Data Analysis

Beate Heinemann

UC Berkeley and Lawrence Berkeley National Laboratory

Hadron Collider Physics Summer School, Fermilab, August 2008

Introduction and Disclaimer

- Data Analysis in 3 hours !
  - Impossible to cover all…
    - There are gazillions of analyses
    - Also really needs learning by doing
      - That's why your PhD takes years!
  - Will try to give a flavor using illustrative examples:
    - What are the main issues
    - And what can go wrong
  - Will try to highlight most important issues
- Please ask during / after lecture and in discussion section!
  - I will post references for your further information also
    - Generally it is a good idea to read theses

Outline

- Lecture I:
  - Measuring a cross section
    - focus on acceptance
- Lecture II:
  - Measuring a property of a known particle
- Lecture III:
  - Searching for a new particle
    - focus on backgrounds

Cross Section: Experimentally

Number of observed events: counted

Background: Measured from data / calculated from theory

$$\sigma = \frac{N_{obs} - N_{BG}}{\int L dt \cdot \varepsilon}$$

Cross section σ

Luminosity: Determined by accelerator, trigger prescale, …

Efficiency: optimized by experimentalist

Uncertainty on Cross Section

- You will want to minimize the uncertainty:

$$\frac{\delta\sigma}{\sigma} = \sqrt{\frac{\delta N_{obs}^2 + \delta N_{BG}^2}{(N_{obs} - N_{BG})^2} + \left(\frac{\delta\mathcal{L}}{\mathcal{L}}\right)^2 + \left(\frac{\delta\epsilon}{\epsilon}\right)^2}$$

- Thus you need:
  - N_{obs}-N_{BG} small (I.e. N_{signal} large)
    - Optimize selection for large acceptance and small background
  - Uncertainties on efficiency and background small
    - Hard work you have to do
  - Uncertainty on luminosity small
    - Usually not directly in your power

Luminosity

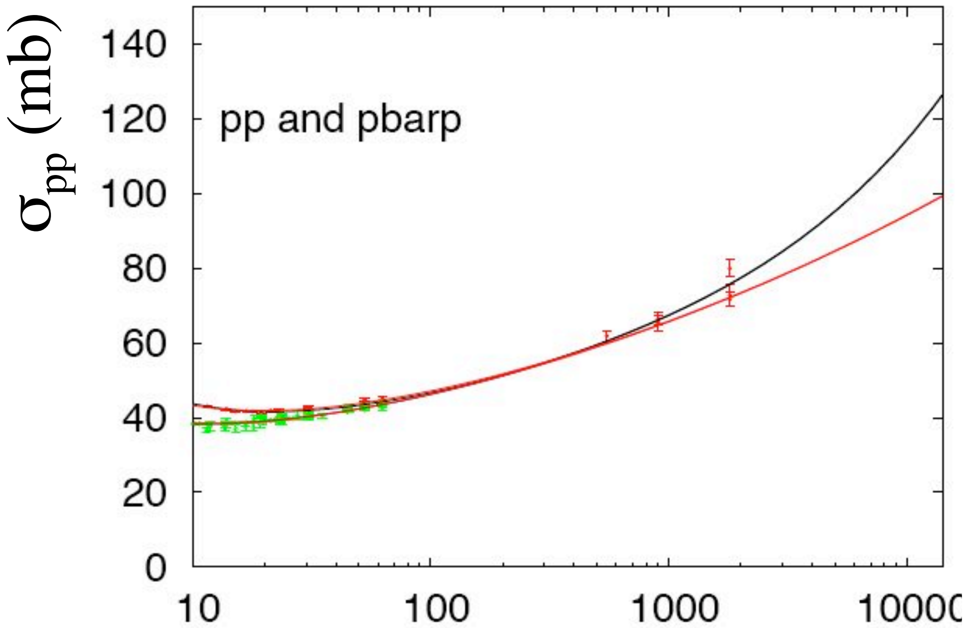
Luminosity Measurement

- Many different ways to measure it:
  - Beam optics
    - LHC startup: precision ~20-30%
    - Ultimately: precision ~5%
  - Relate number of interactions to total cross section
    - absolute precision ~4-6%, relative precision much better
  - Elastic scattering:
    - LHC: abslute precision ~3%
  - Physics processes:
    - W/Z: precision ~2-3% ?
- Need to measure it as function of time:
  - $L = L_0 e^{-t/\tau}$ with $\tau \approx$14h at LHC and L_0 = initial luminosity

