Experimental Search for

Extra Dimensions

ATLAS Studies

[No mini black holes, no string balls]

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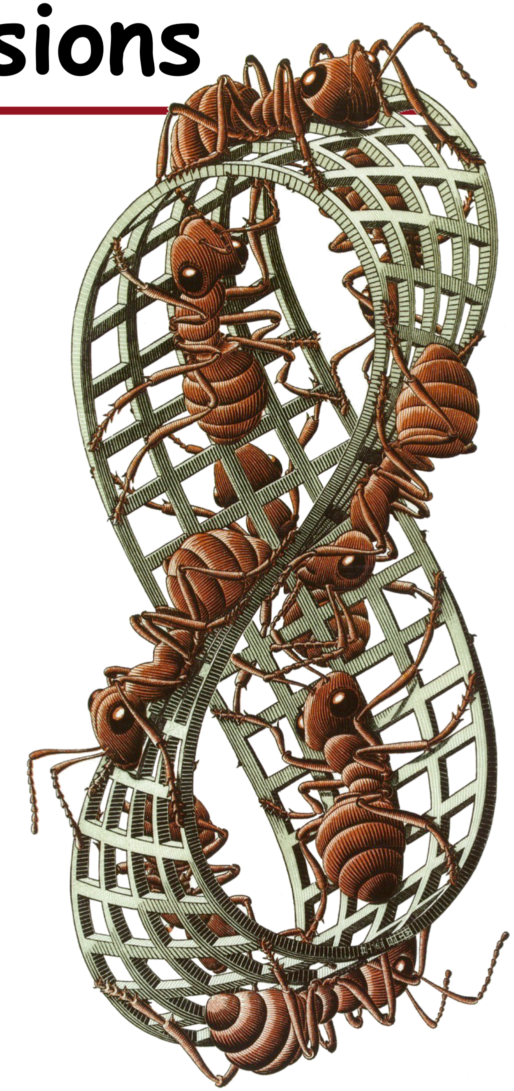
Heidelberg, July 24th, 2009

Models with Extra Dimensions



Large Extra Dimensions

Size: » TeV^{-1}; SM-particles on brane; gravity in bulk
KK-towers (small spacing); KK-exchange; graviton prod.
Signature: e.g. x-section deviations; jet+$E_{T,miss}$ ....

Warped Extra Dimensions

5-dimensional spacetime with warped geometry
Graviton KK-modes (large spacing); graviton resonances
Signature: e.g. resonance in ee, μμ, γγ-mass distributions ...

TeV-Scale Extra Dimensions

SM particles allowed to propagate in ED of size TeV^{-1}
[scenarios: gauge fields only (nUED) or all SM particles (UED)]

nUED : KK excitations of gauge bosons
UED : KK number conservation; KK states pair produced (at tree-level) ...
Signature: e.g. Z'/W' resonances, dijets+$E_{T,miss}$, heavy stable quarks/gluons...

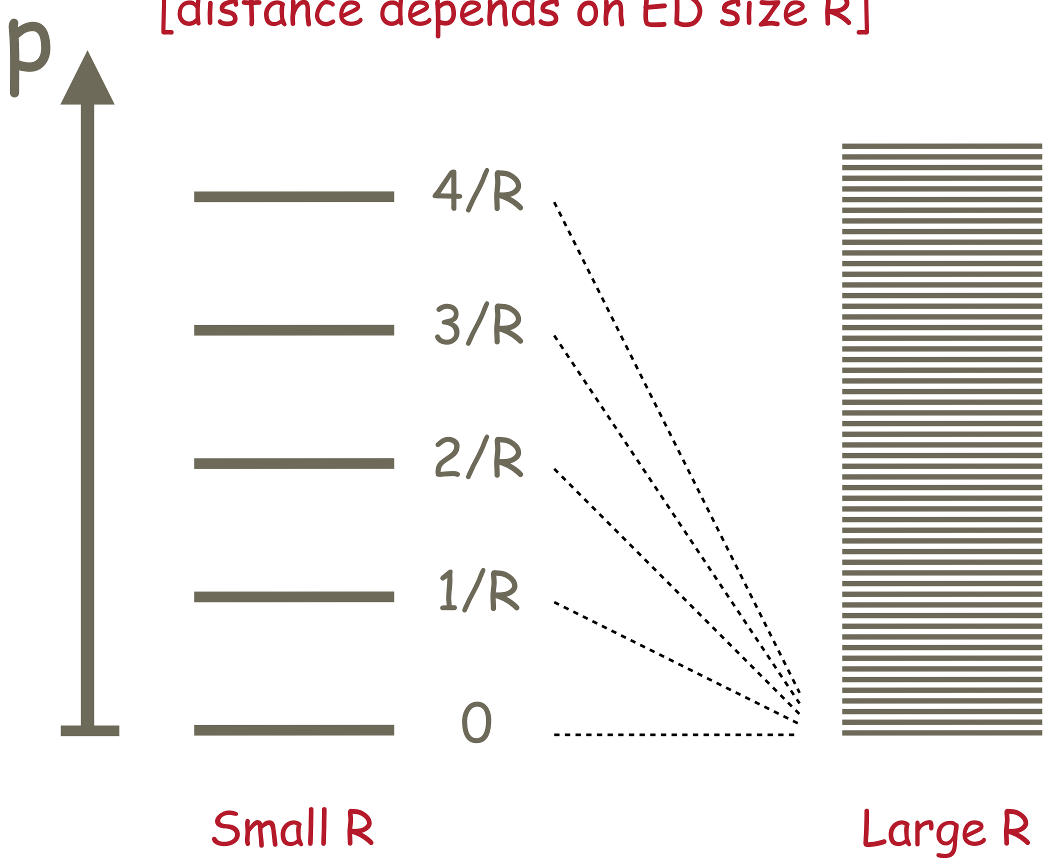
Kaluza-Klein States

$$E^2 = (p_x c)^2 + (p_y c)^2 + (p_z c)^2 + \underbrace{(p_{\text{extra}} c)^2 + (mc^2)^2}$$

Extra mass states
in 4-dim. spacetime

[p_{extra} = n/R quantized]

KK-Towers
[distance depends on ED size R]



Small R:
Well separted KK-states

Large R:
Finely separted KK-states

Possible Signatures & Needs

Dilepton Resonances

e.g.: Z' resonances, graviton production

Photon-Photon Resonances

e.g.: resonant graviton production

Lepton-Neutrino Resonances

e.g.: KK states of W-boson

Compositeness Signatures

e.g.: virtual graviton exchange

Monojets, single photon and $E_{T,miss}$ ...

e.g.: graviton radiation

Exp. needs:

High energy/luminosity

Lepton reconstruction
Photon reconstruction
Jet reconstruction
Good mom./energy resolution
Good $E_{T,miss}$ determination

The ATLAS Detector

EM calorimeter: $\sigma/E \approx 10\%/\sqrt{E} \oplus 0.7\%$

Very good e/γ identification

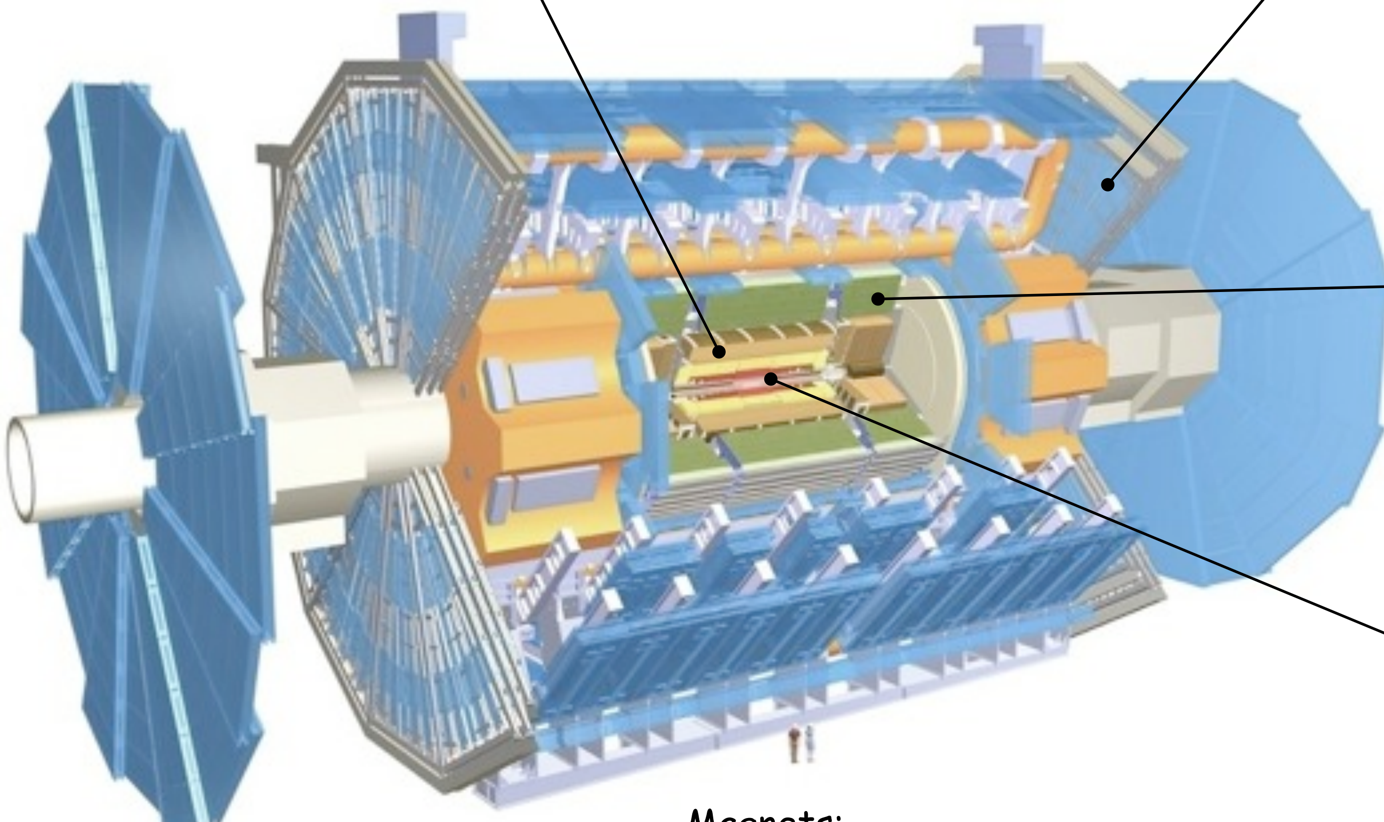
Good energy resolution (e.g. for $G \to \gamma\gamma, ee$)

Fast trigger signals ...

High-precision muon spectrometer: $\sigma/p_t \approx 10\%$ @ 1 TeV

Good momentum resoluton (e.g. $Z' \to \mu\mu$, $G \to \mu\mu$)

Fast trigger signals ...



Hadron calorimeter:

$\sigma/E \approx 50\%/\sqrt{E} \oplus 3\%$

Jet-Trigger

Good jet energy resolution

Good E_T/ $E_{T,miss}$ resolution

(e.g. $qq \to gG$)

Tracking detectors:

Si-pixel & Si-strips; TRT

$\sigma/p_t \approx 5 \cdot 10^{-4}\, p_t \oplus 0.001$

Good impact parameter resol.

$\sigma(d_0) \approx 15\ \mu m$ @ 20 GeV

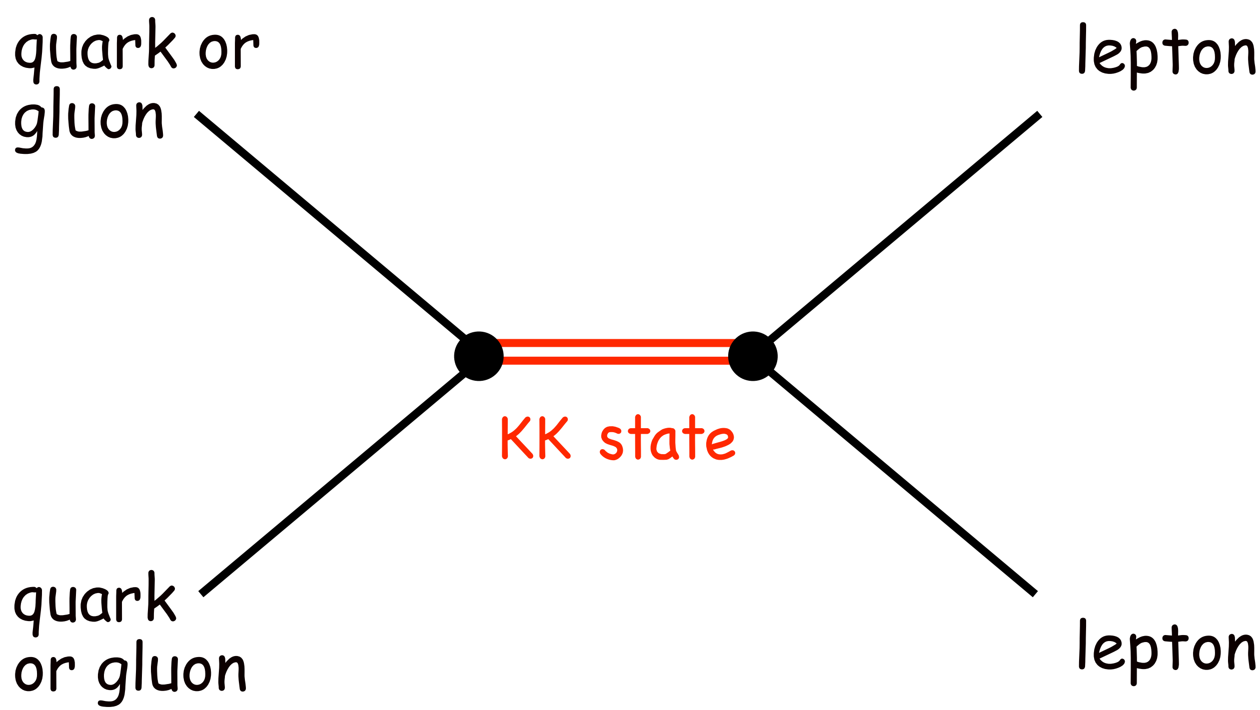
(e.g. tt-resonances)

Magnets:

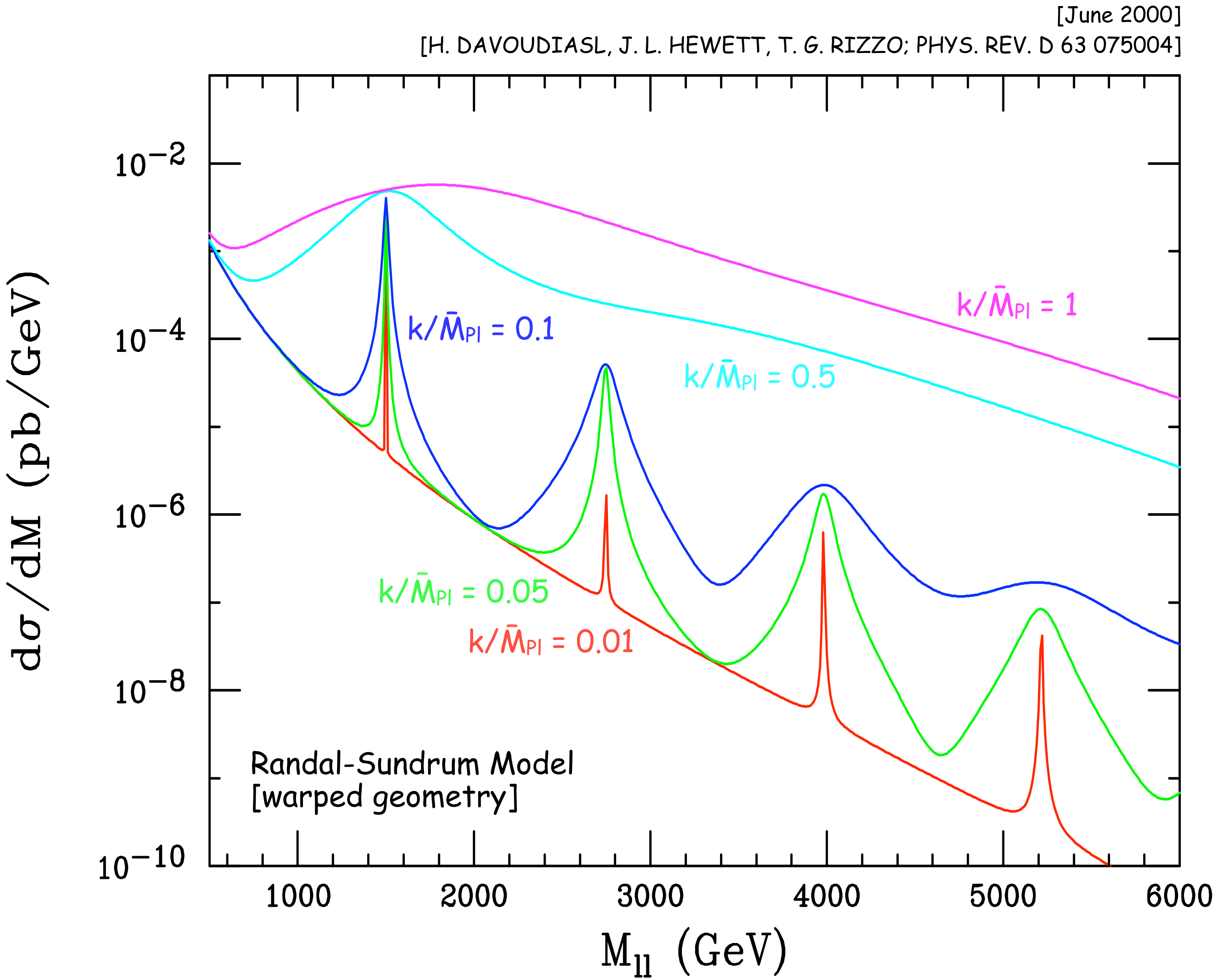
Solenoid (inner detectors): 2 T

Toroid (muon spectrometer): 0.5 T

Dilepton Resonances



KK gravitons @ LHC



1500 GeV

KK graviton

... and subsequent towers

Width:

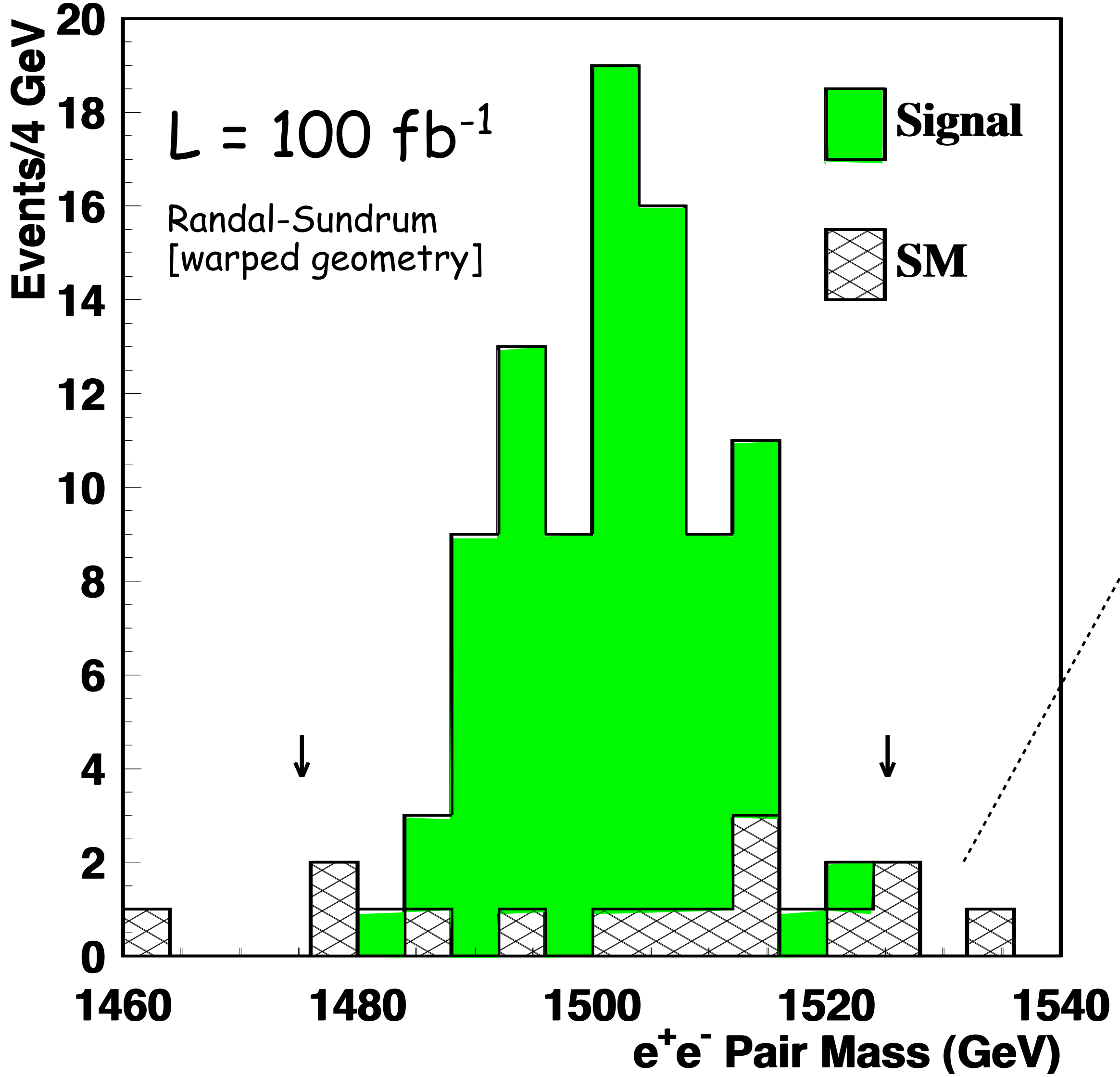
$\Delta M \sim [k/\bar{M}_{Pl}]^2$

k: AdS_5 curvature

$\bar{M}_{Pl}$: red. 4D planck mass

KK graviton detection

[Allanach et al., JHEP 0009:019 (2000)]



ATLFAST Study
from 2000

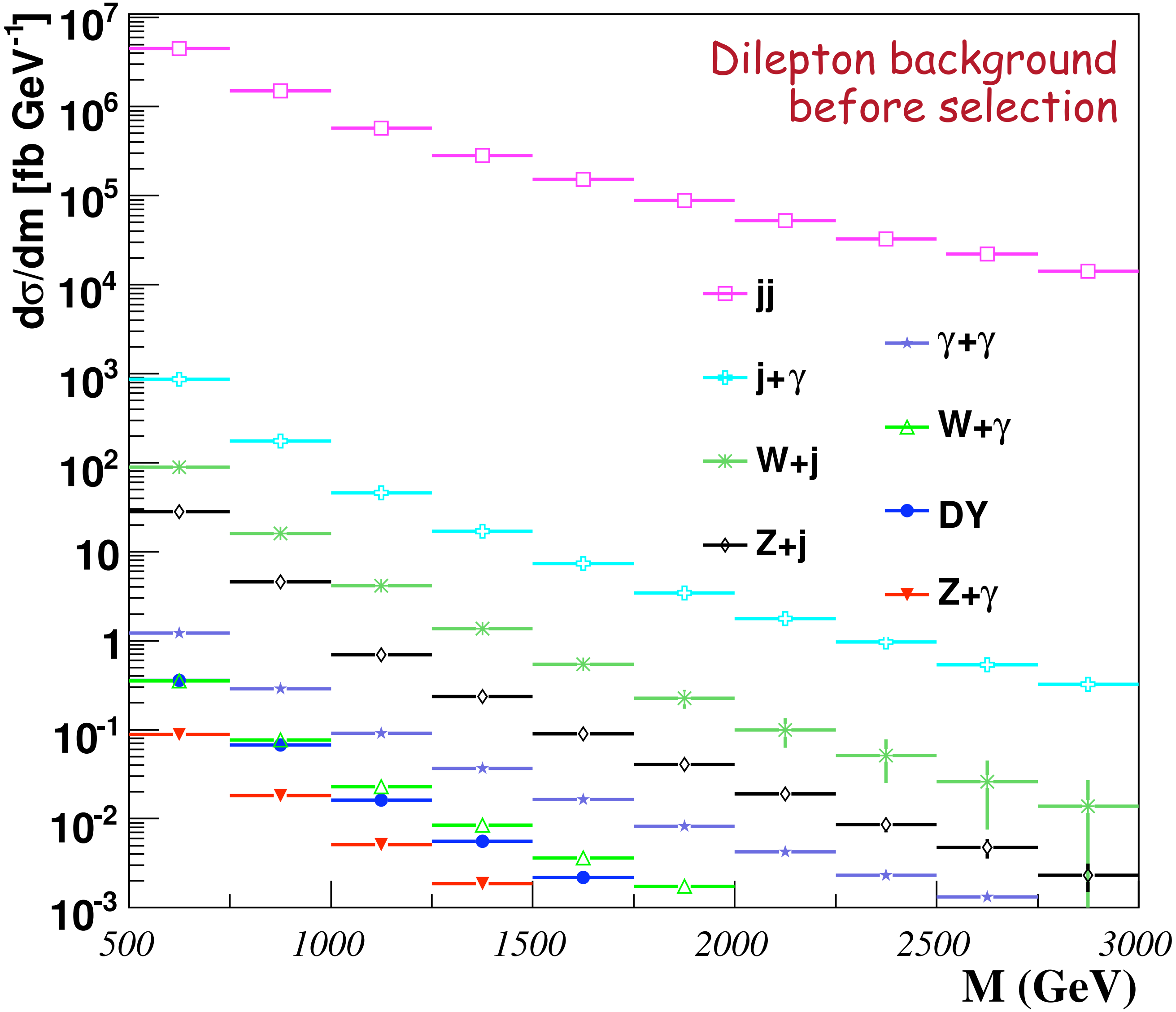
Background:
Drell-Yan only

Selection:
$|\eta| < 2.5$, p » 100 GeV;
electron isolation

Assume 90% tracking eff.

Dilepton Background

[ATLAS "CSC Book", arXiv:0901.0512]

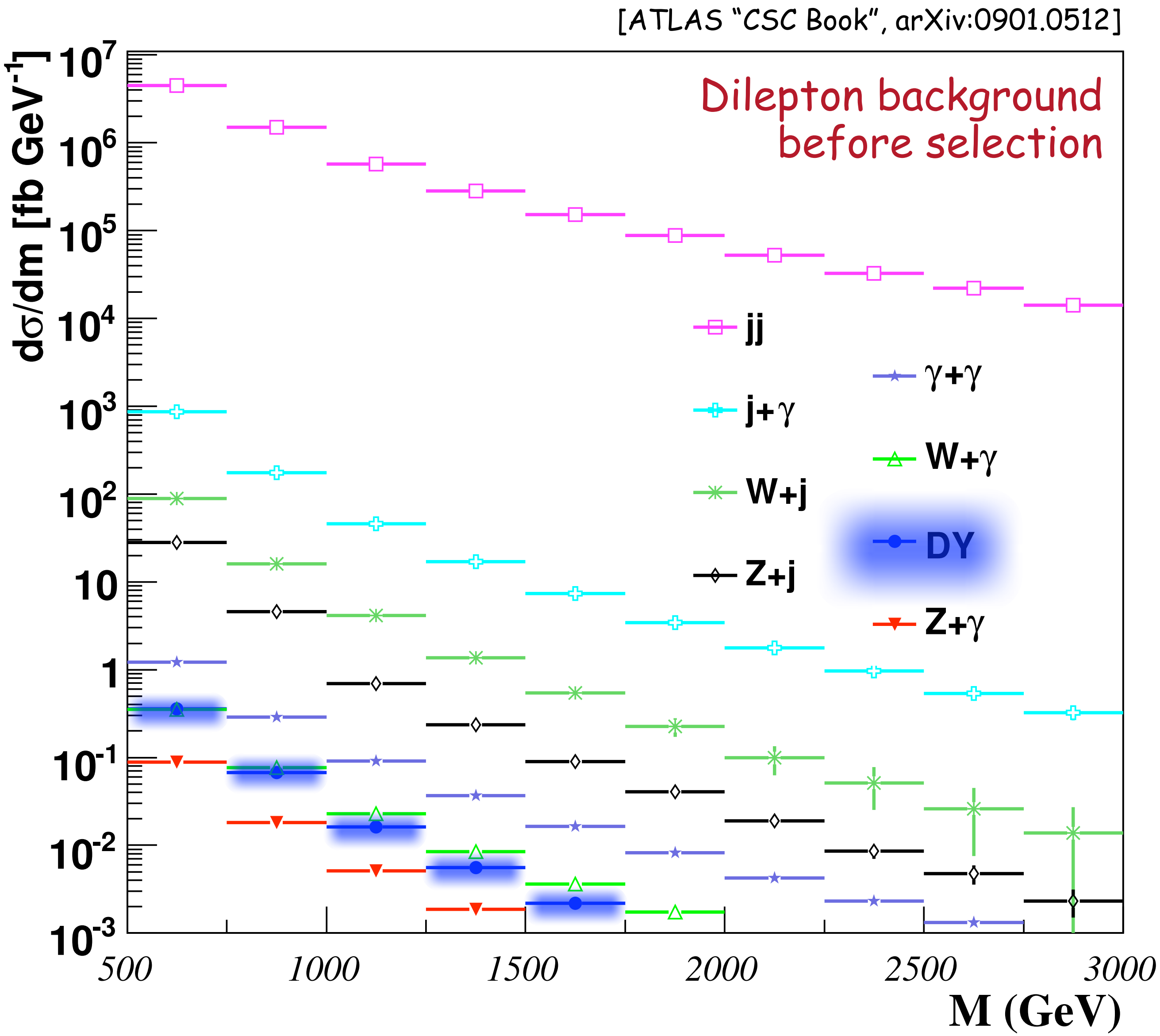


Drell-Yan dominant ?

e.g. jet → e ?

γ → e ?

Dilepton Background



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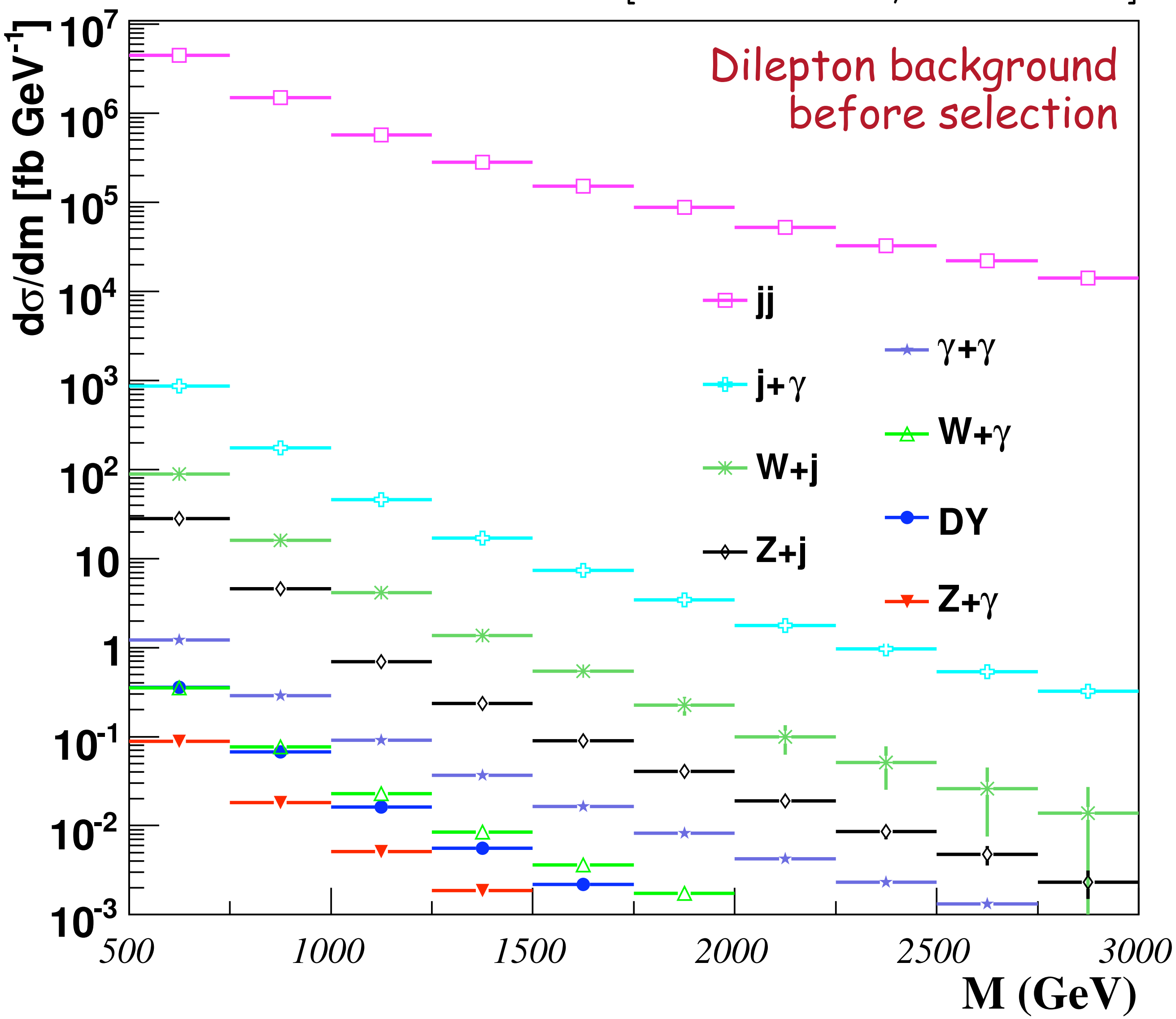
[ATLAS “CSC Book”, arXiv:0901.0512]



Drell-Yan dominant ?

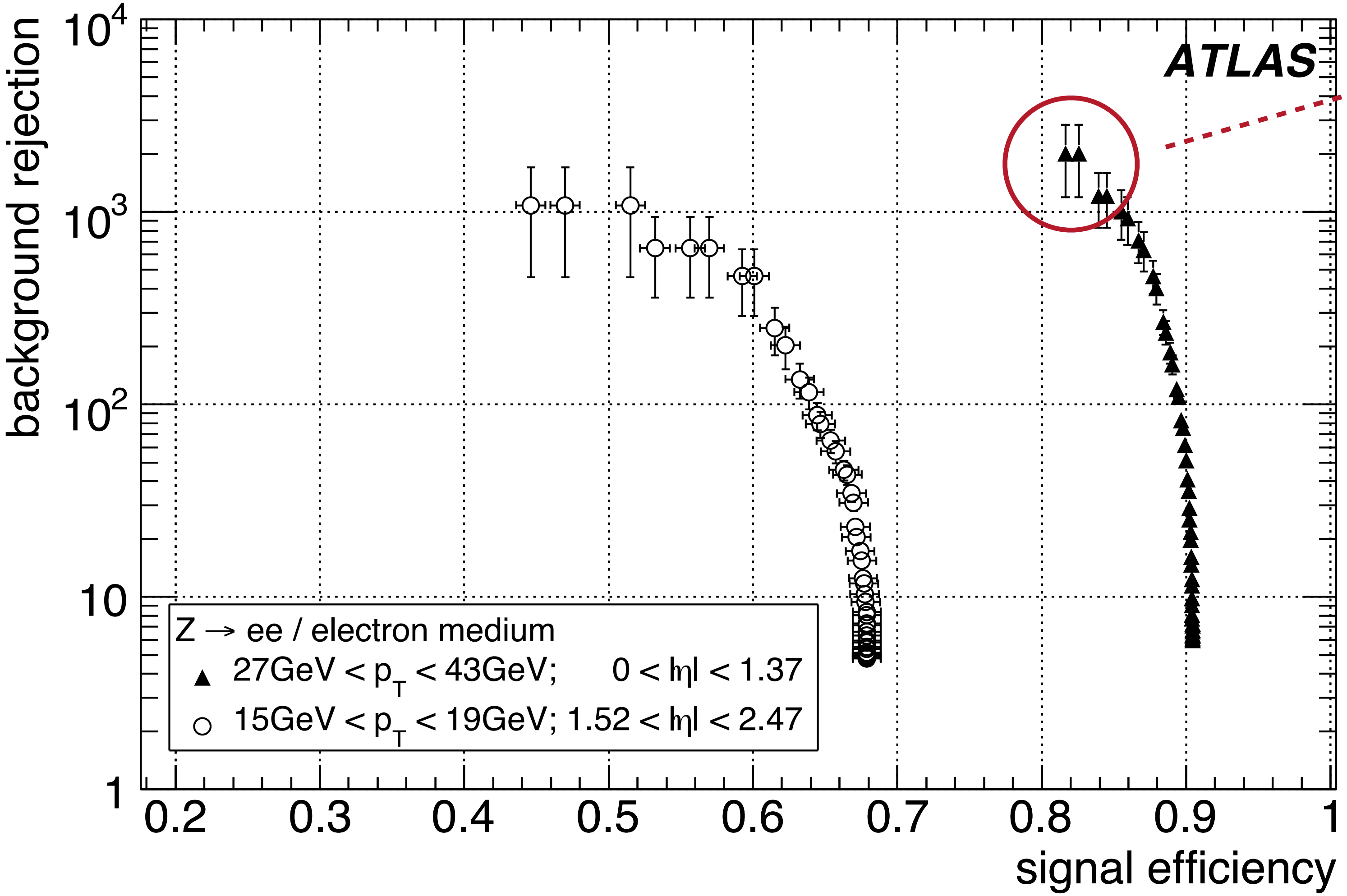
e.g. jet → e ?

γ → e ?

Jet Background Rejection

Background electron rejection versus signal efficiencies for electrons in Z → ee decays

[ATLAS "CSC Book", arXiv:0901.0512]



O(10^3)
@ 80% eff.

