A Search for 2nd-generation Leptoquarks in pp Collisions at $\sqrt{s}$ = 7 TeV with the ATLAS Detector

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Dissertation Defense

20 June 2012

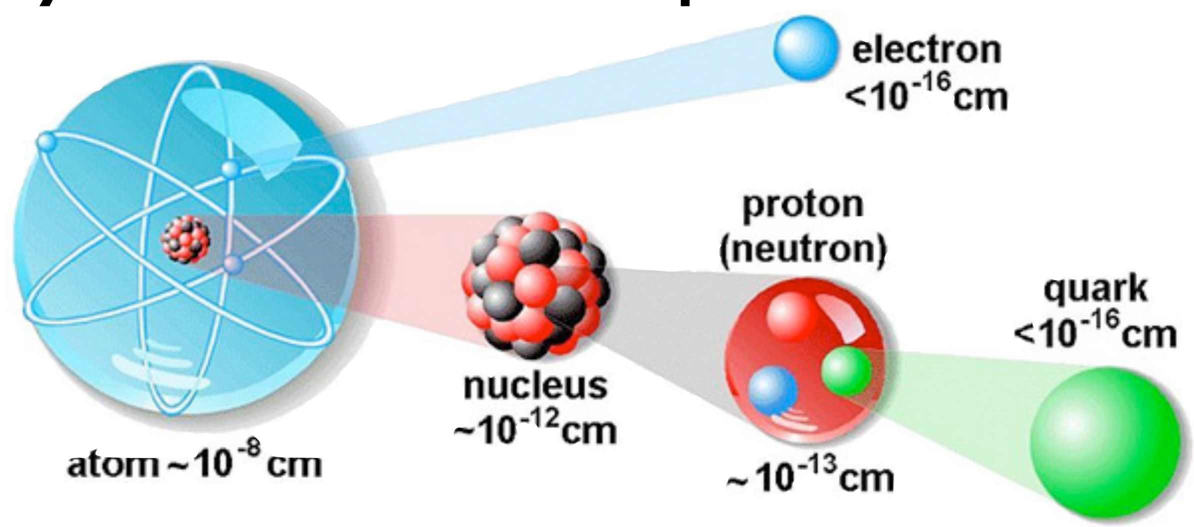
Physics & Astronomy Department

Outline

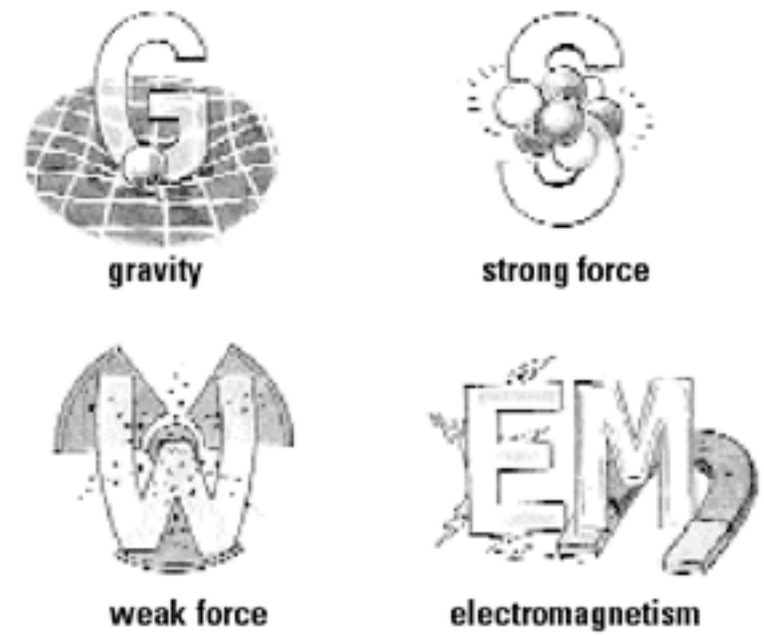
- Introduction
  - Standard Model
  - Leptoquarks
- Experiment
  - Large Hadron Collider
  - ATLAS detector
- Event Simulation and Reconstruction
- A Leptoquark Search
  - physics object and event selection
  - backgrounds and control regions
  - multivariate discriminant
  - limit-setting and results
  - future outlook
- Conclusion

Particle Physics

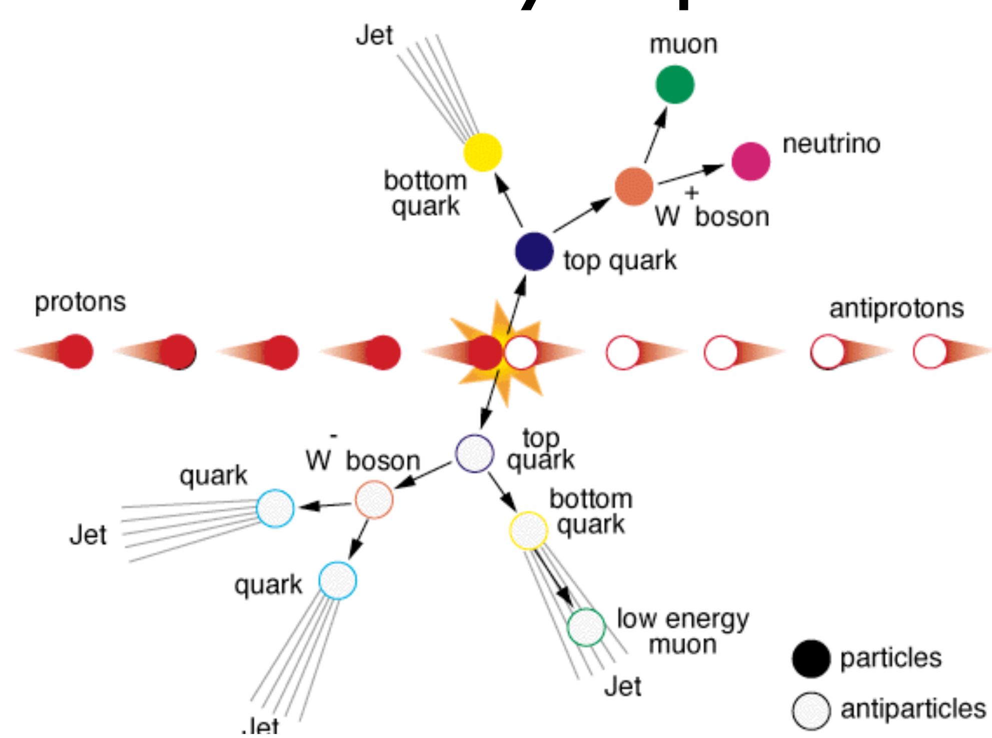
Study of fundamental particles of matter...



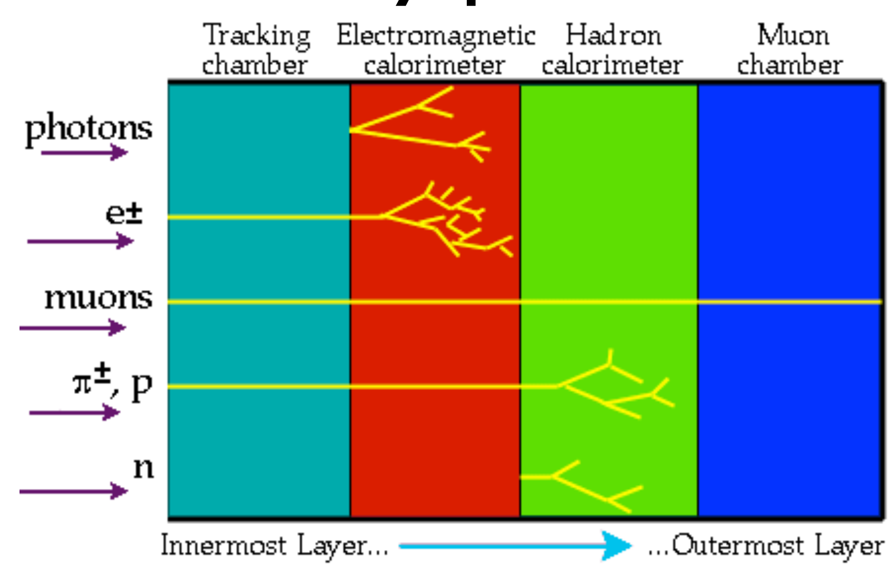
... and their interactions...



... through particle scattering
and decay experiments...

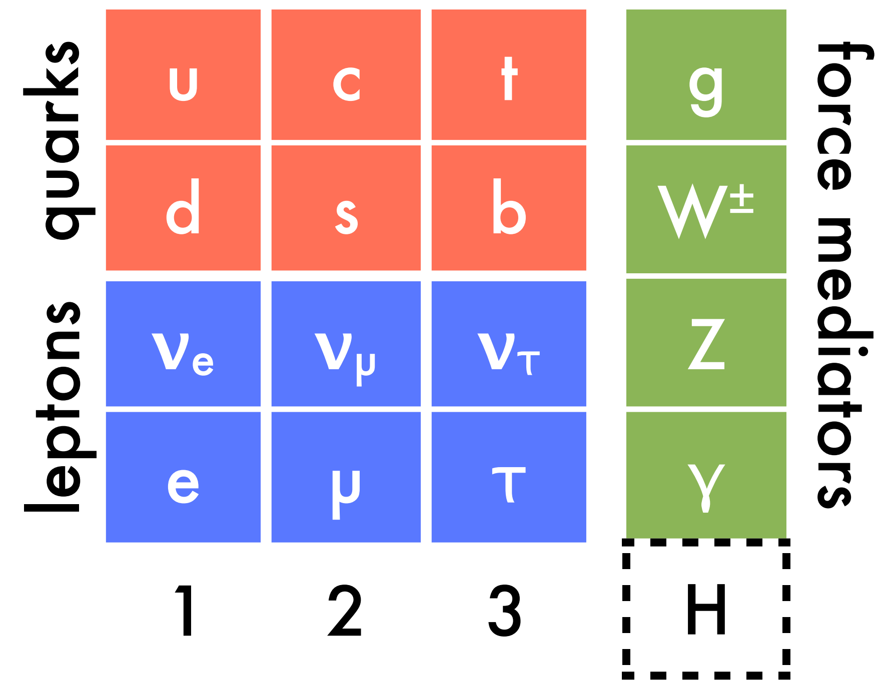


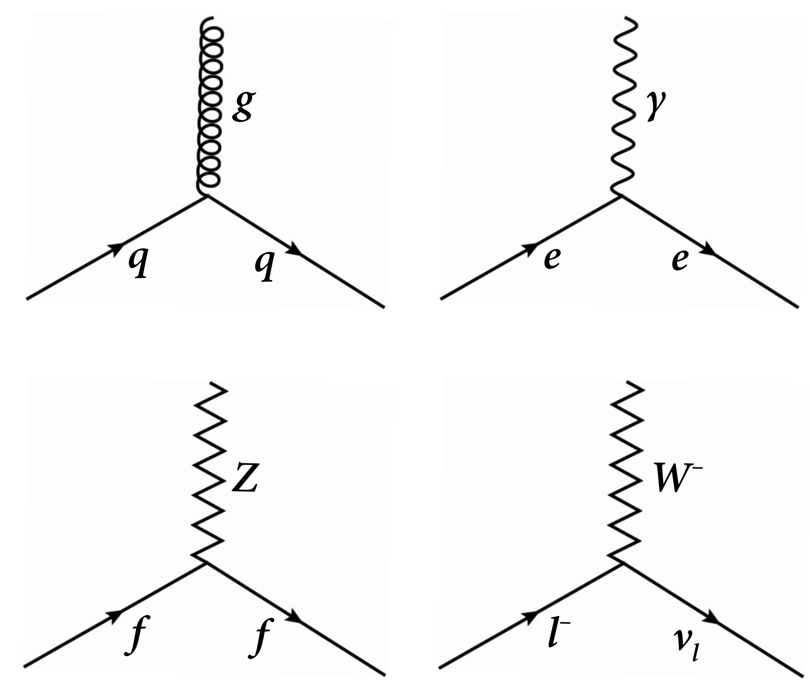
... recorded by particle detectors.



Standard Model (SM)

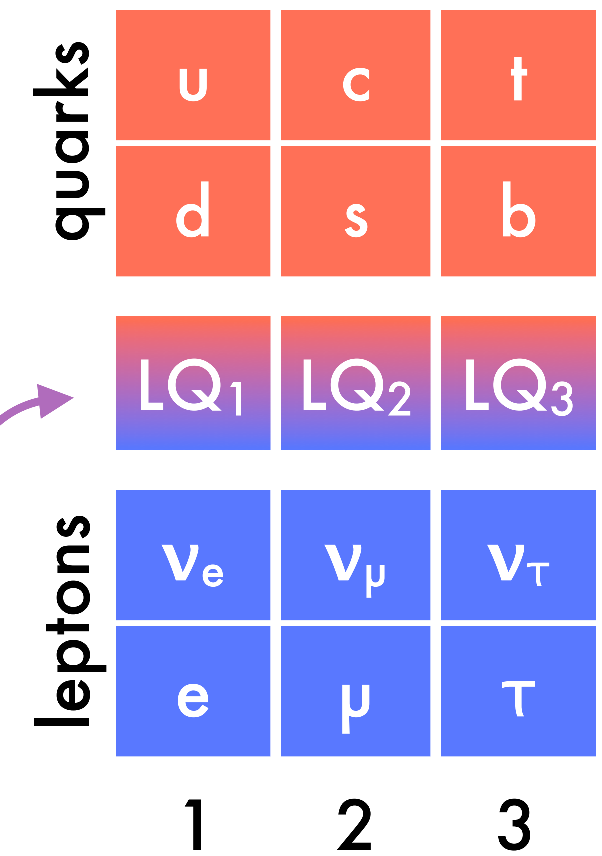
- Quantum Field Theory describing strong, weak, and electromagnetic interactions of elementary particles of matter
- Particles: quarks and leptons (spin-1/2 fermions), force mediators (spin-1 bosons)
  - spin, mass, electric charge, ...
  - three like generations
  - anti-particle for each
- Interactions via boson exchange: strong (gluons), weak ($W^{\pm}$, Z), electromagnetic (γ)
- Incomplete theory
  - no gravity, dark matter/energy
  - many free parameters, unanswered questions, ...

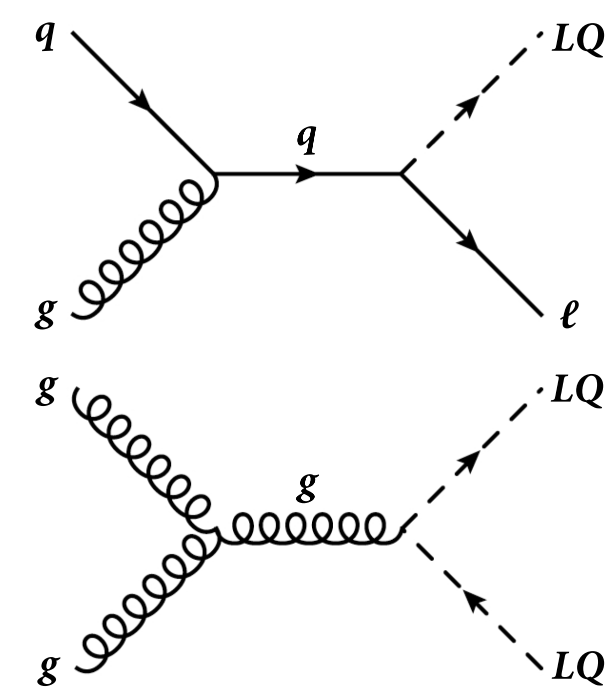




Leptoquarks (LQs)

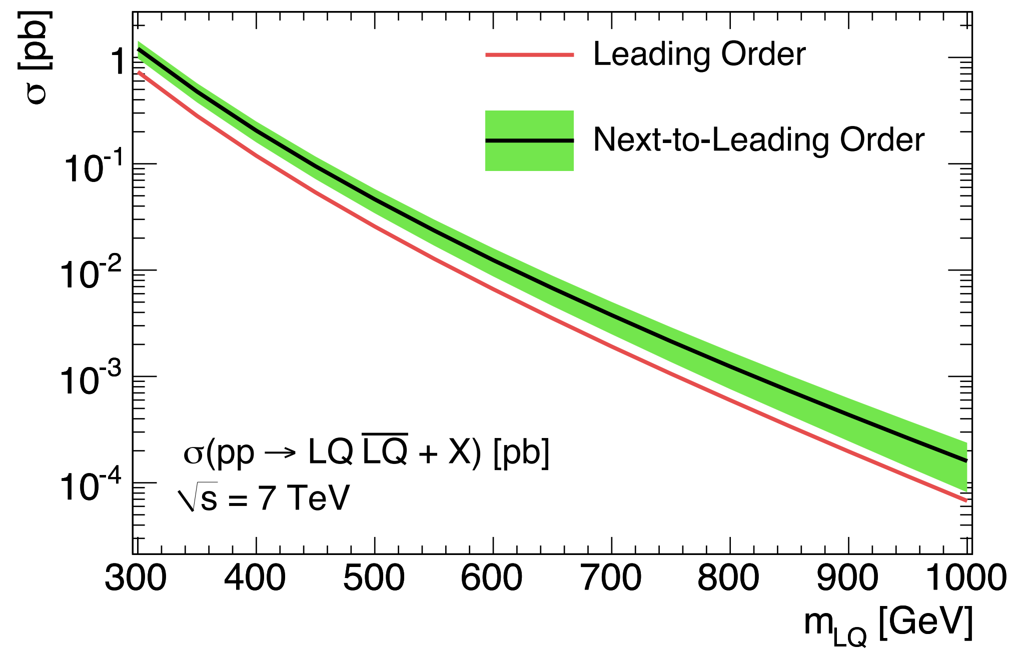
- *Apparent* symmetry between quarks and leptons, suggestive of fundamental relation
- Many "Beyond the SM" theories allow new interactions between quarks and leptons
- Leptoquarks: hypothetical bosons with lepton and baryon number, electric and color charge
  - scalar (spin-0) or vector (spin-1)
  - couple directly to lepton-quark pairs, strength λ_{lq}
- Experimental constraints => three generations, conserve *L* and *B* numbers
- Single- or pair-production at LHC: gluon fusion dominant, plus quark annihilation



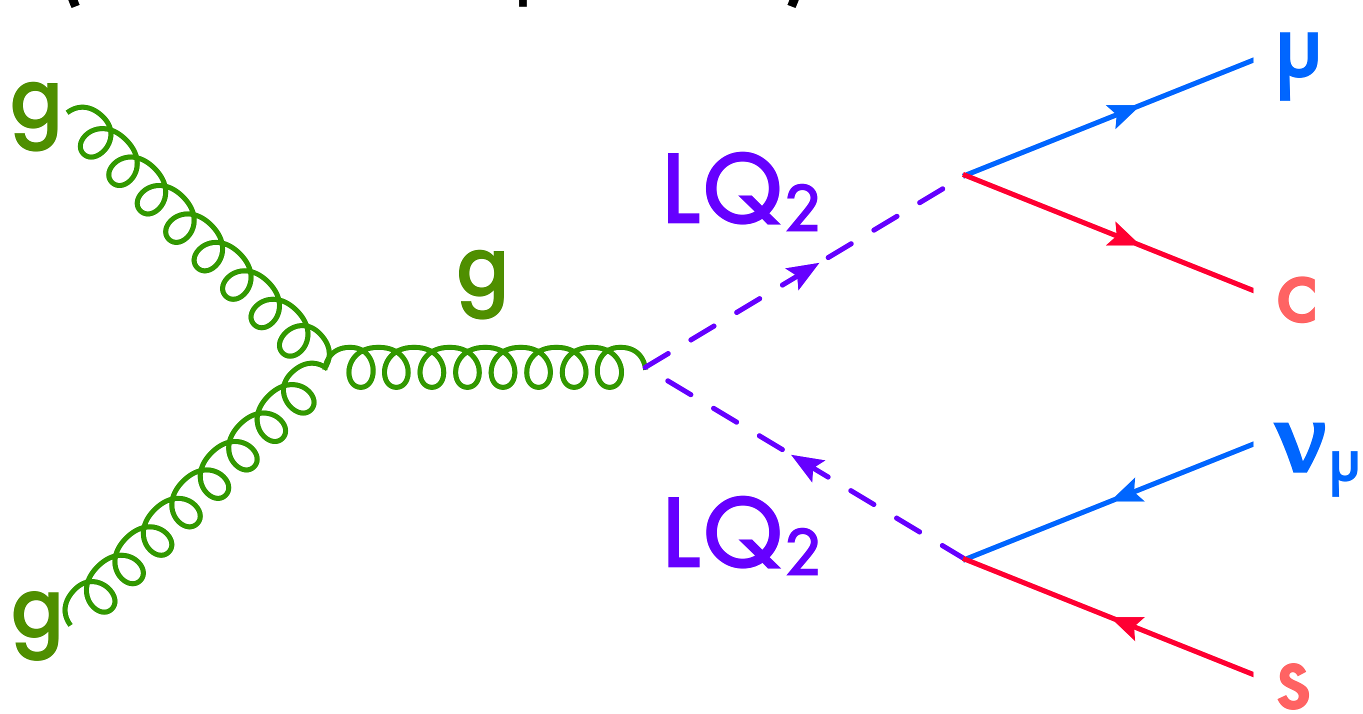


LQ Searches

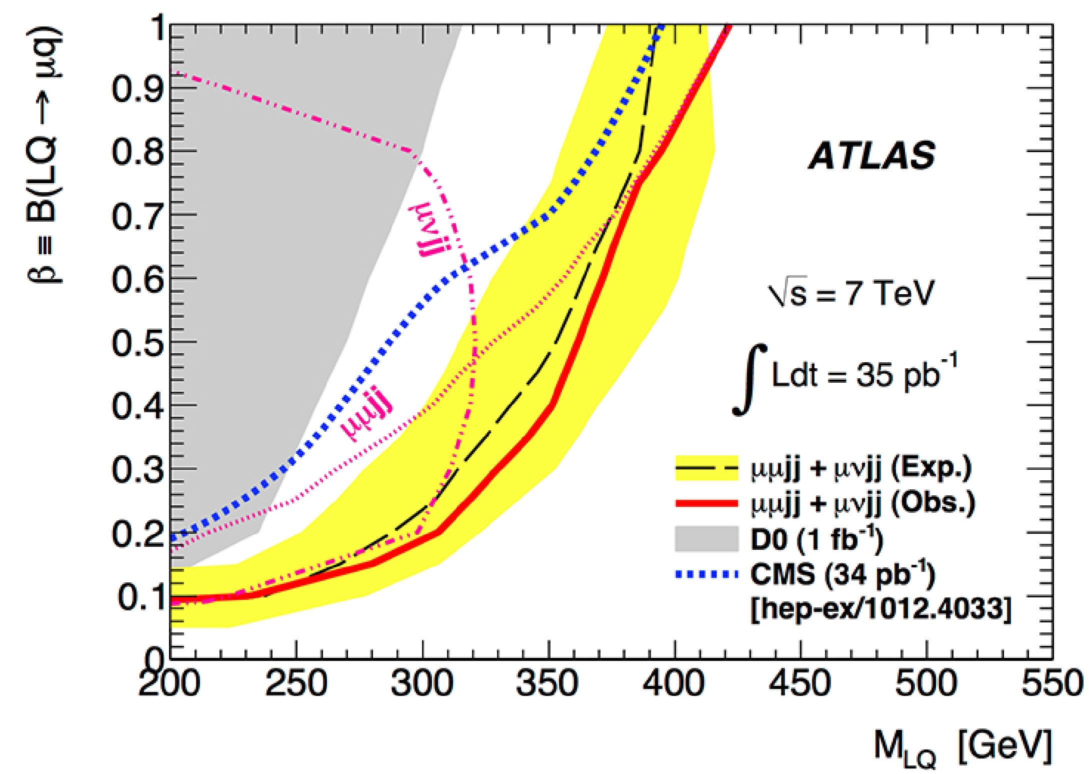
- Scalar, pair-produced
  - large, model-independent cross section σ_{LQ} dependent "only" on m_{LQ}
- Three final states: llqq, lνqq, ννqq
  - branching ratio of LQ to a quark and a charged lepton $\beta = BR(LQ \rightarrow lq)$
- My search: 2nd-generation, μνqq (maximal at $\beta = 0.5$)



c
s
LQ_2
ν_μ
μ



existing experimental limits:



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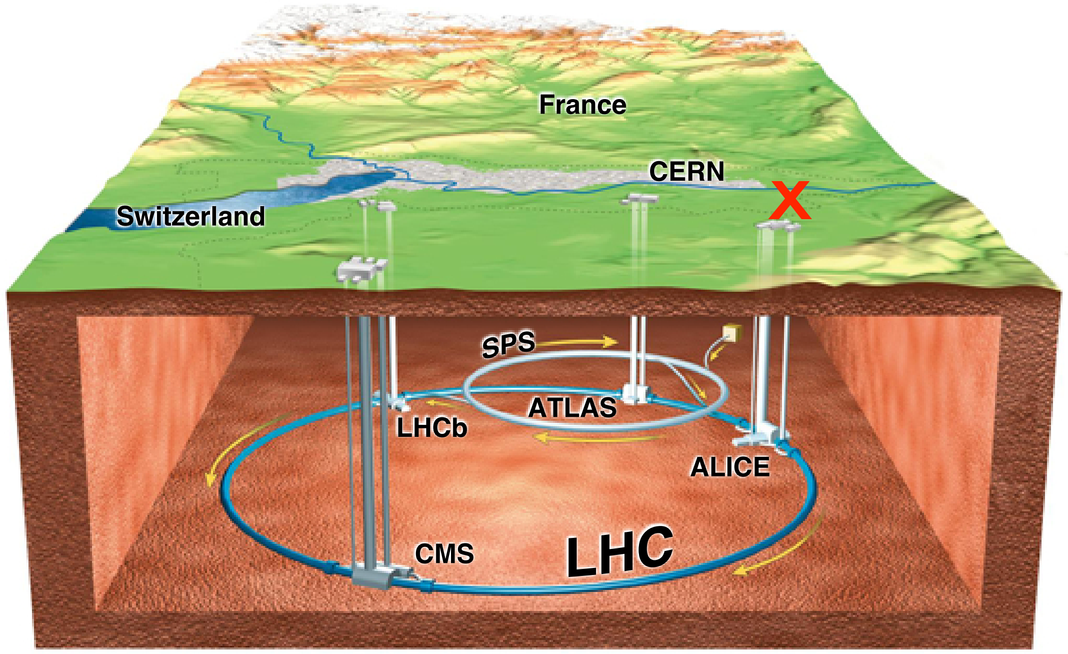
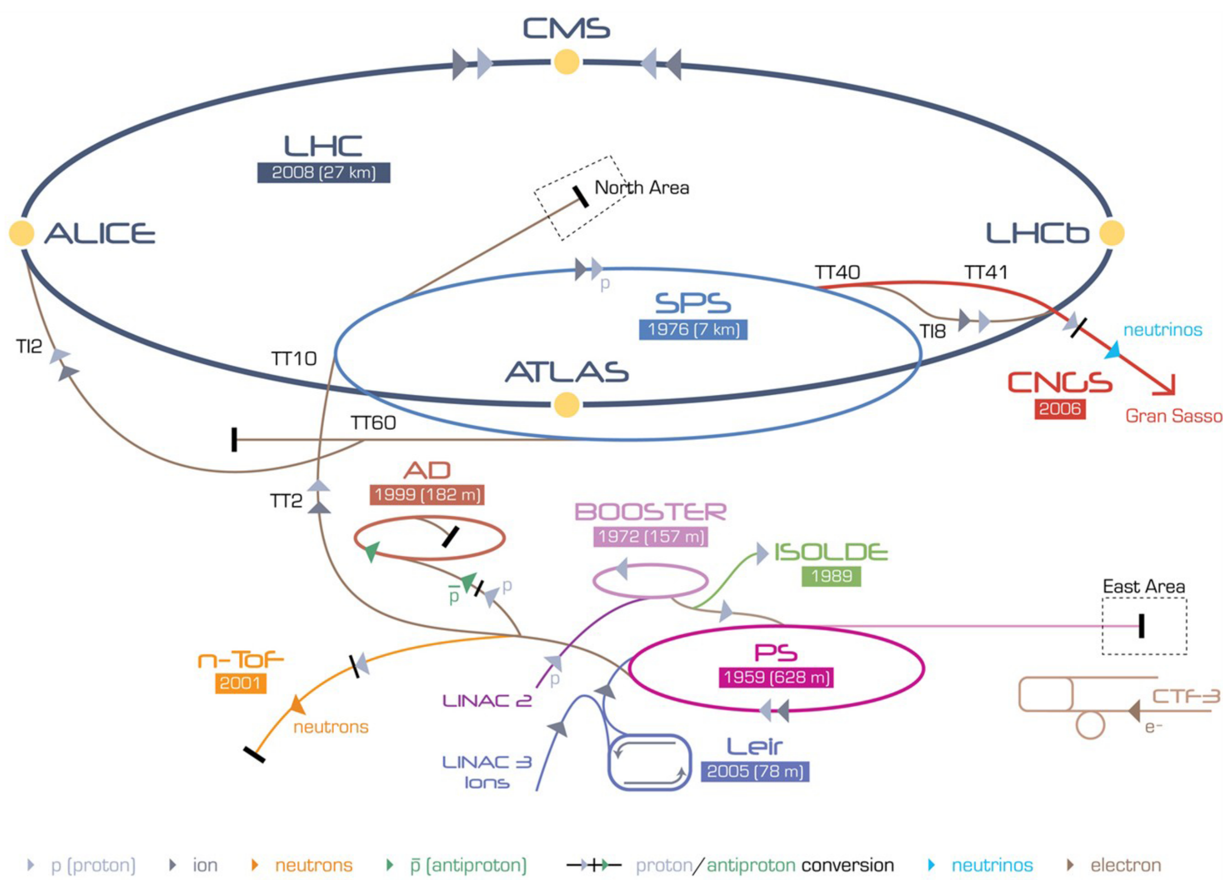
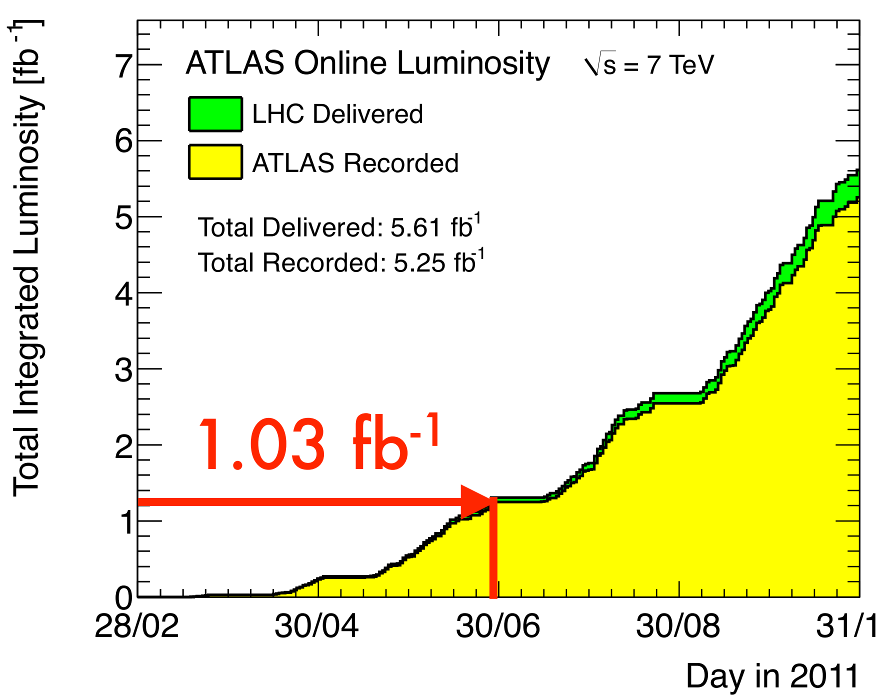


Large Hadron Collider (LHC)





- Last, largest, most powerful link in CERN accelerator complex
- 27 km ring, accelerates then collides protons at $\sqrt{s} = 7$ TeV
    - protons grouped into bunches into beams, cross at four points on ring
    - high energy => small distances, massive particles
    - high luminosity => high rate of interactions, many events
- Number of $LQLQ \to \mu\nu qq$ events:

