Fermions with non-SM Couplings at ATLAS

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2nd WS on Beyond SM3, Taipei, January 15, 2009

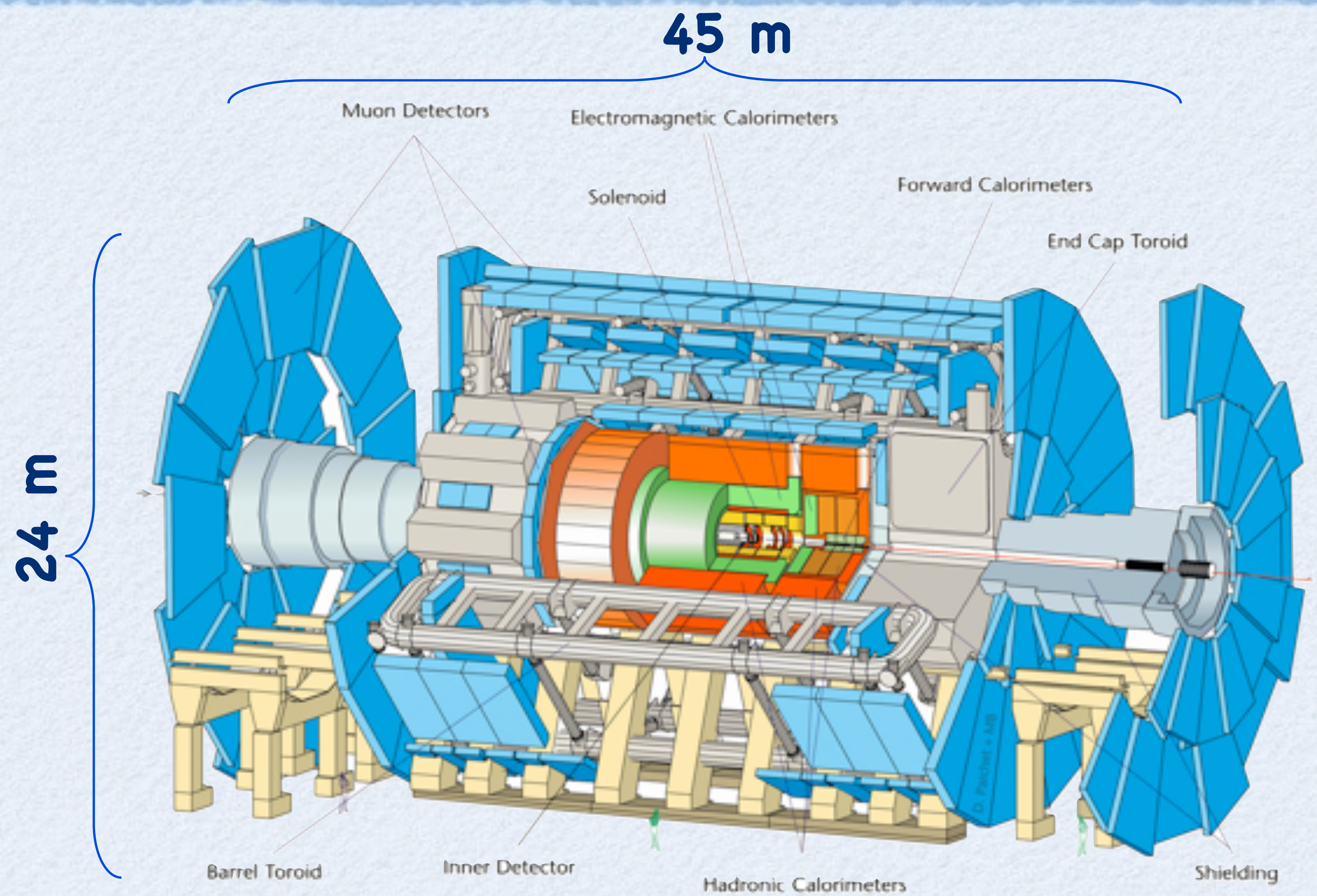
Outline

- What is in this talk?
  - Heavy fermions with non-SM-like decays at ATLAS
    - Quarks with FCNC decays:
      Down-type isosinglets from E6GUT
    - Neutrinos with LFV decays:
      Majorana neutrinos from LRSM models
- What is not in this talk?
  - Heavy quarks with SM-like couplings are covered in talk by Daniel Whiteson.
- Everything at 14 TeV...

Sources

- Details on various aspects of what is in this presentation can be obtained from:
  - Expected Performance of the ATLAS Experiment Detector, Trigger, Physics, CERN-OPEN-2008-020 [arXiv:0901.0512].
  - The ATLAS Experiment at the CERN Large Hadron Collider, J. Instrum. 3 (2008) S08003.
  - Down type isosinglet quarks in ATLAS, R. Mehdiyev et.al., Eur. Phys. J. C 54 (2008) 507 and references therein.
  - E_6 inspired isosinglet quark and the Higgs boson, S. Sultansoy & G. Ünel, Phys. Lett. B 669 (2008) 39.

ATLAS Detector



7000 tones

- Tracking and muon coverage: $|\eta|<2.5$
- Calorimeters with presamplers: $|\eta|<1.8$
- Forward calorimeters : $3.2<|\eta|<5.9$

- e/γ energy resolution

  $\sigma/E \approx 10\text{-}15\%/\sqrt{E} \oplus \sim 1\%$
- Central jet energy resolution

  $\sigma/E \approx 60\%/\sqrt{E} \oplus 3\%$
- Missing $E_{x,y}$ resolution

  $\sigma \approx 0.55\text{GeV} \times \sqrt{(\Sigma E_T)}$
- Track inverse-P_T resolution

  $\sigma_{\{1/PT\}} \approx 35\text{TeV}^{-1} \times (1 \oplus 50/P_T)$
- Muon system standalone momentum resolution (with no inner detector)

  $\sigma/P_T < 4\text{-}10\%$ up to 1 TeV

Backup slides: η dependence

Isosinglet Quarks

- E6GUT: Isosinglet vector-like quarks (ISVLQ) with Q=±1/3
- Down-type ISVLQ for each SM family: D, S and B.
- Assume:
  - $m_D << m_S, m_B$
  - intra-family mixing >> inter-family mixing

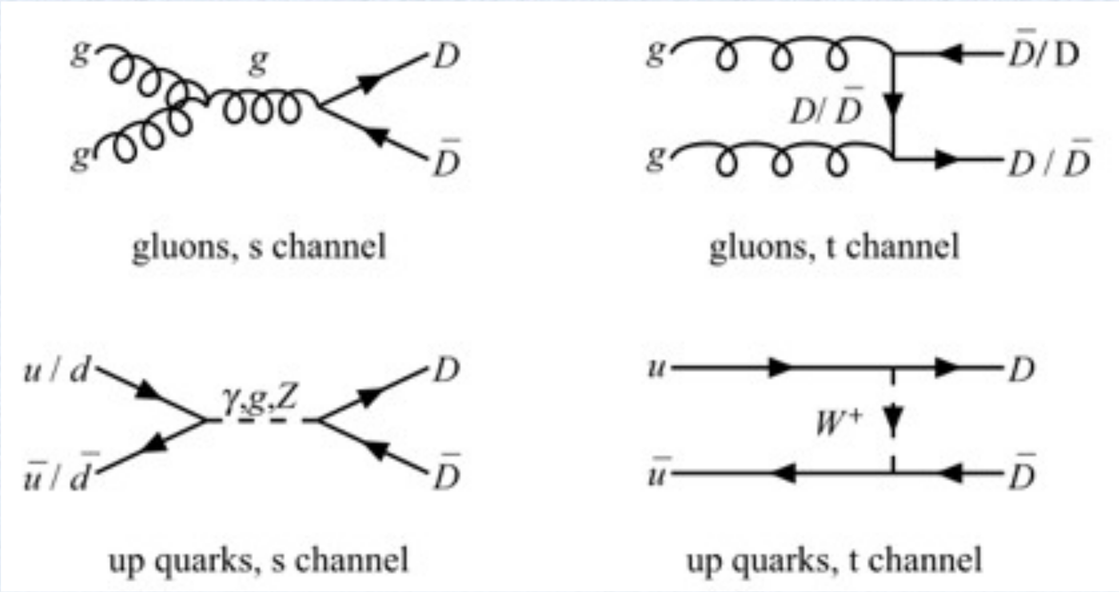
- Lagrangian relevant to weak interactions of D:

$$
\begin{aligned}
L_D = & \frac{\sqrt{4\pi\alpha_{\rm em}}}{2\sqrt{2}\sin\theta_{\rm W}} \left[\bar{u}^\theta \gamma_\alpha (1-\gamma_5) d \cos\phi \right. \\
& \left. + \bar{u}^\theta \gamma_\alpha (1-\gamma_5) D \sin\phi \right] W^\alpha \\
& - \frac{\sqrt{4\pi\alpha_{\rm em}}}{4\sin\theta_{\rm W}} \left[\frac{\sin\phi\cos\phi}{\cos\theta_{\rm W}} \bar{d}\gamma_\alpha (1-\gamma_5) D \right] Z^\alpha \\
& - \frac{\sqrt{4\pi\alpha_{\rm em}}}{12\cos\theta_{\rm W}\sin\theta_{\rm W}} \\
& \times \left[\bar{D}\gamma_\alpha \left(4\sin^2\theta_{\rm W} - 3\sin^2\phi(1-\gamma_5)\right) D \right. \\
& \left. + \bar{d}\gamma_\alpha \left(4\sin^2\theta_{\rm W} - 3\cos^2\phi(1-\gamma_5)\right) d \right] Z^\alpha + {\rm h.c.}
\end{aligned}
$$

