The Road to Discovery

Data Analysis

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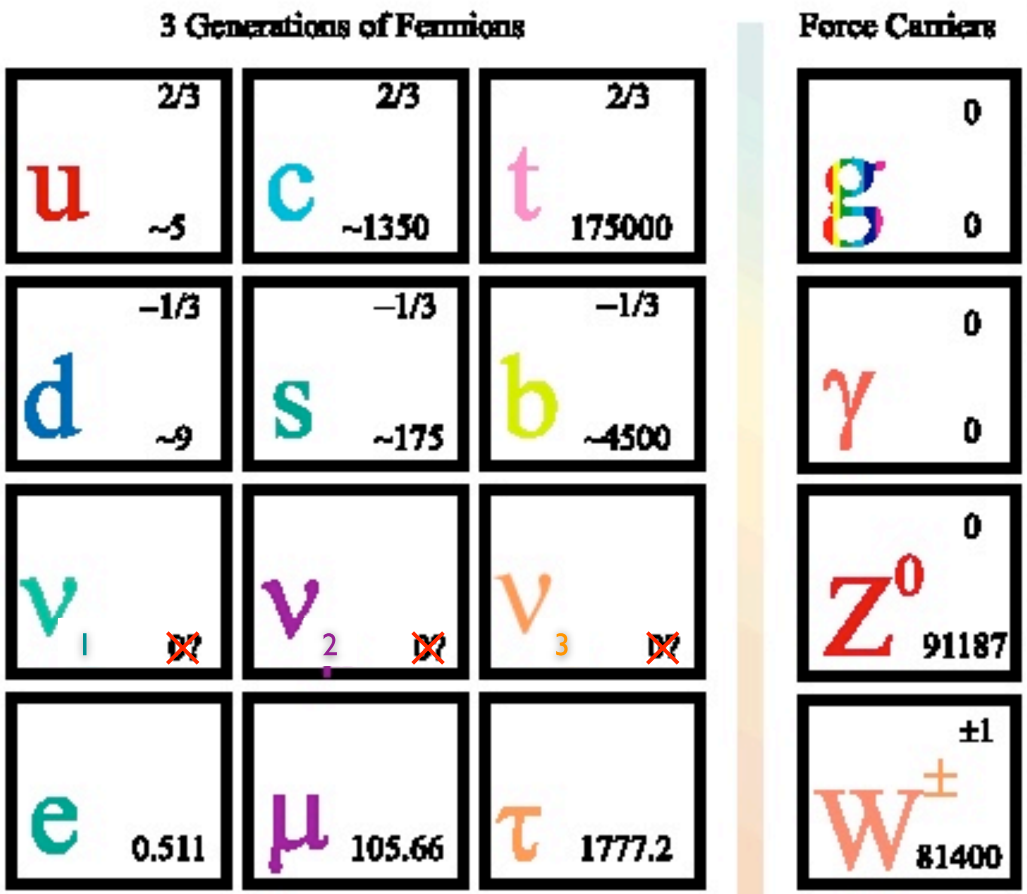
Goals

- For theorists:
  - What is it these experimenters *do*?
    - (Except for using fancy equipment to build fancy detectors...)
  - How come it takes them forever to release a result?
  - Why can't they just give us the 4-vectors as they record the data?
  - What can('t) they look for?
- For experimenters:
  - Why does it take so many layers of review to get a result out? My analysis seems pretty simple at first sight....

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]

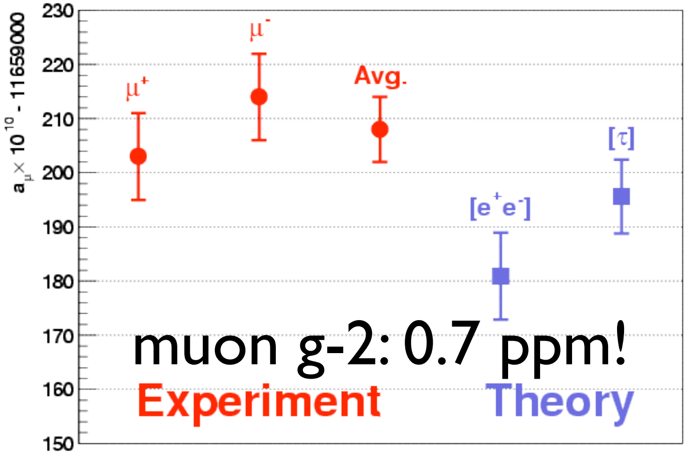
In Words

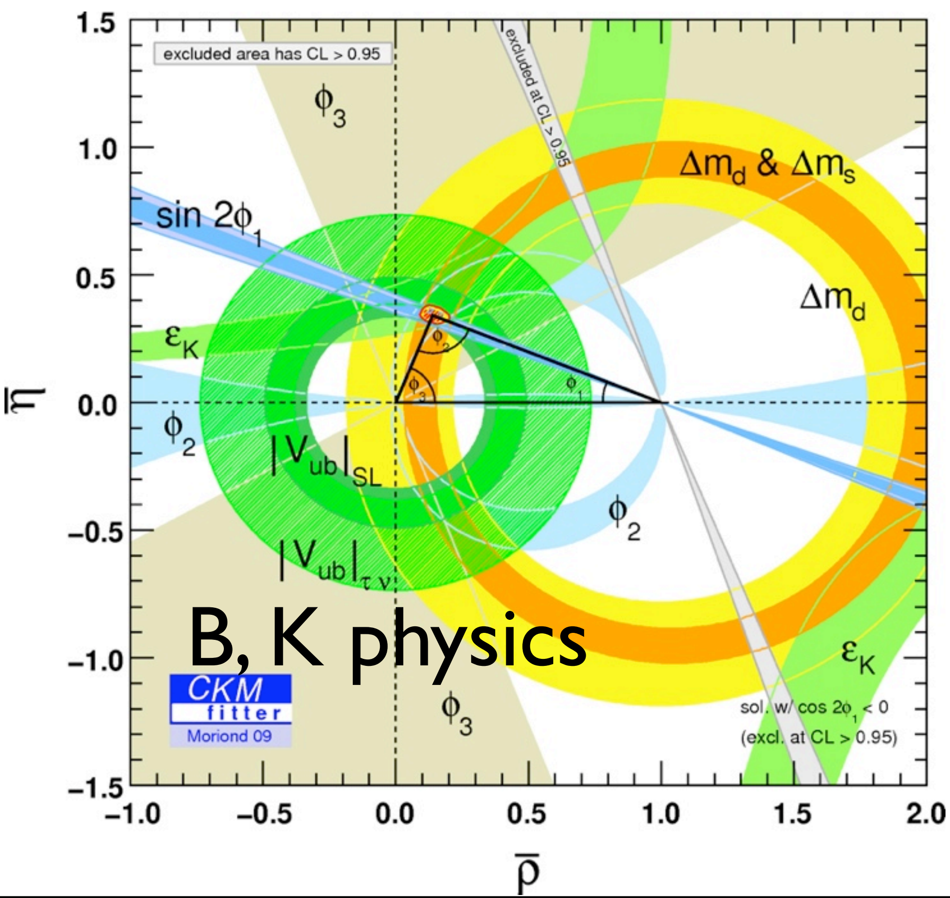
- Matter is built of spin 1/2 particles that interact by exchanging 3 different kinds of spin 1 particles corresponding to 3 different (gauge) interactions
- There appear to be 3 generations of matter particles
- The 4 different matter particles in each generation carry different combinations of quantized 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





LEP, SLD & Tevatron

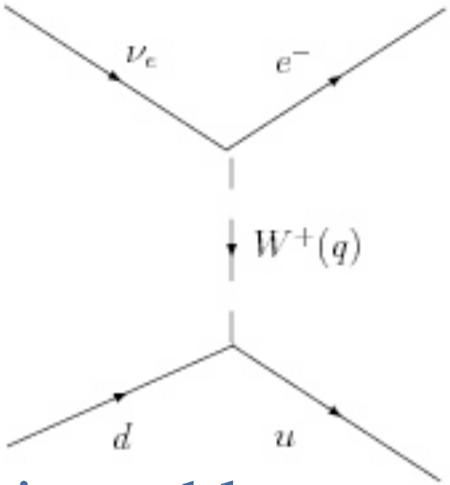
Many Fundamental Questions

- 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/or 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

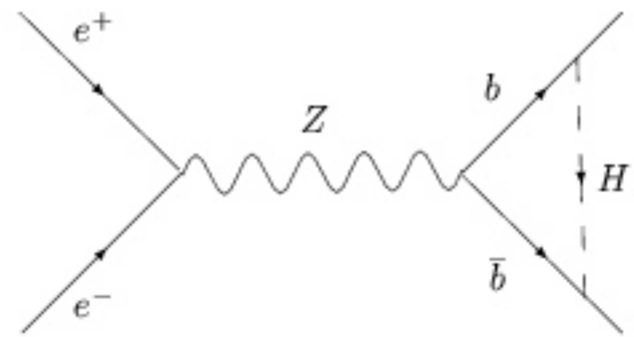


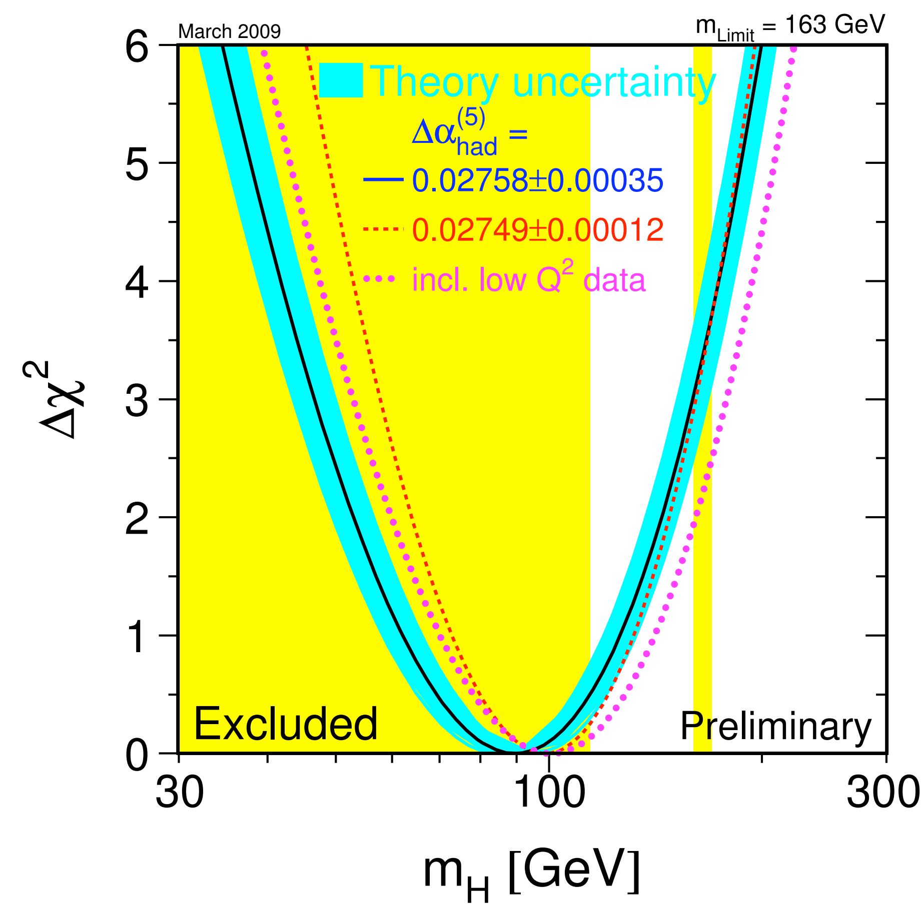
The Higgs Boson

- 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



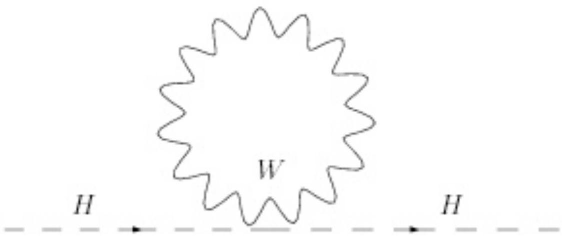


Higgs Drawbacks

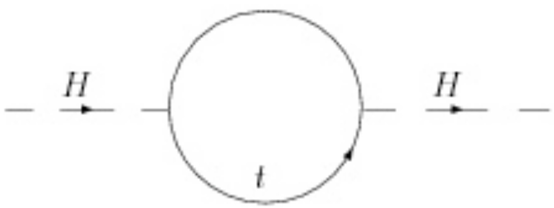
- In principle, with the addition of a Higgs boson around 150 GeV particle physics could be "complete"
  - Like Mendeleev's table for chemistry
- But by itself, the Higgs is very unsatisfactory:
  - Why are the couplings to the fermions what they are?
    - Dumb luck (aka landscape)?
  - What is the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

The Plot Thickens

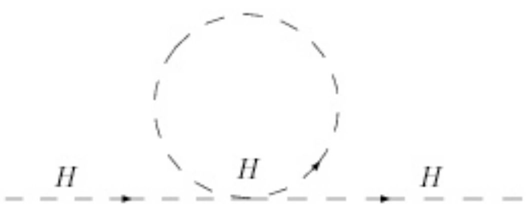
Higgs Mass



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



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



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

- 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?

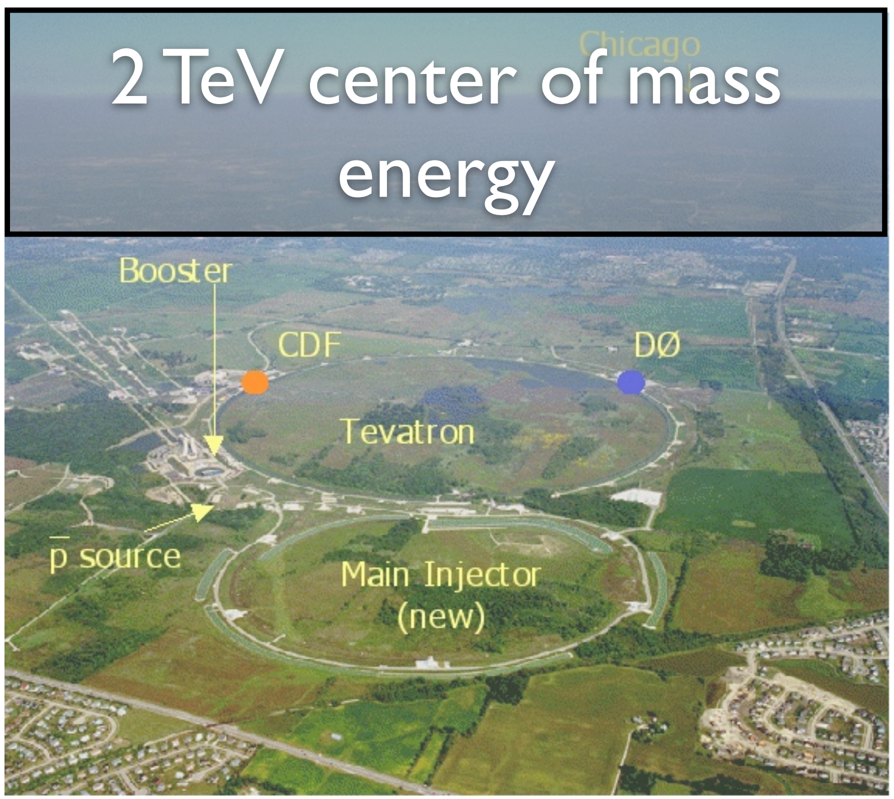
So....

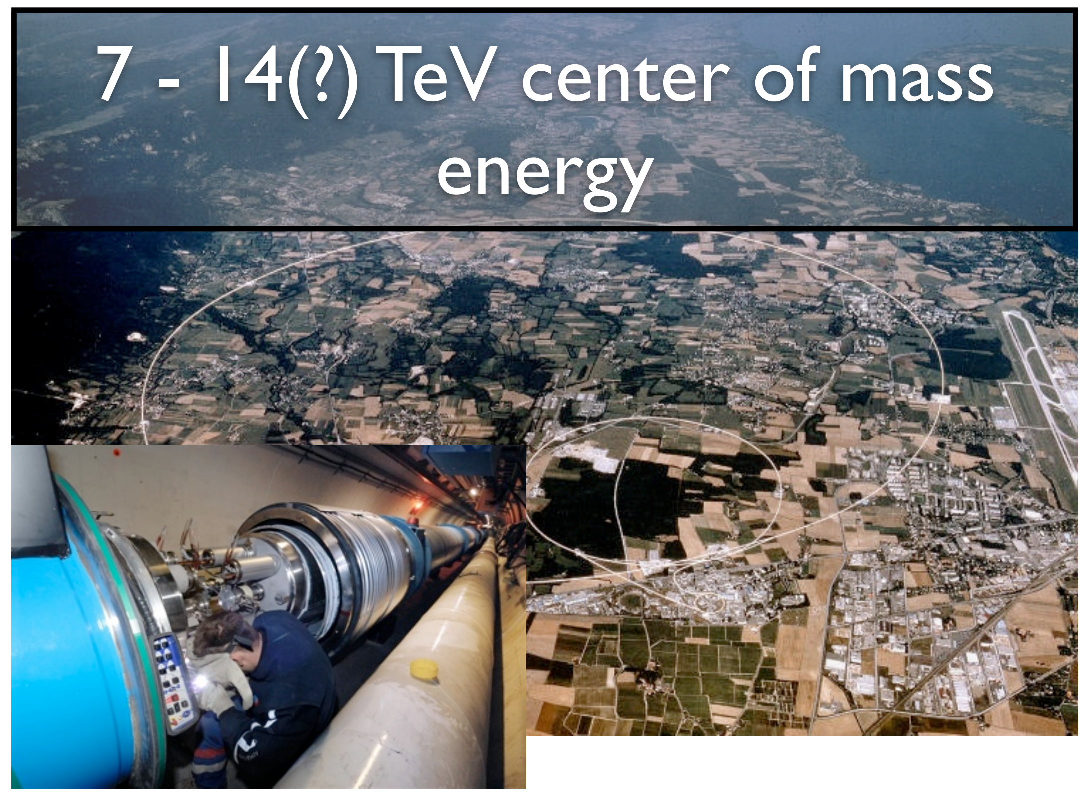
- Go look where the SM breaks down (high energy)...
- ... or for subtle anomalies
- Assume new physics manifestations lead to anomalous production of SM particles
  - Resonant or not (and maybe in loops only)
  - Short-lived or less so
- Rely on guidance from models to some extent
  - What are implications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

The Tools

Colliders

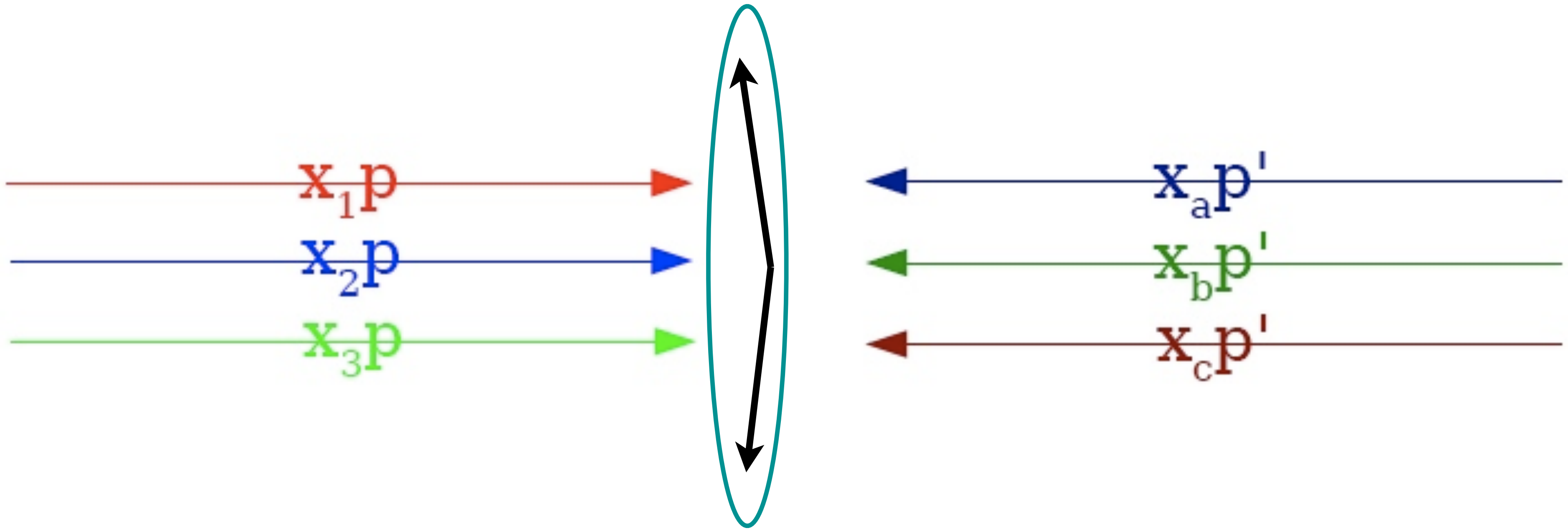
- Currently, hadron colliders:
  - High energy implies probing of short distances, and production of other, massive particles





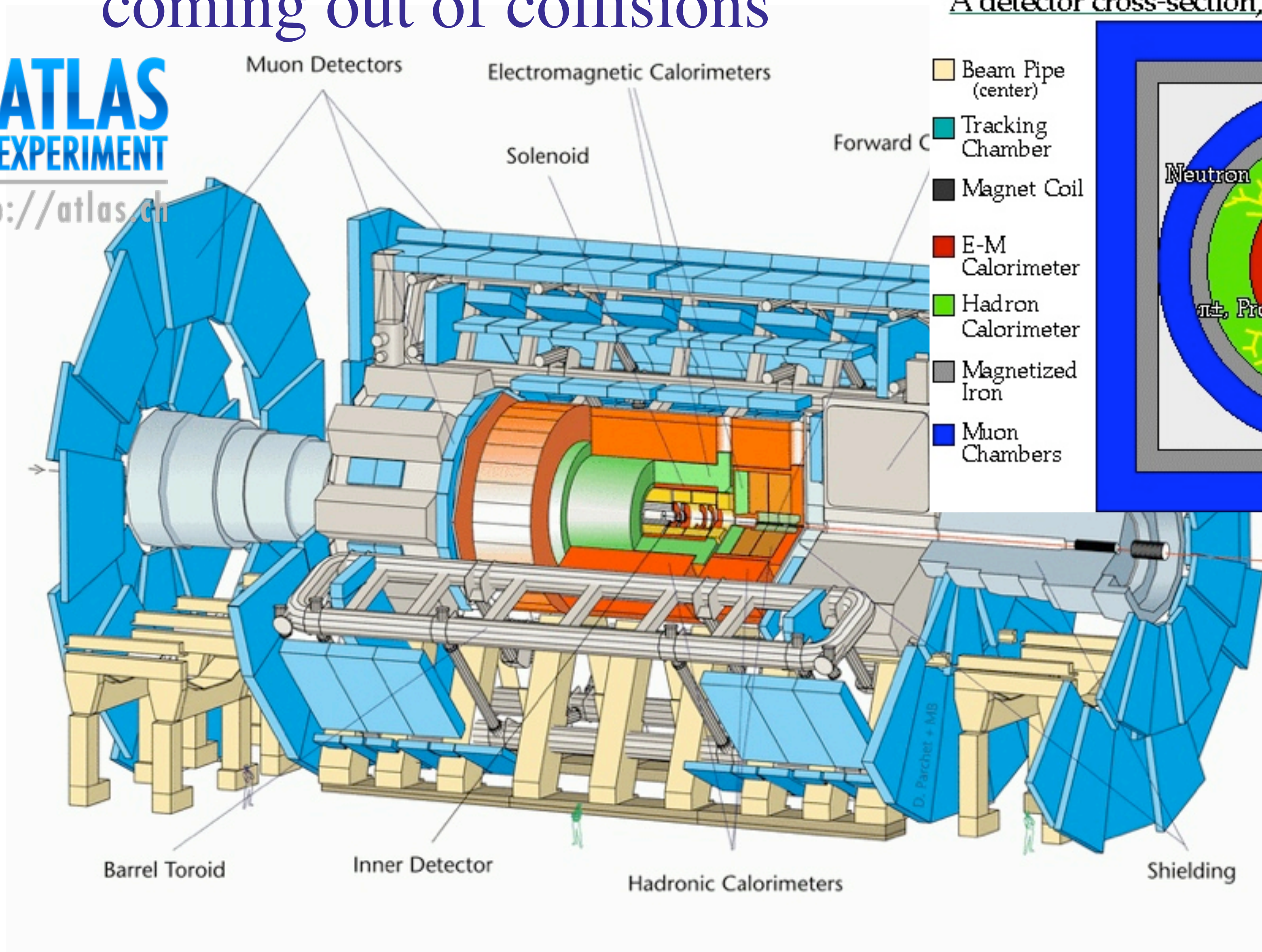
Hadron Colliders

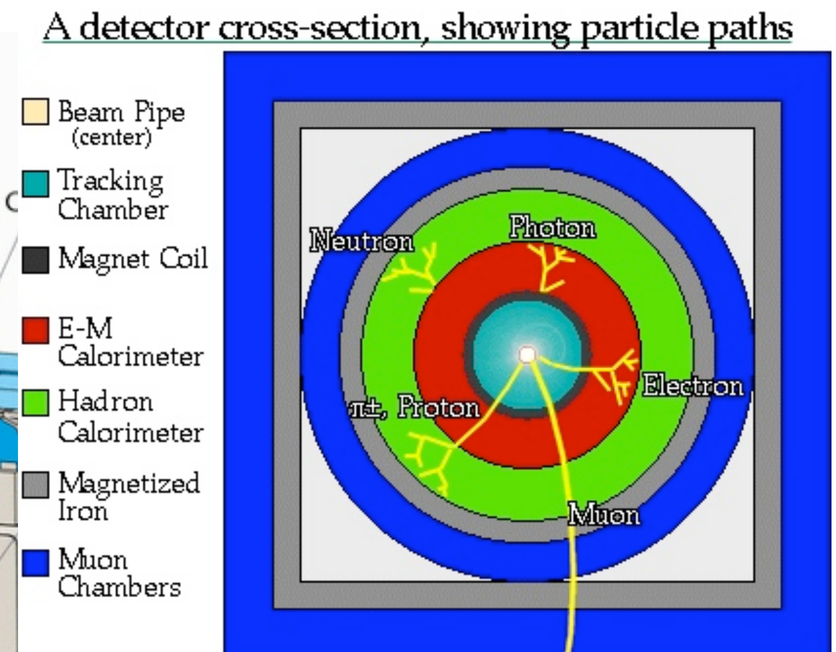
- Incoming longitudinal momentum not known:
  - "Hard interaction" is between one of the quarks and/or gluons from each proton, other quarks/gluons are "spectators"
- Longitudinal boost "flattens" event to a pancake
- We usually work in the plane transverse to the beam



ATLAS

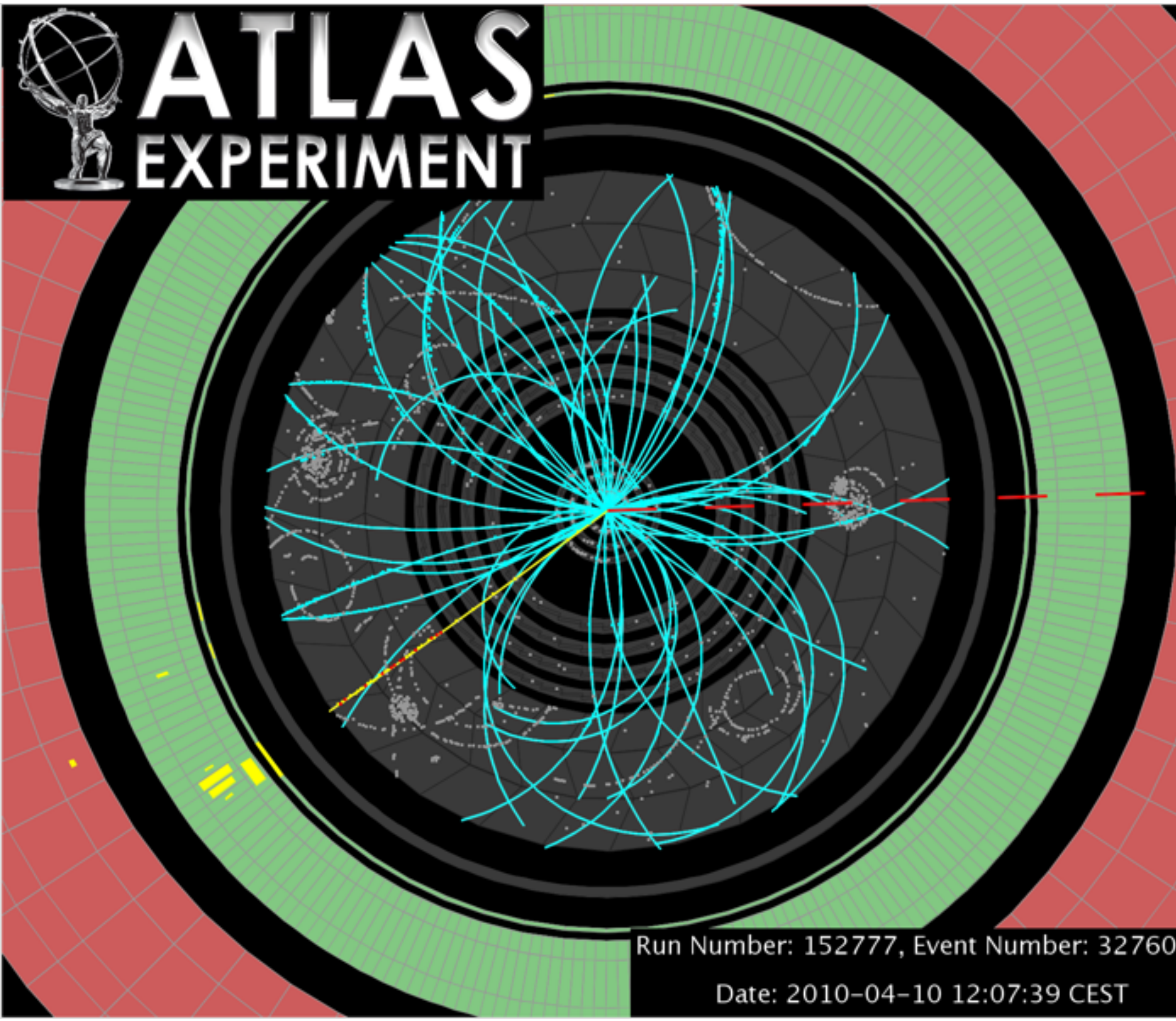
- Make best possible measurement of all particles coming out of collisions

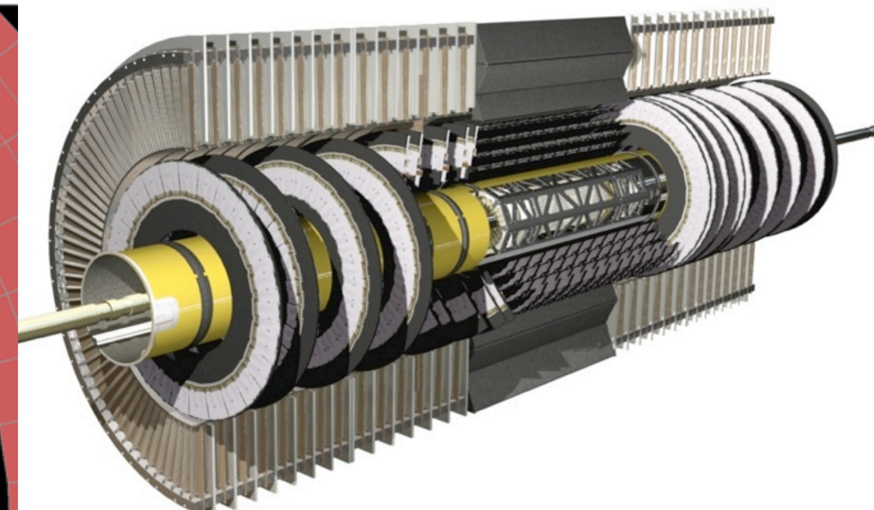


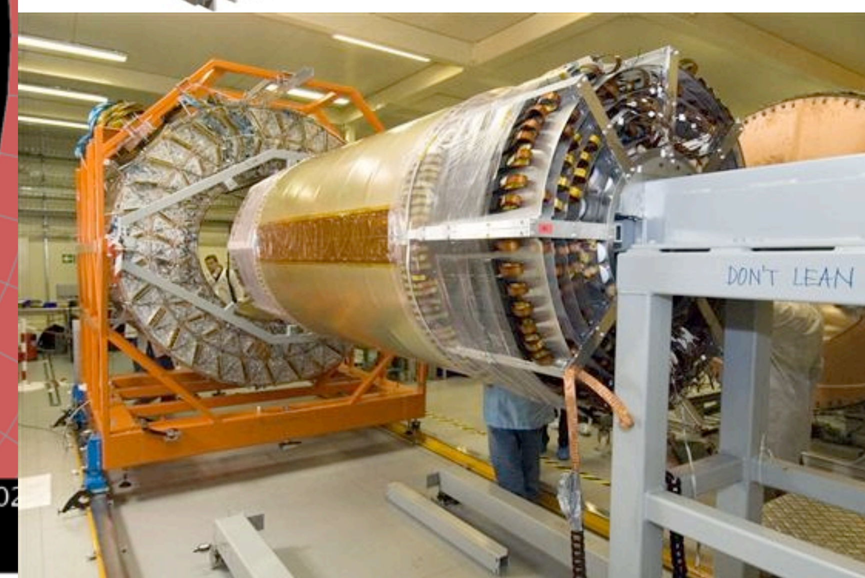


Tracking

- Combination of pixels, silicon strips ("SCT") and straw tube transition radiation tracker (TRT)

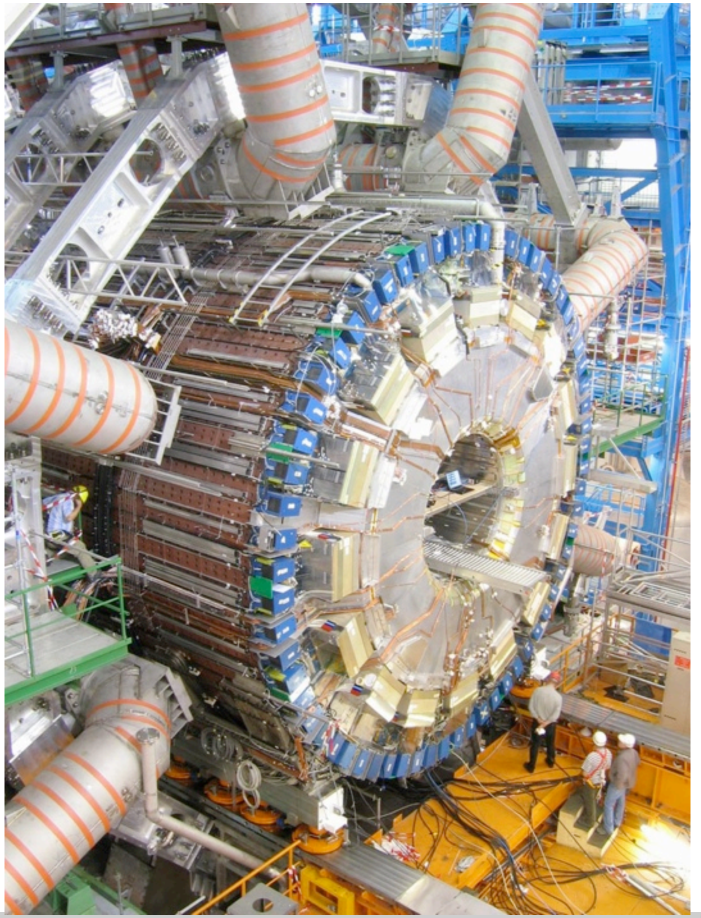


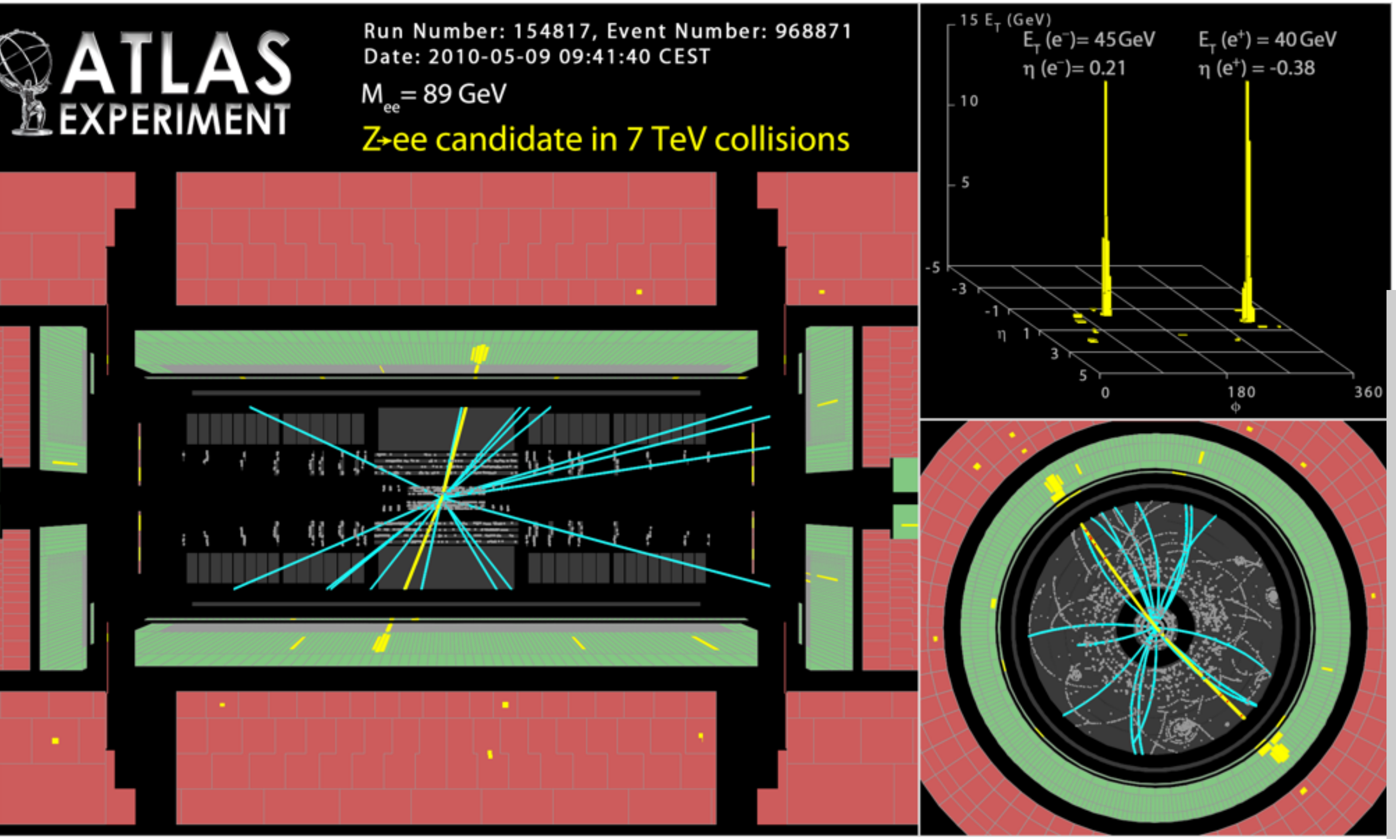


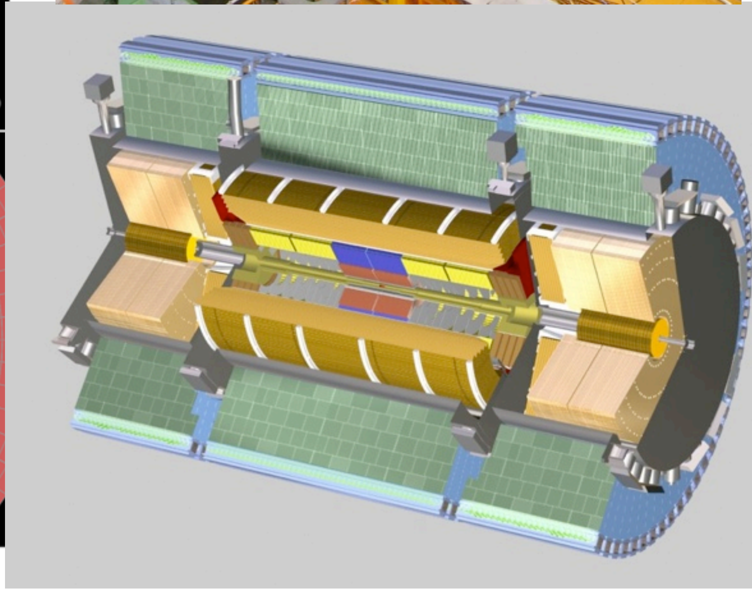


Calorimetry

- Liquid Argon & Pb accordion (EM & forward)
- Scintillator & Pb (hadronic)

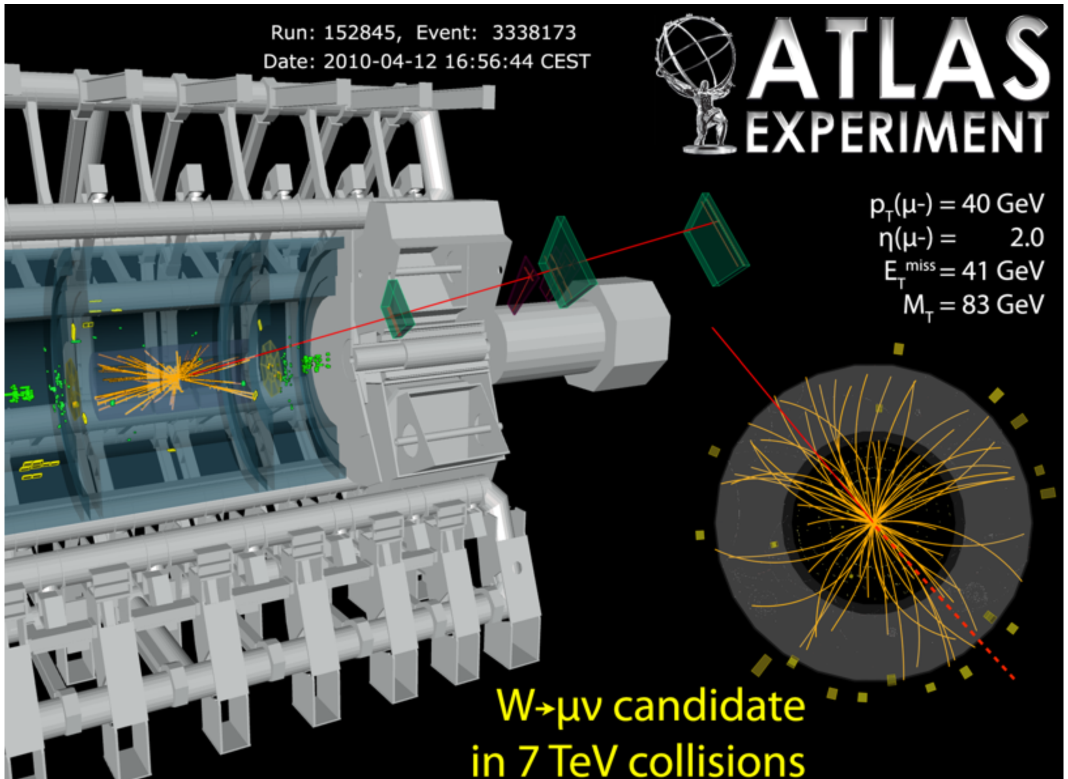


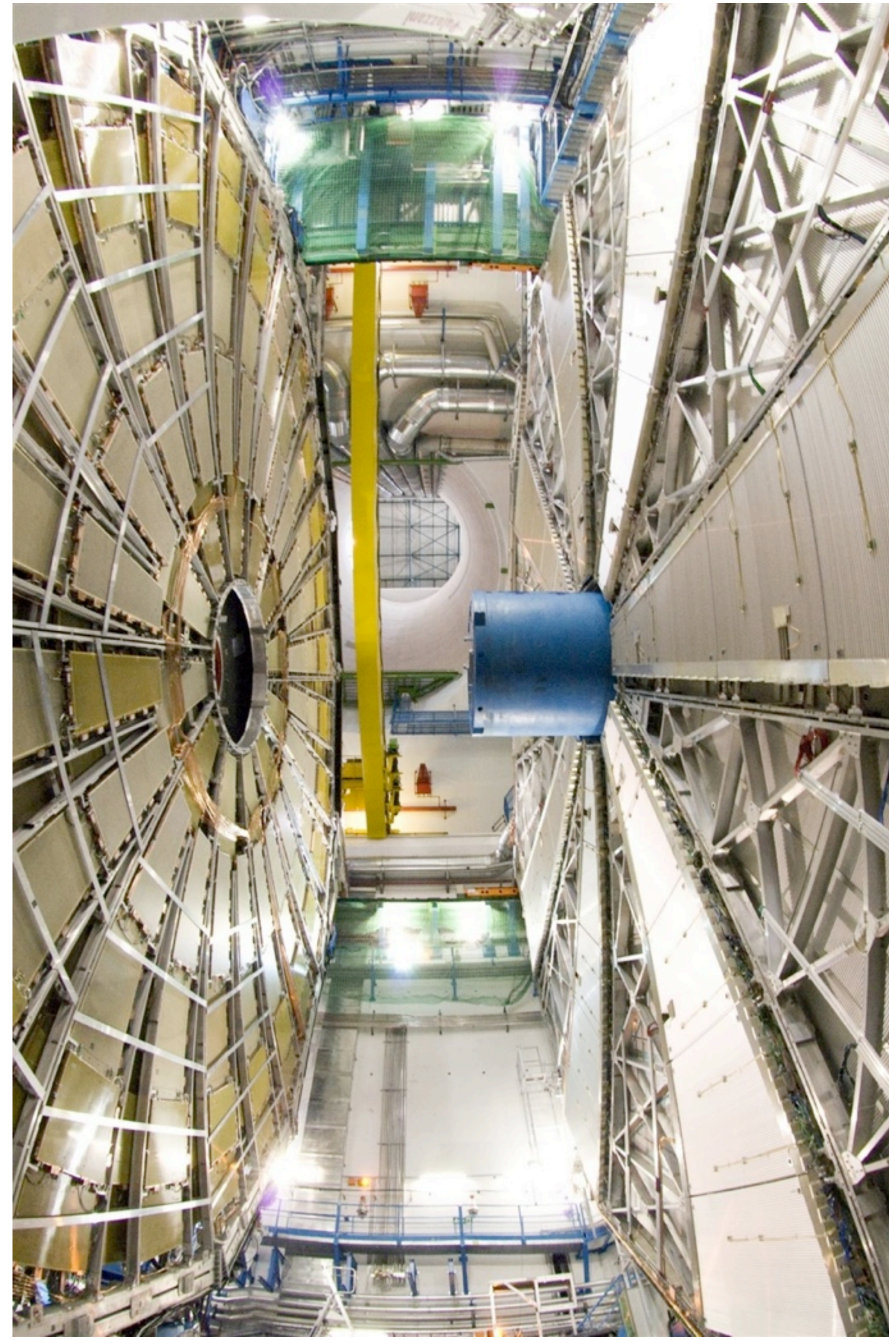




Muons

- Air-core toroids
  - Makes ATLAS big

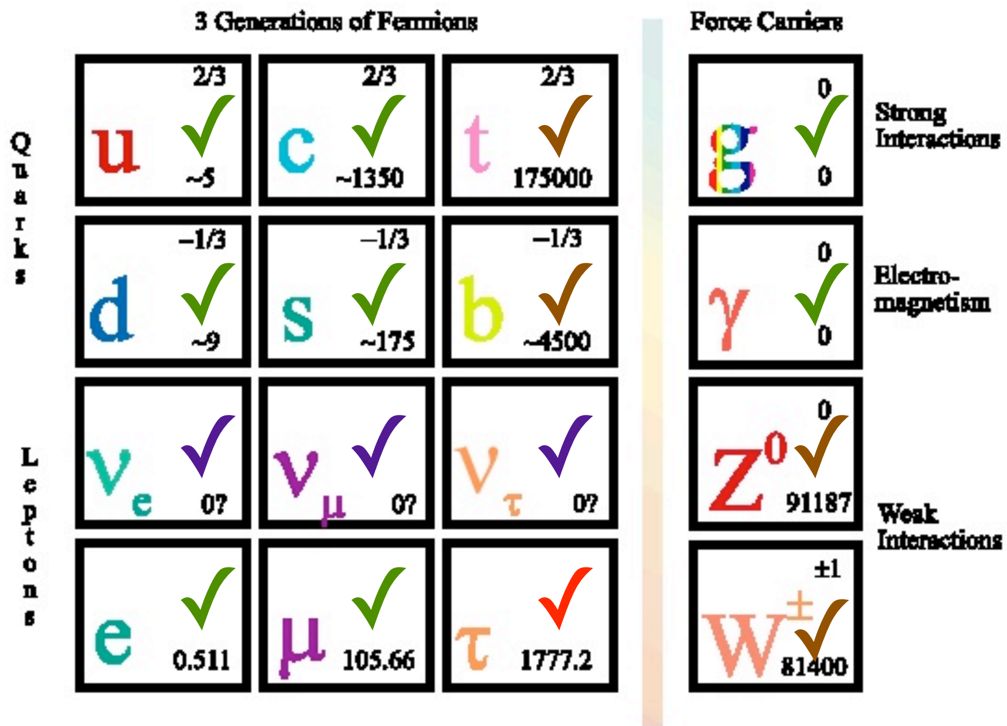




Neutrinos*

*(100% acceptance)

Detecting Particles



Masses are in MeV

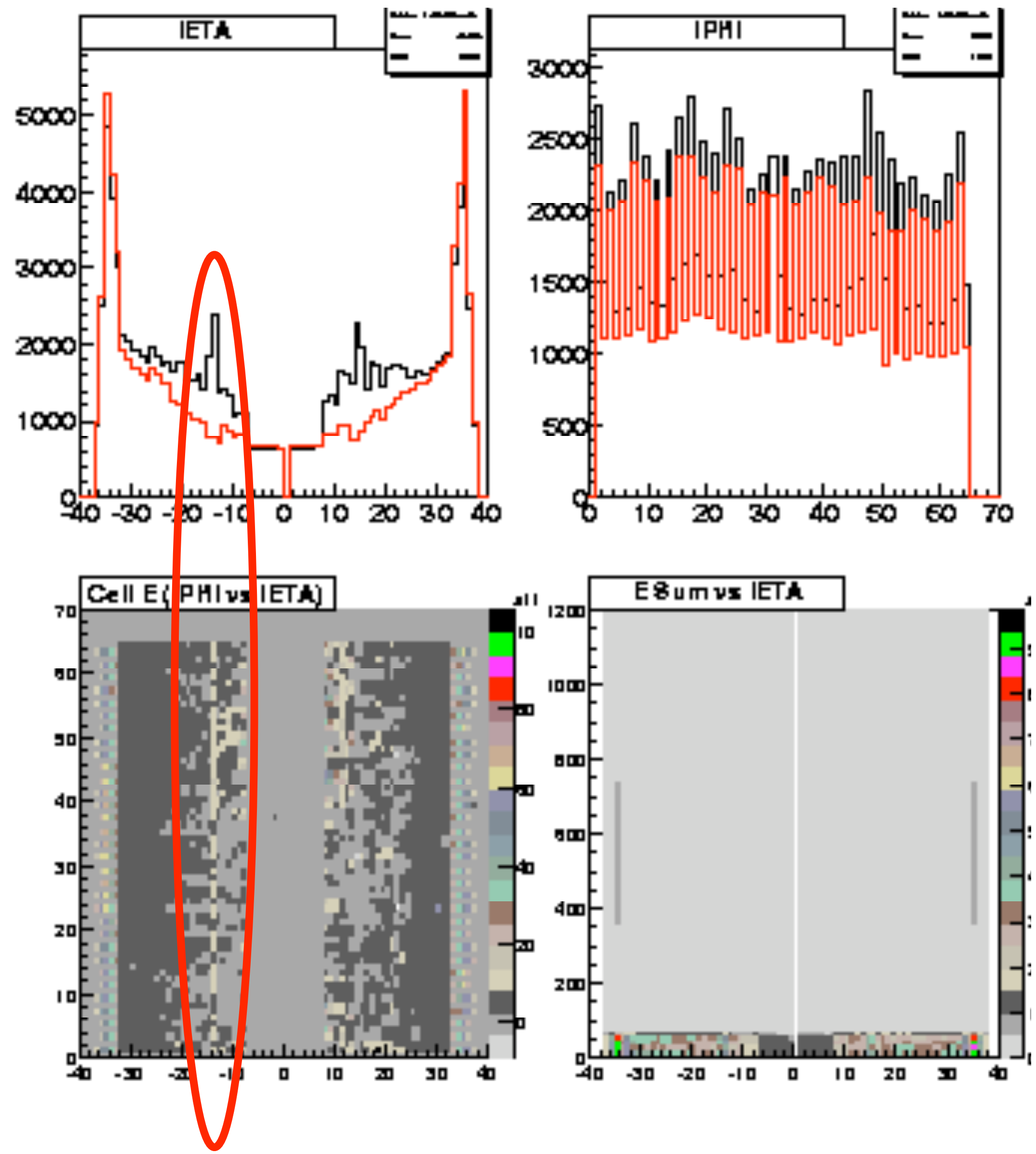
✓: Detect with high efficiency

✓: Detect by missing transverse energy

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

Anecdotes From the Field (I)

- DØ's "ring of fire"
  - Noise in a few "eta rings"
  - Occurred on rare occasions
- Originally thought to be a ground fault in HV distribution
- Found to be concurrent with welding in building
  - Finally traced to liquid Argon purity & temperature monitoring



The Work

Steps in a Physics Search

- What is the final state? $\Rightarrow$ "Preselection"
  - Sufficiently loose to be signal-poor
    - Prove you understand the detector response, physics processes contributing
  - But sufficiently tight to have a manageable data volume
    - ATLAS/CMS write ~200 Hz × 1+ MB/event = 200+ MB/s
    - "4-vectors" is not enough, need some amount of detector info
    - In practice, often have preselected sample for frequent analysis, + looser sample for multijet background with rare passes
- Note that data volume ~ running time, not $\int\mathcal{L}$

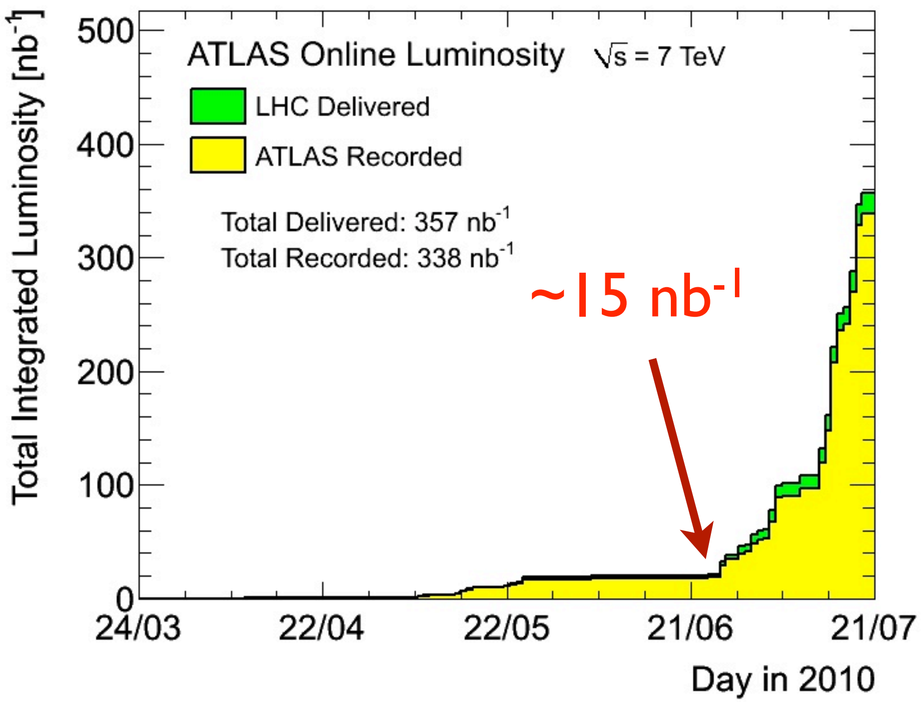
Steps (II)

