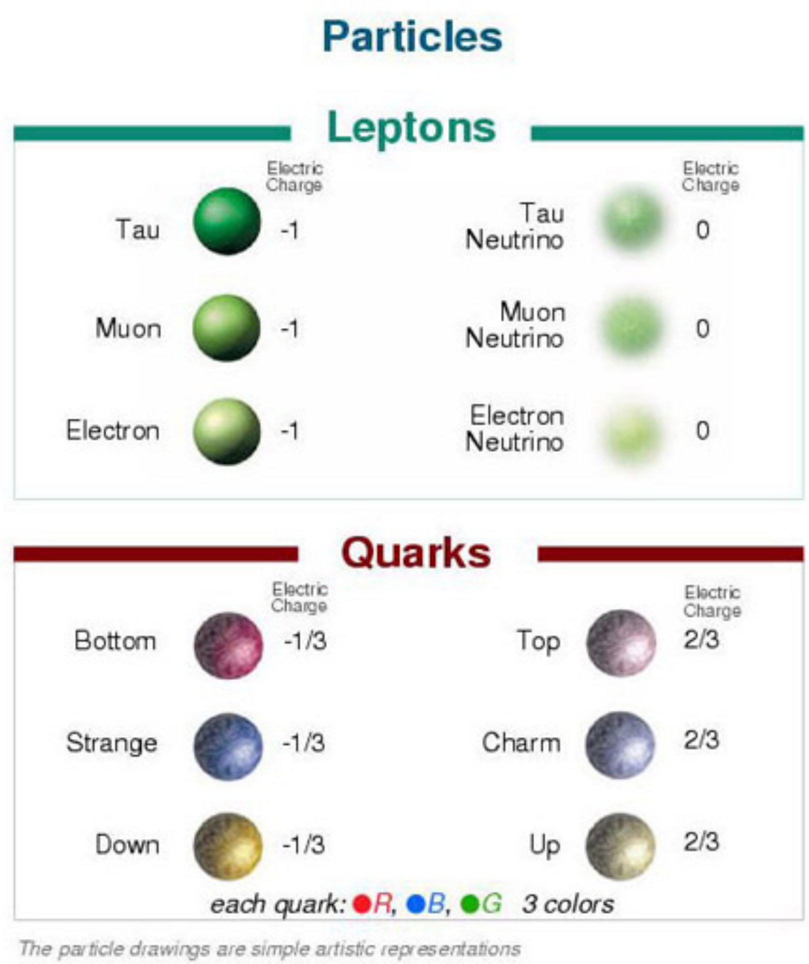
To Boldly Search…

- The Standard Model and Beyond
  - A Brief Introduction to Leptoquarks
- The LHC and the ATLAS detector
- Reconstruction and Identification
- Leptoquark Analysis
- Results and Conclusion



The Standard Model

- Quantum Field Theory
  - particles are fields
  - gauge invariance
  - $SU(3) \times SU_L(2) \times U_Y(1)$ yields 12 gauge bosons
- Forces act on particles
  - fermions - quarks/leptons
- Families have identical gauge interactions
- Differ by mass and flavor quantum number

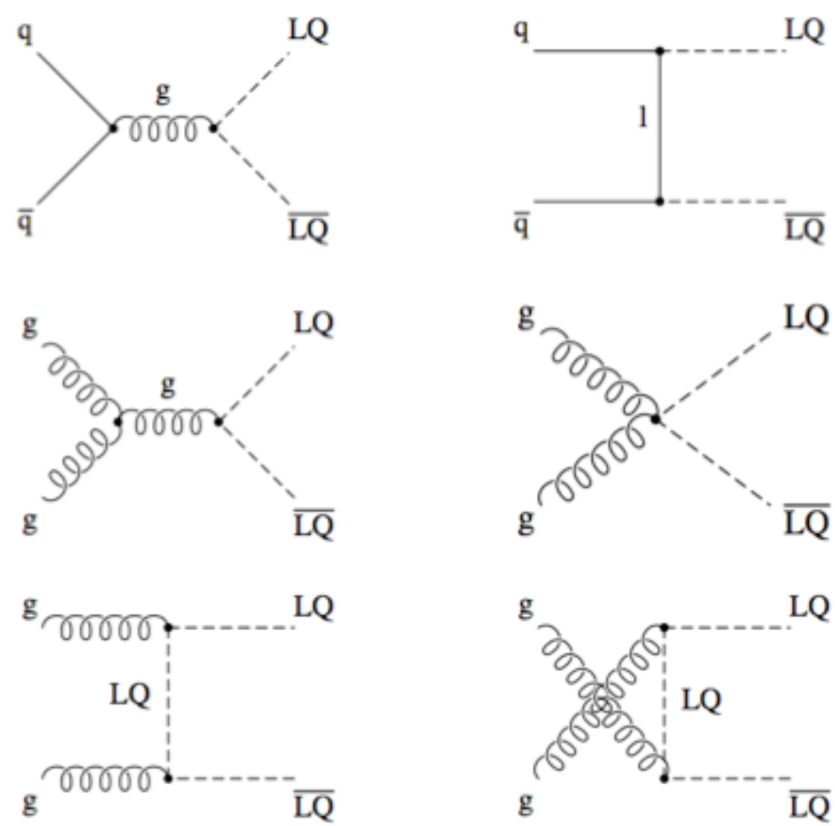


http://www.ipp.phys.ethz.ch/aboutus/?file=institut

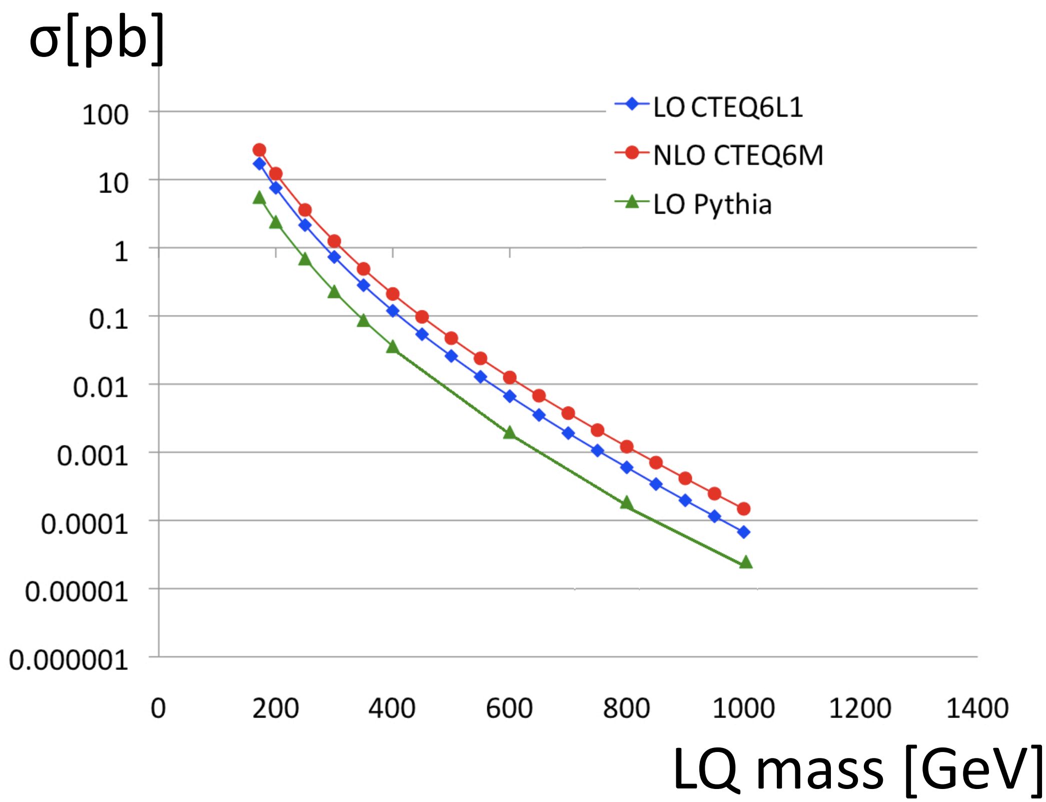
A Brief Introduction to Leptoquarks

- SM provides no communication/symmetry between quarks/leptons
- Leptoquarks: Another Boson
  - baryon and lepton number, couple triplet color charge
  - obey SM group symmetries
  - spin-0 scalar/spin-1 vector
    - 2 couplings: $\ell(\nu)$-q
    - 4 couplings: 2 with λ_G and κ_G
  - Produced singly or in pairs
- Theories predict LQs
  - lepton/quark substructure, Grand Unified Theories (GUTs), technicolor

Born level diagrams for LQ pair production



Production Cross Sections

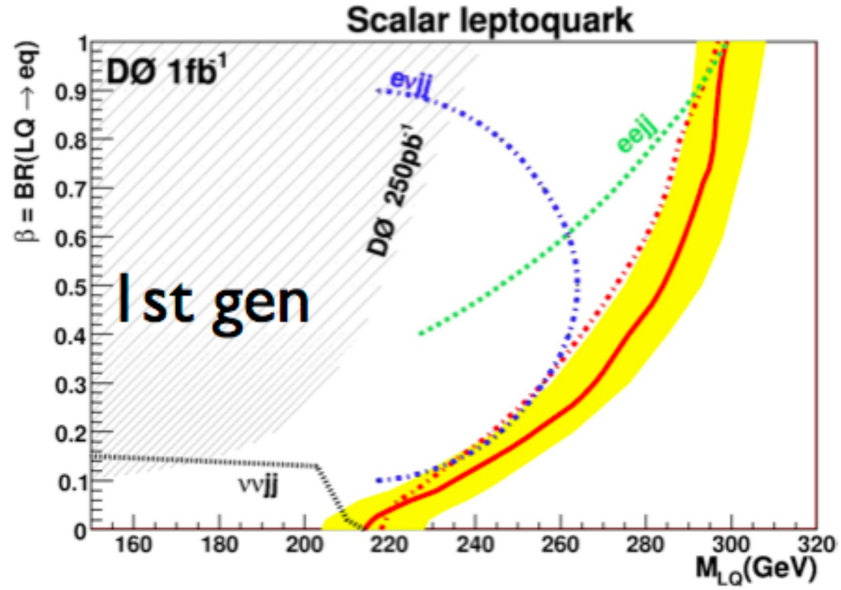


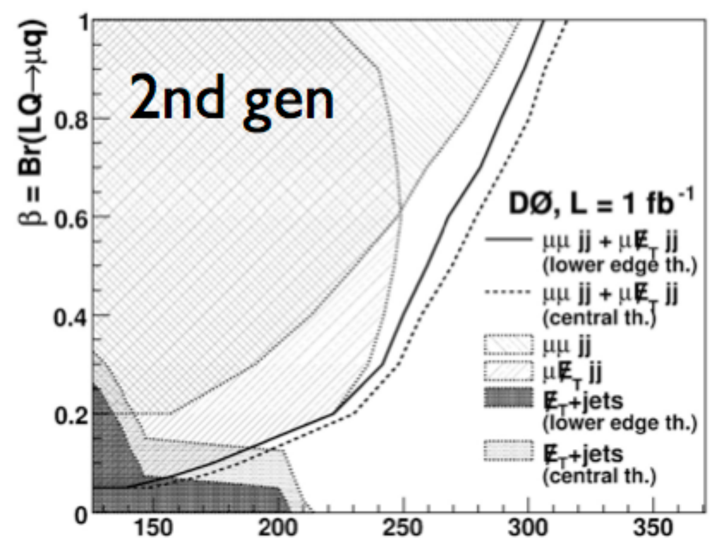
M. Kramer et al., Phys. Rev. D71, 057503 (2005)

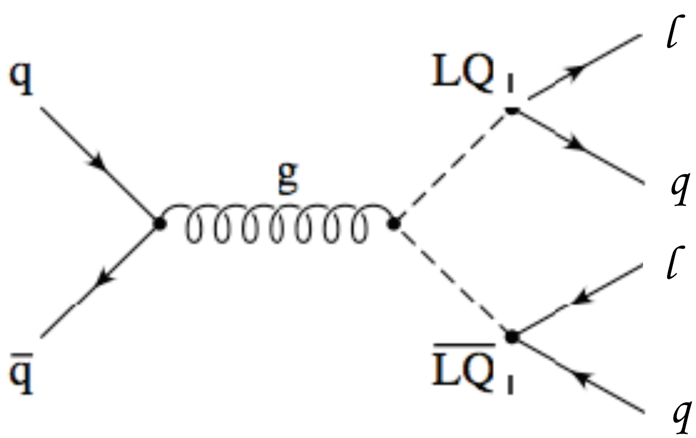
- Focus: scalar LQ pair production
- Use NLO σ for scalar signal
- Early LHC data sensitive to mass range beyond other accelerators

HERA and the Tevatron

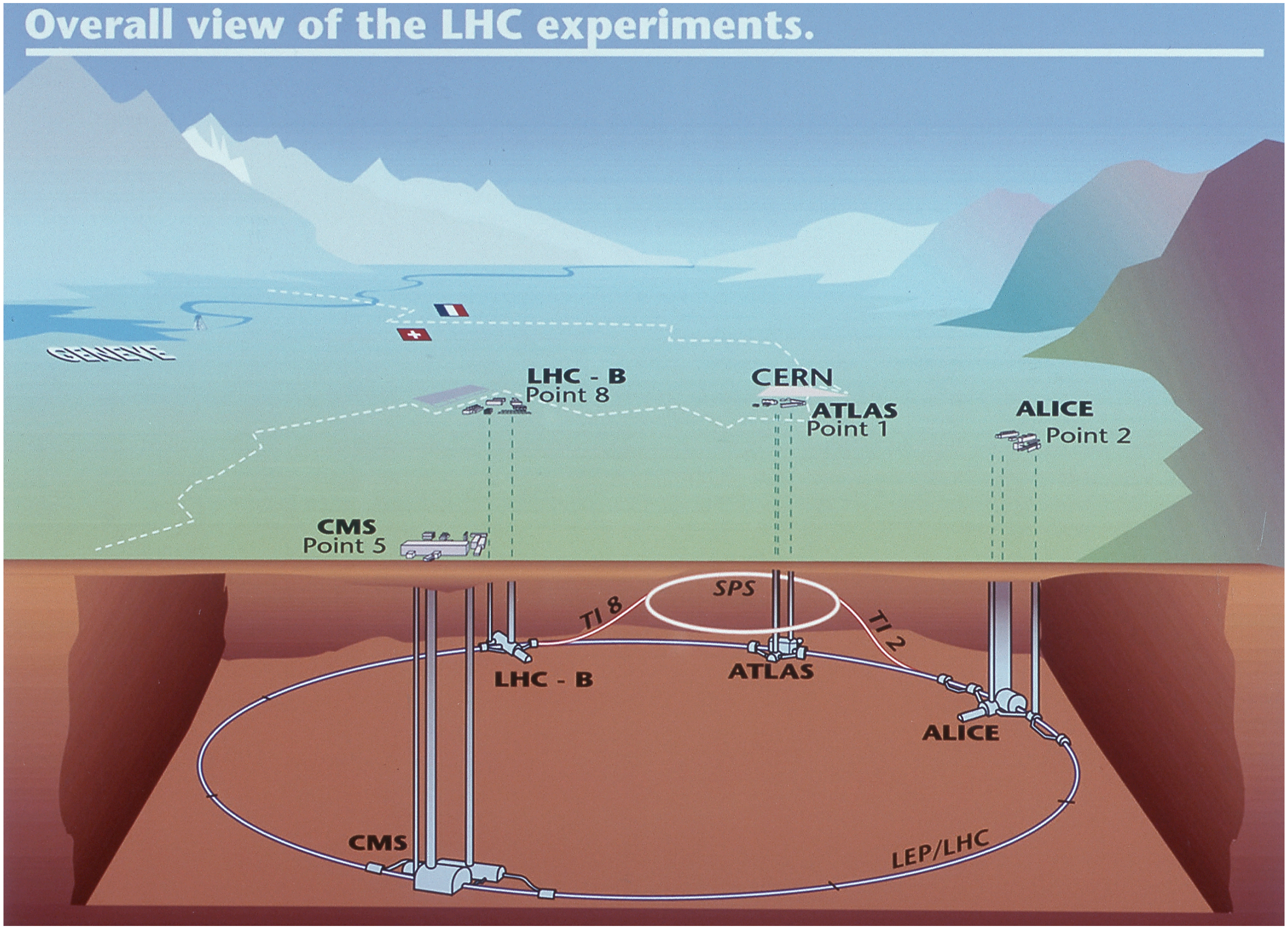
- Excitement from HERA
  - 1997: H1 and ZEUS observed excess at e+jet mass of 200 GeV
- HERA results
  - later ruled out anomaly
- Tevatron results
  - β is branching fraction to charged leptons