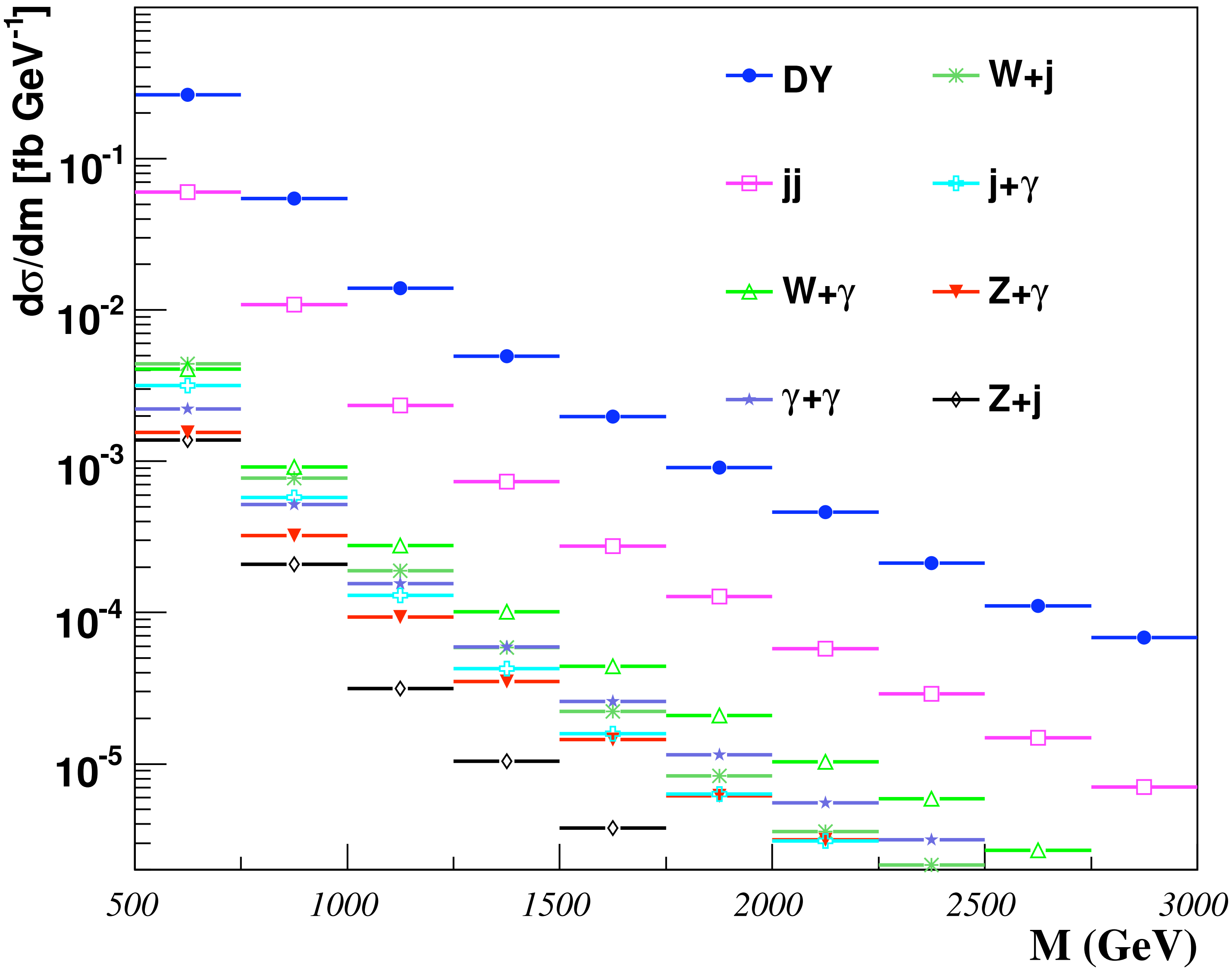
Remark:

10^5 rejection possible with tight selection

Dilepton Background

Dilepton background after selection

[ATLAS "CSC Book", arXiv:0901.0512]



Apply:

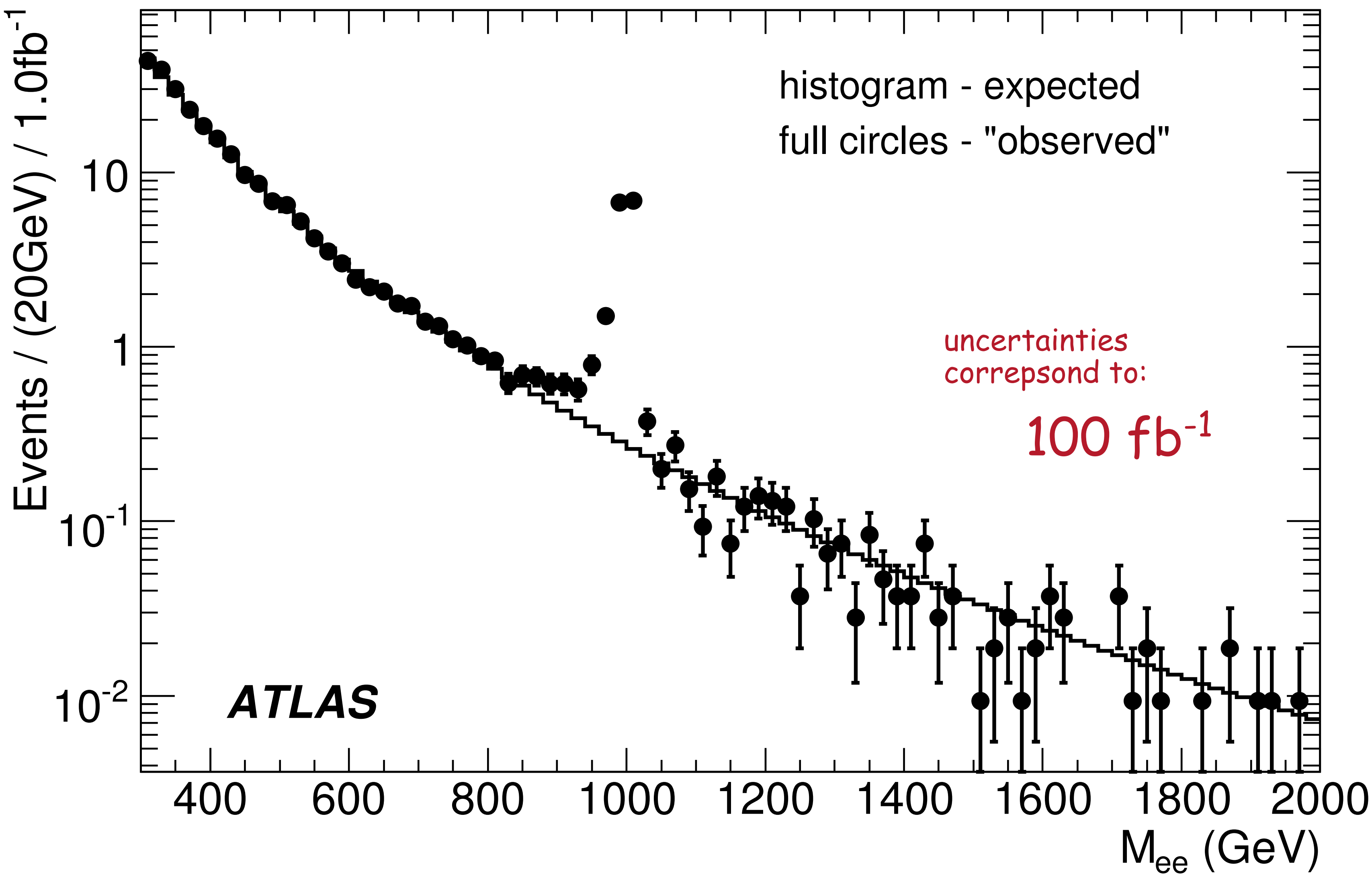
$|\eta| < 2.5$, $p_T > 65$ GeV
Electron selection

➡ Jet-rej. : 4×10^3
γ-rej. : 10

Drell-Yan dominates !

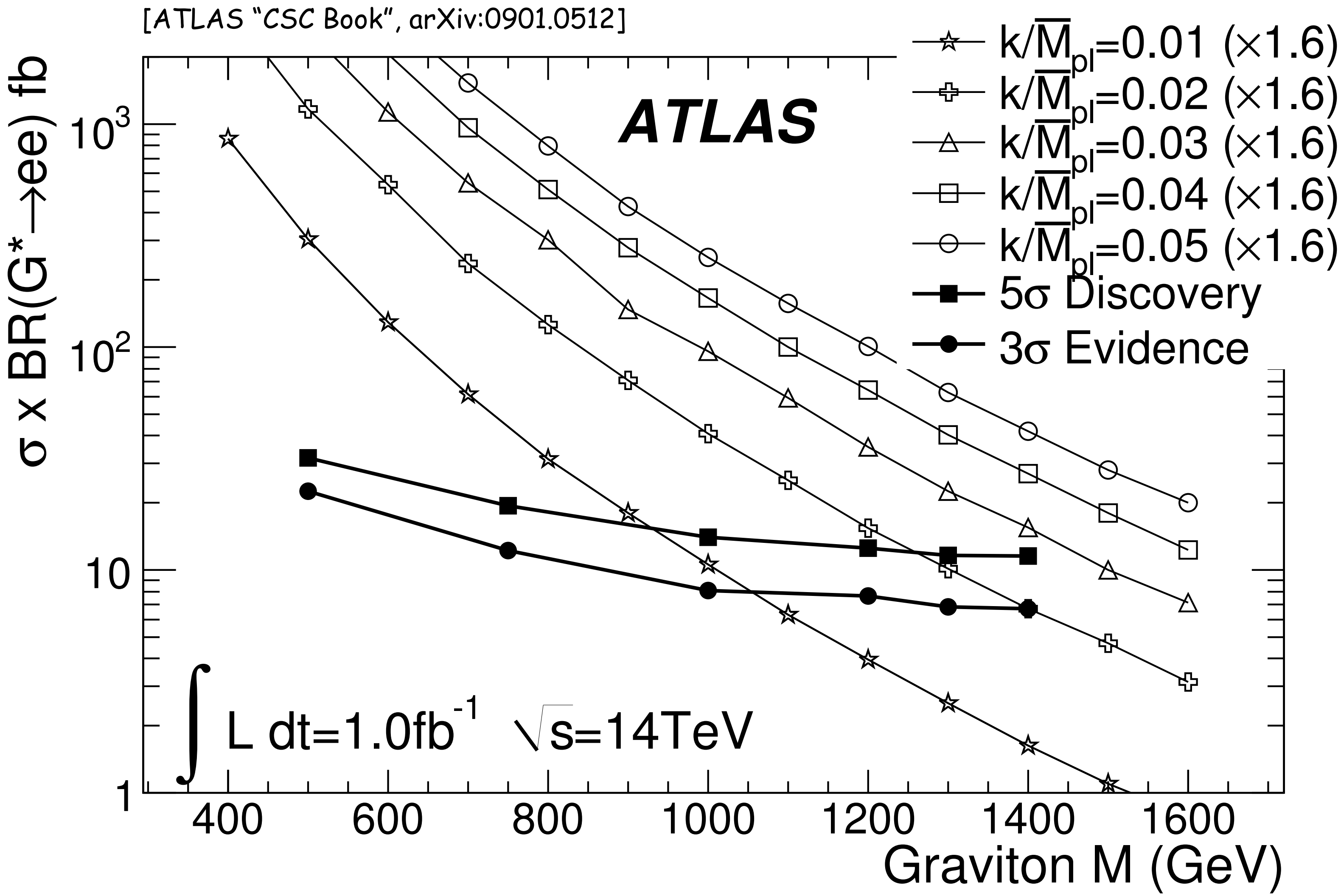
KK Graviton in Full Simulation

[ATLAS "CSC Book", arXiv:0901.0512]



KK Graviton Discovery Potential

[ATLAS "CSC Book", arXiv:0901.0512]



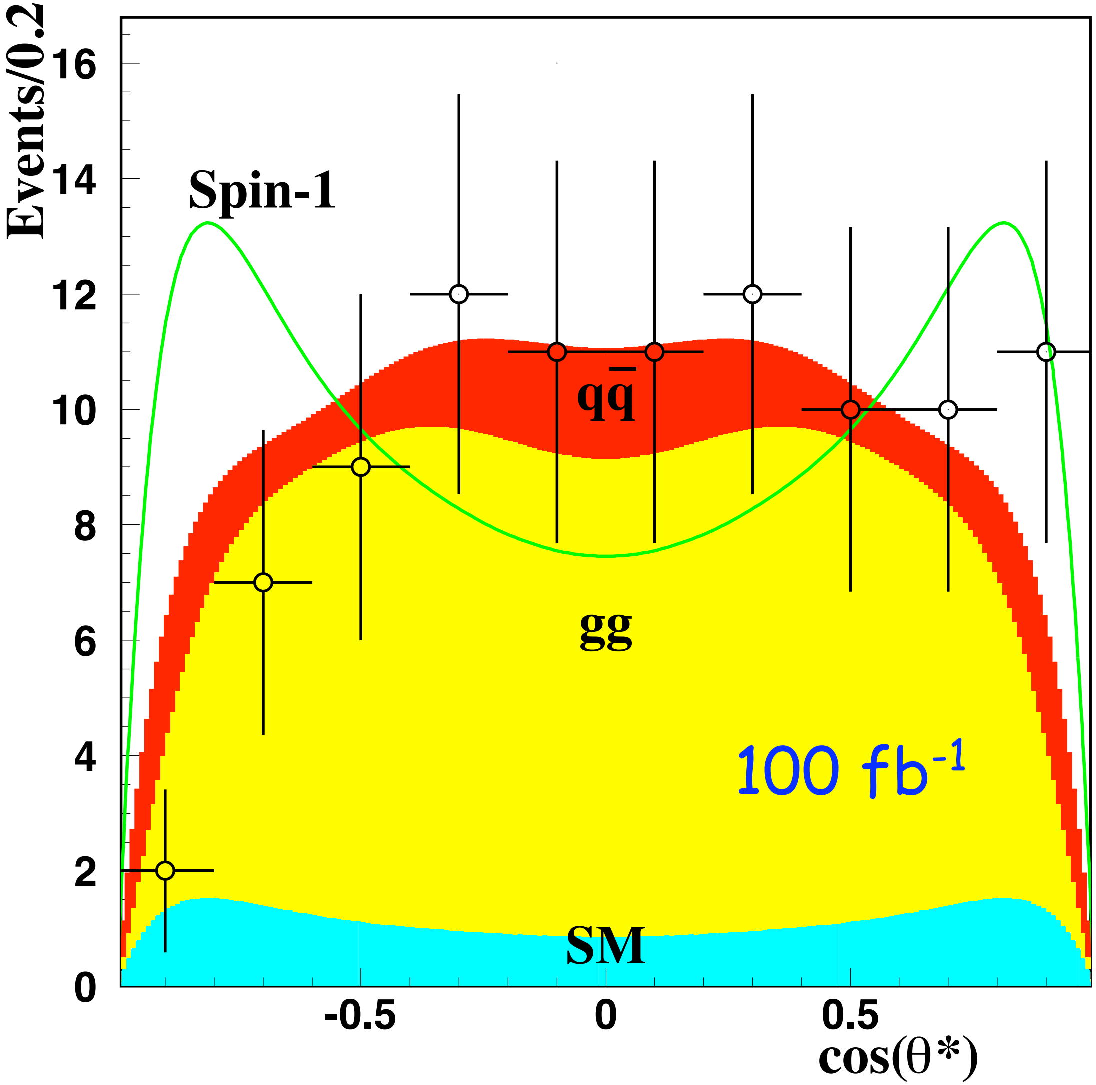
e.g.:

M_G = 1 TeV
→ k/M_{pl} > .012

M_G = 1.2 TeV
→ k/M_{pl} > .019

KK Graviton Spin

[Allanach et al., JHEP 0009:019 (2000)]



Graviton: Spin 2

Characteristic angular distribution of decay products

$qq \to G \to ff$: $1 - 3\cos^2\theta + 4\cos^4\theta$

$gg \to G \to ff$: $1 - \cos^4\theta$

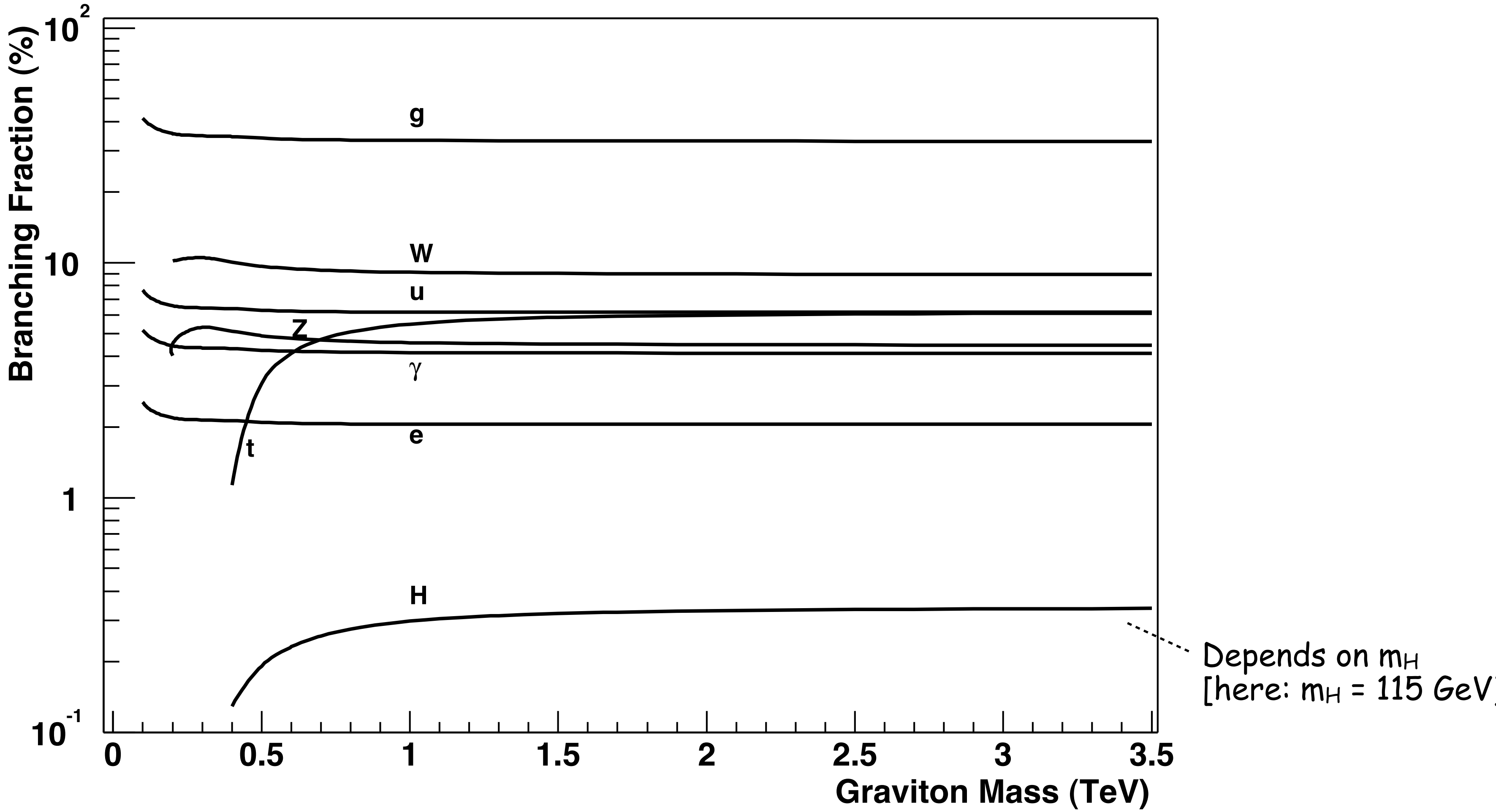
$qq \to G \to VV$: $1 - \cos^4\theta$

$gg \to G \to VV$: $1 + 6\cos^2\theta + \cos^4\theta$

DY background: $1 + \cos^2\theta$

KK Graviton Branching Fractions

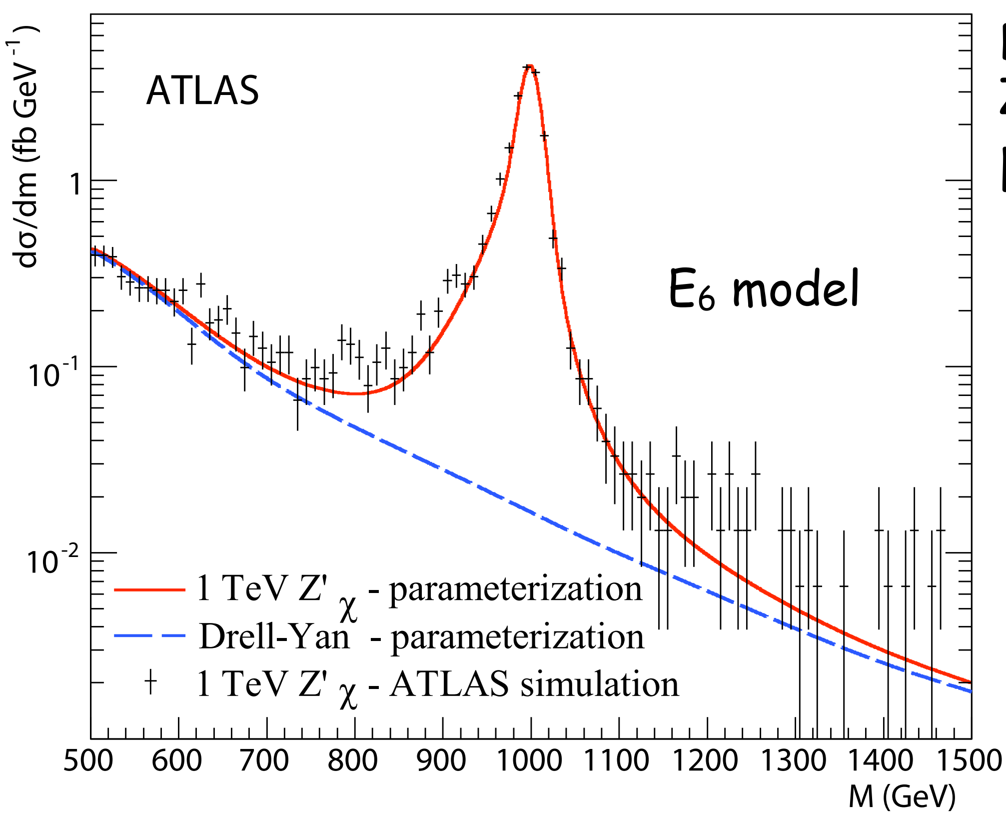
[Allanach et al., JHEP 0012:039 (2002)]



