Physics at the LHC
Lecture 14: New Physics (non-SUSY) scenarios at the LHC

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Wintersemester 2009/2010

Reasons for new physics

The hierarchy problem: How to stabilise the Higgs mass with $M_{\mathrm{pl}} \sim 10^{17} m_{\mathrm{H}}$

- SUSY: contributions from particles and superpartners cancel
- Extra dimensions (ADD type): in reality $M_{\mathrm{pl}} \sim m_{\mathrm{H}}$ but gravity propagates in 3+n dimensions
- Extra dimensions (RS type): a 4th dimension with a "warped" geometry separates the Planck brane with $M_{\mathrm{pl}} \sim m_{\mathrm{H}}$ and our brane (TeV brane)
- Little Higgs: The loops are cancelled by new SM-like particles at one loop, new physics in the 10 TeV range
- Technicolour: the Higgs mechanism in mimicked by new strong interactions at the TeV scale

What is the origin of dark matter?

- We expect a particle with $0.1-1$ TeV mass, neutral, weakly interacting
- Many models contain such a particle which can be made stable with a special parity

Where does the baryon-antibaryon asymmetry come from?

- We can have an additional source of CP violation
- With a more complicated neutrino sector one can first generate a lepton-antilepton asymmetry that is then transferred to the baryon sector
- This requires lepton/baryon number violating interactions

Strategies to find new physics

- Find the Higgs and measure its properties
- Look for particles that are predicted by specific (classes of) models
- Look for generic signals like missing E_T from dark matter production
- Look for an extended gauge sector (Z', W') predicted by many models
- Measure properties and interactions of gauge bosons, top quarks etc.

Search for new gauge bosons

- Many models contain an enhanced gauge group
- The new interactions result in new gauge bosons
- Most models contain a neutral Z'
- Many models also contain a charged W'
- At LHC visible via $\mathrm{q\bar{q}} \to \ell^+\ell^-$ and $\mathrm{q\bar{q}}' \to \ell\nu$

➠ Z' cross section $\propto \left(g_V(q)^2 + g_A(q)^2\right)\left(g_V(\ell)^2 + g_A(\ell)^2\right)/\Gamma$ (interference with Drell Yan plays a minor role)

- The sensitivity gets an additional $1/\Gamma$ factor from the background scaling

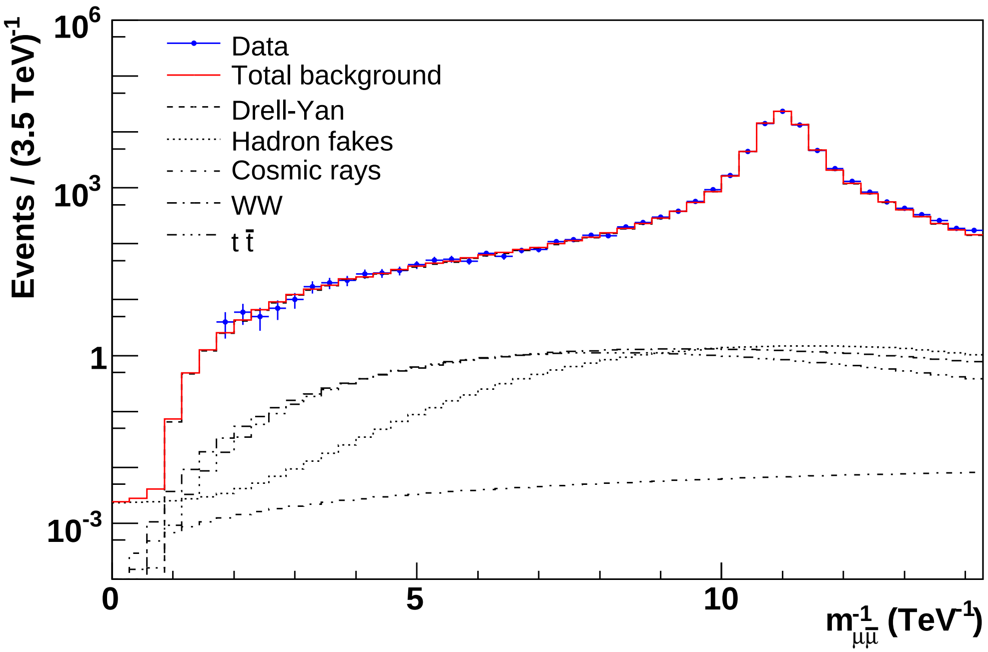
➠ Relatively weak model dependence

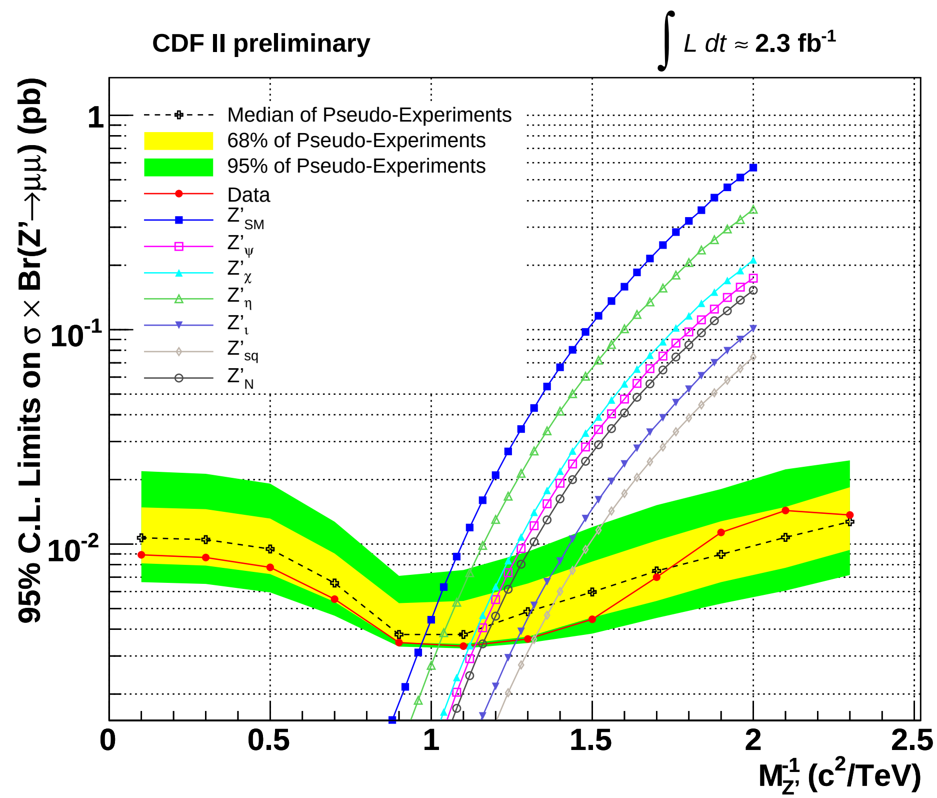
Z' searches

Event selection:

- two high energy, opposite sign, same flavour leptons
- if needed some isolation criteria

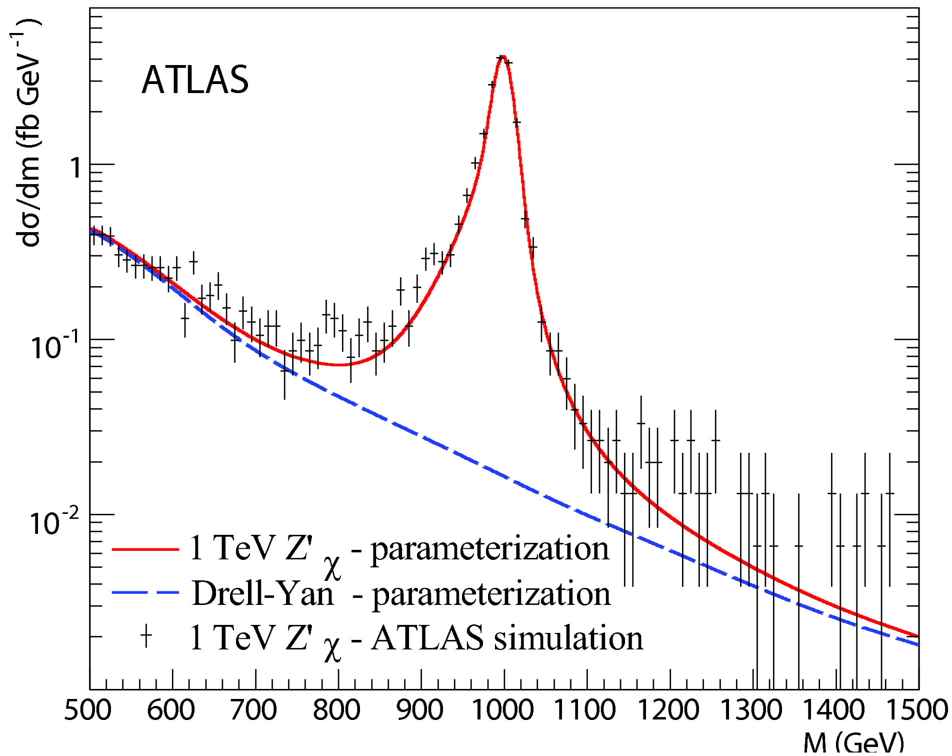
TEVATRON limits $m(Z') \gtrsim 1\,\mathrm{TeV}$ depending on model

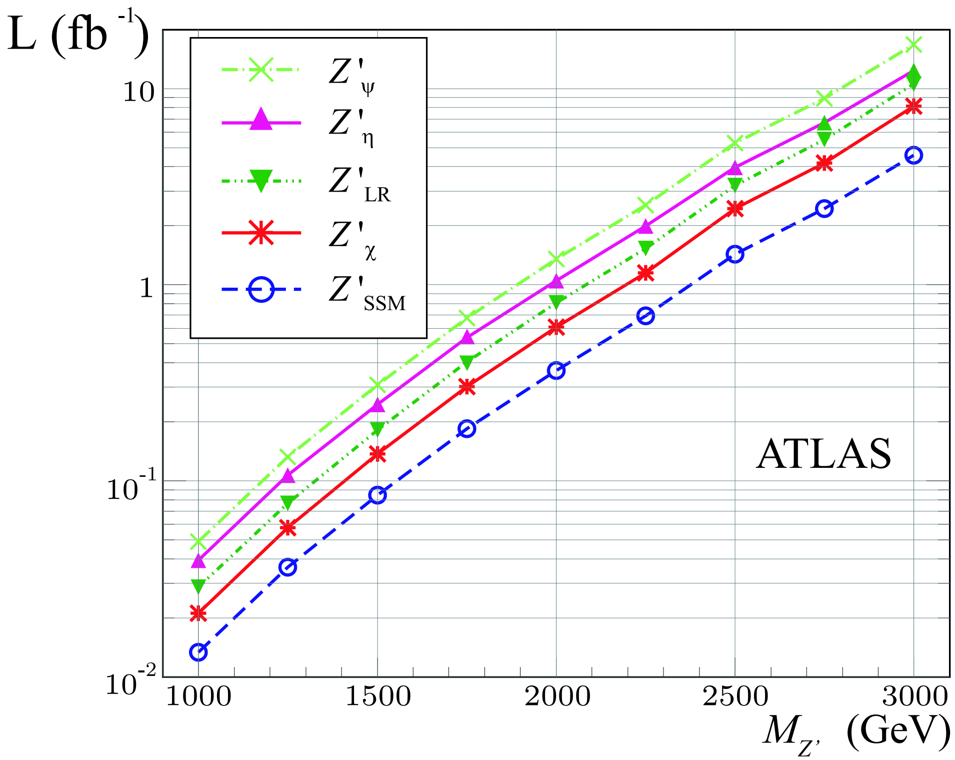




At LHC $m(Z') \gtrsim 3\,\mathrm{TeV}$ with relatively low luminosity

Further improvement difficult due to steeply falling PDFs

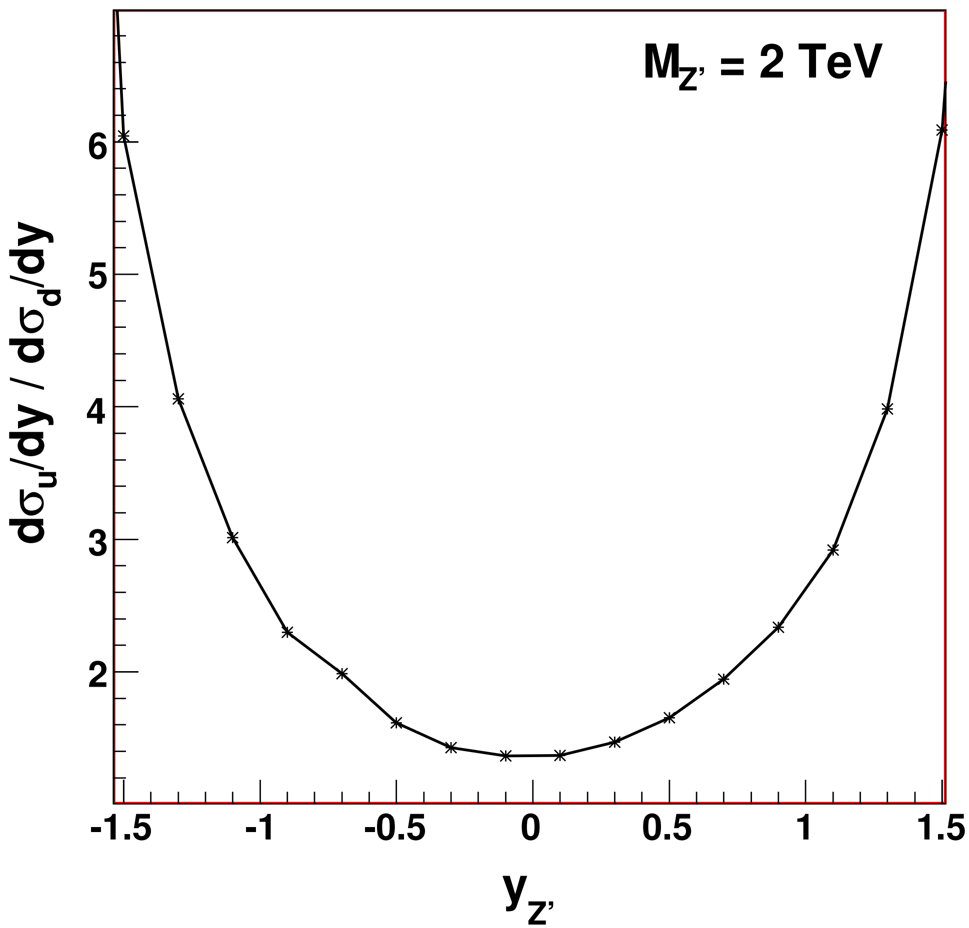




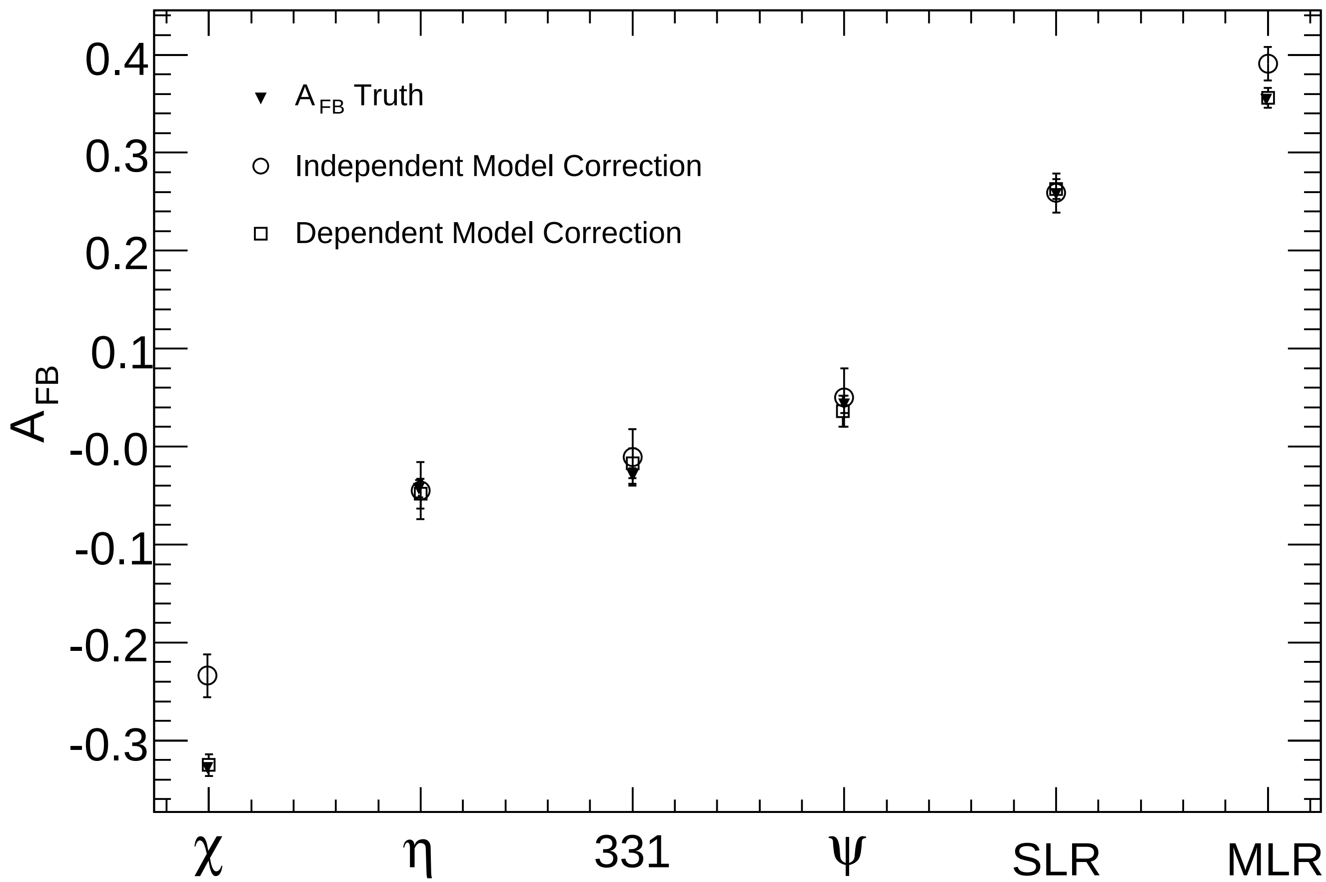
How can one identify the model?