Luminosity Measurement

Rate of pp collisions: $R_{pp} = \sigma_{inel}\, \varepsilon\, L_{inst}$

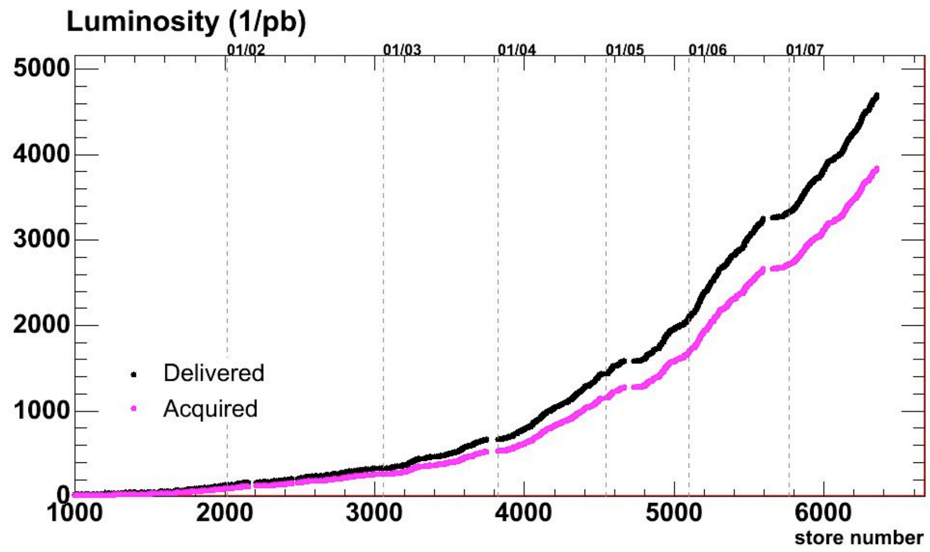
- Measure fraction of beam crossings with no interactions
  - Related to R_{pp}
- Relative normalization possible
  - if Probability for no interaction>0 ($L<10^{32}\ cm^{-2}s^{-1}$)
- Absolute normalization
  - Normalize to measured inelastic pp cross section
  - Measured by CDF and E710/E811
    - Differ by 2.6 sigma
    - For luminosity normalization use the error weighted average

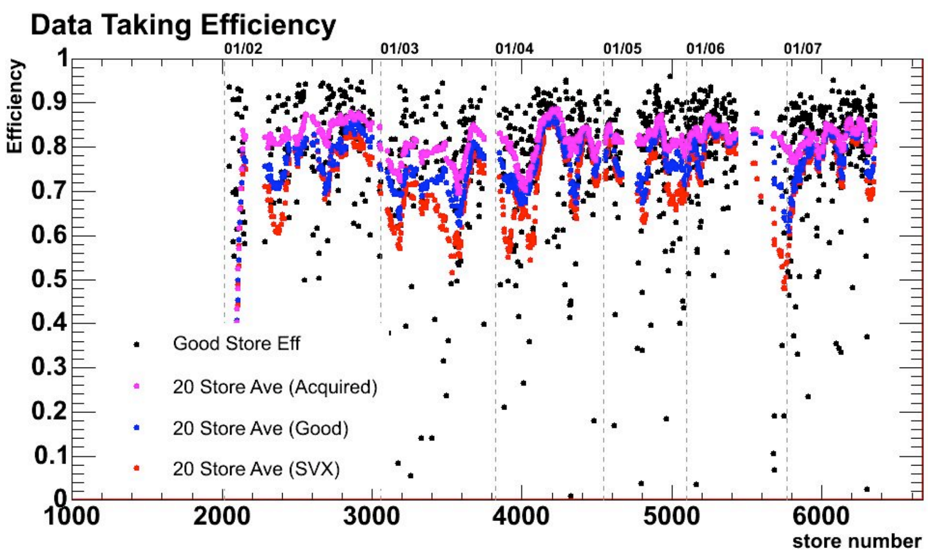


	1.96 TeV	14 TeV
$\sigma_{inelastic}$	60.7±2.4 mb (measured)	125±25 mb (P. Landshoff)

Your luminosity

- Your data analysis luminosity is not equals to LHC/Tevatron luminosity!
- Because:
  - The detector is not 100% efficiency at taking data
  - Not all parts of the detector are always operational/on
  - Your trigger may have been off / prescaled at times
  - Some of your jobs crashed and you could not run over all events
- All needs to be taken into account
  - Severe bookkeeping headache