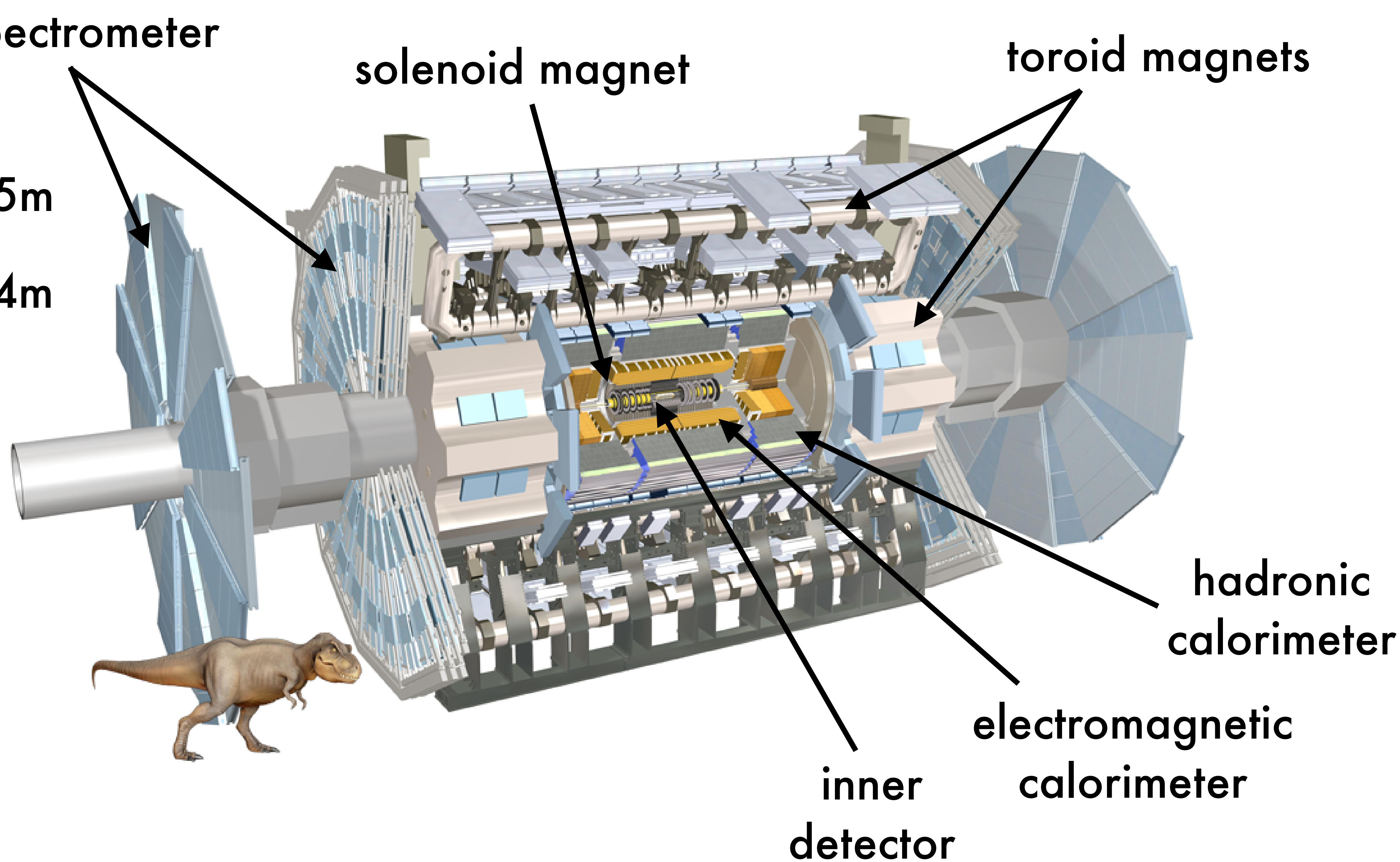
$$N_{evts} = \sigma_{LQ} \times L_{int} \times 2\beta(1-\beta)$$
$$= 0.0124 \text{ pb} \times 1035 \text{ pb}^{-1} \times 0.5$$
$$\approx 6.4$$

For m_{LQ}=600 GeV, β=0.5

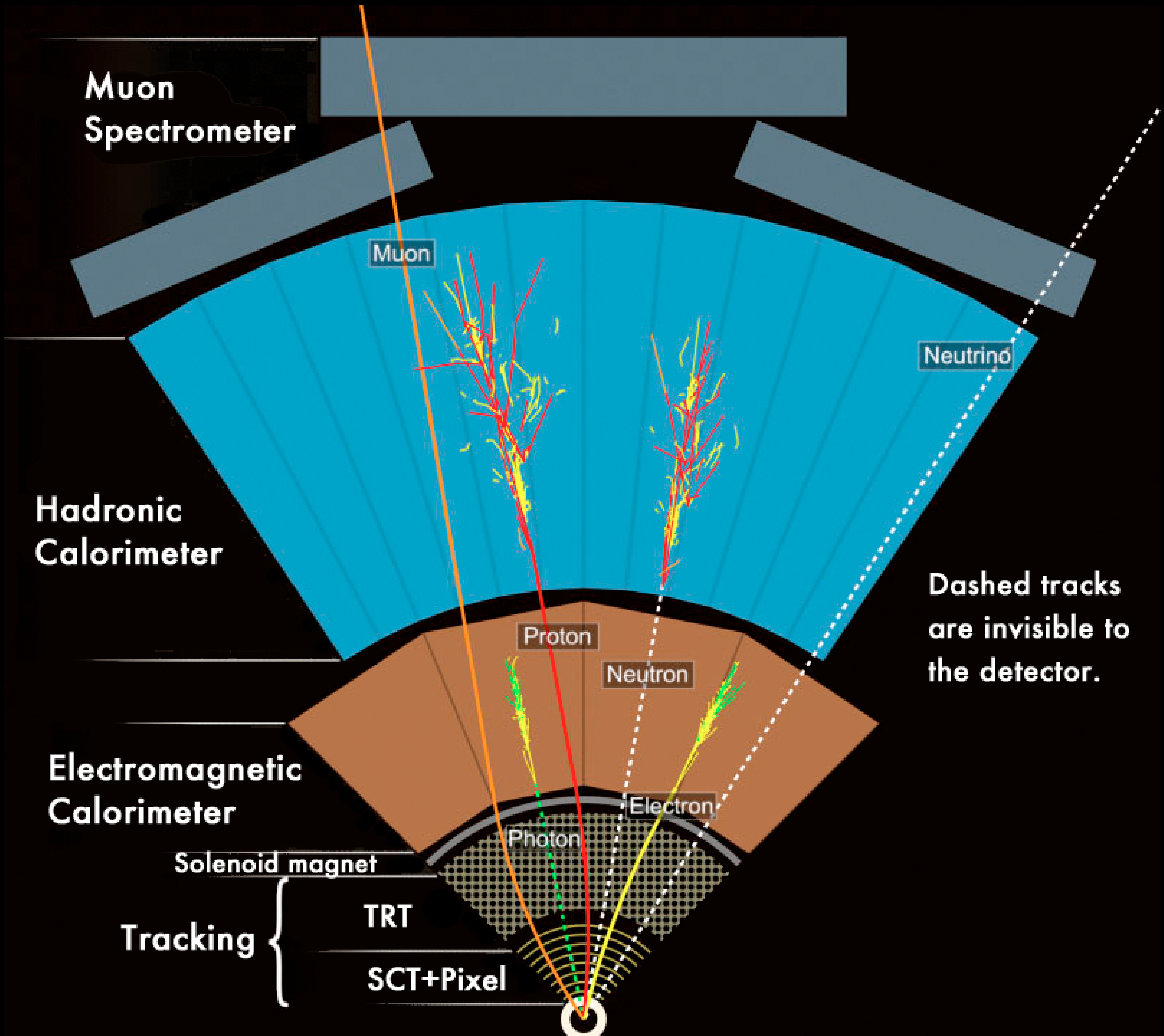
ATLAS Detector

- Multi-purpose detector, forward-backward symmetric cylindrical geometry, nearly 4π coverage in solid angle

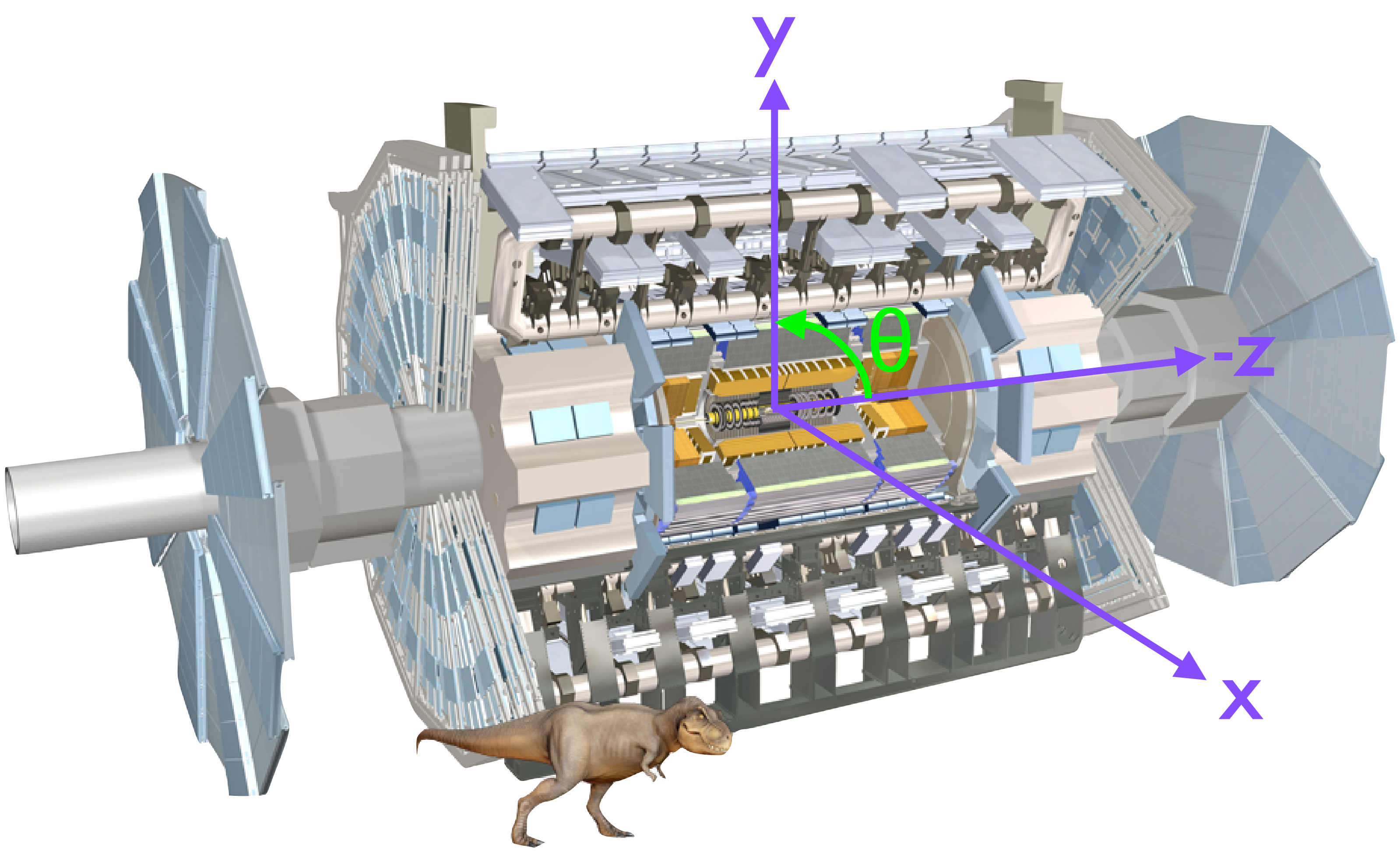
- height: 25m
- length: 44m

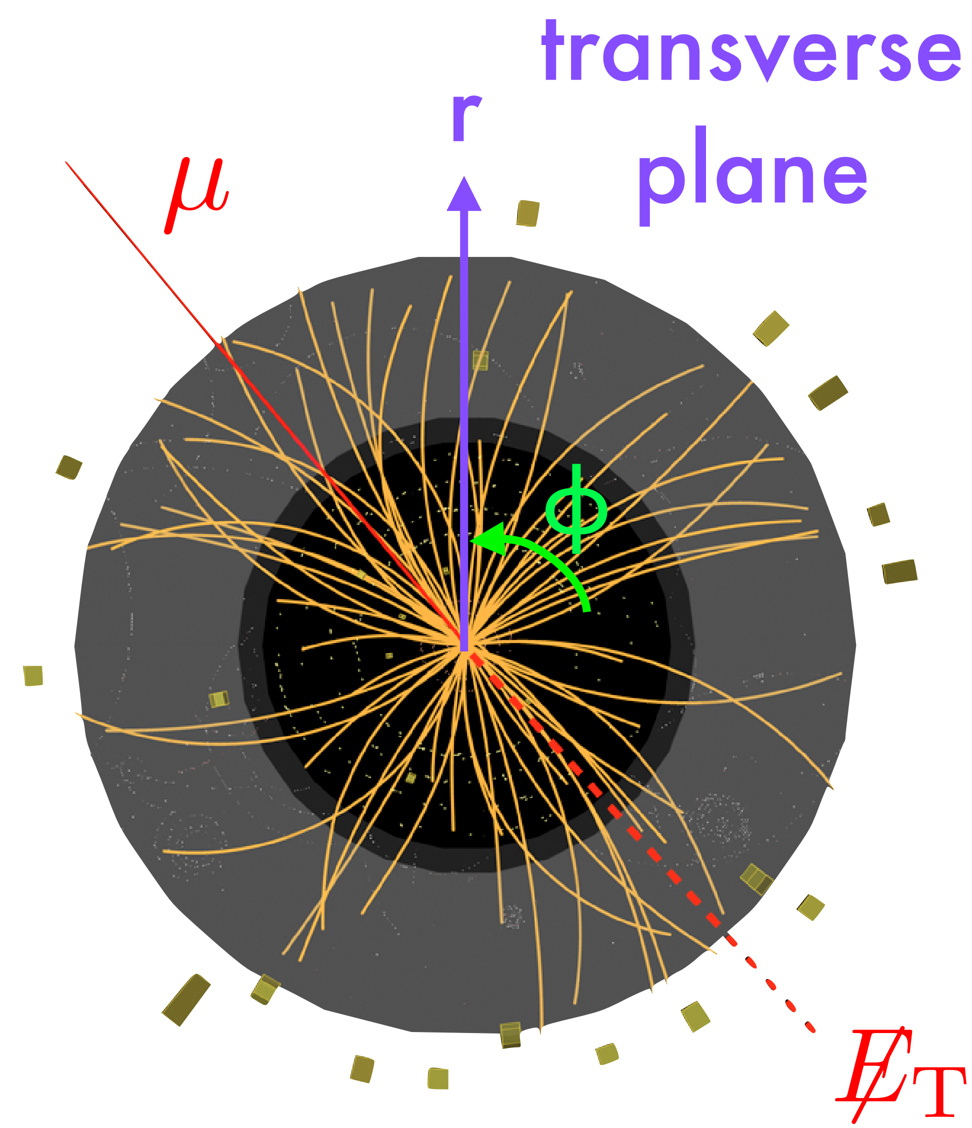


ATLAS Detector



ATLAS Detector





pseudorapidity: $\eta \equiv -\ln\left(\tan\frac{\theta}{2}\right)$

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

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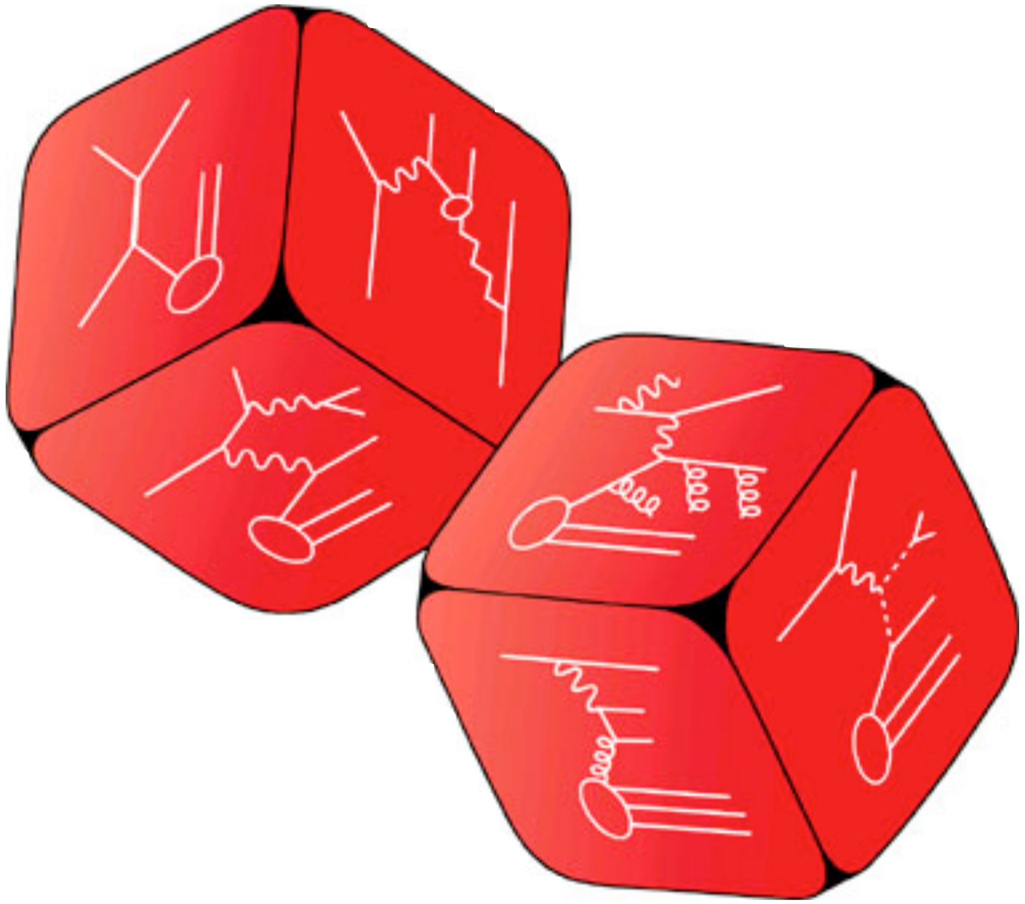
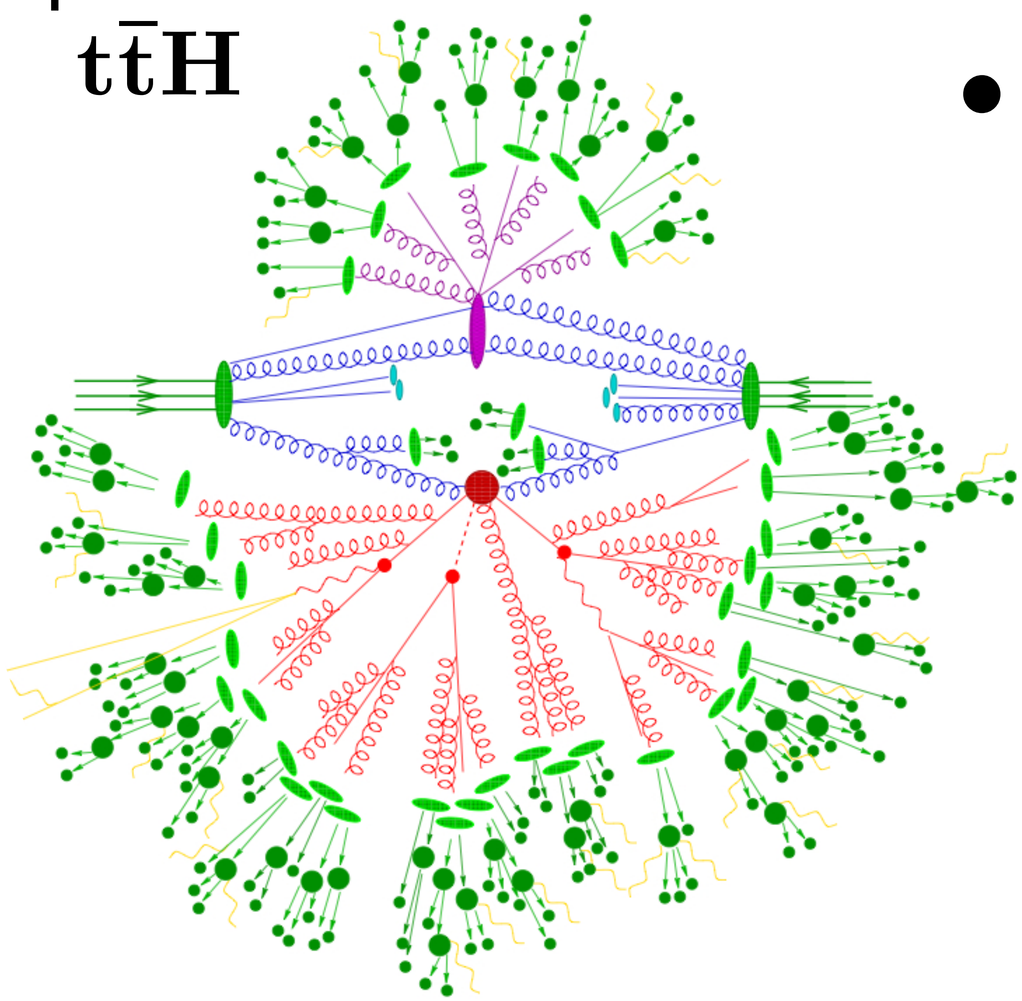


Monte Carlo (MC)

process:
$t\bar{t}H$



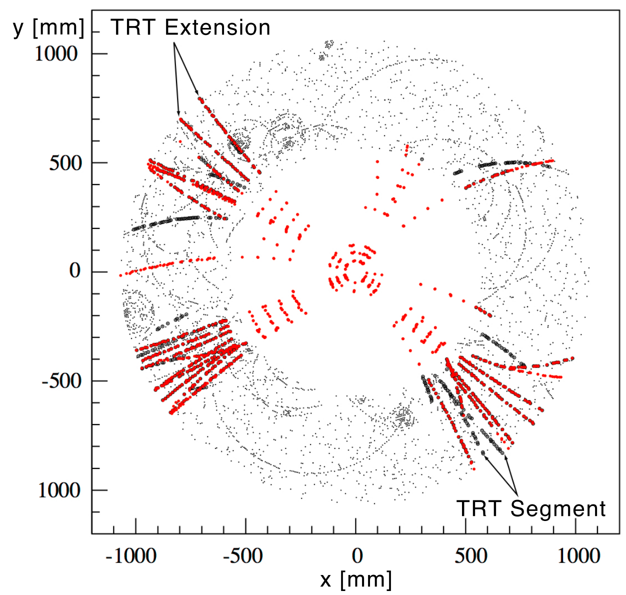
- Need predictions of both SM *background* and LQ *signal* events to compare with data
- Given a theoretical model, event generators use Monte Carlo numerical methods to simulate each "phase" of an event:
  - hard scatter
  - parton showering
  - hadronization
  - decays
  - \+ underlying event

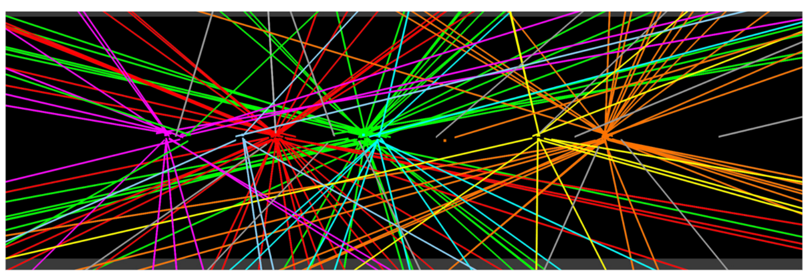
Energy Scale

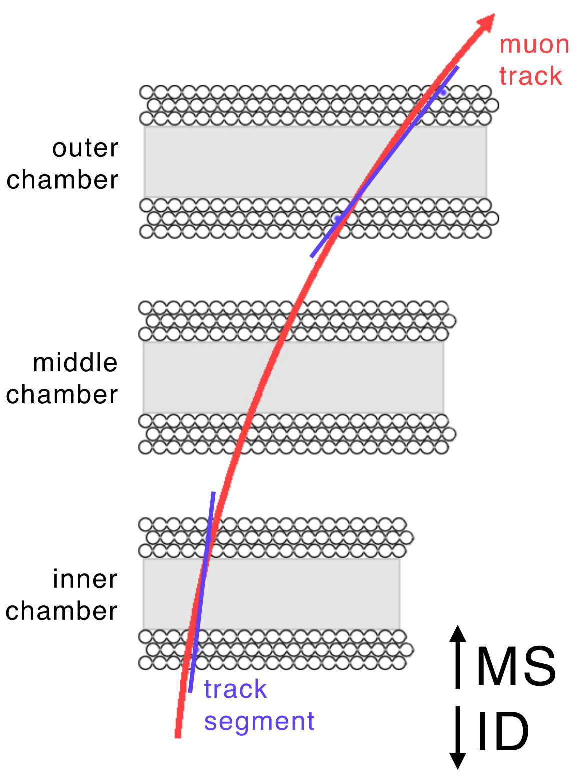
\+ pile-up events from neighbor bunches

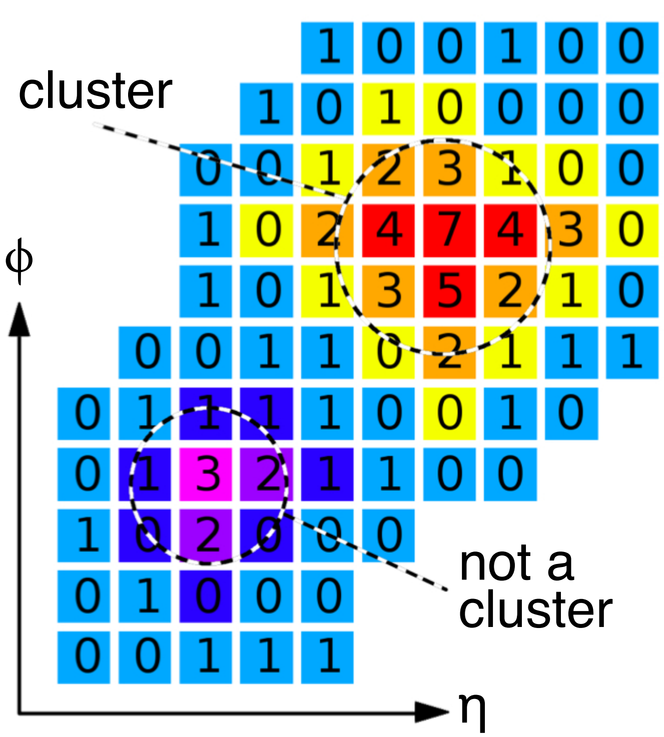
- Result: simulated events samples as expected in Nature
- Propagate MC particles through ATLAS simulation: interactions => measurements => reconstruction, *just like data!*

Event Reconstruction









- Pattern recognition algorithms reconstruct physics objects from raw detector data
  - **tracks:** sets of ID hits matched along trajectory of a charged particle
  - **vertices:** shared origin of neighboring tracks
  - **muons:** standalone MS track, may be statistically combined with matching ID track
  - **electrons:** ID track matched to EM energy cluster
  - **jets:** topologically related energy clusters grouped with anti-k_T algorithm (R_c = 0.4)
  - **MET:** negative vector sum of calorimeter E_T plus muon p_T

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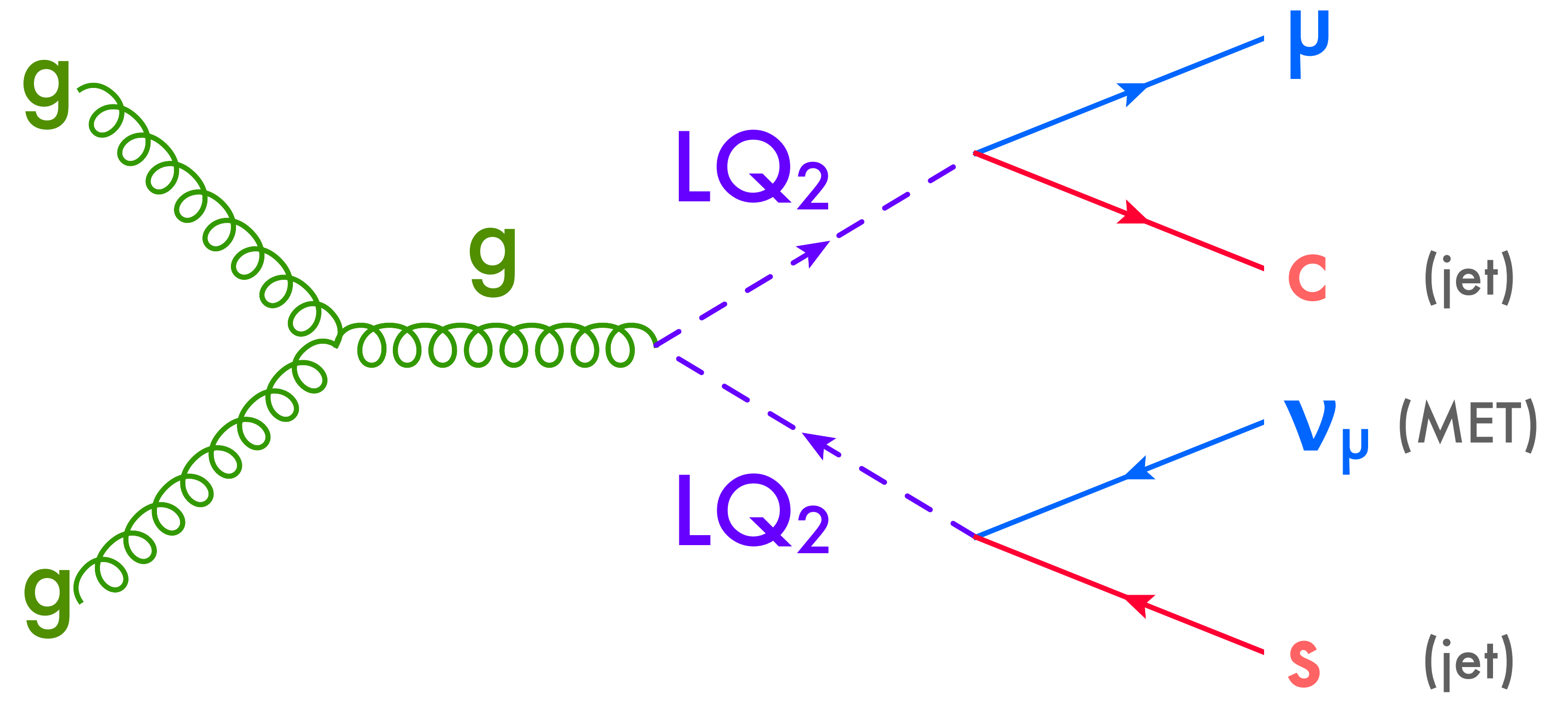
Physics Object Selection

- Physics object and event selections based on LQ event topology
  - high signal efficiency!



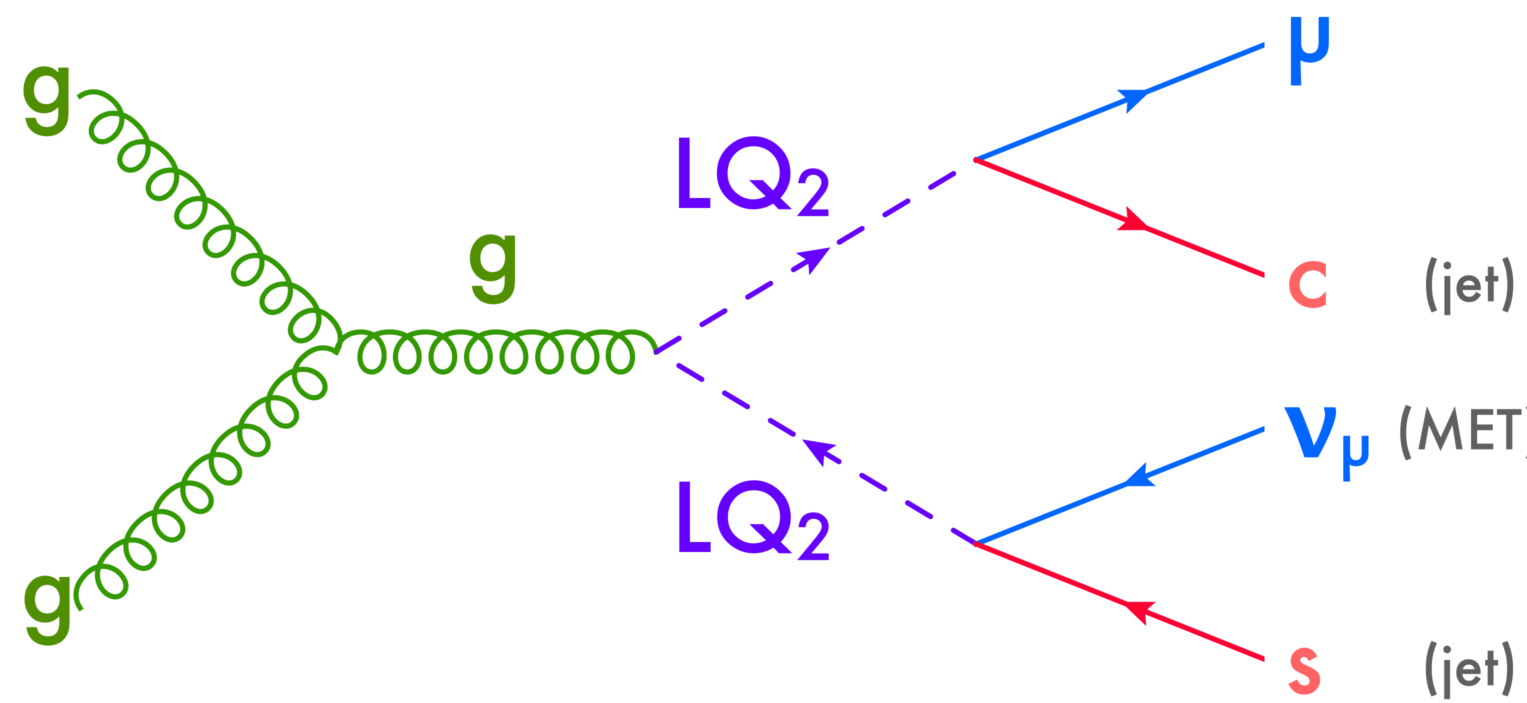
MUONS
ID+MS tracks combined
$\lvert\eta\rvert < 2.4$
$p_T > 30$ GeV
track quality requirements
$\lvert d_0\rvert < 0.1$mm, $\lvert z_0\rvert < 5.0$mm
isolated in tracking

JETS
$\lvert\eta\rvert < 2.8$
$p_T > 30$ GeV
quality requirements
$\Delta R(\text{jet}, l) > 0.4$

ELECTRONS (veto)
$\lvert\eta\rvert < 2.47$
$p_T > 20$ GeV
quality requirements
isolated in calorimeter

Event Selection

- Physics object and event selections based on LQ event topology
  - high signal efficiency!