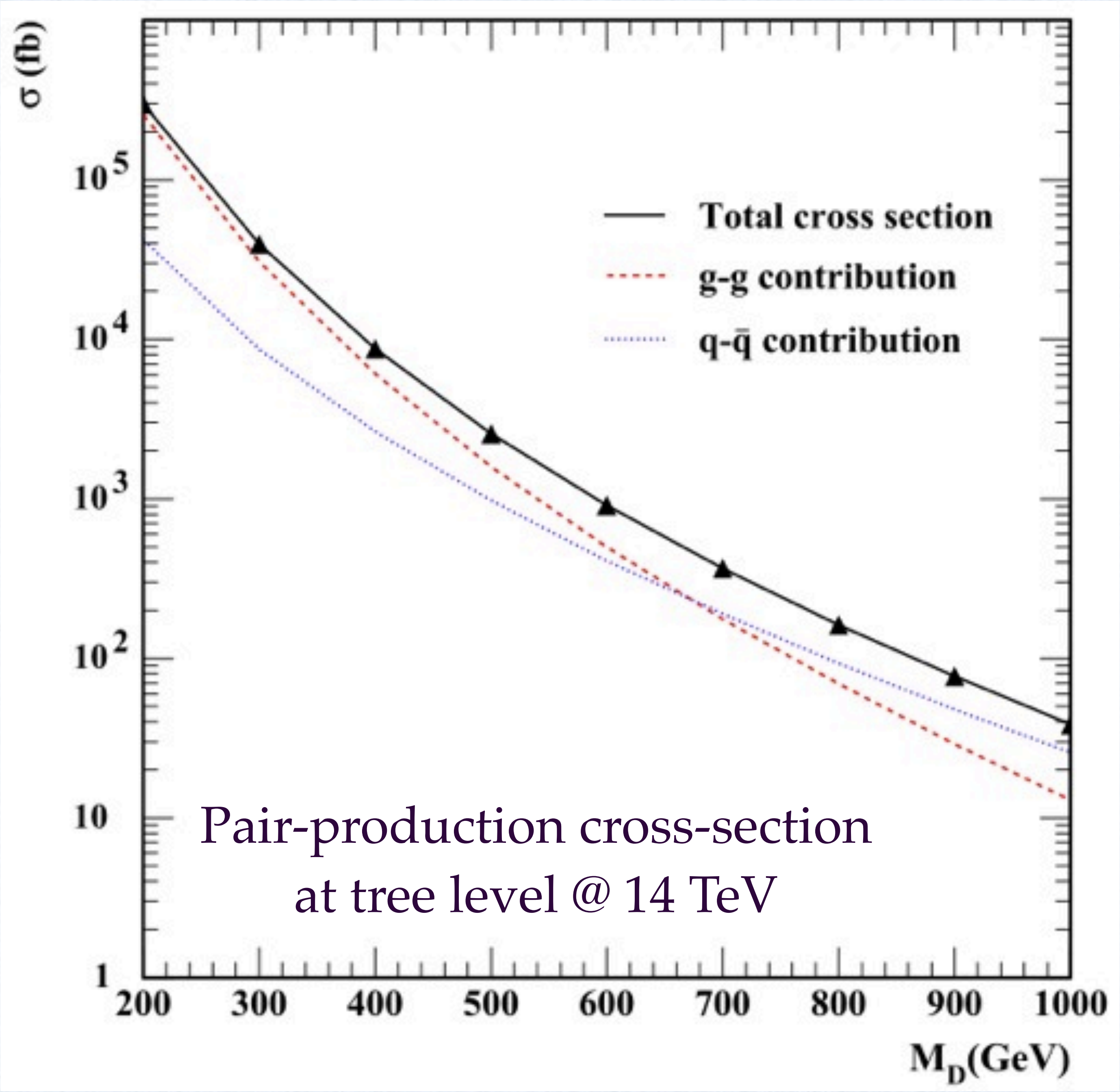
- The mixing angle constrained by 3x4 extension of CKM:
  - $|\sin\Phi| < 0.045$

Production

- Main pair-production diagrams:



- Contribution from t-channel diagrams negligible.
- Cross-section largely independent of the mixing.



Reconstruction

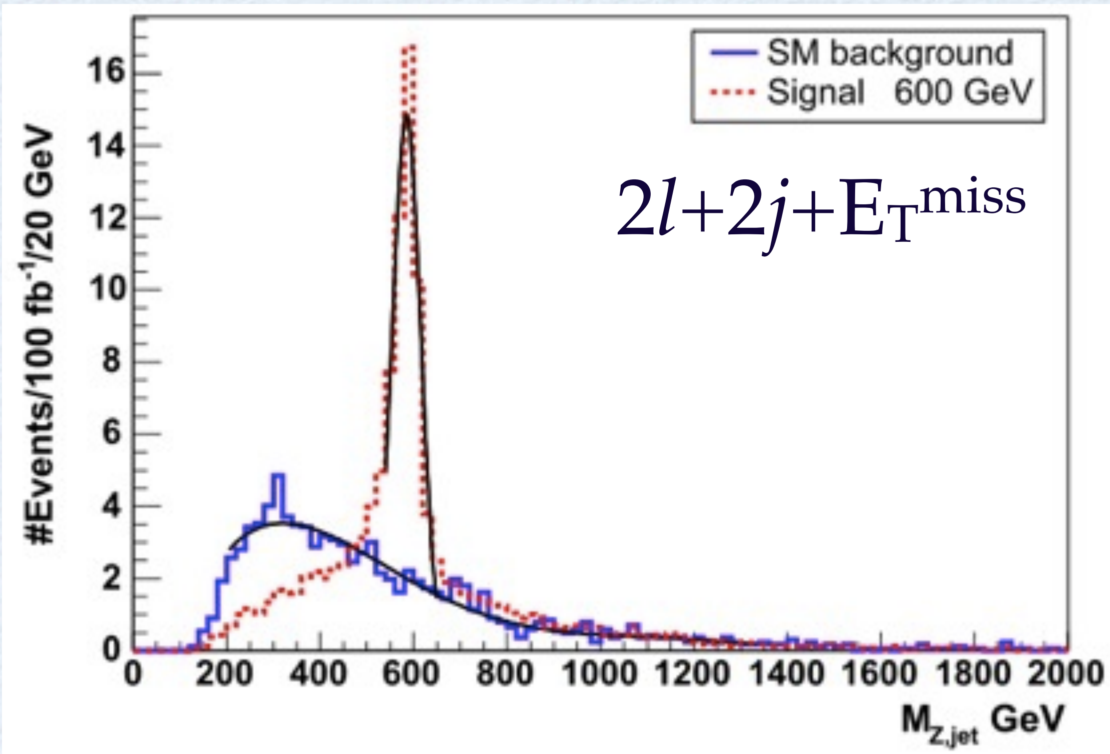
$D\bar{D} \to$	Final state	Expected signal	Decay B.R.	Total B.R.
$ZZd\bar{d}$	$Z \to \ell\bar{\ell}$ $Z \to \ell\bar{\ell}$	$4\ell + 2$jet	0.07×0.07	0.0005
0.33×0.33	$Z \to \ell\bar{\ell}$ $Z \to \nu\bar{\nu}$	$2\ell + 2$jet$+\not{E}_T$	$2 \times 0.07 \times 0.2$	0.0028
	$Z \to \ell\bar{\ell}$ $Z \to q\bar{q}$	$2\ell + 4$jet	$2 \times 0.07 \times 0.7$	0.0107
$ZWdu$	$Z \to \ell\bar{\ell}$ $W \to l\bar{\nu}$	$3\ell + 2$jet$+\not{E}_T$	0.07×0.21	0.0065
$2 \times 0.66 \times 0.33$	$Z \to \ell\bar{\ell}$ $W \to q\bar{q}$	$2\ell + 4$jet	0.07×0.68	0.0211

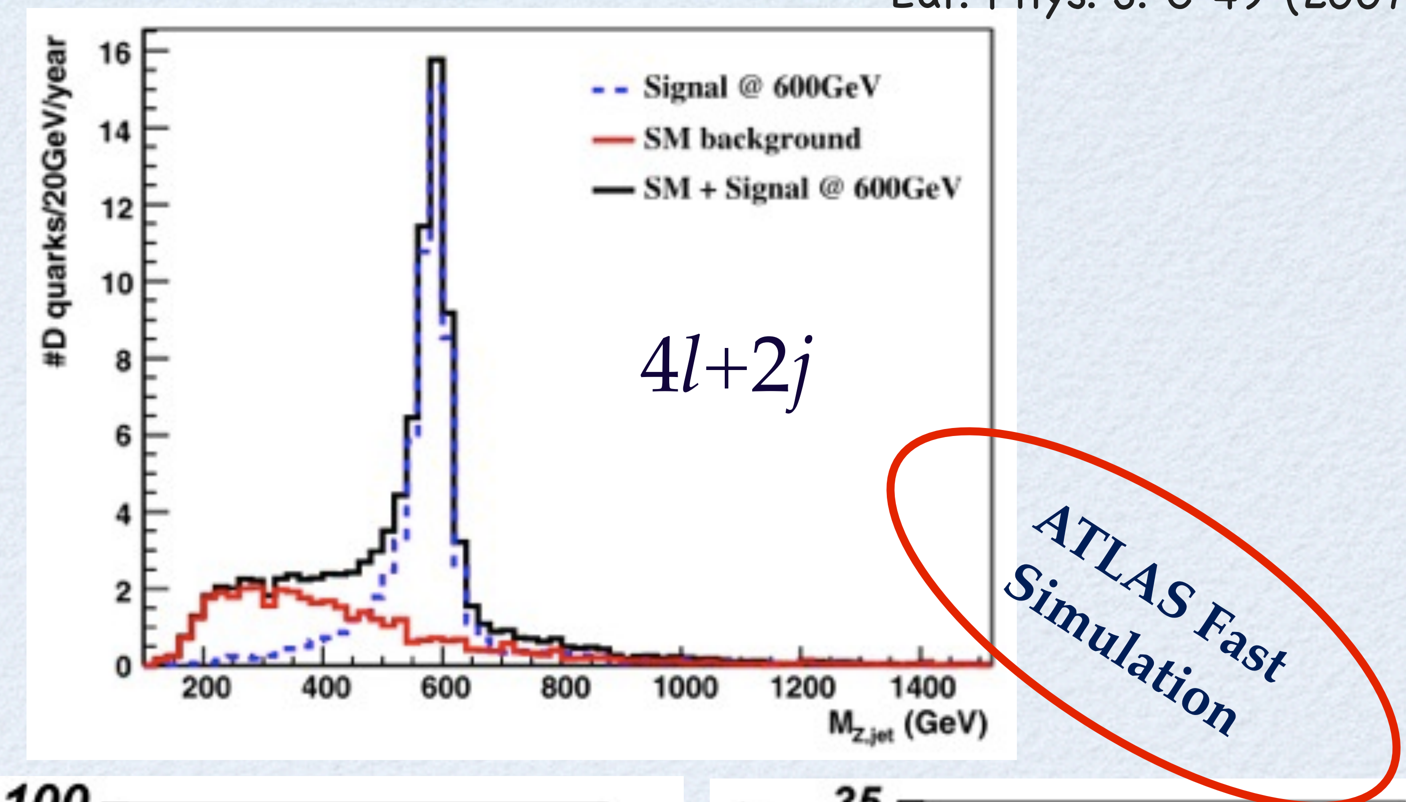
- All final states with at least one leptonic Z are studied.
- Highest P_T objects are used in each event:
  - Two hardest jets are taken to be D-quark daughters.
- Cuts slightly vary for different channels, but roughly:
  - $|\eta_{e,\mu,j}|<2.5$, $P_T^{e,\mu}>20$GeV, $P_T^{j}>80$GeV
  - $|m_{ll}-90|<20$GeV, $|m_{l\nu}^{visible}-80|<20$GeV, $|m_{jj}-85|<25$GeV
- Ambiguity in W/Z-jet assignment resolved by looking at min(Δm_D).

