Exotic searches with complex final states at the LHC

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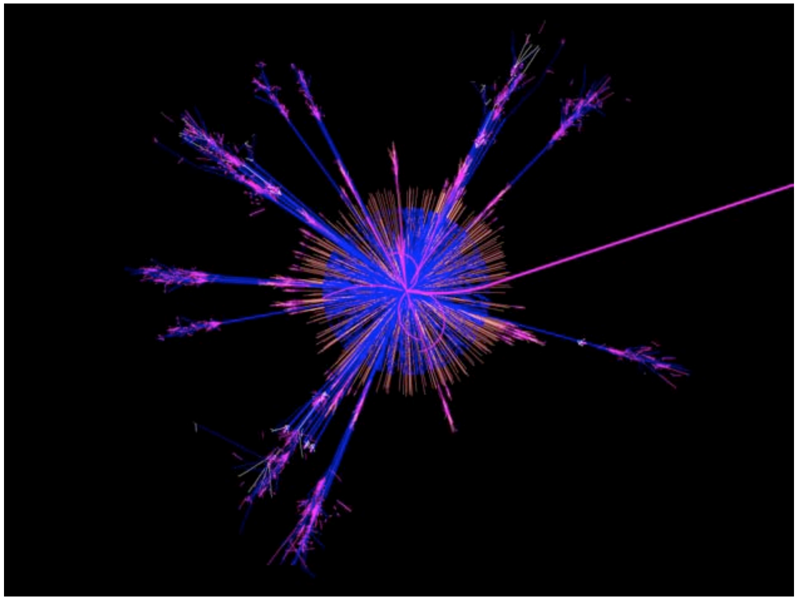
Overview

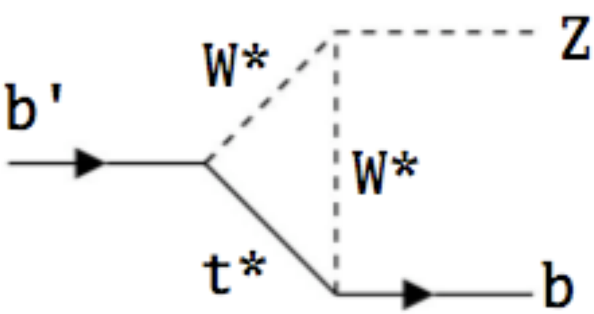
- Complex Final States
  - High multiplicity final states
    - 4th generation quarks
    - Heavy top and bottom partners
    - Di-boson resonances
    - Black Holes
    - String Balls
  - Non-standard final states
    - Hidden valley particles (with displaced vertices)

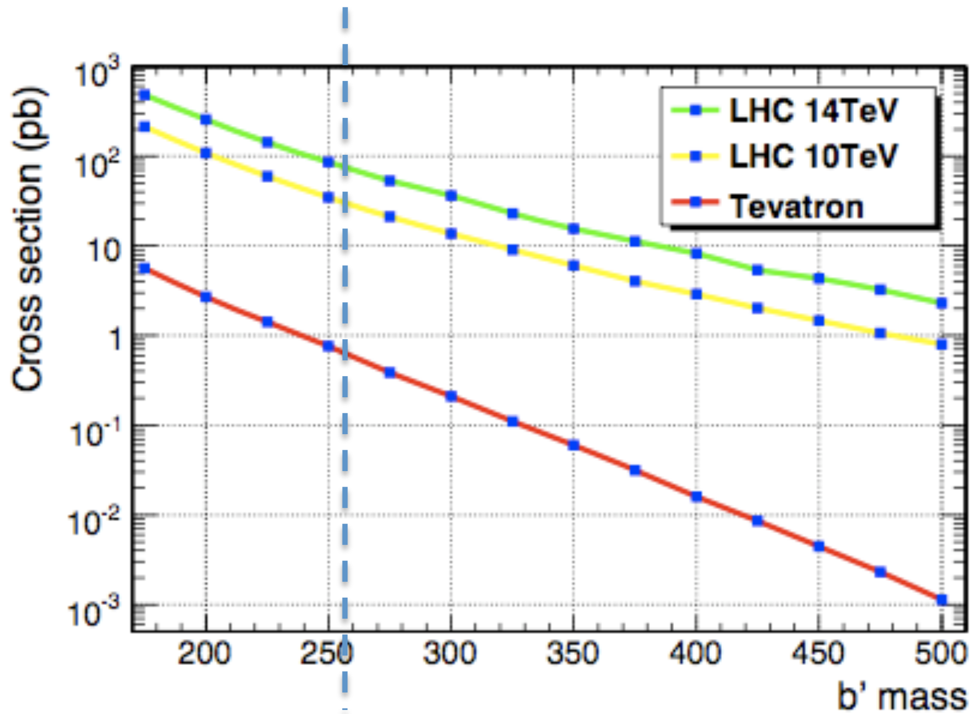


Other reviews of exotic physics @ LHC :
BSM Searches at the LHC with lepton and jets: Kevin Black
Assortment of Di-Lepton Signatures and BSM Physics: Valerie Halyo

4th generation quarks

- Bottom-like (b’) and top-like (t’)
  - Light b’ scenario
    - b’ → cW
    - b’ → bZ



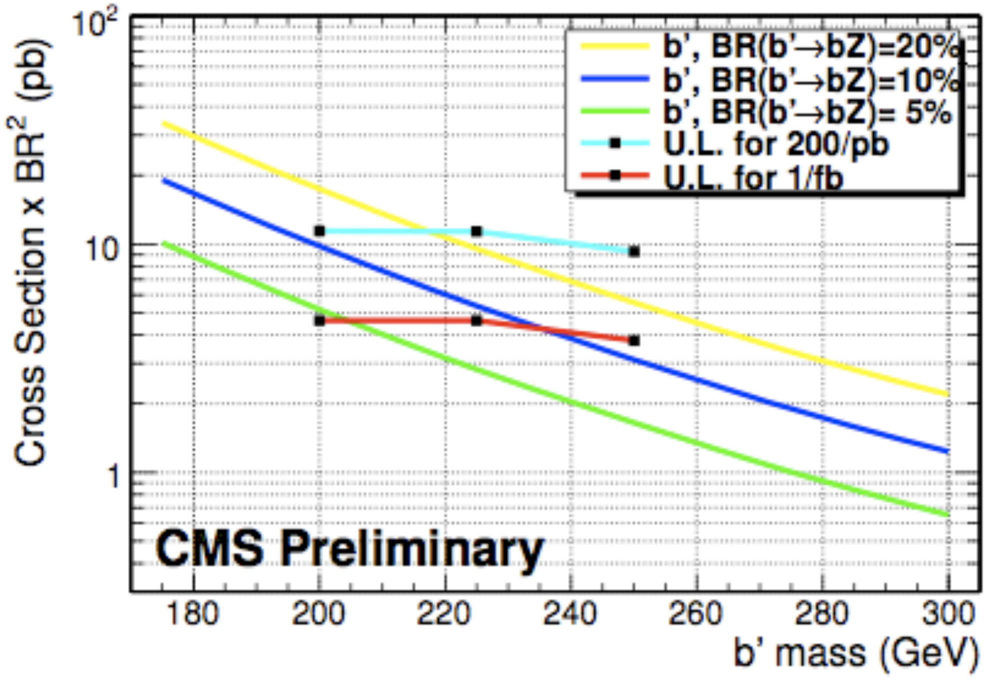


- Heavy b’ scenario
  - b’→tW

Light b'

- Signal: b'b'→ cWbZ
  - Assume BR(b'-->bZ)=10%, BR(b'→cW)=90%
  - Tri-leptonic final state
    - Signature: 3 leptons (WZ) and 2 jets
- Background:
  - Z+jets, WZ+jets, ttbar
    - Use data-driven background estimation methods
      - Matrix method

$\sqrt{s} = 10$ TeV



Heavy b'

- Bottom-like quark that decays to tW
  - Mass > 255 GeV
- Decay chain with 4 W bosons!
  - $b'b' \rightarrow tW\, tW \rightarrow bbW^+W^-W^+W^-$
- Possible final states:
  - 4 leptons + 2 jets, 3 leptons + 4 jets, 2 leptons + 6 jets, 1 lepton + 8 jets, 0 lepton + 10 jets
  - Concentrate on large, clean modes first
    - Standard Model background expected to be small for the 2 same-sign lepton final state
- Background:
  - tt+jets, tt+W/Z+jets, W/Z+jets, di-bosons

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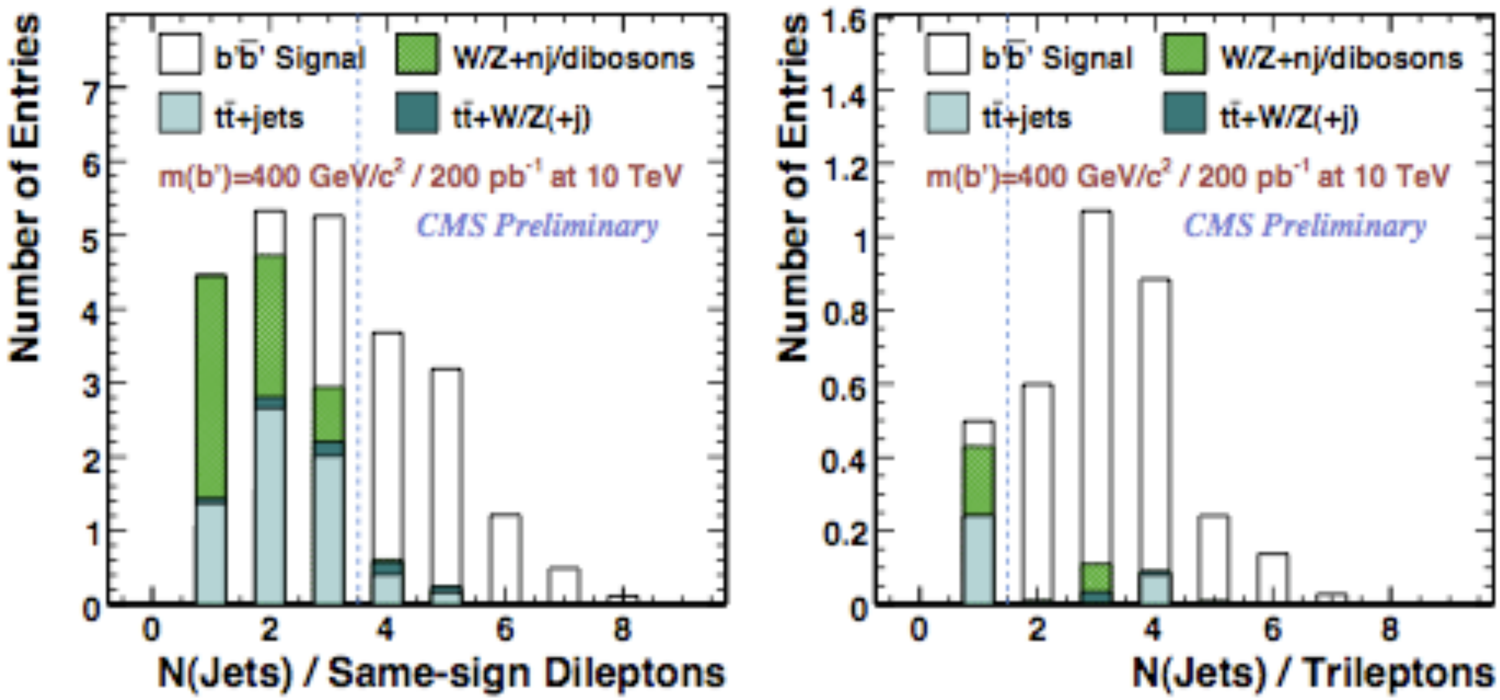
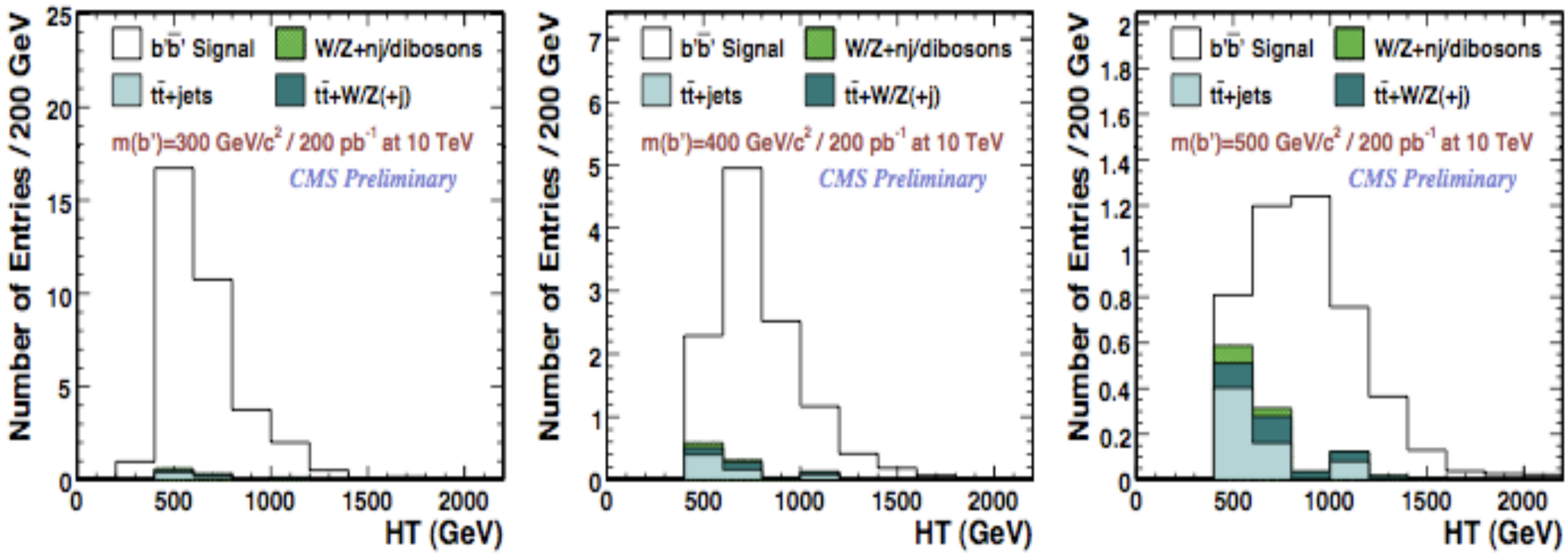