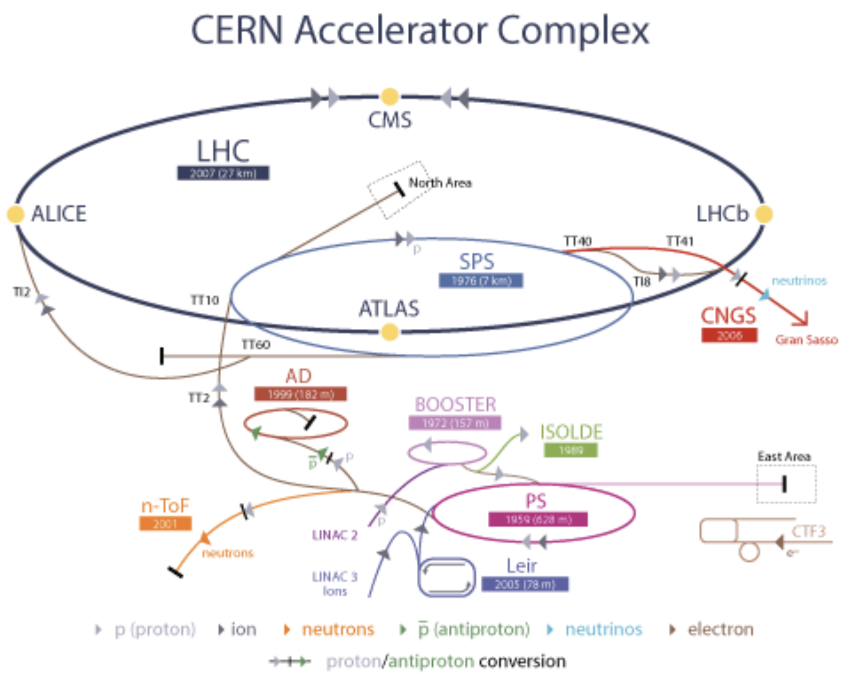


The LHC and the ATLAS Detector



The Large Hadron Collider

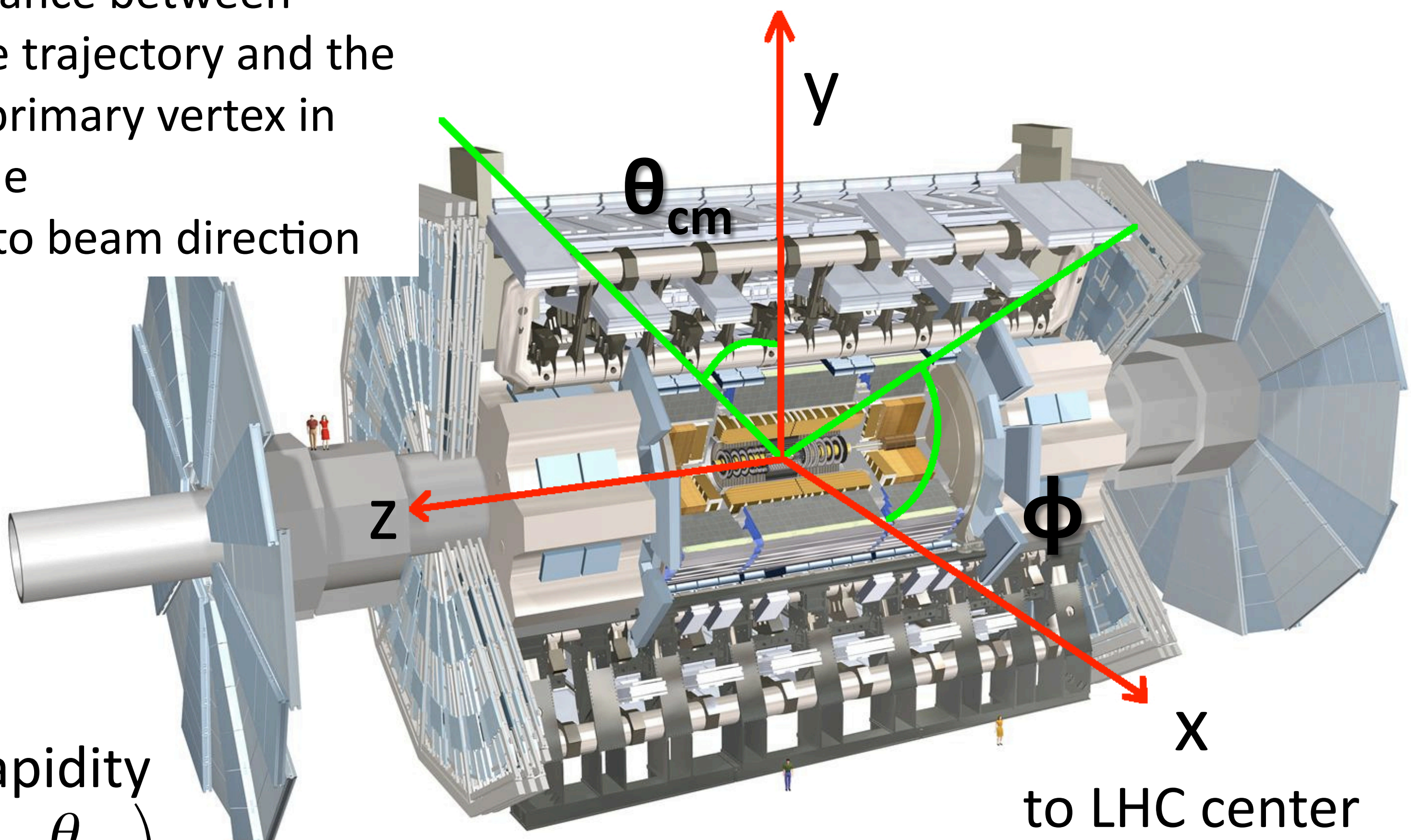
- 27 km long collider ring
  100 m underground
- $\sqrt{s}$ = 7 TeV
- $\mathcal{L}_{inst} = 2.5 \times 10^{32}\ cm^{-2}s^{-1}$
- 200 bunches with
  1.15×10^{11} p/bunch



ATLAS coordinate system

d_0- min distance between particle trajectory and the event primary vertex in xy-plane

z_0- parallel to beam direction



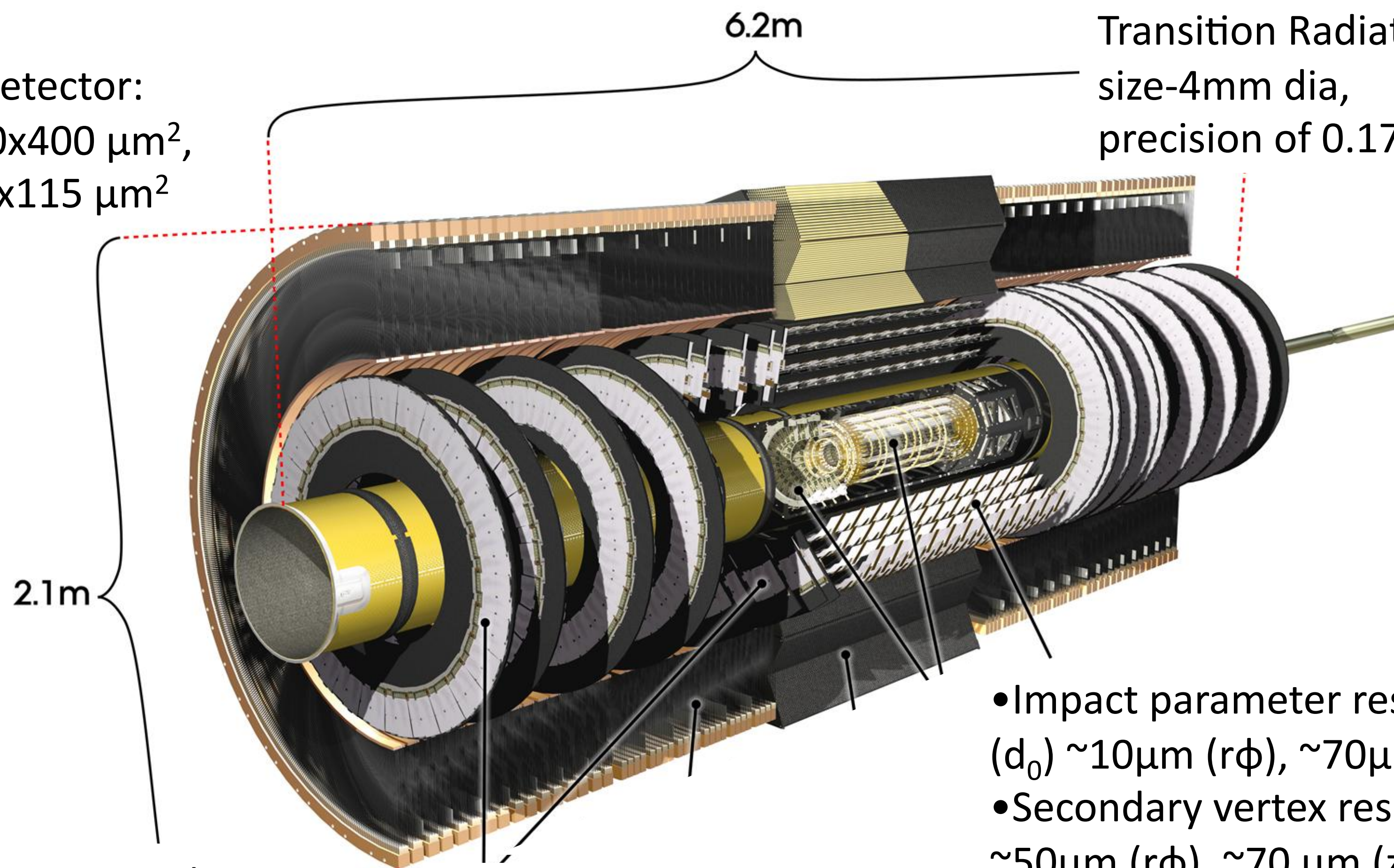
pseudorapidity

$$\eta = -\ln\left(\tan\frac{\theta_{cm}}{2}\right)$$

Inner Detector (Tracking)

Pixel detector:
size-50x400 μm^2,
res-14x115 μm^2

Transition Radiation Tracker:
size-4mm dia,
precision of 0.17 mm



Momentum resolution
dependent on η and p_T
($\sim 5\times10^{-4}\, p_T/\mathrm{GeV} \oplus 0.01$)

Semiconductor Tracker:
size-6.36x6.40 cm^2
accurate to 17mm/layer

- Impact parameter resolution (d_0) ~10μm (rϕ), ~70μm (z)
- Secondary vertex resolution ~50μm (rϕ), ~70 μm (z)
- Primary (main) vertex resolution ~11μm (rϕ), ~45μm (z)

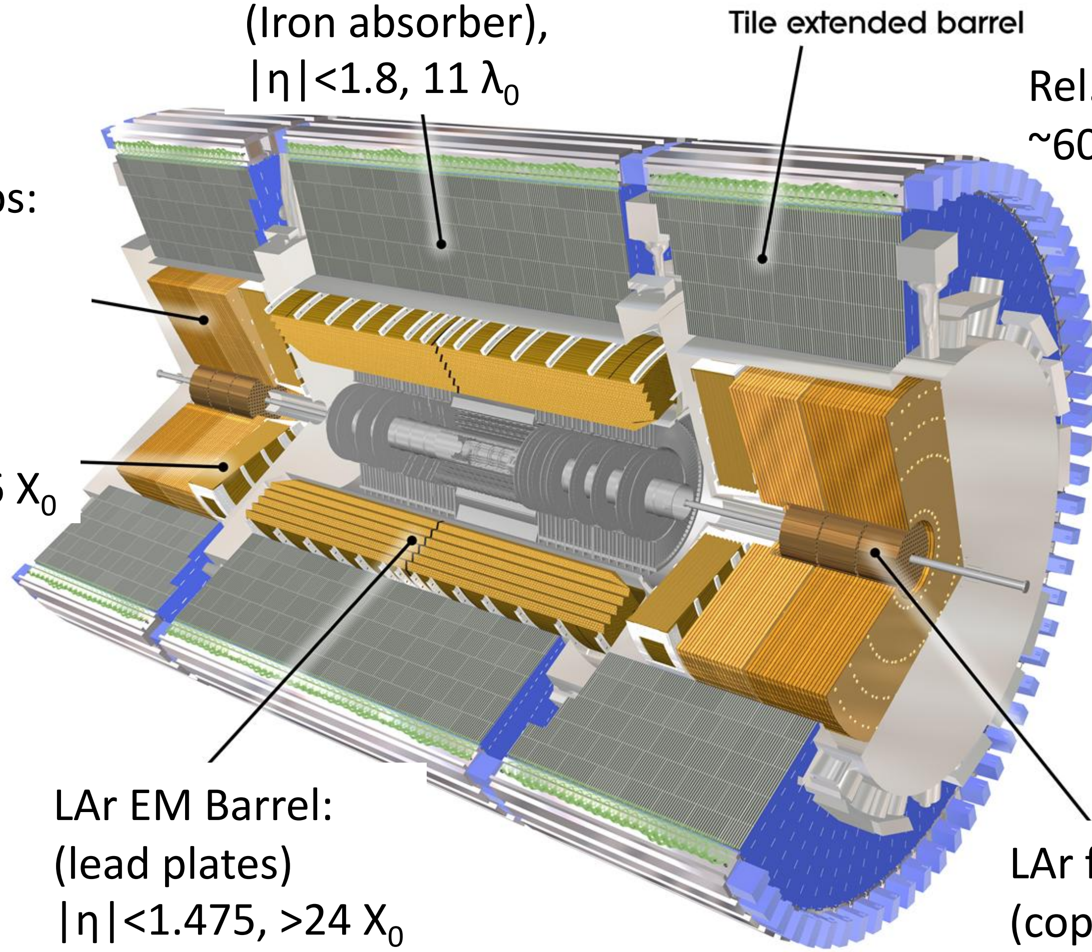
Calorimeters

Scintillating Tile:
(Iron absorber),
|η|<1.8, 11 λ_0

Rel. energy res:
~60%/√(E/GeV) $\oplus$ 0.03

LAr Had End-caps:
(copper plates)
1.5<|η|<3.2

LAr EM End-caps:
1.375<|η|<3.2, >26 X_0



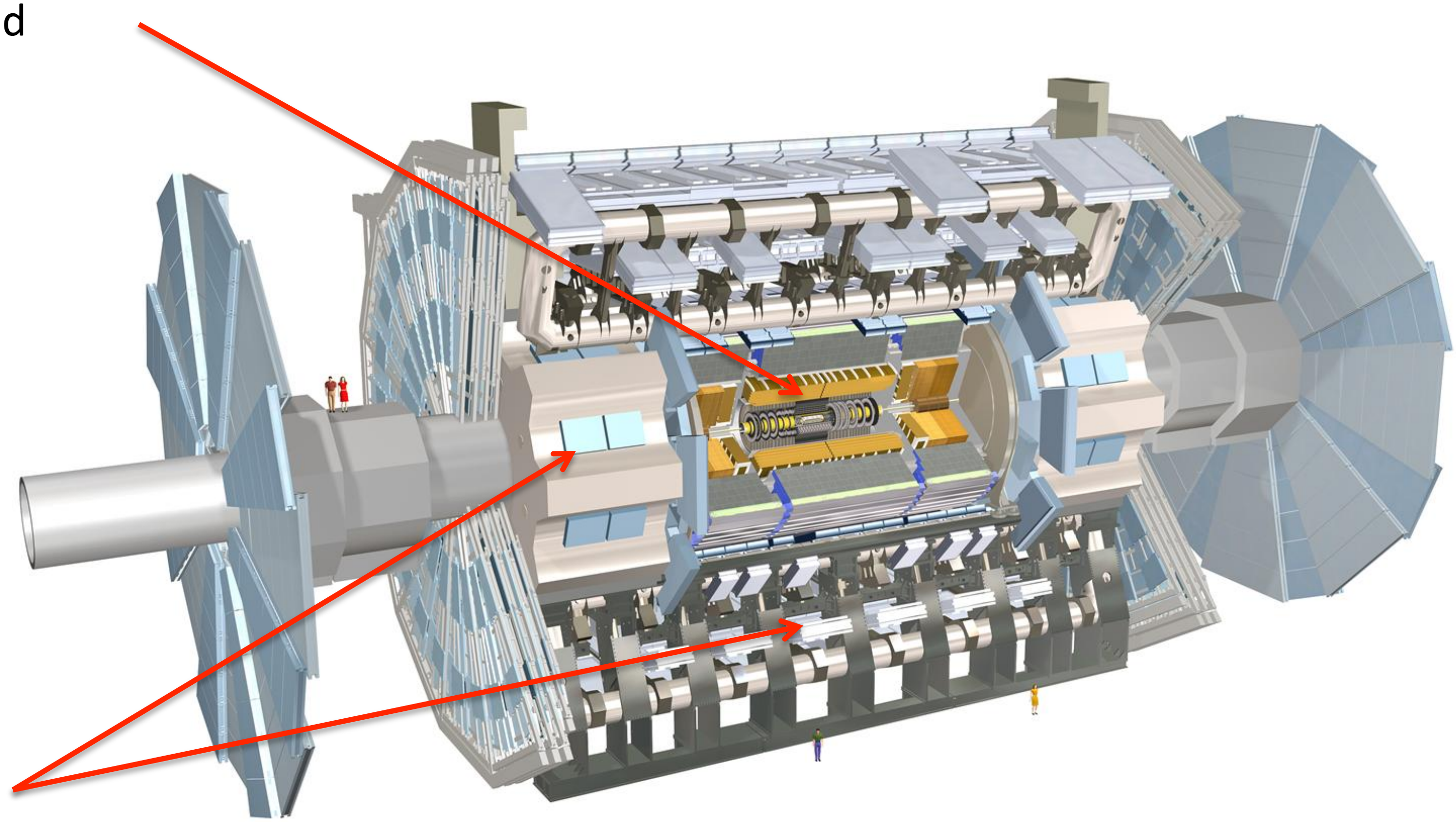
Rel energy res:
~10%/√(E/GeV)

