High Energy Physics

Top Physics

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Outline

- Top quark introduction
- What is interesting about top physics (brief)
- Top Physics program as CMS
  - Emphasis on startup, status report

What is the Top Quark?

$$\text{Quarks:} \quad \begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix} \quad \begin{pmatrix} t \\ b \end{pmatrix}$$

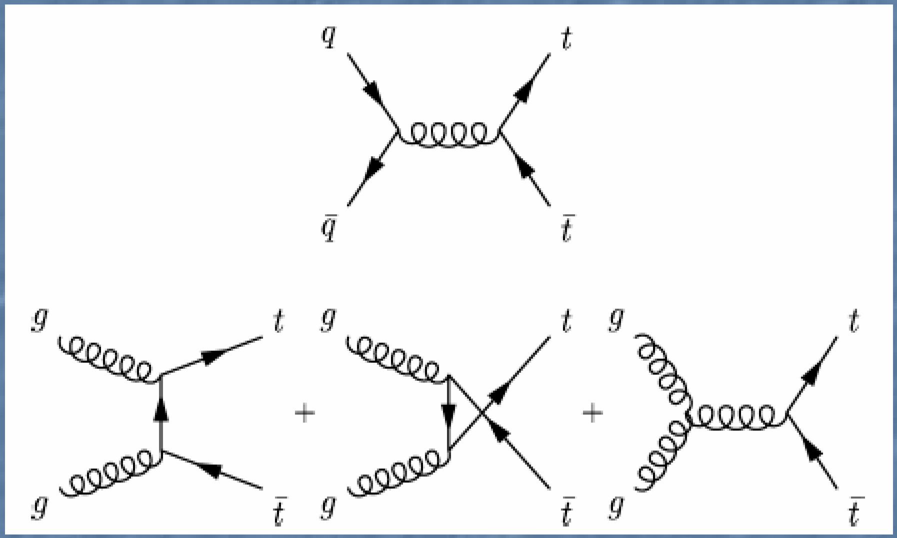
$$\text{Leptons:} \quad \begin{pmatrix} \nu_e \\ e \end{pmatrix} \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \quad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}$$

- Heaviest fundamental particle
  - $M_{top}=172.6 \pm 1.4$ GeV
- Weak isospin partner of the b-quark, a heavier version of the up-quark
  - S=½, Q=2/3, I_3=½
- Completes the SM picture of quarks and leptons
  - 3rd generation

What do we know about the top quark?

- Everything that we know directly about the top quark comes from Tevatron experiments (CDF & D0)
- Was discovered in 1994-5
- Only a few hundreds top quark events have been studied

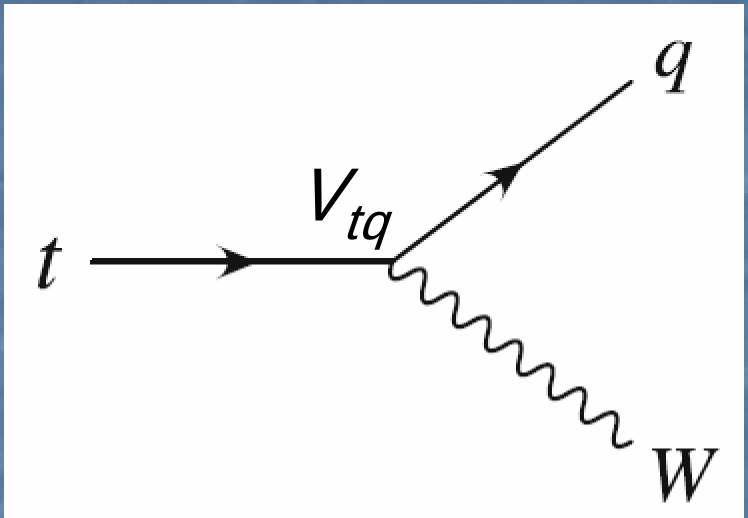
How is the top quark produced?



dominant at TeVatron

dominant at LHC

How does the top quark decay?



- Because V_{tb} ~ 1, almost always t→Wb
- The lifetime is short enough that the top quark decays before hadronization (free quark decay)
- The W is real
  - Can decay W→lν (l=e,μ,τ), BR~1/9 per lepton
  - Can decay W→q$\bar{q}$, BR~2/3

How does a $t\bar{t}$ pair decay?

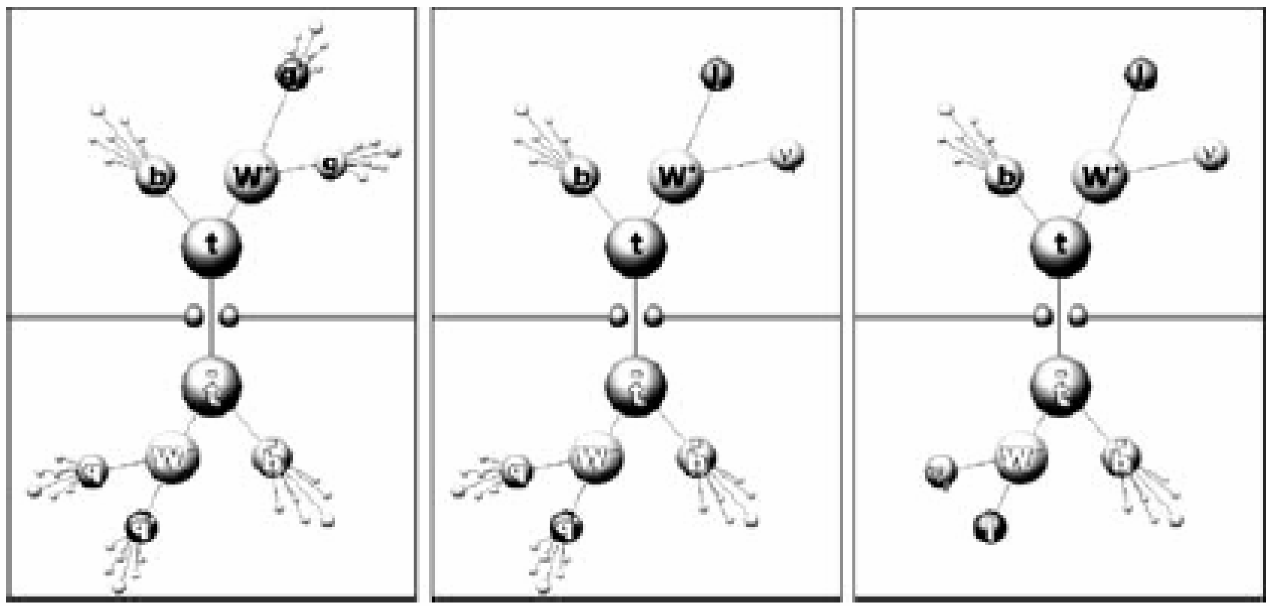


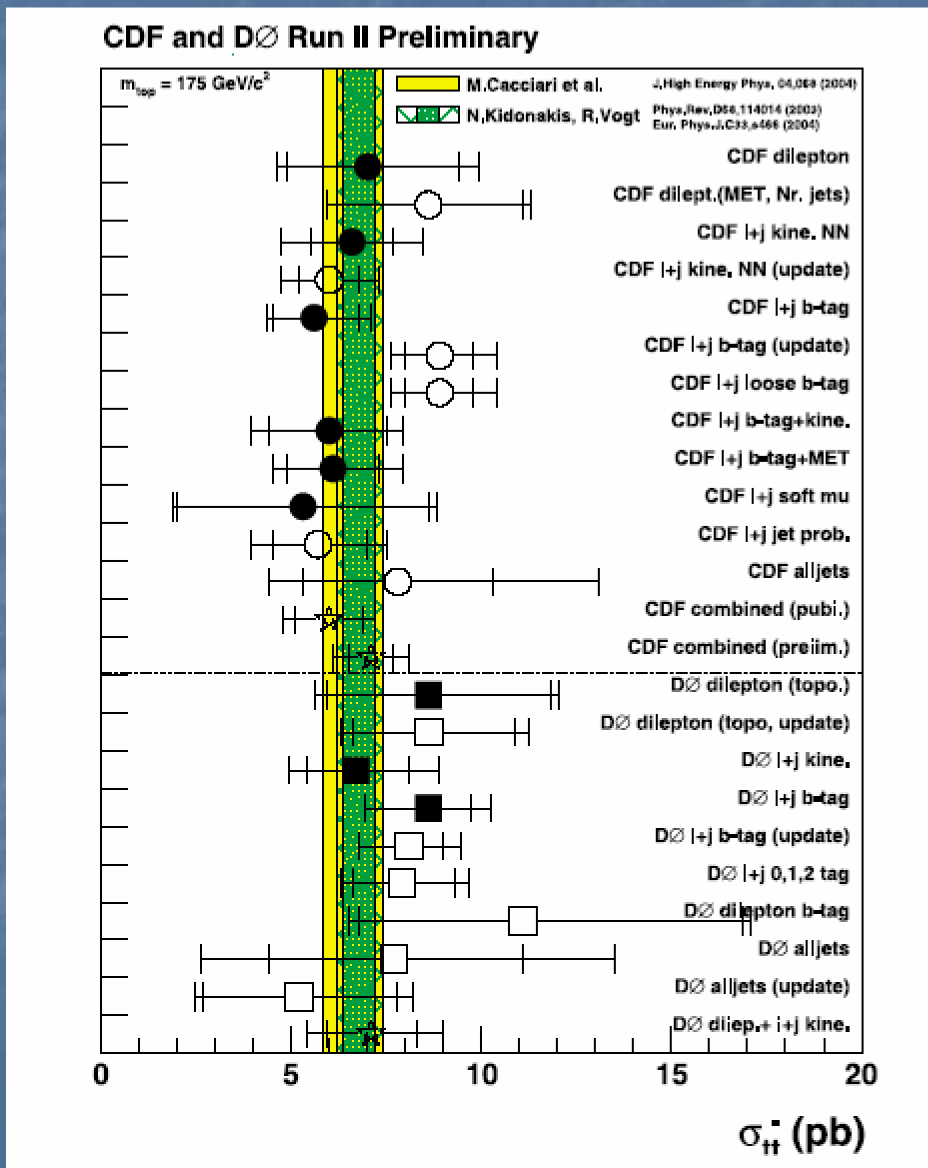
Fig. 22. Schematic diagrams of the three $t\bar{t}$ decay channels: *Left* (A) the alljets channel; *middle* (B) the lepton + jets channel; *right* (C) the dilepton channel

A. $t\bar{t} \to W^{+}bW^{-}\bar{b} \to q\bar{q}'bq''\bar{q}'''\bar{b}$, (46.2%) Hadronic

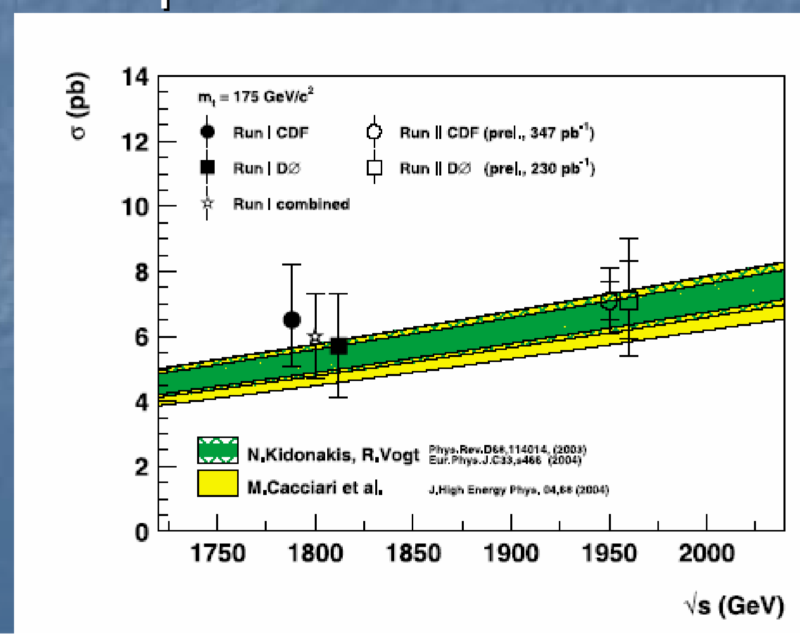
B. $t\bar{t} \to W^{+}bW^{-}\bar{b} \to q\bar{q}'b\ell\bar{\nu}_{\ell}\bar{b} + \bar{\ell}\nu_{\ell}bq\bar{q}'\bar{b}$, (43.5%) l+jets

C. $t\bar{t} \to W^{+}bW^{-}\bar{b} \to \bar{\ell}\nu_{\ell}b\ell'\bar{\nu}_{\ell'}\bar{b}$, (10.3%) dilepton

$t\bar{t}$ cross-section at the Tevatron



- Not the very latest
- Bottom line: agrees wit QCD calculation
- Everything else that we know about the $t\bar{t}$ process, also agrees with expectations



Interesting Physics with Top Quark

- Mass
- Kinematical properties
  - Is there a $X \rightarrow t\bar{t}$?
  - W polarization
  - Spin Correlations
- Rare Decays
- Single top
- More generally: top quark unusually heavy lepton. Maybe there is something different about it? (Yukawa Coupling~1).

