Searches for New Physics

from an Experimental Point of View

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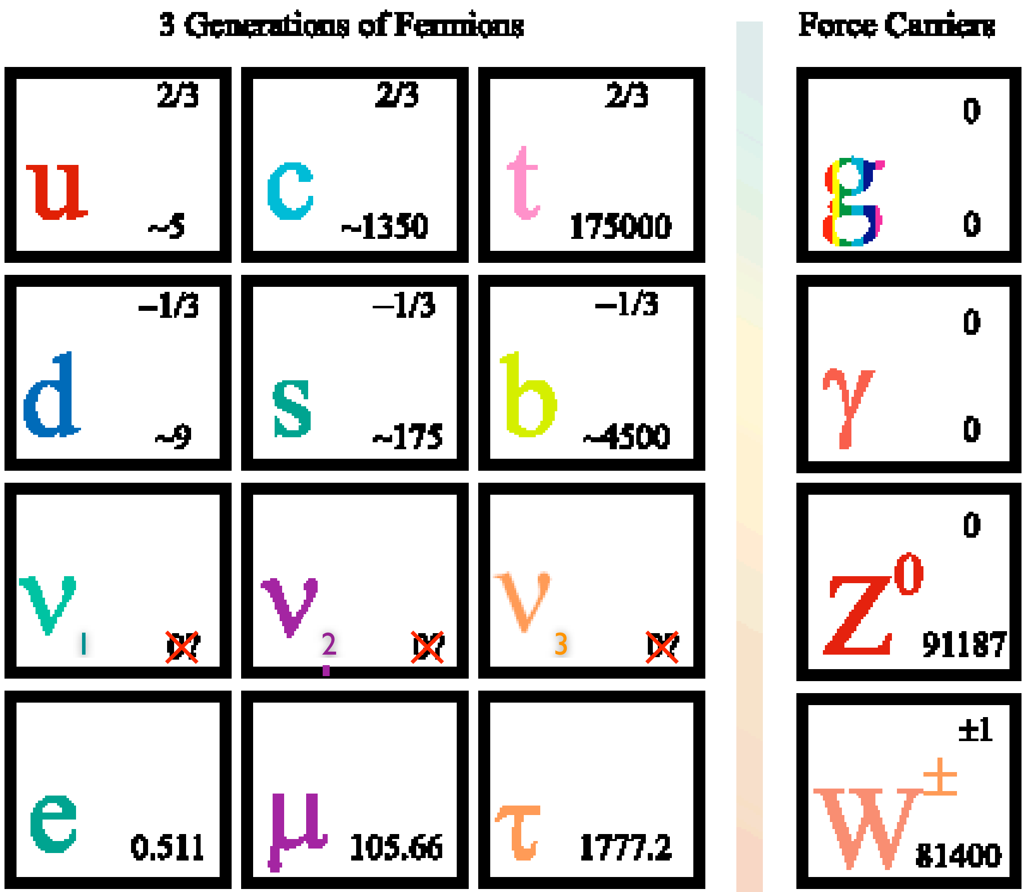
Columbia University in the City of New York

HEP in 2009



Masses are in MeV

CKM elements:

Observable	Central ± 1 σ
$\|V_{ud}\|$	0.97430 [+0.00019 -0.00019]
$\|V_{us}\|$	0.22521 [+0.00082 -0.00082]
$\|V_{ub}\|$	0.00350 [+0.00015 -0.00014]
$\|V_{cb}\|$	0.04117 [+0.00038 -0.00115]
$\|V_{ud}\|$ (meas. not in the fit)	0.97444 [+0.00028 -0.00028]
$\|V_{us}\|$ (meas. not in the fit)	0.2257 [+0.0011 -0.0011]
$\|V_{ub}\|$ (meas. not in the fit)	0.00350 [+0.00015 -0.00016]
$\|V_{cb}\|$ (meas. not in the fit)	0.04399 [+0.00069 -0.00397]
$\|V_{cd}\|$	0.22508 [+0.00082 -0.00082]
$\|V_{cs}\|$	0.97347 [+0.00019 -0.00019]
$\|V_{td}\|$	0.00859 [+0.00027 -0.00029]
$\|V_{ts}\|$	0.04041 [+0.00038 -0.00115]
$\|V_{tb}\|$	0.999146 [+0.000047 -0.000016]

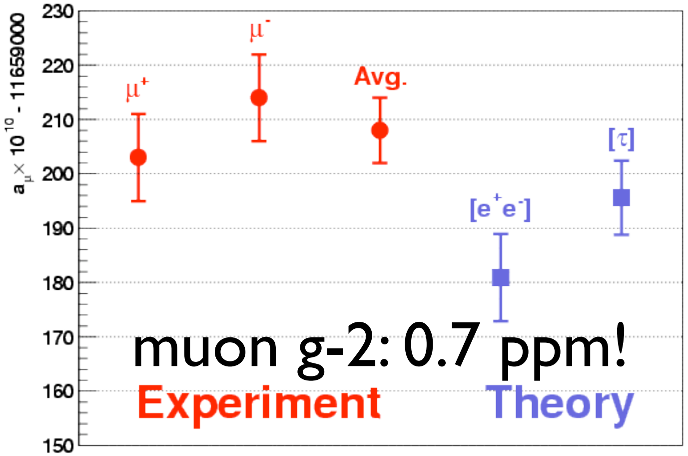
In Words

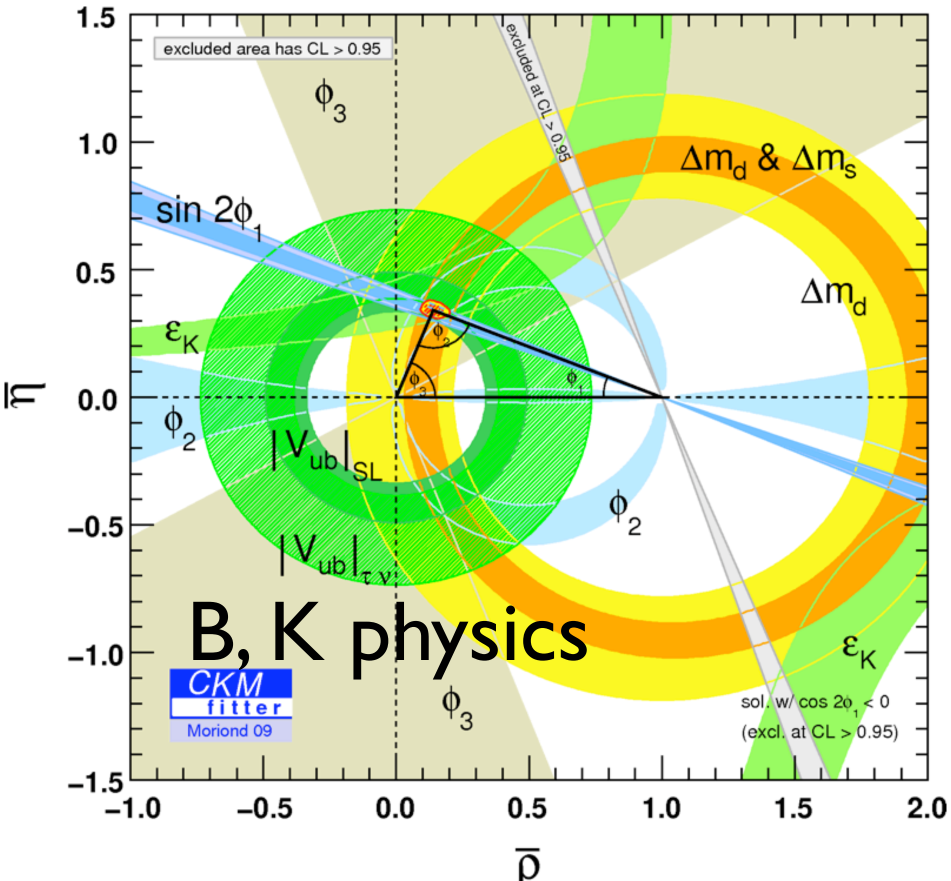
- Matter is built of spin 1/2 particles that interact by exchanging 3 different kinds of spin 1 particles corresponding to 3 different (gauge) interactions
- There appear to be 3 generations of matter particles
- The 4 different matter particles in each generation carry different combinations of quantized charges characterizing their couplings to the interaction bosons
- The matter fermions and the weak bosons have “mass”
- Gravitation is presumably mediated by spin 2 gravitons
- Gravitation is extremely weak for typical particle masses
- There appear to be 3 macroscopic dimensions

About the Standard Model

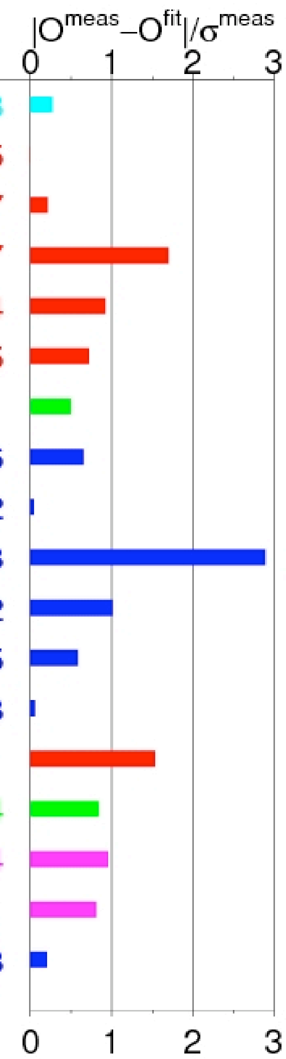
- It's a theory of interactions:
  - Properties of fermions are inputs
  - Properties of interaction bosons in terms of couplings, propagations, masses are linked:
    - Measuring a few allows us to predict the rest, then measure and compare with expectation
- It's remarkably successful:
  - Predictions verified to be correct at sometimes incredible levels of precision
  - After ~30 years, still no serious cracks

Precision Results





	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02768
m_Z [GeV]	91.1875 ± 0.0021	91.1875
Γ_Z [GeV]	2.4952 ± 0.0023	2.4957
σ_{had}^0 [nb]	41.540 ± 0.037	41.477
R_l	20.767 ± 0.025	20.744
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21586
R_c	0.1721 ± 0.0030	0.1722
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1038
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1481
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.398 ± 0.025	80.374
Γ_W [GeV]	2.140 ± 0.060	2.091
m_t [GeV]	170.9 ± 1.8	171.3



LEP, SLD & Tevatron

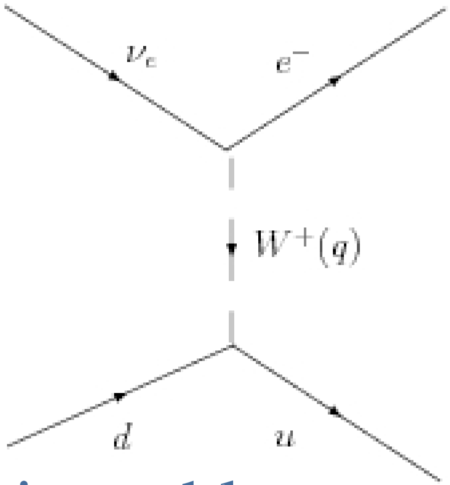
Many Fundamental Questions

- What exactly *is* spin? Or color? Or electric charge? Why are they quantified?
- Are there only 3 generations? If so, why?
- Why are there e.g. no neutral, colored fermions?
- What is mass? Why are particles so light?
- Is there a link between particle and nucleon masses?
- How does all of this reconcile with gravitation? How many space-time dimensions are there really?
- ...

The Plot

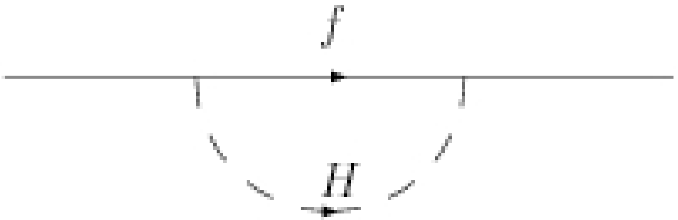
Vector Boson Scattering

- There is in fact one known problem with the standard model:
  - If we collide W's and Z's (not so easy...), the scattering cross-section grows with the center of mass energy, and gets out of control at about 1.7 TeV
- This is similar to "low" energy neutrino scattering:
  - If $q^2 << (M_W)^2$, looks like a "contact interaction", and cross-section grows with center of mass energy
  - But when $q^2 \approx (M_W)^2$, W-boson propagation becomes visible, and "cures" this problem



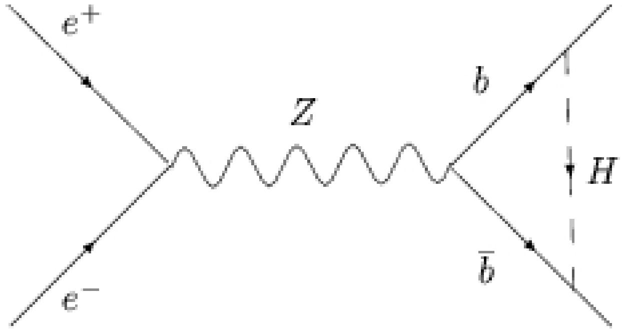
The Higgs Boson

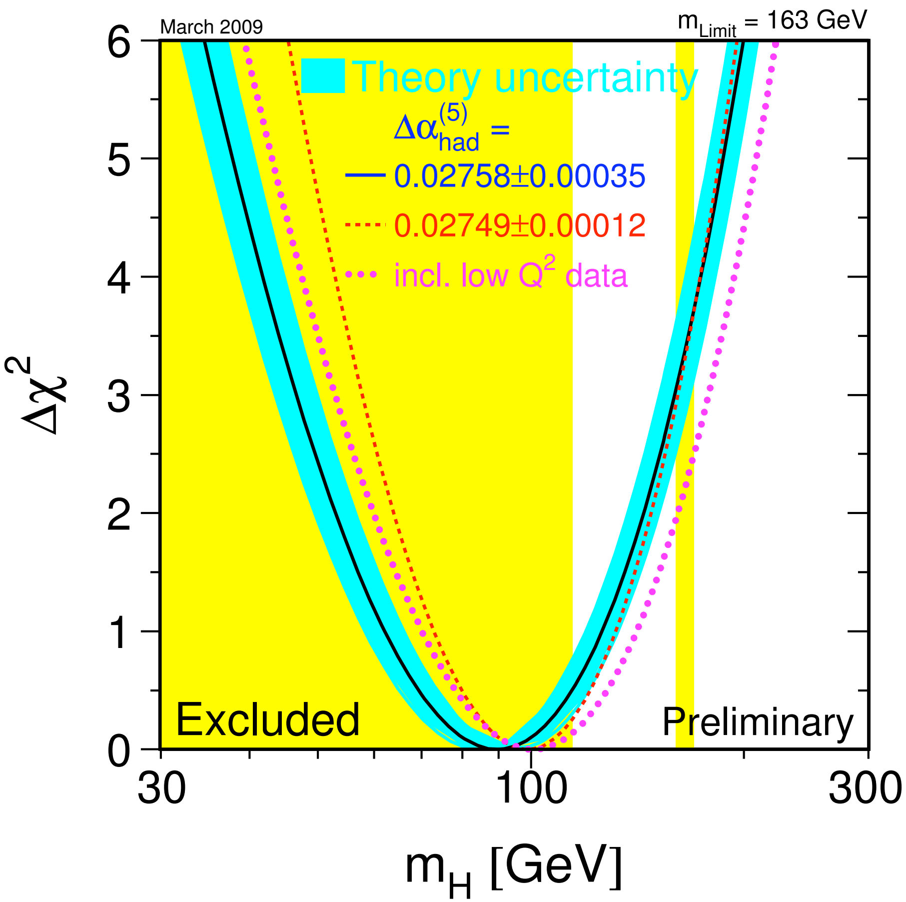
- One way to solve this, is to introduce a massive, spinless particle (of mass < ~1 TeV)
  - Couplings to W and Z are fixed, quantum numbers are known...
  - .... to be those of the vacuum
  - Its mass is unknown, and its couplings to the fermions are unknown.... well, maybe
    - Fermions can acquire mass by coupling to this Higgs boson, so their couplings could be proportional to their masses. This is called the "standard model Higgs"



Precision Measurements

- In fact, we can say something about the standard model Higgs mass
  - If the fermions get their masses from the Higgs, we know all couplings and can infer the Higgs mass from precision measurements
  - Result is very sensitive to measured top quark, W boson masses
    - Really wants a "light" Higgs boson



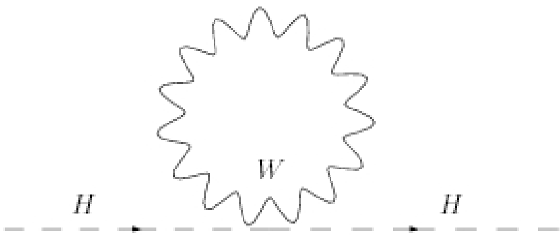


Higgs Drawbacks

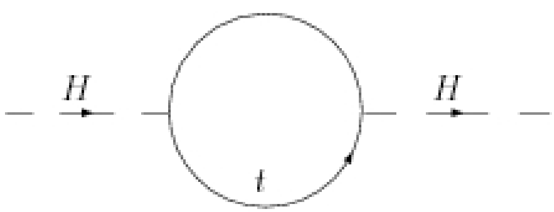
- In principle, with the addition of a Higgs boson around 150 GeV particle physics could be "complete"
  - Like Mendeleev's table for chemistry
- But by itself, the Higgs is very unsatisfactory:
  - Why are the couplings to the fermions what they are?
    - Dumb luck (aka landscape)?
  - What is the link to gravity?
  - Why does the Higgs break the symmetry?
  - Why are there 3....?

The Plot Thickens

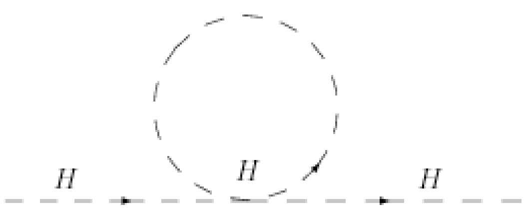
Higgs Mass



$\rightarrow \frac{1}{16\pi^2} g^2 E^2$



$\rightarrow \frac{3}{16\pi^2} y_t^2 E^2$



$\rightarrow \frac{1}{16\pi^2} \lambda E^2$

- Higgs, in fact, also acquires mass from coupling to W's, fermions, and itself!
  - These "mass terms" are quadratically divergent
  - Drive mass to limit of validity of the theory
- So we expect the Higgs mass to be close to the scale where new physics comes in....

Unravelling the Mystery

Hunting for Answers

- Get more information
  - Measure particles and their interactions in detail
    - Precision measurements
  - Observe new particles or interactions
    - Search in new areas in "phase space"
- Find the underlying pattern(s)
  - Hypothesize, build models
    - Consistent? Consistent with data?
    - Suggestions on where to look

Experiment

Theory

Where to Start?

- BSM physics **must** couple to SM (weakly), but is it
  - "SM-like"?
    - Does it have new massive particles decaying to electrons, muons, quarks,...?
  - Quasi "SM-like"?
    - Same but includes some new long-lived particles in the decay chain...
  - No new "particles" in reach
    - Hidden or too heavy or.... don't exist
  - Are there new interactions?

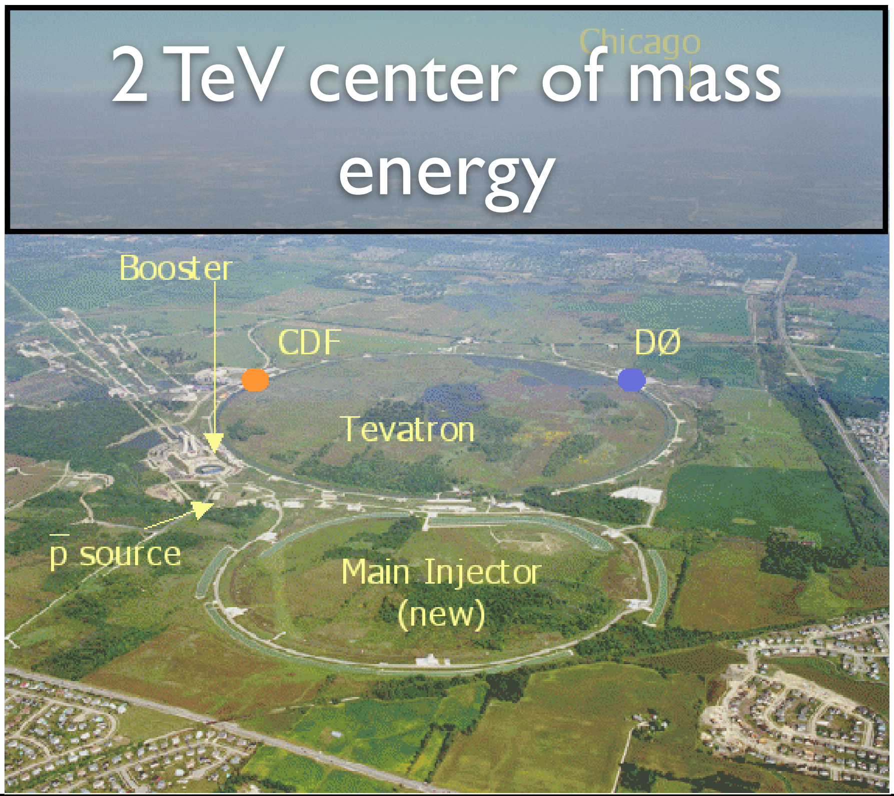
So....

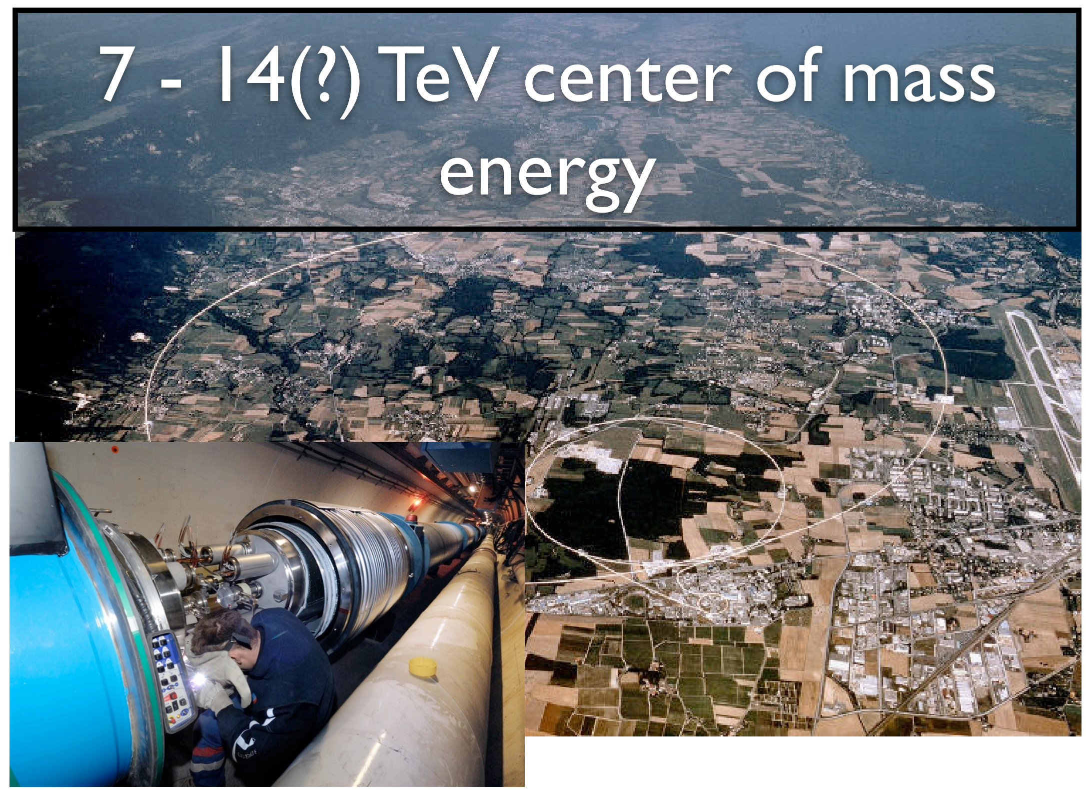
- Go look where the SM breaks down (high energy)...
- ... or for subtle anomalies
- Assume new physics manifestations lead to anomalous production of SM particles
  - Resonant or not (and maybe in loops only)
  - Short-lived or less so
- Rely on guidance from models to some extent
  - What are implications of known constraints? What signatures are "allowed"?
  - Some scenarios do require new approach

The Tools

Colliders

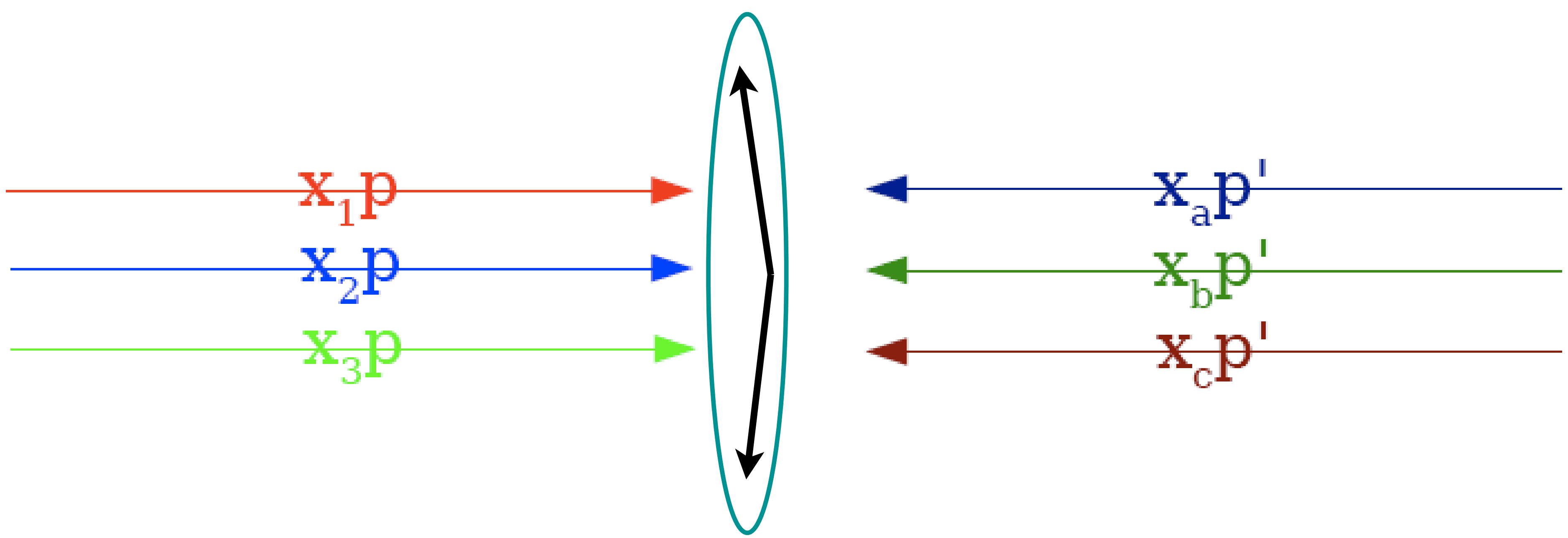
- Currently, most studies done at colliders:
  - Collide beams of electrons and positrons, electrons and protons, protons and (anti)protons
    - High energy implies probing of short distances, and production of other, massive particles





Hadron Colliders

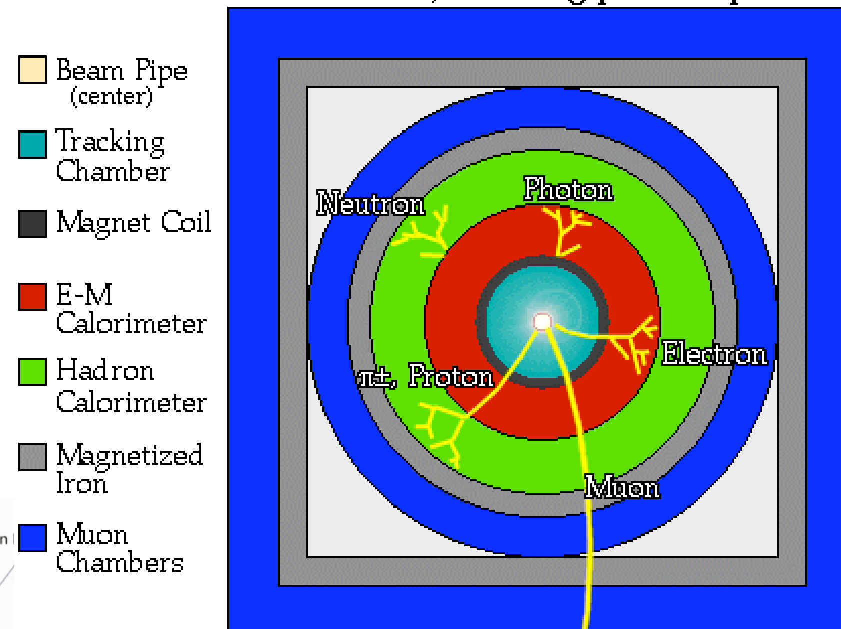
- Incoming longitudinal momentum not known:
  - "Hard interaction" is between one of the quarks and/or gluons from each proton, other quarks/gluons are "spectators"
- Longitudinal boost "flattens" event to a pancake
- We usually work in the plane transverse to the beam

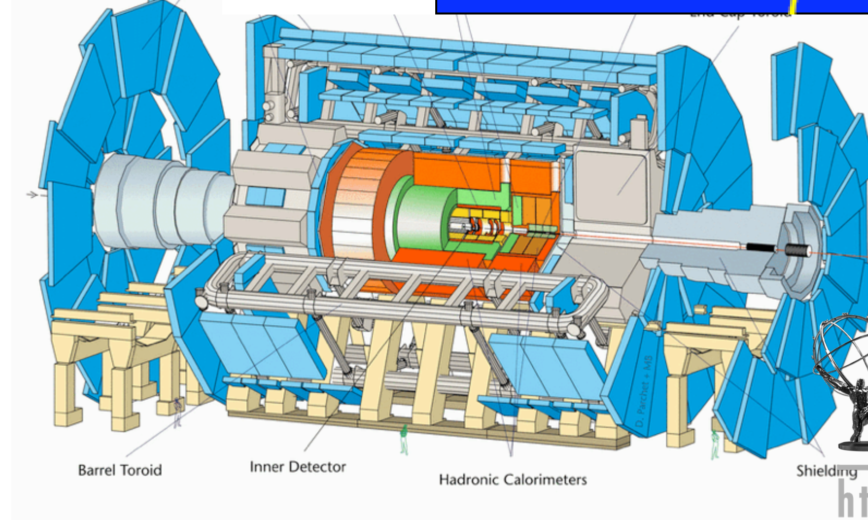


Detectors

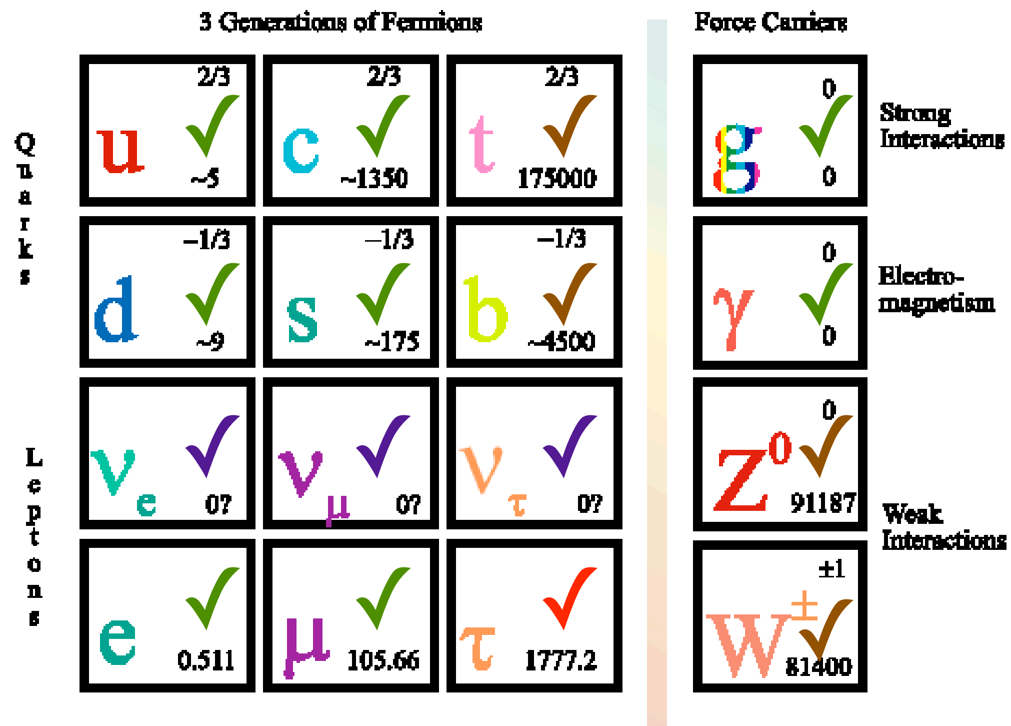
- Make best possible measurement of all particles coming out of collisions

A detector cross-section, showing particle paths





Detecting Particles



Masses are in MeV

✓: Detect with high efficiency

✓: Detect by missing transverse energy

✓: Detect through decays: $t \rightarrow Wb$, $W/Z \rightarrow$ leptons

The Work

Categories

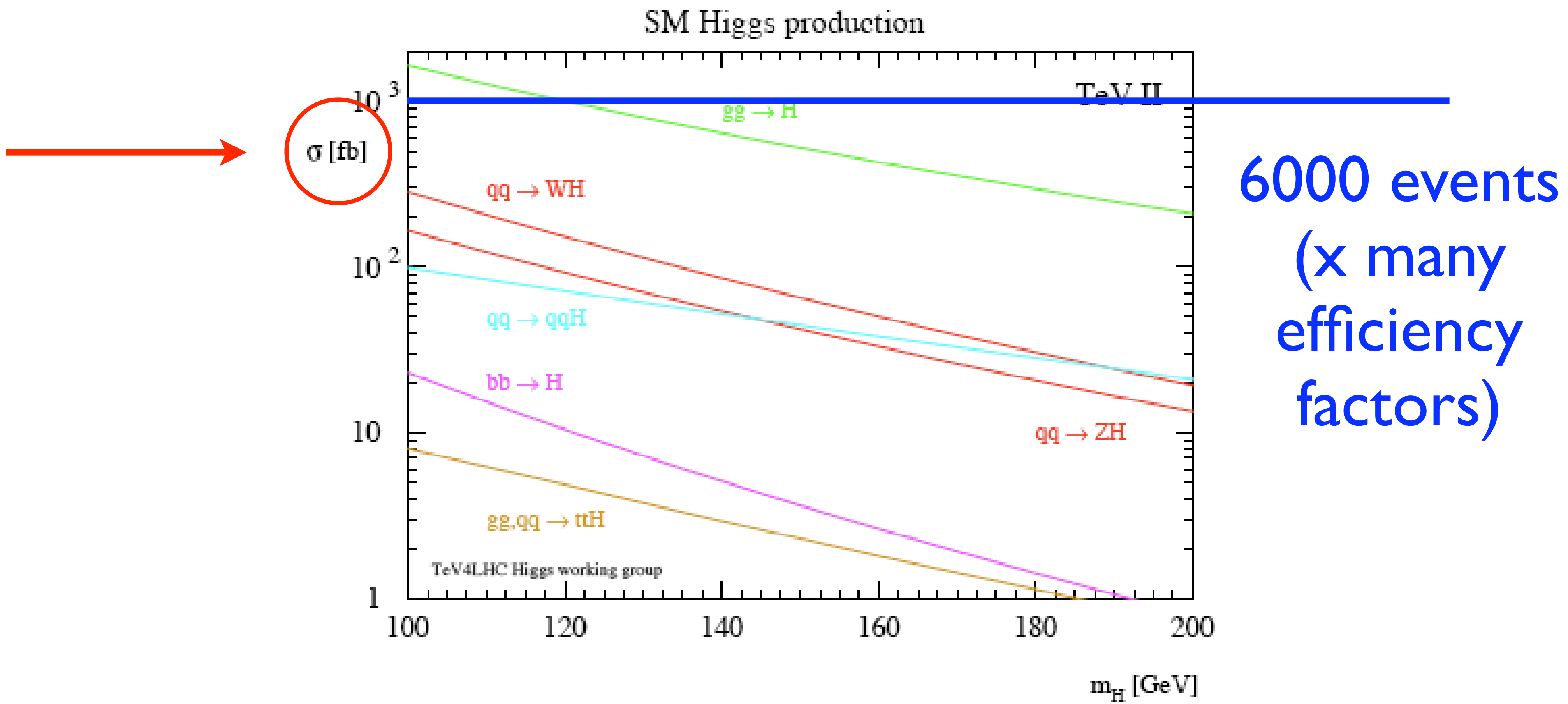
- Is there a SM(-like) Higgs?
  - Can we “explain” particle masses?
- Does particle physics need to provide a CDM candidate?
  - Need to have a massive, ~stable, neutral, colorless particle
- Is LH-ness of weak interaction low-scale only?
- Or is superweak gravity and hierarchy an illusion?
  - Can we link geometry with particle masses and mixings?
- What about just looking for anything anomalous?

The Higgs Hunt

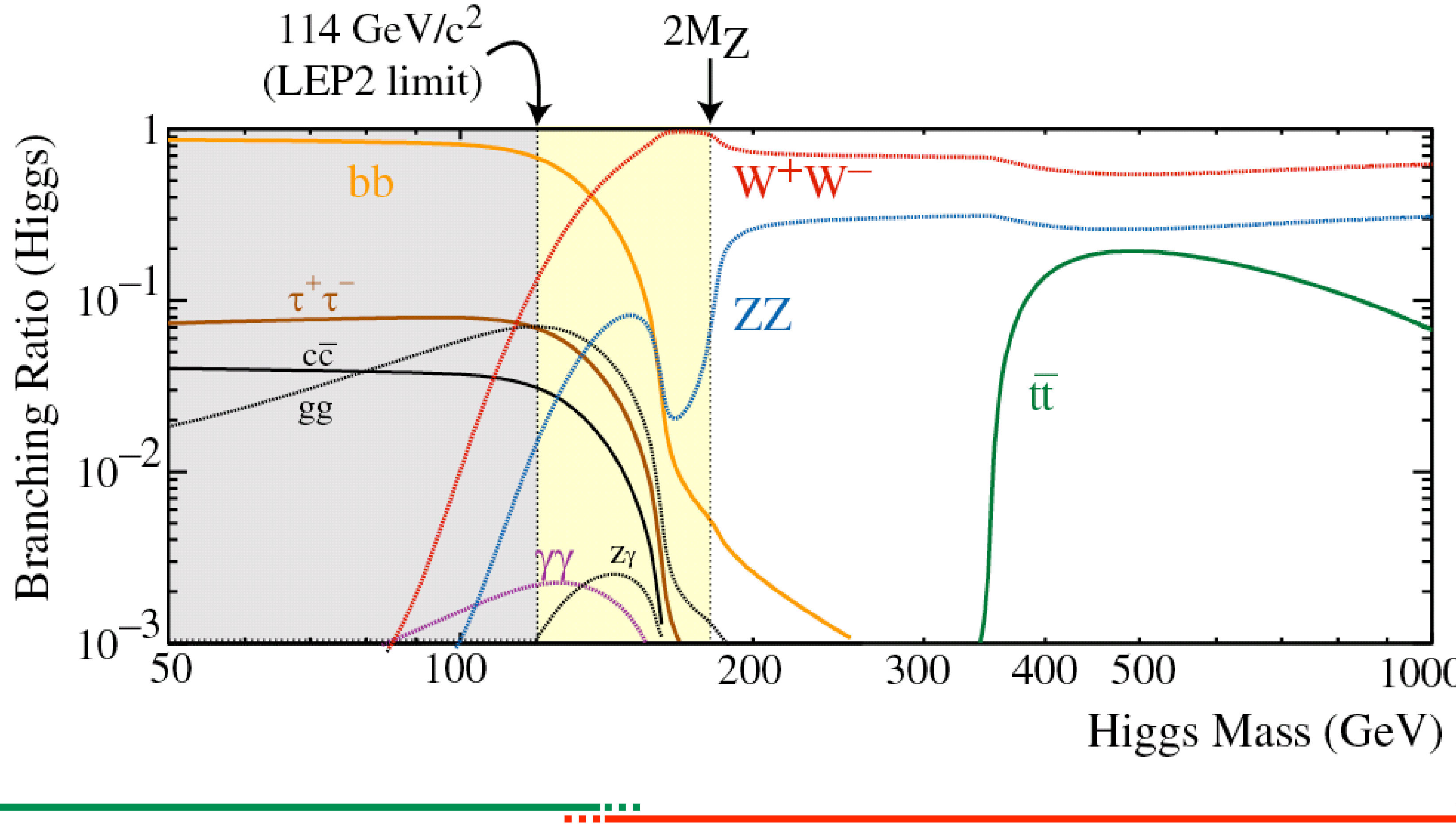
(or: Do We Understand the SM?)