Acceptance / Efficiency

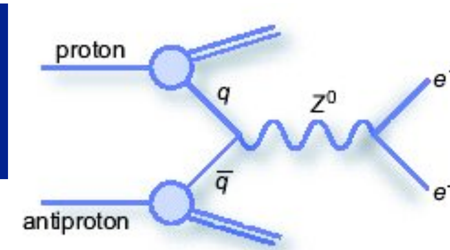
- Actually rather complex:
  - Many ingredients enter here
  - You need to know:

$$\varepsilon_{total} = \frac{\text{Number of Events used in Analysis}}{\text{Number of Events Produced}}$$

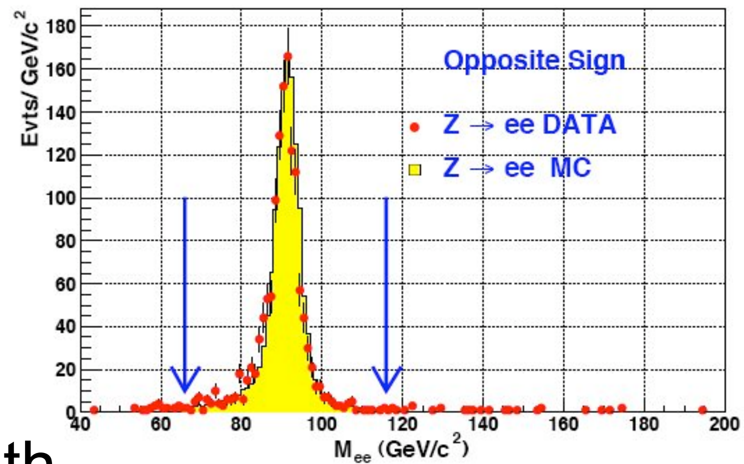
- Ingredients:
  - Trigger efficiency
  - Identification efficiency
  - Kinematic acceptance
  - Cut efficiencies
- Using three example measurements for illustration:
  - Z boson, top quak and jet cross sections

Example Analyses

Z Boson Cross Section



- Trigger requires one electron with E_T>20 GeV
  - Criteria at L1, L2 and L3/EventFilter
- You select two electrons in the analysis
  - With certain quality criteria
  - With an isolation requirement
  - With E_T>25 GeV and |eta|<2.5
  - With oppositely charged tracks with p_T>10 GeV



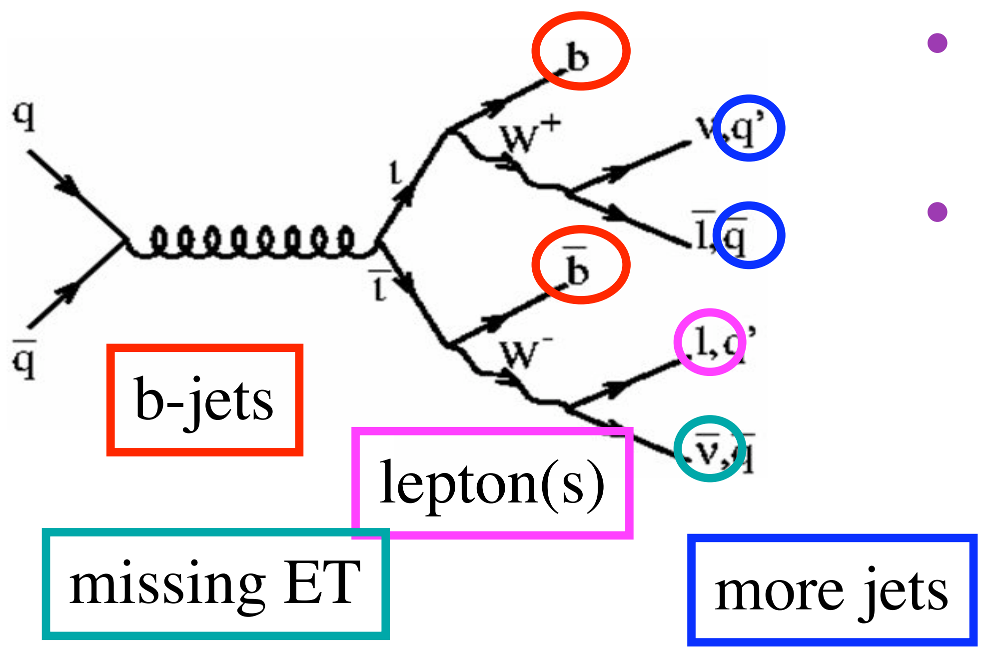
- You require the di-electron mass to be near the Z:
  - 66<M(ll)<116 GeV

=> $\varepsilon_{total} = \varepsilon_{trig}\varepsilon_{rec}\varepsilon_{ID}\varepsilon_{kin}\varepsilon_{track}$