Top Mass

- A very difficult measurement
- Important not just per-se, but as big component of precision EWK fit

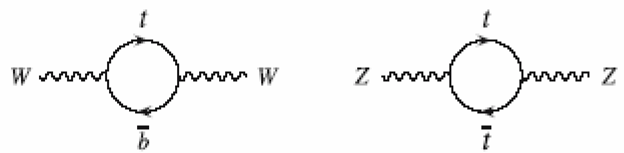


Fig. 8. Virtual top quark loops contributing to the W and Z boson masses

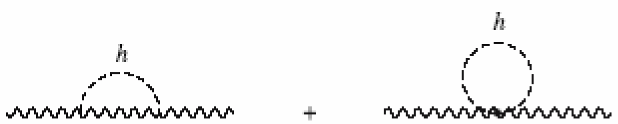
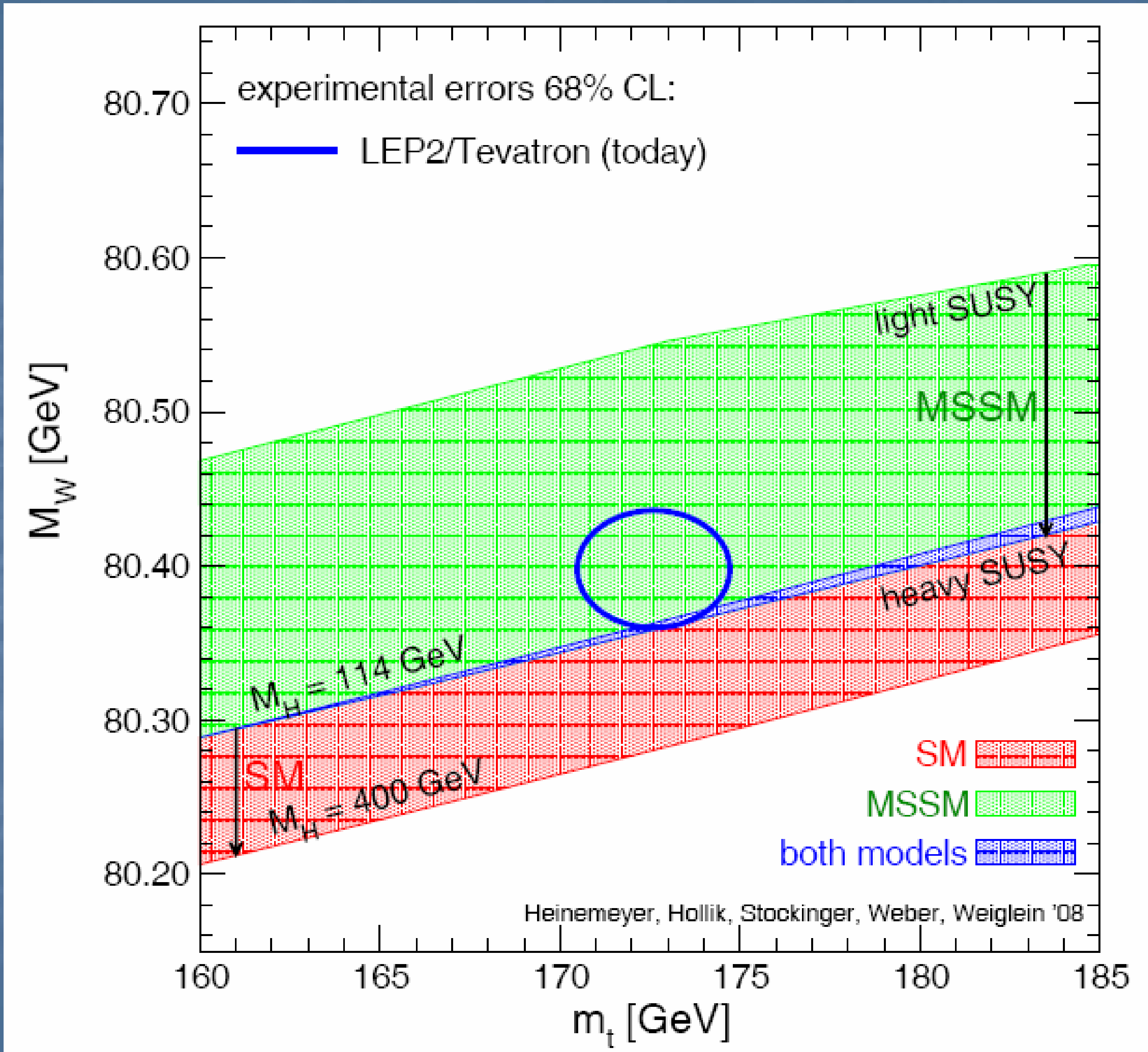


Fig. 9. Virtual Higgs boson loops contributing to the W and Z boson masses

$$m_W^2 = \frac{\frac{\pi\alpha}{\sqrt{2}G_F}}{\sin^2\theta_W(1-\Delta r)},$$

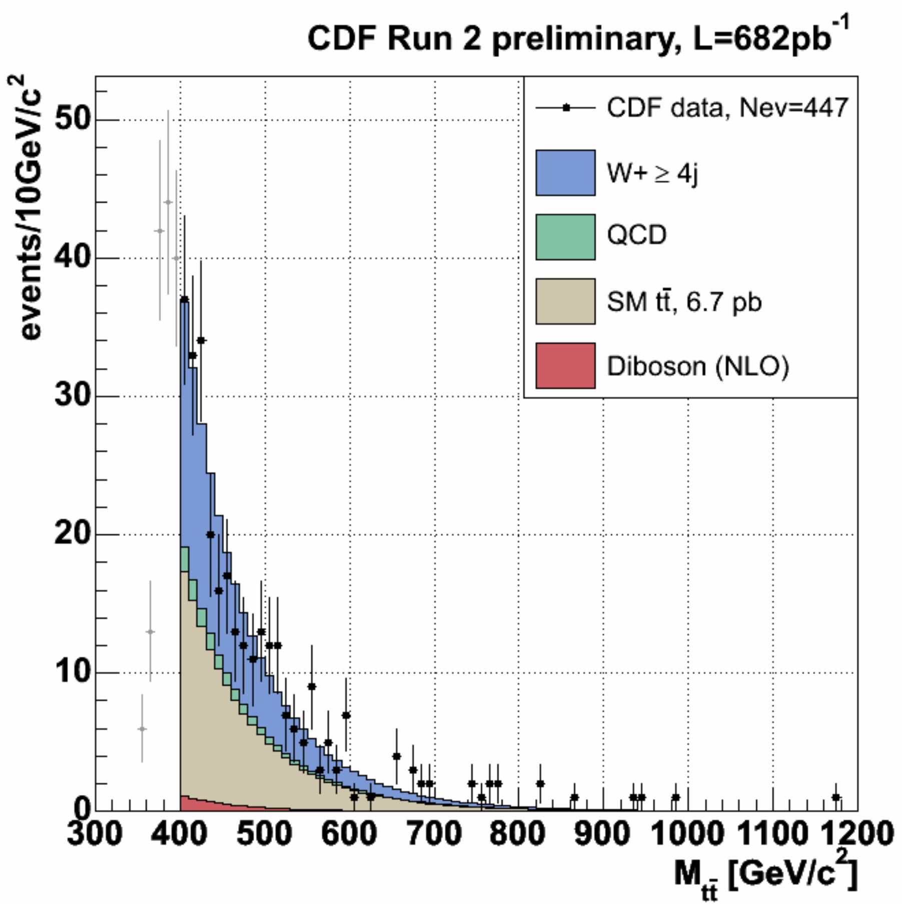
$$(\Delta r)_{top} \simeq -\frac{3G_F}{8\sqrt{2}\pi^2\tan^2\theta_W} m_t^2 .$$

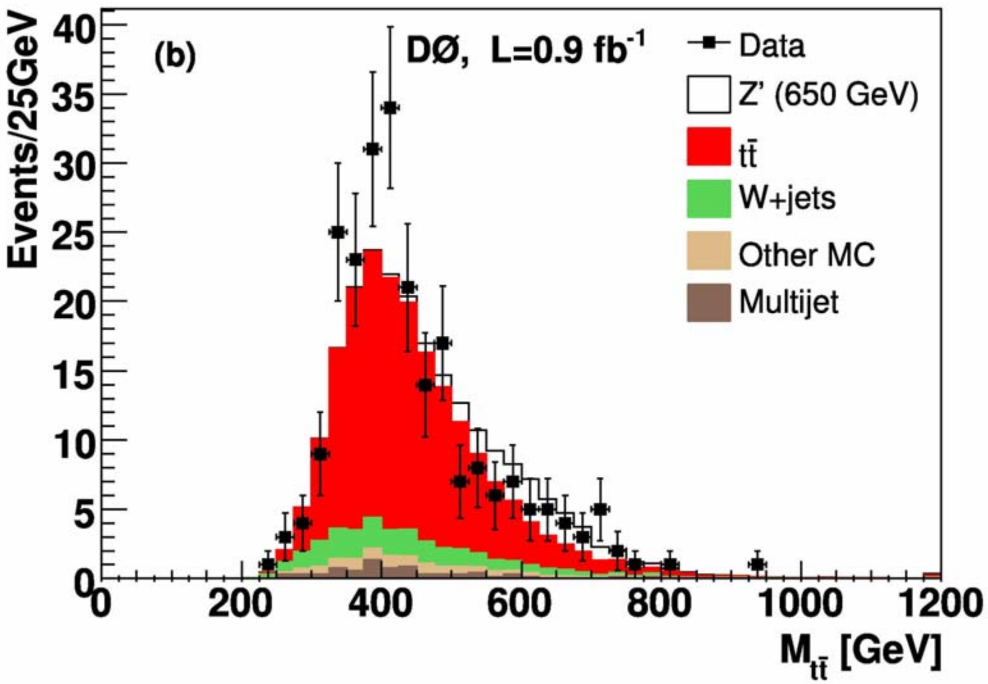
$$(\Delta r)_{Higgs} \simeq \frac{3G_F m_W^2}{8\sqrt{2}\pi^2}\left(\ln\frac{m_H^2}{m_Z^2} - \frac{5}{6}\right) .$$


experimental errors 68% CL:
LEP2/Tevatron (today)
light SUSY
MSSM
heavy SUSY
M_H = 114 GeV
SM
M_H = 400 GeV
SM
MSSM
both models
Heinemeyer, Hollik, Stockinger, Weber, Weiglein '08
M_W [GeV]
m_t [GeV]
80.70
80.60
80.50
80.40
80.30
80.20
160
165
170
175
180
185