Heavy b'

$$H_T = \sum p_T(\text{jets}) + \sum p_T(\text{leptons}) + \text{MET}$$

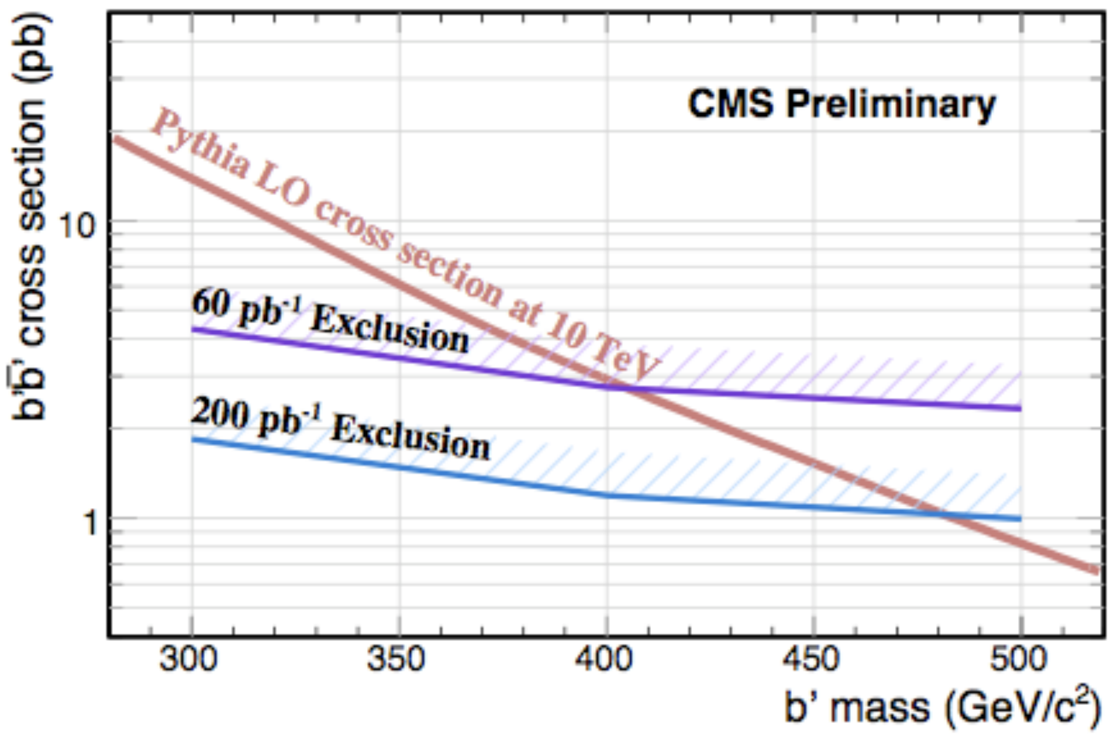


- Use data-driven background estimation techniques
  - Define background rich control samples for normalizing the background contributions

Heavy b' limits

$\sqrt{s} = 10\ \mathrm{TeV}$

Exclude b' masses less than 485 (405) GeV with 200 (60) pb^{-1}

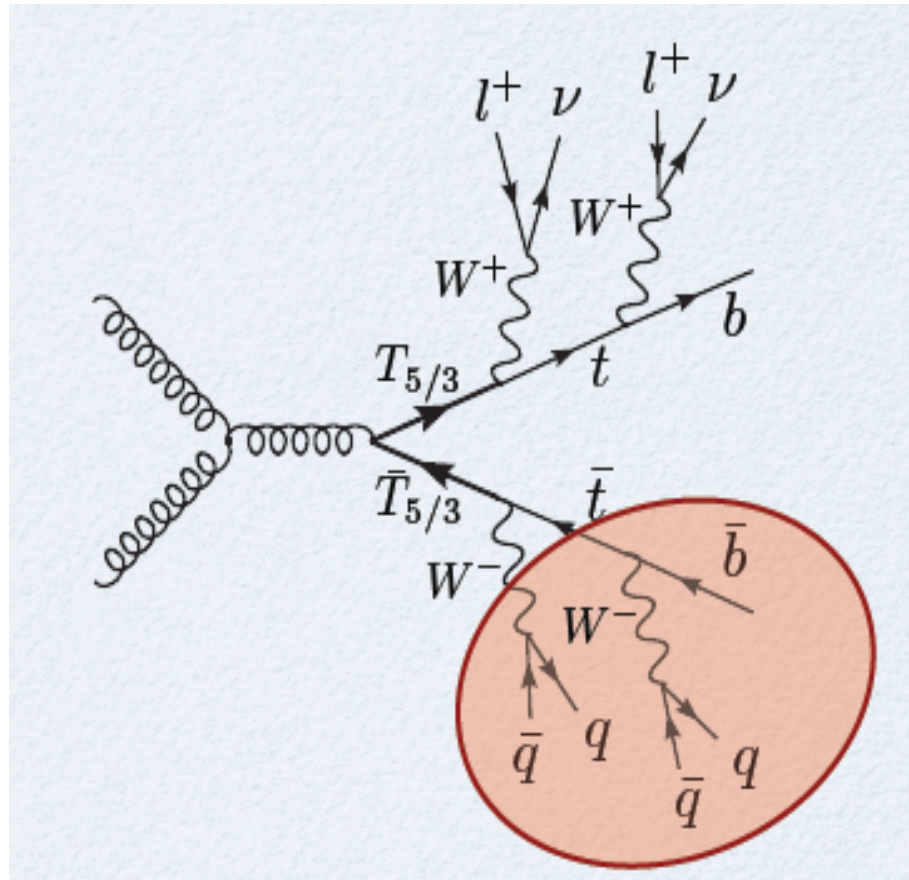


Tevatron limit: b' > 325 GeV

Stringent limits can be set at the LHC with early data

Exotic Top Quark Partner

- Fermionic top partners arise from natural, non-supersymmetric solutions of the hierarchy problem
  - Pseudo-Goldstone boson Higgs
  - $T_{5/3}$ with Q_e = 5/3 and B with Q_e = -1/3 decay into W and top
- tW invariant mass peak ($T_{5/3}$)
- Signature: $l^{\pm} l^{\pm} + n$ jets (n ≥ 5)



Additional details in A. Avetisyan's talk

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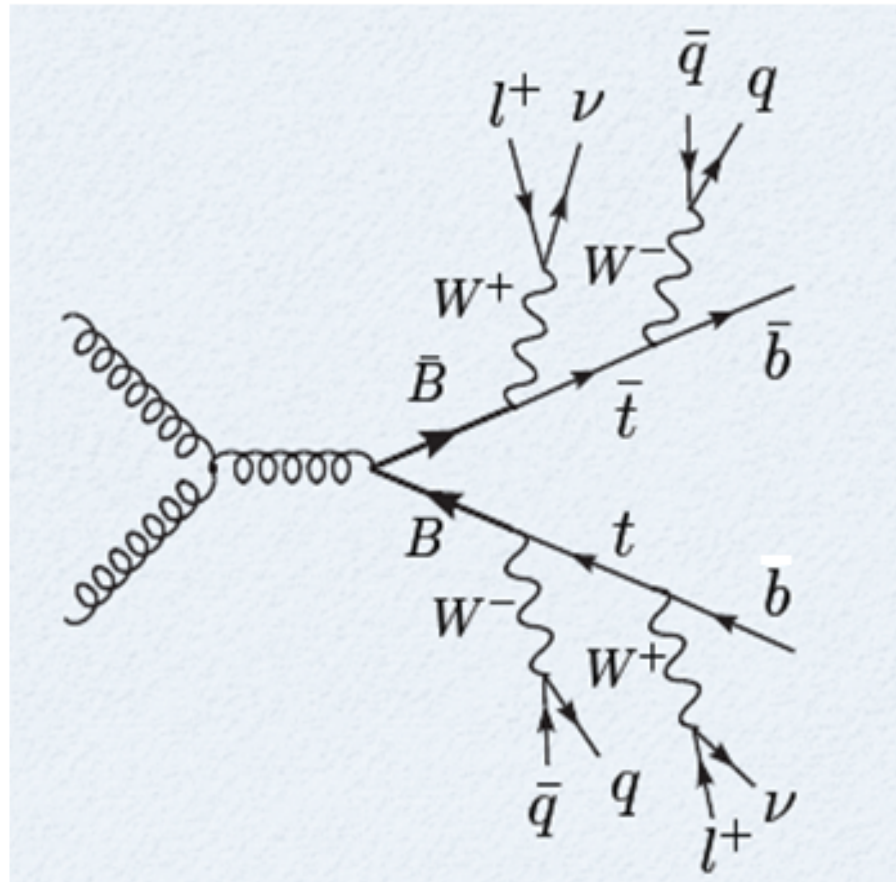
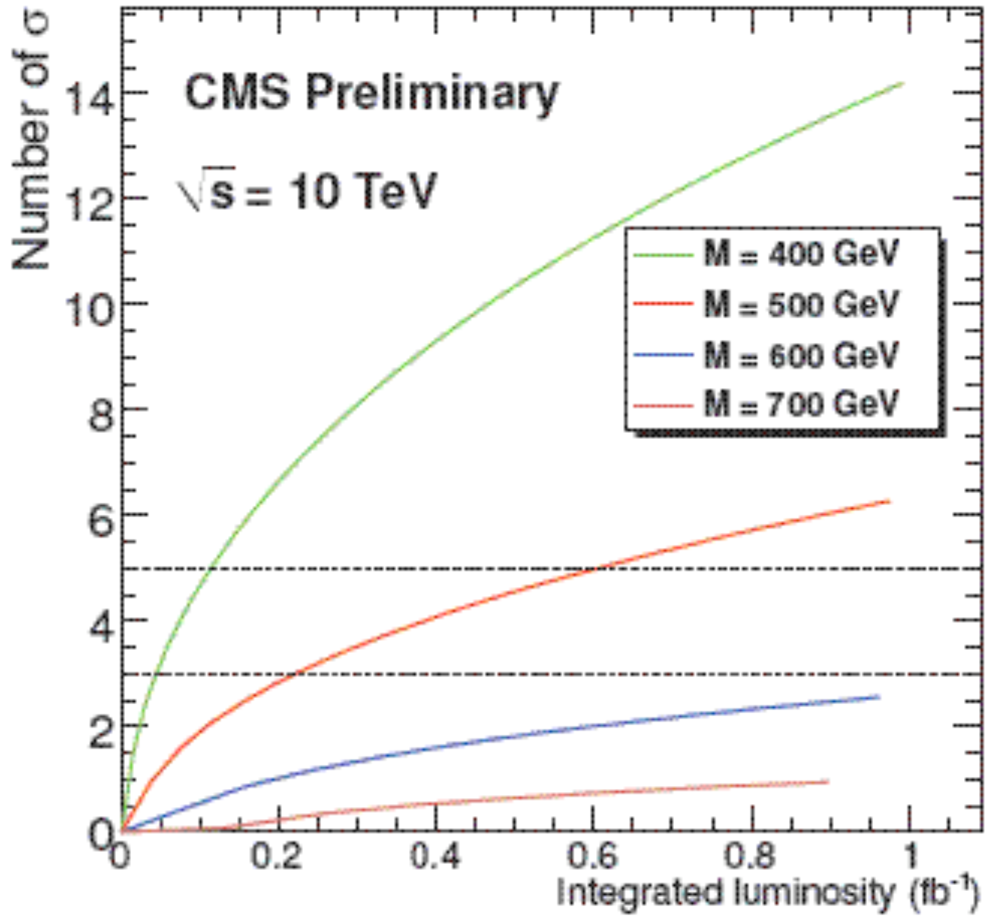


Additional details in A. Avetisyan’s talk

Discovery Potential

- For M = 400 GeV
  - 3σ at ~50pb^{-1}
  - 5σ at ~115pb^{-1}
- For M = 500 GeV
  - 3σ at ~220pb^{-1}
  - 5σ at ~600pb^{-1}
- Only 150pb^{-1} at 14 TeV for M =500 GeV