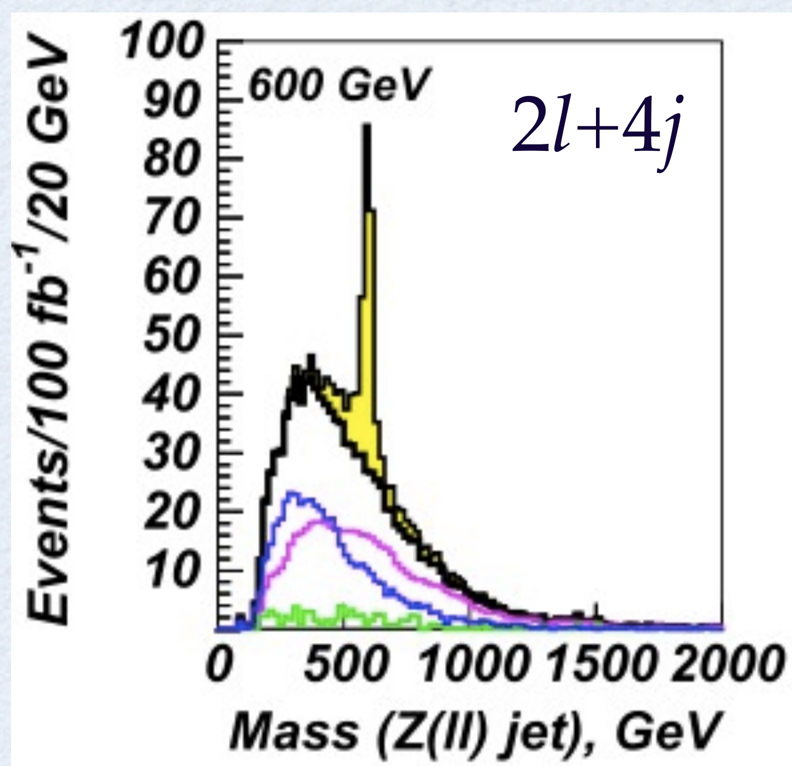
Backup slide: Kinematics

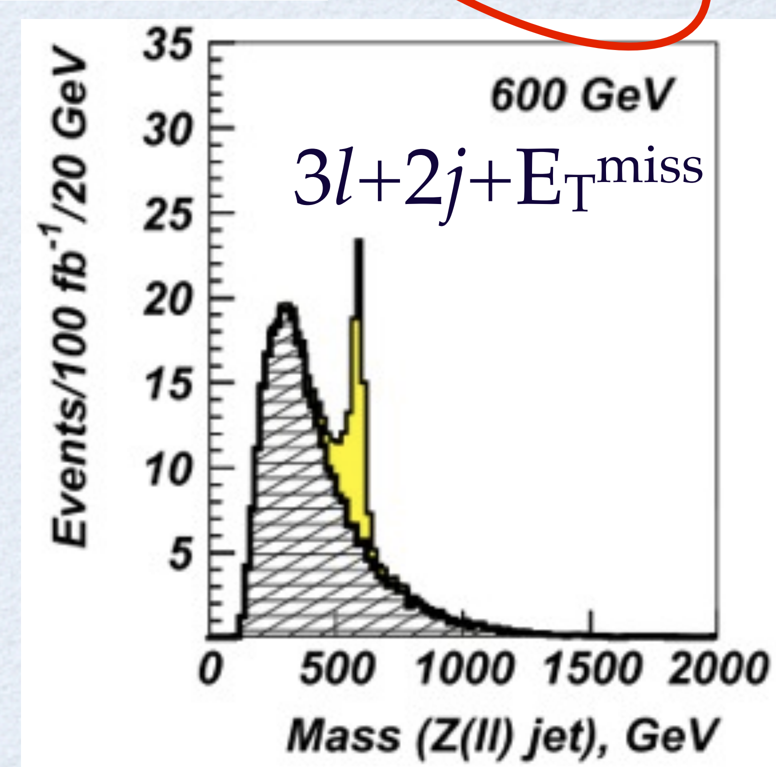
Reconstructed Quarks

Eur. Phys. J. C 54 (2008) 507
Eur. Phys. J. C 49 (2007) 613









- For all final states, clean signal peaks observed on smooth background shapes.

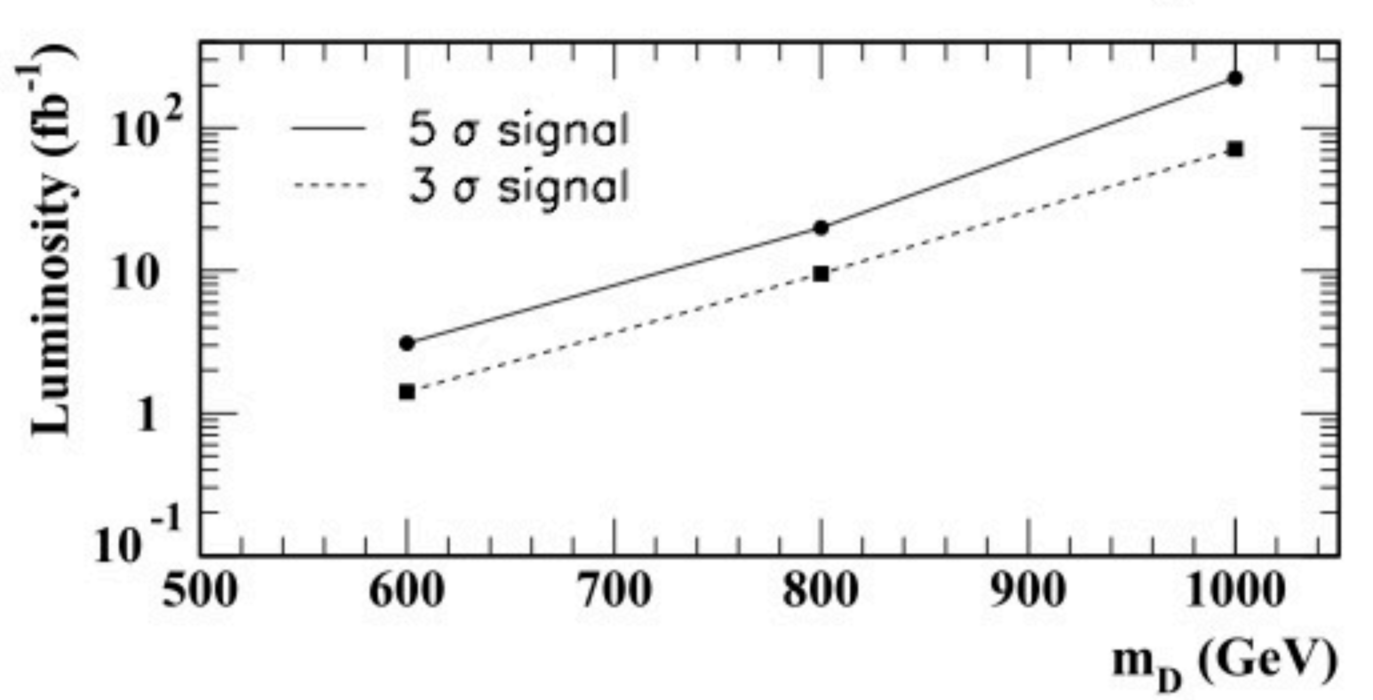
Combined Significance

Eur. Phys. J. C 54 (2008) 507

m_D (GeV)	600	800
$4\ell+2j$ signal	16	3.7
background	3.0	1.3
$-\ln$ p	21.47	4.78
$2\ell+2j+\not{E}_T$ signal	53	19
background	12	13
$-\ln$ p	120	15.81
$3\ell+2j+\not{E}_T$ signal	97	18.3
background	24.9	9.0
$-\ln$ p	191.4	20.66
$2\ell+4j$ signal	133	18
background	9	3
$-\ln$ p	983	25.3
$-\Sigma\ln$ p	1315.9	66.5
combined significance (σ)	51.3	11.3

- Expected number of signal events $\approx 2.8/\text{fb}^{-1}$ for m_D=600GeV

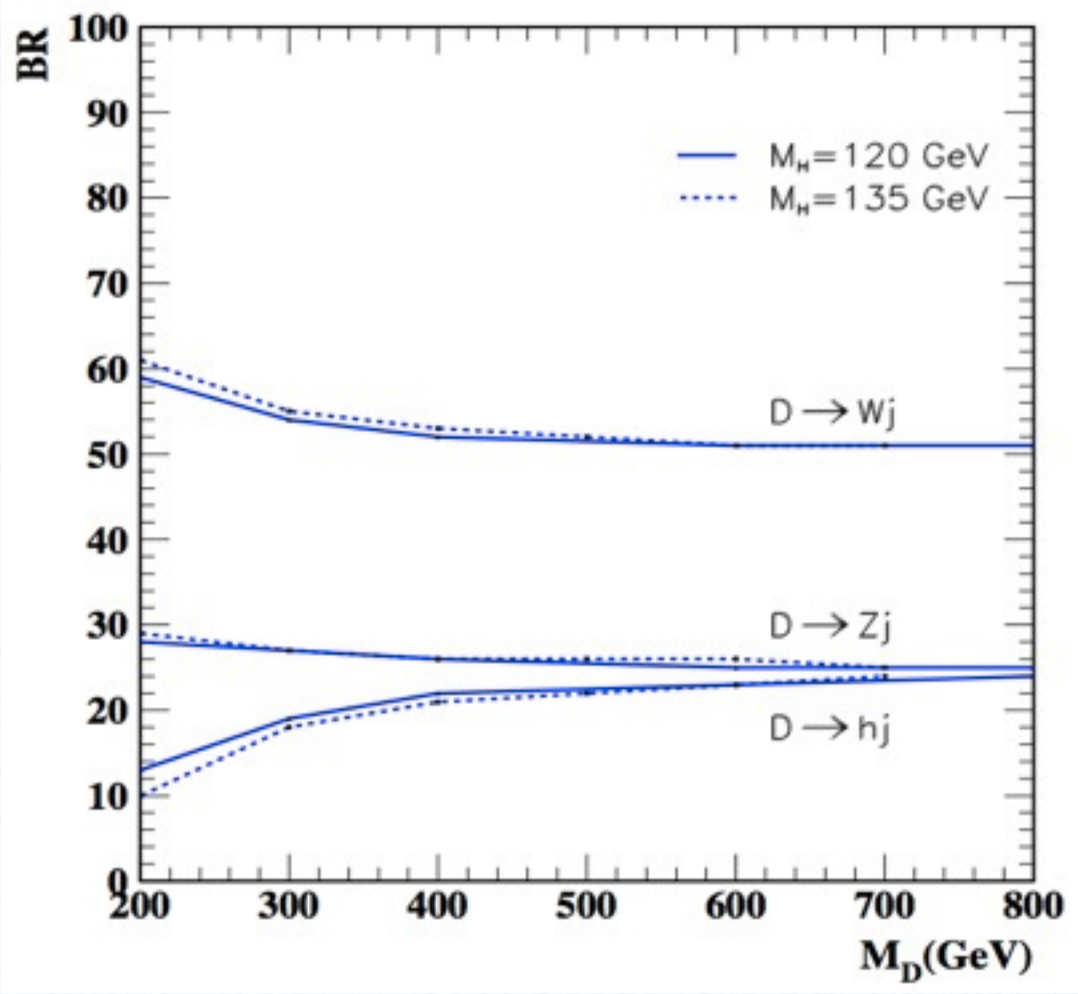
- Smooth background shape, clear signal peaks, extrapolation down:
  - Up to $m_D \approx 500$ GeV could be within reach with $\approx 1\text{fb}^{-1}$.