MUONS

ELECTRONS

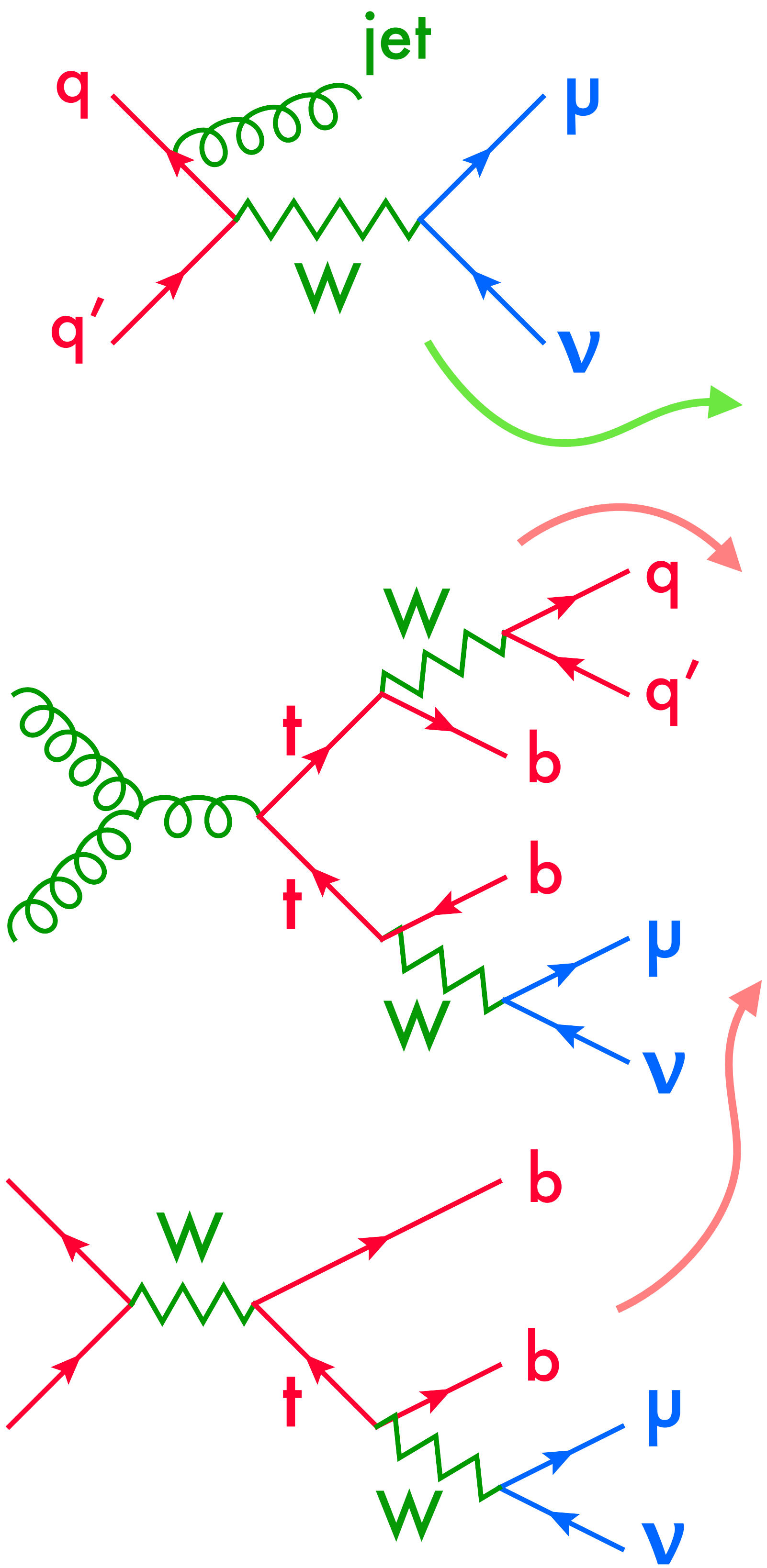
JETS

$$\left(M_T(\mu, \not{E}_T) = \sqrt{2 p_T^\mu \not{E}_T (1 - \cos \Delta\phi)} \right)$$

EVENTS

- fires single-muon trigger (p_T > 18 GeV)
- at least one primary vertex with at least 3 associated tracks
- exactly one good muon and zero good electrons
- missing transverse energy (MET) > 30 GeV
- at least two good jets
- transverse mass M_T(μ,MET) > 40 GeV

SM Backgrounds



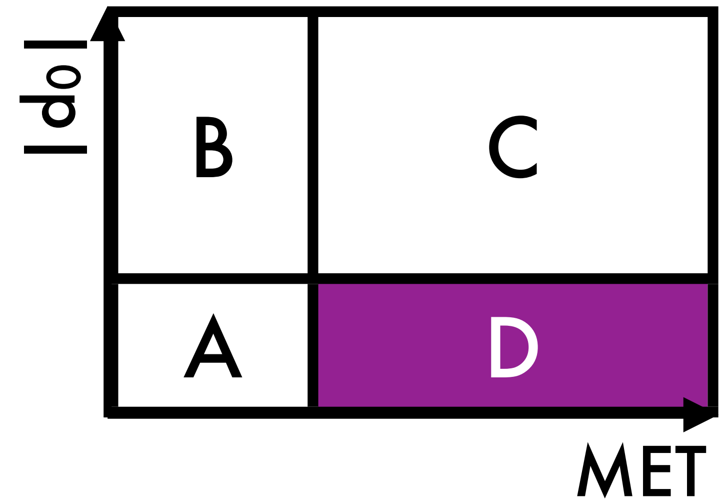
Source	Estimation
V+jets (W+jets and Z+jets)	normalization from control region, shape from MC (Alpgen)
t-tbar	normalization from control region, shape from MC (MC@NLO)
single top	normalization and shape from MC (MC@NLO), NLO cross sections
diboson (WW, WZ, ZZ)	normalization and shape from MC (Herwig), NLO cross sections
multi-jet	normalization and shape from fully data-driven methods

Multi-jet Estimation

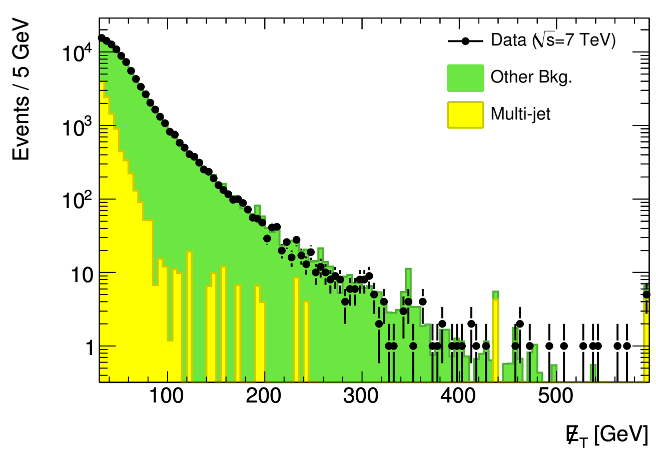
- Method 1: ABCD
  - MET vs muon impact parameter (nominal)
  - MET vs muon track isolation (alternate)
  - shape from region C, scaled to N_D

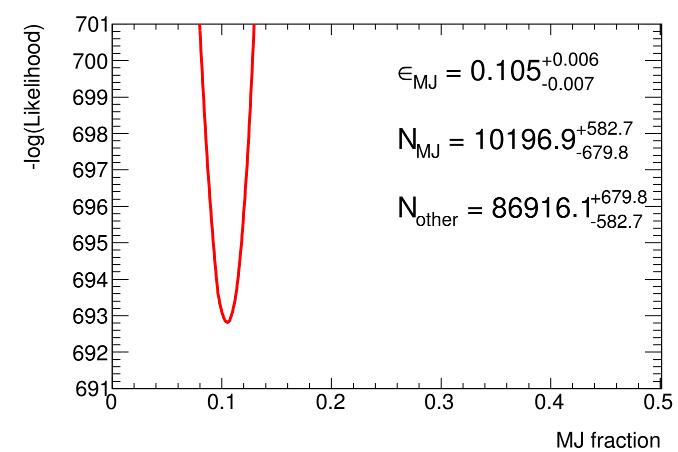
$$N_{\rm D} = \frac{N_{\rm A} N_{\rm C}}{N_{\rm B}}$$

$$h_{\rm D} = h_{\rm C} \cdot \left(\frac{N_{\rm D}}{N_{\rm C}} \right)$$



- Method 2: Fitting
  - fit MET distribution of MC bkg + MJ to data
  - bkg, data yields constrained to be equal
  - MJ fraction as floating parameter





- Combination
  - average normalizations from both methods to get nominal yields
  - nominal shape from C in ABCD, alternate shape used as systematic

Control Regions (CRs)

W+jets CR

passes event selection

$M_T(\mu,\mathrm{MET}) < 120$ GeV

$S_T < 225$ GeV

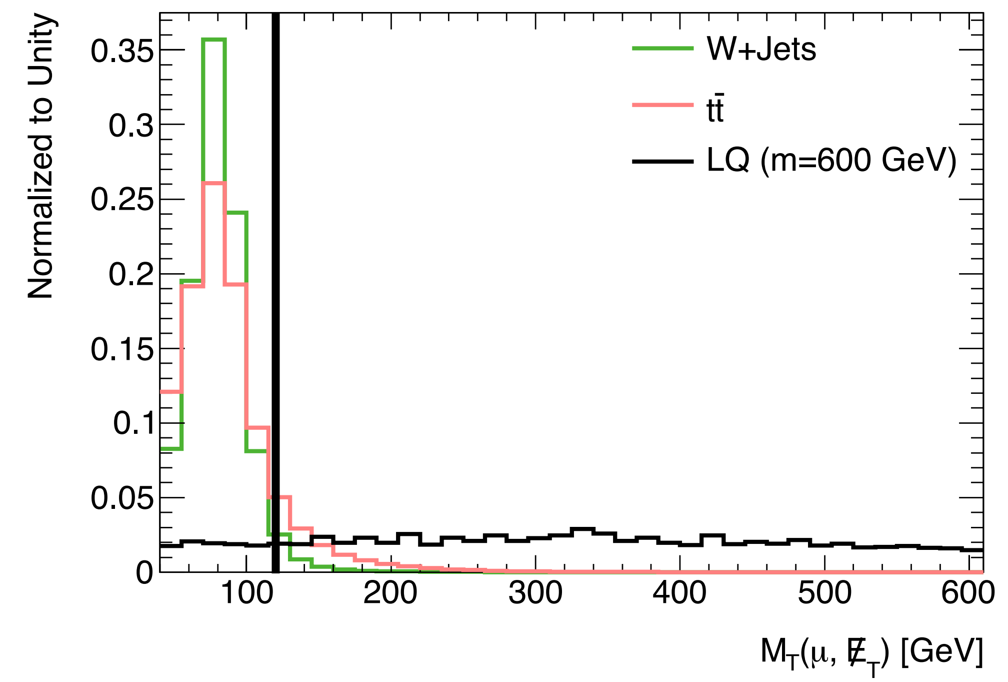
W+2jets: exactly two jets

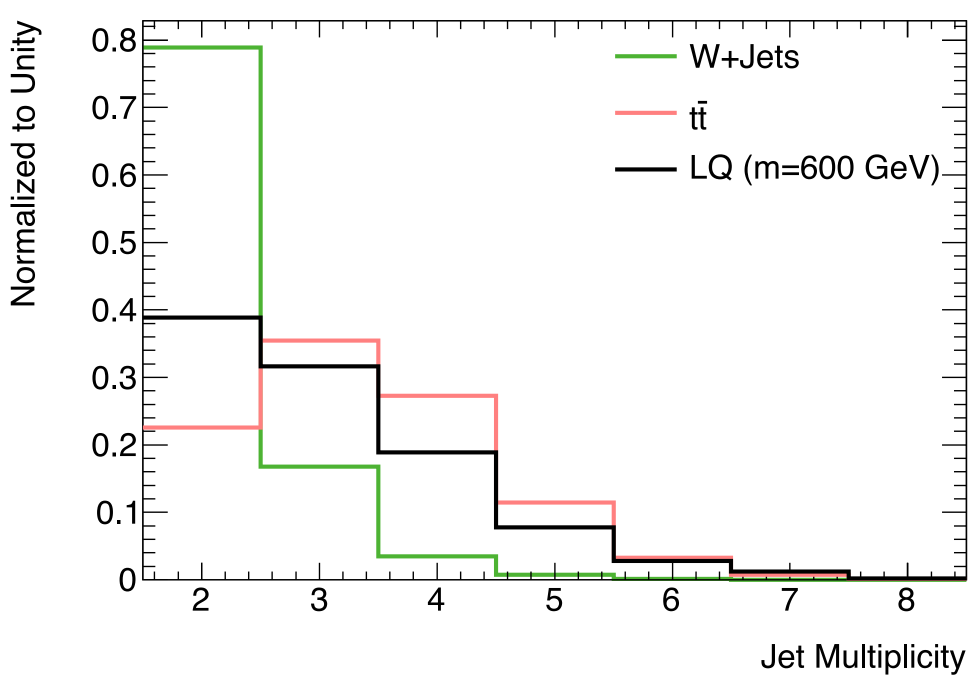
W+3jets: at least three jets

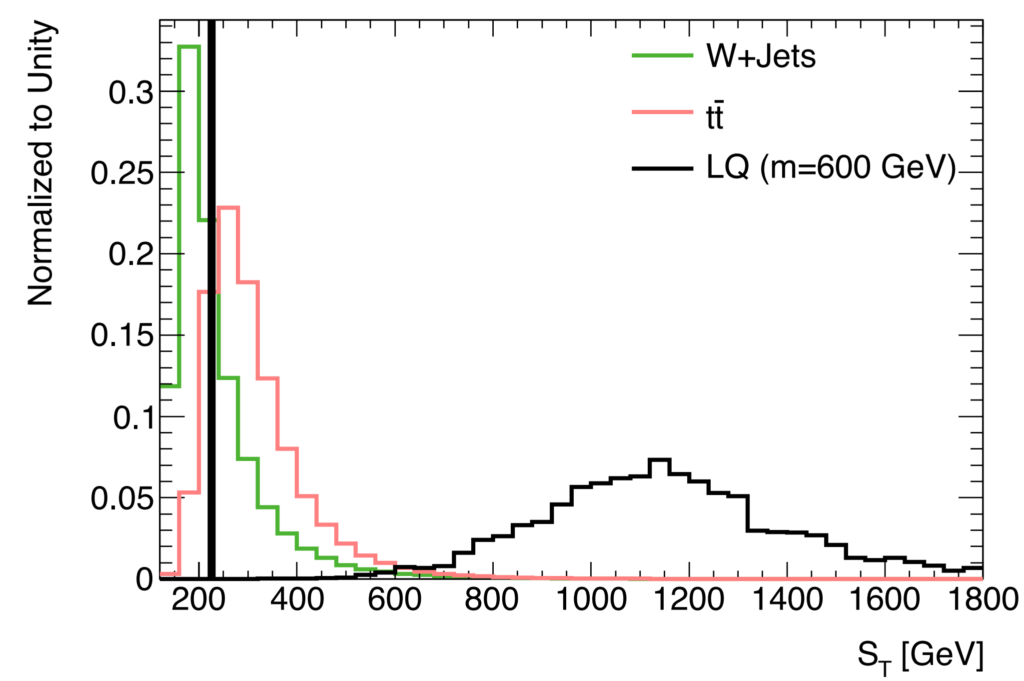
- Defined to enhance dominant backgrounds, minimize signal; verify background modeling

$$M_T(\mu,\not{E}_T) = [2p_T^{\mu}\not{E}_T(1-\cos\Delta\phi)]^{1/2}$$

$$S_T = p_T^{jet1}+p_T^{jet1}+p_T^{\mu}+\not{E}_T$$







Control Regions (CRs)

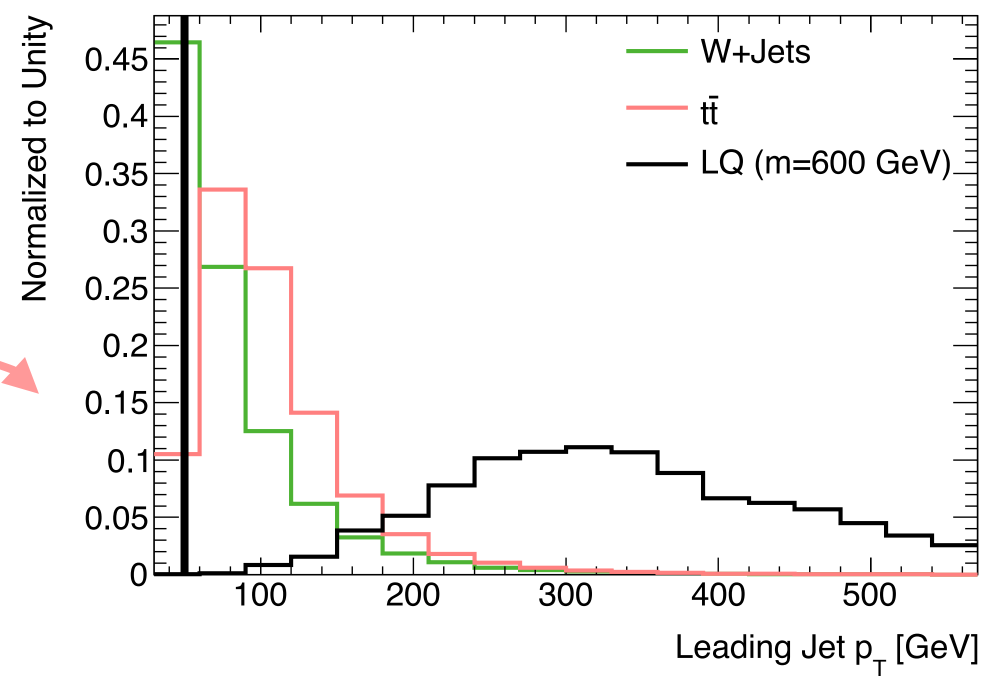
t-tbar CR
passes event selection
$M_T(\mu,\mathrm{MET}) < 120$ GeV
at least four jets
$p_T^{jet1} > 50$ GeV
$p_T^{jet2} > 40$ GeV

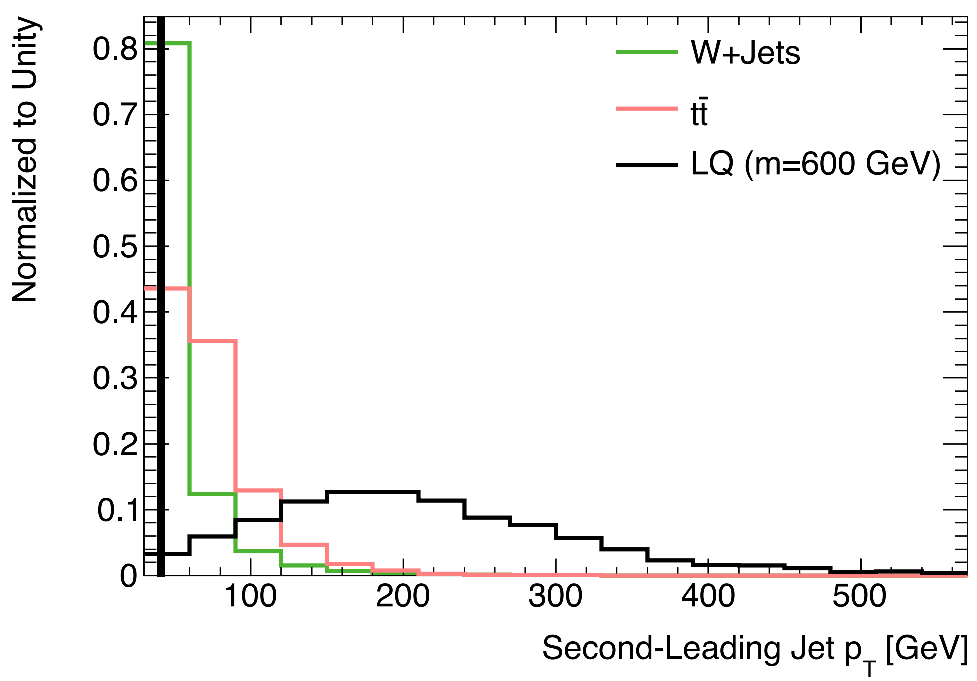
- Modify normalization with scale factors derived from simultaneous χ^2 fit to all CRs

$$\chi^2 = \sum_{\mathrm{CR}} \left[\frac{N_i^{\mathrm{data}} - N_i^{\mathrm{MC}}}{\sigma_i^{\mathrm{data}}} \right]^2,$$

$$N_i^{\mathrm{MC}} \equiv (\mathrm{SF}^{t\bar{t}} \times N_i^{t\bar{t}}) + (\mathrm{SF}^{V} \times N_i^{V}) + N_i^{\mathrm{other}}$$

W+jets SF	0.911 ± 0.005
t-tbar SF	1.092 ± 0.25





	W+2jets CR	W+3jets CR	t-tbar CR
Total Bkg	45100 ± 300	8300 ± 120	7300 ± 80
Data	45213	8125	7303

Control Regions (CRs)

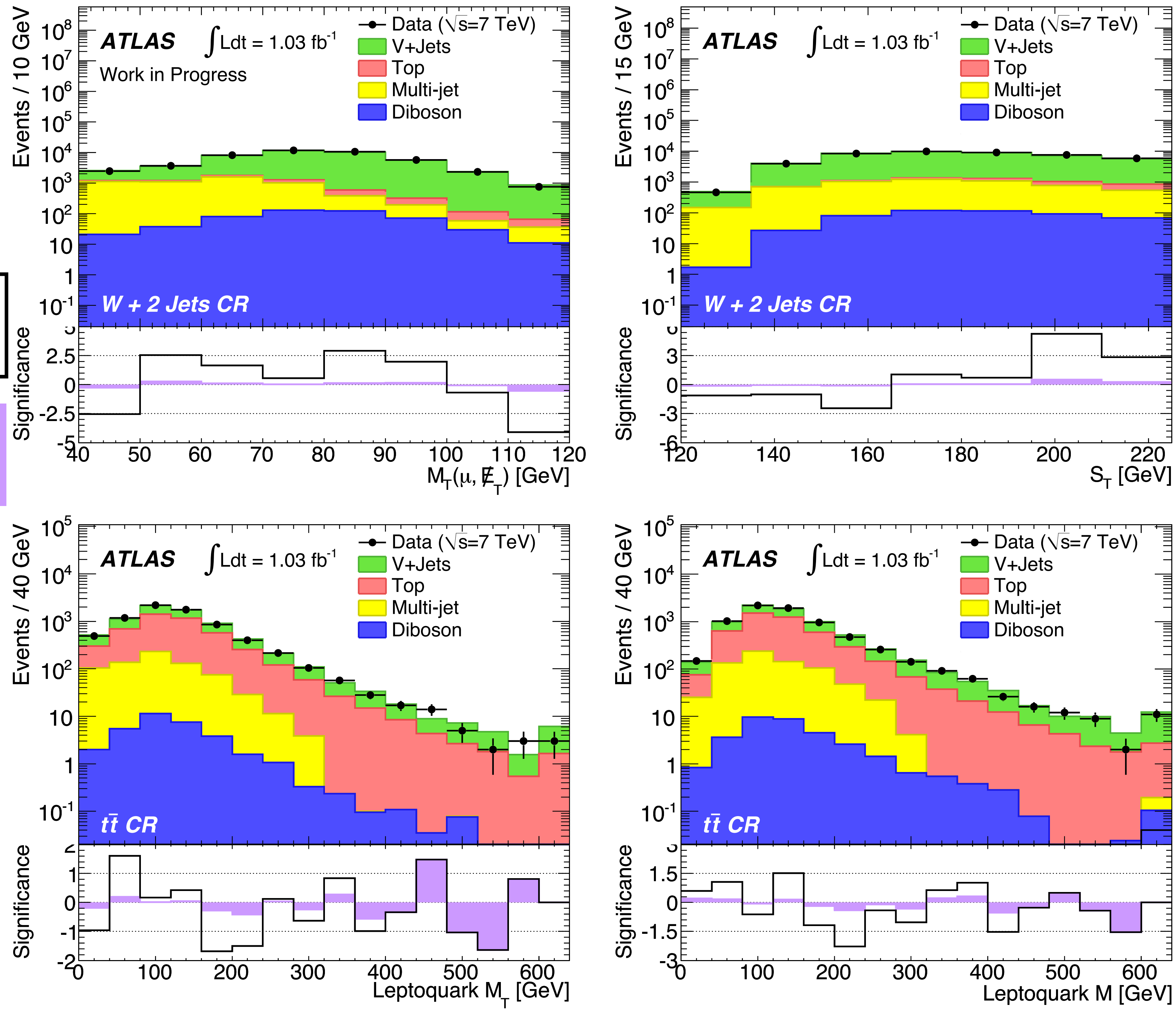
Backgrounds well modeled!

$$\text{Significance} = \frac{\text{(data - prediction)}}{\text{stat. uncert.}}$$

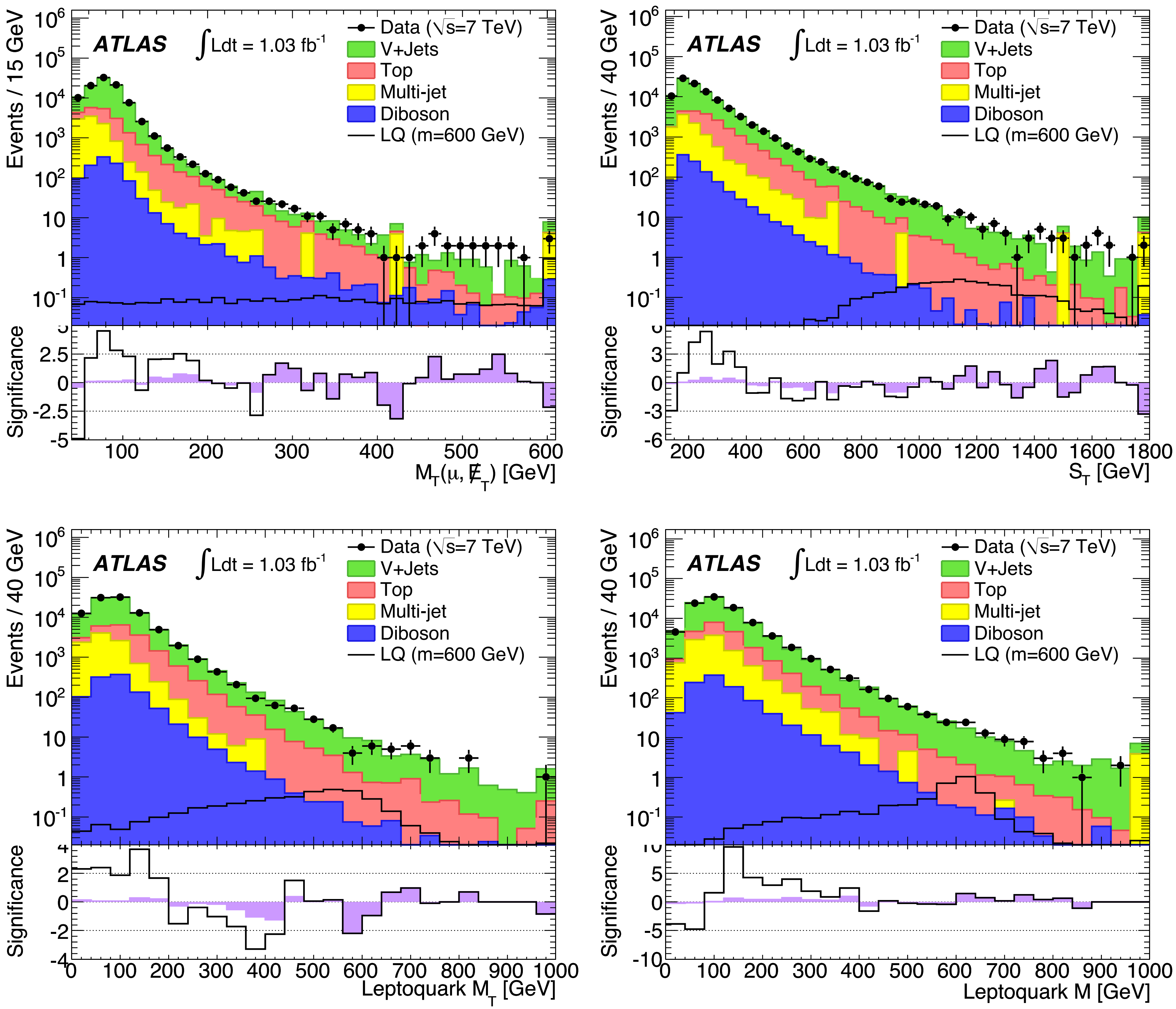
$$\text{Significance} = \frac{\text{(data - prediction)}}{\text{stat. + syst.}}$$

M_T^{LQ} and M^{LQ} from MET-jet and μ-jet such that ΔM is minimum

(negligible signal contribution)



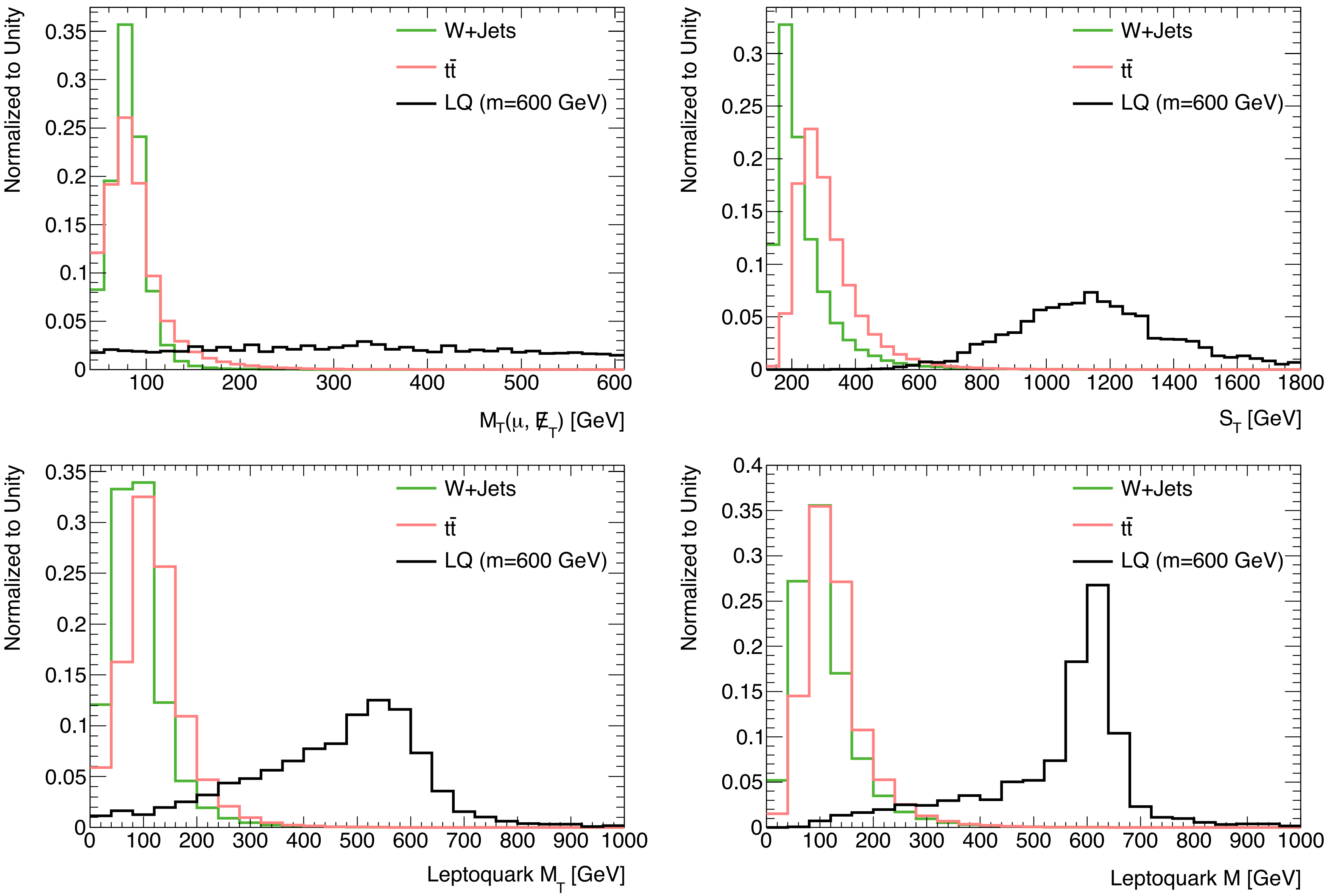
Selected Events



sample	yield
V+jets	74000 ± 17000
top	11600 ± 1900
multi-jet	9690 ± 230
diboson	1020 ± 180
Total Bkg	96000 ± 17000
Data	97113
LQ→μνjj (m=600 GeV)	3.9 ± 0.2

(statistical + systematic uncertainties)

Multivariate Discriminant?