Producing Higgses

- Tevatron experiments currently have ~6 fb^{-1} of data on tape
  - (Data taking efficiency is ~90%)



Higgs Decay



Low Mass

$H \to b\bar{b}$

High Mass

$H \to WW$

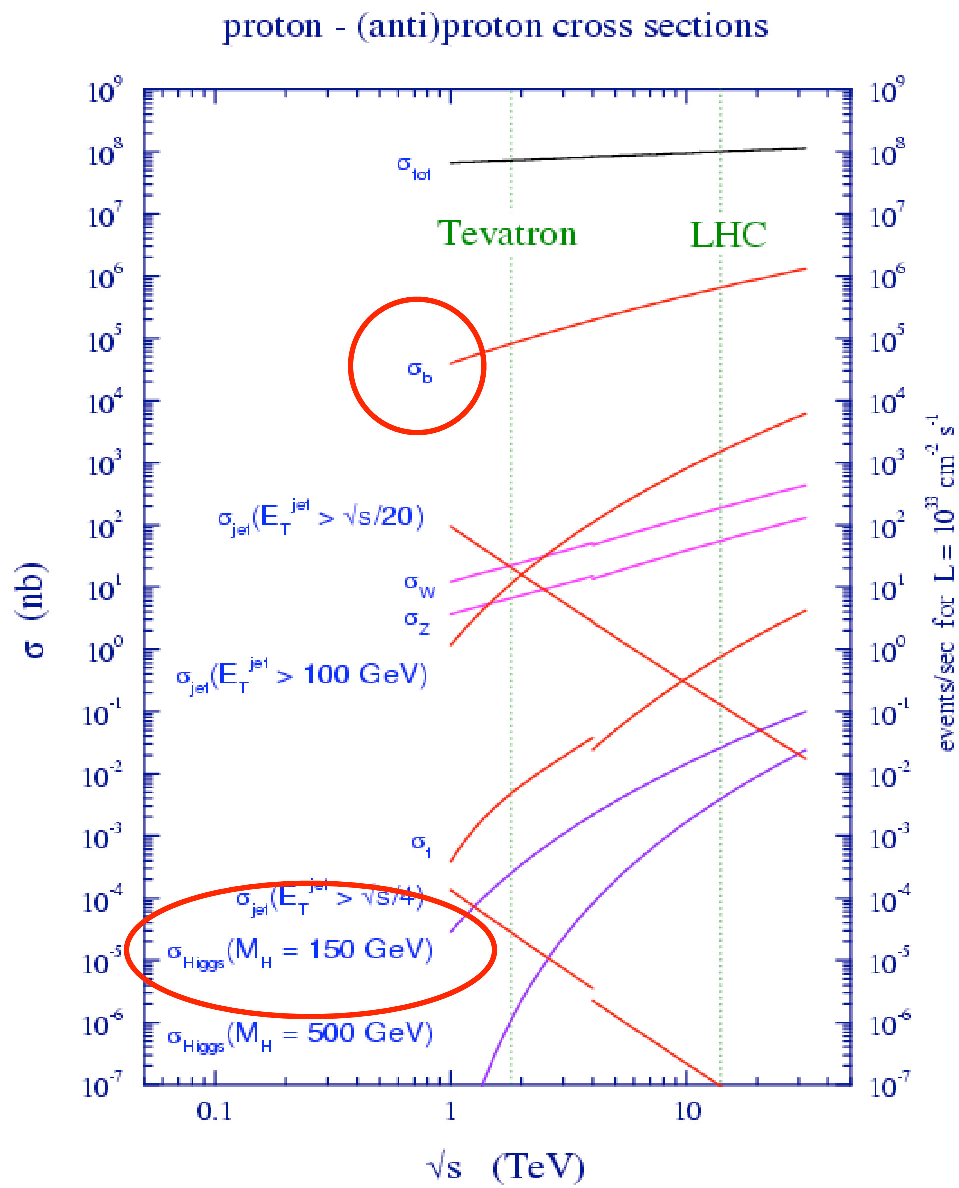
Search Channels

- Hadron colliders
  - $b\bar{b}$ production ~9 orders of magnitude larger than H
  - $gg \rightarrow H \rightarrow b\bar{b}$ swamped

➡ At low mass look for $pp \rightarrow WH$ or $ZH \rightarrow W/Z\, b\bar{b}$

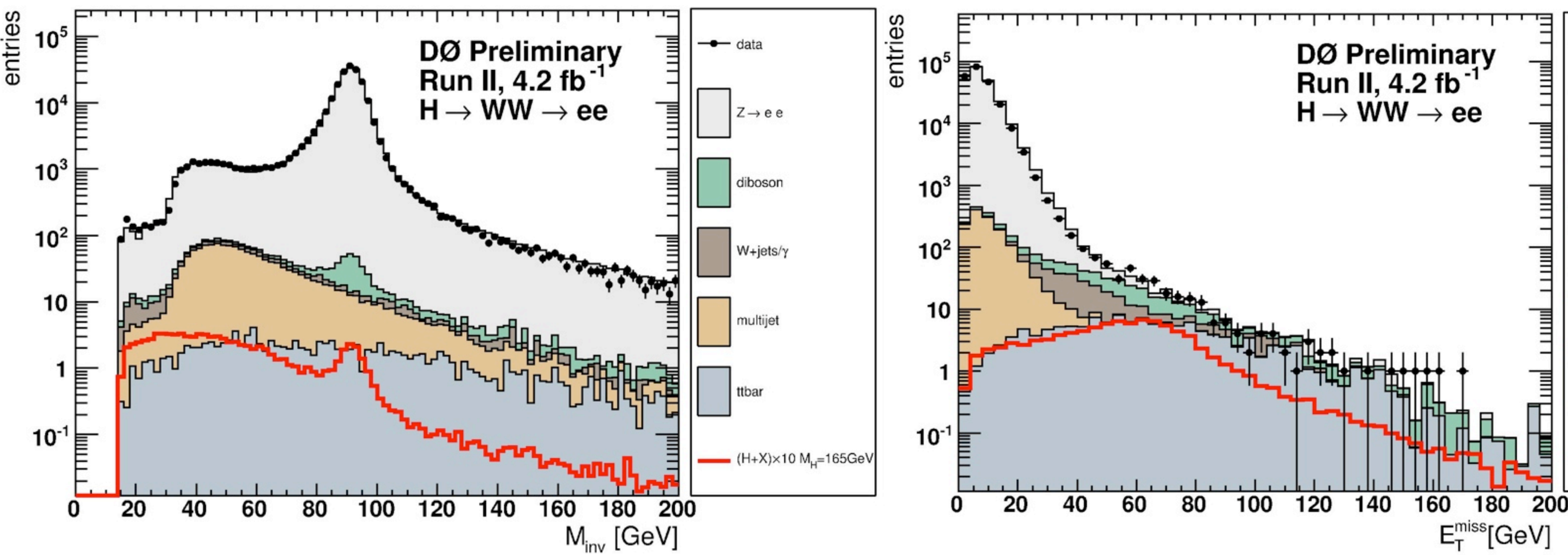
  - With leptonic W, Z decay, so # of events /~50!

- At high mass, $gg \rightarrow H \rightarrow WW$ accessible if at least one W decays leptonically



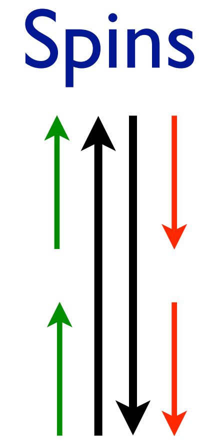
Dilepton + MET

- "Golden" channel:
  - Main background $Z \rightarrow \ell\ell$ also a great reference signal
  - "Easy" to suppress using MET, angle between leptons, ...

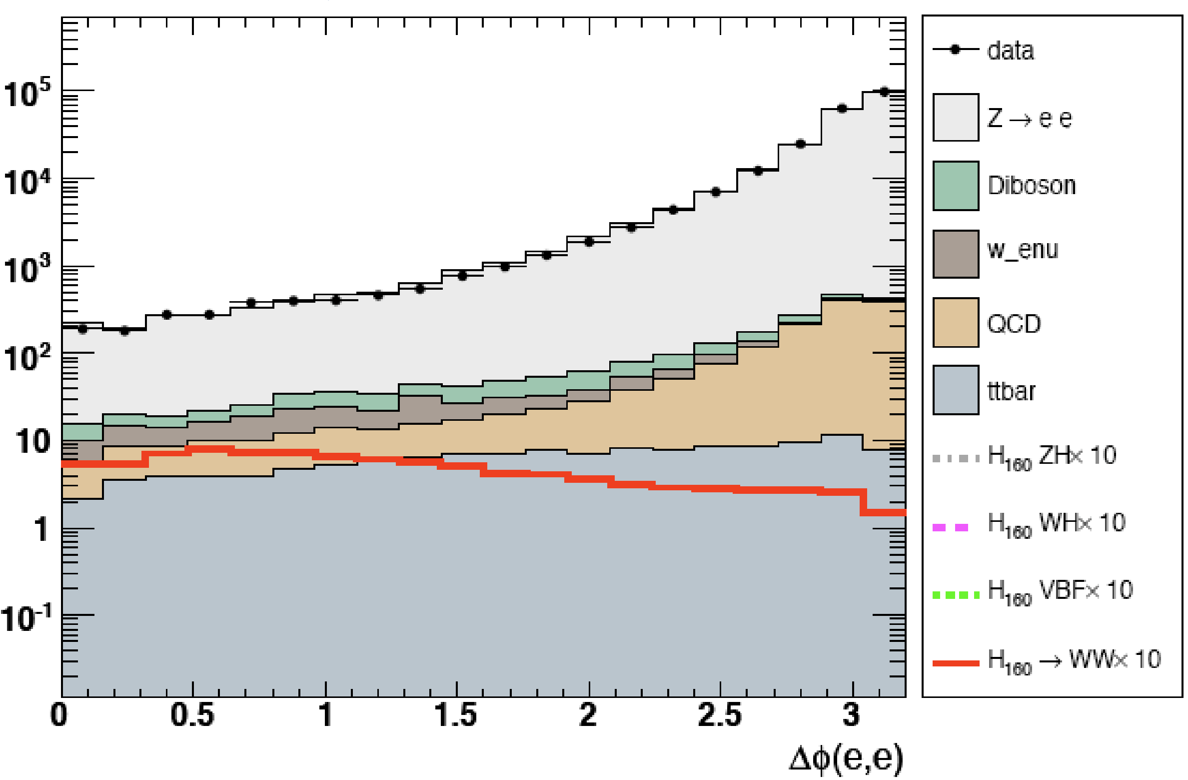


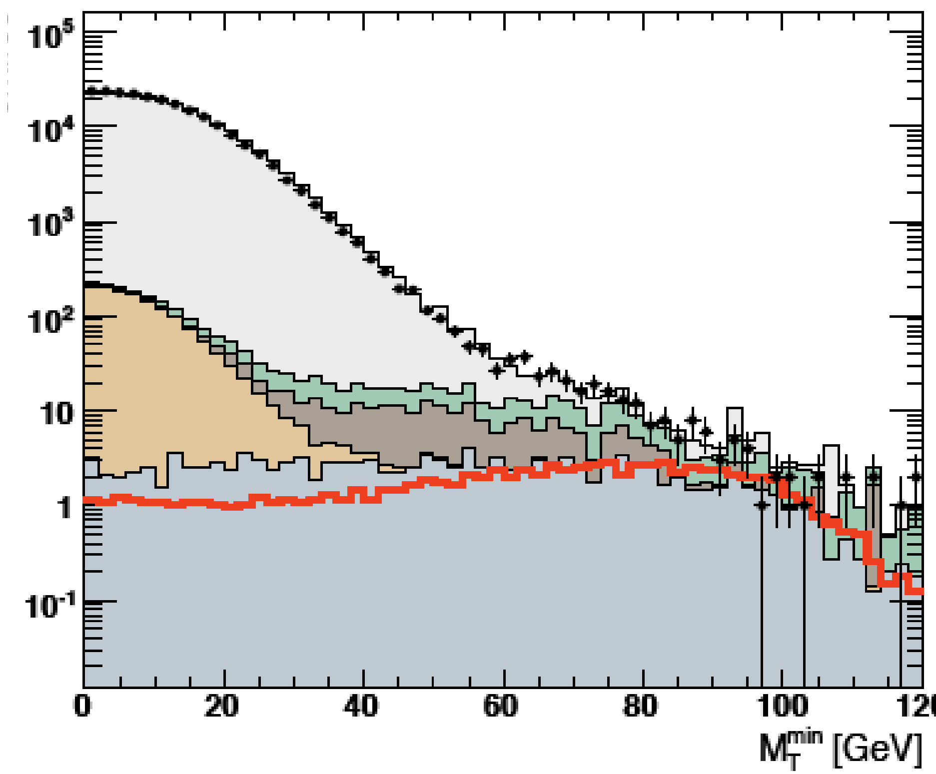
Angles

- In $Z \to \ell\ell$ (and dijets faking leptons), leptons preferentially emitted back-to-back
  - In Higgs decays, W^+W^- spins back-to back, so charged leptons in similar direction! (One LH, other RH)



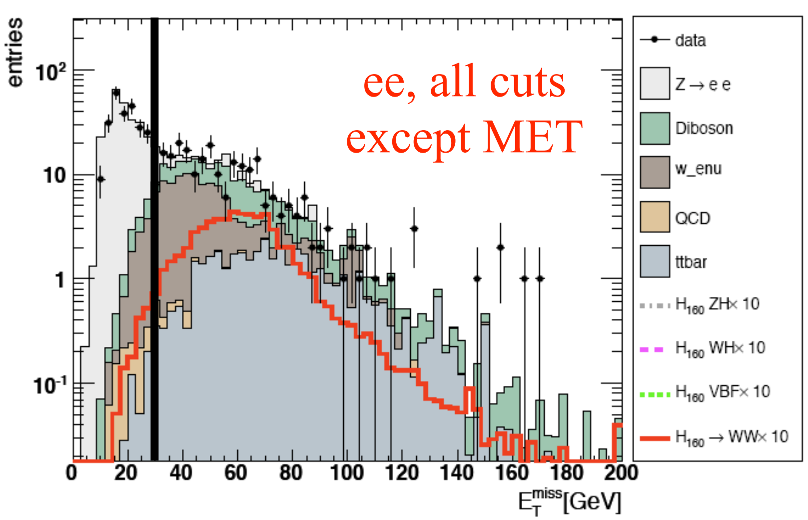
  - In Z, smallest transverse mass tends to be small

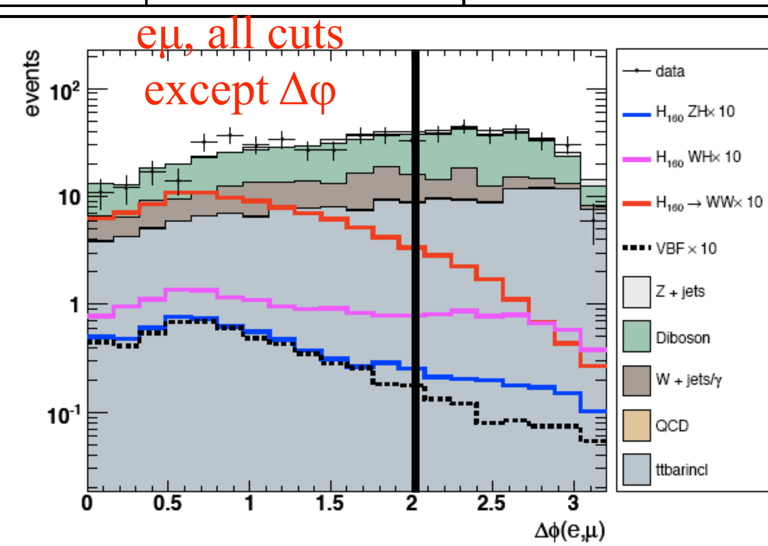




Preselection

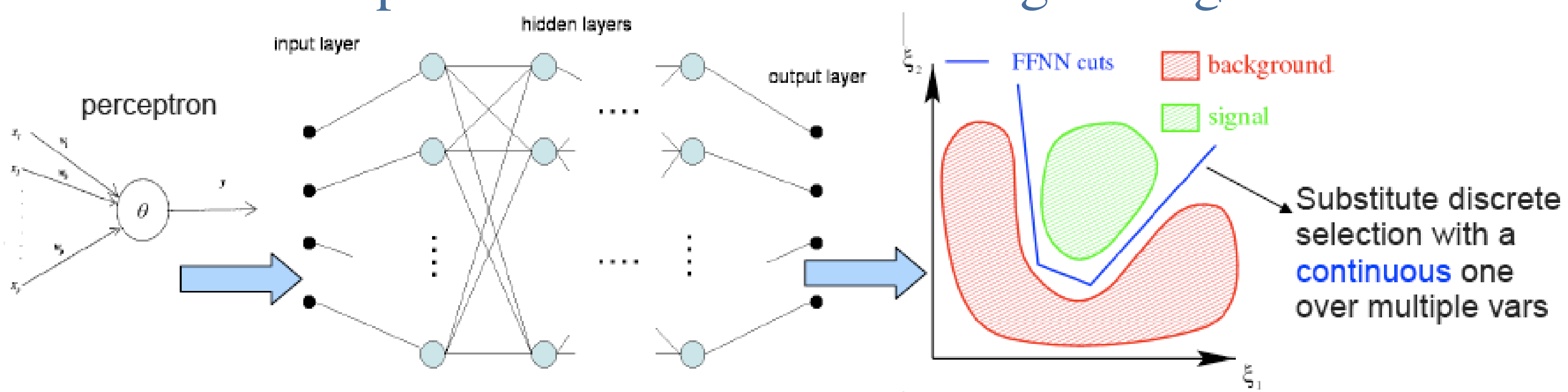
Final state		$e\mu$	ee	$\mu\mu$
Cut 0	Pre-selection	lepton ID, leptons with opposite charge and $p_T^\mu > 10$ GeV and $p_T^e > 15$ GeV invariant mass $M_{\ell\ell} > 15$ GeV $\mu\mu$: $n_{\text{jet}} < 2$ for $p_T^{\text{jet}} > 15$ GeV, $\Delta\mathcal{R}(\mu, \text{jet}) > 0.1$ and $p_T^\mu > 15$ GeV for the leading μ		
Cut 1	Missing Transverse Energy $\not{E}_T$ (GeV)	> 20	> 20	
Cut 2	$\not{E}_T^{\text{Scaled}}$	> 6	> 6	
Cut 3	$M_T^{min}(\ell, \not{E}_T)$ (GeV)	> 20	> 30	
Cut 4	$p_T^{\mu\mu}$ (GeV) for $n_{\text{jet}} = 0$			> 20
	$\not{E}_T$ (GeV) for $n_{\text{jet}} = 1$			> 20
Cut 5	$\Delta\phi(\ell, \ell)$	< 2.0	< 2.0	< 2.5





Multivariate Tools

- After preselection, S/B not good (~1/30, 1/50, 1/1000 in eμ, ee and μμ final states)
- Use multivariate tools to exploit correlations between observables for S ↔ B discrimination
- In the dilepton + MET ($H \to WW \to \ell\nu\ell\nu$), use neural nets
  - MC samples divided in 2 for training/testing

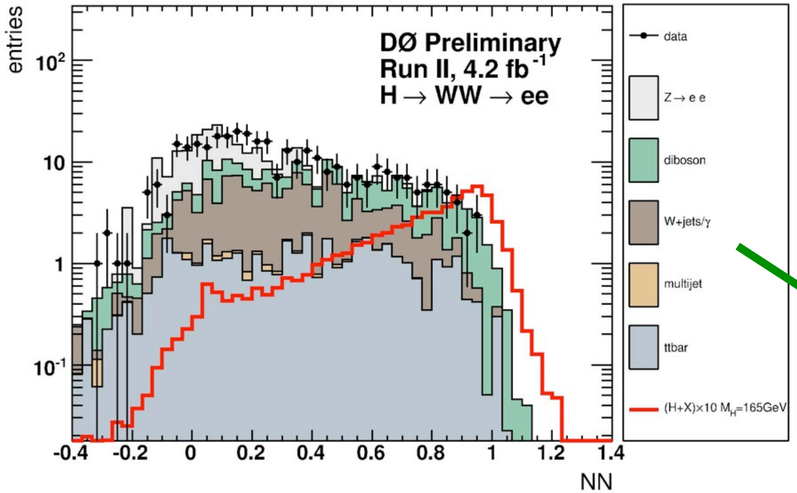


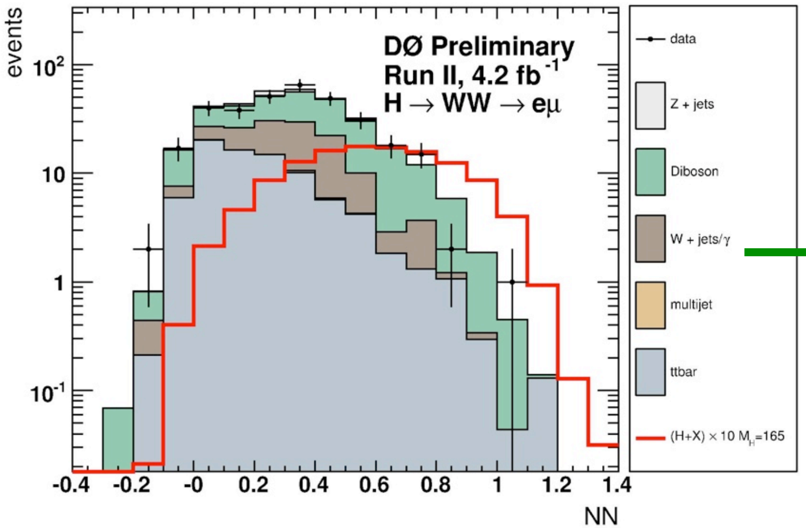
Variables

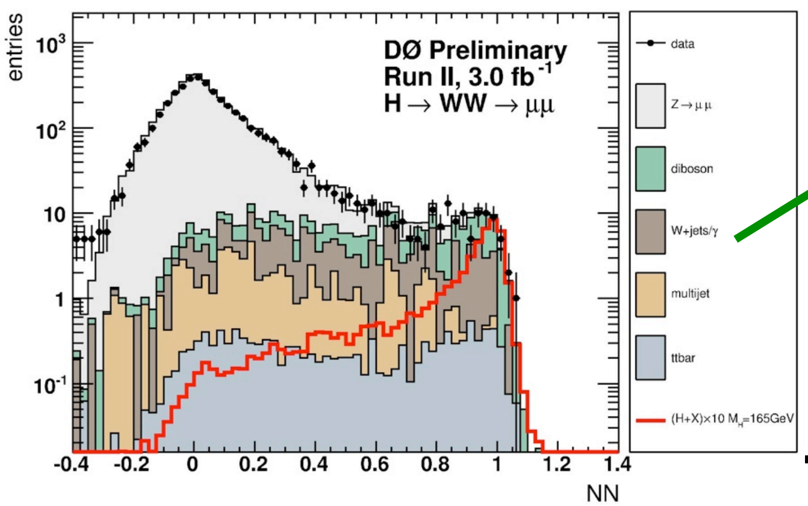
Only accept variables that are well-modeled!

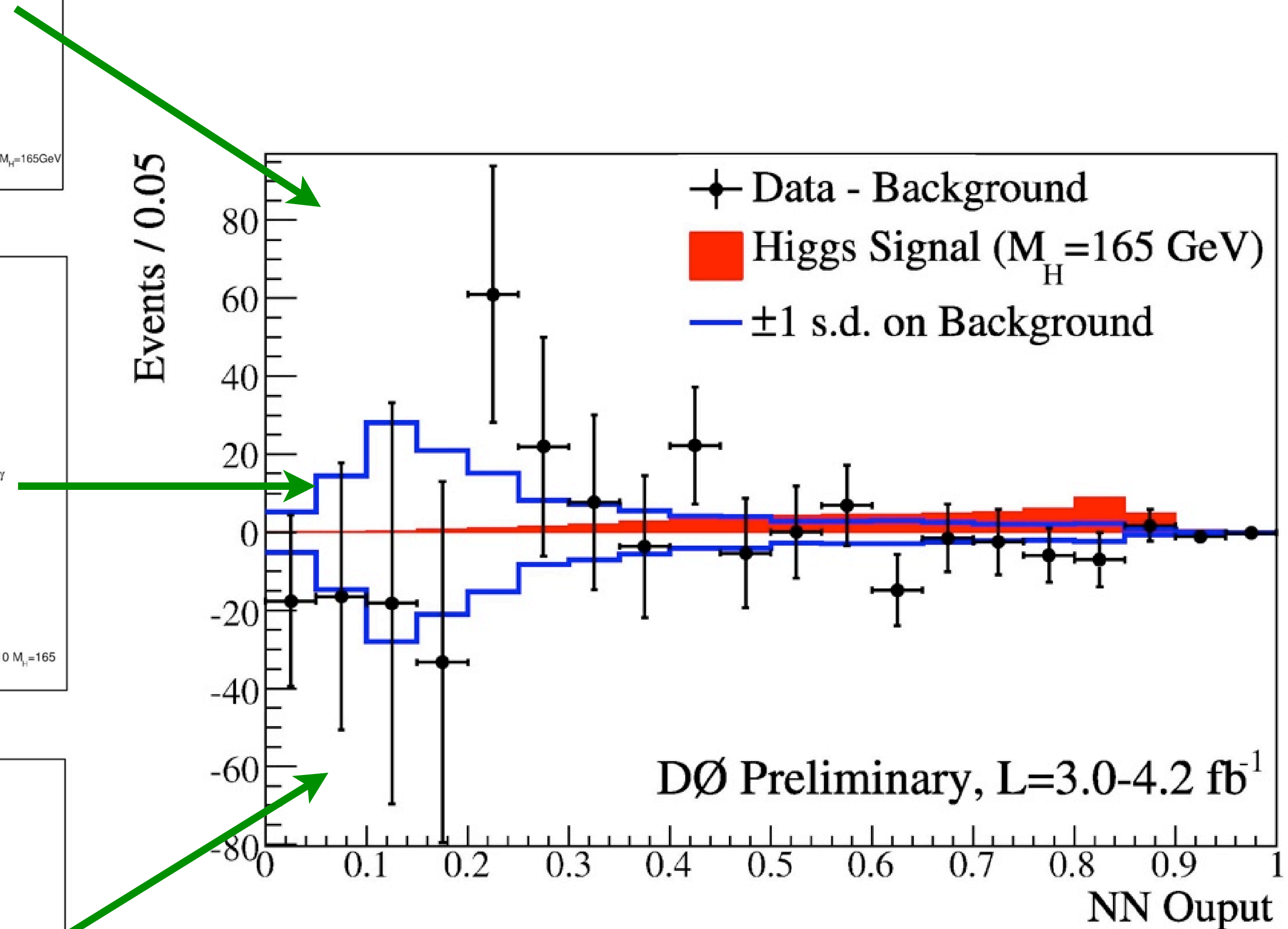
NN Analysis Variables	
p_T of leading lepton	$p_T(\ell_1)$
p_T of trailing lepton	$p_T(\ell_2)$
Minimum of both lepton qualities	$\min(q_{\ell 1}, q_{\ell 2})$
Vector sum of the transverse momenta of the leptons:	$p_T(\ell_1) + p_T(\ell_2)$
Scalar sum of the transverse momenta of the jets:	$H_T = \sum_i \lvert p_T(\mathrm{jet}_i) \rvert$
Invariant mass of both leptons	$M_{\mathrm{inv}}(\ell_1, \ell_2)$
Minimal transverse mass of one lepton and $\not\!\!E_T$	M_T^{min}
Missing transverse energy	$\not\!\!E_T$
Scalar transverse energy	E_T^{scalar}
Azimuthal angle between selected leptons	$\Delta\phi(\ell_1, \ell_2)$
Solid angle between selected leptons ($e\mu$ only)	$\Delta\Theta(\ell_1, \ell_2)$
ΔR between selected leptons ($e\mu$ only)	$\Delta R(\ell_1, \ell_2)$
Azimuthal angle between leading lepton and $\not\!\!E_T$	$\Delta\phi(\not\!\!E_T, \ell_1)$
Azimuthal angle between trailing lepton and $\not\!\!E_T$	$\Delta\phi(\not\!\!E_T, \ell_2)$

NN Outputs


DØ Preliminary
Run II, 4.2 fb-1
H → WW → ee
data
Z → e e
diboson
W+jets/γ
multijet
ttbar
(H+X)×10 MH=165GeV
entries
NN


DØ Preliminary
Run II, 4.2 fb-1
H → WW → eμ
data
Z + jets
Diboson
W + jets/γ
multijet
ttbar
(H+X) × 10 MH=165
events
NN


DØ Preliminary
Run II, 3.0 fb-1
H → WW → μμ
data
Z → μ μ
diboson
W+jets/γ
multijet
ttbar
(H+X)×10 MH=165GeV
entries
NN

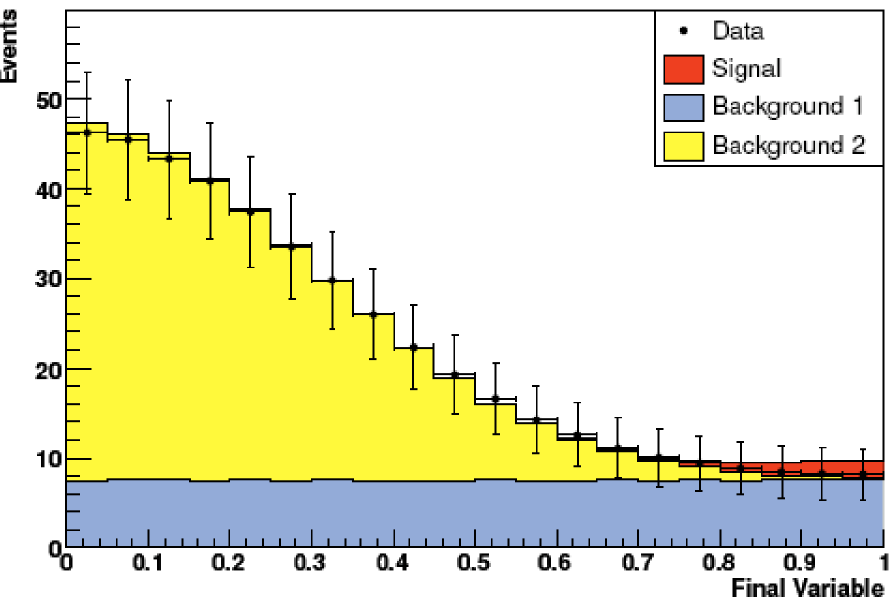

Data - Background
Higgs Signal (MH=165 GeV)
±1 s.d. on Background
DØ Preliminary, L=3.0-4.2 fb-1
Events / 0.05
NN Ouput

Systematics Profiling

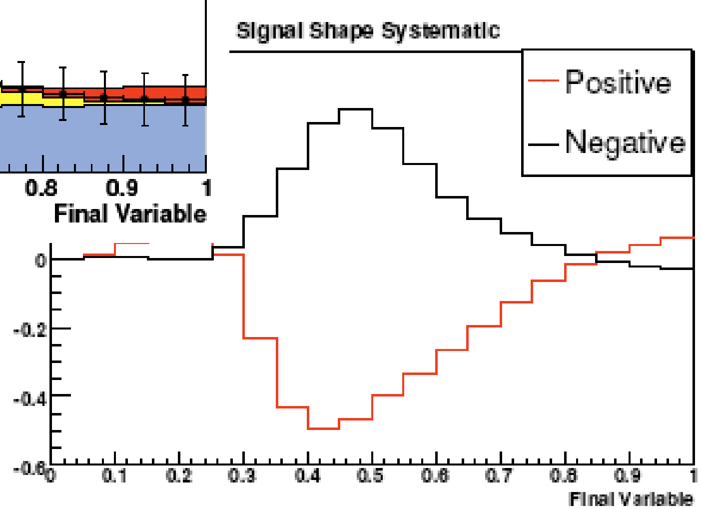
- Systematic uncertainties are propagated through the full analysis chain to the NN output distribution
  - E.g. we repeat the analysis with jet energy scale shifted up & down by 1σ
  - Some systematic uncertainties affect shape (jet reconstruction efficiency, energy scale and resolution, boson p^T distributions), others only normalization (lepton reconstruction efficiencies and momentum calibration, modeling of multijet background, theoretical cross-sections and luminosity)
  - Systematic uncertainties are treated as nuisance parameters

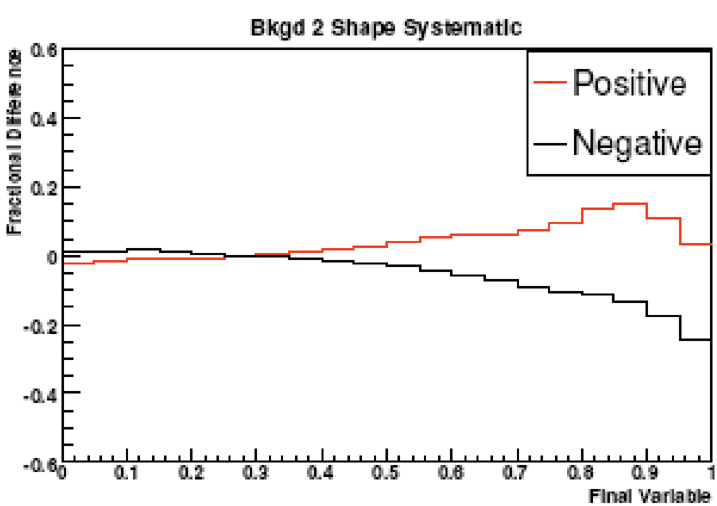
Systematics Profiling

- Nuisance parameters tend to be correlated, but not 100%, among backgrounds
  - Can affect rates, shapes, or both (in any distribution), and often asymmetric and non-gaussian



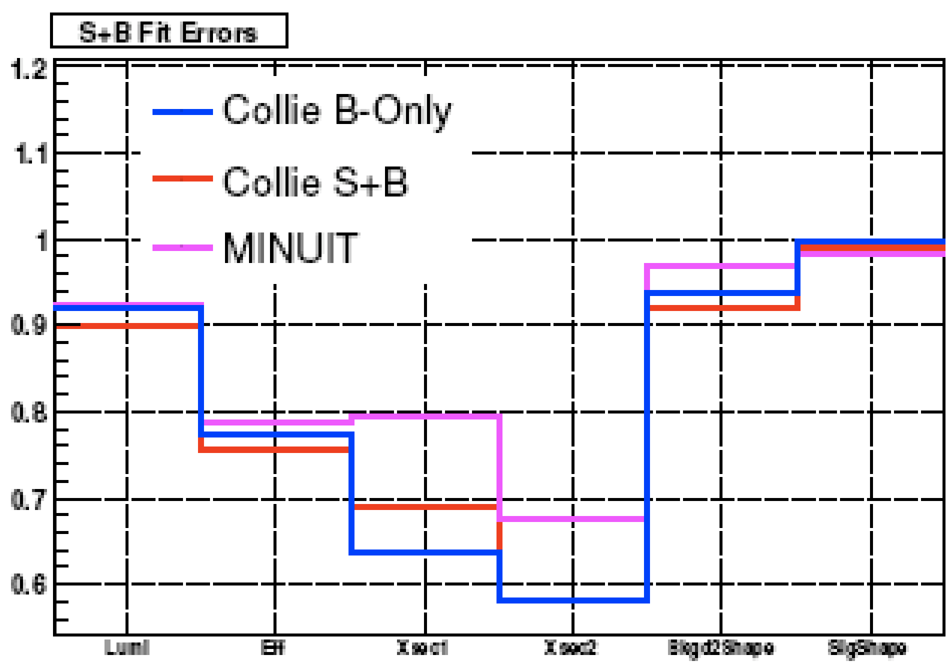
Toy Example

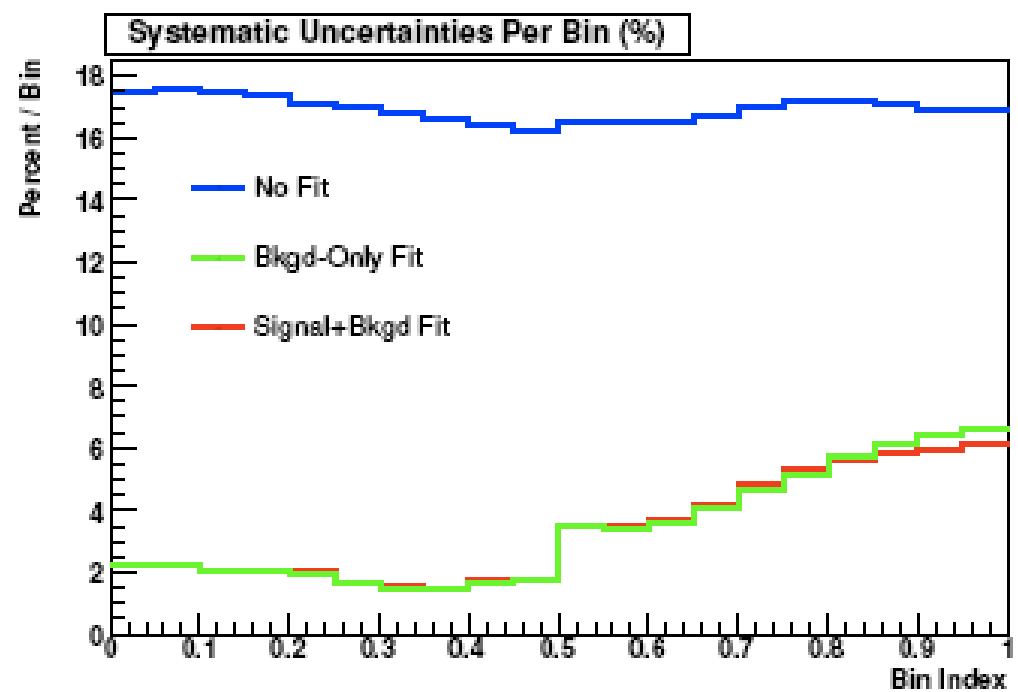




- Can generate pseudo-experiments (events in bins according to poisson), then for each experiment vary nuisance parameters
    - Variations in background (& S+B) prediction
        - Compare results to data using log-likelihood ratio
- So we can maximize likelihood ratio as a function of nuisance parameters → constraint them
    - I.e. use full shape of distribution(s) to see which background uncertainties are over/underestimated
        - Of course limited to size of statistical fluctuations
    - Can remove bins with large S/B if needed
        - Mostly important if uncertainties lead to similar shape distortions

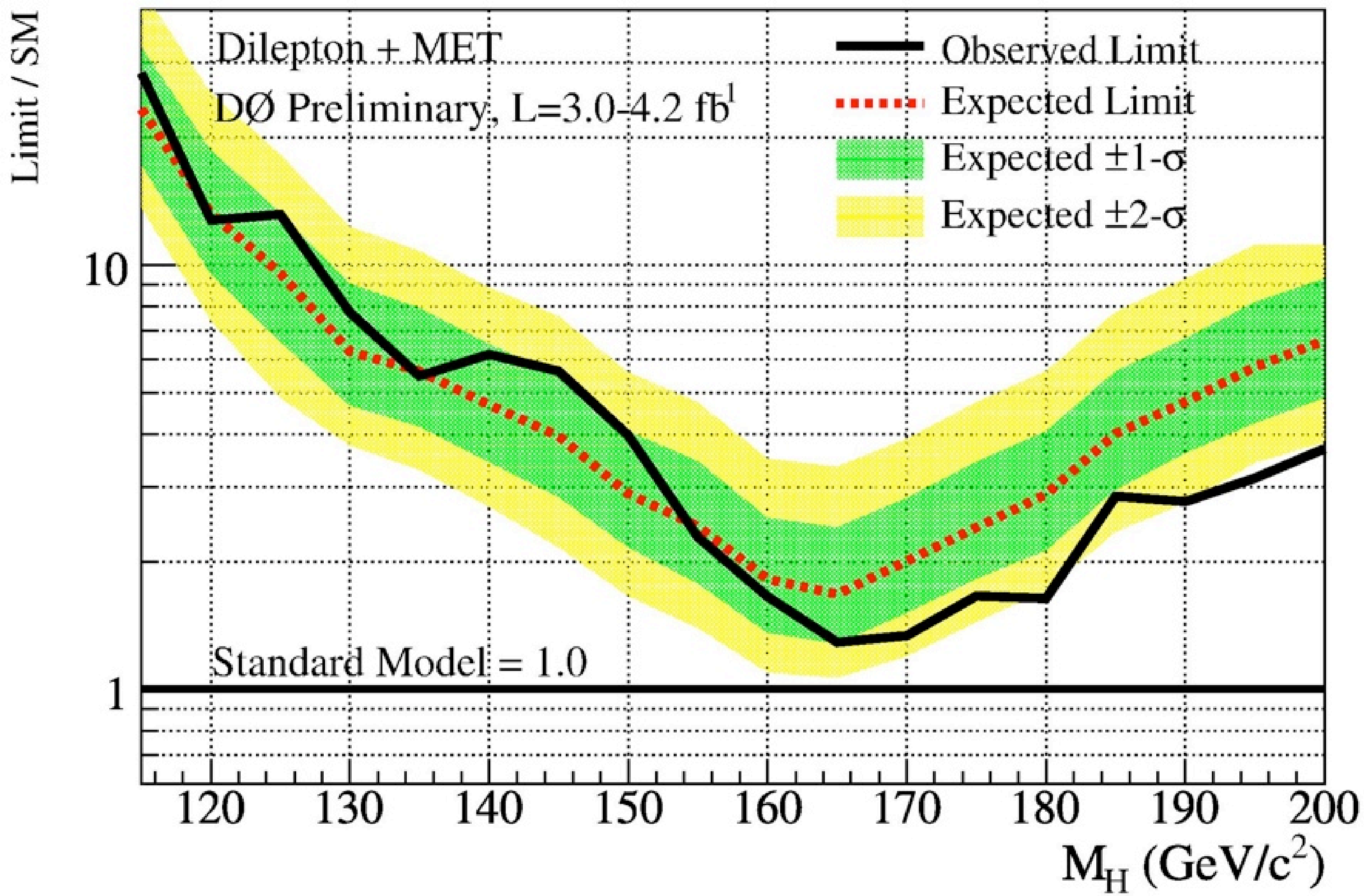
- Test example:
  - Data constructed to disagree with background-only hypothesis (wrong estimates for background uncertainties)
  - But to agree with background-only better than signal+ background
    - Improvement quite spectacular (but by construction)





Dilepton + MET Result

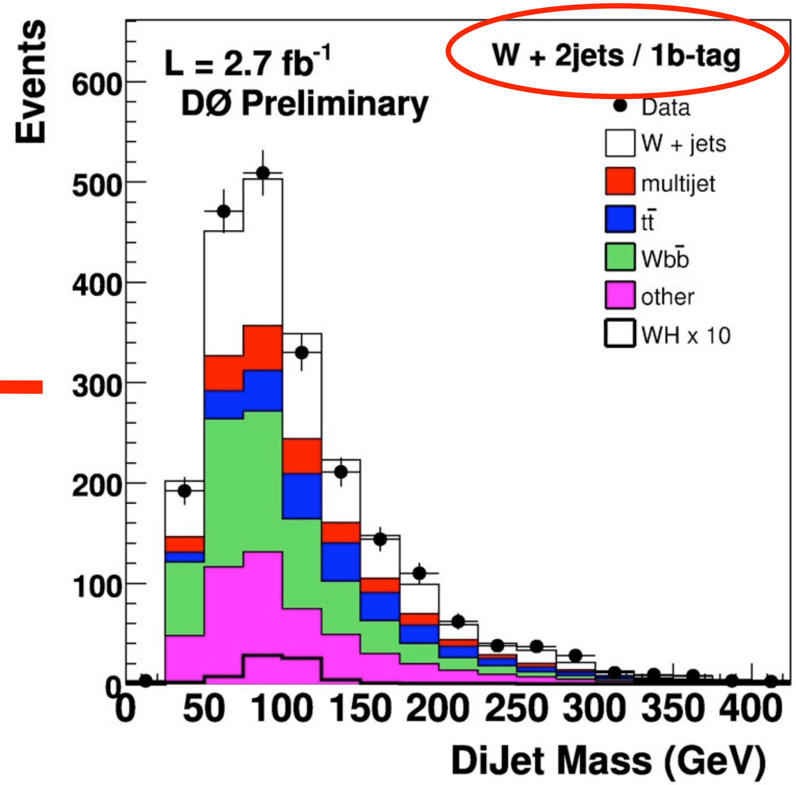
- Present result as a 95% C.L. limit in units of the SM Higgs production x-section



Wjj and the Higgs

- The final state consisting of W + 2 jets is critical
  - At low mass (WH, H→bb), they're b-jets with $m_{bb} = m_H$
  - At high mass (H→WW), $m_{jj} = m_W$, $m_{WW} = m_H$
- But dijet mass resolution is so-so:

And lots more background!