A Word on Higgs

Phys. Lett. B 669 (2008) 39

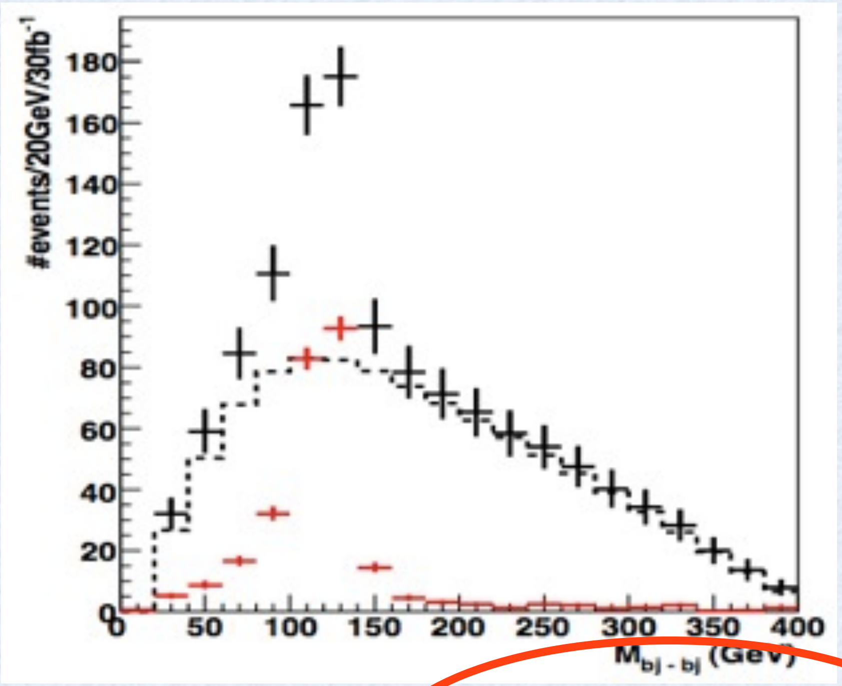
- If Higgs mechanism is still present and $m_h < m_D$, d-D mixing can lead to D->hd decays.
- For $m_h << m_D$, BR(D->hd)=25%.
- Light Higgs (~120GeV) & D quark studied in $H_{bb}jW_{jj}j$ final state.
- Similar cuts as ZjWj, but also b-tagging, $|\cos(\theta_{bb})|>-0.8$, $m_{jj}>90GeV$, $H_T>800GeV$

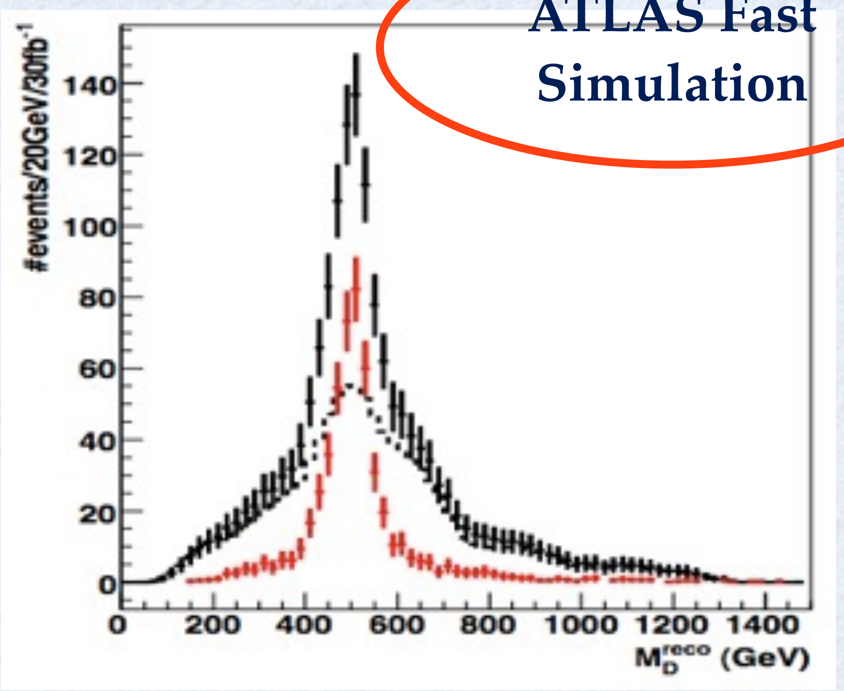


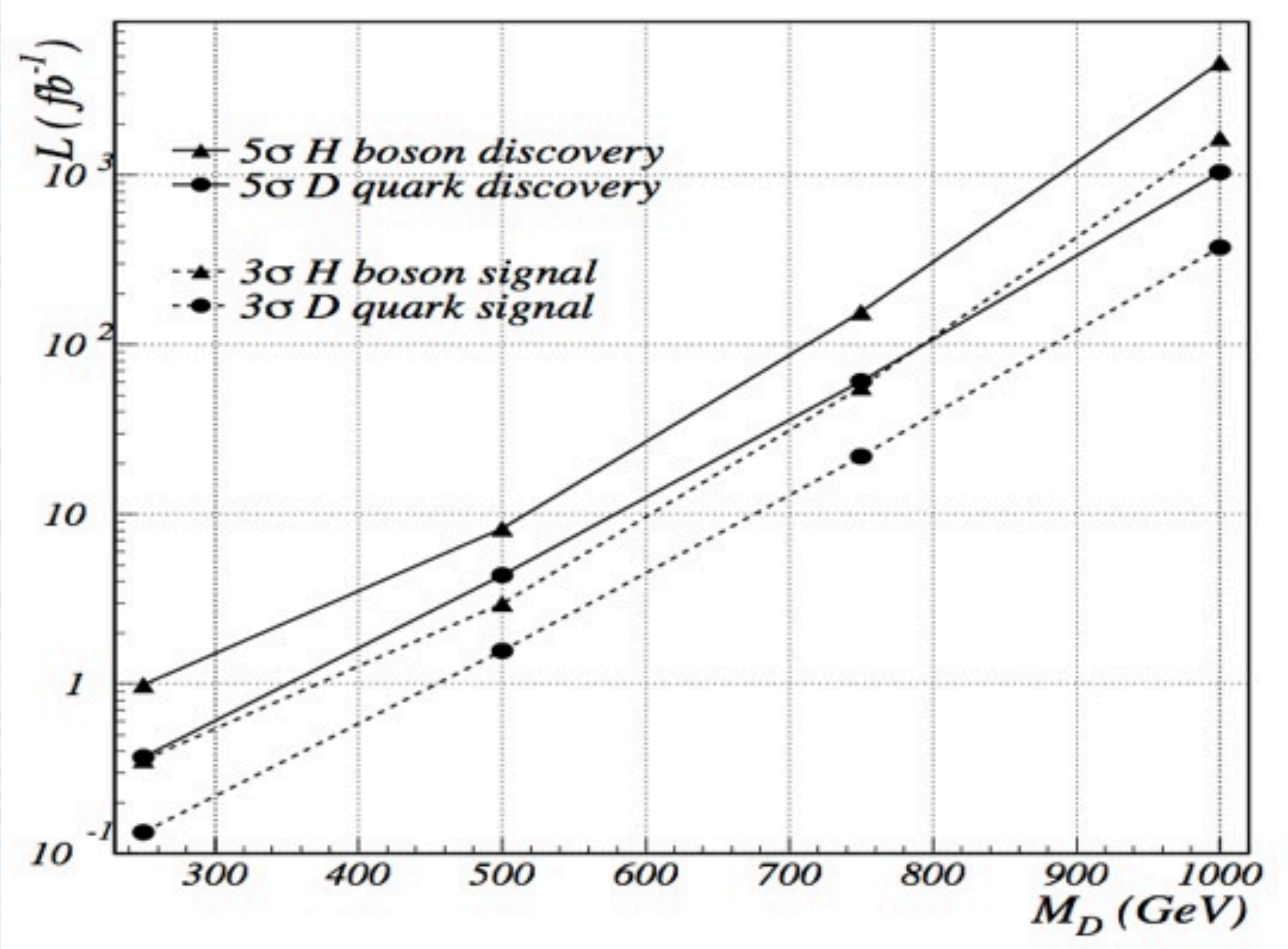
A Word on Higgs

Phys. Lett. B 669 (2008) 39

- With only this final state ($H_{bb}jW_{jjj}$), double discovery could be possible with a few fb^{-1} for mD≲400 GeV.

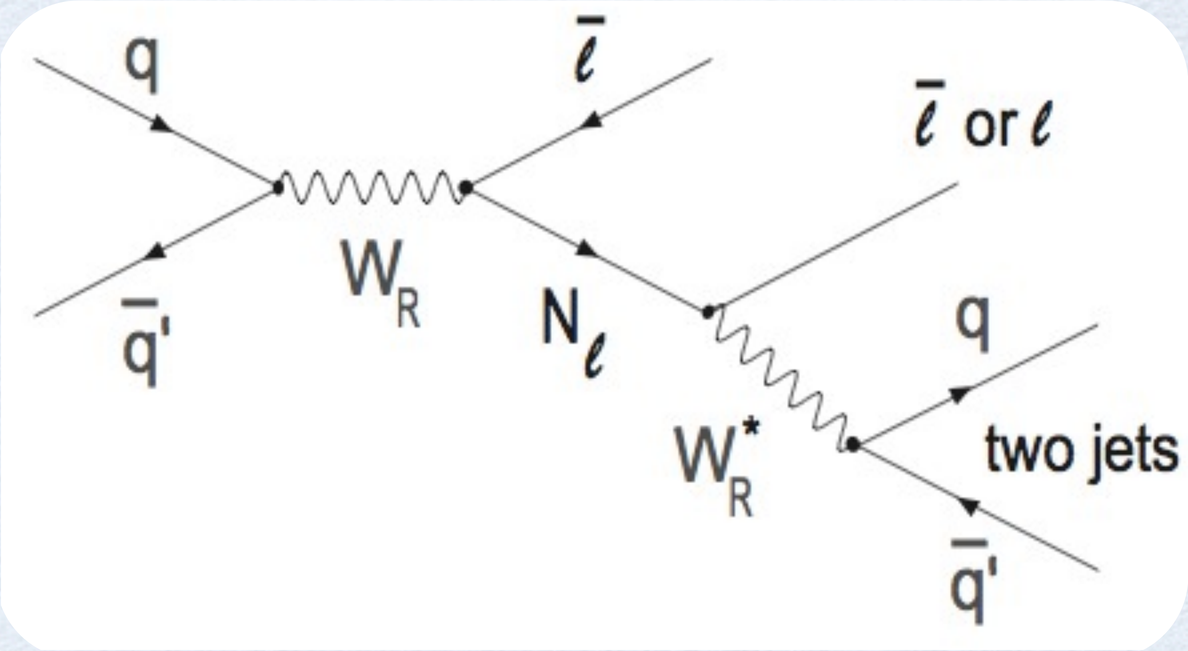






Majorana Neutrinos

- Left-Right Symmetric Models (LRSMs) address non-zero masses of neutrinos and baryogenesis.
  - Introduce 3 new heavy right-handed Majorana neutrinos, new bosons W_R & Z',...
  - Direct searches: $m(W_R) \gtrsim 750$ GeV.
  - W_R can be produced via the Drell-Yan process and decay to heavy neutrinos.