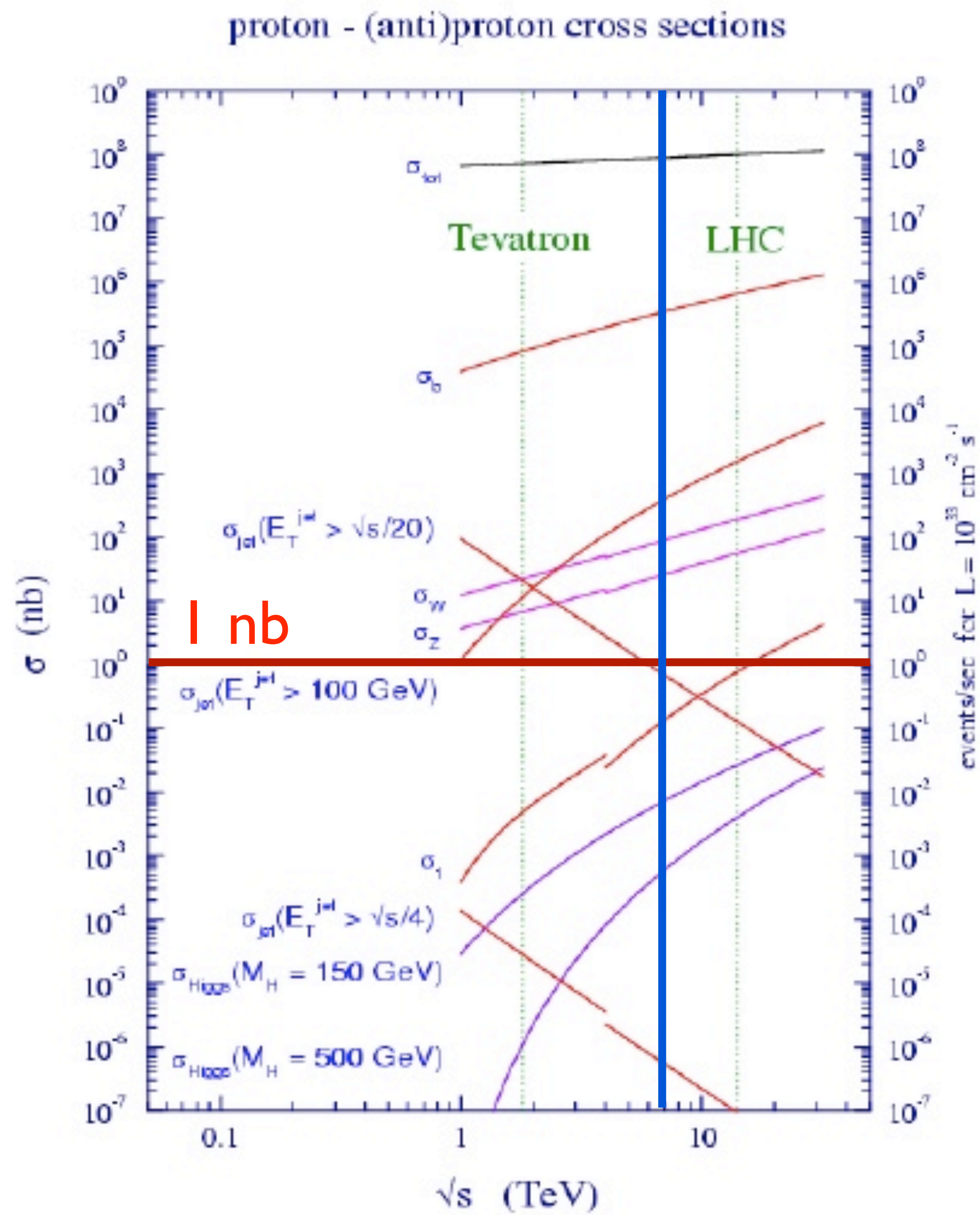
- Determine preselected sample's composition
  - MC and data to understand each contribution
    - QCD multijet background to leptons often extracted from data: rejection factor ~10^{-4}, difficult for simulation to be that accurate
    - MC for most other processes, with corrections from data, since generators are LO or NLO
  - Also need to correct MC for real-life data conditions
    - Different alignment, small fraction of dead channels etc.
  - As statistics increase, more difficult, since mis-modelings not hidden by large statistical uncertainties anymore

“Simple” Stuff

LHC Reality

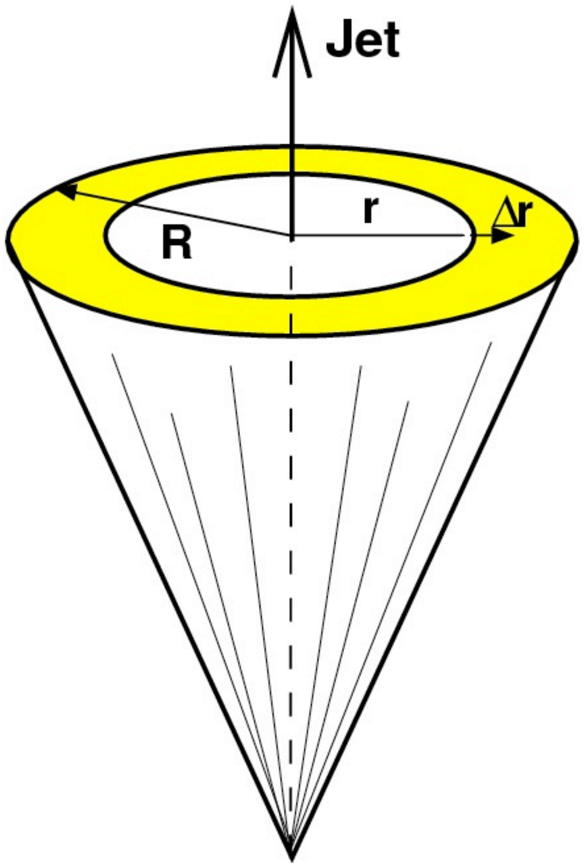
- Rather slow start
  - But use first data to test detector performance

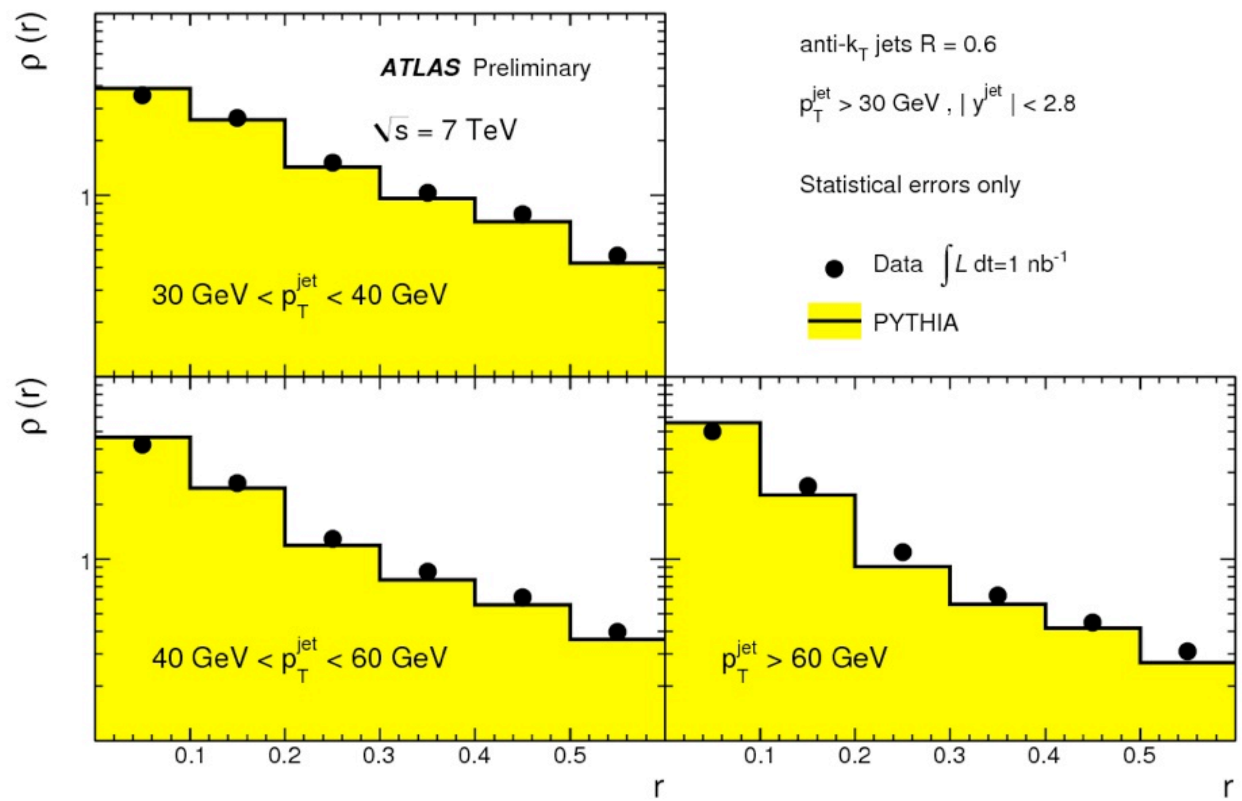




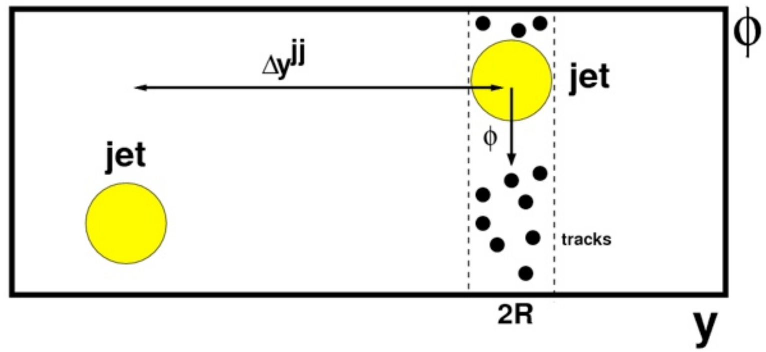
Jets

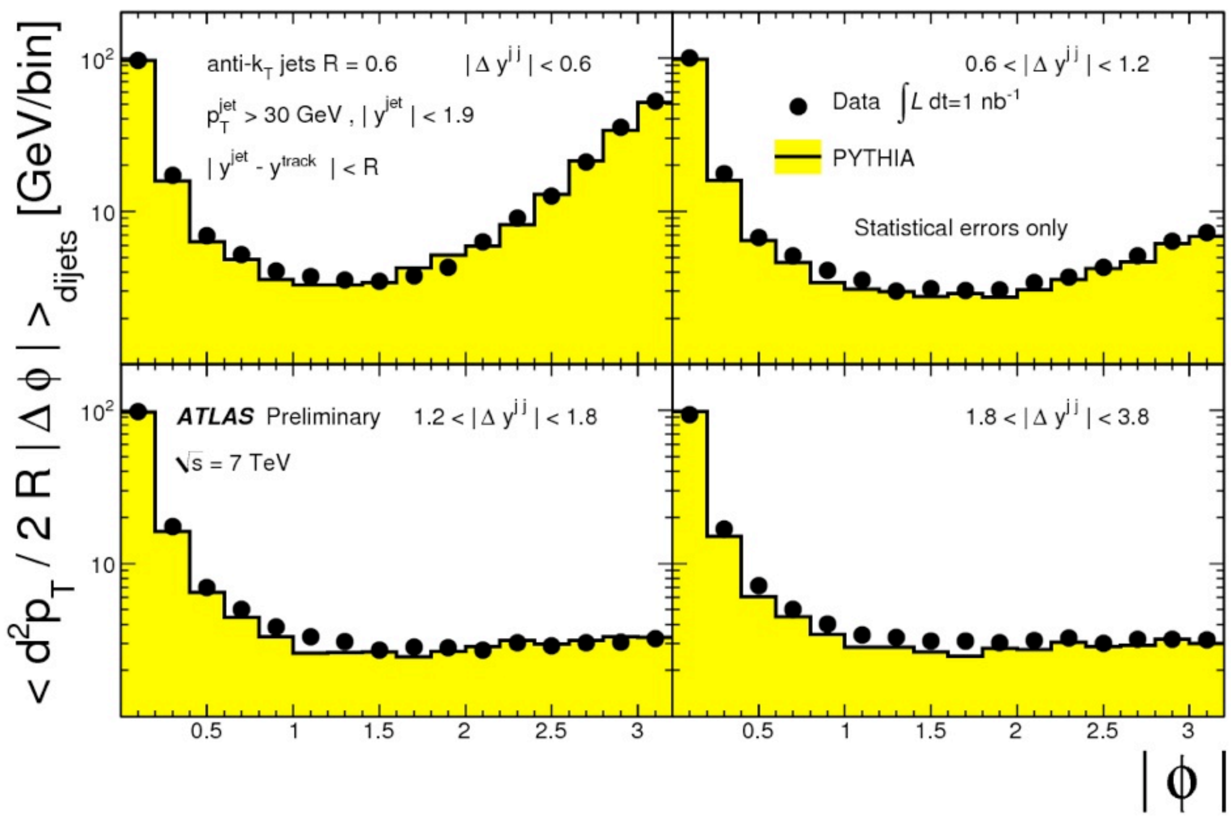
- No lack of jets at LHC!
- Jet shape: $\rho(r) = \frac{1}{\Delta r} \frac{1}{N^{jet}} \sum_{\text{jets}} \frac{p_T(r - \Delta r/2, r + \Delta r/2)}{p_T(0,R)}, \ 0 \leq r \leq R$





- Charged particle flow: $< \frac{d^2 p_T}{|d\phi| dy} >_{jets} = \frac{1}{2R|\Delta\phi|} \frac{1}{N^{jet}} \sum_{jets} p_T(|\phi - \Delta\phi/2|, |\phi + \Delta\phi/2|)$





Jet Energy Scale

- Calorimeters are calibrated to electromagnetic scale
  - Established using test-beam measurements, cosmics, and soon $Z \rightarrow ee$ samples
- But calorimeter is
  - Non-compensating
  - Doesn't measure energy in dead material
  - or leaking out
  - And there are some inefficiencies
- Want reconstructed jet energy = truth jet energy
  - Jets don't exist outside an algorithm

Riddle Me This

- In Run I, the DØ calorimeter was (very close to) compensating
  - A benefit of Uranium...
- We did not change the calorimeter between Run I and Run II...
- ... but in Run II, it is compensating no more!

???

Truth vs Reconstructed Jets

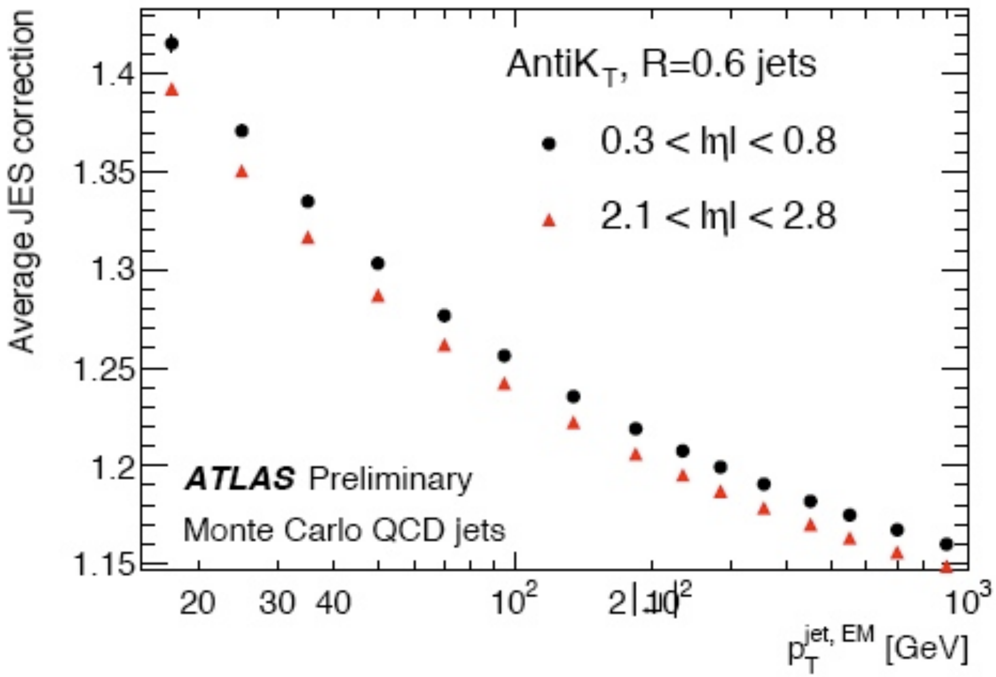
- "Truth jets" are made of MC hadrons, both charged & neutral, clustered with your algorithm of choice
- Reconstructed jets are made of visible things
  - Energy deposits in calorimeters, but jets deposit energy through strong interactions → large invisible fraction (in nuclei)
  - Charged particle tracks: can have "track jets", or use to improve calorimeter energy measurement
- Intrinsically, jet energy resolution is limited by fraction of neutral hadrons depositing "invisible" energy

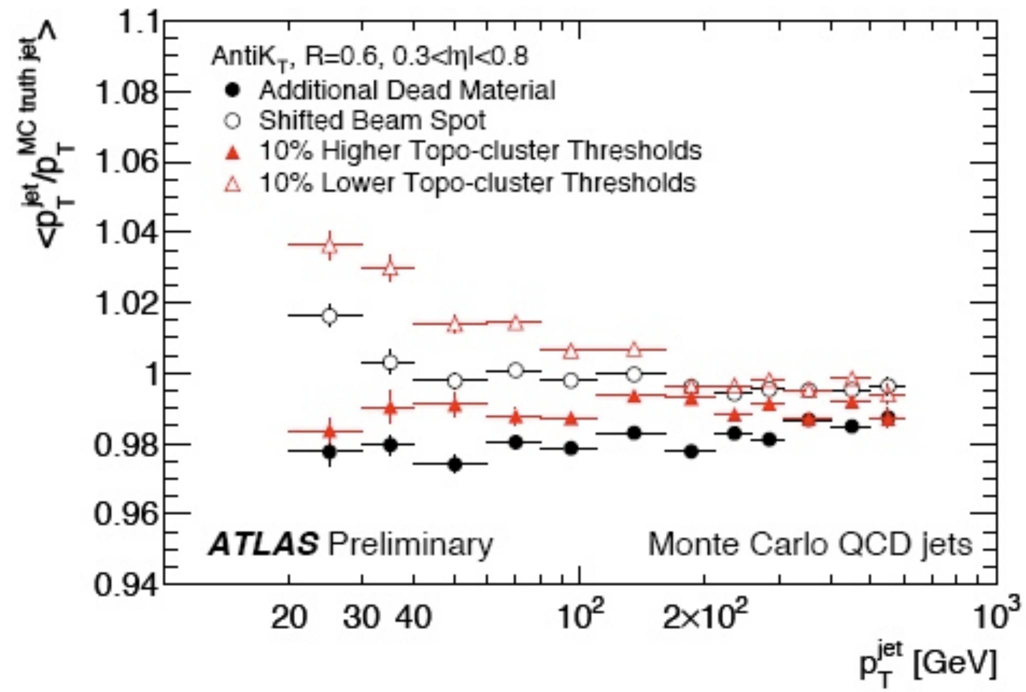
JES in ATLAS

- Jet-by-jet MC correction
  - Function of p_T, η

$$p_T^{\text{jet,calib}} = 1/R^{\text{EM}}(p_T^{\text{jet,EM}}, \eta) \cdot p_T^{\text{jet,EM}}$$

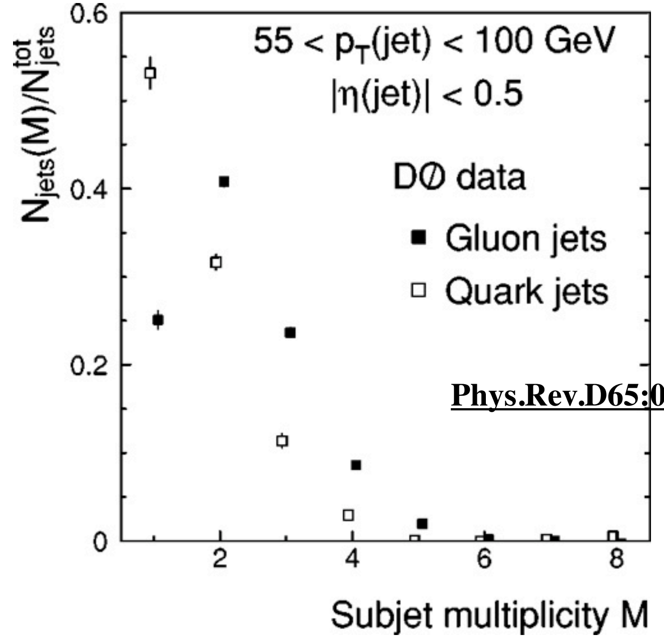
$$1/R^{\text{EM}}(p_T^{\text{jet,EM}}, \eta)$$





Quarks and Gluons

- Quark- vs gluon-initiated jets
  - "Gluon jet" energy spread over more particles
  - Standard JES correction based on certain mixture
  - For different mixture, need to correct
  - Then worry about pile-up



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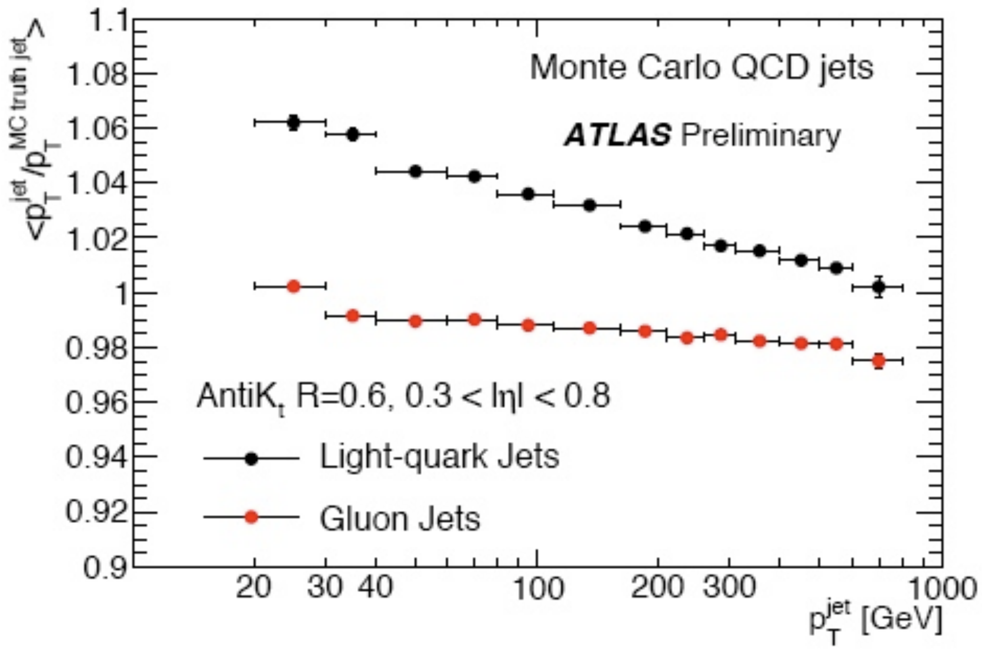
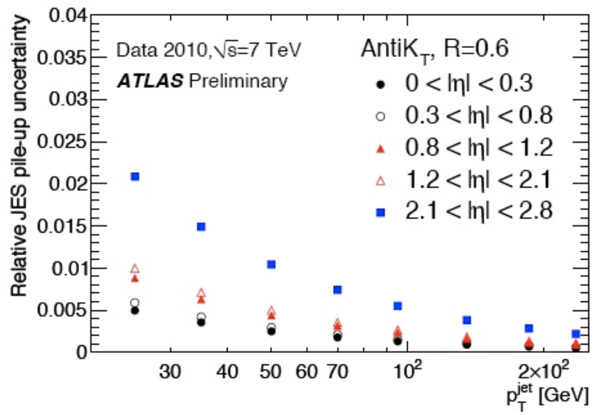
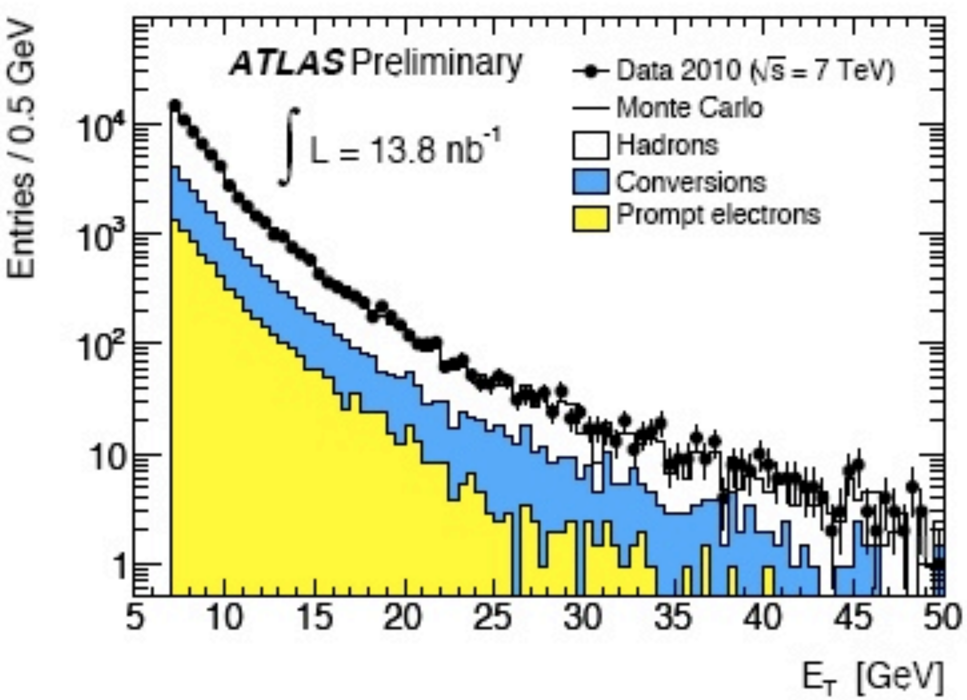
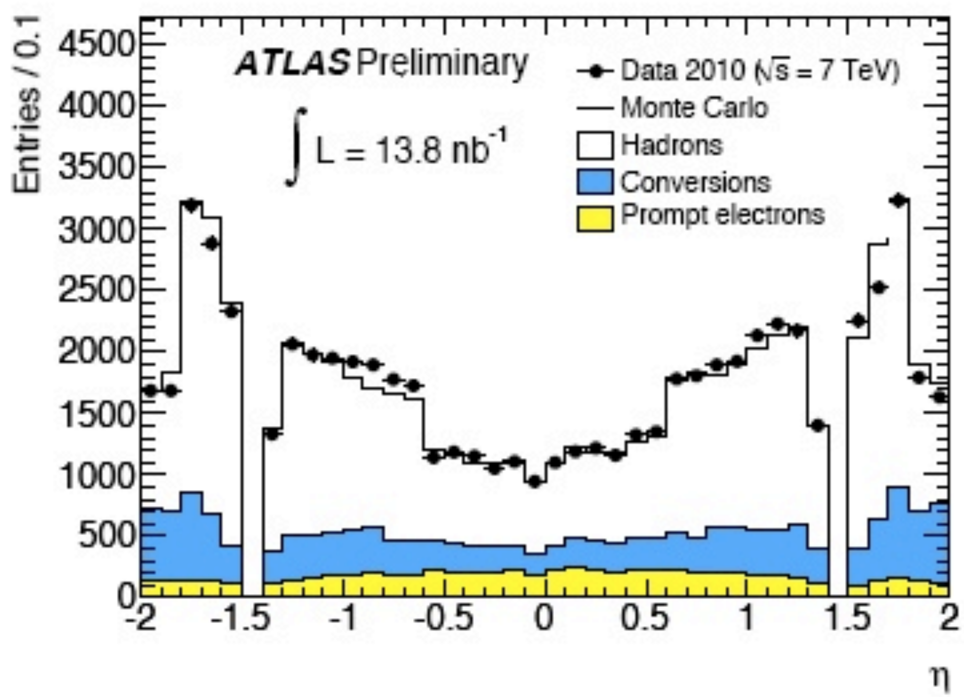




Electrons

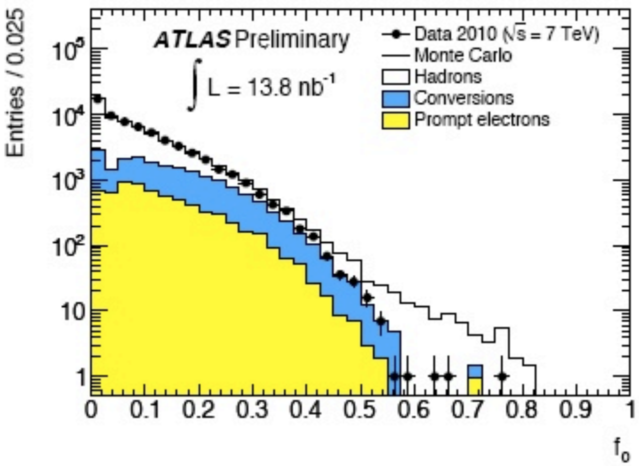
- Not many W's, handful of Z's in 15 nb^{-1}
  - Plenty of b's producing electrons
  - Can we look at characteristic variables?
- "Medium" selection cuts



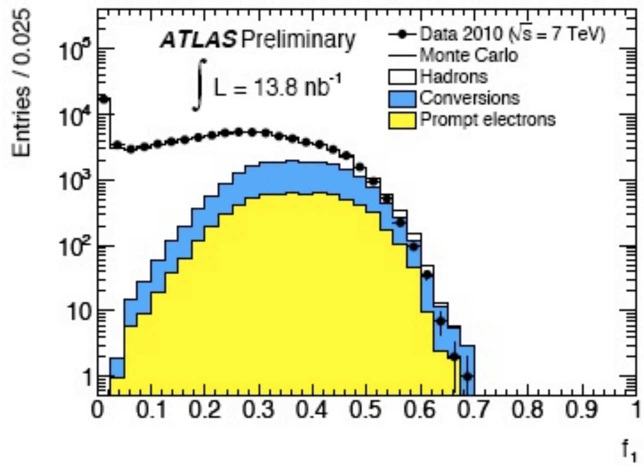


Some Distributions

TRT "high threshold" hits



(a)



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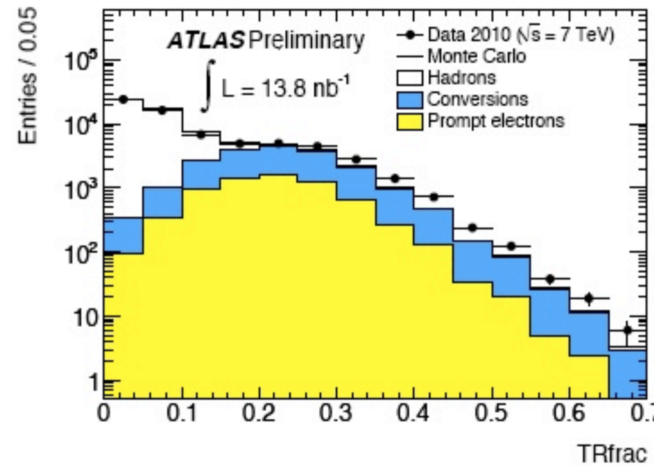

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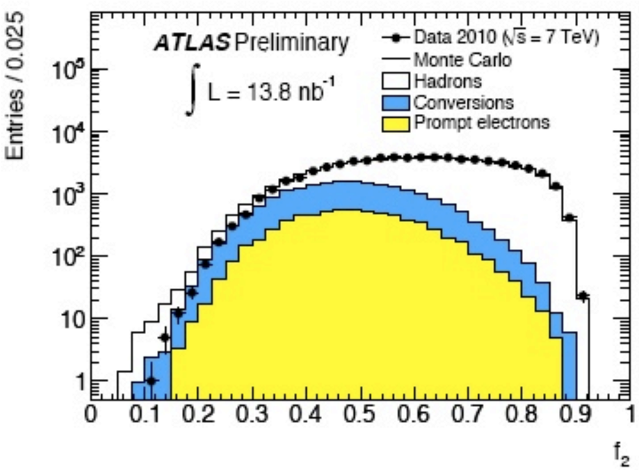
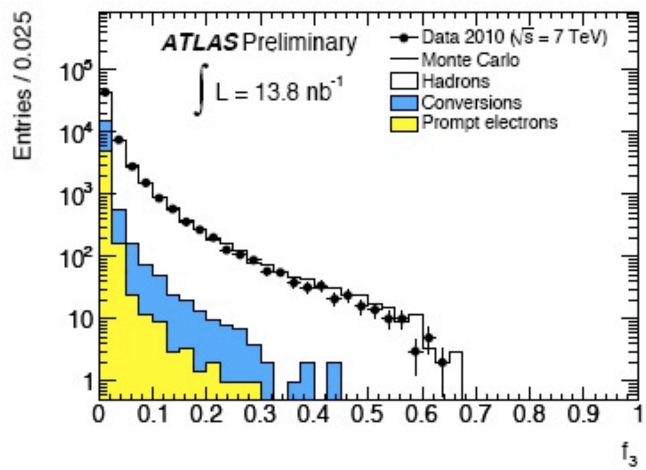
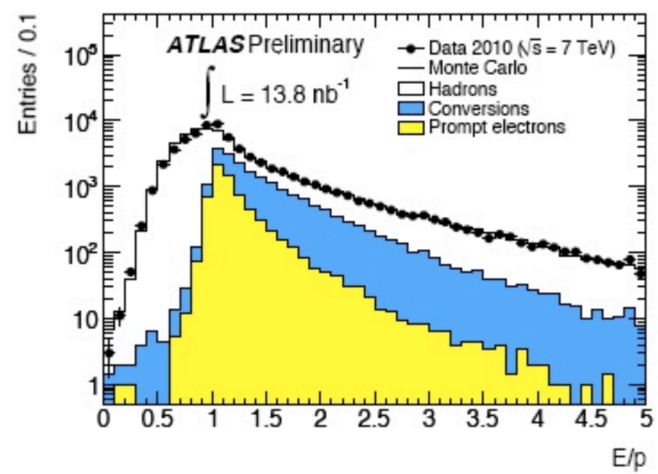






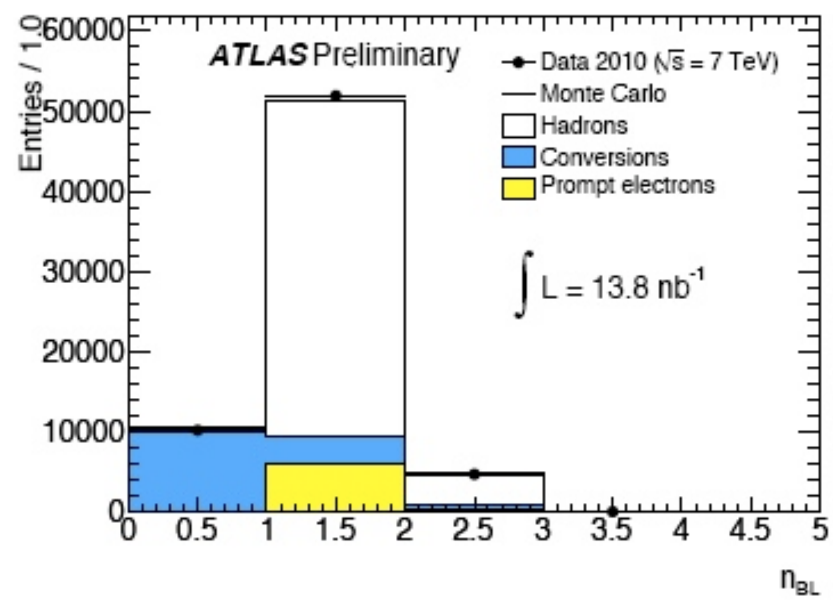
Fraction of energy
in calorimeter layers

“Simple” and Effective

- “Matrix Method”: use TRfrac and number of hits in first pixel layer to derive components in data:

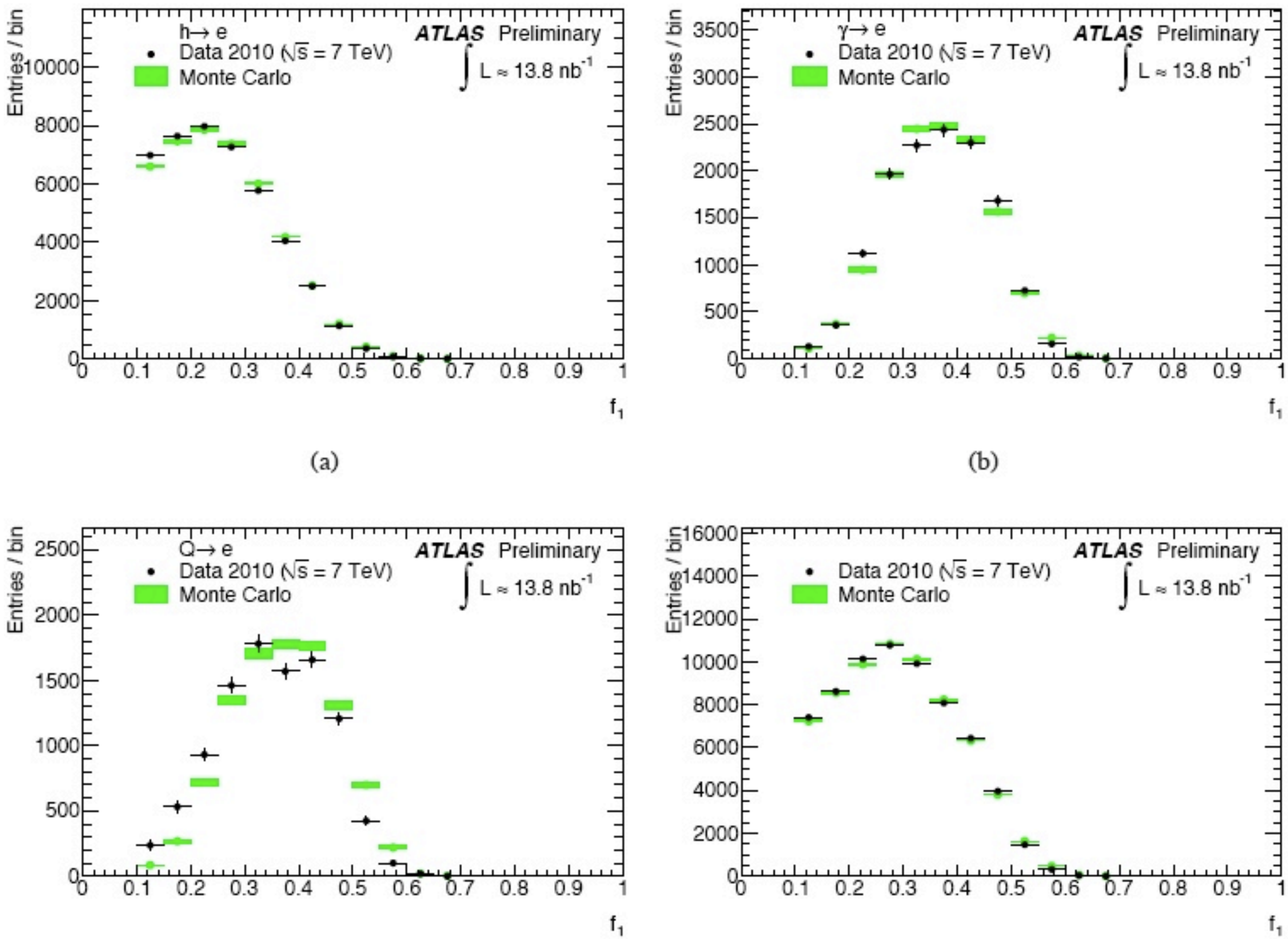
$$\begin{pmatrix} N \\ N_{TR} \\ N_{BL,TR} \end{pmatrix} = \begin{pmatrix} 1 & 1 & 1 \\ \varepsilon^h_{TR} & \varepsilon^\gamma_{TR} & \varepsilon^Q_{TR} \\ \varepsilon^h_{BL}\varepsilon^h_{TR} & \varepsilon^\gamma_{BL}\varepsilon^\gamma_{TR} & \varepsilon^Q_{BL}\varepsilon^Q_{TR} \end{pmatrix} \begin{pmatrix} N^h \\ N^\gamma \\ N^Q \end{pmatrix}$$

- Get ε^h_{TR} and ε^h_{BL} from data
  - Hadron-enriched sample
- Other ε’s from MC
- All as functions of p_T, η



Result

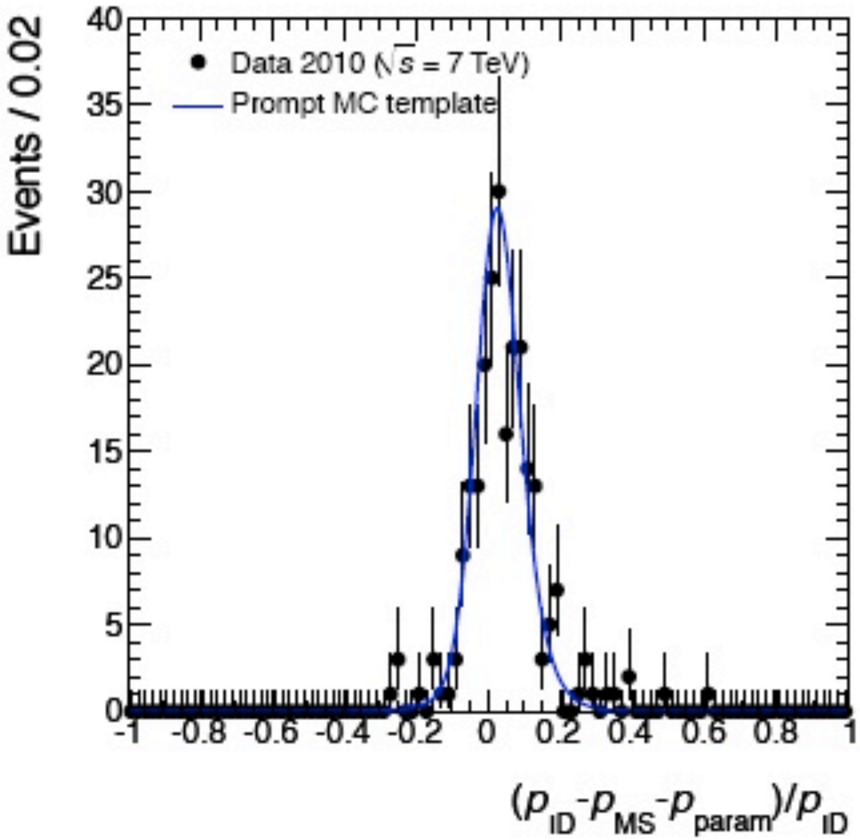
- Can look at any variable now

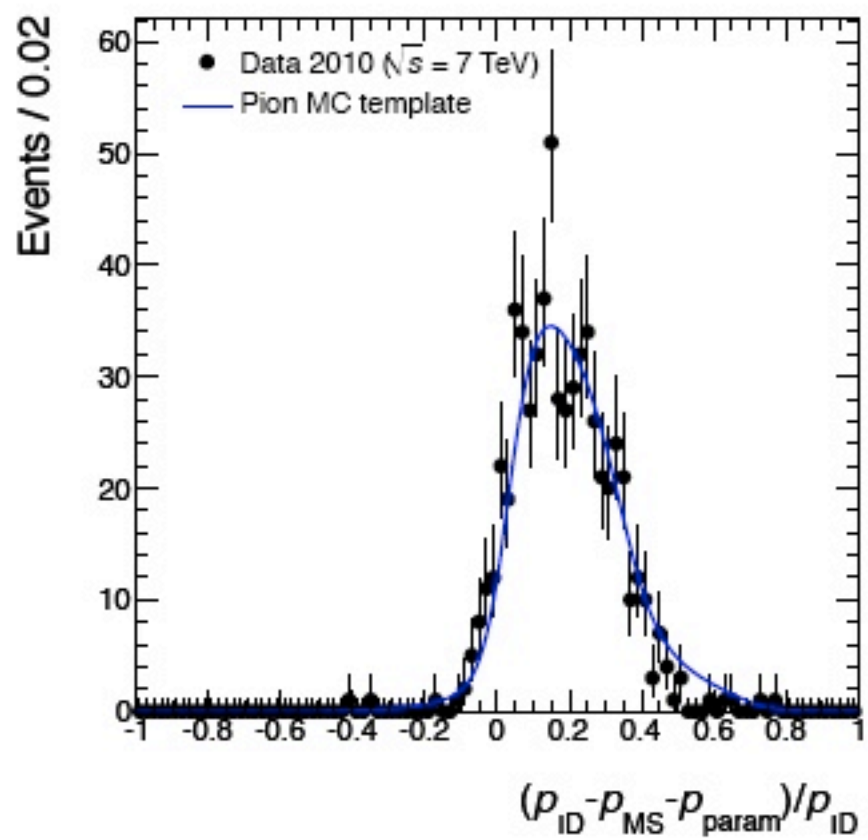


(a) (b)

Muons

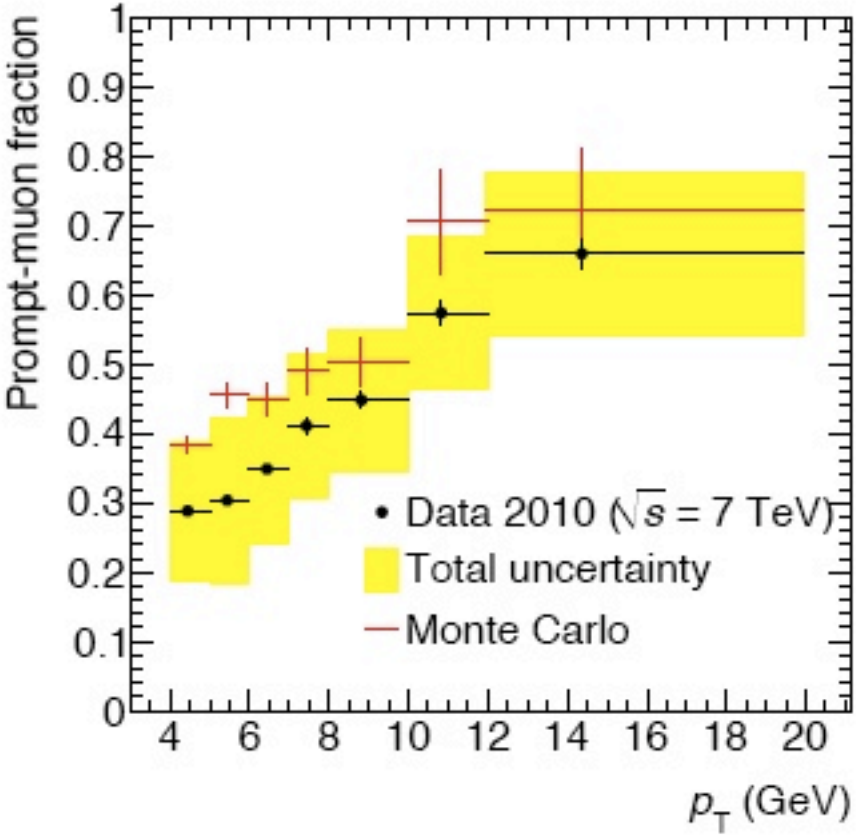
- In the muon system, most tracks are true muons
  - At low pT, fair fraction comes from π, K decays

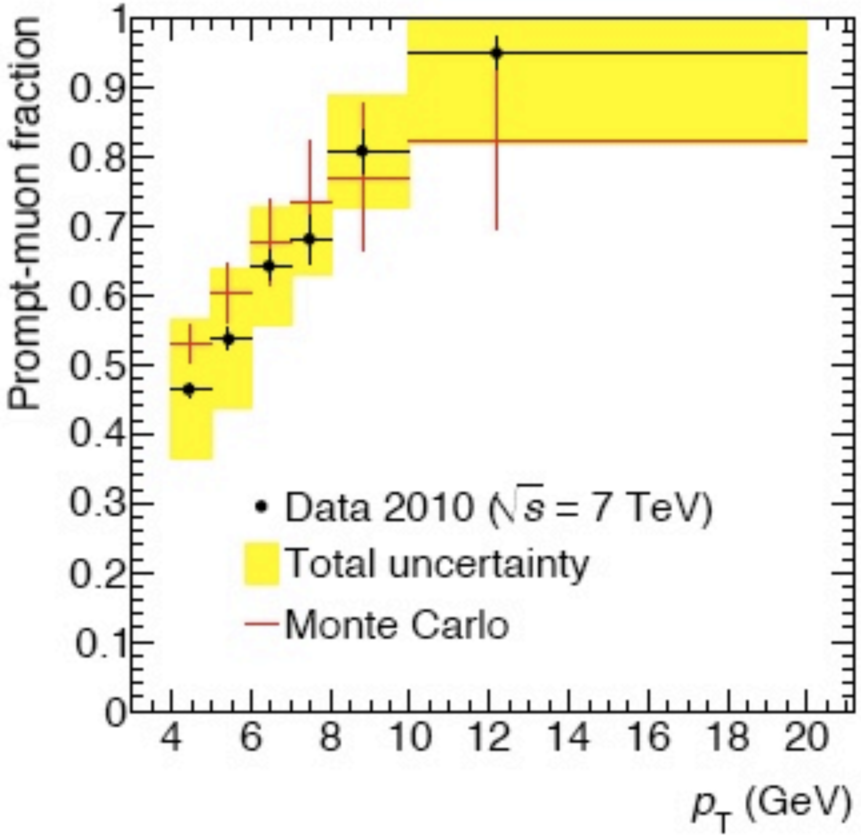




Data control samples selected from J/ψ, K_S decays

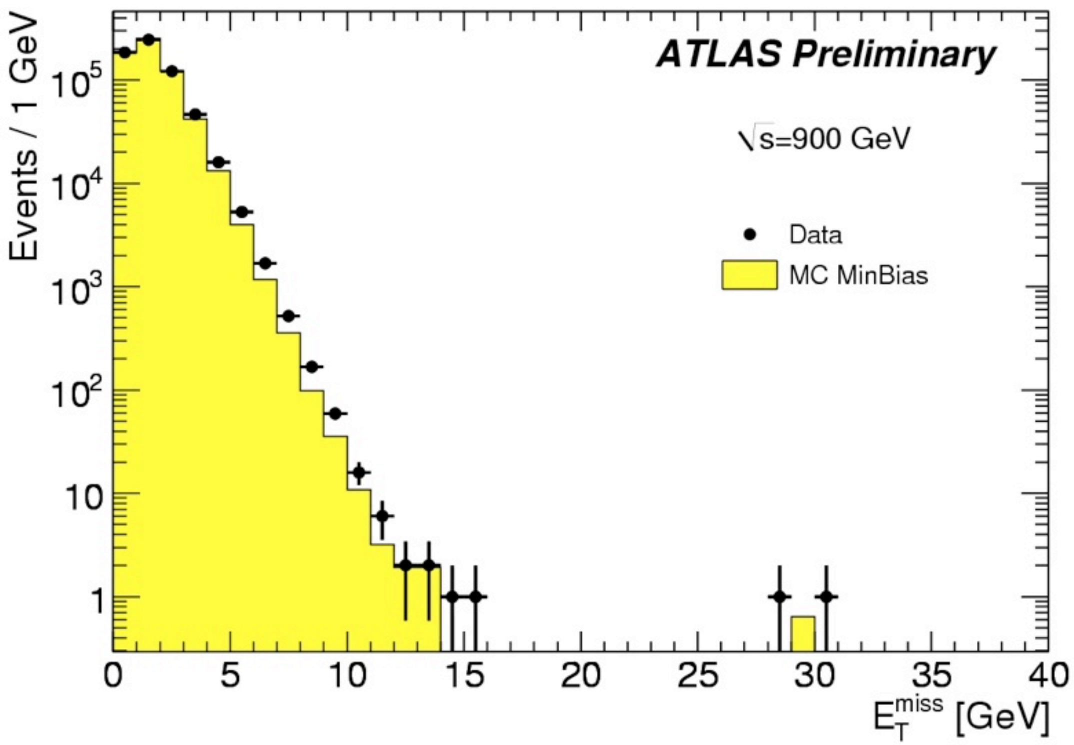
- Heavy flavor likes the forward direction!
  - LHCb...





Anecdotes From the Field (II)

- Everybody wants experimenters to produce results fast
  - Lots of pressure in the early days of LHC...