Universal coupling: branching fractions determined by multiplicity of color, spin and flavour states

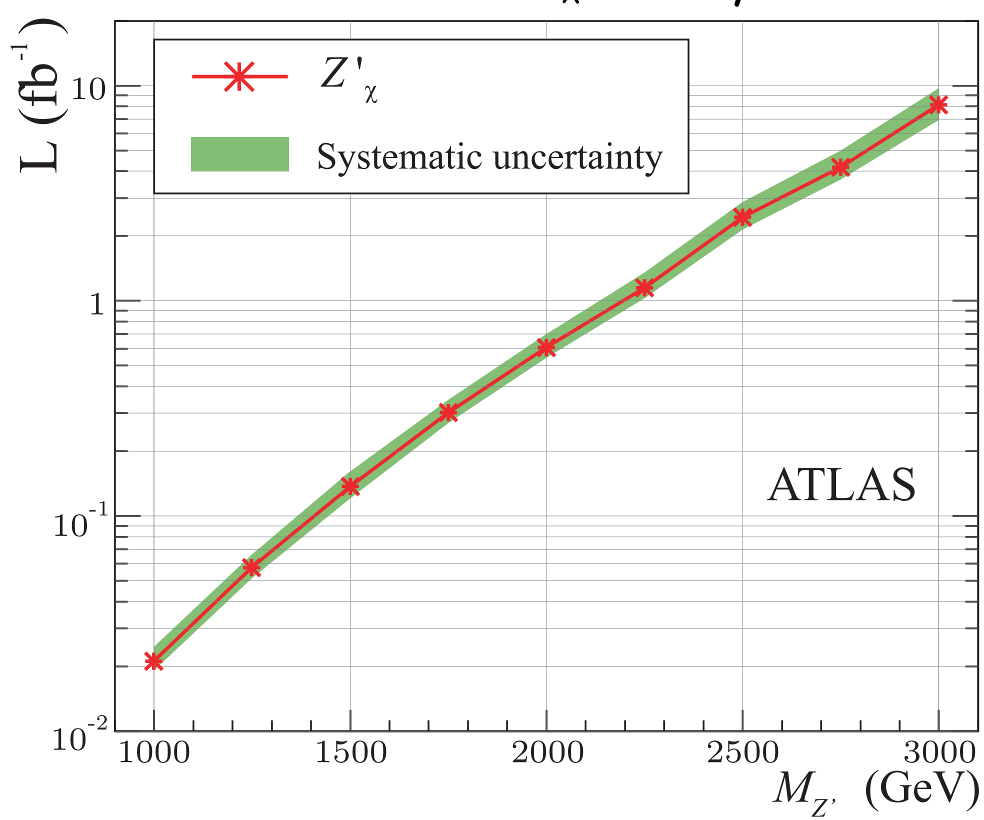
KK Gauge Bosons: Z' → ee

[ATLAS "CSC Book", arXiv:0901.0512]



Dielectron mass spectrum
$Z'_\chi \rightarrow ee$; $m_{Z'}$ = 1 TeV
[Full simulation]

5σ discovery reach
for Z'_χ with systematics

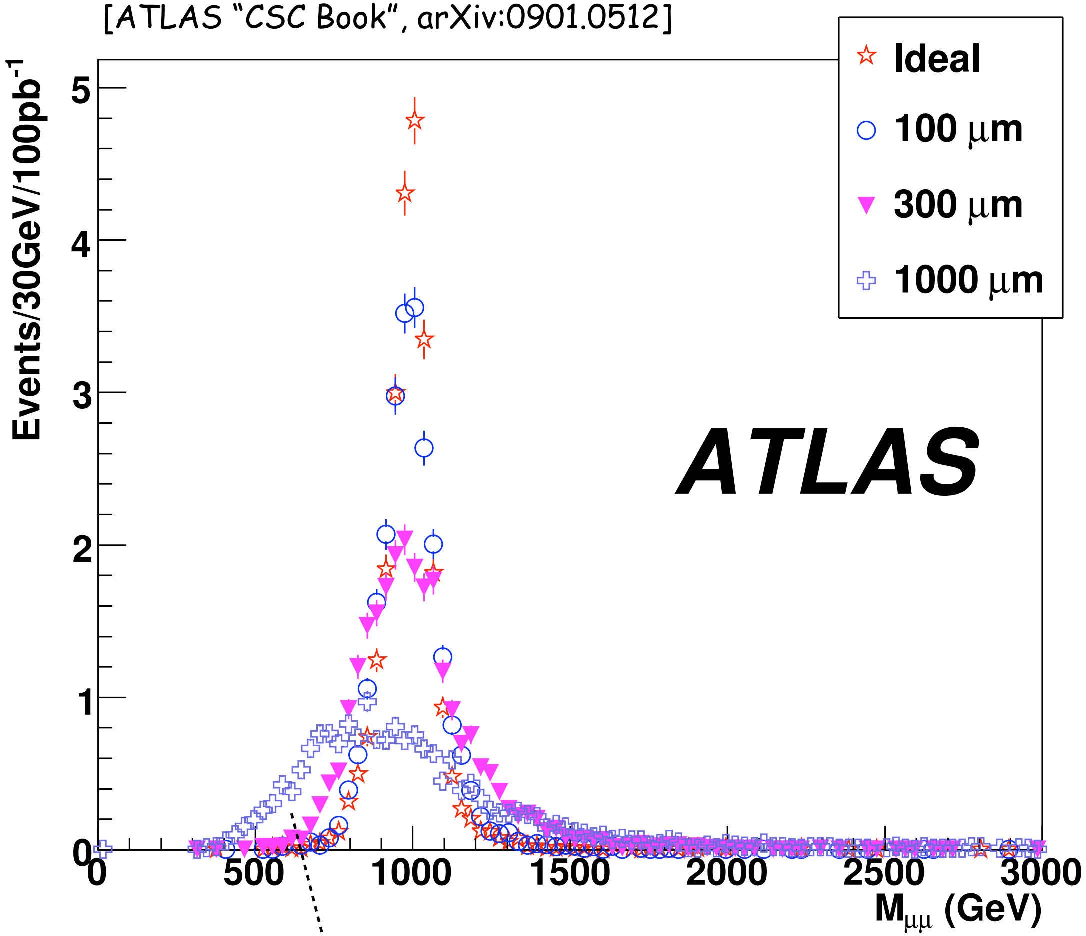


Included systematics

Background	:	~ 1 %
Event selection	:	.6 to 3.6 %
Energy resol./scale	:	2.0 to 5.0 %
Theory	:	8.5 to 14.0 %

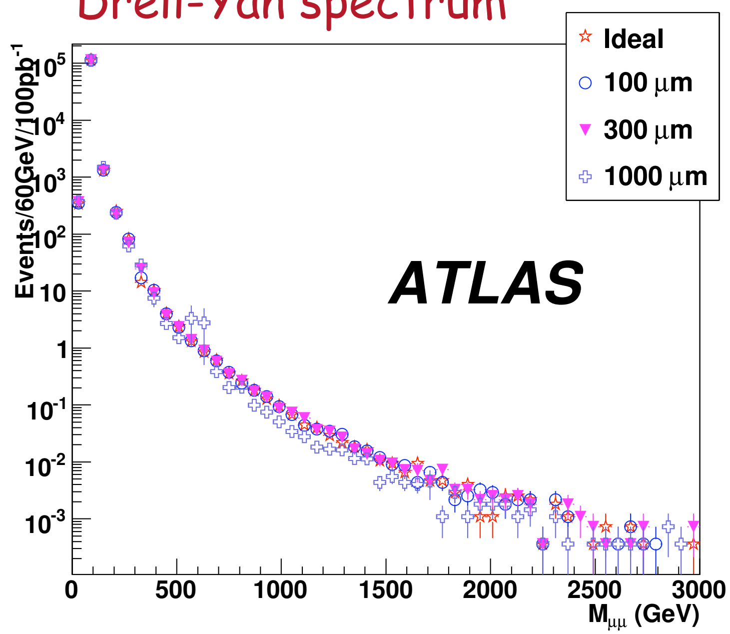
Z' → μμ: Alignment Effects

[ATLAS "CSC Book", arXiv:0901.0512]



Reconstructed
Z'χ mass spectrum
for different misalignment hypotheses

Reconstructed
Drell-Yan spectrum



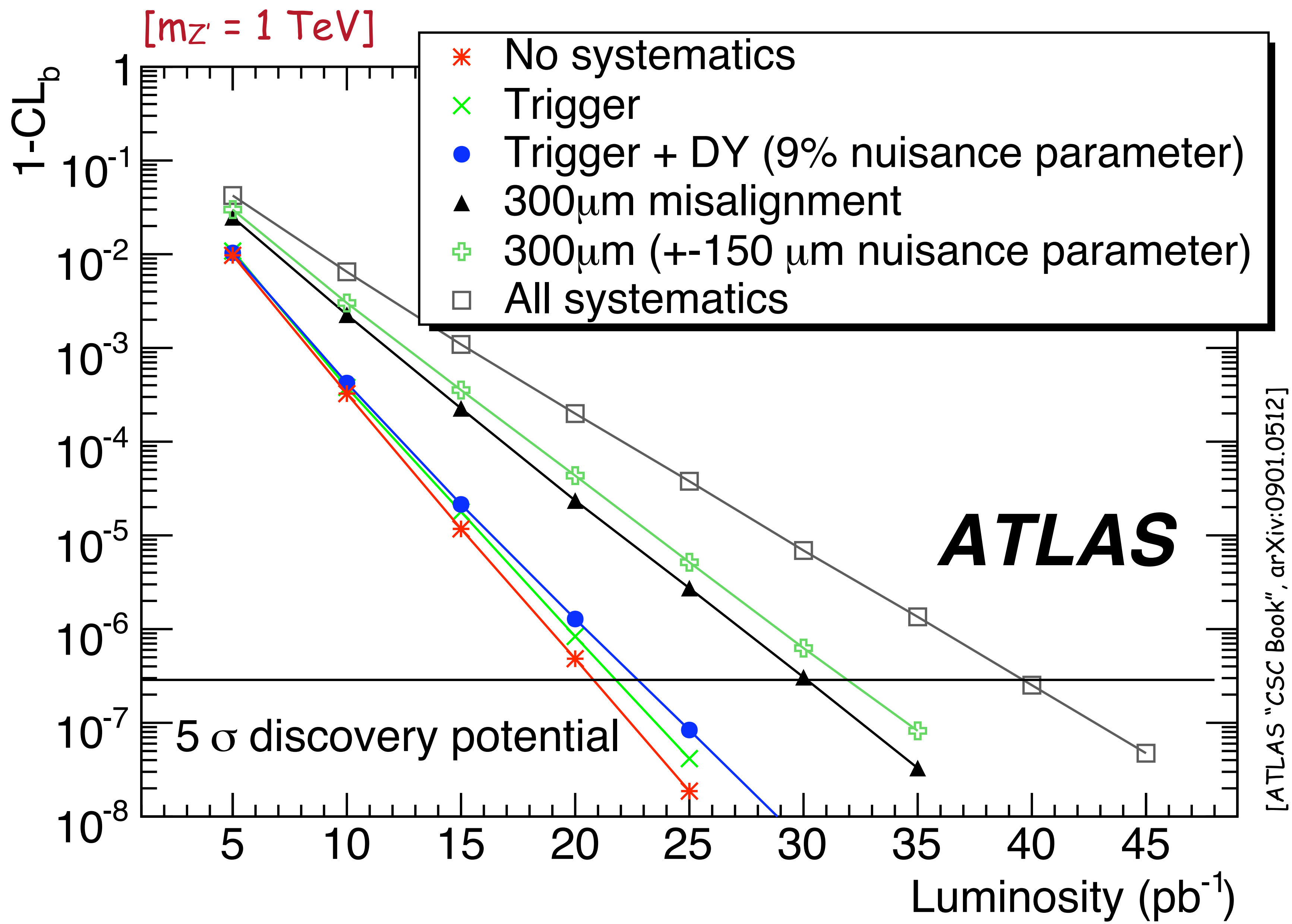
Resolution loss

→ influences charge determination

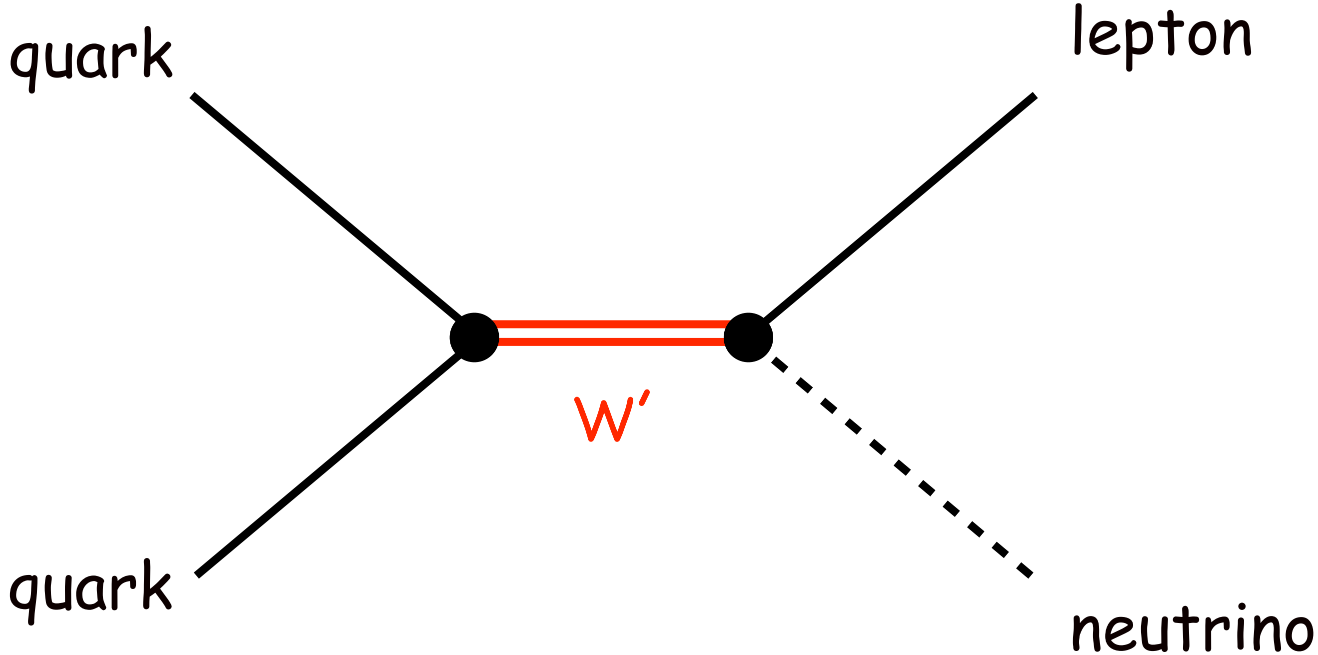
→ signal efficiency drop

[ideal: 98.4%; 1000 μm: 87.7%]

$Z'_\chi \to \mu\mu$: Discovery Reach



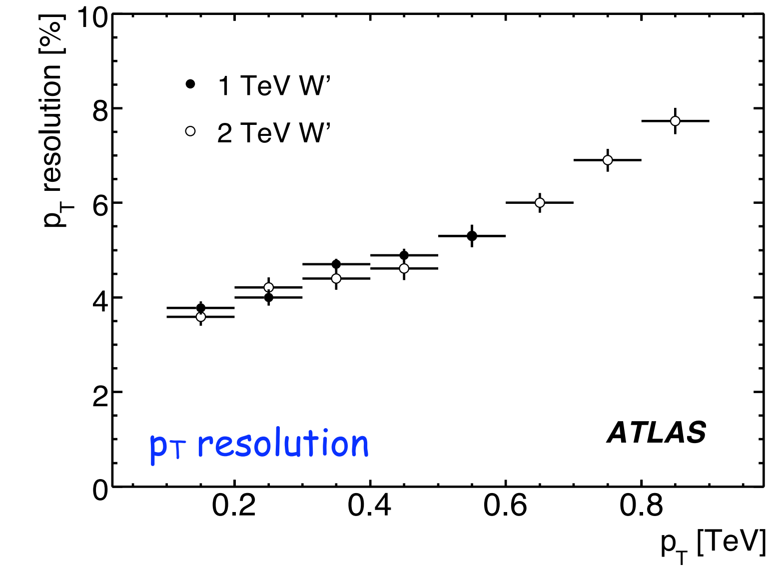
Lepton-Neutrino Resonances

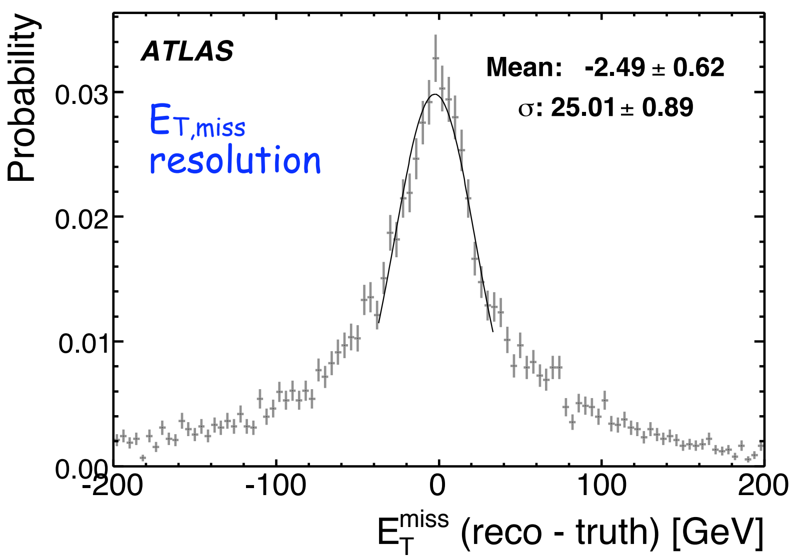


Example: W' → $\mu\nu$

[$m_{W'}$ = 2 TeV]