X→$t\bar{t}$

- A popular New Physics scenario
- No evidence so far



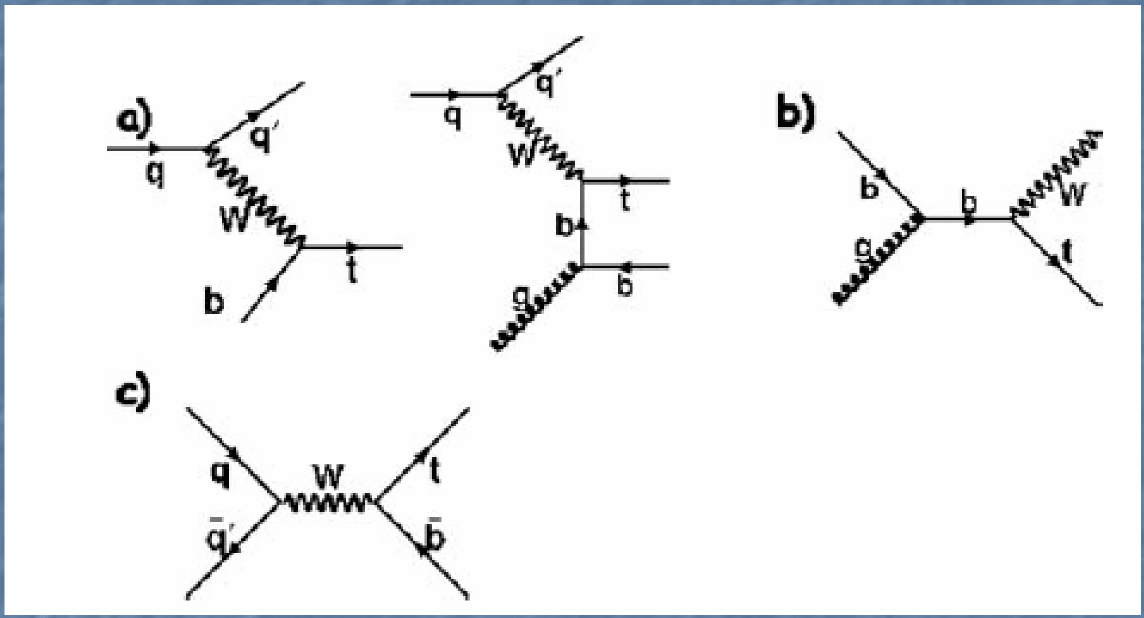


Angular distributions

- Measure fraction of longitudinally polarized Ws (= the Goldstone Boson degree of freedom) in top decay
  - SM predicts ~ 70%

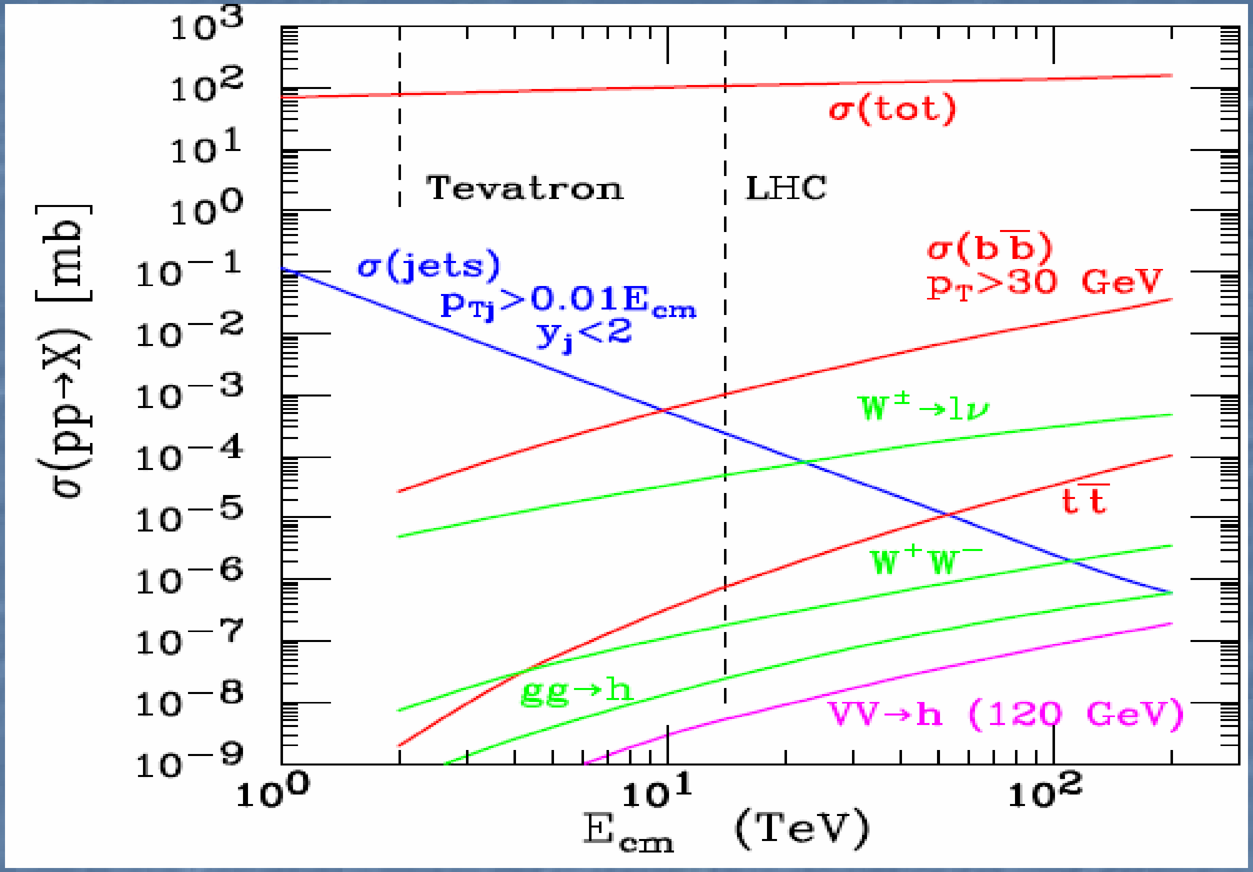
- Measure the spin correlations in production

Single top production



- Evidence starting to emerge from Tevatron

LHC



Compared to TeVatron, a top factory.
x100 the cross-section, much more luminosity

Top at CMS

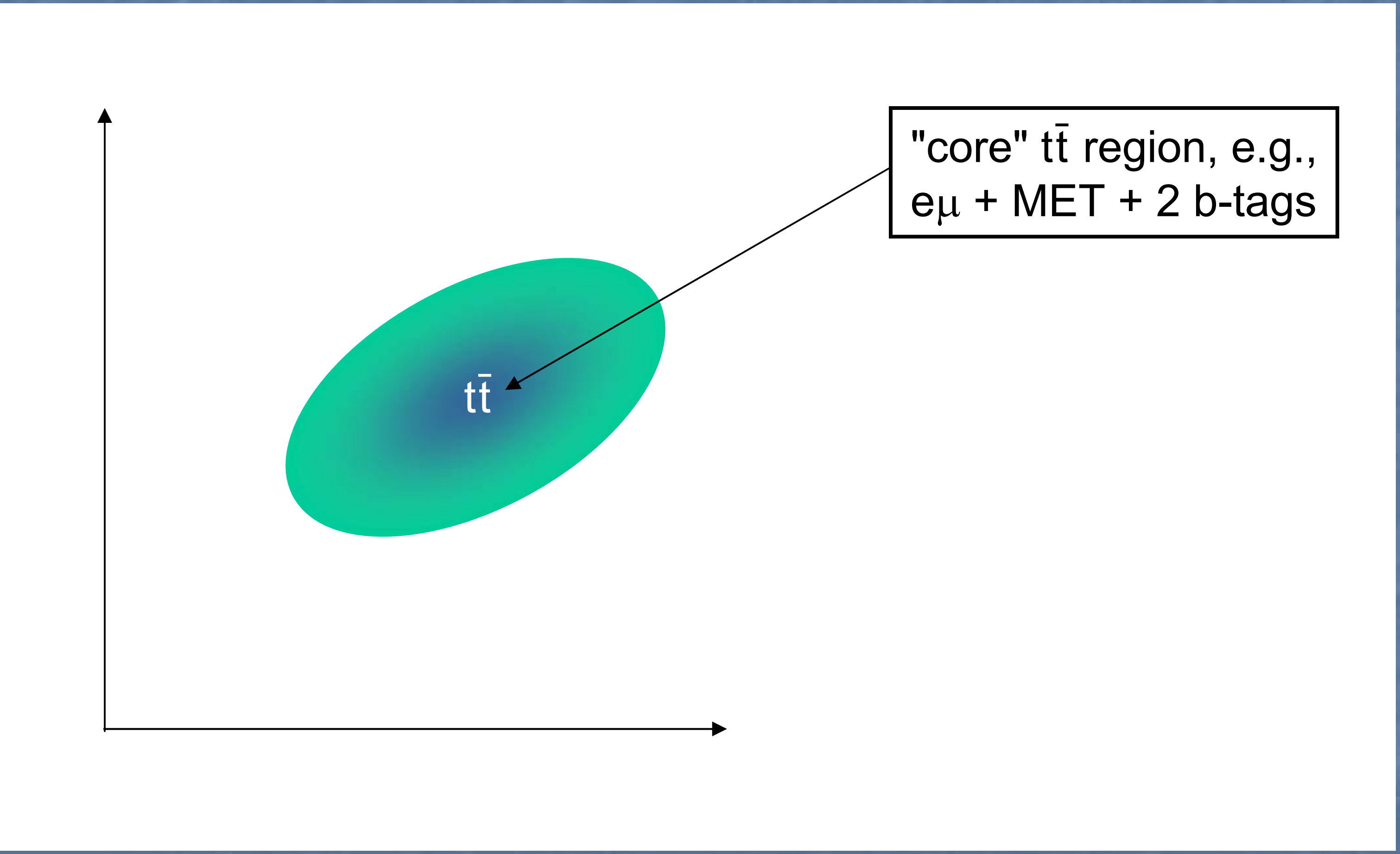
Several phases:

1. Establish $t\bar{t}$ at CMS
2. Basic study of $t\bar{t}$
   - Are we really seeing $t\bar{t}$? Is anything else in the $t\bar{t}$ sample
3. Top as a calibration tool
   - B-tagging, jet energy scale
4. Detailed studies, single top, etc

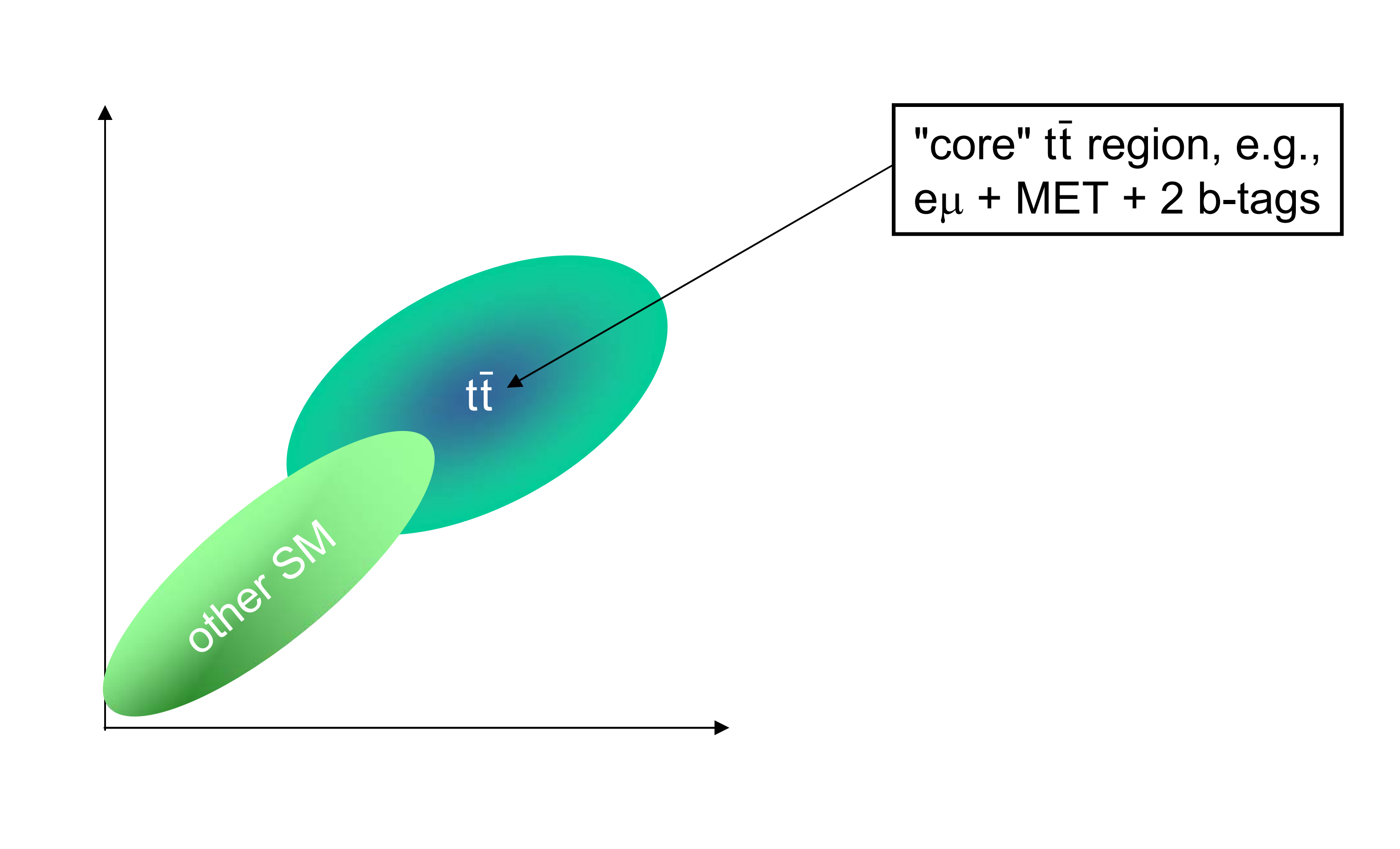
Establishing $t\bar{t}$ at CMS

- The mission of the LHC is to search for New Physics
- Initial $t\bar{t}$ studies should be in this context
  - Demonstrate understanding of SM and detector
    - $t\bar{t}$ Physics requires leptons, jets, MET, b-tags....
  - Measure $t\bar{t}$ cross-section
  - Measure kinematical properties
- Some of these measurements can be considered as searches themselves
  - There can be New Physics is the $t\bar{t}$ sample