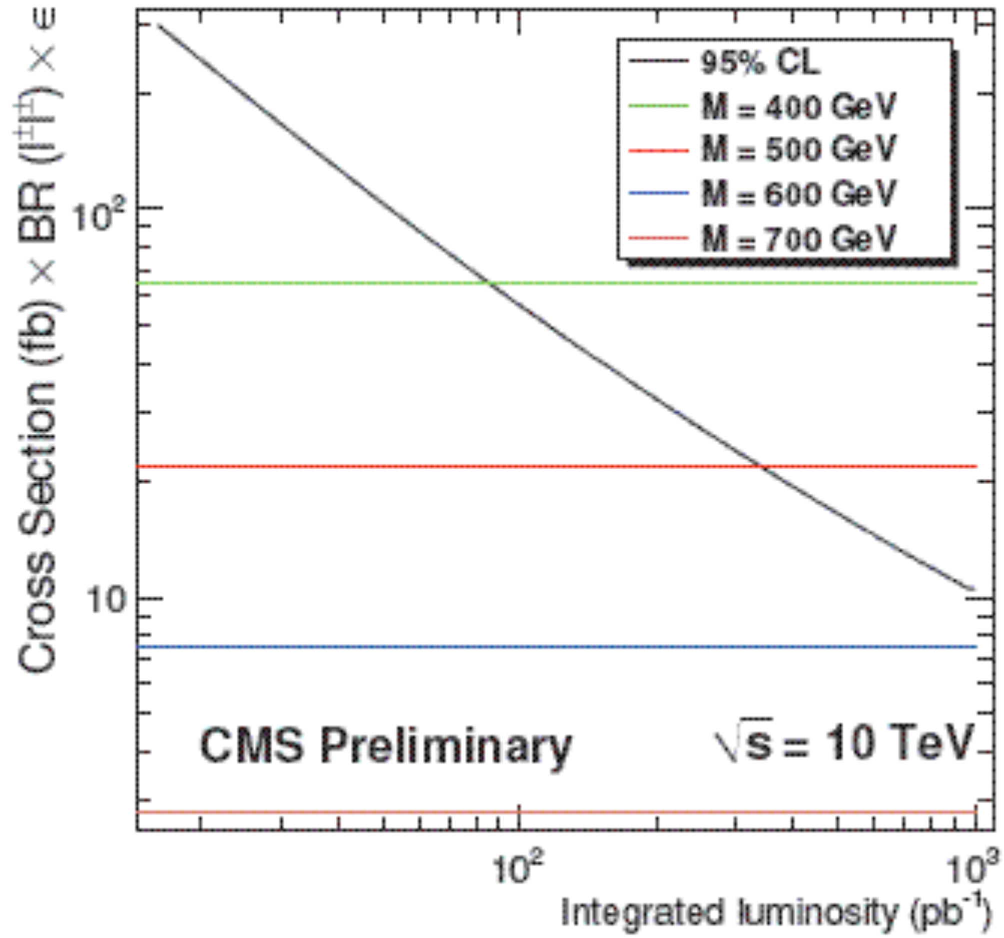


Cross section Limits

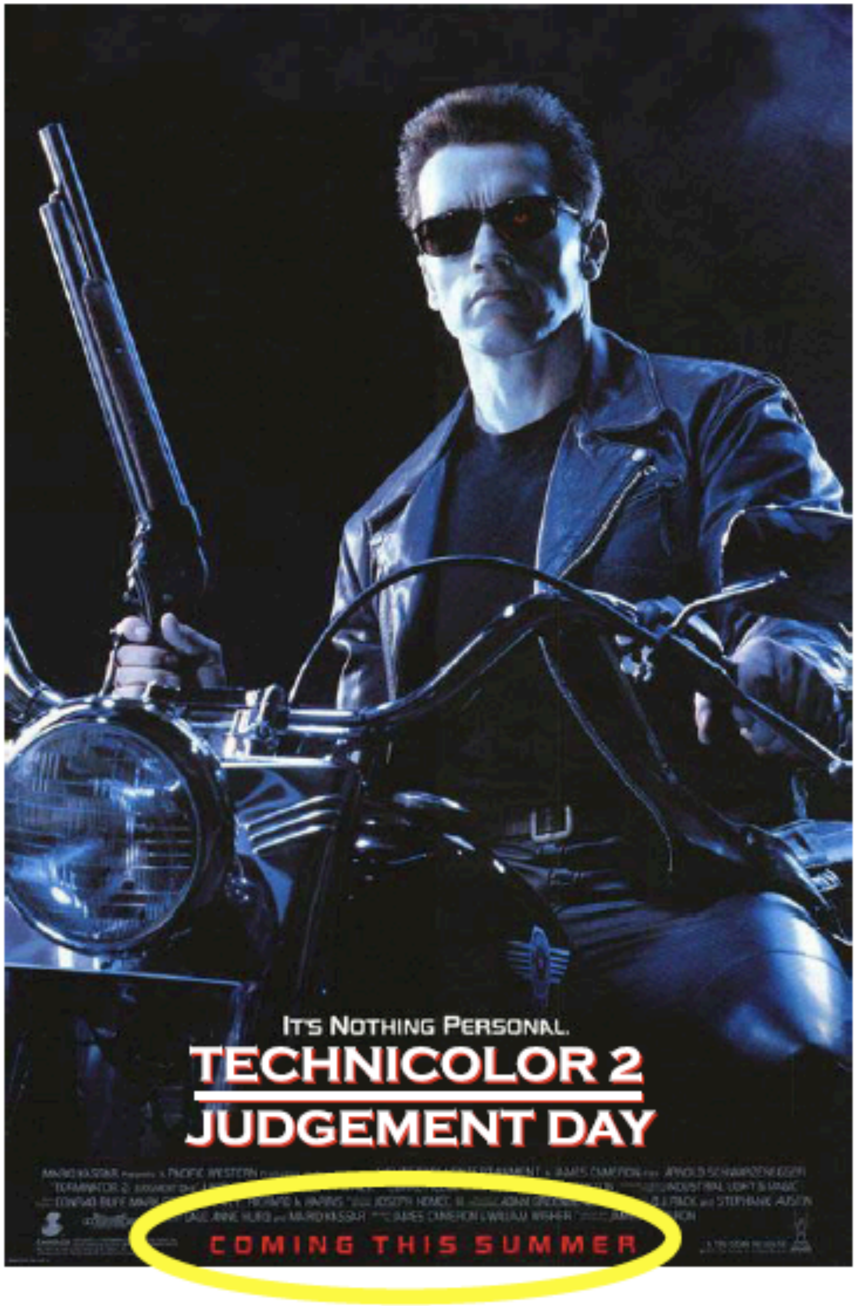
Tevatron limit: $T_{5/3}$ > 351 GeV

Stringent limits can be set at the LHC with early data

- Cross-section lines correspond to sum of $T_{5/3}$ and B expectations
- Exclude masses of up to 400 GeV with 80 pb^{-1}, 500 GeV with 340 pb^{-1}



The Return of Technicolor ?



Courtesy Markus Luty

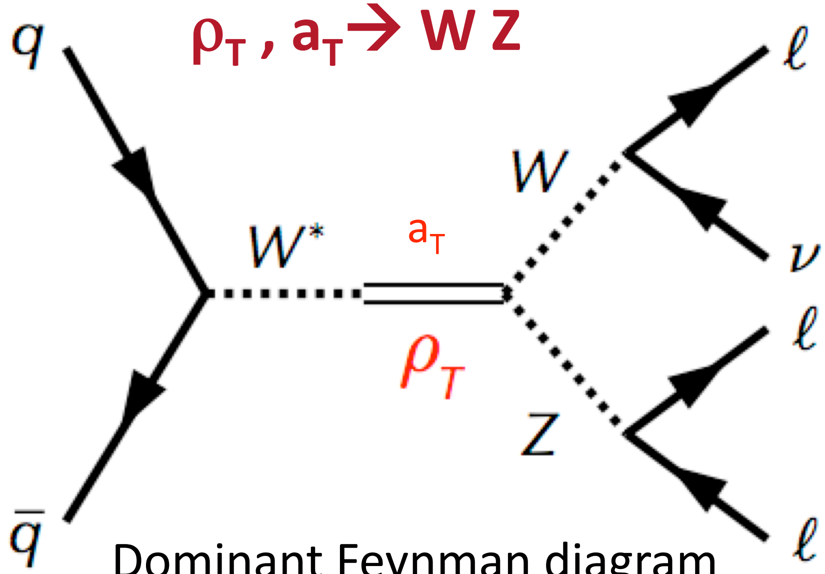
Technicolor

Dynamical breaking of electroweak symmetry: New strong dynamics a la QCD

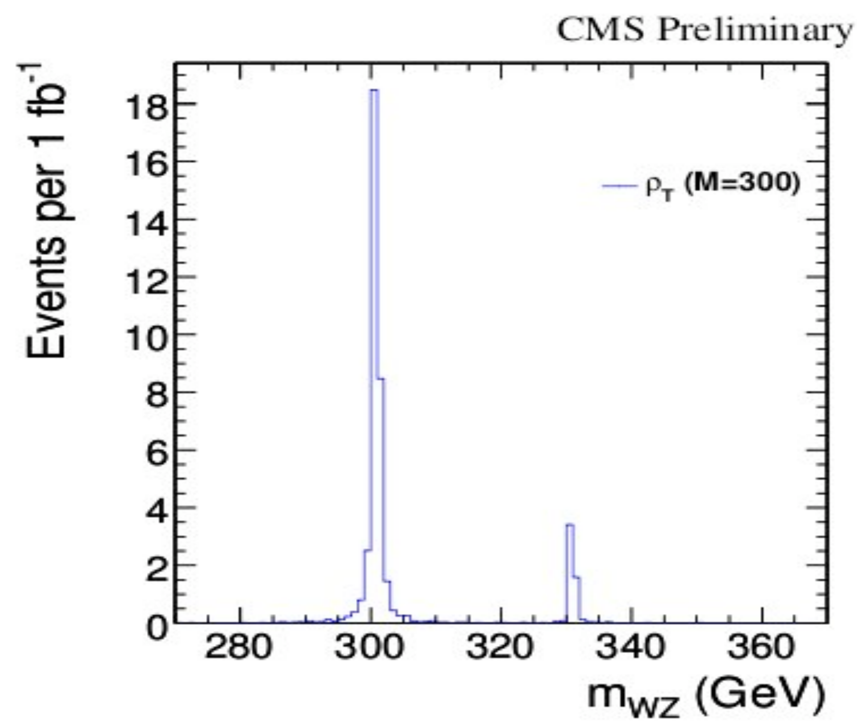
- Extended Technicolor (ETC)
  - Produces fermion masses
- Walking Technicolor (WTC)
  - Flavor changing neutral currents in ETC
- Topcolor-assisted Technicolor (TC2)
  - High value of top mass
- Technicolor models typically associated with problems linked to precision electroweak observables
  - Large S parameter contributions
- Recently proposed that the S parameter can be naturally suppressed if the lightest ρ_T and its axial vector partner, a_T, are nearly degenerate
  - K. Lane, S. Mrenna, Phys. Rev. D67 (2003)
- Phenomenology set forth in the "Technicolor Strawman Model" TCSM
  - Lightest ρ_T and ω_T lie below 0.5 TeV and they decay to γ, W, Z, π_T
  - Channels have distinctive signatures since they are very narrow : $\Gamma < 5$ GeV

Signature

ρ_T , $a_T \rightarrow$ W Z



Dominant Feynman diagram for production at the LHC

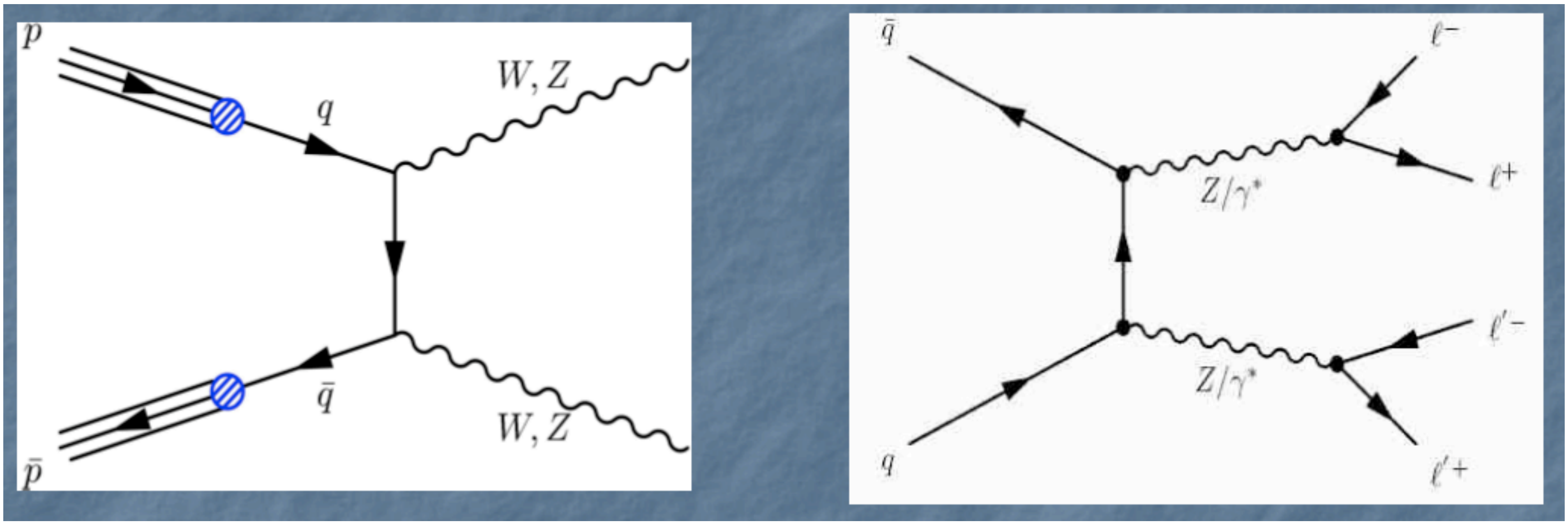


Parameter Set	$m_{\rho_T} = m_{\omega_T}$ (GeV)	m_{a_T} (GeV)	m_{π_T} (GeV)	$M_V = M_A$ (GeV)	$\sigma\times$ BR (fb)
A	225	250	150	225	232
B	300	330	200	300	74
C	400	440	275	400	24
D	500	550	350	500	9