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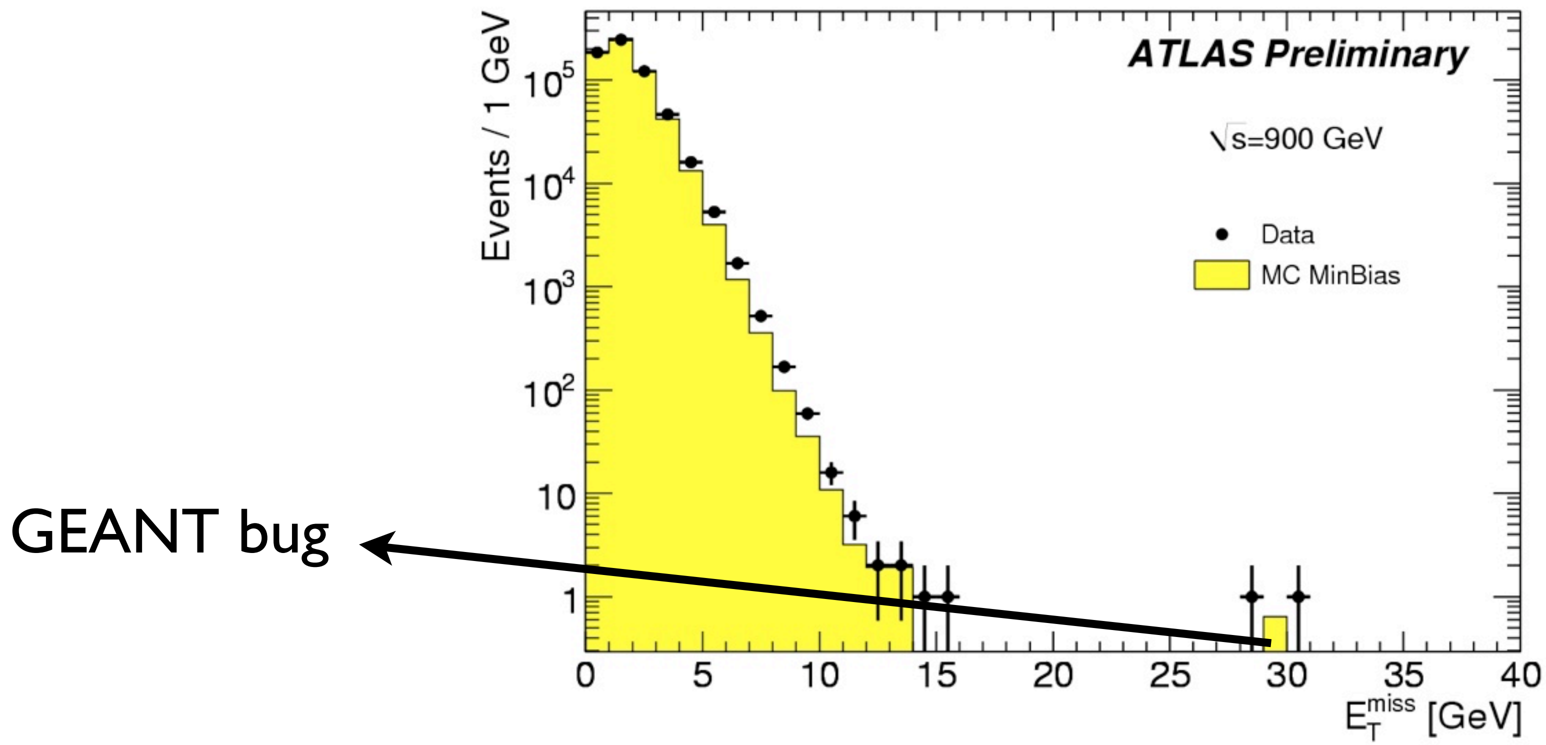

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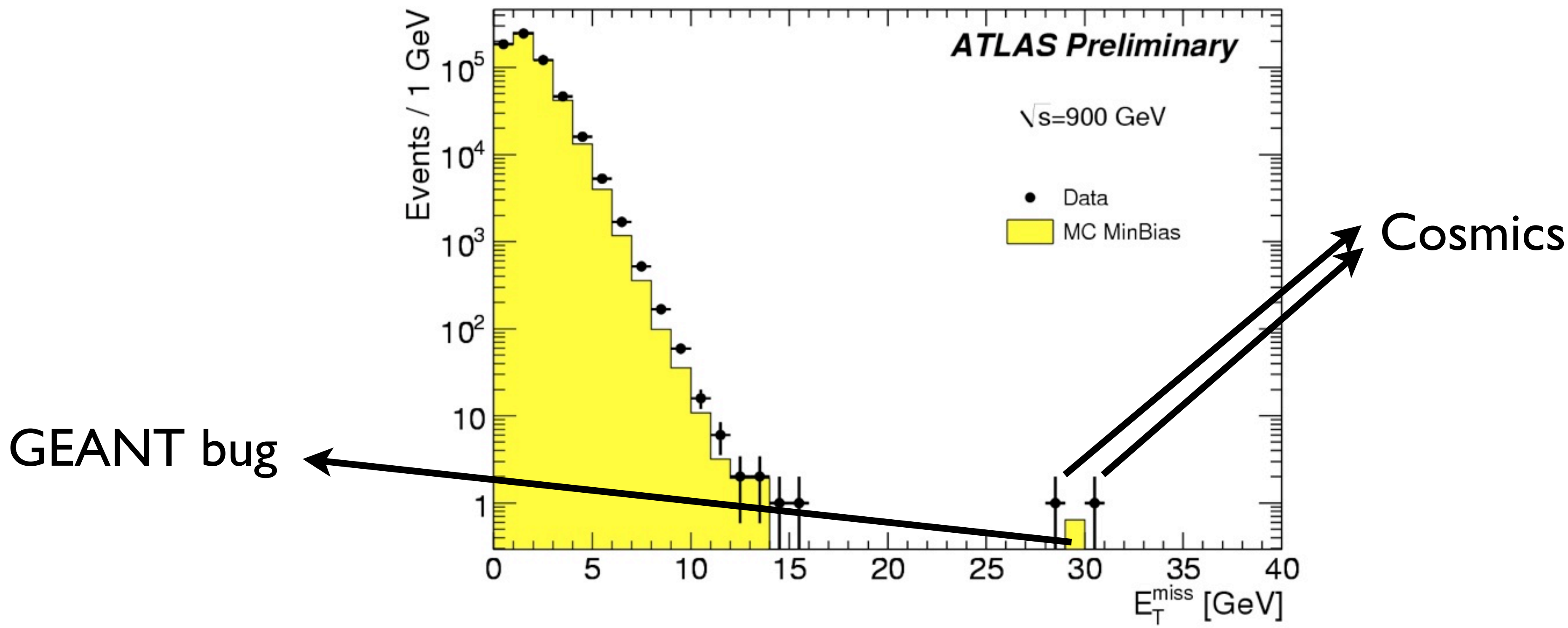
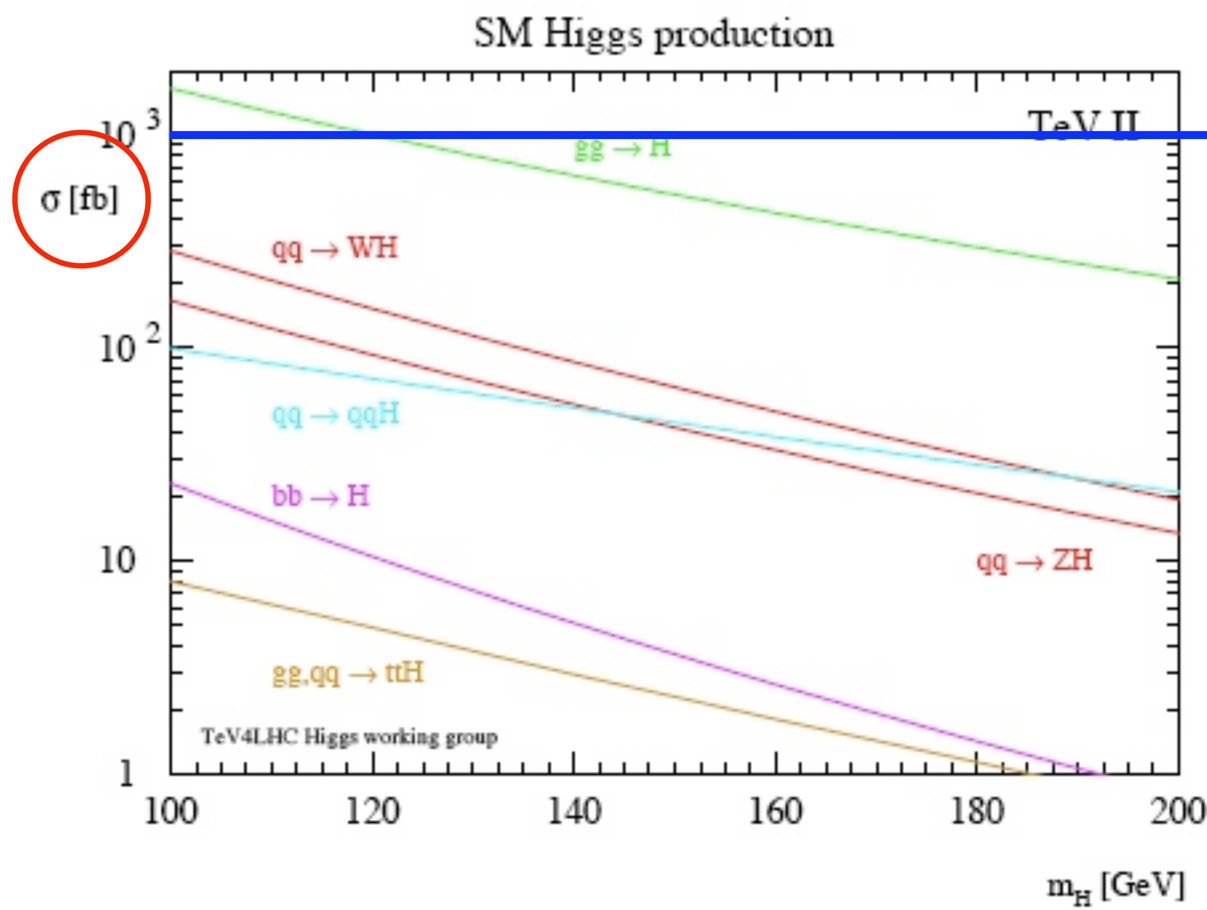


- Sometimes, it's better to take the appropriate time to investigate

A Challenging Search:
The Higgs Hunt at the Tevatron

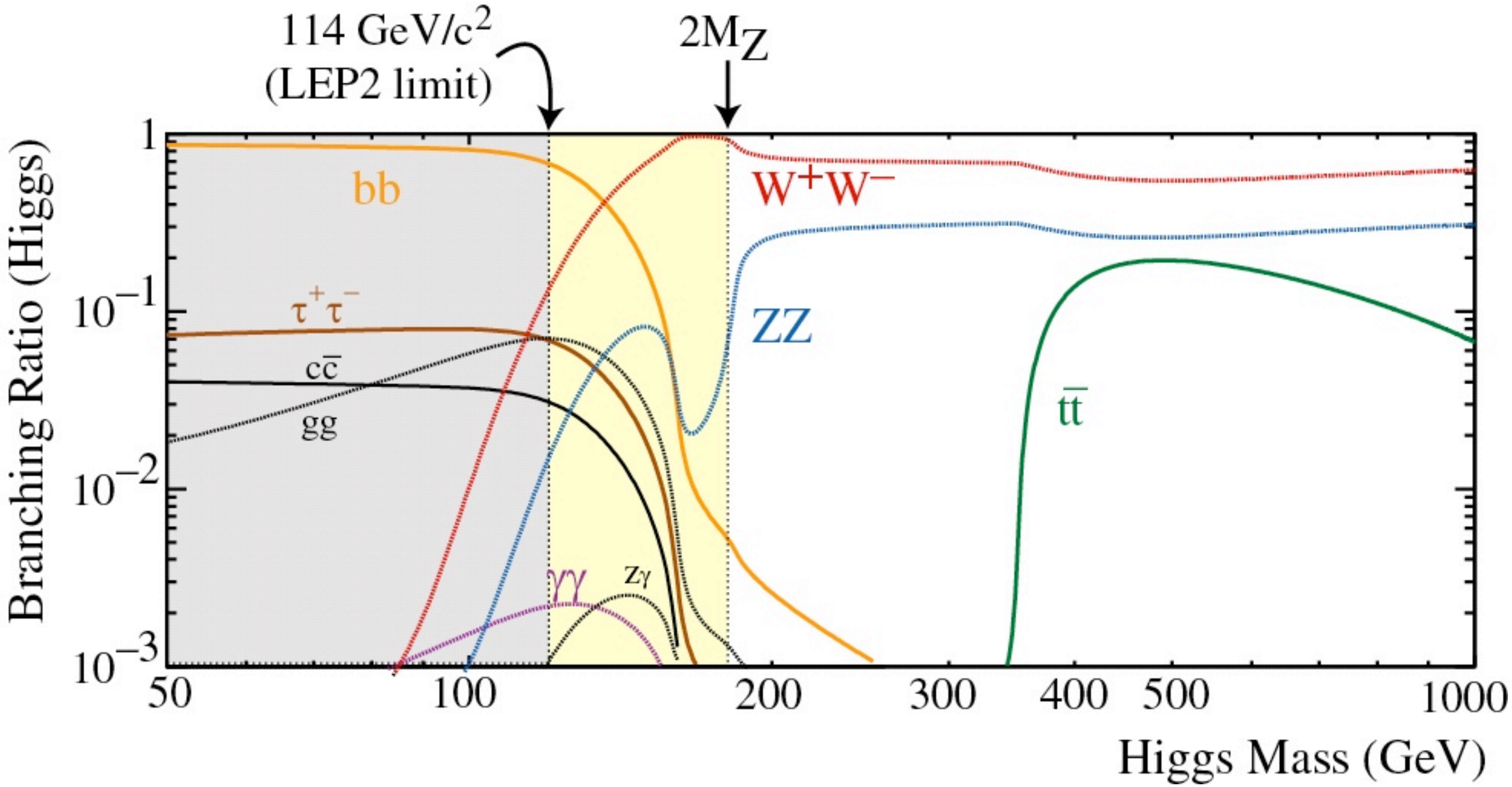
Producing Higgses

- Tevatron experiments currently have ~8 fb^{-1} of data on tape
  - (Data taking efficiency is ~90%)



8000 events (x many efficiency factors)

Higgs Decay



Low Mass

$H \to b\bar{b}$

High Mass

$H \to WW$

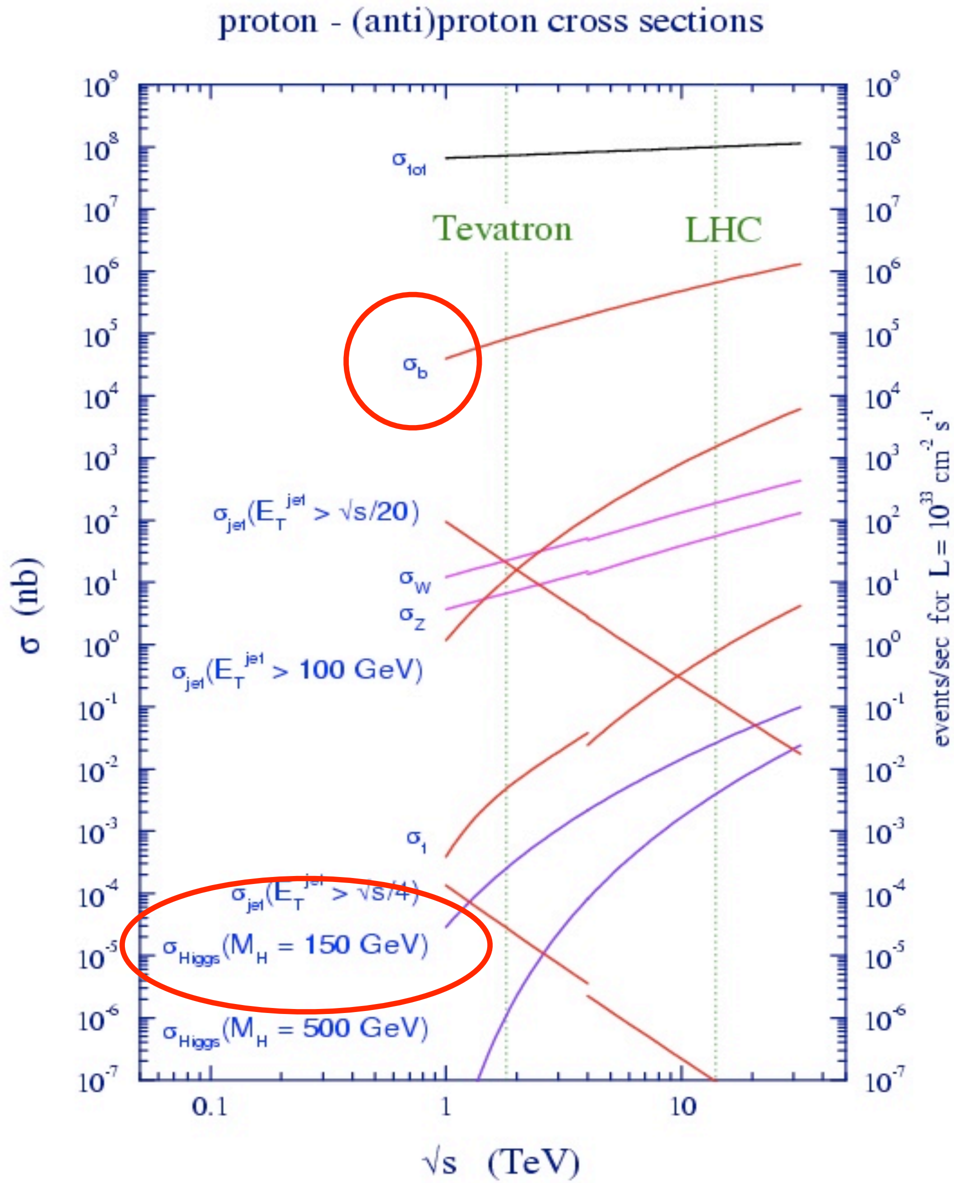
Search Channels

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

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

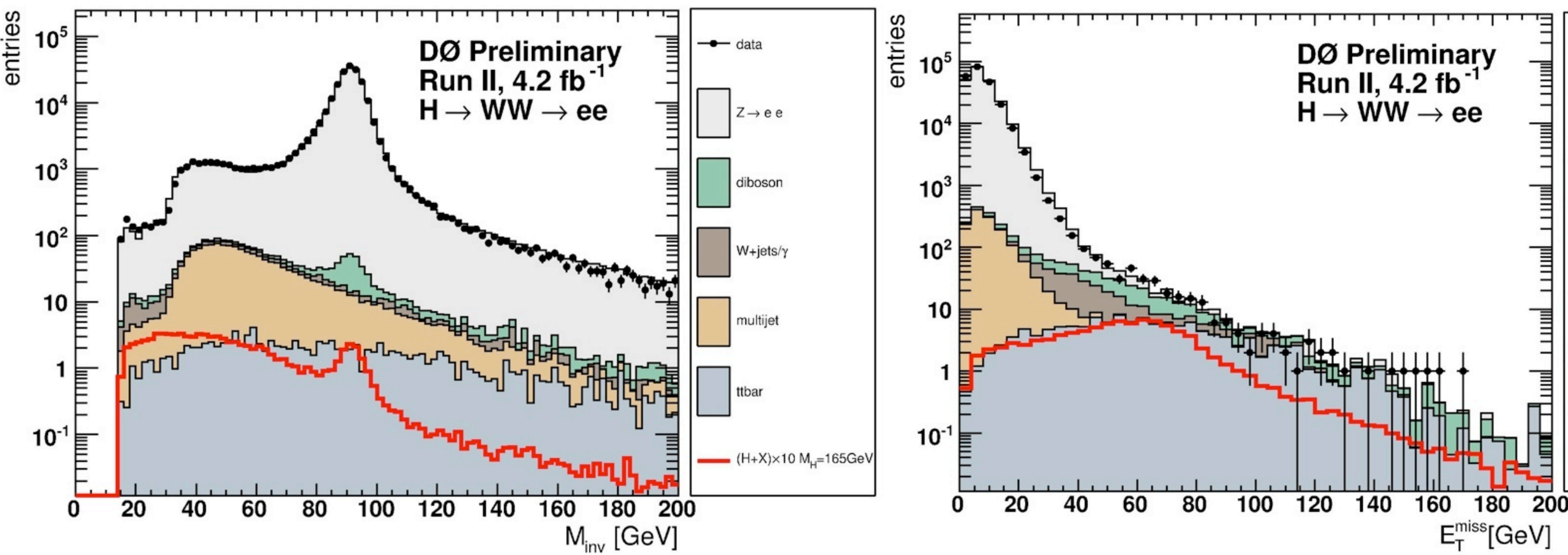
  - With leptonic W, Z decay, so # of events /~50!

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



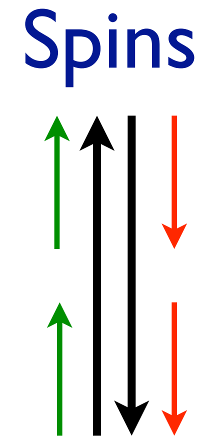
Dilepton + MET

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

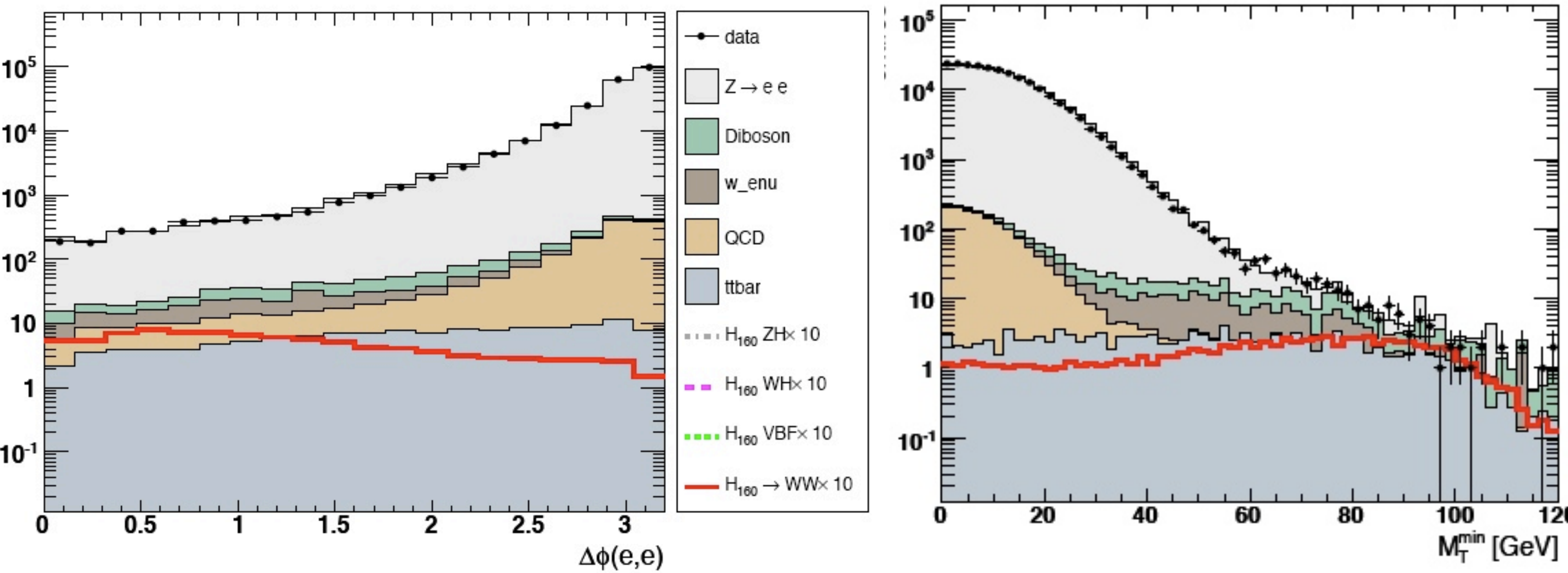


Angles

- 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)

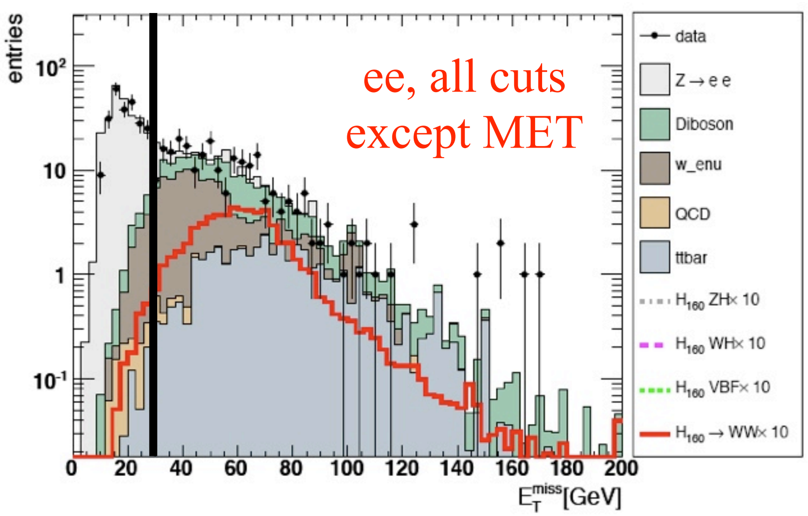


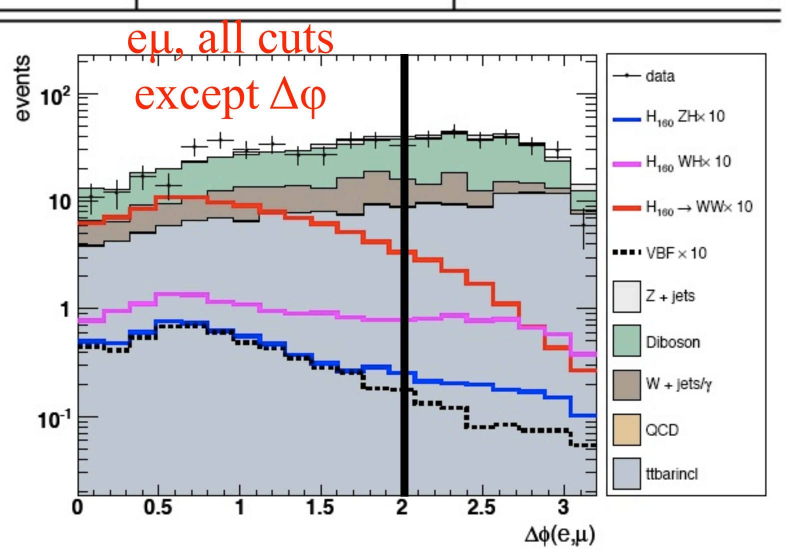
  - In Z, smallest transverse mass tends to be small



Preselection

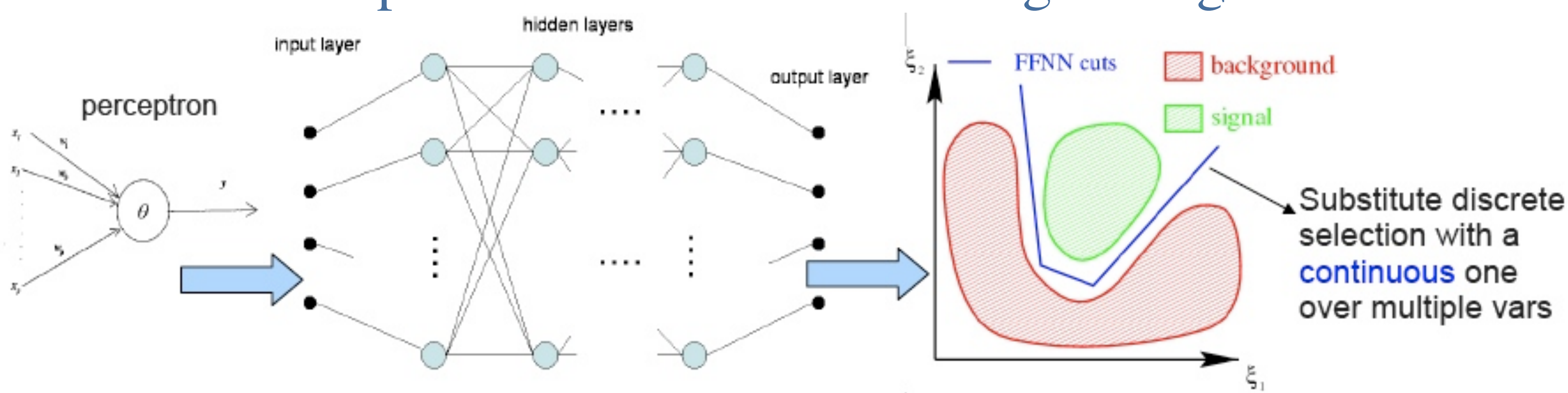
Final state		$e\mu$	ee	$\mu\mu$
Cut 0	Pre-selection	lepton ID, leptons with opposite charge and $p_T^{\mu} > 10$ GeV and $p_T^{e} > 15$ GeV invariant mass $M_{\ell\ell} > 15$ GeV $\mu\mu$: $n_{\rm jet} < 2$ for $p_{\rm T}^{\rm jet} > 15$ GeV, $\Delta\mathcal{R}(\mu, {\rm jet}) > 0.1$ and $p_T^{\mu} >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

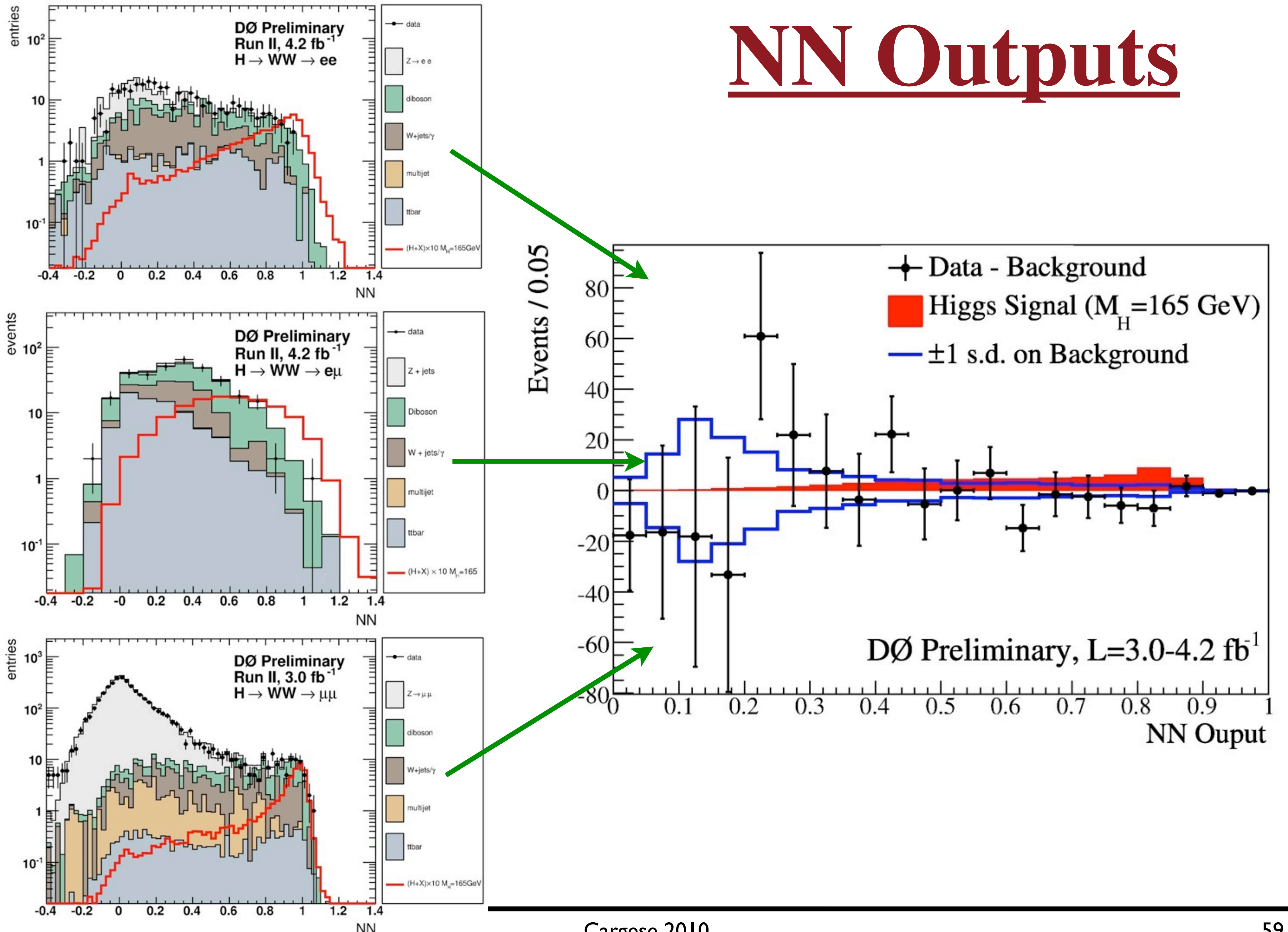


Variables

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:	$H_T = \sum_i \lvert p_T(\text{jet}_i)\rvert$
Invariant mass of both leptons	$M_{\text{inv}}(\ell_1, \ell_2)$
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



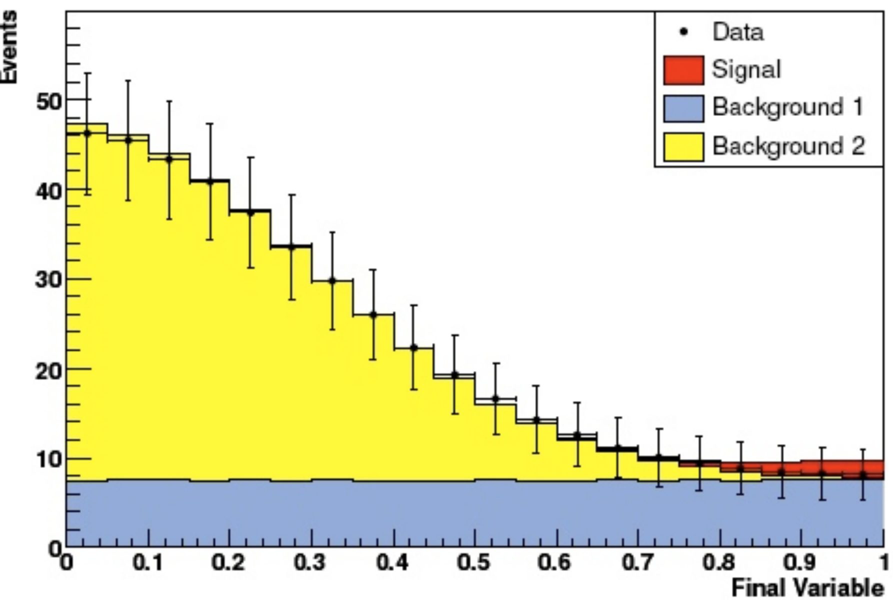
DØ Preliminary
Run II, 4.2 fb-1
H → WW → ee
DØ Preliminary
Run II, 4.2 fb-1
H → WW → eμ
DØ Preliminary
Run II, 3.0 fb-1
H → WW → μμ
NN
Data - Background
Higgs Signal (MH=165 GeV)
±1 s.d. on Background
Events / 0.05
DØ Preliminary, L=3.0-4.2 fb-1
NN Ouput

Systematics Profiling

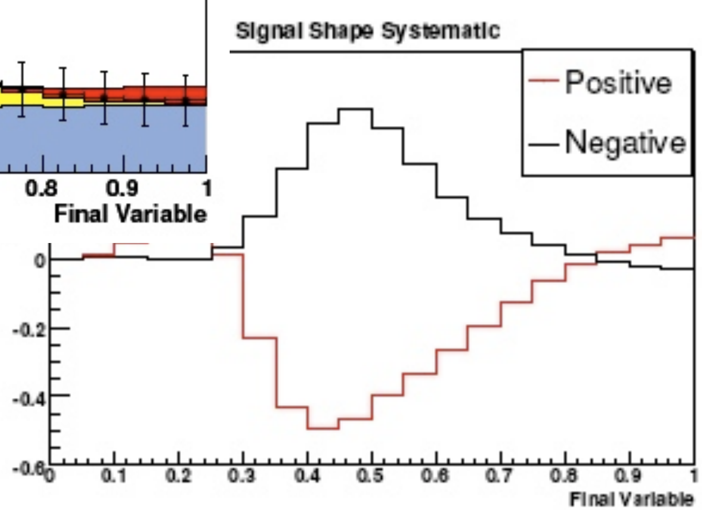
- Systematic uncertainties are propagated through the full analysis chain to the NN output distribution
  - E.g. we repeat the analysis with jet energy scale shifted up & down by 1σ
  - Some systematic uncertainties affect shape (jet reconstruction efficiency, energy scale and resolution, boson p^T distributions), 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

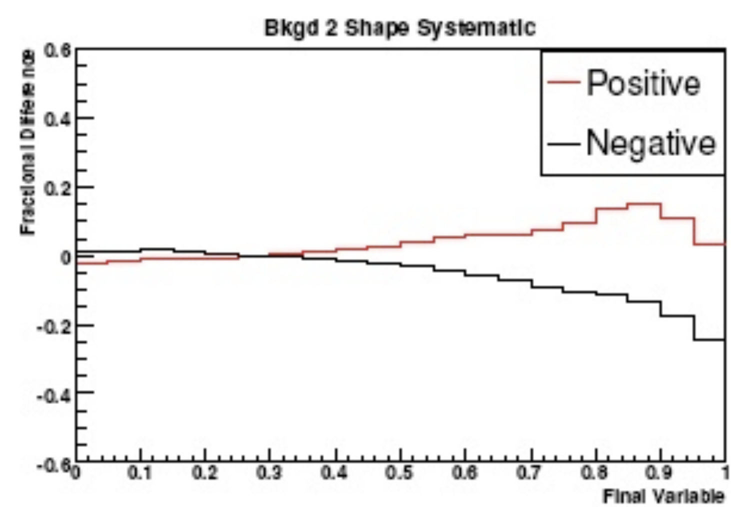
Systematics Profiling

- 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



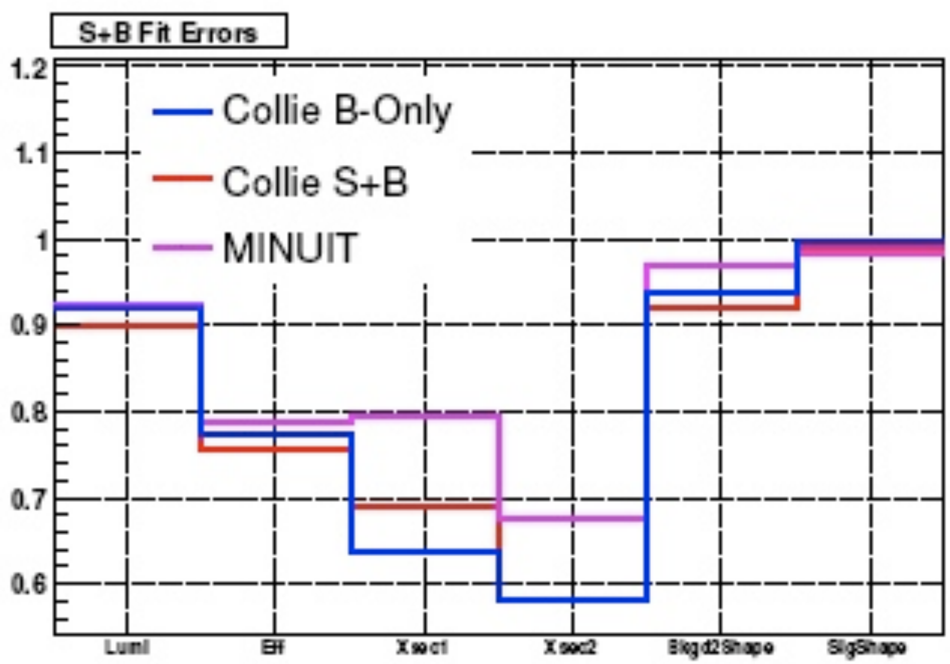
Toy Example

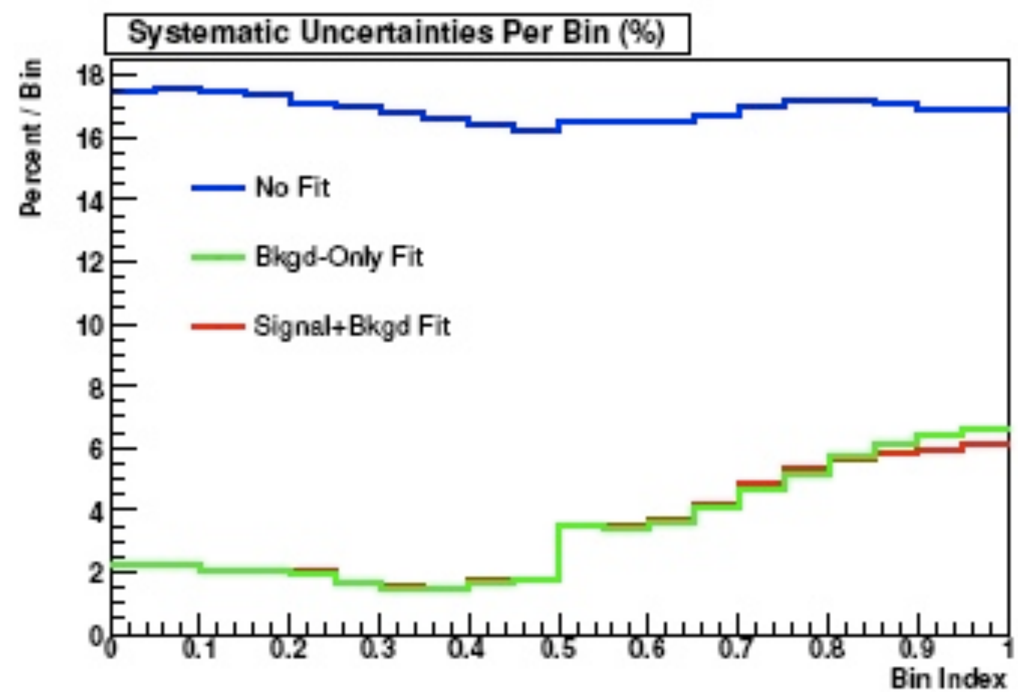




- Can generate pseudo-experiments (events in bins according to poisson), then for each experiment vary nuisance parameters
  - Variations in background (& S+B) prediction
    - Compare results to data using log-likelihood ratio
- So we can maximize likelihood ratio as a function of nuisance parameters → 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)

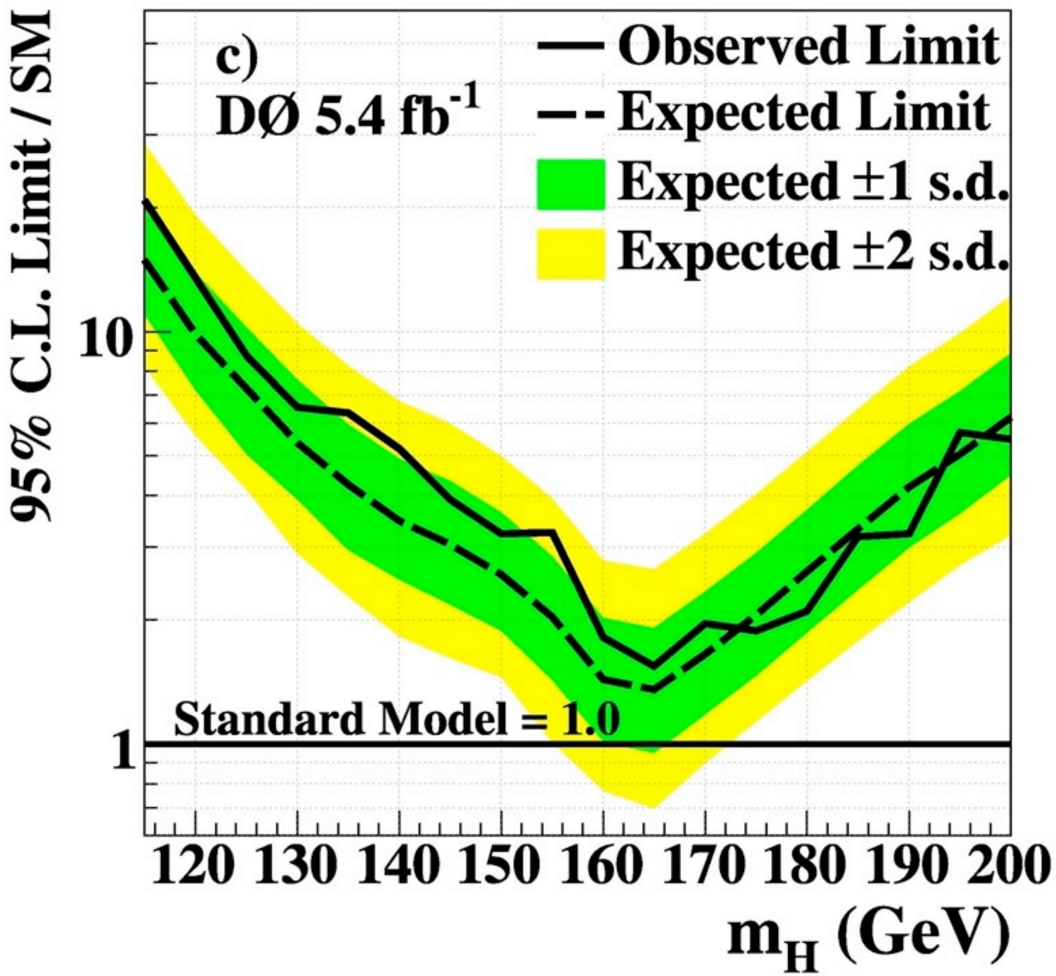




Dilepton + MET Result

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

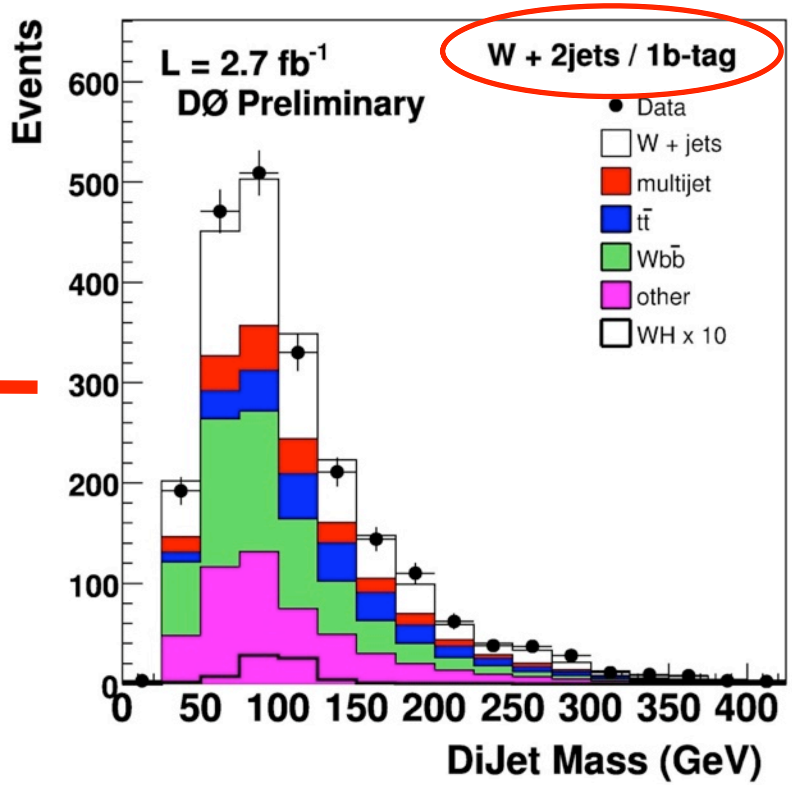
Phys. Rev. Lett. 104, 061804 (2010)



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 <u>with</u> virtual corrections

Correction Factors

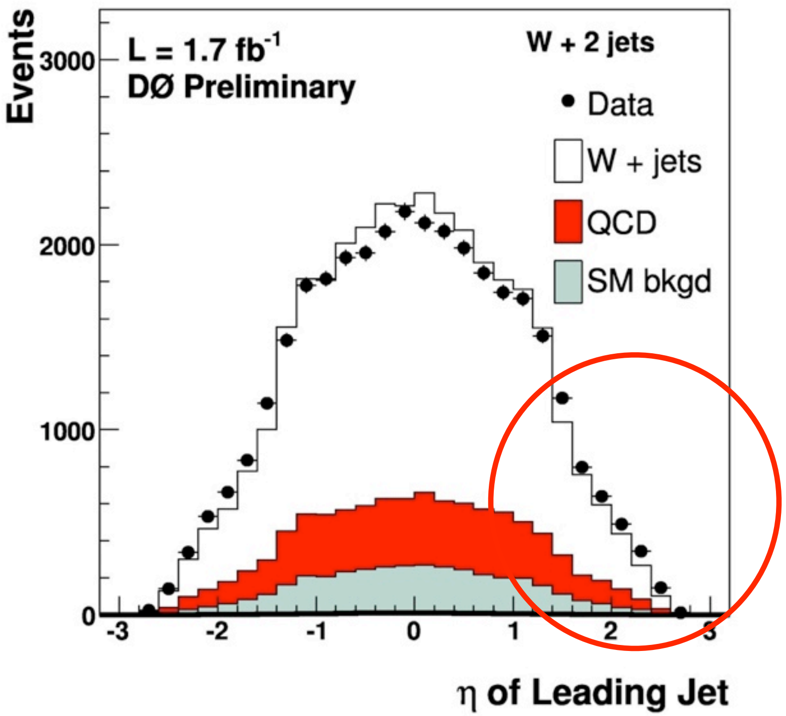
- Of course, the ME's are LO, so "K-factors" needed
  - Different ones for heavy flavor etc..... convention to avoid confusion....

- 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

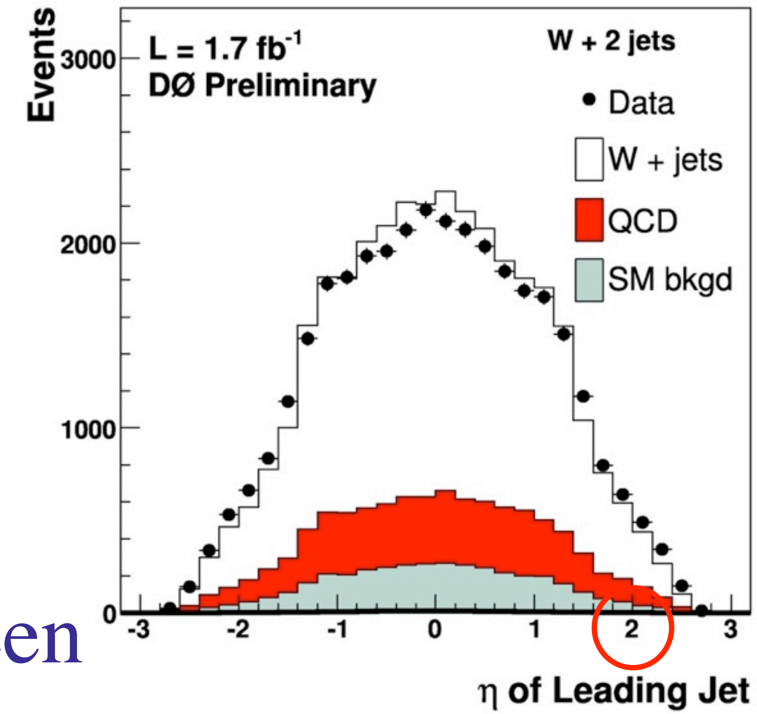
Anecdotes From the Field (III)

- Pile-up events ("minimum bias") do produce jets
  - At high $\mathscr{L}$, require that tracks pointing to jets originate from same vertex as lepton
  - High η excess disappeared!
  - Eta-dependence of jet-vertex match turns out to have shape very very similar to excess
  - After correcting for this, excess is back....

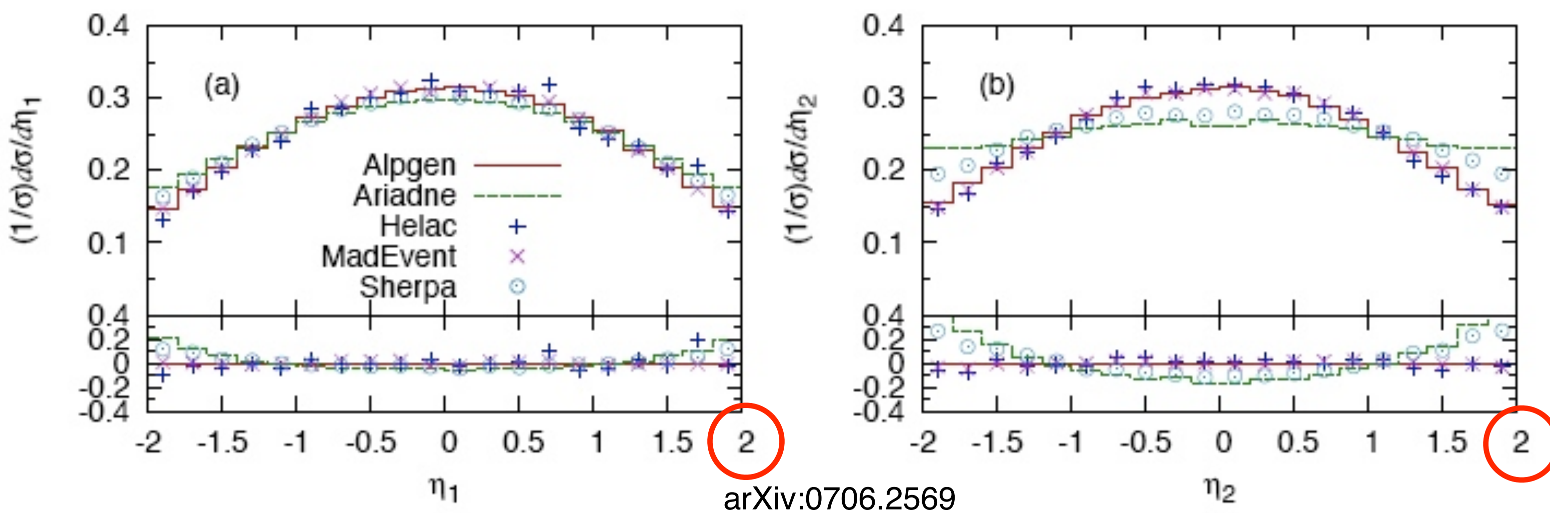


So...