Sample Composition

- After preselection, low S/B allows to verify shapes of dominant backgrounds
  - For WH, first before *b*-tagging, then with 1 tag
- Determining the sample's composition
  - I.e. which processes contribute, and how

Increasing difficulty ↓

- Diboson from MC simulation (usually small, + "trust" MC)
- Top from simulation (relatively small @ Tevatron)
- Z+jets from data & MC ("easy" to get a clean sample, correct MC)
- QCD multijet from data (no choice)
- W + jets from MC, but ....

Generators Used

- We use four kinds of Monte Carlo generators
  - "Calculators" (often NNLO) do not actually generate events, they just calculate some (limited) distributions, like W p^T
  - Traditional $2 \rightarrow 2$ generators: LO, e.g. $q\bar{q} \rightarrow WZ$
    - Include parton shower, i.e. QCD radiation, and hadronization to jets
  - "Matrix Element" $2 \rightarrow n$ ($n < 9$): LO, e.g. $q\bar{q} \rightarrow e\nu jjjj$
    - Necessary to generate events with multiple hard jets
    - Require matching to parton shower to avoid double counting
  - NLOwPS $2 \rightarrow 2$ generators: include NLO corrections
    - I.e. in a sense they are $2 \rightarrow 2$ & 3 with virtual corrections

Correction Factors

- Of course, the ME's are LO, so "K-factors" needed
  - Different ones for heavy flavor etc..... convention to avoid confusion....
    - K-factor is purely theoretical, and denotes a (N)NLO/LO ratio of cross sections;
    - K'-factor is also theoretical, and denotes a (N)NLO/LL ratio of cross sections. According to Steve, ALPGEN cross sections are Leading Log;
    - S-factor is empirical, and comes on top of K or K' to bring MC in agreement with data. MC should be initially normalized to luminosity, and all correction (a.k.a. scale) factors should be applied (trigger, ID...);
    - HF-factor is, in principle, theoretical, but in practice only theory inspired. It tells you by how much heavy flavor production should be increased, on top of K or K', and possibly S;
    - S_HF-factor is empirical, and comes on top of K or K', S, and HF, to bring MC in agreement with data, after b-tagging.

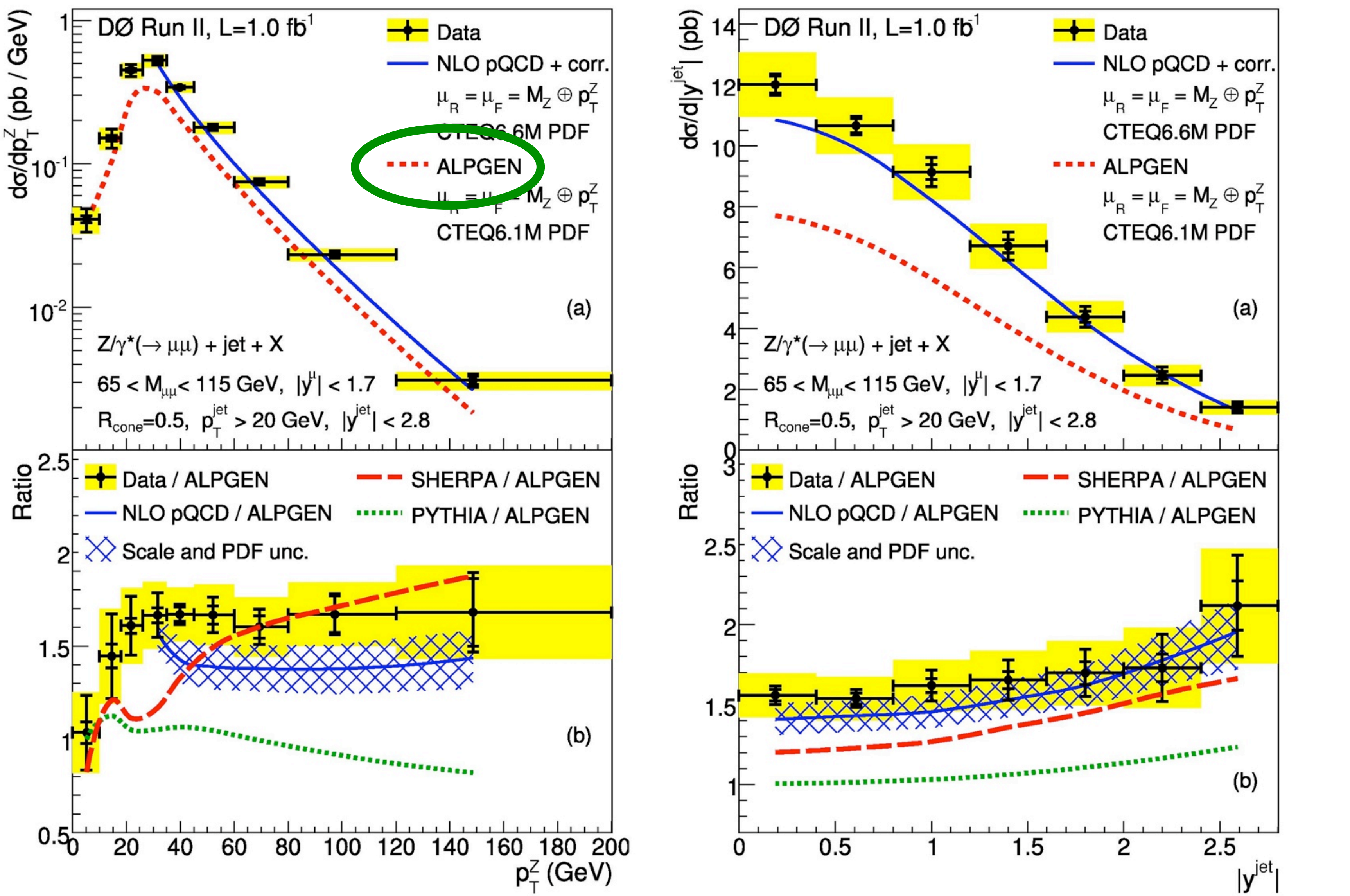
In addition to W/Z p_T reweighting

Z (→ℓℓ) + jets

- Can get a clean sample, check if our simulation reproduces the data

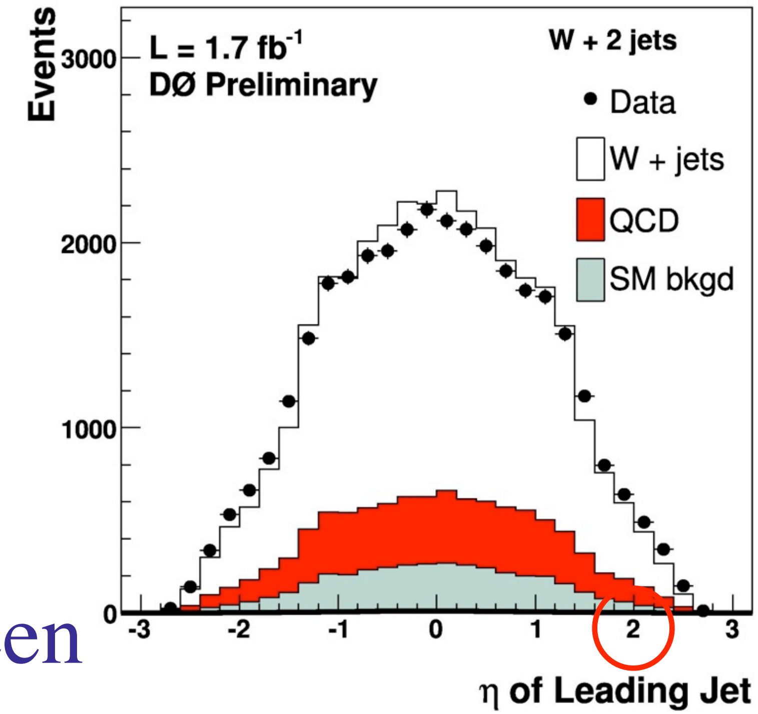
⇒ yes, with expected deviations

Need reweighing of MC

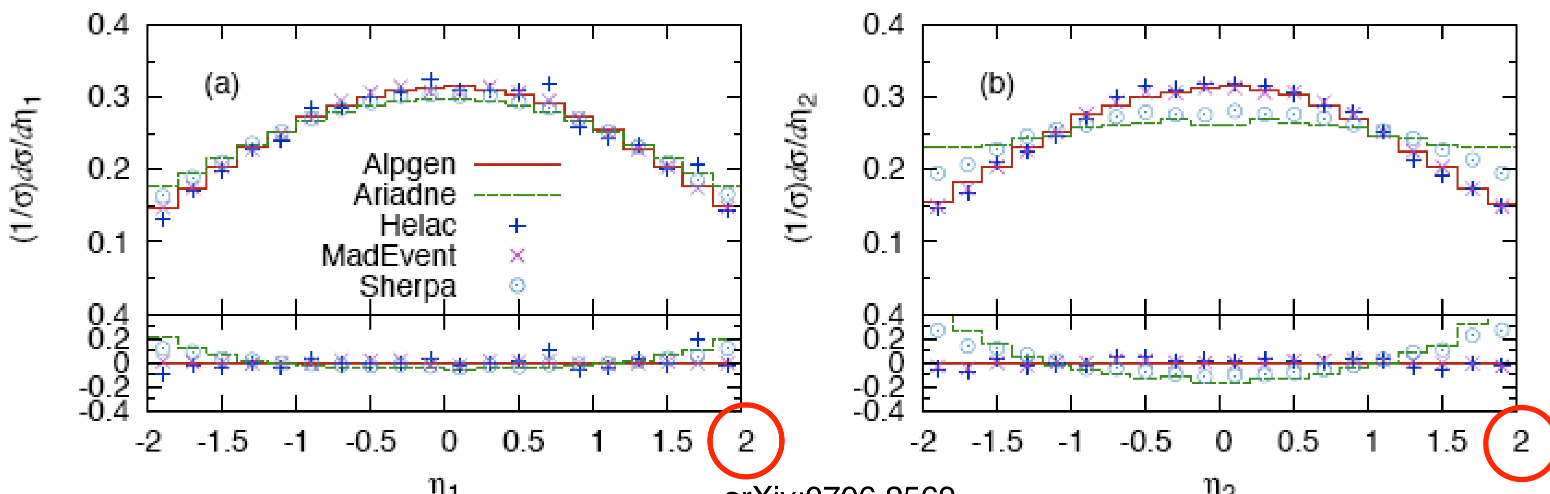


So...

- After all K/K'/S/HF-factors and boson p^T reweighing:



- Similar angular differences between generators: reweigh alpgen to sherpa

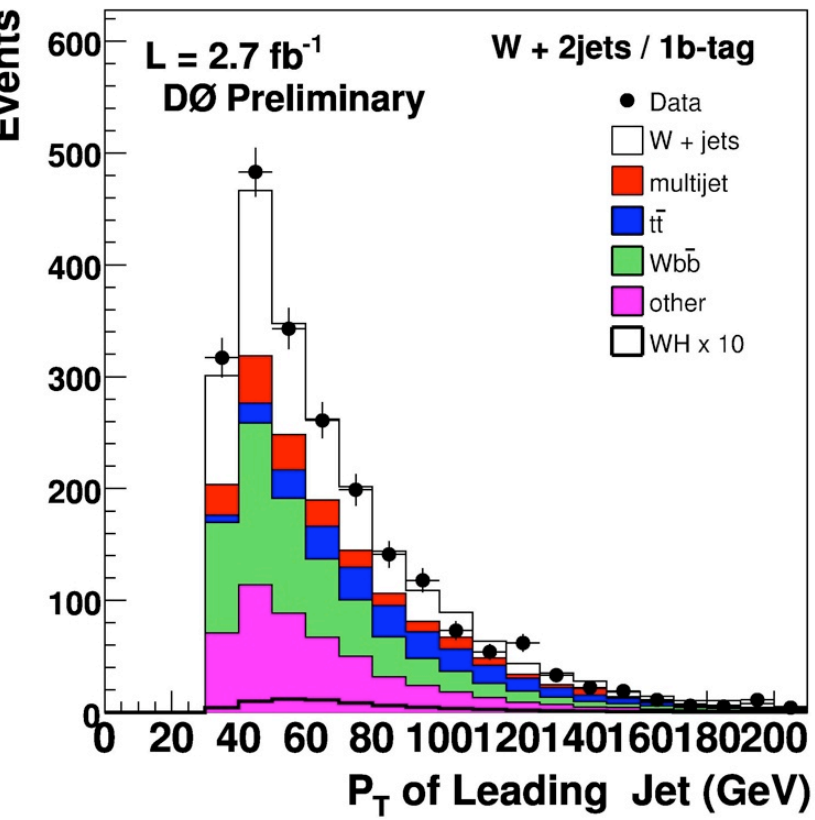


arXiv:0706.2569

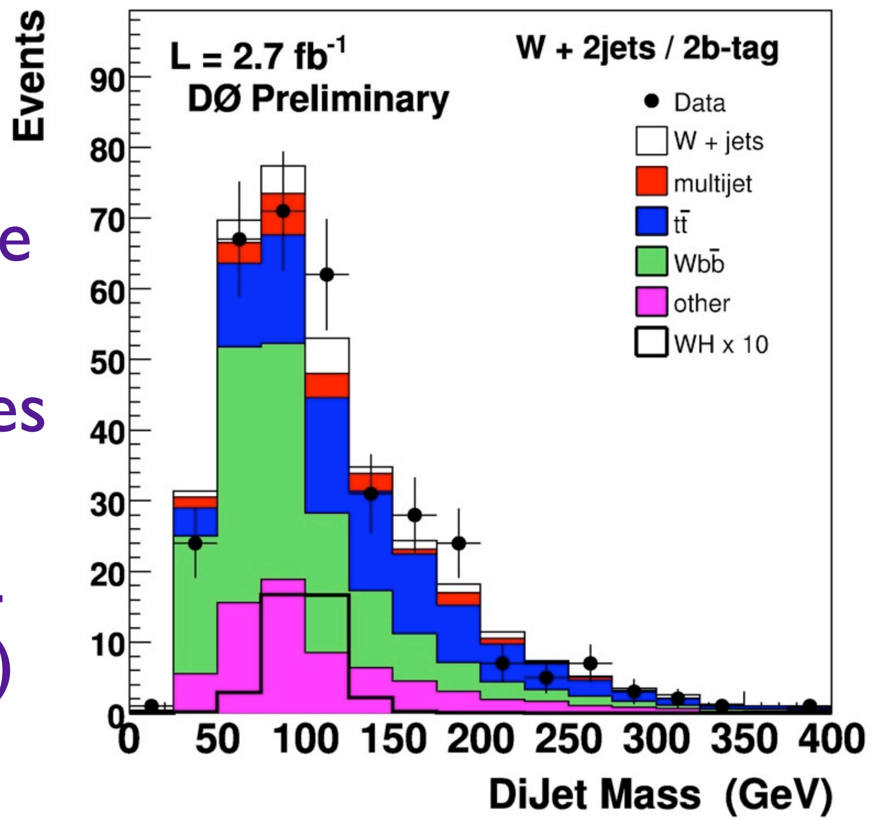
Alpgen, MadEvent, Helac with MLM, Sherpa and Ariadne with CKKW matching

WH Before Multivariate

Exactly one electron or muon, $p^T > 15$ GeV
MET > 20 GeV (25 if "forward" electron)
2 or 3 jets, $p^T > 20$ GeV, leading jet $p^T > 25$ GeV
$H^T > 60/90$ GeV for 2/3 jet events



Analyze single and double tagged samples separately (1 tight or 2 loose b-tags)



Matrix Element Technique

- Currently yields the most precise measurement of the top quark mass, also
  - Major contribution to the observation of single top
  - Used in Higgs searches
- Basically unbinned maximum likelihood fits
  - Event-by-event measured uncertainties
    - More weight for more signal-like event
    - Determine event's "signal probability":

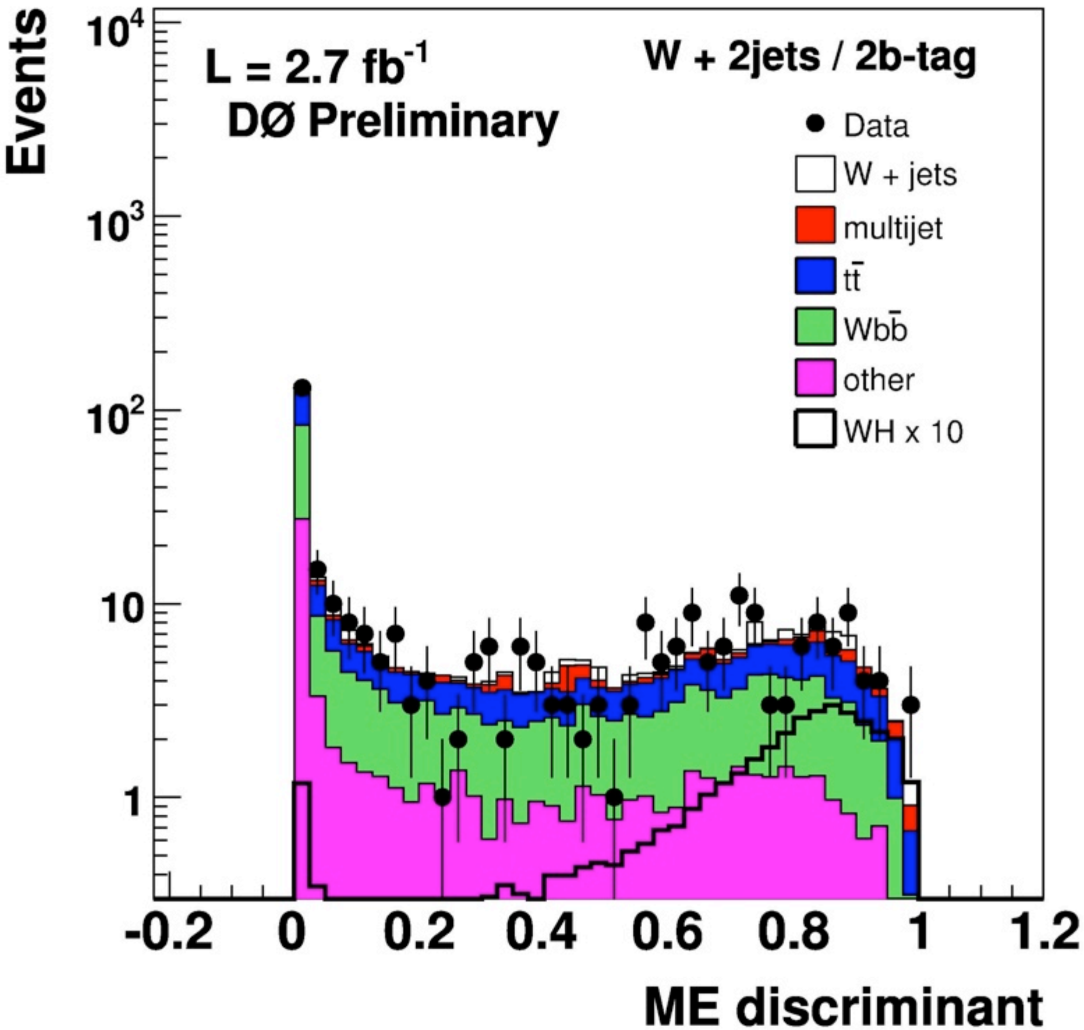
"Transfer functions": generated → measured momenta

b-tag prob

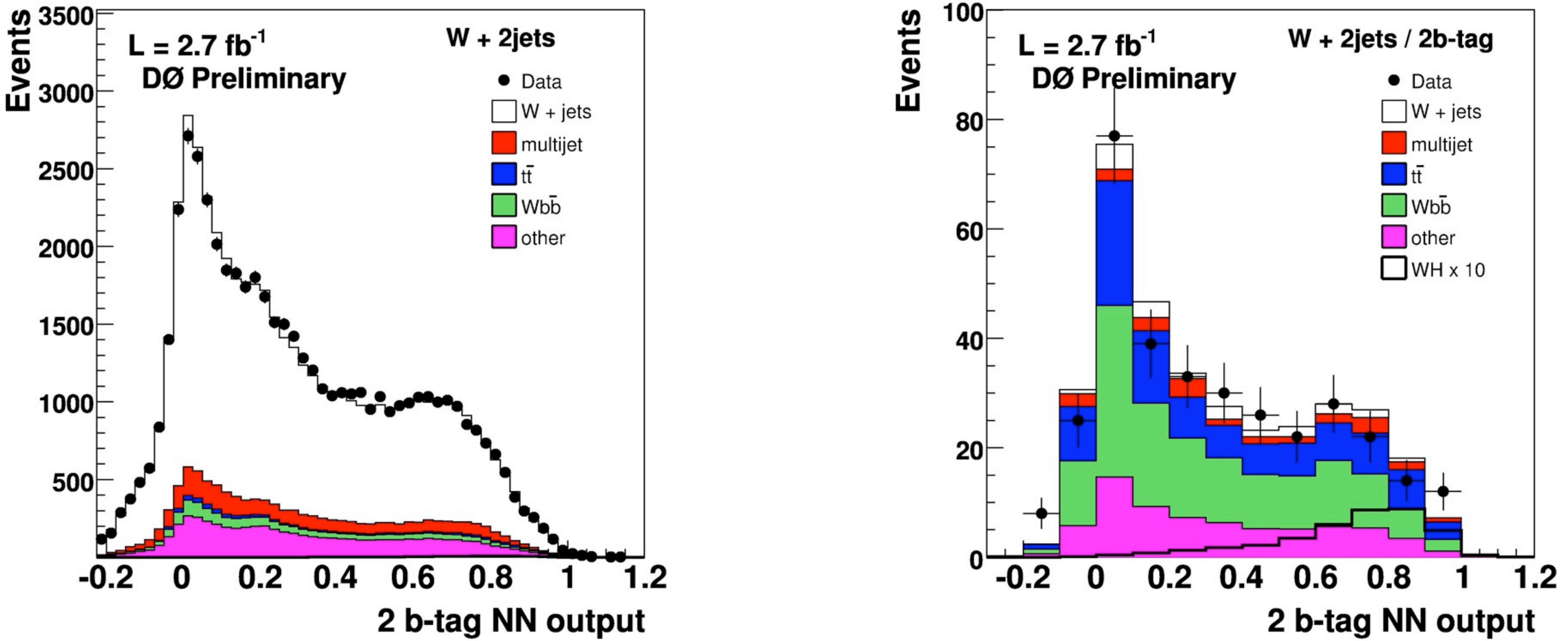
matrix element

$$\sum_{\text{perm}} w_i \int_{q_1,q_2,y} \sum_{\text{flavors}} dq_1 dq_2 f(q_1) f(q_2) \frac{(2\pi)^4 \left|\mathcal{M}(q\bar{q} \to t\bar{t} \to y)\right|^2}{2 q_1 q_2 s} d\Phi_6 W(x,y;JES)$$

- Caveats:
  - LO matrix elements:
    - Require exact number of jets
    - Evaluation of NLO systematic not so easy
  - Recent development: replace madevent with MCFM (NLO)
- Use matrix element output as an extra input for NN
  - Boosts sensitivity by 1.05 for WH (equiv. to 10% more data)

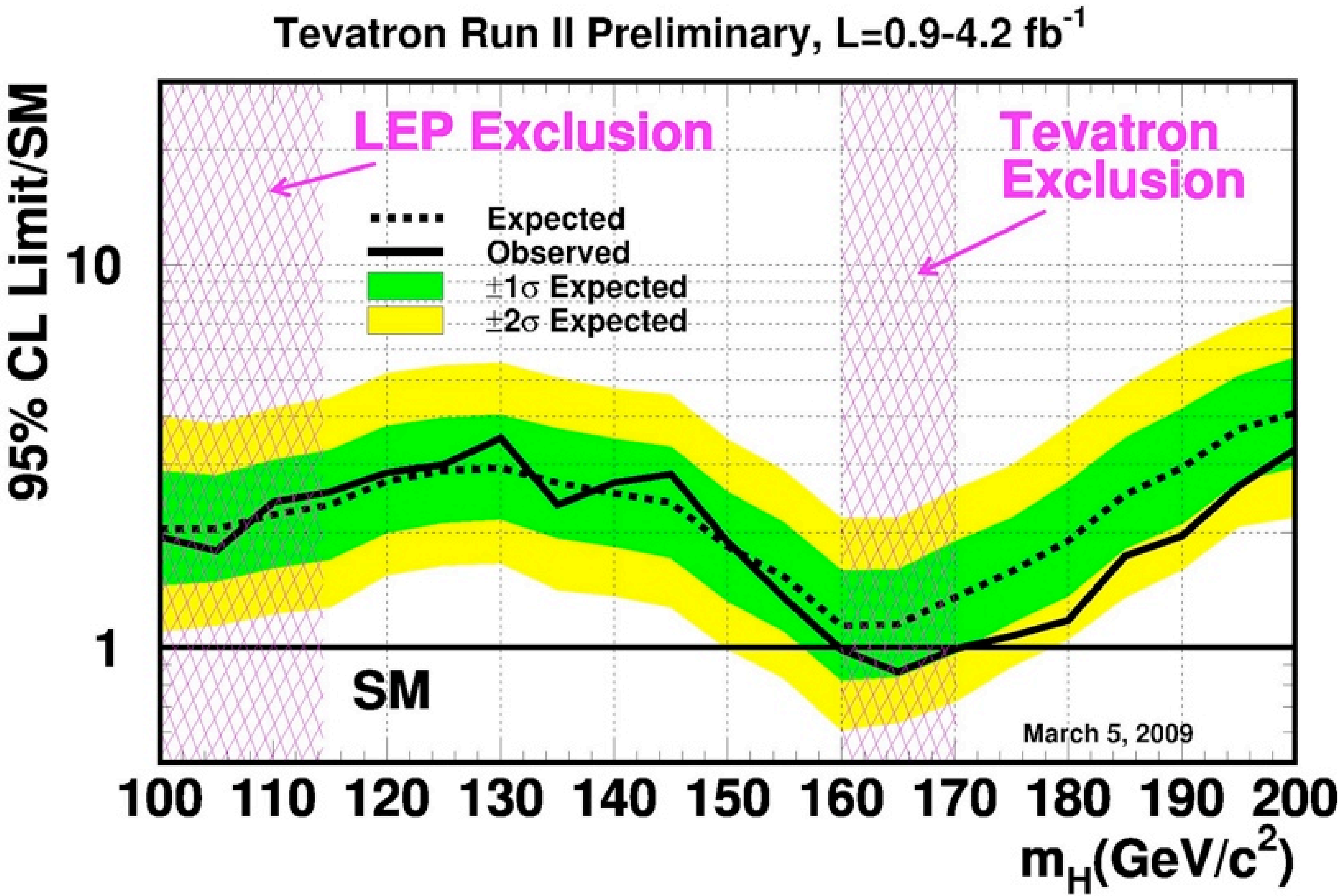


Neural Net Outputs (2 Tags)



- As before, use the distribution to constrain systematics
- Set limit using the full shape of the distribution
  - I.e. no cut: NN > x

All Channels, CDF + DØ



- Average luminosity used ~2.5 fb^{-1}
  - ~3.5 fb^{-1} for H→WW, 2.7 fb^{-1} for WH

So, Do We Understand the SM?

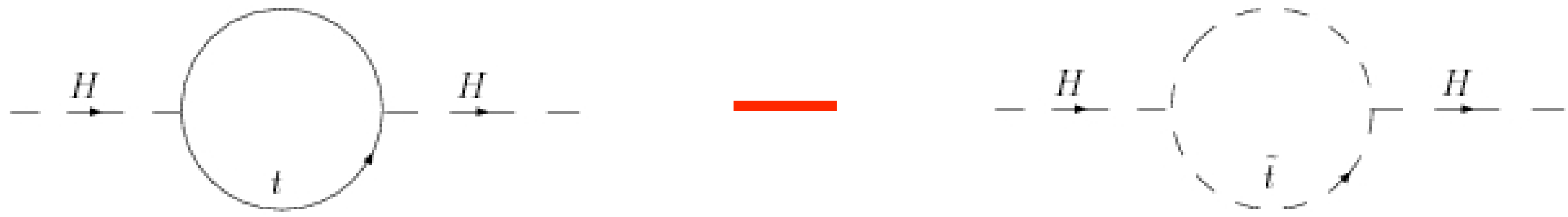
- Not a good question to ask!
- Rather:
  - "*How well* do we understand the SM/data?"
- Given that:
  - Which measurements can we make?
  - What do we need to do to improve our understanding?
- Balance the work!
  - Early, low background searches
  - Detailed understanding/verification of SM predictions

SUSY & Cold Dark Matter?

(or: A Universal Solution?)

Postponing the Hierarchy Problem

- If there is a Higgs, new particles at ~m_H are a good way to stabilize its mass
- E.g. SUSY: Fermionic and bosonic loop corrections to the Higgs mass cancel each other: Higgs mass is naturally at the "electroweak scale" provided SUSY partners exist at that mass



- Little Higgs models have analogous cancelation mechanisms

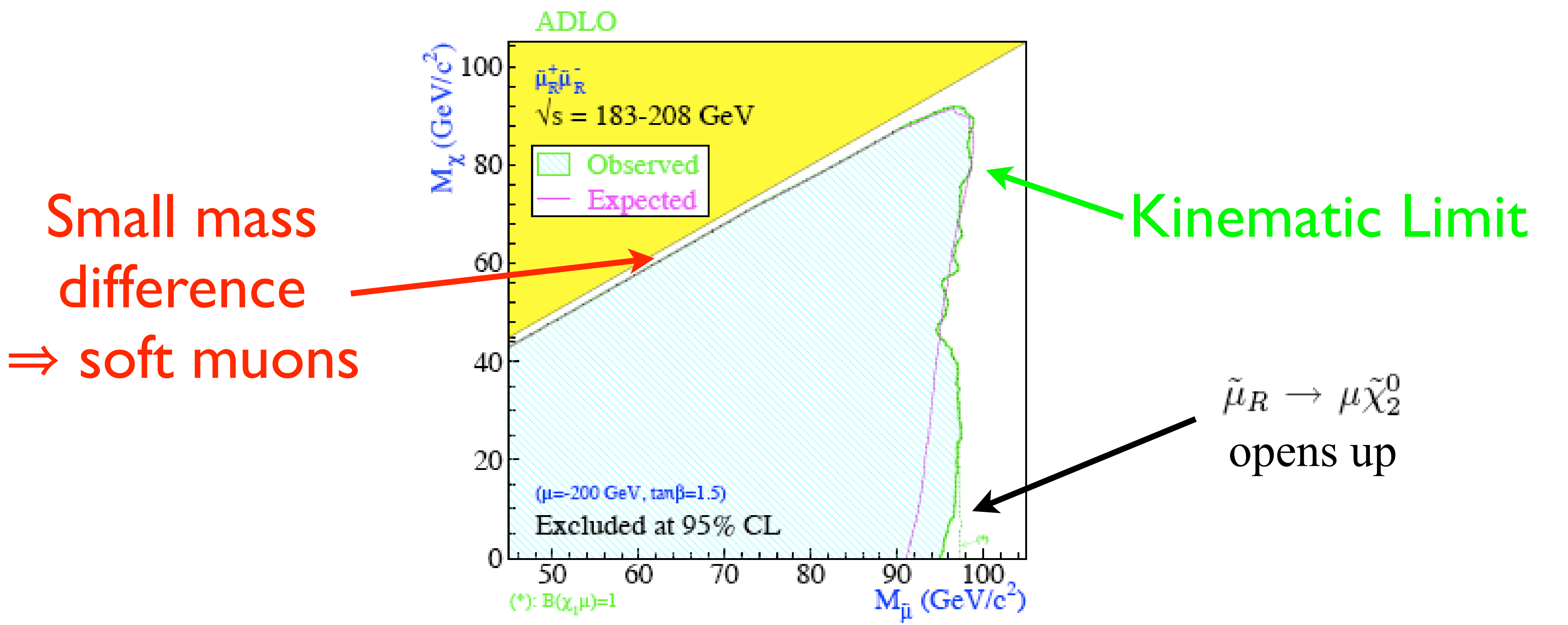
Minimal Supersymmetric SM

- Minimal set of new particles
  - 105 new free parameters (masses, mixings,...)
- Searches make simplifying assumptions, e.g.:
  - R-parity is conserved (or explicitly violated)
  - Search for pair-production of one type of superpartner, which decays to SM particle(s) + LSP
  - More complex decay chains in LHC studies
    - Needs a more complex model, interesting kinematic relations

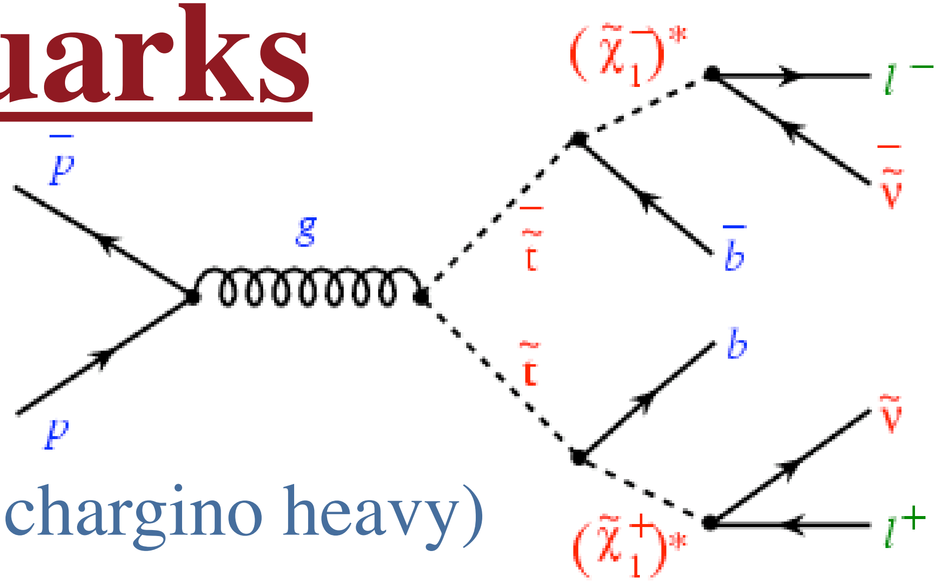
➡ jets and/or leptons + MET.

Smuons

- Pair-production of smuons though *s*-channel γ^*/Z exchange at LEP
  - Assume smuon is NLSP, $\tilde{\mu}_R \to \mu\tilde{\chi}_1^0$
  - Pair of acolinear muons and missing momentum

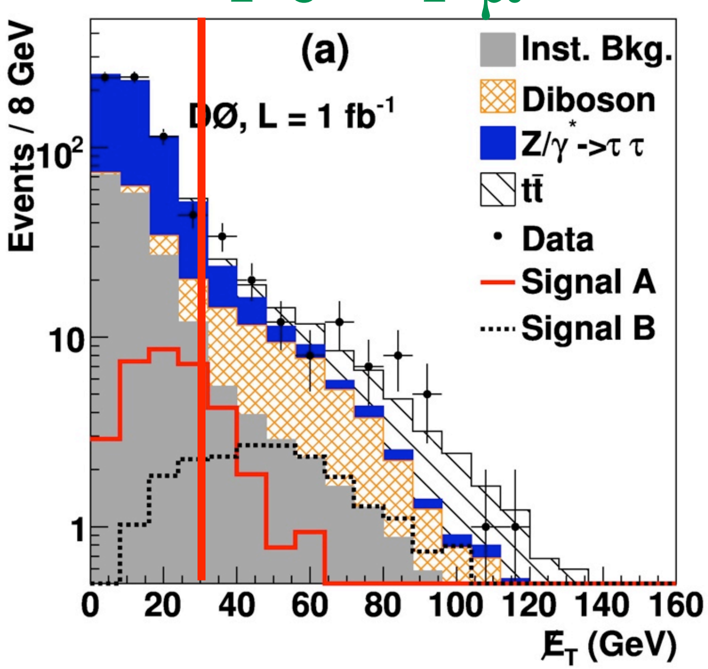


Top Squarks

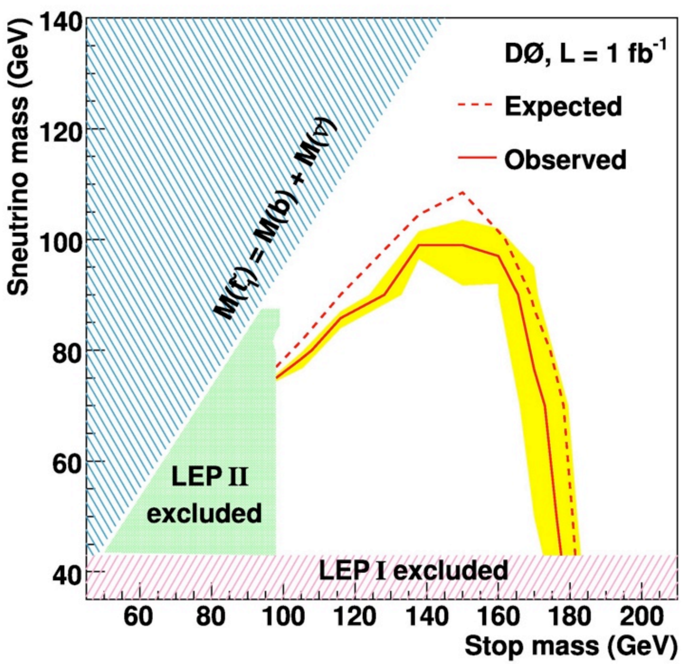


- Potentially lighter than top
  - Sneutrino LSP
  - Three-body decay “b-ℓ-snu” (if chargino heavy)
  - Small visible pT’s if small $\Delta m = m_{\tilde{t}_1} - m_{\tilde{\nu}}$

1 e + 1 μ



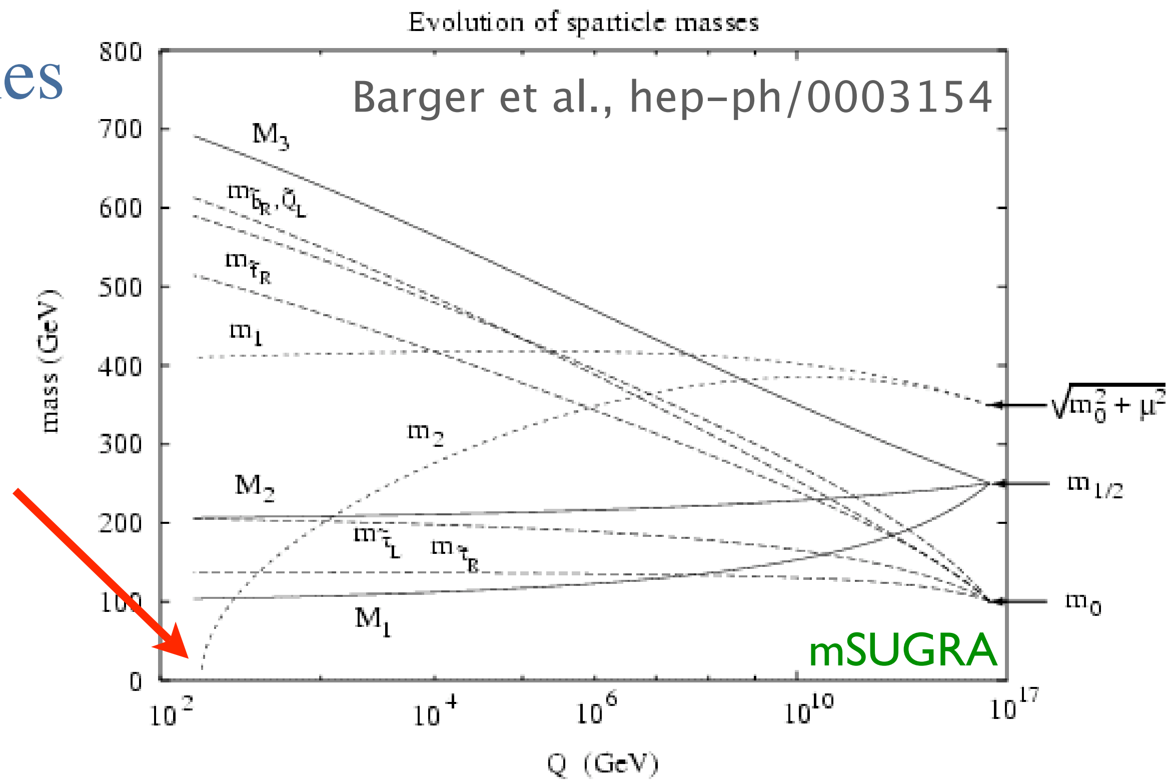
Use MET + lepton-MET angles to reduce backgrounds; add ee channel



SUSY Breaking

- SUSY is broken
  - Sparticle masses ≠ particle masses
- Breaking models lead to predictions for mass hierarchies
  - Specific phenomenologies

Explain Electroweak Symmetry Breaking! (Because top is heavy....)