LAr EM Barrel:
(lead plates)
|η|<1.475, >24 X_0

LAr forward:
(copper/tungsten)
3.1<|η|<4.9

Magnet System

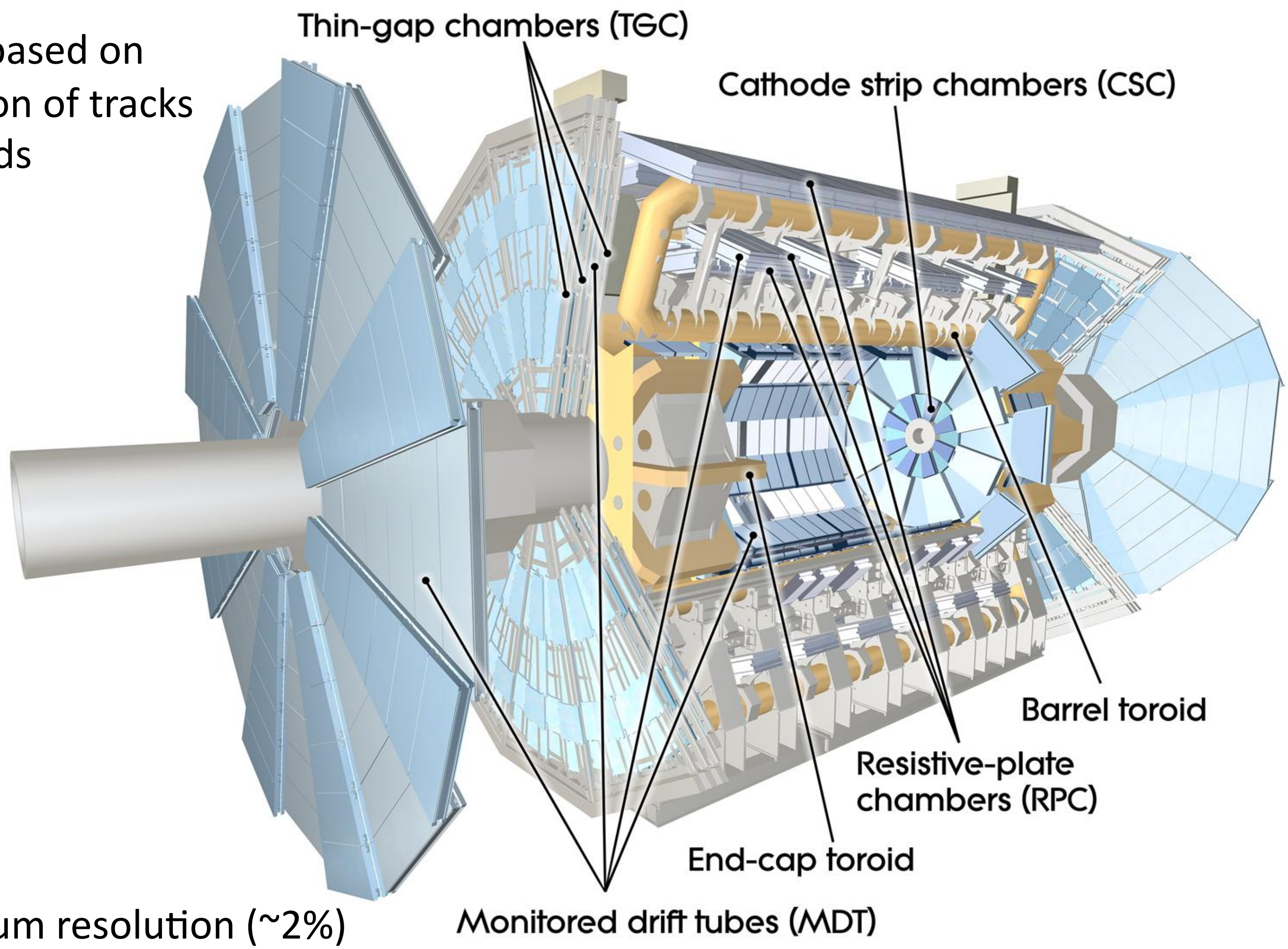
Central Solenoid:
2T field



Toroids:
3-each with 8 coils
Barrel: 3.9 T, End-caps: 4.1 T

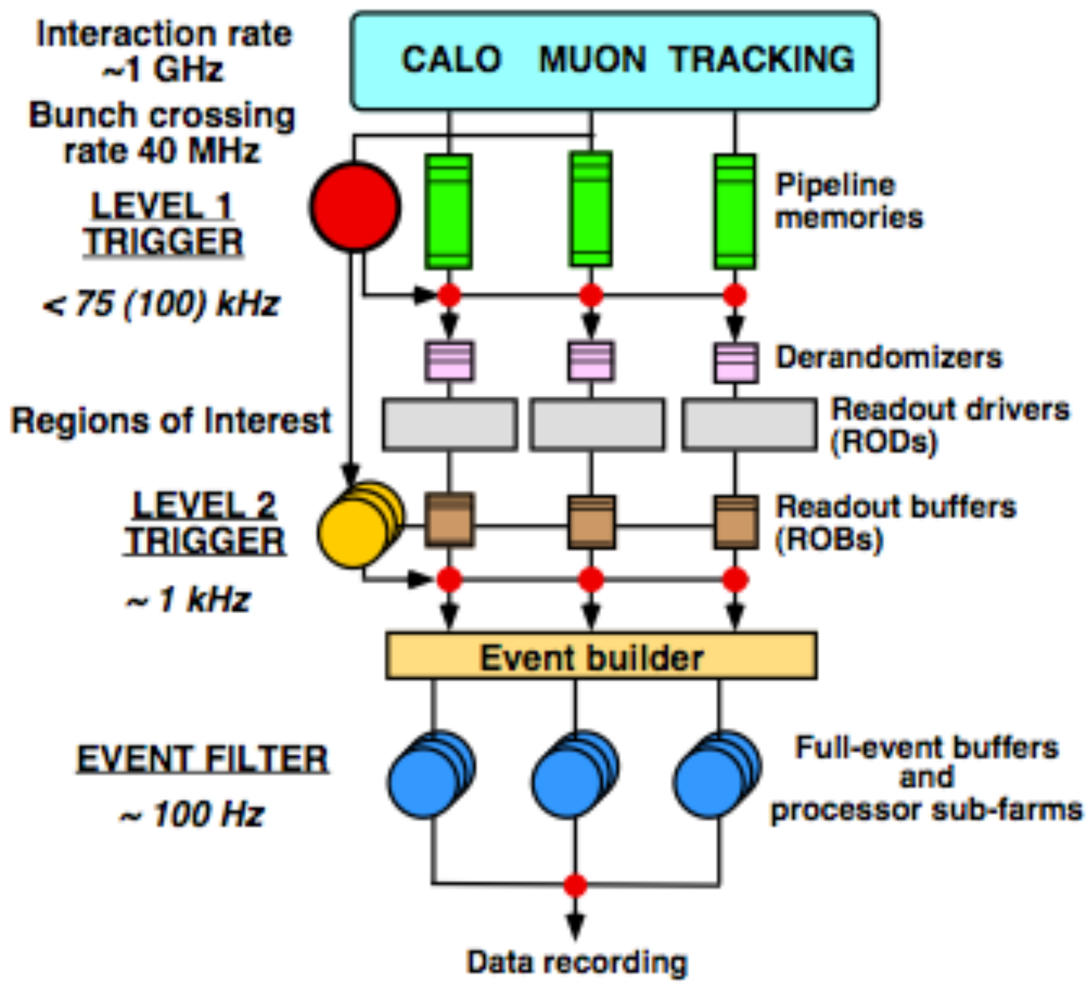
Muon System

Layout based on deflection of tracks by toroids



Momentum resolution (~2%)

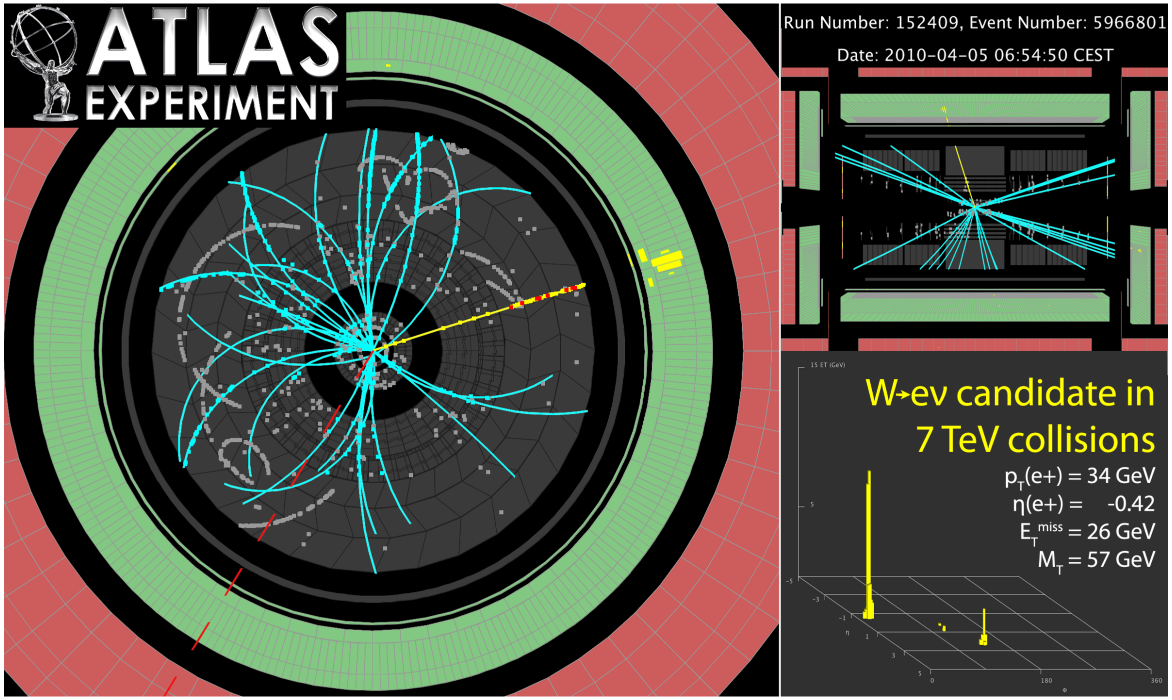
Triggers



Interaction rate
~1 GHz
Bunch crossing
rate 40 MHz
CALO MUON TRACKING
LEVEL 1
TRIGGER
< 75 (100) kHz
Pipeline
memories
Derandomizers
Regions of Interest
Readout drivers
(RODs)
LEVEL 2
TRIGGER
~ 1 kHz
Readout buffers
(ROBs)
Event builder
EVENT FILTER
~ 100 Hz
Full-event buffers
and
processor sub-farms
Data recording

Reconstruction and Identification

- Leptons
  - electrons
  - muons
- Jets
- Missing Energy

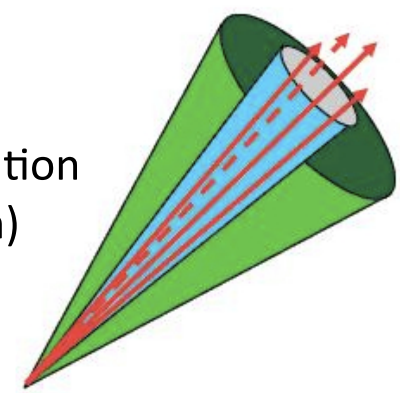


Leptons

Electrons

- Energy clusters in EM calorimeter
- E_T>20 GeV, E_T isolation < 20%
- $|\eta|<2.47$ with crack region removed
- Efficiency ~70%

Lepton isolation Cone (green)



Muons

- Tracks: inner detector and muon system then matched
- p_T>20 GeV, p_T isolation < 25%
- $|\eta|<2.4$
- Rejection of cosmics
  - $|d_0|<0.1$ mm and $|z_0|<1$ cm
- Efficiency ~65%

d_0- min distance between muon trajectory and the event primary vertex in xy-plane

z_0- parallel to beam direction

Jets and E_T^{miss}

Jets

- Anti-k_T algorithm, R=0.4
- p_T>20 GeV, $\Delta R_{jet,lep}$>0.5

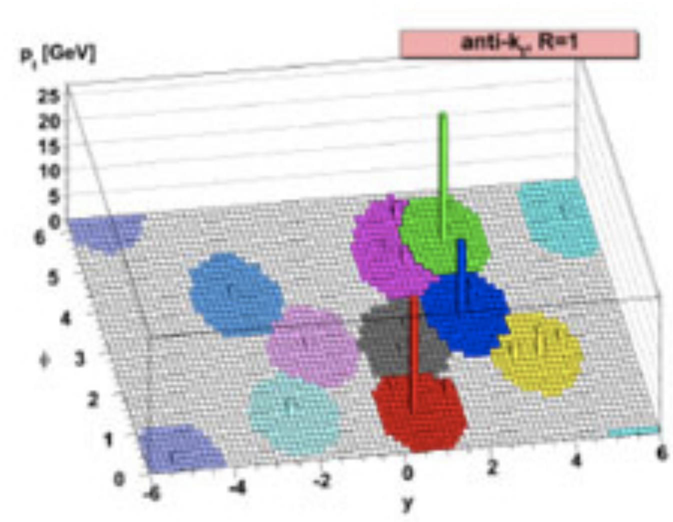
$$\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2}$$

- $|\eta|$<2.8
- "good" jet requirements
  - rejects noise induced jets, vertex confirmation