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



- Similar angular differences between generators: reweigh alpgen to sherpa



arXiv:0706.2569

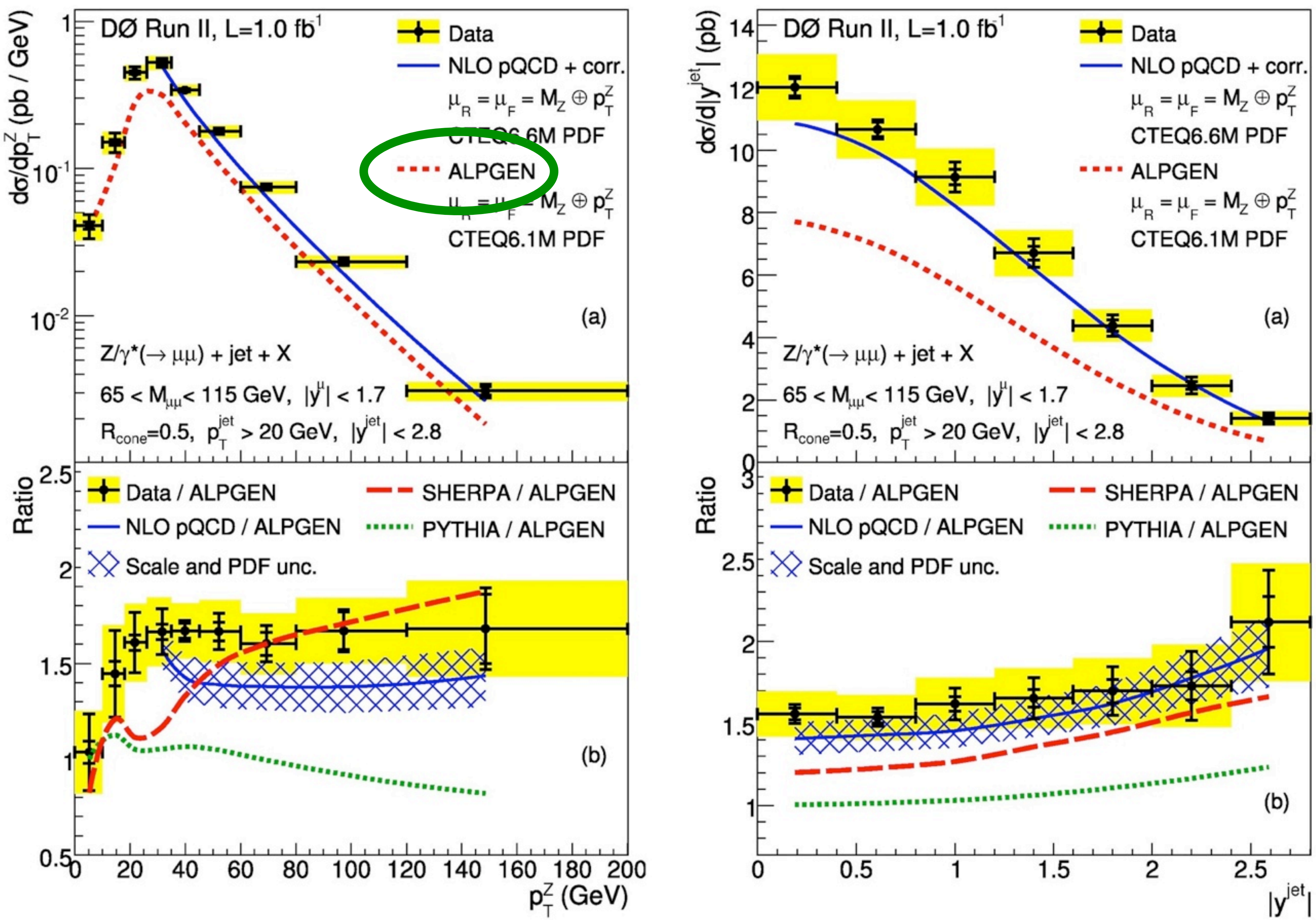
Alpgen, MadEvent, Helac with MLM, Sherpa and Ariadne with CKKW matching

Z (→ℓℓ) + jets

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

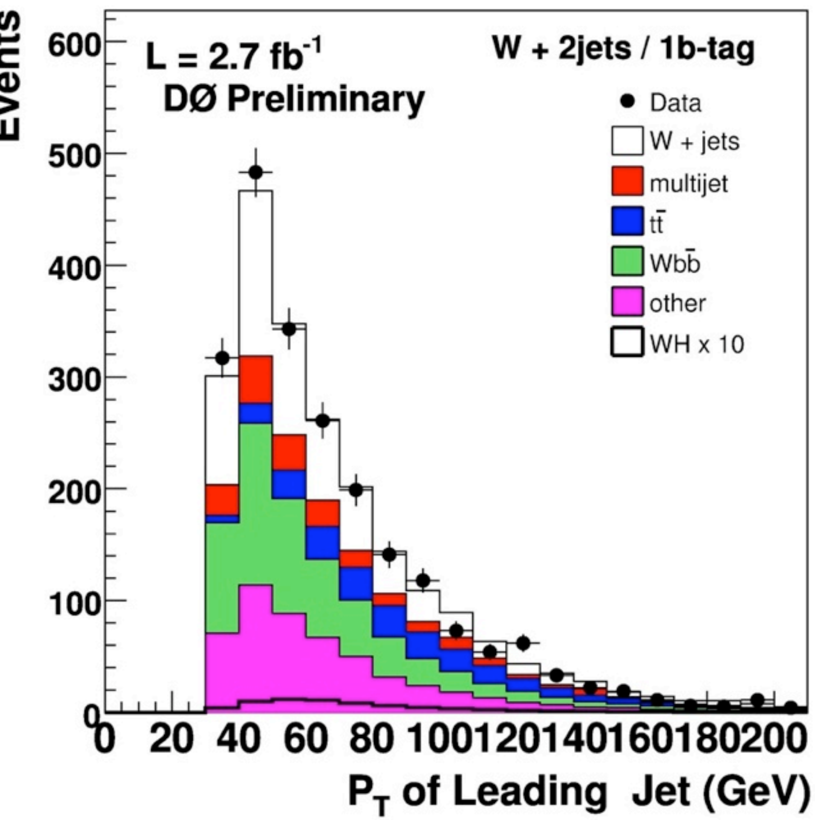
⇒ yes, with ~expected deviations

Need reweighing of MC

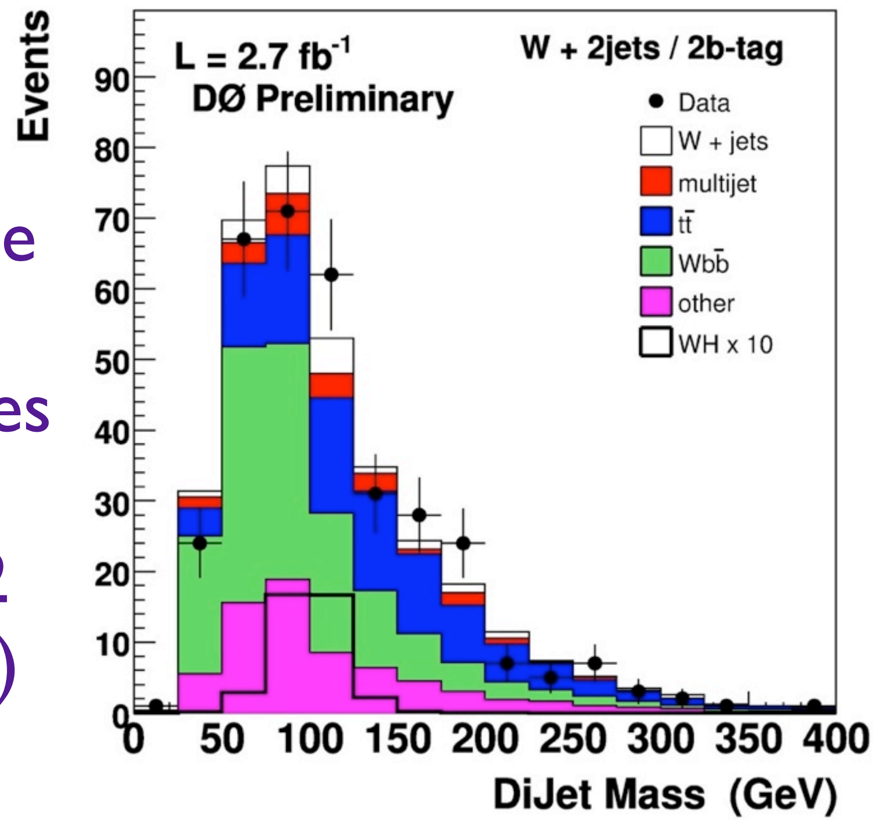


WH Before Multivariate

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":

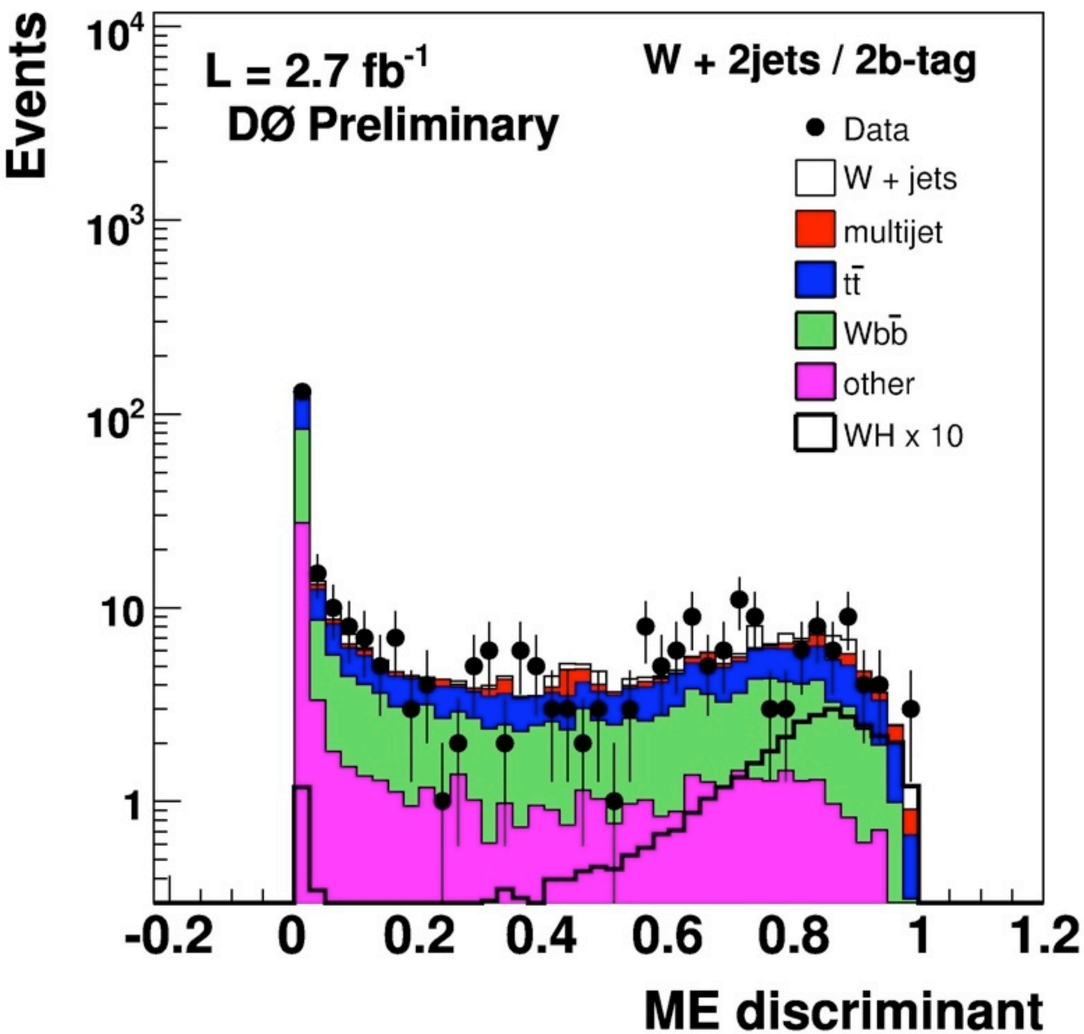
"Transfer functions": generated → measured momenta

b-tag prob

matrix element

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

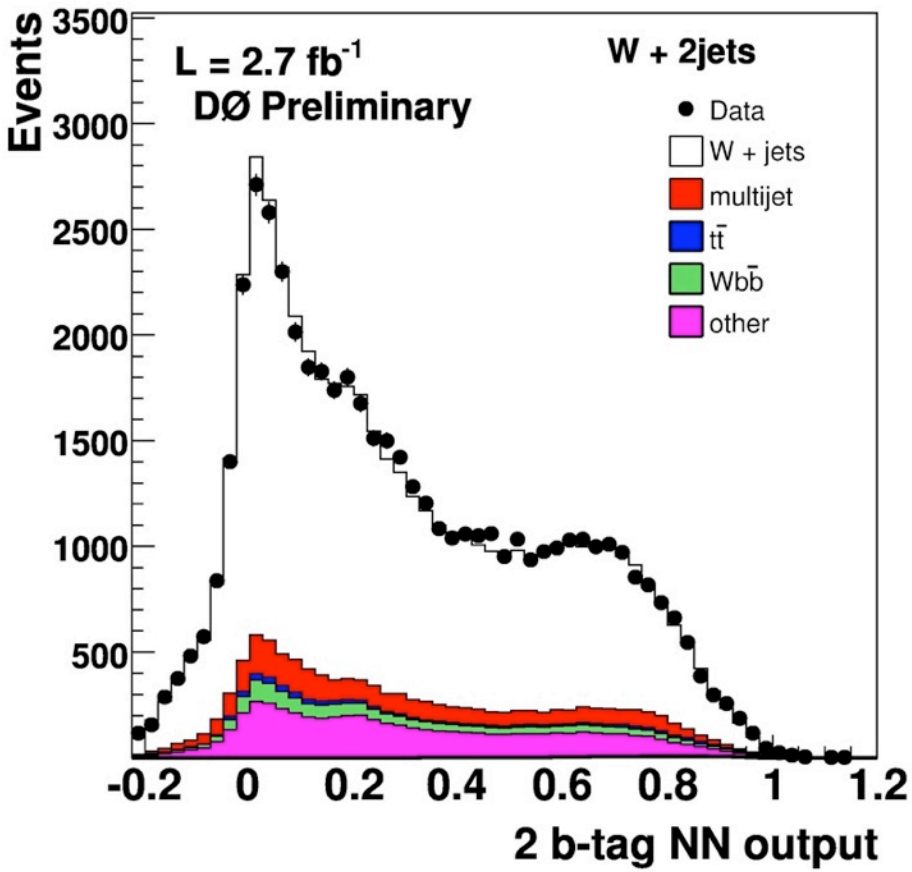
- Caveats:
  - LO matrix elements:
    - Require exact number of jets
    - Evaluation of NLO systematic not so easy
  - Recent development: replace madevent with MCFM (NLO)
- Use matrix element output as an extra input for NN
  - Boosts sensitivity by 1.05 for WH (equiv. to 10% more data)

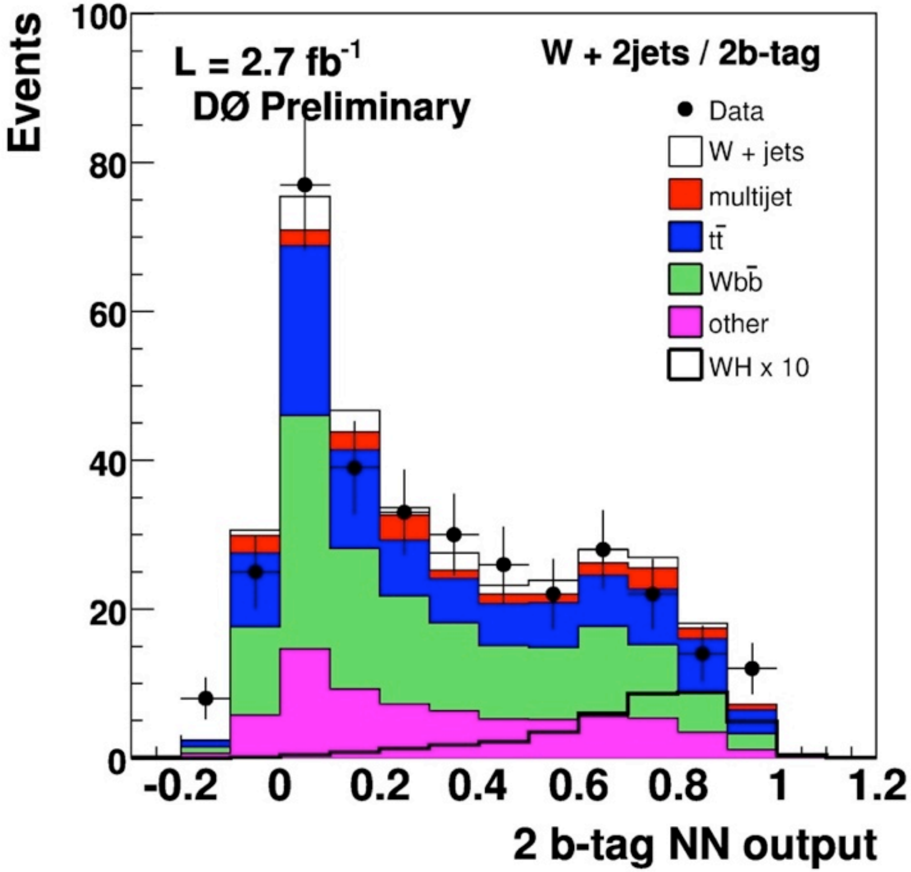


A Comment

- Matrix element technique was designed to extract maximum information from limited statistics
  - Exploit all the features of every event
  - Very CPU-intensive
  - Well suited to low statistics, OR poor S/B cases
    - But probably not necessary/advantageous for top mass @ LHC

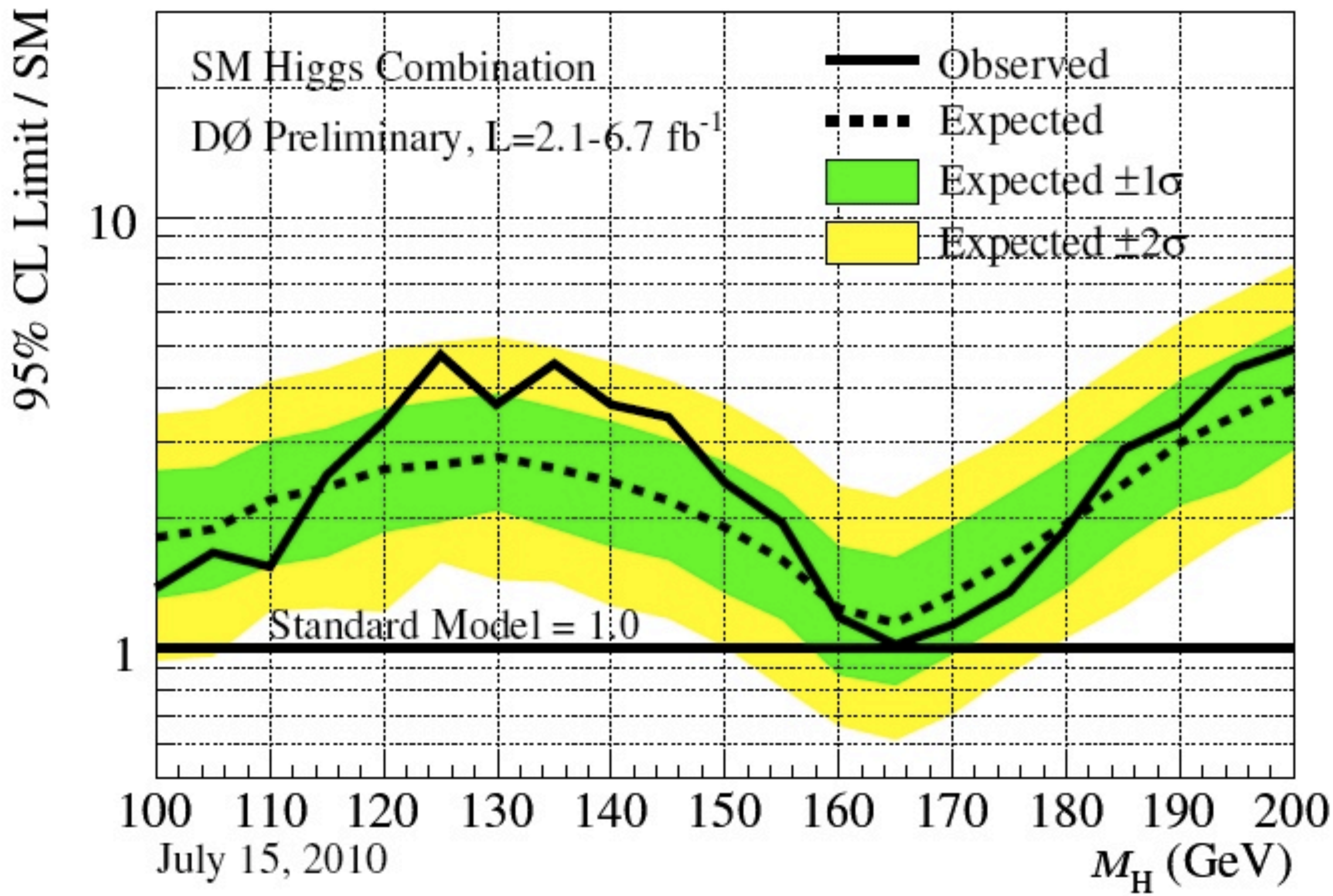
Neural Net Outputs (2 Tags)



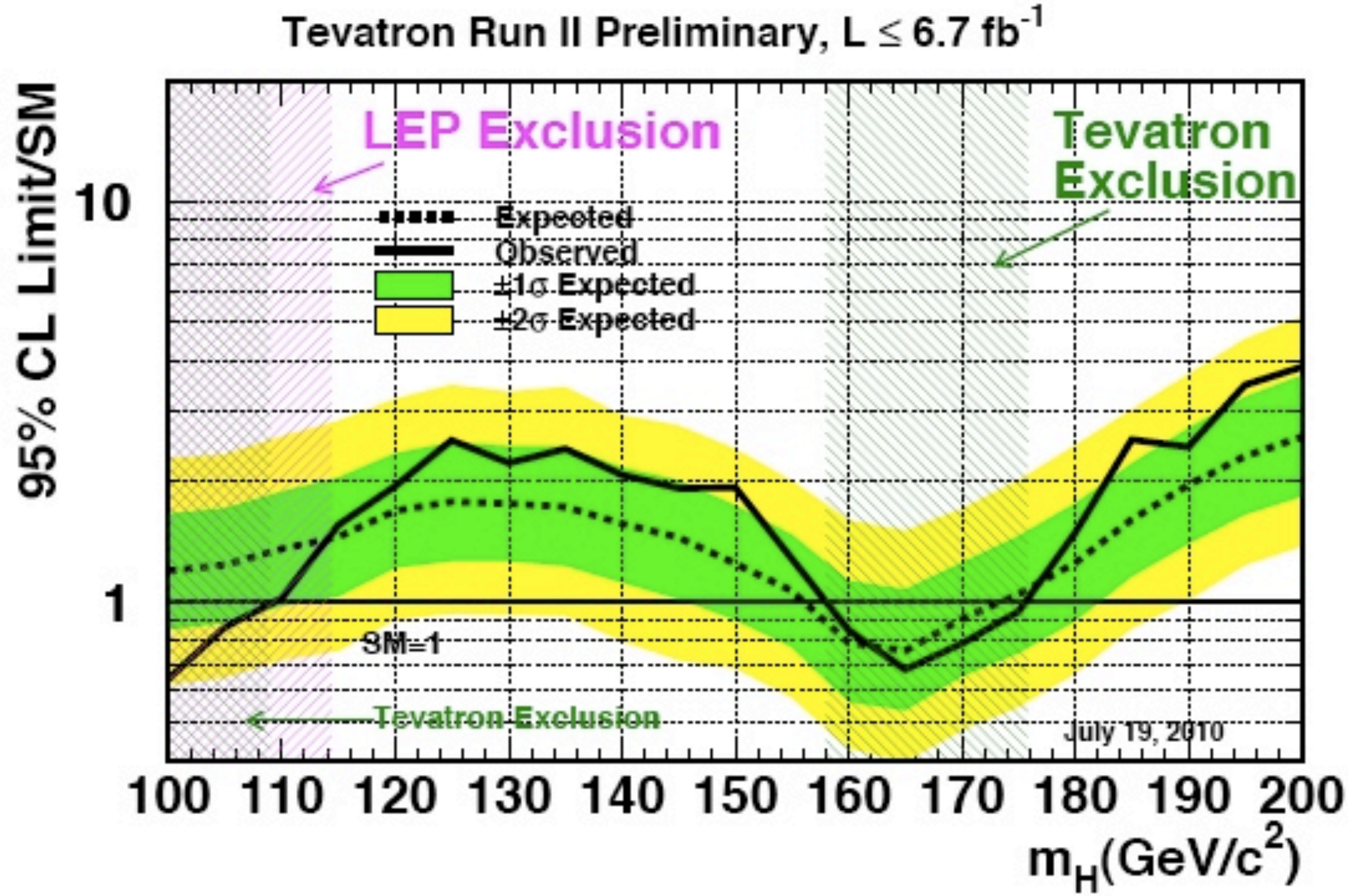


- As before, use the distribution to constrain systematics
- Set limit using the full shape of the distribution
  - I.e. no cut: NN > x

All Channels, DØ



All Channels, CDF + DØ



- Average luminosity used ~5.5 fb^{-1}
  - ~6 fb^{-1} for $H \rightarrow WW$, 5.5 fb^{-1} for WH, ZH

129 Channels!!

So, Physic Analysis

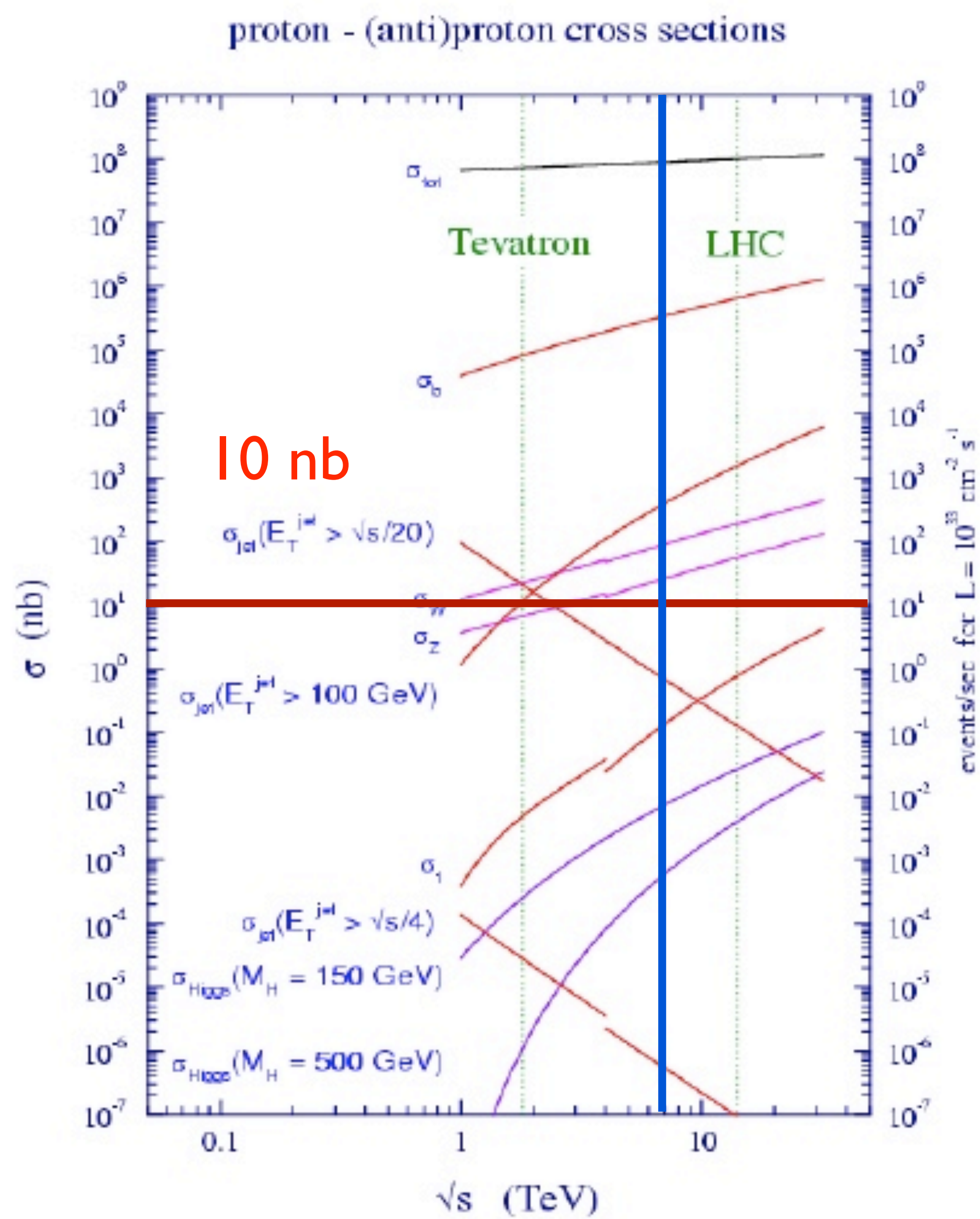
- Start from:
  - "*How well* do we understand data *and* the SM?"
    - How confident are we in corrections we apply?
- Given that:
  - Which measurements can we make?
  - What do we need to do to improve our understanding?
- Balance the work!
  - Early, low background searches
  - Detailed understanding/verification of SM predictions

Intermission

- There are a pair of olive trees just below the cantine's terrace
  - How many olives are growing on them?
- I do not know the true answer
  - But there is one
- What is your best estimate?
  - And more importantly, what is the uncertainty on that estimate?

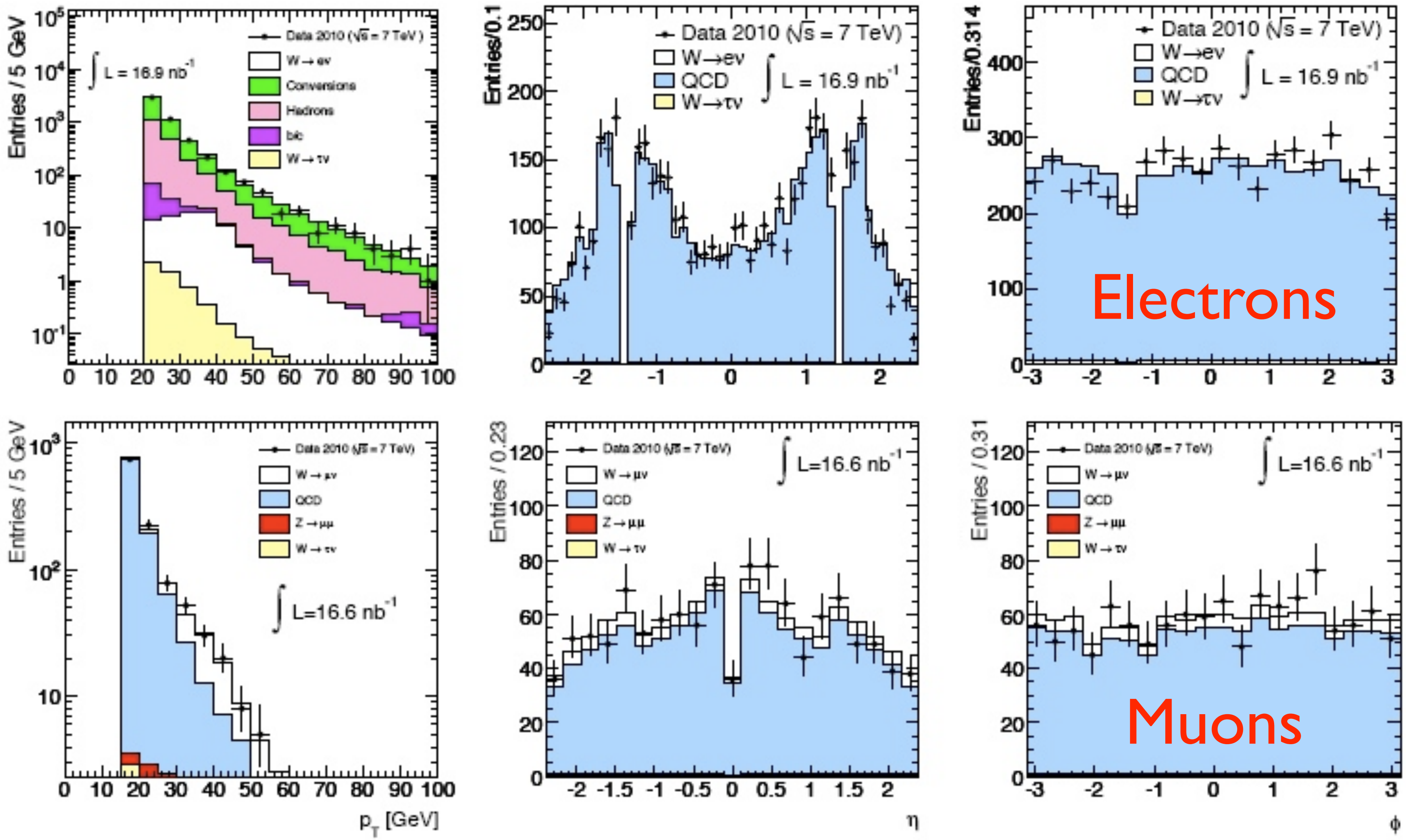
Early LHC Physics Analysis

- Need nb-level x-sections
  - $W \to \ell\nu \approx 10$ nb (NNLO)
    - 6 nb W^+
    - 4 nb W^-
  - $Z \to \ell\ell \approx 1$ nb (NNLO)
  - top pairs ≈ 0.2 nb
  - Multijet, $p_T > 300$ GeV ≈ 1 nb
  - HF, $p_T > 15$ GeV ≈ 10^5 nb



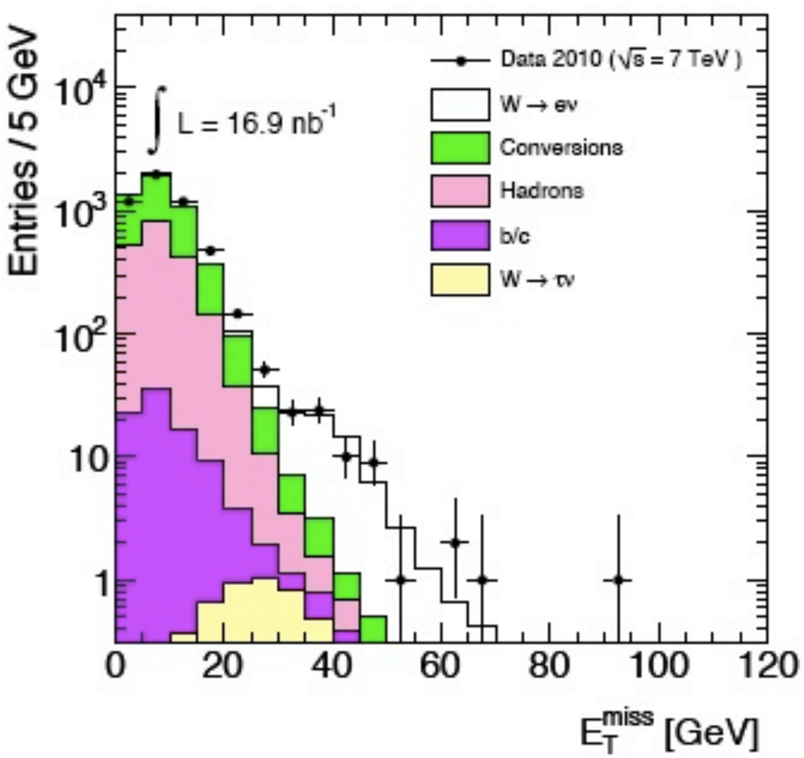
Electrons vs Muons

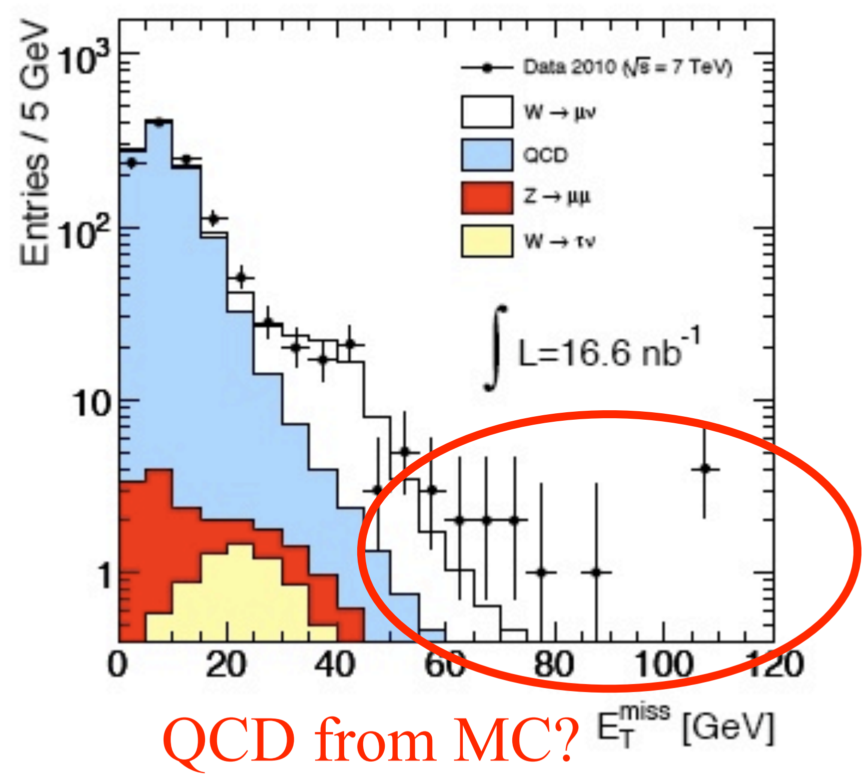
- Different backgrounds and momentum resolution functions!



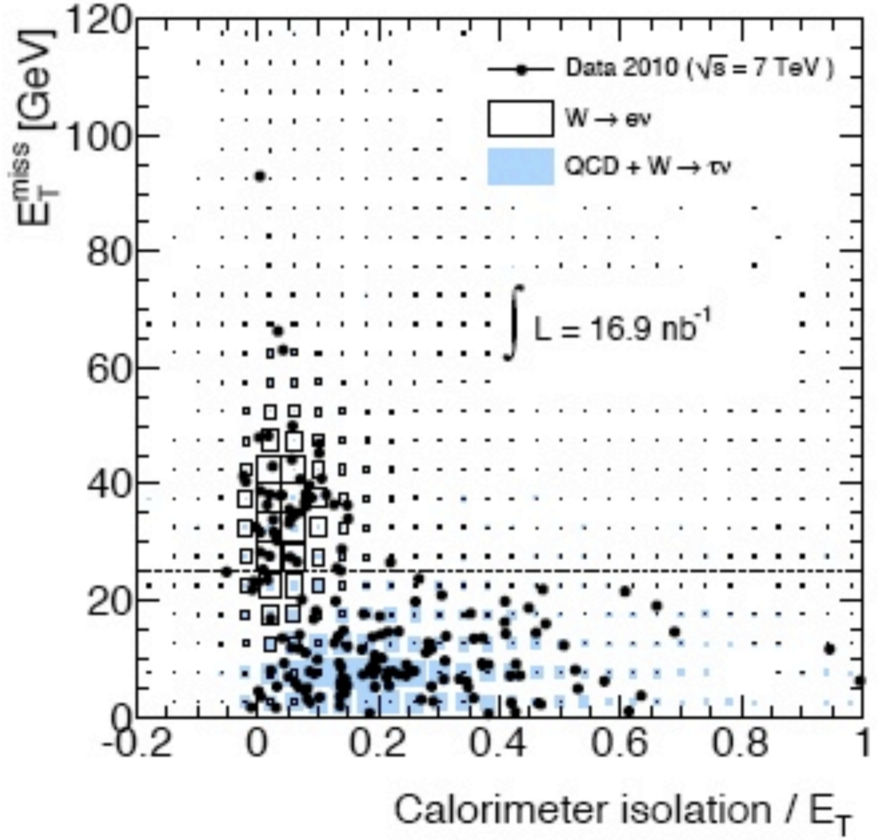
More Variables!

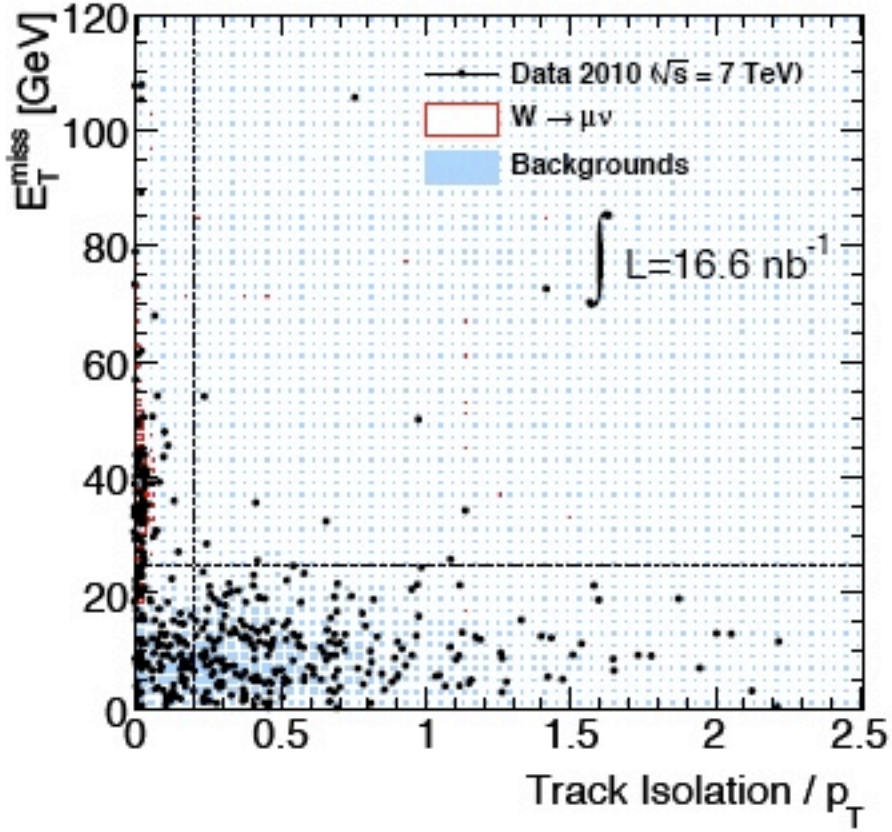
- Experimental physics relies on using multiple observables!
  - At the cost of “freezing” the event topology!!
    - Lepton + MET when searching for W bosons





Optimizing for W

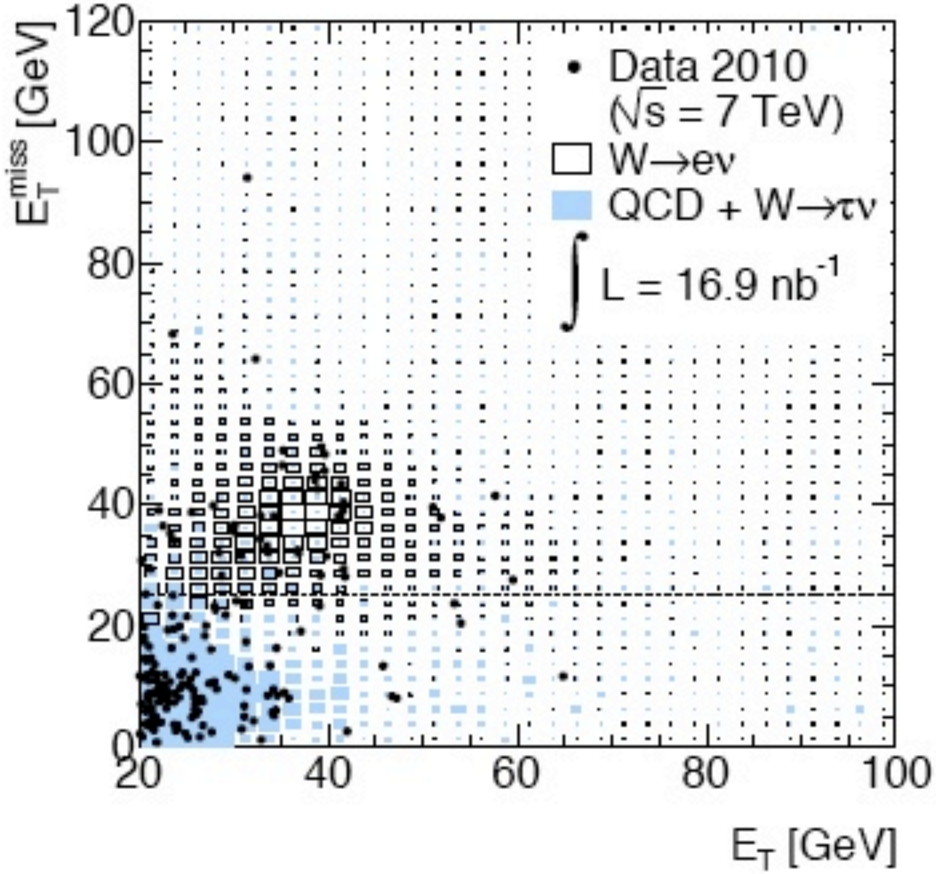


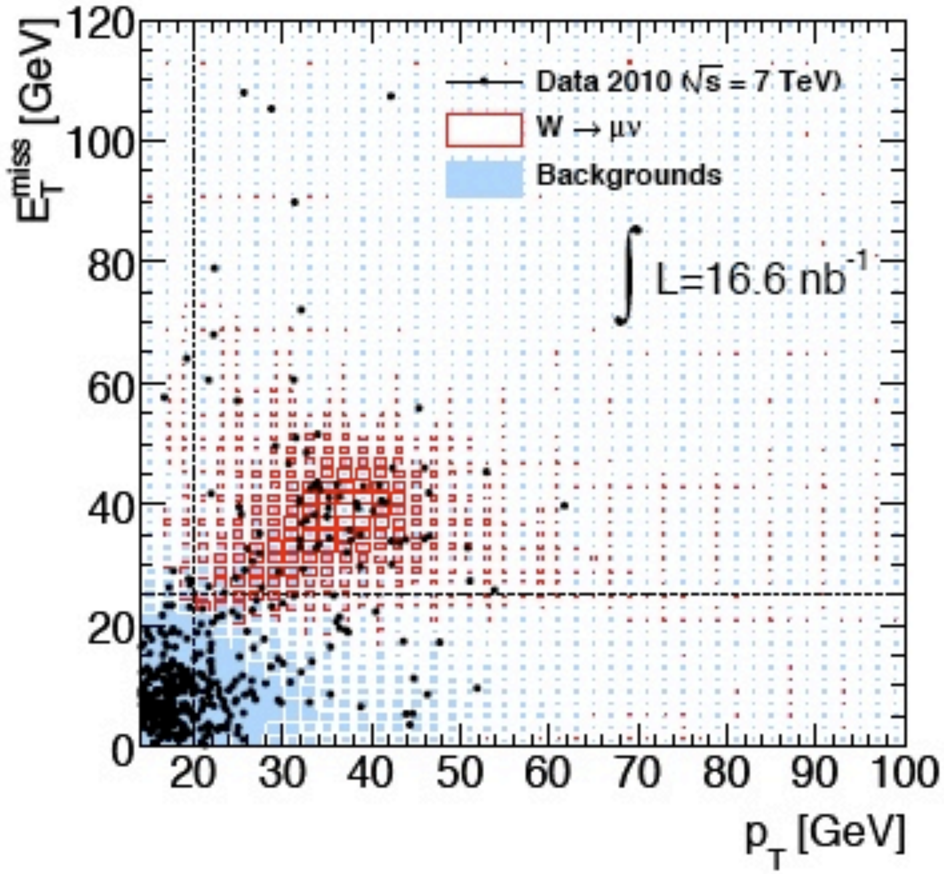


- Most "fake" leptons are leptons from HF decays
  - Usually embedded in a jet, smaller event MET

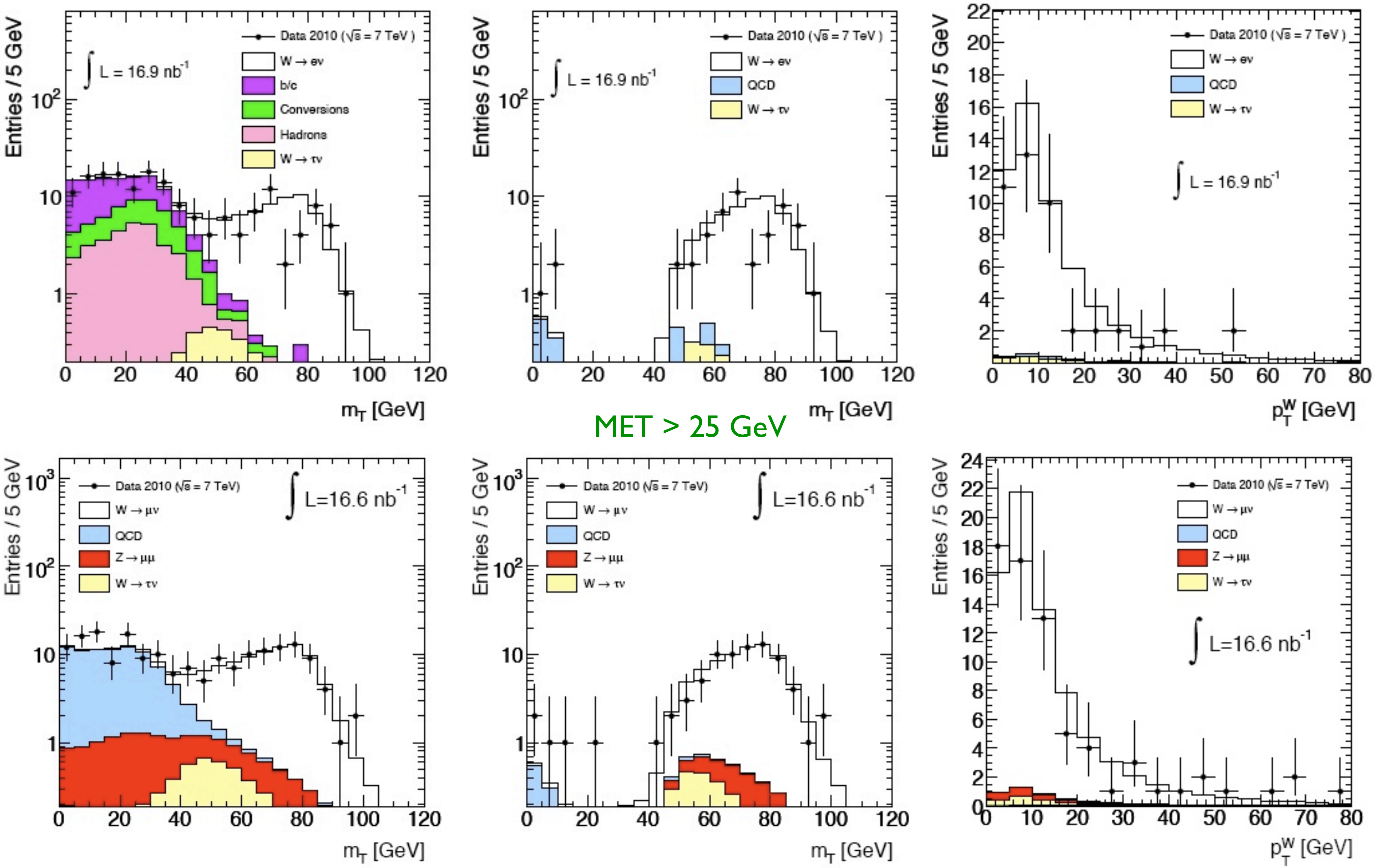
Correlations!

- Under a given hypothesis, can exploit variable correlations
  - Easy for signal, but how well known for background?



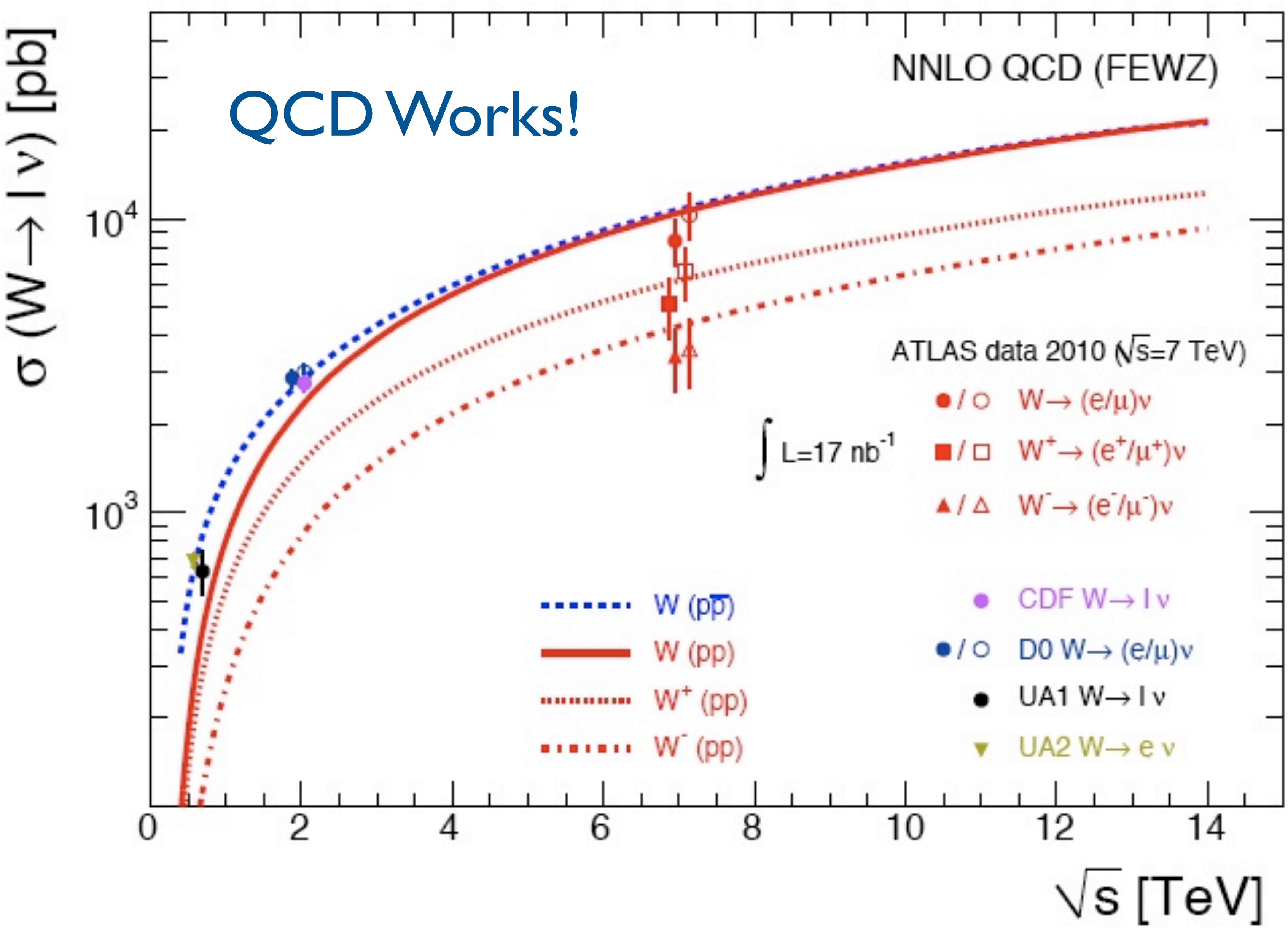


Dessert



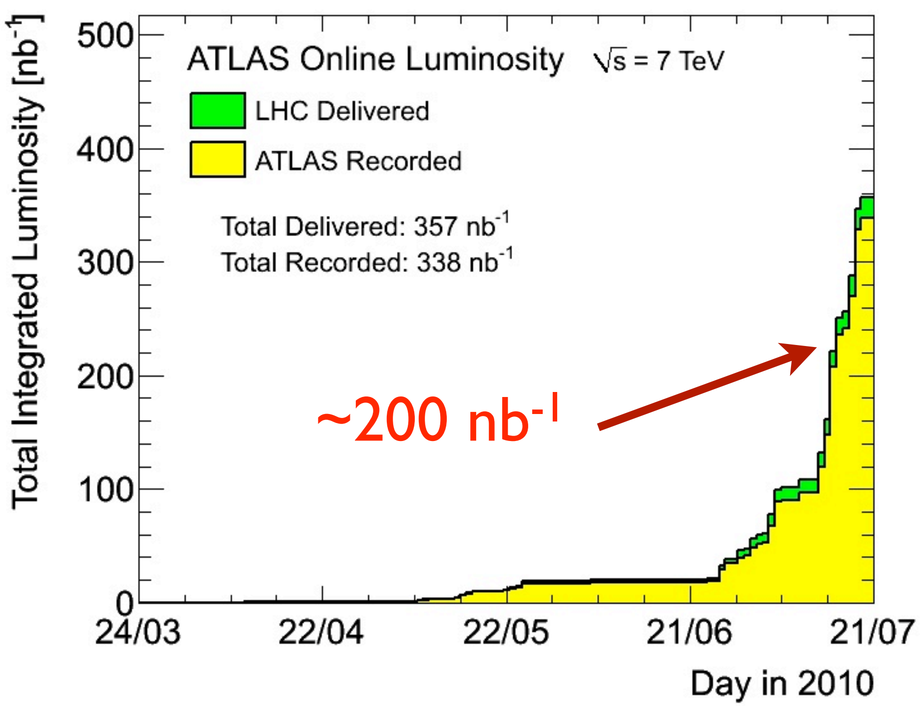
Data 2010 (√s = 7 TeV)
W → eν
b/c
Conversions
Hadrons
W → τν
∫ L = 16.9 nb⁻¹
Entries / 5 GeV
m_T [GeV]
QCD
p_T^W [GeV]
MET > 25 GeV
Data 2010 (√s = 7 TeV)
W → μν
Z → μμ
∫ L=16.6 nb⁻¹

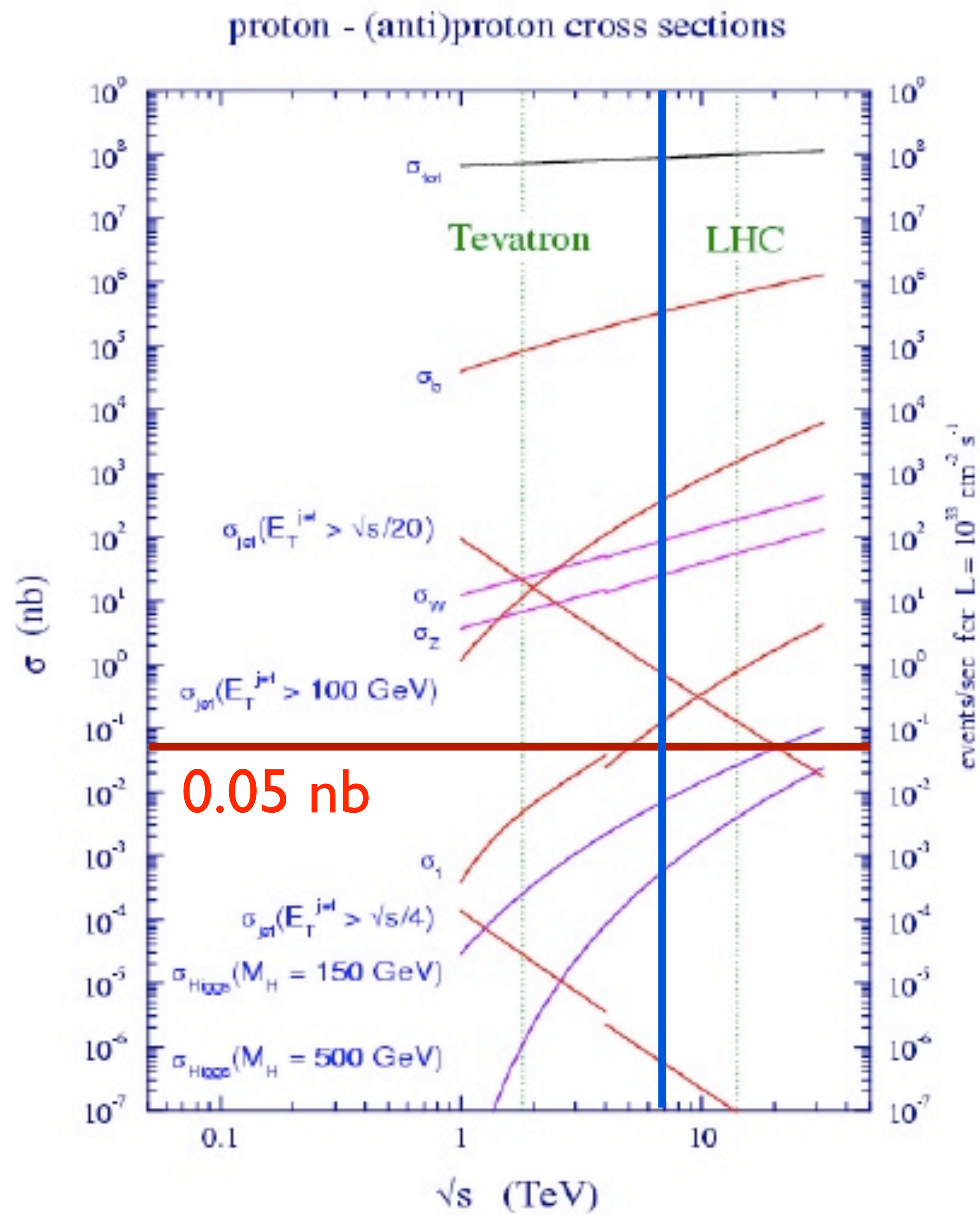
Woohoo!