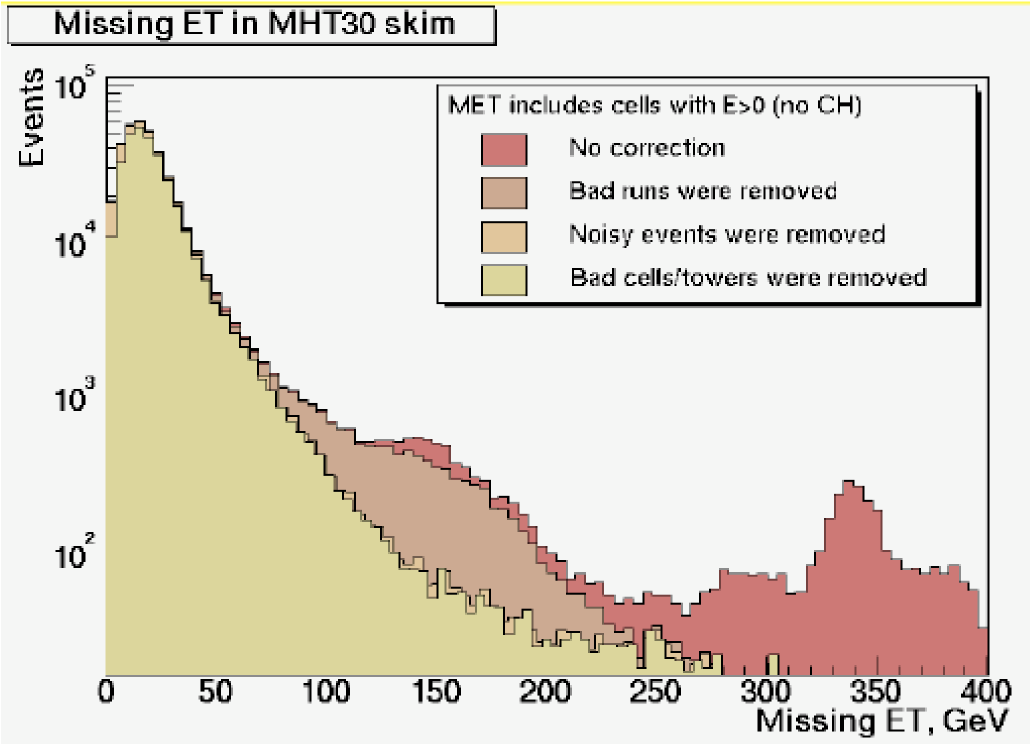
Jets + MET

- Hadron colliders → produce mostly squarks and gluinos (if in reach)
  - Decays to quarks, gluons and LSPs (and maybe a few leptons)
- Jets + MET experimentally difficult
  - Due to the complexity of the detector, it is remarkably easy to take bad data
  - Need to make sure all of detector is on, identify badly behaving channels, etc etc
    - **Data quality!!**
  - We can't measure jets very precisely

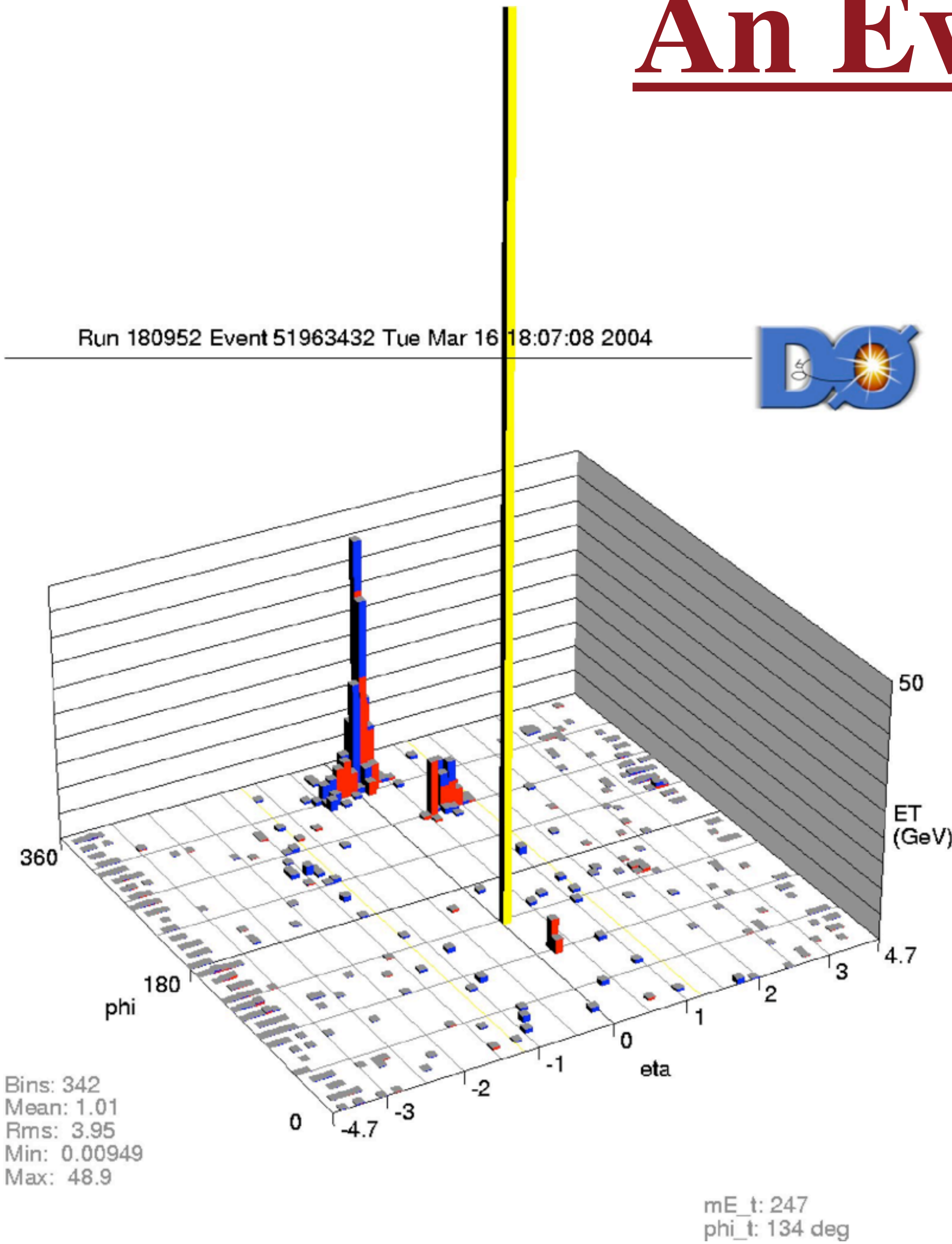
Data Quality

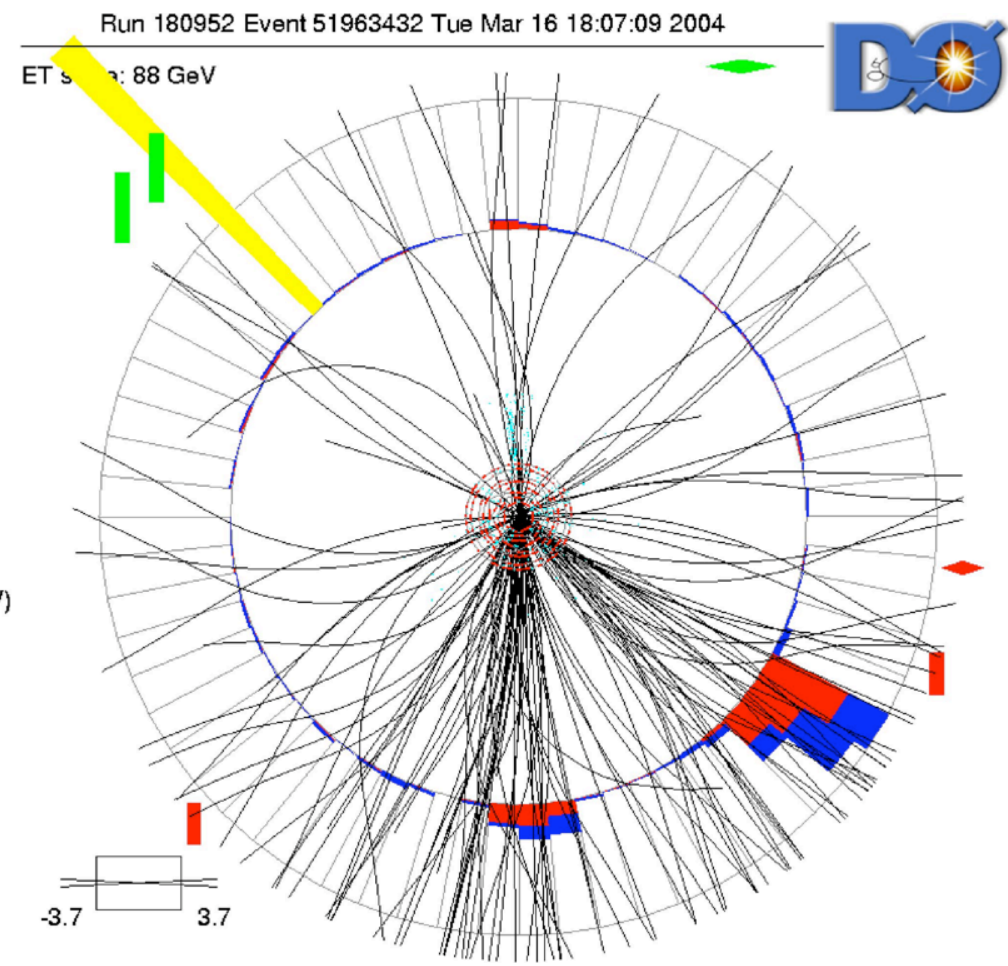
- Online:
  - Event displays, occupancy, reconstruct small fraction of events, etc.
- Anything that happens at < 1% rate is almost impossible to detect online
  - As long as you don't know what to look for
    - Keep track of TGV schedules, TV programs, multitude of cron jobs, people welding in 500 m radius, ...
  - Continuous feedback from analysis is a necessity
    - Really subtle stuff can take years to find

- Analyses using MET are particularly sensitive
  - Requires the full calorimeter to behave, and calorimeter is generally the most sensitive subdetector (analog, ~16 bits)
  - Easy: basic DQ (missing board, etc.)
  - Hard: low frequency
  - Can't spot a 10^{-5} Hz (once a day) effect online or in first pass DQ
    - But can be biggest part of dataset after cuts!
    - Everytime dataset x5, find new source of rare noise...

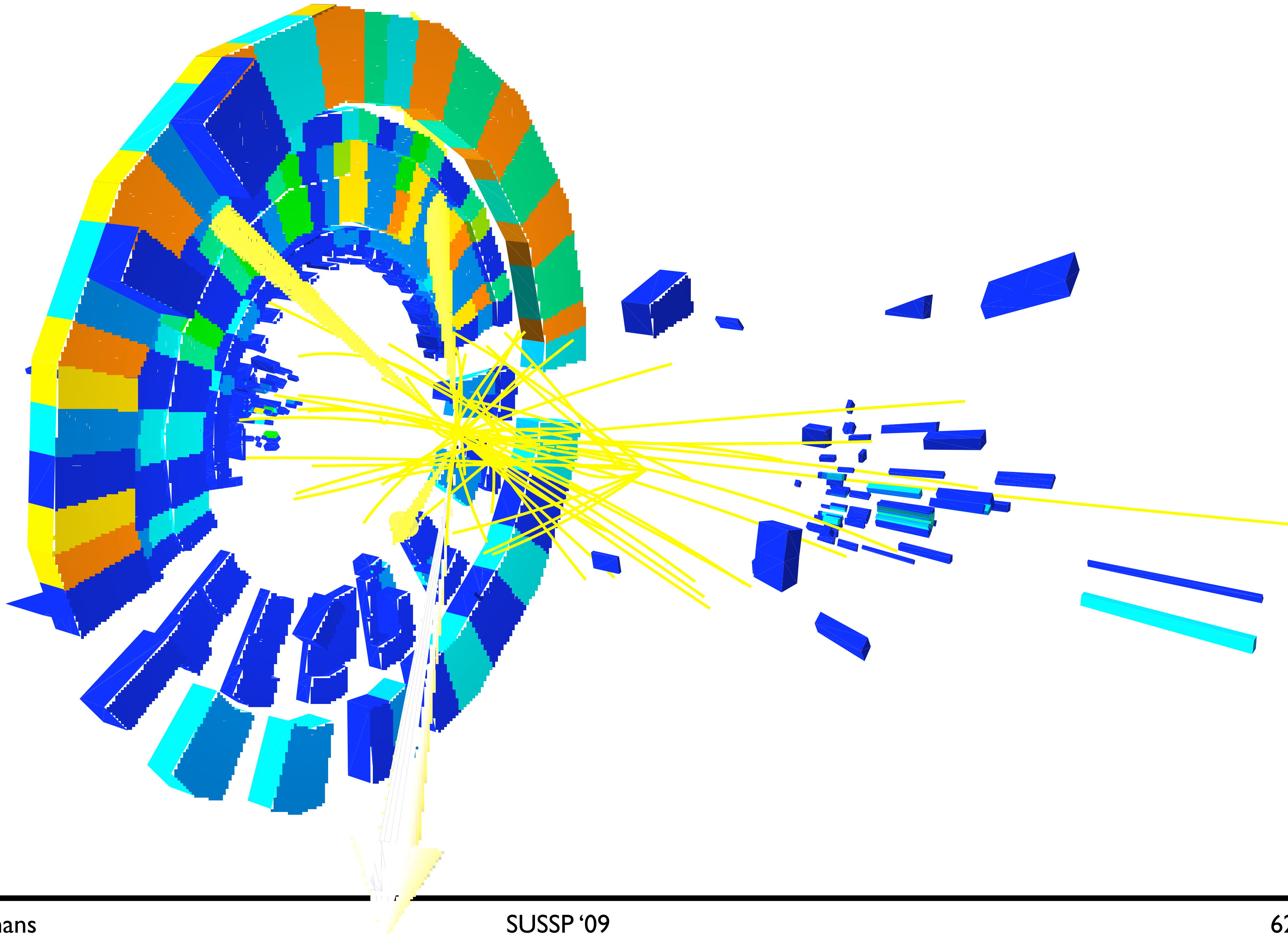


An Event


Run 180952 Event 51963432 Tue Mar 16 18:07:08 2004
50
ET
(GeV)
360
180
phi
0
-4.7
-3
-2
-1
0
1
2
3
4.7
eta
Bins: 342
Mean: 1.01
Rms: 3.95
Min: 0.00949
Max: 48.9
mE_t: 247
phi_t: 134 deg


Run 180952 Event 51963432 Tue Mar 16 18:07:09 2004
-3.7
3.7

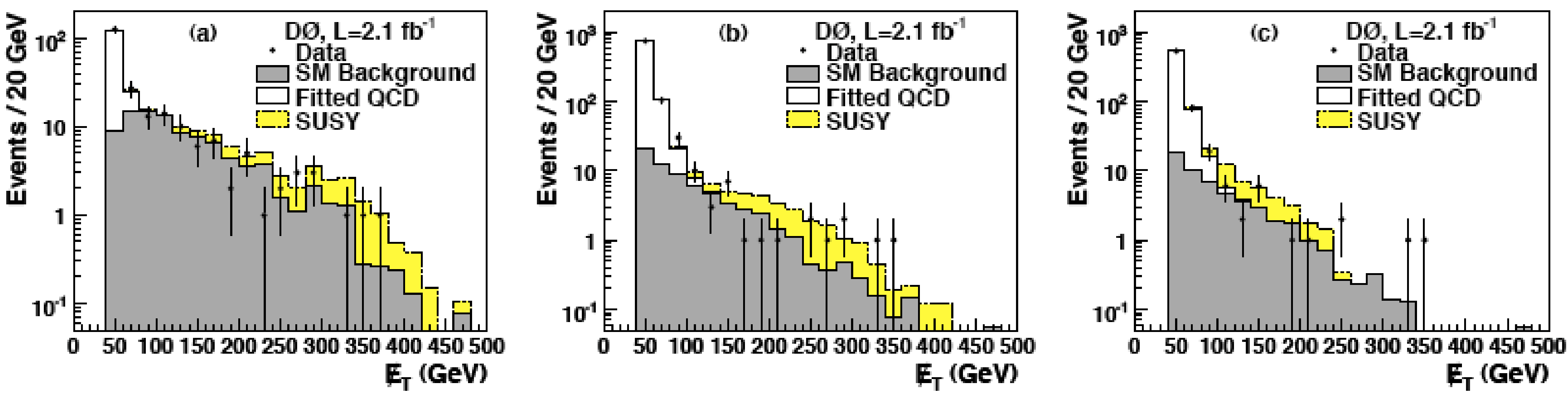
Another: "The Spanish Fan"

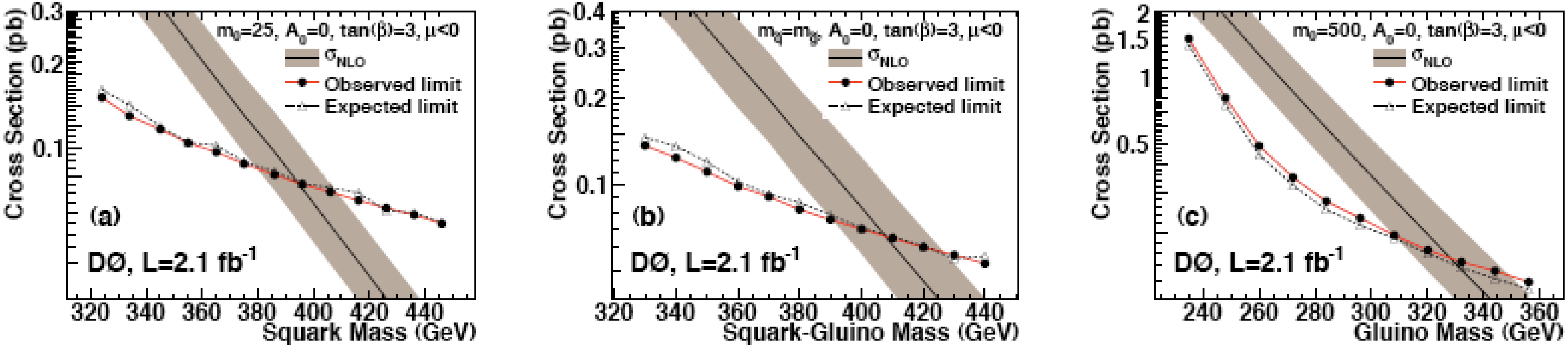


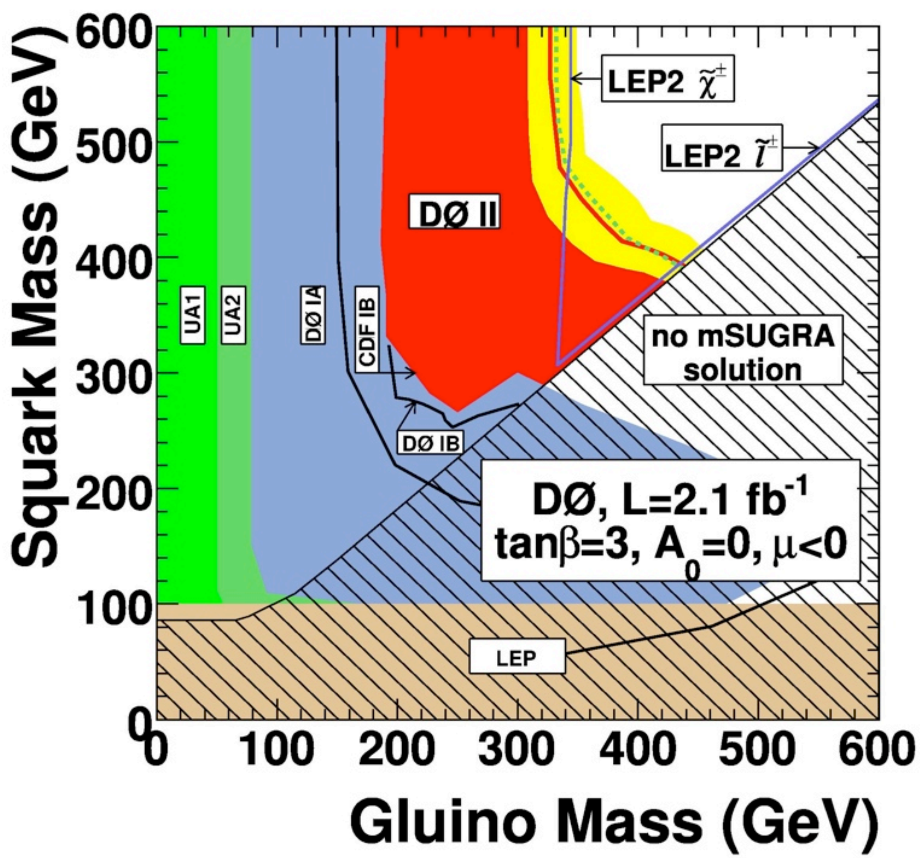
Squark-Gluino Search

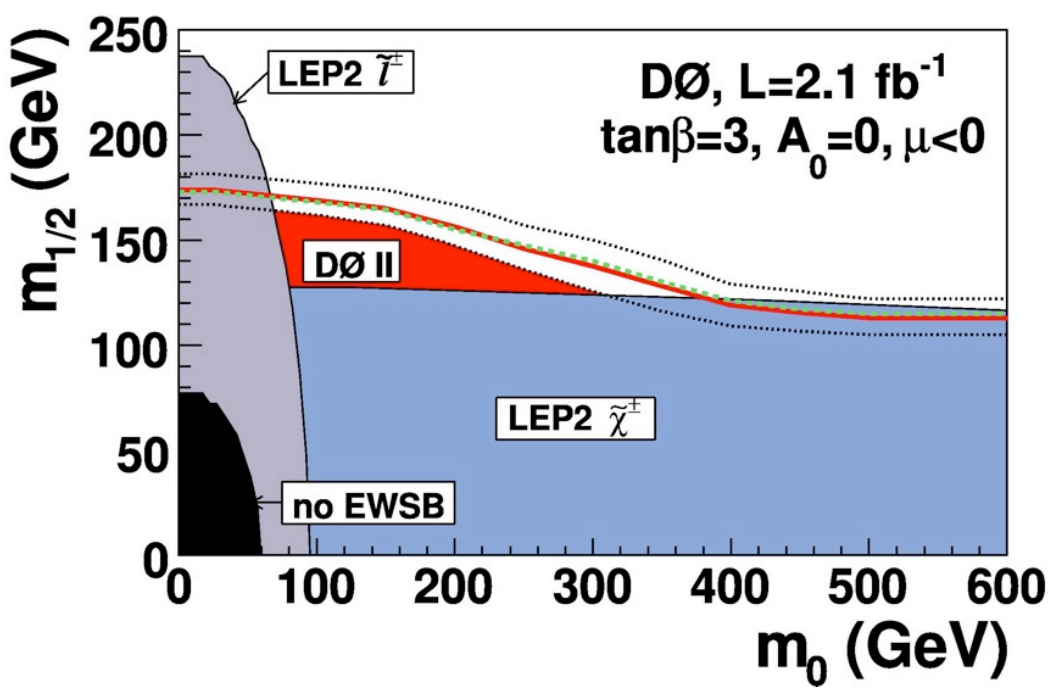
- As always, maximize sensitivity by treating different signals separately
  - $\tilde{q}\tilde{q} \rightarrow q\,\tilde{\chi}_1^0\,q\,\tilde{\chi}_1^0$: "2 jet"
  - $\tilde{q}\tilde{g} \rightarrow q\,\tilde{\chi}_1^0\,q\bar{q}\,\tilde{\chi}_1^0$: "3 jet"
  - $\tilde{g}\tilde{g} \rightarrow q\bar{q}\,\tilde{\chi}_1^0\,q\bar{q}\,\tilde{\chi}_1^0$: "gluino"
- Different trigger, H_T and MET cuts
  - "Acoplanar" dijets vs jets+MET
  - Same center-of-mass energy: tradeoffs between total jet energy and MET

- Dominant backgrounds are
  - Z ($\to\nu\nu$) + jets, W ($\to \ell\nu$) + jets, tt ....
  - ... provided you’ve cleaned up the bad data!
  - (And reduced QCD through $\Delta\phi$ cuts between jets and MET)




Cross Section (pb)
m_0=25, A_0=0, tan(β)=3, μ<0
σ_{NLO}
Observed limit
Expected limit
(a)
DØ, L=2.1 fb^{-1}
Squark Mass (GeV)
$m_{\tilde{q}}=m_{\tilde{g}}$, A_0=0, tan(β)=3, μ<0
(b)
Squark-Gluino Mass (GeV)
m_0=500, A_0=0, tan(β)=3, μ<0
(c)
Gluino Mass (GeV)


Squark Mass (GeV)
UA1
UA2
DØ IA
CDF IB
DØ IB
DØ II
LEP2 $\tilde{\chi}^{\pm}$
LEP2 $\tilde{l}^{\pm}$
no mSUGRA solution
DØ, L=2.1 fb^{-1}
tanβ=3, A_0=0, μ<0
LEP
Gluino Mass (GeV)


$m_{1/2}$ (GeV)
LEP2 $\tilde{l}^{\pm}$
DØ, L=2.1 fb^{-1}
tanβ=3, A_0=0, μ<0
DØ II
LEP2 $\tilde{\chi}^{\pm}$
no EWSB
m_0 (GeV)

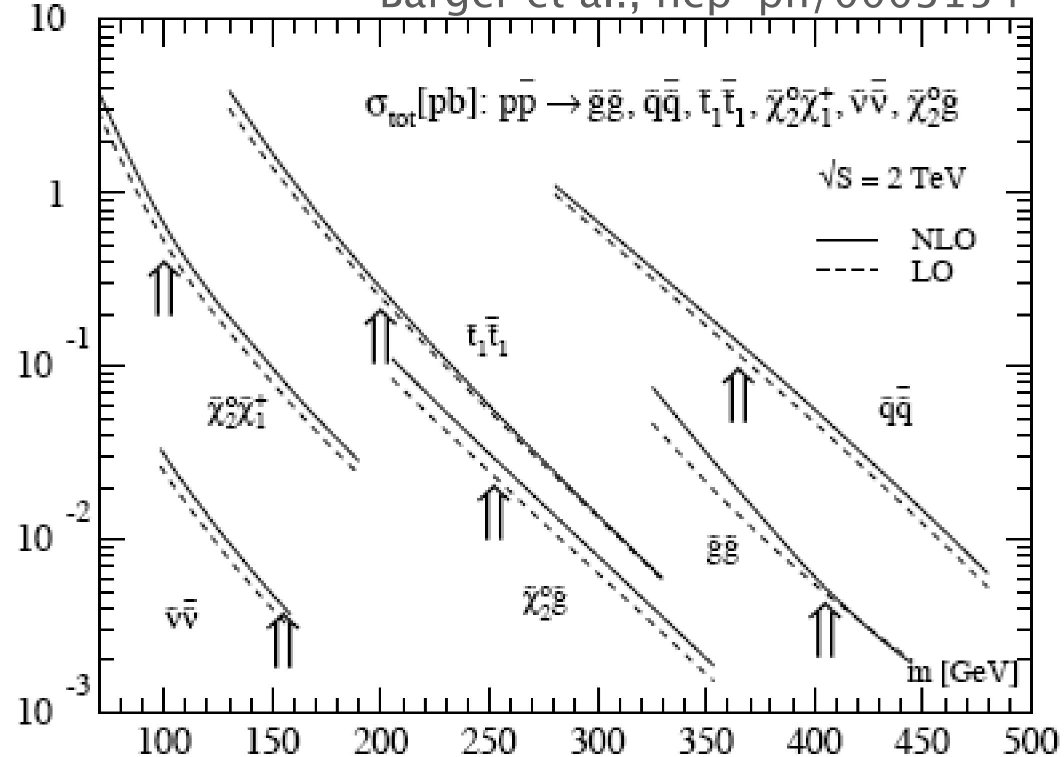
Triletpons

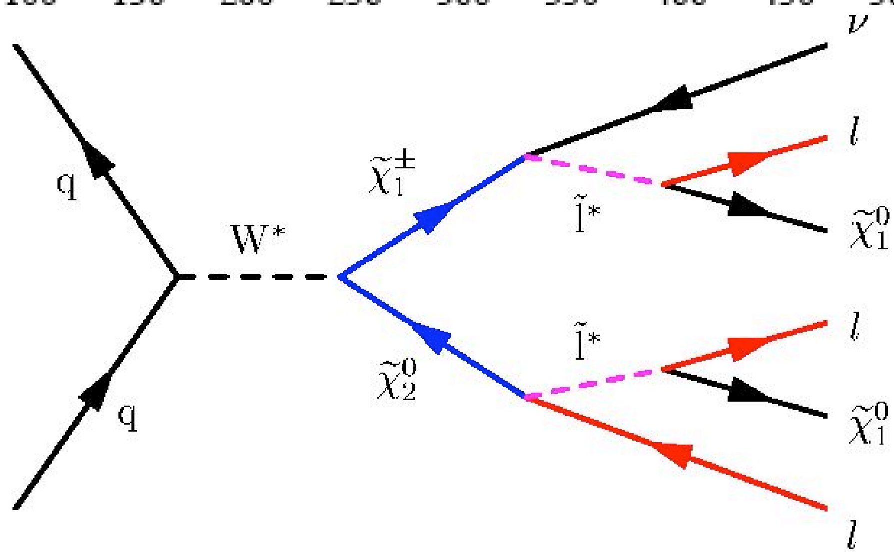
- Typically expect colored superpartners to be heavier
  - May not be accessible

➡ Look for gaugino pair production

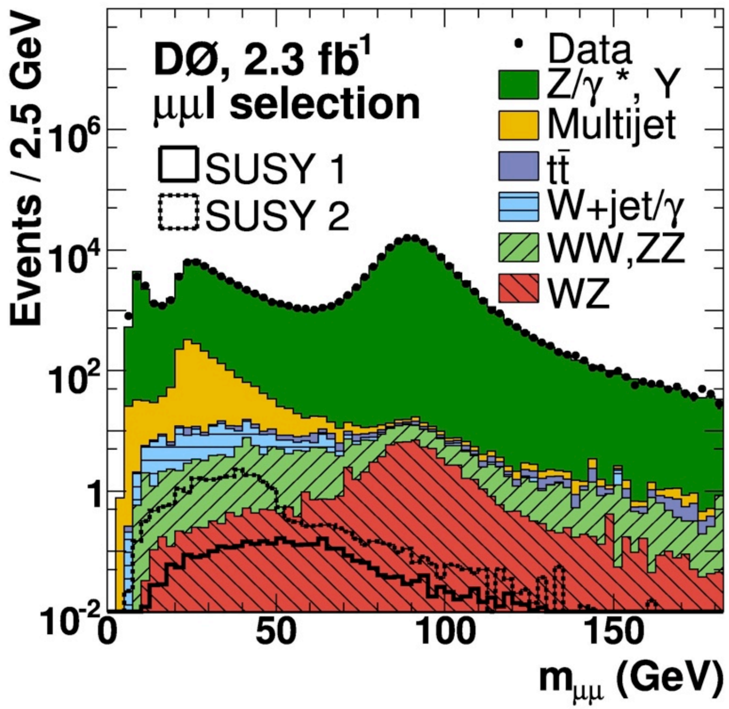
  - Small x-section ...
  - ... but potentially spectacular trilepton signature!
  - Small mass splittings make leptons “soft” though

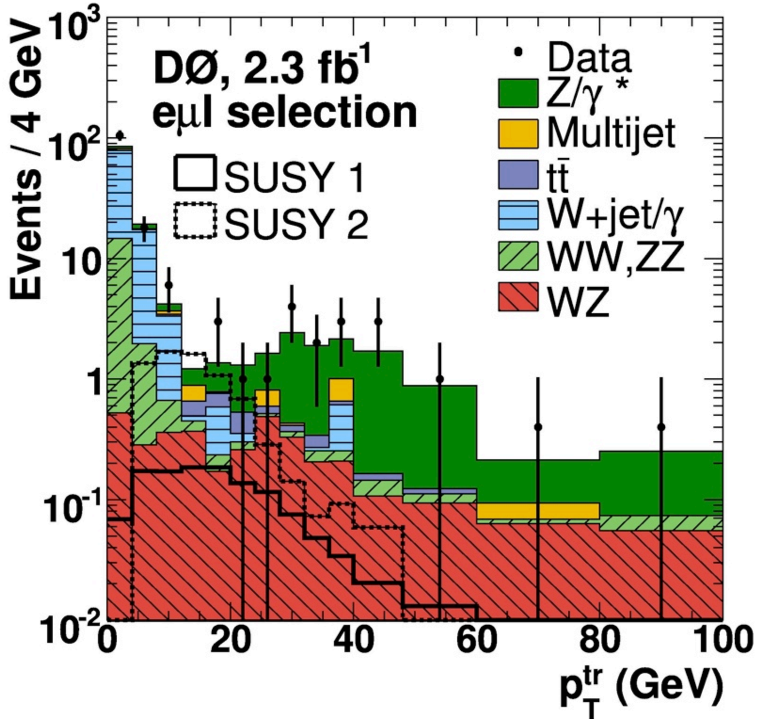
Barger et al., hep-ph/0003154

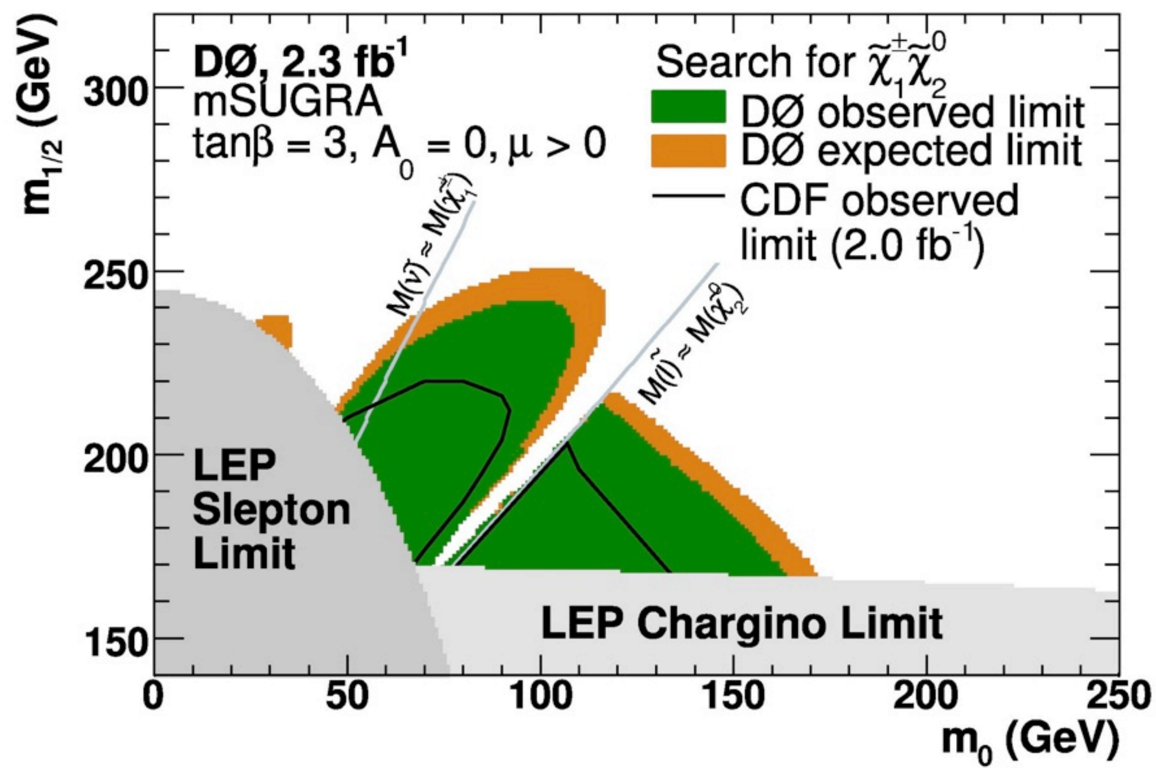




- “Golden” signature (at the Tevatron):
  - Minimal SM backgrounds (WZ, ZZ), so low that 3rd lepton can be “identified” as isolated track

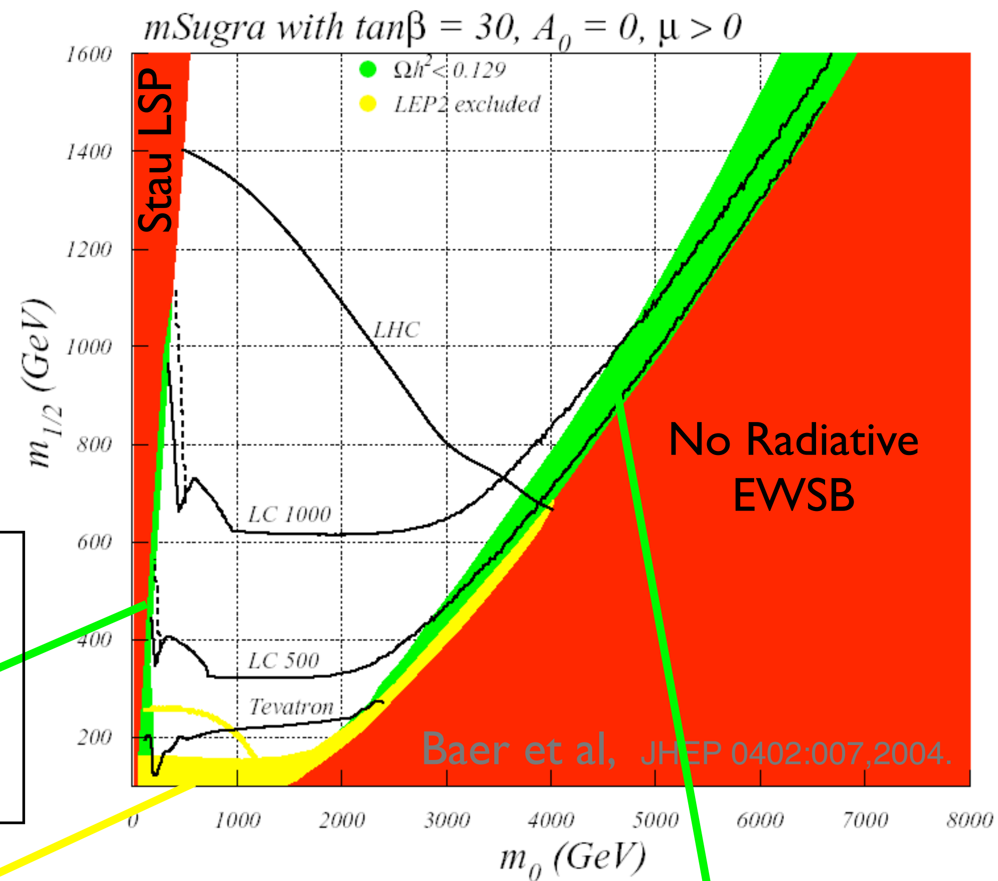




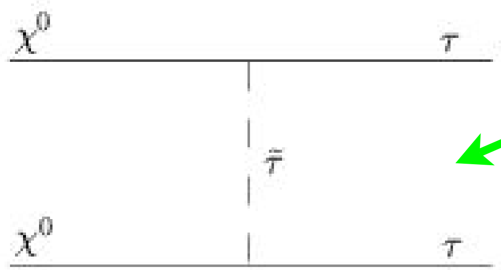


SUSY “Future”

- Can calculate relic LSP density
  - LSP cannot be too heavy, or need an efficient way to annihilate

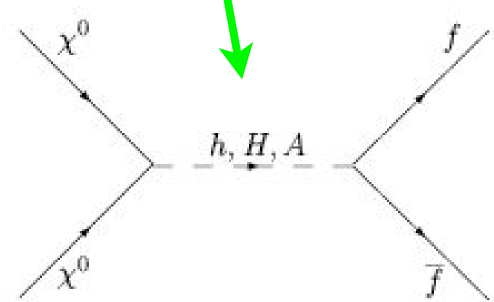


Coannihilation: LSP and NLSP are almost degenerate



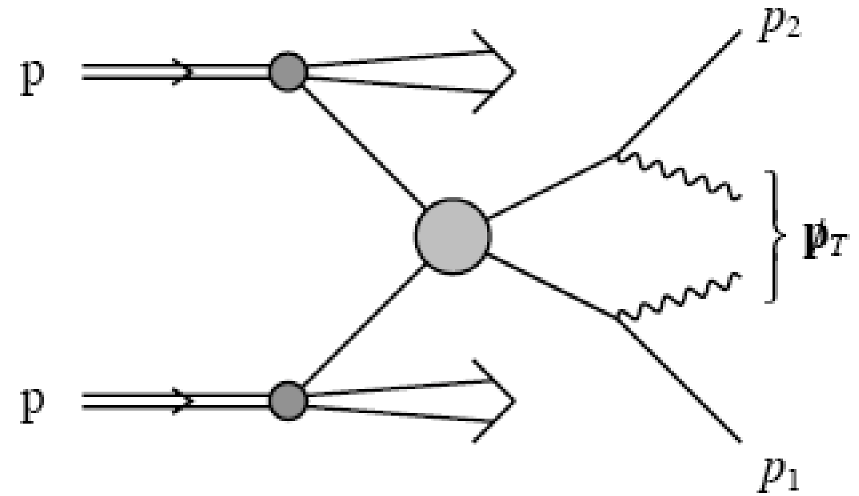
Bulk region: superpartners are light

Focus points: neutralino is mostly higgsino; light charginos, small mass gaps



Sparticle Masses (1)

- If R-parity is conserved, always >1 escaping LSP
  - No "resonant" signature, no direct access to masses
- Simplest case:



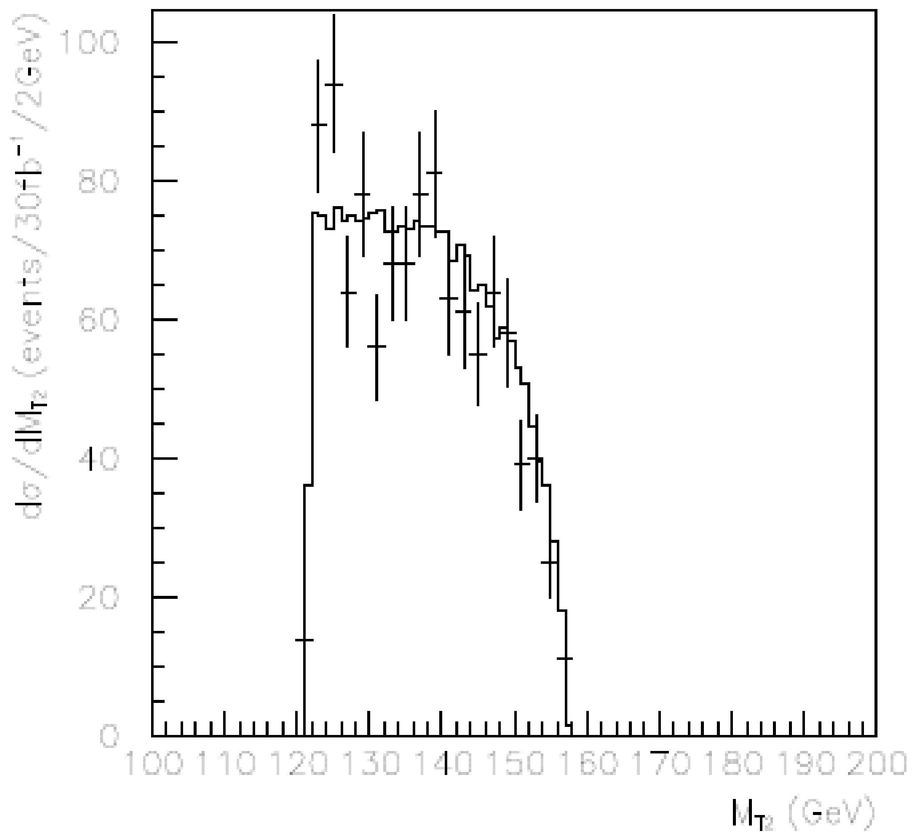
- Introduce M_{T2}:

$$m_{\tilde{l}}^2 \geq M_{T2}^2 \equiv \min_{\not{p}_1 + \not{p}_2 = \not{p}_T} \left[\max \{ m_T^2(\mathbf{p}_{Tl^-}, \not{p}_1), m_T^2(\mathbf{p}_{Tl^+}, \not{p}_2) \} \right]$$

Lester & Summers, **Phys.Lett.B463:99-103,1999**

  - (They chose slepton pair production)

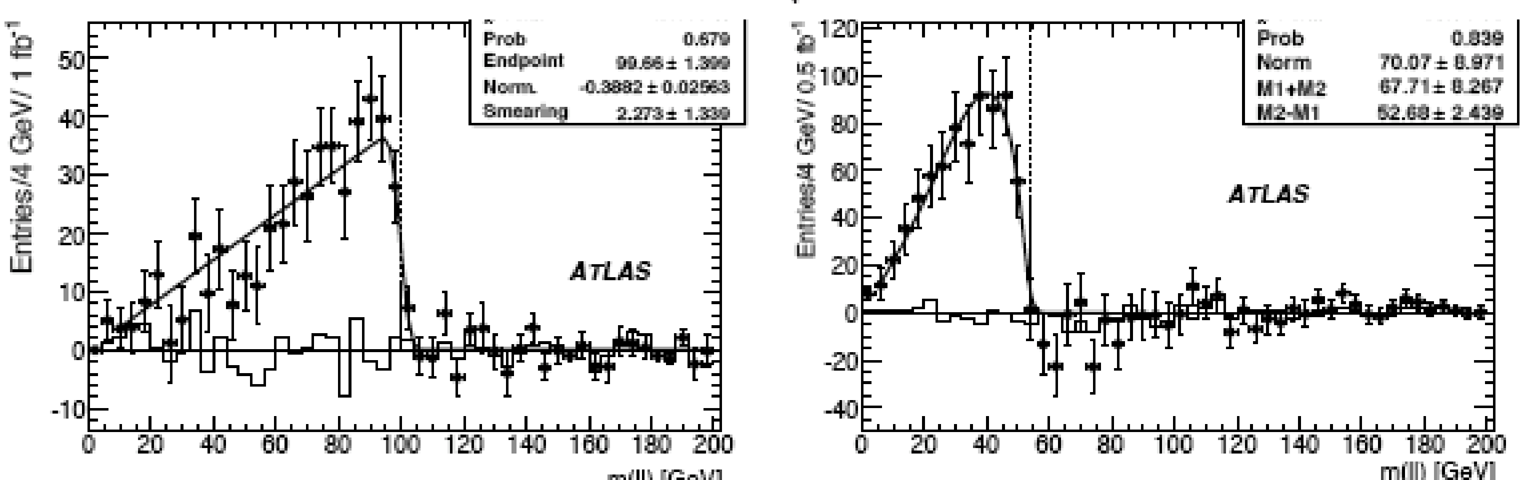
- For M_{T2} to be effective, need to have events close to the max value (like M_T for W)
  - Somewhat process-dependent (spins etc.)



generated $m_{\tilde{l}}$ = 157.1 GeV

Sparticle Masses (2)

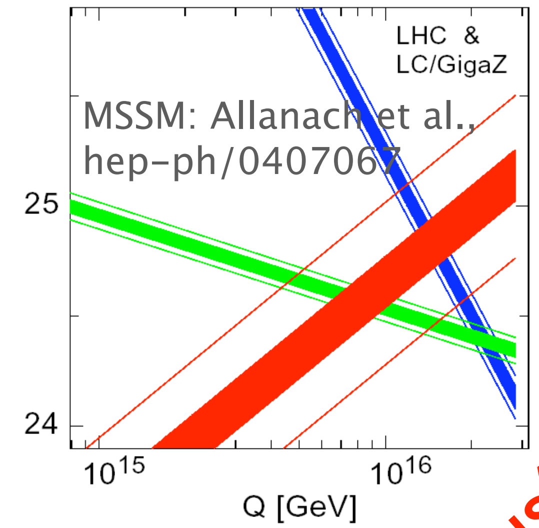
- What about longer decay chains?
  - E.g. $\tilde{q}_L \to \tilde{\chi}_2^0 q (\to \tilde{\ell}^\pm \ell^\mp q) \to \tilde{\chi}_1^0 \ell^+ \ell^- q$
  - Dilepton edge:
    - Heavy slepton: $m_{\ell\ell}^{\text{edge}} = m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0}$
    - Light slepton: $m_{\ell\ell}^{\text{edge}} = m_{\tilde{\chi}_2^0} \sqrt{1 - \left(\frac{m_{\tilde{\ell}}}{m_{\tilde{\chi}_2^0}}\right)^2} \sqrt{1 - \left(\frac{m_{\tilde{\chi}_1^0}}{m_{\tilde{\ell}}}\right)^2}$



ATLAS "CSC book": CERN-OPEN-2008-020

Good or Bad?

- SUSY theories (and others with full or partial set of SM-partners) have a number of attractive features
  - "Explanation" for low Higgs mass (and sometimes EWSB)
  - Gauge coupling unification (often)
  - Dark matter candidate (if introduce a new parity, natural in UED, ~ad-hoc in SUSY)
  - No new interactions (often)



- But answering those questions comes at a large cost
  - Many new particles, with masses and mixing angles
  - Need to explain why mass scale is so low (or high), spin?

Dinosaurs on Venus?

A Simple Observation

Higgs and Fermion Masses

- Inside a generation, the more a fermion interacts, the heavier it is
  - (Of course, we don't know that the τ-ν_τ lepton generation doesn't really match up with the d-u quark generation, only hint is b-τ unification I believe)

➡ Pattern suggests fermion masses might be related to a more complex mechanism

  - Indirect relation to interactions? ("Gauge mediation?")
  - Higgs may then only be relevant for VV scattering, relaxing mass constraints, existing limits (no bb!)

Spin & Mass

- Problem with mass is that it allows a particle to change helicity
  - And, of course, since parity is maximally violated in weak interactions, this “breaks the symmetry”
  - Deeper understanding of spin as useful to making progress as a Higgs observation

➡ Scenario of restoration of parity might lead to *understanding* of fermion masses

  - No necessarily strict left-right...

Parity

(or: Step-By-Step)

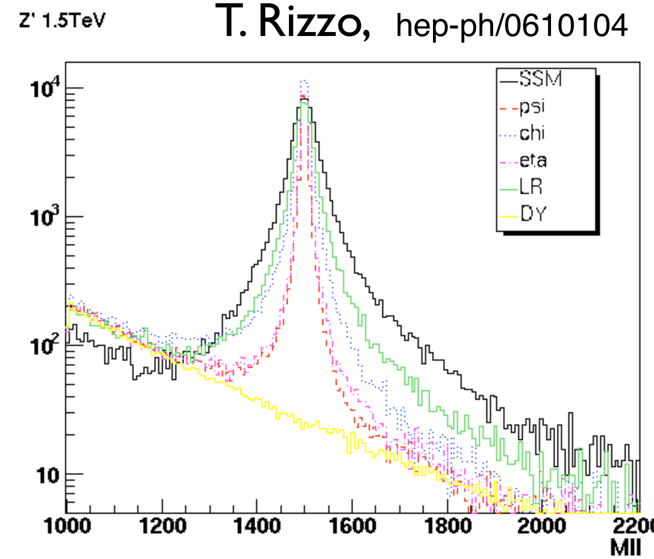
Parity Restoration: Signals

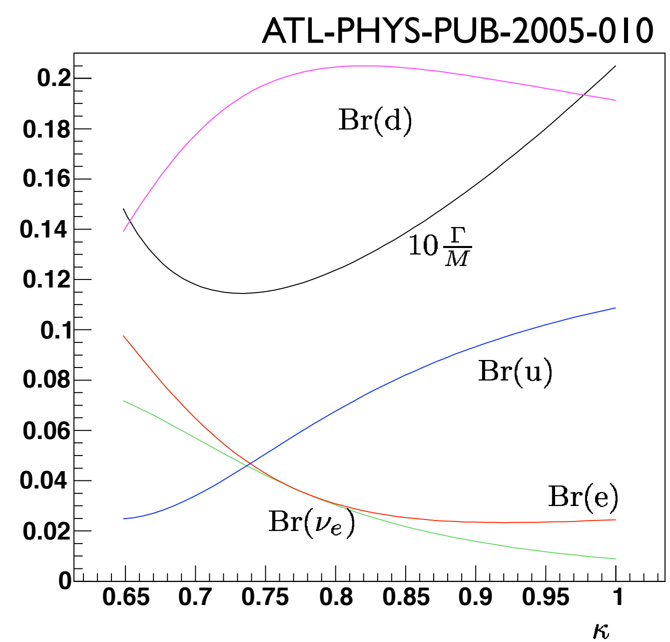
- Primary signals are (right-handed) W' (+ Z')
  - Dilepton resonances offer clean signals, well-understood backgrounds
    - At LHC, some concern about extrapolation of calibration from Z to very high energies
    - Electron/muon resolution improves/degrades with p^T
  - $t\bar{t}$ decays visible (maybe)
  - ν_R is presumably heavy, W' may only decay to quarks
    - If ν_R lighter than W'/Z', ν_R decays become important
- Note: many kinds of Z' - recent review by Langacker

arXiv:0801.1345

Z' Production and Decay

- Production from u, d quarks is dominant at Tevatron/LHC
  - Couplings vary by model
  - E.g. for LR symmetric models, $\varkappa = g_R/g_L$ drives production cross-section (convolute with PDFs) and branching ratios
- Decays somewhat similar to Z (but almost no BR to light neutrinos, decays to top open up), plot assumes ν_R heavier

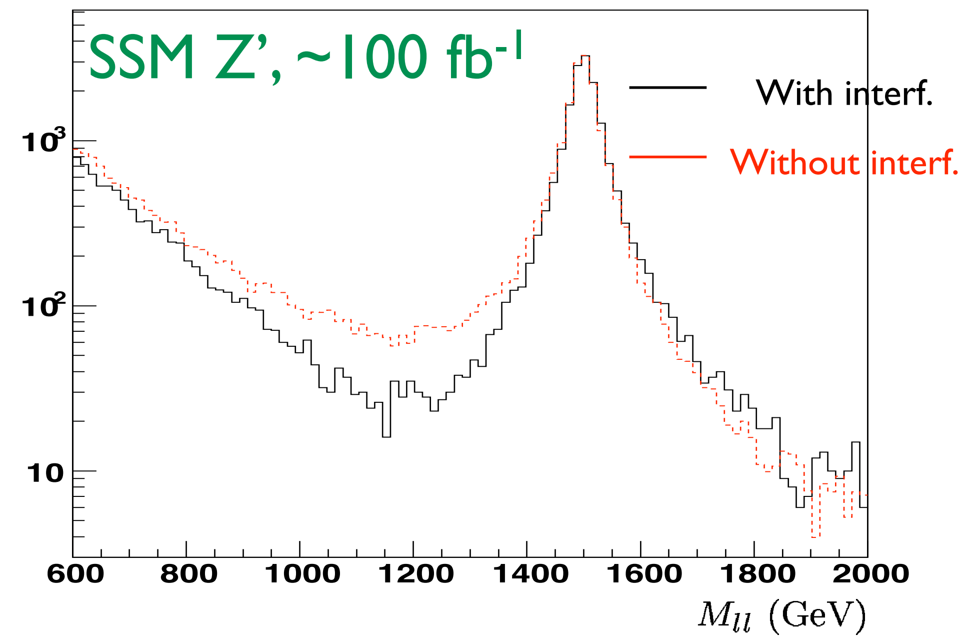


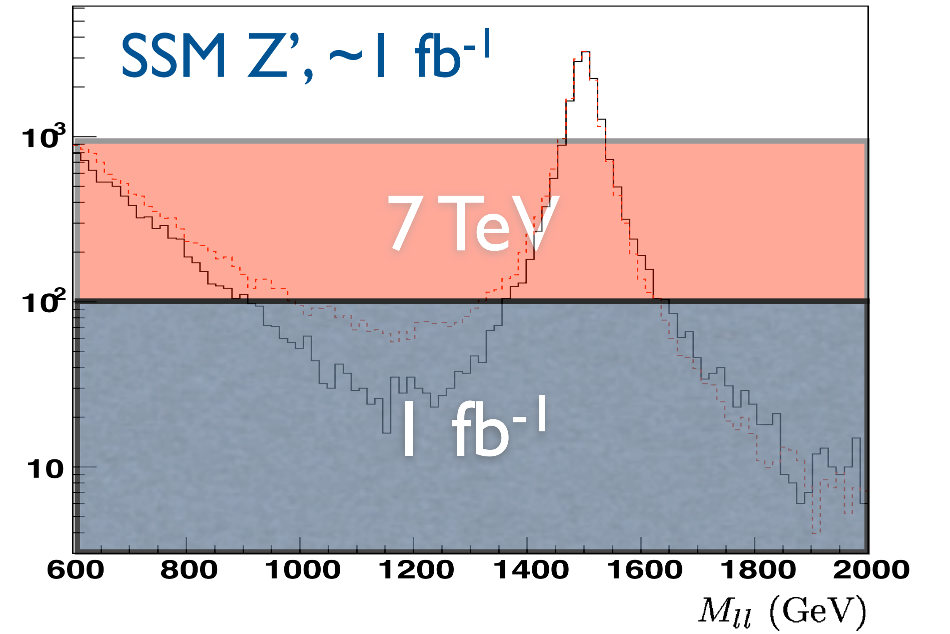


Z’ → ee

- Most promising channel:
  - At Z’ masses, energy resolution dominated by constant term
    - 10 GeV for 1.5 TeV electron
    - Could measure width!
- Extend Tevatron reach (~1 TeV) as soon as understand data
  - Backgrounds very low!
  - “Self-calibrating”

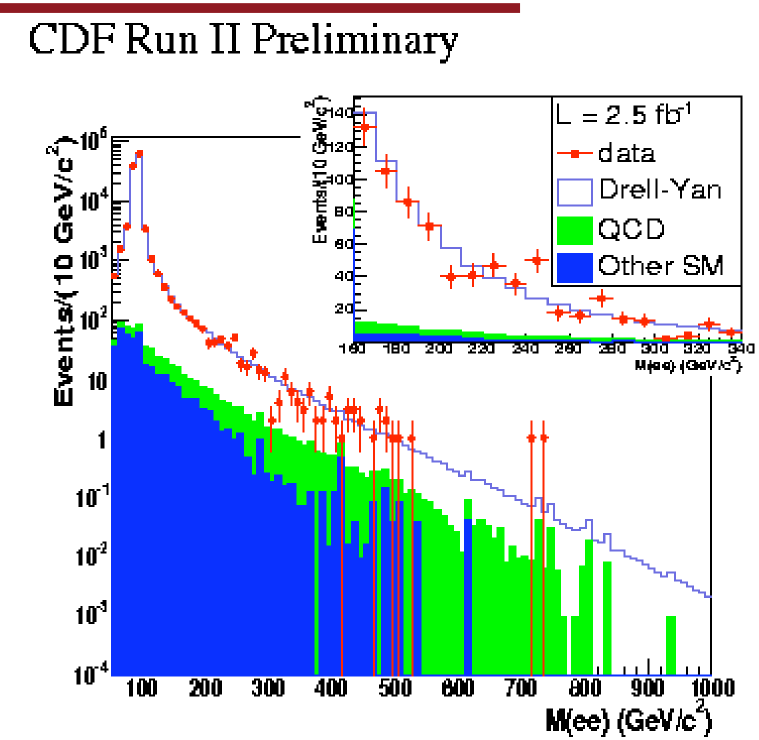
ATL-PHYS-PUB-2005-010

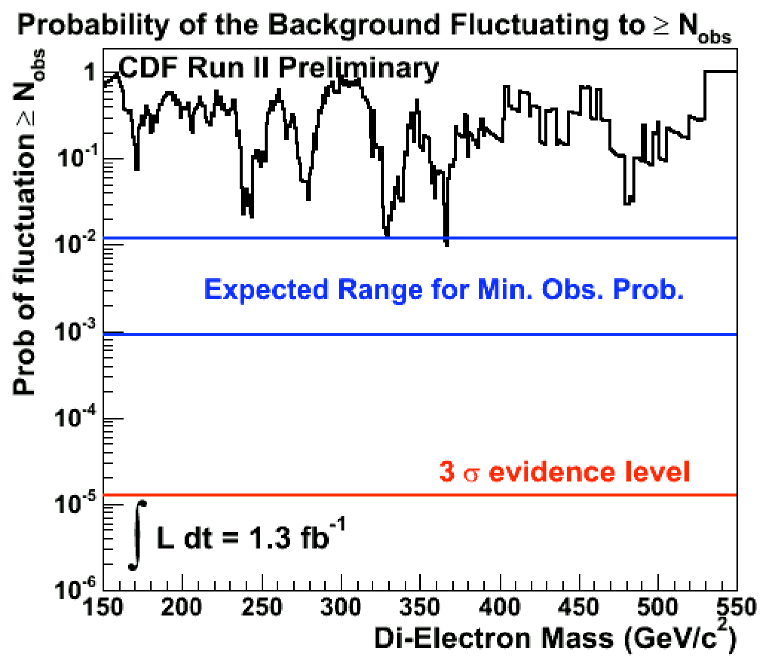




“Look Elsewhere” Effect

- If search is done by counting experiment in a shifting mass window, need to factor in “look elsewhere” effect (# of windows)
  - Always an excess if look at sufficient distributions…
- Global fit to the (DY) spectrum is another approach
  - Let fit find the mass
  - Shape analysis more sensitive
- Need to run pseudo-experiments!

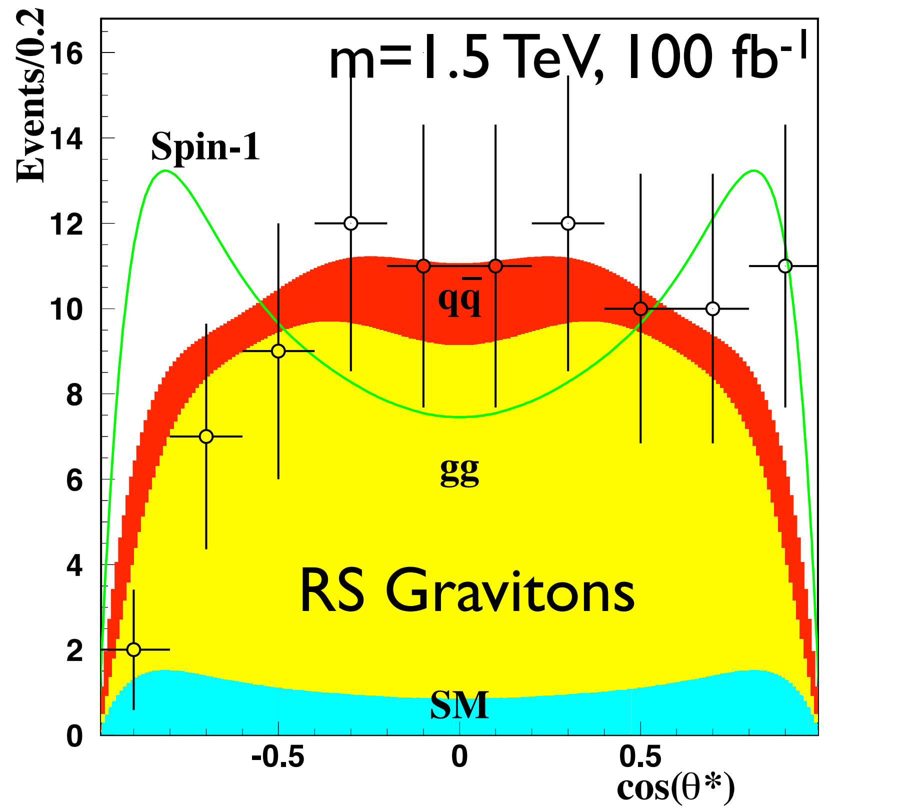




Spin Determination

- Look at angle between lepton and beam direction
  - Spin 1 particles tend to emit leptons closer to beam
- Plot is potentially optimistic: sensitivity is in the forward region where lepton identification not nearly as efficient or pure
  - But for heavy resonances decay products are central…

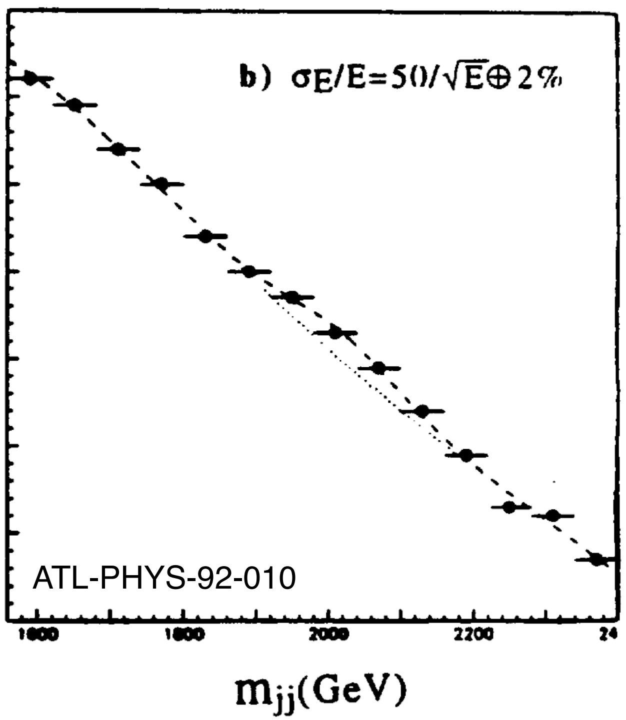
B. Allanach et al, JHEP 0009:019,2000

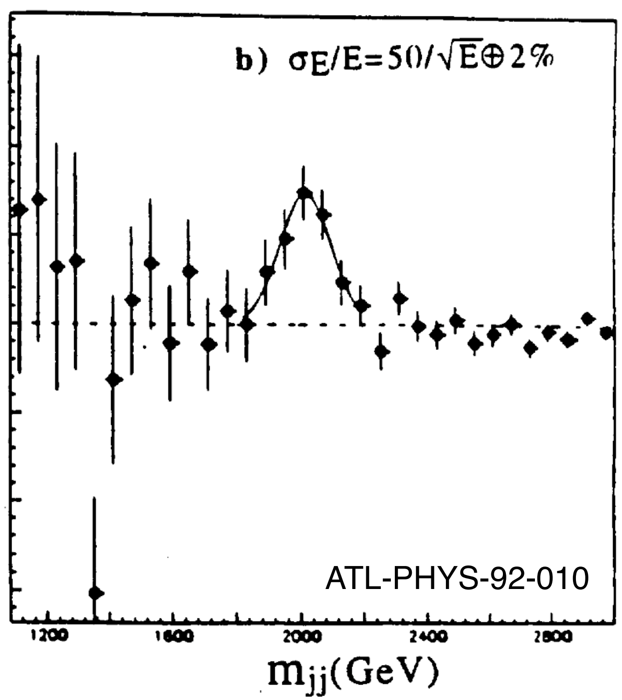


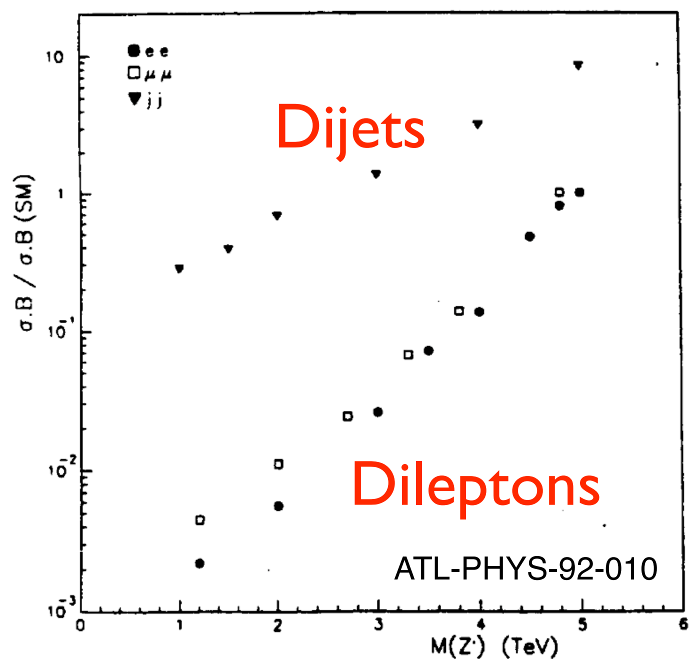
Z'/W' → jj

- In the dijet channel, the backgrounds are obviously much larger
  - But not necessarily unmanageable: DØ published a Run 1 search for resonances in the dijet channel

(PRD Rapid Comm. {69}, 111101 (2004))

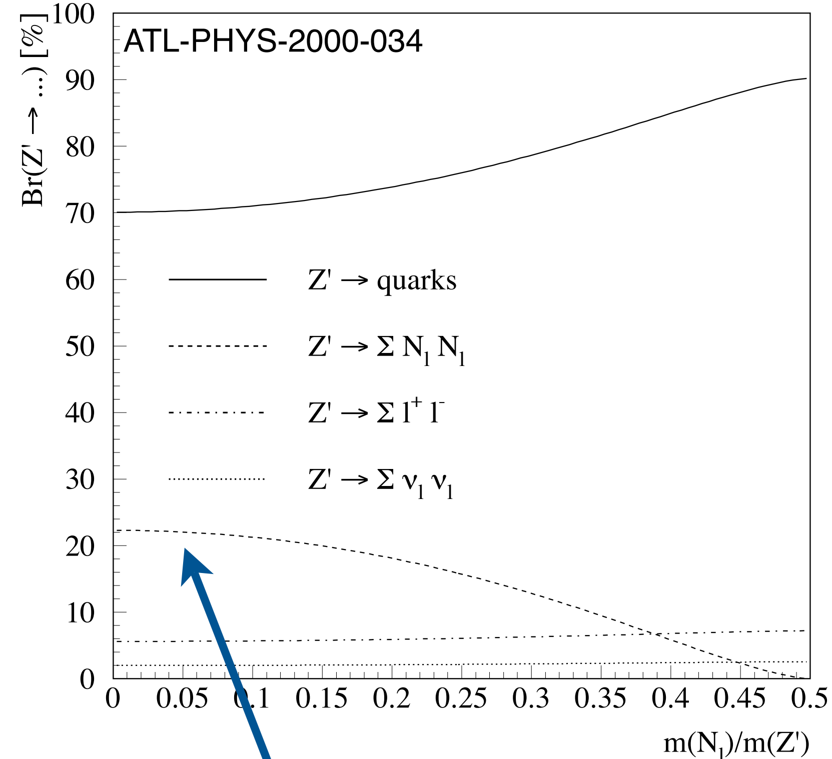






$Z' \rightarrow \nu_R \nu_R$

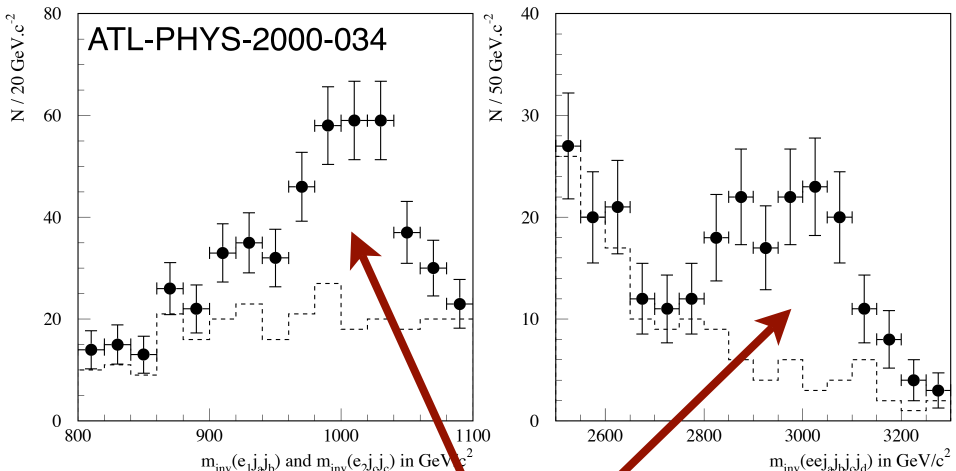
- If ν_R is lighter than m(Z')/2, decay channel opens up
- ν_R subsequently decays to lW_R^* (assuming W_R is heavier than ν_R), leading to signature with two leptons and 4 jets
  - Or other combinations if $m(\nu_R') < m(\nu_R)$, for example more leptons
  - Since ν_R is majorana, can get same-sign leptons!



If ν_R is light, lepton and jets collimated → leptons embedded in merged jets

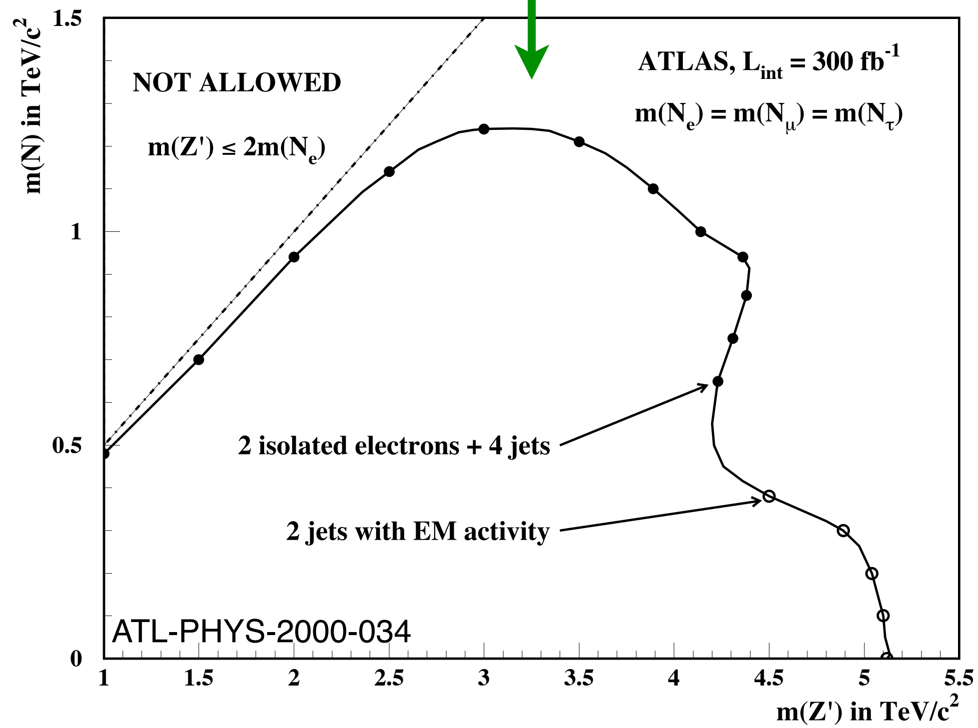
$Z' \rightarrow \nu_R \nu_R$ (2)

- Backgrounds include $t\bar{t}$, ZZ, ... + jets, but also W_R!



Reconstruction of ν_R (ejj) and Z' (eejjjj) masses

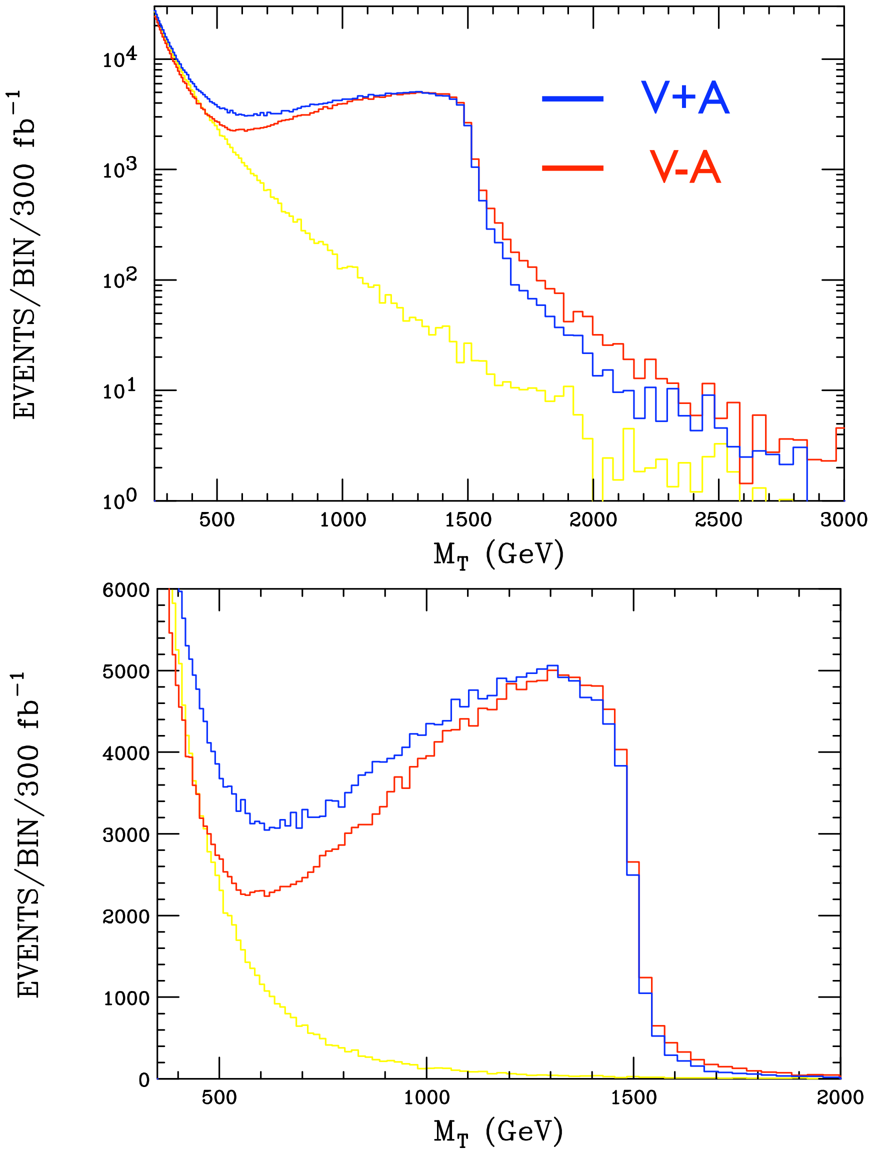
Discovery Potential



W' Production

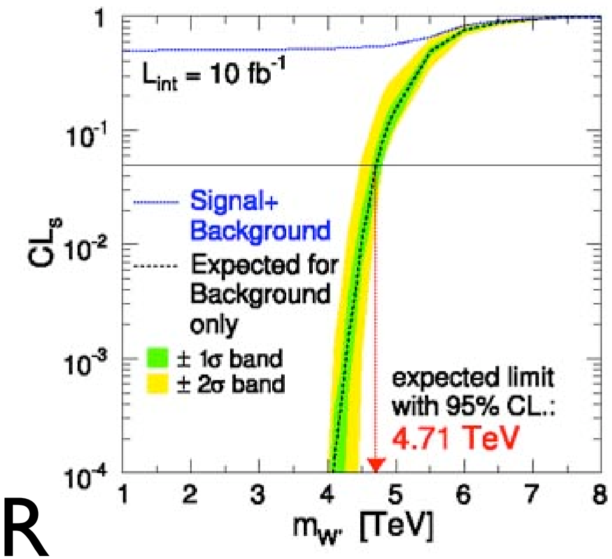
- W' production rate not very dependent on couplings
- But interference with W important (and not in most experimental studies)!
  - Key in identifying W' coupling helicity in fact
- (This plot is for e+MET transverse mass, which may not be a signature)

T. Rizzo, hep-ph/0704.0235

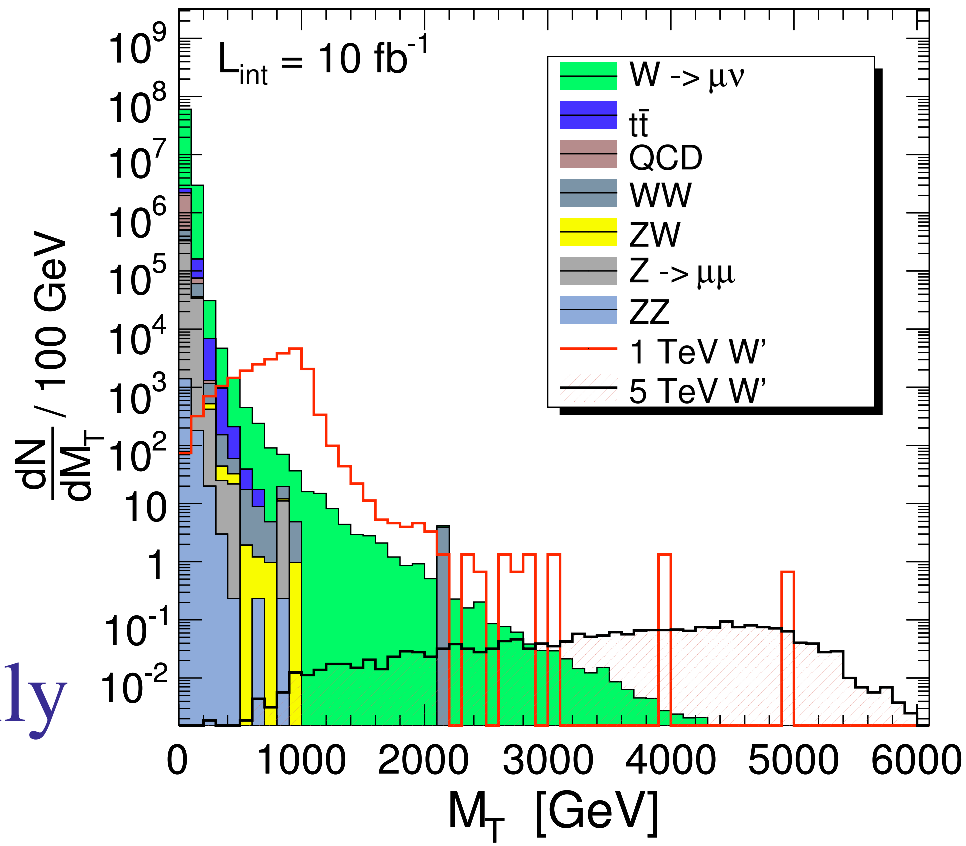


$W' \rightarrow \mu\nu_{(R)}$

- SSM W'
  - "Standard" M_T plot
- Discovery reach ~4.5 TeV with 10 fb^{-1}
- Similar reach with electrons
  - Note very different resolution effects in electrons vs muons
- Decay does not necessarily exist!