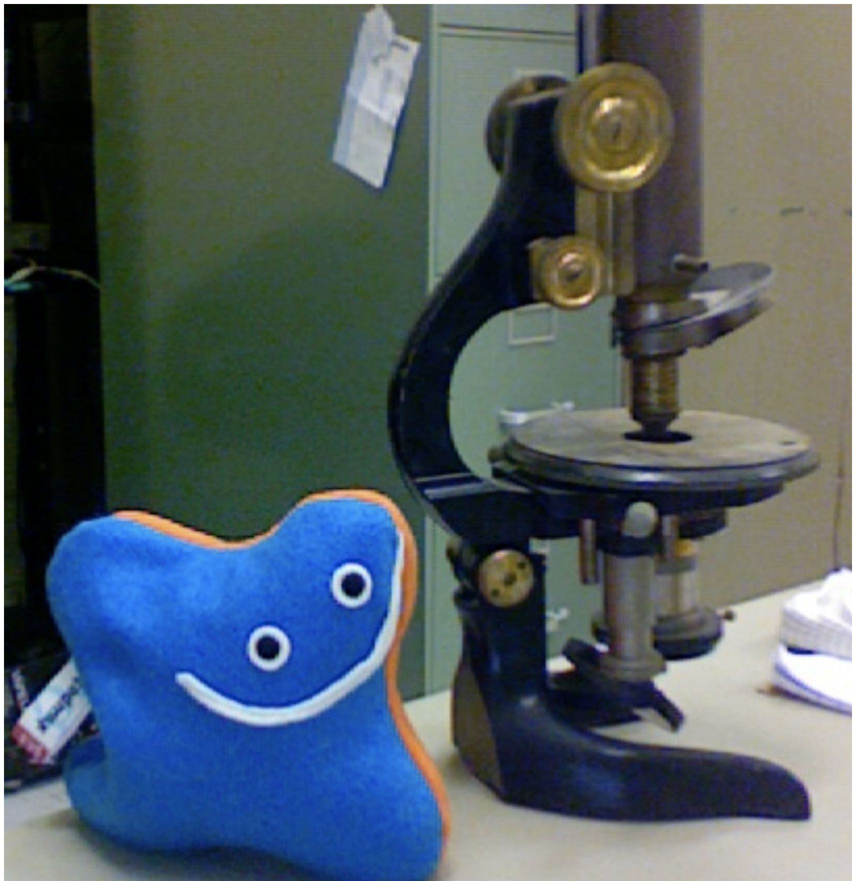
M. Cacciari, G.P. Salam, Phys Lett. B 641 (2006)

E_T^{miss}

- Negative vector sum of E_T and muon p_T
- E_T^{miss} > 25 GeV
- Removed if "bad" jets are present



Leptoquark Analysis



Leptoquark sighting made possible by the Particle Zoo

- Background Yield Determination
- Base Event Selection
- Control Regions
- Optimized LQ Selection
- Limit Setting

Background Yield Determination

- Simulated Background and Signal Samples
  - PDF Set: CTEQ 6.6
  - Generators:
    - ALPGEN (V+jets) (Z+jets in dilepton is semi-data driven)
    - HERWIG, MC@NLO ($t\bar{t}$, single top, VV)
    - Pythia
- N_{pred}= acceptance*σ*$\mathcal{L}_{integrated}$
- Multijet background determined by data driven methods
- Control regions
  - V+jets and $t\bar{t}$ enhanced to validate modeling

Data Driven Background

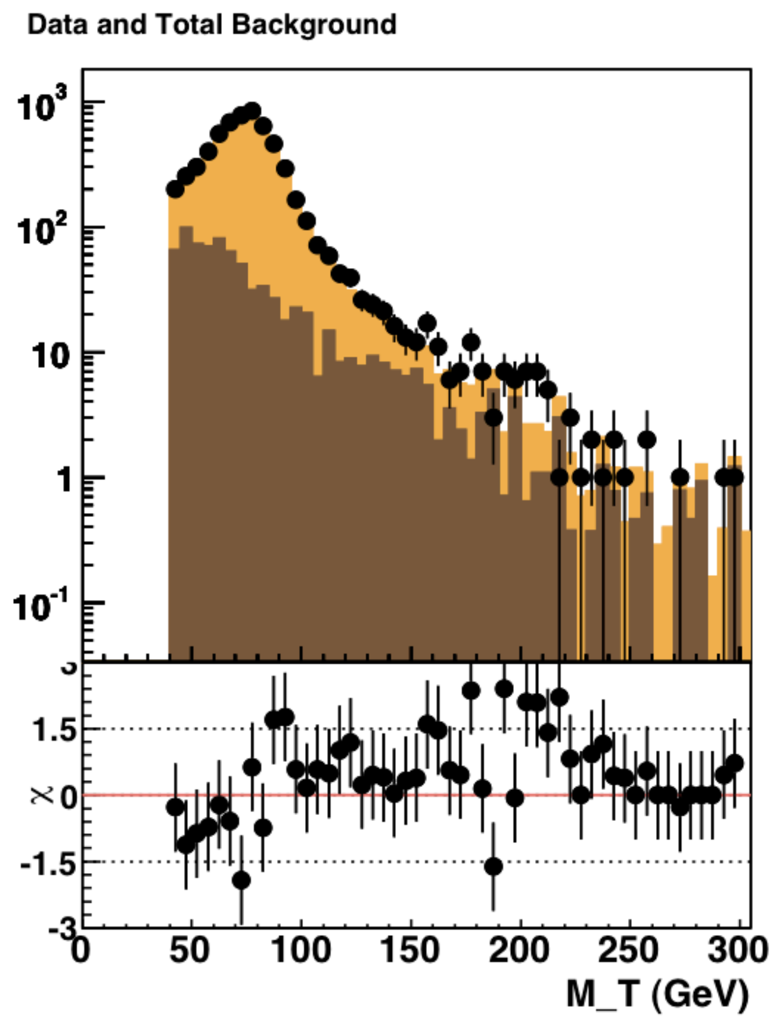
- Data Driven method
  - tails not modeled well by MC
  - not enough events generated
- lljj (Z+jets)
  - signal region: tails of Z+jet dist
  - fitting method for 1 lepton and a fake (relative iso variable)

$$N_D^{sig} = N_D^Z \frac{N_{MC}^{sig}}{N_{MC}^Z}$$

- eνjj (QCD): Fit to M_T
  - Σbkgs = data yield
  - minimize LLR

$$M_T(l, E_T^{miss}) = \sqrt{2 p_T^l E_T^{miss}(1-\cos(\Delta\phi))}$$

- μνjj (QCD): ABCD method
  - E_T^{miss} and $|d_0|$ (uncorrelated)
  - signal region: high E_T^{miss} and low $|d_0|$
  - Assumes EWK contribution in region C is negligible, QCD shape same in C and D



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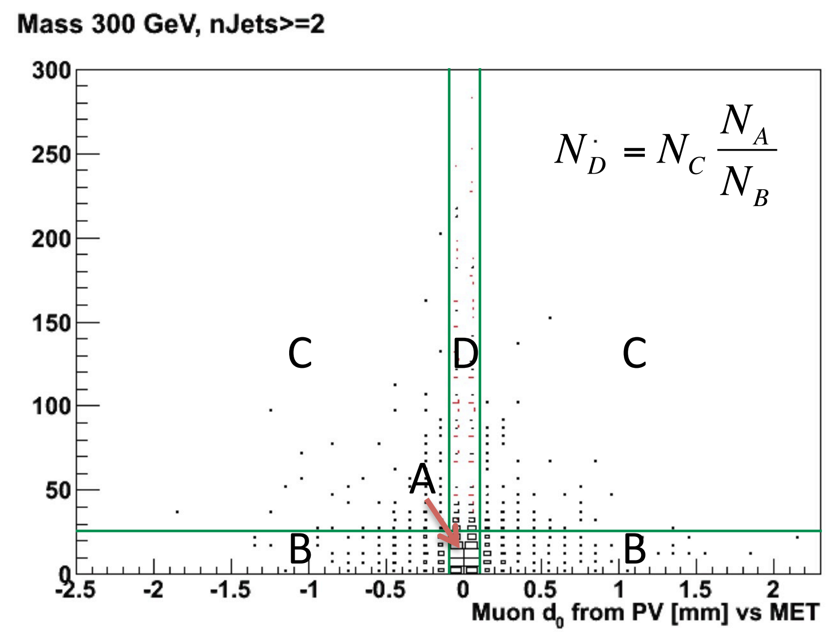

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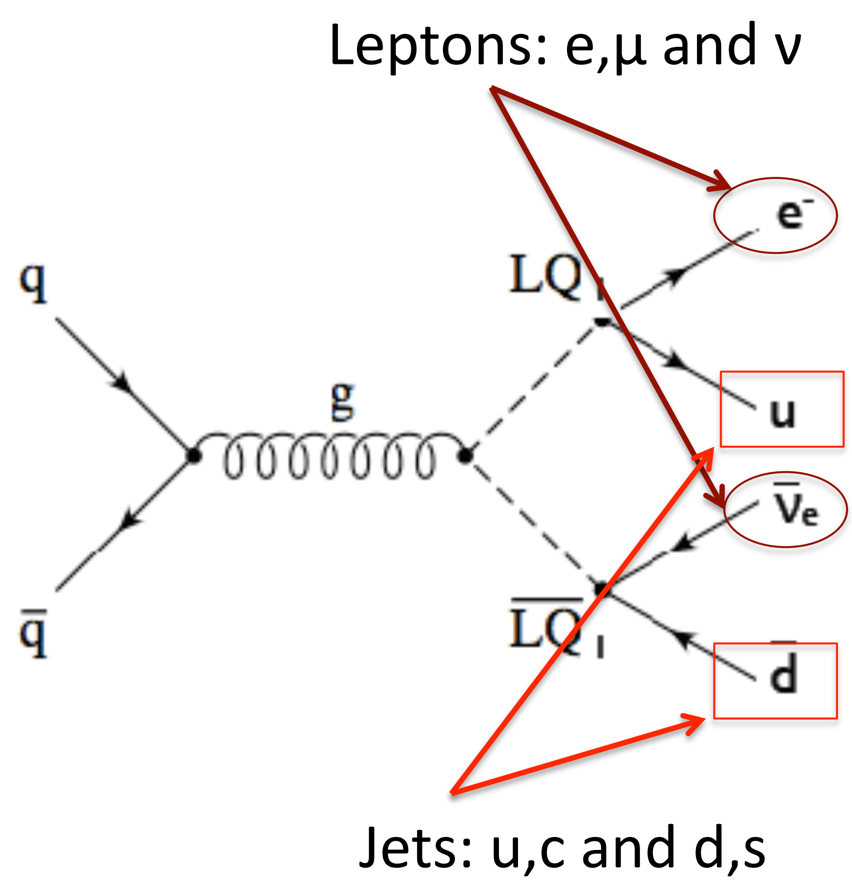
N_A, N_B, and N_C are yields from data in regions A, B, and C after EWK contribution is eliminated (using MC)

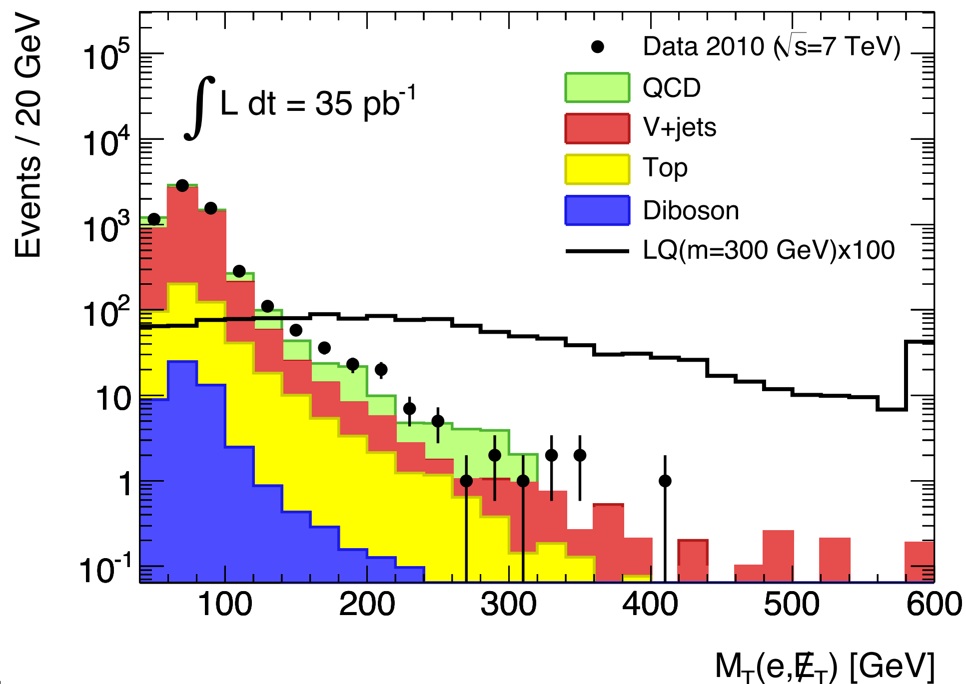
Base Event Selection

- Event Selection
  - At least 1 good primary vertex
    - ≥ 3 ID tracks
    - $|z_{vtx}| < 15$ cm
  - = 1 good lepton (=2 for dilepton analysis)
  - ≥ 2 good jets
- Event Selection for lvjj
  - pass E_T^{miss}
  - $M_T(l,E_T^{miss}) > 40$ GeV
  - triangle cut for QCD removal – extra rejection of residual events with badly measured jets (evjj) ($\Delta\phi(E_T^{miss}$,jet) vs. E_T^{miss})
  - opposite lepton veto



Base Event Selection Plots

channel	predicted	observed
eejj	610±240	626
eνjj	6090^{+990}_{-1130}	6088
μμjj	830^{+200}_{-150}	853
μνjj	9490±2490	9248



uncertainties are systematic and statistical
systematic uncertainty from V+jets
is dominant uncertainty

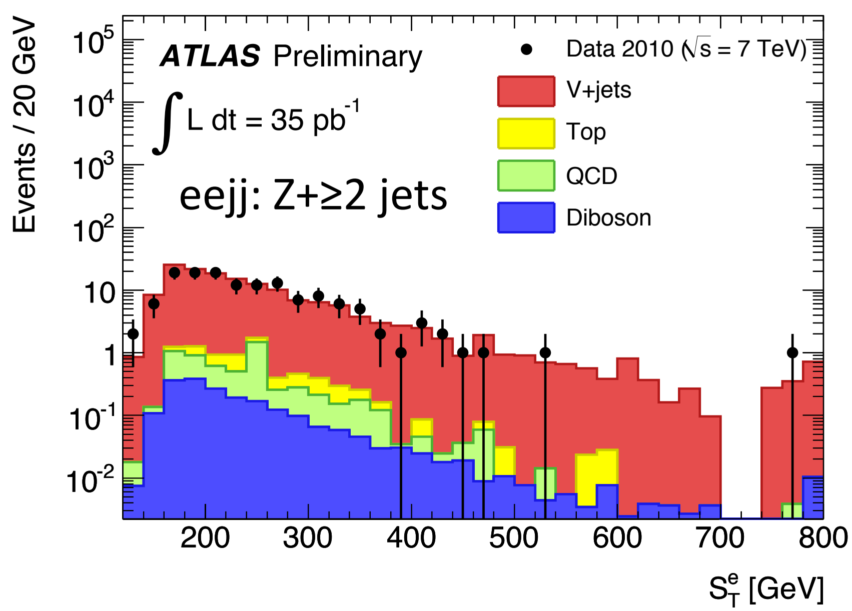
$$M_T(l,E_T^{miss}) = \sqrt{2p_T^l E_T^{miss}(1-\cos(\Delta\phi)}$$

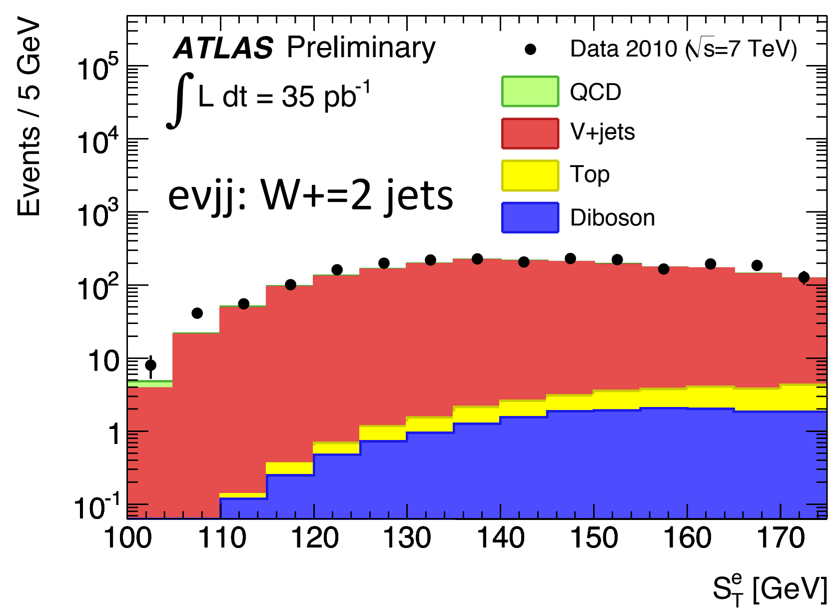
$$S_T = \sum p_T(jet_1, jet_2, lepton_1, E_T^{miss}/lepton_2)$$