- The total cross section is proportional to $\left(g_{V,q}^2 + g_{A,q}^2\right)\left(g_{V,\ell}^2 + g_{,A,\ell}^2\right)/\Gamma$
- The total width can be fitted from the data and is $\propto \sum_i \left(g_{V,i}^2 + g_{A,i}^2\right)$
- To get information on the couplings from the width all decay modes must be known
- The proton contains two valence up-quarks and only one valence down-quark
  $\Rightarrow$ at high x up-quarks dominate
  $\Rightarrow$ at high Z' rapidity more Z' originate from up-quarks

➠ The Z' rapidity distribution contains information in the up/down-quark coupling ratio

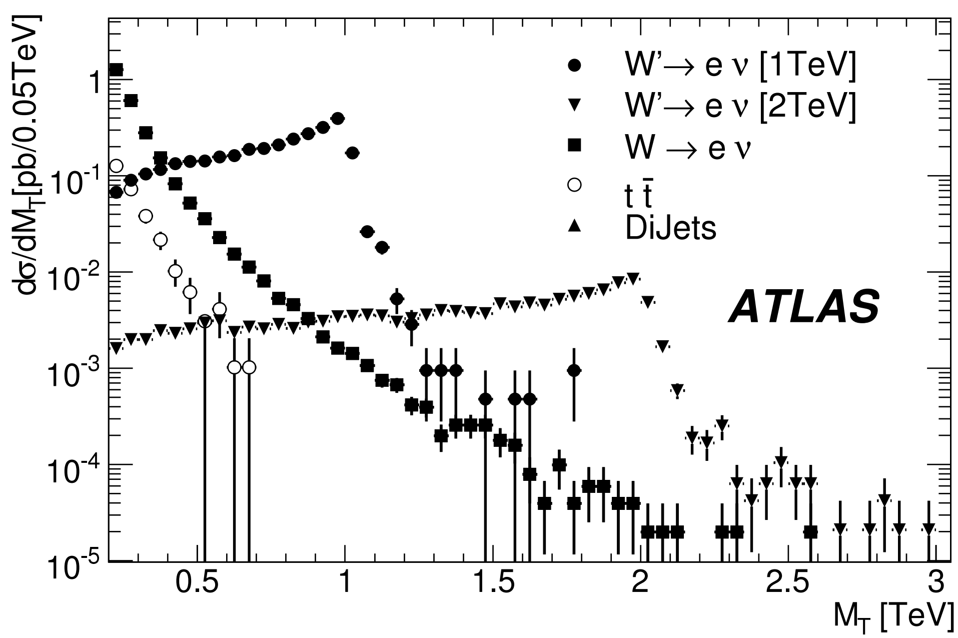


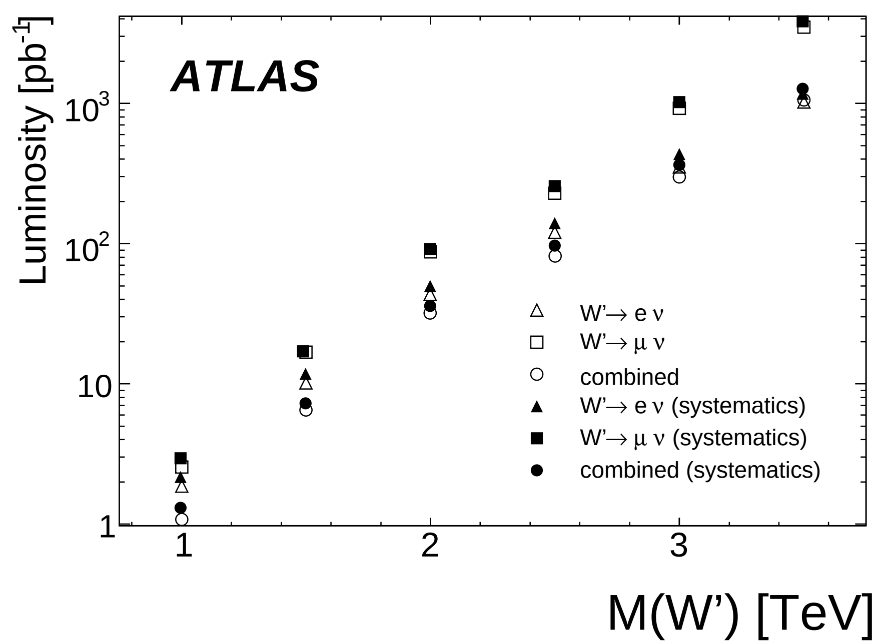
- The forward backward asymmetry depends on the ratio of the vector and axial vector coupling
- At high mass usually the boost direction determines the direction of the quark
- This gives some distinction between the models if the mass is not too high



W' searches

- Only one lepton and missing E_T from neutrino
- Longitudinal ν-momentum unknown $\Rightarrow$ only m_T can be calculated
- In general W' cross section larger than Z' cross section
- Event selection: one (isolated) high energy lepton, missing E_T and some jet veto
- Reach similar to Z'





Models with extra dimensions

Several models contain extra dimensions

- Large extra dimensions (ADD):
  - several (2-7) extra dimensions
  - extra dimensions are large (μm − nm)
  - only gravitation can live in the bulk
- Universal extra dimensions:
  - All fields live in the bulk
  - This limits the size of the extra dimensions to several hundred GeV
- Randall Sundrum models
  - One extra dimension with warped geometry
  - Gravity is located on different brane than TeV physics
  - Only gravity or all fields can live in the bulk
- String theories
  - in general no visible signal since extra dimensions on Planck scale

ADD type extra dimensions

- Only gravity lives in the bulk
- Size of the extra dimensions is $\mathcal{O}(\text{eV})$ or nm $-$ μm
- This is also the spacing of the KK graviton resonances
- For LHC energies this is a continuous spectrum of resonances
- Physics interest:
  - In reality Planck mass is on TeV scale
  - Planck mass appears so large because gravity escapes into extra dimensions

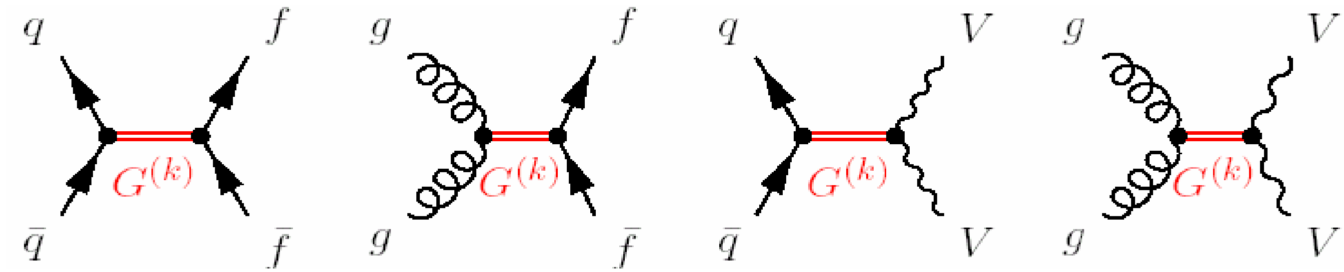
$$\mathrm{M_{pl}^2 = M_D^{2+n} R^n} \quad \left(\Rightarrow \mathrm{R} \sim 10^{\frac{30}{n}-17} \left(\frac{1\,\mathrm{TeV}}{\mathrm{M_D}} \right)^{1+\frac{2}{n}} [\mathrm{cm}] \right)$$

R : compactification radius of extra dimensions

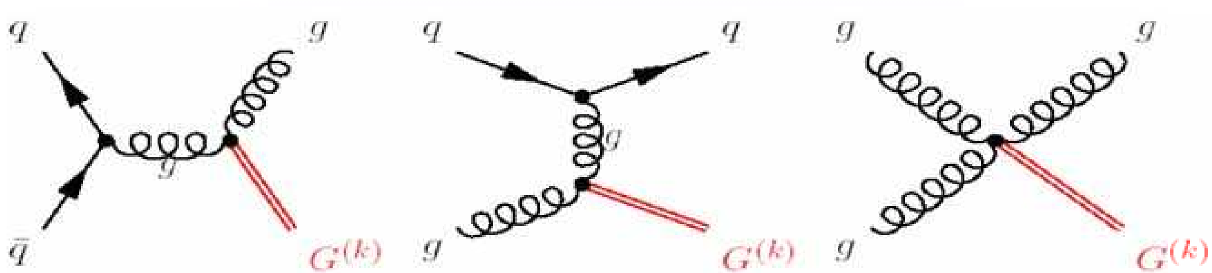
- Experimentally get limit on R for assumed n
- This is turned into a limit on M_D

Visible processes:

Virtual Graviton Exchange



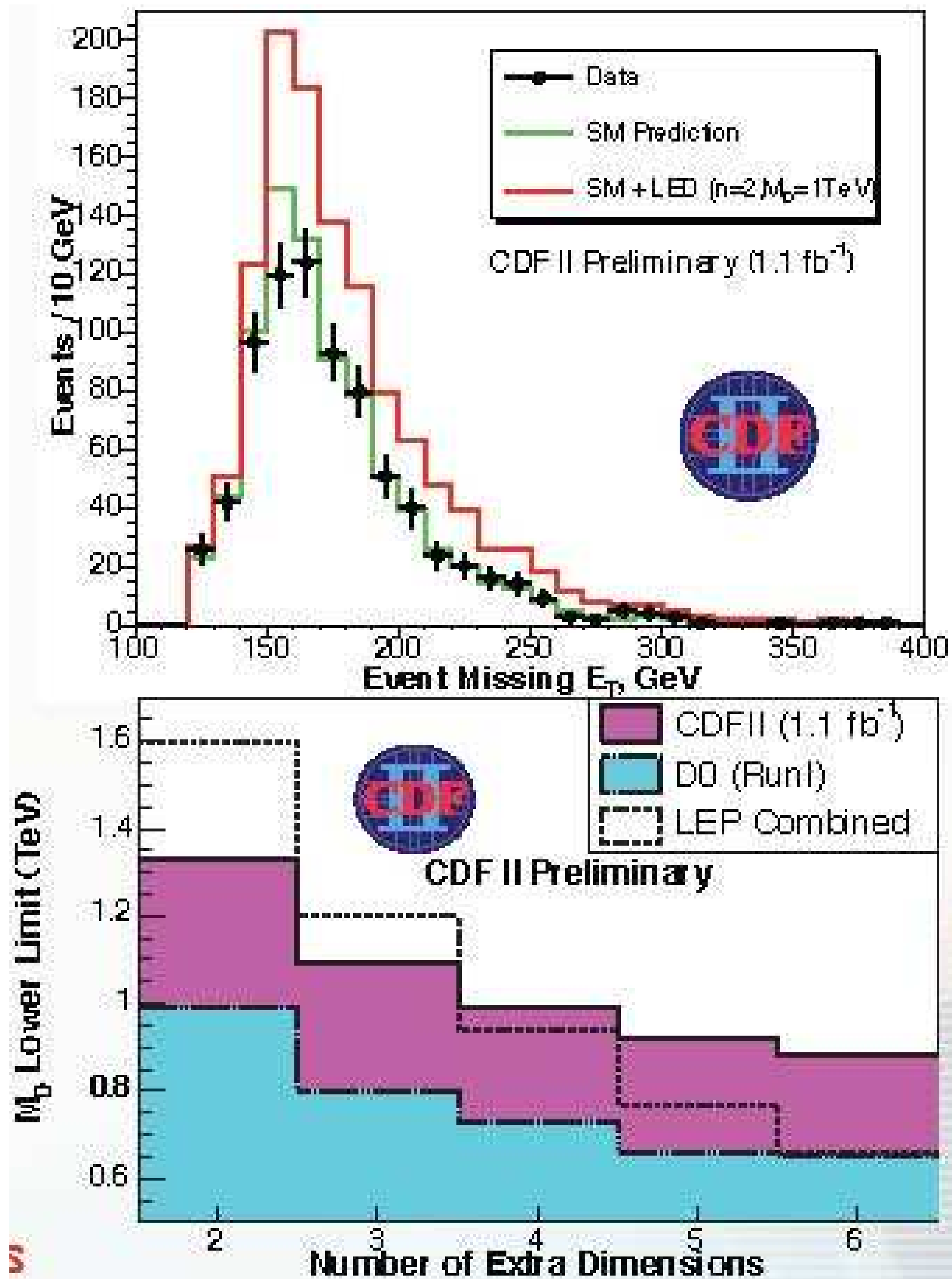
Direct Graviton Production



- The cross section for a single KK graviton is negligibly small
- However due to the large number of excitations the total effect has the size of an electroweak cross section

Limits from the Tevatron

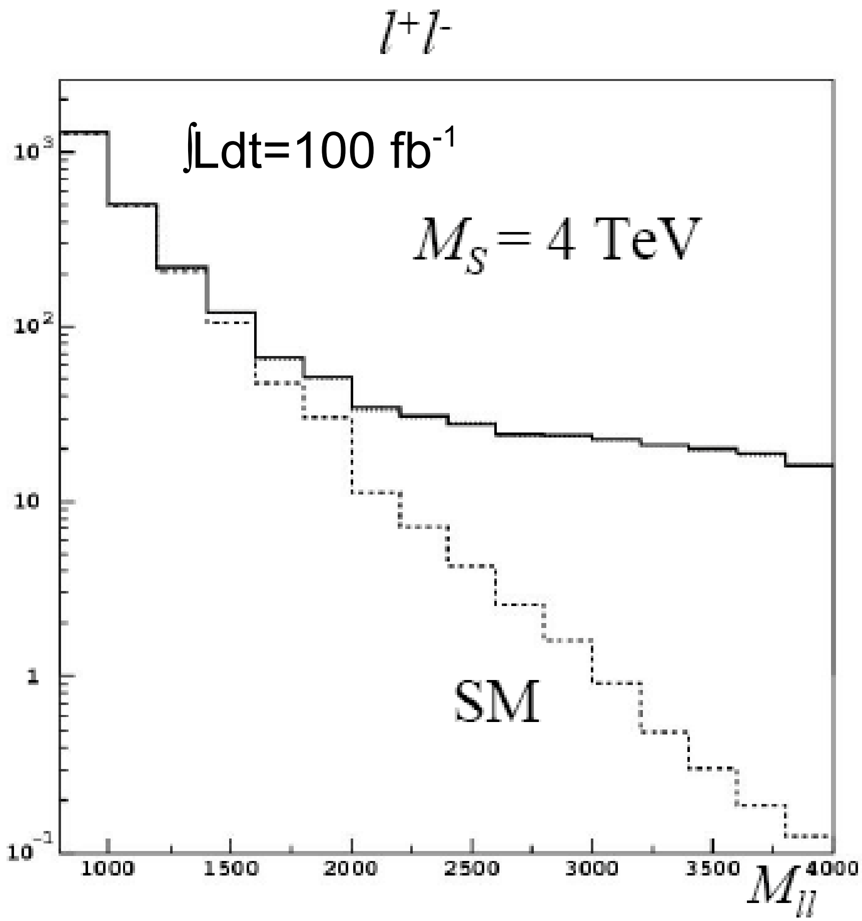
- At the Tevatron analyses are done with jets + missing E_t and Drell-Yan type events
- The analyses give limits around 1 TeV almost independent of the number of extra dimensions
- LEP has analysed the data with one photon and missing energy
- The LEP limits depend stronger on the number of demmensions



Expected effects

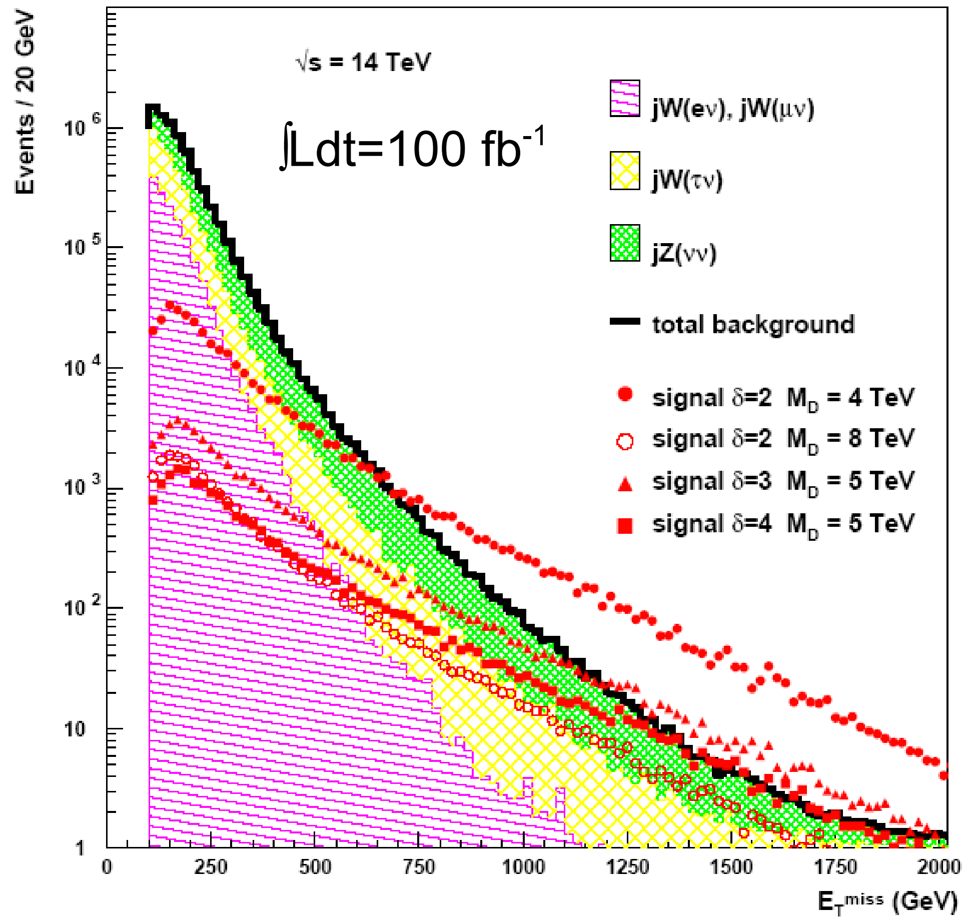
Virtual graviton exchange:

Expect broad enhancement of Drell Yan production



Graviton radiation:

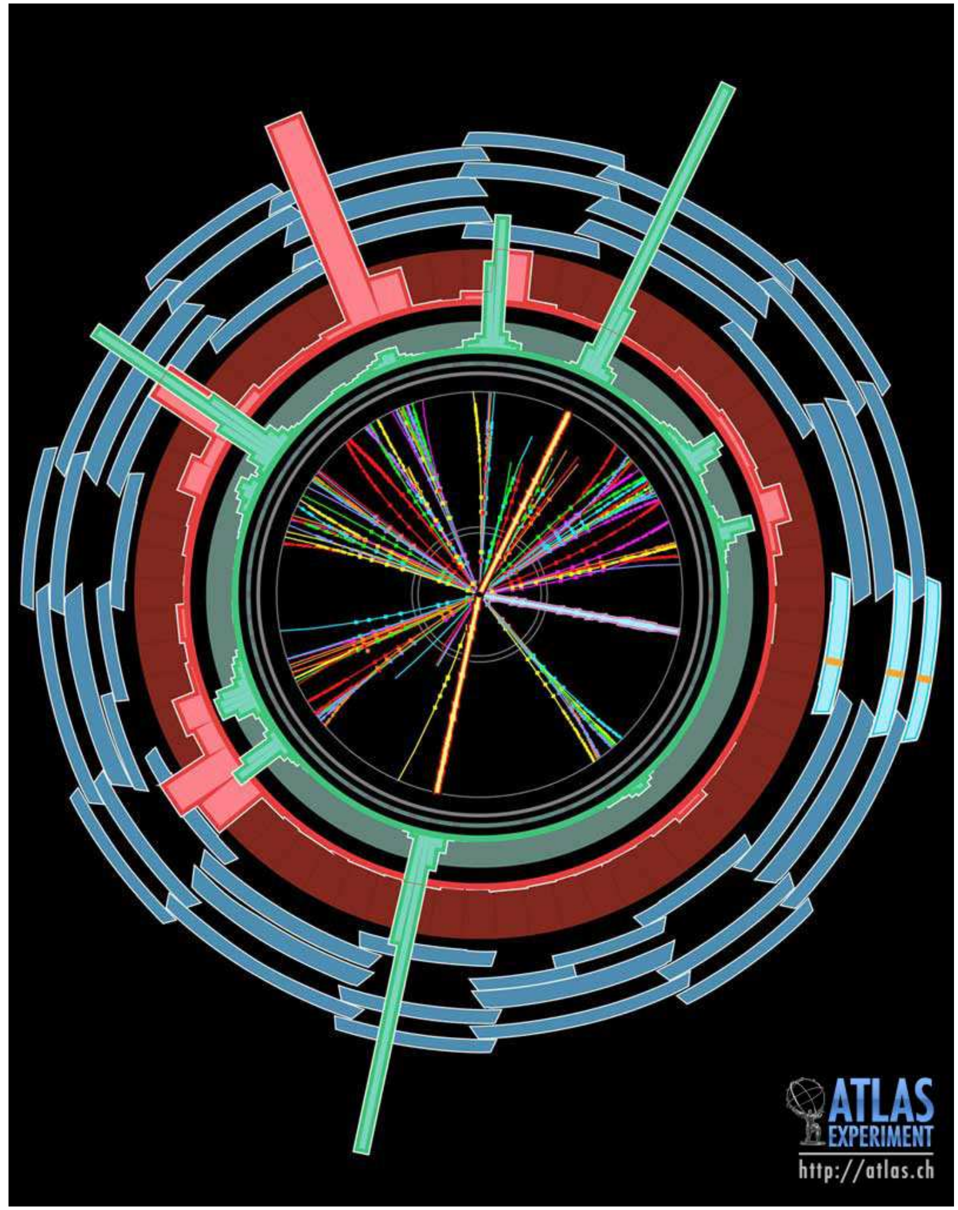
Jet events with large missing energy



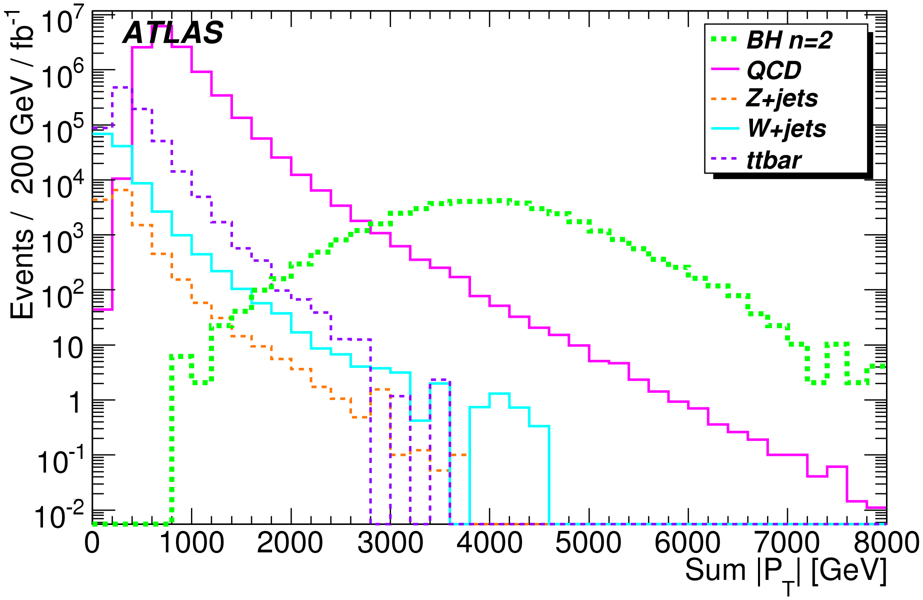
Both effects are sensitive to $M_D \lesssim 6 - 9\,\mathrm{TeV}$