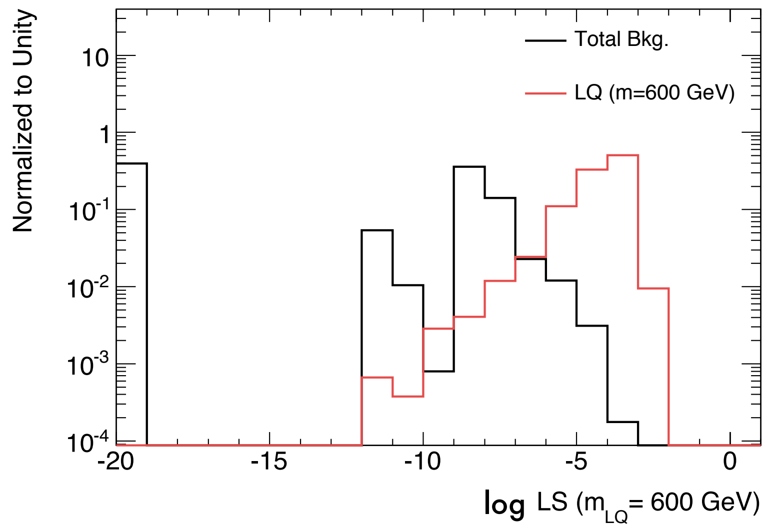


$M_T(\mu,MET)$	discriminate against $W \rightarrow \mu\nu$ decays
M_T^{LQ}	resonance in LQ events discriminates against all bkgs
M^{LQ}	
S_T	selects LQ events, large m_{LQ} => large S_T

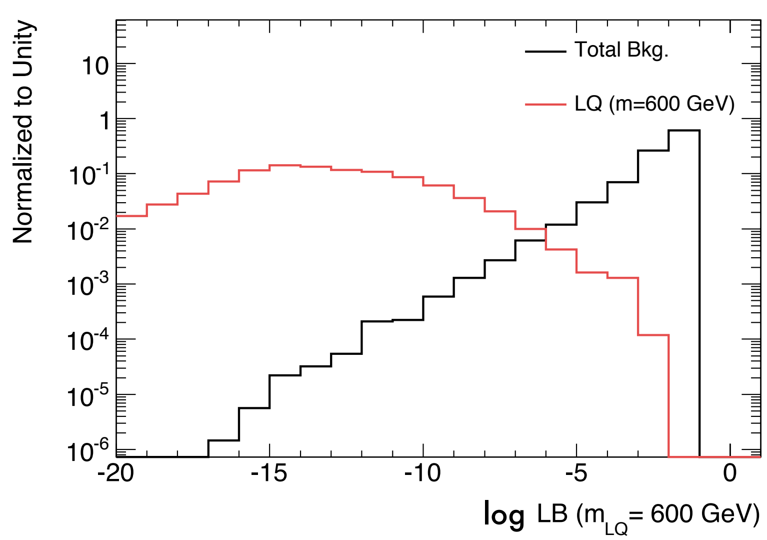
- Choose kinematic variables with strong signal-bkg discrimination
- Combine in a multivariate discriminant to test bkg-only, signal+bkg hypotheses and compute a final result

Log-likelihood Ratio (LLR)

- From PDFs for background (P^i_B) and signal (P^i_S), compute background and signal likelihoods (L_B and L_S) for each event

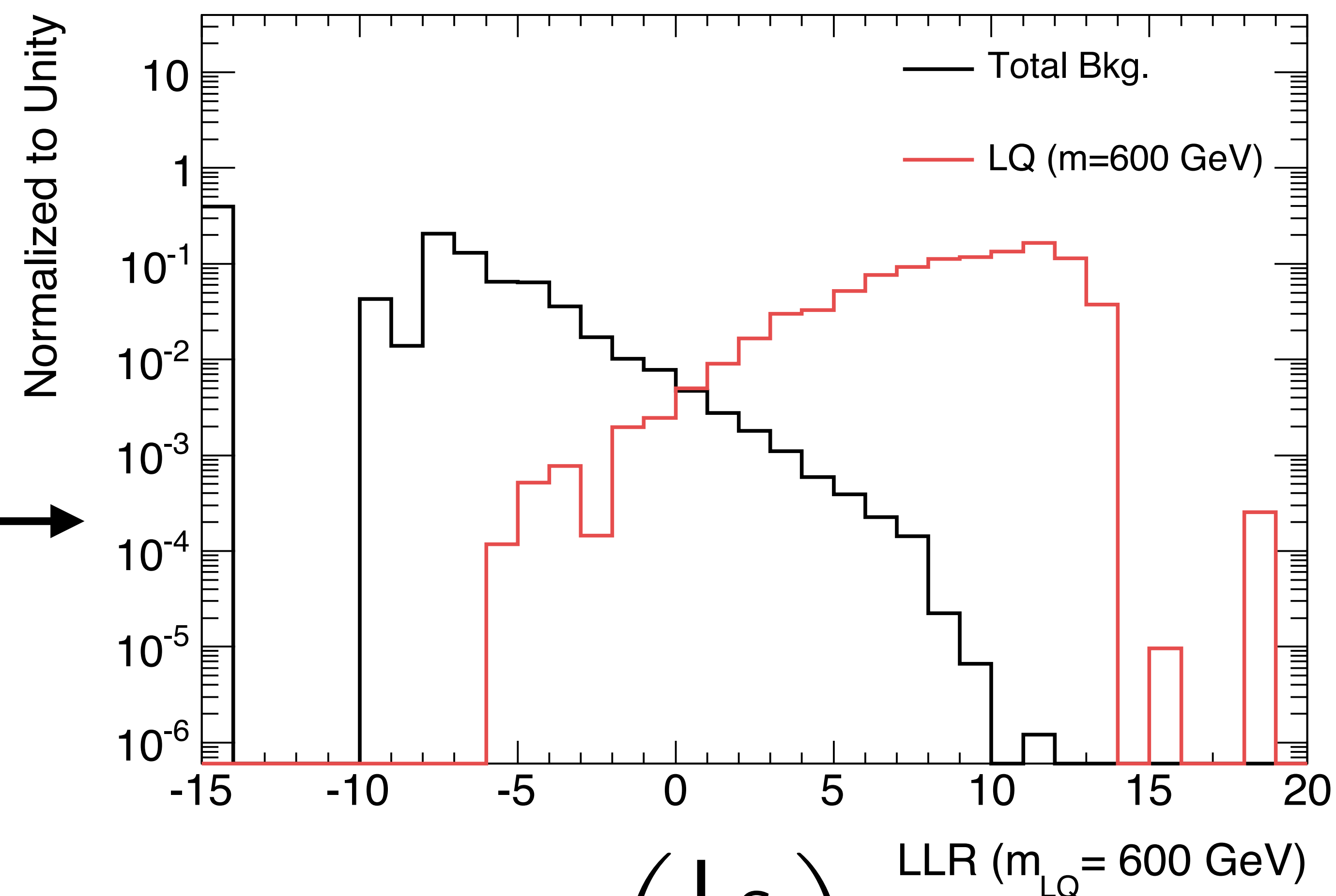


$$L_S = \prod_i P^i_S$$



$$L_B = \prod_i P^i_B$$

- Unique LLR distributions for each m_{LQ} point

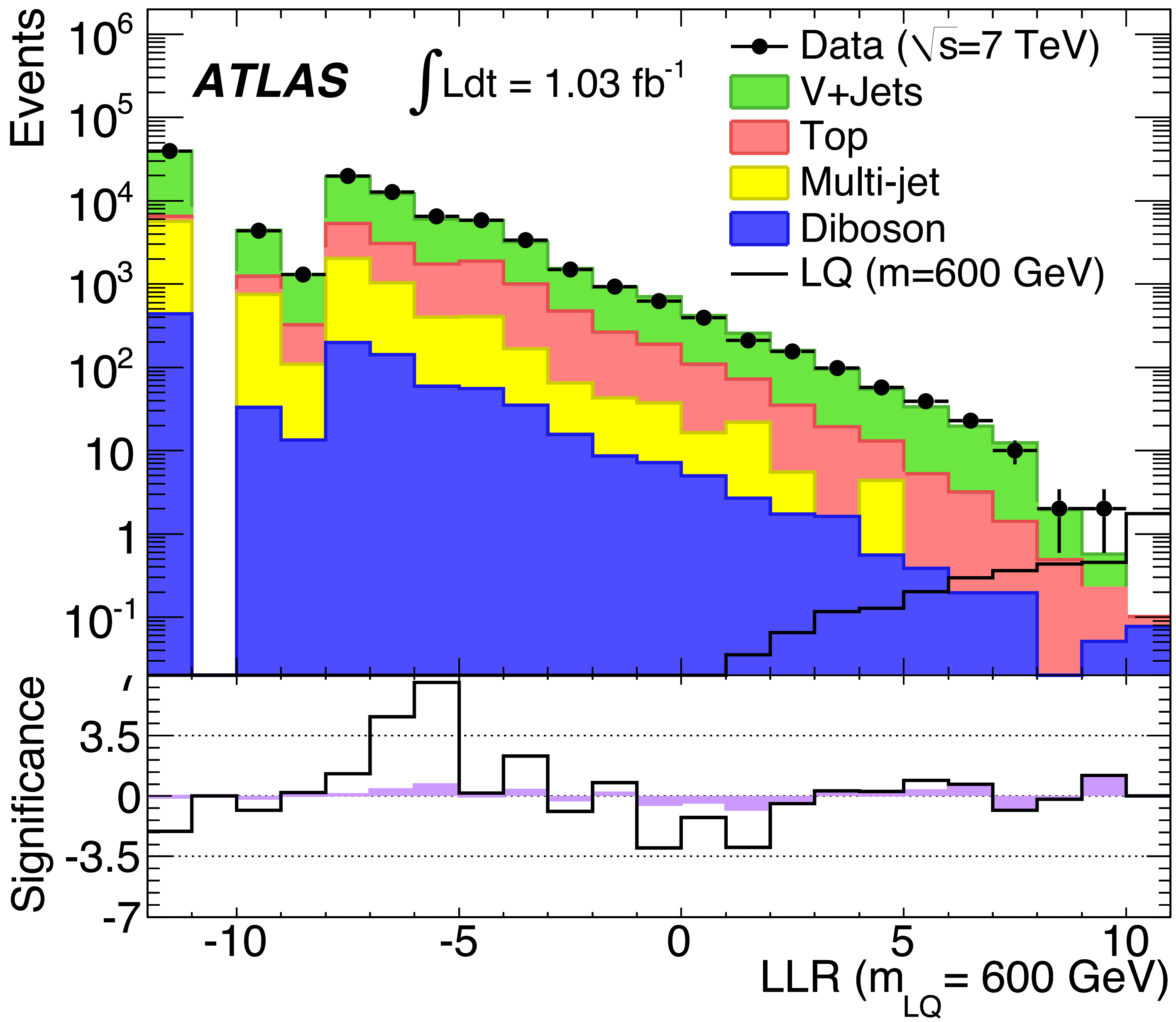


$$\mathrm{LLR}(m_{LQ}) = \log\left(\frac{L_S}{L_B}\right)$$

Systematic Uncertainties

	Source	Handling
!	V+jets and t-tbar modeling	use different generators, vary top mass (m = 170, 175 GeV), vary ISR/FSR up and down
	MC samples cross-section, normalization	use theoretical uncertainties on x-sections, account for SF variation at high/low p_T
	integrated luminosity	flat 3.7% applied to single top and diboson backgrounds, plus signal
!	jet energy scale, jet energy resolution	vary jet energy scale $\pm 1\sigma$, smear jet energy by 1σ Gaussian
	muon momentum resolution, muon reconstruction efficiency	vary muon p_T smearing $\pm 1\sigma$, vary ID efficiency event weights $\pm 1\sigma$
	Multi-jet	use $\pm 1\sigma$ normalization, alternate shape
	Signal PDFs	re-weight signal LLR by CTEQ errors
	LLR input PDFs	statistics in LLR input PDFs propagated onward

Results



sample	yield (LLR ≥ 7)
V+jets	12.9 ± 9.9
top	1.9 ± 1.2
multi-jet	< 0.1
diboson	0.3 ± 0.1
Total Bkg	15 ± 10
Data	14
LQ→μνjj (m=600 GeV)	3.2 ± 0.2

(statistical + systematic uncertainties)

Data in good agreement with SM background expectation!
No evidence for LQ production...

Limit-Setting

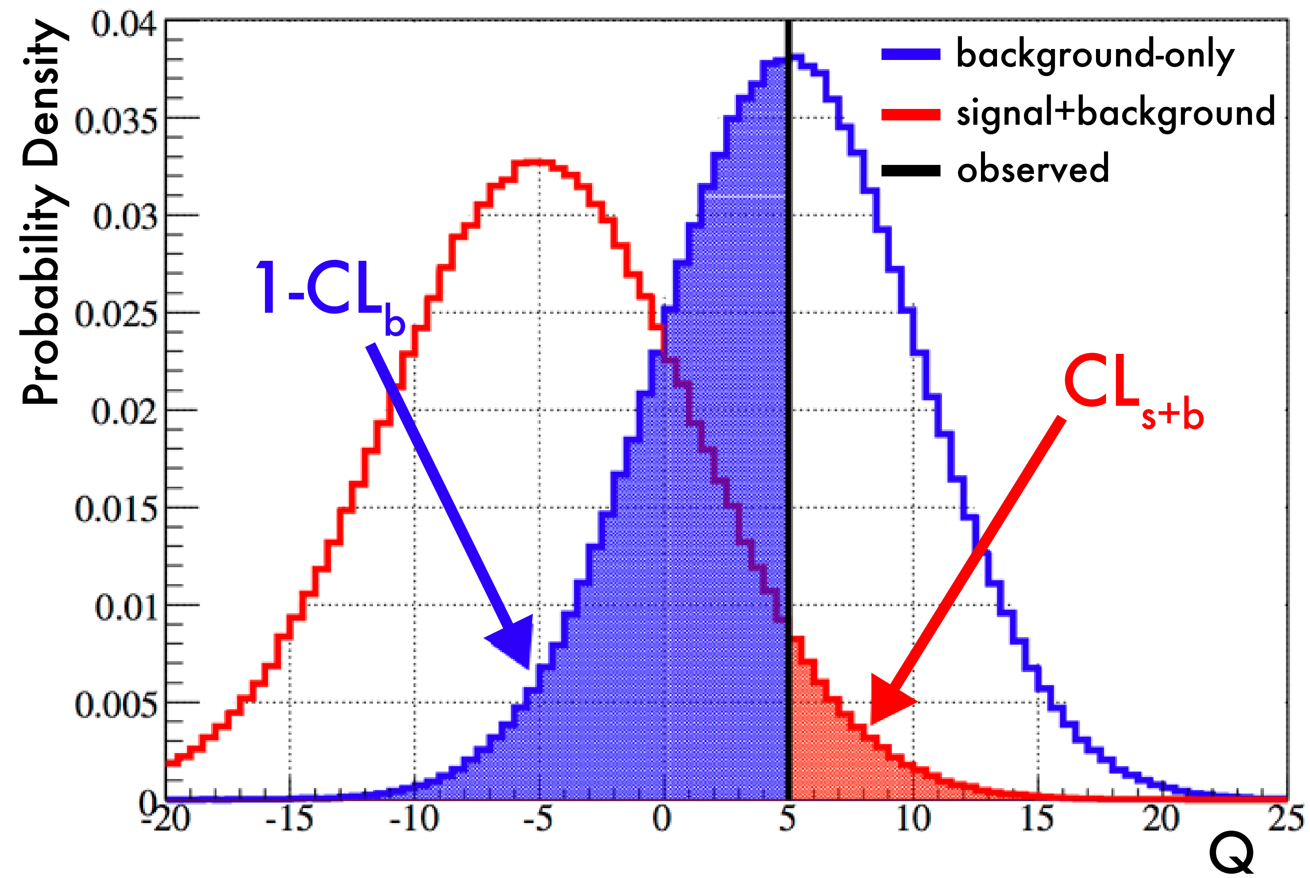
- Want to quantify agreement between experimental outcome and two hypotheses: background-only (H_0) and signal+background (H_1)
- Counting experiment test statistic: $Q(x) = \frac{\mathcal{L}(x|H_1)}{\mathcal{L}(x|H_0)} = \frac{(s+b)^x e^{-(s+b)}/x!}{(b)^x e^{-(b)}/x!} \rightarrow -2\ln(Q)$
  - perform many pseudo-experiments

    x = data, *b* = background, *s* = signal yields
  - systematic uncertainties as "nuisance parameters"
  - generalizes to multiple channels, discriminant bins:

$$Q(\vec{x}) = \prod_i^{\text{chans}} \prod_j^{\text{bins}} Q_{ij}(x_{ij})$$

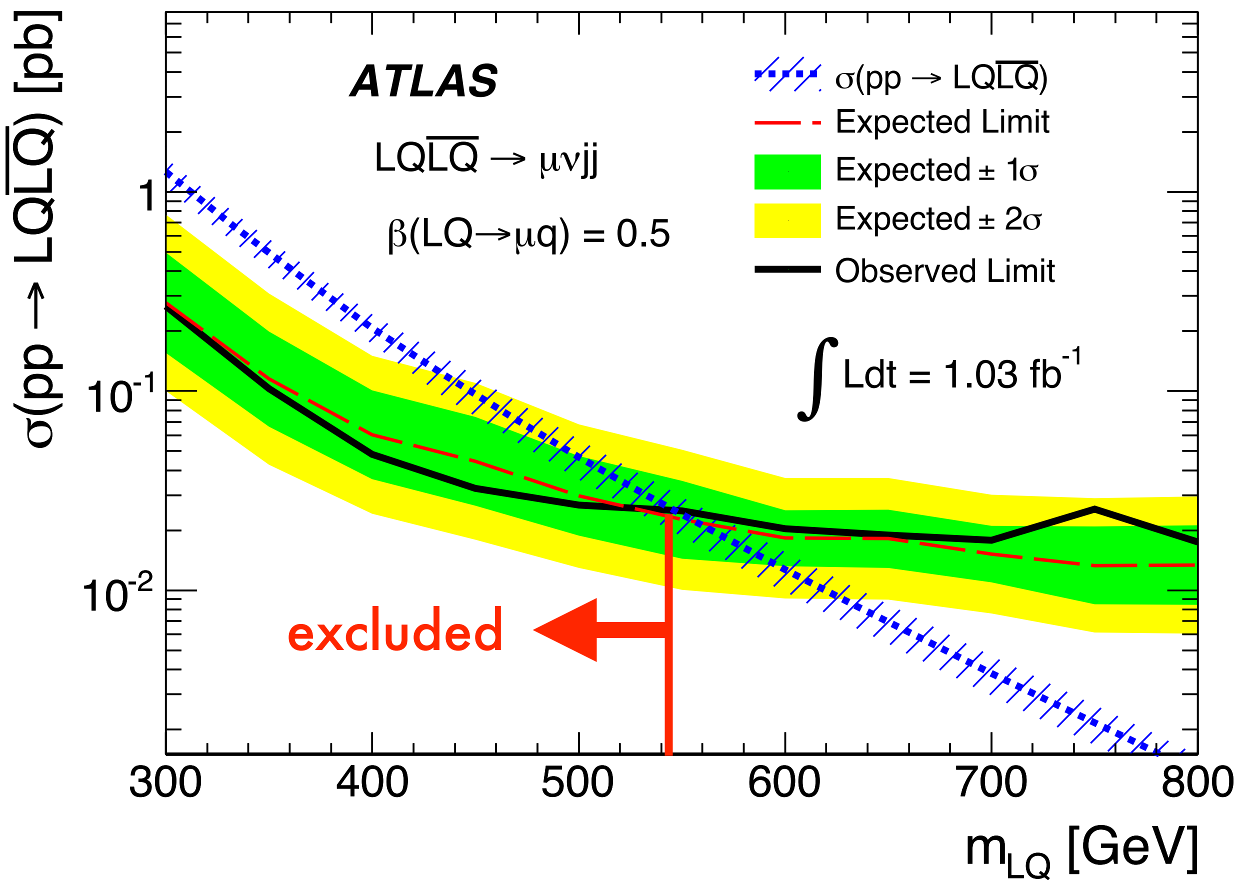
- Compute confidence levels CL_{s+b} (CL_b): probability for H_1 (H_0) to produce an outcome more *background-like* than observation in data
- Modified Frequentist: $CL_s \equiv \frac{CL_{s+b}}{CL_b}$

exclude H_1 at 95% CL
if $1-CL_s \geq 0.95$

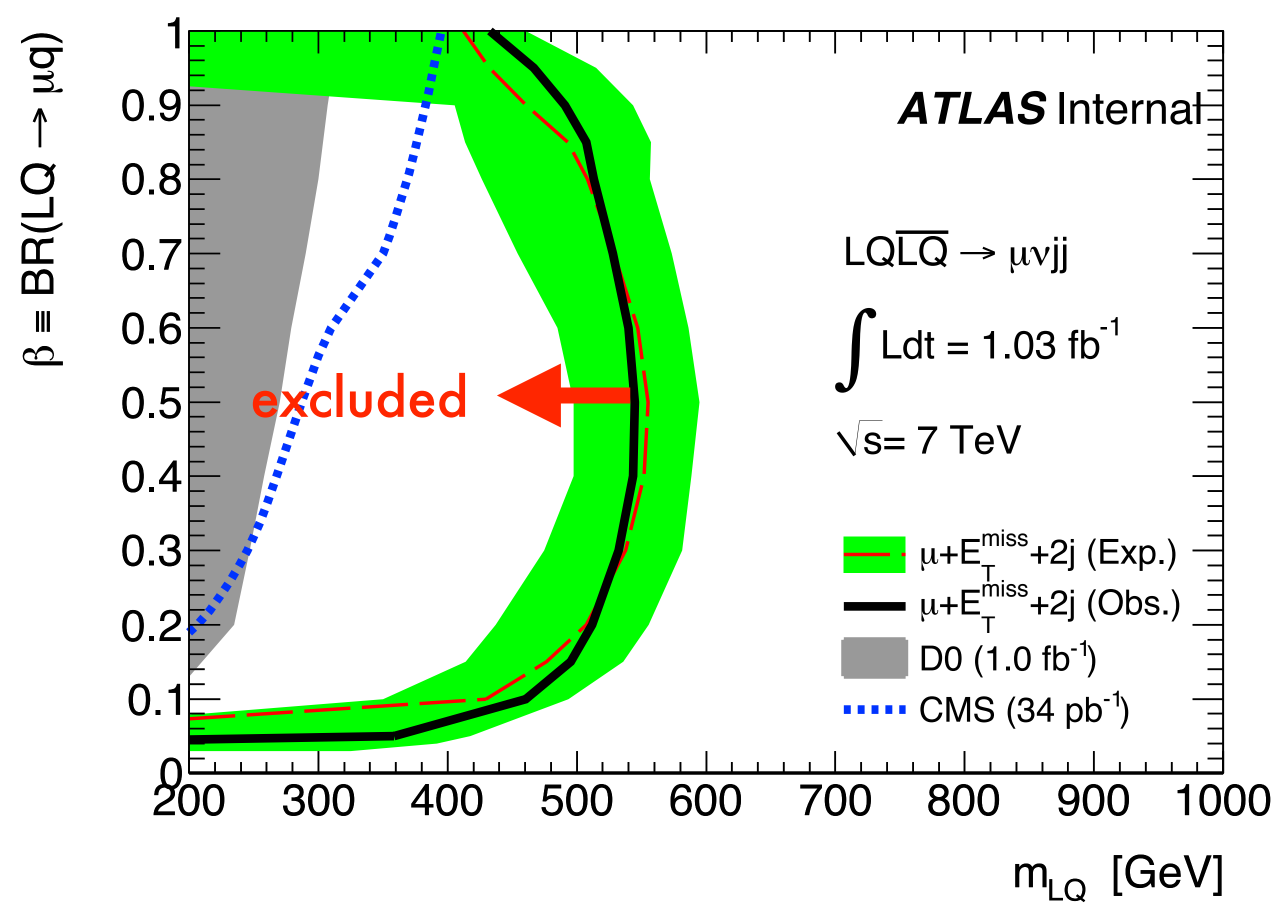


Final Limits

cross section upper bounds

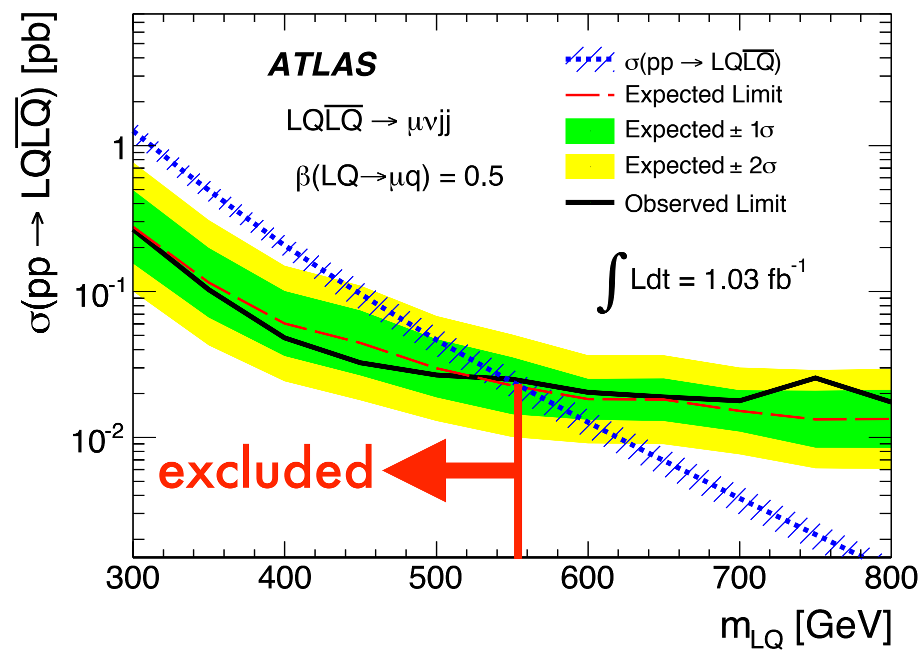


reinterpret in m_{LQ}–β plane

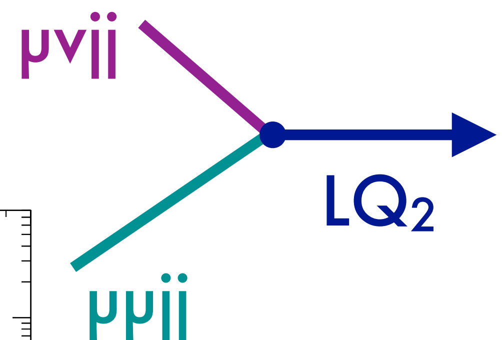


m_{LQ} Limits	μνjj (β=0.5)
Expected [GeV]	555
Observed [GeV]	545

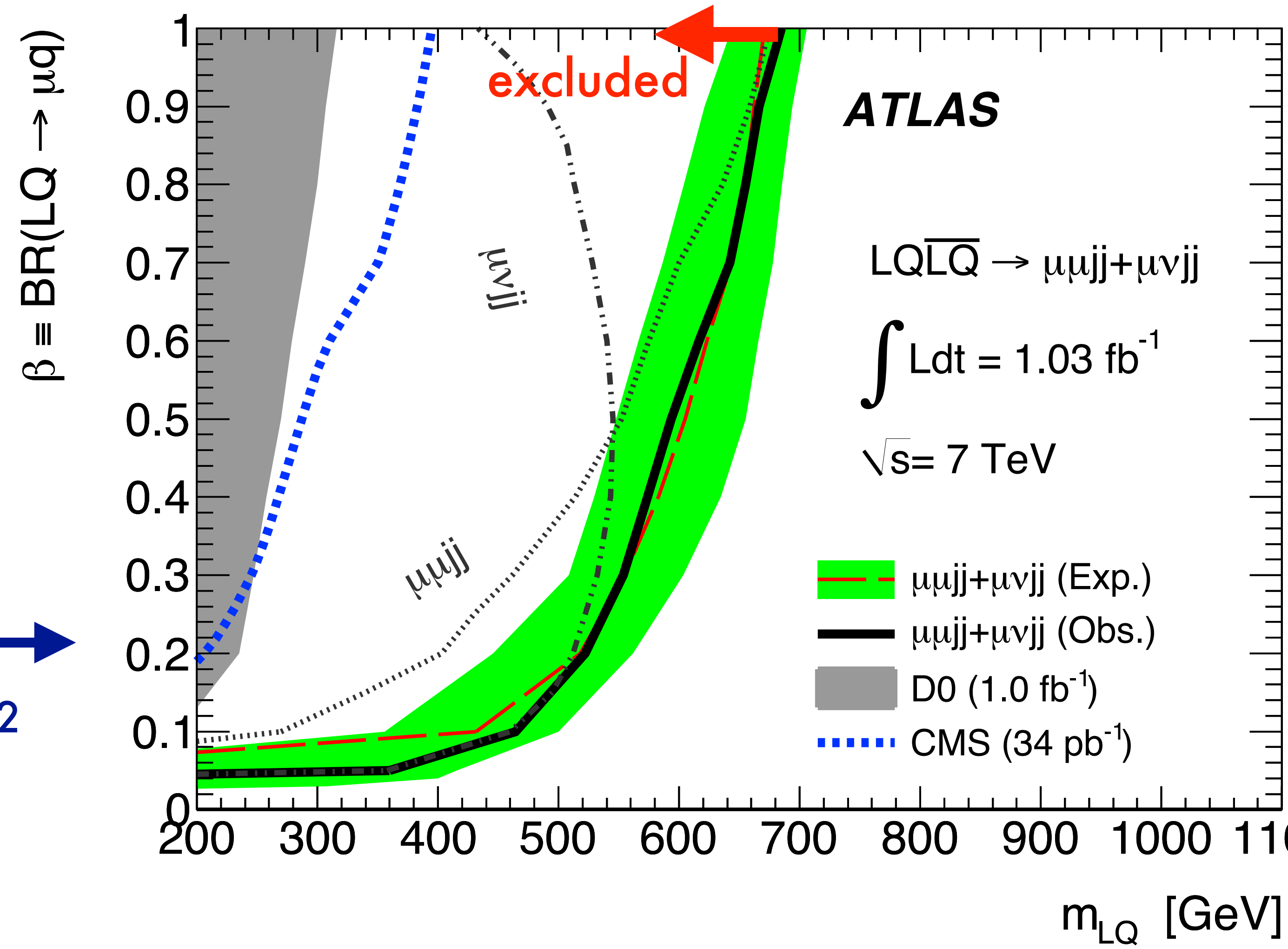
Final Limits

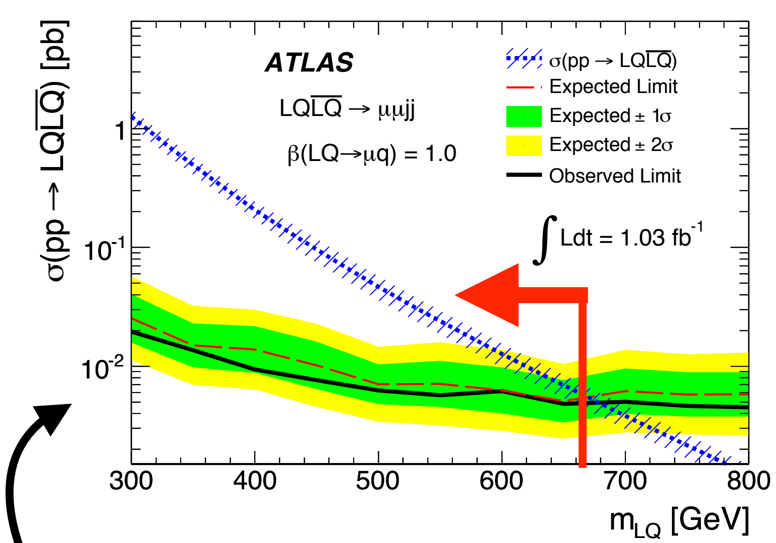


cross section upper bounds



combine, reinterpret limits in m_{LQ}–β plane



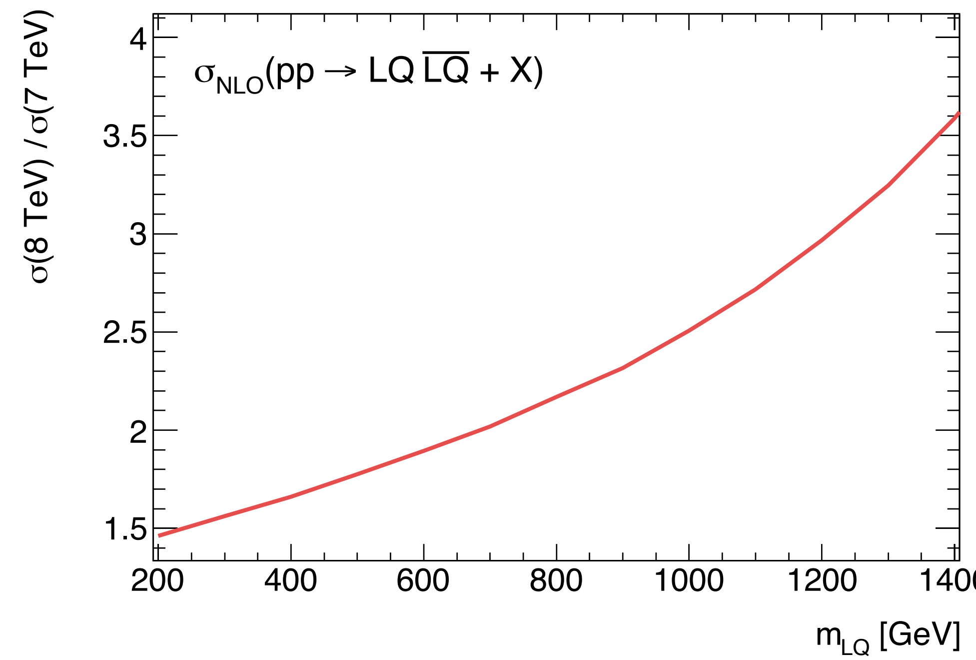


complementary search in μμjj final state

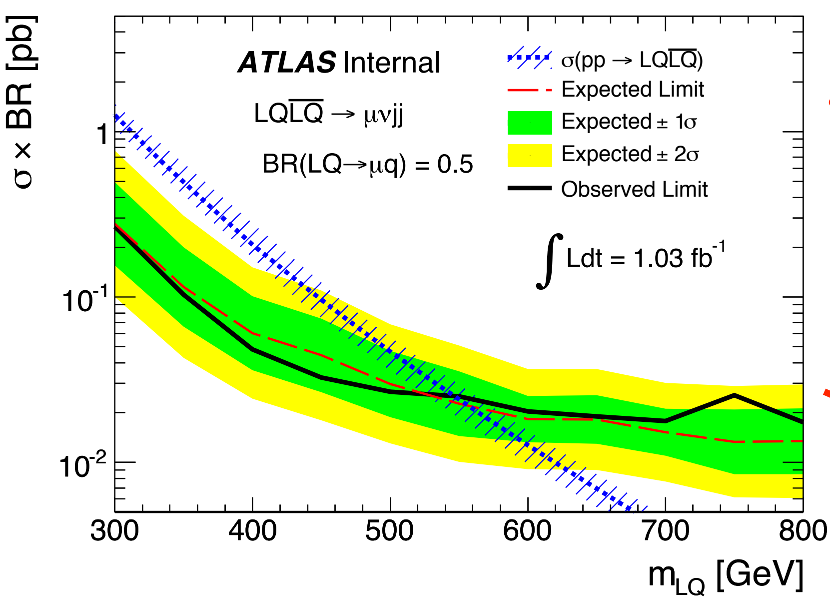
m_{LQ} Limits	μνjj (β=0.5)	μμjj (β=1.0)	LQ_2 (β=0.5)	LQ_2 (β=1.0)
Expected [GeV]	555	665	605	671
Observed [GeV]	545	675	594	685