- $t\bar{t}$ events live in some complicated multidimensional space of event requirements



- $t\bar{t}$ events live in some complicated multidimensional space of event requirements
- SM backgrounds to top (e.g. W+jets, Drell-Yan, QCD) populate a separate, but not completely disjointed region



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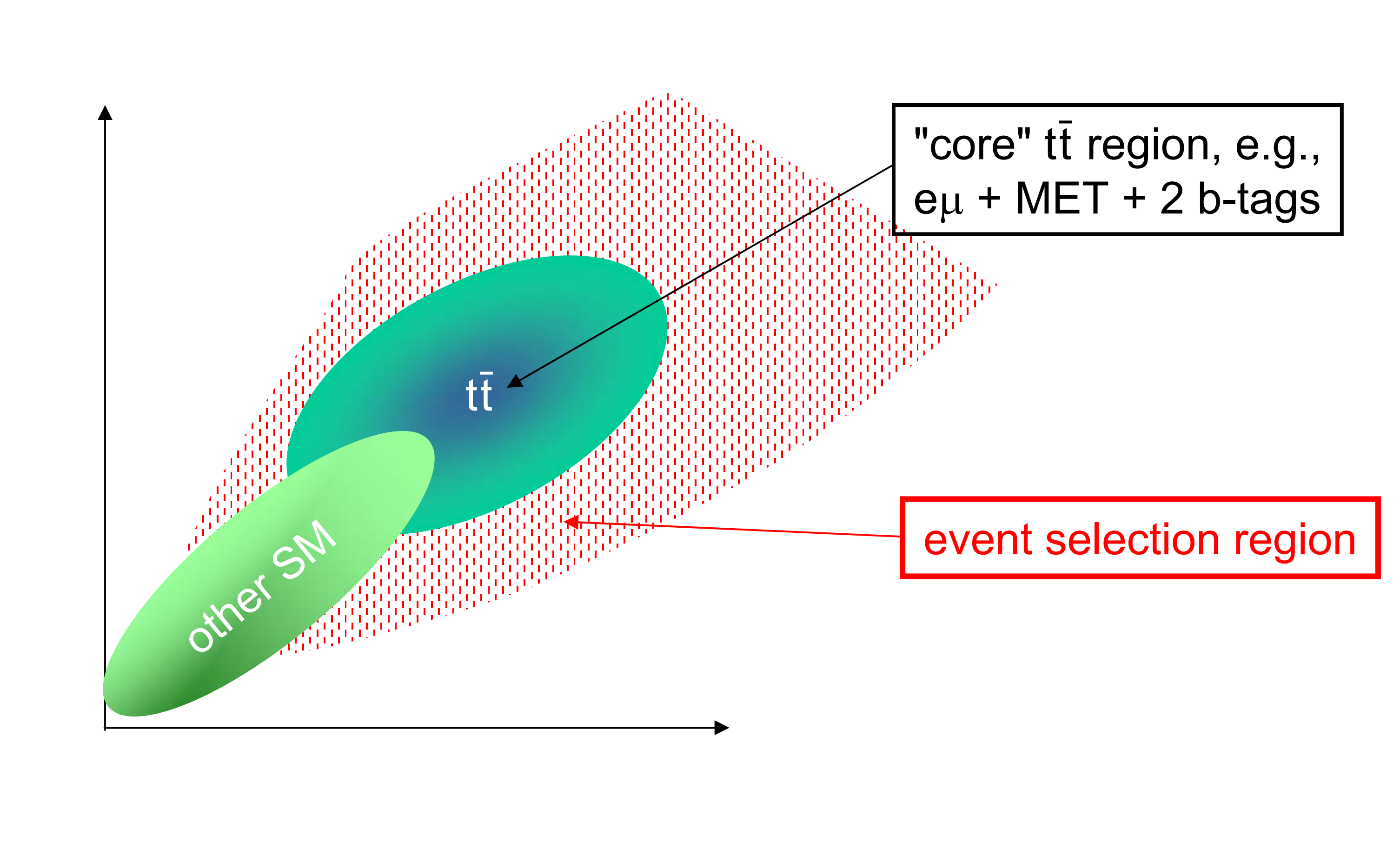


The basic event selection for $t\bar{t}$ cross-section-type analyses encompass a SM control region and is not limited to the core $t\bar{t}$ region

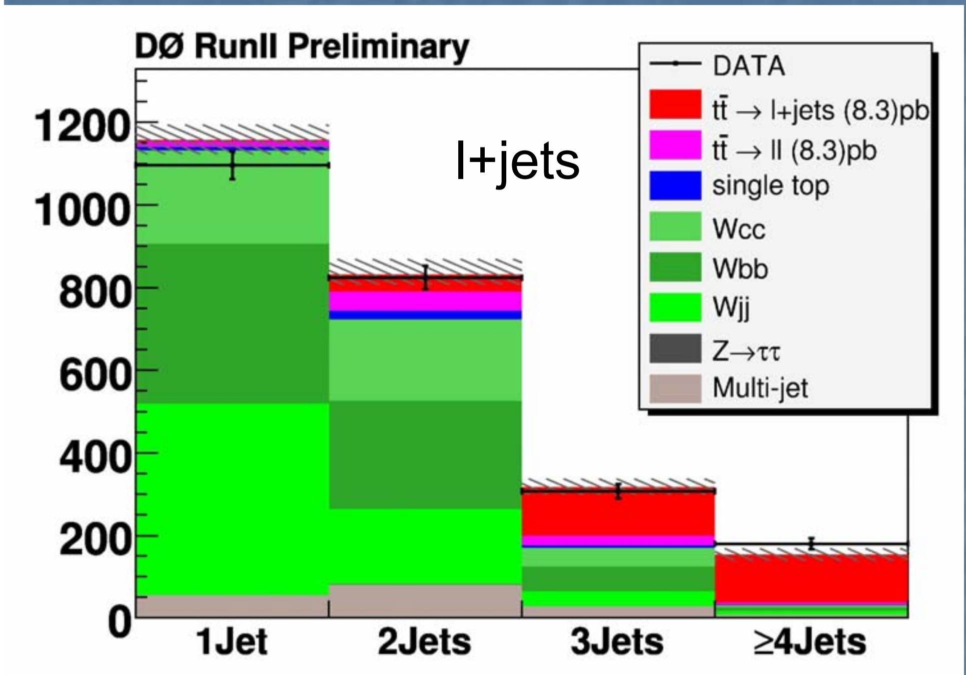
Event Selection for $t\bar{t}$ Analysis

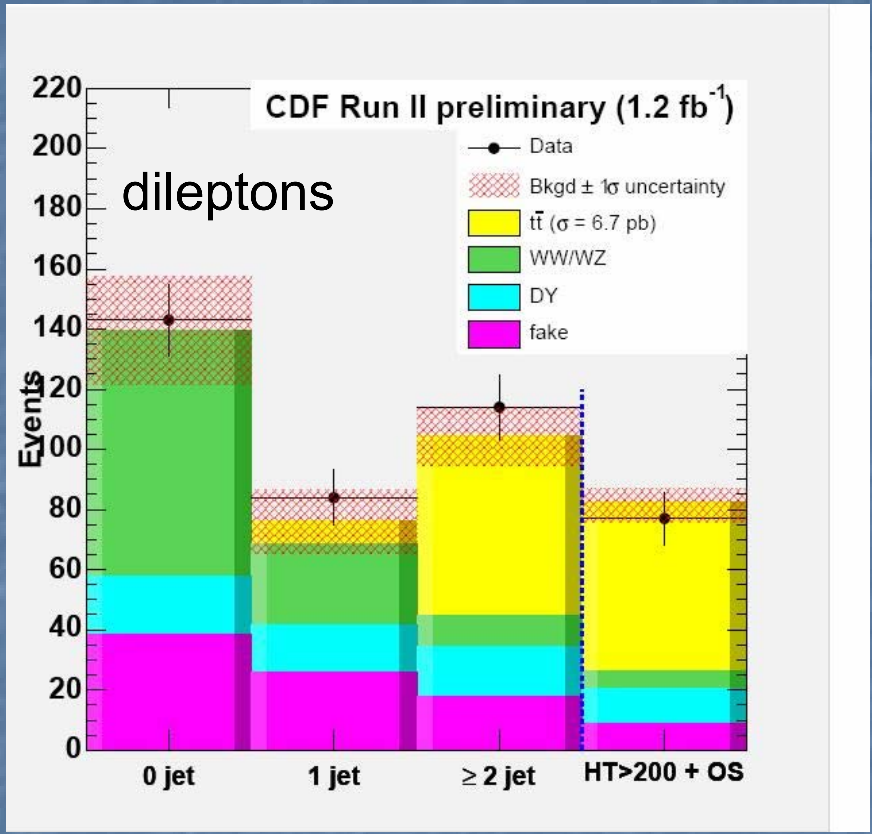
- The event selection for $t\bar{t}$ analyses includes a large SM control region
- Because the $t\bar{t}$ signature is not clean and well defined as, for example, a mass peak
- Need to demonstrate understanding of control region before moving on to $t\bar{t}$ studies
- In practice, all SM BG have lower jet multiplicity than $t\bar{t}$

  → Analyses as a function of N_{jets}

  (Also with & without b-tags)

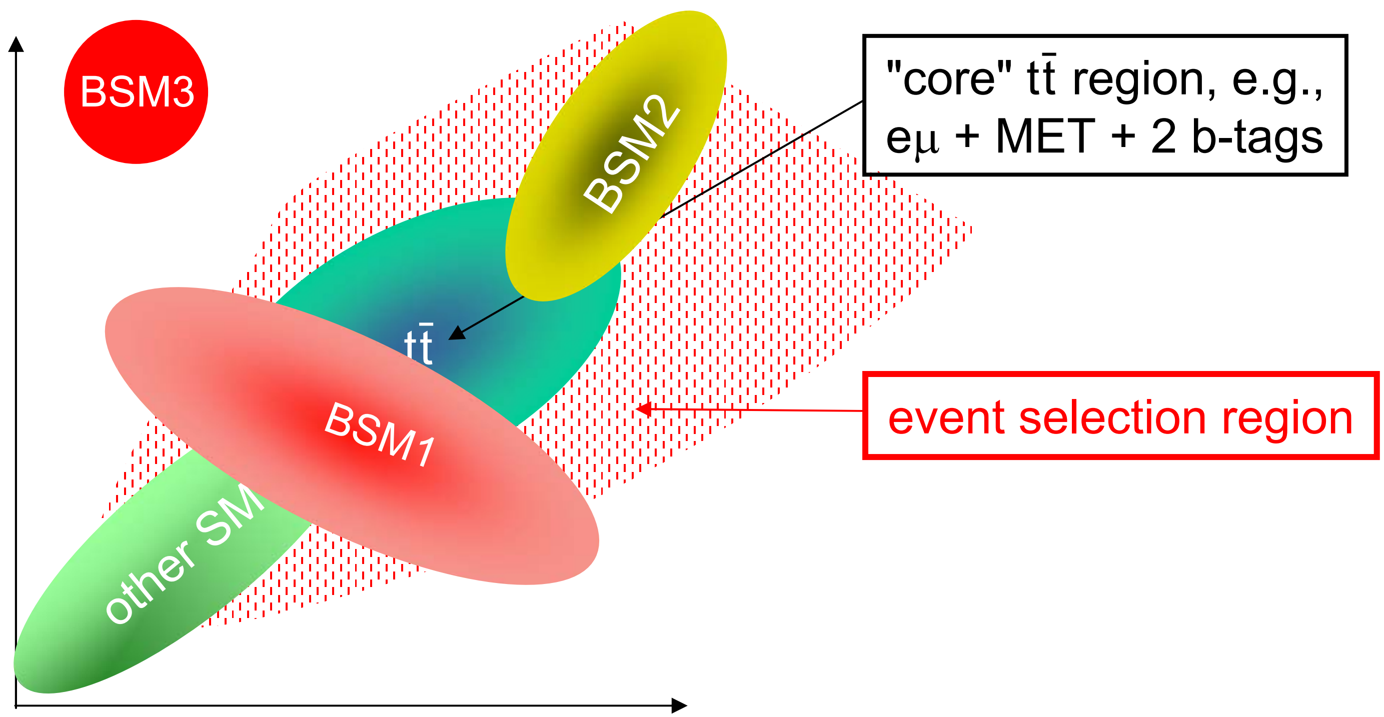
Tevatron Analyses





It will also be crucial to look at higher jet multiplicities, since $t\bar{t}$+jets is an important background for, e.g., SUSY