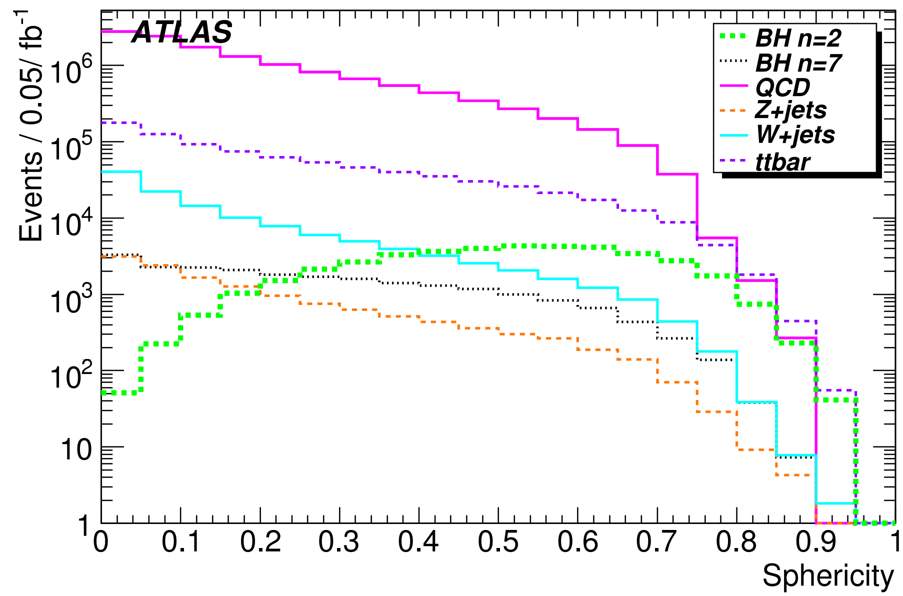
Black holes at the LHC

- Black hole production is possible, when the centre of mass energy gets into the region of the Planck mass
- This would be fulfilled for ADD models
- Schwarzschild-Radius $R_S = \frac{2GM_{BH}}{c^2}$
- Cross section $\sigma \sim \pi R_S^2 \sim 100\,\mathrm{pb}$
- Black holes decay by Hawking radiation with $\tau_{BH} \sim 10^{-27} - 10^{-25} s$
- Decay is thermal: high multiplicity, symmetric, democratic in particle species (⇒ leptons, neutrinos)

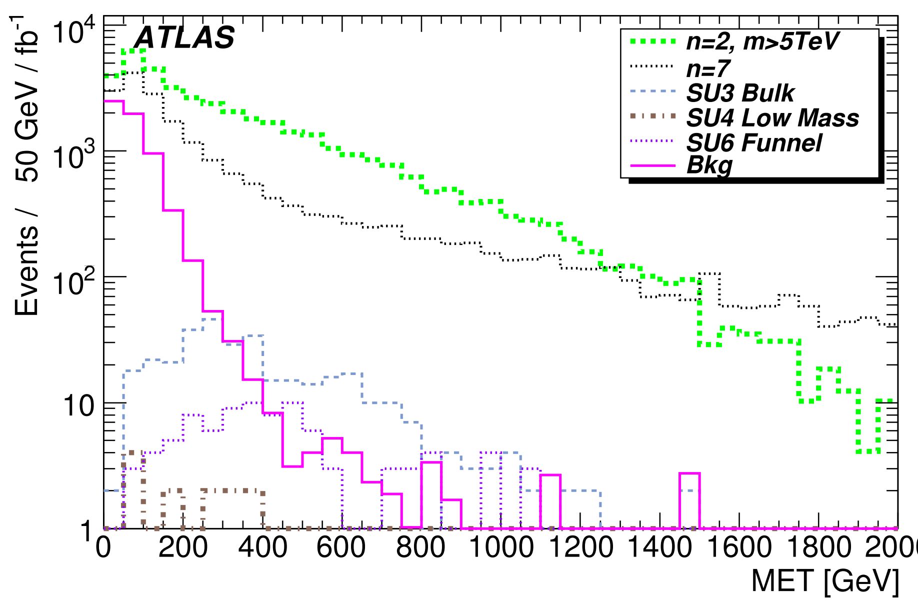


Black holes are easy to separate from background by lepton number, $\sum p_T$ and by event shape variables that are sensitive to the isotropy of the decay

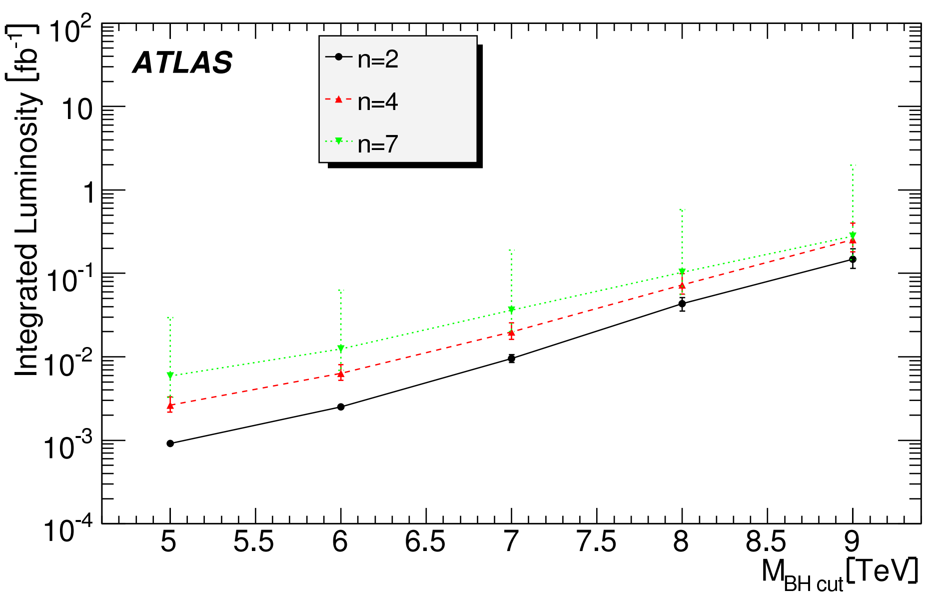


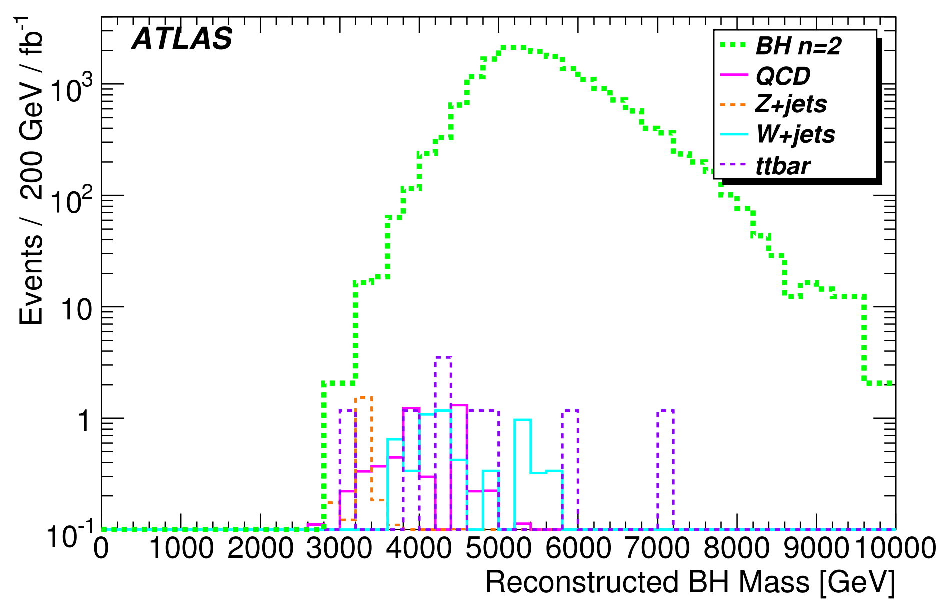


From other new physics like SUSY they can be separated e.g. wih missing E_T



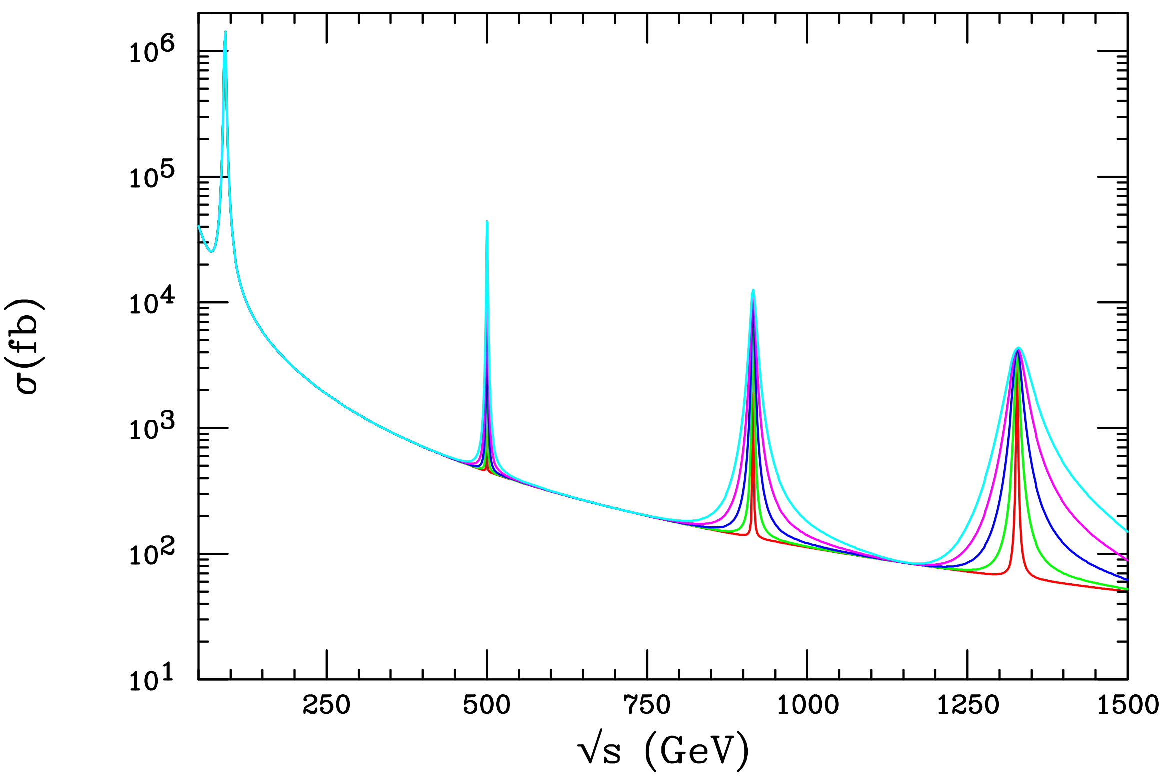
- Black holes can be found up to around 10 TeV with almost no luminosity
- The mass can be reconstructed from the visible decay products
- Some information on the number of extra dimensions can be obtained from other variables like decay-multiplicity





Randall Sundrum models

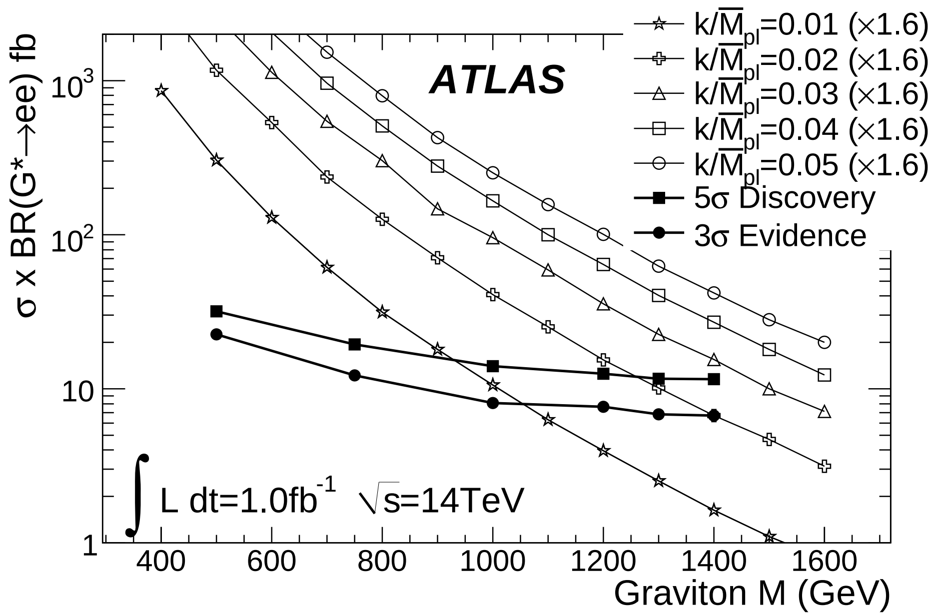
- Two branes separated in a 5th dimension with an deSitter geometry
- Mass scale on SM brane exponentially suppressed w.r.t. Planck brane
  $ds^2 = e^{-2ky}\eta_{\mu\nu}dx^\mu dx^\nu + dy^2 \quad y = \phi r_c$
- Scale $\Lambda = M_{Pl}e^{-kr_c\pi} \sim 1\,\mathrm{TeV}$
- Equally spaced KK resonances with mass $m_1 = x_1 k/M_{Pl}\Lambda$
  $0.01 < k/M_{Pl} < 0.1$

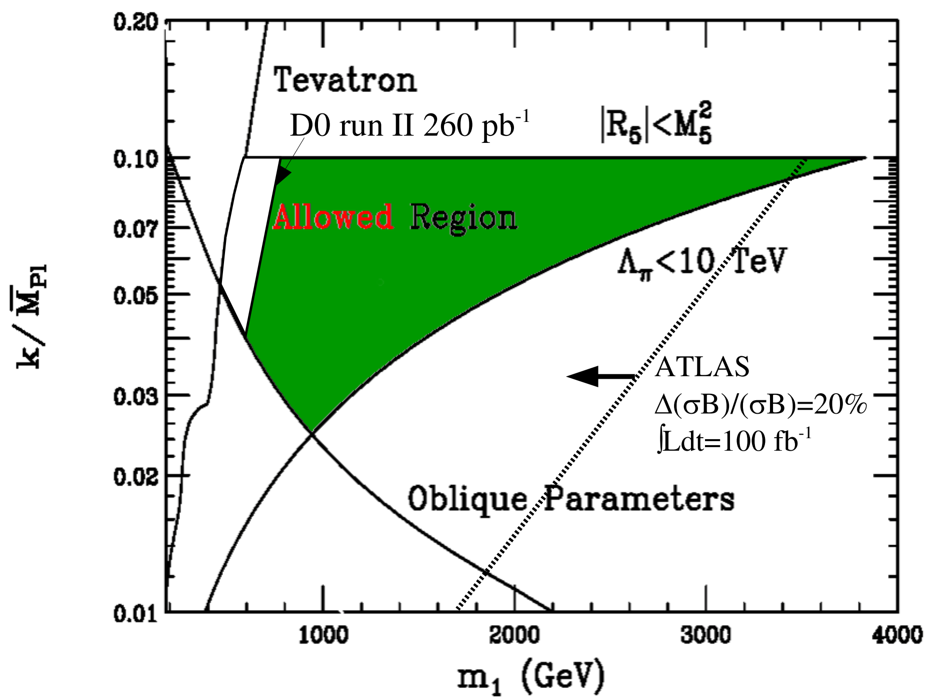


- Original version only gravitation in the bulk
- KK-graviton decays symmetric in flavours
- Graviton has spin 2

Search for RS-Gravitons

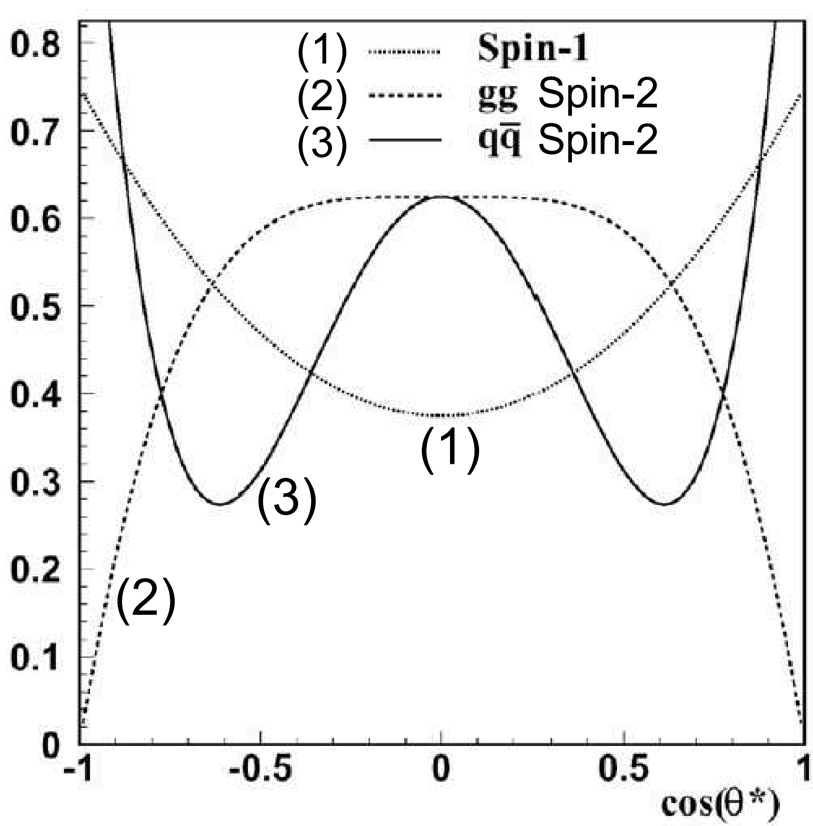
- Most efficient search is in leptonic decay channel
- In this channel the search is identical to the Z' search
- At low luminosity 1-2 TeV, at high luminosity 2-3 TeV reach are possible
- This excludes the entire region allowed by the model

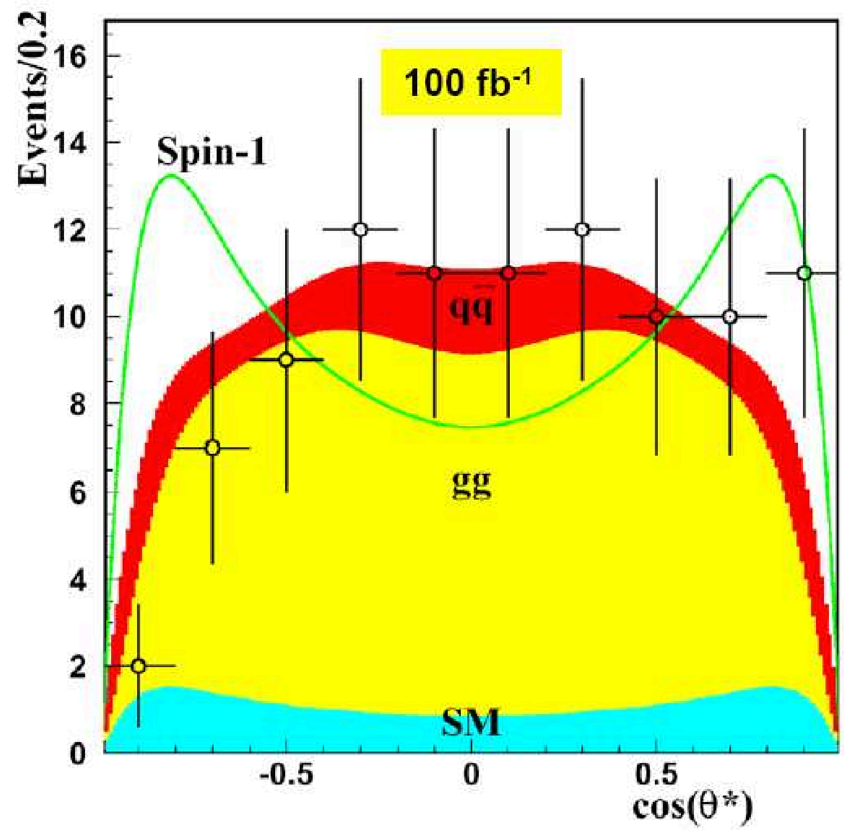




How to identify that this is a KK graviton and not a Z'