QCD Works!
NNLO QCD (FEWZ)
σ (W→ l ν) [pb]
√s [TeV]
ATLAS data 2010 (√s=7 TeV)
W→ (e/μ)ν
W⁺→ (e⁺/μ⁺)ν
W⁻→ (e⁻/μ⁻)ν
∫ L=17 nb⁻¹
W (pp̄)
W (pp)
W⁺ (pp)
W⁻ (pp)
CDF W→ l ν
D0 W→ (e/μ)ν
UA1 W→ l ν
UA2 W→ e ν

LHC Reality

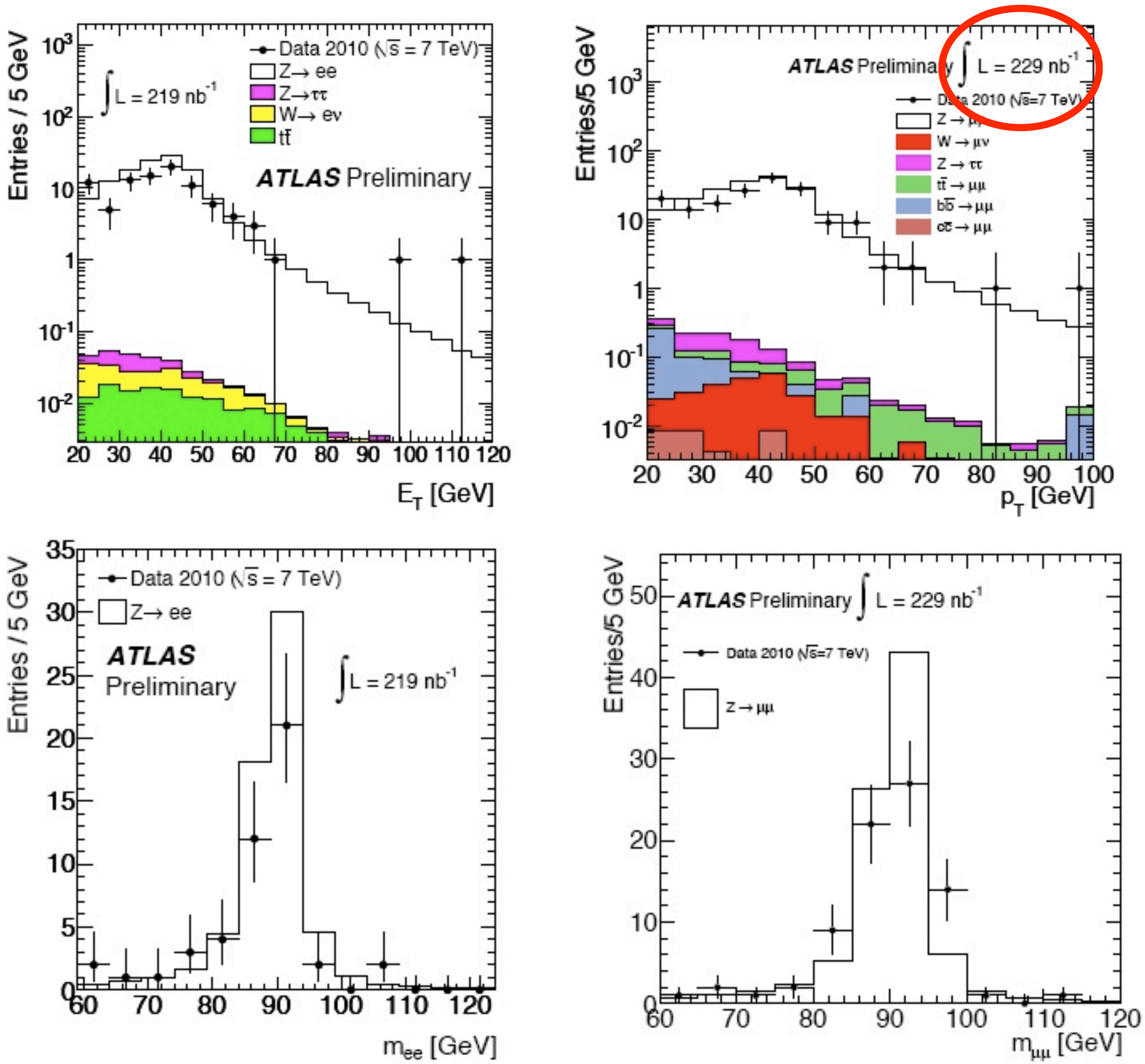
- Rather slow start
  - But use first data to test detector performance



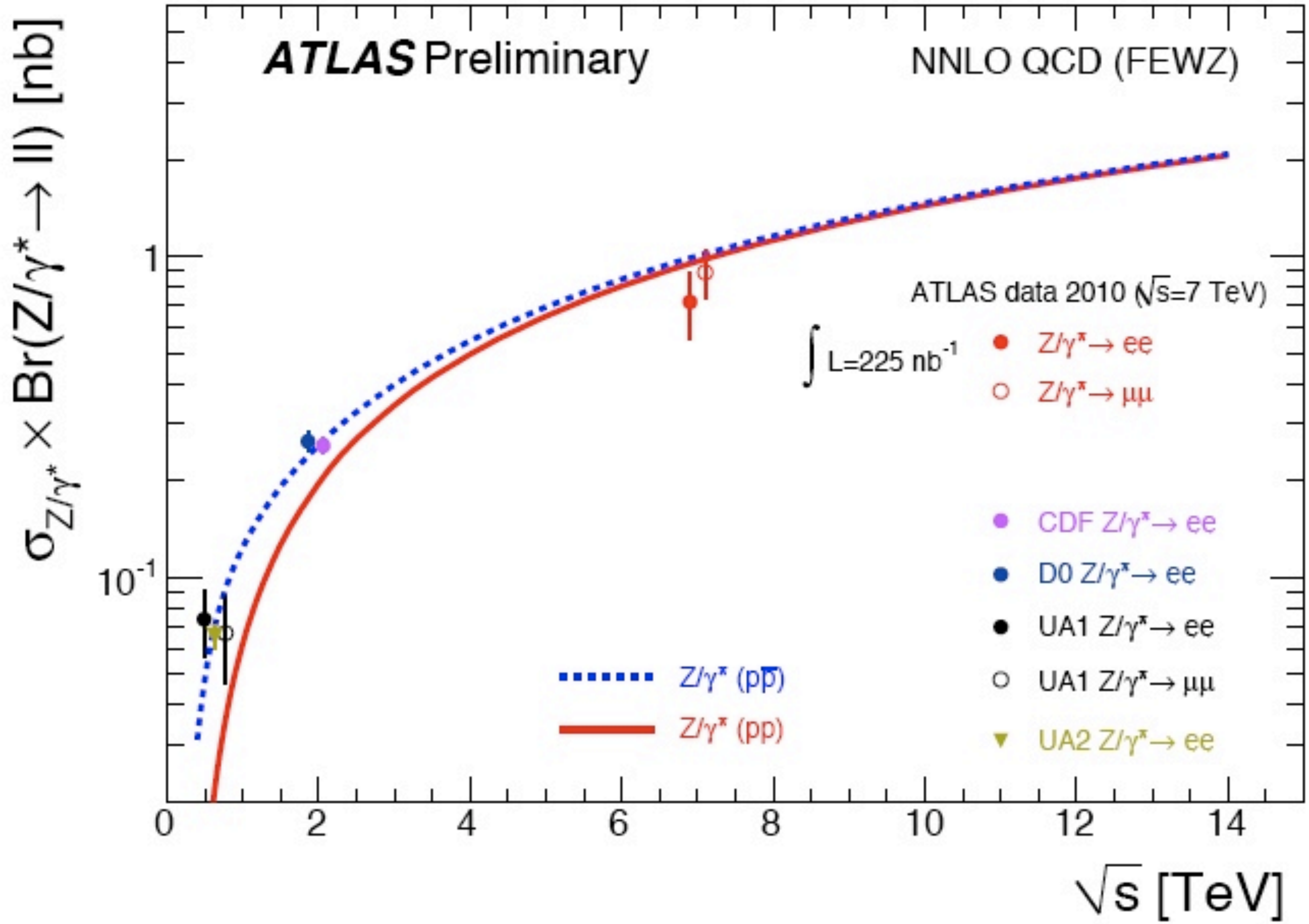


Z Bosons

- Jets have a harder time faking a charged lepton...



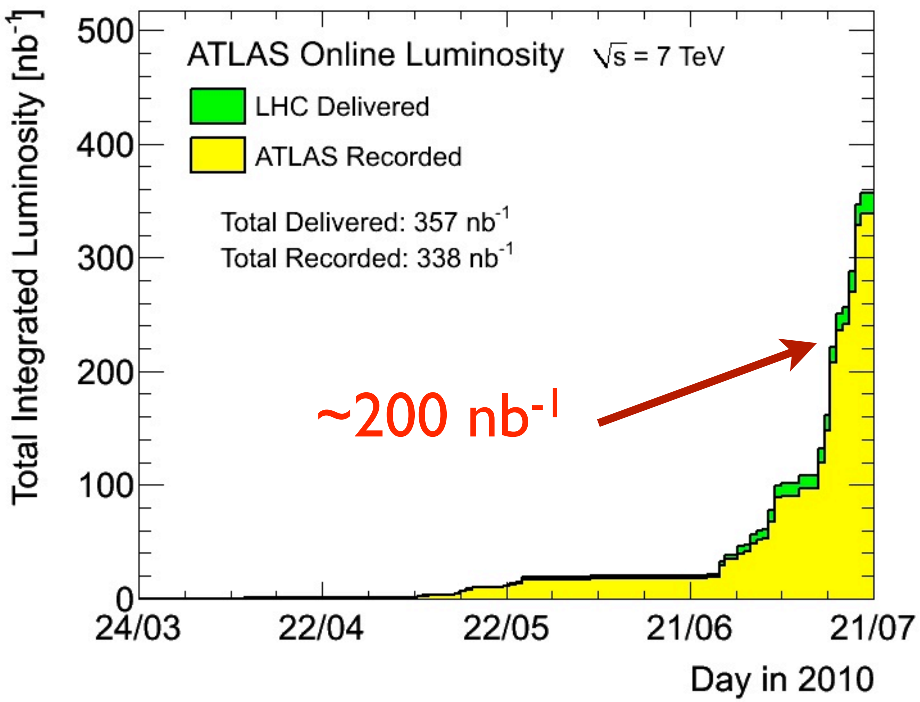
Still Works!

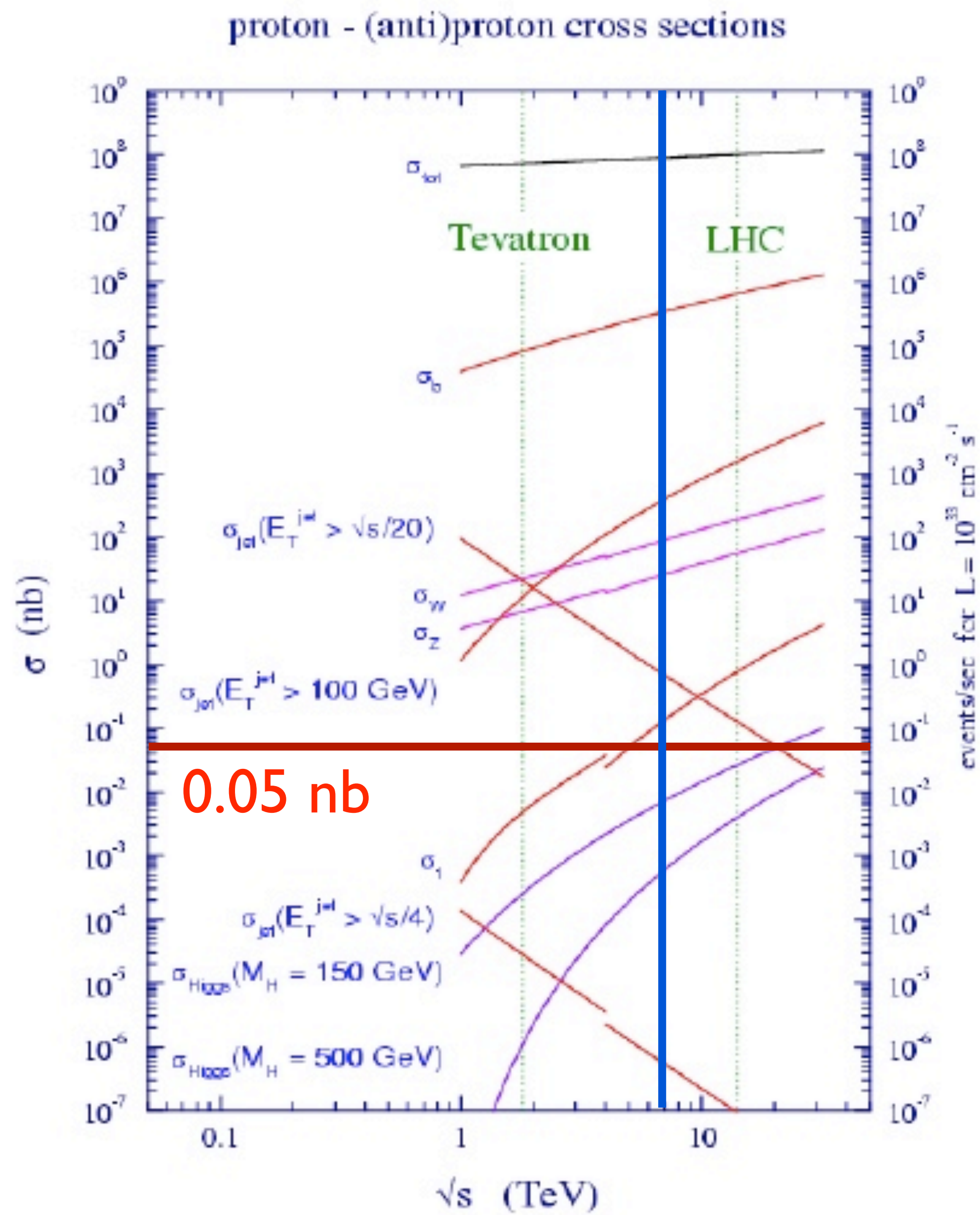


ATLAS Preliminary
NNLO QCD (FEWZ)
ATLAS data 2010 (√s=7 TeV)
∫L=225 nb⁻¹
Z/γ*→ ee
Z/γ*→ μμ
CDF Z/γ*→ ee
D0 Z/γ*→ ee
UA1 Z/γ*→ ee
UA1 Z/γ*→ μμ
UA2 Z/γ*→ ee
Z/γ* (pp̄)
Z/γ* (pp)
σZ/γ* × Br(Z/γ* → ll) [nb]
√s [TeV]

LHC Reality

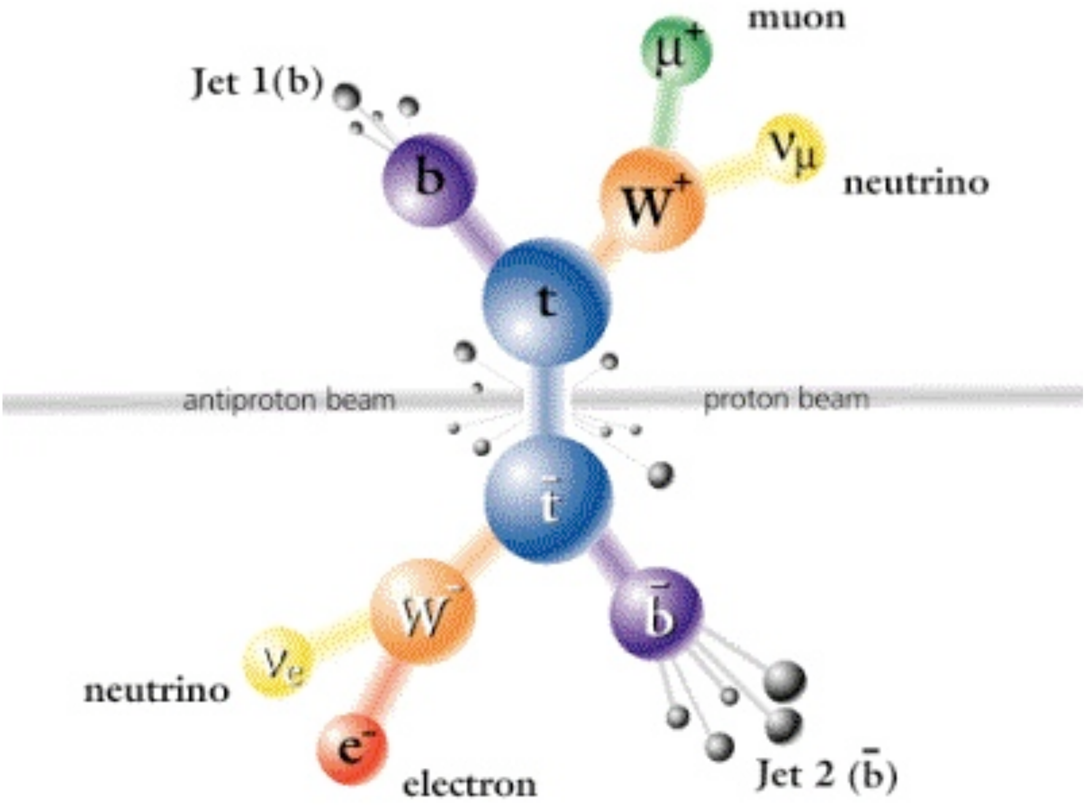
- Rather slow start
  - But use first data to test detector performance





The Top Quark

- A W+jets process with 1000× smaller x-section...
- Many objects ⇒ many acceptance and efficiency factors
  - Typical (loose) detection ε (in ℓ + jets) ~ 10-20%



Back-of-an-envelope:
$200\ \text{nb}^{-1} \times 160\ \text{pb}$

$\times\ (2/9 \times 6/9 \times 2) = 9.5$

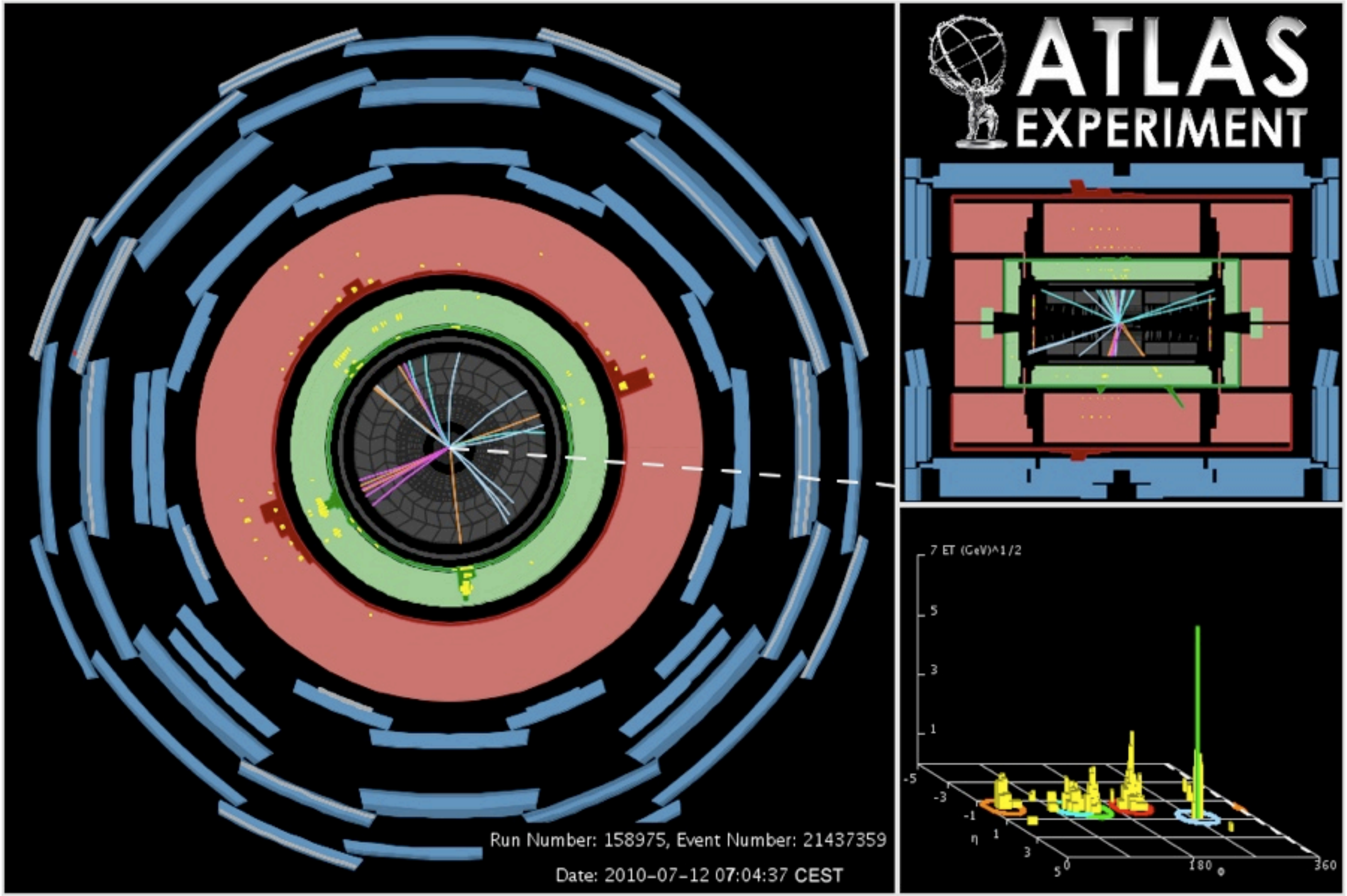
$\times\ (2/9 \times 2/9) = 1.6$

to be multiplied by

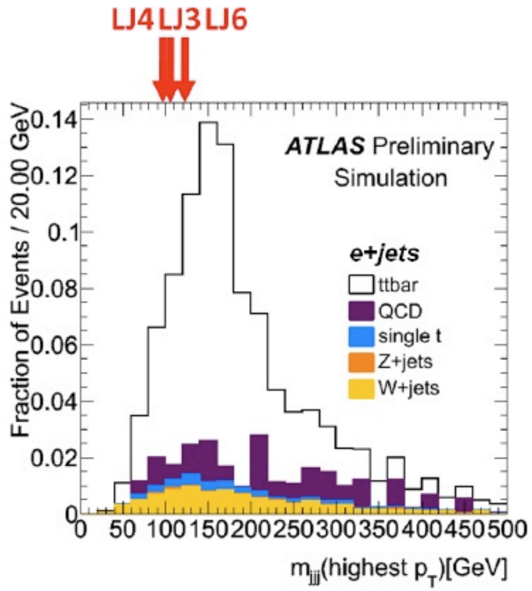
$\varepsilon_{\ell\text{+jets}},\ \varepsilon_{\ell\ell}$

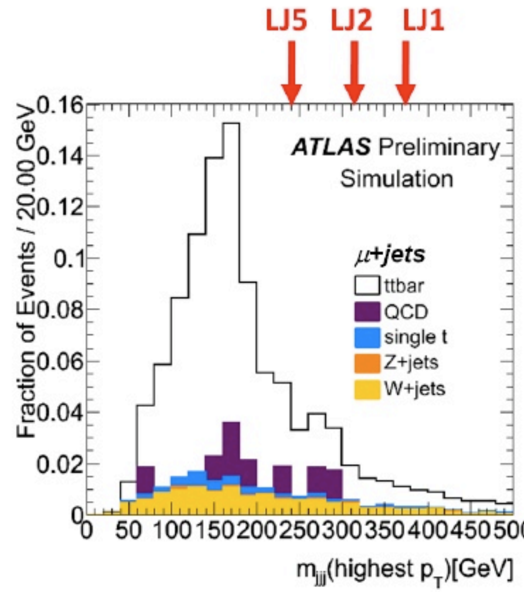
Top Candidates

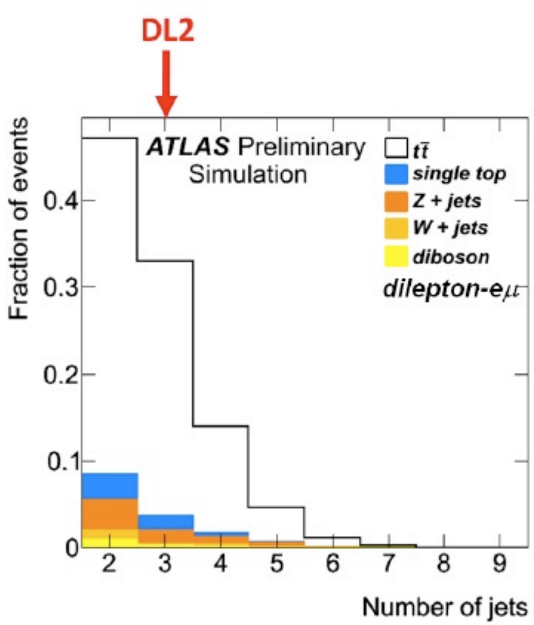
- 200 nb^{-1}: 6 lepton+jets, 2 dilepton candidates

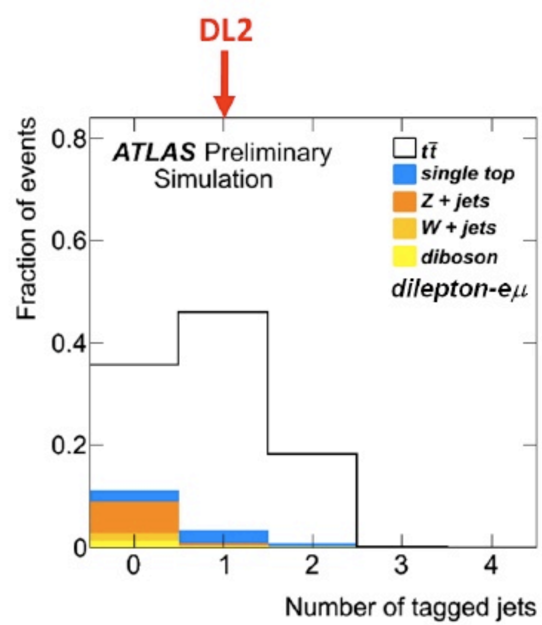


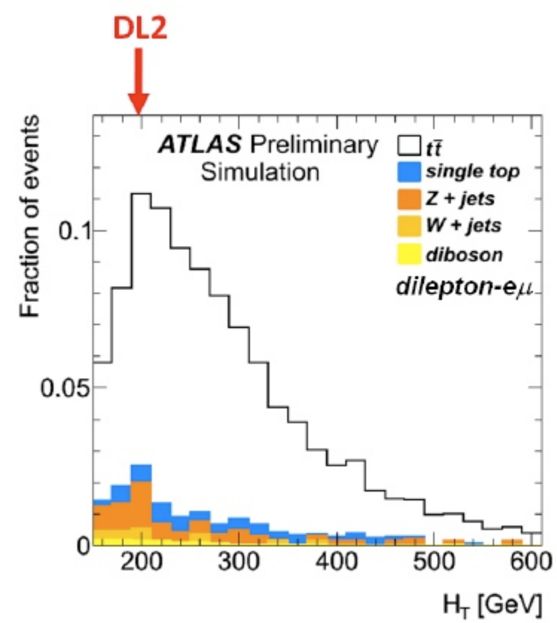
A Candidate is But a Candidate







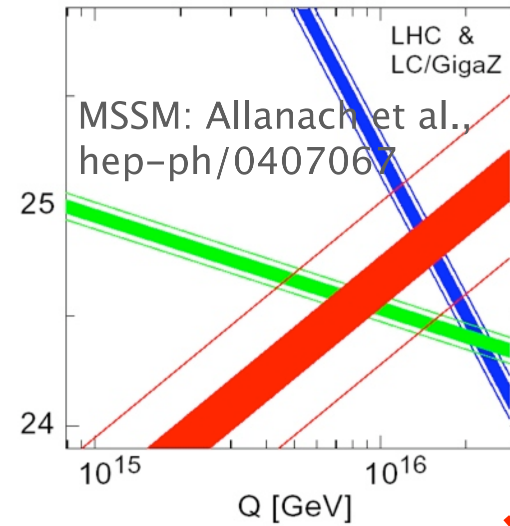




New Physics @ LHC

Not SUSY?

- 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

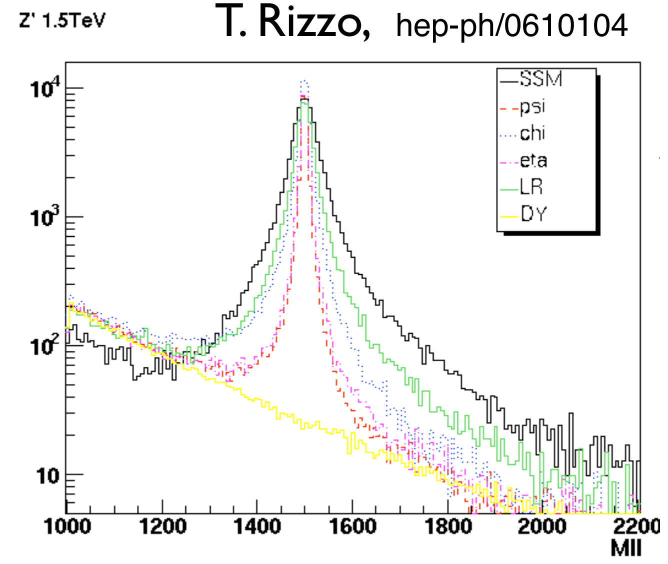
- Primary signals are (right-handed) W' (+ Z')
  - Dilepton resonances offer clean signals, well-understood backgrounds
    - At LHC, some concern about extrapolation of calibration from Z to very high energies
    - Electron/muon resolution improves/degrades with p^T
  - $t\bar{t}$ decays visible (maybe)
  - 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

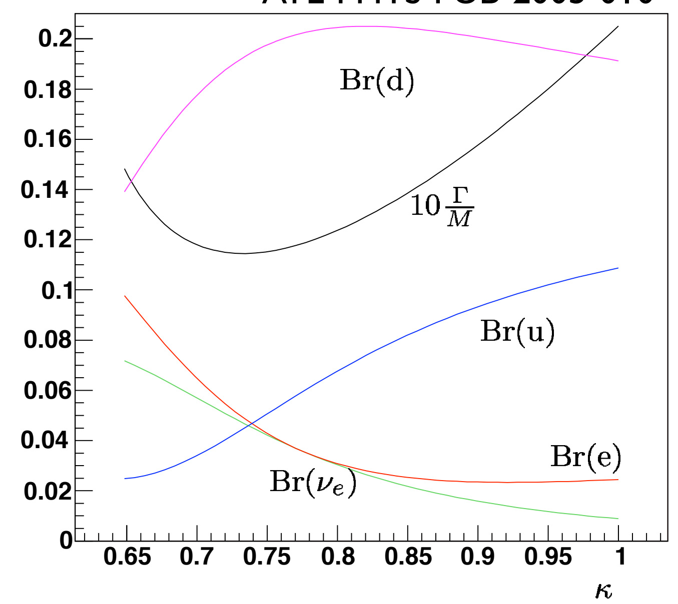
Z' Production and Decay

- 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

T. Rizzo, hep-ph/0610104



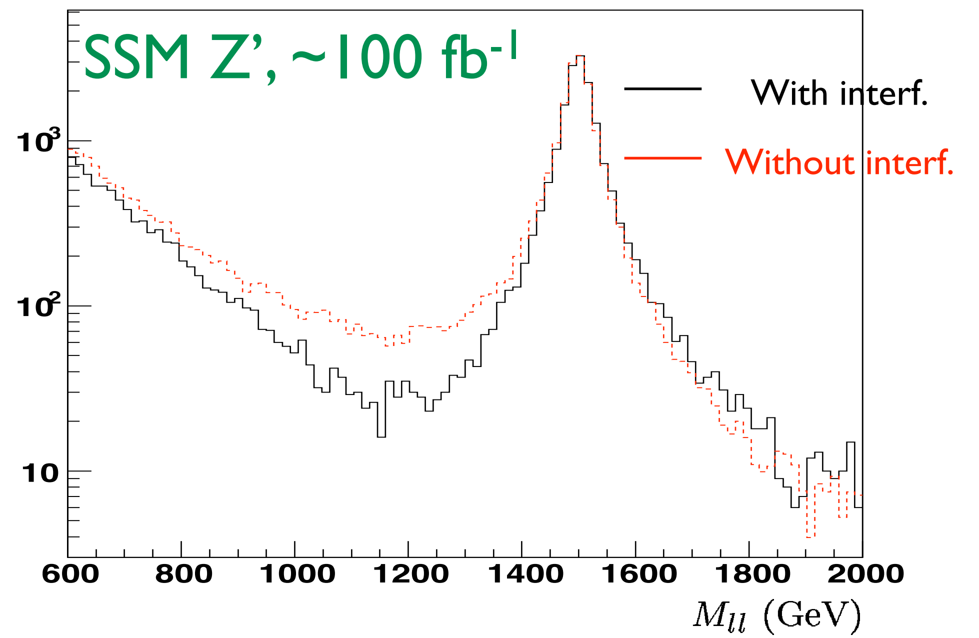
ATL-PHYS-PUB-2005-010

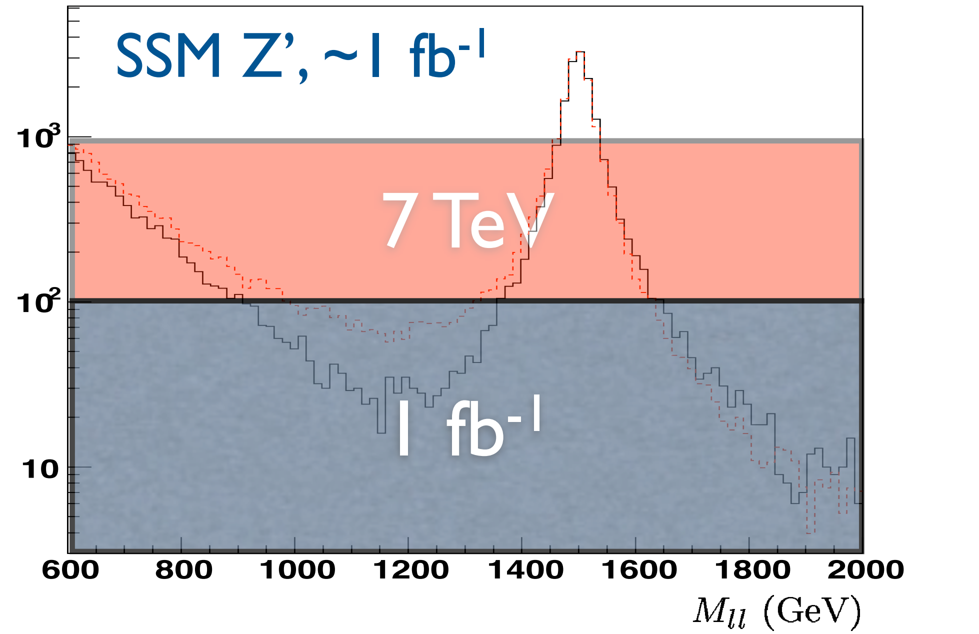


Z' → ee

- 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"

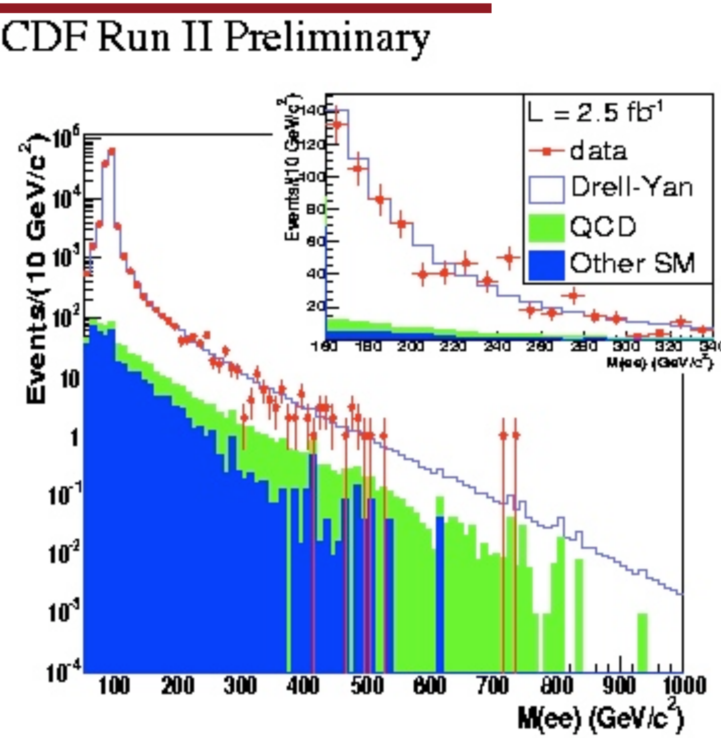
ATL-PHYS-PUB-2005-010

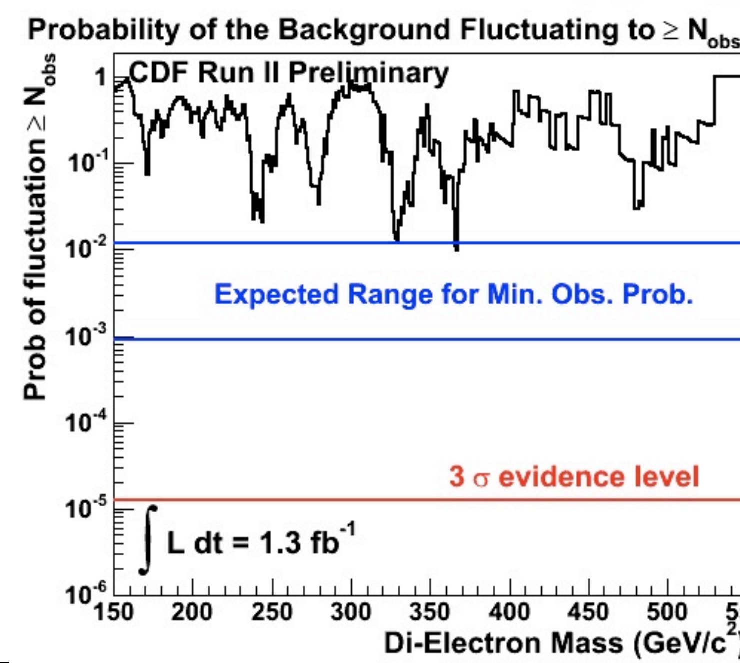




"Look Elsewhere" Effect

- 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!

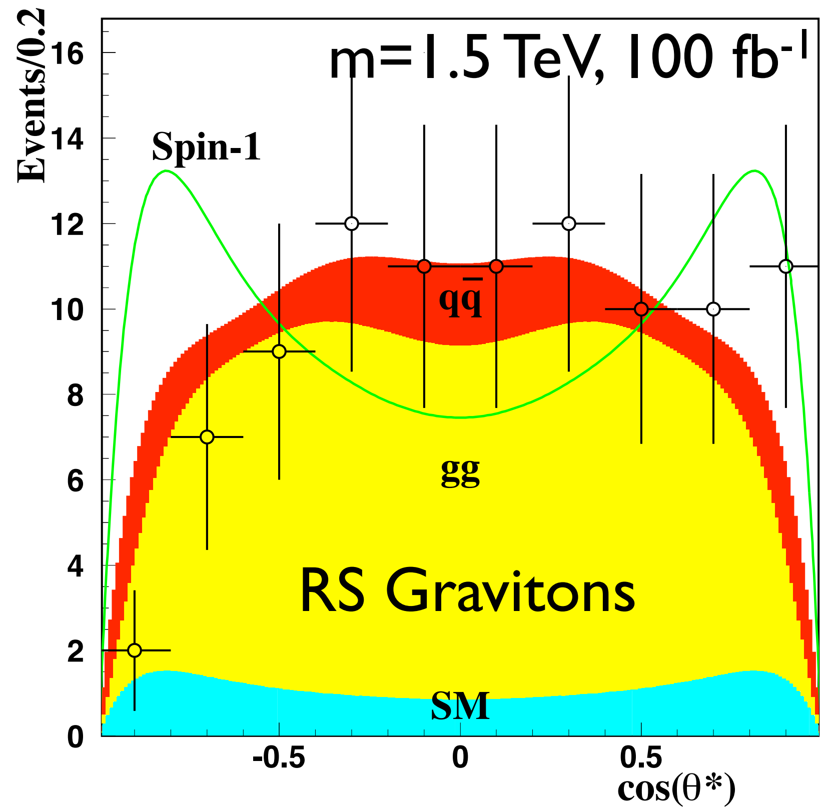




Spin Determination

- 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…

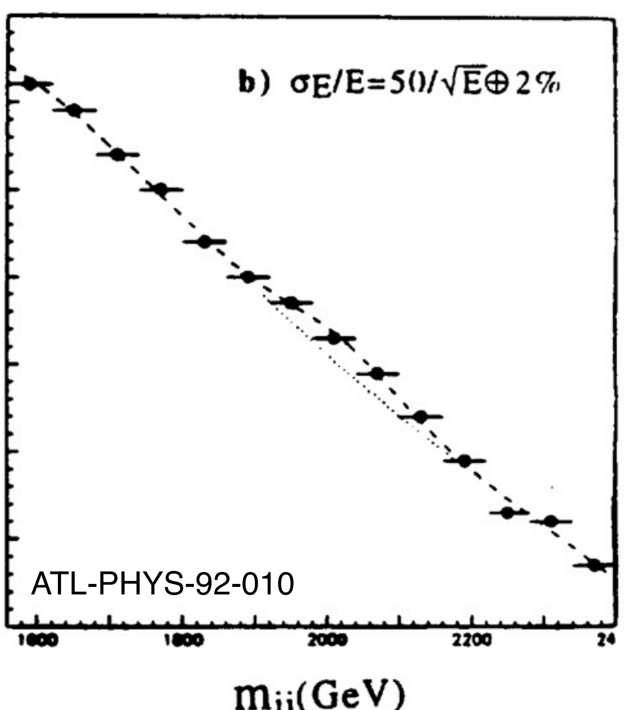
B. Allanach et al, JHEP 0009:019,2000

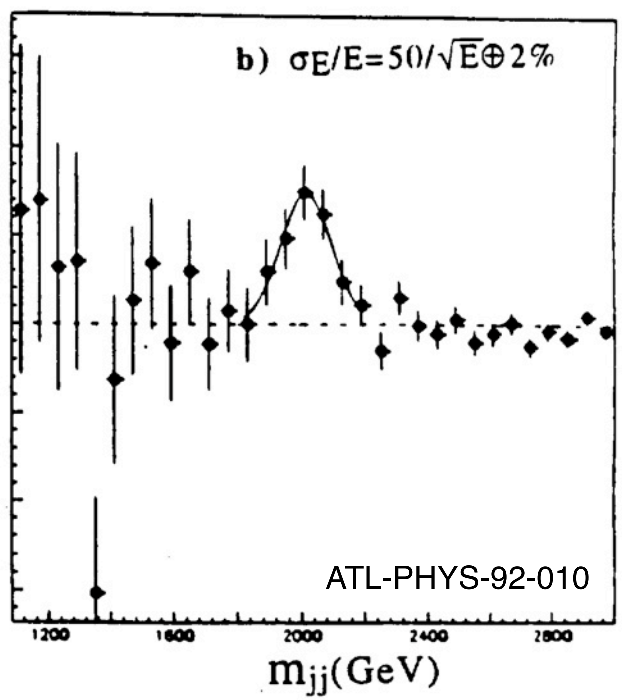


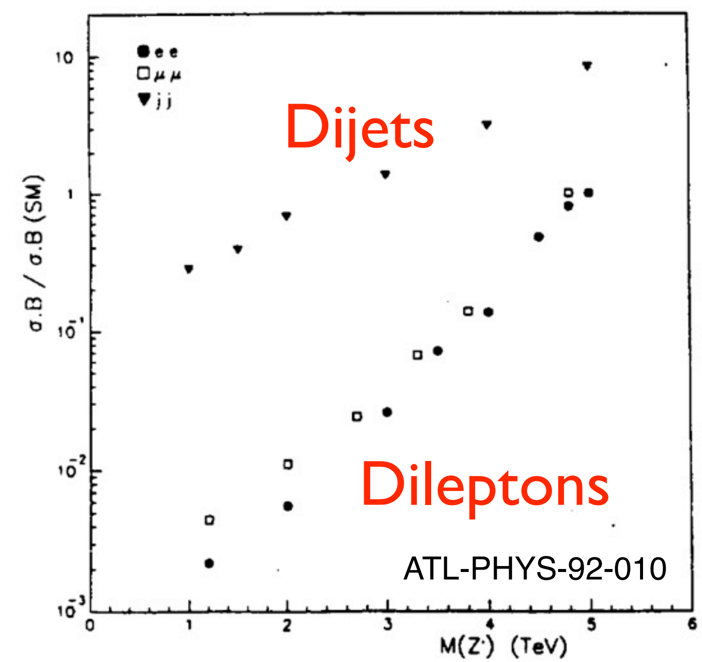
Z’/W’/q* → jj

- 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))



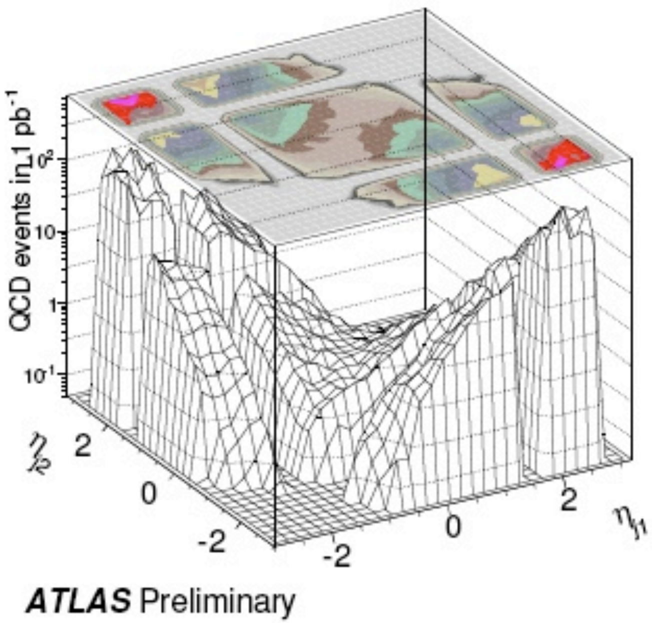


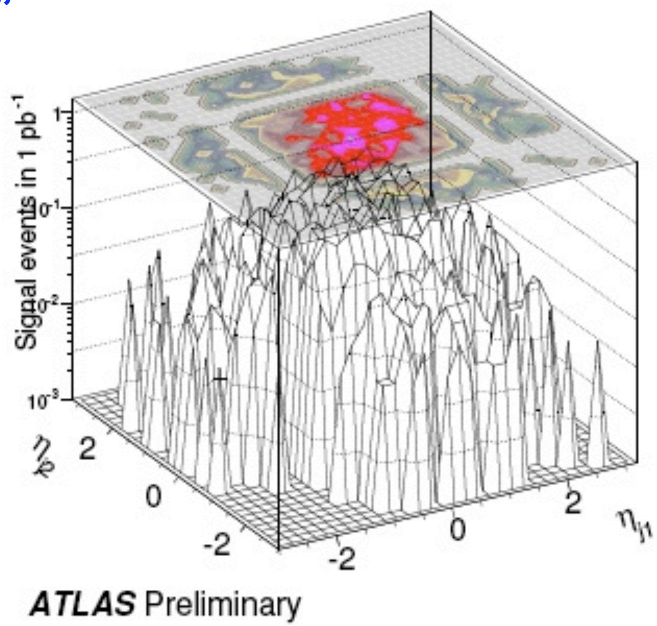


Angles

875 GeV < m_{jj} < 1020 GeV

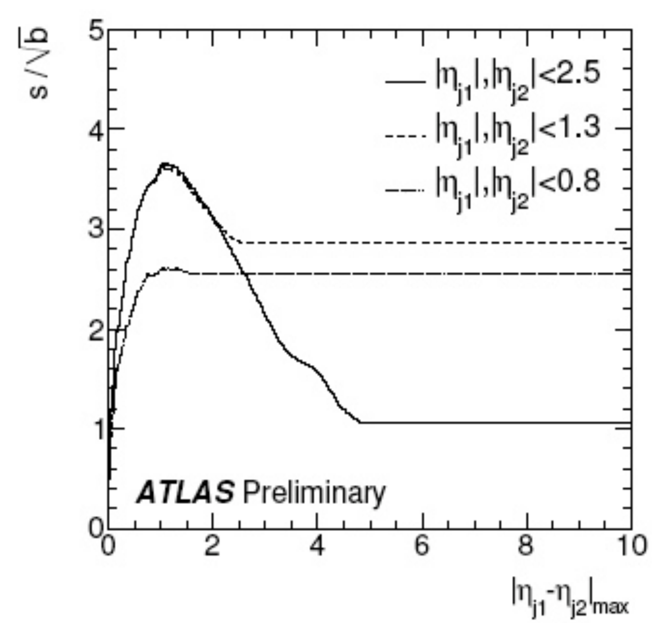
QCD





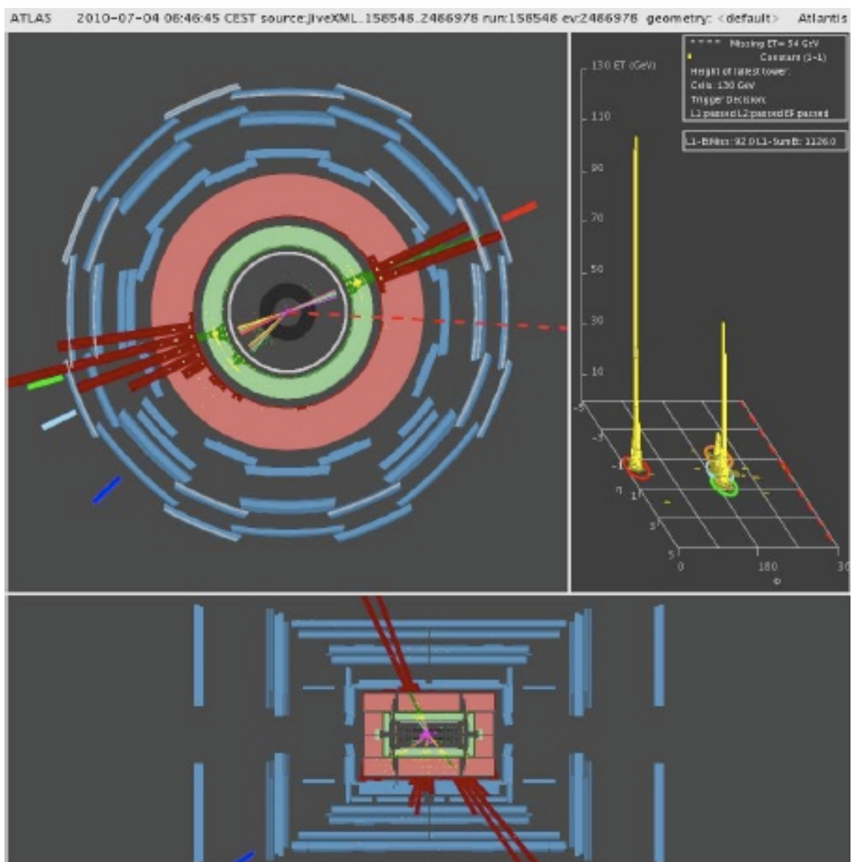
q*

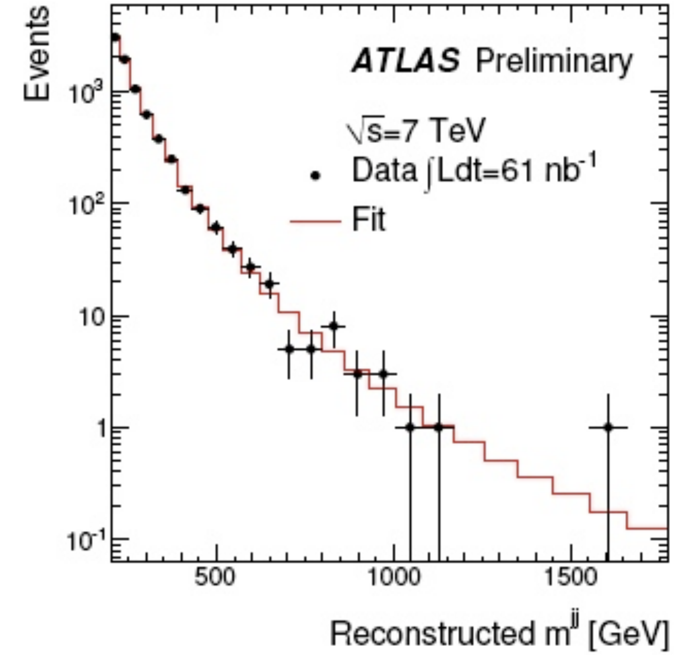
- High mass object → large boost → central
  - But background dominated by QCD "elastic" scatters and larger angle = higher mass

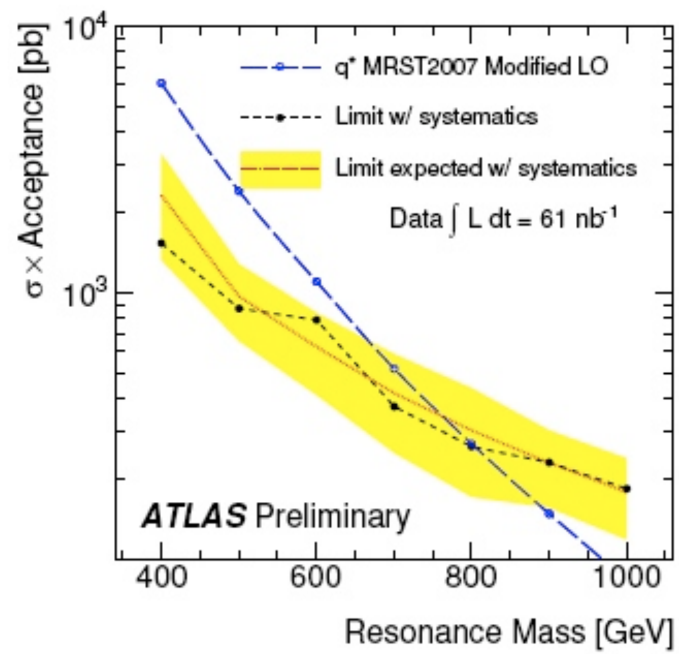


ATLAS Search

- Look for bump in mjj
  - No bump, set limit
- Note 1.6 TeV event!