- $t\bar{t}$ events live in some complicated multidimensional space of event requirements
- SM backgrounds to top (e.g. W+jets, Drell-Yan, QCD) populate a separate, but not completely disjointed region
- Simplifying a lot, BSM can
  - strongly overlap with the core $t\bar{t}$ region (BSM1)
  - be only affected by the tail of $t\bar{t}$ (BSM2)
  - be almost totally distinct (BSM3)



Studies of $t\bar{t}$ sample (I)

- First: prove that we understand the control regions
  - this is a big task – most challenging part of a $\sigma(t\bar{t})$ analysis
- Then, ask: <u>is the $t\bar{t}$ sample consistent with the $t\bar{t}$ hypothesis?</u>
  - Automatically a broad search for BSM physics.
  - You may think: already covered at the Tevatron. I wouldn't bet on it
  - Regardless: needs to be done to establish good understanding of $t\bar{t}$ sample for searches where tail of $t\bar{t}$ is a background.
  - $\sigma(t\bar{t})$ measurement comes out of this program
- <u>In practice what does it mean?</u>
  - Compare all sorts of kinematical distributions with $t\bar{t}$ expectations (ie, $t\bar{t}$ MonteCarlo) + other BG
    - H_T, P_T of various objects, MET, $P_T(t\bar{t})$, $M(t\bar{t})$....
    - Some of these are more challenging than others

Studies of $t\bar{t}$ sample (II)

- We'll see discrepancies. Maybe even big ones. What causes them?
  - Did we do something wrong? (most likely at beginning)
    - Wrong efficiencies? Wrong SM non-$t\bar{t}$ background? Simulation? .....
  - Or something else?
    - Wrong $t\bar{t}$ generator (eg, tails)? BSM?
- How can we tell?
- Important tool: <u>ability to play $t\bar{t}$ channels against each other</u>
  - e+jets vs. μ+jets
  - ee vs. $\mu\mu$
  - eμ vs. $\mu\tau$
  - lepton+jets vs. dileptons

Exploit the power of canceling systematics by taking ratios, for example

Studies of $t\bar{t}$ sample (III)

- Example: $\mu\tau$ yield is off
  - Off w.r.t what: off w.r.t μe yield
  - If done judiciously, all systematics except τ ID/BG vs e ID/BG cancel
    - Now you know what you should be checking
- Example: tail of the H_T or N_{jet} distribution doesn't agree
  - We convinced ourselves that we have not made a mistake
  - Is it BSM or is it Alpgen $t\bar{t}$+jets that doesn't work?
  - Compare related distributions in l+jets and dileptons
    - Alpgen would make same mistake in both channels; BSM could contribute differently in the two channels (probably....)
- Consequence: design event selections to facilitate comparisons
  - No reasons for e+jets and μ+jets kinematical selections to be different
    - Same for ee and $\mu\mu$
  - Other aspects of selections should be as uniform as possible, eg, consistent jet selections, same b-tag operating points, etc.

A word about b-tagging

- Large samples of $t\bar{t}$ events that we will collect will enable us to use $t\bar{t}$ as a calibration sample.
- b-tagging efficiency, jet energy scale, ...

A slightly different twist

Would like to use b-tagging as a probe:

- Isolate $t\bar{t}$ signal with minimal b-tagging requirements (or none).
- Compare rates (and kinematics, and...) of events with 0,1,2,3.. b-tags with expectations for $t\bar{t}$.
  - Big part of program to establish whether data look like $t\bar{t}$ or not
  - **If there is BSM mixed into the $t\bar{t}$ signal region, this may be one of the most powerful tools that we have**

b-tagging as a probe, consequence:

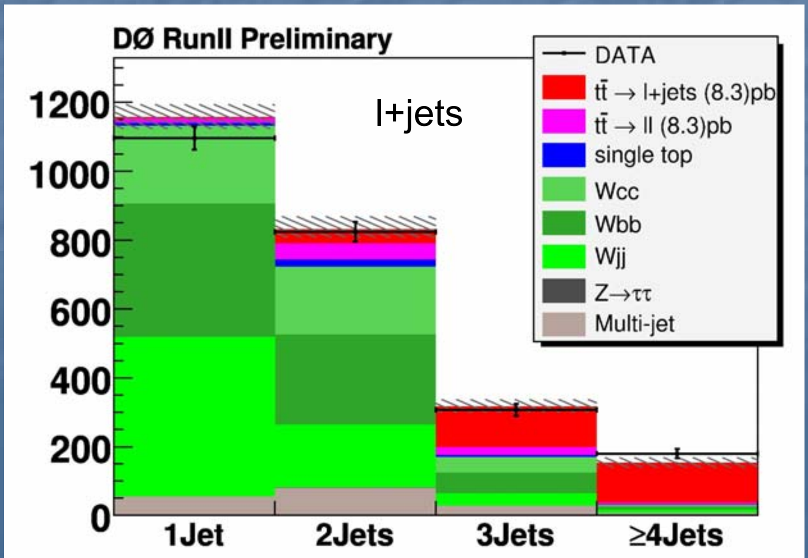
- Need ε(b-tagging) measured in data from sample orthogonal to the $t\bar{t}$ sample.
  - Otherwise: circular argument and you may even reabsorb BSM contribution into ε(b-tagging).

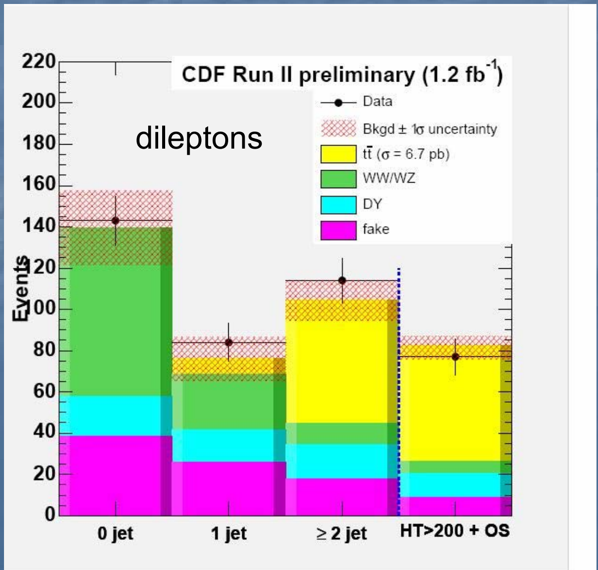
- There is a program to do this using $pp \rightarrow b\bar{b}$ followed by $b \rightarrow \mu$

- Where are we in this program?
- What are the challenges?

Plan of action & status (I)

1. Design basic event selection, identify tools that are needed, identify challenges
   - eg: triggers, lepton ID levels, thresholds, etc
   - Will of course have to be re-evaluated with data
2. Survey expectation for $t\bar{t}$ + SM
   - What do we expect CMS plots like the ones below to look like?





Plan of action & status (II)

3. Understand how to fill out the non-$t\bar{t}$ SM expectations in data driven way (where applicable)
4. Plan the program of comparisons

<u>Status</u>

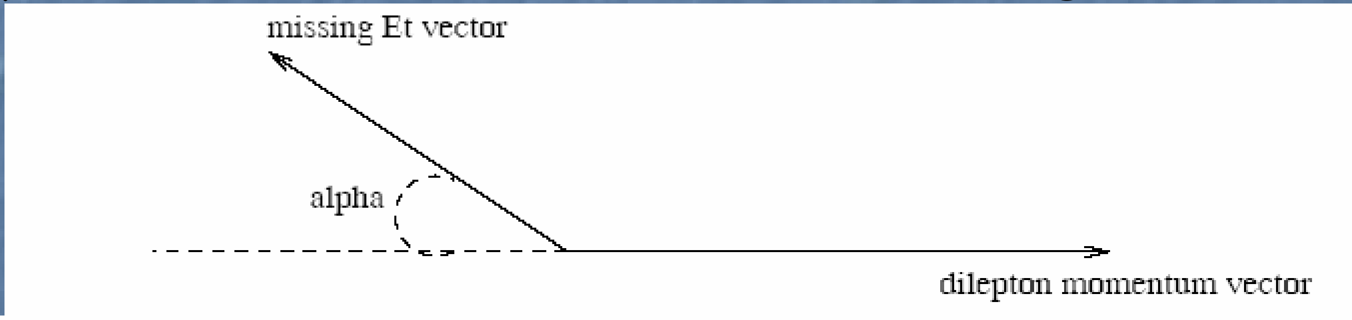
- 1 & 2 in good shape
- 3 has started
- No real work on 4 yet

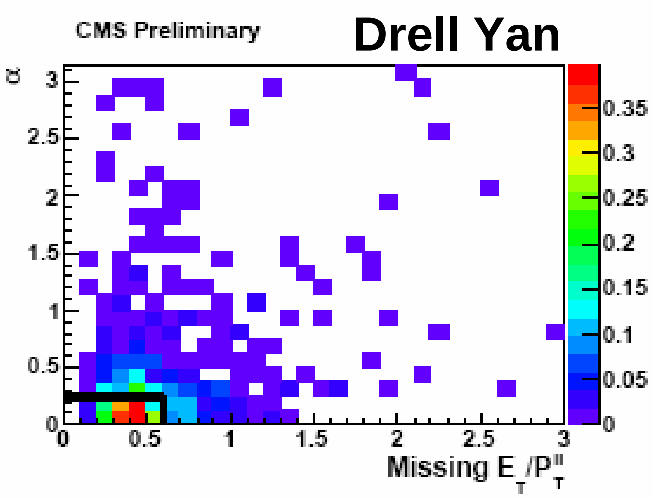
Dilepton Channel (I)

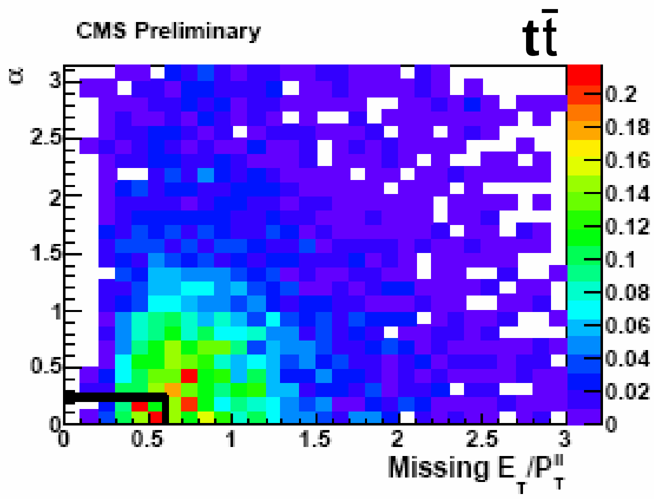
- pp → $t\bar{t}$ → Wb W$\bar{b}$, both W decay to leptons (l=e or μ)
- BR ~ 4/81
- Signal: two high P_T leptons, MET, ≥ 2 jets, possible b-tags
- SM BG: Drell-Yan, WW, WZ, ZZ, W+jets with fake lepton
  - Here fake lepton includes b→l and c→l