[ATLAS "CSC Book", arXiv:0901.0512]

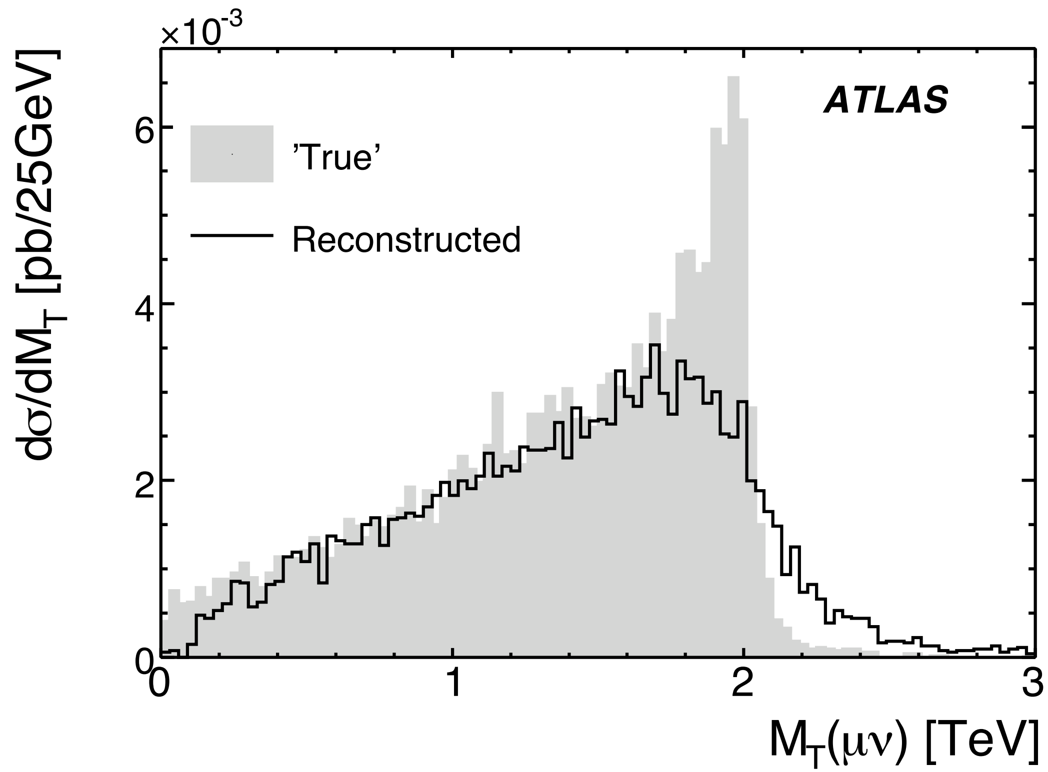




Selection:

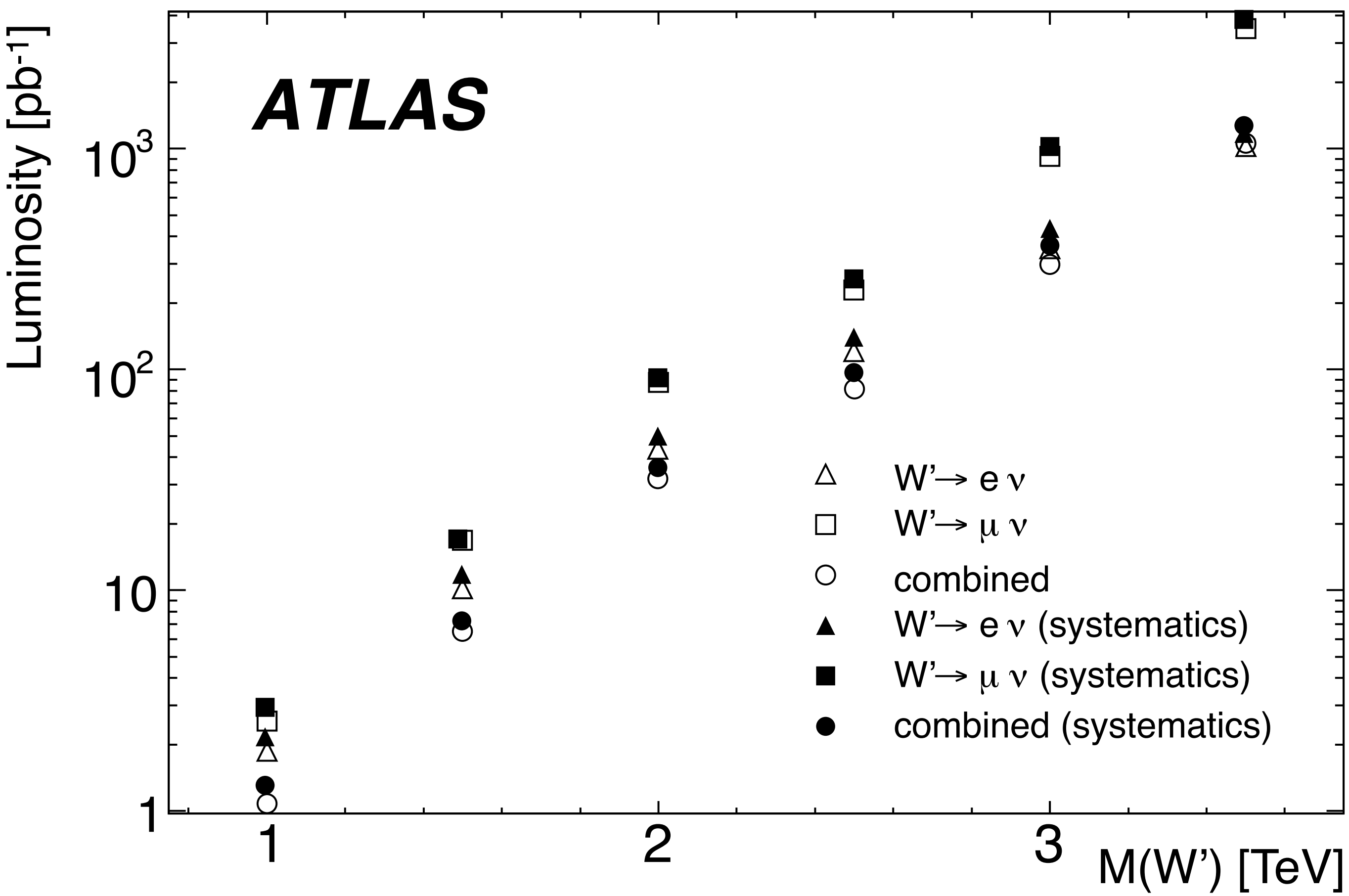
Muon with p_T > 50 GeV; $|\eta|$ < 2.5

Missing E_T > 50 GeV



W' Discovery Reach

[ATLAS "CSC Book", arXiv:0901.0512]



Integrated Luminosity needed for 5σ discovery

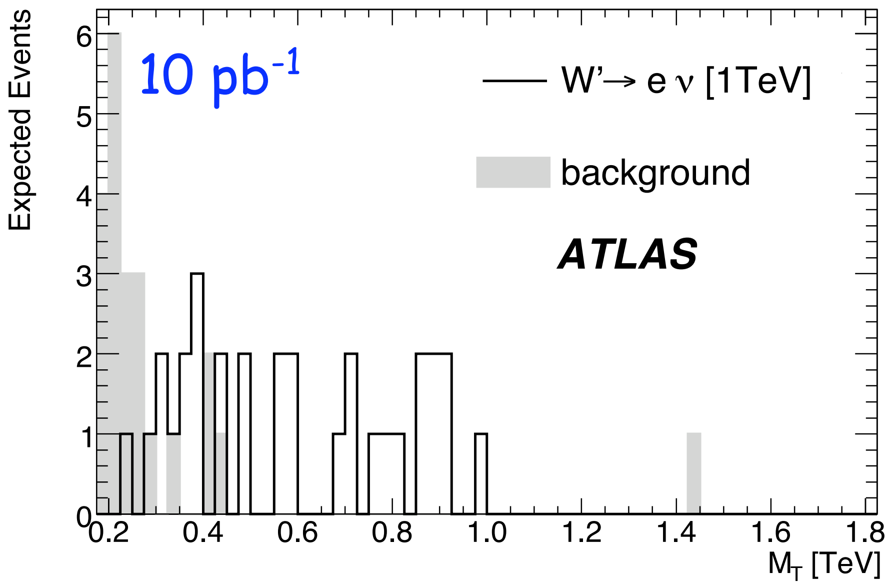
Combined:

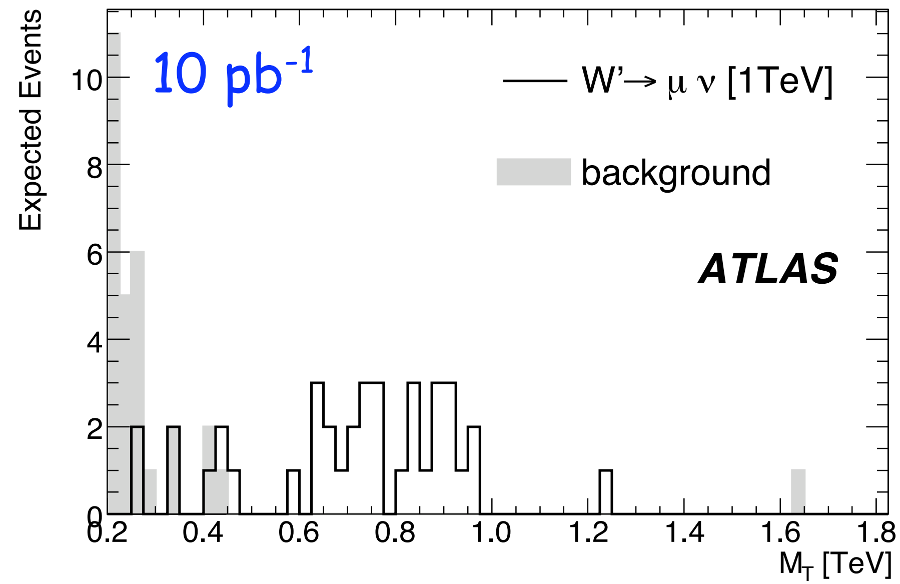
10 pb^{-1}: ~ 1.5 TeV
100 pb^{-1}: ~ 2.5 TeV

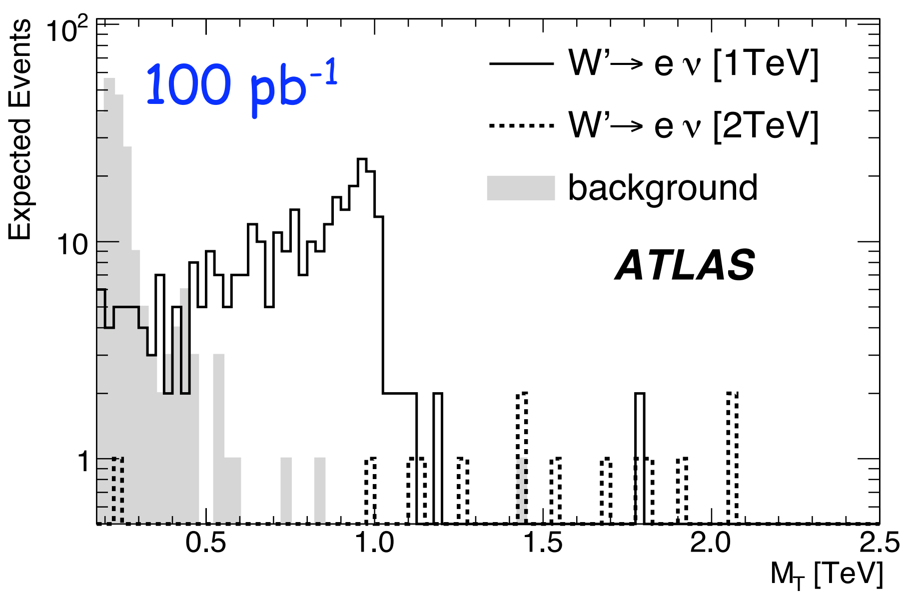
Included Systematics: Lepton identification, p_T/E_T scale and energy resolution, Luminosity error, NLO contributions, PDF uncertainties, ...

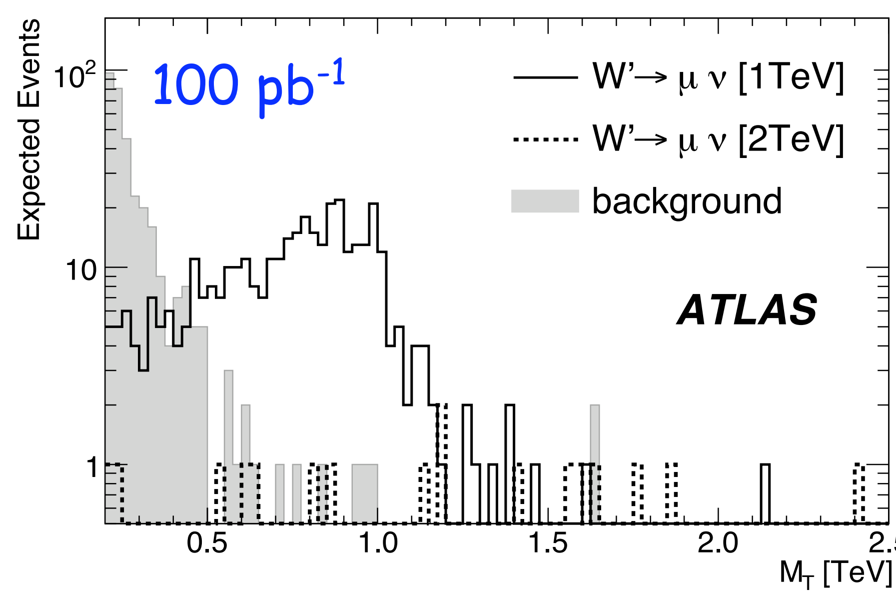
W' Discovery Reach

[ATLAS "CSC Book", arXiv:0901.0512]





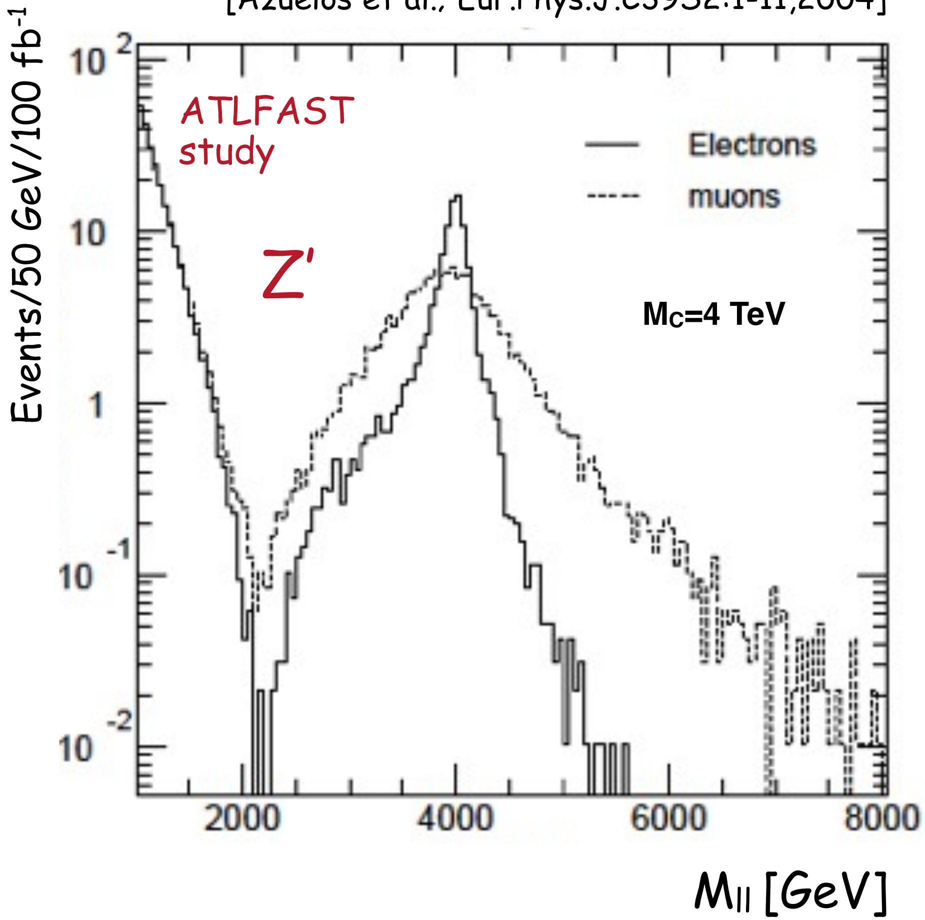




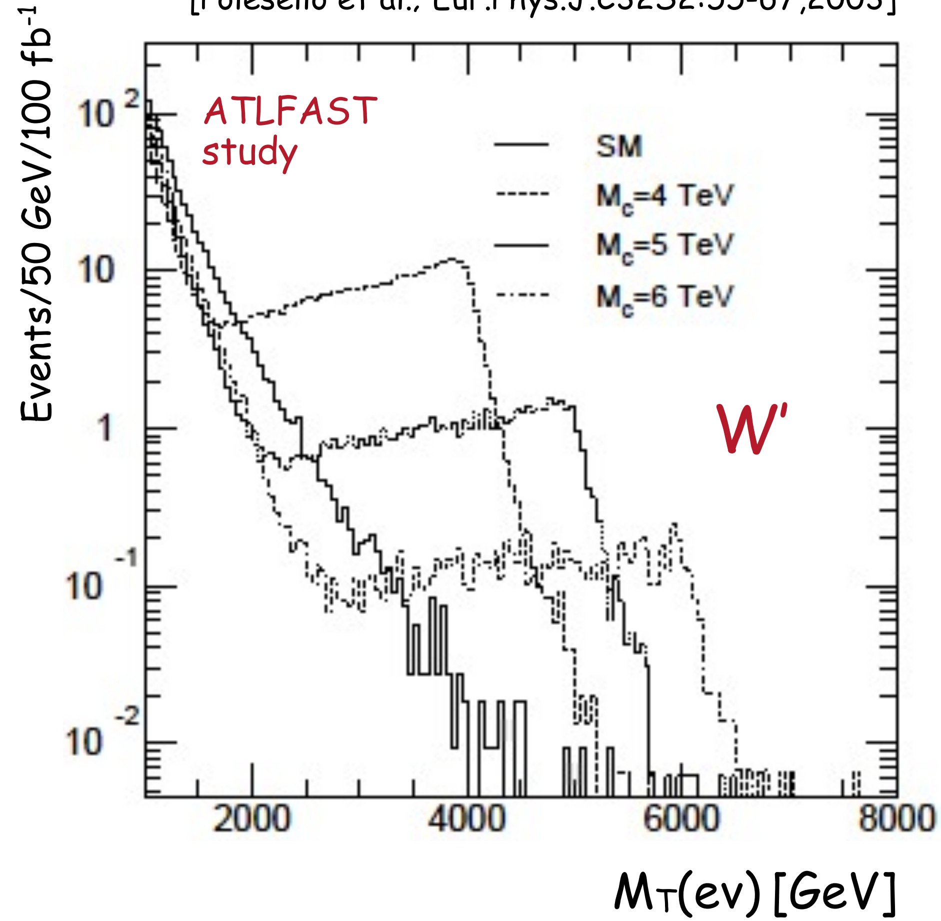
Z'/W' Discovery Reach

for high luminosity, i.e. 100 fb^{-1}

[Azuelos et al.; Eur.Phys.J.C39S2:1-11,2004]



[Polesello et al.; Eur.Phys.J.C32S2:55-67,2003]



ATLAS reach
fo 100 fb^{-1}: 5.8 TeV

ATLAS reach
fo 100 fb^{-1}: 6 TeV

Missing E_T Reconstruction

Input: calorimeter cells, topo clusters, muon tracks

Cryostat term

Recovers energy loss in cryostat ...