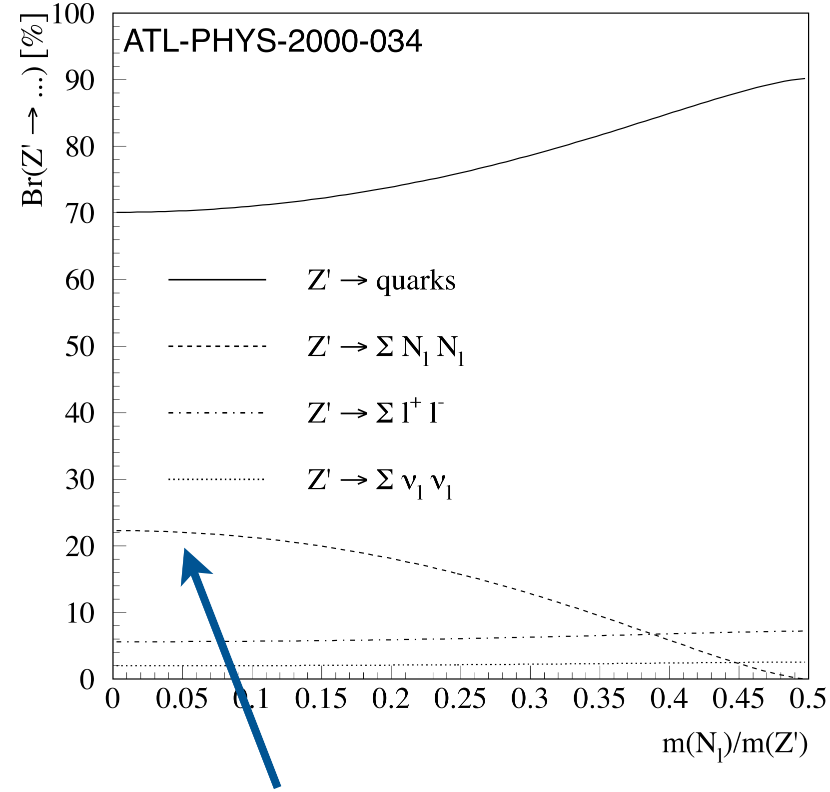






$Z' \to \nu_R\nu_R$

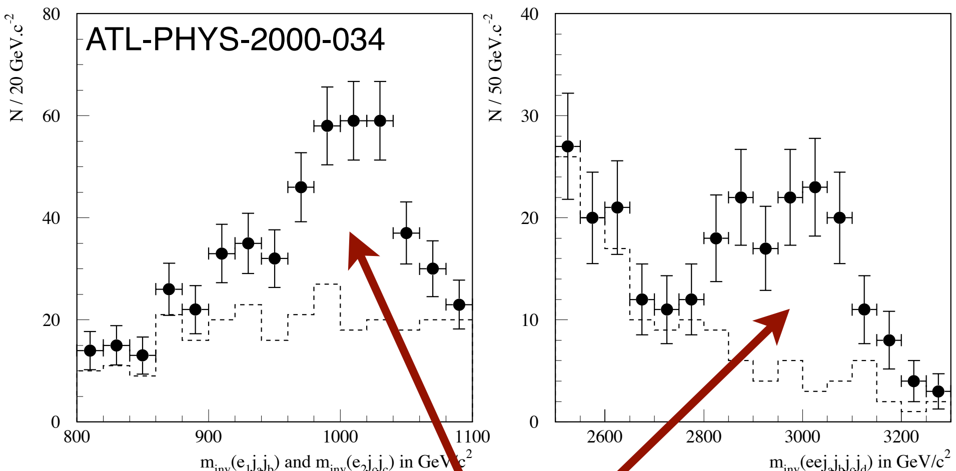
- If ν_R is lighter than m(Z')/2, decay channel opens up
- ν_R subsequently decays to lW_R^* (assuming W_R is heavier than ν_R), leading to signature with two leptons and 4 jets
  - Or other combinations if $m(\nu_R') < m(\nu_R)$, for example more leptons
  - Since ν_R is majorana, can get same-sign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



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

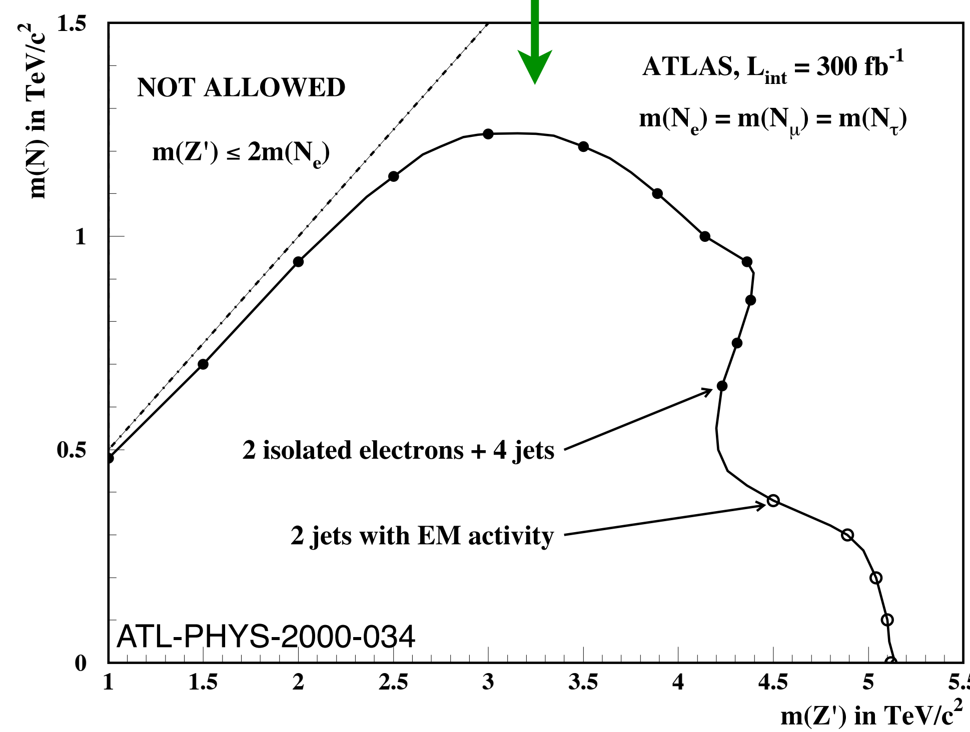
Z’ → $\nu_R \nu_R$ (2)

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



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

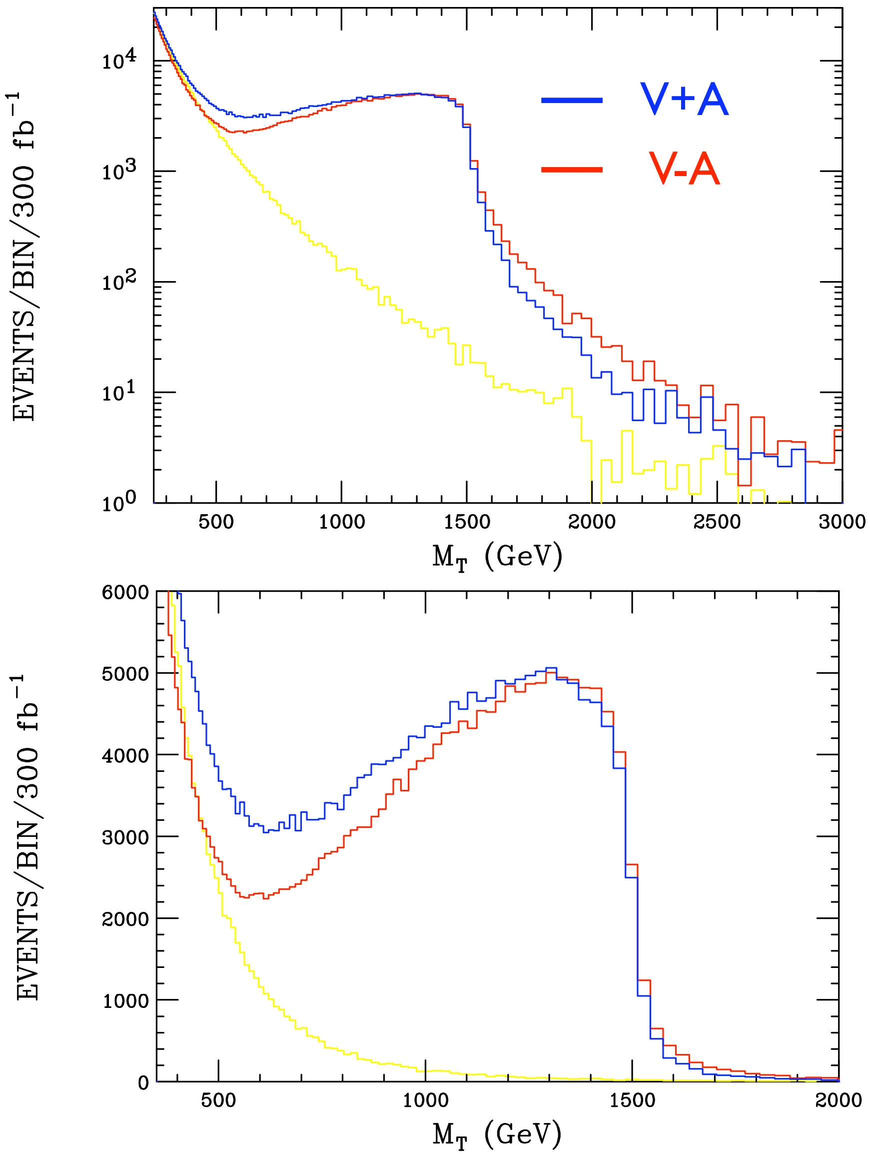
Discovery Potential



W’ Production

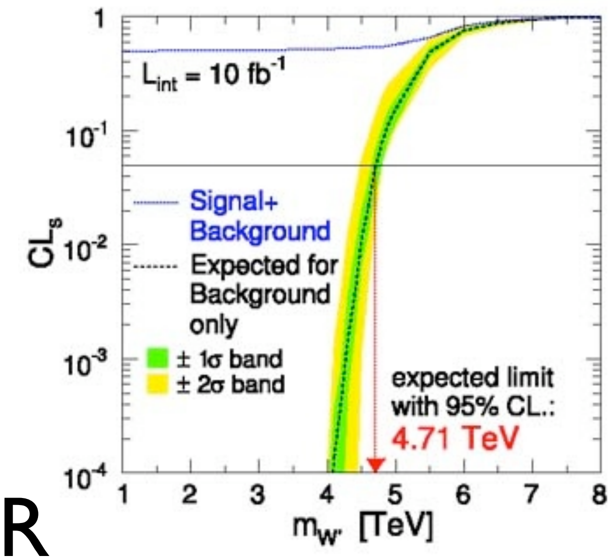
- W’ production rate not very dependent on couplings
- But interference with W important (and not in most experimental studies)!
  - Key in identifying W’ coupling helicity in fact
- (This plot is for e+MET transverse mass, which may not be a signature)

T. Rizzo, hep-ph/0704.0235

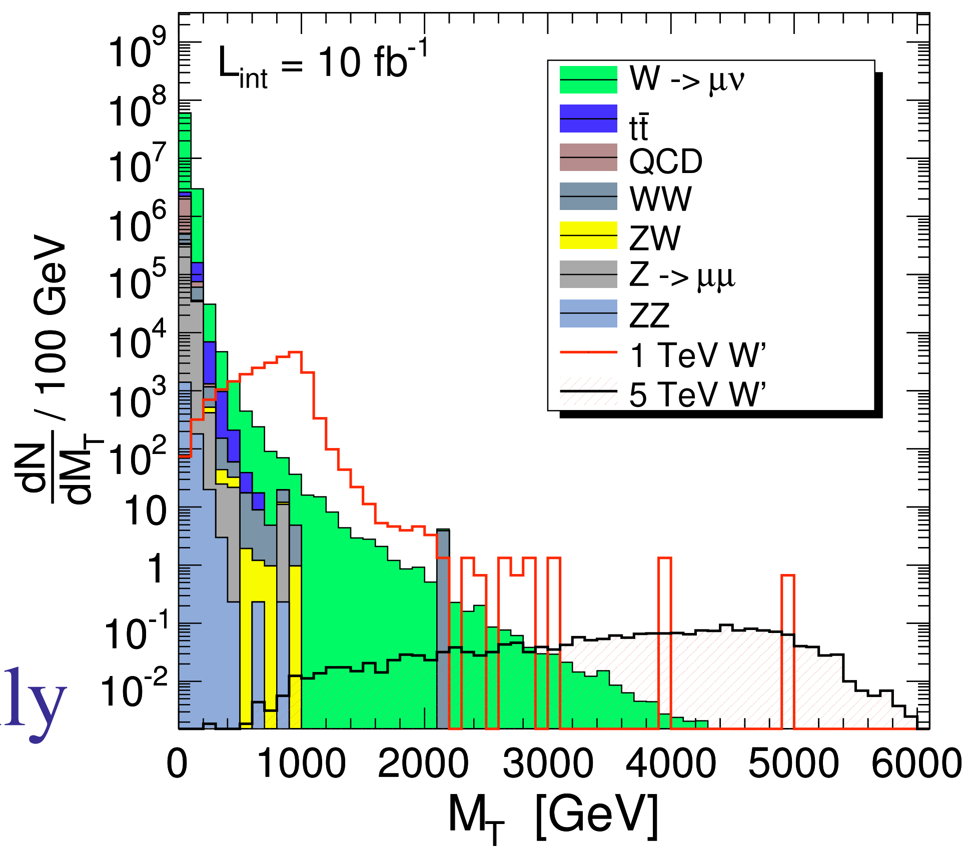


$W' \rightarrow \mu\nu_{(R)}$

- 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!

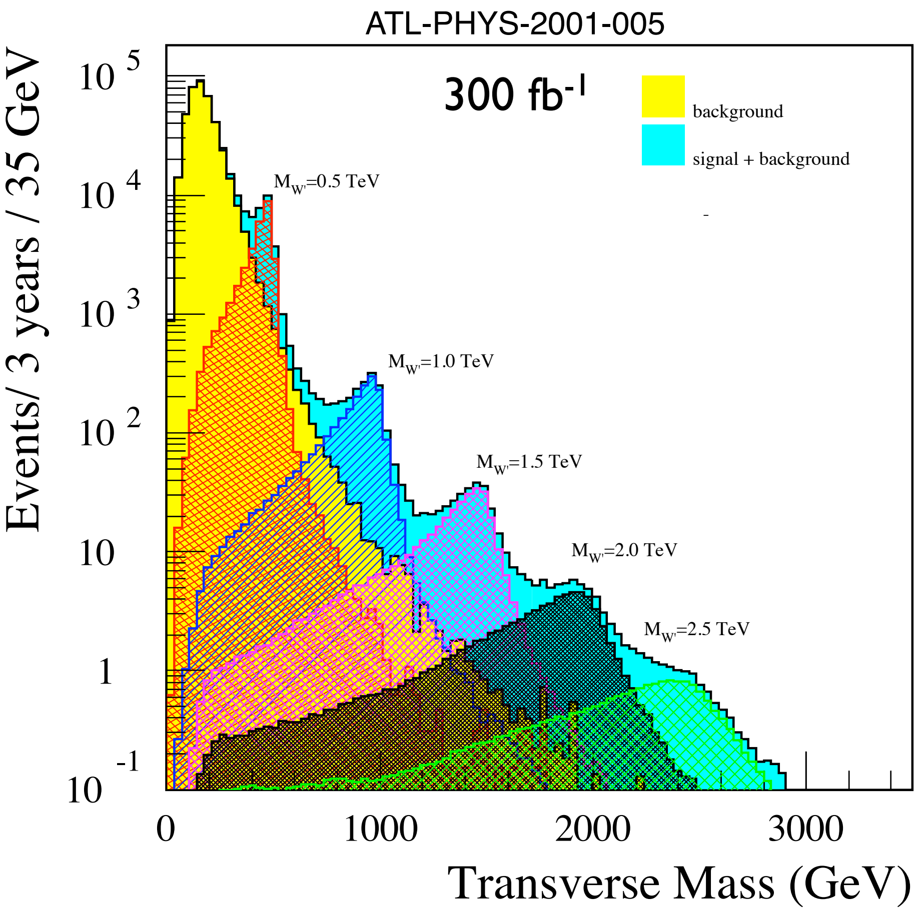


CMS TDR



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)



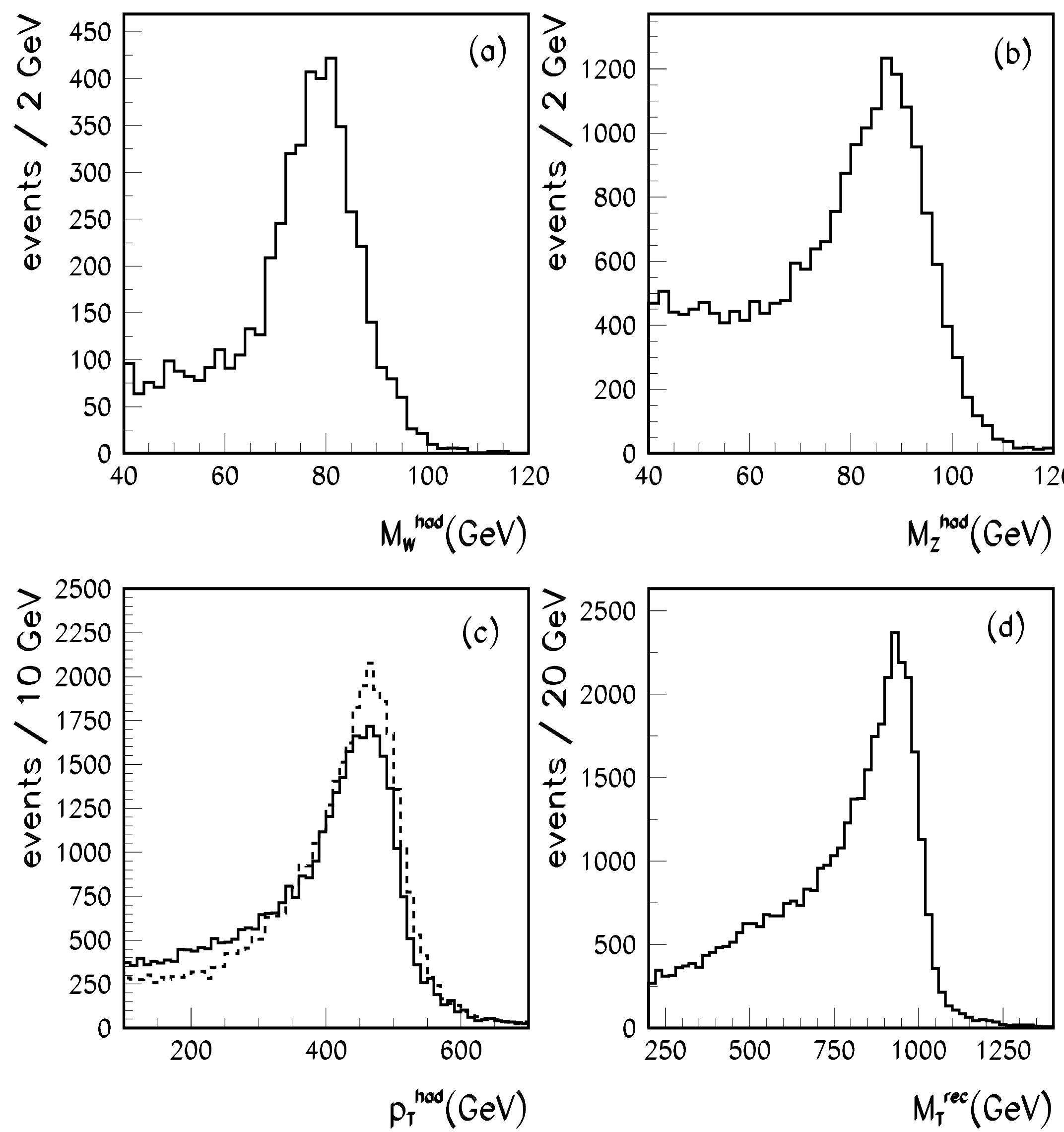
-Trileptons at low mass

-Lepton(s) + jets for high mass reach

W' → WZ (2)

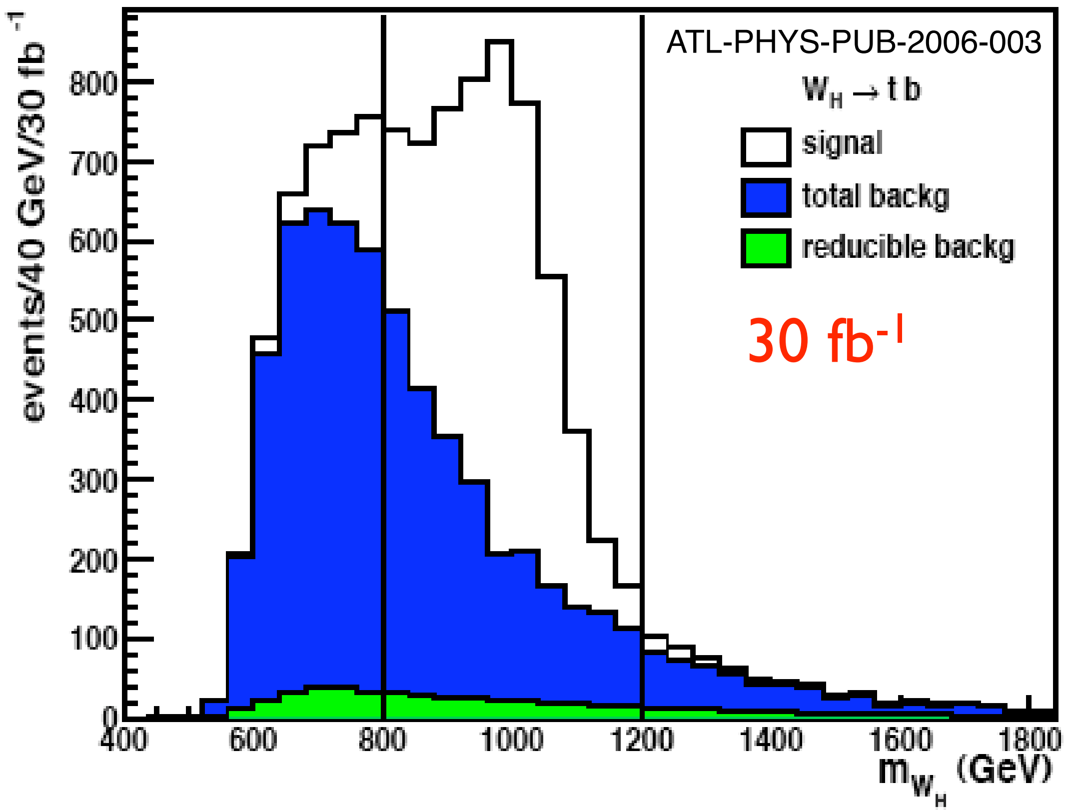
- If allow one boson to decay hadronically, higher BR (4.6/15%) but higher backgrounds
  - Hadronically decaying boson has large boost, so jets are merged → rely on jet mass
  - W/Z + jets background not well known

ATL-PHYS-2001-005



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!

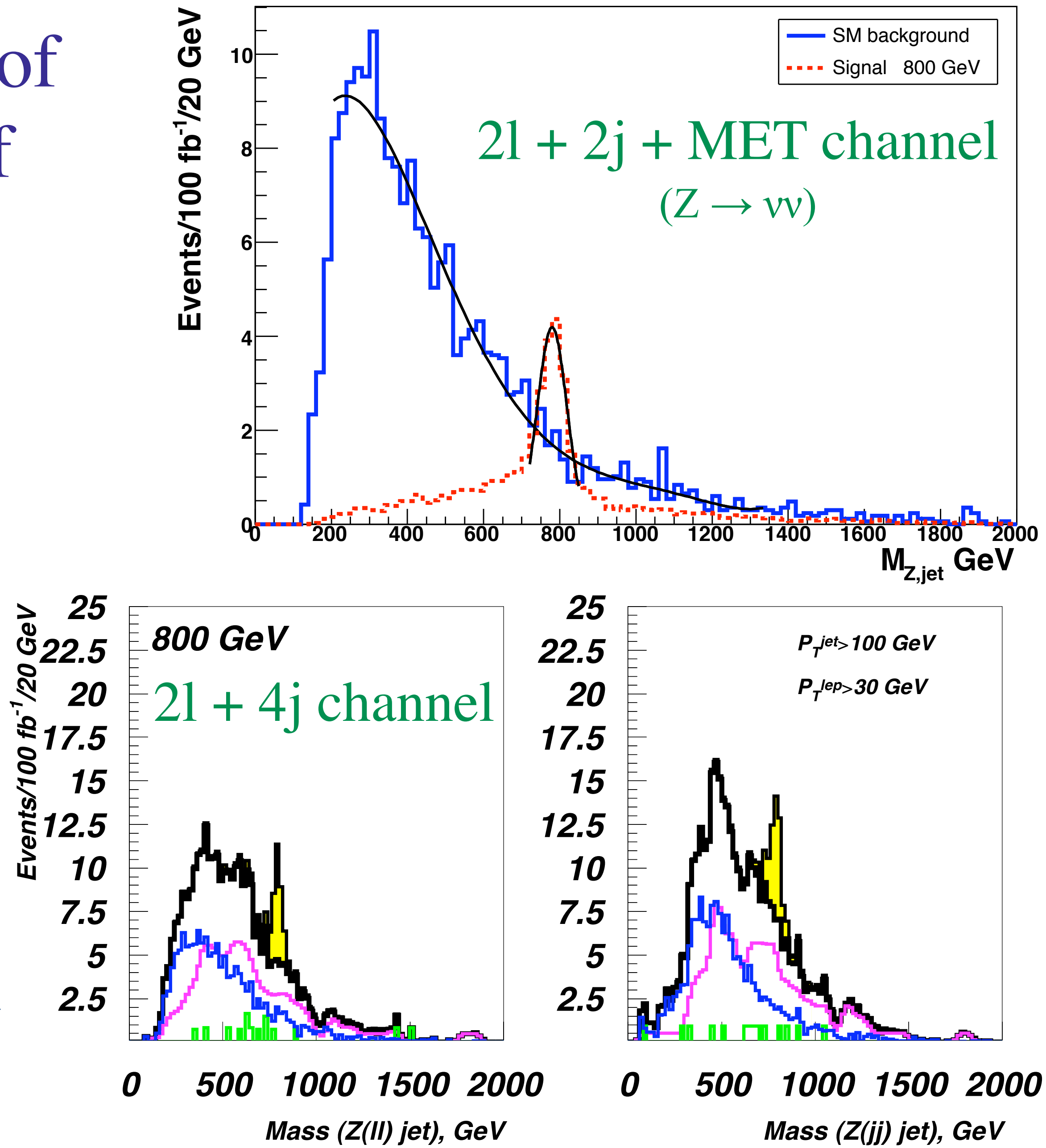


Note: This is for W_H from Little Higgs

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



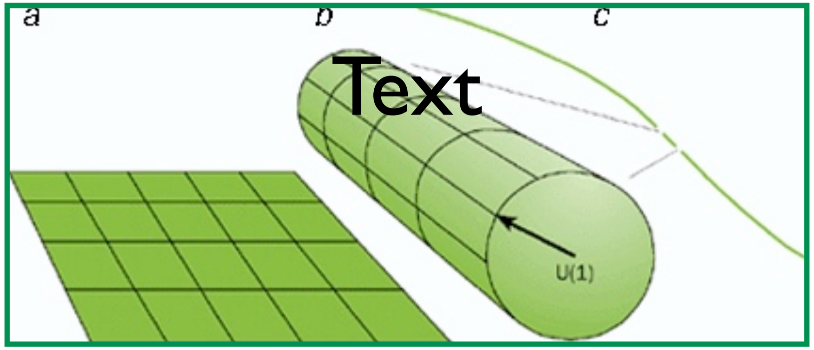
Gravity and Hierarchy

(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

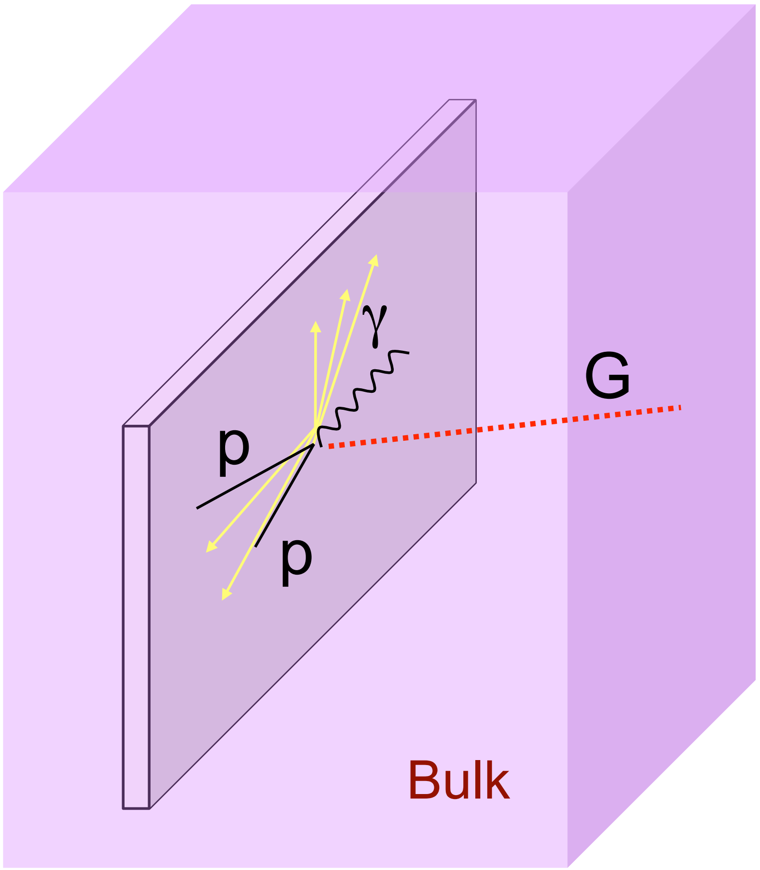


- Radius of compactification usually assumed to be at the scale of gravity, i.e. 10^{18} GeV
  - In ’90 Antoniadis realized they may be much larger...

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"

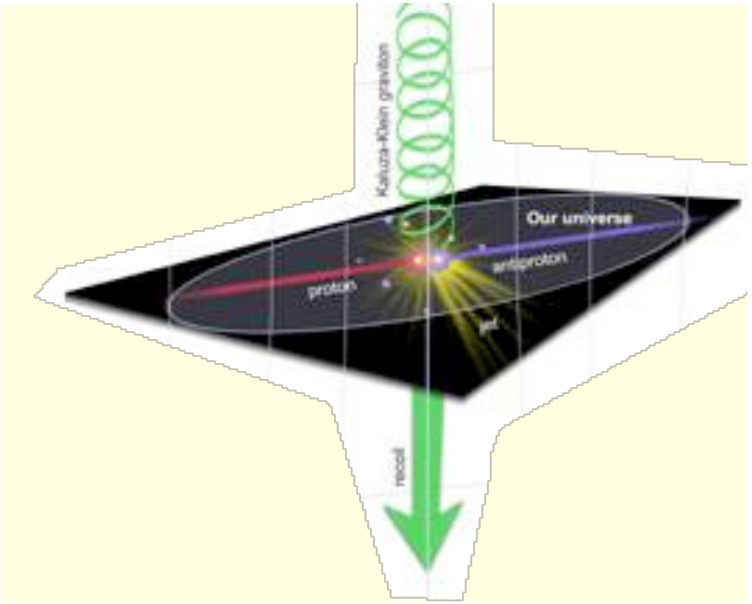


Drawing by K. Loureiro

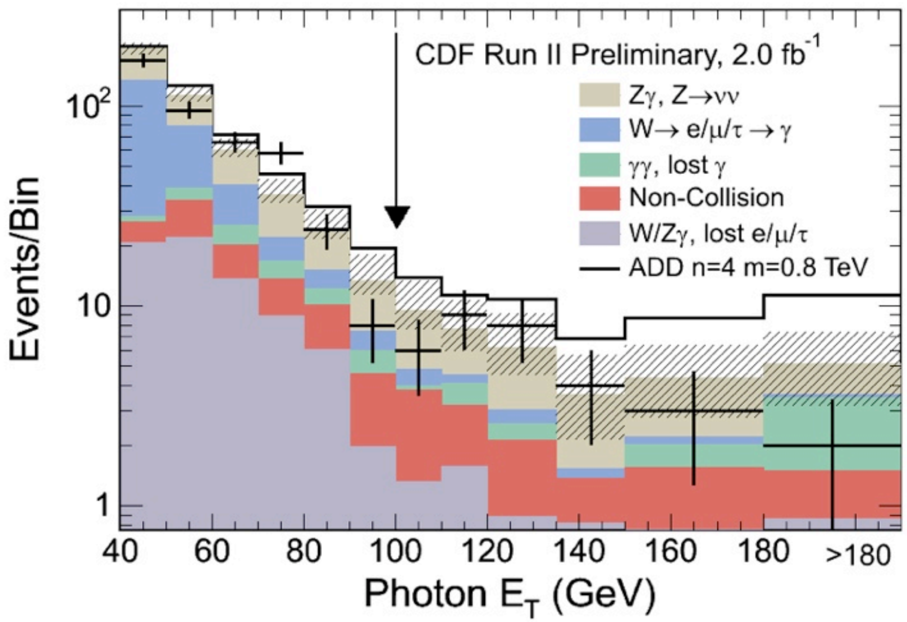
ADD Signatures

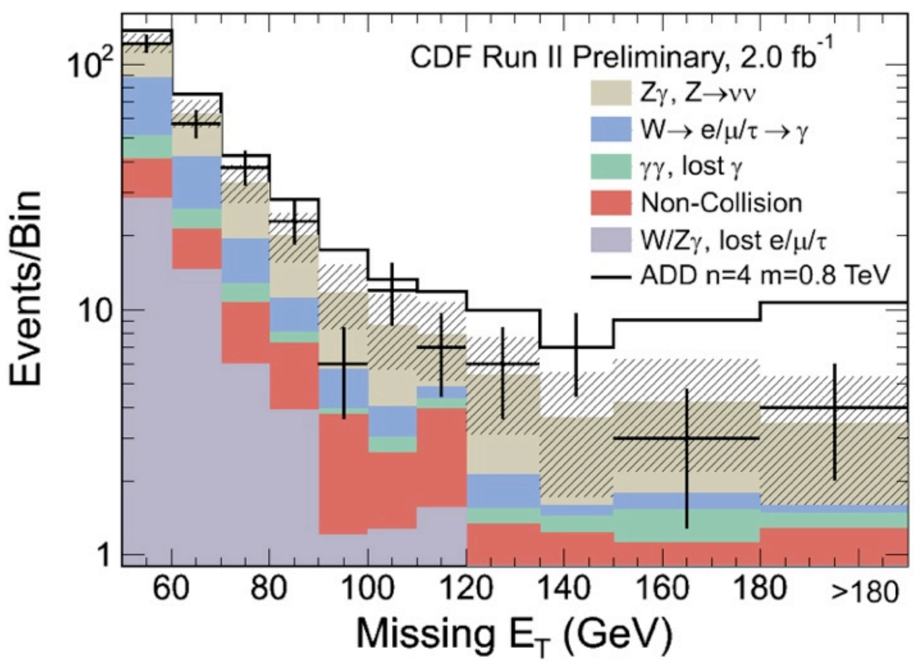
- Edges of extra dimensions identified
  - ➡ Boundary conditions
  - ➡ Momentum along extra dimension is quantified
  - Looks like mass to us
  - Very small separations → looks like continuum
  - Called Kaluza-Klein tower
- Coupling to single graviton very weak, but there are *lots* of them!
  - Large 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

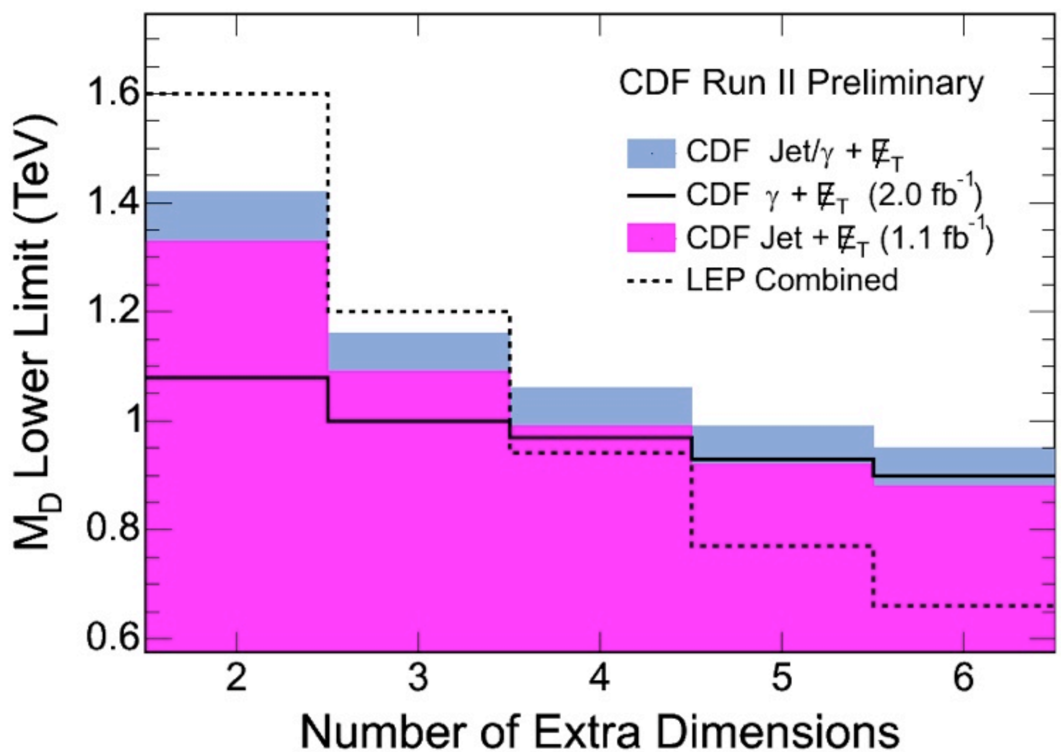


Jet/Photon + Graviton

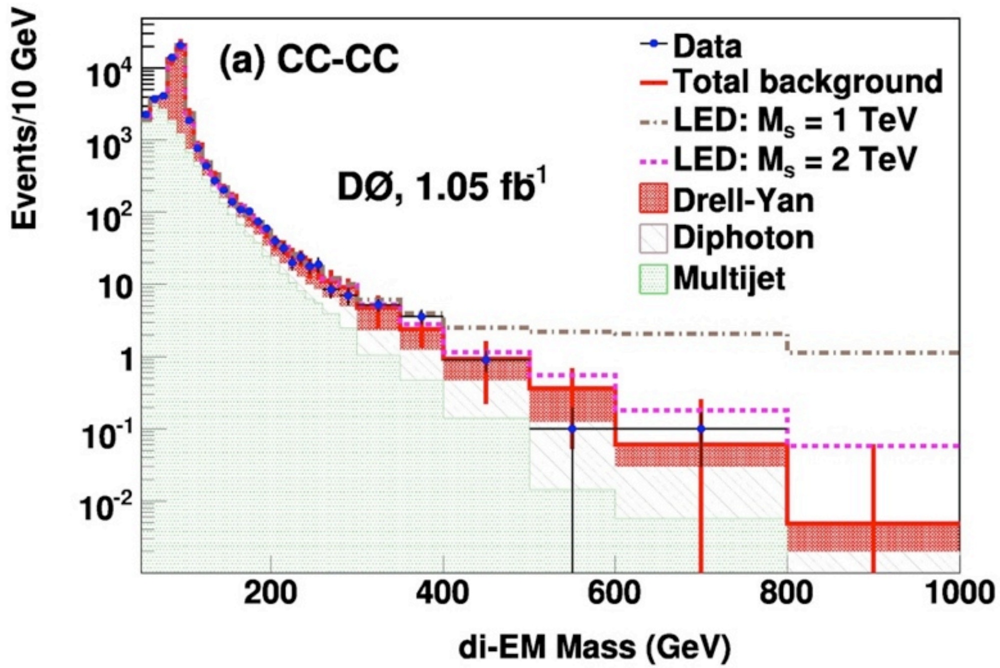


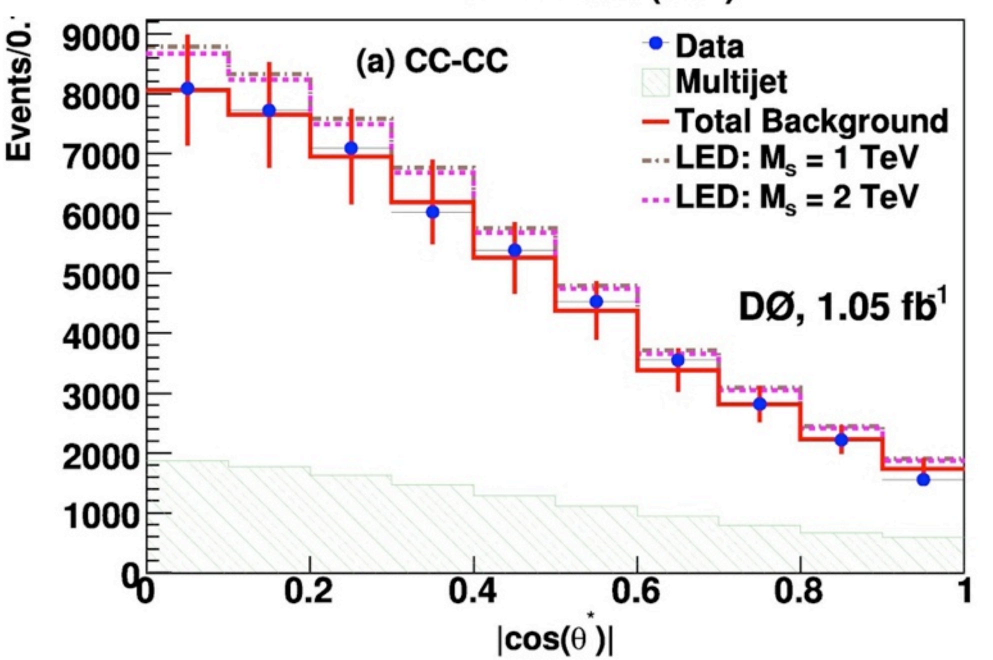


Jet/Photon + MET Combined Limit (Based on event counting only)

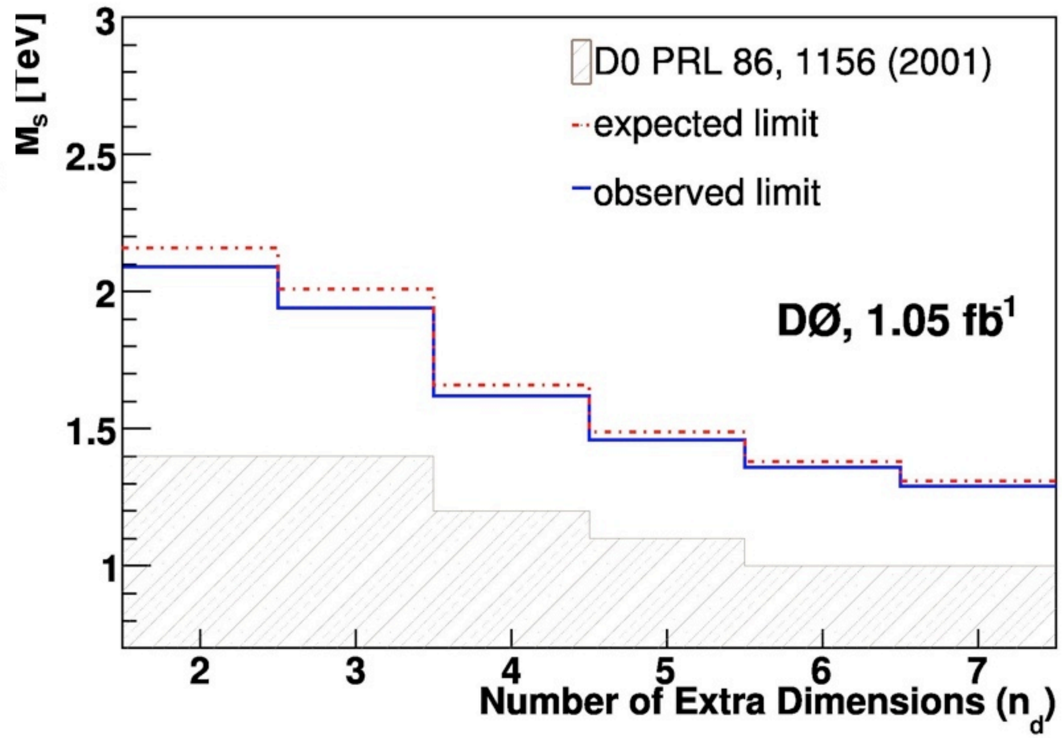


Dielectrons and Diphotons



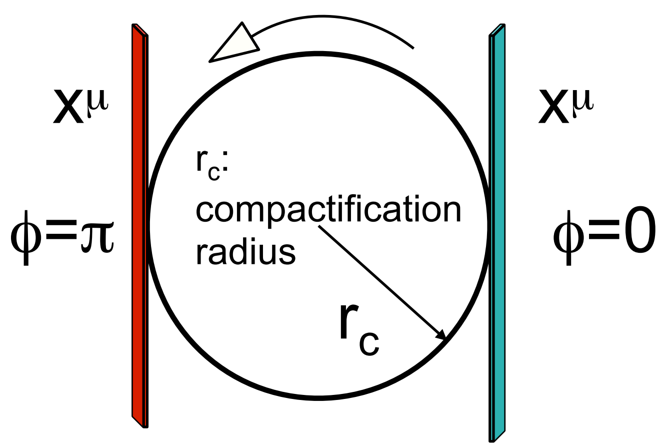


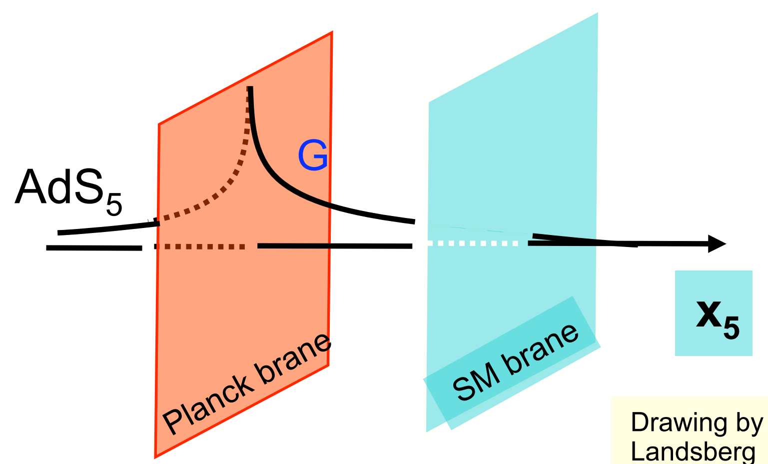
~10% of sensitivity
from angular distribution



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)



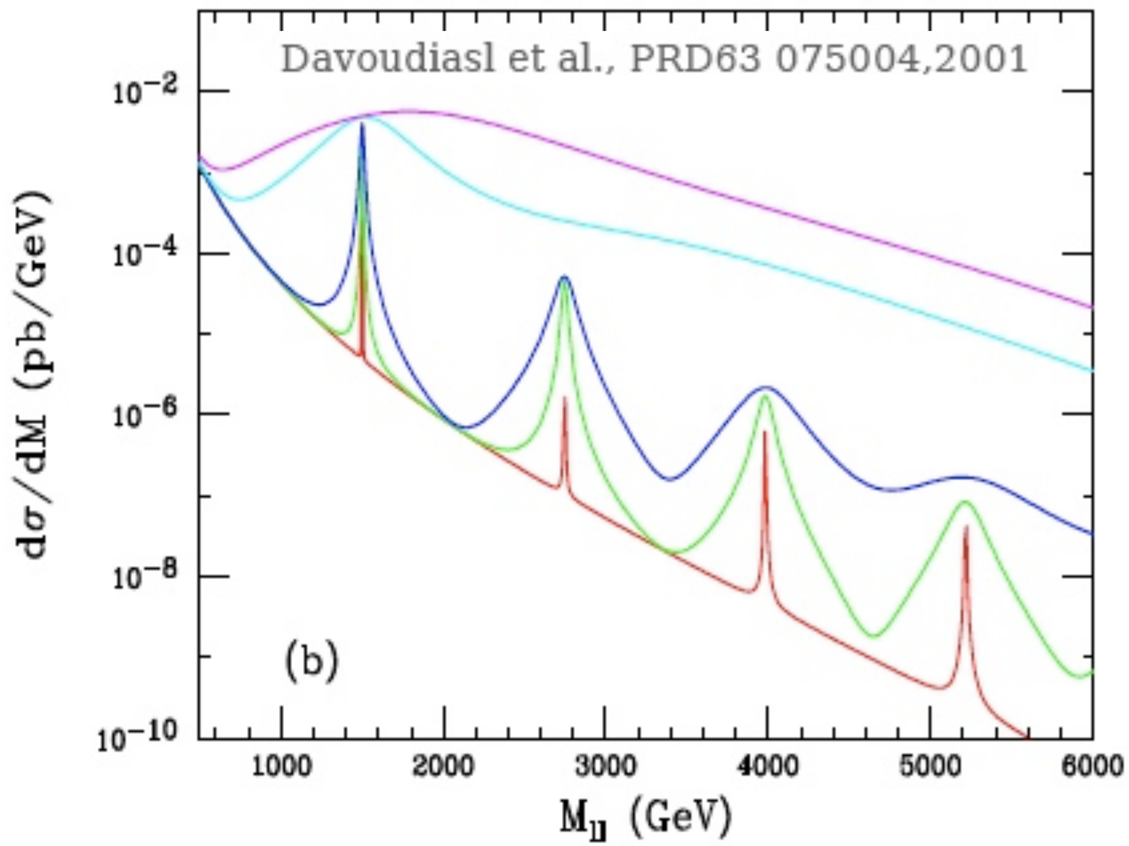


Drawing by G. Landsberg

Graviton Excitations

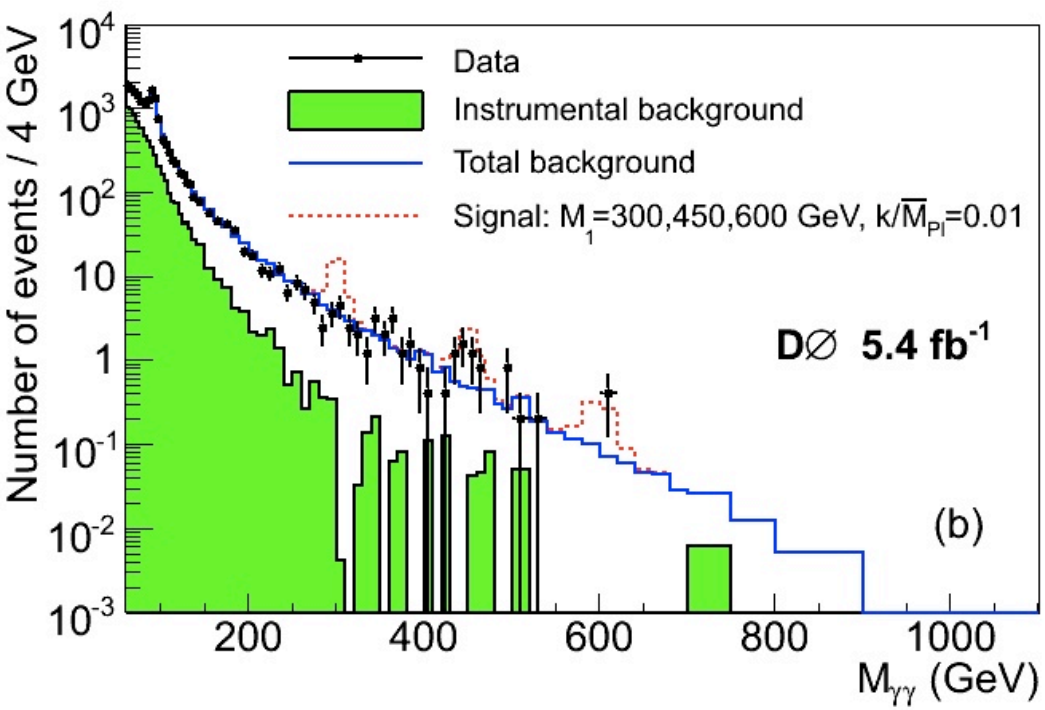
- In RS, get a few massive graviton excitations
  - Widths depend on warp factor k
  - Mass separation = zeros of Bessel function
    - ➡ Smoking gun!

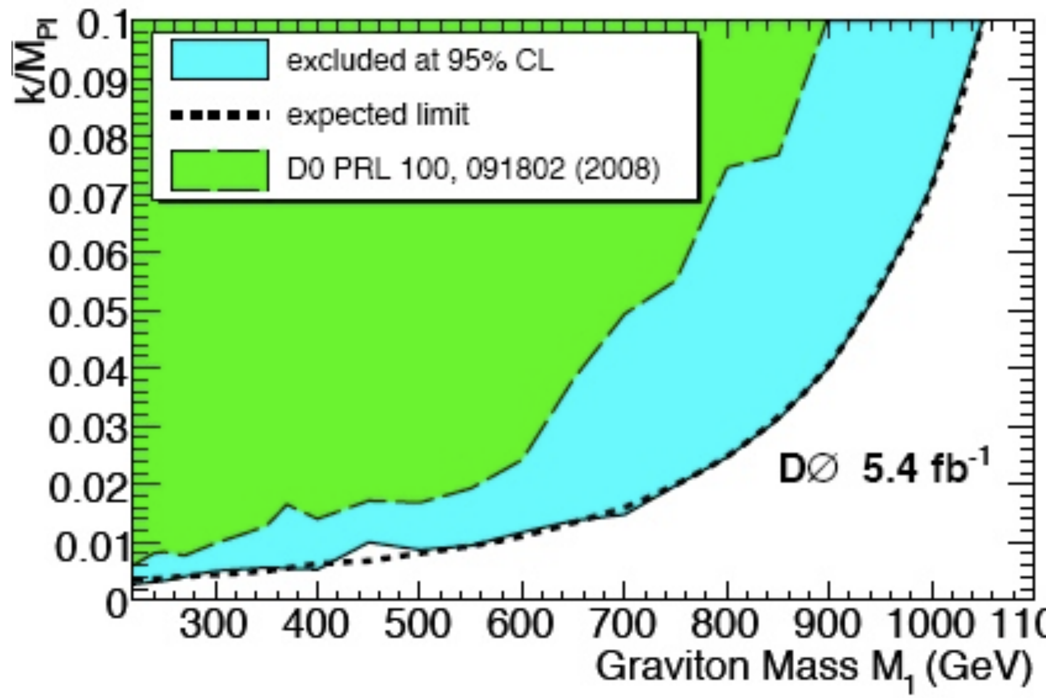
(BRs also different than Z':
e.g. γγ allowed)



Dielectrons/Diphotons

DØ, Phys. Rev. Lett. 104, 241802 (2010)

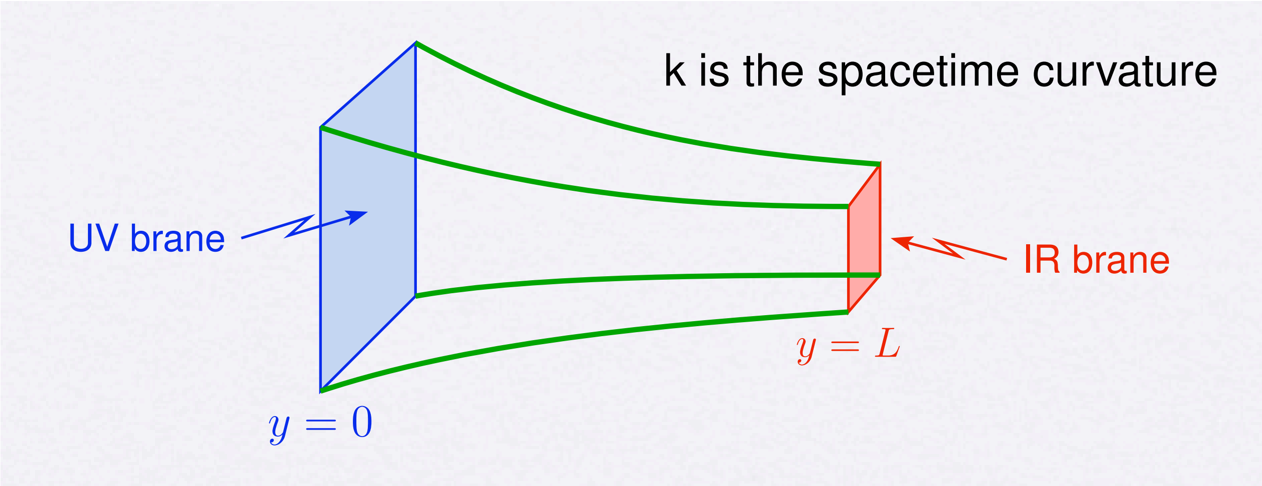




- Separate dielectrons from diphotons:
  - Targeted background rejection yields better limits
  - Diphotons more sensitive

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!)