Dilepton jet-counting, no b-tags

- Isolated leptons, P_T > 20 GeV
- Remove Z peak
- Count jets with E_T(corrected)>30 GeV and $|\eta|<2.4$
- For eμ, MET>20 GeV (very loose)
- For ee and $\mu\mu$, MET>30 GeV and MET not anti-aligned with dilepton P_T

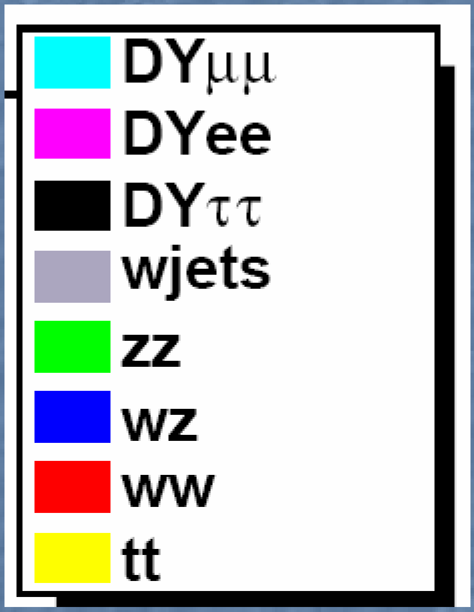


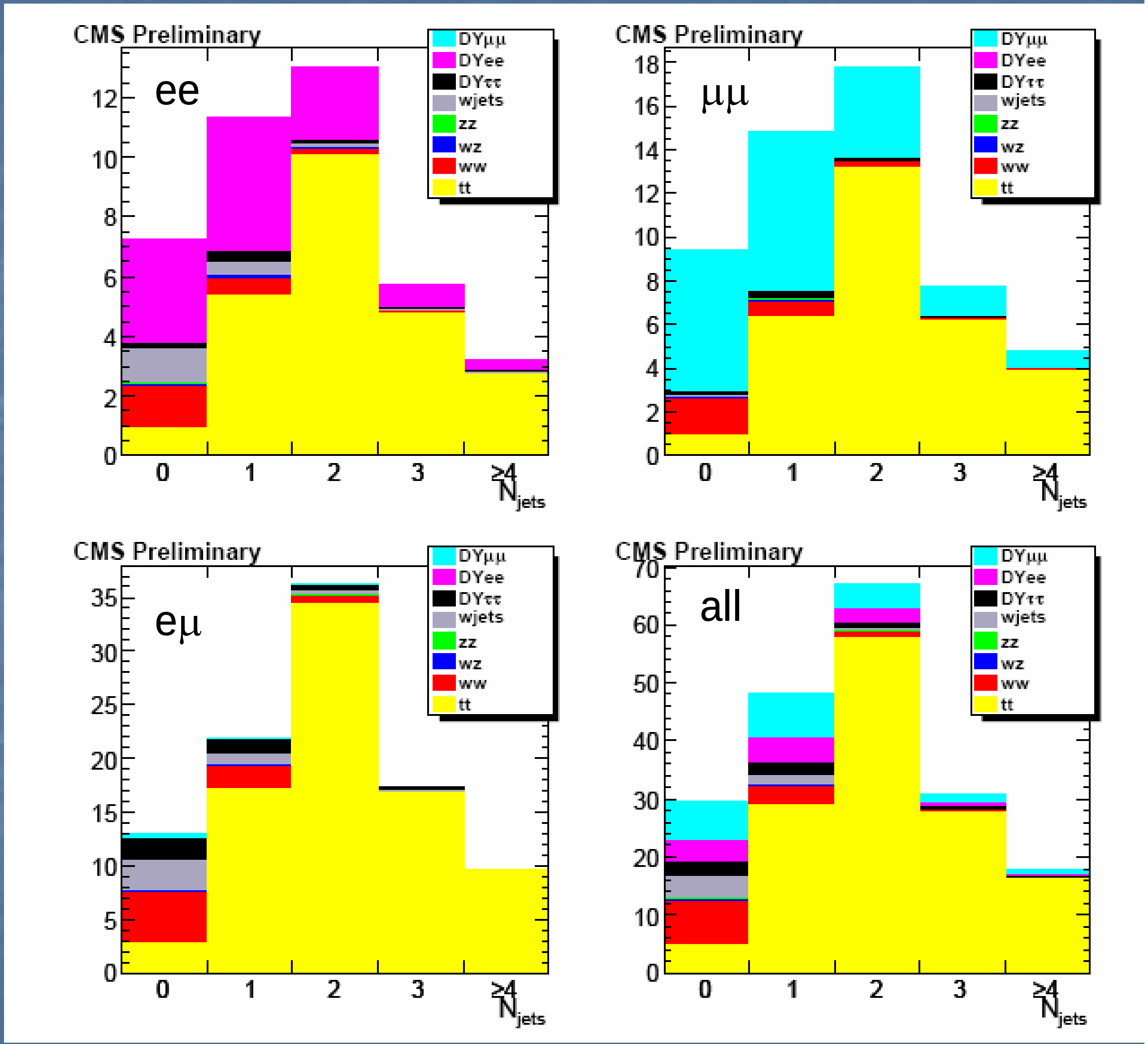




Dilepton jet-counting, no b-tags

Expectations in 10 pb^{-1}

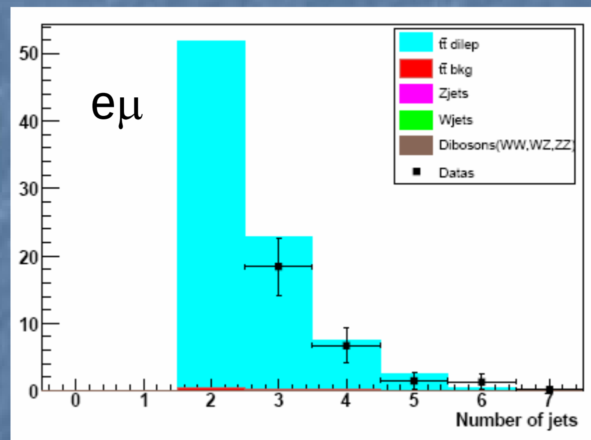


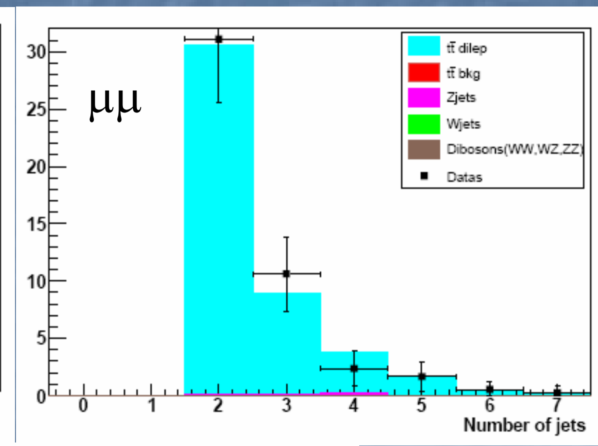


Dilepton jet counting, with b-tags

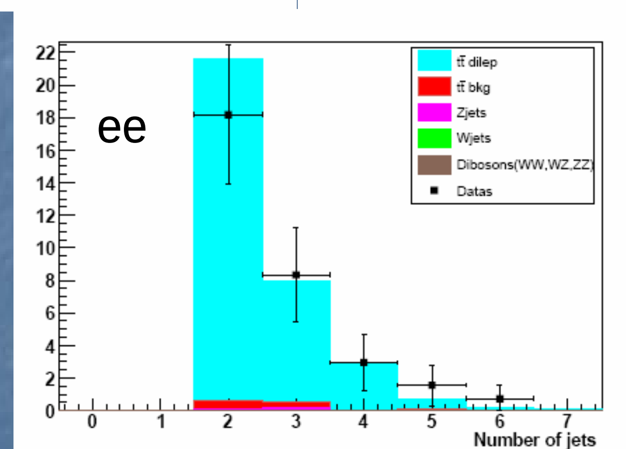
- Same basic event selection but different details
  - Different leptonID
  - Tight MET (>50 GeV) cut in all channels
  - Require two jets to be b-tagged
    - Selection aimed at clean $\sigma(t\bar{t})$ measurement
- Different details of event selection look a bit strange from the outside, but internally it is reasonably healthy
  - Want to explore at this stage!

Dilepton jet counting, with b-tags





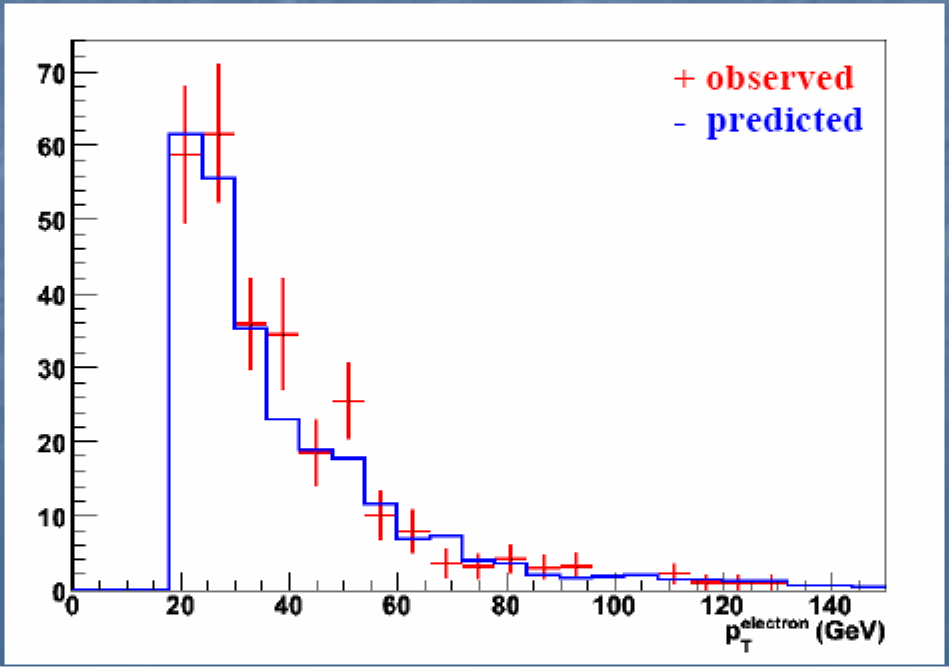
Expectations in 100 pb^{-1}



Dilepton jet counting, comments

- Without b-tagging: clean signal in eμ, Drell Yan background in ee and $\mu\mu$
- With 2 b-tags: very clean
- Of order 100 events in 10 pb^{-1}, no b-tags.
- MET critical to control Drell Yan before b-tags
  - Performance will be monitored on Z decays
  - BG prediction for Drell Yan will be tied to the Z peak
- Some BG from W+jets with fake electron
  - Data driven to estimate being developed
    - Example in next page

- Electron fake rate "measured" in Monte Carlo QCD jet events
- Fake rate applied to jets in Monte Carlo W+jets events to "predict" rate of dileptons in MC W+jets events
- Compare with "observed" rate of dileptons in MC W+jet events