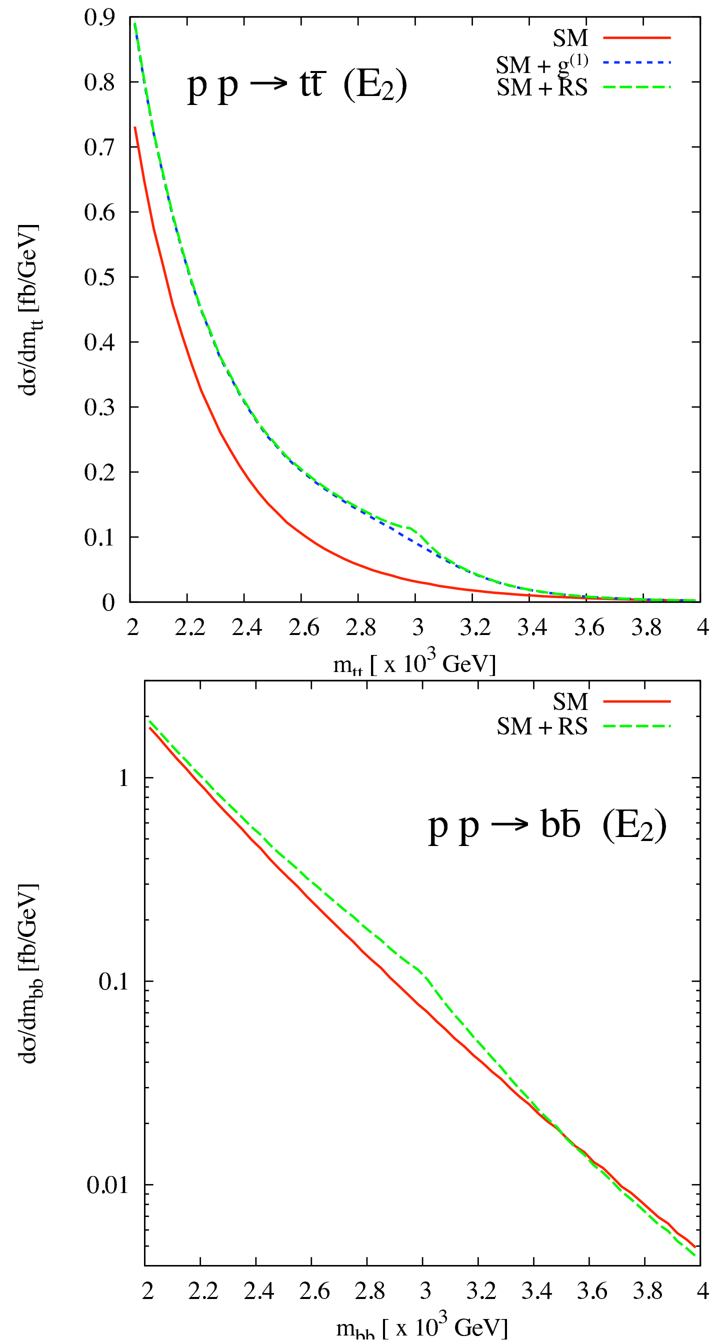
- Gravitons have spin two resulting in a different decay angle distribution
- For the decay angle distribution it is important that the KK-Graviton can also be produced by gluons
- In most of the parameter space spin 1 can be excluded





RS with matter in the bulk

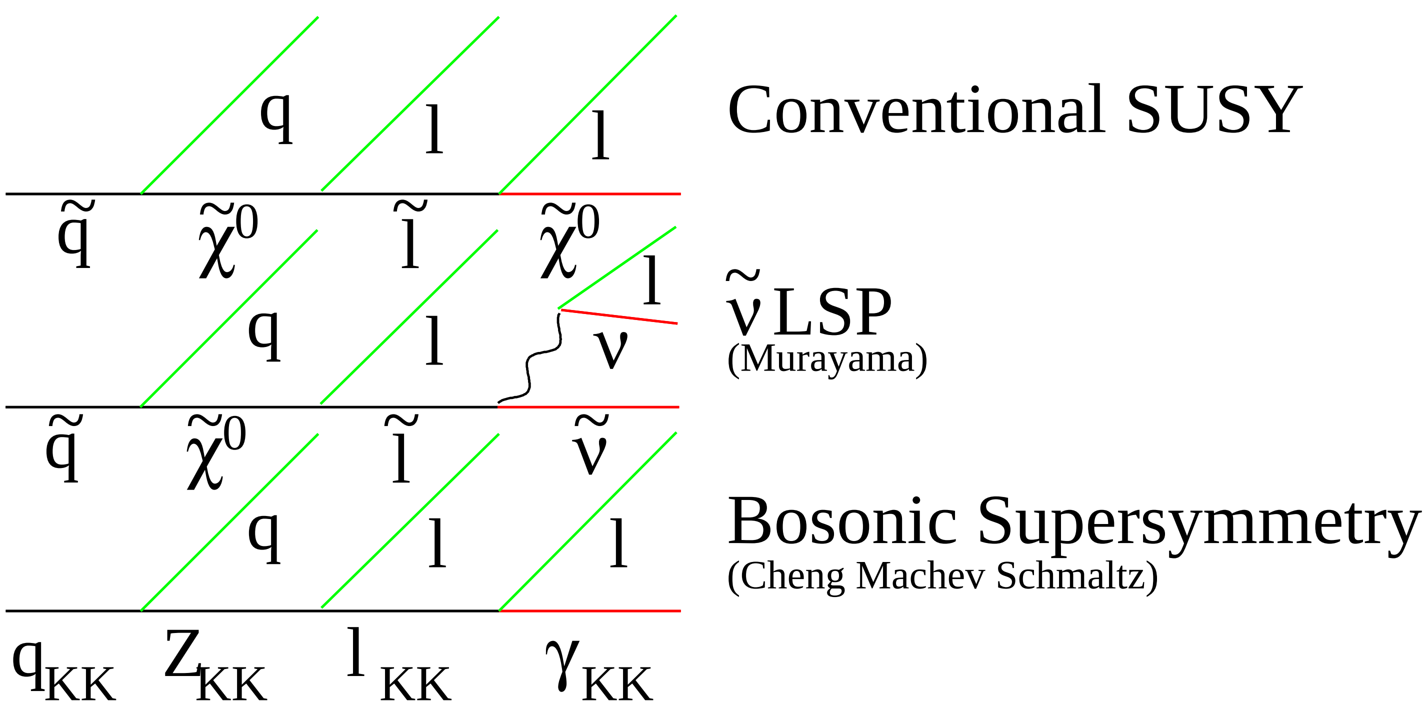
- New versions of the RS model allow matter in the bulk
- A new parity can produce dark matter
- The matter fields are located in different positions in the bulk generating the large mass differences in the SM
- This causes the KK resonances to decay dominantly into heavy fermions
- First studies show large effects from the KK graviton, but only very small effects from the γ and Z excitation



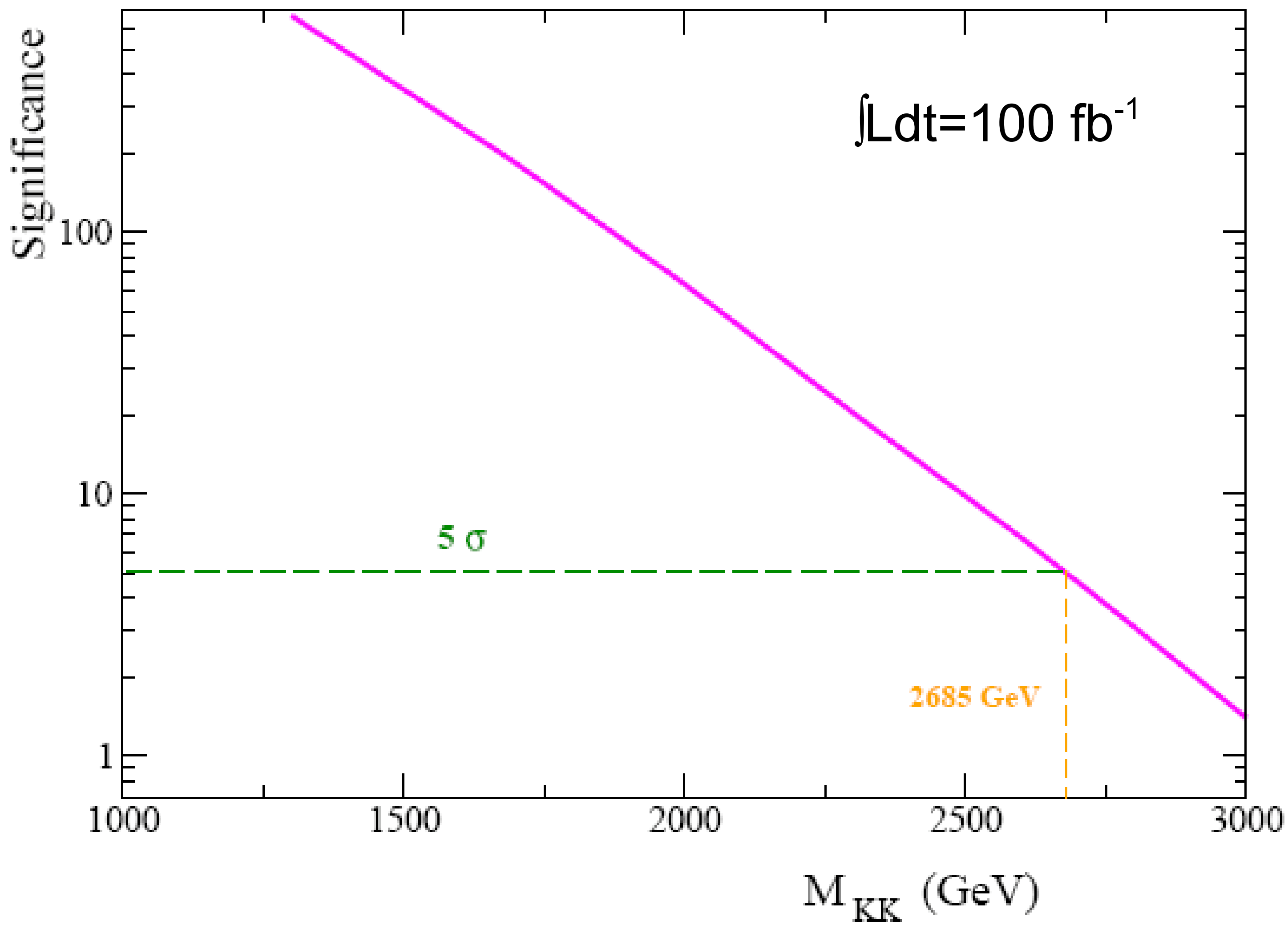
Universal extra dimensions

- If all fields live in the bulk the compactification scale must be at least a few hundred GeV
- A KK parity can be defined that forbids even-odd transitions of KK resonances and allows even-even and odd-odd transitions only on loop level
- If the higher resonances are not seen the model is very SUSY like

M. Peskin, Victoria

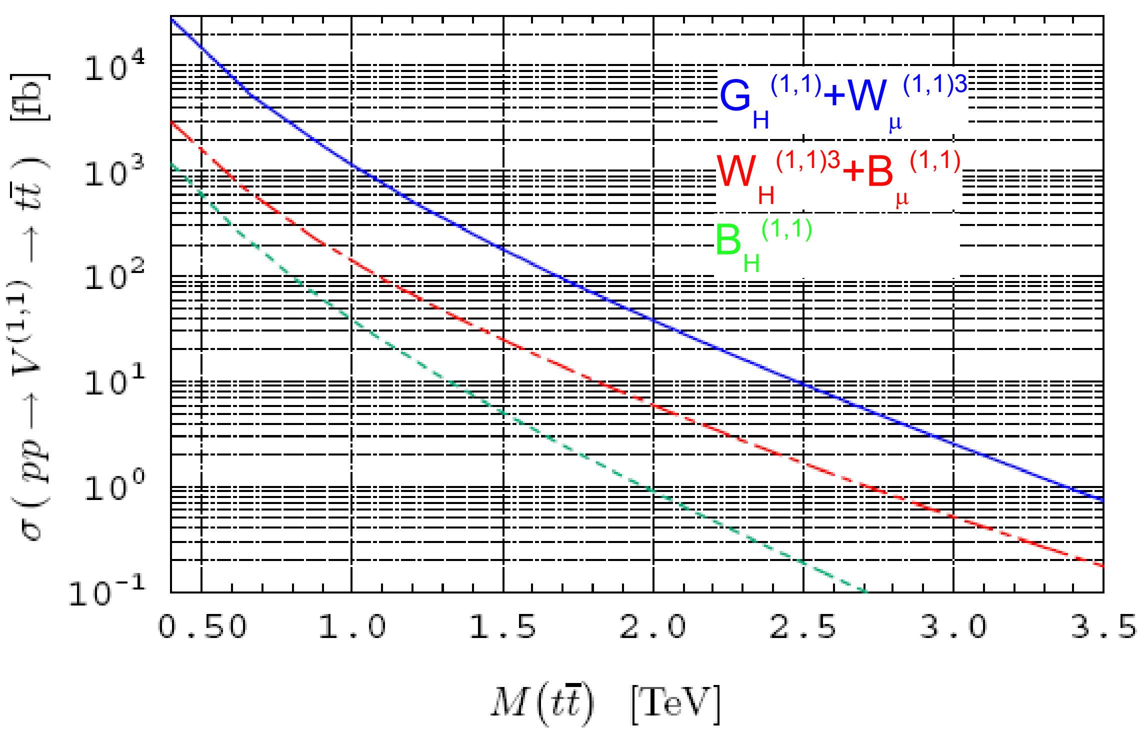


- Most efficient search: jets plus missing E_T
- This allows to find UED scenarios up to 2.7 TeV



Search for higher resonances

- For one extra dimension the next resonance has twice the mass of the first one
- For two extra dimensions the (1,1) resonance has $\sqrt{2}$ times the mass of the first resonance
- The (1,1) resonances should have a large branching ratio to $t\bar{t}$
- Unfortunately the cross section is still low
- According to present studies the LHC can find these resonances only up to around 1.5 TeV

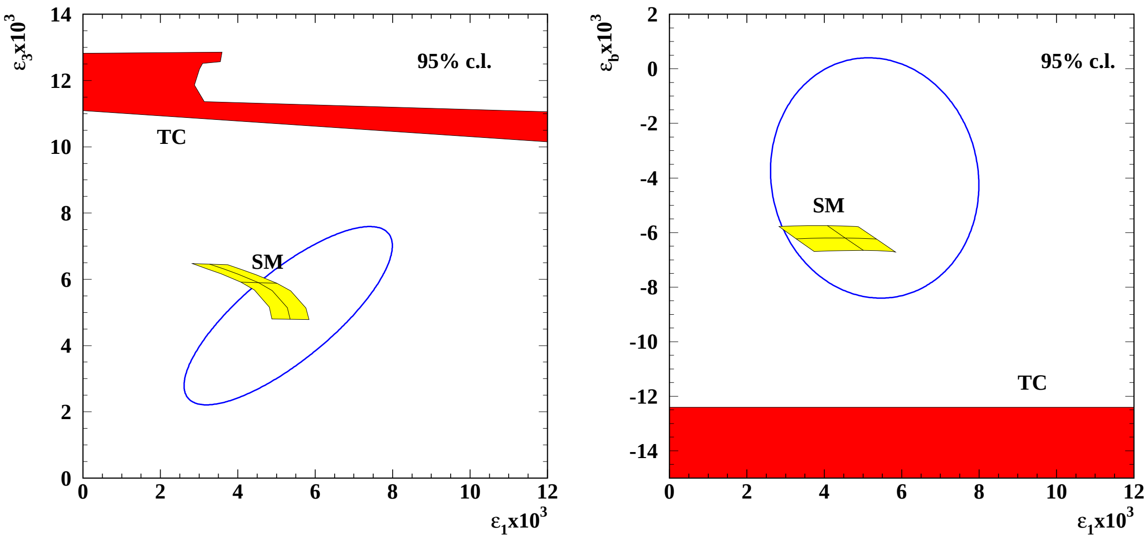


Strong Electroweak Symmetry Breaking

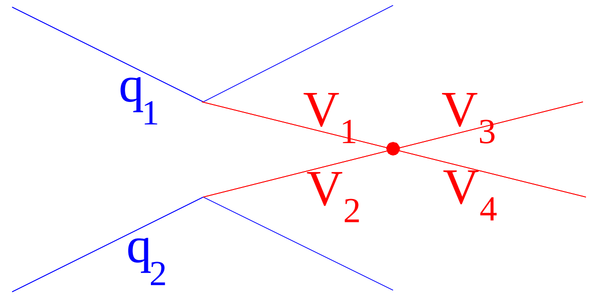
- If no Higgs exists electroweak interactions become strong at high energy and e.g. WW scattering violates unitarity at $\sqrt{s_{WW}} \sim 1.2\,\mathrm{TeV}$.