Control Regions: Electron channels

eejj	Z+≥2jets	ttbar
V+jets	150±23	0.3±0.1
Top	2.0±0.3	24±4
diboson	2.0±0.3	0.8±0.1
QCD	4.0+14.-4.	0.+0.1-0.
Total	158±25	25±4
Data	140	22

evjj	W+=2 jets	W+≥3jets	ttbar
V+jets	2080±680	580±190	180±60
Top	21±4	44±9	210±40
diboson	17±4	8.3±1.9	2.1±0.5
QCD	64±14	68±15	29±7
Total	2180±710	700±200	420±80
Data	2344	722	425





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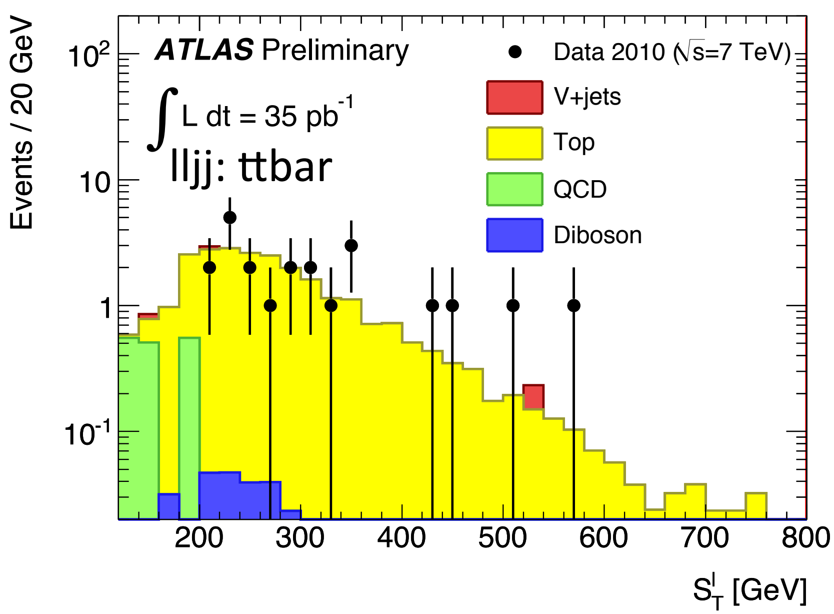
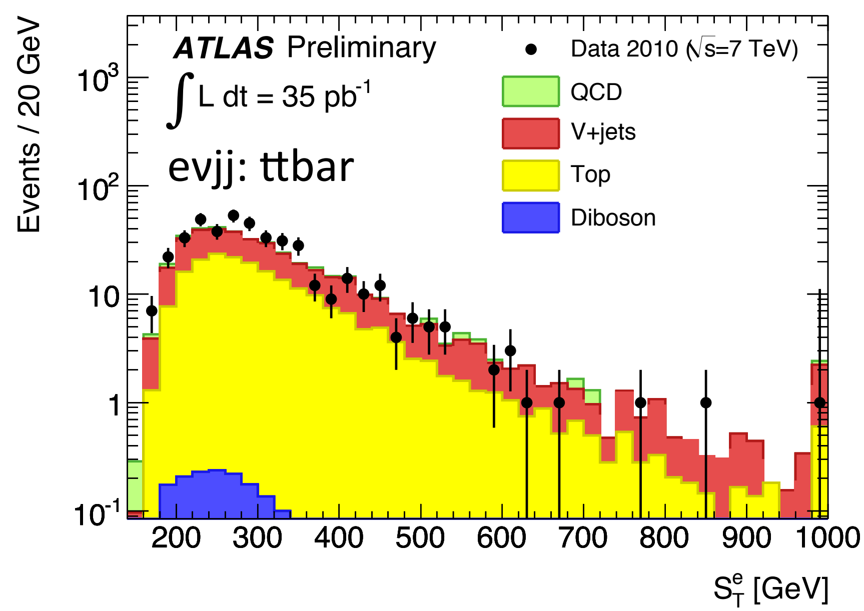
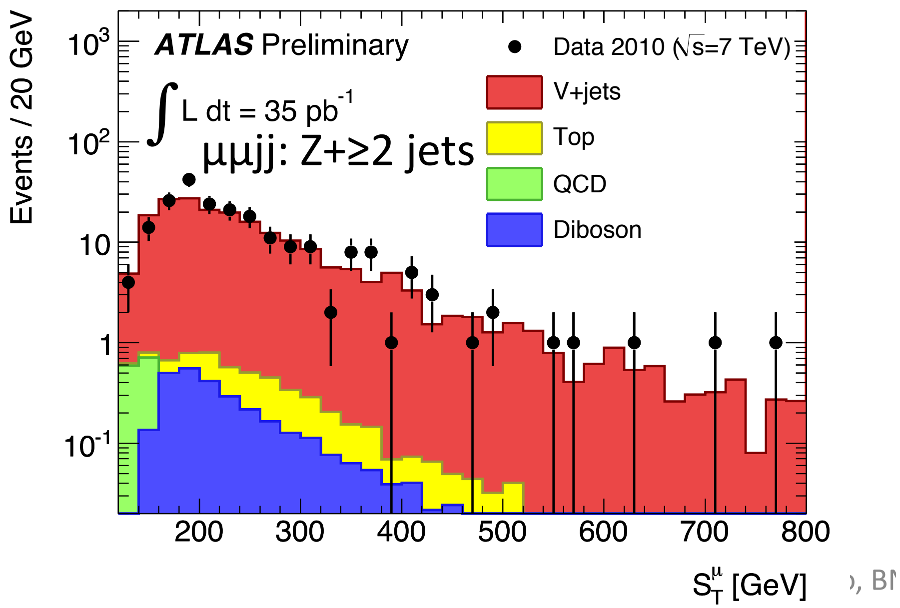


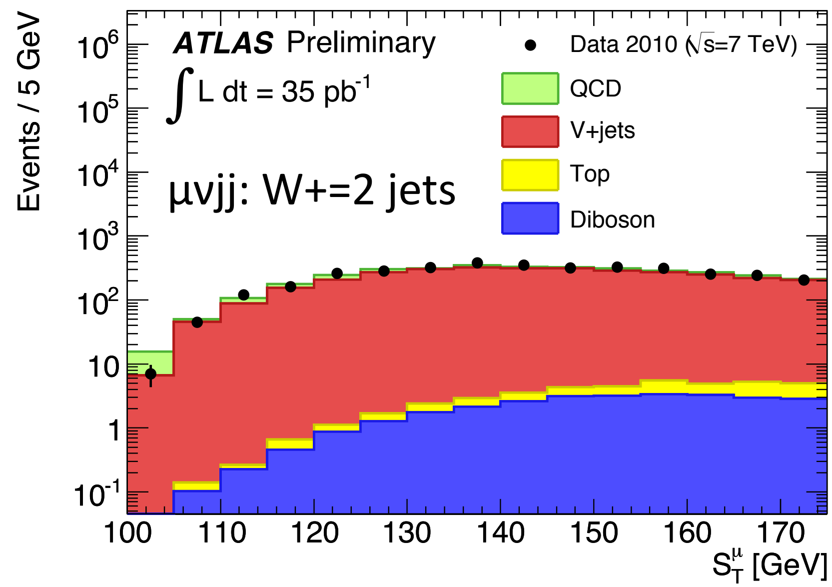


Control Regions: Muon channels

μμjj	Z+≥2jets	ttbar
V+jets	190±24	0.3±0.1
Top	2.7±0.5	24±4
diboson	0.2±0.1	0.8±0.1
QCD	6.+11.-5.5	0.+0.1-0.
Total	200±25	25±4
Data	216	22

μνjj	W+=2 jets	W+≥3jets	ttbar
V+jets	3250±1060	900±30	250±80
Top	14±3	53±1	260±50
diboson	28±6	14±3	3.0±0.7
QCD	300±100	130±50	54±32
Total	3590±1080	1100±330	570±120
Data	3588	1120	547





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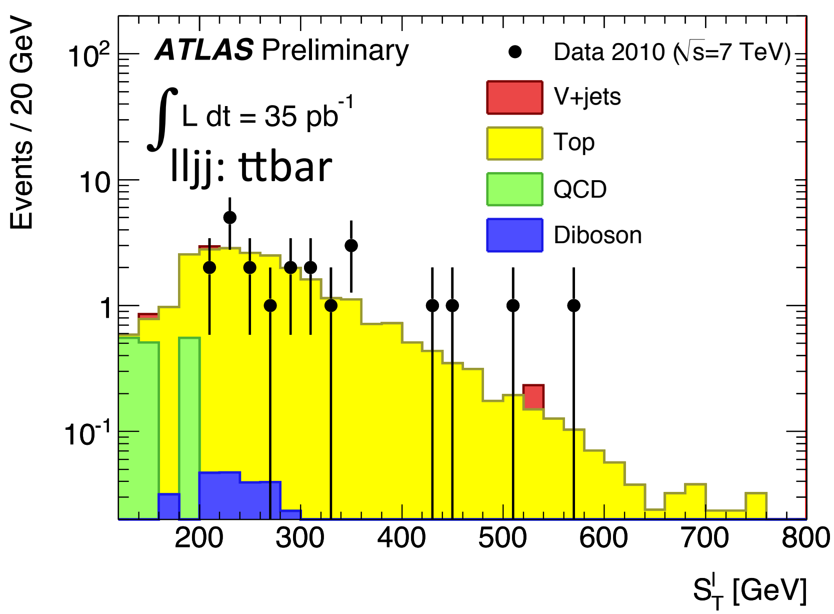
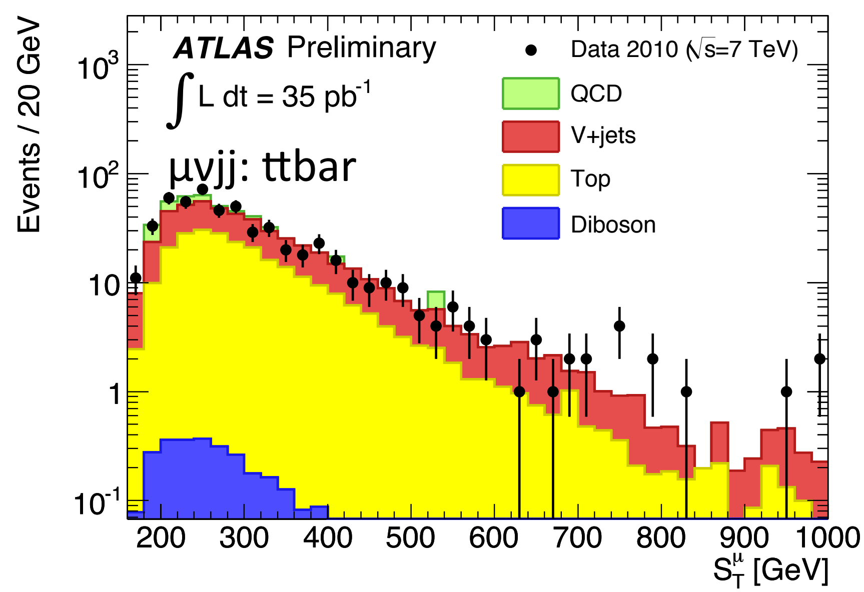
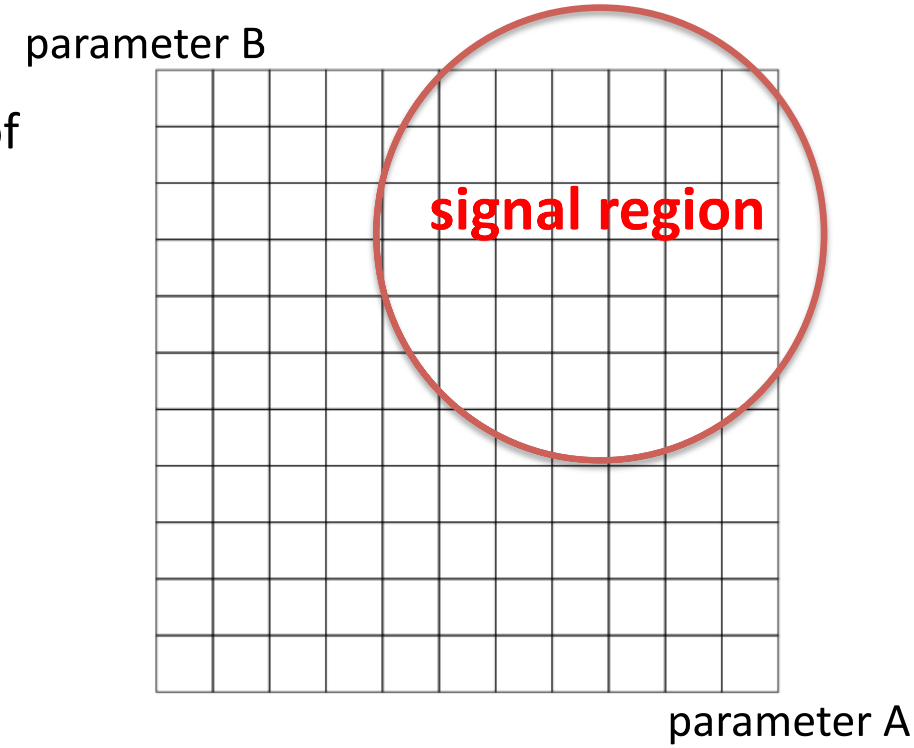




Optimized Leptoquark Selection

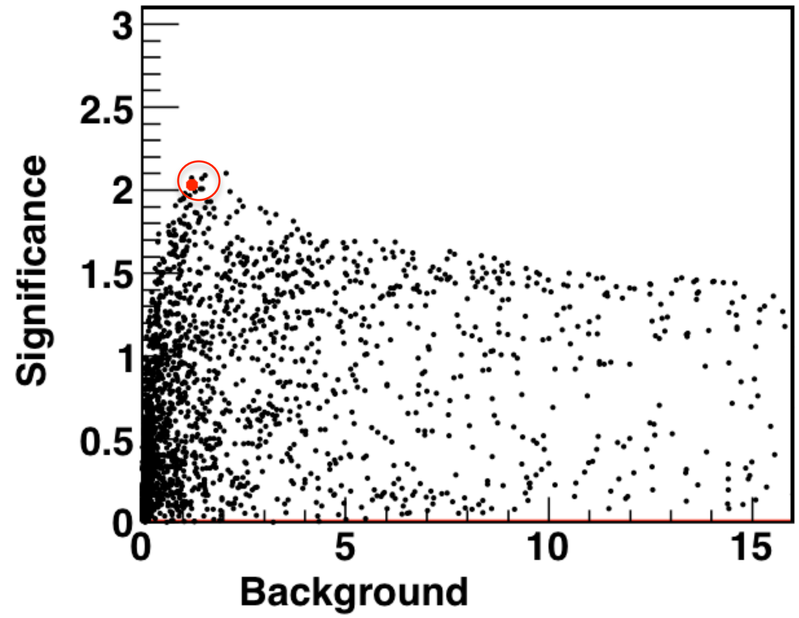
- Grid Search
  - systematic Search over a grid of points
  - regular grid inefficient
- Search region: value of MC signal events
  - use every signal event to form grid
  - n-Dimensional
- Significance calculated and plotted
  - matched to each cut
- Minimize Poisson probability
  - background fluctuation is signal + background



$$\frac{1}{\sqrt{2\pi}\sigma_B}\int dBe^{\frac{-(B-\overline{B})^2}{2\sigma_B^2}}\sum_{i=N}^{\infty}P(i;B)$$