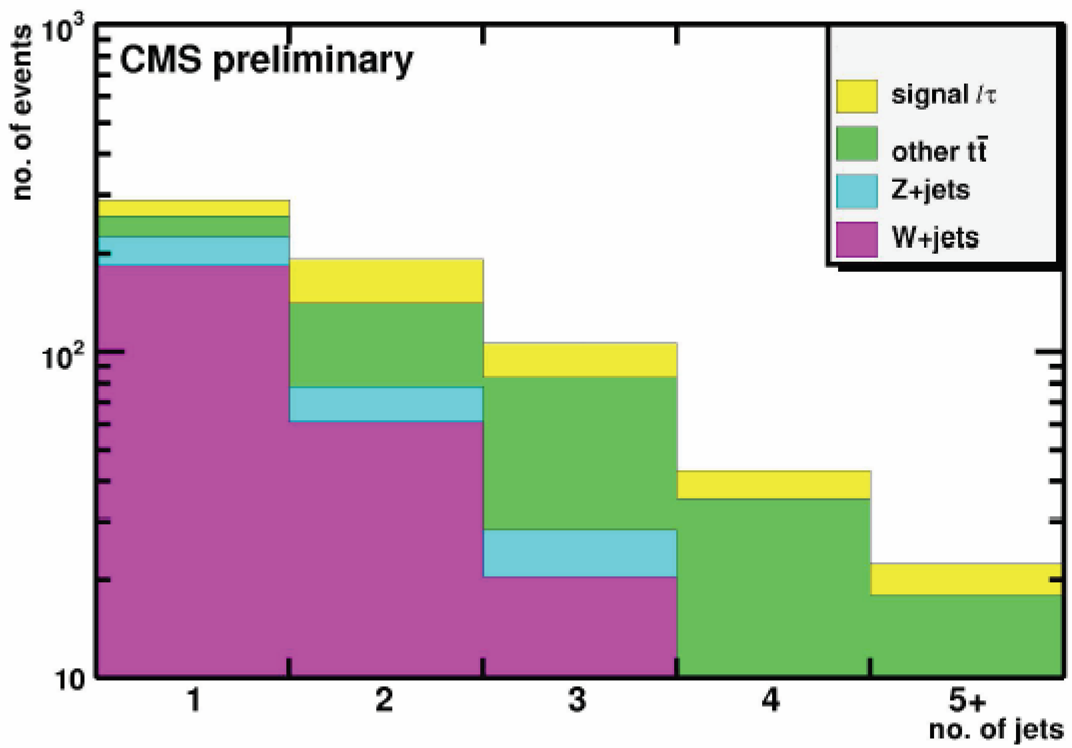


Dilepton tau analysis

- pp → $t\bar{t}$ → Wb W$\bar{b}$, one W→lν and one W→$\tau\nu$ decay (l=e or μ)
- BR ~ 4/81
- Signal: one high P_T lepton, one τ, MET, ≥ 2 jets, possible b-tags
- SM BG: Drell-Yan, WW, WZ, ZZ, W+jets with fake τ

Dilepton tau analysis

- Isolated lepton, P_T > 20 GeV
- Tau as narrow jet with leading track P_T>20 GeV
- Count other jets with E_T(corrected)>30 GeV and $|\eta|$<2.4
- MET >60 GeV



Expectations in 100 pb^{-1}

Dilepton tau analysis: fake tau estimation

Same approach as for electron fakes

- "Measure" τ fake rate in MC QCD events
- Apply to MC W+jets sample to prdict l+τ rate
- Compare to l+τ rate measured in W+jets MC

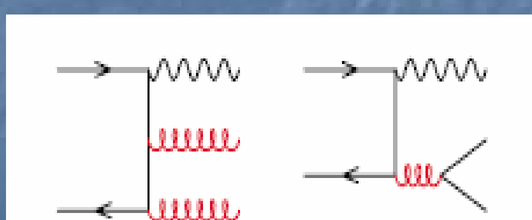
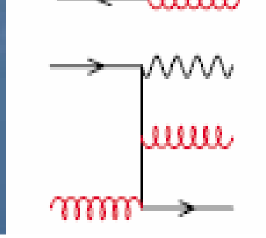
Good to about 30%

Table 3: Expected number of τ-fake events (from "data" and from MC expectations) in $\mathcal{L}$ = 100 pb^{-1}. Uncertainties are statistical only.

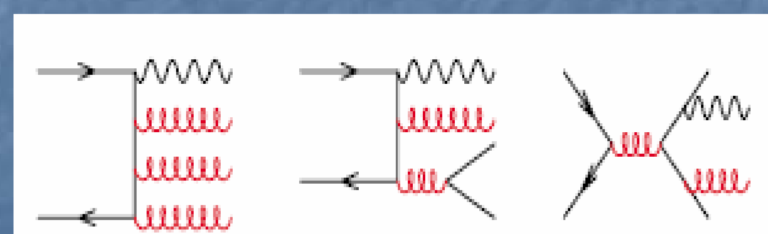
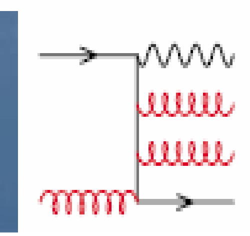
Method		τ-fakes from "data"	expected from event selection
1- or 3-prongs	γ+jets	523±8	438±20
	"all" jets	542±9	
	leading jet	639±10	
	next-to-leading	498±9	
	back-to-back	577±10	
1-prong	γ+jets	308±5	278±16
	"all" jets	361±7	
	leading jet	417±7	
	next-to-leading	341±7	
	back-to-back	385±7	

Lepton + jets

- pp → $t\bar{t}$ → Wb W$\bar{b}$, one W→lν and one W→$q\bar{q}$ decay (l=e or μ)
- BR ~ 24/81
- Signal: one high P_T lepton, MET, ≥ 4 jets, possible b-tags
- SM BG: W+jets, QCD ($p\bar{p}$→multi-jets)

some W+2 jets diagrams

some W+3 jets diagrams

Lepton + jets Challenge

- QCD is a challenge
  - One fake lepton or one b→l + many jets
- At the Tevatron this is almost eliminated by MET cut of order 25 GeV
- The typical MET of a $t\bar{t}$ event is 40 GeV
- At CMS, QCD events with 4 jets of E_T~30 GeV have typical MET of the same order as the MET in $t\bar{t}$
- Instead: at the moment rely on high thresholds for jets and lepton P_T and very tight isolation
  - Loose quite a bit of efficiency

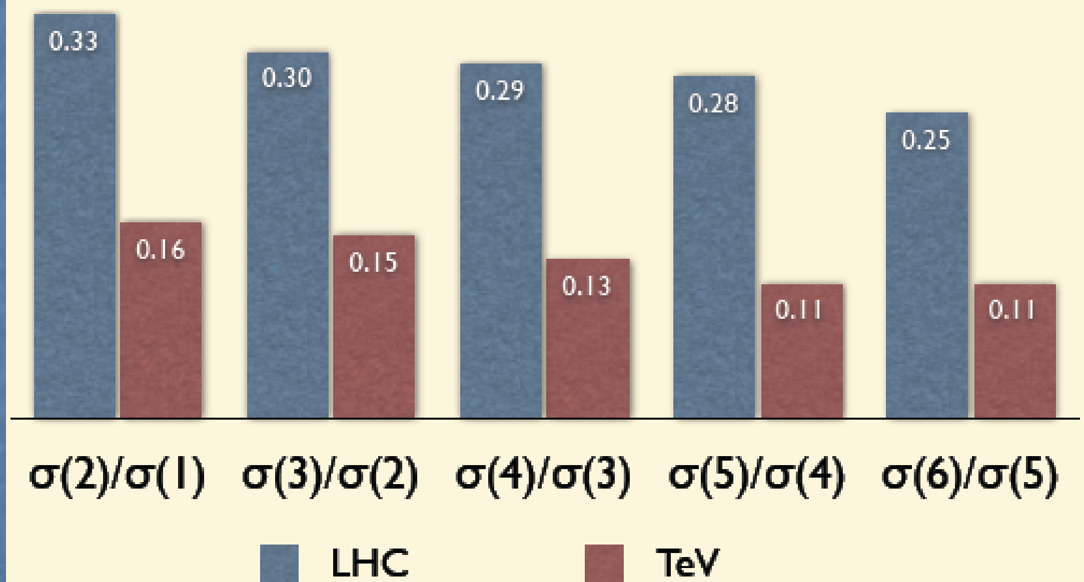
Aside: a lepton + jets curiosity

- Tevatron W+jets is the main BG
- Going from Tevatron to LHC:
  - $\sigma(t\bar{t})$ increases by x100
  - $\sigma(W)$ increases by x10
- Would conclude that W+jets is negligible at LHC
- Wrong!

W+Multijet rates

$\sigma \times B(W \rightarrow e\nu)$[pb]	N jet=1	N jet=2	N jet=3	N jet=4	N jet=5	N jet=6
LHC	3400	1130	340	100	28	7
Tevatron	230	37	5.7	0.75	0.08	0.009

E_T(jets) > 20 GeV , $|\eta|<2.5$, $\Delta R>0.7$



- Ratios almost constant over a large range of multiplicities
- $O(\alpha_s)$ at Tevatron, but much bigger at LHC

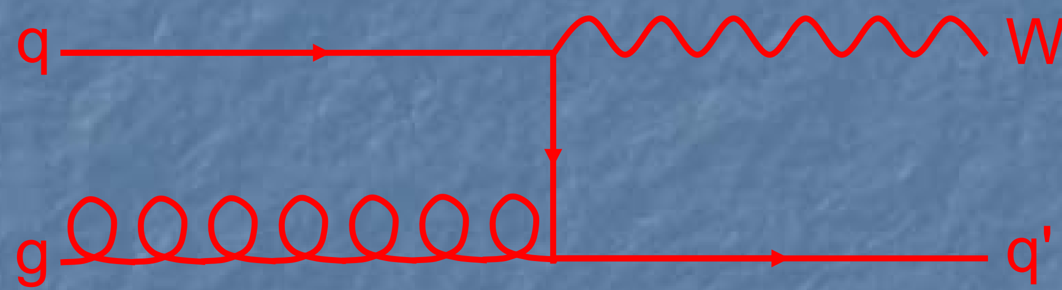
Slide stolen from a talk by Michelangelo Mangano

σ(W) increases by x10

σ(W+4 jets) increases by x100

Why are TeV and LHC so different?

- Lowest order W production: $q\bar{q} \rightarrow W$
- At higher order qg initial states also contribute
  - These give W+jets
  - Lumi(qg) high at LHC, a lot of QCD radiation from gluons



- In addition: emission of QCD radiation requires more CM energy for parton-parton interaction
  - And parton-parton luminosities fall less steeply around E_{CM}~100 GeV at LHC compared with Tevatron

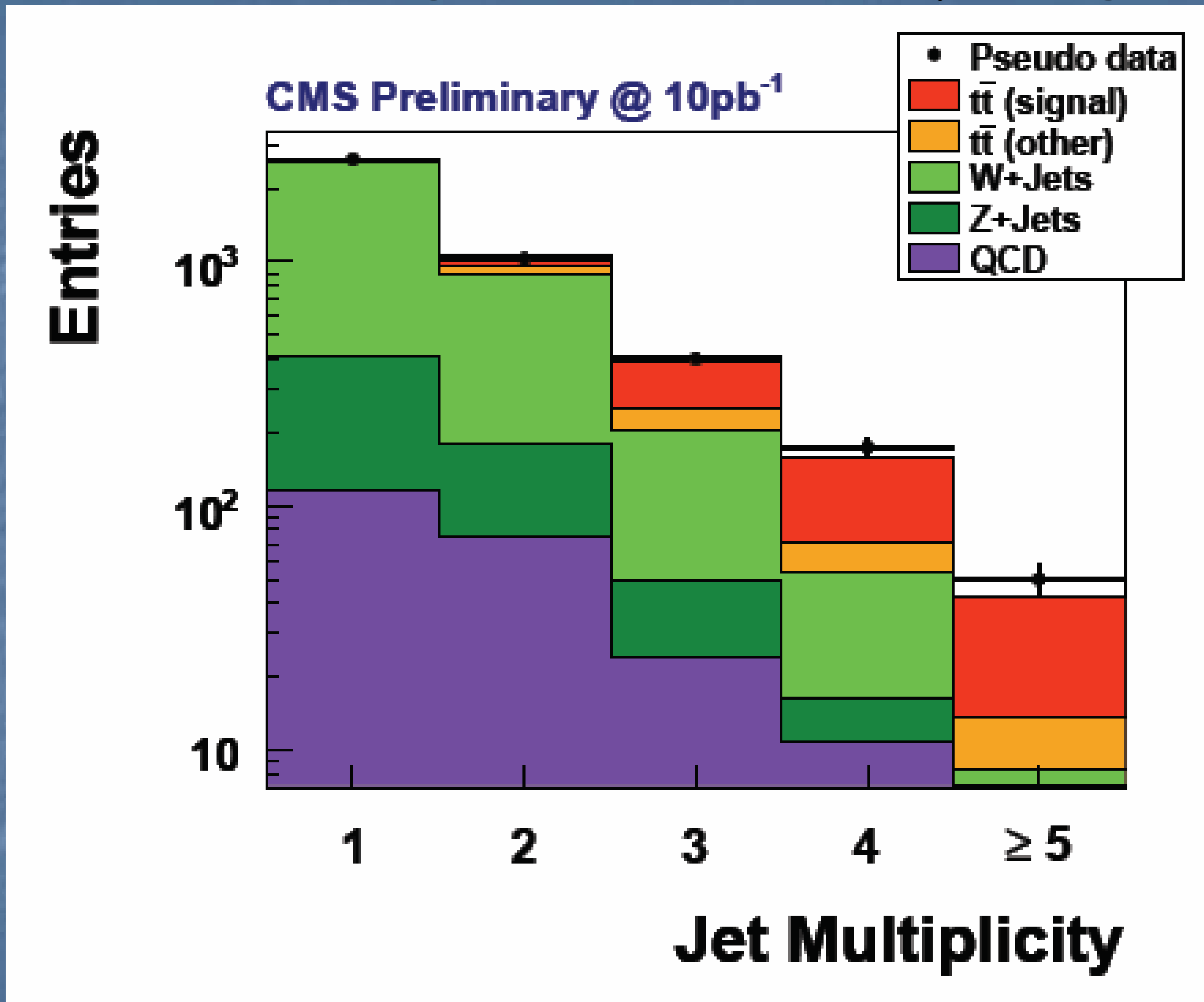
Muon + Jets event selection

- Isolated muon, P_T>30 GeV
  - very tight isolation: only 70% efficient on MC
- Count jets with E_T(corrected)>40 GeV,$|\eta|<2.4$
  - Leading jet must have E_T>65 GeV (technicality)
- No MET requirement
- No b-tagging yet

QCD BG expectation

- "Fake" μ rate dominated by b→μ and c→μ
  - At least, this is what the MC says
- Take QCD BG expectation from Pythia
  - With all its caveats

Expected jet counts, μ + jets



What about electron+jets?