➠ expect new effects at this energy

- Typical models invoke a new strong interaction at the TeV scale (Technicolour)
- The Goldstone-bosons (Pions) of the new theory become the longitudinal degrees of freedom of the vector-bosons
- Warning: simple copy of QCD is excluded by LEP/SLD precision data



Systematic treatment



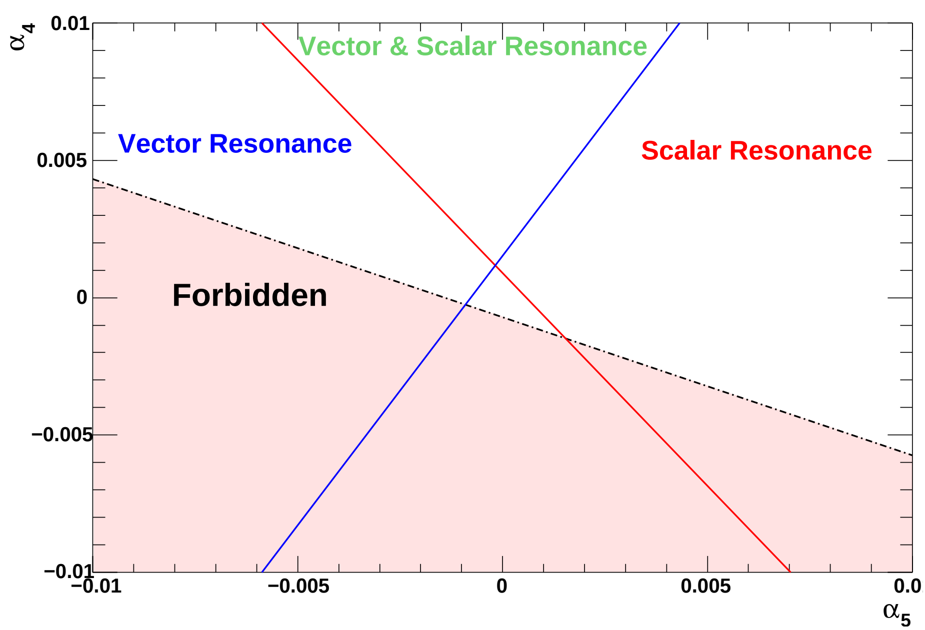
Effective Lagrangian for VV scattering:

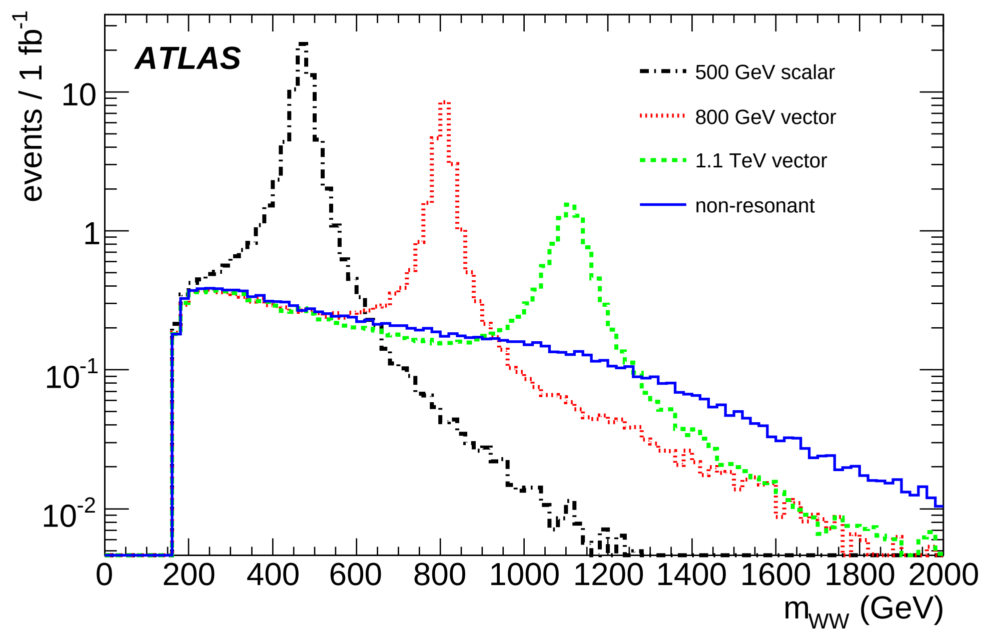
$$\mathcal{L}_4 = \alpha_4 \left[\frac{g^4}{2} \left[(W^+_\mu W^{-\mu})^2 + (W^+_\mu W^{+\mu})(W^-_\nu W^{-\nu}) \right] + \frac{g^4}{c_w^2}(W^+_\mu Z^\mu)(W^-_\nu Z^\nu) + \frac{g^4}{4c_w^4}(Z_\mu Z^\mu)^2 \right]$$

$$\mathcal{L}_5 = \alpha_5 \left[g^4 (W^+_\mu W^{-\mu})^2 + \frac{g^4}{c_w^2}(W^+_\mu W^{-\mu})(Z_\nu Z^\nu) + \frac{g^4}{4c_w^4}(Z_\mu Z^\mu)^2 \right]$$

(assuming custodial symmetry, C, P conservation)

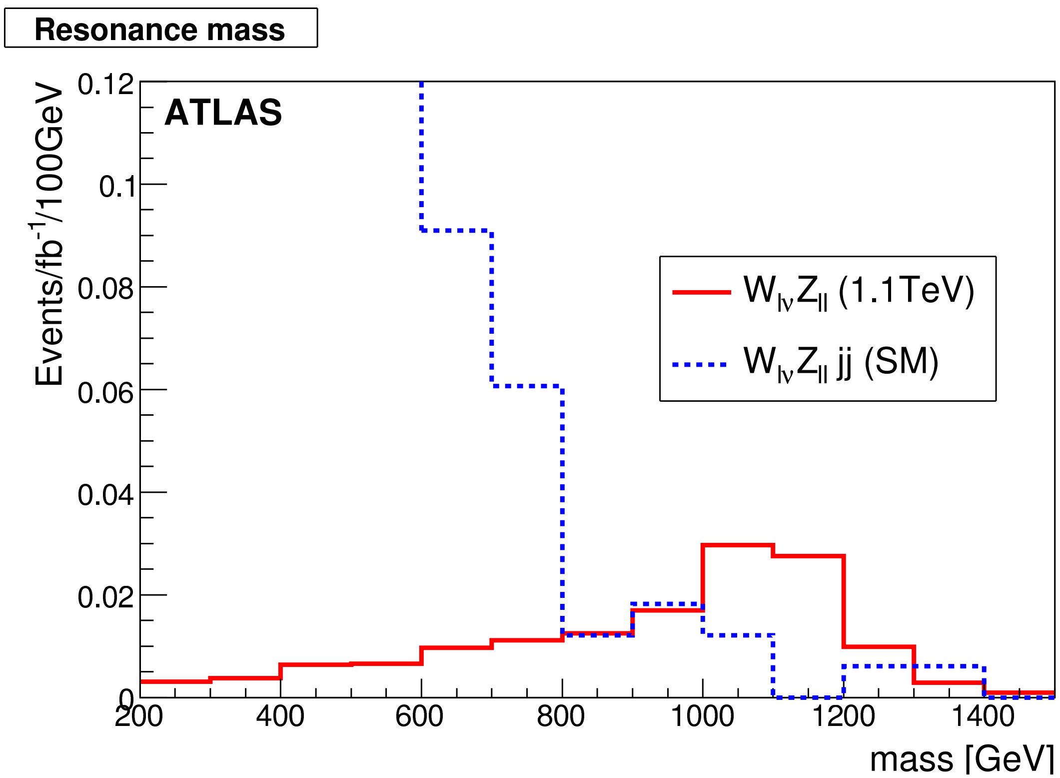
- Effective theory valid up to $\Lambda = 4\pi v$
- Expect $|\alpha_i| \lesssim v/\Lambda = 1/4\pi$
- Need unitarisation procedure, e.g. Pade unitarisation (works well in meson physics)
- Most likely get resonances (like ρ and ω in QCD)
- However also models without resonances are possible

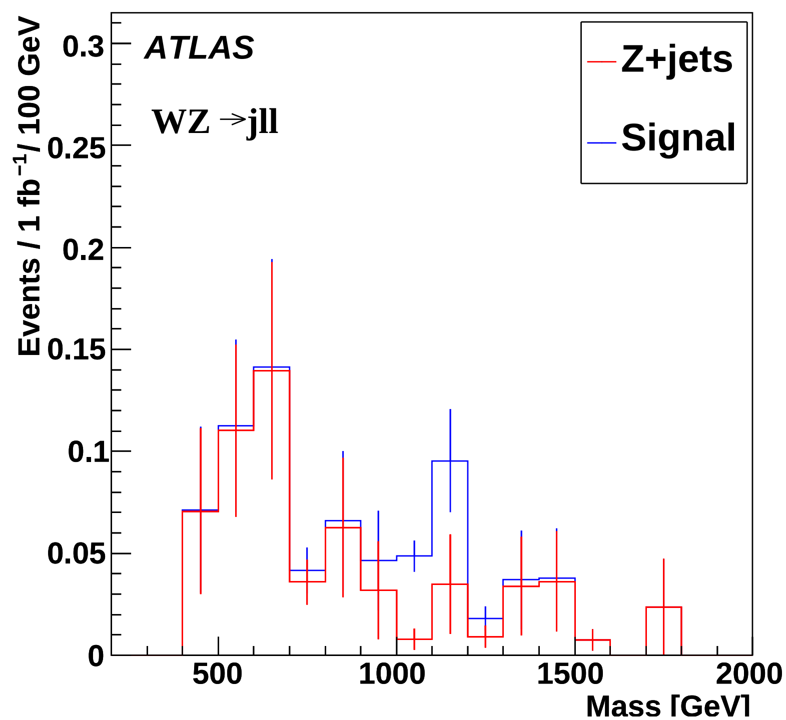




Event selection:

- At least one W,Z decays leptonically
- One W or Z can decay into one or two jets
- For ZZ one Z can decay into neutrinos
- Forward jet tagging and central jet veto similar to Higgs fusion channel
- Sensitivity up to around 1 TeV no results for no-resonance case yet





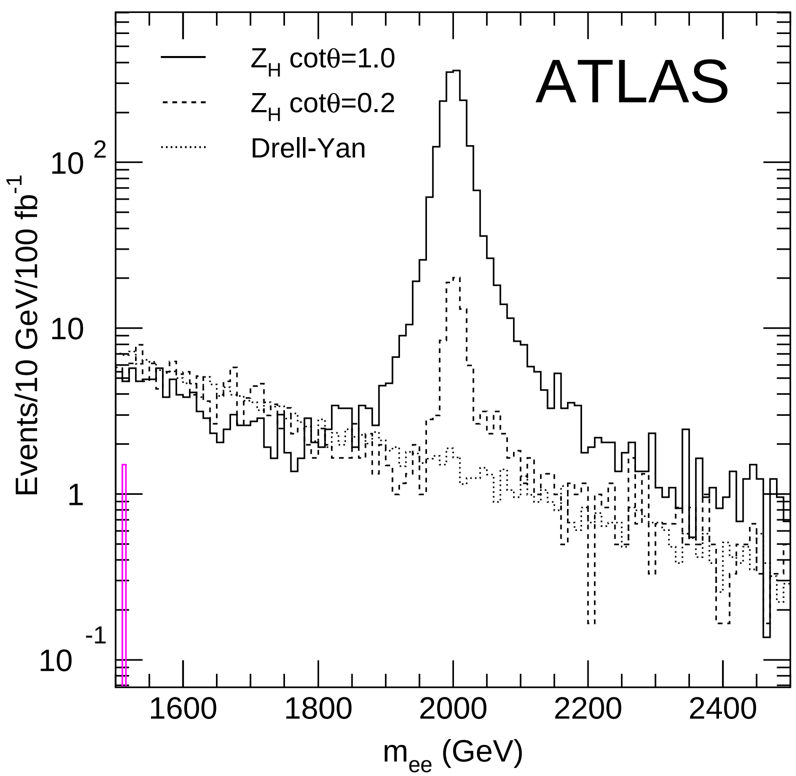
Little Higgs models

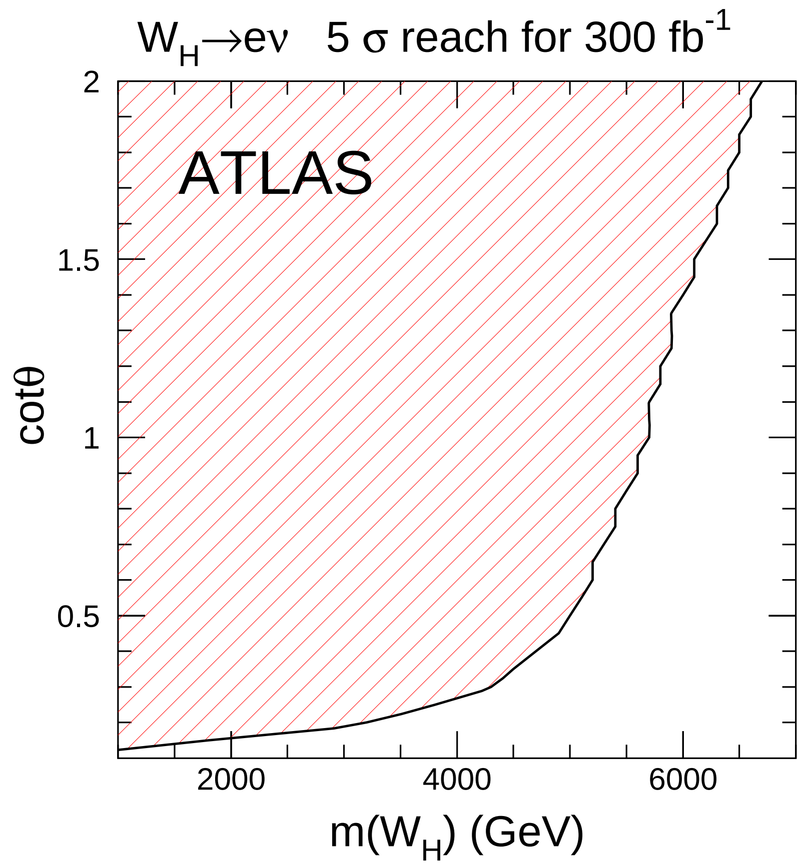
- In the SM the Higgs-mass receives large loop corrections
  - from the top loop $\delta m_h^2 = \frac{3}{8\pi^2}\lambda_t^2\Lambda^2 \sim (2\text{ TeV})^2$ $(\Lambda = 10\,\text{TeV})$
  - from the W/Z loops $\delta m_h^2 \sim \alpha_w \Lambda^2 \sim -(750\text{ GeV})^2$
  - from the Higgs loop $\delta m_h^2 \sim \frac{\lambda}{16\pi^2}\Lambda^2 \sim -(1.25 m_h)^2$
- The SM is embedded in a larger gauge group at $\Lambda_H = \mathcal{O}(10\,\text{TeV})$
- The Higgs is a pseudo-Goldstone boson of this breaking
- This protects the Higgs from one-loop corrections $\propto \Lambda_H^2$
- Technically this is done by new particles of same spin and $\mathcal{O}(1\,\text{TeV})$ mass:
  - An extended Higgs sector
  - New gauge bosons $A_H Z_H$, $W_H^\pm$ with mass $\lesssim 6\,\text{TeV}\left(\frac{m_\text{H}}{200\,\text{GeV}}\right)^2$
  - A new top-like quark T with mass $\lesssim 2\,\text{TeV}\left(\frac{m_\text{H}}{200\,\text{GeV}}\right)^2$

Search for the new gauge bosons

Discovery channel: leptonic decays

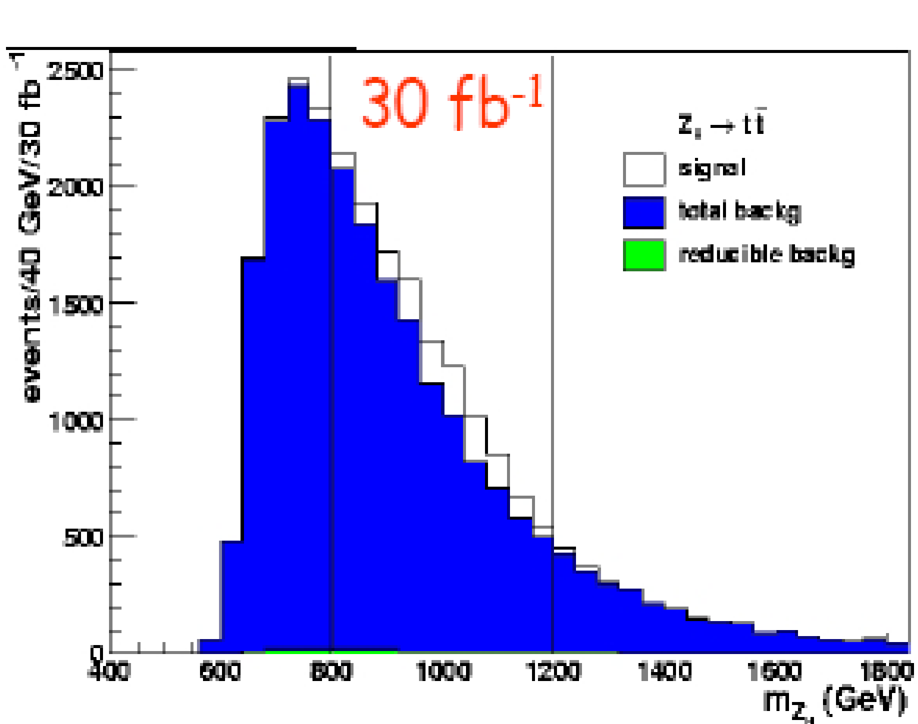
- Search equal to Z', W' searches already shown
- Cross section in general very large depending on a mixing angle θ
- Discovery up to ~ 6 TeV depending on mixing angle



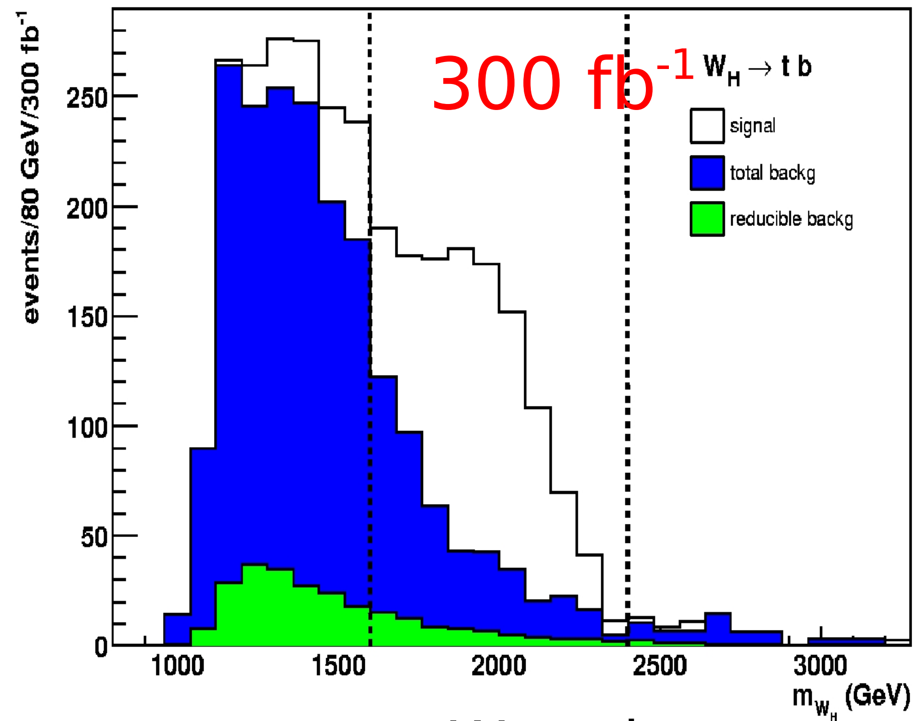


How to identify the little Higgs model?

- Decays to heavy quarks are predicted by the model
- Measurement of them helps to identify the model
- Can be seen up to 3 TeV



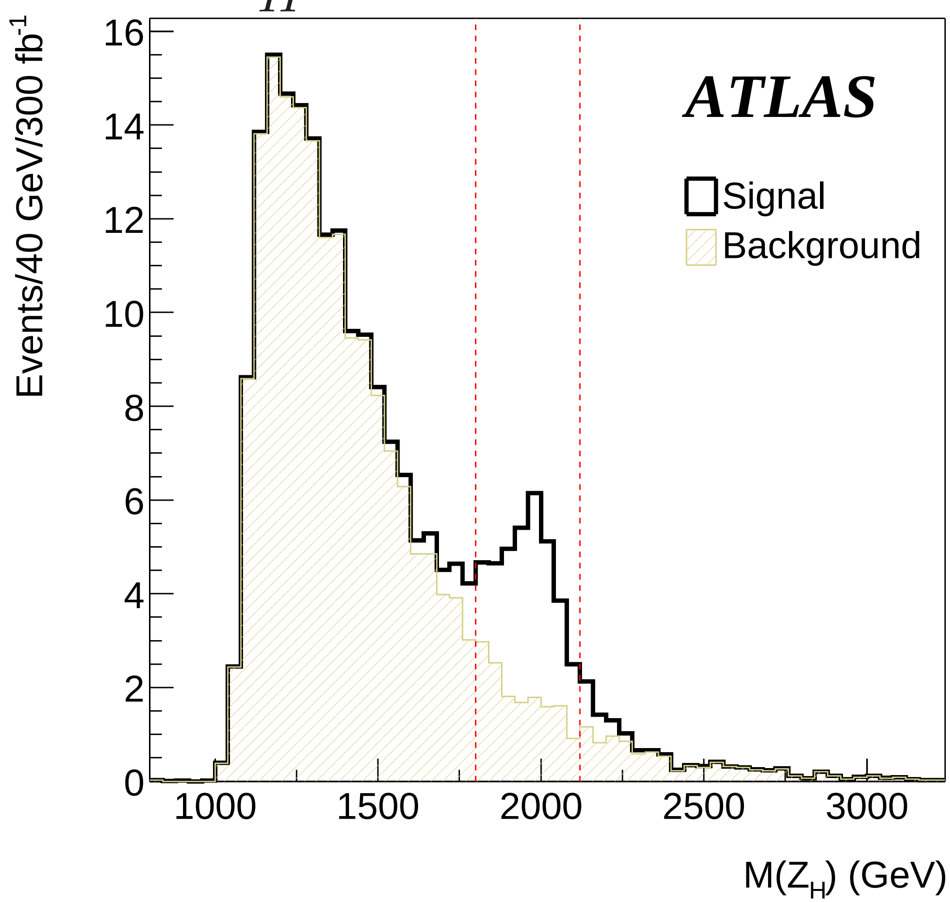
Z_H->tt

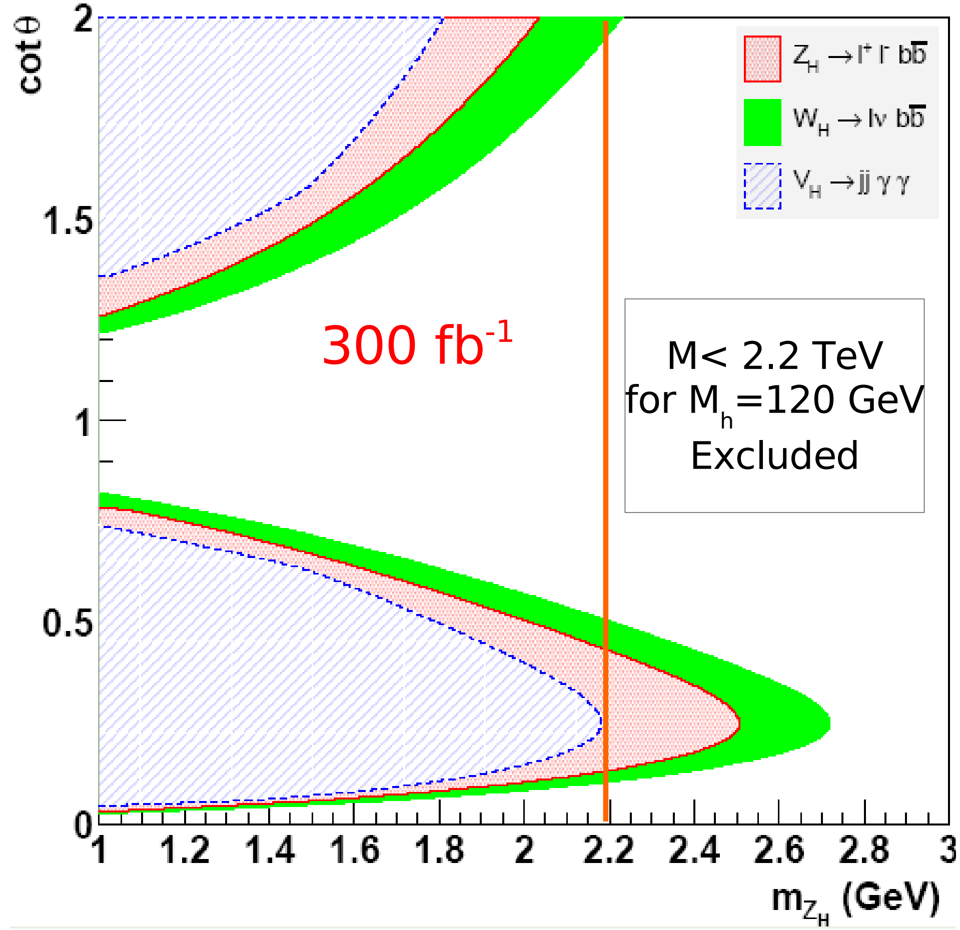


W_H->tb

- Very important W_H, Z_H decay to Higgses which are needed to cancel the W and Z loops
- Can use $W_H \to WH \to \ell\nu b\bar{b}$, $Z_H \to ZH \to \ell\ell b\bar{b}$, $W_H, Z_H \to W, Z\, H \to jj\gamma\gamma$
- However decay only visible in limited parameter space