LO PYTHIA cross sections (include branching fractions into electrons/muons)

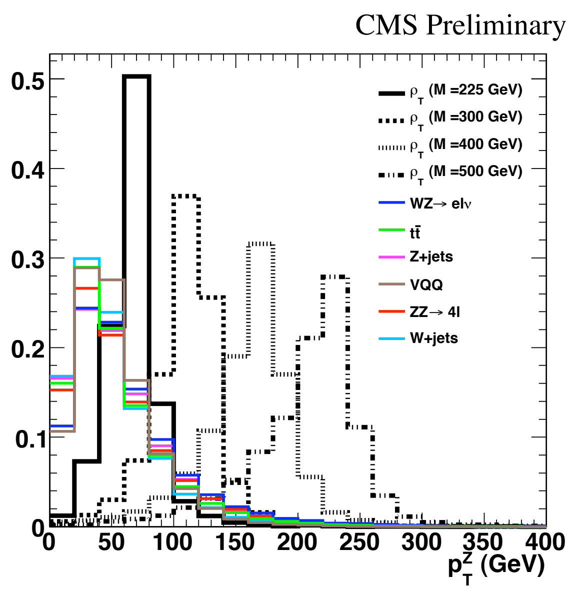
Backgrounds

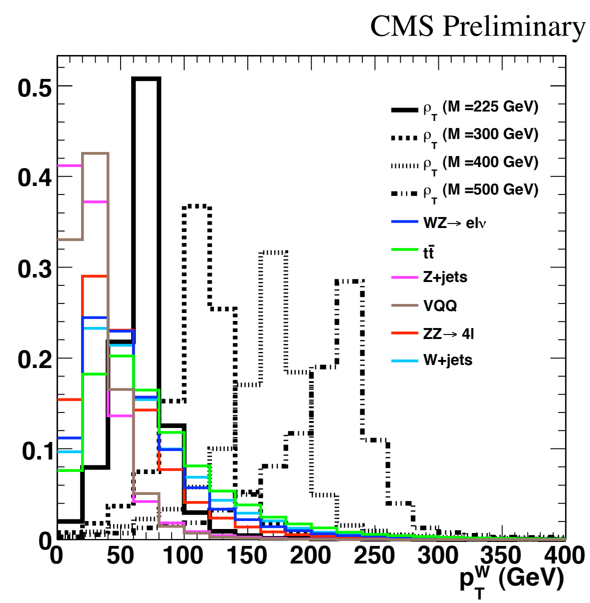
Mostly SM diboson production (WZ, ZZ)

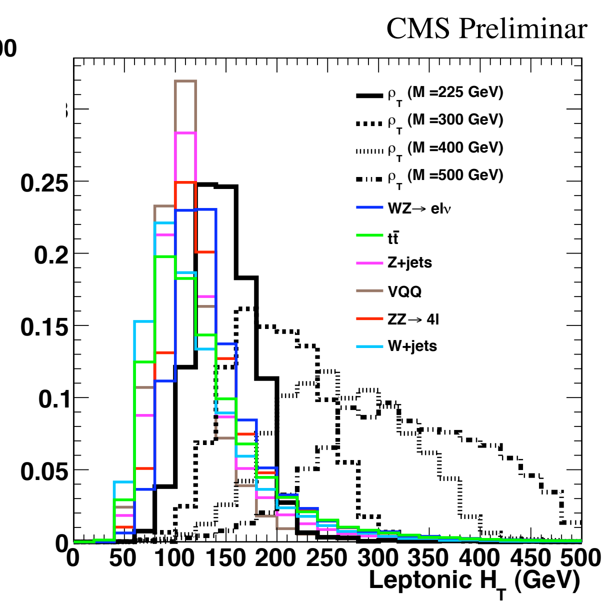


+ components of top pair production, Z+ jets, VQQ

Signal/Background

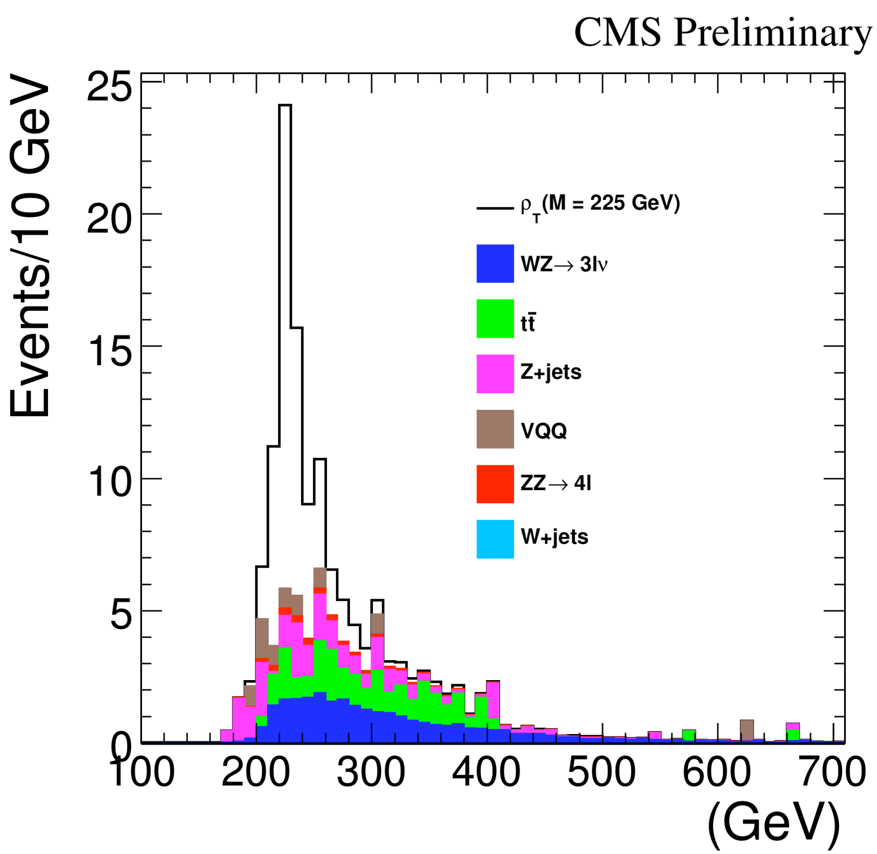


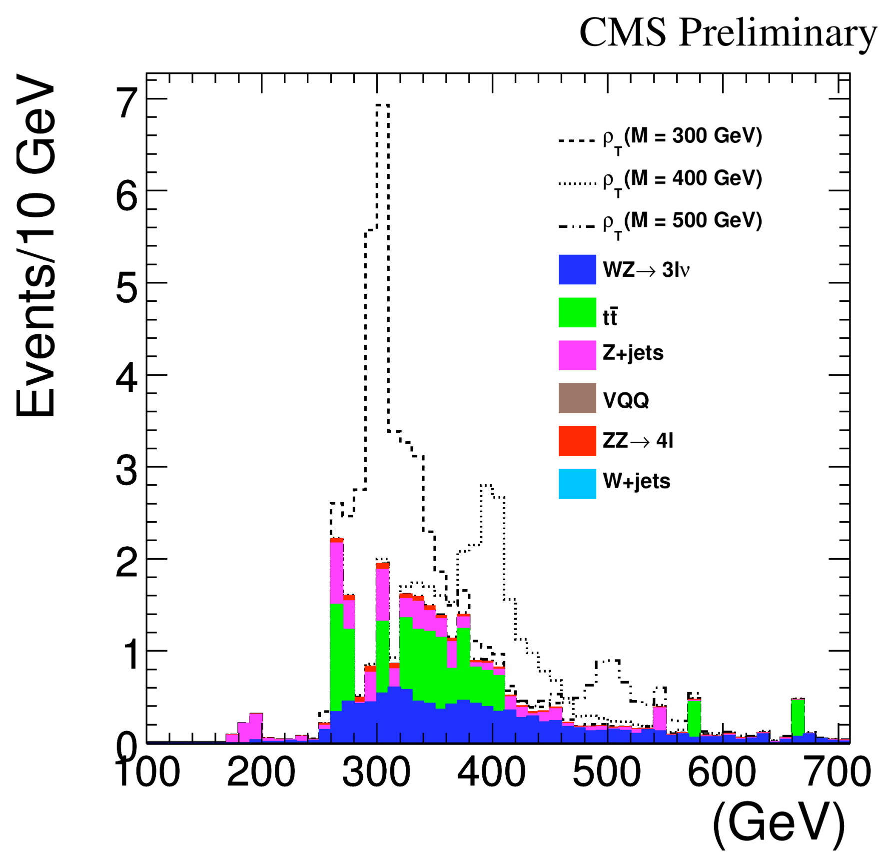




WZ Invariant Mass

@ $1fb^{-1}$

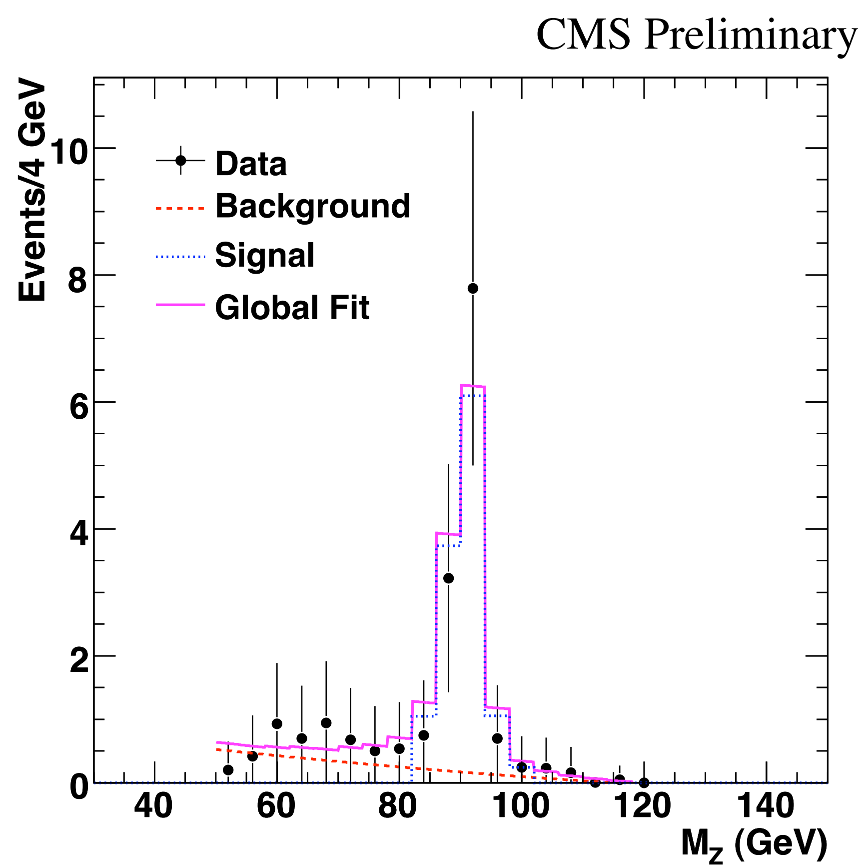




$$\sqrt{s} = 10\ \text{TeV}$$

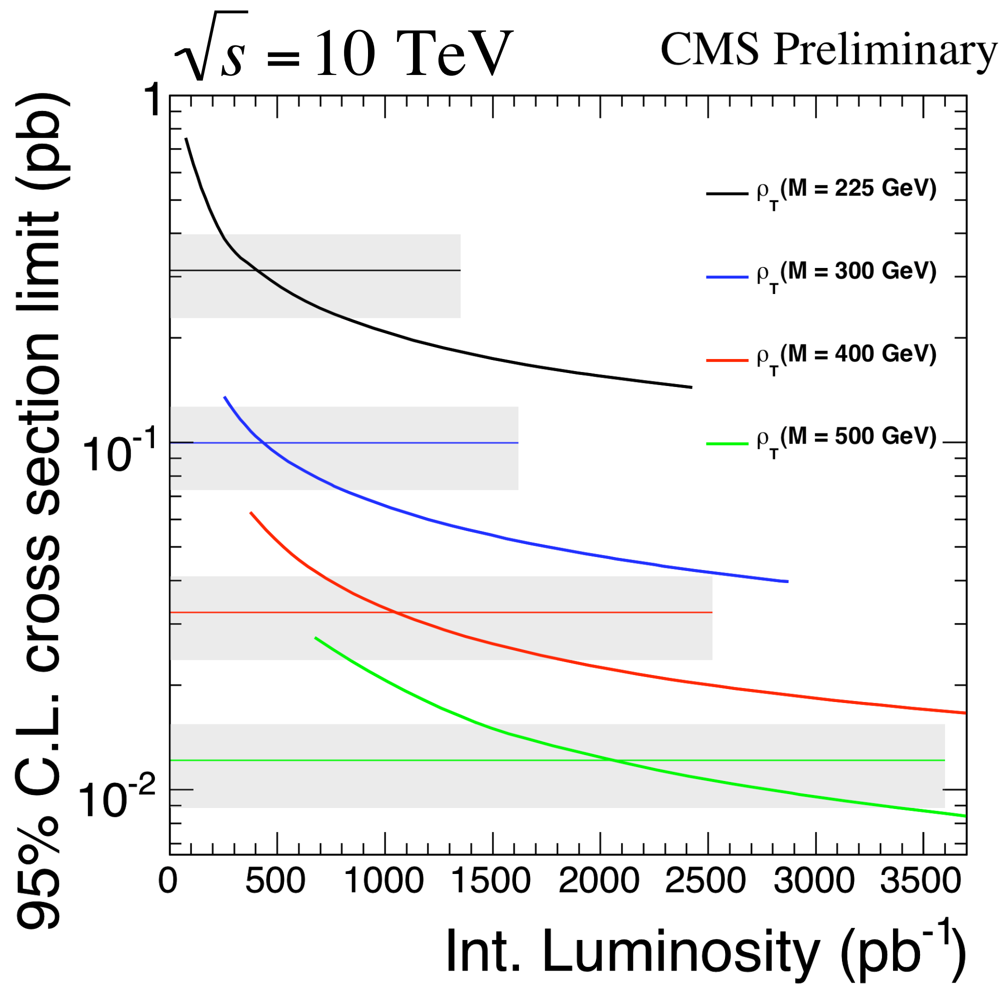
Background estimation

- Physics Background
  - SM di-boson
- Instrumental Background
  - With a genuine Z boson
    - Z+jets, Zbb
      - (Matrix Method)
  - Without a genuine Z boson
    - ttbar, W+jets
      - (Sideband subtraction method)