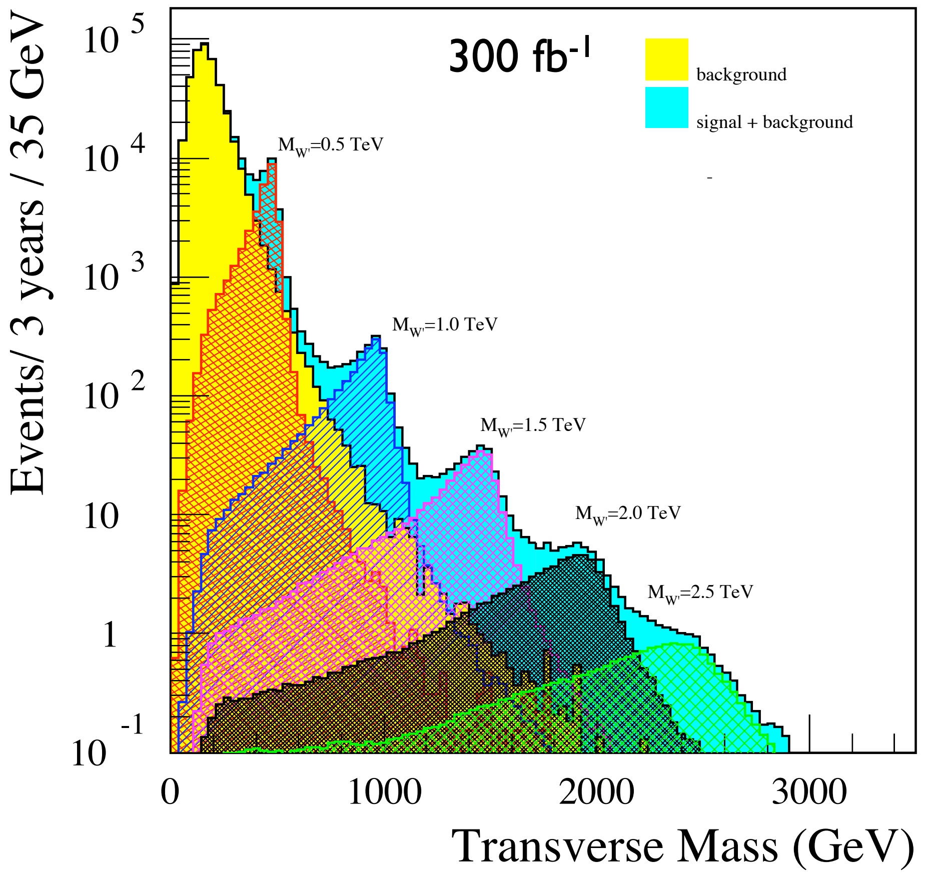
CMS TDR



W’ → WZ

- Require at least one of the W, Z to decay leptonically to suppress backgrounds
  - Then use mass constraints to improve S/B further
- Cleanest channel is obviously when both decay leptonically (but BR only 1.4%)
  - LR model study by ATLAS
  - (Also a technicolor signature, probably at lower mass)

ATL-PHYS-2001-005

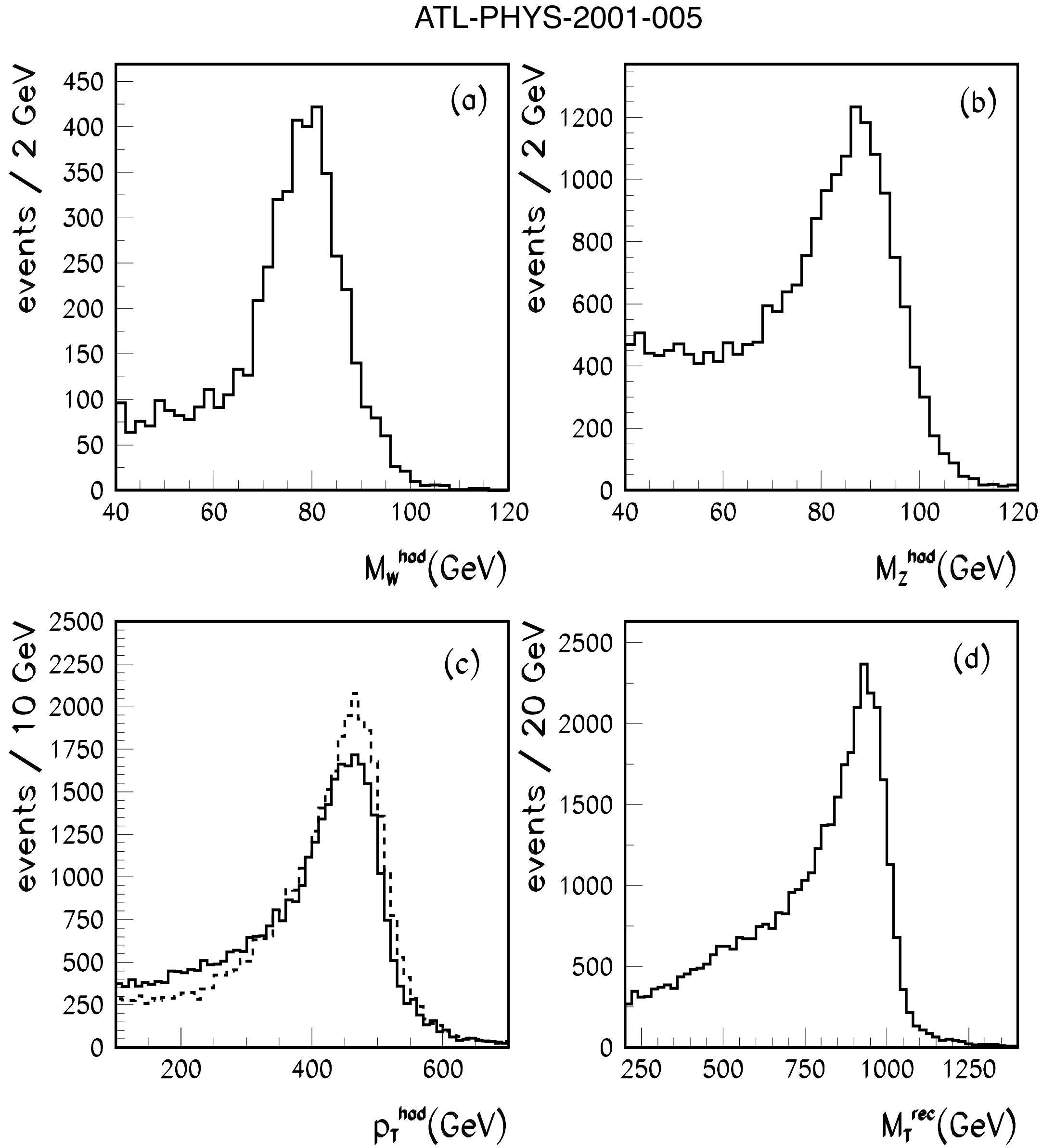


-Trileptons at low mass

-Lepton(s) + jets for high mass reach

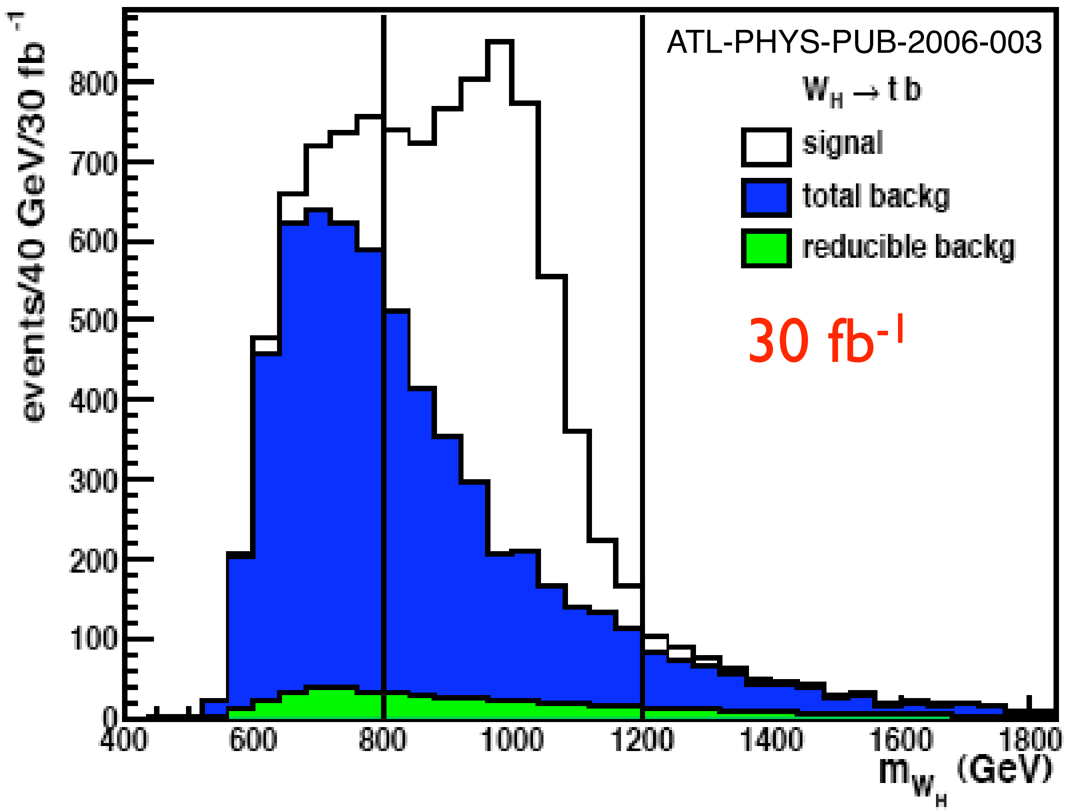
W' → WZ (2)

- If allow one boson to decay hadronically, higher BR (4.6/15%) but higher backgrounds
  - Hadronically decaying boson has large boost, so jets are merged → rely on jet mass
  - W/Z + jets background not well known



W' → tb

- ATLAS fast simulation study
  - Use of very high p^T b-tagging
    - B meson decays *outside* firs pixel layer!
    - High p^T top (more later)
- Overall, could already make a (BR) statement very early on
  - Important clue!

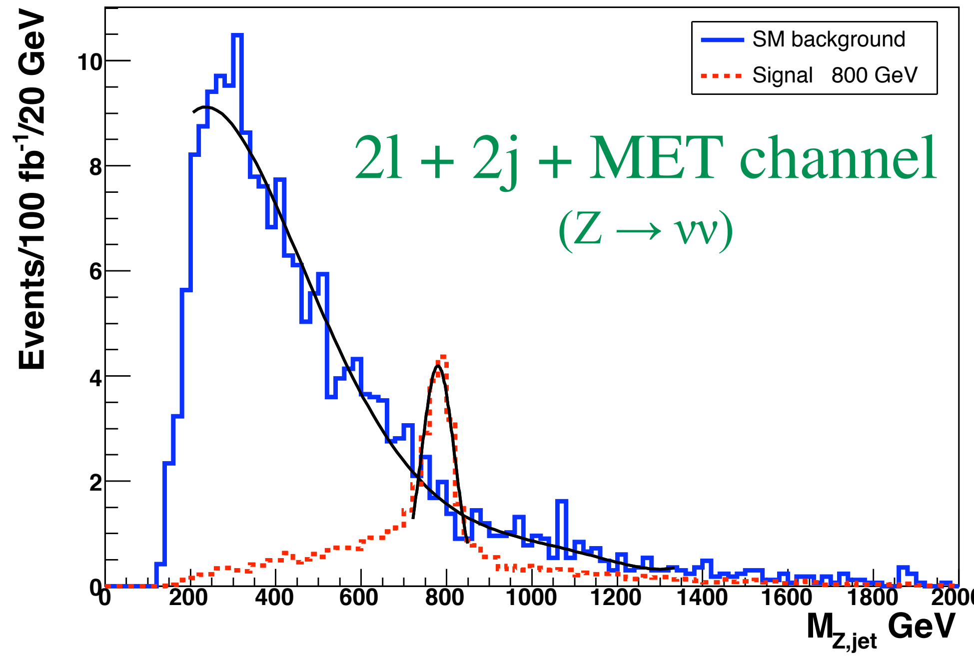


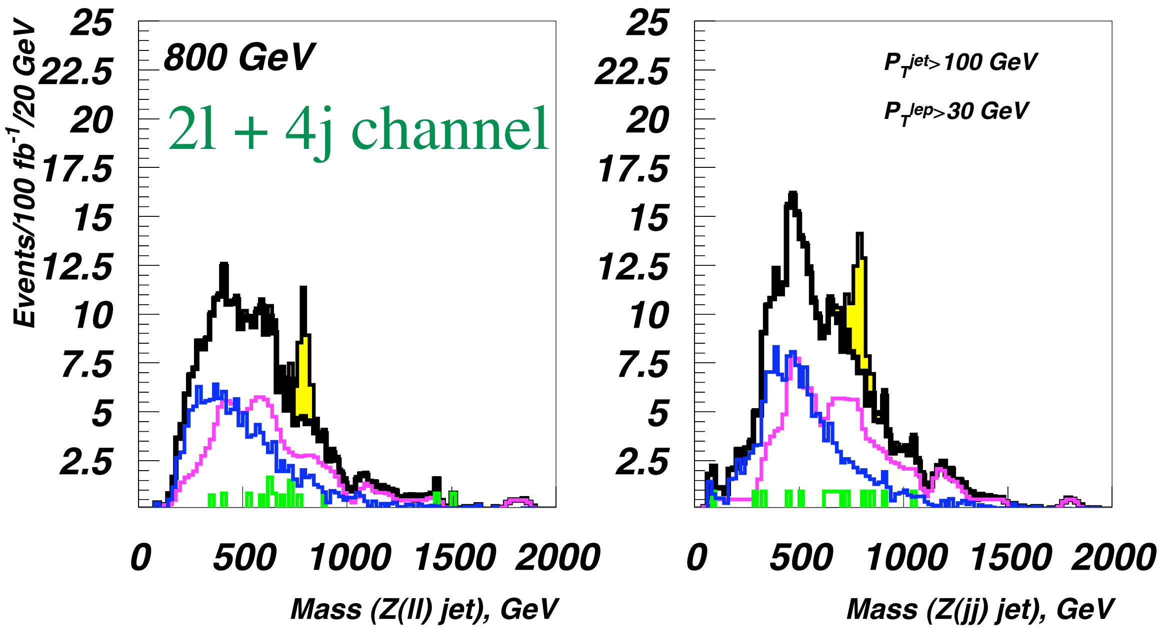
Note: This is for W_H from Little Higgs

Exotic Quarks

ATL-PHYS-PUB-2007-012

- In most cases, existence of a Z' requires existence of new fermions to cancel anomalies
    - Exotic leptons or quarks
- Quarks could be pair-produced, then decay
    - $D \rightarrow Zd,\ D \rightarrow Wu$
    - Then require one or both W/Z to decay leptonically





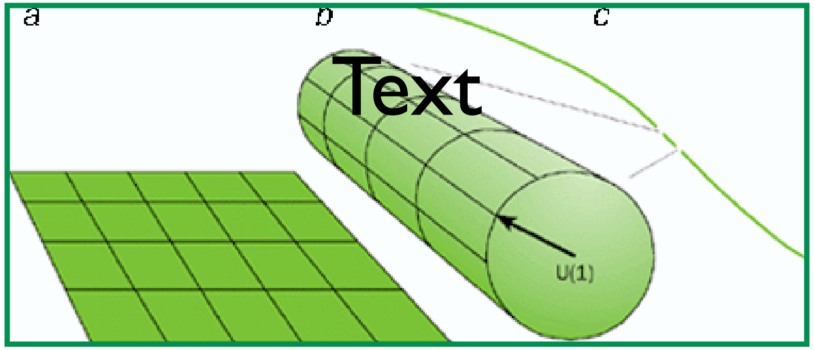
Gravity and Hierarchy

(or: Out of This World?)

Extra Dimensions

- A promising approach to quantum gravity consists in adding extra space dimensions: string theory
  - Additional space dimensions are hidden, presumably because they are compactified

Source: PhysicsWorld

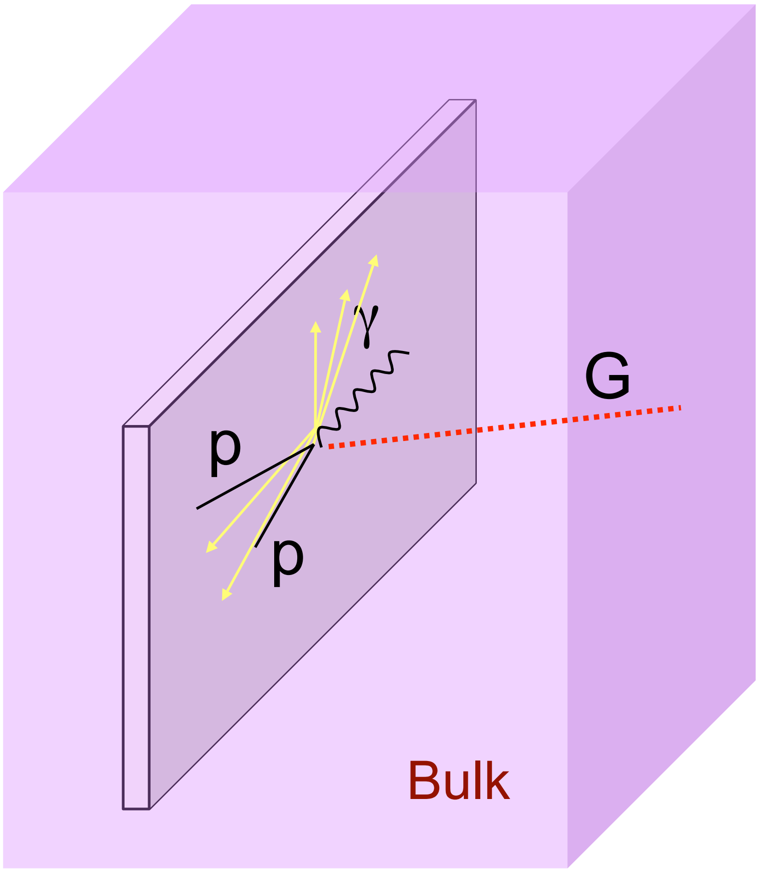


- Radius of compactification usually assumed to be at the scale of gravity, i.e. 10^{18} GeV
  - In '90 Antoniadis realized they may be much larger...

Phys.Lett.B246:377-384,1990

"ADD"

- "Large extra dimension" scenario (developed by Arkani-Hamed, Dimopoulos and Dvali):
  - Standard model fields are confined to a 3+1 dimensional subspace ("brane")
  - Gravity propagates in all dimensions
  - Gravity appears weak on the brane because only felt when graviton "goes through"

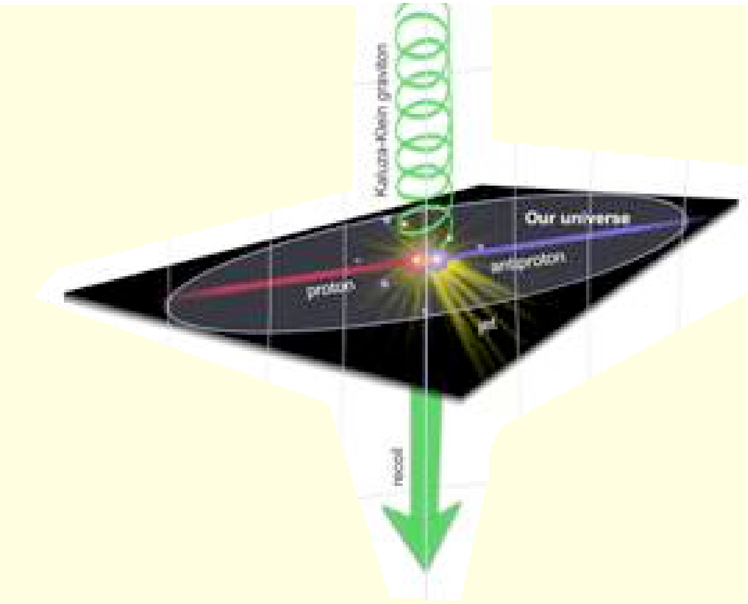


Drawing by K. Loureiro

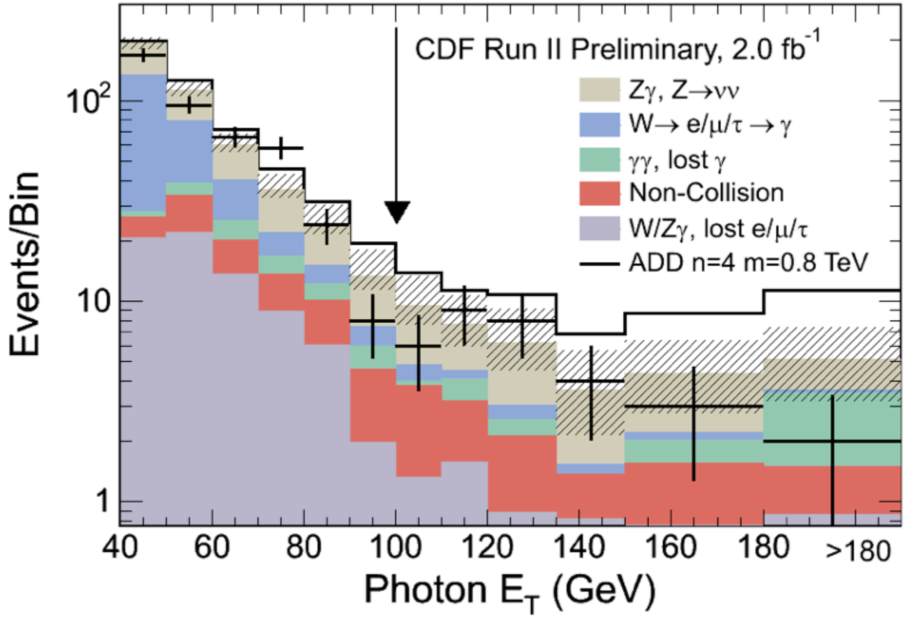
ADD Signatures

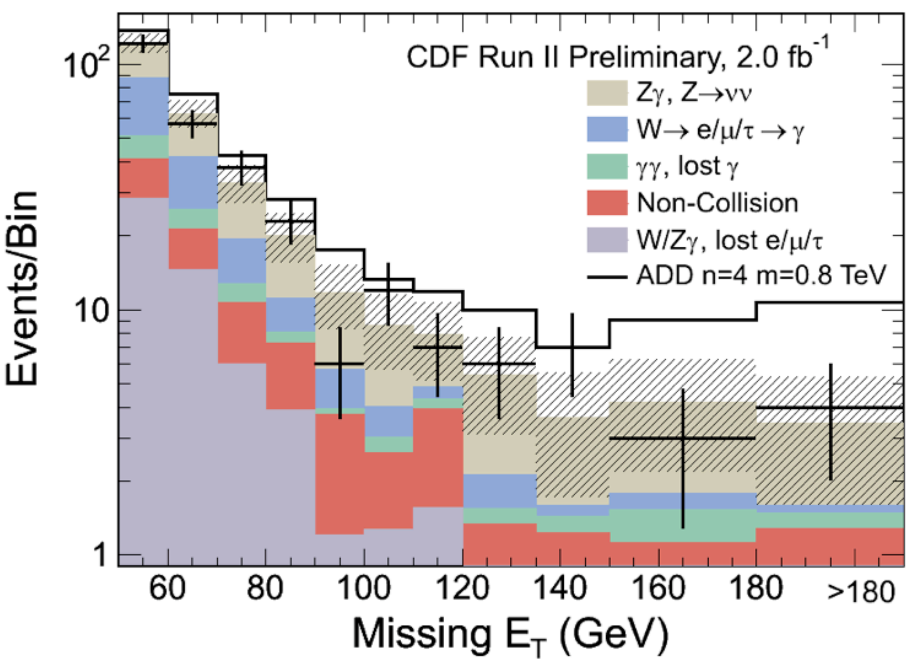
- Edges of extra dimensions identified
  - ➡ Boundary conditions
  - ➡ Momentum along extra dimension is quantified
  - Looks like mass to us
  - Very small separations → looks like continuum
  - Called Kaluza-Klein tower
- Coupling to single graviton very weak, but there are *lots* of them!
  - Large phase space → observable cross-section
    - Impacts all processes (graviton couples to energy-momentum)

- Consider processes that involve the bulk (i.e. gravitons)
  - Translational invariance is broken
    - ➡ Momentum is not conserved ...
    - ... because graviton disappears in bulk right away
- Look for p p → jet/photon + nothing (i.e. $\not{E}_T$), or deviations in high mass/angular behavior in standard model processes
  - Graviton has spin 2, couples to energy-momentum!
- Limit size of ED at ~1 TeV

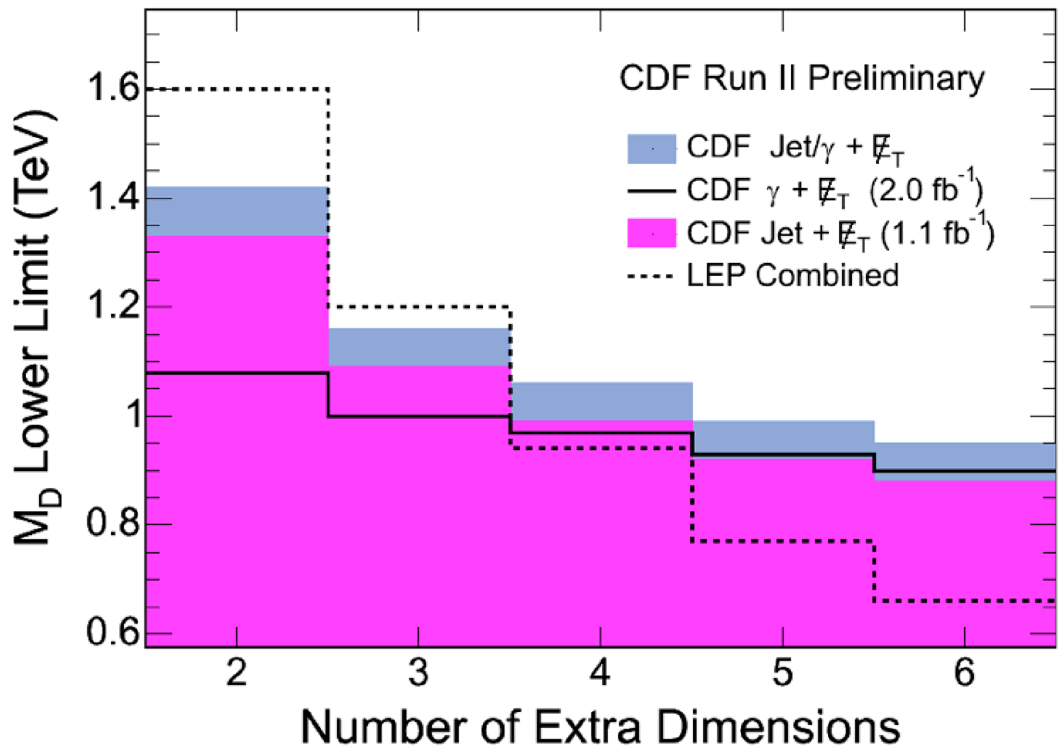


Jet/Photon + Graviton

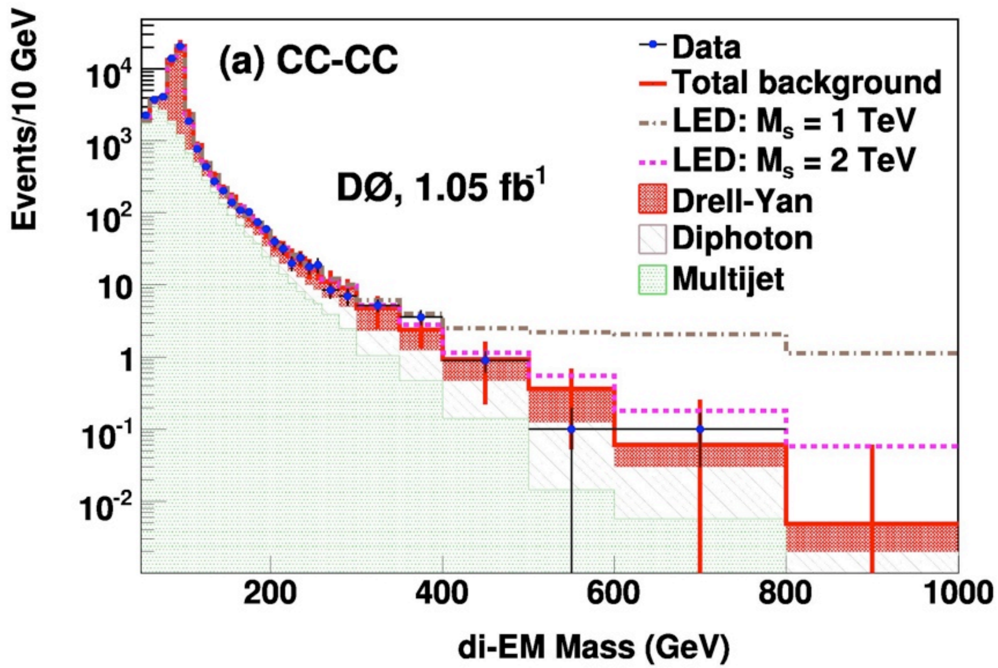


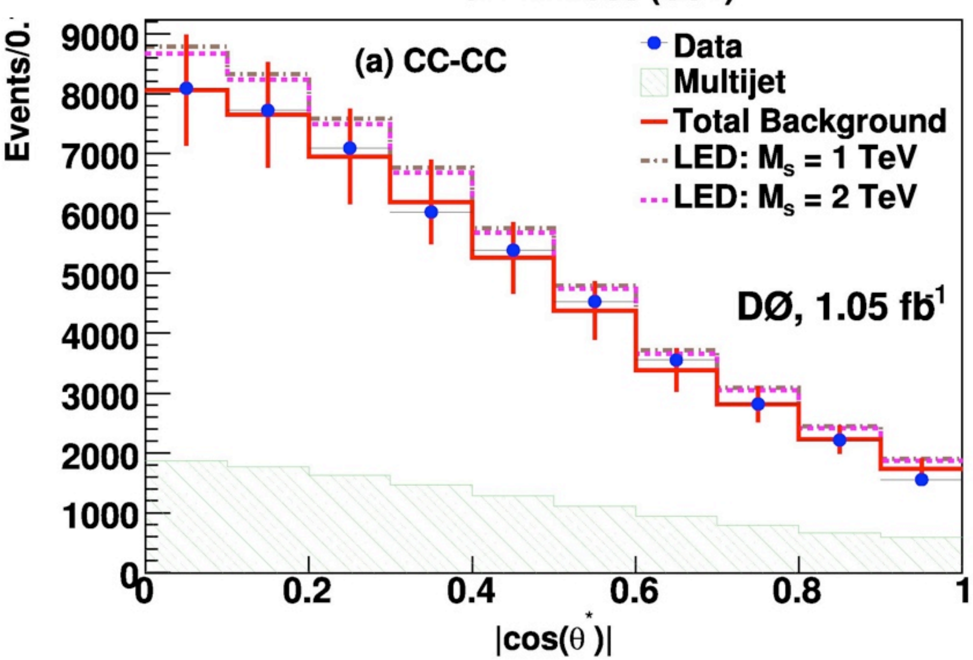


Jet/Photon + MET Combined Limit (Based on event counting only)

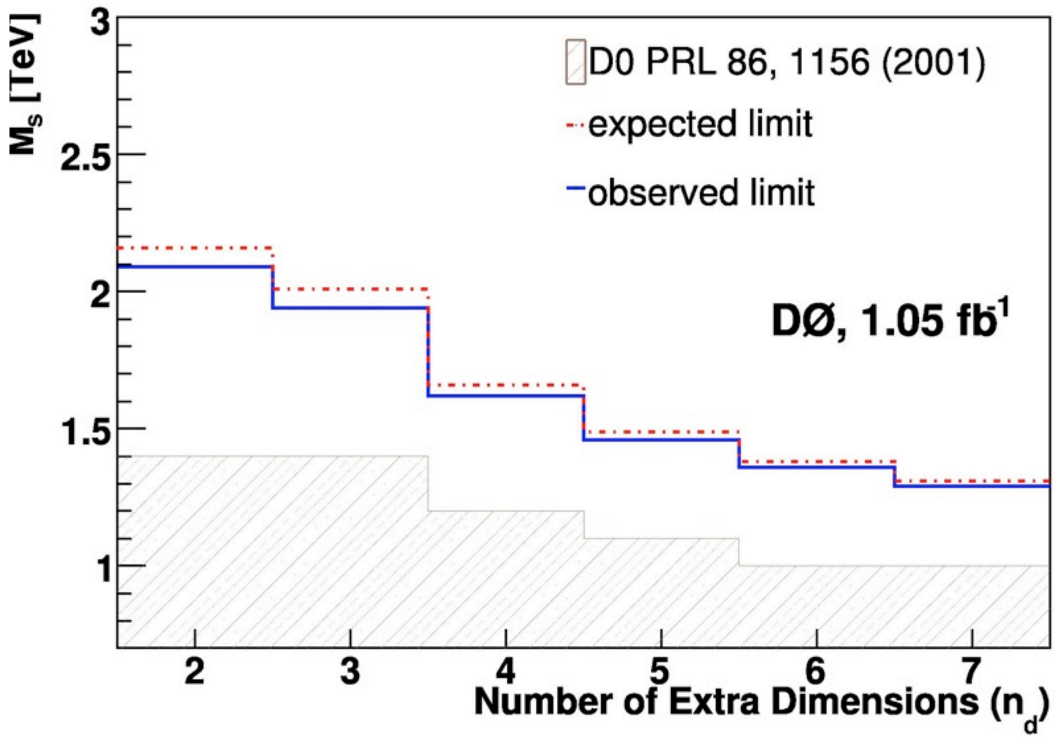


Dielectrons and Diphotons



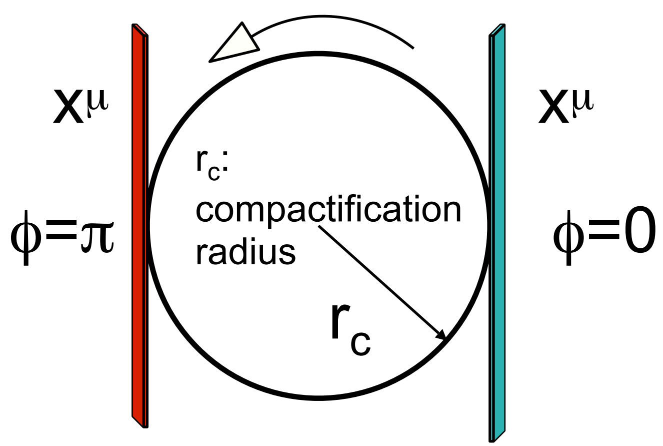


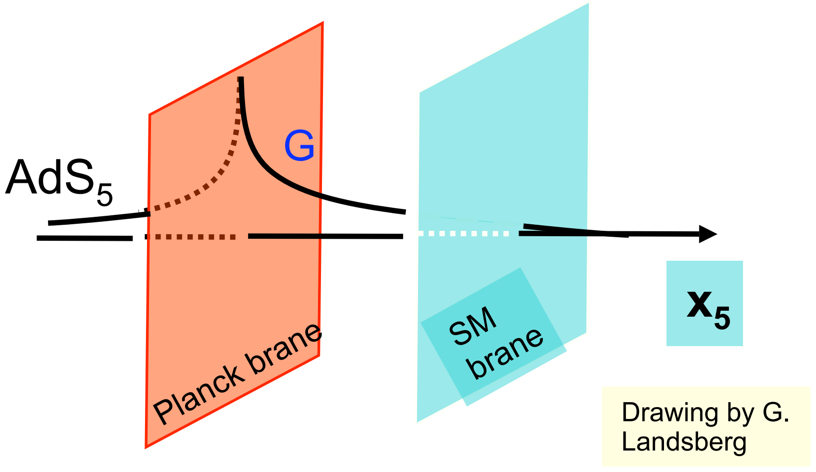
~10% of sensitivity from angular distribution



Warped Extra Dimensions

- "Simple" Randall-Sundrum model:
  - SM confined to a brane, and gravity propagating in an extra dimension
  - As opposed to the original ADD scenario, the metric in the extra dimension is "warped" by a factor $\exp(-2kr_c\phi)$
  - (Requires 2 branes)



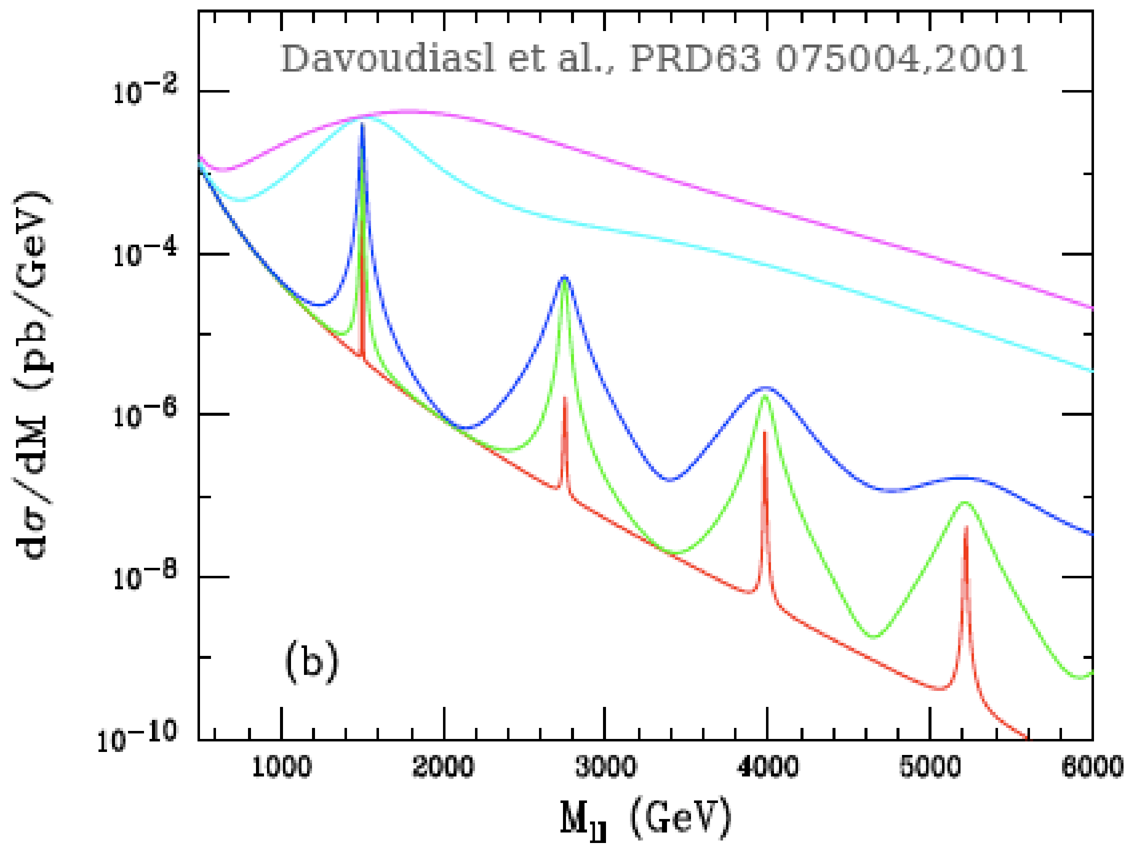


Graviton Excitations

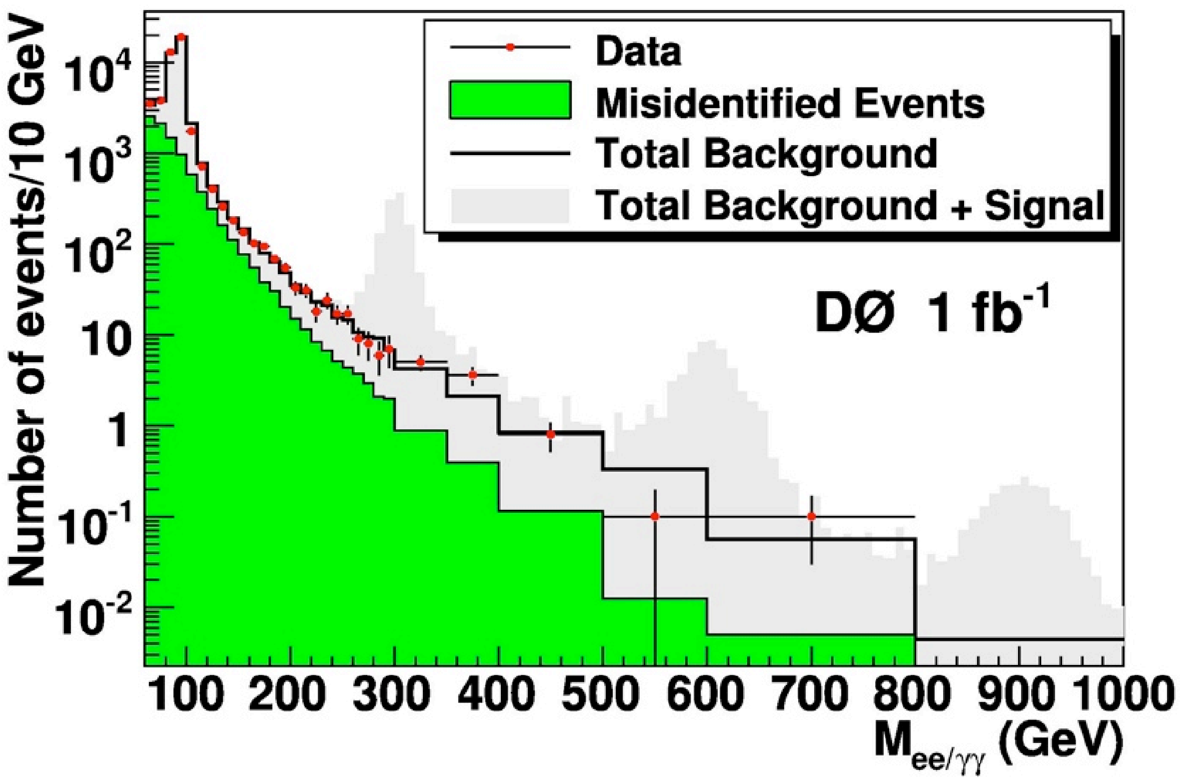
- In RS, get a few massive graviton excitations
  - Widths depend on warp factor k
  - Mass separation = zeros of Bessel function

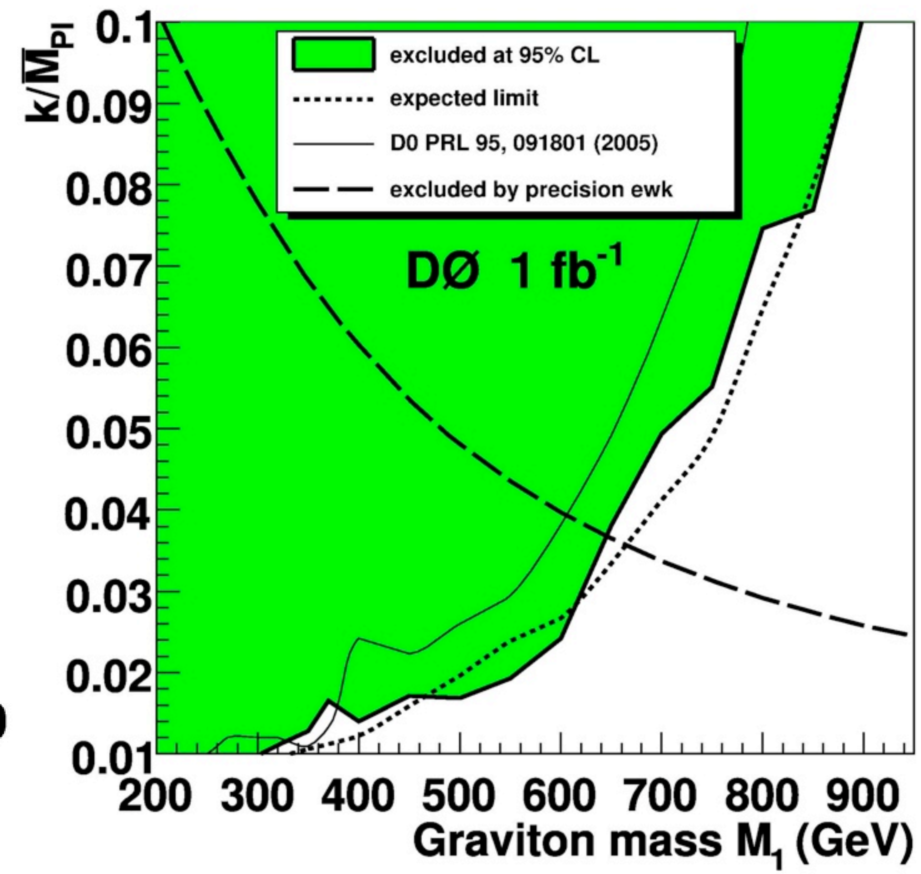
➡ Smoking gun!