Future Outlook

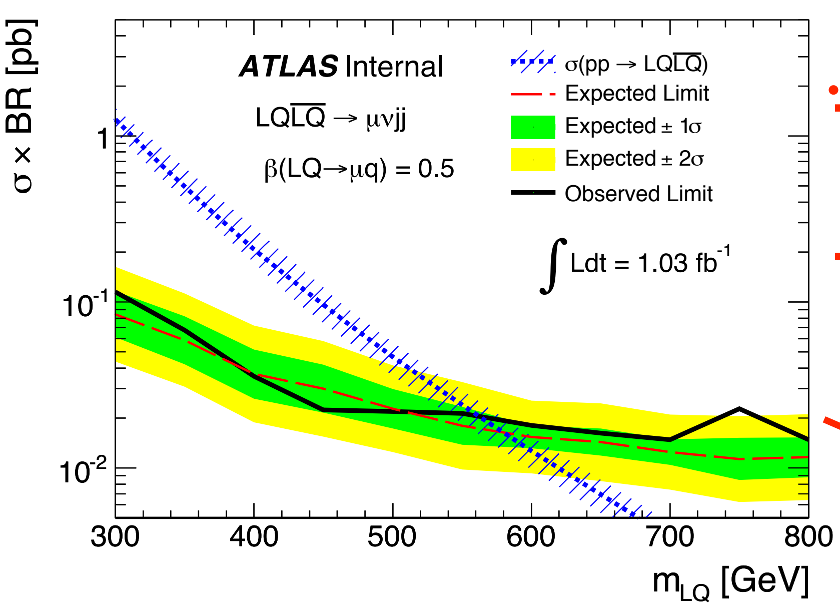
- 2012 LHC run: $L \approx 15\ \mathrm{fb}^{-1}$, $\sqrt{s} = 8$ TeV
  - more events, larger σ_{LQ} => extend sensitivity!



- Better control of systematic uncertainties



w/ systematics



w/o systematics

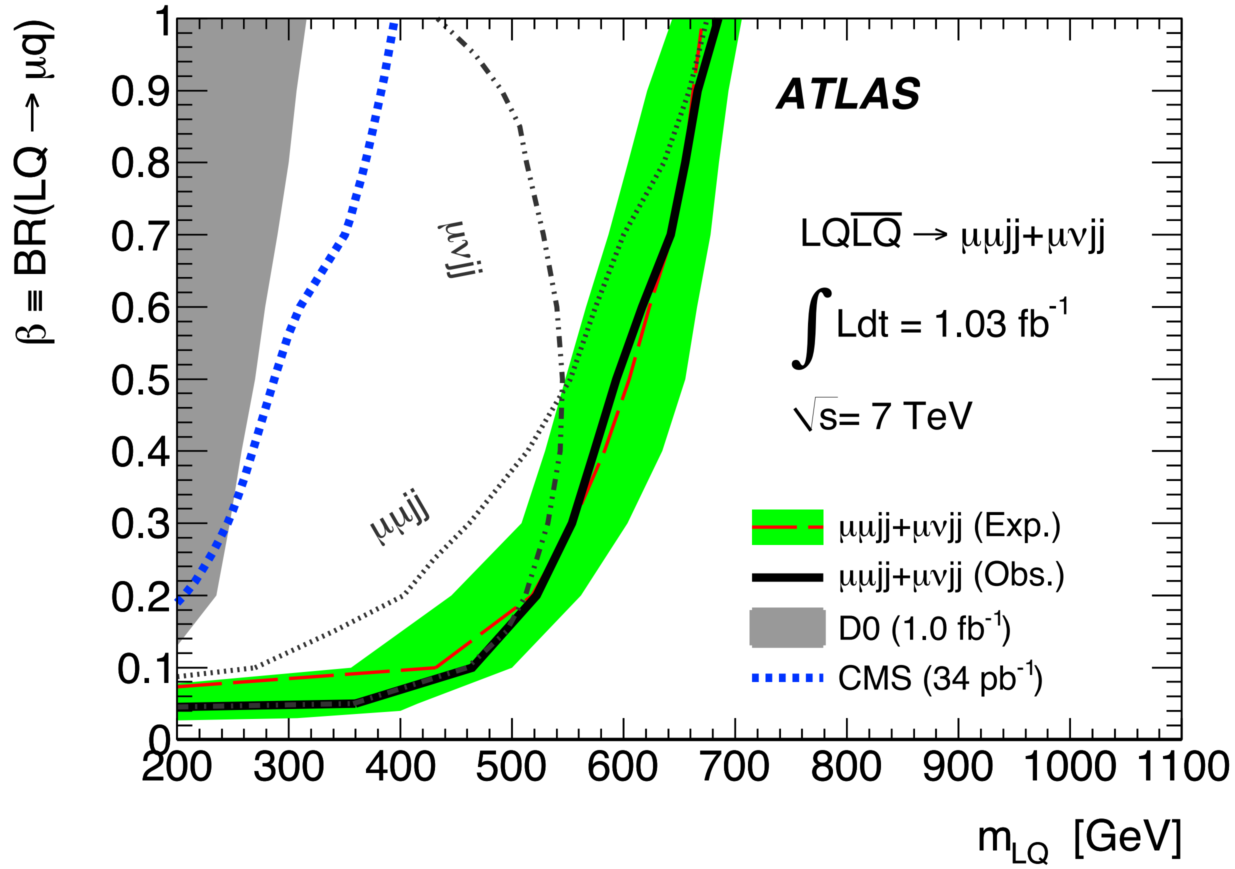
- Stronger signal-background discriminant
  - additional/other LLR variables?
  - fancier MVA technique, e.g. neural networks
- Add complementary νvjj final state for sensitivity at low-β

Outline

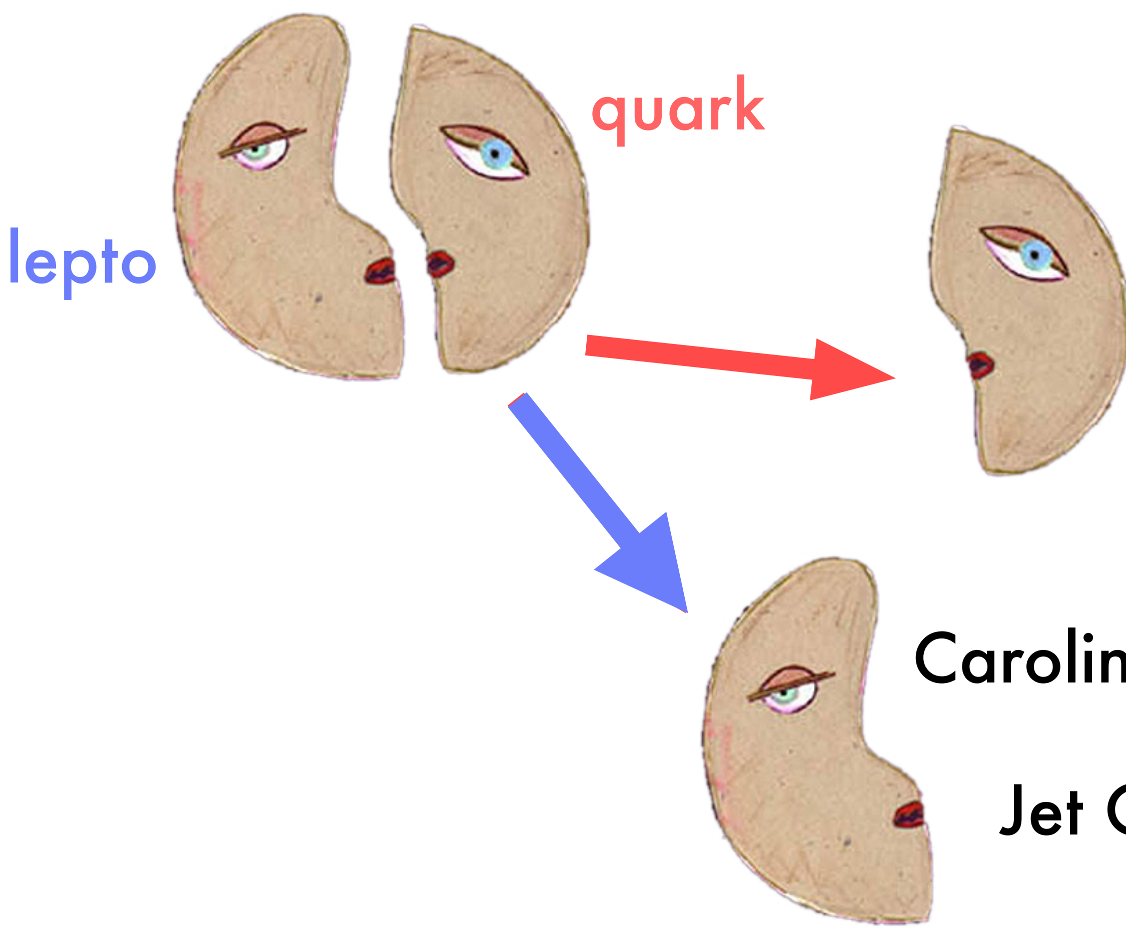
- Introduction
  - Standard Model
  - Leptoquarks
- Experiment
  - Large Hadron Collider
  - ATLAS detector
- Event Simulation and Reconstruction
- A Leptoquark Search
  - physics object and event selection
  - backgrounds and control regions
  - multivariate discriminant
  - limit-setting and results
  - future outlook
- Conclusion

Conclusion

- Searched for 2nd-generation scalar LQs in the μνjj channel
- Agreement within uncertainties between data and SM predictions in selected event samples... no evidence of LQs
- 2nd-generation scalar LQ pair-production excluded at 95% CL for m_{LQ} < 594 (685) GeV at β = 0.5 (1.0)
  - most stringent limits to date!
- Publication submitted to European Physical Journal C, currently online: hep-ex > arXiv:1203.3172



Thank you!



Dissertation Committee

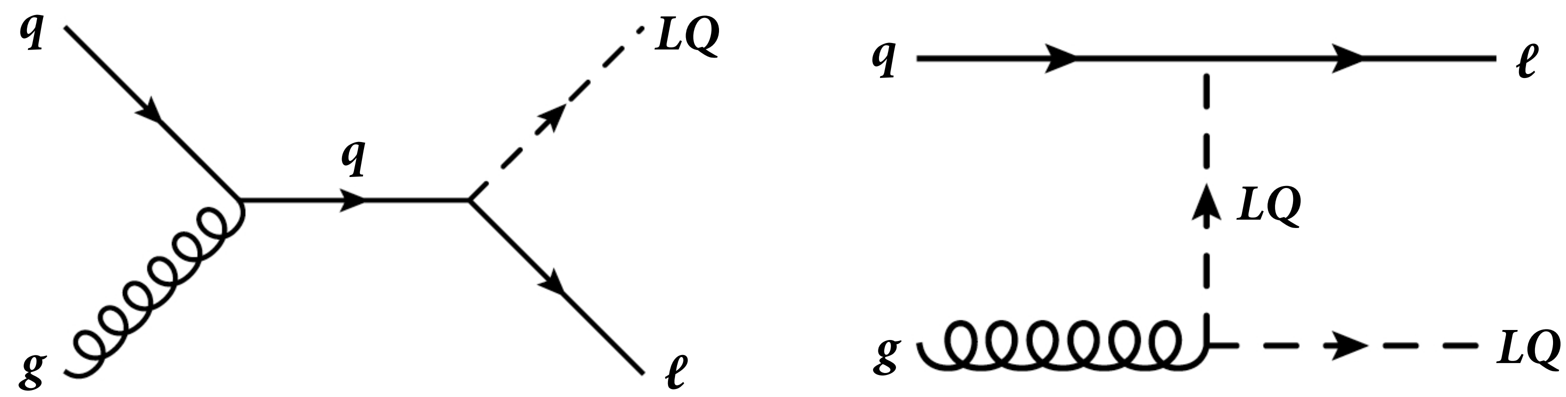
Dmitri Tsybychev & John Hobbs

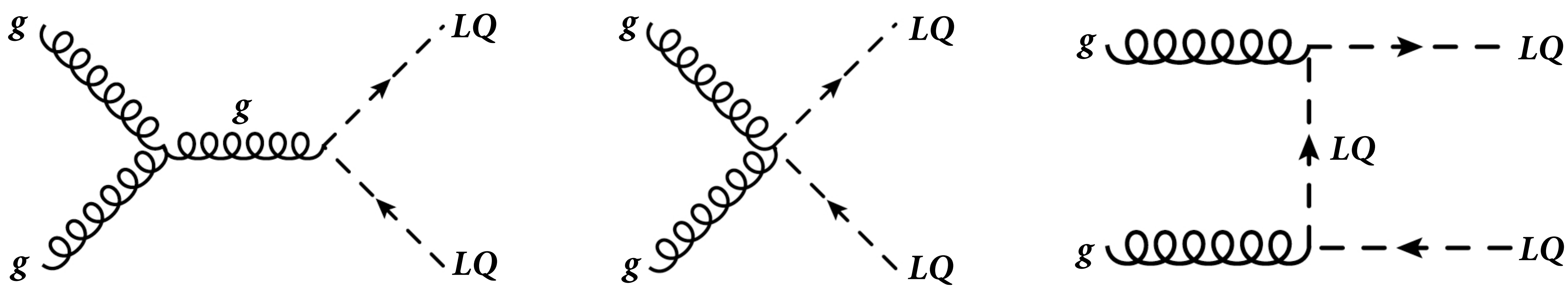
Carolina Deluca & Regina Caputo

Jet Goodson & John Stupak 3

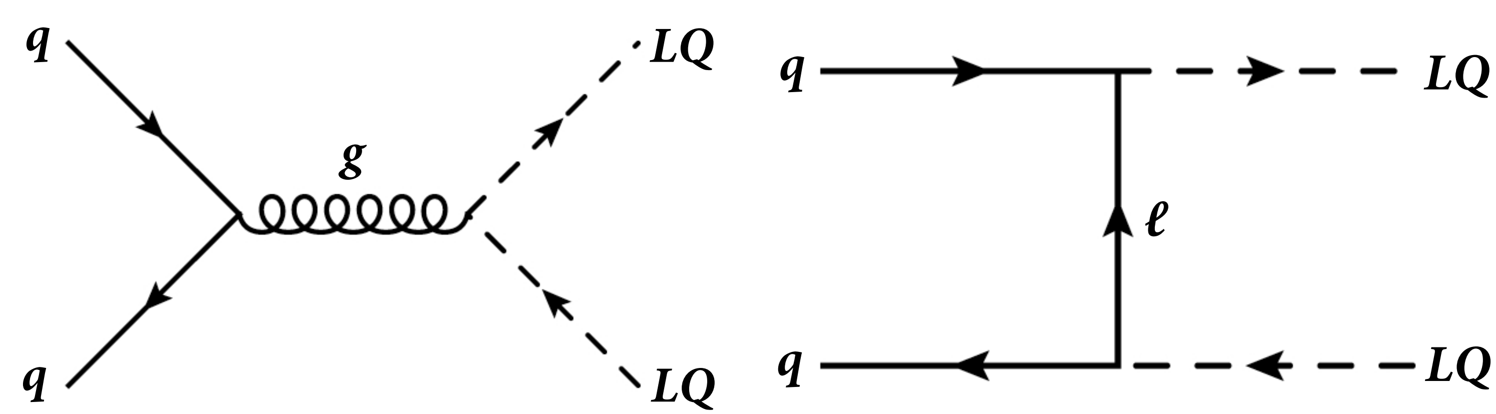
LQ Production in *pp* Collisions

single →





pair

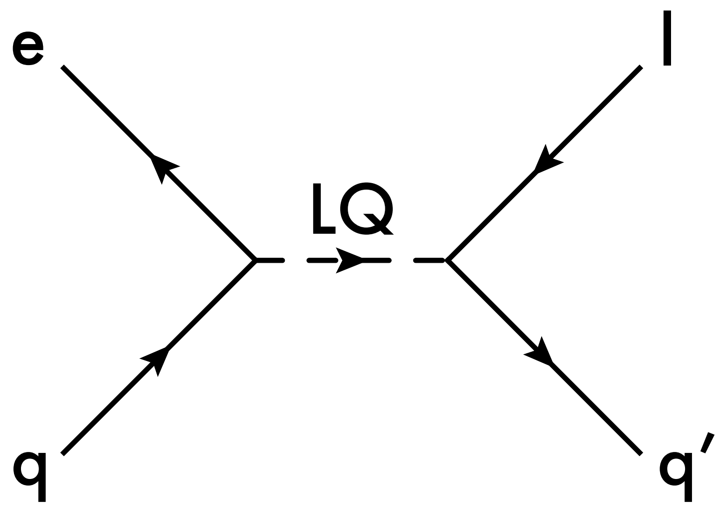


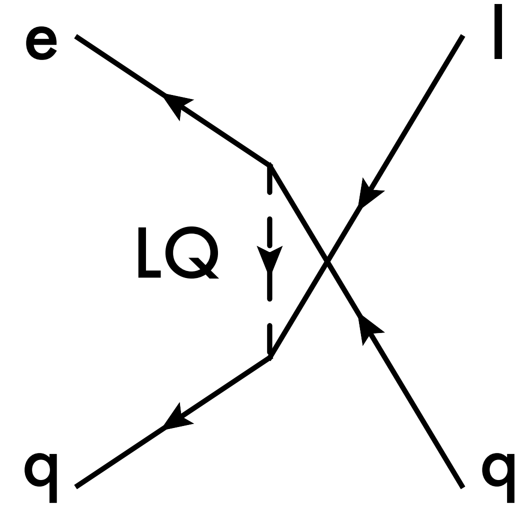
$$\hat{\sigma}_{\mathrm{LO}}\left[q\bar{q} \to LQ\overline{LQ}\right] = \frac{2\alpha_s^2\pi}{27\hat{s}}v^3, \quad v \equiv \left(1 - 4m_{\mathrm{LQ}}^2/\hat{s}\right)^{1/2}$$

$$\hat{\sigma}_{\mathrm{LO}}\left[gg \to LQ\overline{LQ}\right] = \frac{\alpha_s^2\pi}{96\hat{s}}\left[v\left(41 - 31v^2\right) + \left(18v^2 - v^4 - 17\right)\log\frac{1+v}{1-v}\right]$$

Other LQ Processes

HERA (ep) →

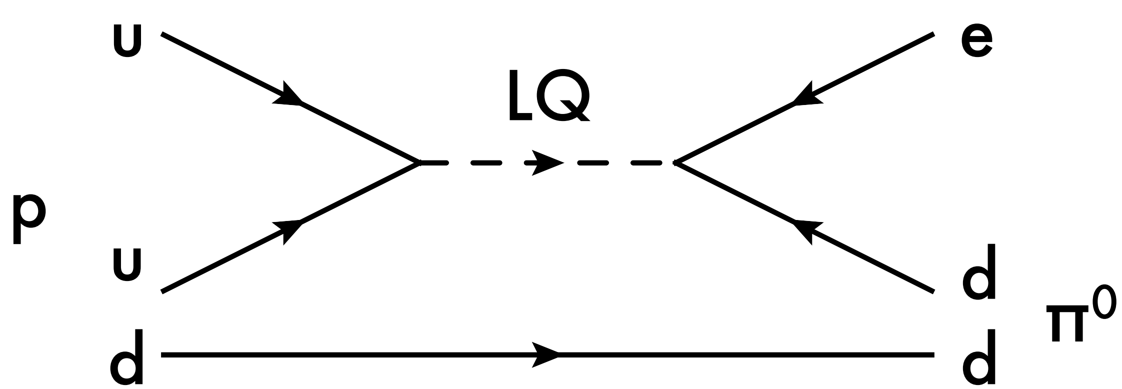




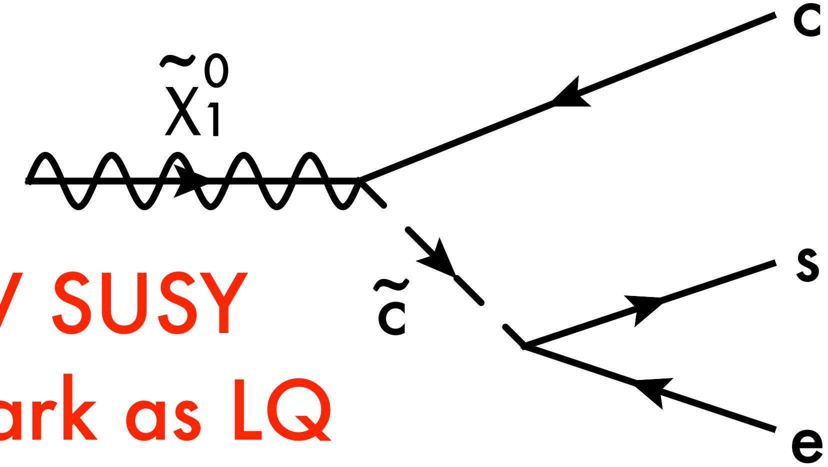
LFV?

$ep \to \mu$+jet

$ep \to \tau$+jet



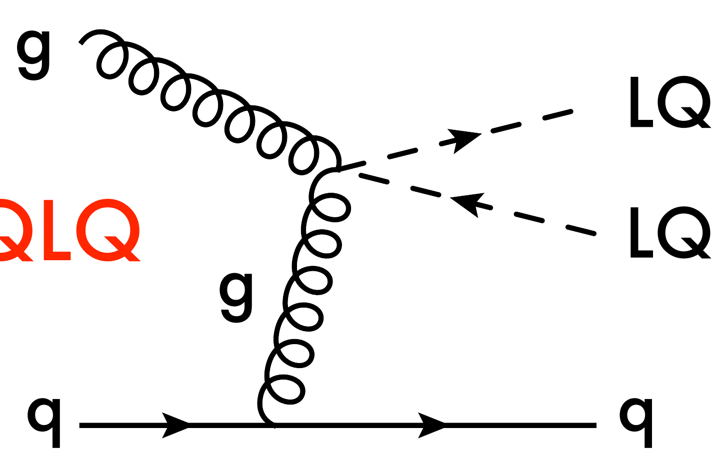
proton decay via LQ

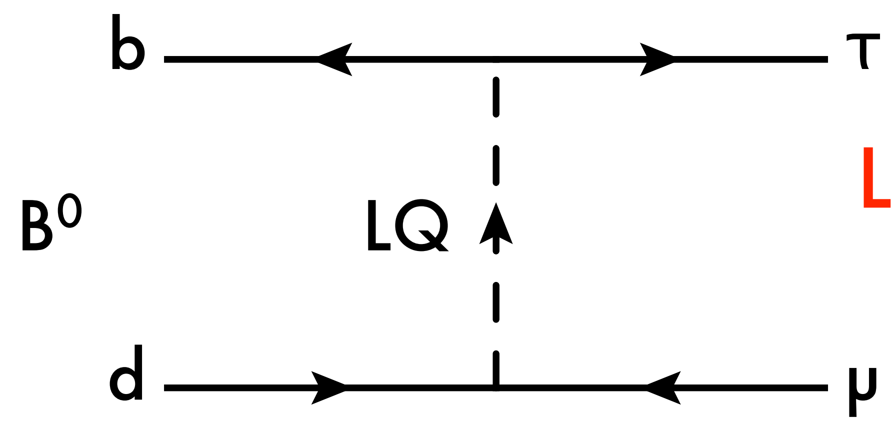


RPV SUSY

c squark as LQ

$qg \to$ LQLQ





LQ-mediated FCNC

LQ States in BRW Model

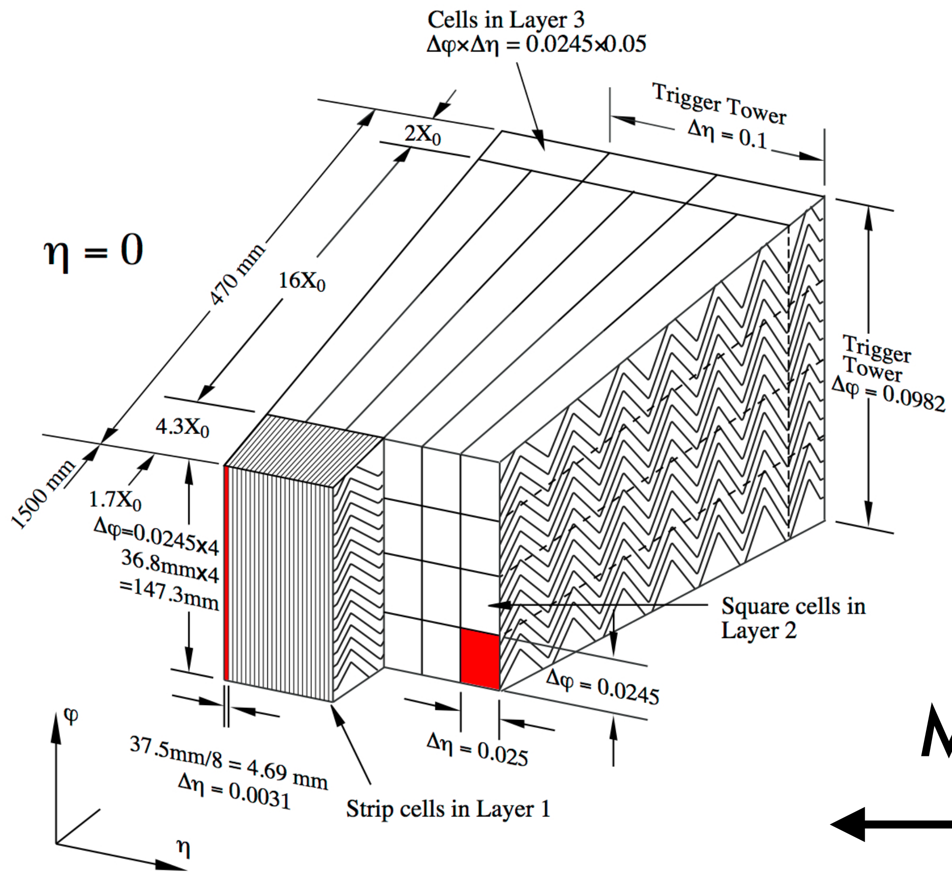
LQ Type	Q [e]	T^3	$\lvert F \rvert$	LQ Decay	BR(LQ$\rightarrow eq$)
S_0^L	$-1/3$	0	2	$e_L u_L$	0.5
				$\nu_e d_L$	0.5
S_0^R	$-1/3$	0	2	$e_R u_R$	1
$\tilde{S}_0^R$	$-4/3$	0	2	$e_R d_R$	1
S_1^L	$-4/3$	-1	2	$e_L d_L$	1
	$-1/3$	0	2	$e_L u_L$	0.5
				$\nu_e d_L$	0.5
	$+2/3$	$+1$	2	$\nu_e u_L$	0
$V_{1/2}^L$	$-4/3$	$-1/2$	2	$e_L d_R$	1
	$-1/3$	$+1/2$	2	$\nu_e d_R$	0
$V_{1/2}^R$	$-4/3$	$-1/2$	2	$e_R d_L$	1
	$-1/3$	$+1/2$	2	$e_L u_L$	1
$\tilde{V}_{1/2}^L$	$-1/3$	$-1/2$	2	$e_L u_R$	1
	$+2/3$	$+1/2$	2	$\nu_e u_R$	0