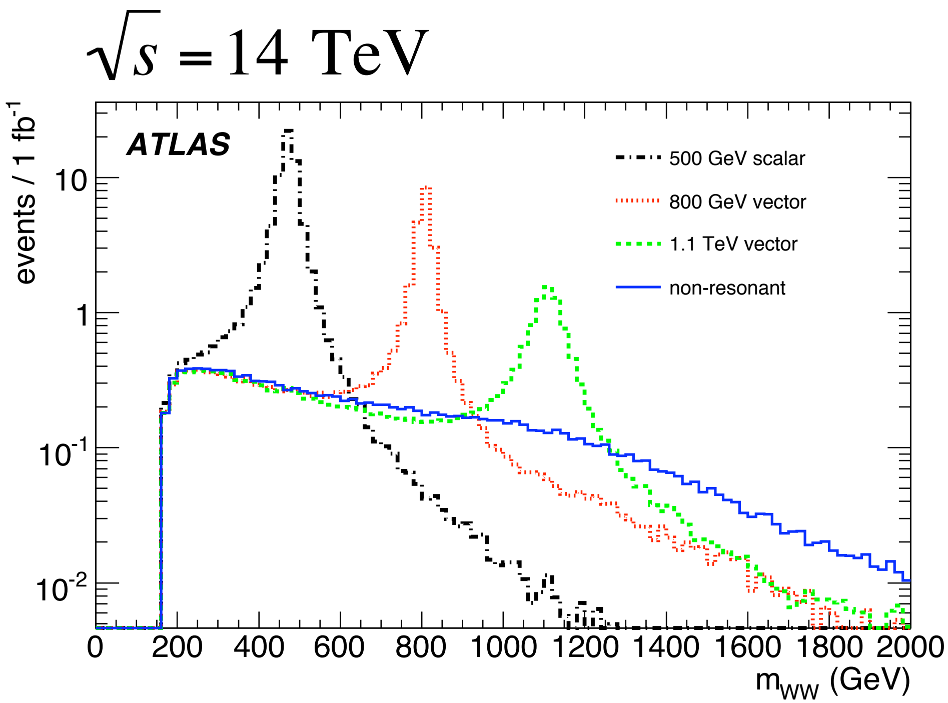
Exclusion Limits

- Exclude masses of up to 300 GeV with 450 pb^{-1}
- > 1fb^{-1} needed for excluding higher masses at 10 TeV



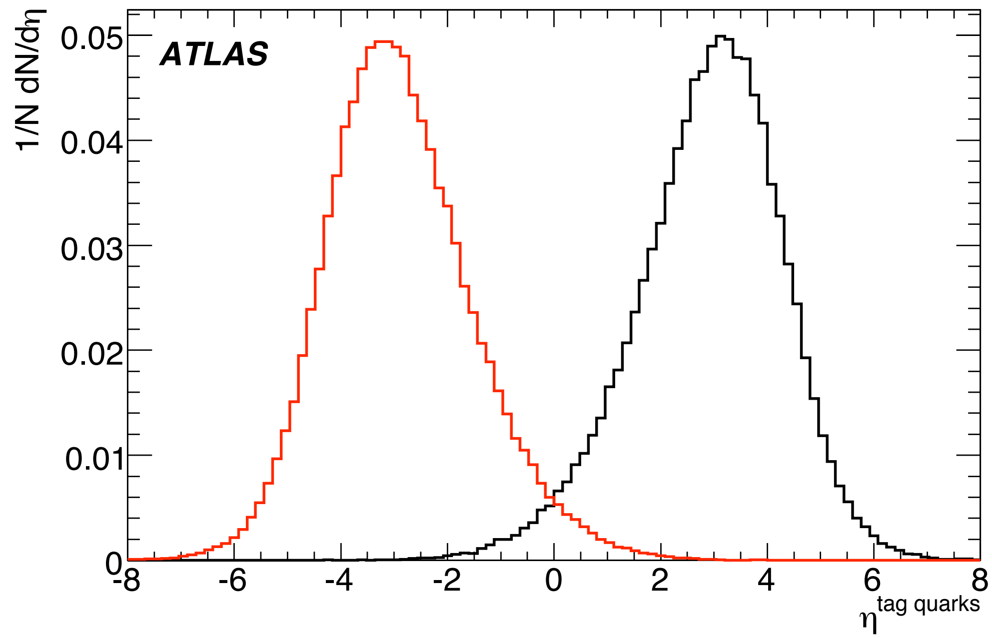
Vector Boson Scattering

- Without a Higgs, WW cross-section violates unitarity
- Some new physics may exist in the form of vector boson pair resonances



Tag Jets

- Forward jets expected from VBF
- Tag forward jets
- Reject events with additional central jets (central jet veto)

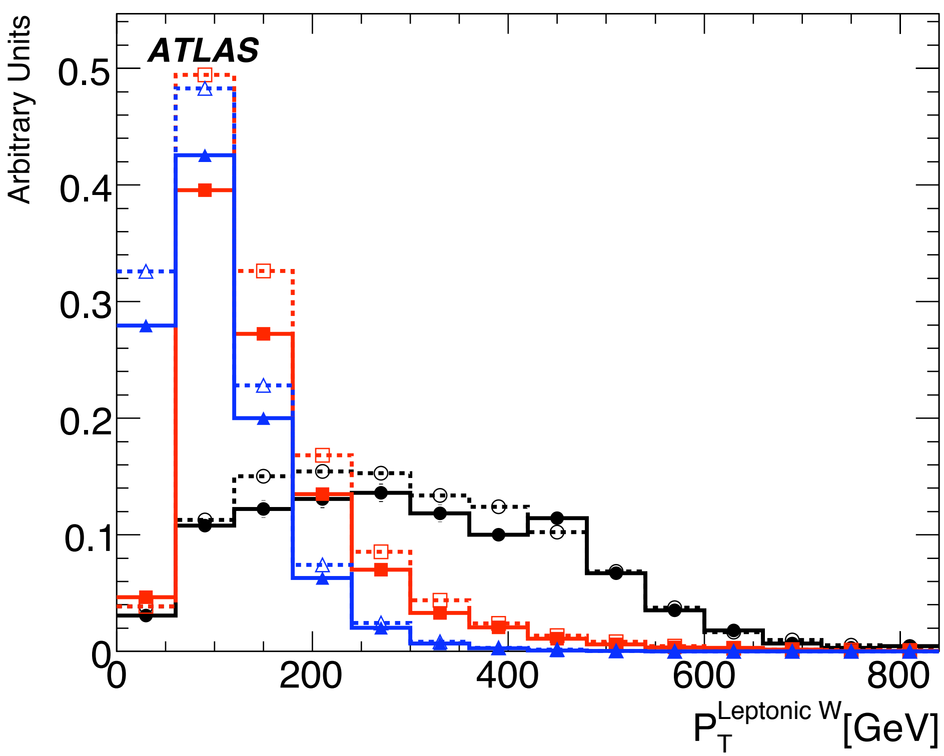


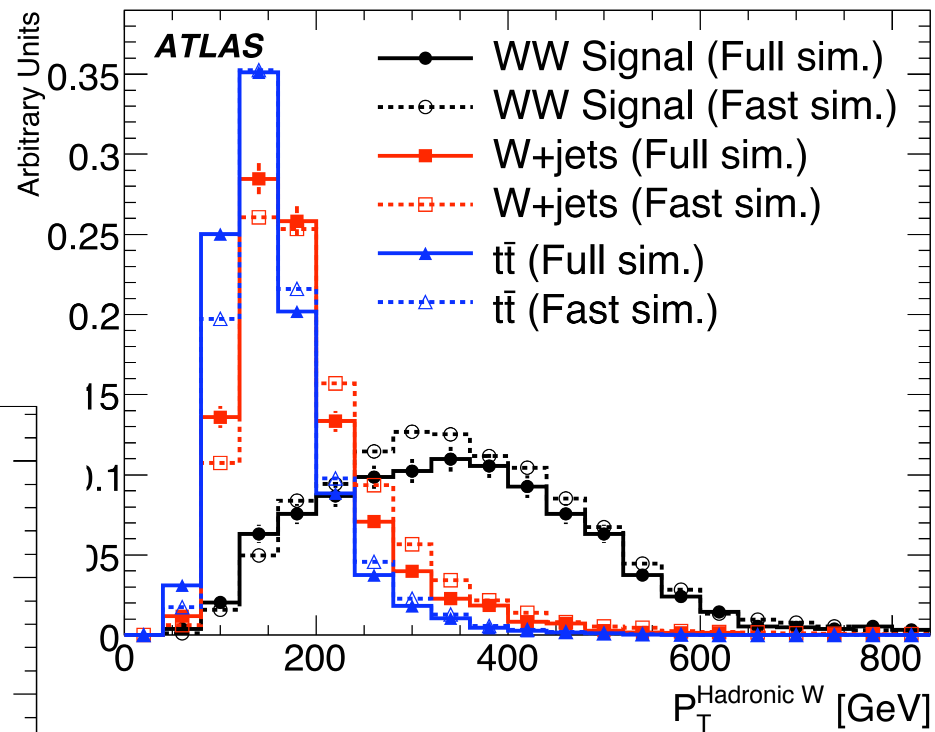
1. Require two jets with
   - $|\eta(jet)| > \eta_{\text{cut}}$ and $p_T(jet) > p_{T\text{cut}}$
   - opposite signed rapidity
   - at least one of them has an energy greater than a critical value E_{cut}
2. If more than one jet with the same sign rapidity satisfies the above cuts, choose the most energetic, labelled FJ1. The next one is labelled FJ2.
   - Require the tag-jet with the opposite sign of rapidity to satisfy $\Delta\eta(FJ1, FJ2) > \Delta\eta_{\text{cut}}$ and $E(FJ2) > E_{2\text{cut}}$

Backgrounds

Main backgrounds

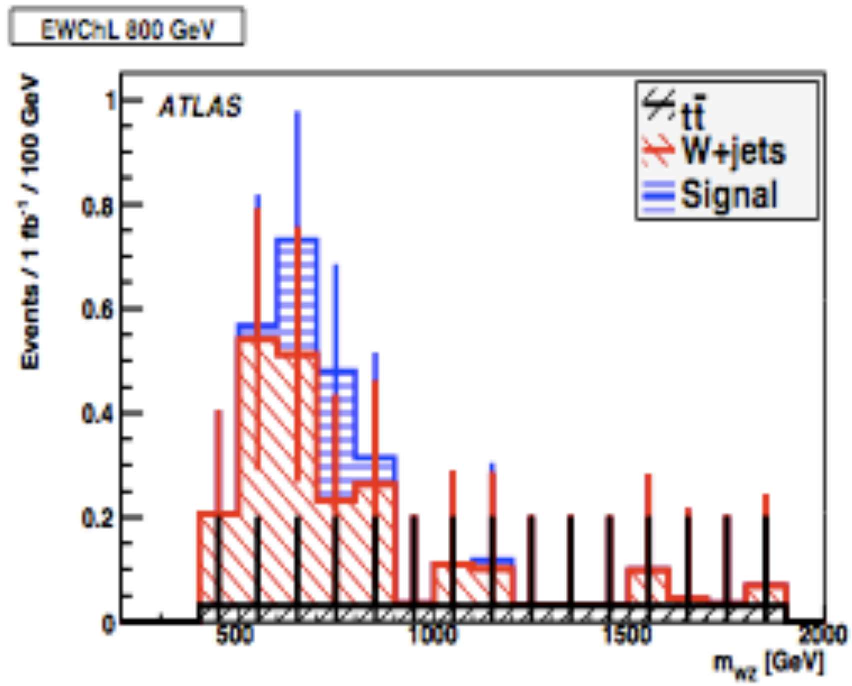
- Top, W/Z+jets
- Reduce with central jet veto