(BRs also different than Z':
e.g. γγ allowed)



Dielectrons/Diphotons

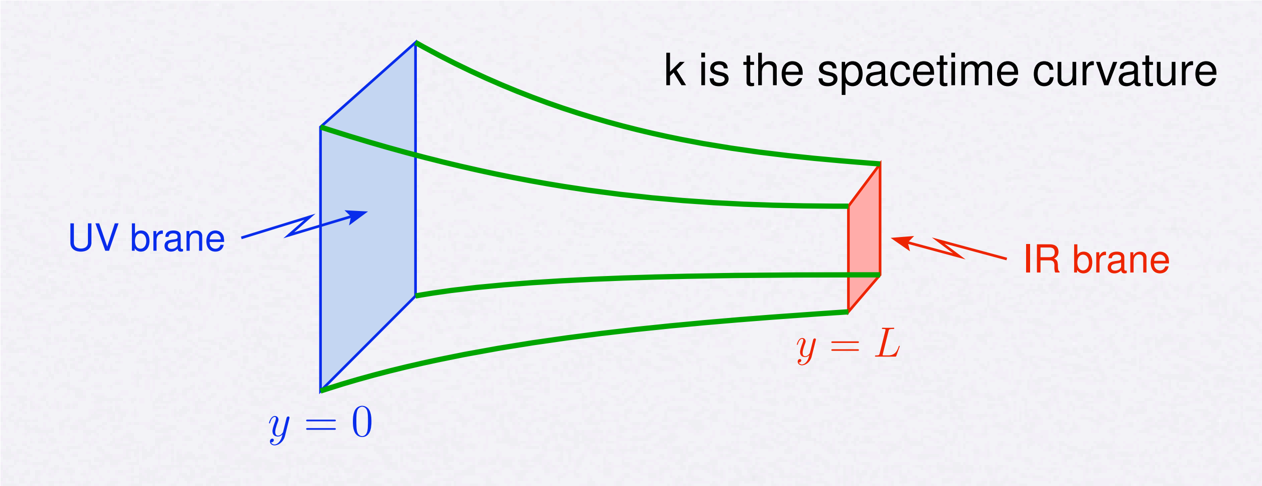




- Single search: no attempt to distinguish electrons from photons...

Hierarchies

- Physics on a curved gravitational background:



- Scales depend on position along extra dimensions
  - UV brane scale is $M_{Pl} = 2 \times 10^{18}$ GeV
  - IR brane scale is $M_{Pl}\, e^{-kL} \sim 1$ TeV if $kL \sim 30$
- If were to localize Higgs on IR brane, naturally get EW scale ~ 1TeV (from geometry!)

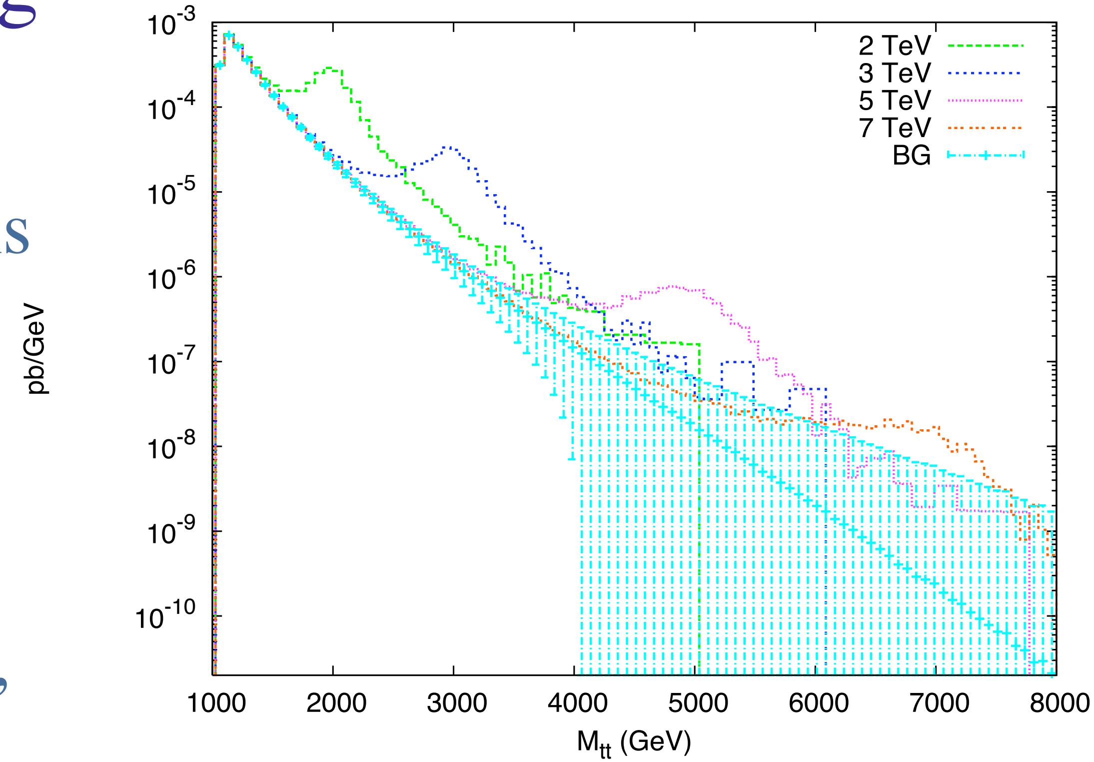
Flavor

- Interesting variation has fermions located along the extra dimension
  - Fermion masses generated by geometry
  - Heavier fermions are closer to IR brane, and gauge boson excitations as well
    - Gauge boson excitations expected to have masses in the 3-4 TeV range (bounds from precision measurements)
    - Couple mainly to top/W/Z (!)
  - Flavor changing determined by overlap of fermion "wave function" in the ED
    - Nice suppression of FCNC etc.

Gauge Boson Excitations

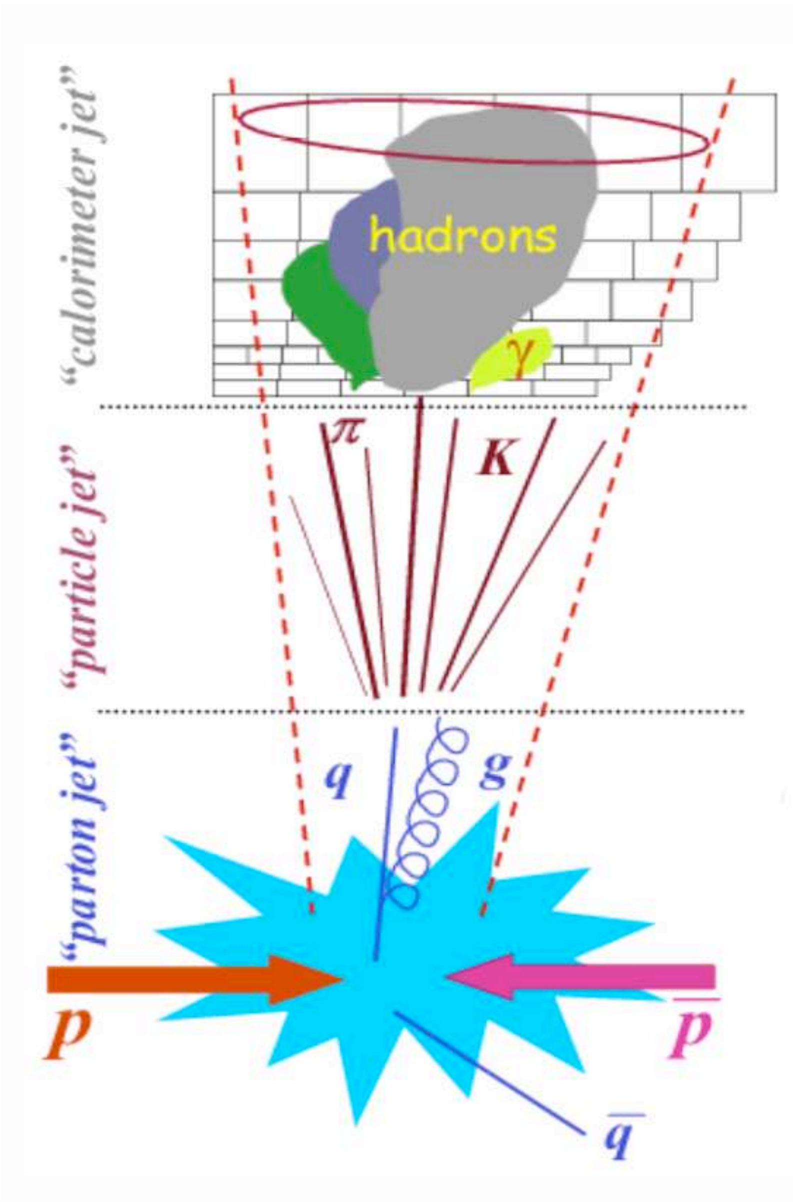
- Excitations of the gauge bosons are very promising channels for discovery
  - Couplings to light fermions are small
    - Small production cross-sections
  - Large coupling to top, W_L, Z_L
    - Look for $t\bar{t}$, WW, ZZ resonances (that can be wide)

B. Lillie et al., JHEP 0709:074,2007



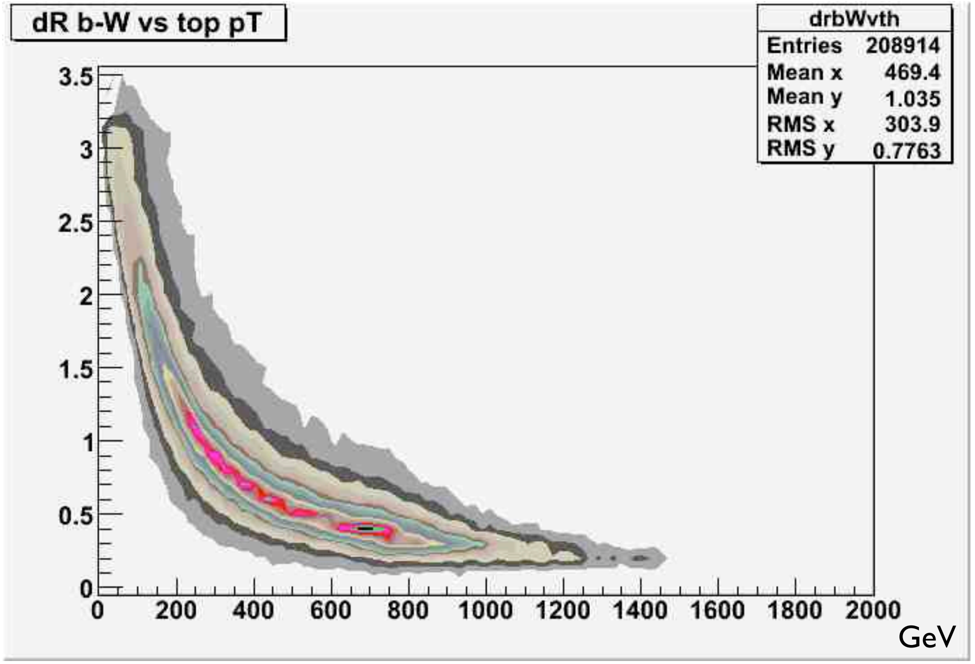
New Experimental Phenomenology

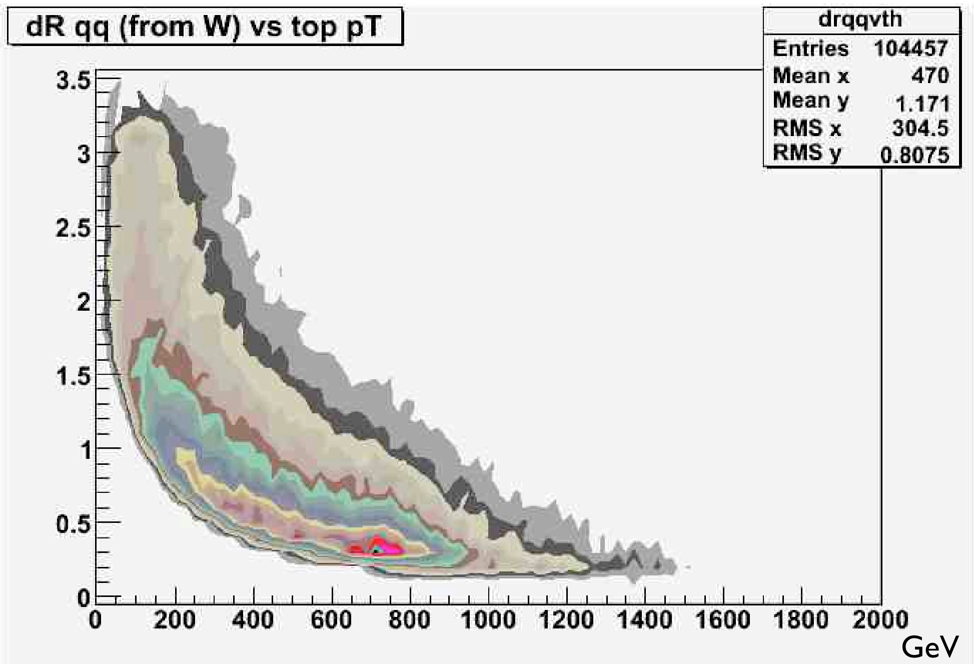
- Possibility to produce heavy resonances decaying to top quarks, W and Z bosons
  - Heavy objects with momentum >> mass
    - Decay products collimated
  - For leptonic W/Z decays, not a big issue since we measure isolated tracks very well
  - But hadronic decays lead to jets, which are intrinsically wide



Top Quark Decays

- Simulated decays:
  - $dR = \sqrt{(\Delta\eta^2 + \Delta\phi^2)}$
  - Typical jet radius ~0.5
  - LHC calorimeters have granularity 0.1 x 0.1 or better
- For top p_T > ~300 GeV
  - dR ($q\bar{q}$' from W) < 2 R_{jet}
  - dR (bW) < 2 R_{jet}
    - (No isolated lepton!)





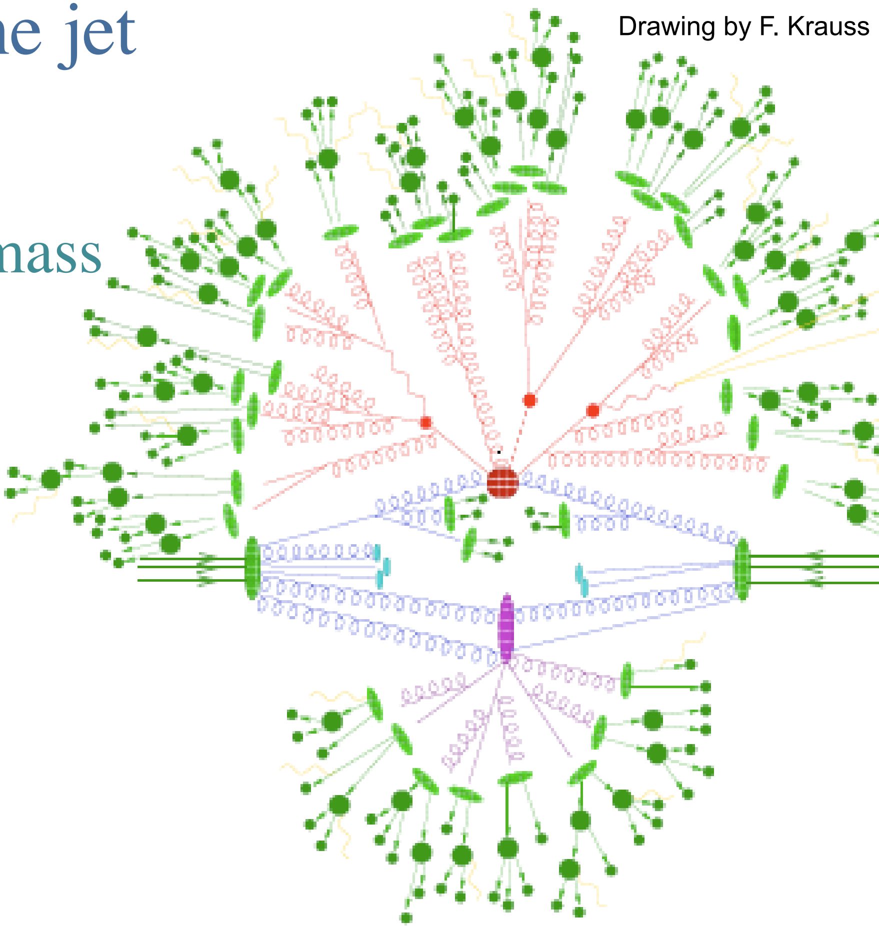
ATLAS Study

- Can we distinguish hadronic & semileptonic decays of high p_T top quarks from light/b jets?
  - Develop tools and evaluate efficiency/rejection
- Use fully simulated samples of:
  - Z' → $t\bar{t}$ events with m(Z') = 2 and 3 TeV
    - Yields top quarks with 500 GeV $< p_T <$ 1500 GeV
    - (Not many in "transition region": 200-600 GeV)
  - QCD multijet events with 280 GeV $< p_T <$ 2240 GeV
    - Generated in 3 bins of p_T

Fully Hadronic Decays

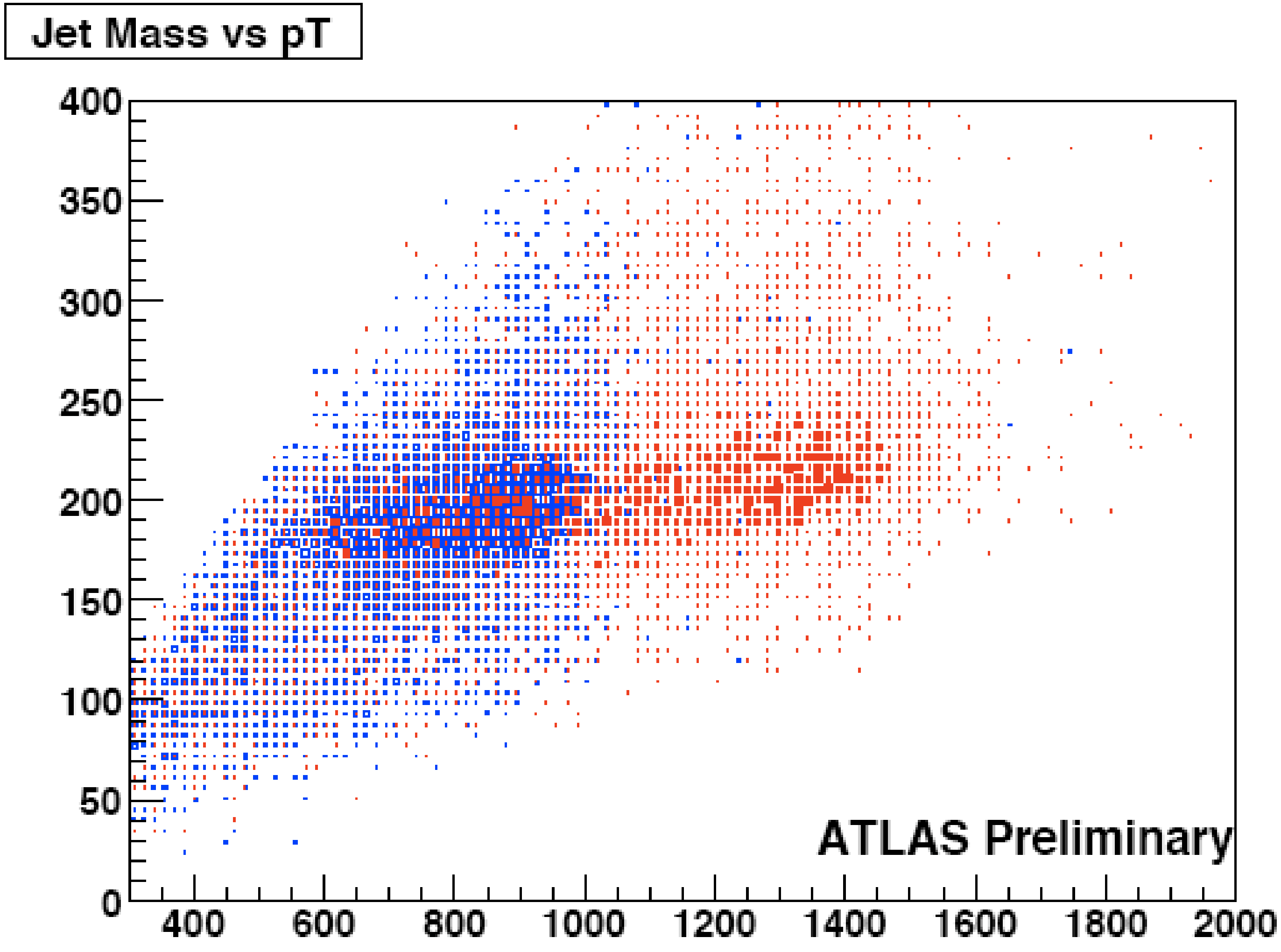
- Decay hadrons reconstructed as a single jet
  - But even if it looks like a single jet, it originates from a massive particle decaying to three hard partons, not one
- If I measured each of the partons in the jet perfectly, I would be able to:
  - Reconstruct the "originator's" invariant mass
  - Reconstruct the direct daughter partons
- But
  - Quarks hadronize → cross-talk
  - My detector can't resolve all individual hadrons

Drawing by F. Krauss



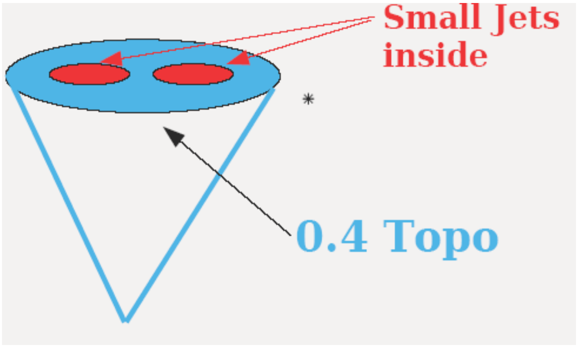
Jet Mass

- Jet mass: invariant mass of all jet constituents
  - In principle, ≥ top quark mass



Subjets

- Jet mass is not sensitive to structure
  - Can't tell whether a jet is isotropic or not
- Expect "blobs" with higher concentration of energy for jets from top/W/Z decays



- Multiple ways of exploiting this....
  - This study: k_T splitting scales

J. M. Butterworth, B. E. Cox, and J. R. Forshaw, *Phys. Rev.* **D65** (2002) 096014

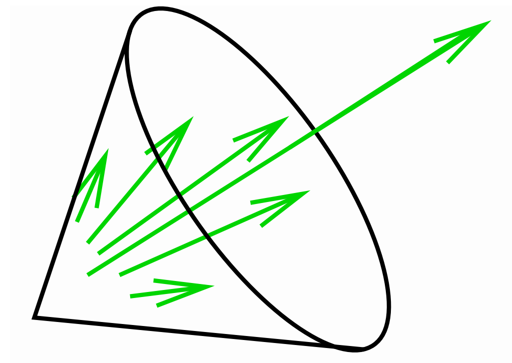
k_T Splitting Scales

- k_T jet algorithm is much better suited to understand jet substructure than cone:
  - Cone maximizes energy in an η x ϕ cone
  - k_T is a "nearest neighbor" clusterer

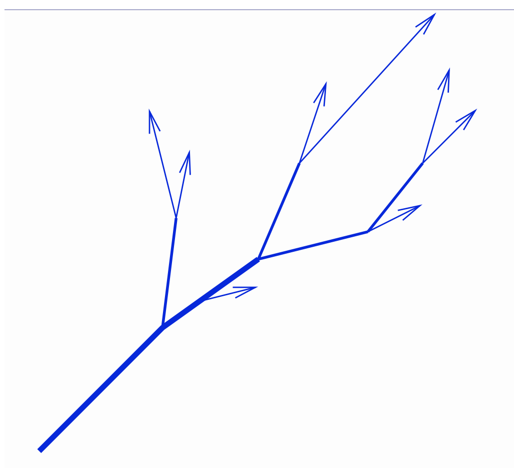
$$y_2 = \min\left(E_a^2, E_b^2\right) \bullet \theta_{ab}^2 / p_{T\,(jet)}^2$$

$$Y \text{ scale } = \sqrt{p_{T\,(jet)}^2 \bullet y_2}$$

- Can use the k_T algorithm on jet constituents and get the (y-)scale at which one switches from 1 → 2 (→ 3 etc.) jets
  - Scale is related to mass of the decaying particle

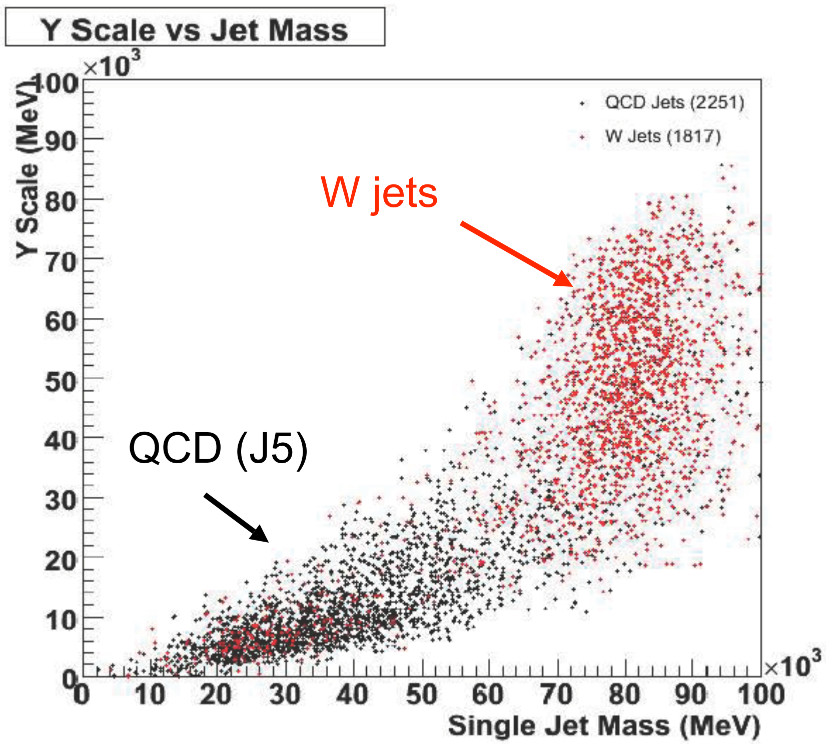


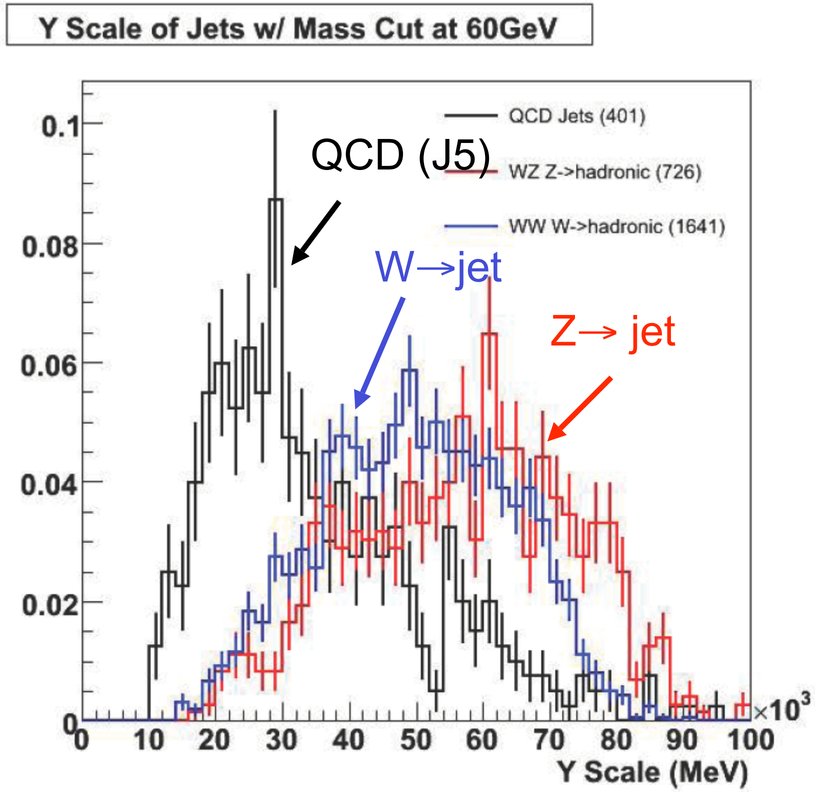
Cone



k_T

- Applied to high p_T WW scattering:



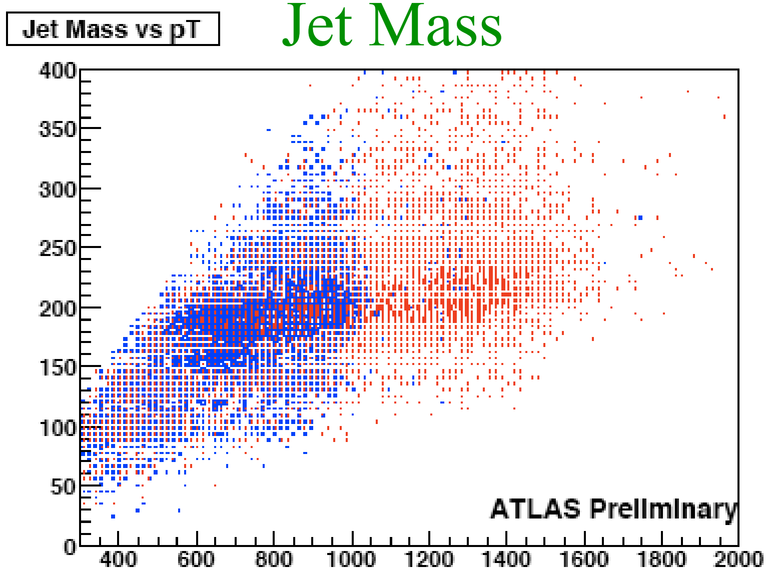


- k_T jet algorithm, with R = 0.5
- Cuts applied : p_T(jet) > 300 GeV,

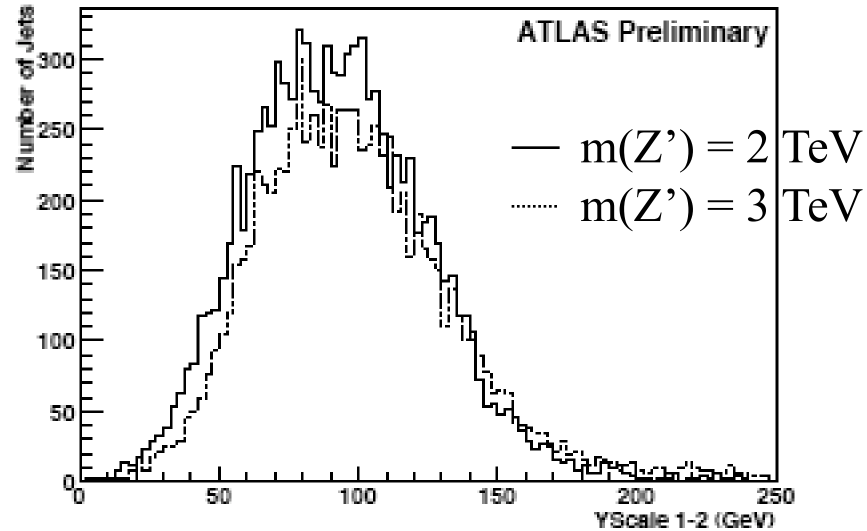
Techniques also believed to allow recovery of H → bb at LHC!

Variables

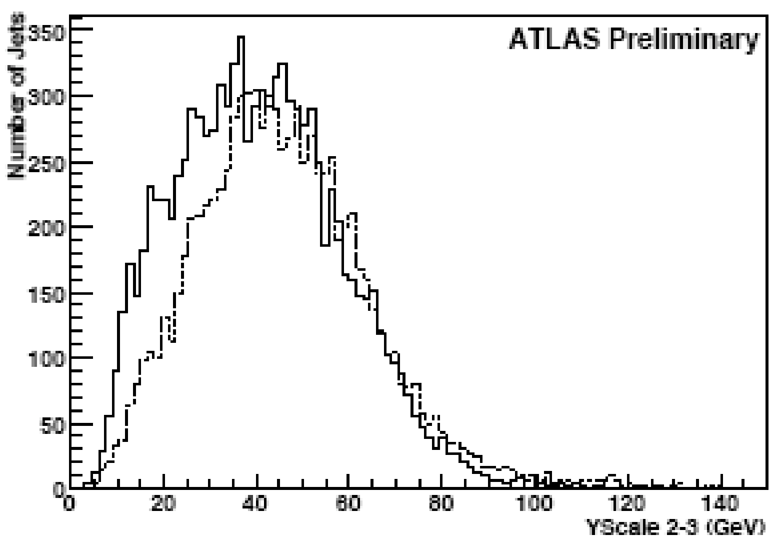
Jet Mass



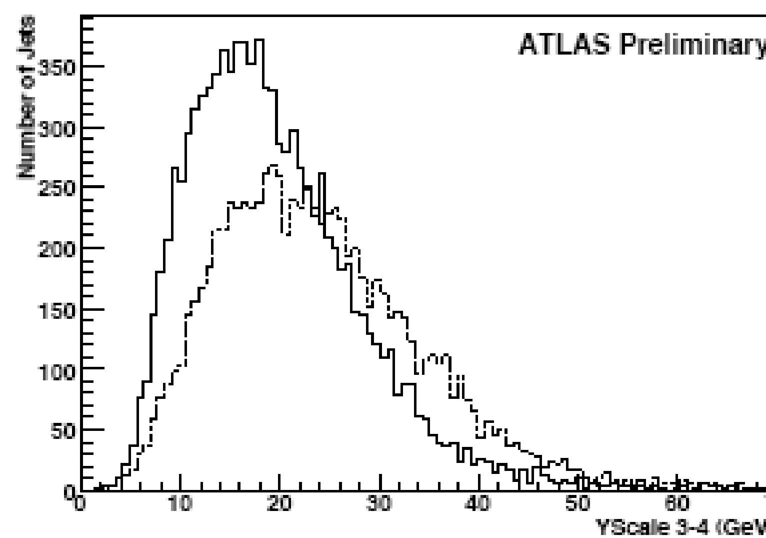
$1 \rightarrow 2$ Jet Scale



$2 \rightarrow 3$ Jet Scale



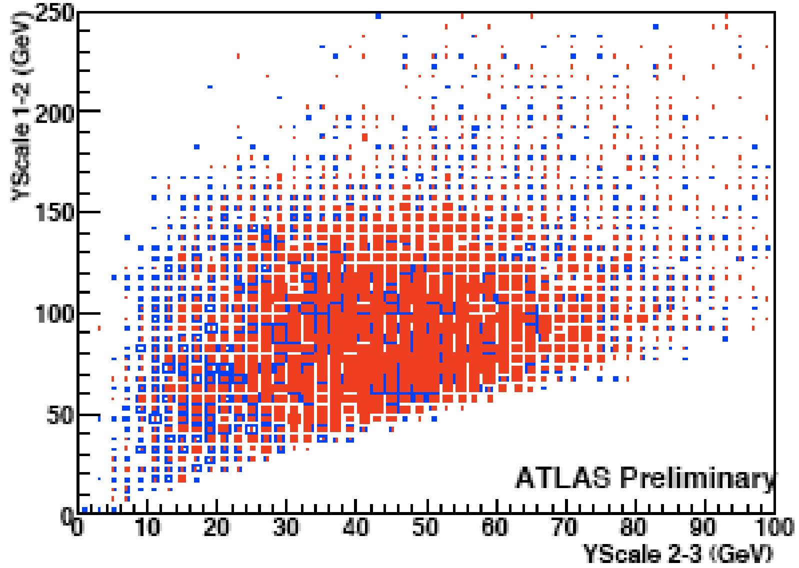
$3 \rightarrow 4$ Jet Scale



Slow p_T Dependence!

e

- Observations:
  - Variables show slow dependence on top (jet) p_T
  - Only weakly correlated



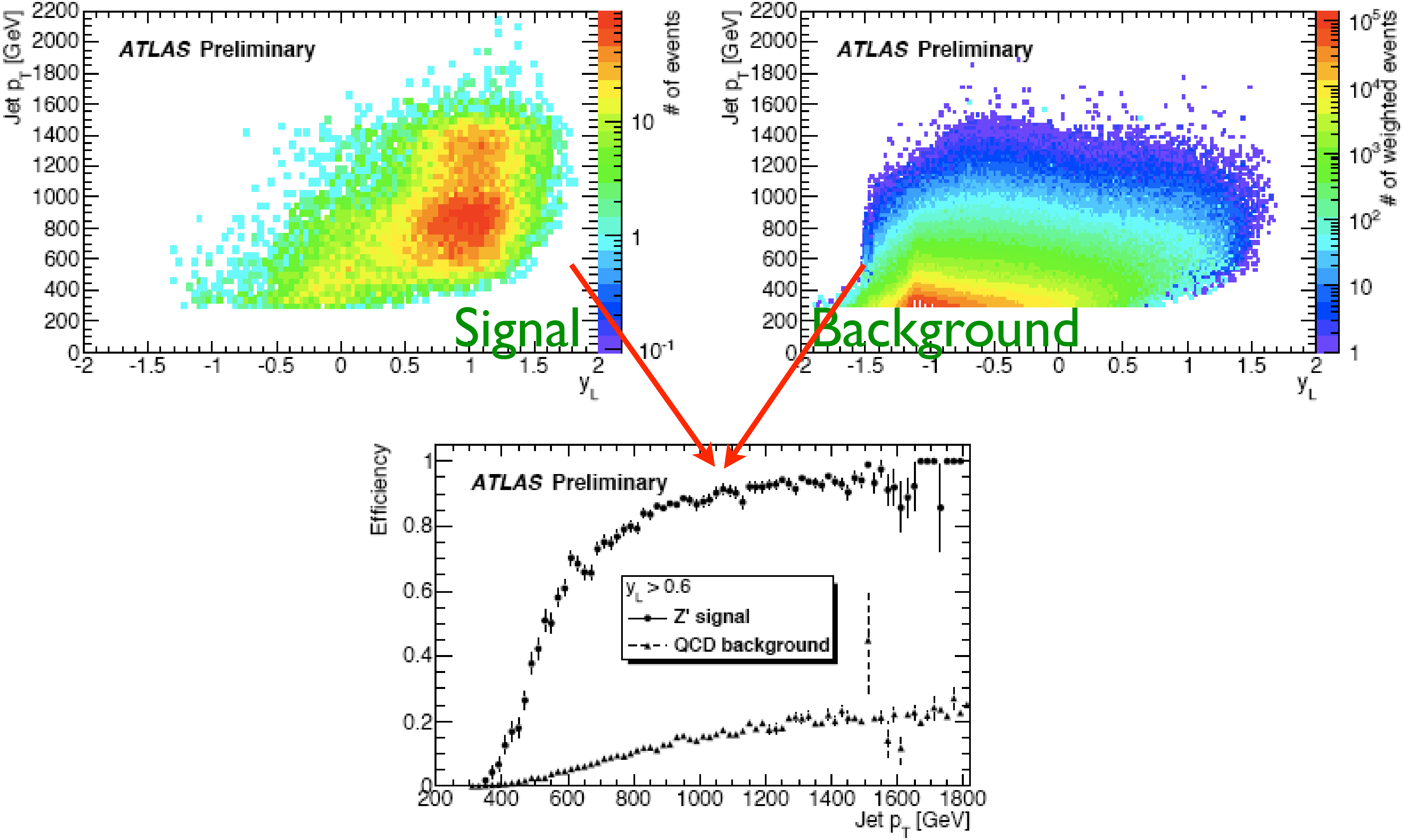
m(Z') = 2 TeV

m(Z') = 3 TeV

  - For light jets, all the variables drop off exponentially

➡ Combine into a likelihood

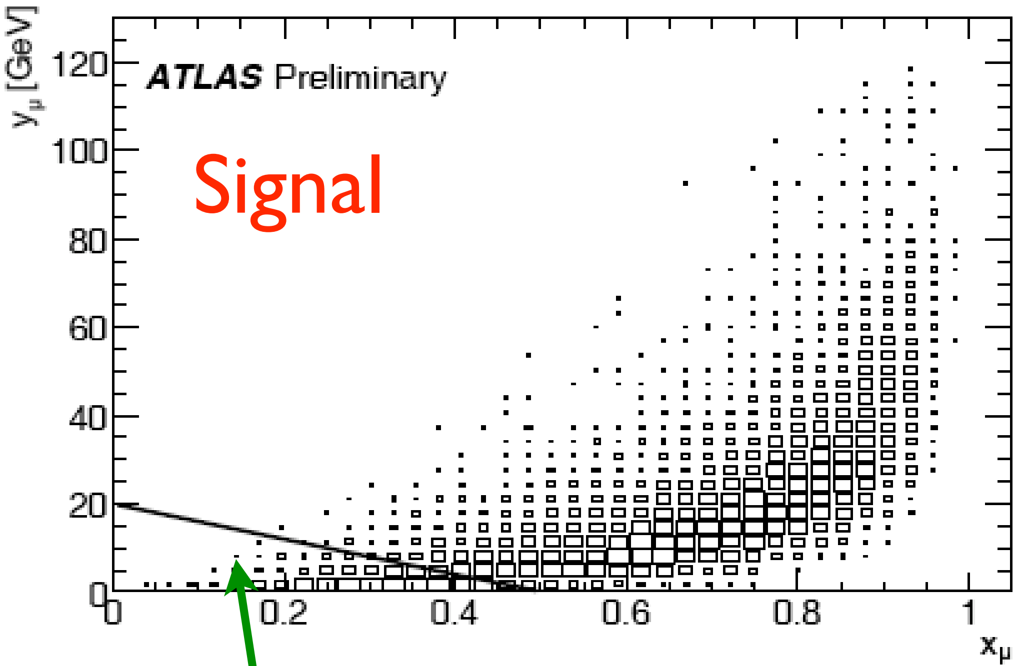
Hadronic Decays: Result

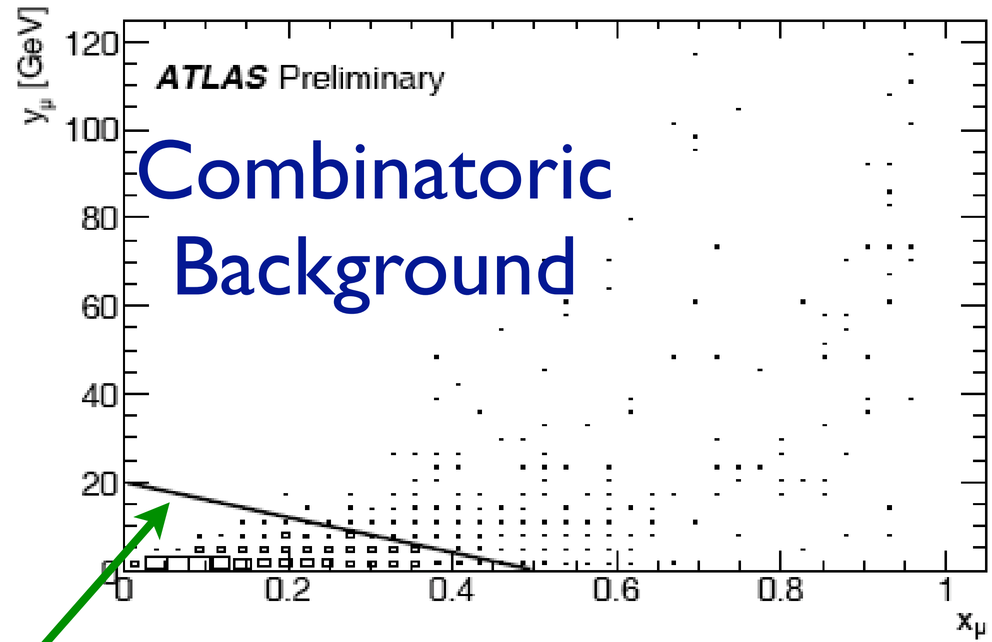


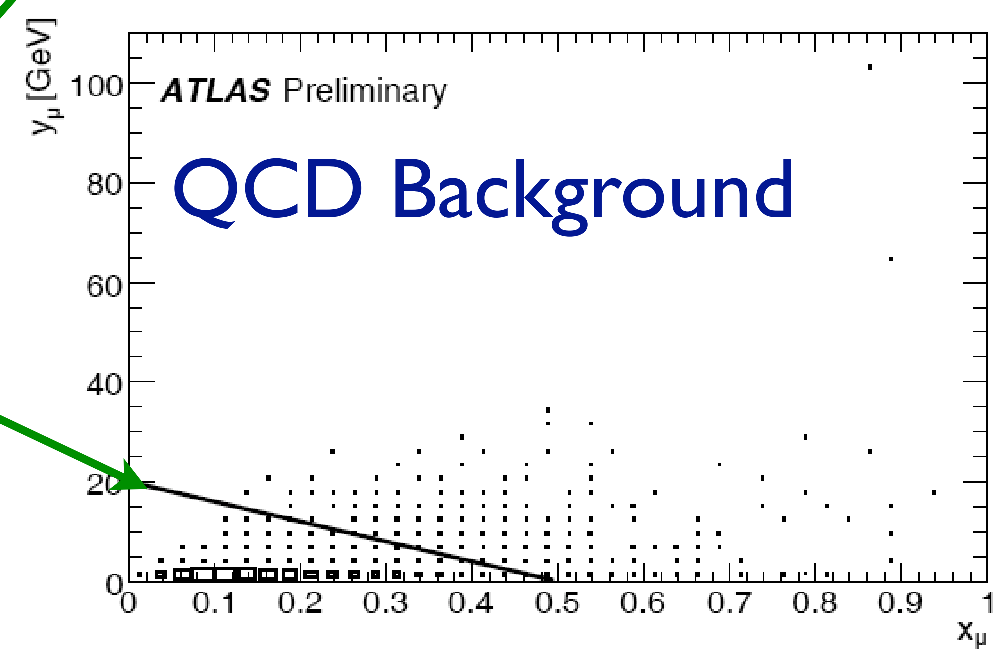
Semileptonic Decays: Muons

- Require a good muon, $p_T > 20$ GeV, $|\eta| < 2.5$, and a $p_T > 200$ GeV jet within ΔR=0.6 (call it "*b*-jet")
- Reduce "fakes" from b/c-decays (or other decays in flight):
  - Isolation not useful (signal muon close to *b* from top decay)
  - Two new variables (better than increase in muon p_T cut):
    - $x_\mu \equiv 1 - m_b^2/m_{visible}^2$ fraction of visible top mass carried by muon*
    - $y_\mu \equiv p_{\mu \perp b} \times \Delta R(\mu, b)$ relative p^T of muon wrt jet
    - (We do **not** use *b*-tagging: we assume the jet close to the lepton comes from a *b* quark so call it that)

*J. Thaler and L.-T. Wang, *JHEP* **07** (2008) 092, arXiv:0806.0023 [hep-ph].