Top Quark Cross Section

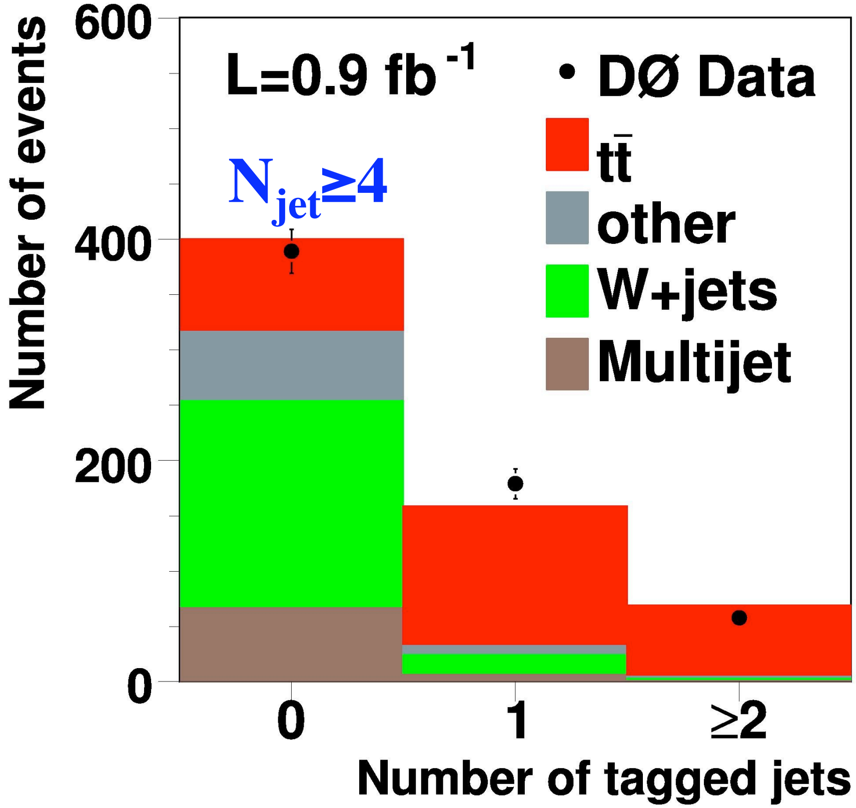
SM: tt pair production, Br(t→bW)=100% , Br(W->lν)=1/9=11%

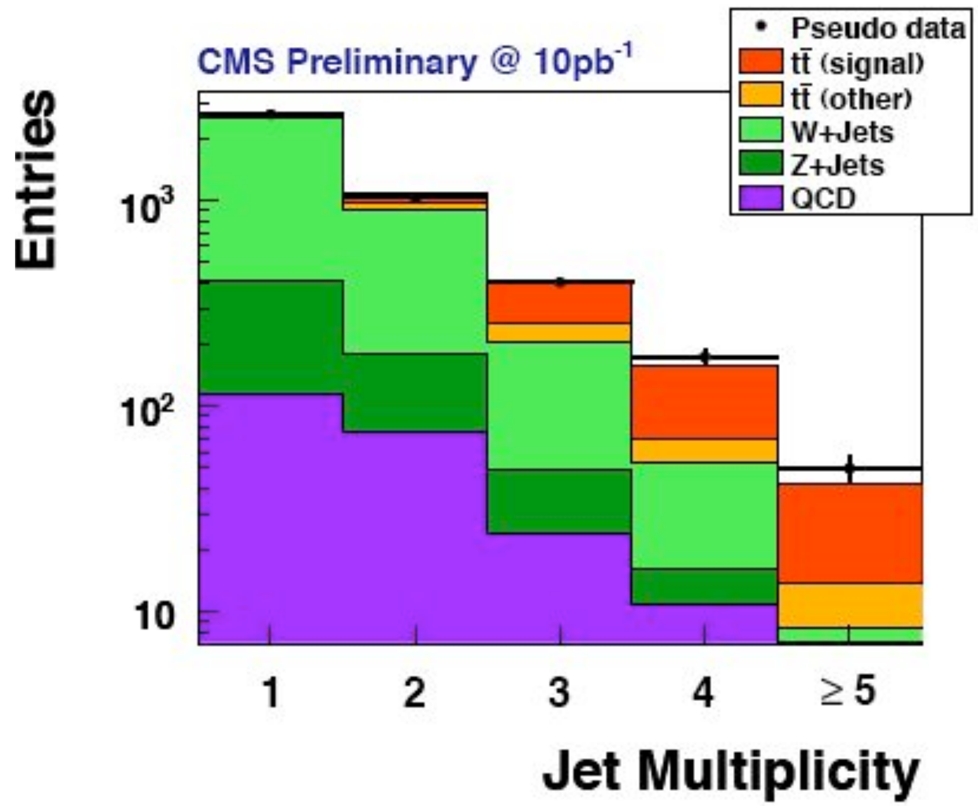
dilepton	*(4/81)*	2 leptons + 2 jets + missing E_T
lepton+jets	*(24/81)*	1 lepton + 4 jets + missing E_T
fully hadronic	*(36/81)*	6 jets