Signal and Backgrounds

Sample (l=e,μ)	Generator	x-section (pb)		
		no cuts	basic cuts, e-channel	basic cuts, μ-channel
pp->W_RX, W_R->lljj m(W_R,$N_{e,\mu}$)=1800,300 GeV	pythia	LO 0.25	0.088	0.145
pp->W_RX, W_R->lljj m(W_R,$N_{e,\mu}$)=1500,500 GeV	pythia	LO 0.47	0.220	0.328
pp->Z_{ll}X, mll>60GeV P_T^l>10GeV, $\lvert\eta^l\rvert$<2.7	pythia, herwig	NLO 1808	49.8	80.0
pp->tt, at least one e,μ with P_T^l>1GeV	mc@nlo	NLO+NLL 450	3.23	4.17
pp->VV, V=Z,W, m_{Z/γ^*}>20GeV, P_T^l>10GeV, $\lvert\eta^l\rvert$<2.8	herwig	NLO 60.9	0.610	0.876
multi-jet	pythia	10^8	20.5	0.0

- Basic cuts: 2e or 2μ well-identified, 2jets with cone0.4, ΔR(jet,any e)>0.1, $P_T^{l,j}$>20GeV, $\lvert\eta^l\rvert$<2.5, $\lvert\eta^j\rvert$<4.5, m_{ll}>70GeV

Event Selection

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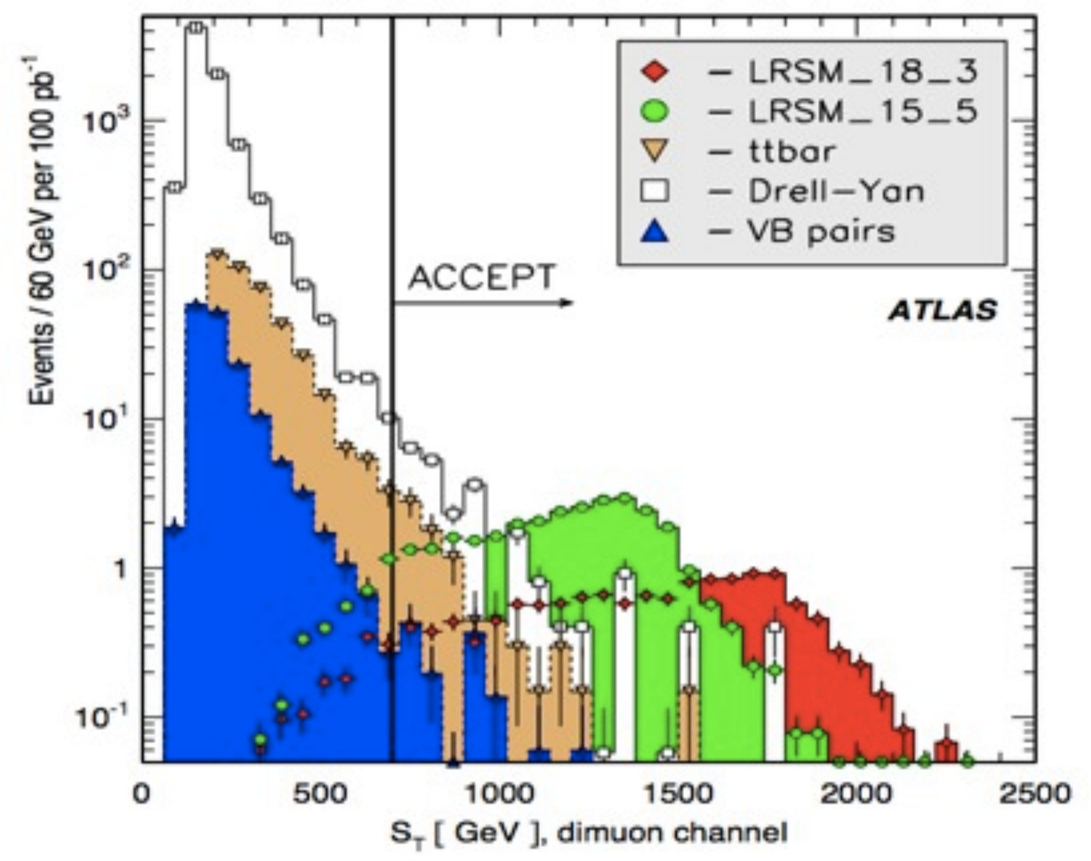
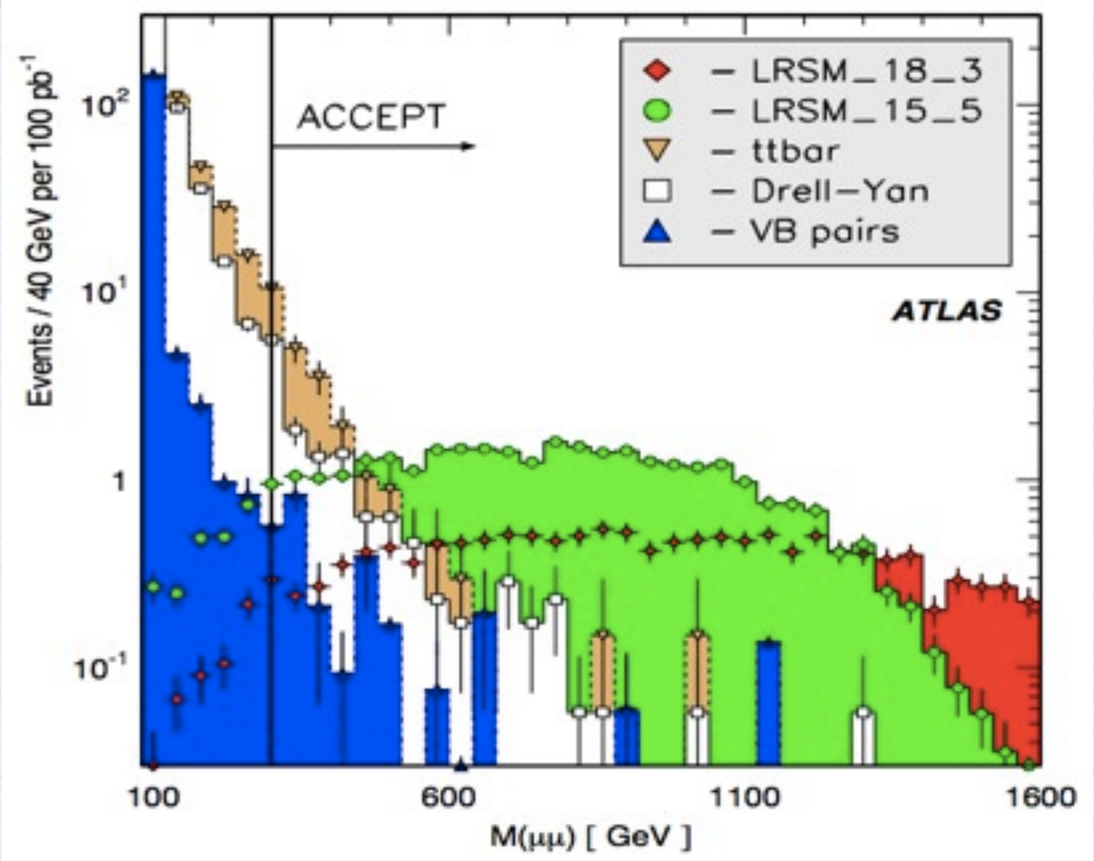




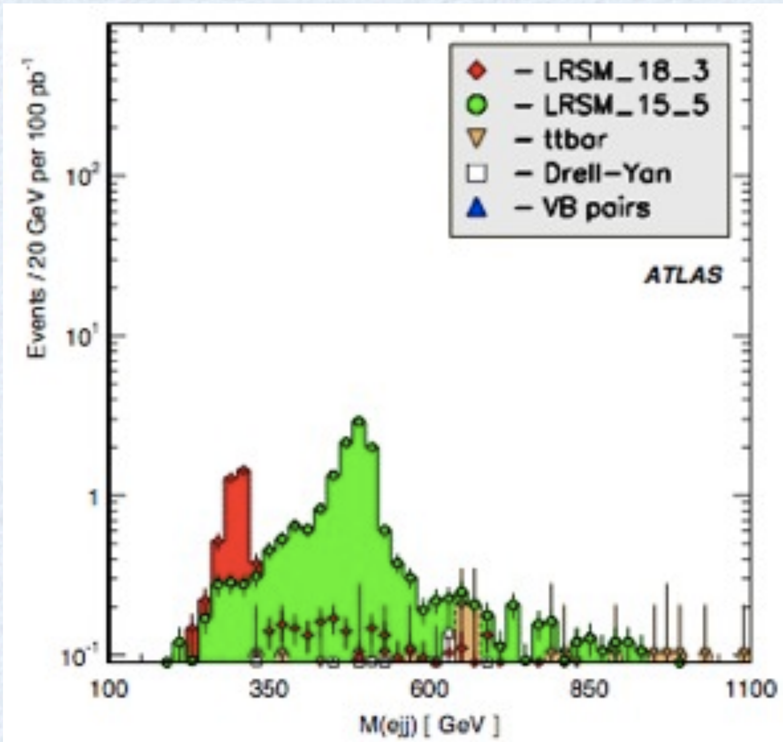
- Reconstruct from 2 highest-P_T jets and leptons
- S_T>700GeV (scalar ΣP_T of 2 jets and leptons), m_{ll}>300GeV
- Final signal region: m_{ljj}>100GeV, m_{lljj}>1000GeV