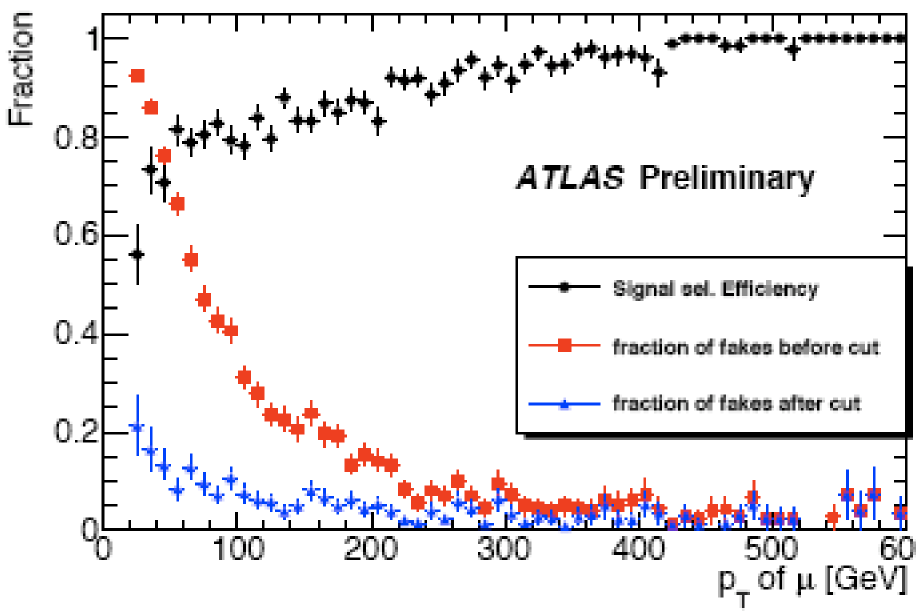


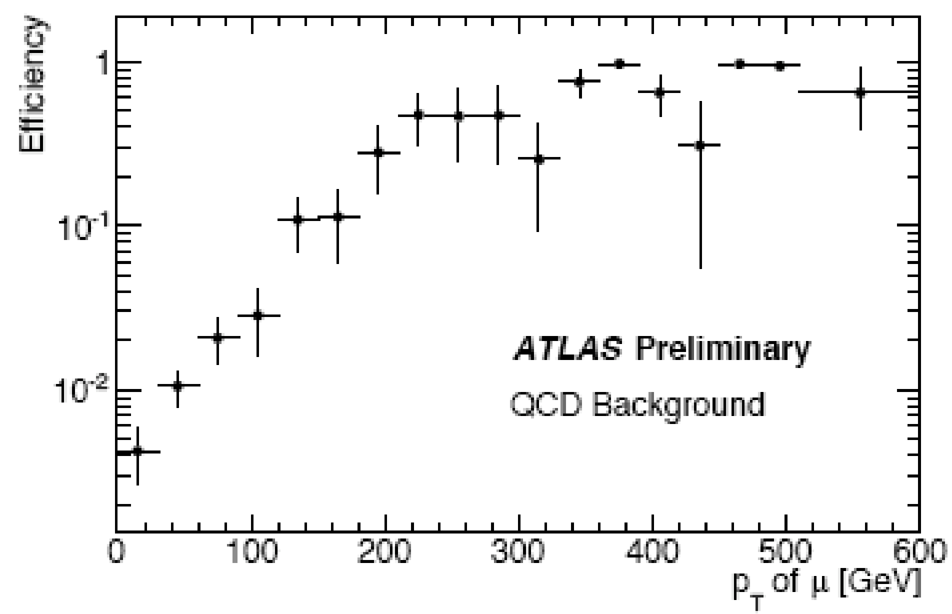




Apply a “diagonal” cut

- "Muonic top" efficiency after preselection (i.e. a good muon was found close to a high-p_T jet)
  - We find *a* muon in 88% of events where the W from top decay yielded a muon of 20 GeV p_T or more

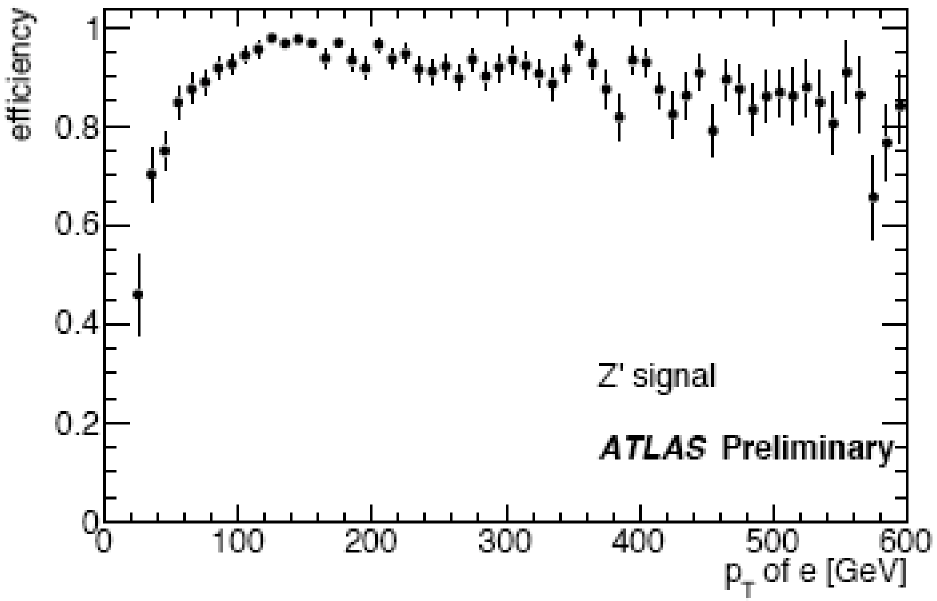


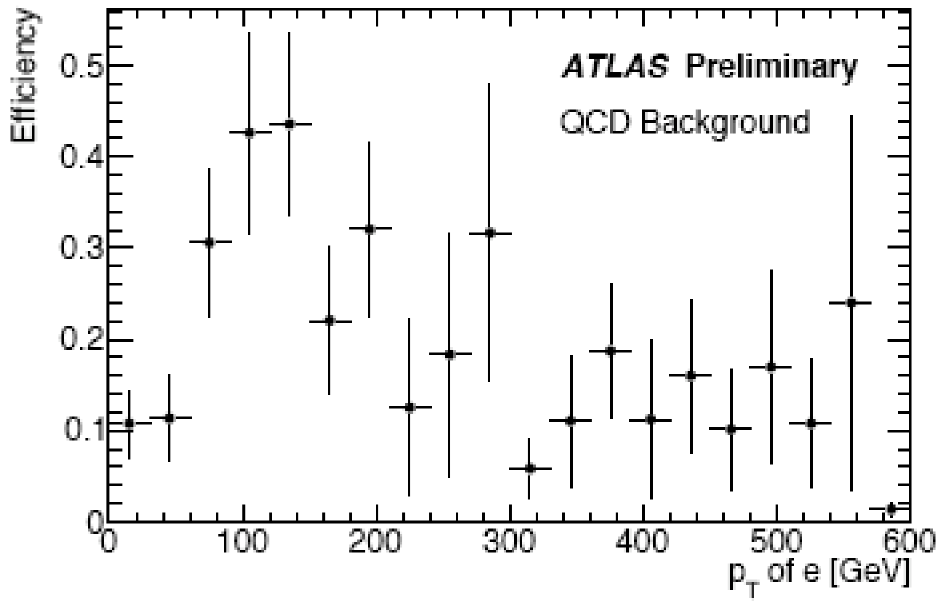


Semileptonic Decays: Electrons

- Trickier, since electron is embedded in the jet, but candidates can be reconstructed with good efficiency thanks to fine calorimeter granularity
  - 57% of events with top → e have a well-reconstructed electron
- So, require a good electron ($p_T > 20$ GeV, $|\eta| < 2.5$, excluding cracks), and a $p_T > 300$ GeV jet within $\Delta R = 0.6$ (also require jet's first k_T splitting scale > 10 GeV, i.e. electron component of jet)
  - Subtract the electron 4-momentum from the jet to obtain the "*b*-jet" and define x_e and y_e as in muon case
  - Also define $y'_e \equiv p_{e\perp j} \times \Delta R(e,j)$ (i.e. y_e but without subtracting electron 4-momentum from jet), require that $y'_e > 1$

- For electrons, combinatoric background not an issue
  - Harder to see electrons from *b* decays
- Efficiencies after preselection:



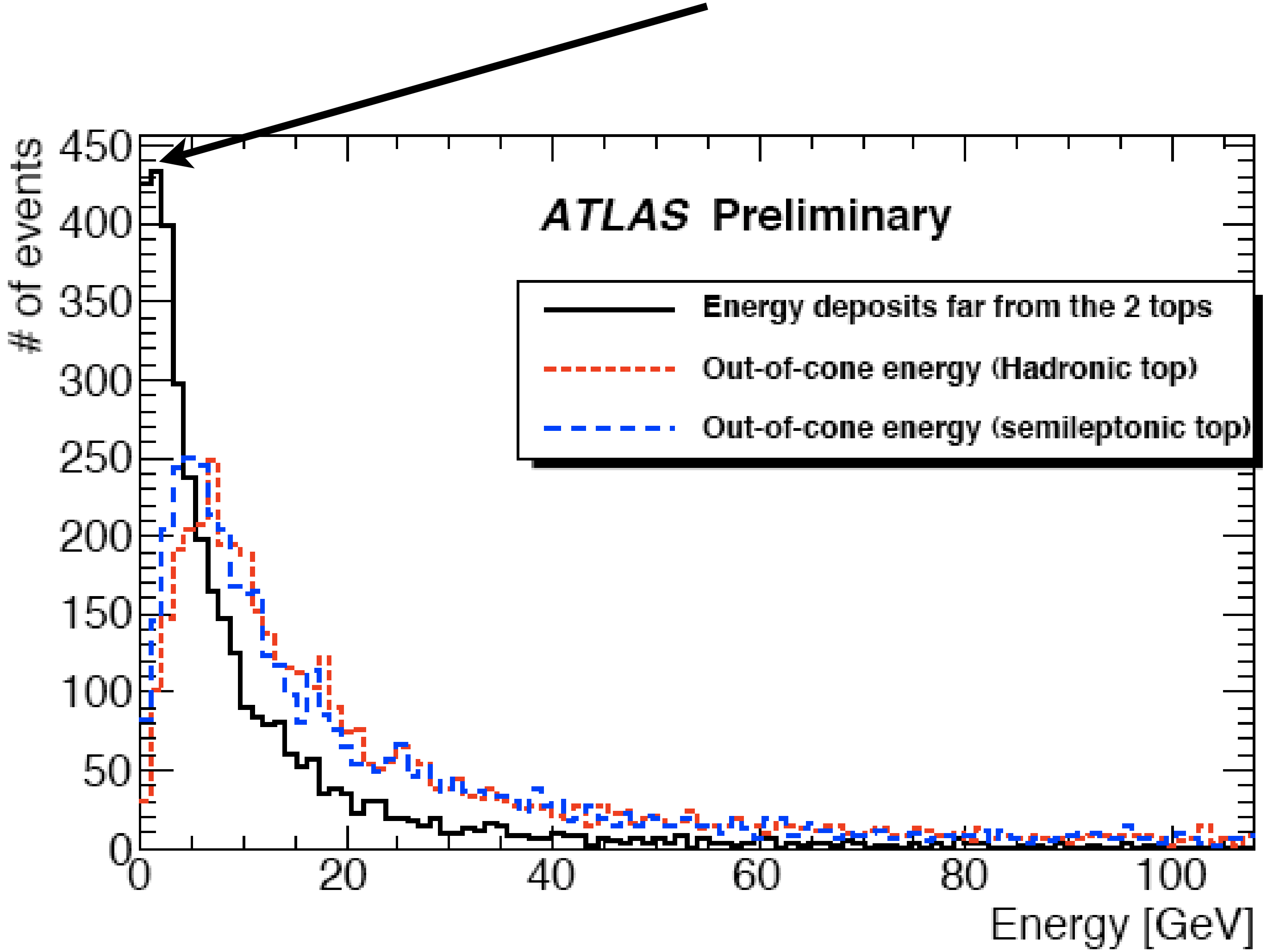


  - Of course, preselection has very large impact on multijet background!

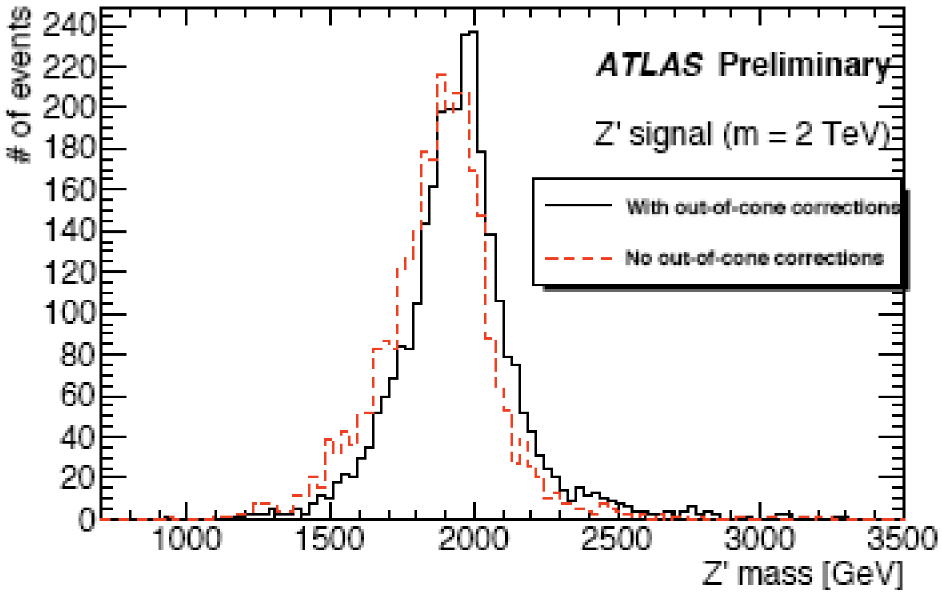
Z' Mass Reconstruction

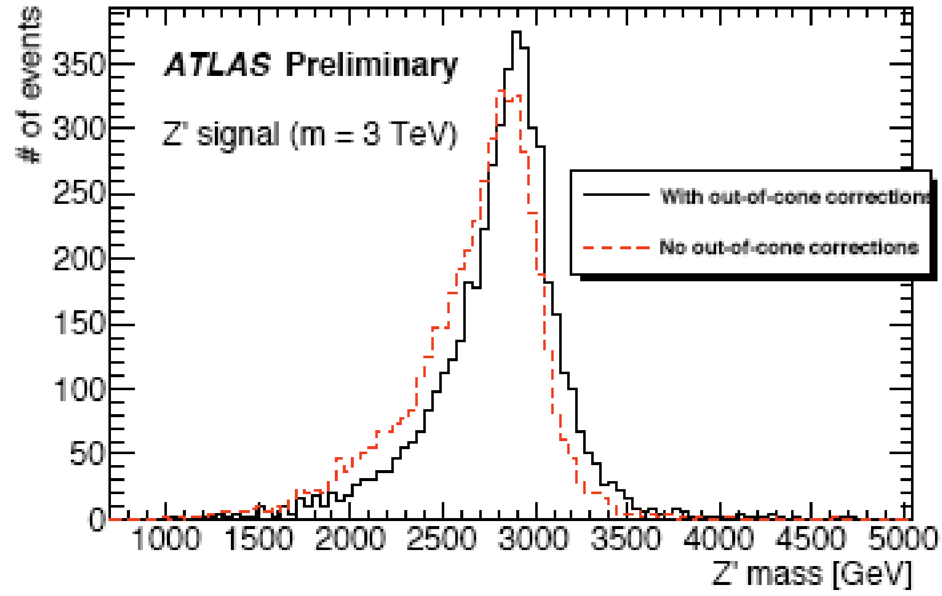
- W mass constraint to determine neutrino p_z (take smallest value, or real part of imaginary solution)
  - Require $\Delta R(\nu,\ell) < 1.0$
- Apply "local" out-of-cone energy correction:
  - Use cone 0.7 "topocluster" jets
  - Add topoclusters in $0.7 < R < 1.2$ to jet
  - Reasonable? Look for energy deposits (in a cone of radius 0.4) far away from top candidates
    - 30% of the time, no topoclusters, rest of the time, energy much lower than the local out-of-cone correction.

Large peak at 0 is suppressed



Z' Peaks

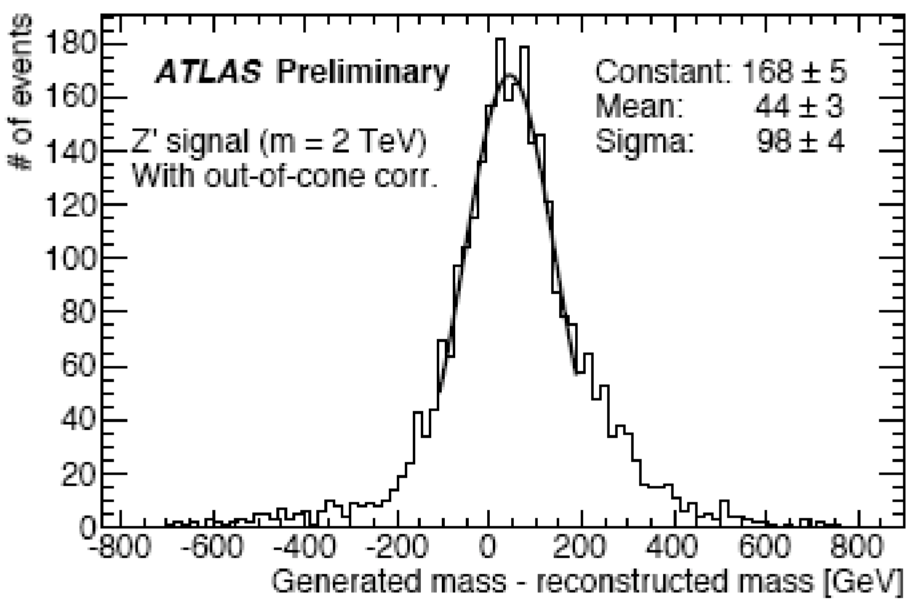


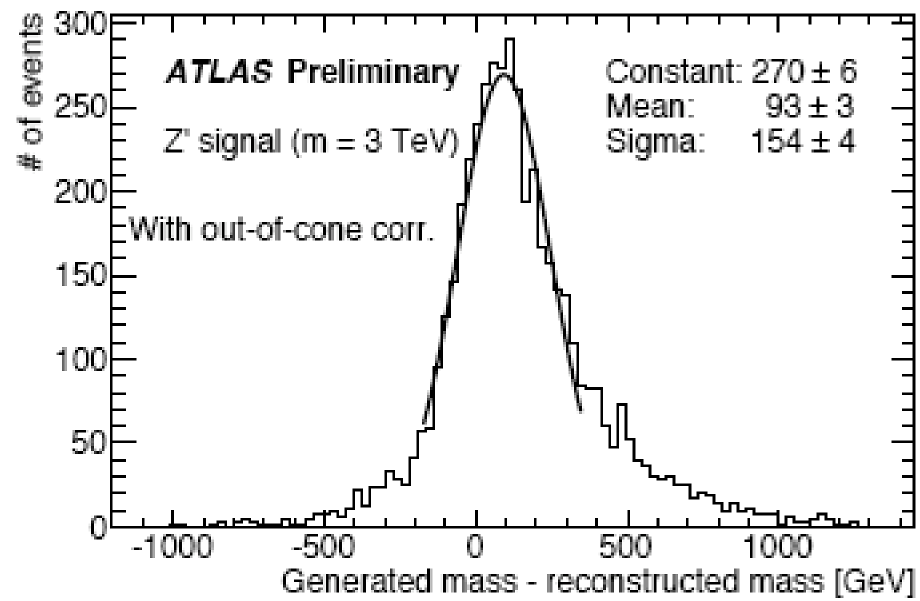


- Correction helps peak, but does not improve tails!

Z' Mass Resolution

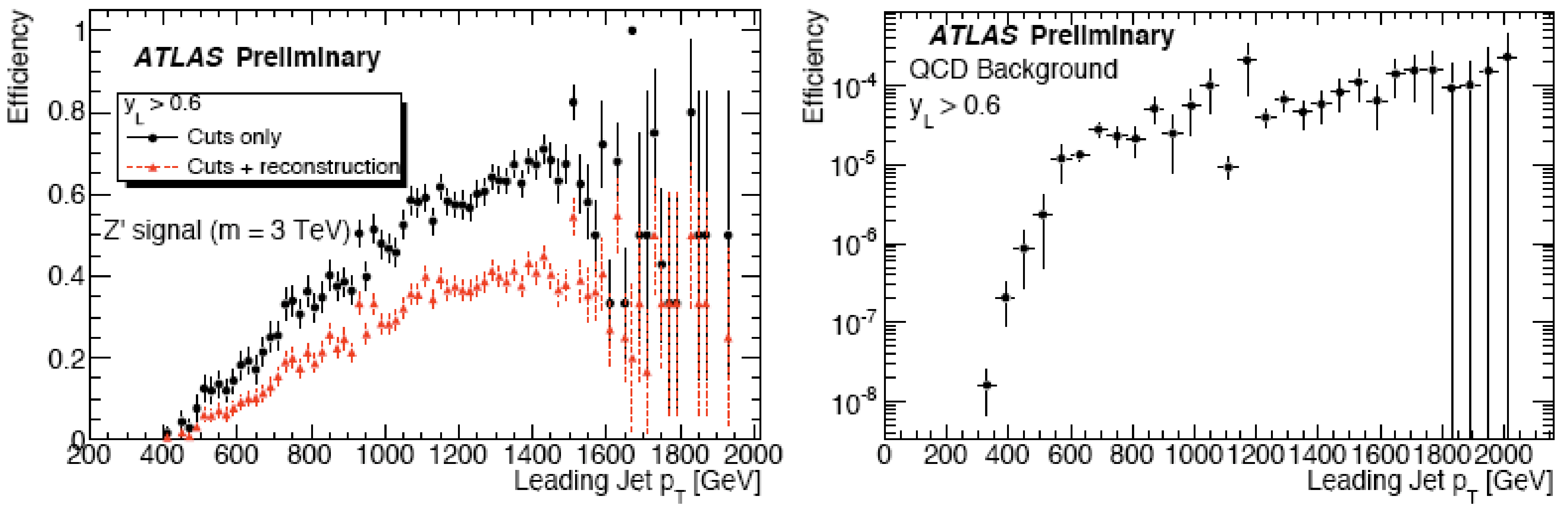
- SSM Z' at this mass narrower than detector/method resolution, but not negligibly so:





Also still have a substantial offset!
⇒ work to do!

Selection Efficiency



- For multijet background, rate determined by factorizing leptonic and hadronic rejection
    - (Limited MC statistics)

Sensitivity

- Number of events in mass windows [1800,2100] ([2700,3100]) GeV for 2 (3) TeV Z'

Signal Efficiencies

	$y_L > 0.6$	$y_L > 0.9$	$y_L > 1.2$
l+jets $Z' \to t\bar{t}$ (2 TeV)	0.094 ± 0.002	0.063 ± 0.002	0.016 ± 0.001
l+jets $Z' \to t\bar{t}$ (3 TeV)	0.136 ± 0.002	0.101 ± 0.002	0.034 ± 0.001

Backgrounds, 1 fb^{-1}

$m = 2$ TeV	$y_L > 0.6$	$y_L > 0.9$	$y_L > 1.2$
QCD multijet (J5 + J6 + J7)	1.9 ± 0.5	0.7 ± 0.2	0.16 ± 0.04
SM $t\bar{t}$	$17.1 \pm 0.8 \pm 2.6$	$11.1 \pm 0.7 \pm 1.7$	$3.1 \pm 0.4 \pm 0.5$
Total	19 ± 2.8	11.8 ± 1.9	3.3 ± 0.6
$m = 3$ TeV	$y_L > 0.6$	$y_L > 0.9$	$y_L > 1.2$
QCD multijet (J5 + J6 + J7)	0.5 ± 0.2	0.2 ± 0.1	0.07 ± 0.03
SM $t\bar{t}$	$2.3 \pm 0.1 \pm 0.3$	$1.4 \pm 0.1 \pm 0.2$	$0.52 \pm 0.07 \pm 0.08$
Total	2.8 ± 0.4	1.6 ± 0.2	0.6 ± 0.1

(W+jets shown to be much smaller than top)

Limits

- Set limits for 1 fb^{-1} of data
  - 15% uncertainty on signal acceptance
  - 10% on luminosity
  - 15% on $t\bar{t}$ background
- 95% CL upper limits on signal cross-section using Bayesian technique

95% C.L. limits on σ x BR($t\bar{t}$) (fb)	$y_L > 0.6$	$y_L > 0.9$	$y_L > 1.2$
$m = 2$ TeV	550	650	1400
$m = 3$ TeV	160	180	450

Too Short

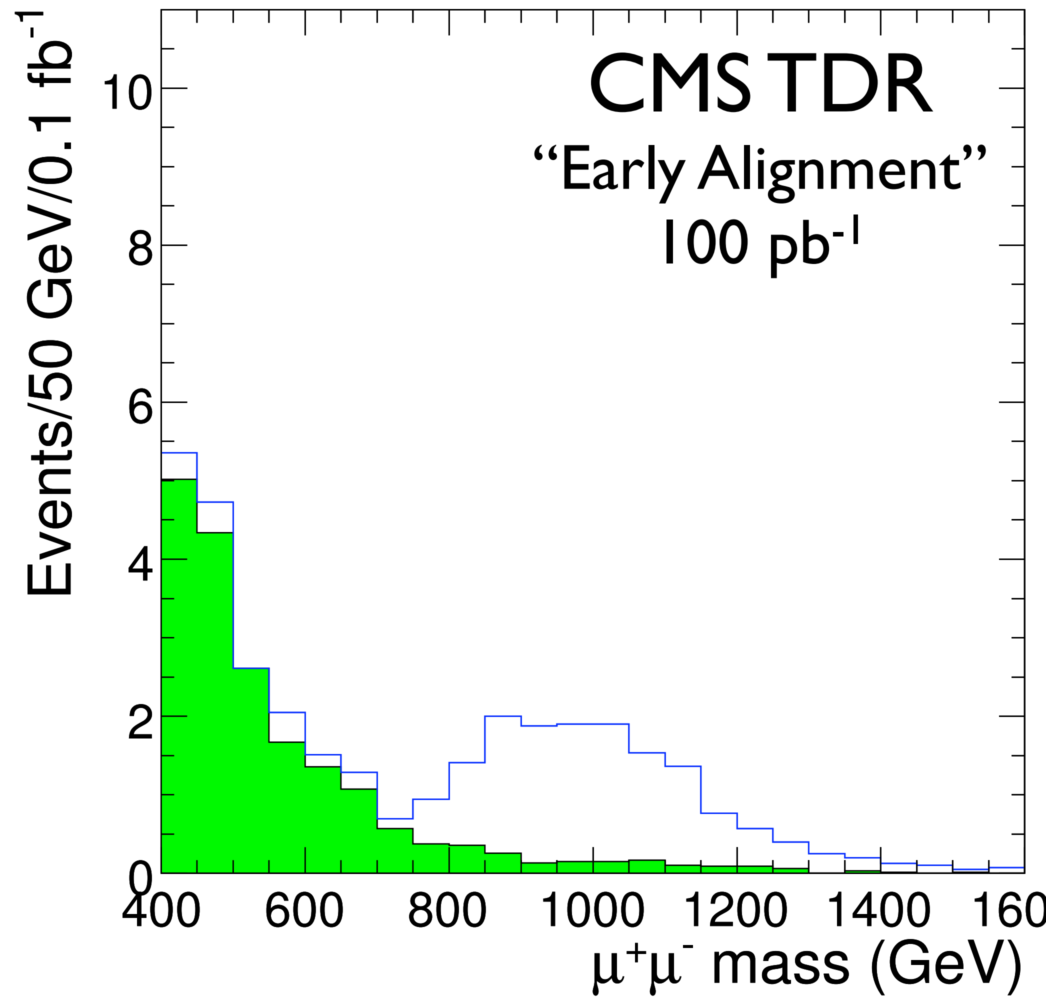
- Many topics not or barely addressed
  - Long-lived particles, can decay halfway or outside detector, or get stuck and decay later...
  - "Quirks"
  - "Lepton jets"
  - RPV SUSY
  - Model-independent searches
  - ...
- Many new models have signatures that exist in other models!

But...

- We do expect to see something new in the next few years
  - Is there a Higgs?
    - Does it generate fermion masses? Does something "material" stabilize its mass? Does that something tell us why the fermion masses are so? Why there are three?
  - No Higgs?
    - More space? New interactions?
- We can hope for a very rich phenomenology which will help understand more than the question of mass
  - Towards Mendeleev's table's physics equivalent

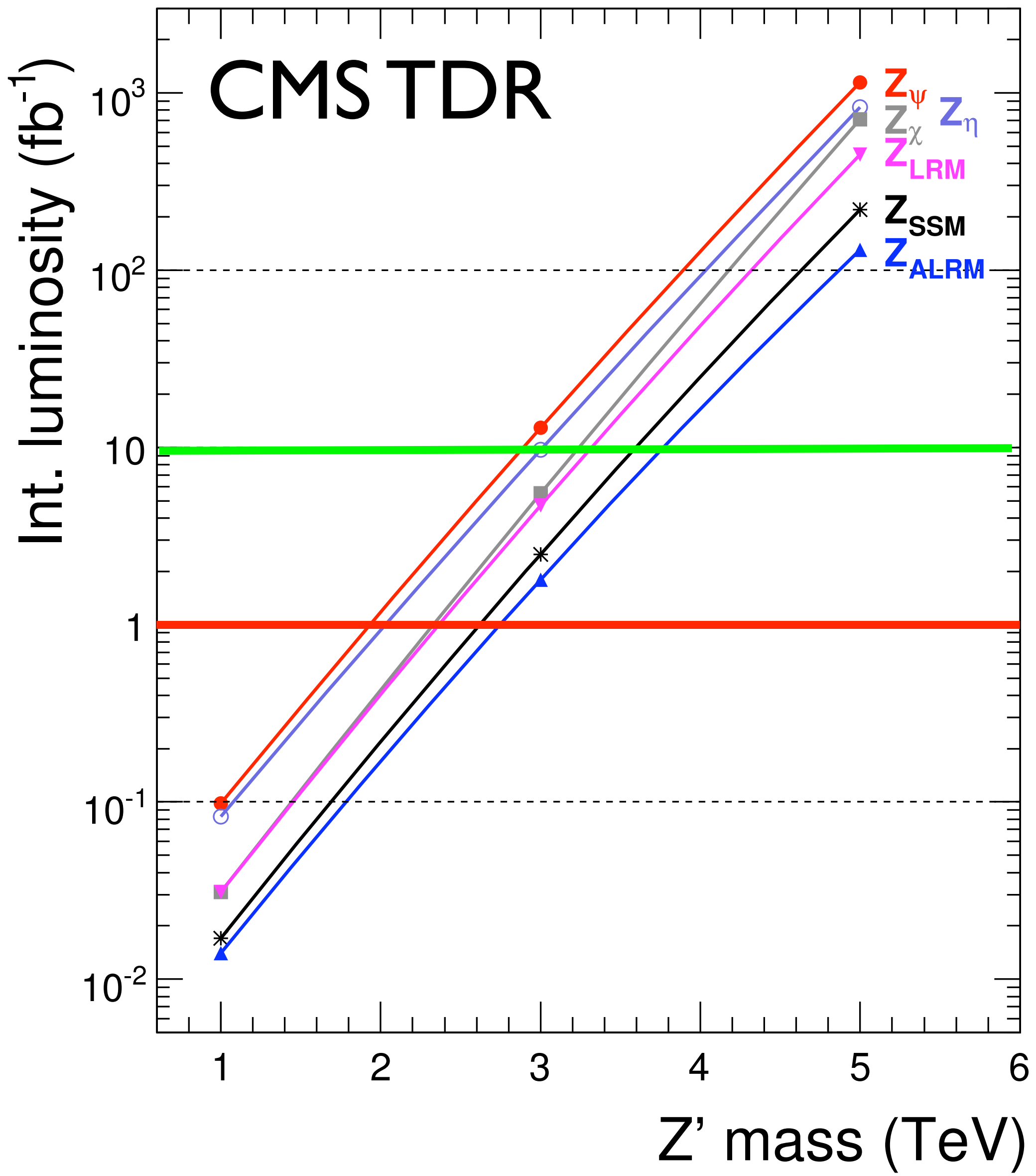
$Z' \rightarrow \mu\mu$: Early Potential

- CMS 1 TeV Z_η study
  - Narrower than SSM (7 vs 31 GeV), but dominated by detector anyway
  - Cross-section 2-3 times smaller than SSM
  - Note: statistics scaled down, so fluctuations "not to scale"
- (At the Tevatron, not competitive due to limited muon p_T resolution)



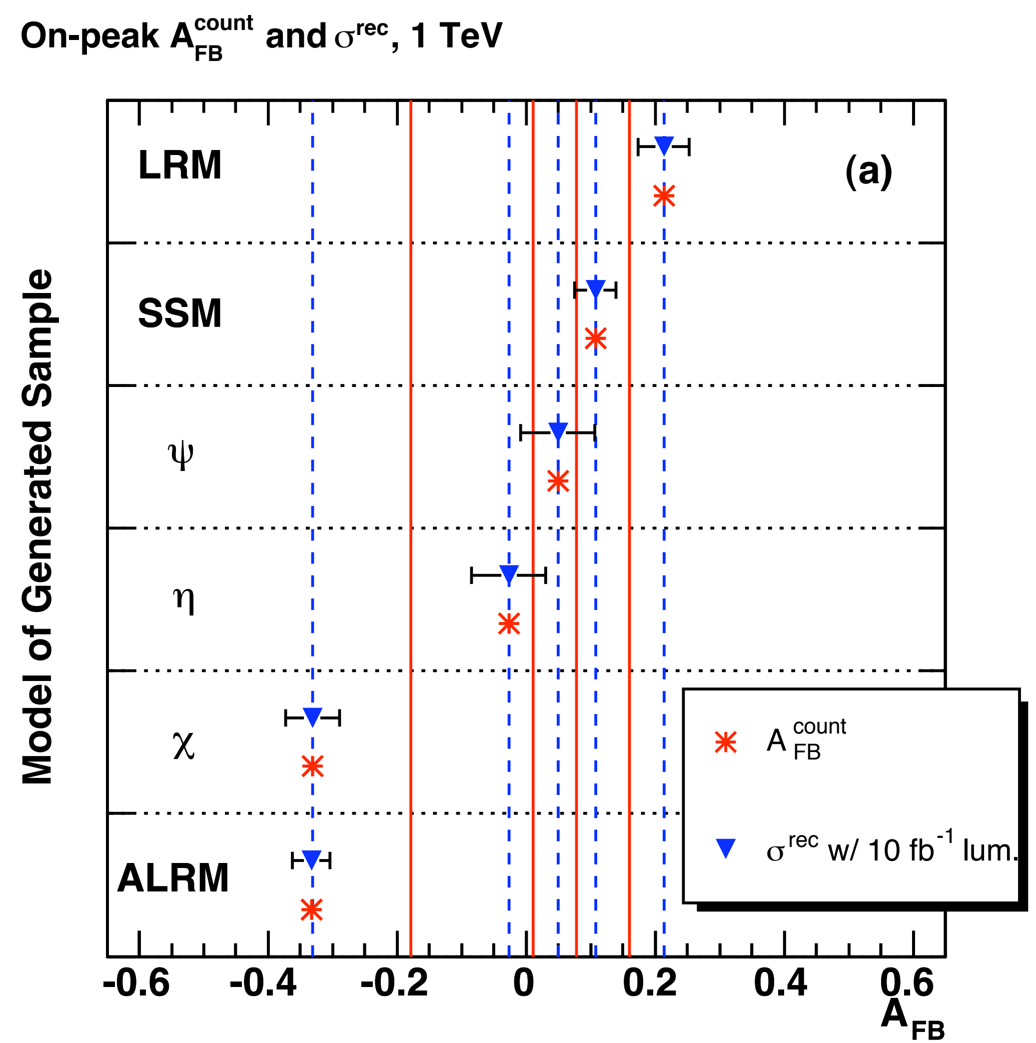
$Z' \to \mu\mu$ Reach

- 5σ discovery reach
- Systematics don't change these results much
- 2-3 TeV with 1 fb^{-1}
- 3-4 TeV with 10 fb^{-1}
- Again, assumes no "exotic" decays
- Discovery reach about 700 GeV below 95% CL limit at highest masses



Model Determination

- Angular distribution gives excellent handle on g_V, g_A for various fermions
  - Charm may be possible
- This will come after an initial determination of branching ratios (obviously)
  - Complementary information in determining nature of resonance



CMS Note 2005/022