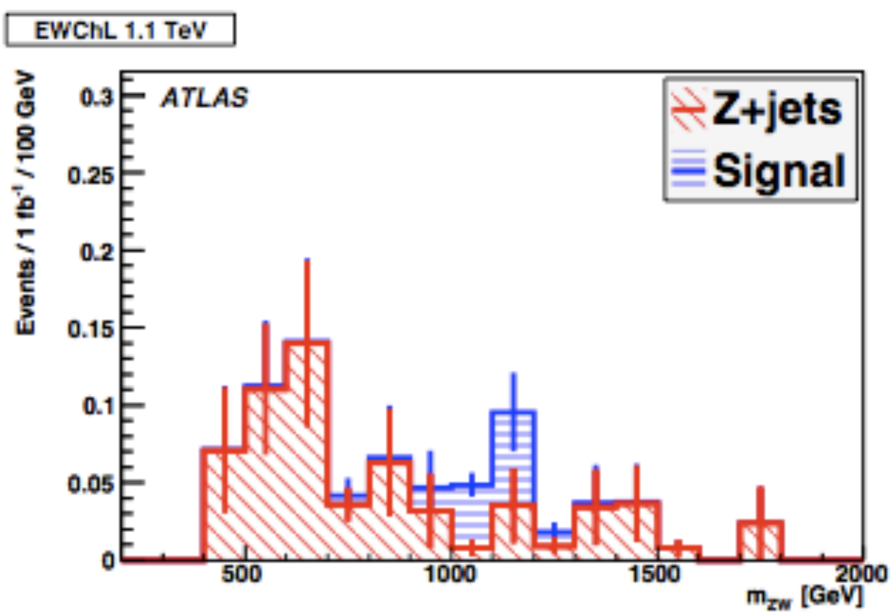




Signal over background

- Difficult Signal to reconstruct over background





Discovery Potential

Process	Cross section (fb)		Luminosity (fb^{-1})		Significance
	signal	background	for 3σ	for 5σ	for 100 fb^{-1}
$WW/WZ \to \ell\nu\, jj$, $m = 500$ GeV	0.31 ± 0.05	0.79 ± 0.26	85	235	3.3 ± 0.7
$WW/WZ \to \ell\nu\, jj$, $m = 800$ GeV	0.65 ± 0.04	0.87 ± 0.28	20	60	6.3 ± 0.9
$WW/WZ \to \ell\nu\, jj$, $m = 1.1$ TeV	0.24 ± 0.03	0.46 ± 0.25	85	230	3.3 ± 0.8
$W_{jj}Z_{\ell\ell}$, $m = 500$ GeV	0.28 ± 0.04	0.20 ± 0.18	30	90	5.3 ± 1.9
$W_{\ell\nu}Z_{\ell\ell}$, $m = 500$ GeV	0.40 ± 0.03	0.25 ± 0.03	20	55	6.6 ± 0.5
$W_{jj}Z_{\ell\ell}$, $m = 800$ GeV	0.24 ± 0.02	0.30 ± 0.22	60	160	3.9 ± 1.2
$W_{j}Z_{\ell\ell}$, $m = 800$ GeV	0.20 ± 0.02	0.09 ± 0.06	30	90	5.3 ± 1.3
$W_{j}Z_{\ell\ell}$, $m = 1.1$ TeV	0.11 ± 0.01	0.10 ± 0.06	90	250	3.1 ± 0.8
$W_{\ell\nu}Z_{\ell\ell}$, $m = 1.1$ TeV	0.070 ± 0.004	0.020 ± 0.009	70	200	3.6 ± 0.5
$Z_{\nu\nu}Z_{\ell\ell}$, $m = 500$ GeV	0.32 ± 0.02	0.15 ± 0.03	20	60	6.6 ± 0.6

$\sqrt{s} = 14$ TeV

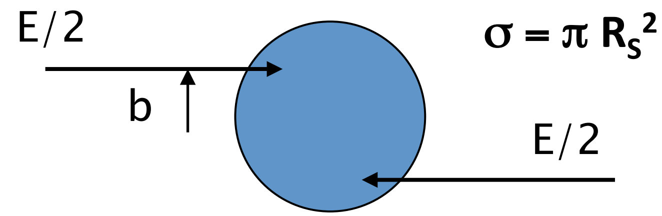
Not an early data search but need to establish strategy for such searches

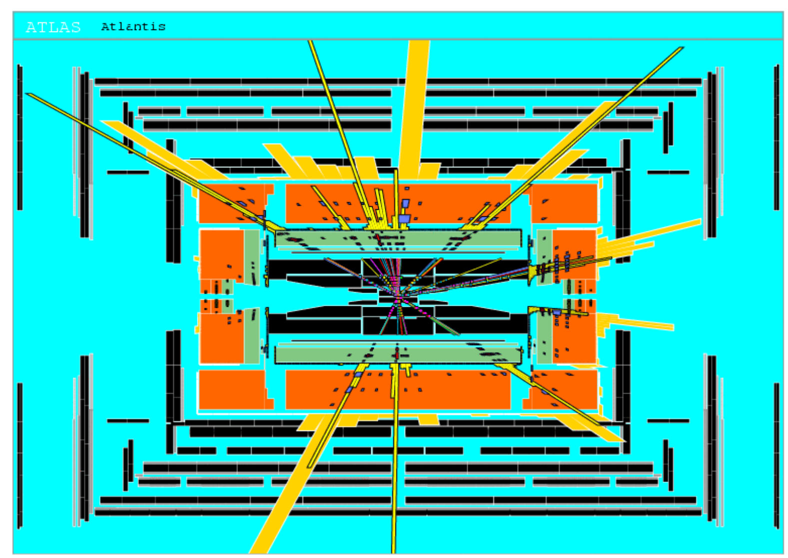
Black Hole Formation

- Dimopolous, Landsberg
  - Black holes could form if two colliding partons have impact parameter smaller than R_S
- Partonic cross-section given by geometry, total cross-section convoluted with PDFs
- Decay by Hawking Radiation
  - Democratic decay
  - Spherically symmetric

b < R_s(E) ⇒ BH forms

$$M_* R_s = \left[\frac{\Gamma(\frac{n+3}{2})}{(n+2)\pi^{(n+3)/2}} \frac{M_{BH}}{M_*} \right]^{1/(n+1)}$$





Event Selection

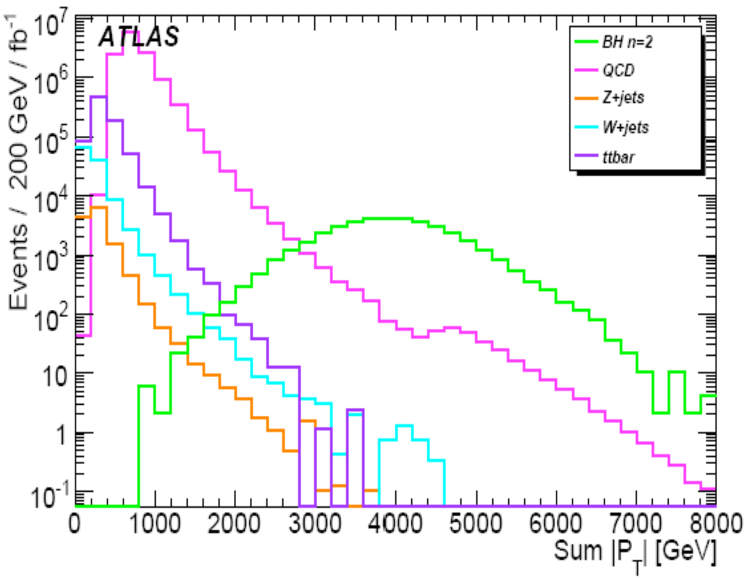
- Event Selection
  - Electron or muon with $|\eta| < 2.5$, $p_T > 50$ GeV
  - Two approaches (almost identical results)
    - $|\Sigma p_T| > 2.5$ TeV (jets + leptons)
    - At least 4 jets and lepton $p_T > 200$ GeV

A n=2,m = 5-14 TeV

B n=4,m = 5-14 TeV

C n=2,m = 8-14 TeV

D n=7,m = 8-14 TeV



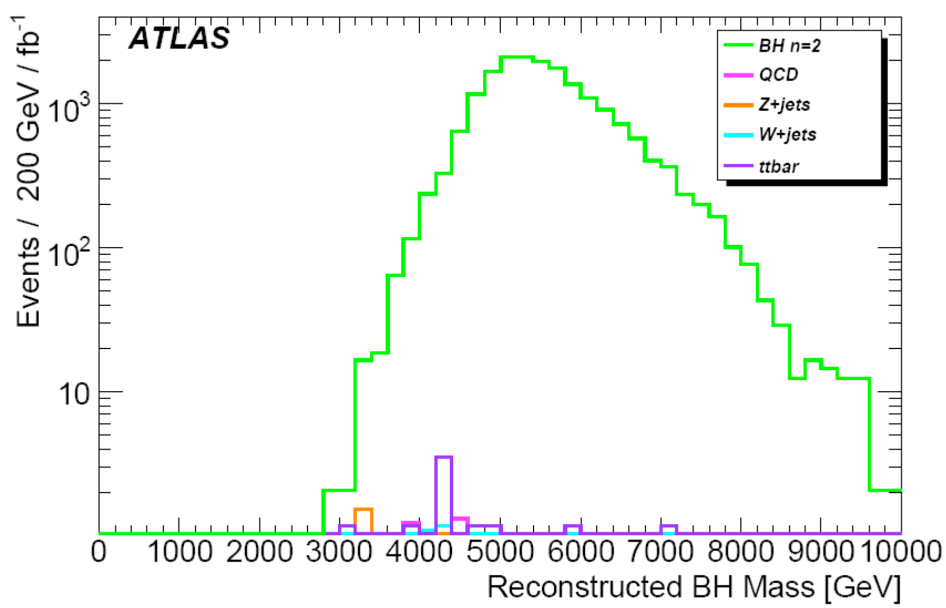
Dataset	Events before cuts (1 fb^{-1})	Events passing $\sum \lvert p_T \rvert$ > 2.5 TeV (1 fb^{-1})	After requiring lepton Events in (1 fb^{-1})	Acceptance
A	40690 ± 116	39182 ± 305	20887 ± 156	0.51
B	24320 ± 53	22591 ± 222	7071 ± 86	0.29
C	22270 ± 42	20082 ± 195	3762 ± 62	0.17
D	338.2 ± 1	338.1 ± 2.5	254.4 ± 16	0.75
$t\bar{t}$	833000 ± 100000	$23.6^{12.2}_{6.7}$	$8.2^{2.43}_{2.43}$	9.8×10^{-6}
QCD dijets	12836347 ± 3850000	6115^{4251}_{2548}	$5.51^{10.3}_{1.7}$	4.3×10^{-7}
$W(\rightarrow e,\mu) + \geq 2$ jets	1911300 ± 38200	$12.3^{9.0}_{1.8}$	$4.67^{8.75}_{0.93}$	5.1×10^{-6}
$Z(\rightarrow e,\mu) + \geq 3$ jets	51807 ± 1036	$2.75^{0.96}_{0.65}$	$2.57^{0.95}_{0.64}$	5.8×10^{-6}

Reconstruction

- Reconstruct the visible mass of the black hole from all objects and MET
- Very dramatic signature + large signal cross-sections

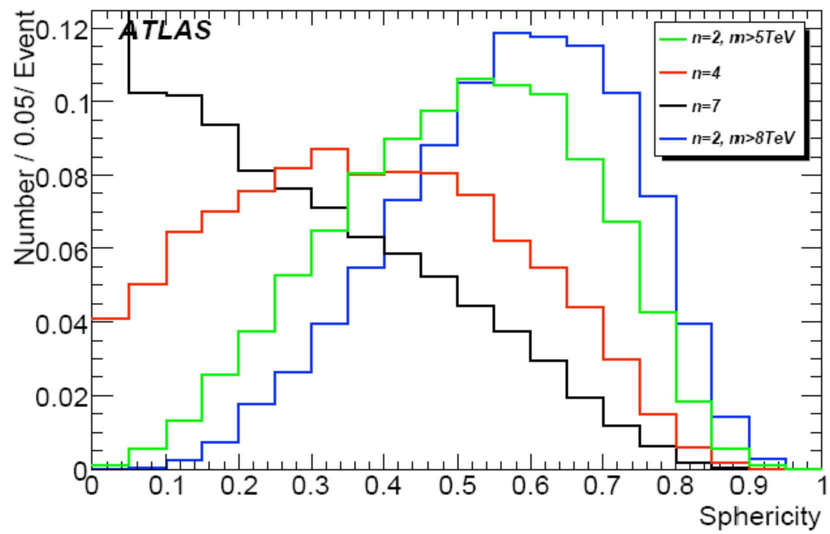
$$p_{\rm BH} = \sum_{i={\rm objects}} p_i + (\not{E}_T, \not{E}_{T_x}, \not{E}_{T_y}, 0)$$

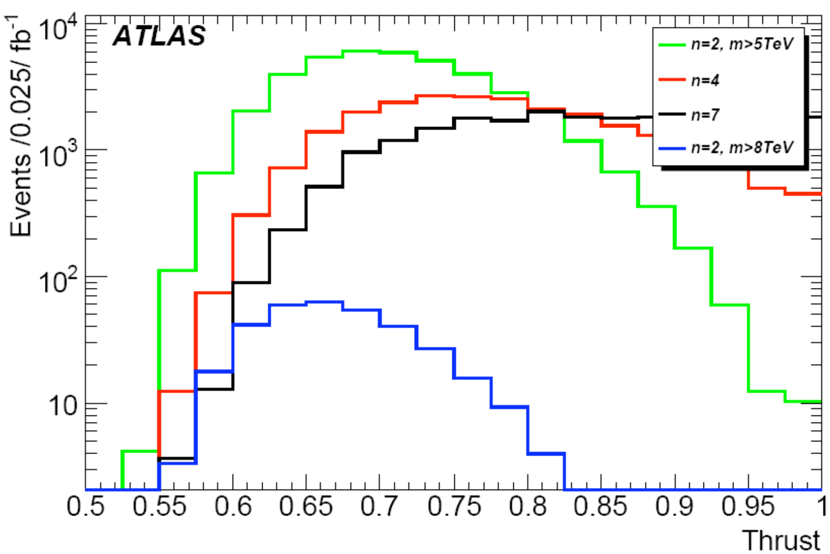
$$M_{\rm BH} = \sqrt{p_{\rm BH}^2} \, .$$