Calibrated calorimeter cell energies

Muon momenta

$$\not{E}_{x,y}^{RefFinal} = \not{E}_{x,y}^{RefCalib} + \not{E}_{x,y}^{Cryo} + \not{E}_{x,y}^{Muon}$$

$$\not{E}_{x,y}^{RefCalib} = \not{E}_{x,y}^{\gamma/e} + \not{E}_{x,y}^{\tau} + \not{E}_{x,y}^{(b)jet} + \not{E}_{x,y}^{\mu} + \not{E}_{x,y}^{out}$$

Refined, object-based calibration

Cells associated with identified physics objects e/γ,τ, jets, μ, ... are calibrated accordingly; unassociated cells H1 calibrated.

Missing E_T Reconstruction

Noise suppression:

Cell based:

Cells with energy $|E_{cell}| > 2\sigma_{noise}$

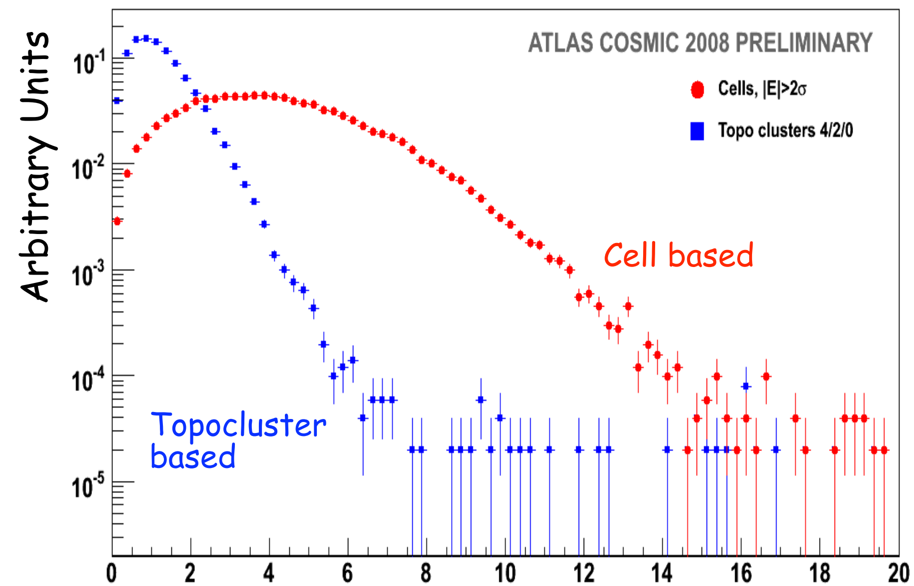
Topocluster based:

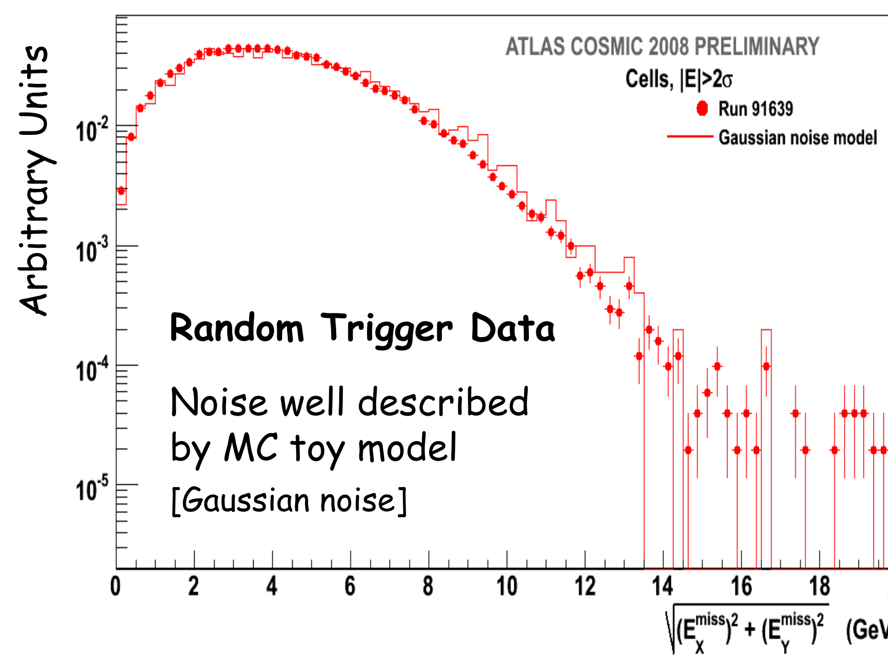
Cells in 3D clusters reconstructed with noise threshold 4/2/0

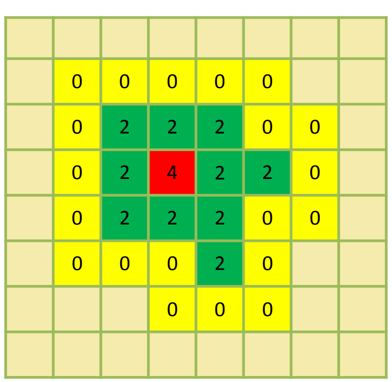
[4σ seed; 2σ neighbour, 0σ counter cells]

better noise suppression;

needs accurate noise description





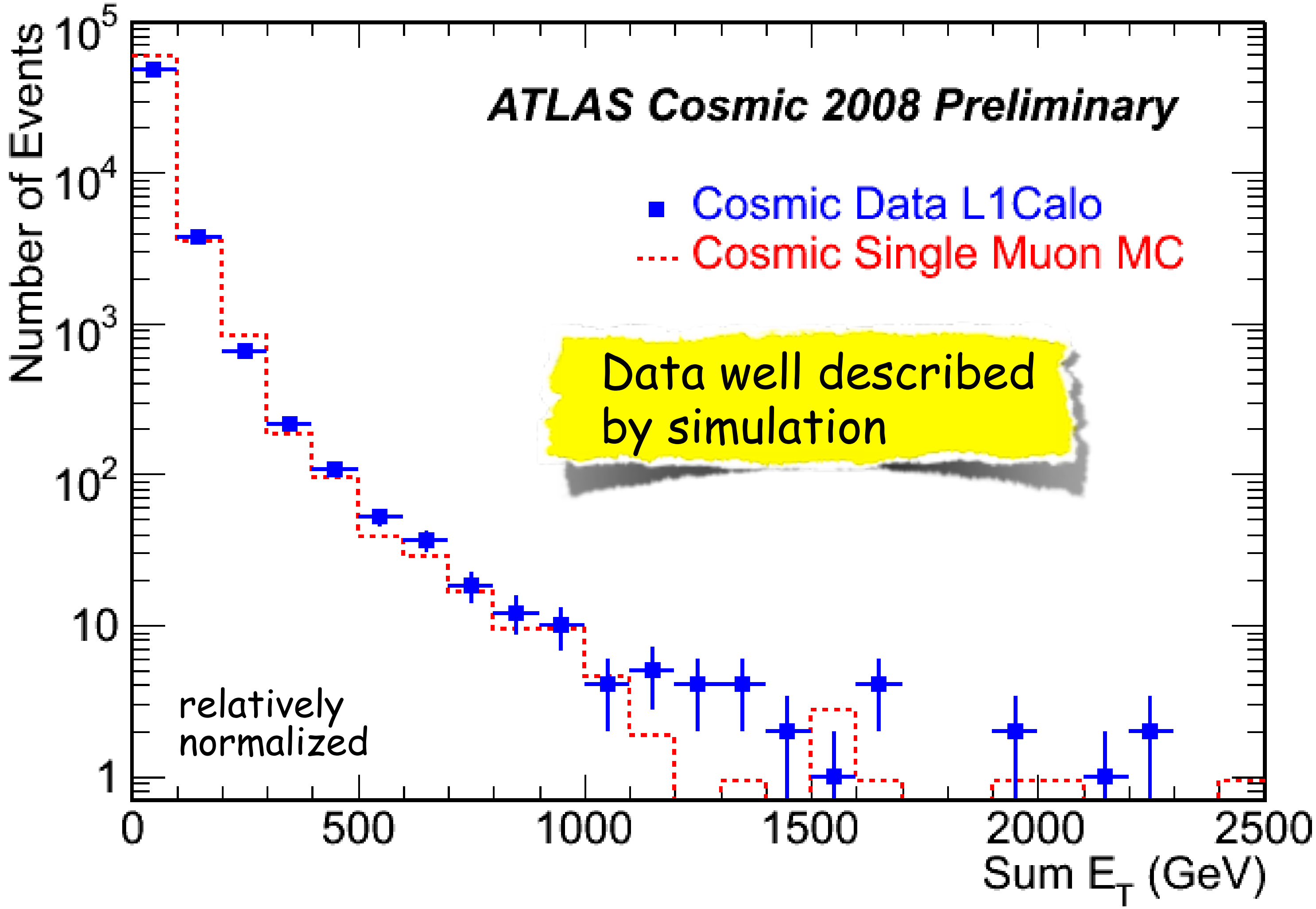


Topocluster based noise suppression

[4/2/0 scheme]

“Missing E_T” in Cosmic Data

Cosmic muons can be a source of fake missing E_T and fake jets when they deposit high energy in the calorimeter by emitting a hard photon ...



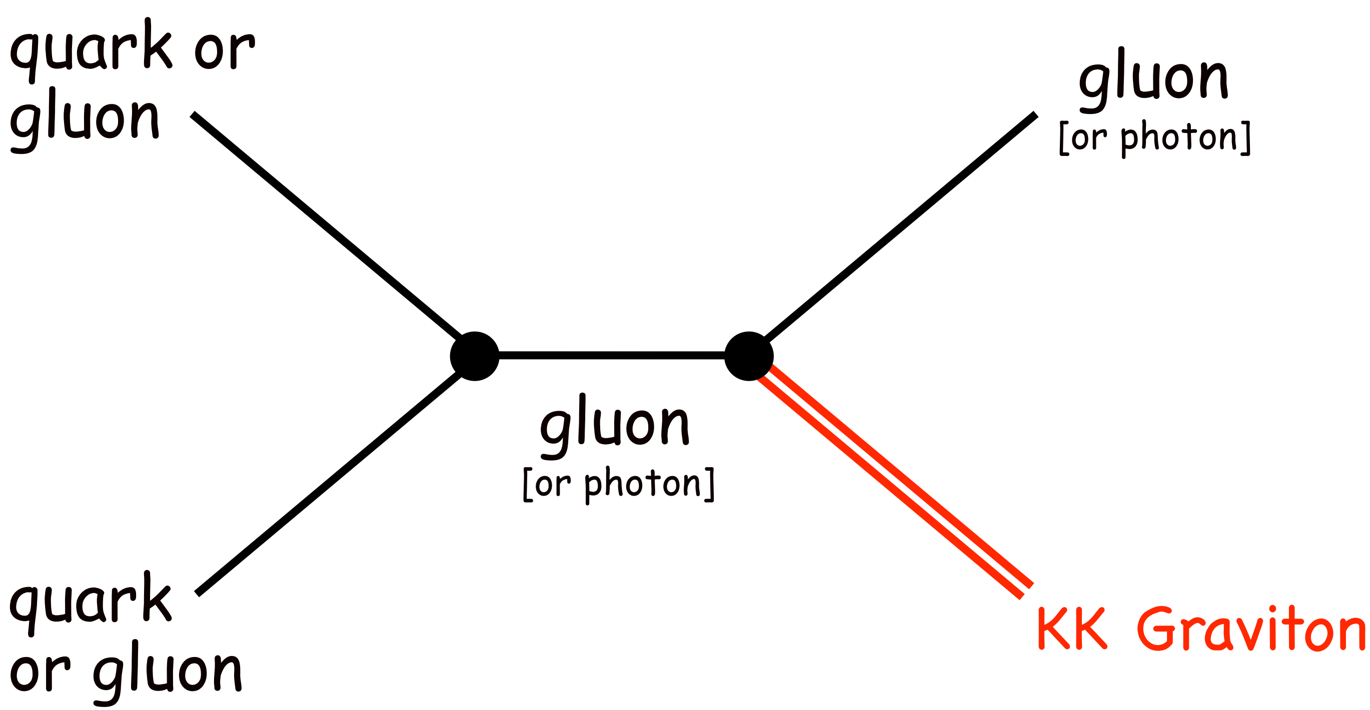
2008
Cosmic Data vs. Monte Carlo

EM Scale
[no calibration]

$E_{T,jet}$ > 20 GeV

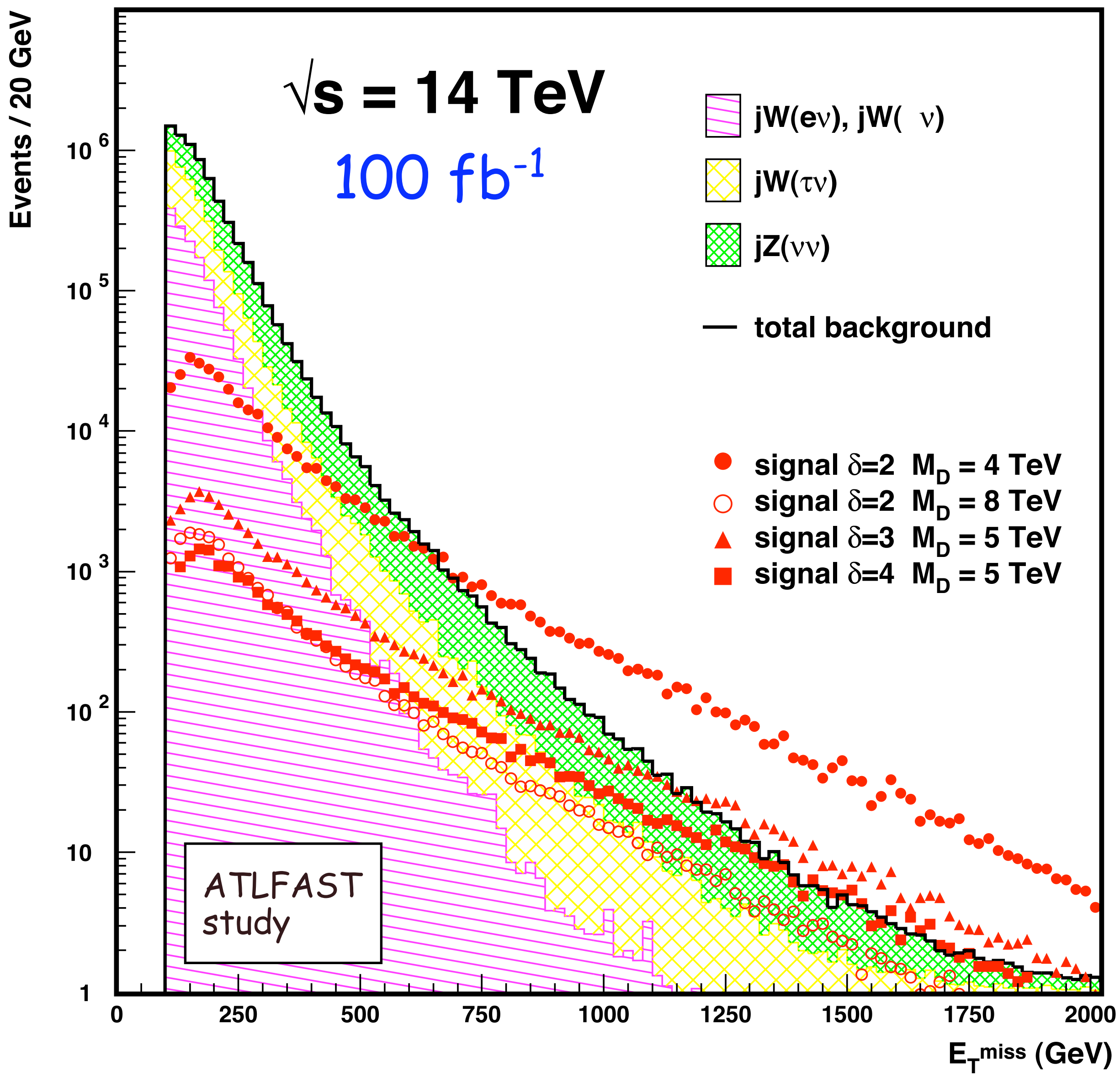
Cell-based noise suppression

Graviton Radiation

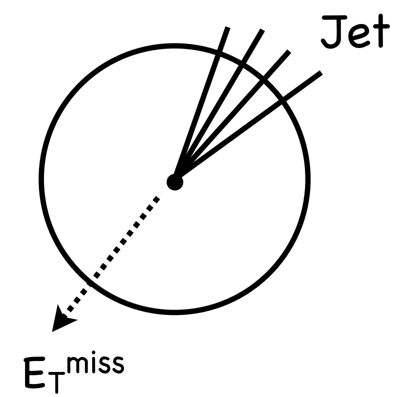


Monojets + Missing Energy

[Hinchliffe, Vacavant; J. Phys. *G27* (2001) 1839]



Clear signature:



Discovery potential:

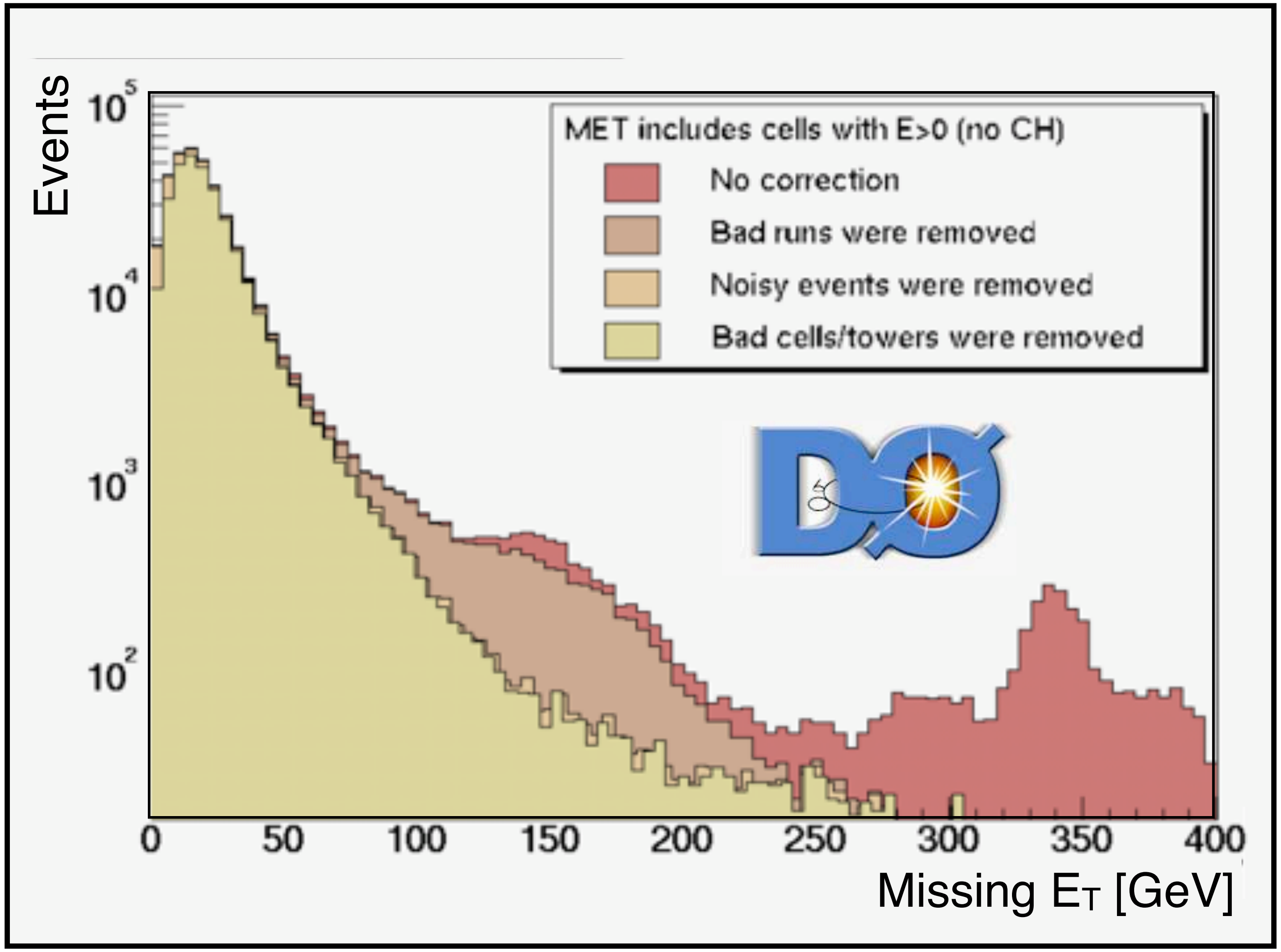
[no instrumentation effects included]

n	2	3	4
M_D [GeV]	9	7	6

[J. Phys. *G27* (2001) 1839]

Monojets + Missing Energy

Studying Monojets requires
good understanding of detector ...



$E_{T,miss}$ influenced by:

Jet loss in dead regions

Calorimeter noise

Beam induced background signals

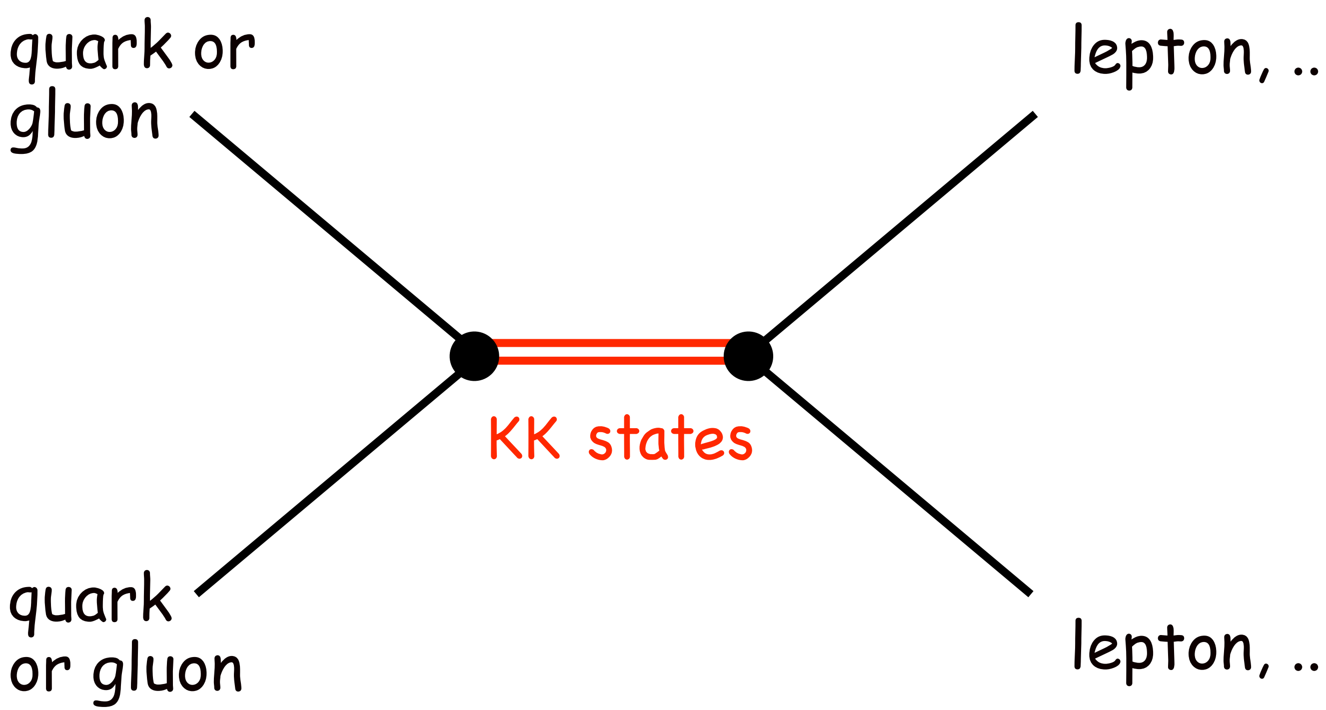
Cosmics ...

Example D0:

Run I results published 2003 [1994-1996 data]

Run II prel.: $M_D < O(1\ \text{TeV})$ [based on 1.1 fb^{-1}]

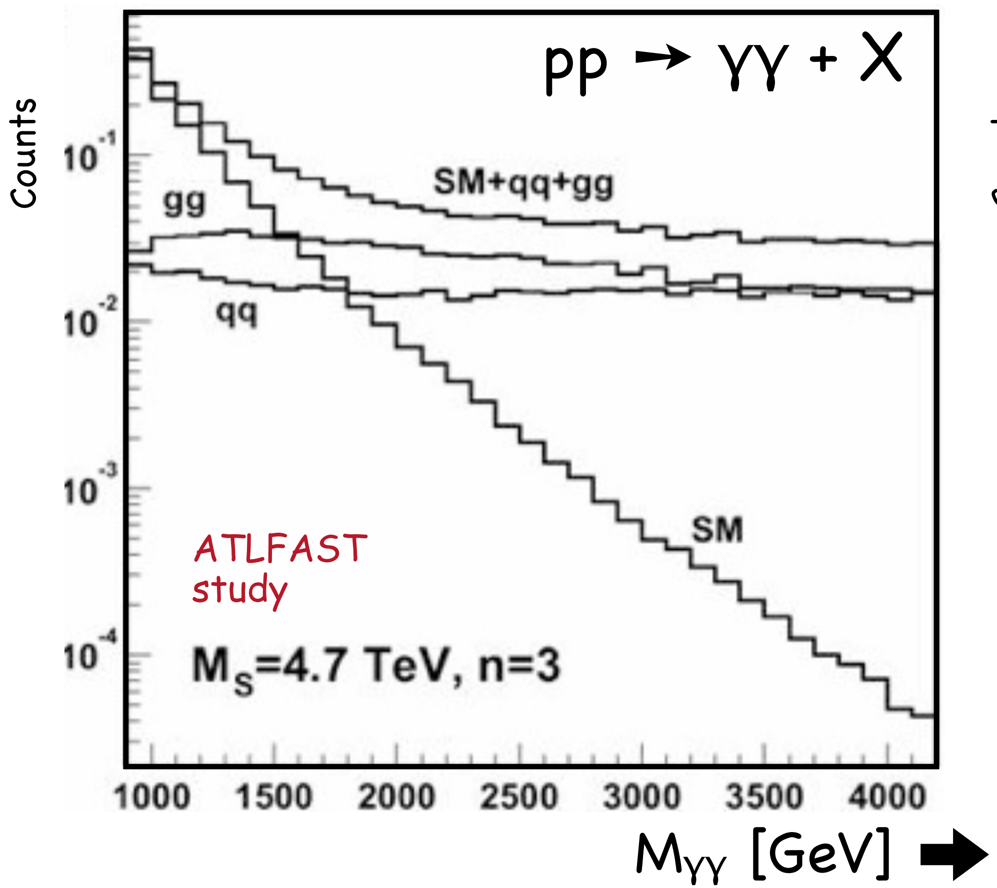
Virtual Graviton Exchange

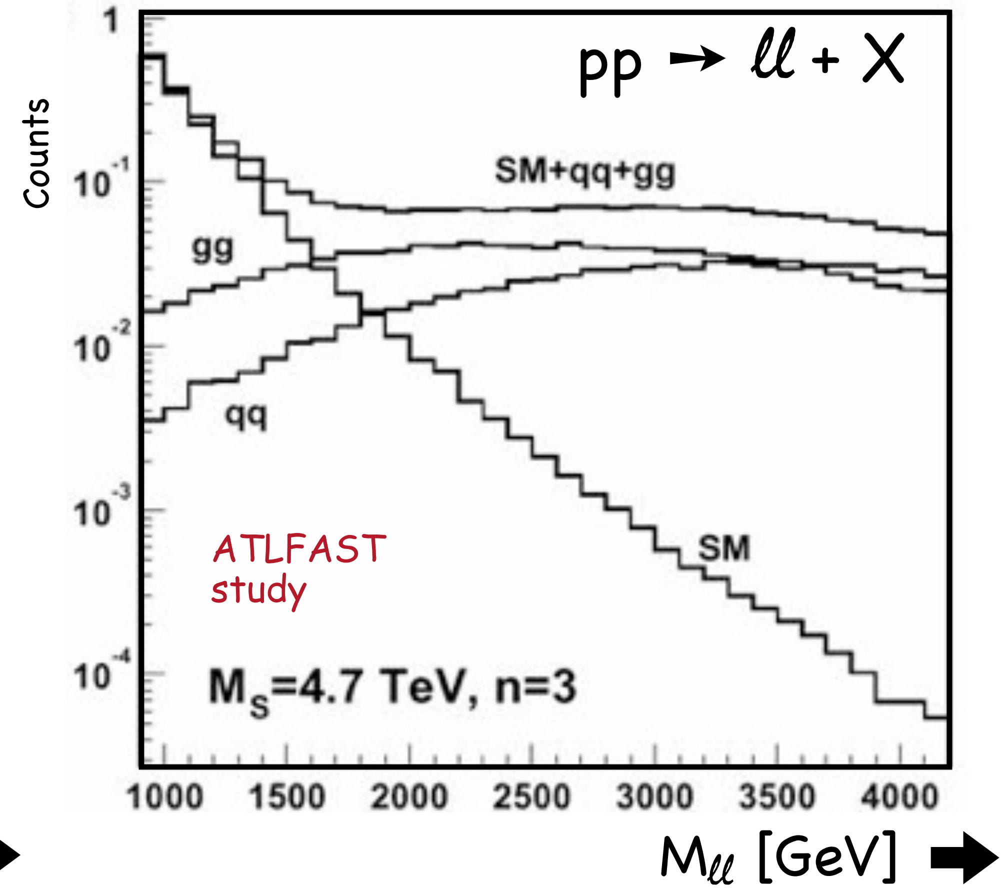


Di-Photon & Di-Lepton Production

Large Extra Dimension Scenario → finely separated KK states
KK state exchange gives extra contribution to pair production x-section

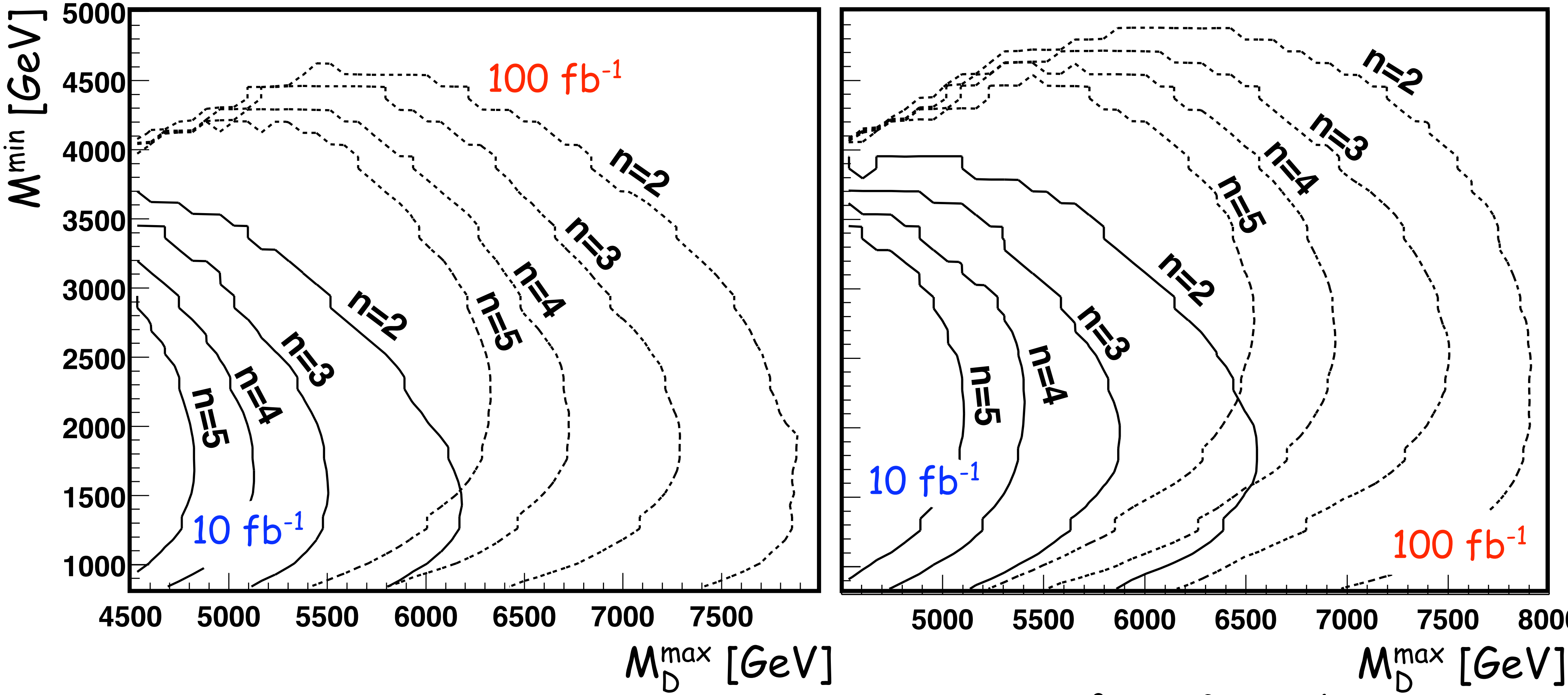
[Kabachenko et al.; ATL-PHYS-2001-012]





Di-Photon & Di-Lepton Production

ATLAS Discovery Potential



[Kabachenko et al.; ATL-PHYS-2001-012]

Combined Reach:
[ATLFAST]

			n=2	n=3	n=4	
γγ + ll	10 fb^{-1}	M_D^{max}	7.0	6.3	5.7	5.4
	100 fb^{-1}	M_D^{max}	8.1	7.9	7.4	7.0

Universal Extra Dimensions

Pair Production of KK states

[Tree-level KK number conservation]

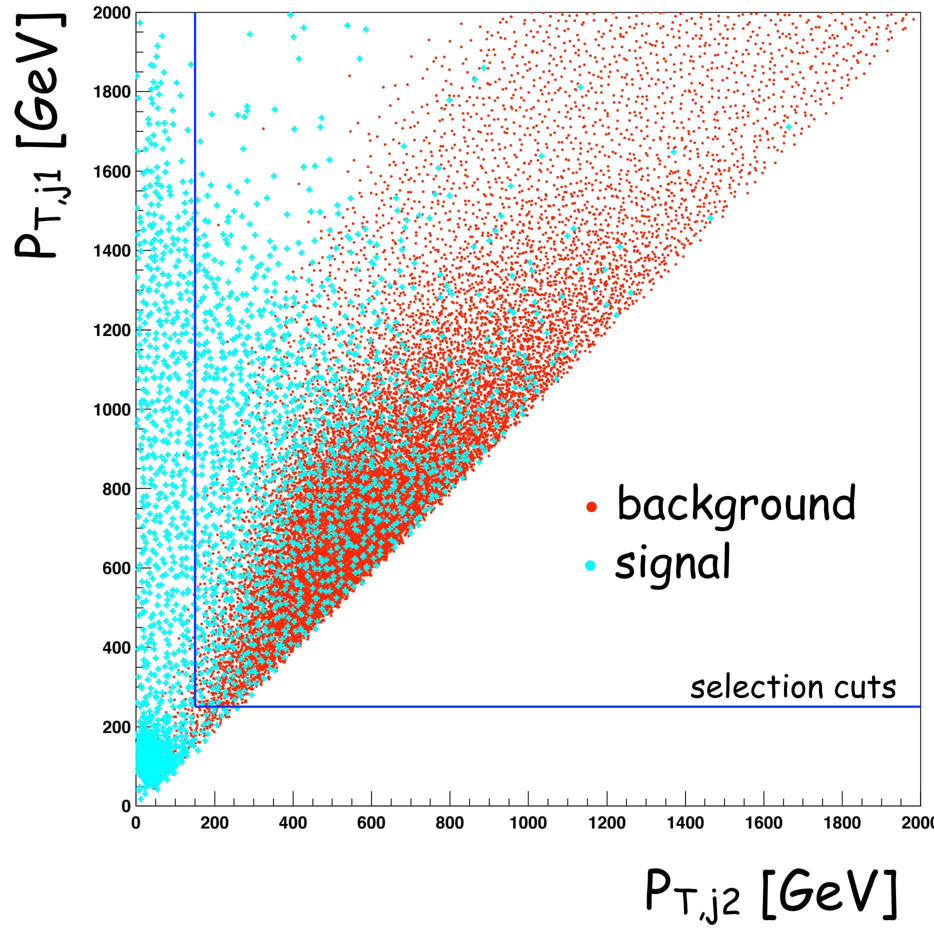
Signatures similar to SUSY

e.g.:	$qq \rightarrow q_{KK}q_{KK}$	:	Multijets + Missing E_T
	$gg \rightarrow q_{KK}W_{KK}$	:	Jet + Lepton + Missing E_T
	$gg \rightarrow q_{KK}Z_{KK}$	:	Jet + Leptons + Missing E_T
	…		