Optimization on LQ signal

- 4-D grid space
  - dilepton channels:
    - M(l,l) - Invt. mass of leptons
    - M_{ave}(LQ) - Ave. LQ mass
    - p_T^{all}
    - S_T – Σp_T(2 jets, 2 leptons)
  - single lepton channels:
    - $M_T(l, E_T^{miss})$
    - M(LQ) – Invt. LQ mass
    - M_T(LQ) – Transverse LQ mass
    - S_T– Σp_T(2 jets, lepton, E_T^{miss})



$eejj$ and $\mu\mu jj$	$e\nu jj$	$\mu\nu jj$
$M_{ll} > 120$ GeV	$M_T > 200$ GeV	$M_T > 160$ GeV
$M_{LQ} > 150$ GeV	$M_{LQ} > 180$ GeV	$M_{LQ} > 150$ GeV
$p_T^{all} > 30$ GeV	$M_{LQ}^T > 180$ GeV	$M_{LQ}^T > 150$ GeV
$S_T^\ell > 450$ GeV	$S_T^\nu > 410$ GeV	$S_T^\nu > 400$ GeV

Systematics

Channel	V+jets $lljj$	V+jets $l\nu jj$	Top $lljj$	Top $l\nu jj$	Diboson $lljj$	Diboson $l\nu jj$	LQ (300 GeV) $lljj$	LQ (300 GeV) $l\nu jj$
Production Cross Section	—	4	13	13	5	5	18	18
Modeling	34*, 45**	40	35	35	—	—	—	—
Electron Energy Scale & Resolution*	+13, -0.2	5	10	2	7	1	8	1
Muon Momentum Scale & Resolution**	20	5	7	2	8	1	6.7	1
Jet Energy Scale	6	+22, -13	+9, -18	32	+16, -6	+17, -24	2	3
Jet Energy Resolution	16	10	0.3	26	4	14	0.3	3
Luminosity	0.3	11	11	11	11	11	11	11
Pile up	< 0.1	5	< 0.1	4	< 0.1	6	< 0.1	2
Total Systematics	39*	+49, -45	47*	57	(+22, -16)	+26,- 31	22	22

Numbers are in percentages

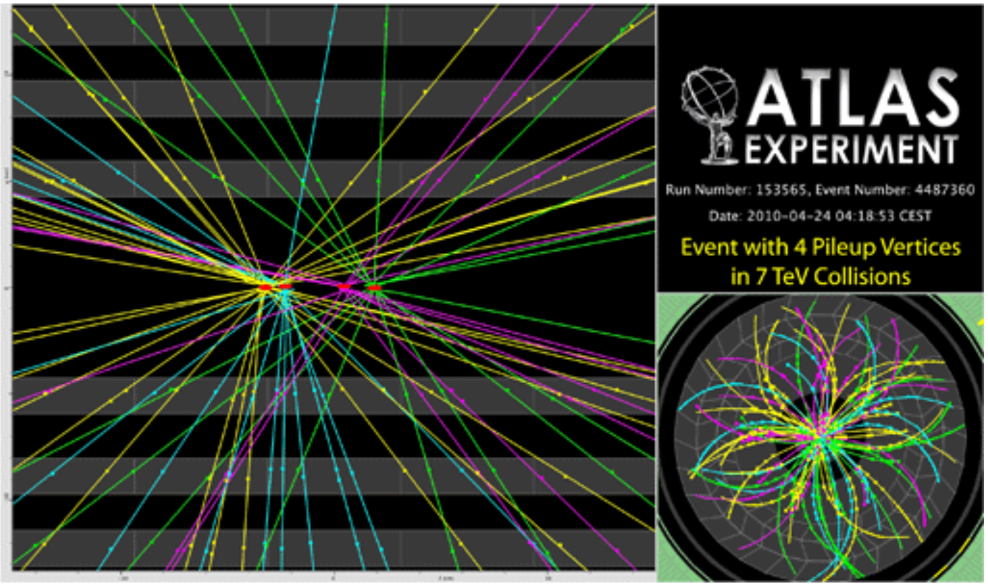
Systematics

Channel	V+jets $lljj$	V+jets $l\nu jj$	Top $lljj$	Top $l\nu jj$	Diboson $lljj$	Diboson $l\nu jj$	LQ (300 GeV) $lljj$	LQ (300 GeV) $l\nu jj$
Production Cross Section	—	4	13	13	5	5	18	18
Modeling	34*, 45**	40	35	35	—	—	—	—
Electron Energy Scale & Resolution*	+13, -0.2	5	10	2	7	1	8	1
Muon Momentum Scale & Resolution**	20	5	7	2	8	1	6.7	1
Jet Energy Scale	6	+22, -13	+9, -18	32	+16, -6	+17, -24	2	3
Jet Energy Resolution	16	10	0.3	26	4	14	0.3	3
Luminosity	0.3	11	11	11	11	11	11	11
Pile up	< 0.1	5	< 0.1	4	< 0.1	6	< 0.1	2
Total Systematics	39*	+49, -45	47*	57	(+22, -16)	+26,- 31	22	22

Numbers are in percentages

Systematics

- Modeling
  - varying event generator-level parameters
- Jet Energy Scale and Resolution
  - varied by uncertainties
  - 5% added (quark/gluon response)
  - included in E_T^{miss}
- Pile-up
  - multiple minimum bias events per bunch crossing
  - sub-detectors sensitive to bunch crossings before and after interesting physics interaction



Confidence Level Evaluation

- Overview
- Semi-Frequentist approach
- Log-Likelihood Ratio Test
- Confidence levels

Semi-Frequentist approach

- "Frequency" a result will occur
- Collie (COnfidence Level LImit Evaluator)
  - likelihood Ratio test
  - "as Frequentist as possible"
    - Bayesian treatment of systematics

T. Junk, arXiv:hep-ex/9902006v1

$$L(b \mid x) = \frac{(b)^x e^{-b}}{x!}$$

$$\Lambda(\vec{x}) = \prod_{i}^{channel} \prod_{j}^{bin} \frac{L((s+b)_{ij} \mid x_{ij})}{L(b_{ij} \mid x_{ij})}$$

$$s = signal$$

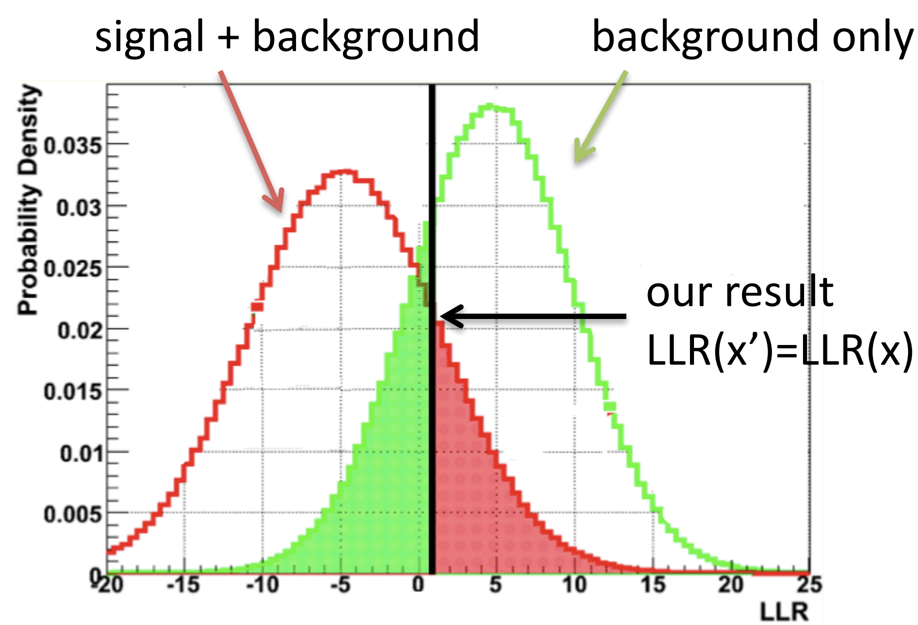
$$b = background$$

$$x = data$$

$$L = likelihood$$

Log-Likelihood Ratio Test

- Generate Null and Test hypothesis
- Distributions of LLR(s+b) and LLR(b)



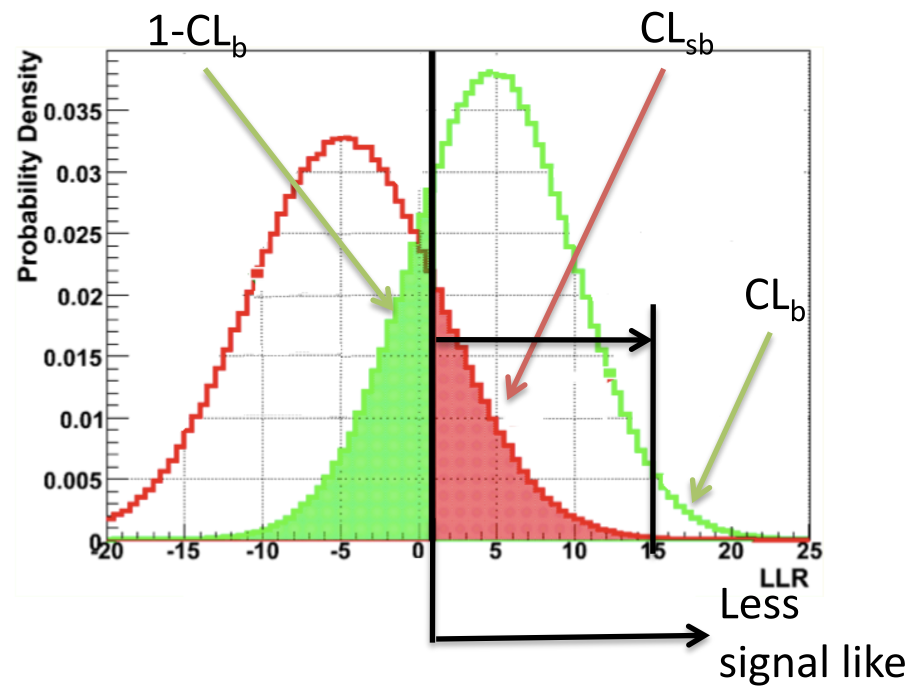
W. Fisher, Fermilab-TM-2386-E

$$LLR(x) = -2\log(\Lambda)$$

$$LLR(x) = \sum_{i}^{channels} \sum_{j}^{bins} s_{ij} - x_{ij} \ln\left(1 + \frac{s_{ij}}{b_{ij}}\right)$$

Confidence levels

- Confidence levels integral of LLR distribution
- CL relative to outcome
  - observed/expected limits
- Expected data
  - median bkg outcome
  - CL_b is 50% if bkg is well modeled
- Poor modeling -> CL_s method
- Exclusion: 95% CL
  - increase parameter until $1\text{-}CL_s=0.95$



$$CL_s = \frac{CL_{s+b}}{CL_b}$$

Results

Source	$eejj$	$e\nu jj$	$\mu\mu jj$	$\mu\nu jj$
V+jets	0.50 ± 0.28	0.65 ± 0.38	0.28 ± 0.22	2.6 ± 1.4
Top	0.51 ± 0.23	0.67 ± 0.39	0.52 ± 0.23	1.6 ± 0.9
Diboson	0.03 ± 0.01	0.10 ± 0.03	0.04 ± 0.01	0.10 ± 0.03
Other Bkg.	$0.02^{+0.03}_{-0.02}$	0.06 ± 0.01	$0.00^{+0.01}_{-0.00}$	0.0 ± 0.0
Total Bkg	1.1 ± 0.4	1.4 ± 0.5	0.8 ± 0.3	4.4 ± 1.9
Data				
LQ(250 GeV)	38 ± 8	9.6 ± 2.1	45 ± 10	13 ± 3
LQ(300 GeV)	17 ± 4	5.1 ± 1.1	21 ± 5	6.4 ± 1.4
LQ(350 GeV)	7.7 ± 1.7	2.6 ± 0.6	9.4 ± 2.1	3.0 ± 0.7
LQ(400 GeV)	3.5 ± 0.8	—	4.4 ± 1.0	—

Results

Z+jets top W+jets

Source	$eejj$	$e\nu jj$	$\mu\mu jj$	$\mu\nu jj$
V+jets	0.50 ± 0.28	0.65 ± 0.38	0.28 ± 0.22	2.6 ± 1.4
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Total Bkg	1.1 ± 0.4	1.4 ± 0.5	0.8 ± 0.3	4.4 ± 1.9
Data	2	2	0	4
LQ(250 GeV)	38 ± 8	9.6 ± 2.1	45 ± 10	13 ± 3
LQ(300 GeV)	17 ± 4	5.1 ± 1.1	21 ± 5	6.4 ± 1.4
LQ(350 GeV)	7.7 ± 1.7	2.6 ± 0.6	9.4 ± 2.1	3.0 ± 0.7
LQ(400 GeV)	3.5 ± 0.8	—	4.4 ± 1.0	—

Results

Source			$\mu\mu jj$	$\mu\nu jj$
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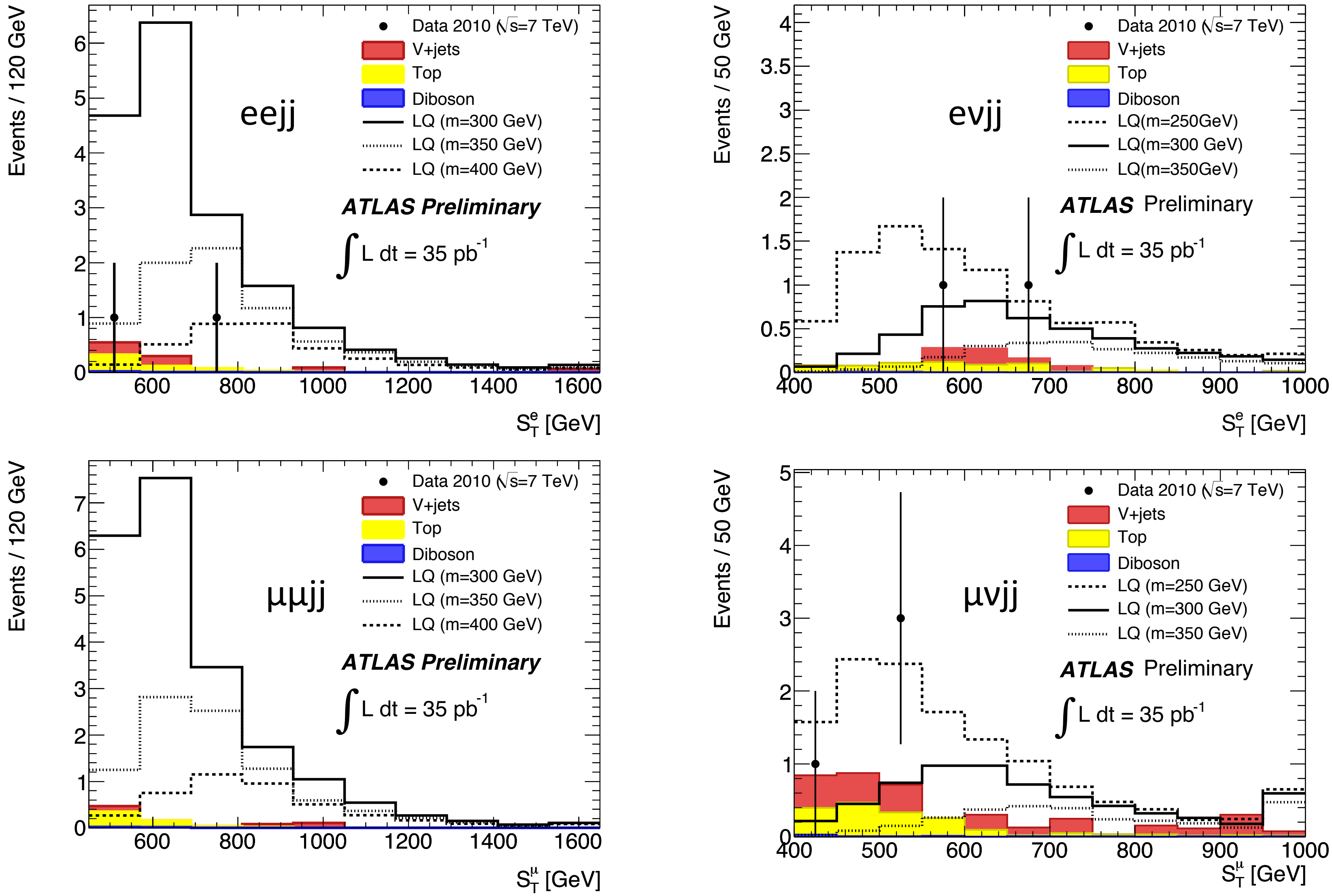
Other Bkg.	0.02		$^{+0.01}_{-0.00}$	0.0 ± 0.0
Total Bkg	1.1		± 0.3	4.4 ± 1.9
Data			0	4
LQ(250 GeV)	38		± 10	13 ± 3
LQ(300 GeV)	17		± 5	6.4 ± 1.4
LQ(350 GeV)	7.7		± 2.1	3.0 ± 0.7
LQ(400 GeV)	3.5 ± 0.8	—	4.4 ± 1.0	—