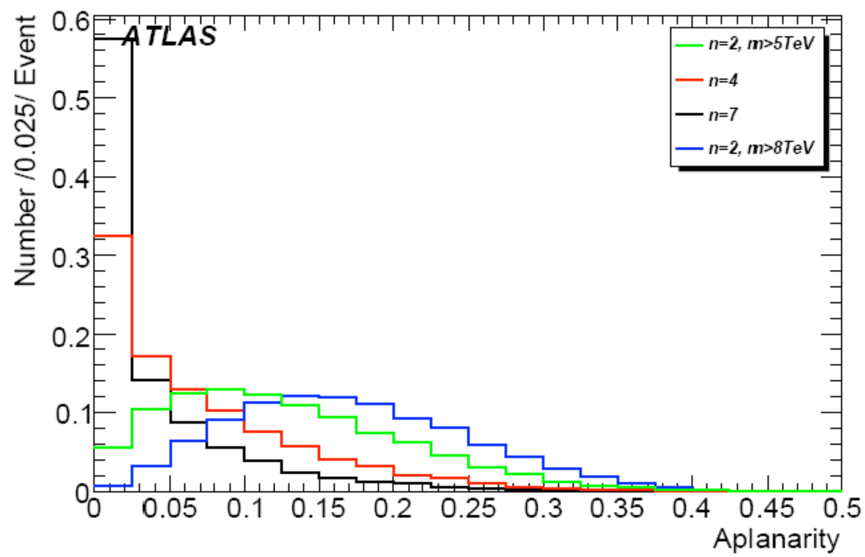


Event Shapes

- Investigated Event Shapes
  - Do give separation with background
  - Very different for different parameters



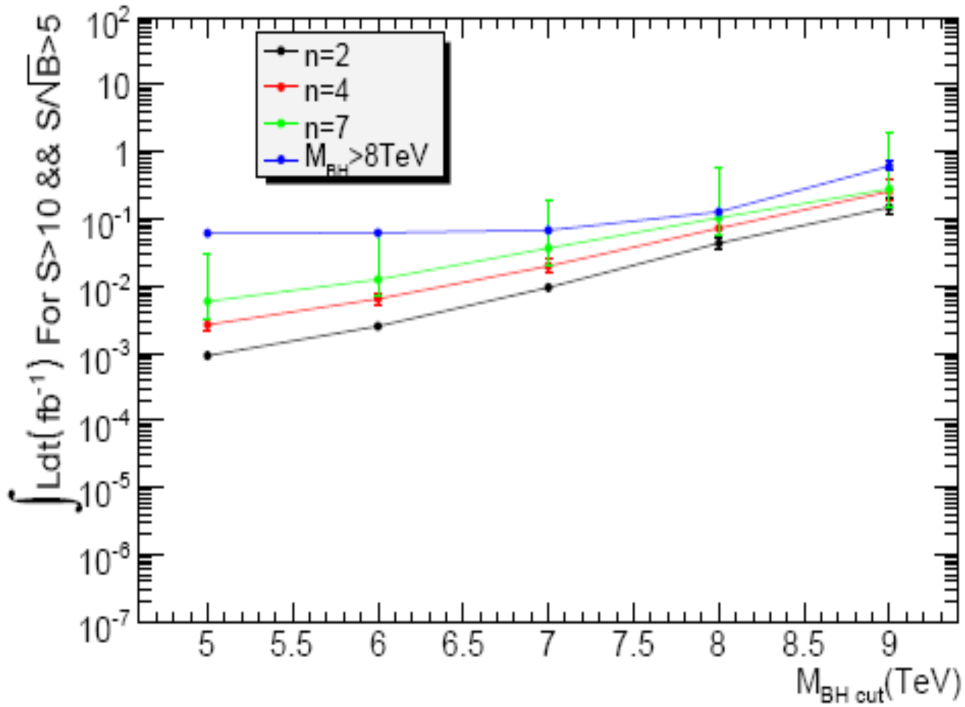




Discovery

- Discovery potential
  - $S/\sqrt{B} > 5$
  - S > 10
- Discovery possible ranging from
  - Few pb for 5 TeV
  - ~1 fb for 9 TeV

$$\sqrt{s} = 14\ \text{TeV}$$



String Balls

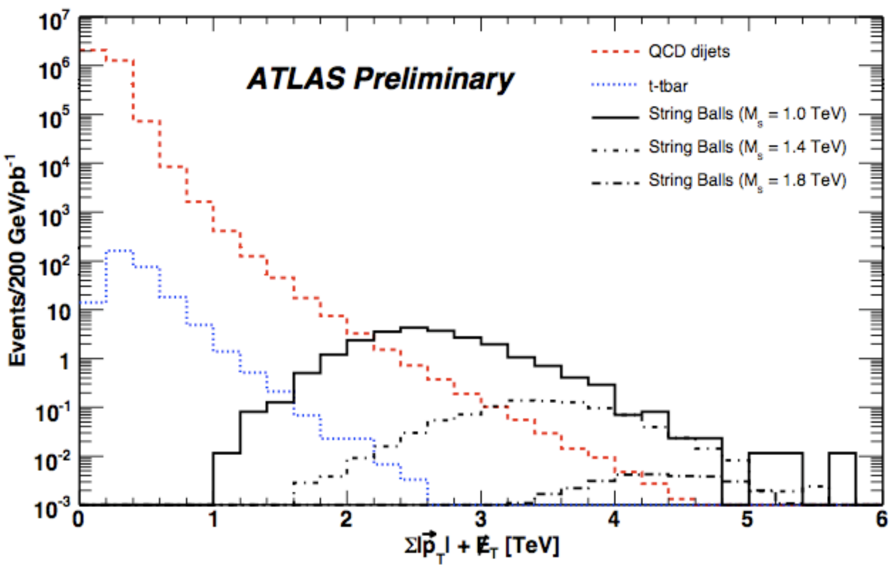
- Highly-excited string states (string balls) could be produced at the LHC

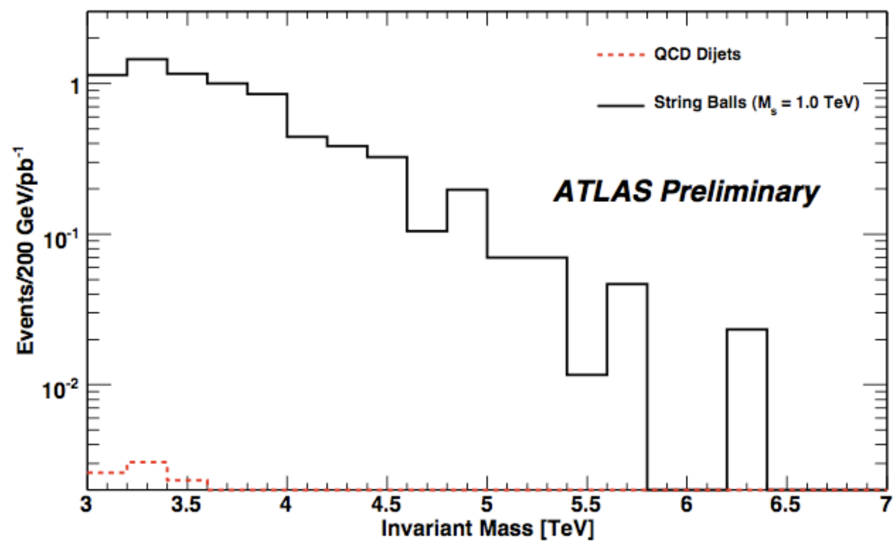
  ⇒ decay thermally (but more jet-like than BHs)
- New mass scale introduced ⇒ string scale ($M_S < M_D$)
- Thus, string ball cross-section higher than that of BHs
- Each string ball produces multiple visible decay products (jets, leptons, photons…)
  - Main backgrounds: top quark and QCD dijets events

M_s (TeV)	M_D (TeV)	M_{thresh} (TeV)	σ (pb)
1.0	1.5	3.0	$2.3 \times 10^{+1}$
1.2	1.8	3.6	$4.7 \times 10^{+0}$
1.4	2.1	4.2	9.6×10^{-1}
1.6	2.4	4.8	1.9×10^{-1}
1.8	2.7	5.4	3.3×10^{-2}

$\sqrt{s} = 10$ TeV

String Ball Selection





$$\sum\left|\overrightarrow{p_T}\right| + \not{E}_T > 2.4 \text{ TeV};$$

$$\text{lepton } p_T > 100 \text{ GeV}$$

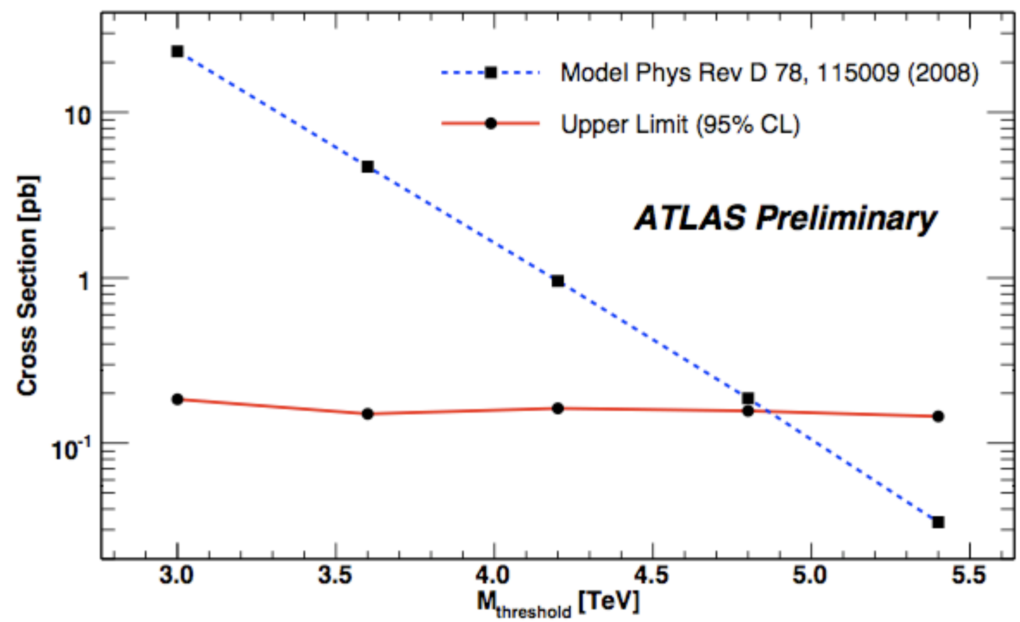
Exclusion Limits

$\sqrt{s} = 10 \text{ TeV}$

- Set limits on string-ball cross section for given mass threshold and 100 pb^{-1} int. luminosity.
- $M_{thresh} > 4.85$ TeV @95% C..L.

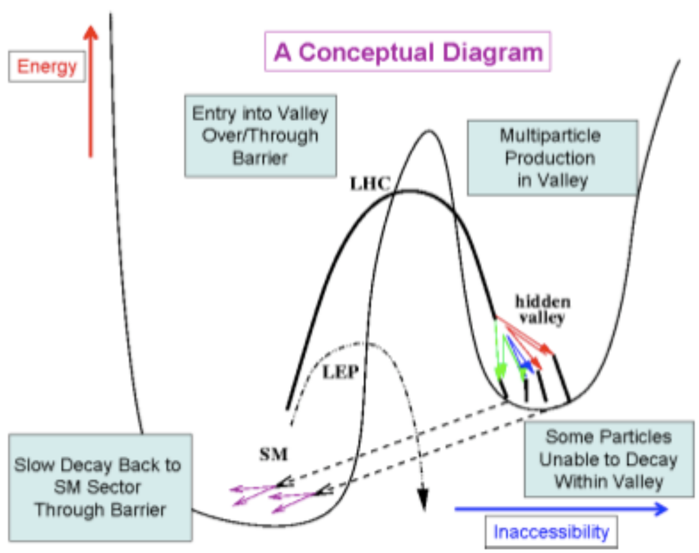
  $M_S > 1.6$ TeV

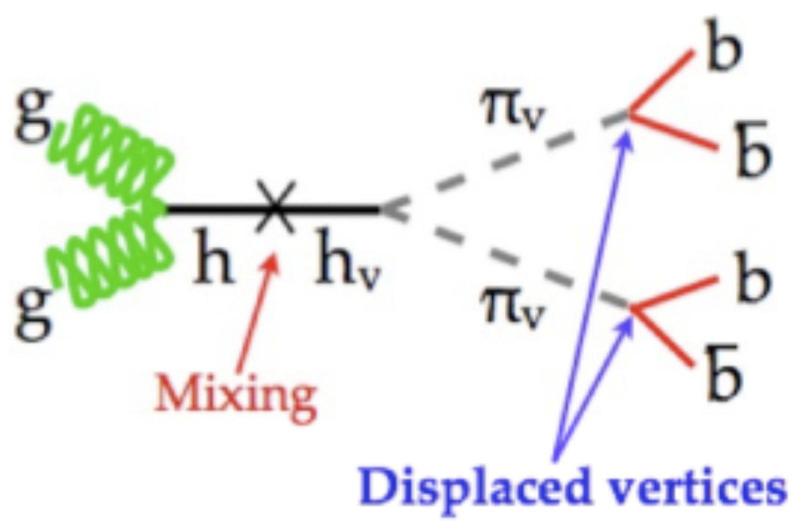
  $M_D > 2.4$ TeV



Long Lived Particles

- Hidden Valley scenario
- Benchmark process: $h \rightarrow \pi_v \pi_v \rightarrow b\bar{b}b\bar{b}$
- π_v is a pseudo-scalar, neutral and long lived
- Signature: highly displaced b-jet vertices