- In progress.
- Similar status as μ+jets.
- BG here is more severe because of fake electrons in QCD jets

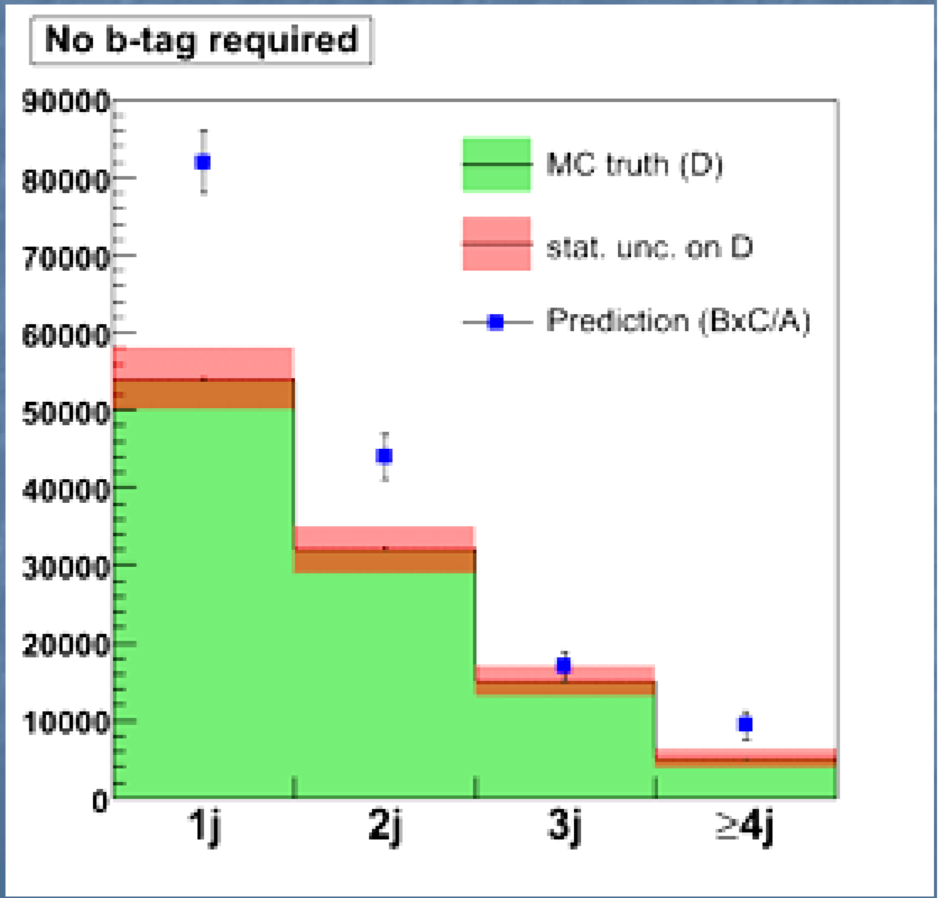
Comments on QCD BG

- With high E_T/P_T thresholds and very tight isolation QCD background appears under control

- Working to develop method to estimate QCD background in lepton+jets directly from the data

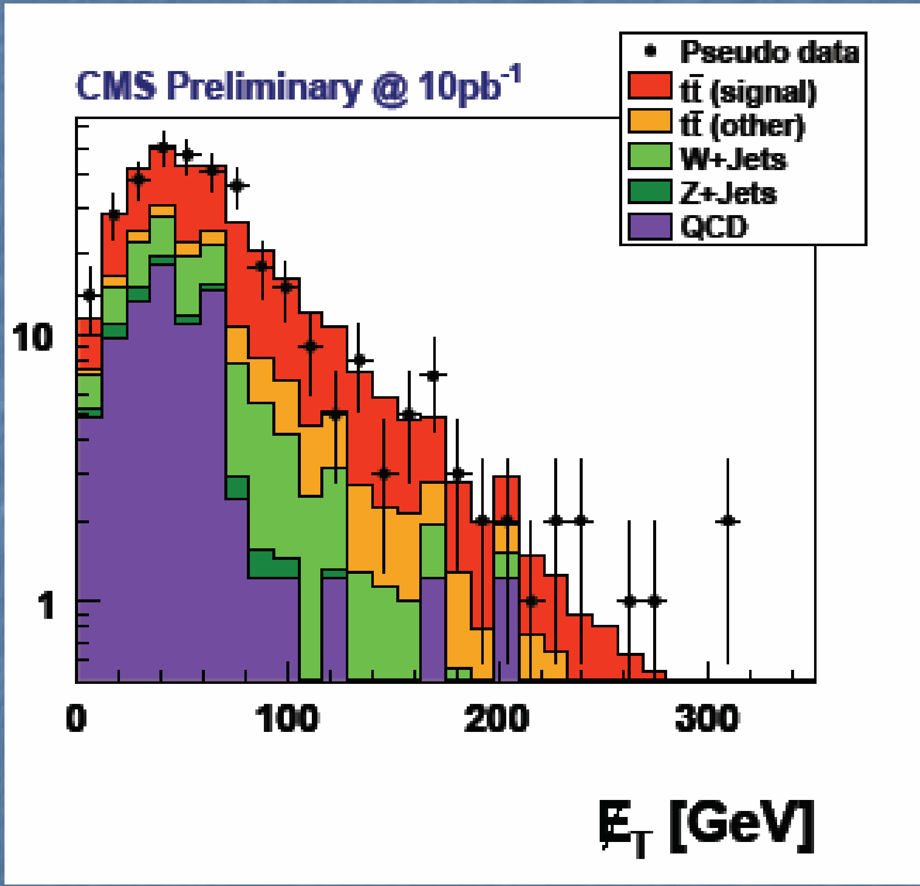
First attempt to data driven QCD BG estimates in lepton+jets

- e+jets channel; uses MET vs Isolation Tevatron method
  - Assume MET,ISO uncorrelated
  - Use Low Met, bad ISO to predict High MET, good ISO
- good to ~30%
  - Still problems
- more work needed
- Methods being explored:
  - Iso vs d_0 (muons)
  - Iso vs P_T^{lepton}
  - Ad-hoc Iso extrapolation



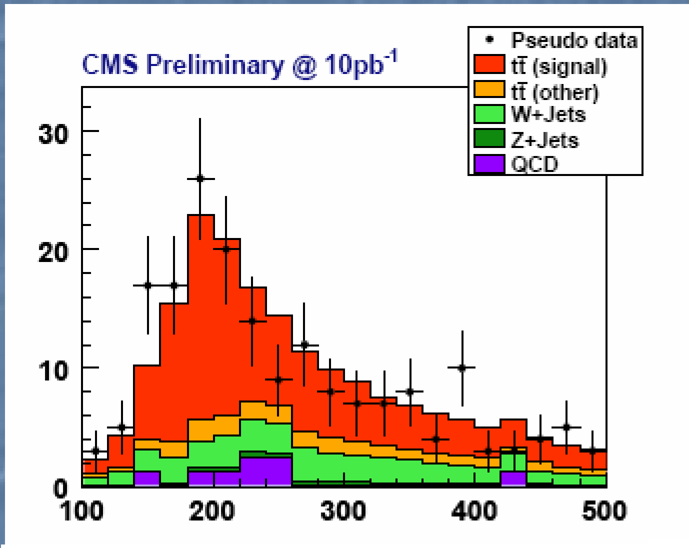
Comment on MET for top

- The ν's in top events give a MET of order 40 GeV
- Multi-jet QCD BGs have MET that is comparable
- It is a challenge to separate QCD from $t\bar{t}$ and W+jets without using the neutrino signature!

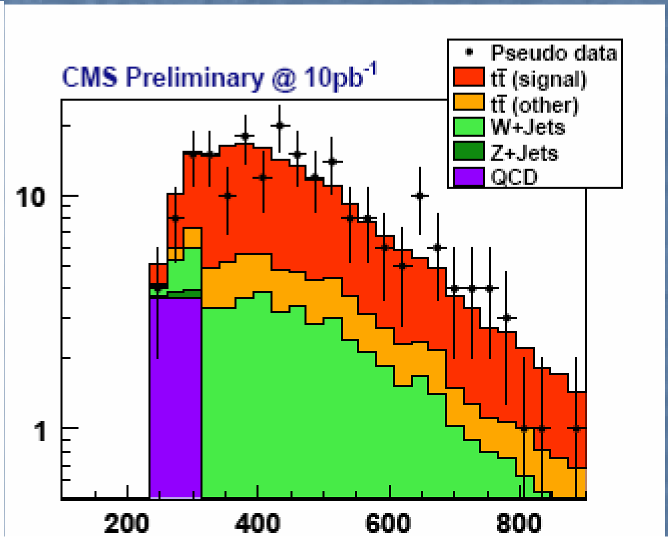


Next Step In lepton+jets

Separate $t\bar{t}$ from W+jets using kinematics

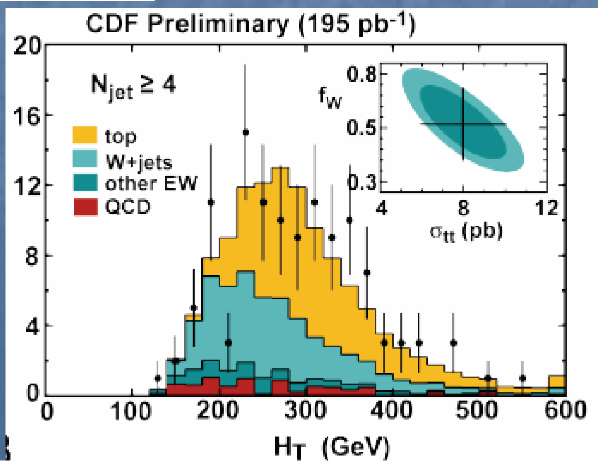


Mass of 3 jets with highest summed P_T in μ+4 jets



H_T=scalar sum of jet P_T (μ+4jets)

Working on defining optimal strategy. Worry about MC systematics!



Next-to-Next Step: b-tagging

- Use b-tag efficiency measured from orthogonal sample to verify that $t\bar{t}$ sample behaves as expected (and to search for BSM)
- Eventually, can use $t\bar{t}$ sample to calibrate b-tag efficiency
- Work on this will start this summer. Many issues to worry about, e.g., $Wb\bar{b}$:

$$N_{Wbb}^{data} = \left(\frac{N_{Wbb}}{N_{W+jets}}\right)^{MC} \cdot K_{HF} \cdot N_{W+jets}^{data}$$

CDF method

Conclusions

- With the startup of the LHC this summer, the top-physics baton is passing from Fermilab to CERN
- The LHC is a top factory
- Initially, however, the top program at CMS is centered towards preparing the experiment for the searches
  - Commissioning of physics objects in a complicated physics signature
  - Establishing good understanding of Standard Model processes at LHC
- Detailed, high statistics, precision measurement will follow