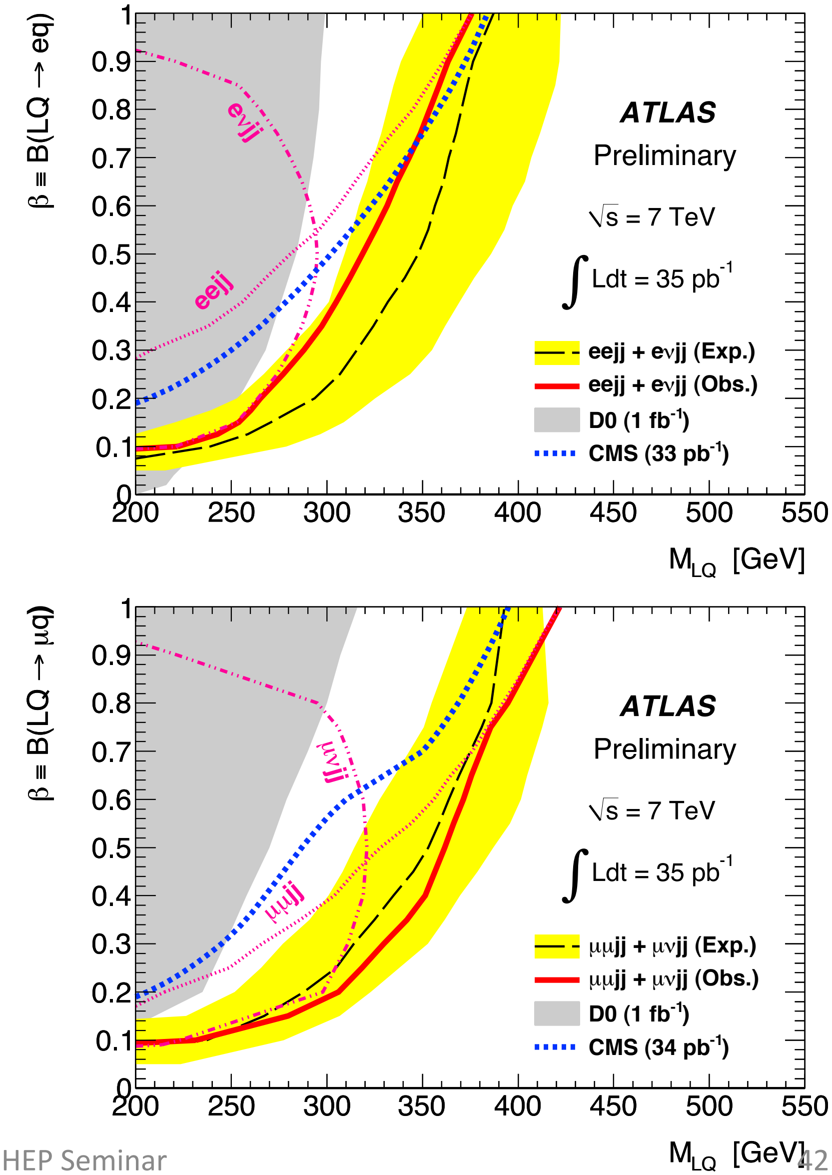
Results

$$S_T = \sum p_T(jet_1, jet_2, lepton_1, E_T^{miss} / lepton_2)$$

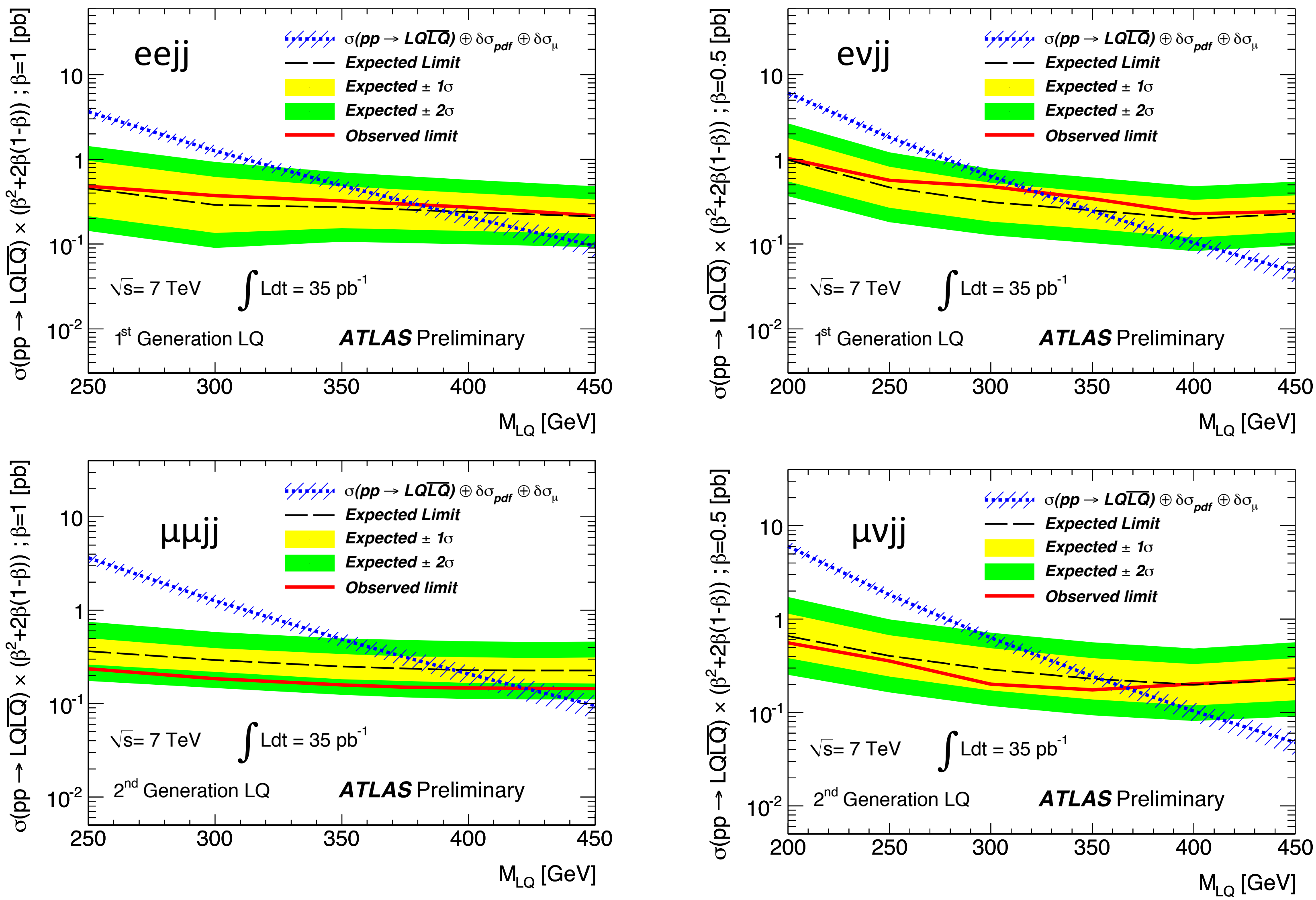


Cross Section Limits

- ATLAS combined result
  - observed: red
  - expected: blue dashed
- Max Sensitivity
  - dilepton: β=1
  - single lepton: β=0.5
- Stronger exclusion in di-muon channel
- CMS
  - dilepton results published
  - publishing single-lepton channel and combined results

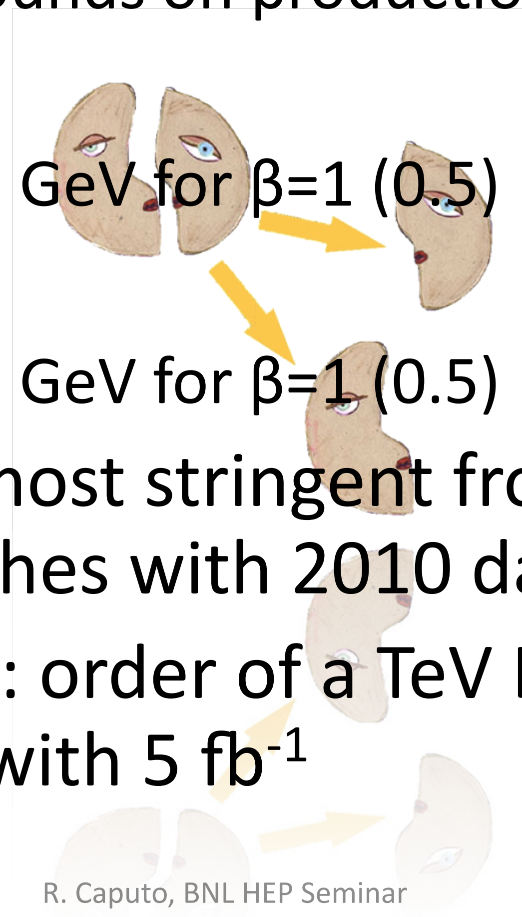


Cross Section Limits



In Summary

- Data in high signal-to-background matches background-only predictions
  - 95% CL upper bounds on production cross section
- 1st generation:
  - MLQ > 376 (319) GeV for β=1 (0.5)

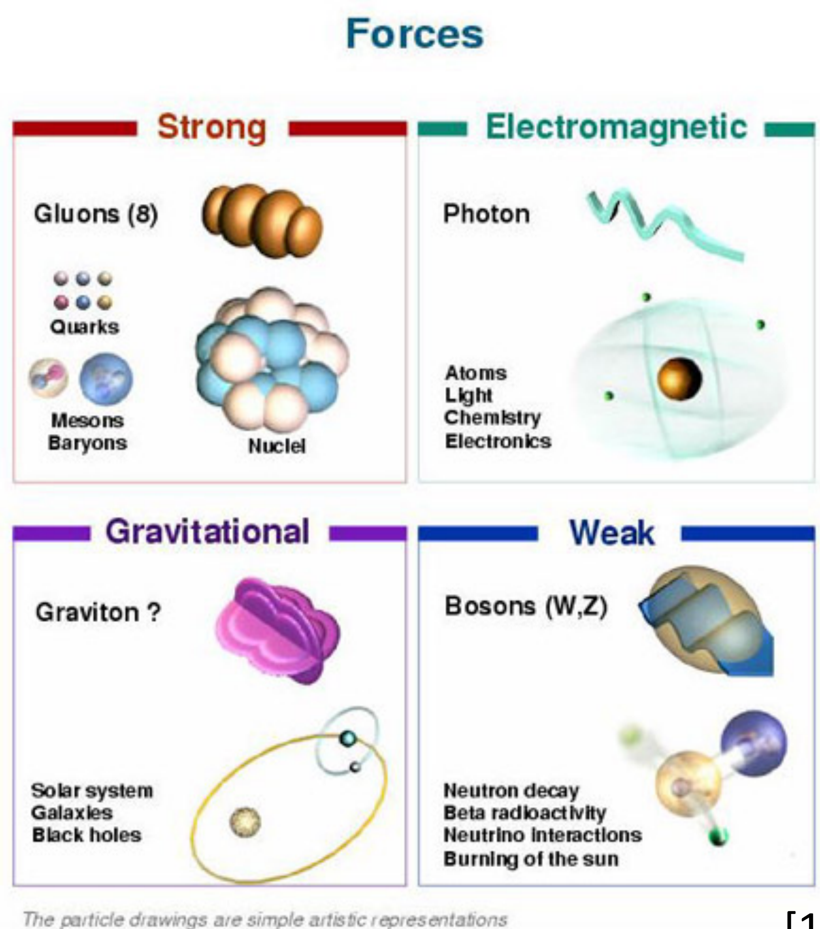


- 2nd generation:
  - MLQ > 422 (362) GeV for β=1 (0.5)
- LHC set world's most stringent from direct LQ pair production searches with 2010 data
- Future Prospects: order of a TeV LQ (discovery – hopefully) 2011 with 5 fb^{-1}

Backups!

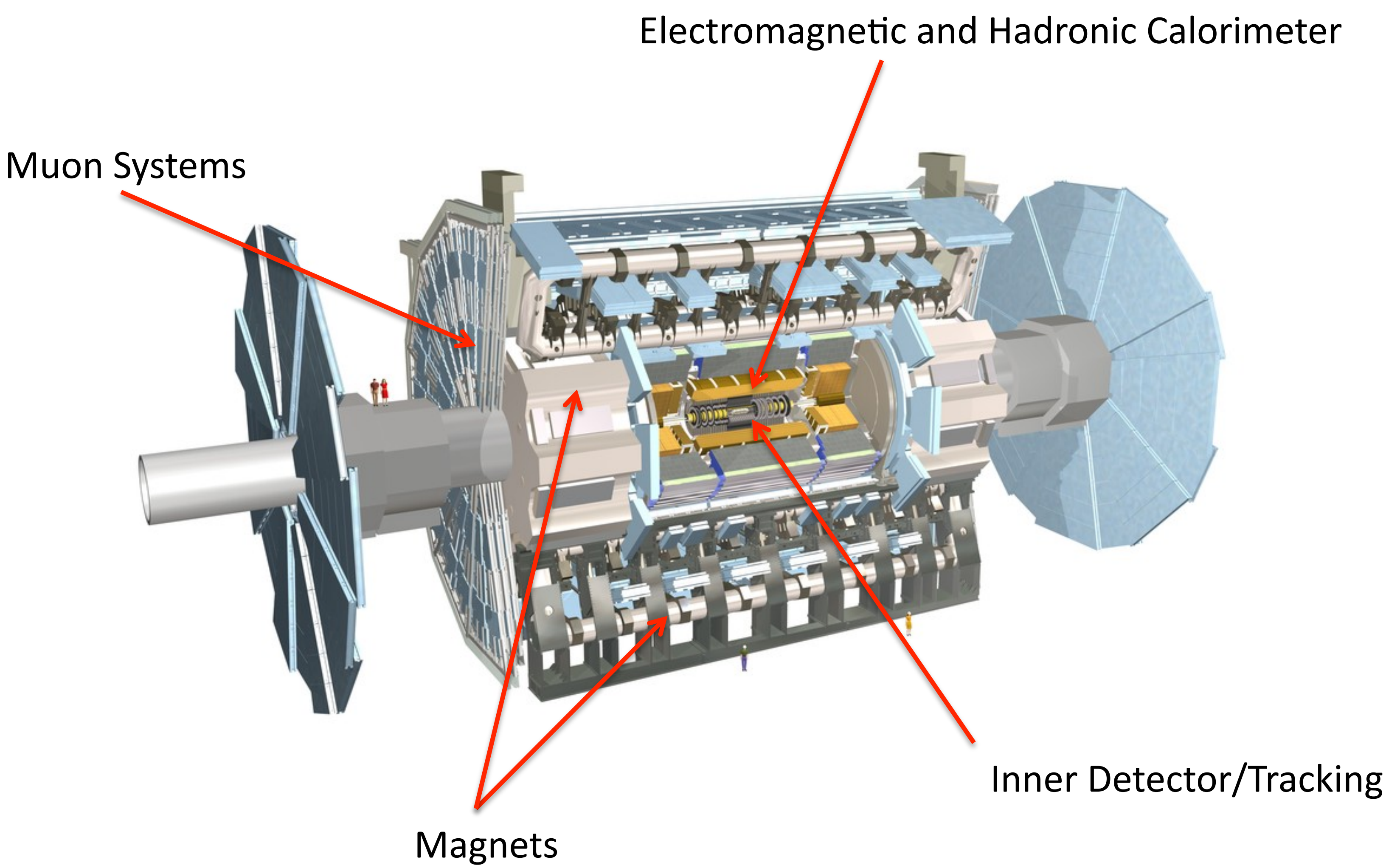
The Standard Model

- Forces Mediated by integer spin bosons
  - Strong
    - 8 massless gluons, couple only to quarks, confinement
    - relative strength of 1 with 10^{-15} m (~nucleus) range
  - Electromagnetic
    - photons, couple to charged particles
    - relative strength 10^{-3} with infinite range
  - Weak
    - $W^{\pm}/Z$, couple to all SM particles
    - relative strength of 10^{-6} with 10^{-18} m (~0.1% dia. proton) range