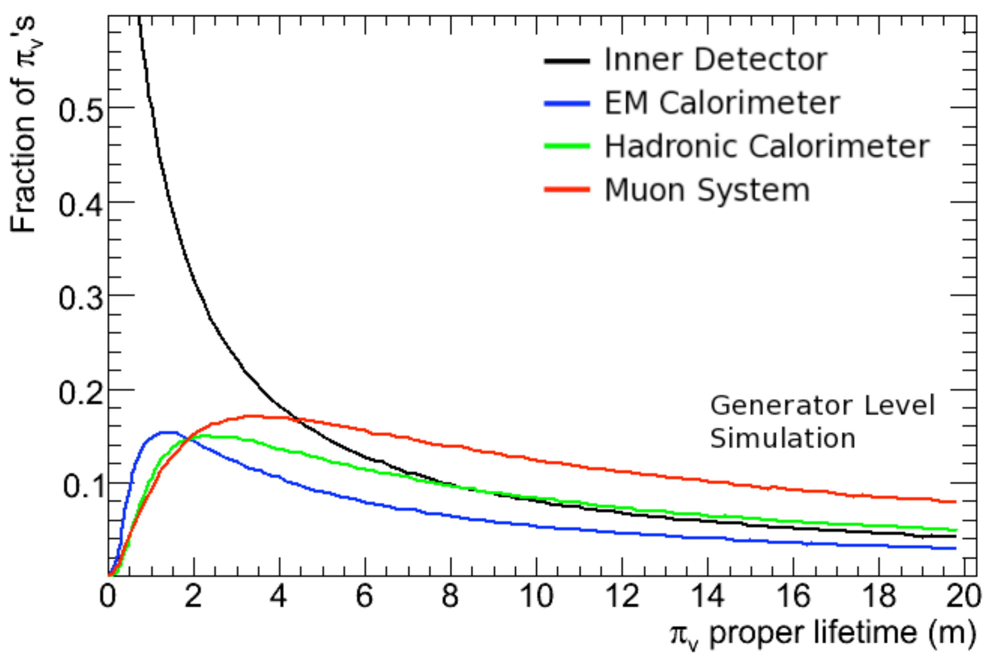




Heavy stable charged particles, stopped gluino covered in Nurcan Ozturk's talk

Hidden Valley decays

- Unique signal (no SM background!)
  - potentially an early discovery channel
- Decay of a hidden valley particle can happen in any part of the detector

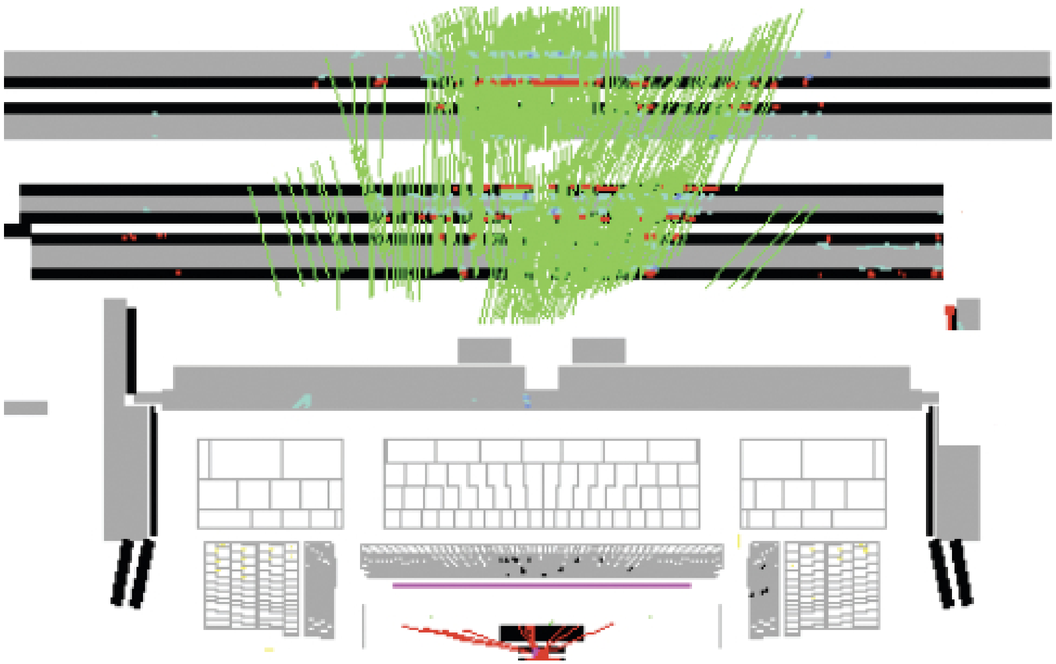


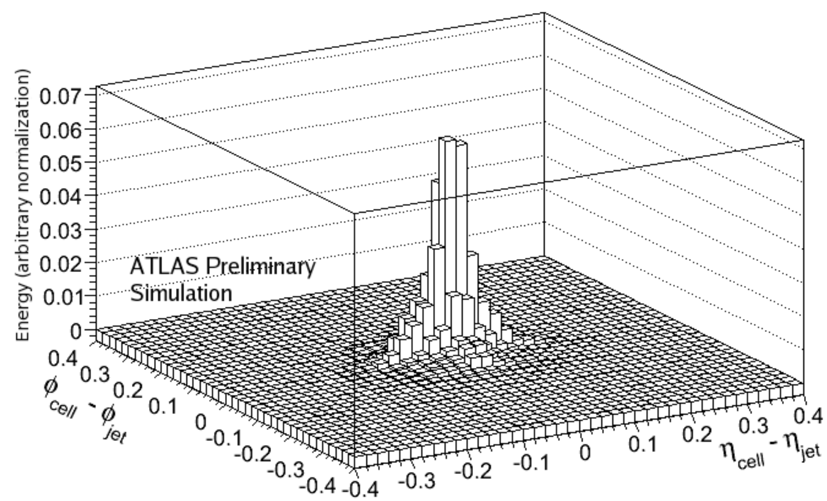
Three dedicated triggers:

1. Muon Cluster Trigger
2. Trackless jet w/ high log(H/E)
3. Trackless jet w/ associated muon

Muon Cluster Triggers

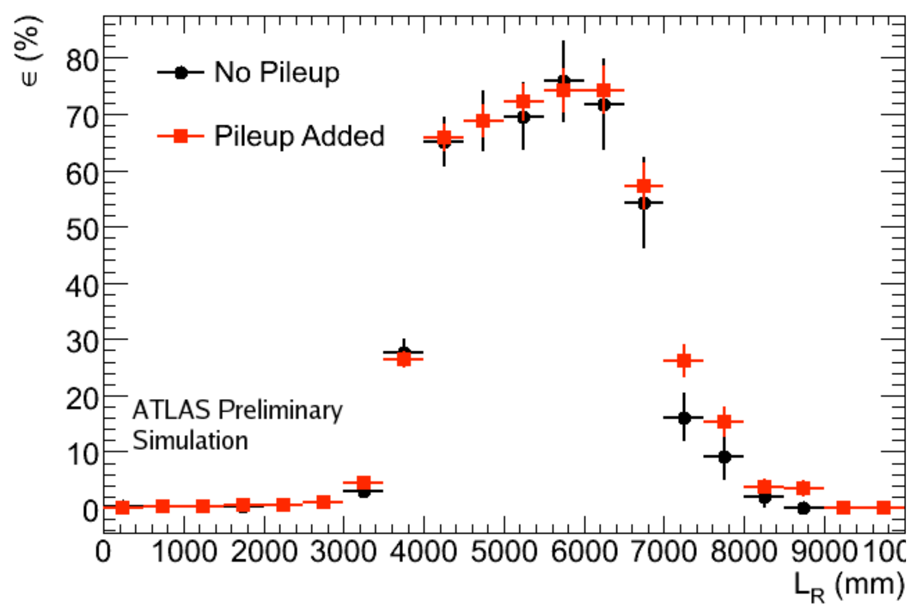
- Decays in the muon system have a large number of tracks
- Small deposition of energy in the calorimeter

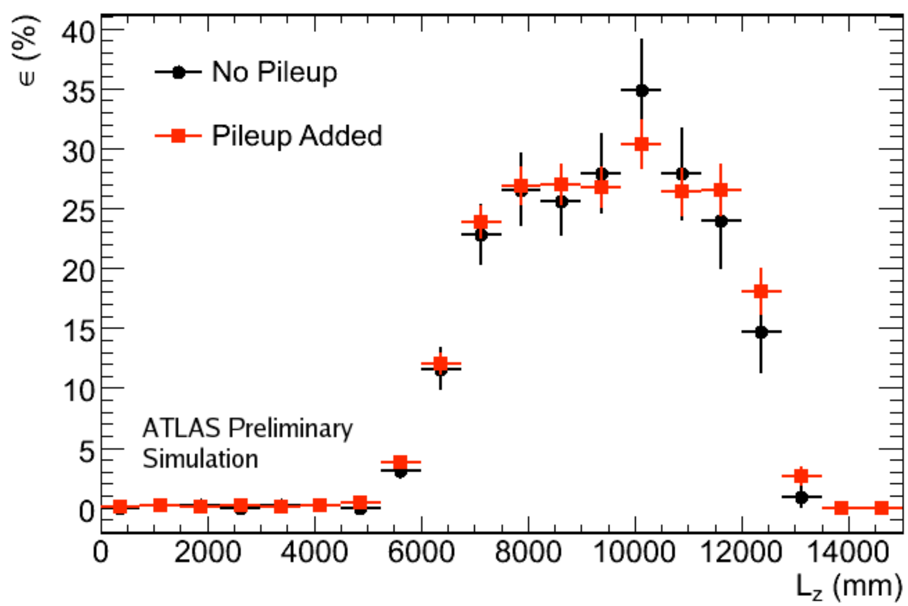




Trigger Efficiencies

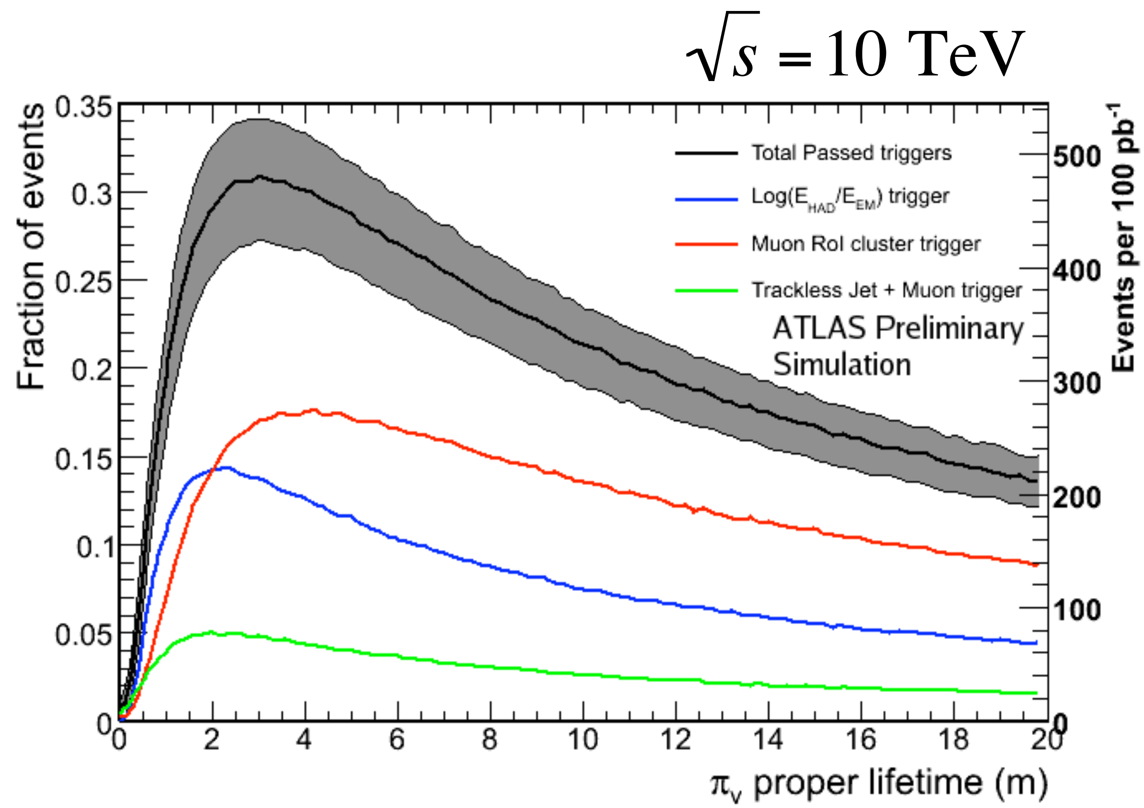
- Efficiency ~70% barrel
- Efficiency ~25% endcaps (isolation fails)





Hidden Valley Particle Detection

- Benchmark point:
- m_h = 140 GeV
- $m_{\pi v}$ = 40 GeV



Left axis: fraction of events accepted by triggers
Right axis: Number of expected events at 100 pb^{-1}
assuming Br(h->$\pi_v\pi_v$)=100%

Conclusions

- Many exotica searches at the LHC offer unusual and/or spectacular signatures
- Early discoveries are possible in many cases
- Some cases (eg. hidden valley searches) are particularly challenging and require dedicated techniques for triggering and offline reconstruction
- A very exciting time is ahead of us; we need to keep an open mind and be prepared for the unexpected!