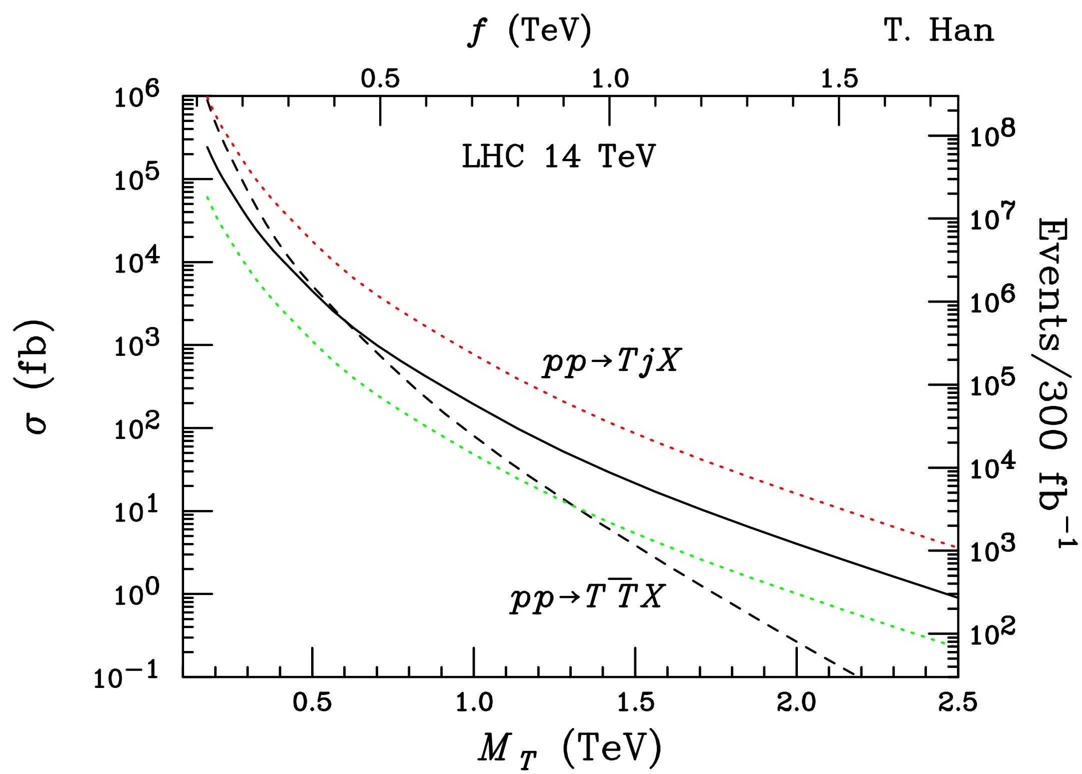
$Z_H \to ZH \to \ell\ell b\bar{b}$

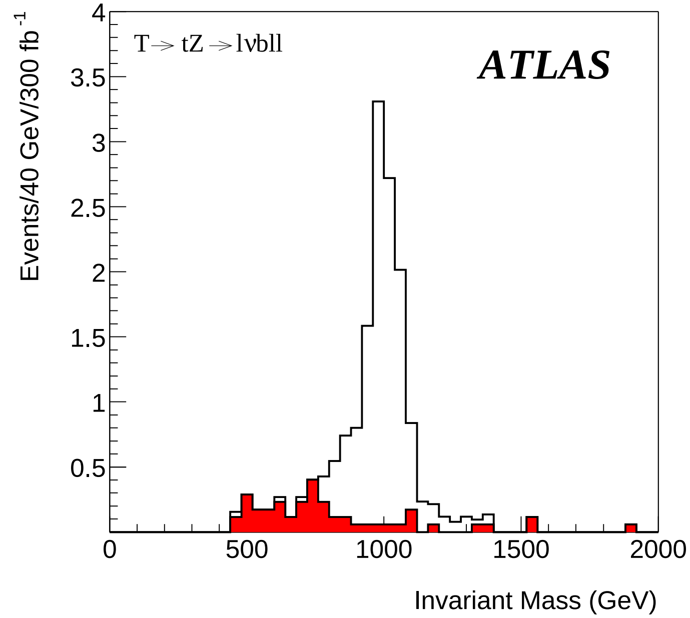


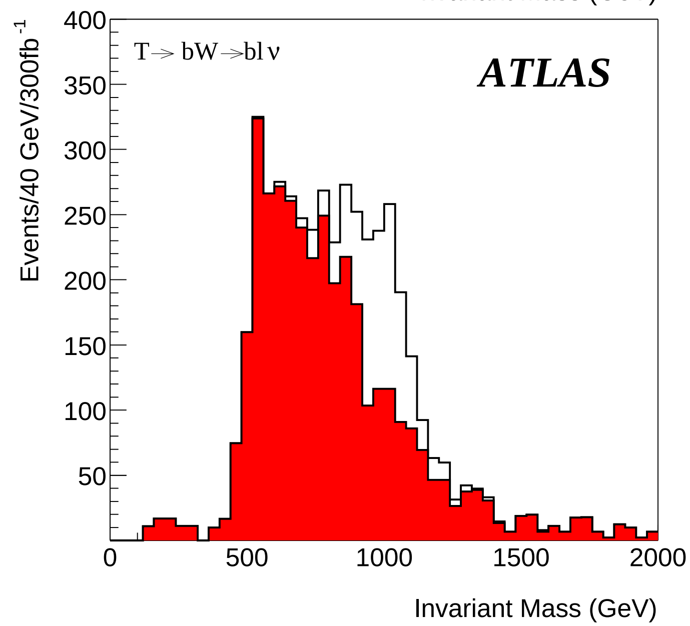


Search for the T-quark

- T and t mix with mixing parameter λ_1/λ_2
- Production via $qq, gg \to T\overline{T}$ or $qb \to q'T$, cross sections depend on λ_1/λ_2

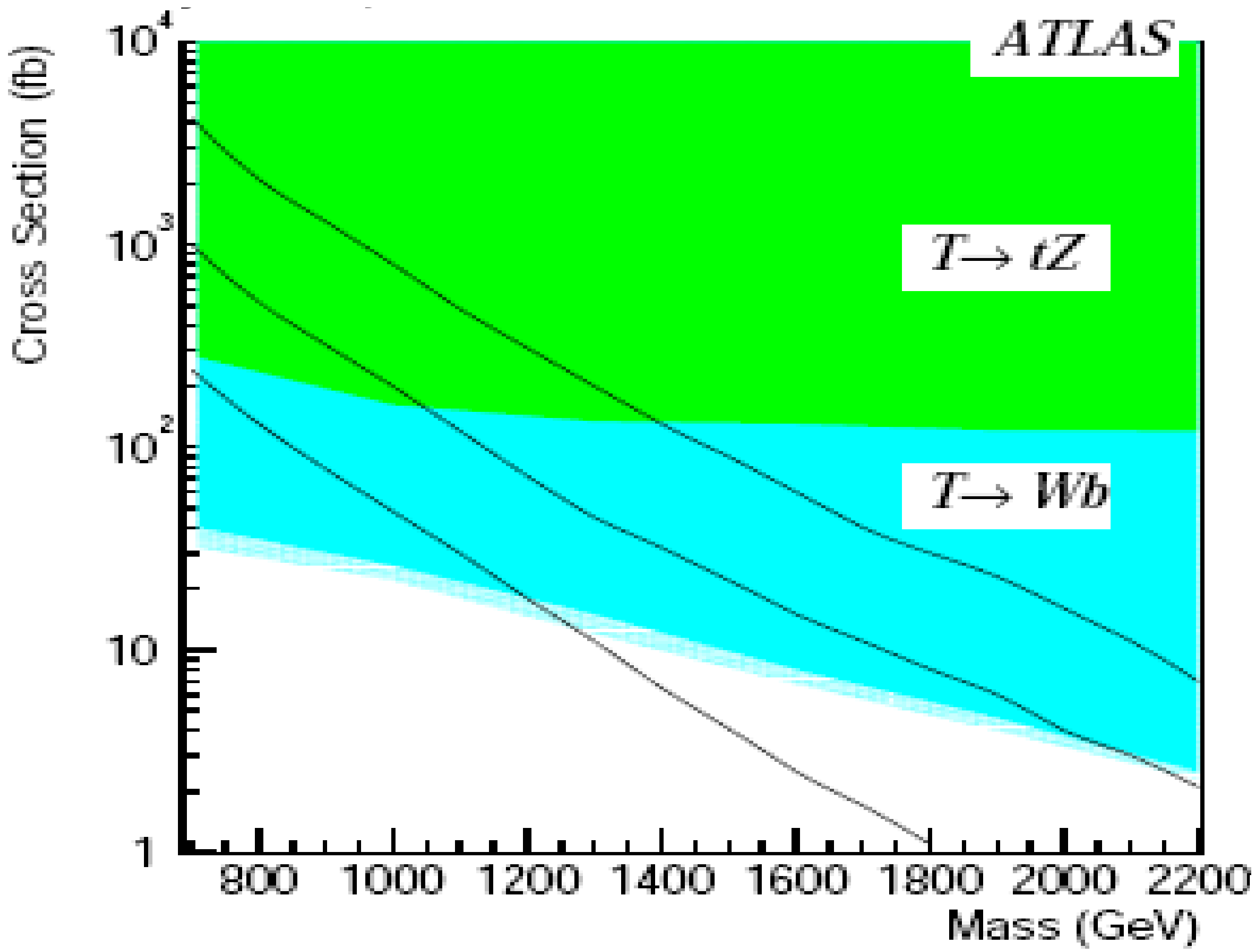






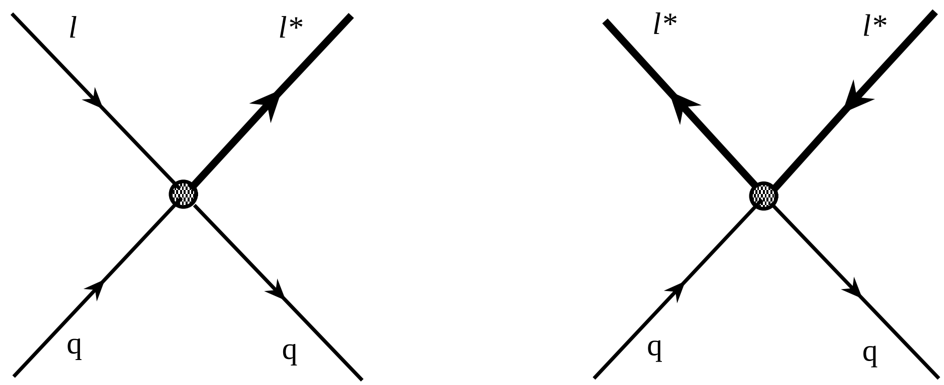
- T decays dominantly in Zt, Wb and ht
- Search for Zt, Wb with leptonic W,Z decays

- Wb can be reconstructed with high efficiency but significant background
- Zt much cleaner but lower efficiency
- Mass reach 1-2 TeV depending on model parameters



Fermion substructure

- The fermions can have a substructure at a high scale
- In this case excitations of the fermions should exist
- Also the scattering cross section should be modified
- The interaction can be parametrised with a contact interaction



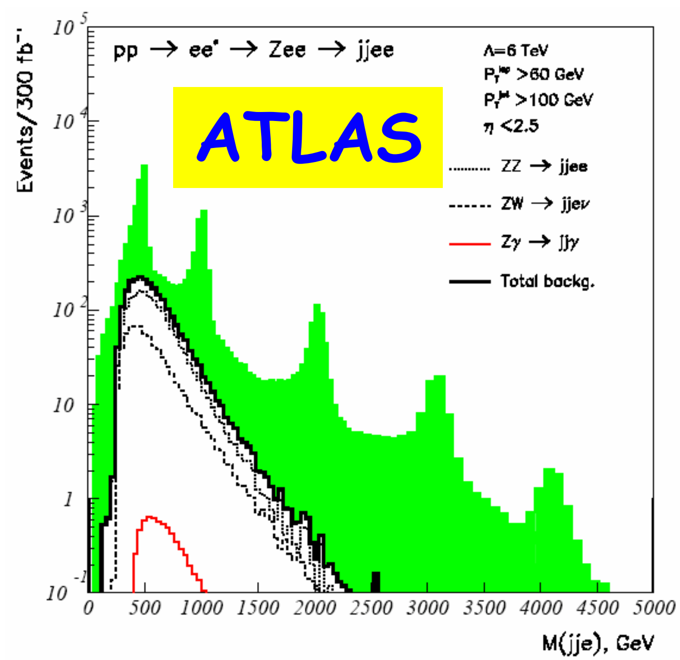
$$\mathcal{L}_{eff} = \frac{4\pi}{\Lambda^2} \sum_{i,k=L,R} \alpha^{ik} (\bar{q}_i \gamma^\mu q'_i)(\bar{f}_k \gamma^\mu f'_k)$$

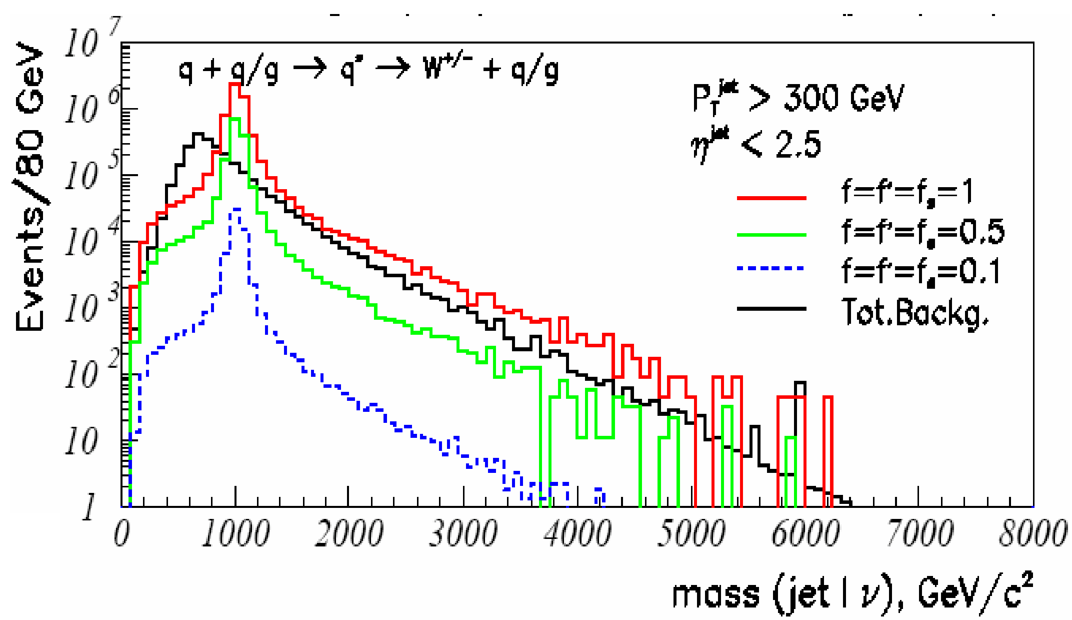
$\Rightarrow$ cross section rises with s

- Λ: contact interaction scale. Must be $>$ few TeV from previous experiments

Excited fermions

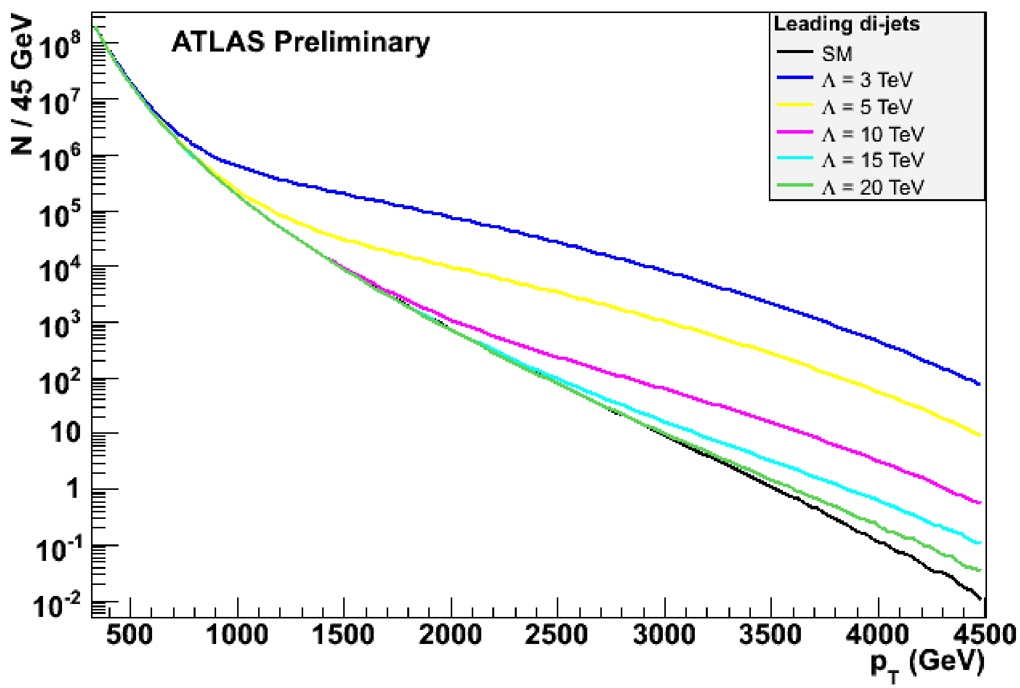
- Excited fermions could exist at a scale around or smaller than Λ
- Single and pair production is possible
- Single production has a much larger cross section due to the smaller needed s'
- They decay into a fermion and a gauge boson (γ,W,Z)
- The mass reach is 4-7 TeV for 300 fb^{-1}