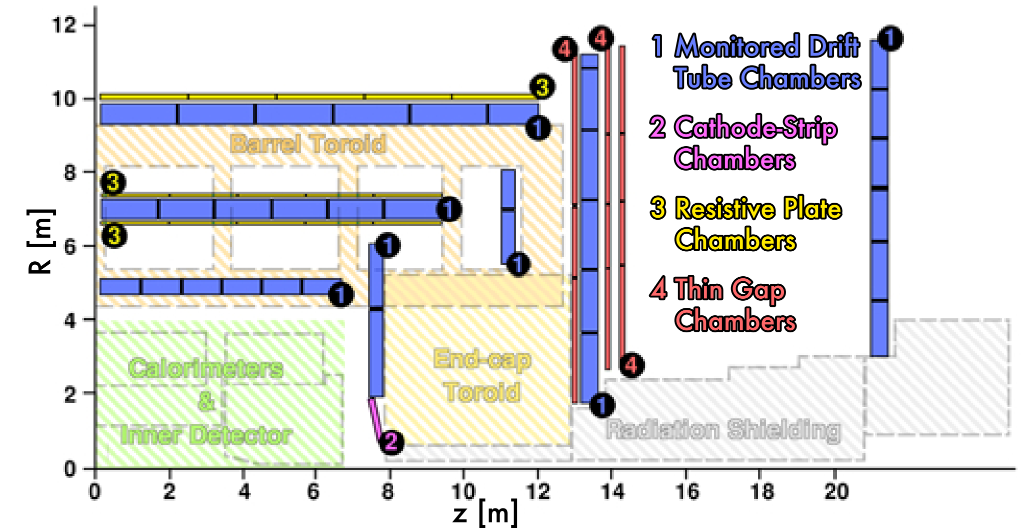
V_0^L	$-2/3$	0	0	$e_L \bar{d}_R$	0.5
				$\nu_e \bar{u}_R$	0.5
V_0^R	$-2/3$	0	0	$e_R \bar{u}_L$	1
$\tilde{V}_0^R$	$-5/3$	0	0	$e_R \bar{u}_L$	1
V_1^L	$-5/3$	-1	0	$e_L \bar{u}_R$	1
	$-2/3$	0	0	$e_L \bar{d}_R$	0.5
				$\nu_e \bar{u}_R$	0.5
	$+1/3$	$+1$	0	$\nu_e \bar{d}_R$	0
$S_{1/2}^L$	$-5/3$	$-1/2$	0	$e_L \bar{u}_L$	1
	$-2/3$	$+1/2$	0	$\nu_e \bar{u}_L$	0
$S_{1/2}^R$	$-5/3$	$-1/2$	0	$e_R \bar{u}_R$	1
	$-2/3$	$+1/2$	0	$e_R \bar{d}_R$	1
$\tilde{S}_{1/2}^L$	$-2/3$	$-1/2$	0	$e_L \bar{d}_L$	1
	$+1/3$	$+1/2$	0	$\nu_e \bar{d}_L$	0

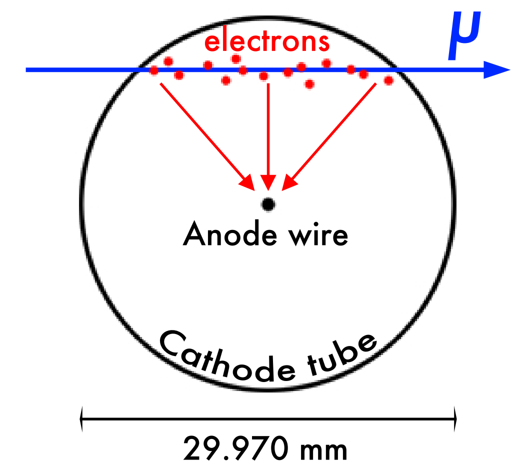
scalar particle S_1^L couples to L-handed leptons

weak isospin

ATLAS Sub-detectors



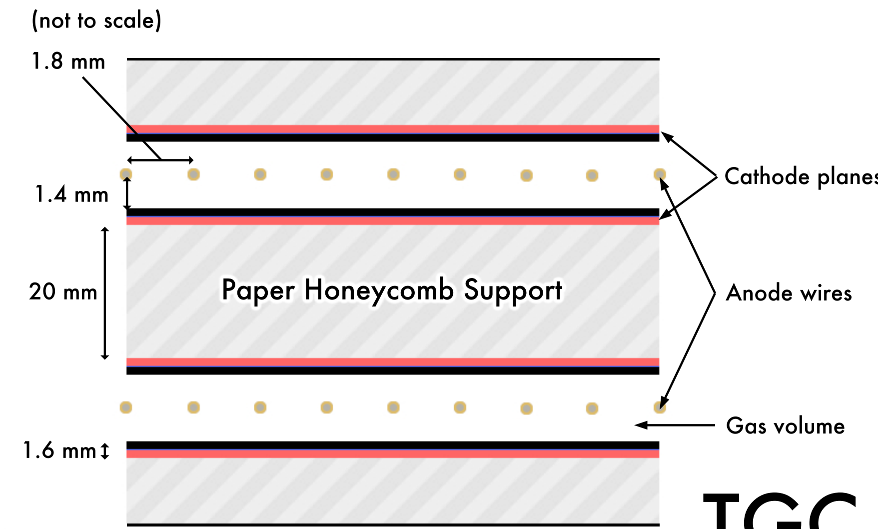




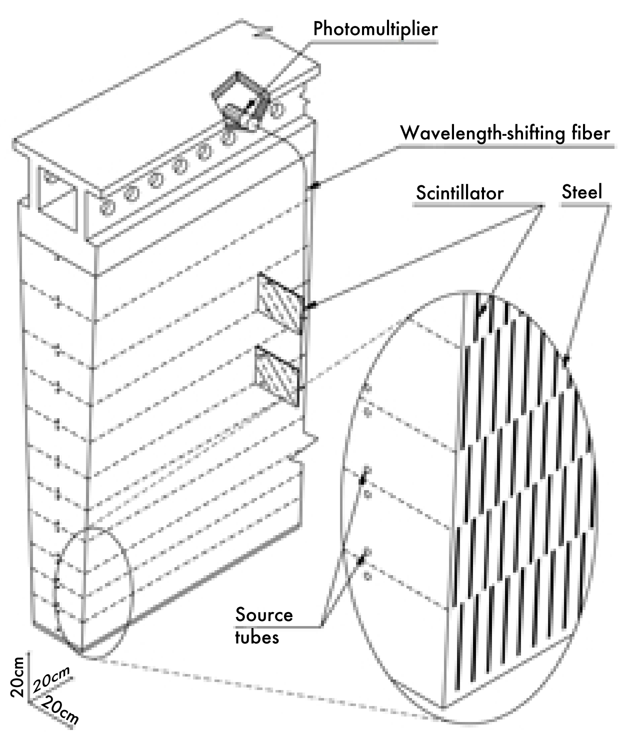
Muon Spectrometer

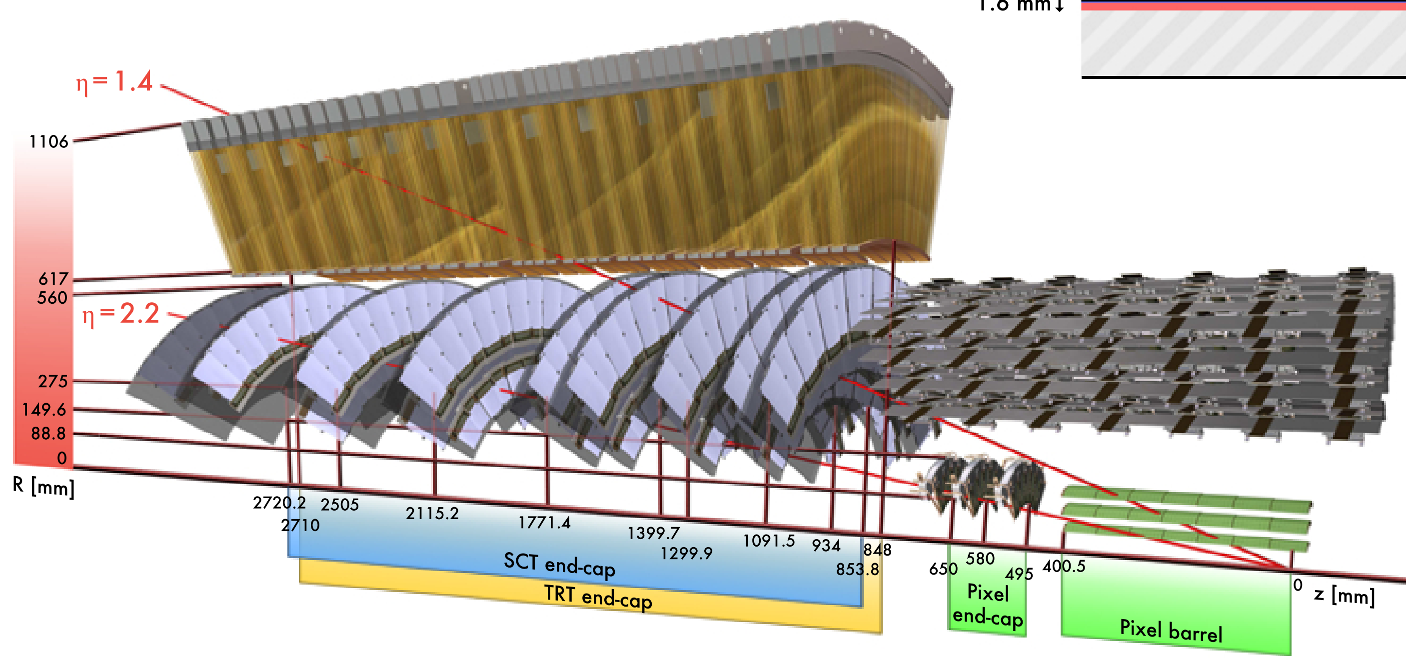
Calorimeter

Inner Detector



TGC Doublet

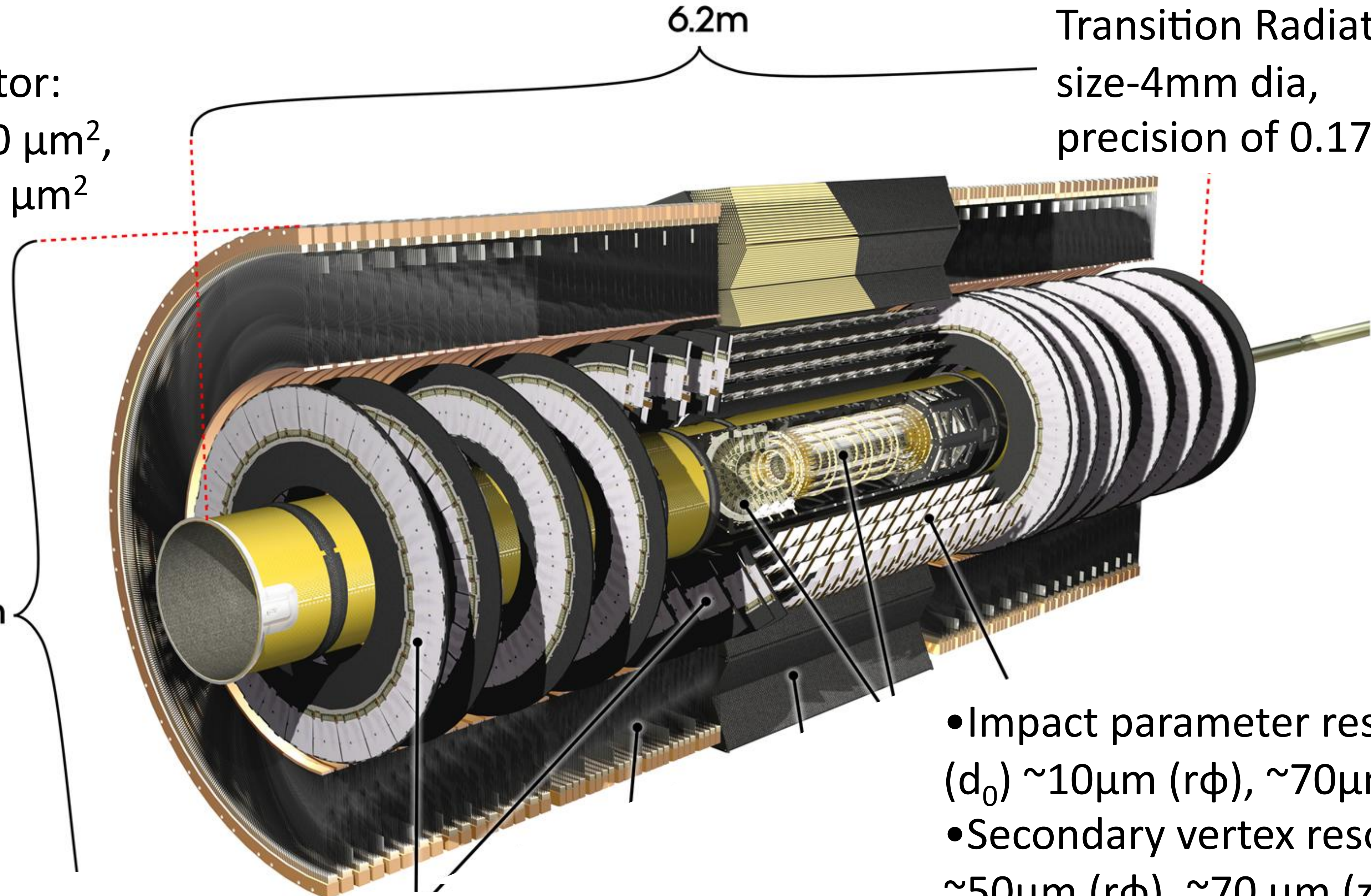




ATLAS Inner Detector

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

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



•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)

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

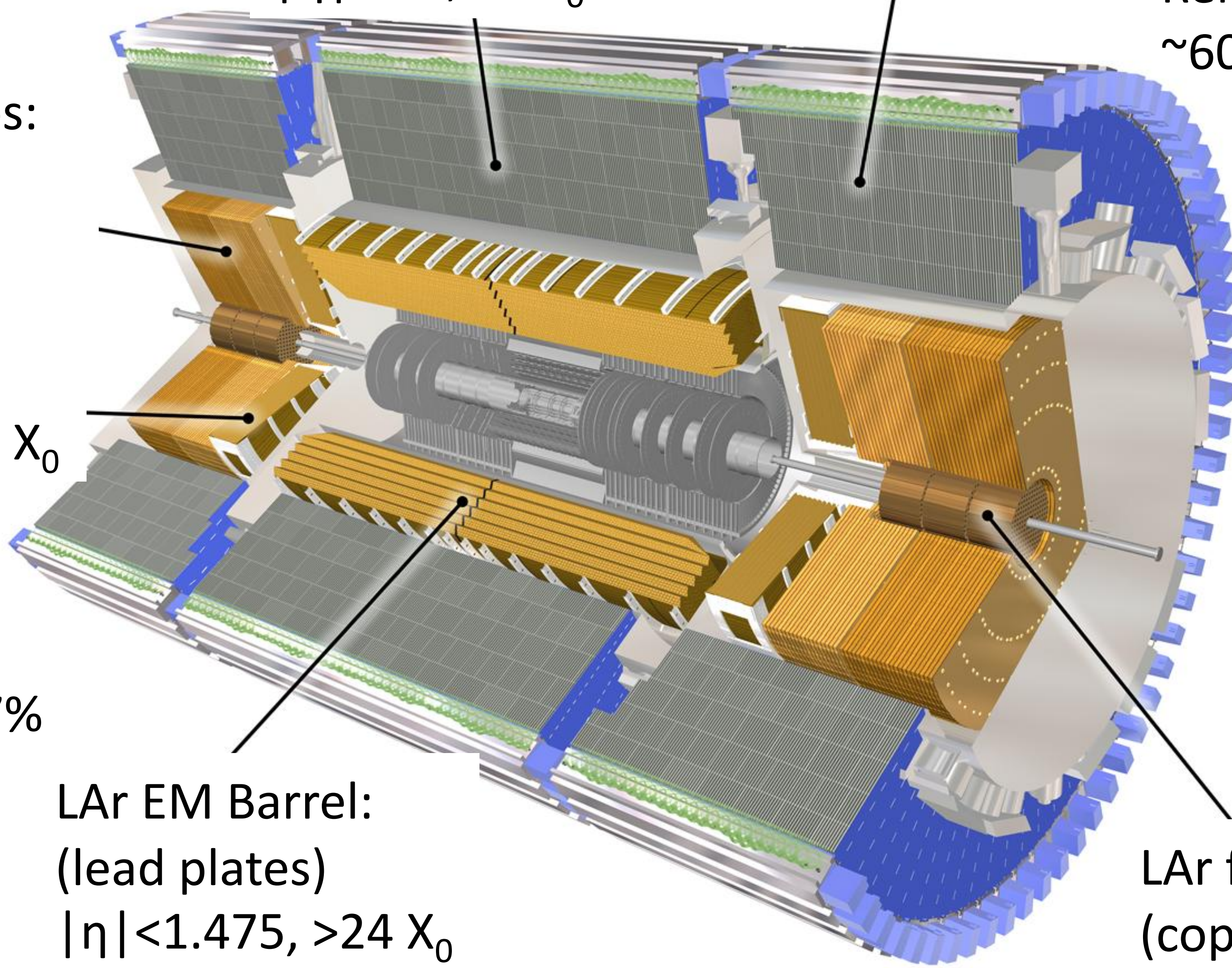
ATLAS Calorimetry

Scintillating Tile:
(Iron absorber),
$|\eta|<1.8$, 11 λ_0

Rel. energy res:
$\sim 60\%/\sqrt{(E/GeV)} \oplus 0.03$

LAr Had End-caps:
(copper plates)
$1.5<|\eta|<3.2$

LAr EM End-caps:
$1.375<|\eta|<3.2$, $>26\ X_0$



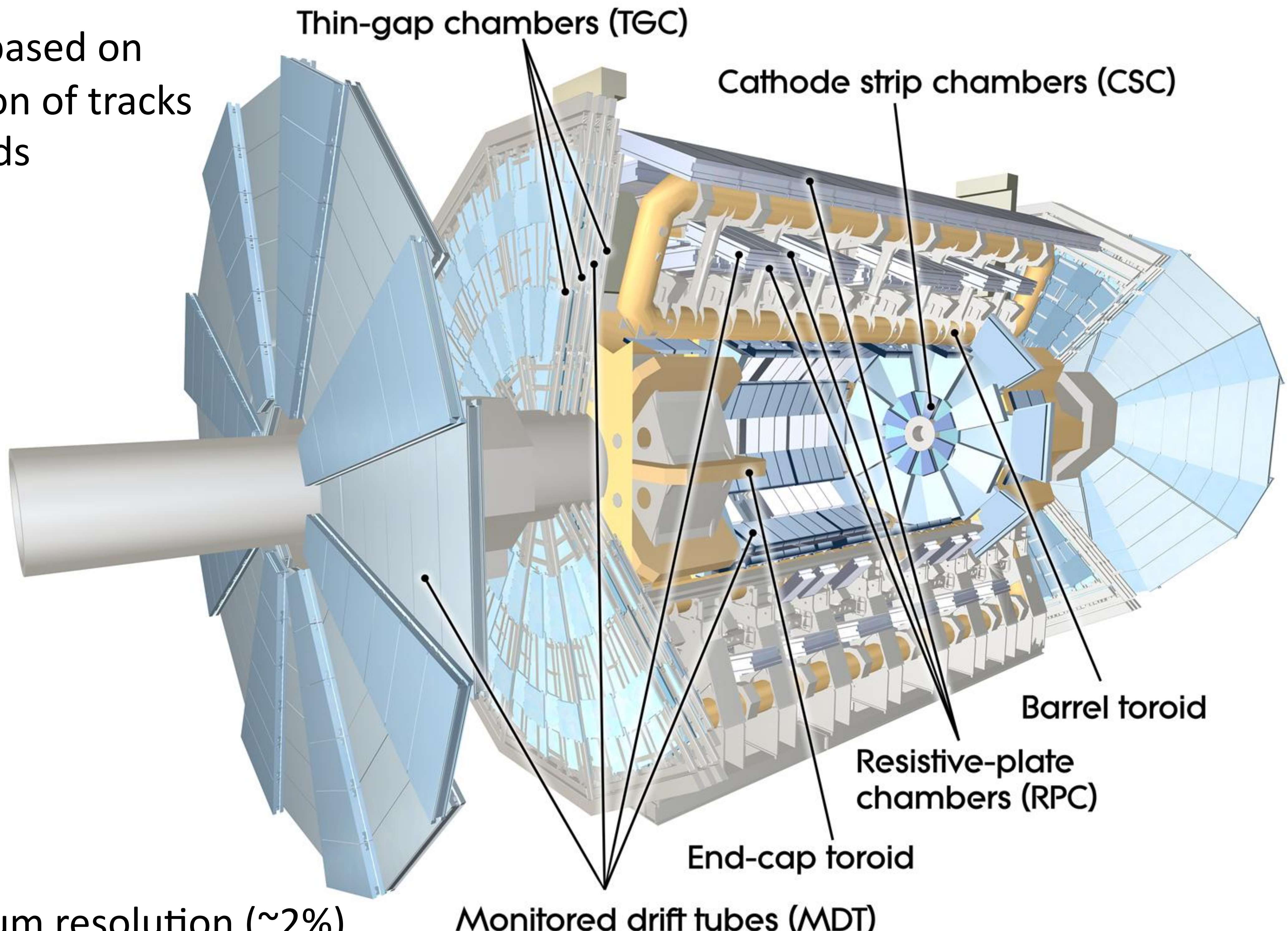
Rel energy res:
$\sim 10\%/\sqrt{(E/GeV)}+0.7\%$

LAr EM Barrel:
(lead plates)
$|\eta|<1.475$, $>24\ X_0$

LAr forward:
(copper/tungsten)
$3.1<|\eta|<4.9$

ATLAS Inner Detector

Layout based on deflection of tracks by toroids



Momentum resolution (~2%)

Full Selection

MUONS

ID+MS tracks combined

$|\eta| < 2.4$

$p_T > 30$ GeV

nBLHits > 0 OR expectBLayerHit FALSE

nPixHits + nPixDeadSensors > 1
nSCTHits + nSCTDeadSensors > 5

nPixHoles + nSCTHoles < 3

if $|\eta| < 1.9$: nTRTHits > 5 AND nTRTOutliers < 0.9*nTRTHits
if $|\eta| \geq 1.9$: if nTRTHits > 5, nTRTOutliers < 0.9*nTRTHits

$|d_0| <$ 0.1mm, $|z_0| <$ 5.0mm

isolated: $p_T^{cone20}/p_T < 0.2$

trigger matched (MC only)

EVENTS

Passes SUSY GRL (data only)

fires EF_mu18_MG OR EF_mu40_MSonly_barrel trigger

at least one primary vertex with at least 3 associated tracks

exactly one good muon and zero good electrons

missing transverse energy (MET) > 30 GeV

at least two good jets

transverse mass $M_T(\mu,MET) > 40$ GeV

zero jets in LAr hole and no “LAr Error”

ELECTRONS (veto)

Author = 1 OR 3

$|\eta| < 2.47$ (w/o crack)

$p_T > 20$ GeV

“isEM Medium”

$E_T^{cone20}/E_T < 0.1$

JETS

$|\eta| < 2.8$

$p_T > 30$ GeV

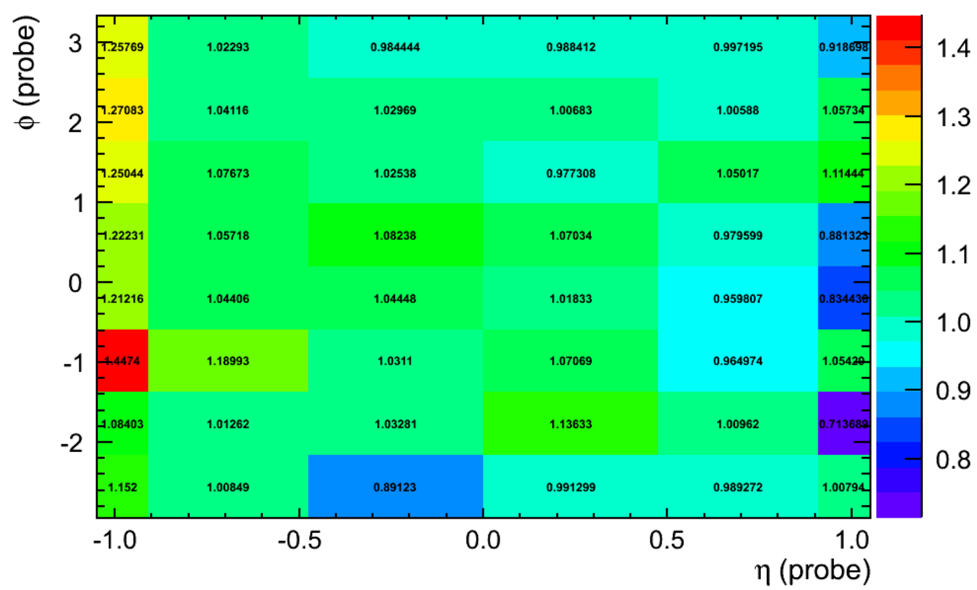
“loose cleaning” (data only)

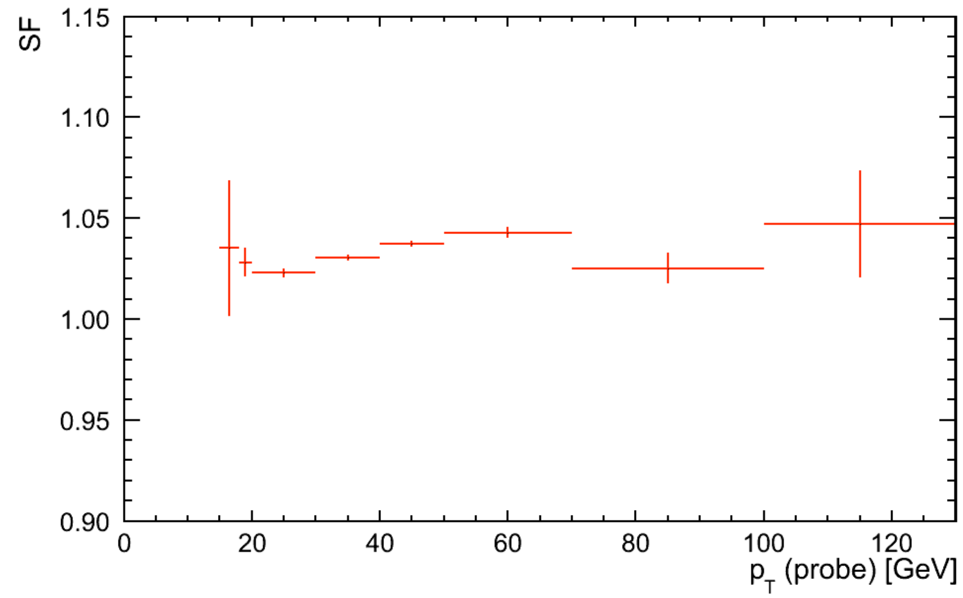
TileGap3 > 0.5 OR BCH_CORR_CELL > 0.5

$\Delta R(\text{jet}, l) > 0.4$

	Loose
HEC spikes	HECf>0.5 && |HECQ|>0.5 or |neg. E|>60GeV
EM coherent noise	EMf>0.95 &&|LArQ|>0.8 && |eta|<2.8
Non-collision background & Cosmics	|t|>25ns or EMf<0.05 && Chf<0.05 && |eta|<2 or EMf<0.05 && |eta|>=2 or FMax>0.99 && |eta|<2

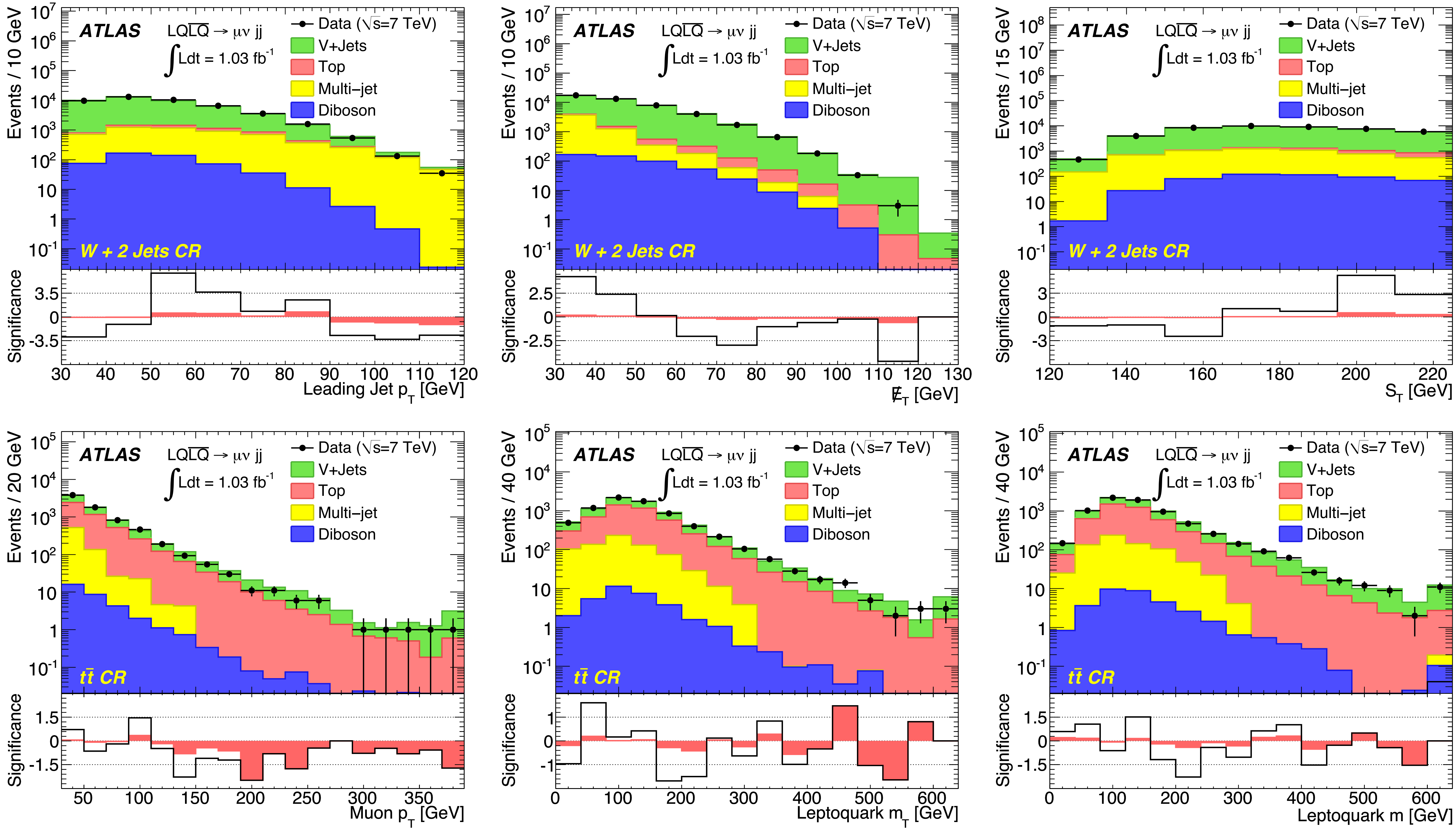
MC Corrections





- Muon trigger and identification efficiencies
    - tag-and-probe study of $Z \rightarrow \mu\mu$ events; η, ϕ (p_T) dependent in barrel (end-cap)
- Muon momentum resolution “smeared” to match data
- Pile-up re-weighting
    - average number of interactions per bunch crossing made to match that in data
- “LAr Hole” (dead region of LAr barrel calorimeter)
    - veto good electrons in the LAr hole, veto events with a good jet in the LAr hole

More CR Plots



W+jets, t-tbar Normalization

- Discrepancy between data and MC resulting in large deviation from unity of SFs is attributed to mis-modeling of pileup in MC samples
  - occurs in low-p_T regime
  - first appeared when switching from MC10a to MC10b
  - SFs closer to unity when p_T thresholds are raised
  - SFs closer to unity when |JVF| > 0.75 cut to remove pileup is applied, as shown in table below

	t-tbar SF	W+jets SF
nominal	1.092 ± 0.25	0.911 ± 0.005
|JVF|>0.75	1.066 ± 0.025	1.063 ± 0.026

Systematic Uncertainties

- Full shape information taken into account in limit-setting procedure
- Summary table of approximate values shown below: L' is nominal LLR distribution, $\delta L'$ is difference between LLR with $\pm 1\sigma$ systematic uncertainty applied and nominal distributions

$$\overline{\text{systematic}} = \left| \frac{\int L' + \frac{1}{2}\left(|\delta L'_{+1\sigma}| + |\delta L'_{-1\sigma}|\right) dL'}{\int L' dL'} - 1 \right|$$

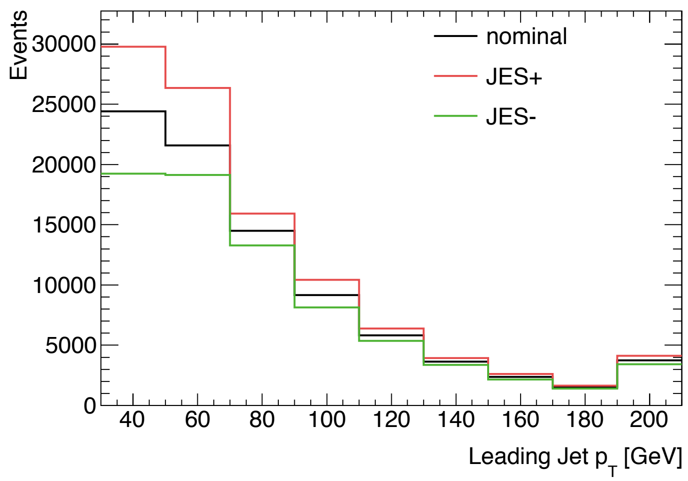
Systematic	V+jets	$t\bar{t}$	Single top	Dibosons	MJ	LQ Signal
Muon Eff. SF	0.011	0.019	0.067	0.060	–	0.045
Muon pT Res.	<0.01	0.018	0.076	0.063	–	0.046
Jet Energy Scale	0.102	0.040	0.124	0.094	–	0.056
Jet Energy Res.	0.128	0.054	0.164	0.120	–	0.040
Top Mass	–	0.087	–	0.060	–	–
ISR/FSR	–	0.098	–	0.060	–	–
POWHEG/MC@NLO	–	0.062	–	0.060	–	–
PYTHIA/HERWIG	–	0.049	–	0.060	–	–
SHERPA/ALPGEN	0.030	–	–	–	–	–
MJ Normalization	–	–	–	–	0.916	–
PDF, signal	–	–	–	–	–	0.086
LLR Input pdf	0.044	0.064	0.092	0.061	–	0.034
Luminosity	–	–	0.037	0.037	–	0.037
Data Normalization	0.100	0.036	–	–	–	–
Total	0.20	0.18	0.25	0.22	0.92	0.14