[1]

The ATLAS Detector



Monte Carlo

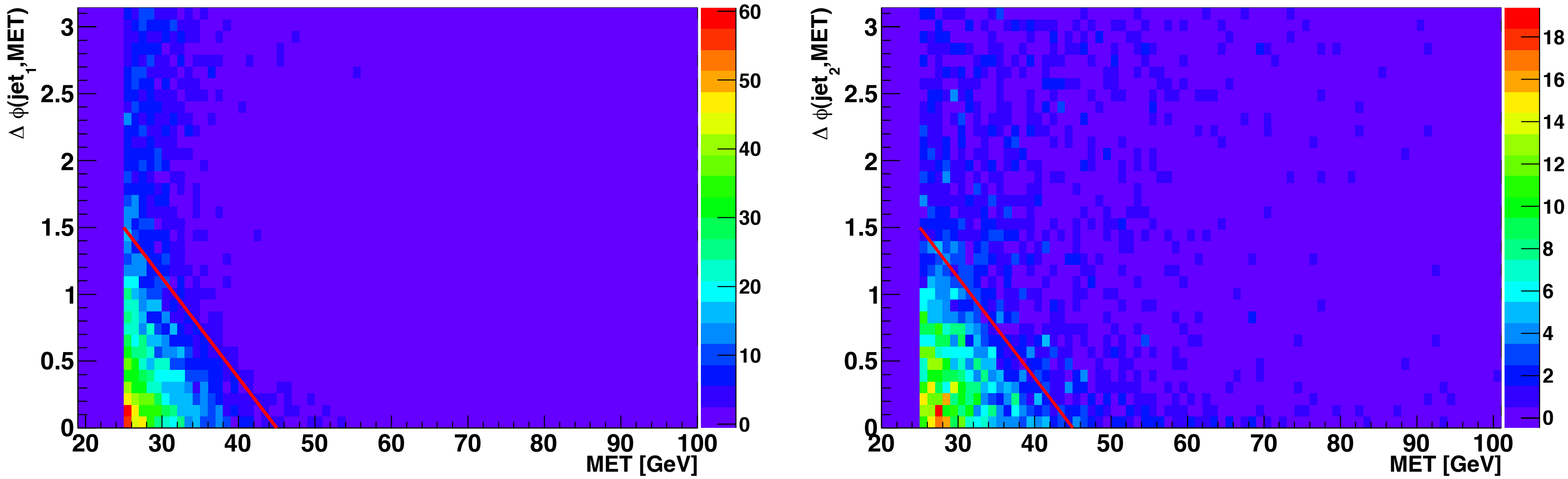
- Signal and background samples
  - ALPGEN interfaced to HERWIG and JIMMY and PYTHIA
- Designed to model interactions
  - Hard Scatter, Initial and Final State Radiation, Hadronization, Soft Interactions… etc.
- PYTHIA and HERWIG/JIMMY - Parton Shower model
- ALPGEN - Matrix Element model
  - useful for multi-jet events but other generators handle hadronization and shower more completely
- Detailed detector simulation: GEANT4
  - Ionization and showering in detector, energy deposition in calorimeters, trajectory in magnetic field

GRL and Trigger lists

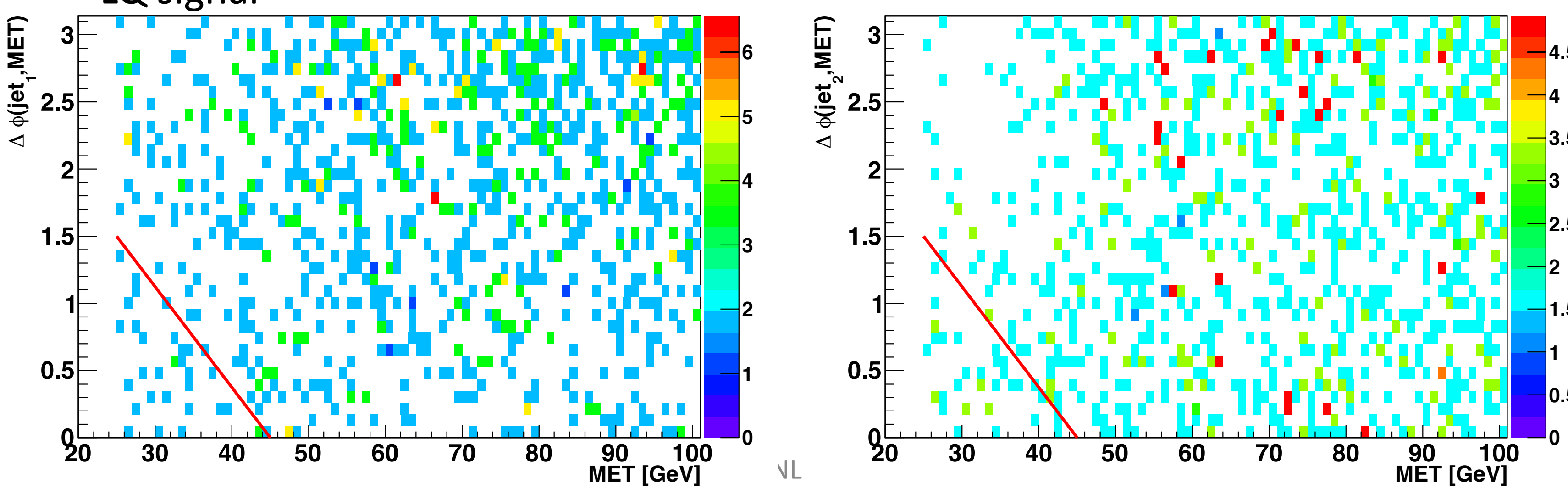
- Good Runs List
  - All parts of detector working nominally, LHC running nominally
  - General requirements (ptag data10 7TeV and db DATA and partition ATLAS) LHC beam energy at 3.5 TeV (lhc beamenergy 3400-3600)
  - The stable beam flag (lhc stablebeams T)
  - Silicon and muon systems warm starts completed (ready 1)
  - The magnets on (mag s > 6000 and mag t > 18000)
  - Data quality flags (dq GLOBAL STATUS, CP TRACKING, CP EG ELECTRON BARREL, CP EG ELECTRON ENDCAP, CP MU MSTACO, CP JET JETB, CP JET JETEA, CP JET JETEC, CP MET METCALO, CP MET METMUON, LUMI, L1CAL, L1MUE, L1MUB, TRELE, TRMUO)
  - Run period dependent luminosity block and summary flags equal to good status. For periods A and B, this is LBSUMM#DetStatus-v03-repro04-01 g.
  - For other periods this is LBSUMM#DetStatus-v03-pass1-analysis-2010X g with X the period (C-J).
- Electron Trigger
  - E_T>15 GeV
  - "medium" electron requirement

Triangle cut for QCD removal

QCD



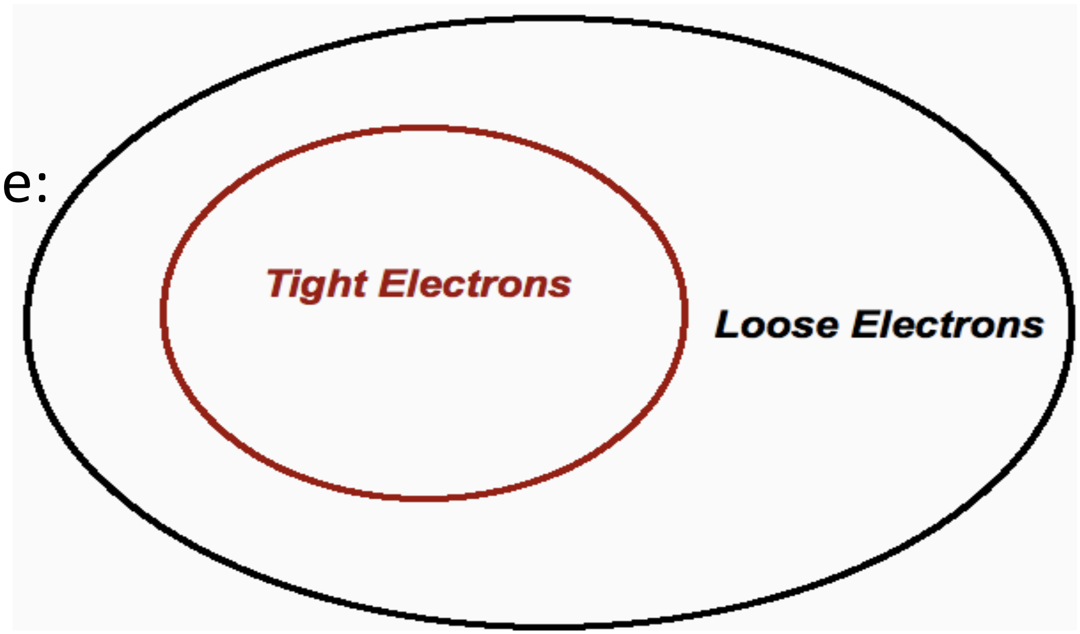
LQ signal



Data/MC Scale Factors

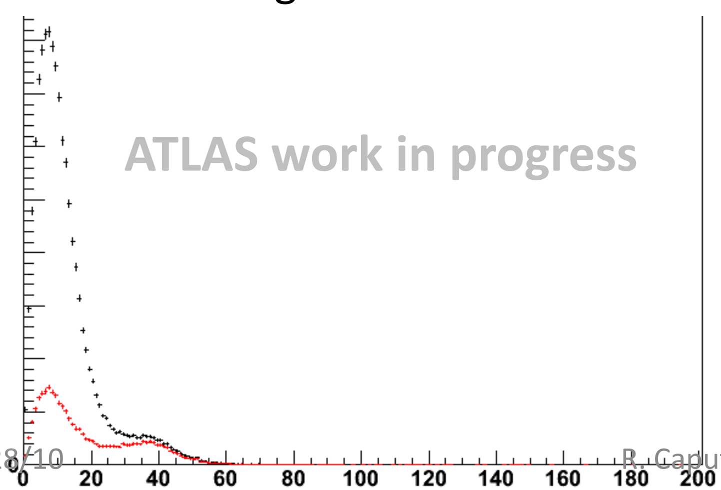
QCD Estimation: Matrix Method

Loose Sample:
Low $\not{E}_T$

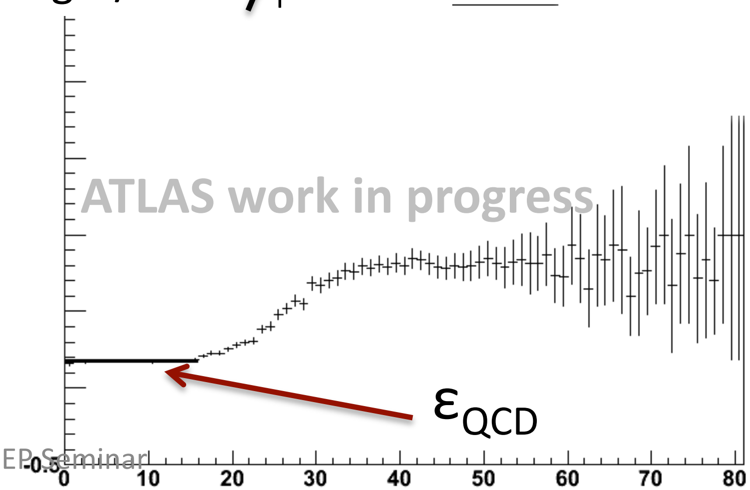


Tight Sample:
2 high p_T
Electrons

$\not{E}_T$ for loose and tight e's



tight/loose $\not{E}_T$ ratio



Methodology

Bin by Bin

- QCD normalization and shape comes from following:
  - $N_l^i = N_{ele}^{real\ i} + N_{QCD}^{fake\ i}$
  - $N_t^i = \varepsilon_{ele}^{real} N_{ele}^{real\ i} + \varepsilon_{QCD}^{fake} N_{QCD}^{fake\ i}$
  - fill i^{th} bin

$$\varepsilon_{QCD}^{fake} N_{QCD}^{i} = \varepsilon_{QCD}^{fake} \frac{\varepsilon_{ele}^{real} N_l^{\ i} - N_t^{\ i}}{\varepsilon_{ele}^{real} - \varepsilon_{QCD}^{fake}}$$

Reverse Isolation

- shape from loose-tight
- normalization from following:

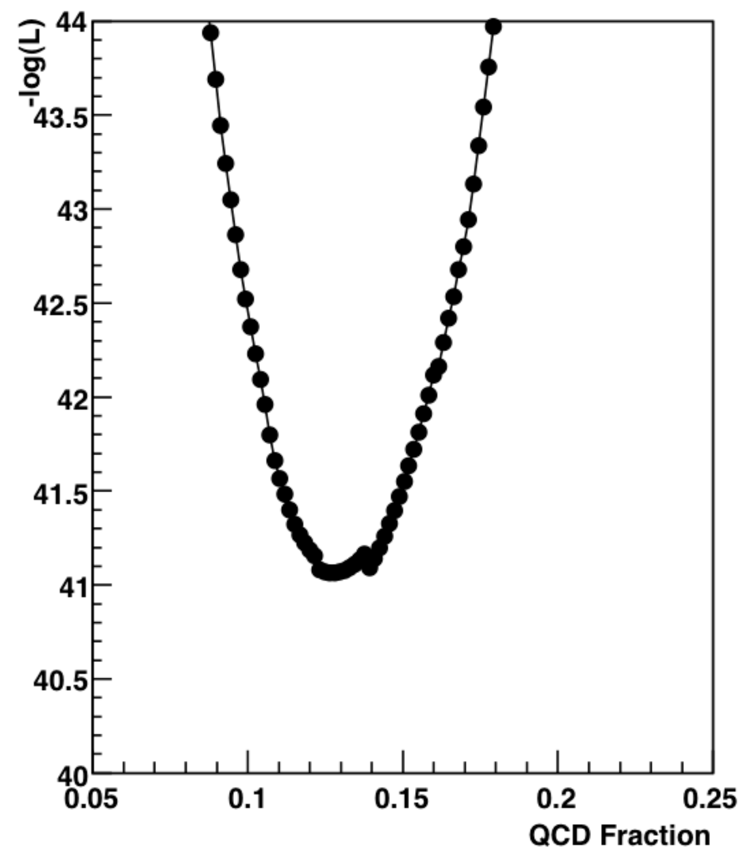
$$\varepsilon_{QCD}^{fake} N_{QCD} = \varepsilon_{QCD}^{fake} \frac{\varepsilon_{ele}^{real} N_l - N_t}{\varepsilon_{ele}^{real} - \varepsilon_{QCD}^{fake}}$$

- depends on tight/loose definition
- ε_{QCD} ~ 45%
- ε_{ele} ~ 95%
  - from Z->ee+N_{jets} MC
  - data/MC correction factor ~1.0

Multijet Background: M_T fit method

- Data Driven method
  - not modeled well by MC
  - not enough events generated
- Fit to M_T
  - Σbkgs = data yield

$$M_T(l, E_T^{miss}) = \sqrt{2 p_T^l E_T^{miss}(1 - \cos(\Delta\phi))}$$



Control Regions

- lljj
- Z+jets
  - 81 <Z_{mass}<101 GeV
- ttbar
  - both e and μ
  - ≥2 jets

- lnujj
- W+jets
  - M_T < 150 GeV
  - exactly 2 jets
    - S_T< 175 GeV
  - ≥3 jets
    - S_T < 200 GeV
- ttbar
  - M_T < 150 GeV
  - ≥4 jets
  - $p_T(j_1)$< 50 GeV, $p_T(j_2)$< 40 GeV, $p_T(j_3)$< 30 GeV