Quark substructure

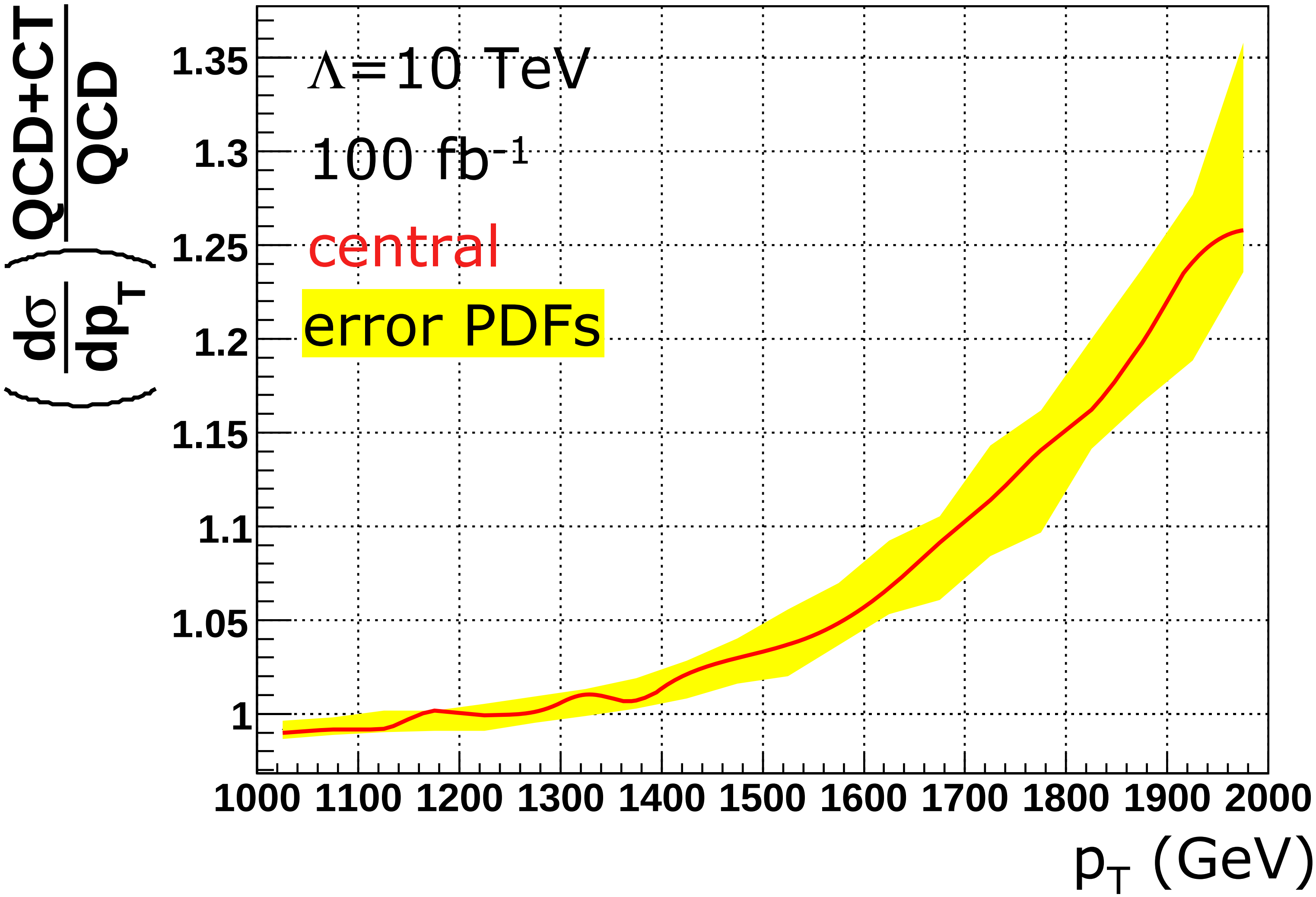
- Quark substructure will also be visible in the inclusive jet cross section at large p_T
- Effect gets large close to the compositnes scale



- Statistically no problem to get up to around $\Lambda = 40\,\text{TeV}$

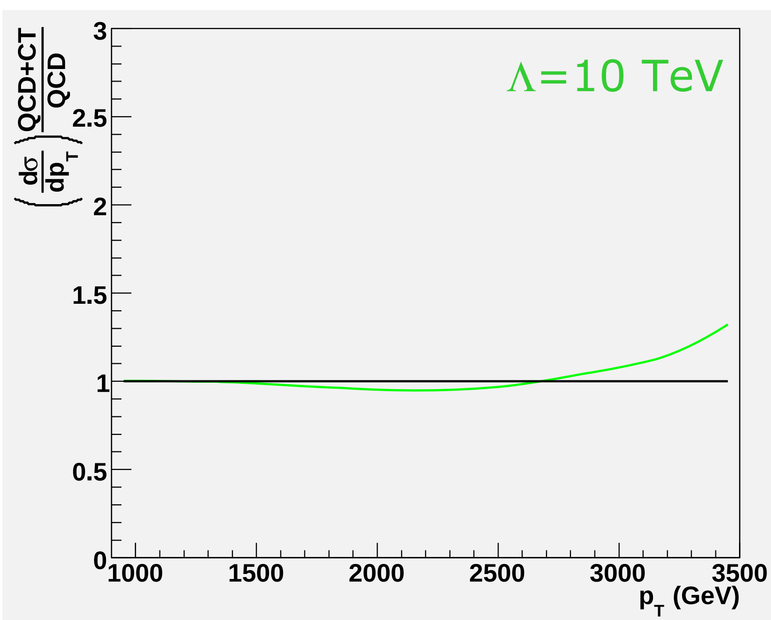
However systematics are an issue:

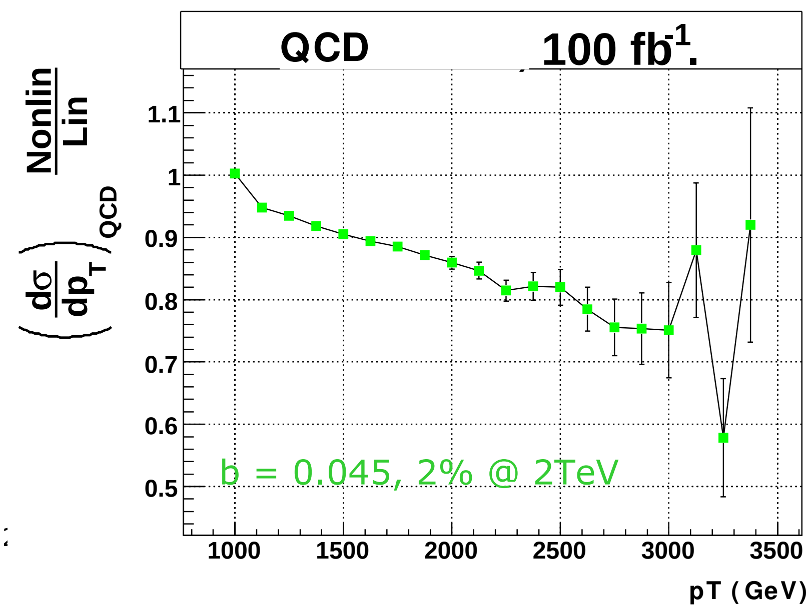
PDFs uncertainties start to get relevant but are not the limiting factor



Limiting systematics: linearity of energy scale

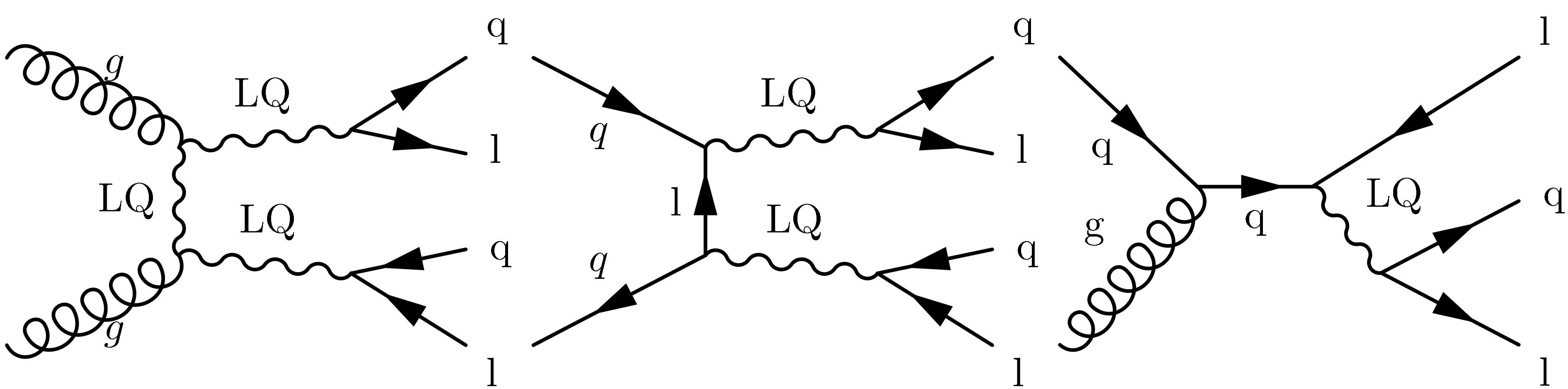
- At lower energy the jet-energy scale can be measured very precisely from Z+jets events
- At higher energy the scale can be estimated from boot-strap methods e.g. using three jet events
- This introduces some non-linearity in the energy scale
- Since the QCD cross section falls so steeply this introduces a large uncertainty in the jet rate
- A 2% non linearity at 2 TeV limits the sensitivity to $\Lambda = 10 - 20\,\mathrm{TeV}$





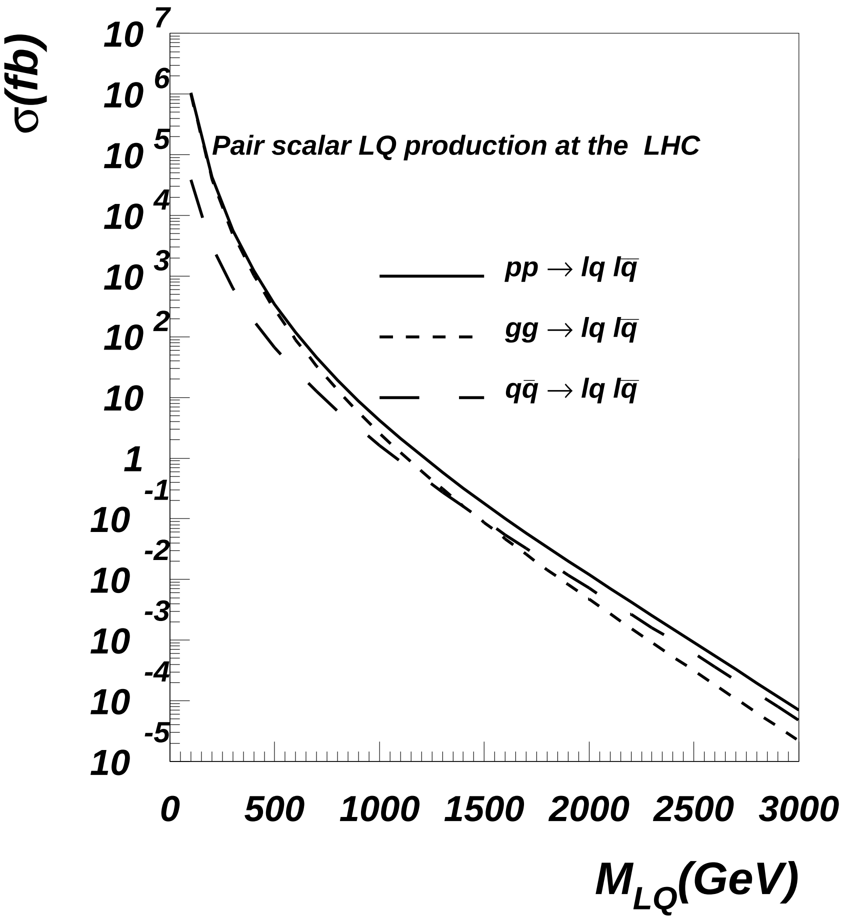
Leptoquarks

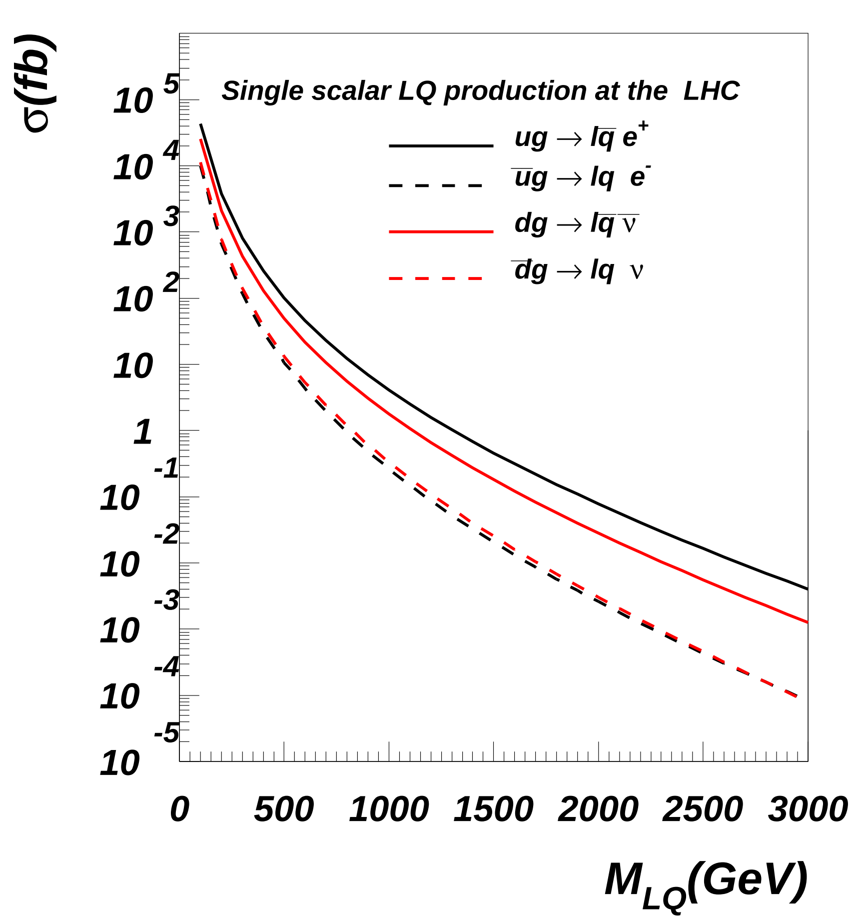
- Grand unification models try to embed the SM gauge group into a larger group like SU(5)
- Such a group contains new interaction which are lepton- and baryon-number violating
- The corresponding gauge bosons have baryon and lepton number $\neq 0$ and decay into quark-lepton (leptoquarks)
- Some production channels:



Cross section

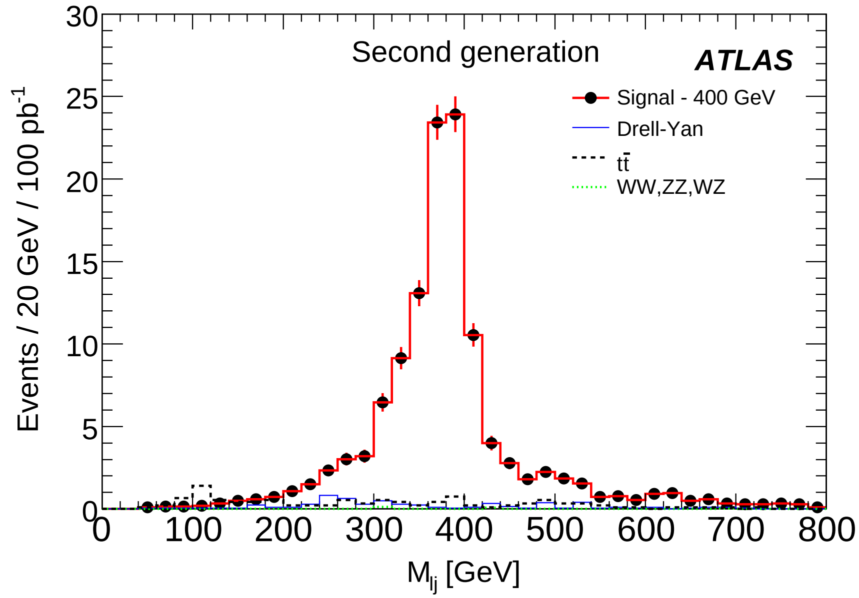
- For low masses the cross sections are very high
- However they fall steeply for higher masses
- In general the single LQ cross section is higher than the pair-production one

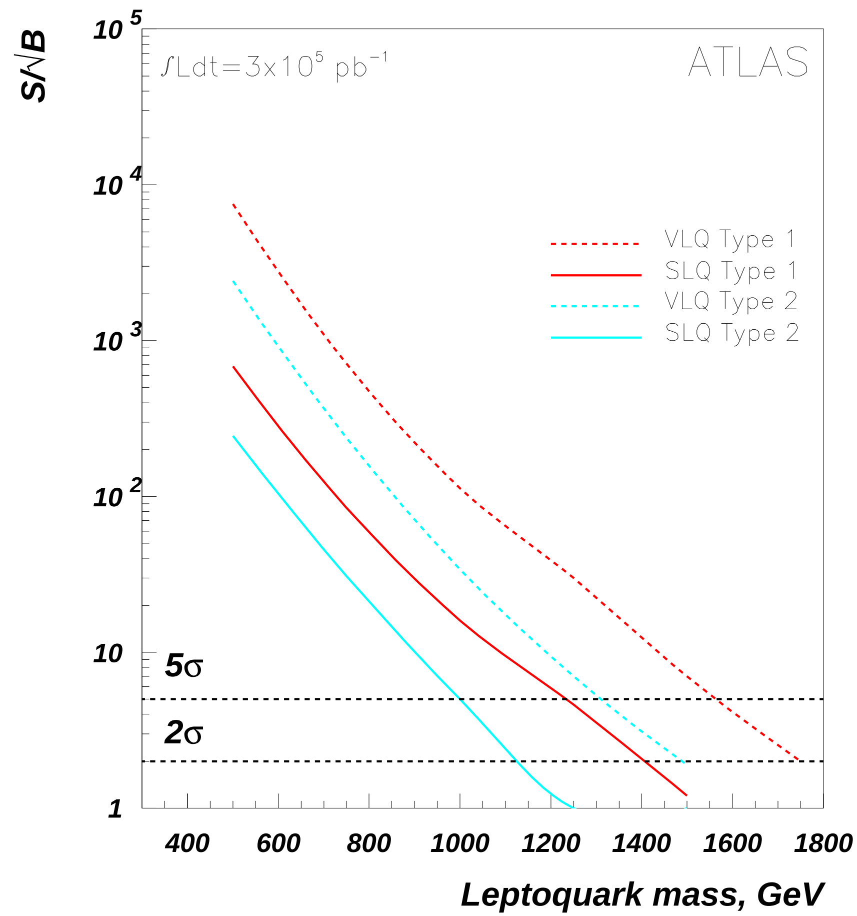




Event selection

- Two same flavour leptons with high p_t
- High E_T jets
- Large $\ell\ell$ mass to suppress Drell-Yan
- With these cuts a clean selection is possible
- Leptoquarks up to $\sim 800\,\mathrm{GeV}$ can be discovered with very low luminosity
- For high luminosity only about 1.5 TeV are possible due to fast falling cross section





Model independent searches

Idea:

- Plot as many distributions as possible and compare with prediction
- New physics will show up in deviations of the data from the prediction

Problem:

- Impossible to understand all variables at hadron colliders with good precision
- All problems in detector understanding will appear as deviations in the plots (can try to fit some correction factors)
- With many variables expect some deviations from statistical fluctuations (can be corrected for)

Advantages:

- Model independent
- Don't overlook unexpected new physics

Disadvantages:

- Non-optimal cuts since one wants to stay model independent

➡ signals may remain hidden under background

The CDF VISTA approach

- Plot as many distributions as possible
- Derive correction factors from a fit
- Correct significance for trial factor

Global result

CDF Run II Preliminary (2.0 fb^{-1})
The calculation of σ accounts for the trials factor