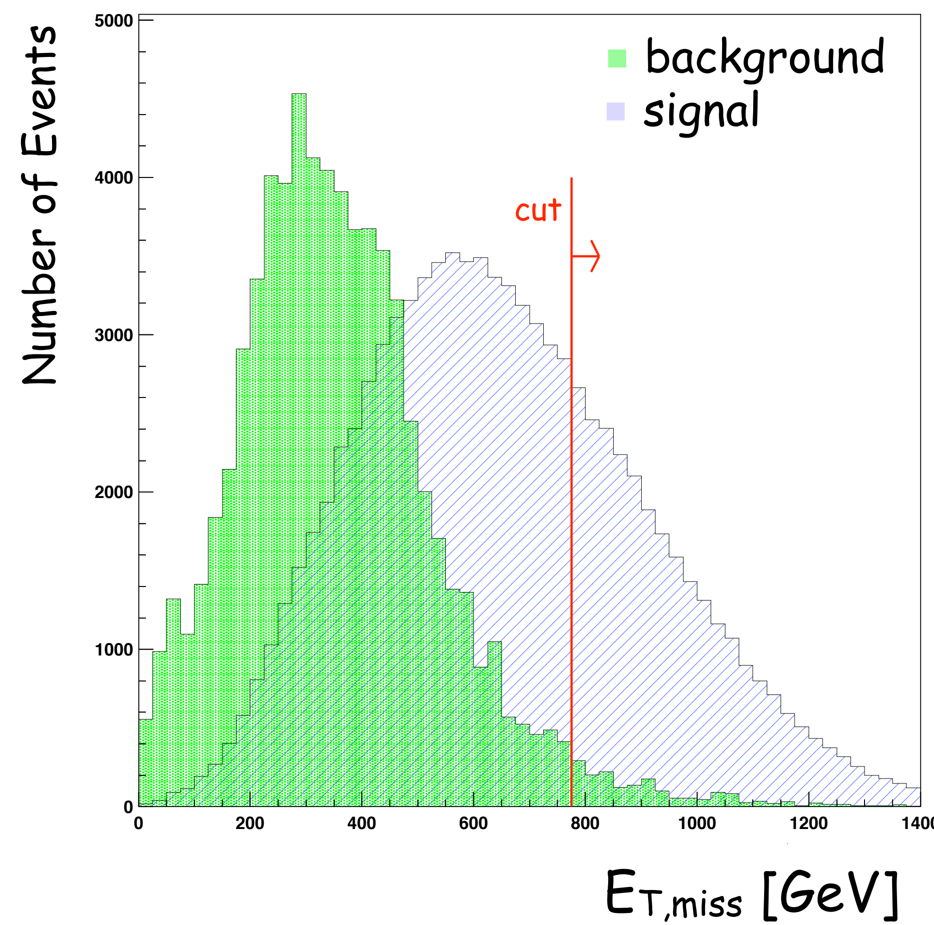
Example: Dijets + Missing E_T

Selection: High p_T dijet system; large $E_{T,miss}$

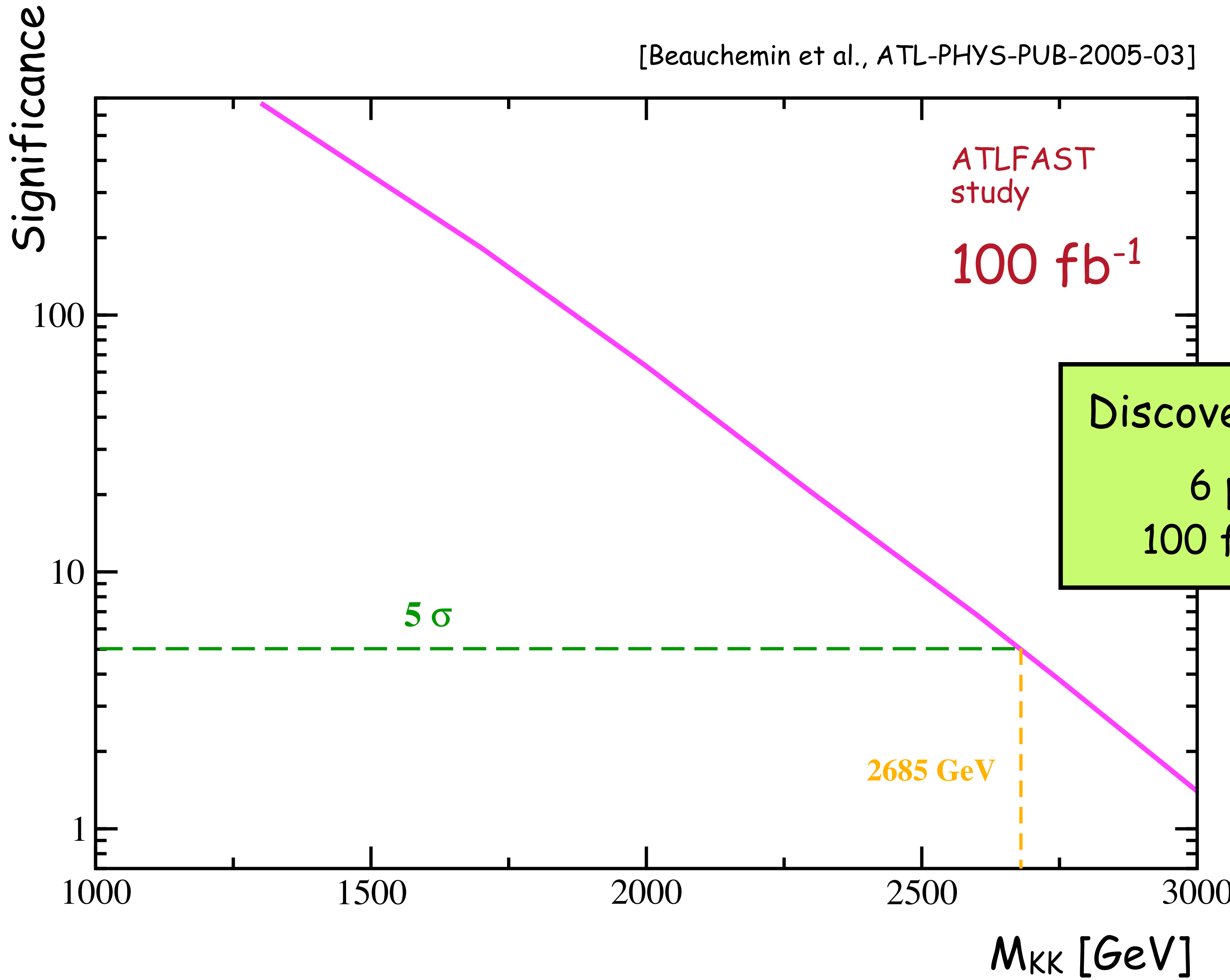
Veto isolated leptons and back-to-back jets



[Beauchemin et al., ATL-PHYS-PUB-2005-03]



Example: Dijets + Missing E_T



Discovery reach:

6 pb^{-1} : M_C > 1.3 TeV

100 fb^{-1} : M_C > 2.7 TeV

Existing bounds:
350 - 400 GeV [Tevatron]

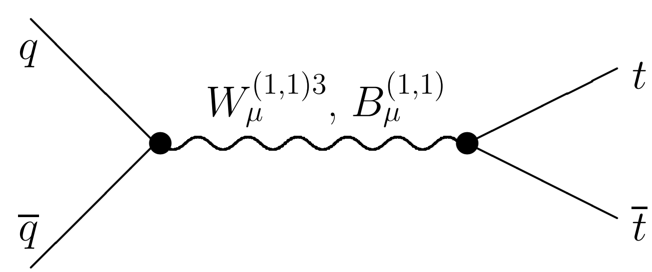
Example: 2 UED Scenario

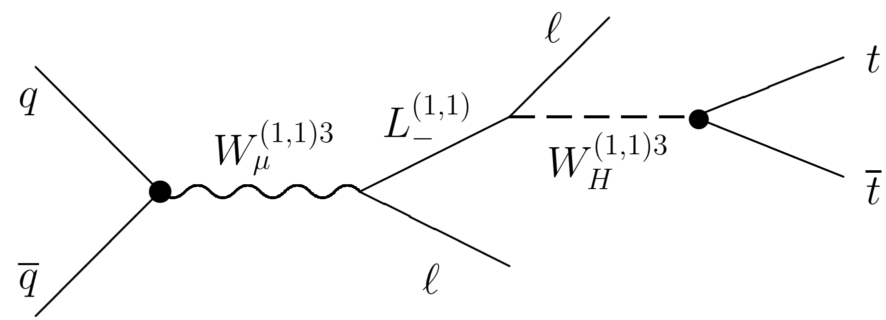
(1,1) KK modes could be singly produced

Cascade decays lead to a narrow-spaced tt-resonances (+ leptons or jets)

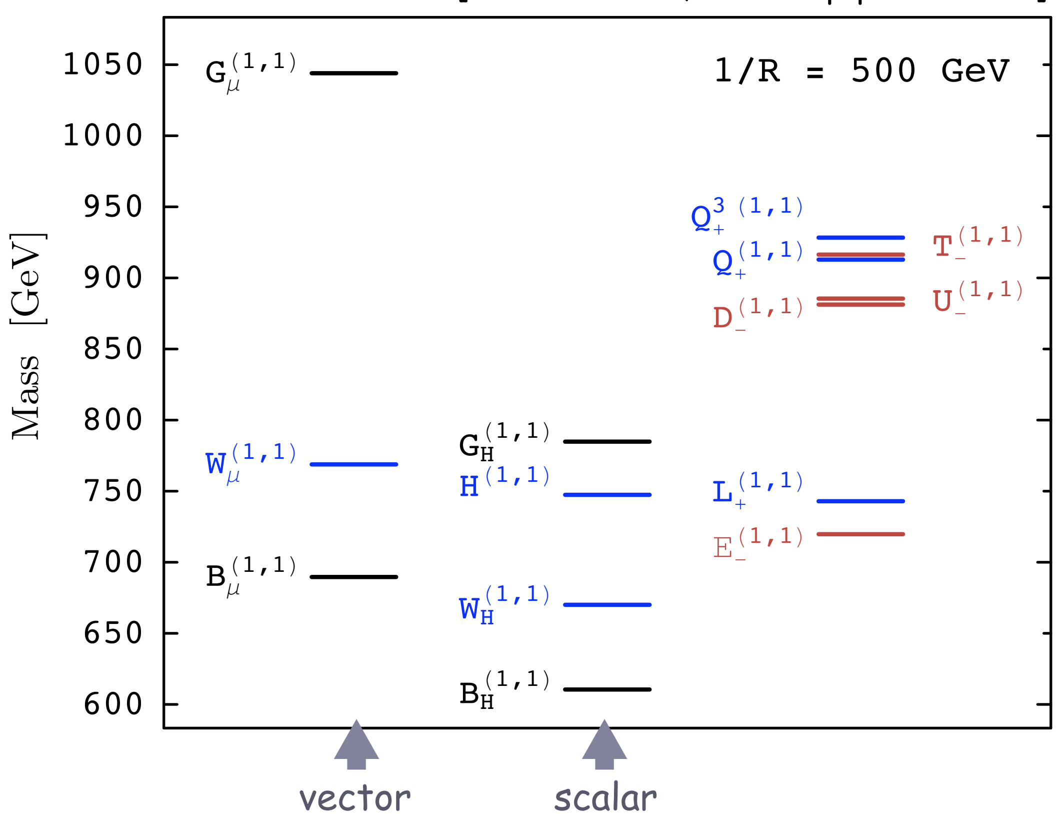
EW constraints: 1/R < 500 GeV

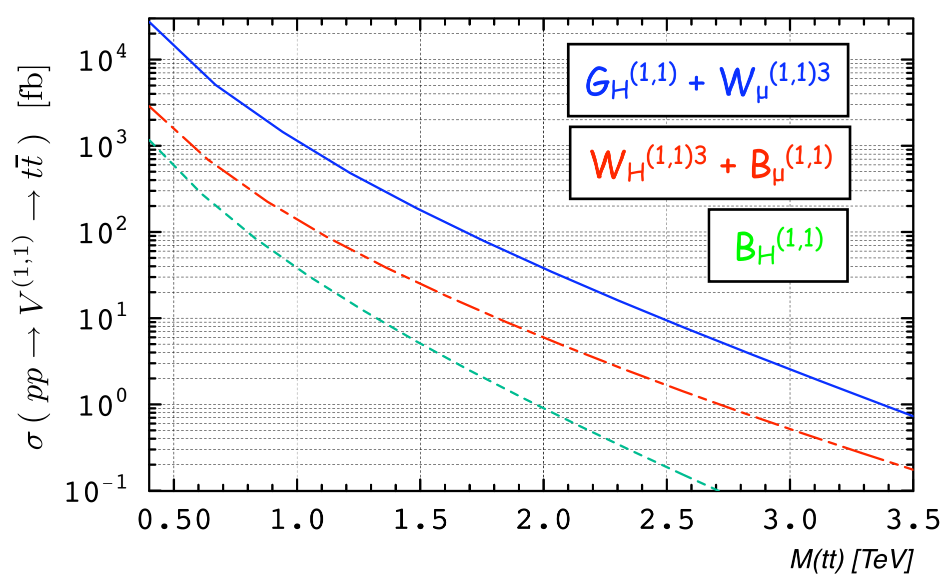
[R: compactification radius]





[Burdman et al., arXiv:hep-ph/0601186]



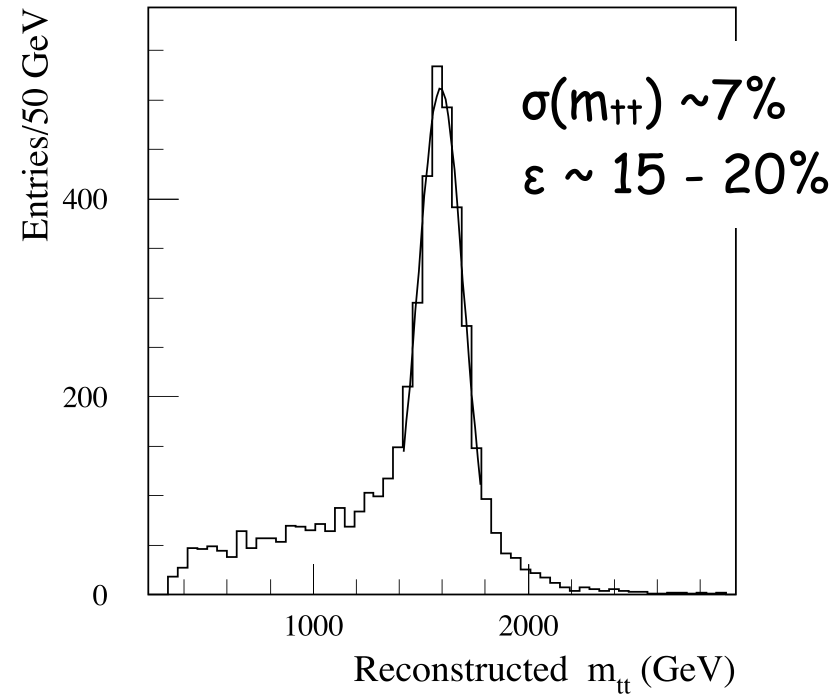


Example: 2 UED Scenario

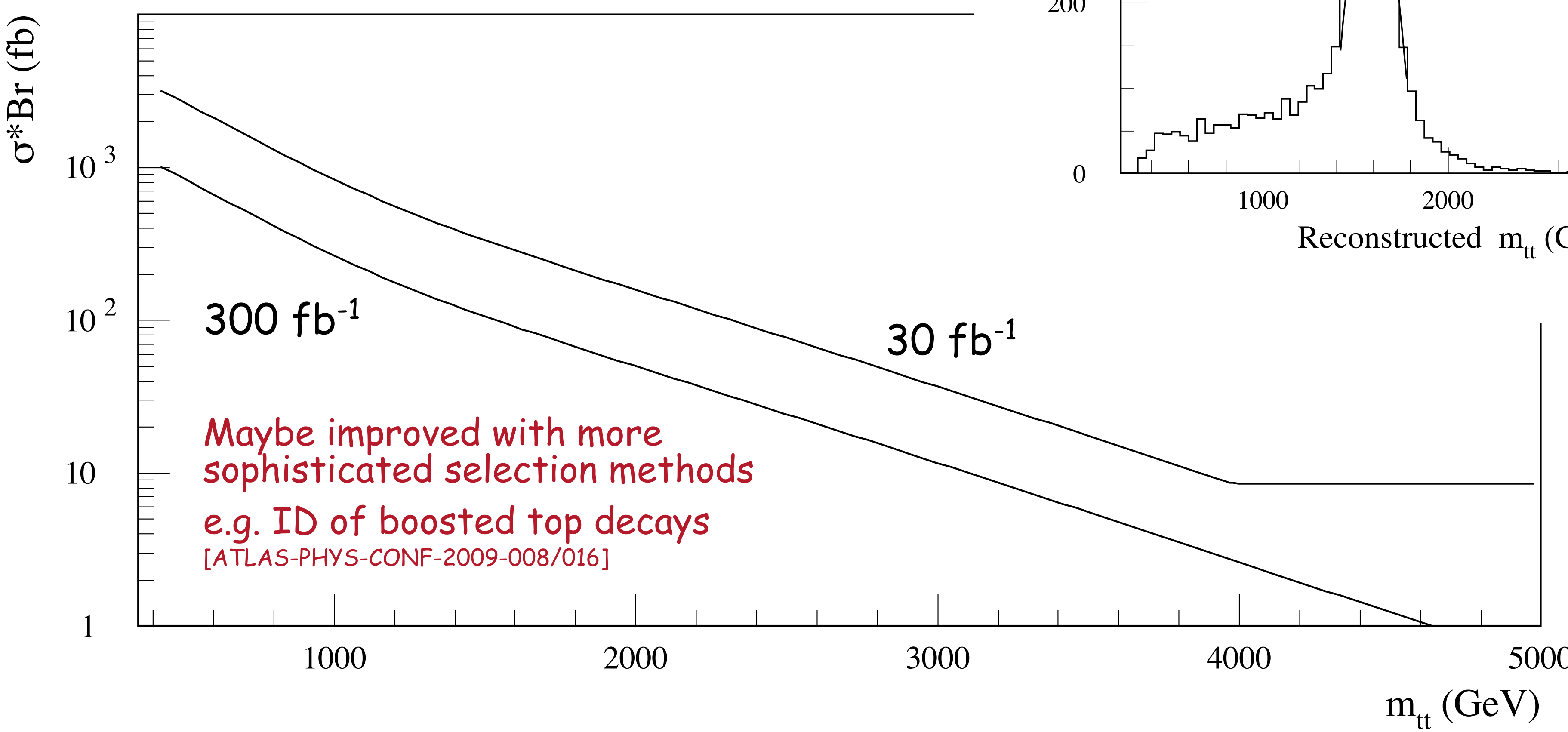
Sensitivity:

1 TeV tt-resonance in reach with 30 fb^{-1}

Re-interprete of previous tt resonance studies
[Burdman et al., arXiv:hep-ph/0601186]



[ATLAS TDR, CERN-LHCC-99-15]



Maybe improved with more sophisticated selection methods

e.g. ID of boosted top decays
[ATLAS-PHYS-CONF-2009-008/016]

Concluding Remarks

Existence of extra dimensions could provide many striking signatures due to production of KK excitations

Many studies have been done to determine the ATLAS discovery reach for extra dimensions

Evidence for low lying KK states possible with luminosities of order 1 fb^{-1}, sometimes even less

Desperately waiting for data.