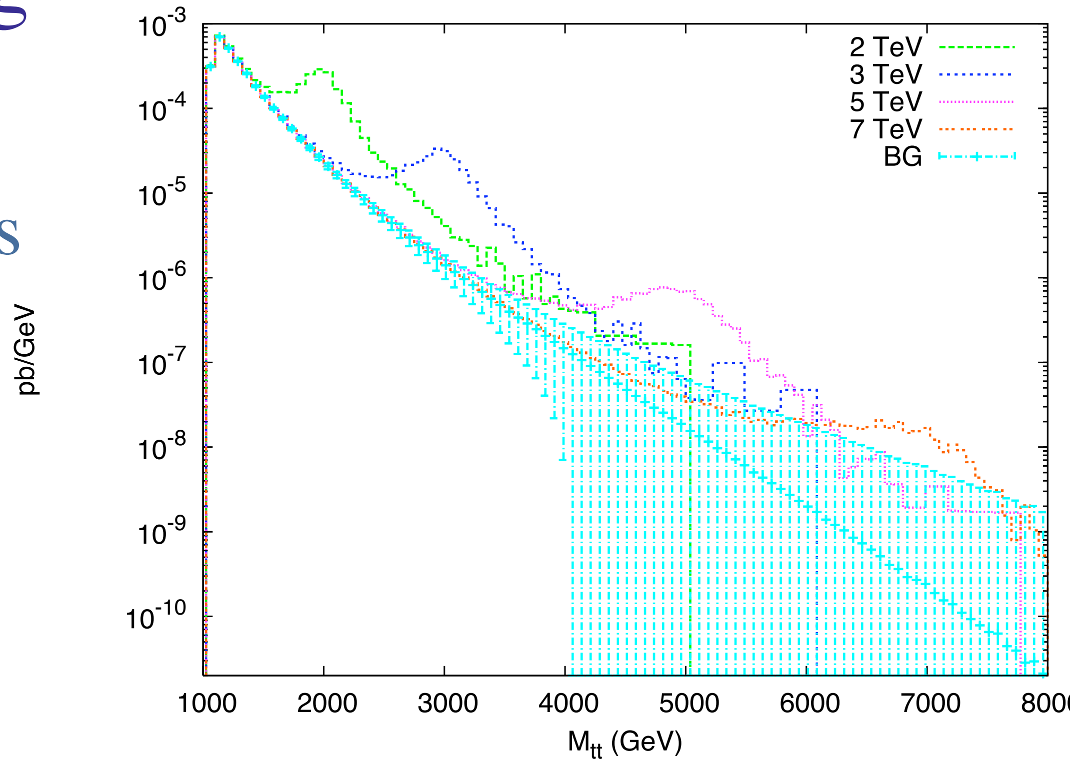
Flavor

- 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

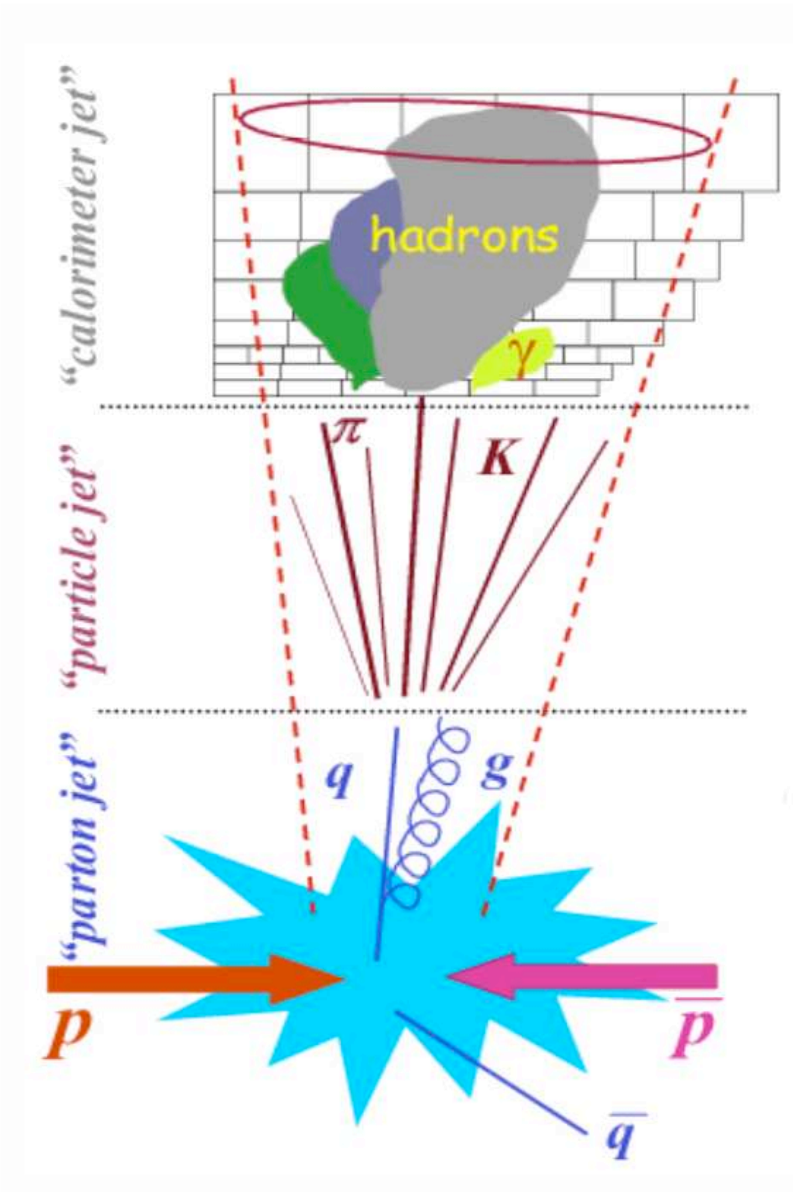
- Excitations of the gauge bosons are very promising channels for discovery
  - Couplings to light fermions are small
    - Small production cross-sections
  - Large coupling to top, W_L, Z_L
    - Look for $t\bar{t}$, WW, ZZ resonances (that can be wide)

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



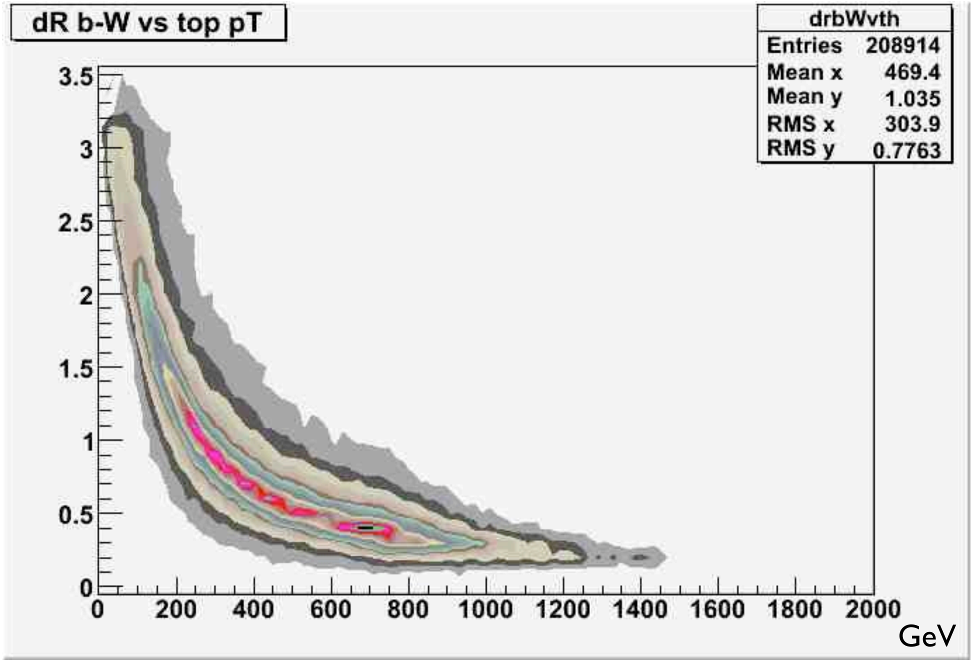
New Experimental Phenomenology

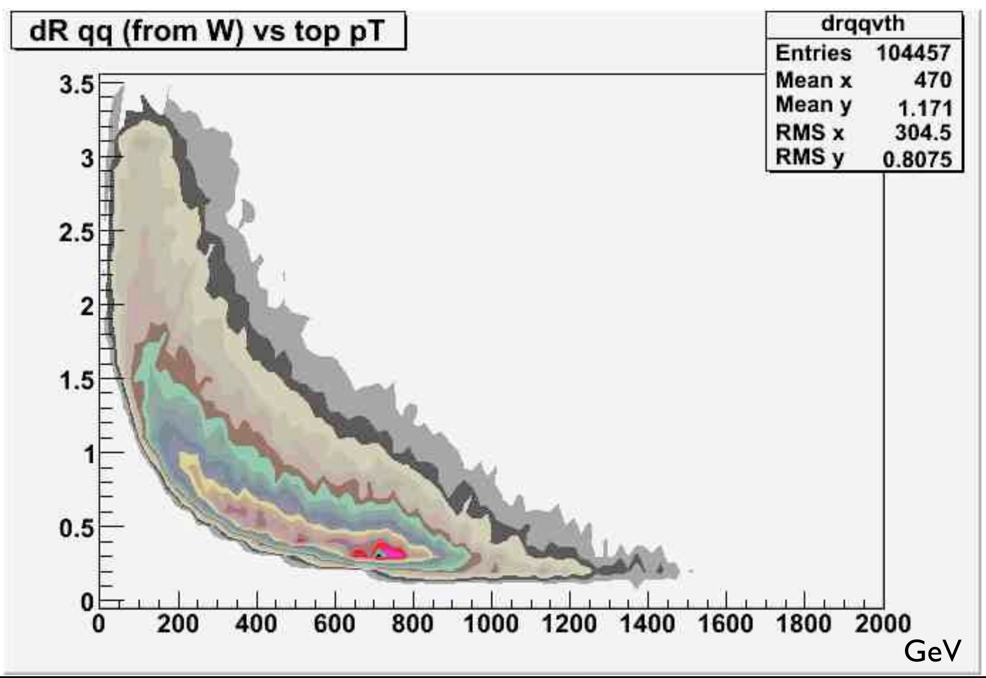
- Possibility to produce heavy resonances decaying to top quarks, W and Z bosons
  - Heavy objects with momentum >> mass
    - Decay products collimated
  - For leptonic W/Z decays, not a big issue since we measure isolated tracks very well
  - But hadronic decays lead to jets, which are intrinsically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



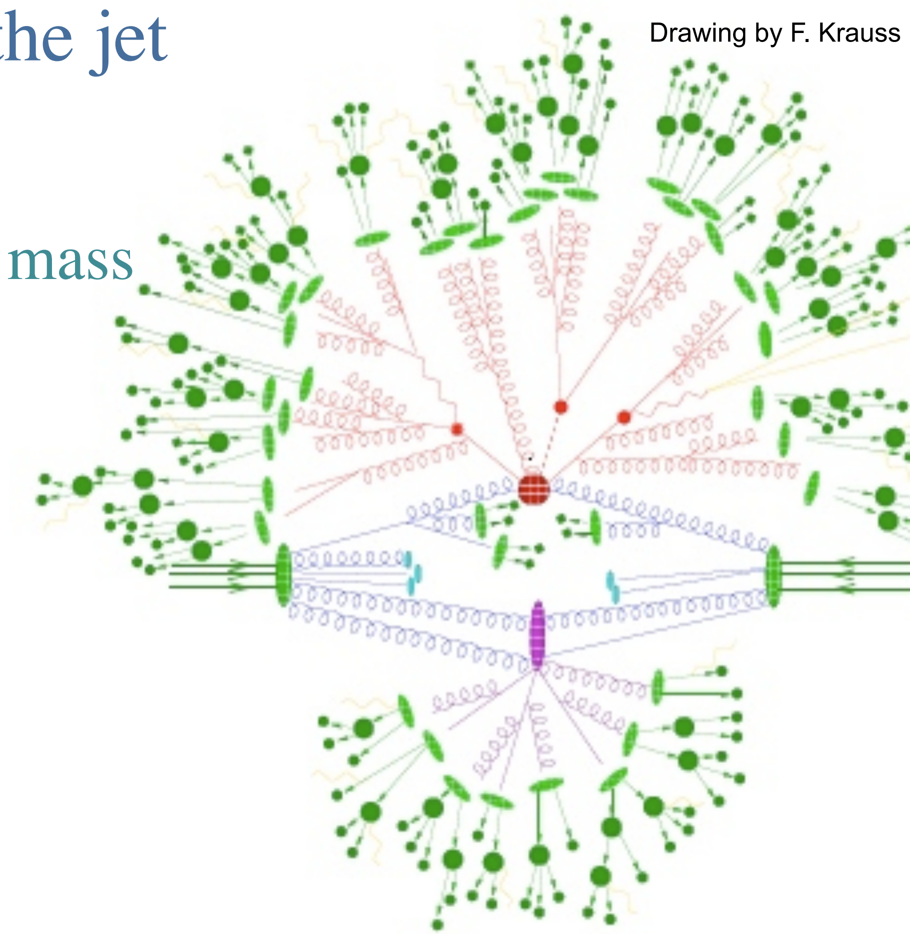


ATLAS Study

- 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:
  - $Z' \rightarrow t\bar{t}$ 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

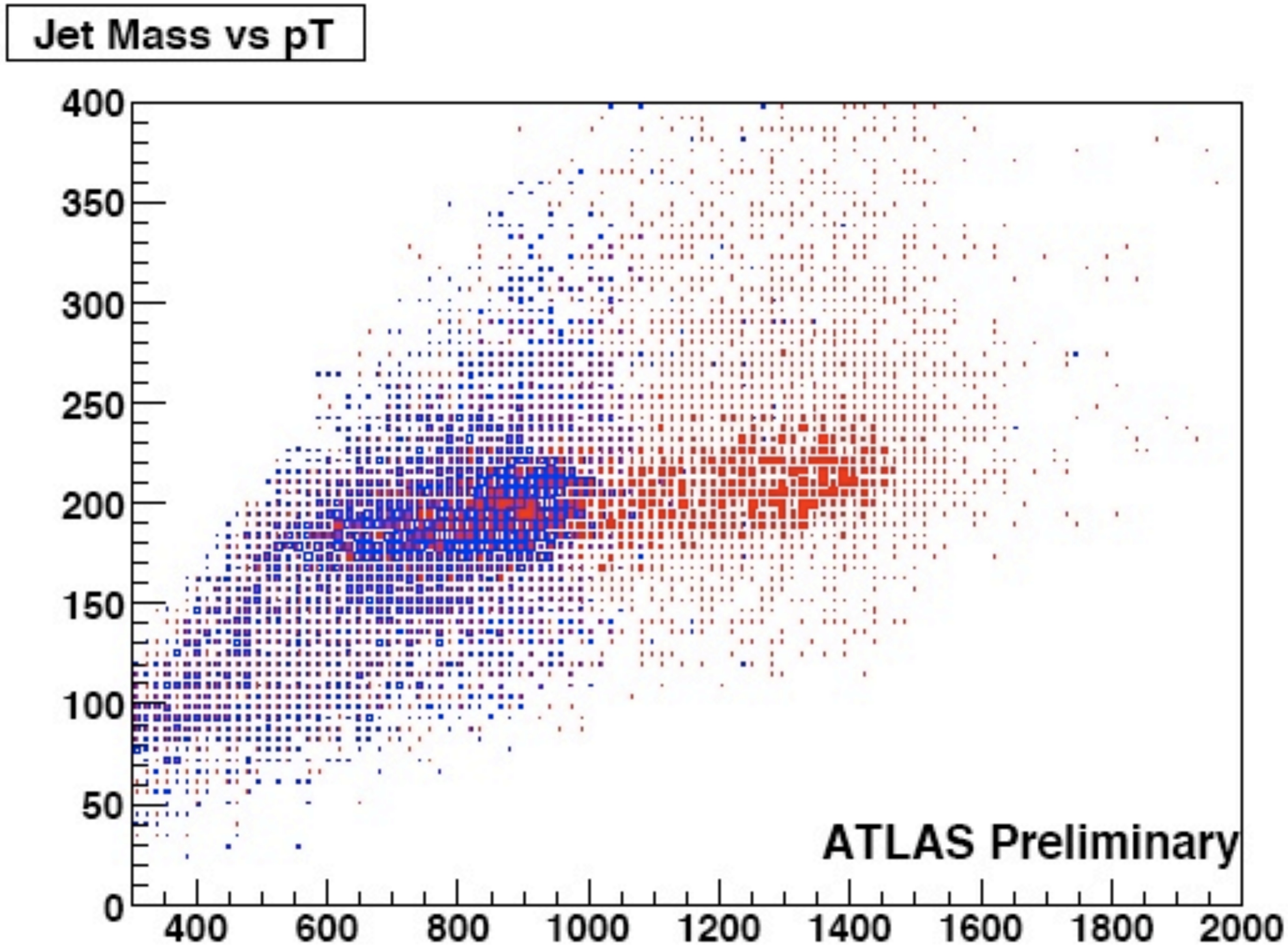
- Decay hadrons reconstructed as a single jet
  - But even if it looks like a single jet, it originates from a massive particle decaying to three hard partons, not one
- If I measured each of the partons in the jet perfectly, I would be able to:
  - Reconstruct the "originator's" invariant mass
  - Reconstruct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



Drawing by F. Krauss

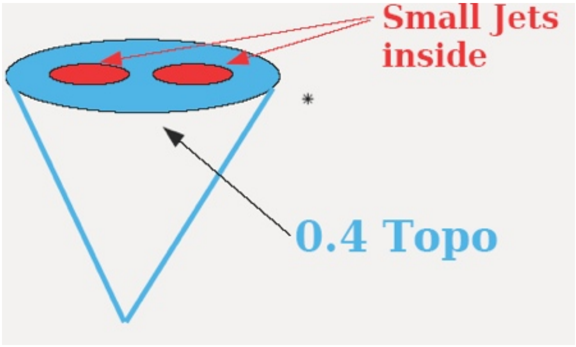
Jet Mass

- 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

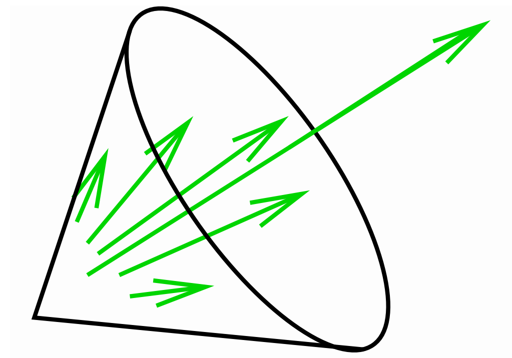


- Multiple ways of exploiting this....
  - This study: k_T splitting scales

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

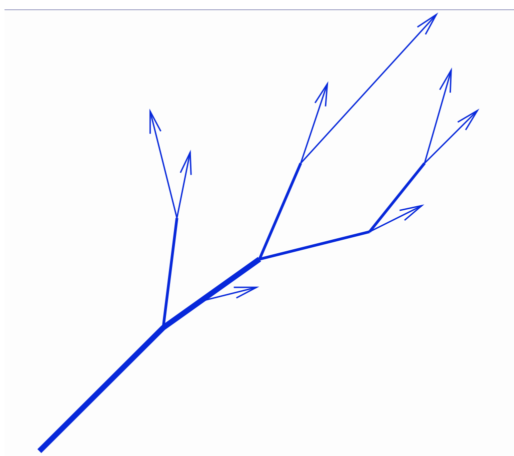


Cone

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

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

- 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

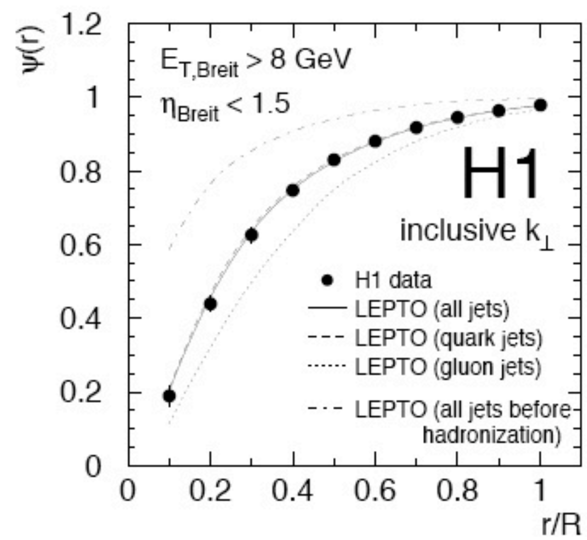


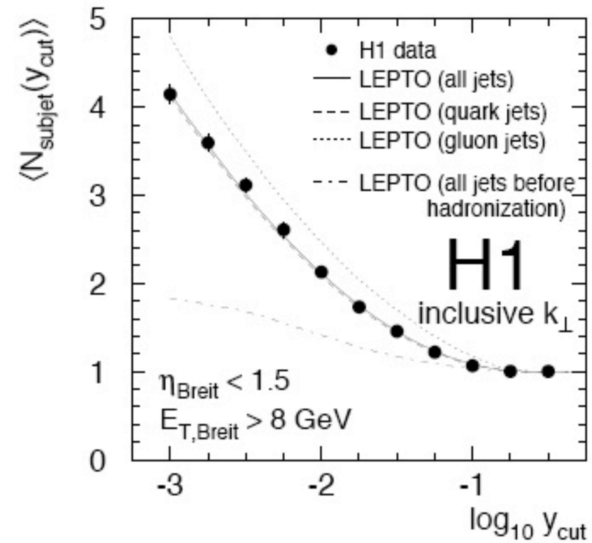
k_T

Subjets in History

- Jet shapes and number of subjets

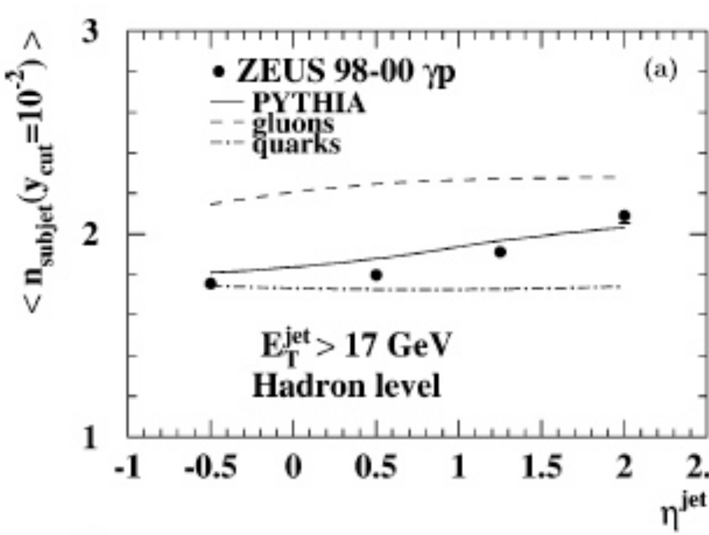
Nucl.Phys.B545:3-20,1999.

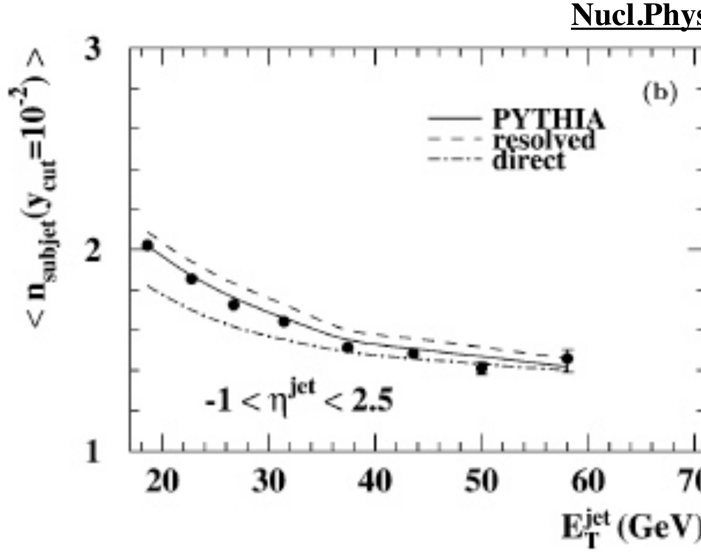




Nucl.Phys.B700:3-50,2004

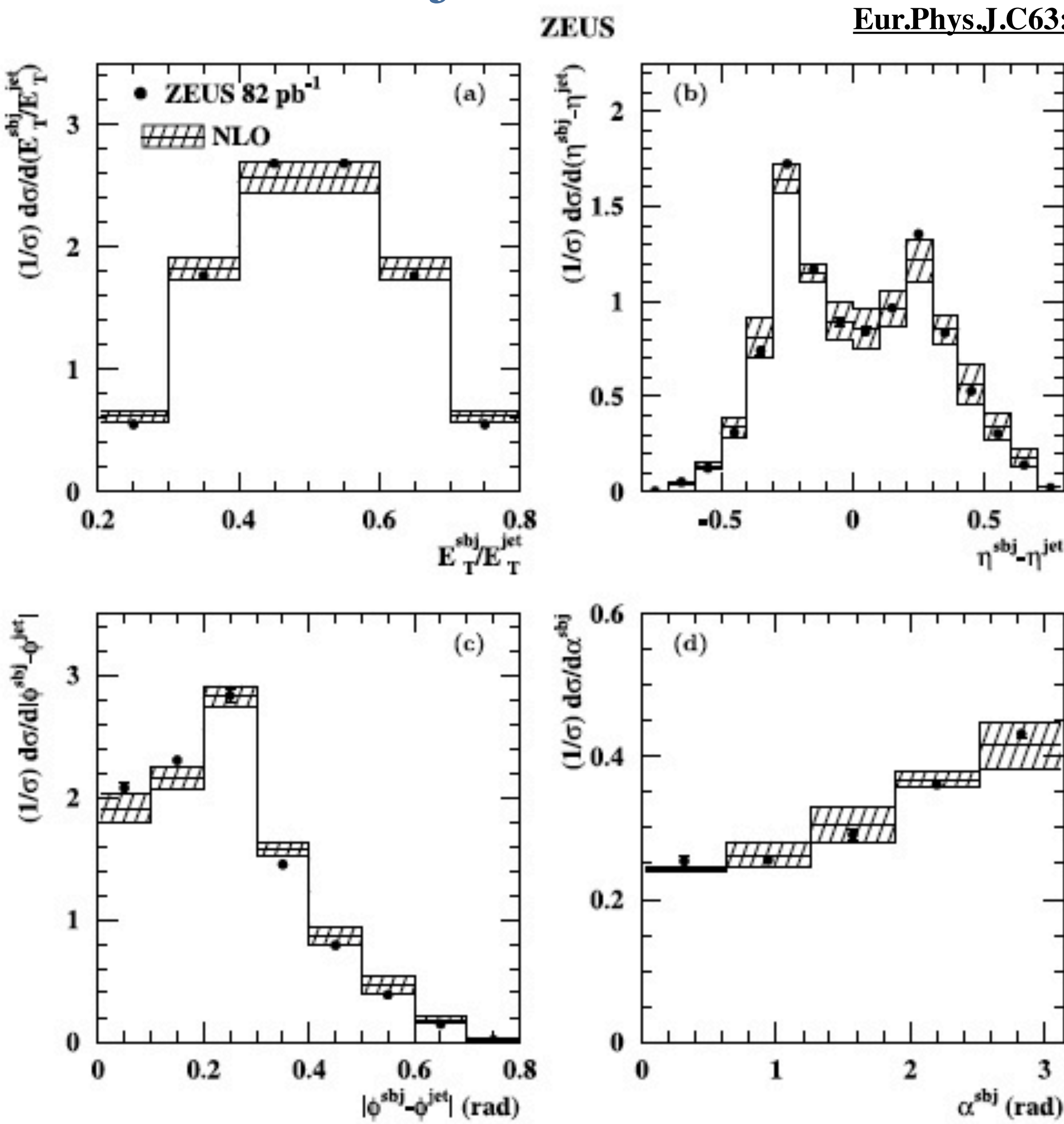
ep collisions!



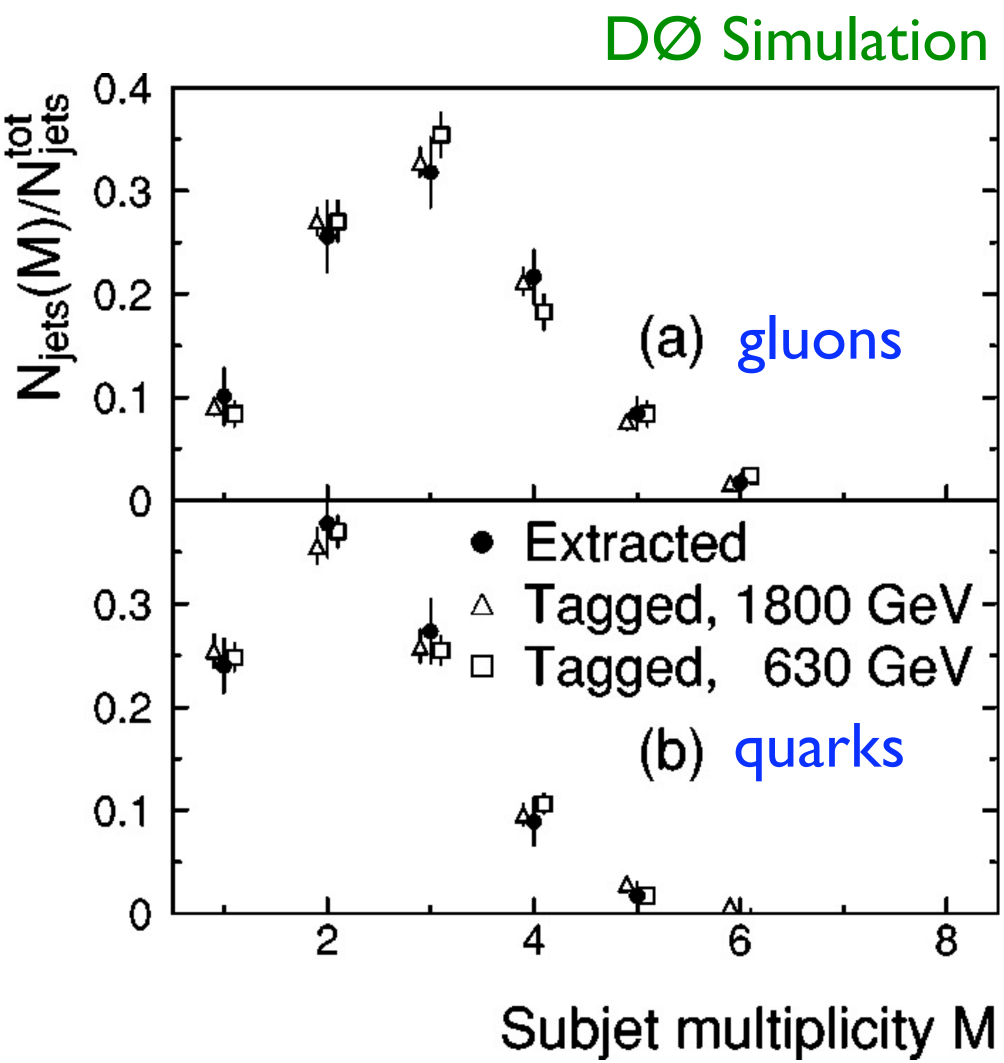


- Subjet properties
  - Events with two subjets

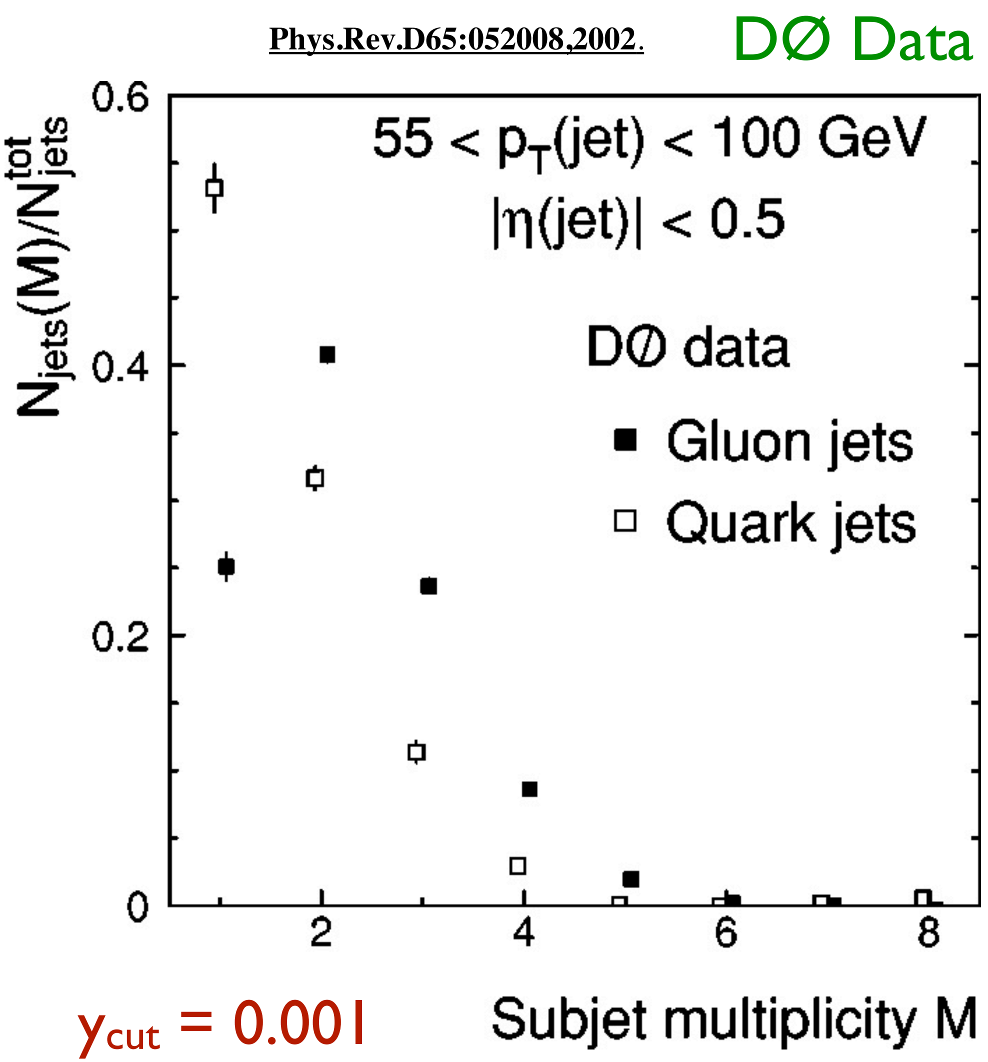
Eur.Phys.J.C63:527-548,2009



Quarks and gluons

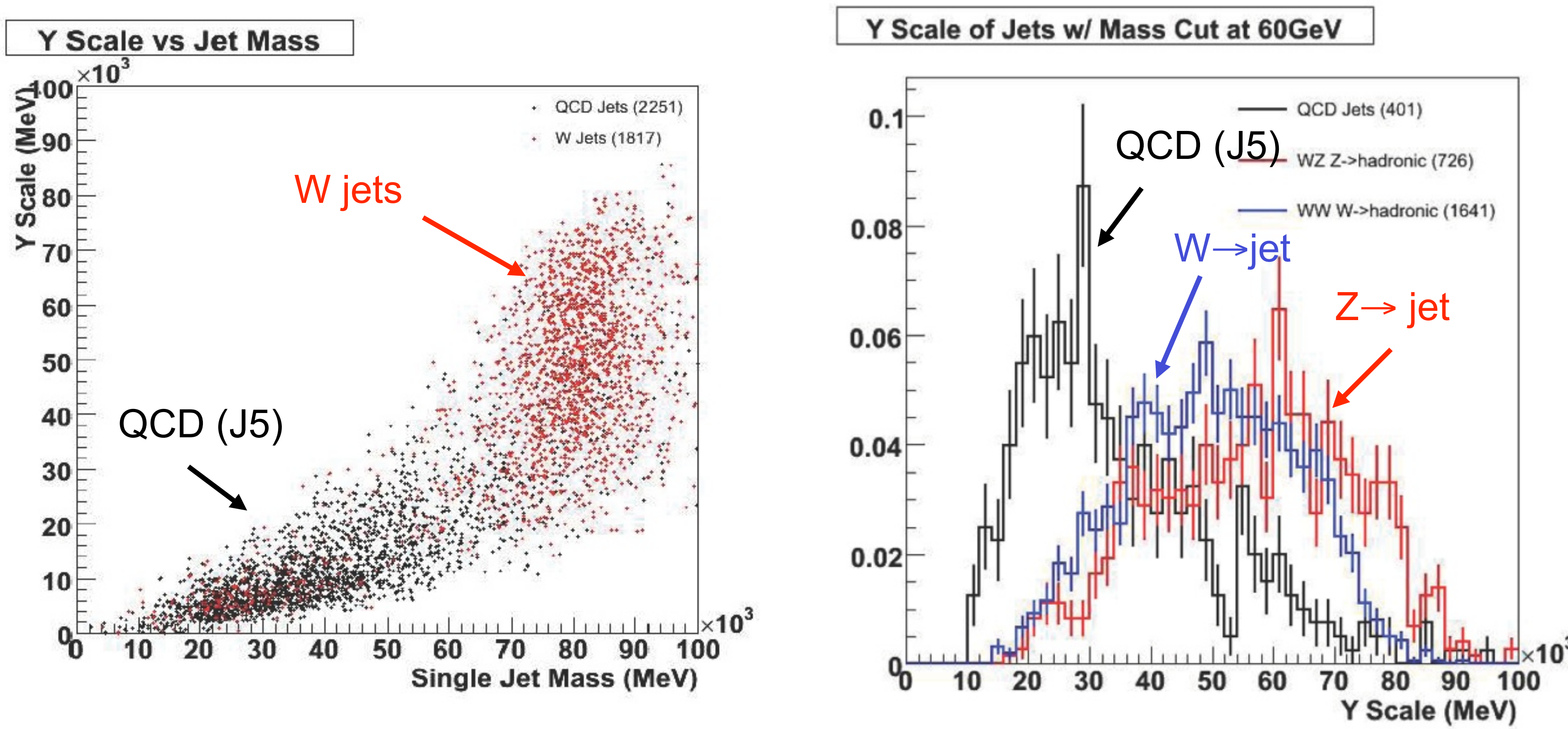


Phys.Rev.D65:052008,2002.



$y_{cut} = 0.001$

- Applied to high p_T WW scattering:

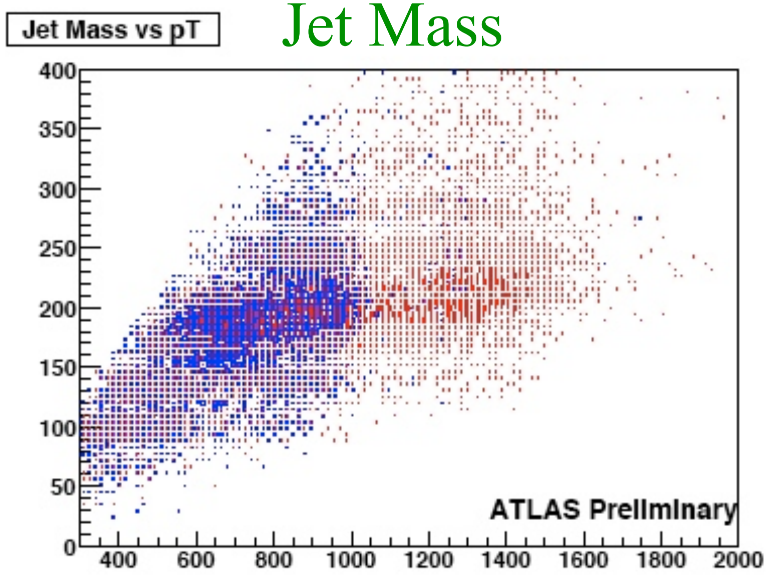


- k_T jet algorithm, with R = 0.5
- Cuts applied : p_T(jet) > 300 GeV,

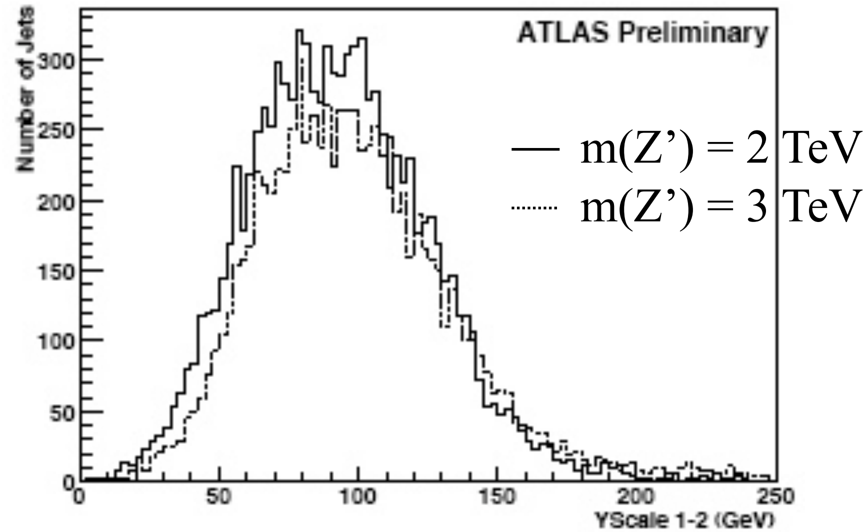
Techniques also believed to allow recovery of H → bb at LHC!

Now Hadronic Top

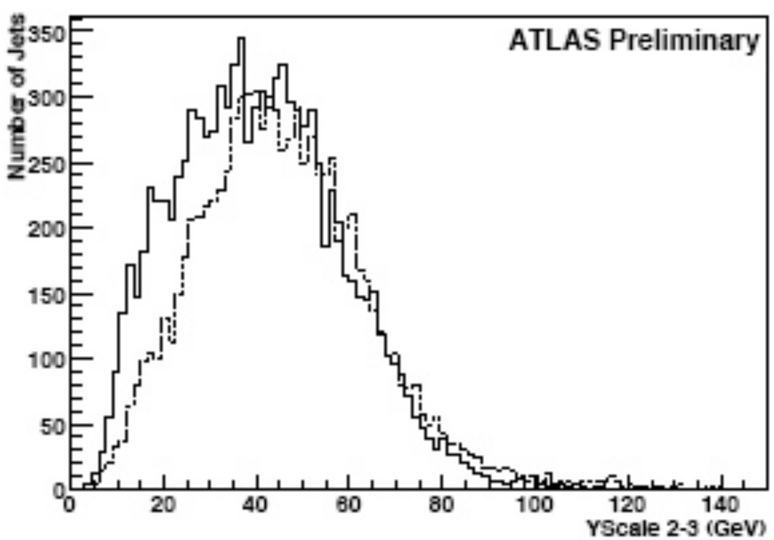
Jet Mass



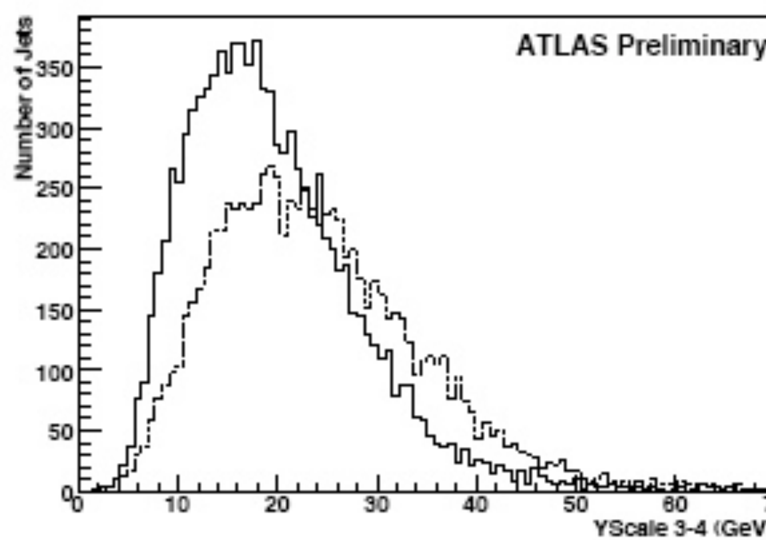
1 → 2 Jet Scale



2 → 3 Jet Scale

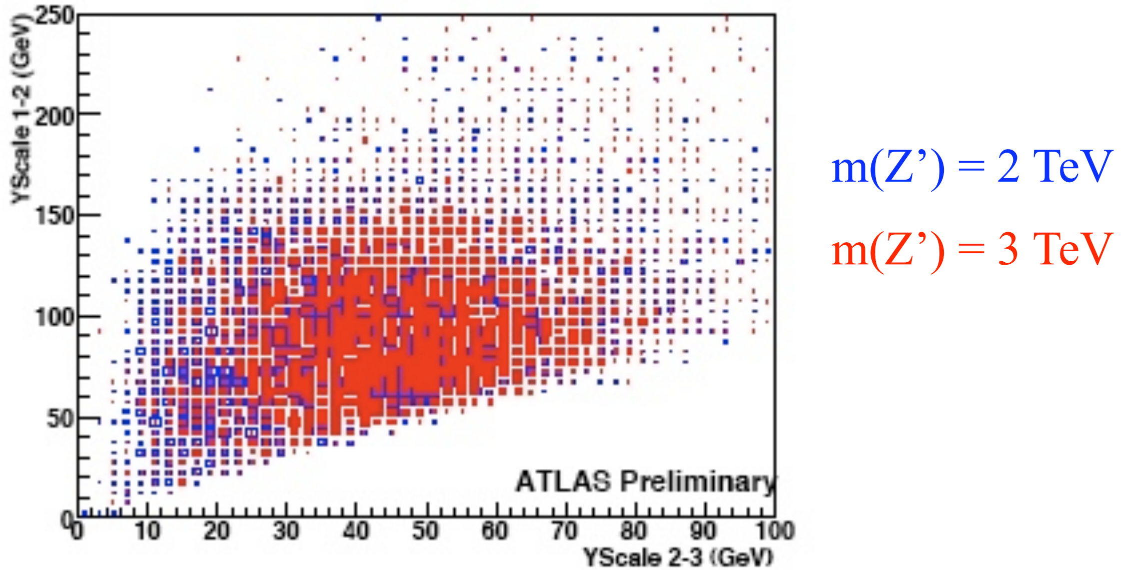


3 → 4 Jet Scale



Slow p_T Dependence!

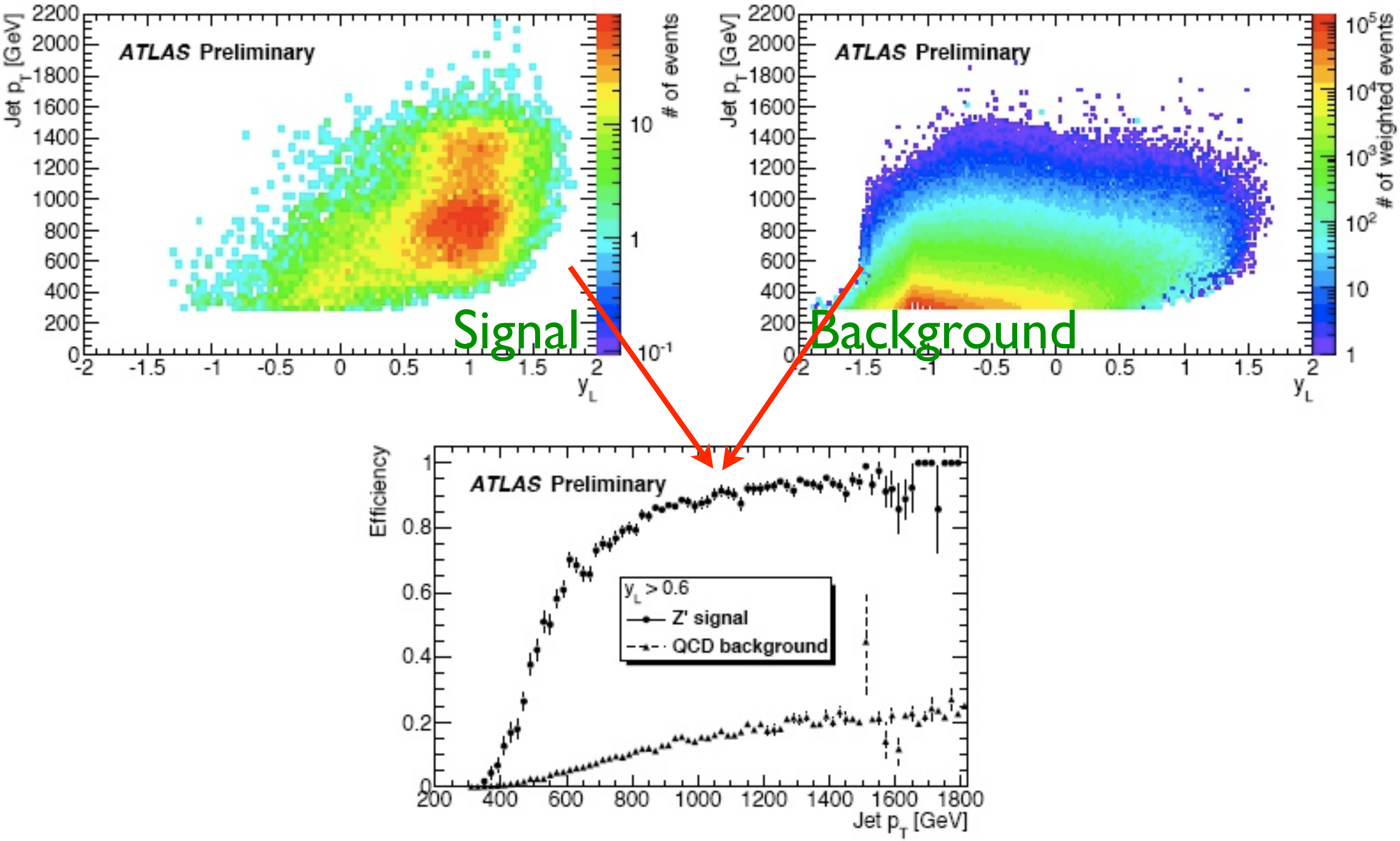
- Observations:
  - Variables show slow dependence on top (jet) p_T
  - Only weakly correlated



  - For light jets, all the variables drop off exponentially

➡ Combine into a likelihood

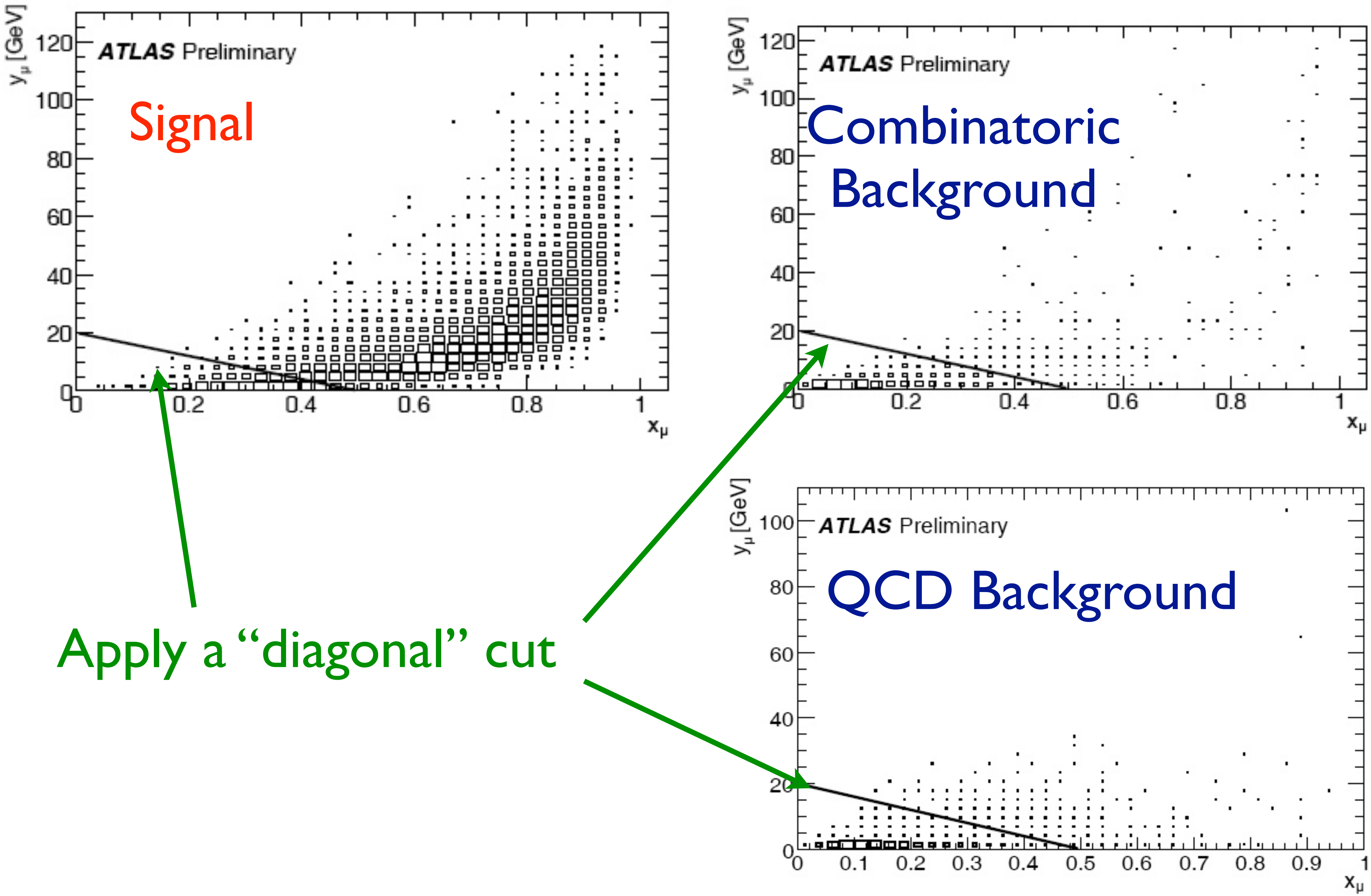
Hadronic Decays: Result



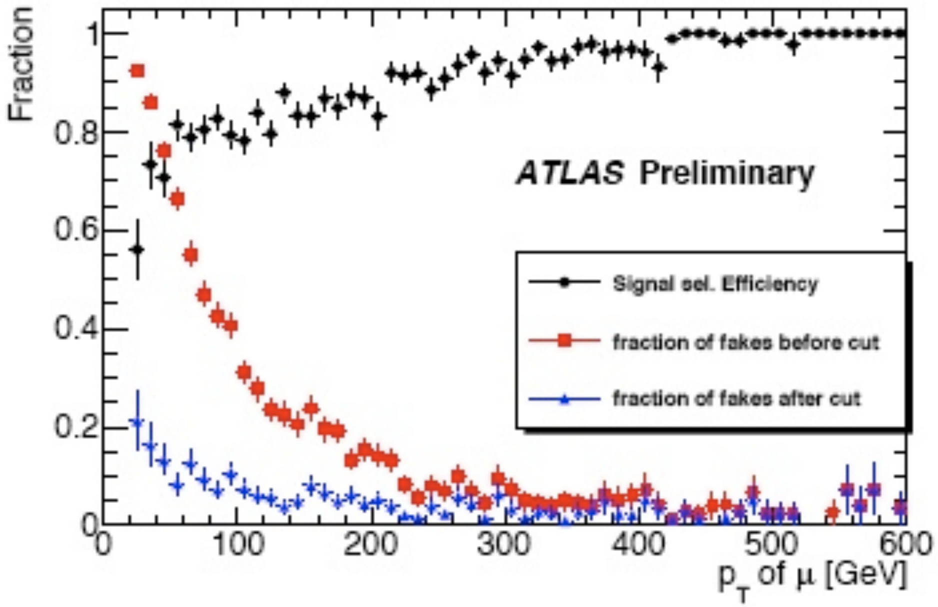
Semileptonic Decays: Muons

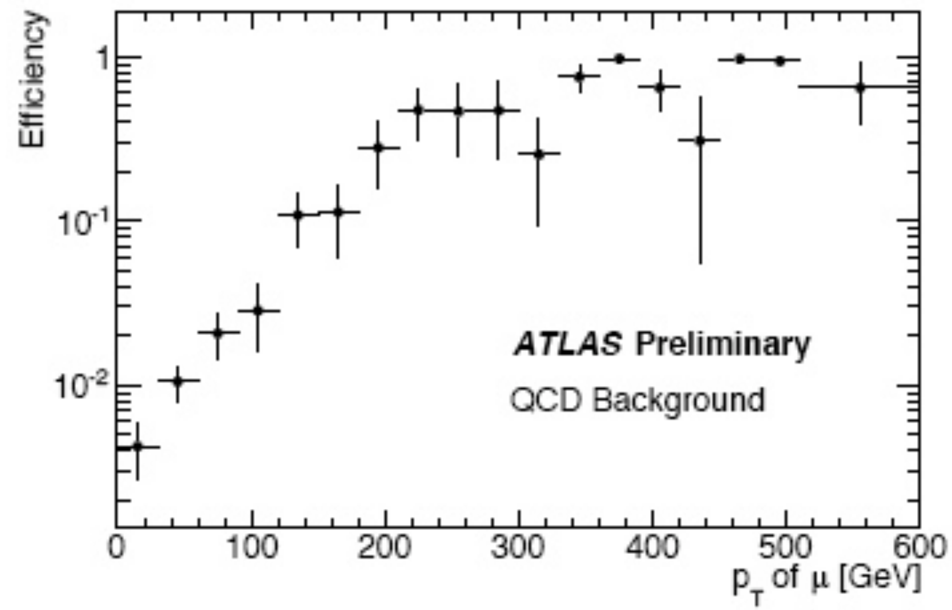
- Require a good muon, $p_T > 20$ GeV, $|\eta| < 2.5$, and a $p_T > 200$ GeV jet within $\Delta R=0.6$ (call it "*b*-jet")
- Reduce "fakes" from b/c-decays (or other decays in flight):
  - Isolation not useful (signal muon close to *b* from top decay)
  - Two new variables (better than increase in muon 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].