Final State	Data	Background	σ
b$e^\pm \not p$	690	817.7 ± 9.2	−2.7
$\gamma\tau^\pm$	1371	1217.6 ± 13.3	+2.2
$\mu^\pm\tau^\pm$	63	35.2 ± 2.8	+1.7
b2j$\not p$ high-Σp_T	255	327.2 ± 8.9	−1.7
2j$\tau^\pm$ low-Σp_T	574	670.3 ± 8.6	−1.5
3j$\tau^\pm$ low-Σp_T	148	199.8 ± 5.2	−1.4
$e^\pm \not p \tau^\pm$	36	17.2 ± 1.7	+1.4
2j$\tau^\pm\tau^\mp$	33	62.1 ± 4.3	−1.3
$e^\pm$j	741710	764832 ± 6447.2	−1.3
j2$\tau^\pm$	105	150.8 ± 6.3	−1.2
$e^\pm$2j	256946	249148 ± 2201.5	+1.2
2bj low-Σp_T	279	352.5 ± 11.9	−1.1
j$\tau^\pm$ low-Σp_T	1385	1525.8 ± 15	−1.1
2b2j low-Σp_T	108	153.5 ± 6.8	−1
b$\mu^\pm \not p$	528	613.5 ± 8.7	−0.9
$\mu^\pm\gamma \not p$	523	611 ± 12.1	−0.8
2bγ	108	70.5 ± 7.9	+0.1
8j	14	13.1 ± 4.4	0
7j	103	97.8 ± 12.2	0
6j	653	659.7 ± 37.3	0
5j	3157	3178.7 ± 67.1	0
4j high-Σp_T	88546	89096.6 ± 935.2	0
4j low-Σp_T	14872	14809.6 ± 186.3	0
4j2γ	46	46.4 ± 3.9	0
4j$\tau^\pm$ high-Σp_T	29	26.6 ± 1.7	0
4j$\tau^\pm$ low-Σp_T	43	63.1 ± 3.3	0
4j$\not p$ high-Σp_T	1064	1012 ± 62.9	0
4j$\gamma\tau^\pm$	19	10.8 ± 2	0
4j$\gamma \not p$	62	104.2 ± 22.4	0
4jγ	7962	8271.2 ± 245.1	0
4j$\mu^\pm \not p$	574	590.5 ± 13.6	0
4j$\mu^\pm\mu^\mp$	38	48.4 ± 6.2	0
4j$\mu^\pm$	1363	1350.1 ± 37.7	0
3j high-Σp_T	159926	159143 ± 1061.9	0
3j low-Σp_T	62681	64213.1 ± 496	0
3j2γ	151	177.5 ± 7.1	0
3j$\tau^\pm$ high-Σp_T	68	76.9 ± 3	0
3j$\not p$ high-Σp_T	1706	1899.4 ± 77.6	0
3j$\not p$ low-Σp_T	42	36.2 ± 5.7	0
3j$\gamma\tau^\pm$	39	37.8 ± 3.6	0
3j$\gamma \not p$	204	249.8 ± 24.4	0
3jγ	24639	24899.4 ± 372.4	0
3j$\mu^\pm \not p$	2884	2971.5 ± 52.1	0
3j$\mu^\pm\gamma \not p$	10	3.6 ± 1.9	0
3j$\mu^\pm\gamma$	15	7.9 ± 2.9	0
3j$\mu^\pm\mu^\mp$	175	177.8 ± 16.2	0
3j$\mu^\pm$	5032	4989.5 ± 108.9	0
3b2j	23	28.9 ± 4.7	0
3bj	82	82.6 ± 5.7	0
3b	67	85.6 ± 7.7	0
2$\tau^\pm$	498	512.7 ± 14.2	0
2$\gamma \not p$	128	107.2 ± 6.9	0
2γ	5548	5562.8 ± 40.5	0
2j high-Σp_T	190773	190842 ± 781.2	0
2j low-Σp_T	165984	162530 ± 1581	0
2j2$\tau^\pm$	22	40.6 ± 3.2	0
2j2$\gamma \not p$	11	8 ± 2.4	0
2j2γ	580	581 ± 13.7	0
2j$\tau^\pm$ high-Σp_T	96	114.6 ± 3.3	0

Final State	Data	Background	σ
2j$\not p$ high-Σp_T	87	80.9 ± 6.8	0
2j$\not p$ low-Σp_T	114	79.5 ± 100.8	0
2j$\not p \tau^\pm$	18	13.2 ± 2.2	0
2j$\gamma\tau^\pm$	142	144.6 ± 5.7	0
2j$\gamma \not p$	908	980.3 ± 63.7	0
2jγ	71364	73021.4 ± 595.9	0
2j$\mu^\pm\tau^\mp$	16	19.3 ± 2.2	0
2j$\mu^\pm \not p$	17927	18340.6 ± 201.9	0
2j$\mu^\pm\gamma \not p$	31	27.7 ± 7.7	0
2j$\mu^\pm\gamma$	57	58.2 ± 13	0
2j$\mu^\pm\mu^\mp \not p$	11	7.8 ± 2.7	0
2j$\mu^\pm\mu^\mp$	956	924.9 ± 61.2	0
2j$\mu^\pm$	22461	23111.4 ± 366.6	0
2$e^\pm$j	14	13.8 ± 2.3	0
2$e^\pm e^\mp$	20	17.5 ± 1.7	0
2$e^\pm$	32	49.2 ± 3.4	0
2b high-Σp_T	666	689 ± 9.4	0
2b low-Σp_T	323	313.2 ± 10.3	0
2b3j low-Σp_T	53	57.4 ± 6.5	0
2b2j high-Σp_T	718	803.3 ± 12.7	0
2b2j$\not p$ high-Σp_T	15	21.8 ± 2.8	0
2b2jγ	32	39.7 ± 6.2	0
2b2j$\mu^\pm \not p$	14	17.3 ± 1.9	0
2b2j$\mu^\pm$	22	21.8 ± 2	0
2b$\mu^\pm \not p$	11	14.4 ± 2.1	0
2bj high-Σp_T	891	967.1 ± 13.2	0
2bj$\not p$ high-Σp_T	25	31.3 ± 3.1	0
2bjγ	71	54.5 ± 7.1	0
2bj$\mu^\pm \not p$	12	10.7 ± 1.9	0
2b$e^\pm$2j$\not p$	30	27.3 ± 2.2	0
2b$e^\pm$2j	72	66.5 ± 2.9	0
2b$e^\pm \not p$	22	19.1 ± 2.2	0
2b$e^\pm$j$\not p$	19	19.4 ± 2.2	0
2b$e^\pm$j	63	63 ± 3.4	0
2b$e^\pm$	96	92.1 ± 4.1	0
$\tau^\pm\tau^\mp$	856	872.5 ± 19	0
$\gamma \not p$	3793	3770.7 ± 127.3	0
$\mu^\pm\tau^\mp$	381	440.9 ± 7.3	0
$\mu^\pm \not p \tau^\mp$	60	75.7 ± 3.4	0
$\mu^\pm \not p \tau^\pm$	15	12 ± 2	0
$\mu^\pm \not p$	734290	734296 ± 4897.8	0
$\mu^\pm\gamma$	475	469.8 ± 12.5	0
$\mu^\pm\mu^\mp \not p$	169	198.5 ± 8.2	0
$\mu^\pm\mu^\mp\gamma$	83	60 ± 3.1	0
$\mu^\pm\mu^\mp$	25283	25178.5 ± 86.5	0
j2$\gamma \not p$	36	30.4 ± 4.2	0
j2γ	1822	1813.2 ± 27.4	0
j$\tau^\pm$ high-Σp_T	52	56.2 ± 2.5	0
j$\tau^\pm\tau^\mp$	203	252.2 ± 8.7	0
j$\not p$ high-Σp_T	4432	4431.7 ± 45.2	0
j$\gamma\tau^\pm$	526	476 ± 9.3	0
j$\gamma \not p$	1882	1791.9 ± 72.3	0
jγ	103319	102124 ± 570.6	0
j$\mu^\pm\tau^\mp$	71	98 ± 3.9	0
j$\mu^\pm\tau^\pm$	15	12 ± 2	0
j$\mu^\pm \not p \tau^\mp$	26	30.8 ± 2.6	0
j$\mu^\pm \not p$	109081	108323 ± 707.7	0
j$\mu^\pm\gamma \not p$	171	171.1 ± 31	0
j$\mu^\pm\gamma$	152	190 ± 39.3	0

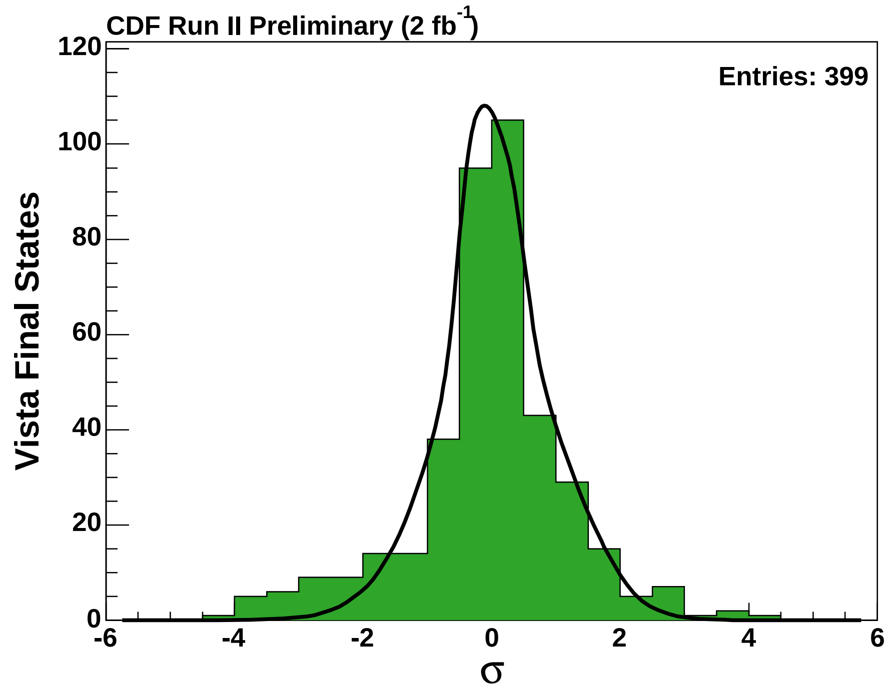
Final State	Data	Background	σ
j$\mu^\pm\mu^\mp \not p$	32	32.2 ± 10.9	0
j$\mu^\pm\mu^\mp\gamma$	14	11.5 ± 2.6	0
j$\mu^\pm\mu^\mp$	4852	4271.2 ± 185.4	0
j$\mu^\pm$	77689	76987.5 ± 930.2	0
$e^\pm$4j$\not p$	903	830.6 ± 13.2	0
$e^\pm$4jγ	25	29.2 ± 3.6	0
$e^\pm$4j	15750	16740.4 ± 390.5	0
$e^\pm$3j$\tau^\mp$	15	21.1 ± 2.2	0
$e^\pm$3j$\not p$	4054	4077.2 ± 63.6	0
$e^\pm$3jγ	108	79.3 ± 5	0
$e^\pm$3j	60725	60409.3 ± 723.3	0
$e^\pm$2γ	41	34.2 ± 2.6	0
$e^\pm$2j$\tau^\pm$	37	47.2 ± 2.2	0
$e^\pm$2j$\tau^\mp$	109	95.9 ± 6.8	0
$e^\pm$2j$\not p$	25725	25403.1 ± 209.4	0
$e^\pm$2j$\gamma \not p$	30	31.8 ± 4.8	0
$e^\pm$2jγ	398	342.8 ± 15.7	0
$e^\pm$2j$\mu^\mp \not p$	22	14.8 ± 1.9	0
$e^\pm$2j$\mu^\mp$	23	15.8 ± 2	0
$e^\pm\tau^\pm$	437	387 ± 5.3	0
$e^\pm\tau^\mp$	1333	1266 ± 12.3	0
$e^\pm \not p \tau^\mp$	109	106.1 ± 2.7	0
$e^\pm \not p$	960826	956579 ± 3077.7	0
$e^\pm\gamma \not p$	497	496.8 ± 10.3	0
$e^\pm\gamma$	3578	3589.9 ± 24.1	0
$e^\pm\mu^\pm \not p$	31	29.9 ± 1.6	0
$e^\pm\mu^\mp \not p$	109	99.4 ± 2.4	0
$e^\pm\mu^\pm$	45	28.5 ± 1.8	0
$e^\pm\mu^\mp$	350	313 ± 5.4	0
$e^\pm$j2γ	13	16.1 ± 3.9	0
$e^\pm$j$\tau^\mp$	386	418 ± 18.9	0
$e^\pm$j$\tau^\pm$	160	162.8 ± 3.5	0
$e^\pm$j$\not p \tau^\mp$	48	44.6 ± 3.3	0
$e^\pm$j$\not p \tau^\pm$	11	8.3 ± 1.5	0
$e^\pm$j$\not p$	121431	121023 ± 747.6	0
$e^\pm$j$\gamma \not p$	159	192.6 ± 10.9	0
$e^\pm$jγ	1389	1368.9 ± 38.9	0
$e^\pm$j$\mu^\mp \not p$	42	33 ± 2.9	0
$e^\pm$j$\mu^\pm \not p$	16	9.2 ± 1.9	0
$e^\pm$j$\mu^\mp$	62	63.8 ± 3.2	0
$e^\pm$j$\mu^\pm$	13	8.2 ± 2	0
$e^\pm e^\mp$4j	148	159.1 ± 7	0
$e^\pm e^\mp$3j	717	743.6 ± 24.4	0
$e^\pm e^\mp$2j$\not p$	32	41.4 ± 5.6	0
$e^\pm e^\mp$2jγ	10	11.4 ± 2.9	0
$e^\pm e^\mp$2j	3638	3566.8 ± 72	0
$e^\pm e^\mp\tau^\pm$	18	16.1 ± 1.7	0
$e^\pm e^\mp \not p$	822	831.8 ± 13.6	0
$e^\pm e^\mp\gamma$	191	221.9 ± 5.1	0
$e^\pm e^\mp$j$\not p$	155	170.8 ± 12.4	0
$e^\pm e^\mp$jγ	48	45 ± 3.9	0
$e^\pm e^\mp$j	17903	18258.2 ± 204.4	0
$e^\pm e^\mp$	98901	99086.9 ± 147.8	0
b6j	51	42.3 ± 3.8	0
b5j	237	192.5 ± 7.1	0
b4j high-Σp_T	26	23.4 ± 2.6	0
b4j low-Σp_T	836	821.7 ± 15.9	0
b3j high-Σp_T	12081	12071 ± 84.1	0
b3j low-Σp_T	2974	2873 ± 31	0

10 most discrepant variables

CDF Run II Preliminary (2.0 fb^{-1})

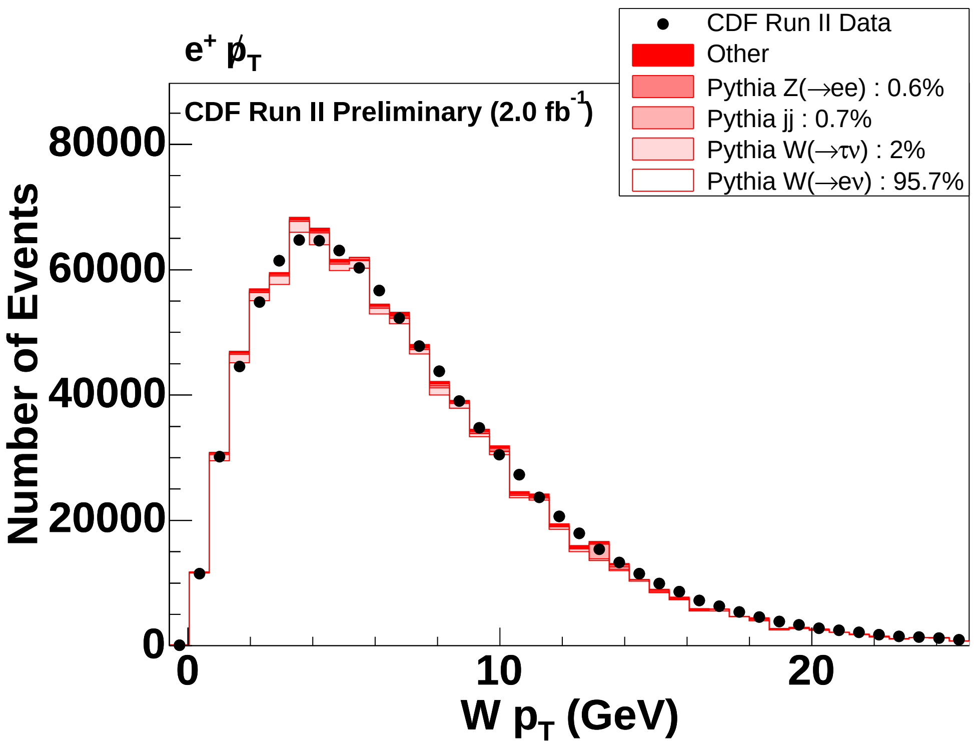
Final State	**Data**	**Background**	σ	σ_t
$\text{b}e^{\pm}\not{p}$	690	817.7 ± 9.2	-4.3	-2.7
$\gamma\tau^{\pm}$	1371	1217.6 ± 13.3	$+4.0$	$+2.2$
$\mu^{\pm}\tau^{\pm}$	63	35.2 ± 2.8	$+3.7$	$+1.7$
$\text{b2j}\not{p}$ high-Σp_T	255	327.2 ± 8.9	-3.7	-1.7
$2\text{j}\tau^{\pm}$ low-Σp_T	574	670.3 ± 8.6	-3.6	-1.5
$3\text{j}\tau^{\pm}$ low-Σp_T	148	199.8 ± 5.2	-3.5	-1.4
$e^{\pm}\not{p}\tau^{\pm}$	36	17.2 ± 1.7	$+3.5$	$+1.4$
$2\text{j}\tau^{\pm}\tau^{\mp}$	33	62.1 ± 4.3	-3.5	-1.3
$e^{\pm}\text{j}$	741710	764832 ± 6447.2	-3.5	-1.3
$\text{j}2\tau^{\pm}$	105	150.8 ± 6.3	-3.4	-1.2

Significance of all VISTA variables

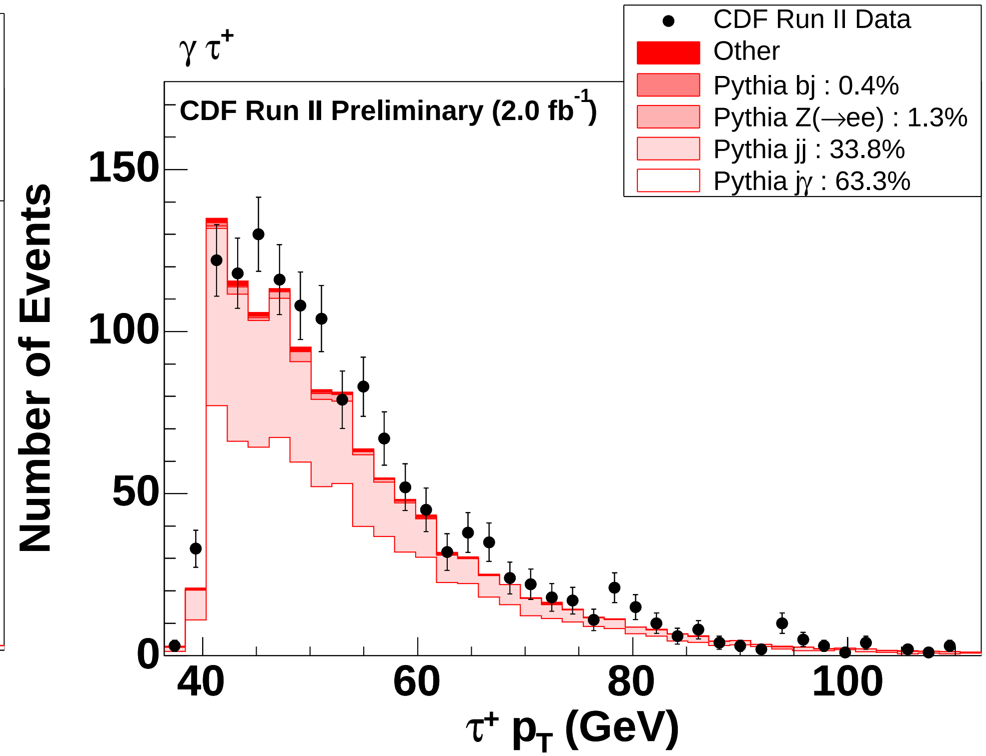


- General agreement is good
- Largest deviation even is a deficit
- No sign of new physics

“Typical” variable: W p_T



Largest excess: $\gamma\tau$



- Up to now no indications from this approach
- However should be followed not to miss anything
- Makes only sense to plan for LHC once data are there and detector and SM physics is well understood

Conclusions

- The LHC can search for many new physics channels
- As a general rule new particles can be found up to $2-3\,\text{TeV}$
- However many models are not well defined, so limits should not be taken literally in many cases

Commercial

Diploma/Master thesis in the ATLAS group at DESY in Zeuthen

Summary of available thesis at:

https://znwiki3.ifh.de/ATLAS/ThesesZeuthen

Please contact us in case you are interested!