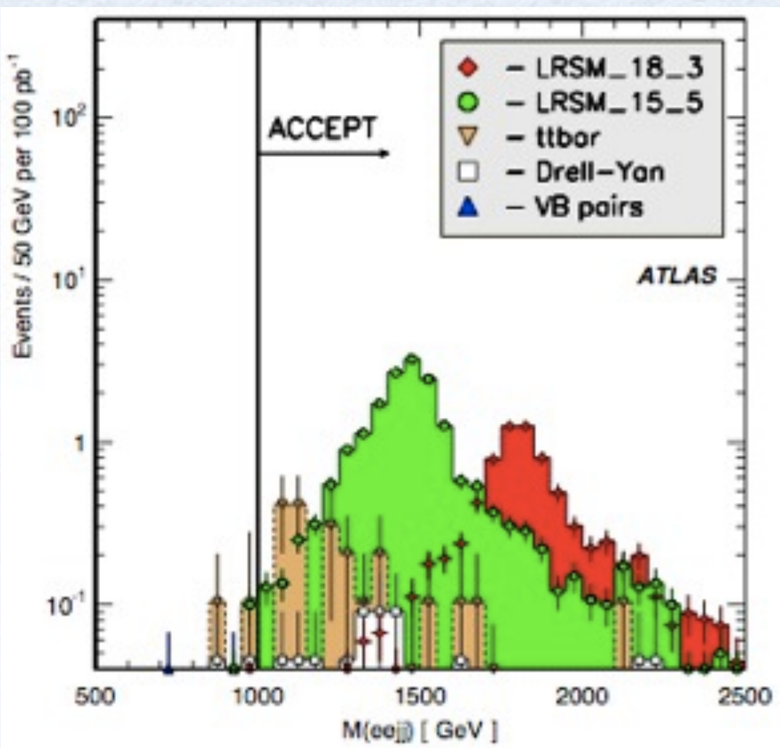
ATLAS Full Simulation

Reconstructed W_R & ν

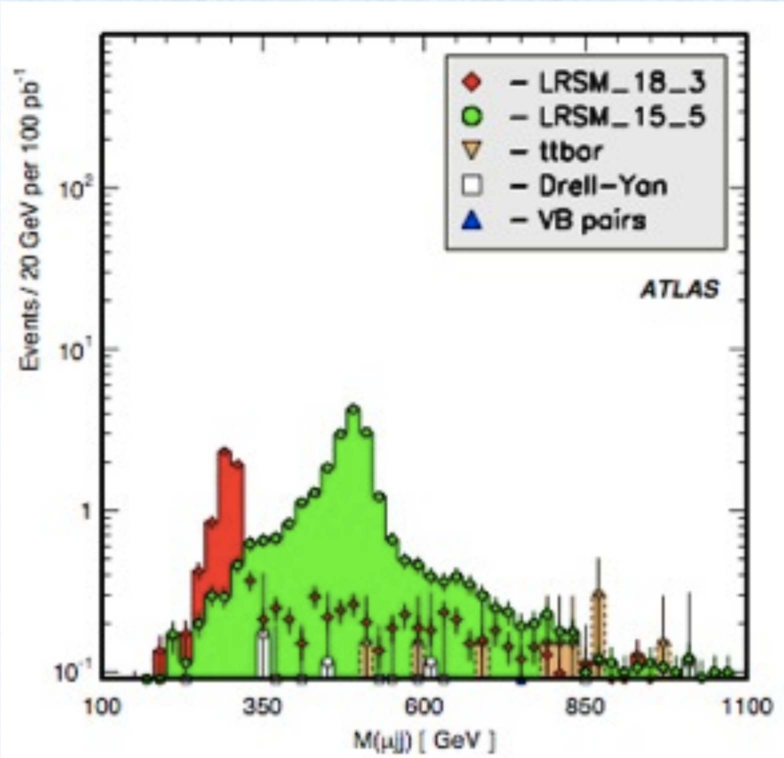
CERN-OPEN-2008-020

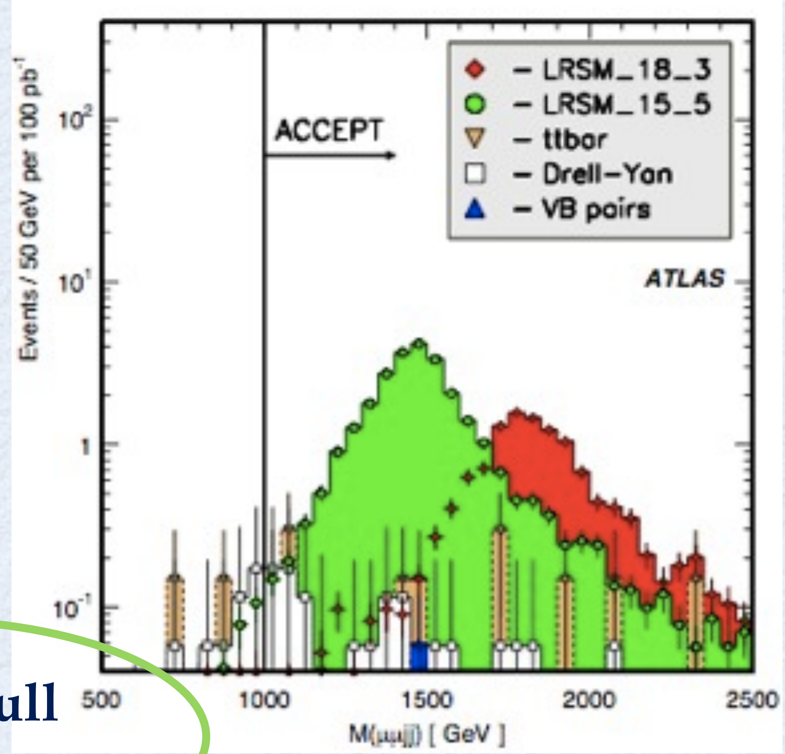
Electron channel





- After all cuts, backgrounds are about an order of magnitude smaller.
- 9-45 signal events @ 100pb^{-1}
- Multi-jet background not shown.
  - Can be important for e-channel.





Muon channel

ATLAS Full Simulation

Results

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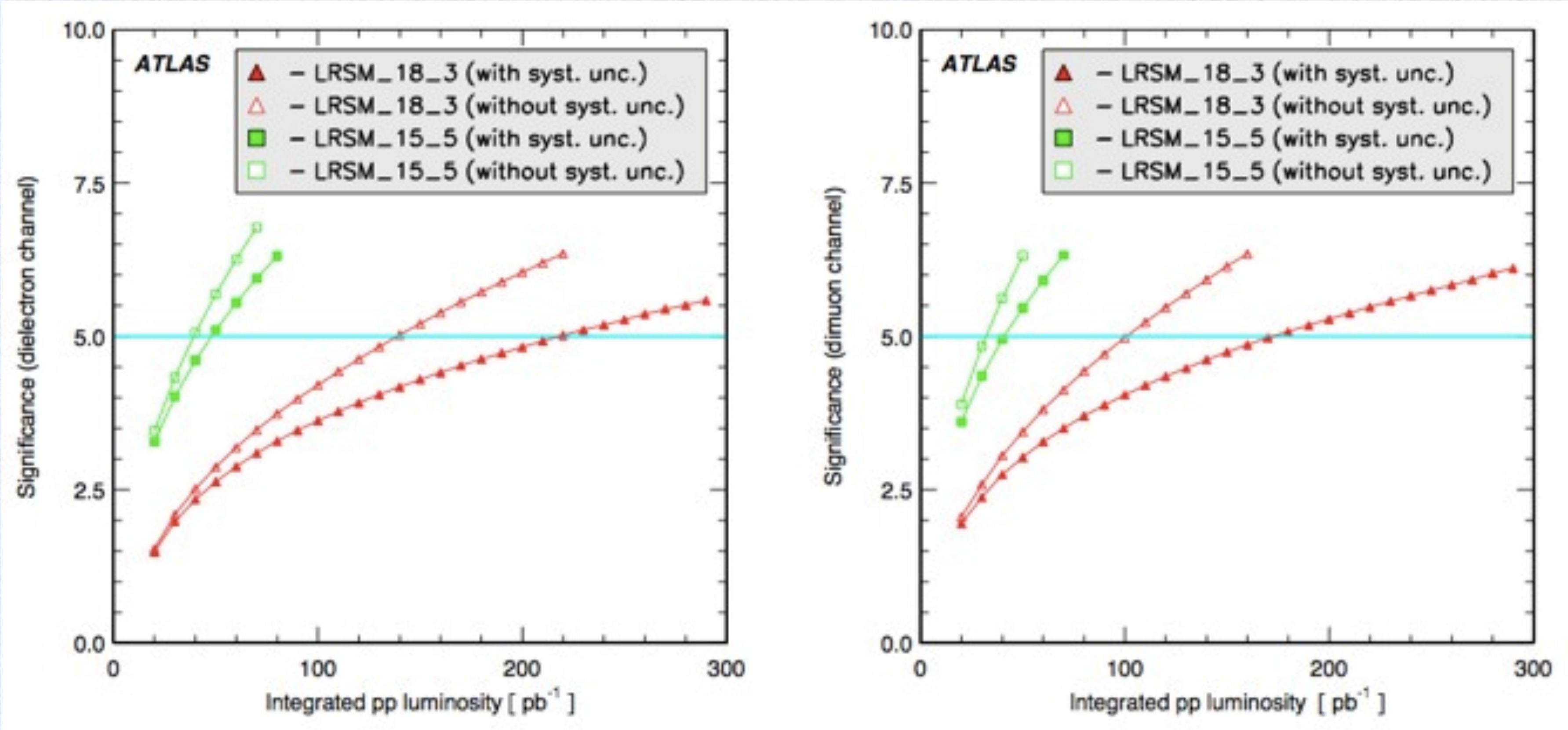
- Trigger efficiency (single e or μ triggers) ≳ 95%
- Systematics on the background estimation ≈ 40-45%
  - Largest contributors: Integrated luminosity measurement, jet energy scale and resolution, limited MC statistics.
  - Multi-jet background in e-channel & pileup not considered.



5σ discovery expected at **150pb^{-1}** and **40pb^{-1}** for $m(W_R,N_{e,\mu})$ = 1800,300 and 1500,500 scenarios respectively.

Conclusion

- New heavy fermions will be in the reach of ATLAS starting with the first $100pb^{-1}$ of data.
  - With 2010 data at low CM energy, heavy quark searches in FCNCs are likely to improve on Tevatron exclusion limits - discovery at high significance will probably require more data.
  - Heavy neutrino searches more promising. Same-sign leptons 50% of the time: Could further optimize cuts to focus on SS final states if needed.
- Looking forward to the 3rd WS† with results from data!

† In Istanbul???