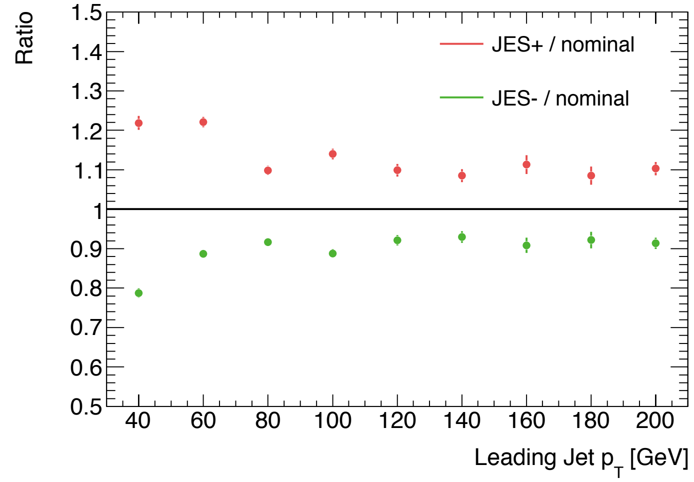
μμjj

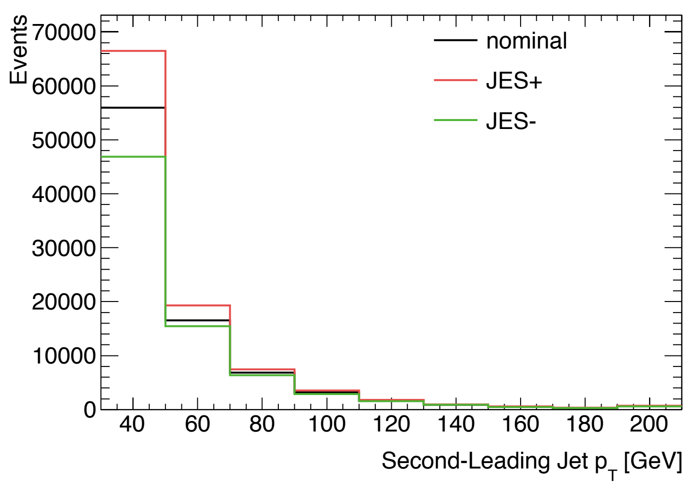
Systematic	W+jets	Z+jets	$t\bar{t}$	Single top	Dibosons	MJ	LQ Signal
Muon Eff. SF	<0.01	0.022	<0.01	0.015	<0.01	–	0.041
Muon Energy Res.	<0.01	0.024	<0.01	0.015	<0.01	–	0.038
Jet Energy Scale	0.170	0.176	0.054	0.060	0.127	–	0.067
Jet Energy Res.	0.126	0.102	0.039	0.053	0.109	–	0.056
Top Mass	–	–	0.039	–	<0.01	–	–
ISR/FSR	–	–	0.051	–	<0.01	–	–
POWHEG/MC@NLO	–	–	0.064	–	<0.01	–	–
PYTHIA/HERWIG	–	–	0.031	–	<0.01	–	–
SHERPA/ALPGEN	0.021	0.022	–	–	–	–	–
MJ Normalization	–	–	–	–	–	0.332	–
PDF, signal	–	–	–	–	–	–	0.067
LLR Input pdf	0.046	0.045	0.114	0.080	0.067	–	0.057
Luminosity	–	–	–	0.037	0.037	–	0.037
Data Normalization	0.100	0.100	0.100	–	–	–	–
Total	0.24	0.23	0.19	0.12	0.18	0.33	0.14

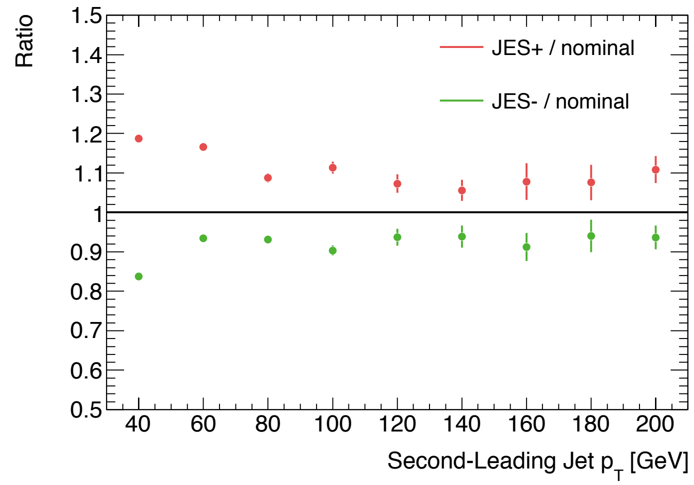
μνjj

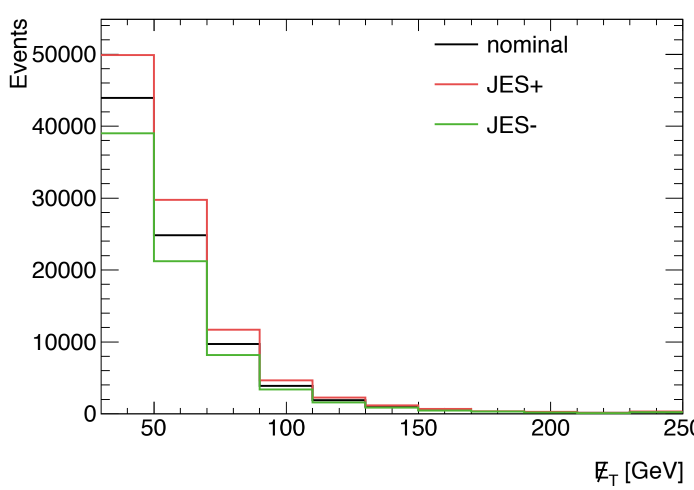
JES Systematic Variation

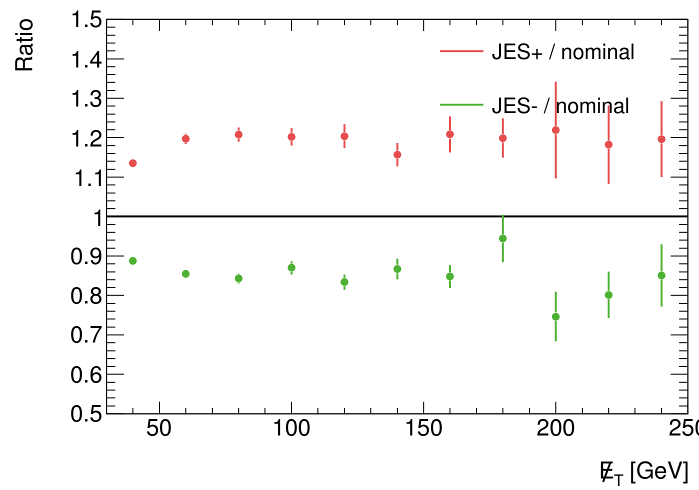




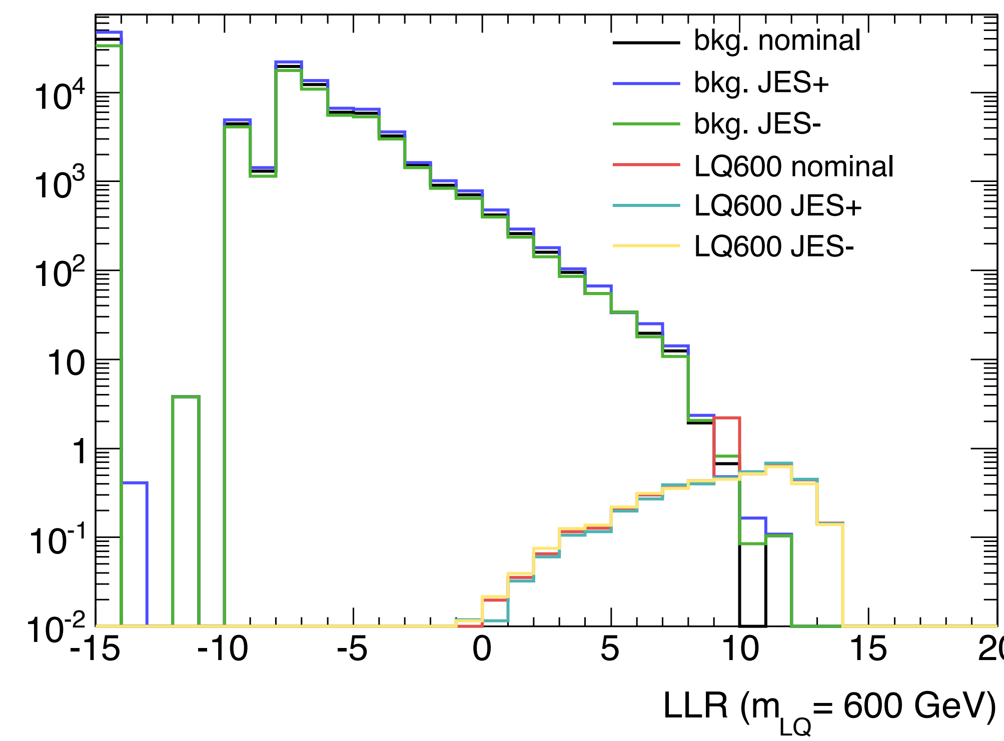






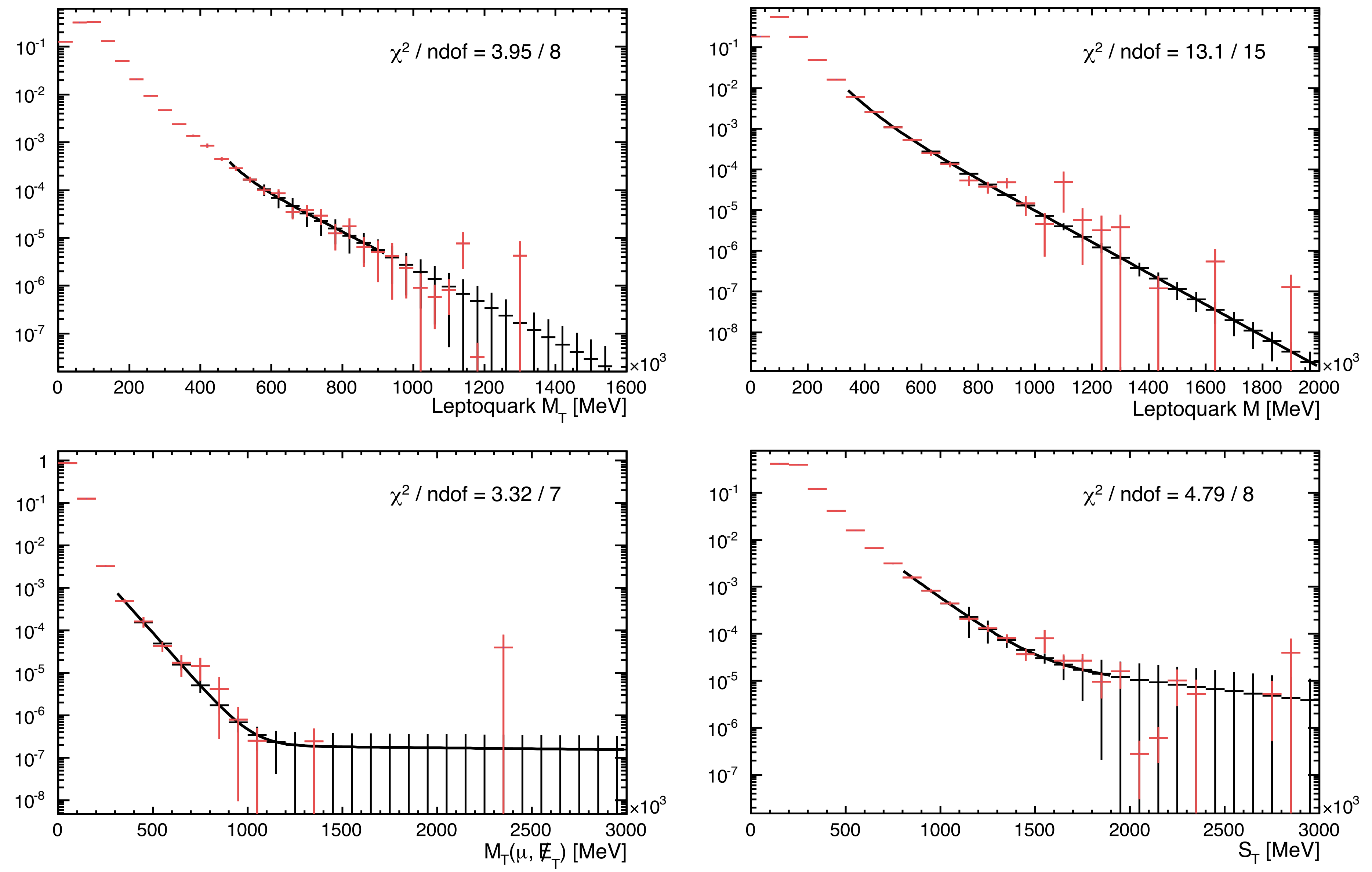


- jet energy scale: large systematic uncertainty
  - significant impact on jet p_T and MET distributions
  - relatively small impact on LLR distribution



PDF Fits as LLR Input

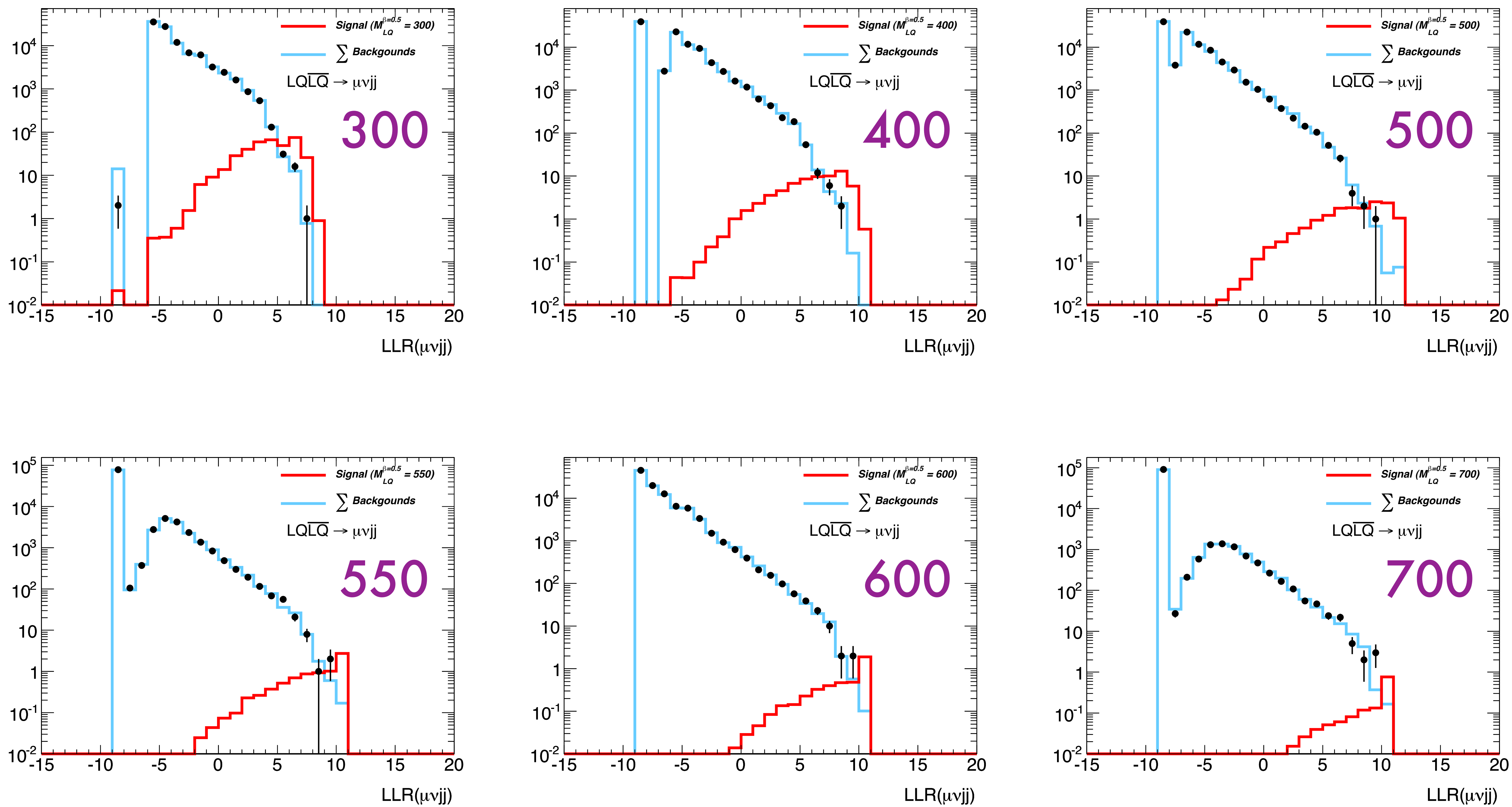
- Low stats in tails => event weights driven by fluctuations
- Fit double exponential to good stat range, extrapolate out
- Replace bin contents with fit value if n_{evts}=0 or stat uncertainty > 0.1 * n_{evts}



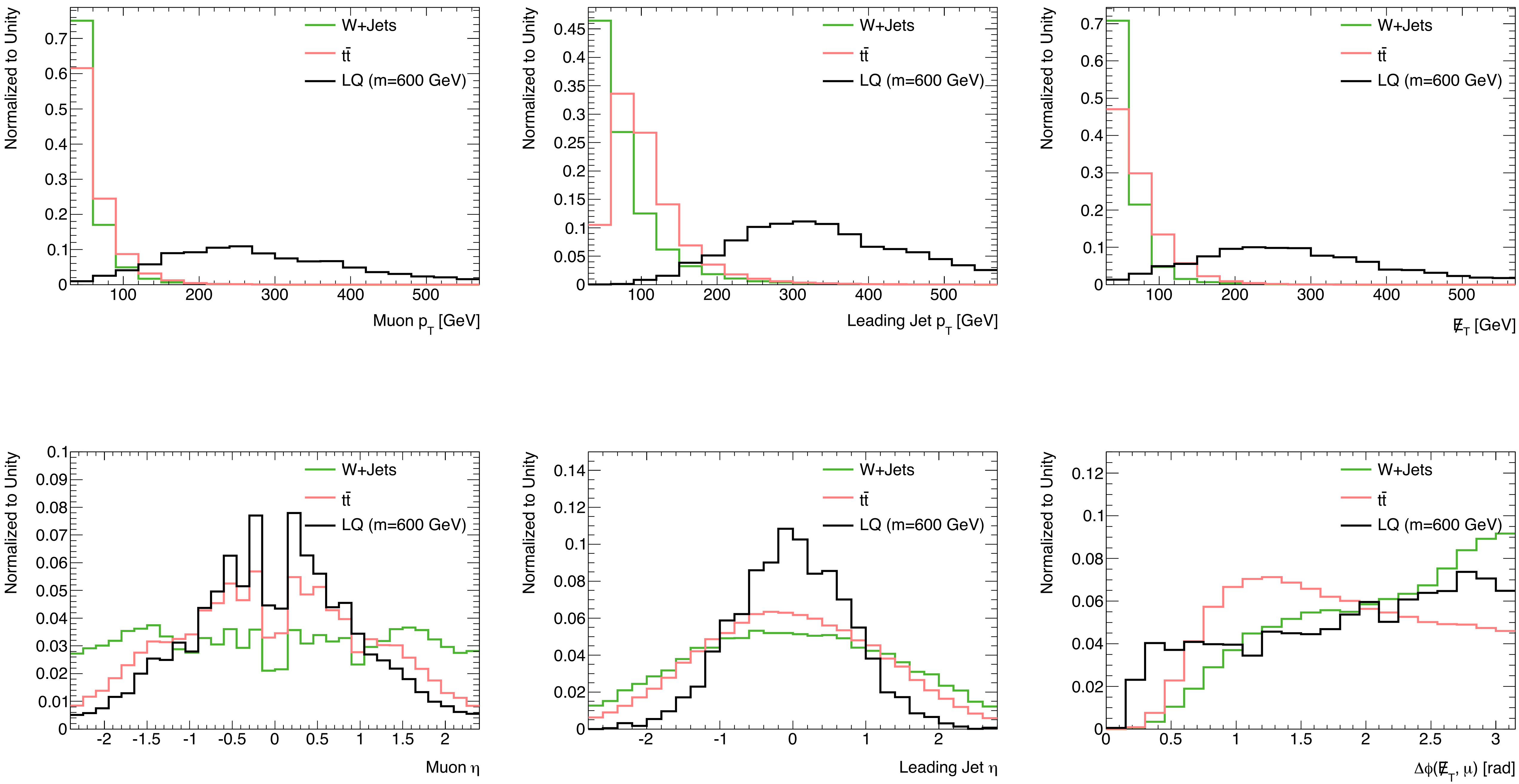
$$f(x) = N \cdot \frac{a \cdot e^{-x/b} + (1-a) \cdot e^{-x/c}}{ab \cdot e^{-d/b} + (1-a)c \cdot e^{-d/c}}$$

N is overall normalization, *a* (1–*a*) is fraction of first (second) exponential, *b* (*c*) is normalization of first (second) exponential's slope, *d* is maximum x-value included in fit

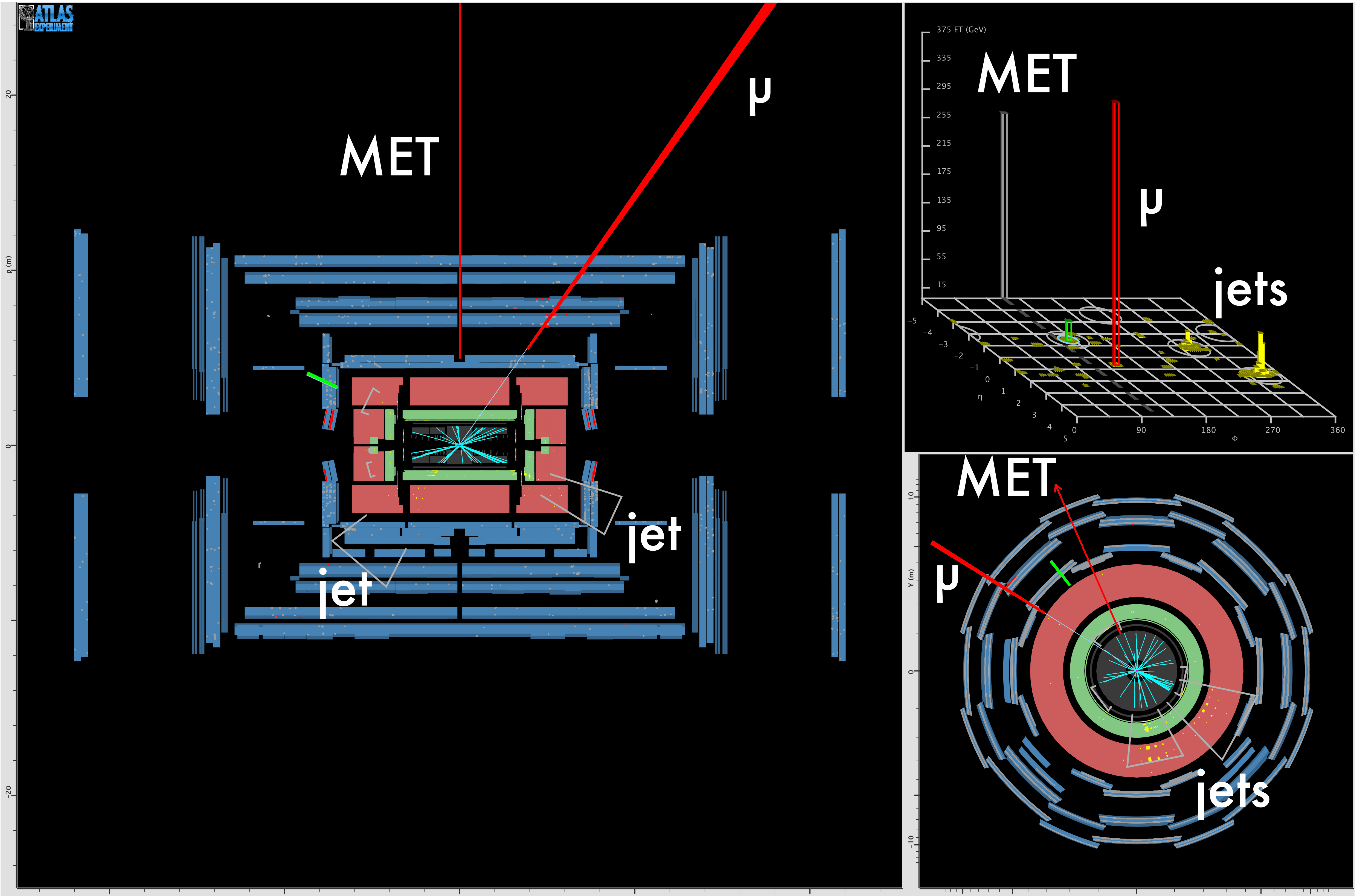
Re-binned LLR(m_{LQ})



More Shape Comparisons



Event Display



Simple Case, Generalized

- *x* is data, s and *b* are expected signal and background yields; likelihoods $\mathcal{L}$ are Poisson probability distribution functions

$$Q(x) = \frac{\mathcal{L}(x \mid H_1)}{\mathcal{L}(x \mid H_0)} = \frac{(s+b)^x e^{-(s+b)}/x!}{(b)^x e^{-(b)}/x!}$$

- bin discriminating variable? $\mathcal{L}$ is product of bin-by-bin likelihoods; combine orthogonal channels? also product of individual $\mathcal{L}$'s!

$$Q(x) = \prod_i^{\text{channels}} \prod_j^{\text{bins}} \frac{(s_{ij}+b_{ij})^{x_{ij}} e^{-(s_{ij}+b_{ij})}/x_{ij}!}{(b_{ij})^{x_{ij}} e^{-(b_{ij})}/x_{ij}!} = \prod_i^{\text{channels}} \prod_j^{\text{bins}} e^{-(s_{ij})} \left(\frac{s_{ij}+b_{ij}}{b_{ij}} \right)^{x_{ij}}$$

- take log-likelihood ratio for convenience/stability

$$\mathrm{LLR}(x) = -2\ln(Q(x)) = \sum_i^{\text{channels}} \sum_j^{\text{bins}} \left[s_{ij} - x_{ij} \ln\left(1 + \frac{s_{ij}}{b_{ij}}\right) \right]$$

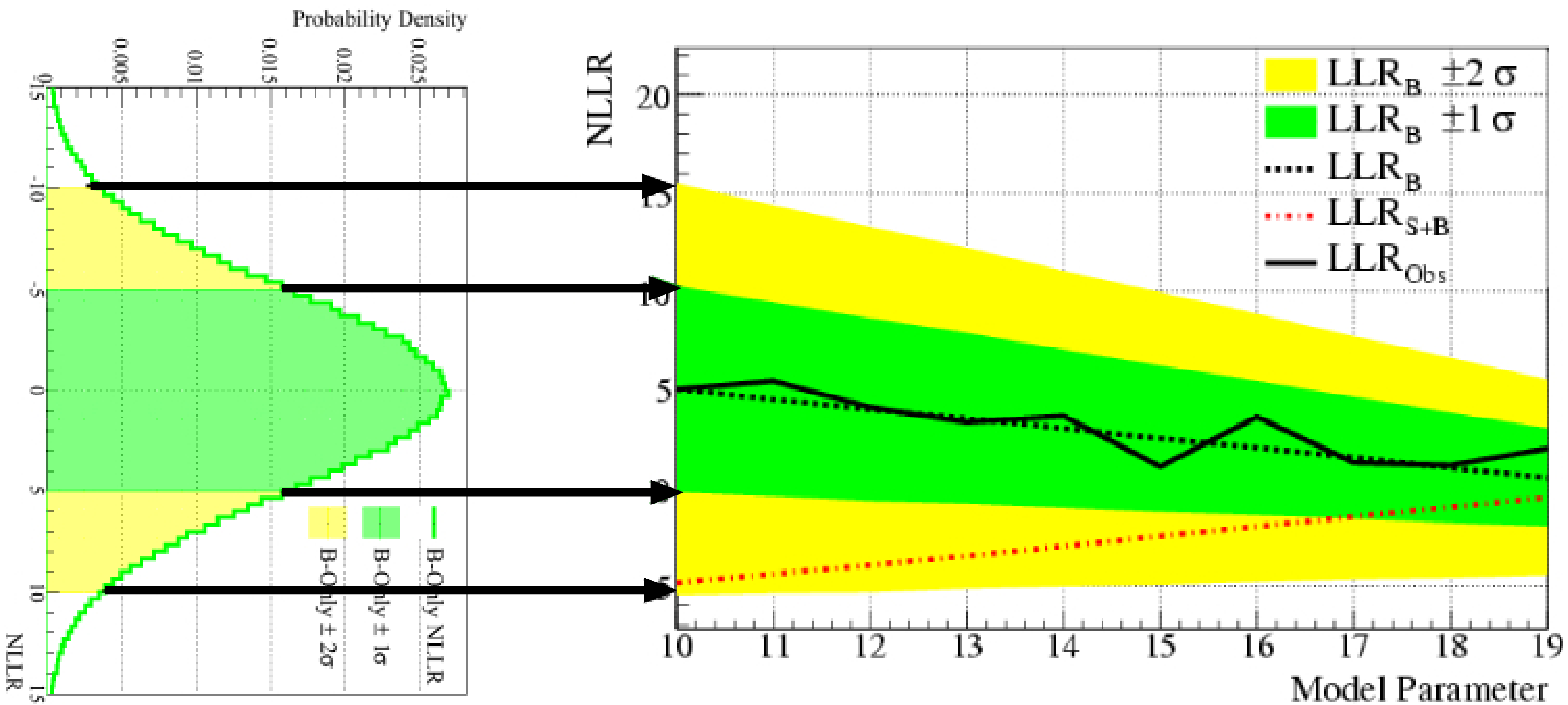
- compute p-*values,* confidence levels, etc. as before

$$CL_b = \int_{\mathrm{LLR}(b|\mathbf{x})}^{\infty} \mathrm{P}(b|x') d(\mathrm{LLR}(b|x')) \ \ , \ CL_{s+b} = \int_{\mathrm{LLR}(s+b|\mathbf{x})}^{\infty} \mathrm{P}(s+b|x') d(\mathrm{LLR}(s+b|x'))$$

$$CL_s = CL_{s+b}/CL_b$$

The CL_s Method

- "Modified-Frequentist" approach: $\mathrm{CL}_s \equiv \mathrm{CL}_{s+b}/\mathrm{CL}_b = p_{s+b}/(1-p_b)$
  - normalize CL_{s+b} by CL_b, "penalizing" when sensitivity is poor
- CL_s can be interpreted as the approximate confidence obtained if background events were removed from selected event sample
- Gives *conservative* limits! Exclusion when $CL_s \leq \alpha$ (0.05 => 95% CL)
  - CL_s is always larger than CL_{s+b}, so upper limit is higher (weaker)



Wade Fisher, Collie: A Confidence Level Limit Evaluator

$LLR_b - LLR_{s+b}$ separation => discriminating power

LLR_b width => sensitivity to signal

LLR_{obs} relative to LLR_b and LLR_{s+b} evaluated with CL_s

Bayesian-Frequentist Hybrid

- In Bayesian statistics, our *degree of belief* is a probability associated with a hypothesis, given by a *prior PDF* $\pi(\theta)$
  - e.g. a Gaussian distribution: $\left(1/\sqrt{2\pi}\sigma\right) e^{-\frac{(x-\mu)^2}{2\sigma^2}}$
- Bayes' theorem tells how our beliefs should be updated, given data:

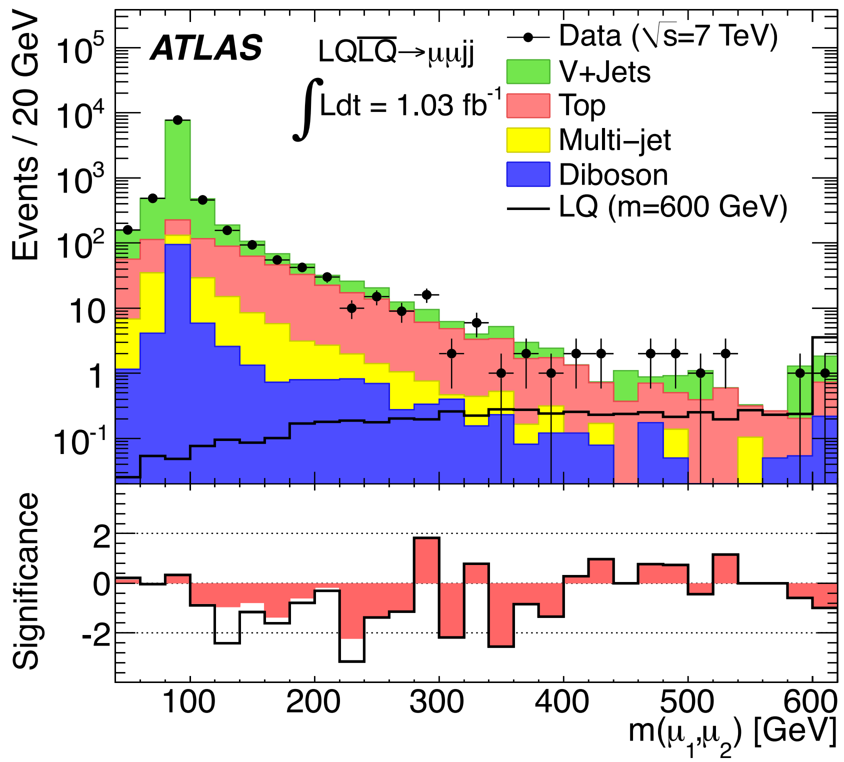
"posterior PDF" → $$\mathrm{P}(\theta \mid x) = \frac{\mathrm{P}(x \mid \theta)\ \pi(\theta)}{\mathrm{P}(x)}$$ ← normalization

- Integrate over ("marginalize") nuisance parameters:

$$p(x \mid \theta) = \int \mathrm{P}(x \mid \theta, \nu)\ \pi(\nu)\ d\nu$$

  - numerically: in each pseudo-exp., sample Gaussian (μ=0, σ=frac. uncert.) for each systematic, shift nominal mean of Poisson likelihood by that value
- Hybrid approach: Use Modified-Frequentist methods for central value, Bayesian methods for treatment of nuisance parameters

μμjj: Selected Events



EVENTS

good detector status (data only)

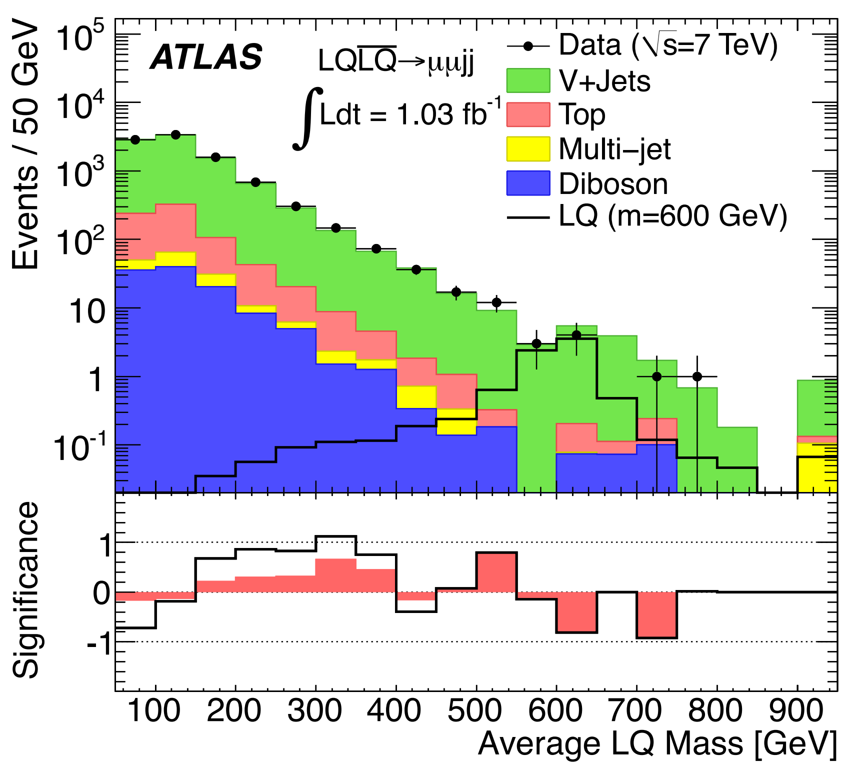
fires muon trigger

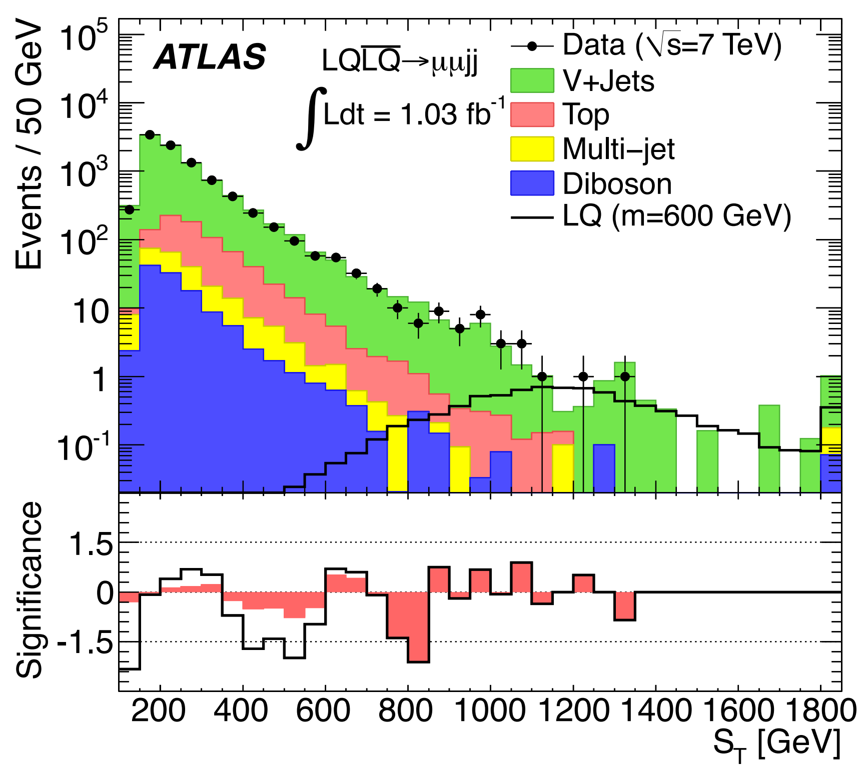
≤1 primary vertex with ≤3 associated tracks

exactly two good muons, Δϕ(μ,μ) > 3.125

at least two good jets, zero "bad" jets

invariant mass M(μ,μ) > 40 GeV



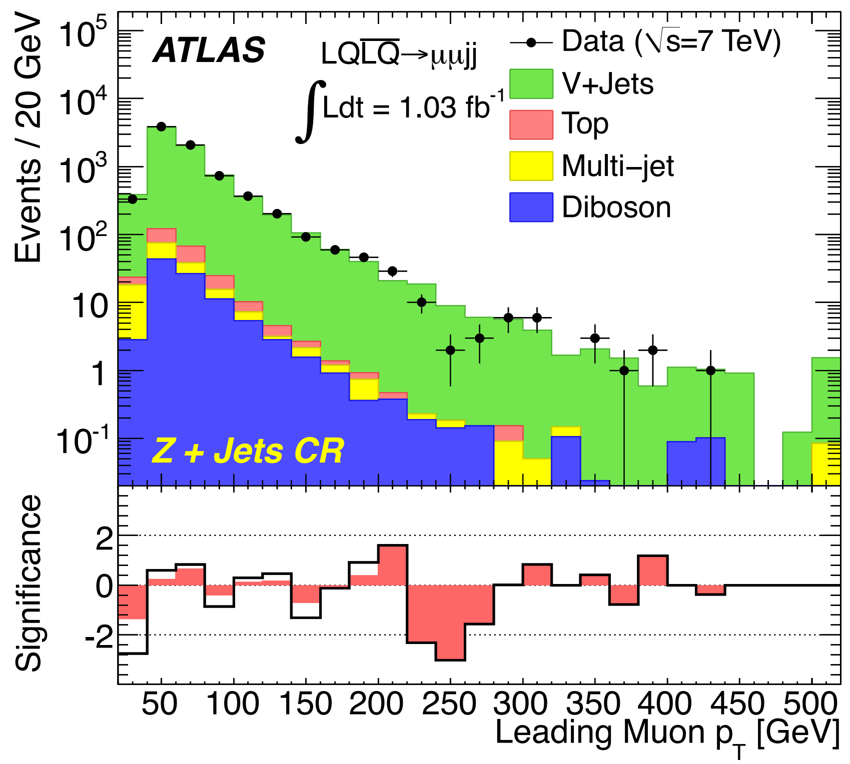


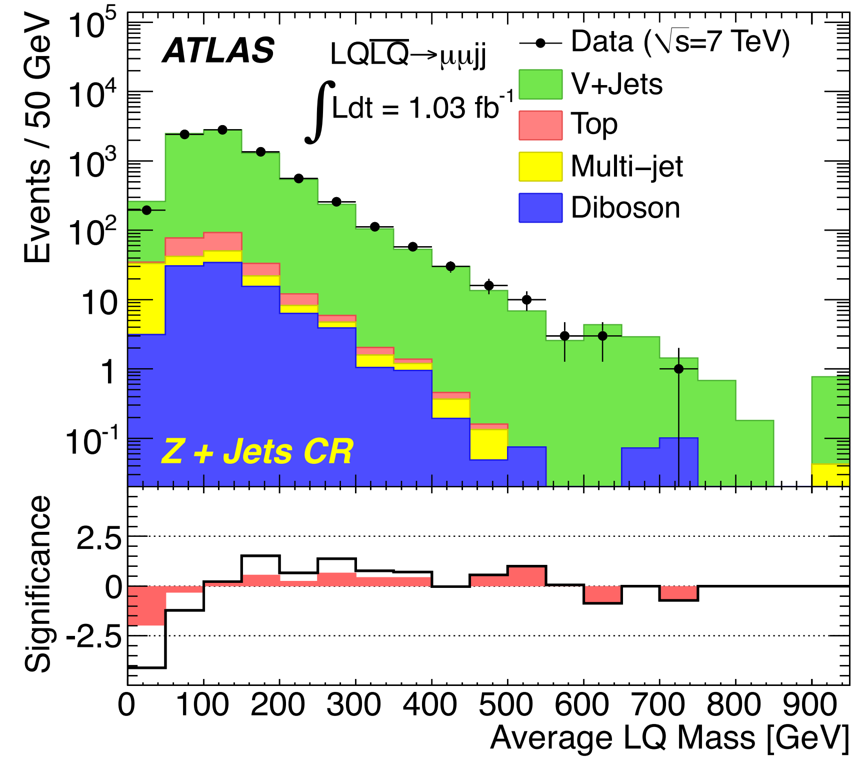
μμjj: Control Regions

Z+jets CR

passes event selection

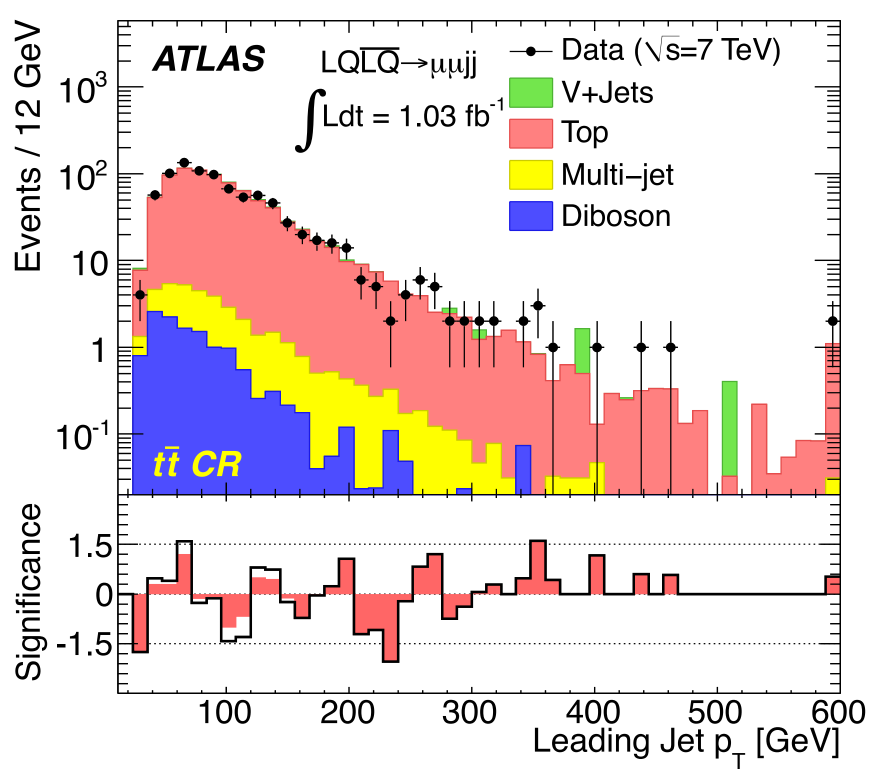
81 < M(μ,μ) < 101 GeV (window around Z peak)

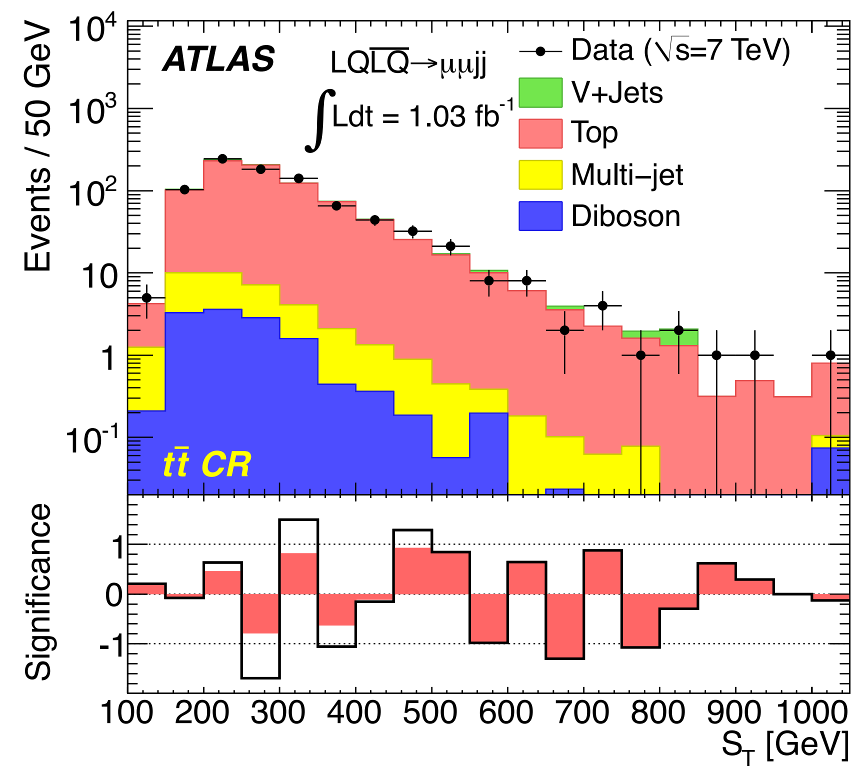




t-tbar CR

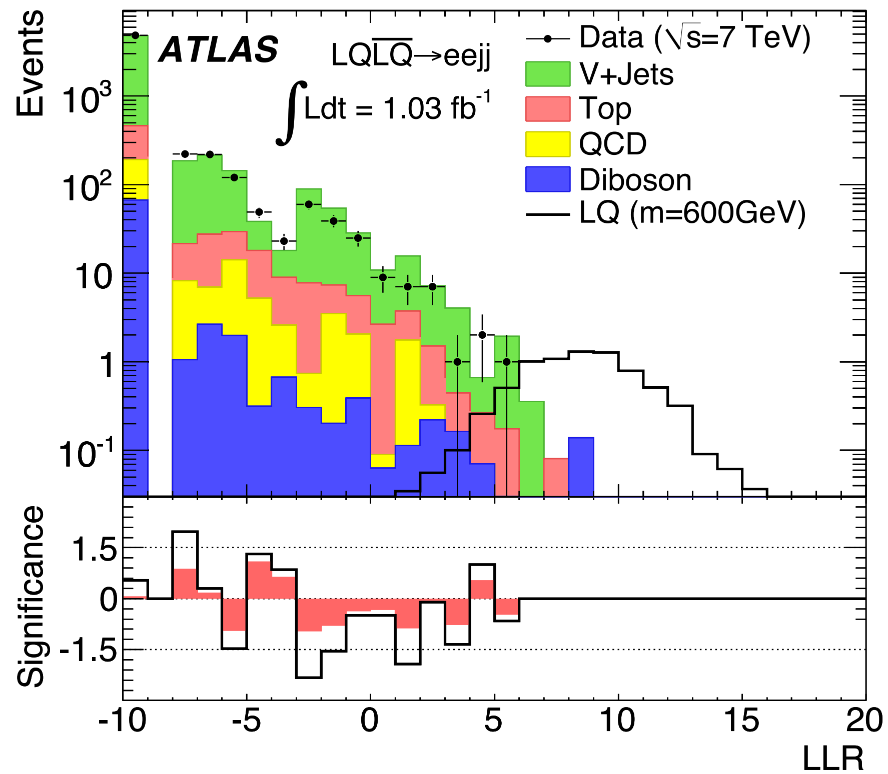
same as event selection, but "two muons" requirement replaced by "one electron and one muon"

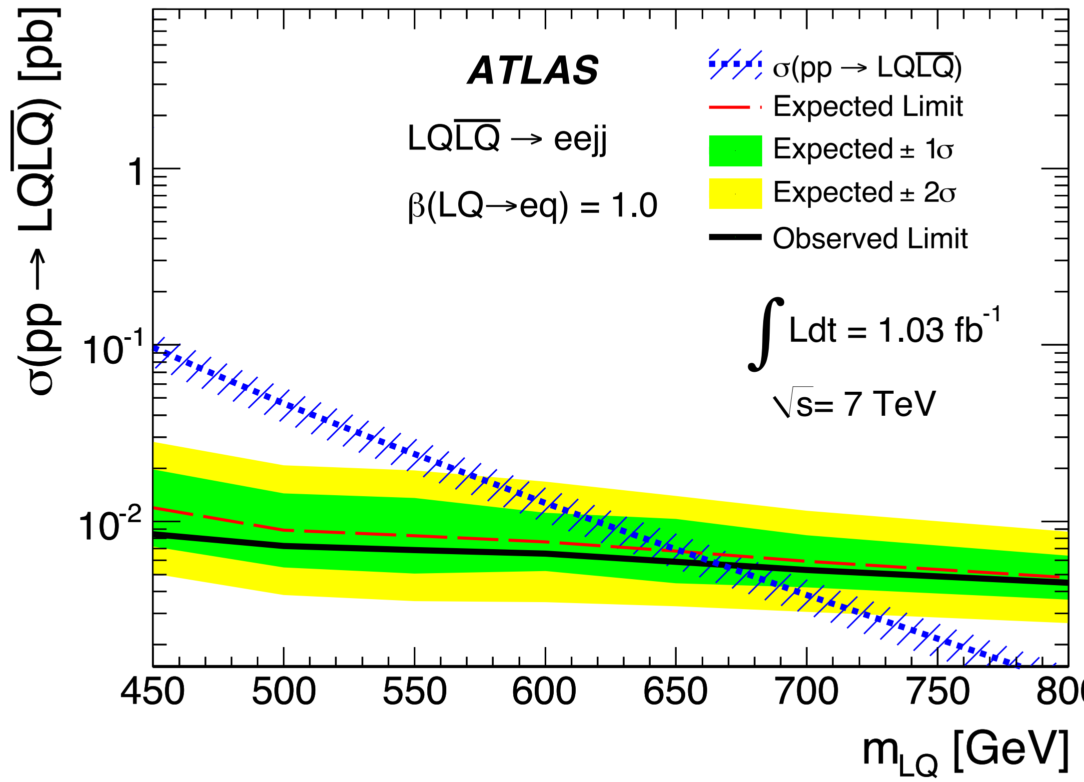




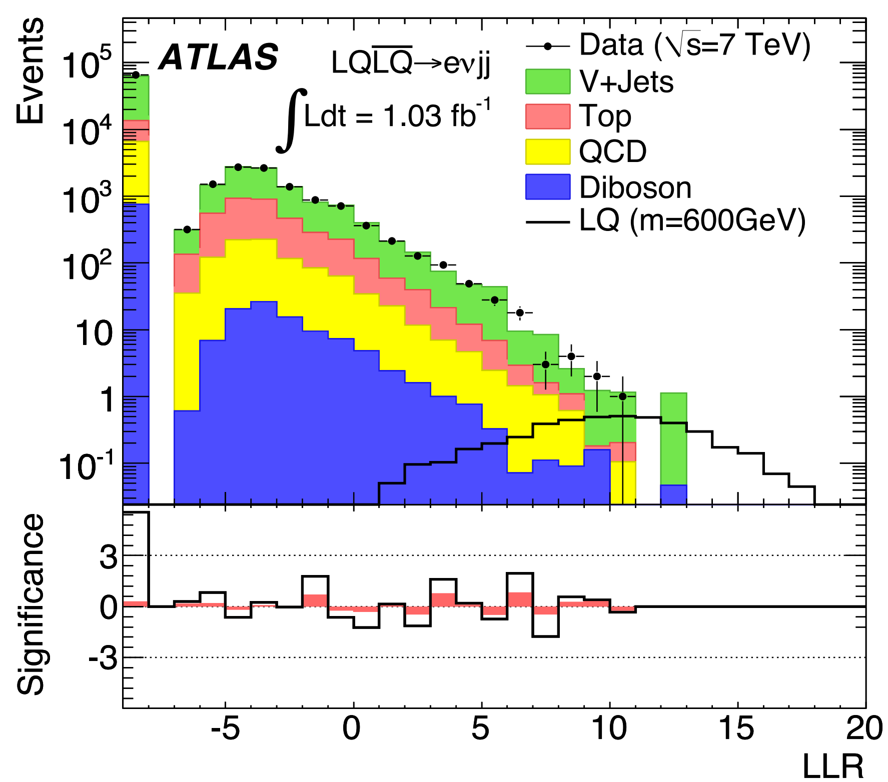
1st-generation LQ LLRs & Limits

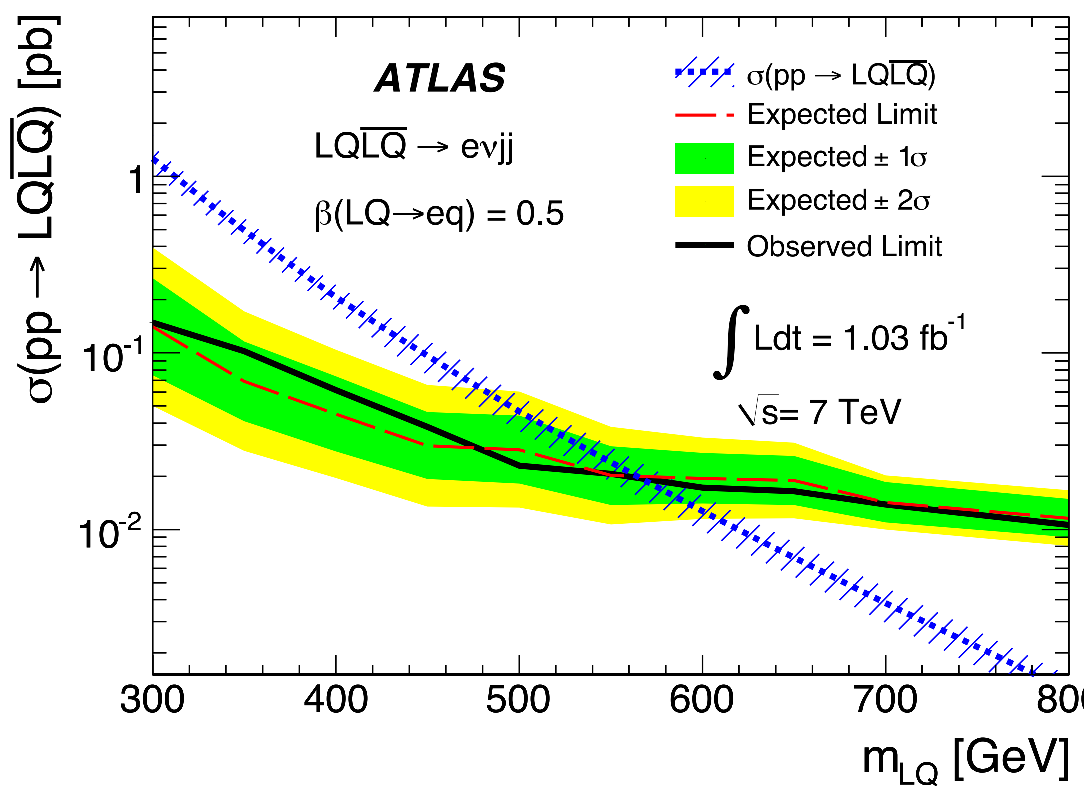
eejj



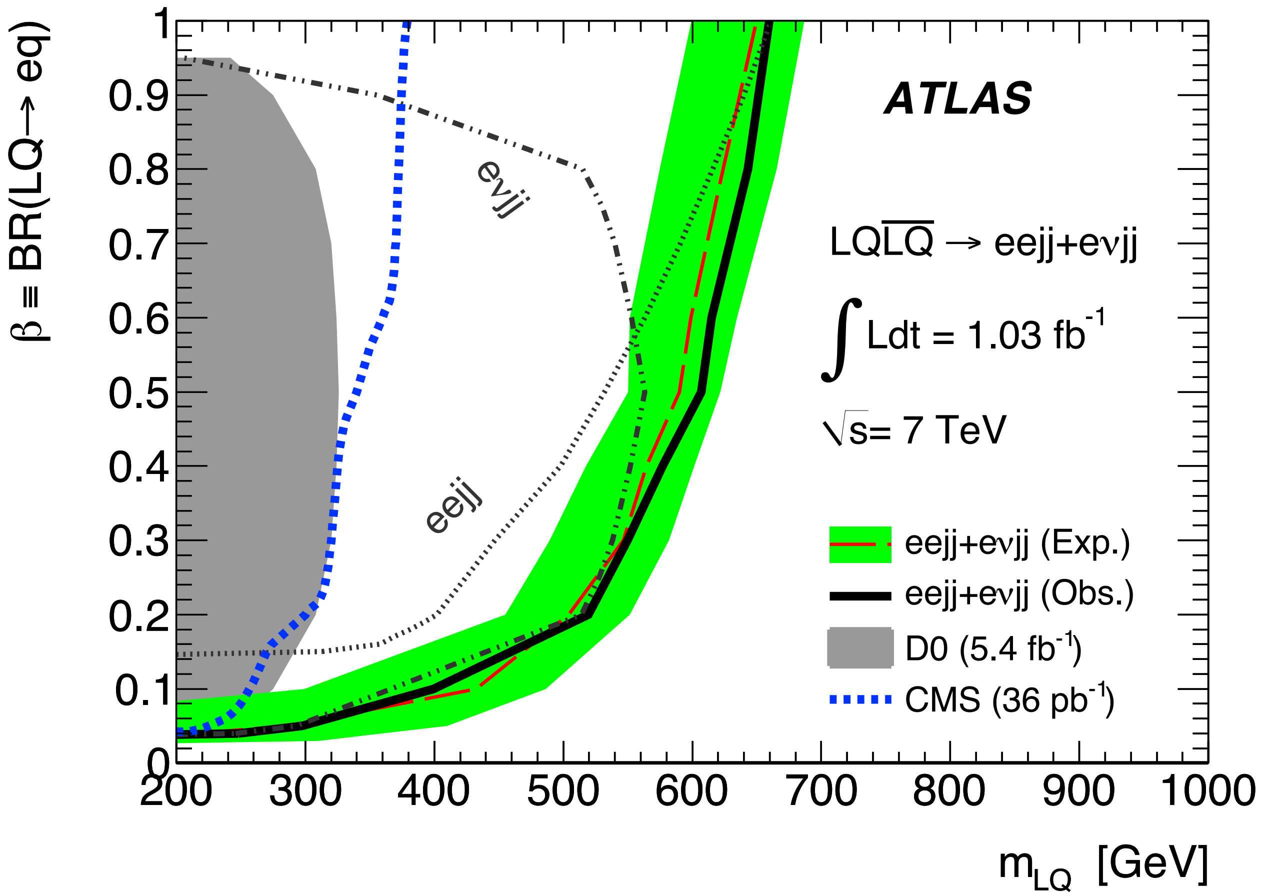


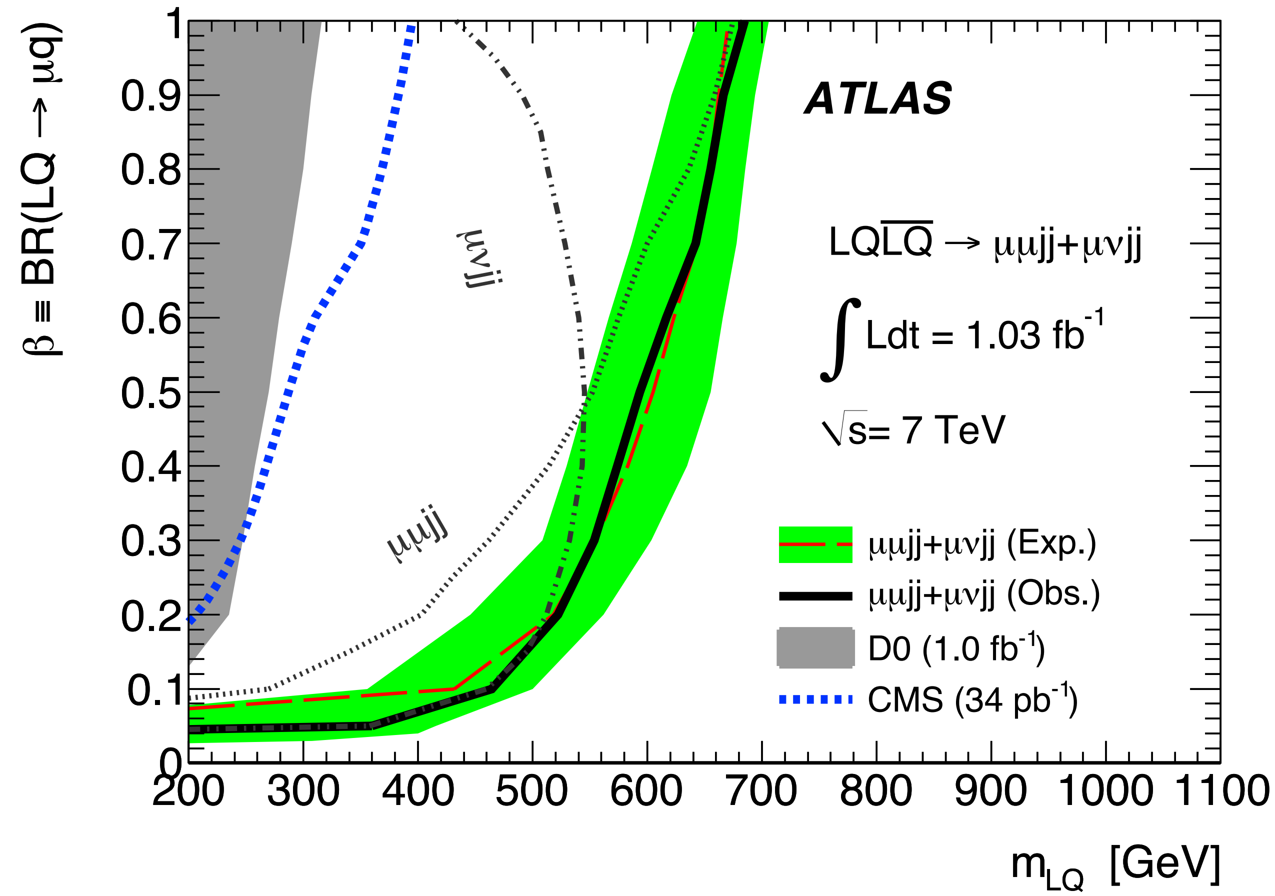
eνjj





LQ Limits Comparison





m_{LQ} Limits	LQ_1 (β=0.5)	LQ_1 (β=1.0)	LQ_2 (β=0.5)	LQ_2 (β=1.0)
Expected [GeV]	587	650	605	671
Observed [GeV]	605	660	594	685