ATLAS Preliminary
Signal
Combinatoric Background
QCD Background
Apply a "diagonal" cut
y_μ [GeV]
x_μ

- "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

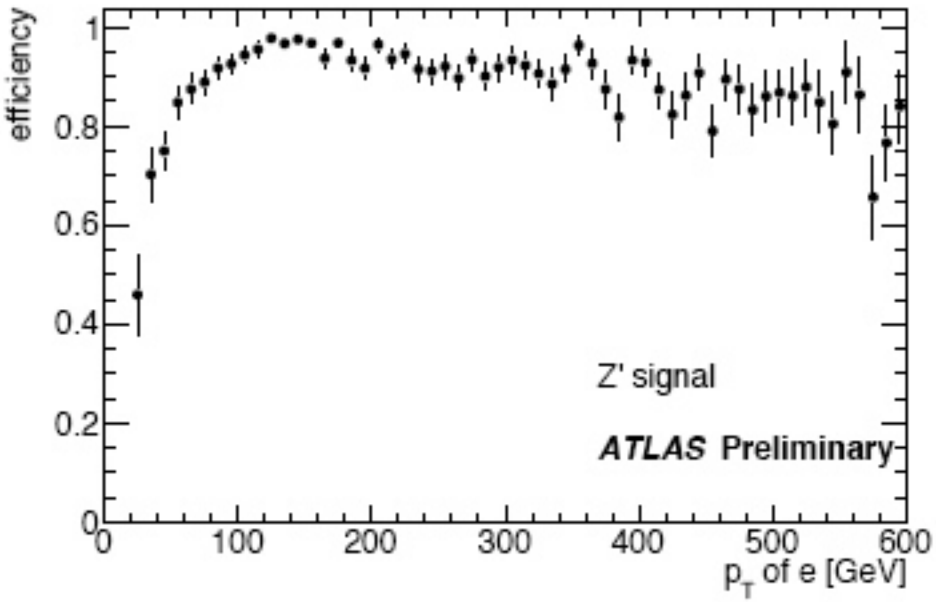


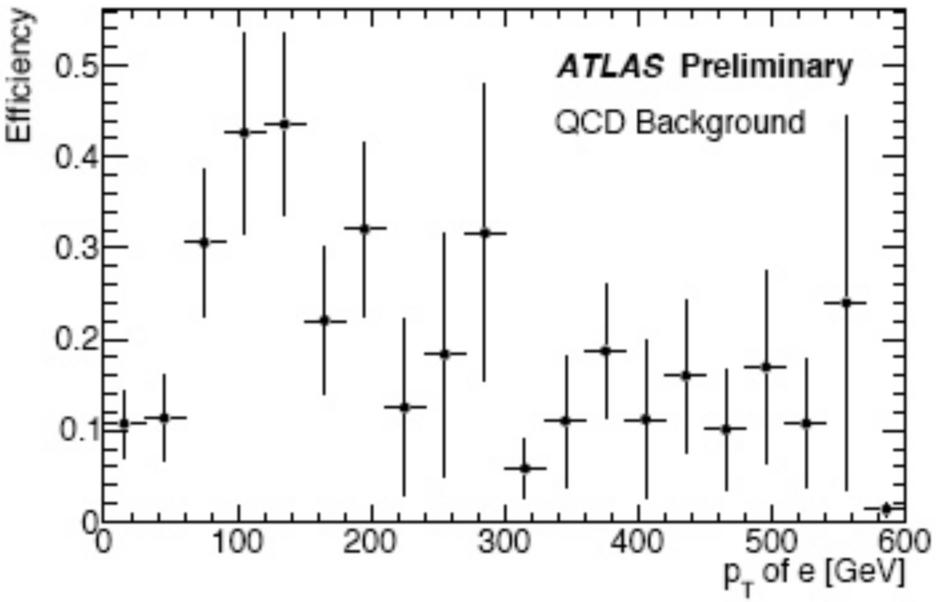


Semileptonic Decays: Electrons

- 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 ΔR=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:



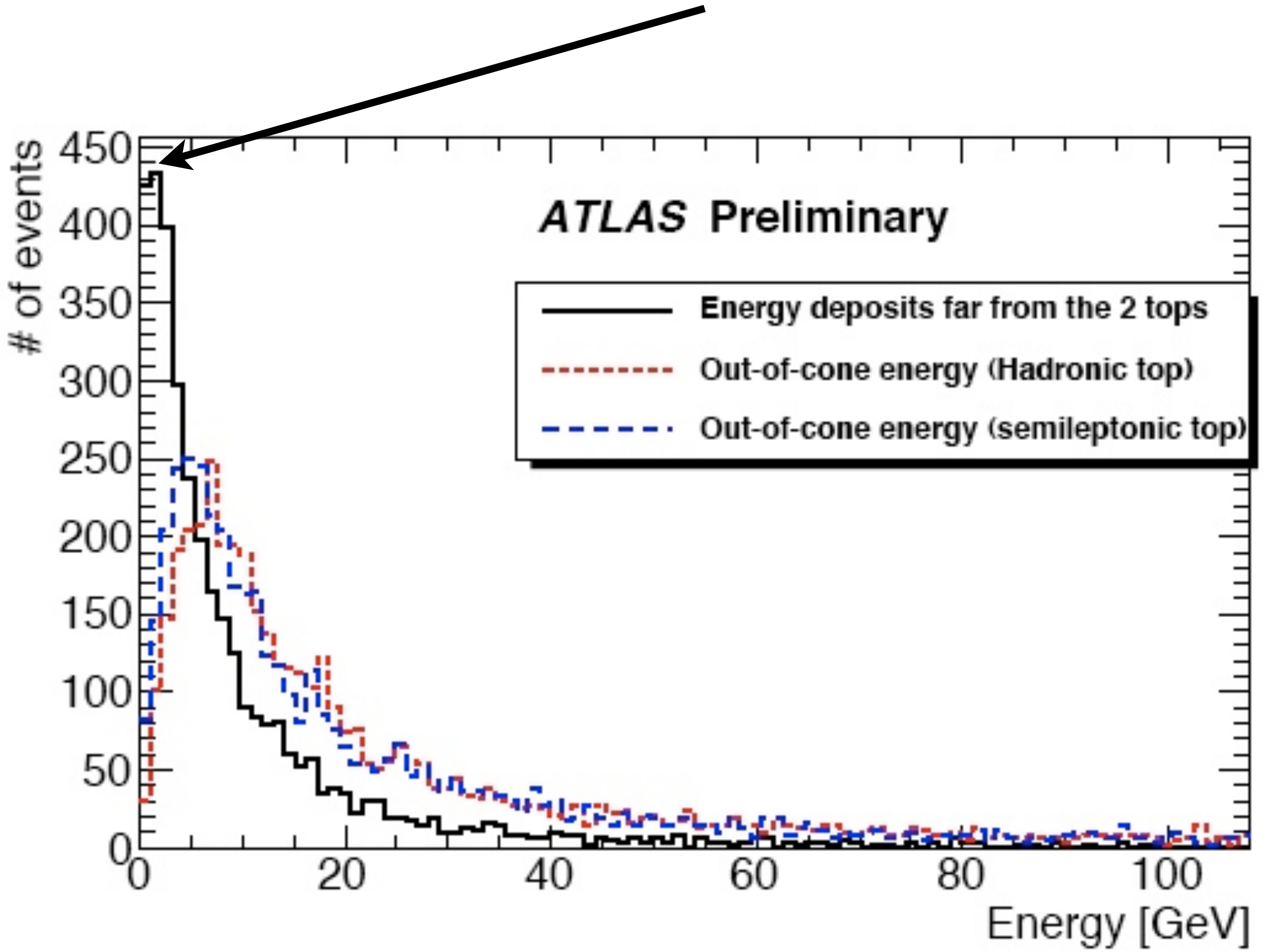


- Of course, preselection has very large impact on multijet background!

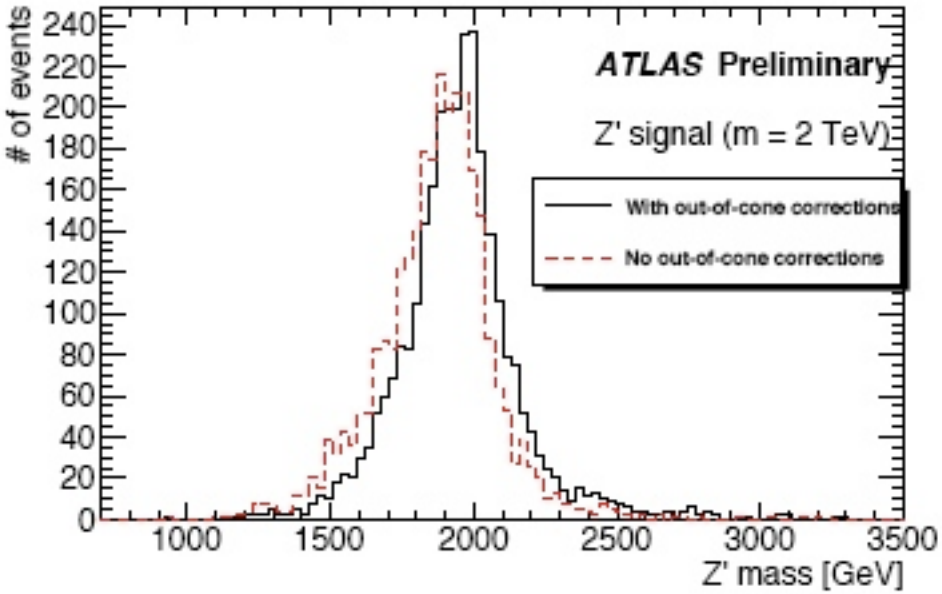
Z' Mass Reconstruction

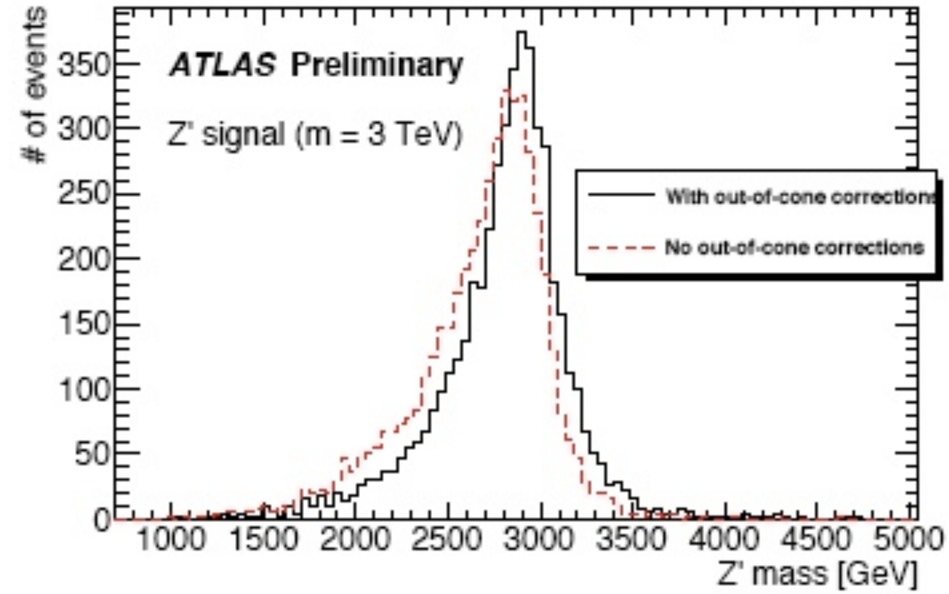
- W mass constraint to determine neutrino p_z (take smallest value, or real part of imaginary solution)
  - Require $\Delta R(\nu,\ell) < 1.0$
- Apply "local" out-of-cone energy correction:
  - Use cone 0.7 "topocluster" jets
  - Add topoclusters in $0.7 < R < 1.2$ to jet
  - Reasonable? Look for energy 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

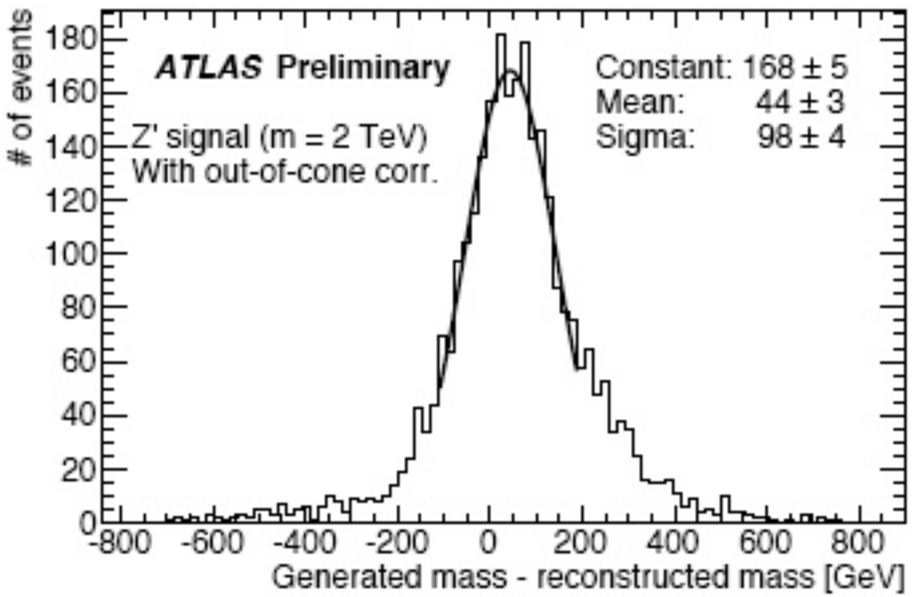


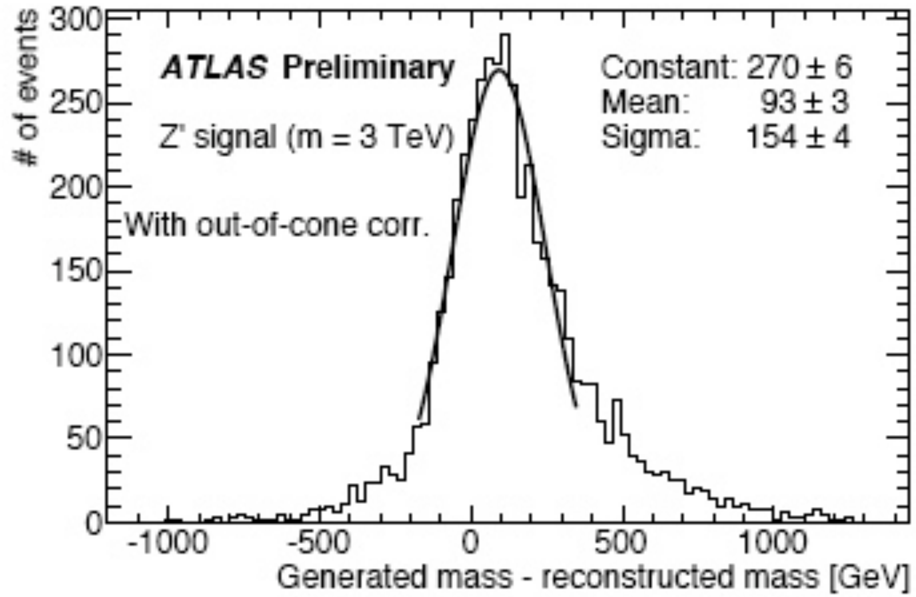


- Correction helps peak, but does not improve tails!

Z’ Mass Resolution

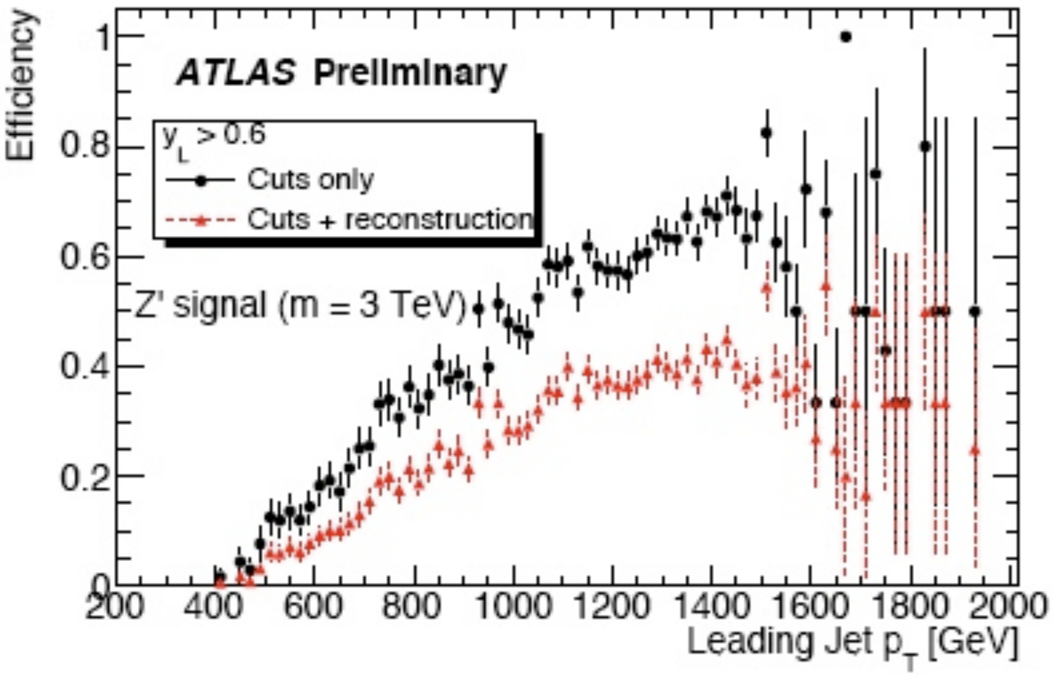
- SSM Z’ at this mass narrower than detector/method resolution, but not negligibly so:

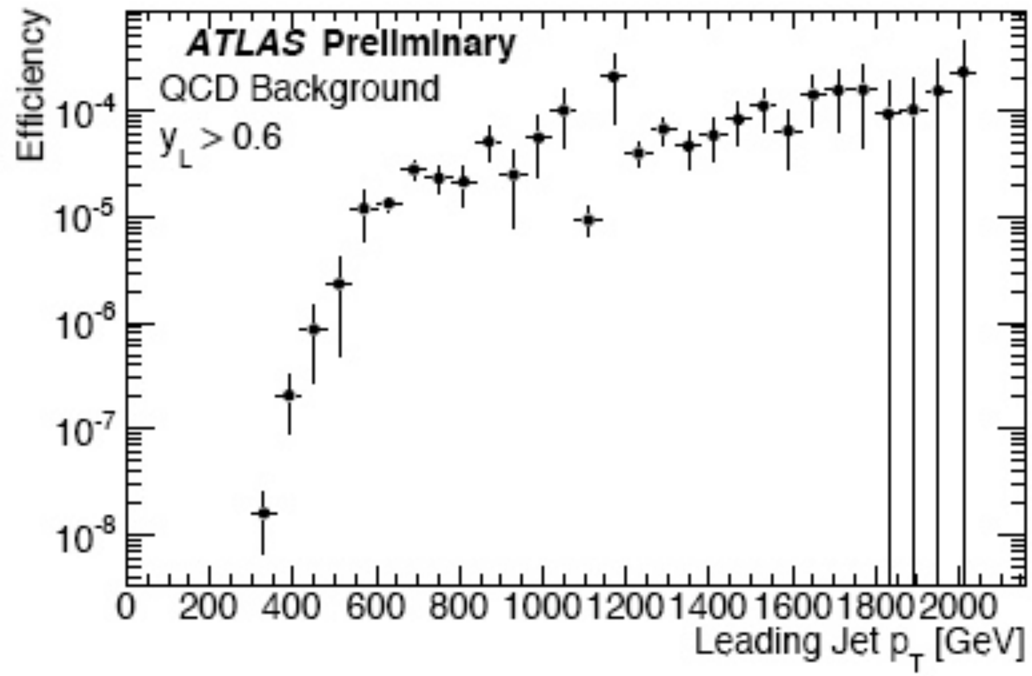




Also still have a substantial offset!
⇒ work to do!

Selection Efficiency

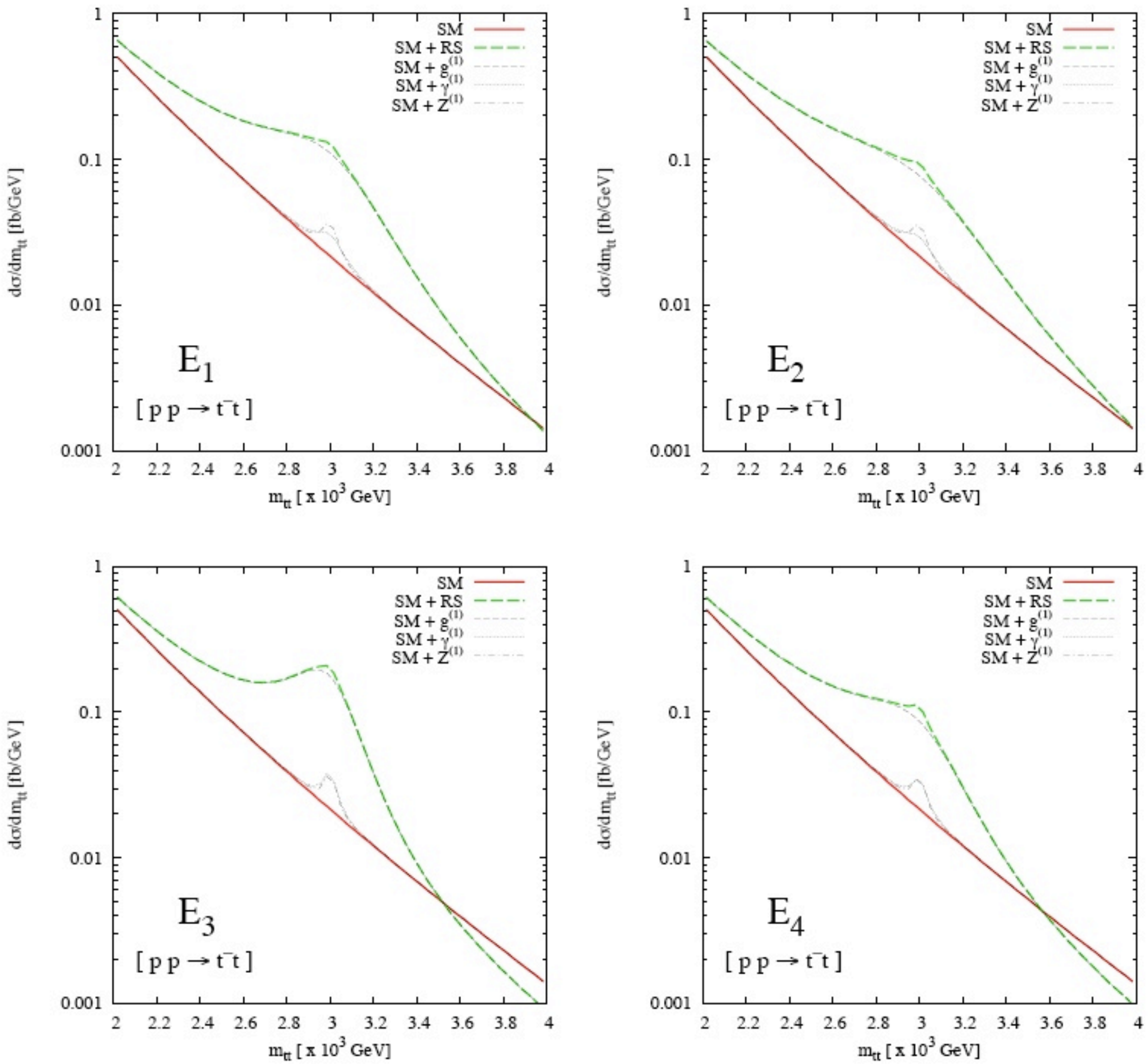




- For multijet background, rate determined by factorizing leptonic and hadronic rejection
  - (Limited MC statistics)

- ATLAS ℓ+jets result was used to estimate sensitivity to a specific RS scenario:

Djouadi, Moreau, Singh: Nucl.Phys.B797:1-26,2008



Use ATLAS study, apply efficiencies and smear resonance with ATLAS mass resolution

GB, G. Moreau, R. Singh in Les Houches 2009: **arXiv:1005.1229**

Signal Model	Integrated Luminosity for 95% C.L. Exclusion (fb^{-1})
E1 + SM	2.5
E2 + SM	5.4
E3 + SM	1.8
E4 + SM	6.7

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

Why you should be wary of existing background estimates...

GB: "I wonder what the cross section for $t\bar{t} + \mathbf{6jets}$ is."

FK: "45 Picobarn!"[a]

GB: "Oh!"

To be continued ...

Les Houches 2009

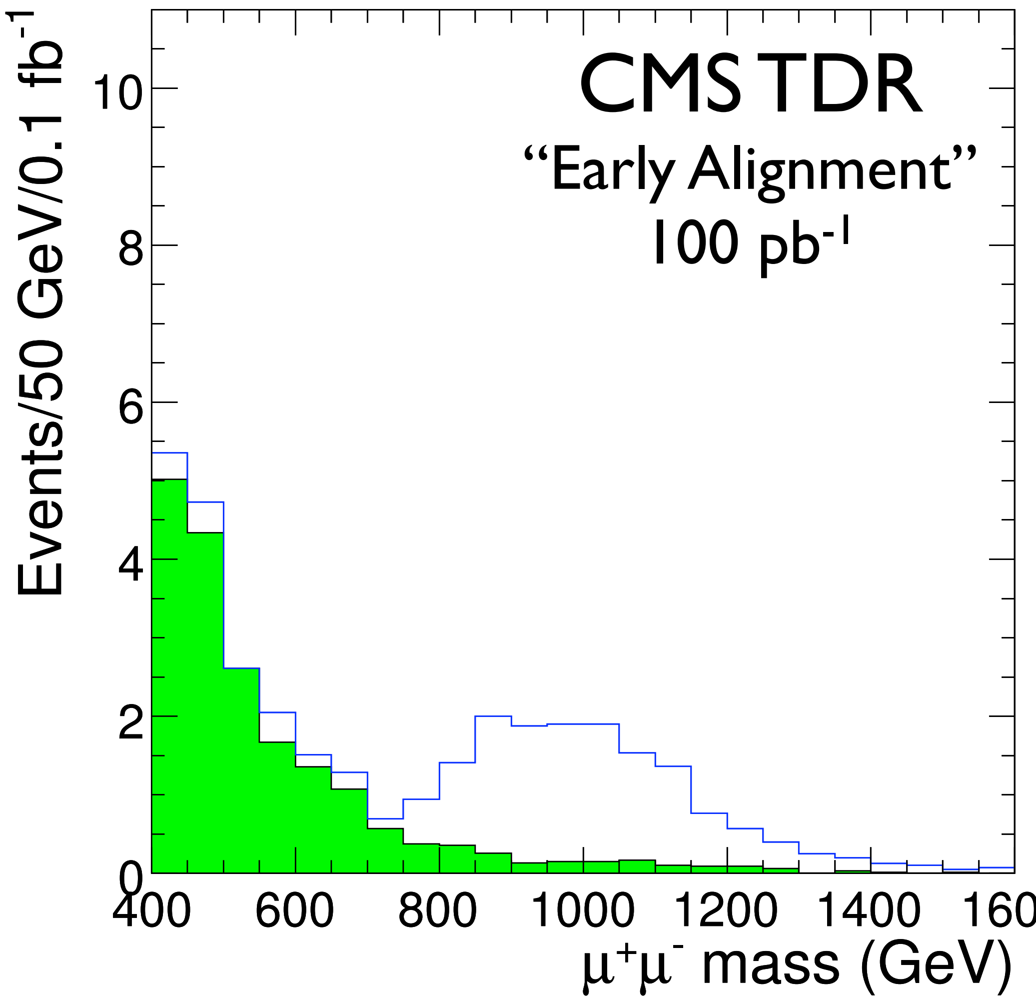
[a] see arXiv:0808.3674 [hep-ph]

Thanks

(and mainly: stay critical of what you're told!
and more important: how many olives on the trees?)

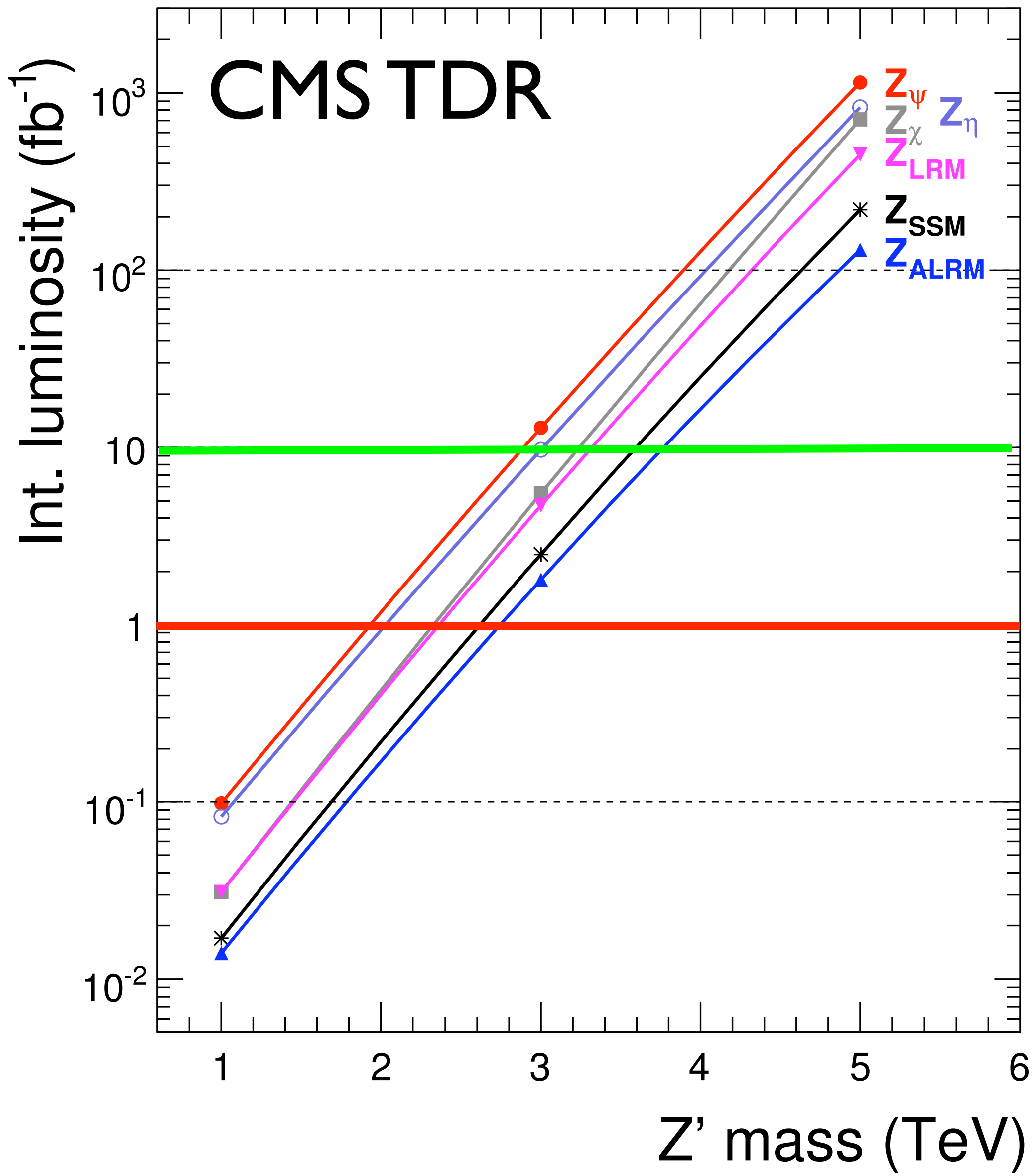
Z' → μμ: Early Potential

- 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)



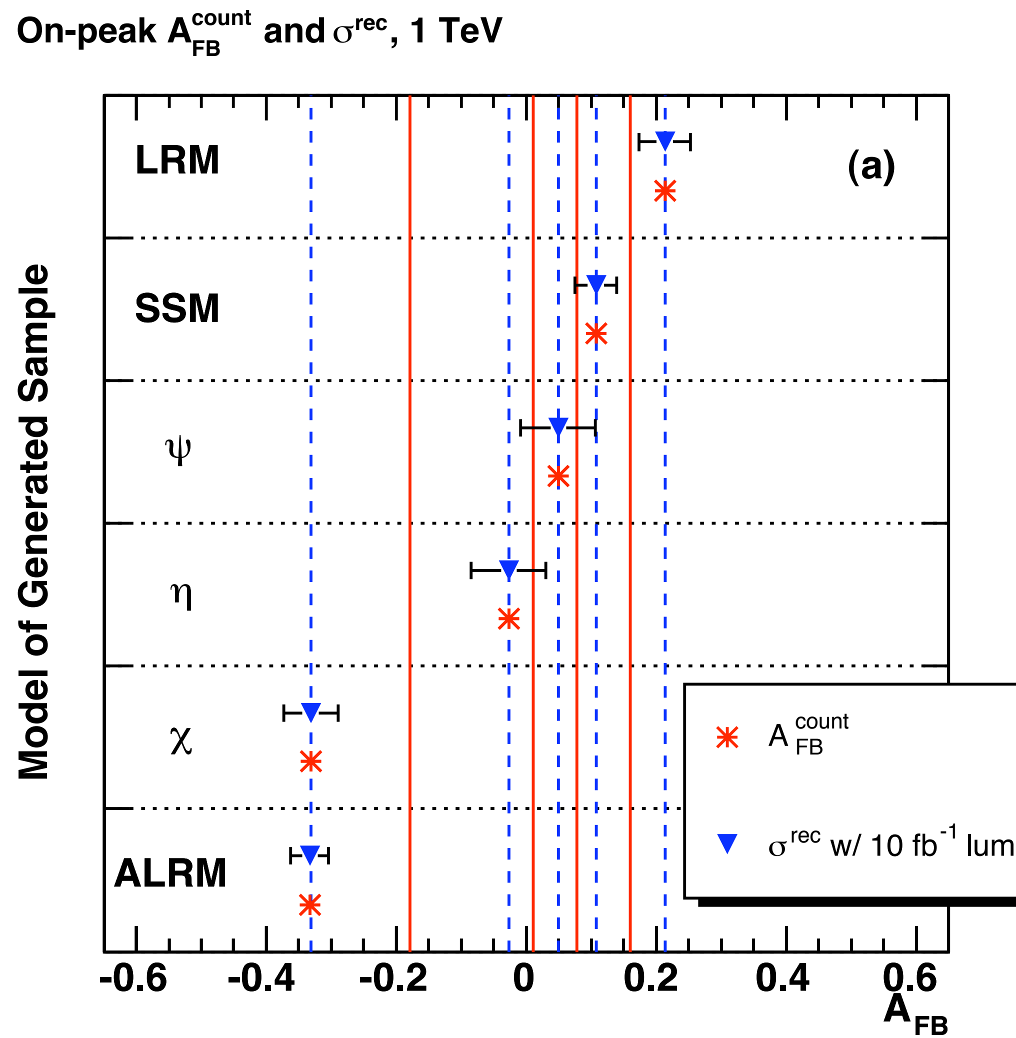
Z' → μμ Reach

- 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

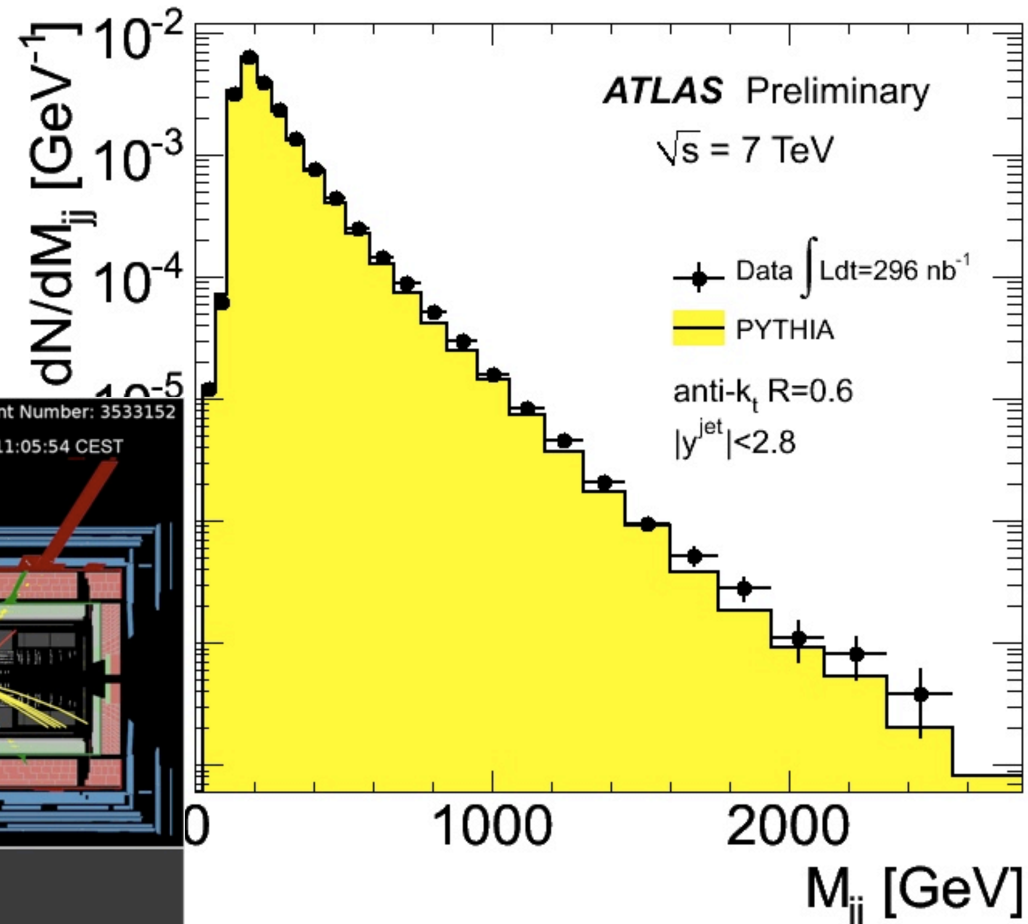
- Angular distribution gives excellent handle on g_V, g_A for various fermions
  - Charm may be possible
- This will come after an initial determination of branching ratios (obviously)
  - Complementary information in determining nature of resonance

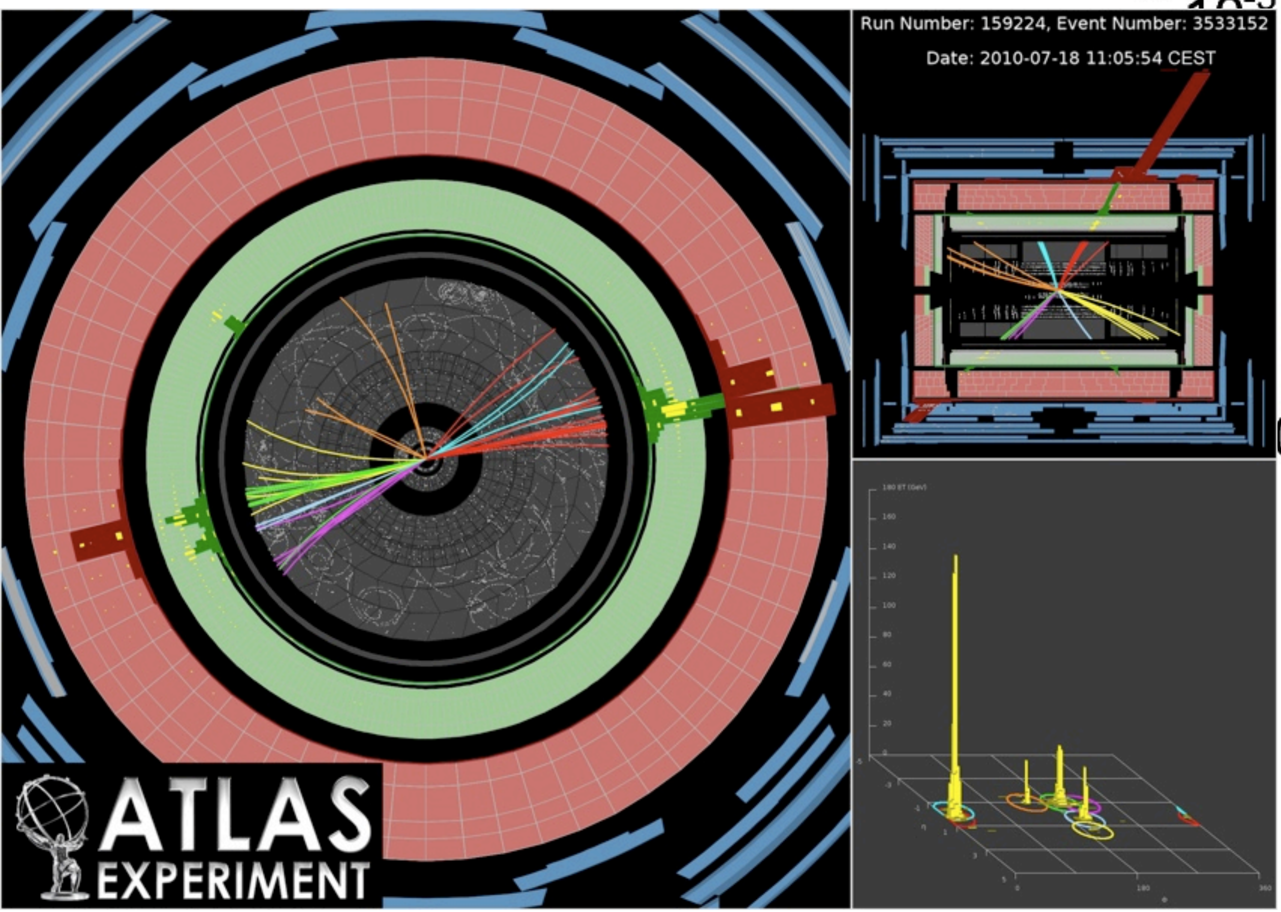


CMS Note 2005/022

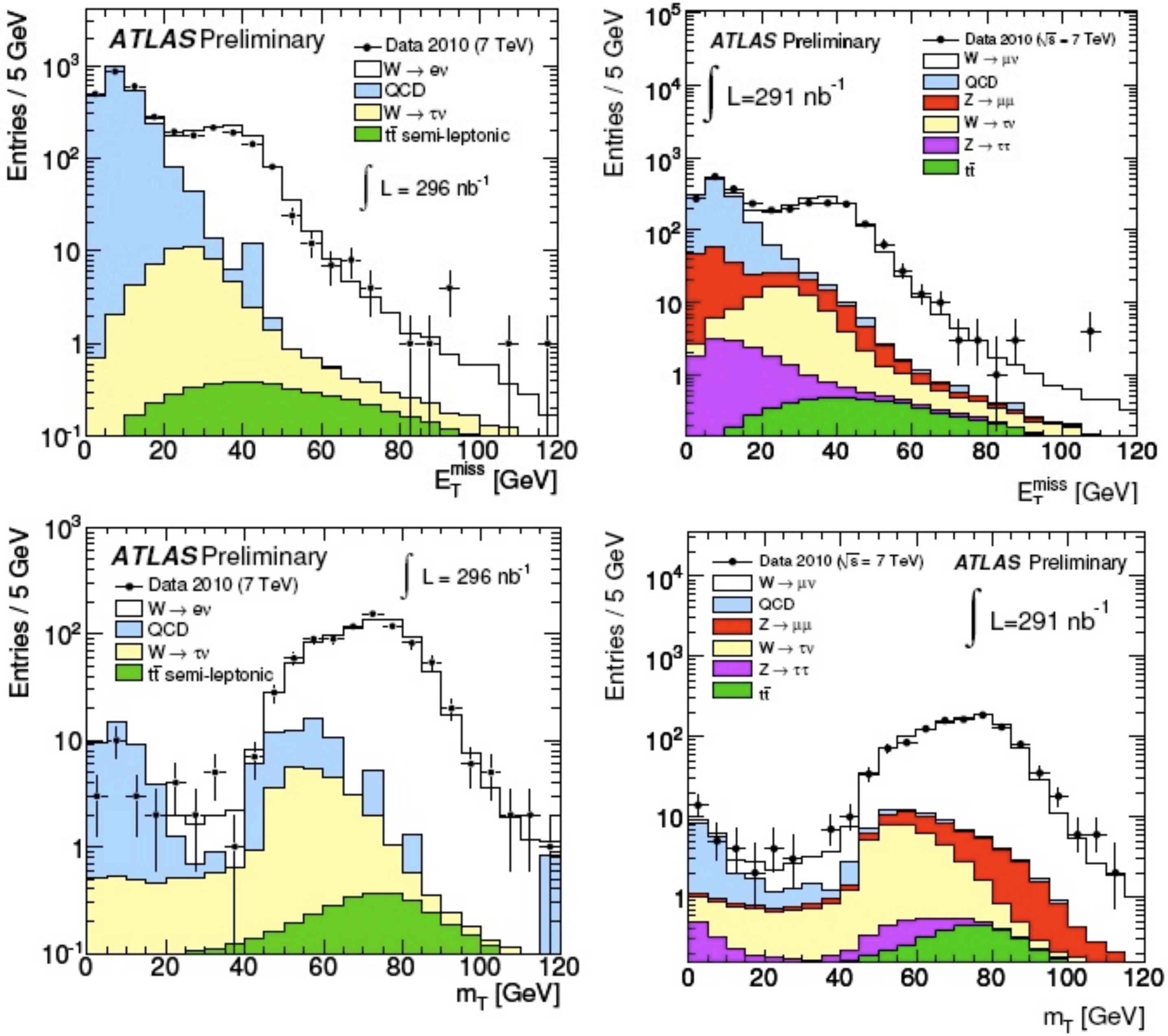
Highest Energy Jets Ever

- At hadron colliders

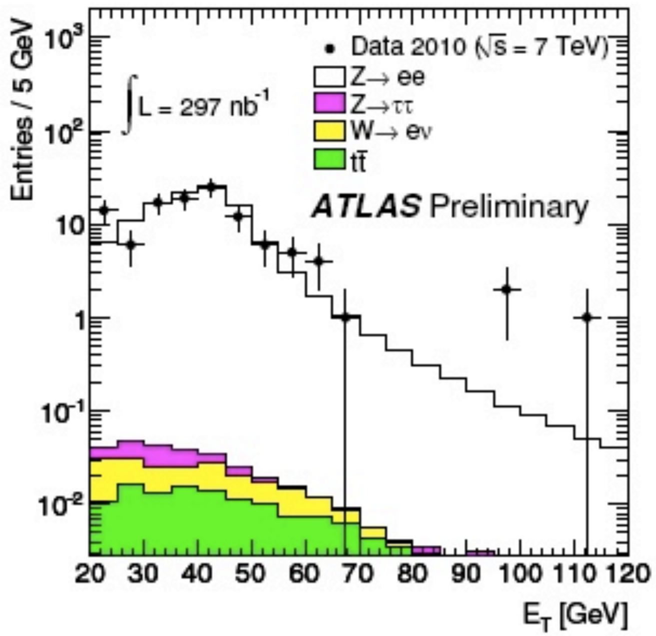




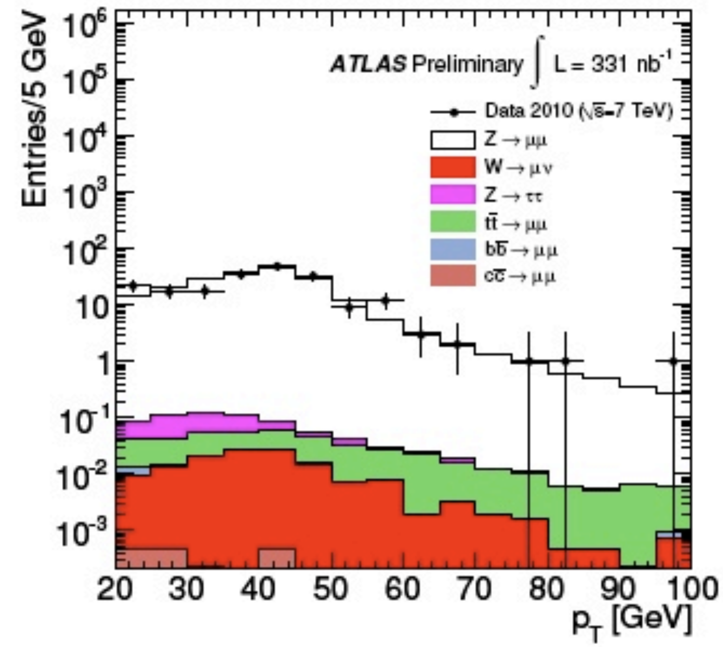
More W’s


ATLAS Preliminary
Data 2010 (7 TeV)
W → eν
QCD
W → τν
tt̄ semi-leptonic
∫ L = 296 nb-1
Entries / 5 GeV
E_T^miss [GeV]
Data 2010 (√s = 7 TeV)
W → μν
Z → μμ
Z → ττ
tt̄
∫ L=291 nb-1
m_T [GeV]

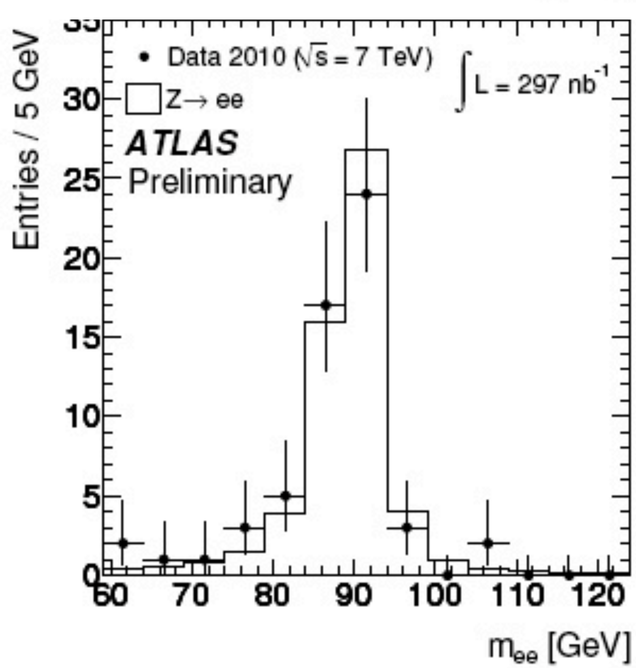
More Z’s



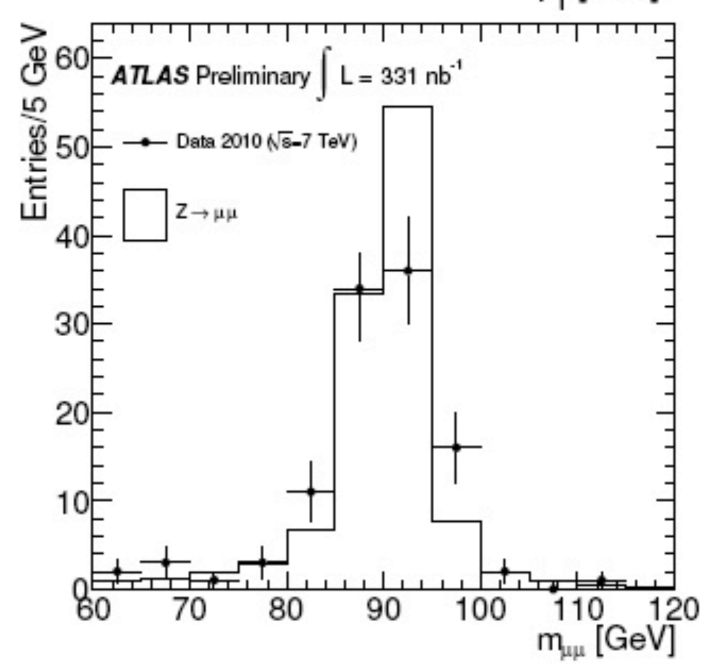
Data 2010 (√s = 7 TeV)
Z→ ee
Z→ττ
W→ eν
tt̄
∫L = 297 nb⁻¹
ATLAS Preliminary
Entries / 5 GeV
E_T [GeV]



ATLAS Preliminary ∫L = 331 nb⁻¹
Data 2010 (√s=7 TeV)
Z → μμ
W → μν
Z → ττ
tt̄ → μμ
bb̄ → μμ
cc̄ → μμ
Entries/5 GeV
p_T [GeV]



Data 2010 (√s = 7 TeV)
Z→ ee
ATLAS
Preliminary
∫L = 297 nb⁻¹
Entries / 5 GeV
m_ee [GeV]



ATLAS Preliminary ∫L = 331 nb⁻¹
Data 2010 (√s=7 TeV)
Z → μμ
Entries/5 GeV
m_μμ [GeV]