Backups

CERN-OPEN-2008-020

Expected performance of ATLAS

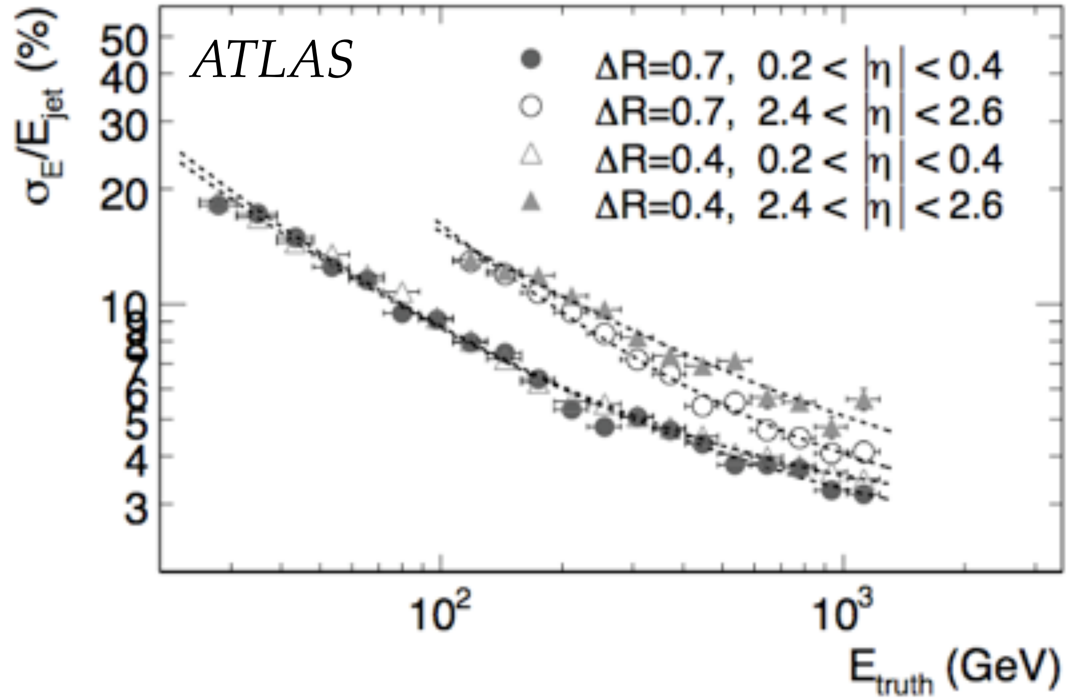
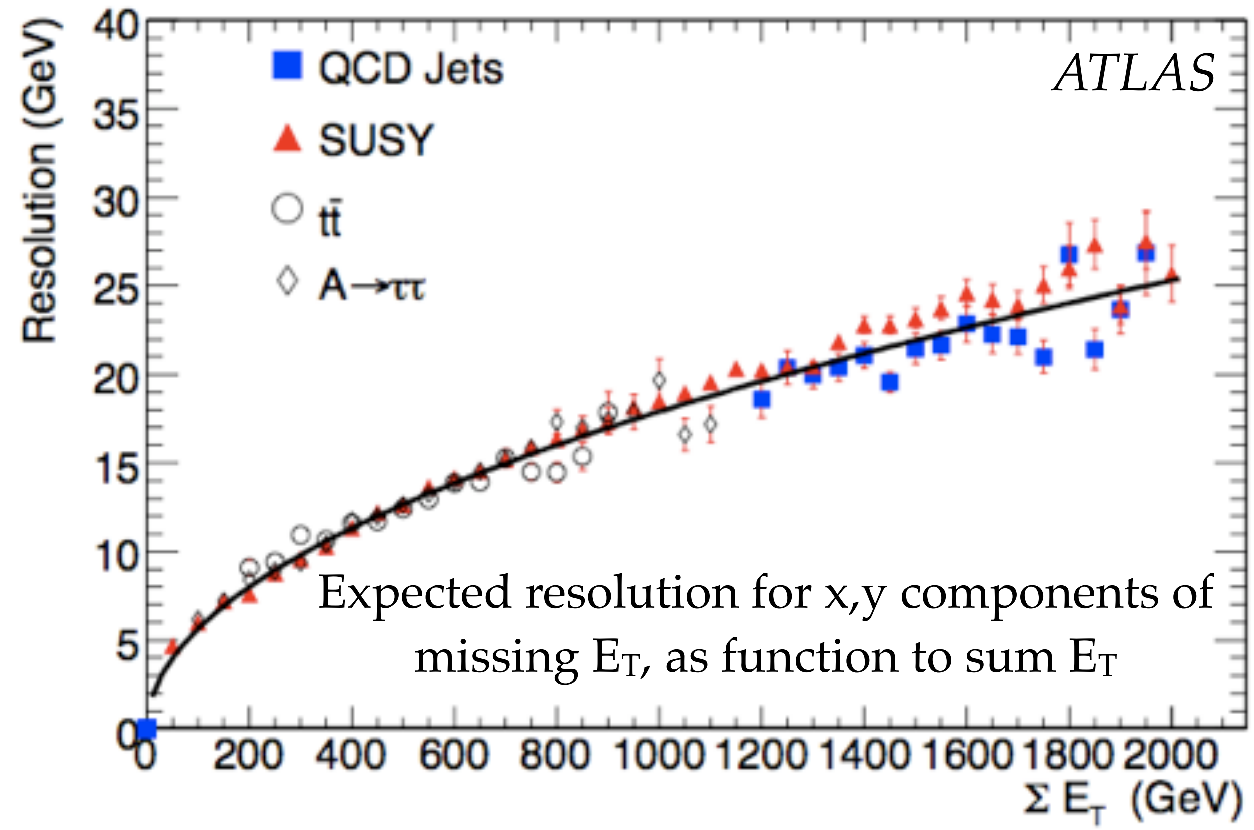


Figure 10.71: Fractional energy resolution for calibrated cone-tower jets reconstructed with $\Delta R = 0.7$ and Δ … of $|\eta|$ and as a …



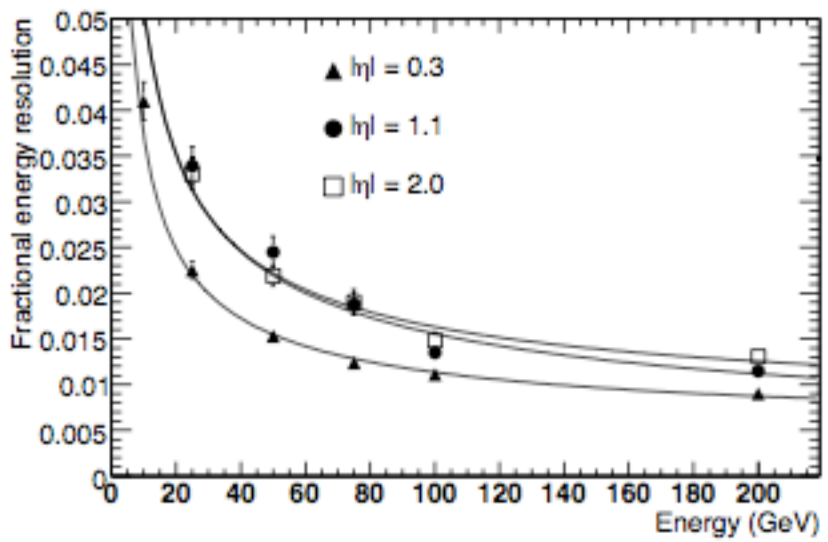


Figure 10.50: Expected relative energy resolution as a function of energy for electrons at $|\eta| = 0.3$, 1.1, and 2.0. The curves represent fits to the points at the same $|\eta|$ by a function containing a stochastic term, a constant term and a noise term.

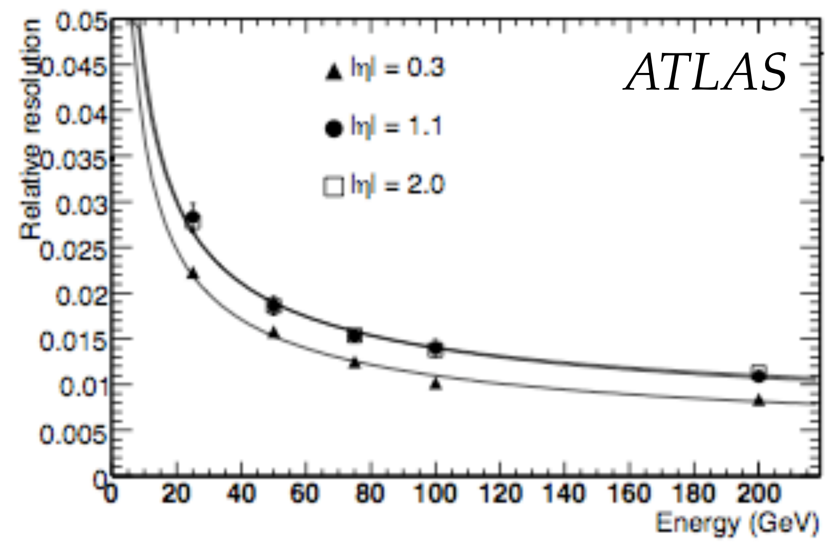


Figure 10.51: Expected relative energy resolution as a function of energy for photons at $|\eta| = 0.3$, 1.1, and 2.0. The curves represent fits to the points at the same η by a function containing a stochastic term, a constant term and a noise term.

Expected performance of ATLAS

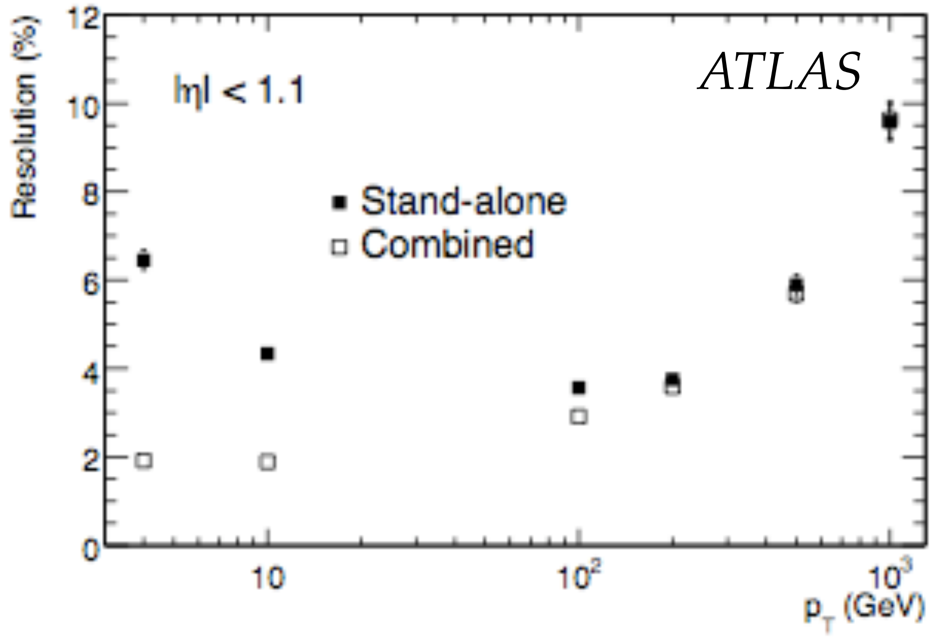


Figure 10.35: Expected stand-alone and combined fractional momentum resolution as a function of p_T for single muons with $|\eta| < 1.1$.

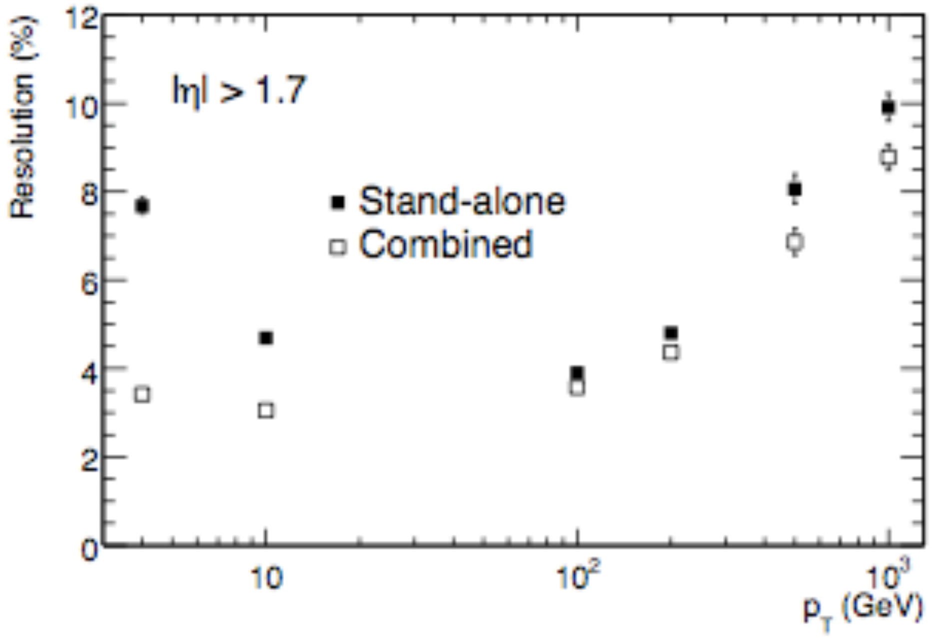


Figure 10.36: Expected stand-alone and combined fractional momentum resolution as a function of p_T for single muons with $|\eta| > 1.7$.

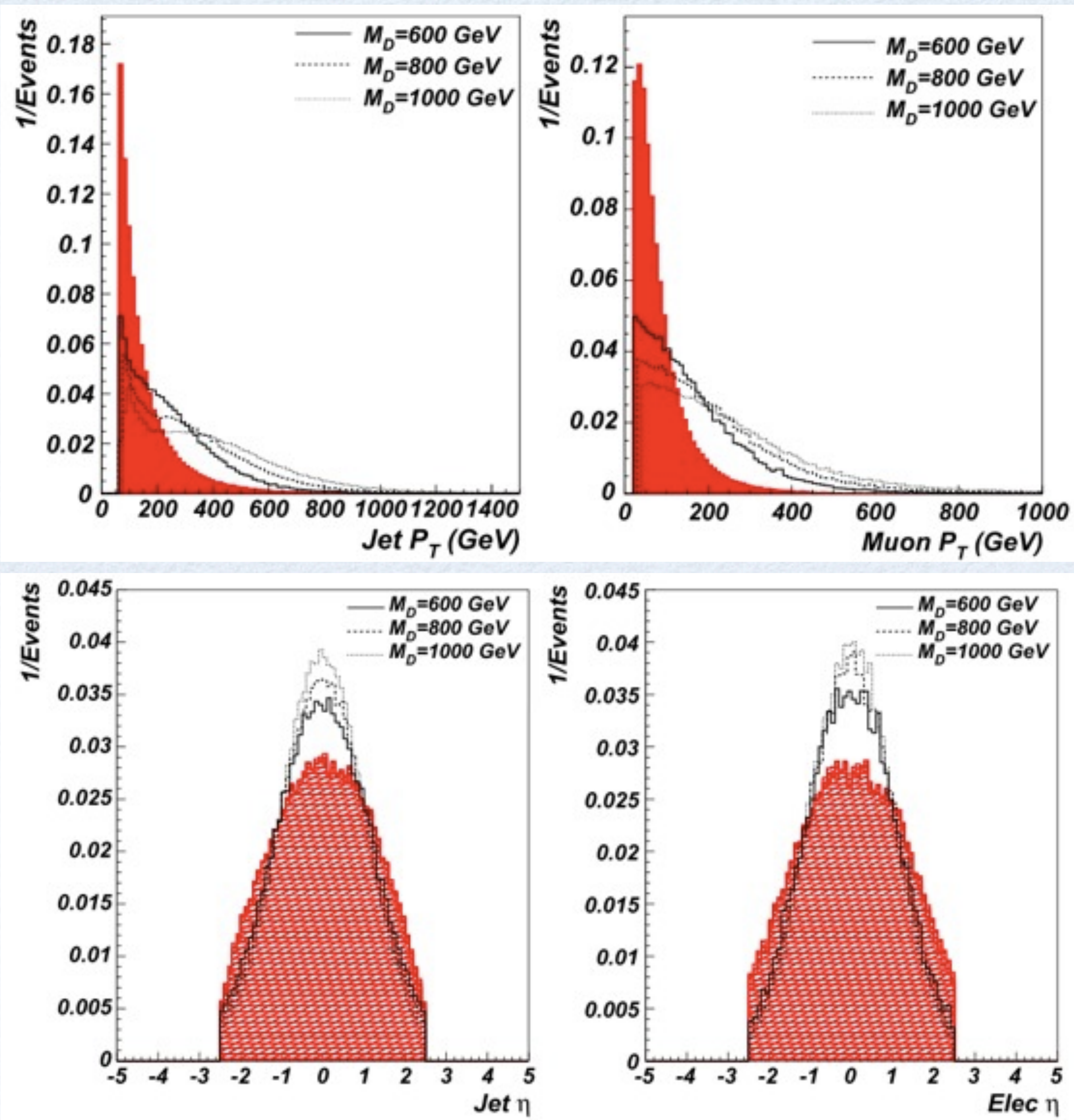
Track parameter	$0.25 < \|\eta\| < 0.50$		$1.50 < \|\eta\| < 1.75$	
	$\sigma_X(\infty)$	p_X (GeV)	$\sigma_X(\infty)$	p_X (GeV)
Inverse transverse momentum (q/p_T)	0.34 TeV^{-1}	44	0.41 TeV^{-1}	80
Azimuthal angle (ϕ)	70 μrad	39	92 μrad	49
Polar angle ($\cot\theta$)	0.7×10^{-3}	5.0	1.2×10^{-3}	10
Transverse impact parameter (d_0)	10 μm	14	12 μm	20
Longitudinal impact parameter ($z_0 \times \sin\theta$)	91 μm	2.3	71 μm	3.7

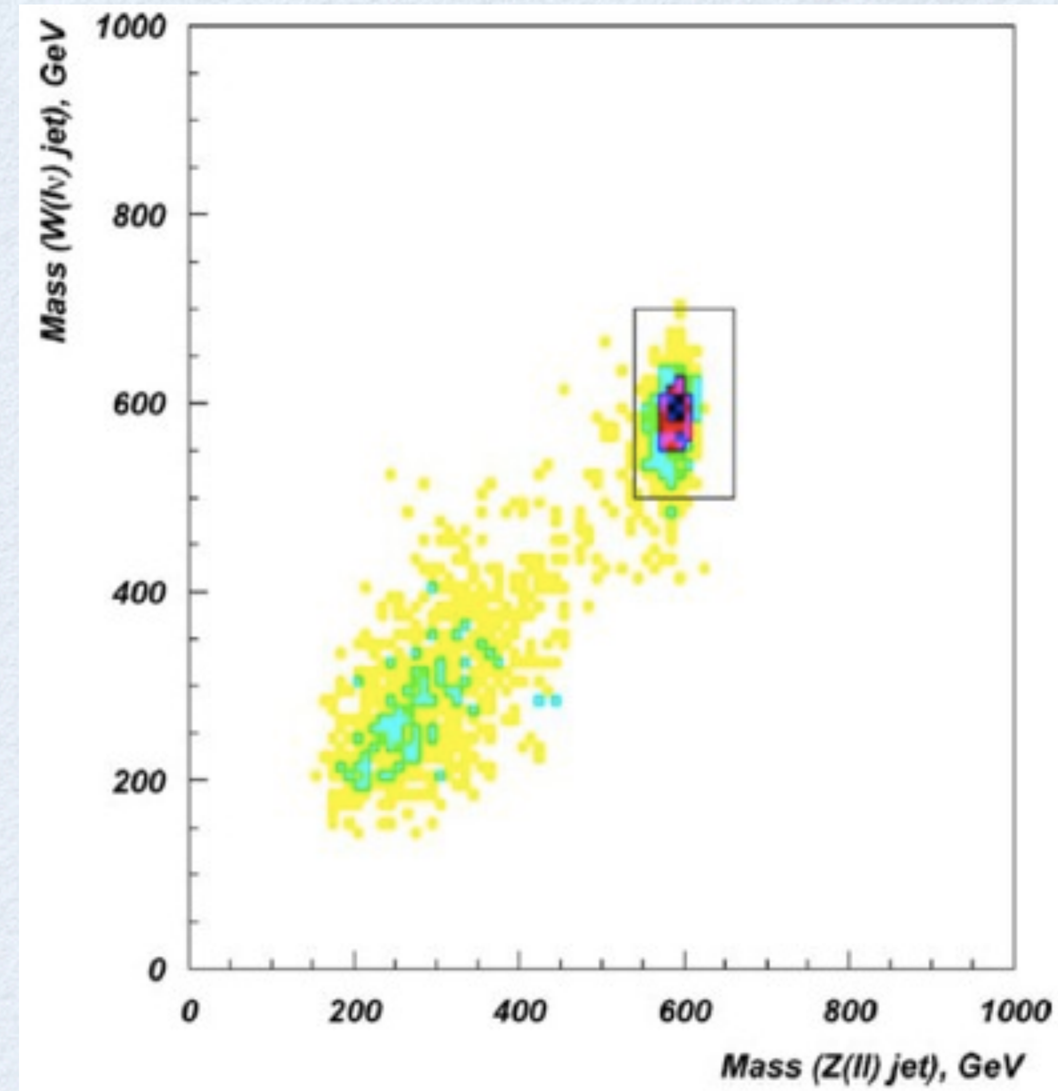
Table 3: Expected track-parameter resolutions (RMS) at infinite transverse momentum, $\sigma_X(\infty)$, and transverse momentum, p_X, at which the multiple-scattering contribution equals that from the detector resolution (see Eq. (1)). The momentum and angular resolutions are shown for muons, whereas the impact-parameter resolutions are shown for pions (see text). The values are shown for two η-regions, one in the barrel inner detector where the amount of material is close to its minimum and one in the end-cap where the amount of material is close to its maximum. Isolated, single particles are used with perfect alignment and calibration in order to indicate the optimal performance.

$$\sigma_X(p_T) = \sigma_X(\infty)(1 \oplus p_X/p_T)$$

Kinematics for ISVLQ reconstruction

Eur. Phys. J. C 54 (2008) 507





- Various distributions from the ISVLQ analyses (ATLAS fast simulation)