- Trigger on electron/muon
  - Like for Z's
- Analysis cuts:
  - Electron/muon p_T>25 GeV
  - Missing E_T>25 GeV
  - 3 or 4 jets with E_T>20-40 GeV

Finding the Top Quark

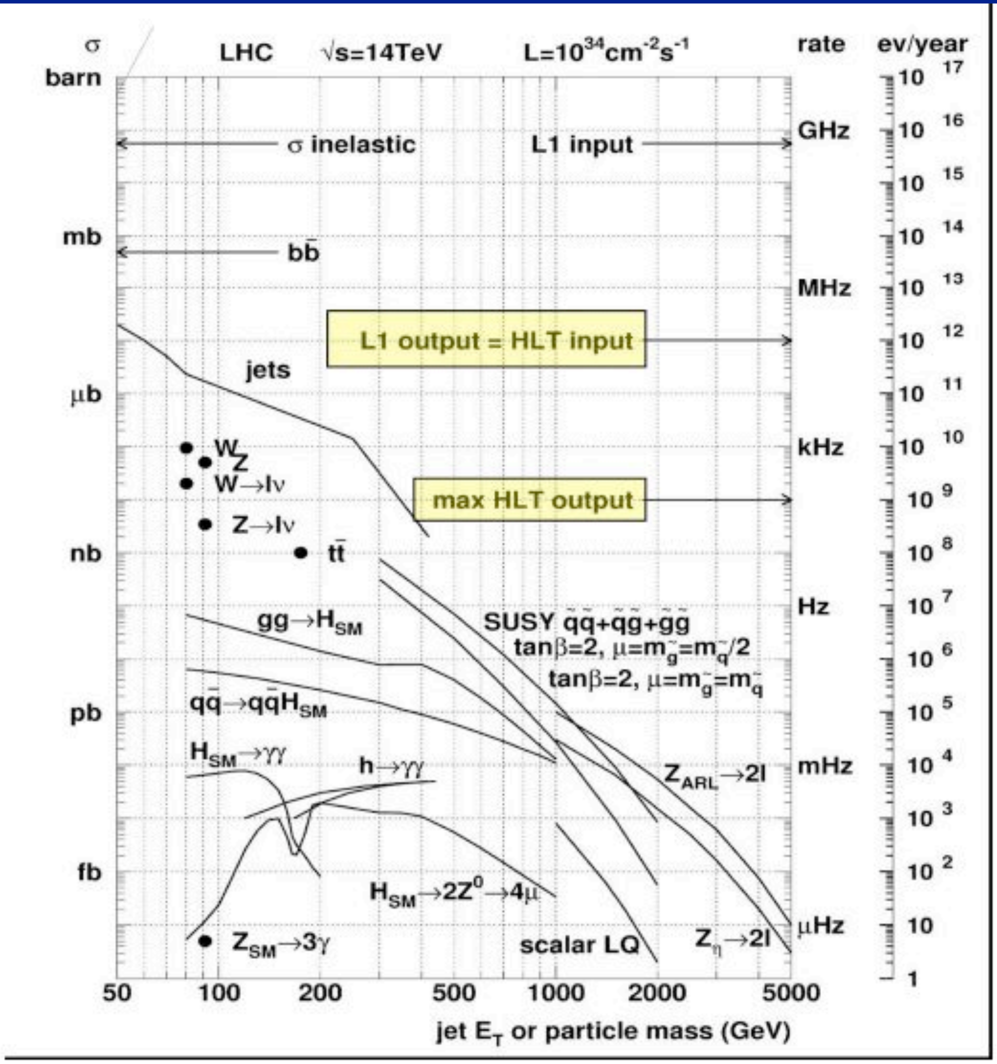




- **Tevatron**
  - Top is overwhelmed by backgrounds:
  - Top fraction is only 10% (≥3 jets) or 40% (≥4 jets)
  - Use b-jets to purify sample => purity 50% (≥3 jets) or 80% (≥4 jets)
- **LHC**
  - Purity ~70% w/o b-tagging (90% w b-tagging)

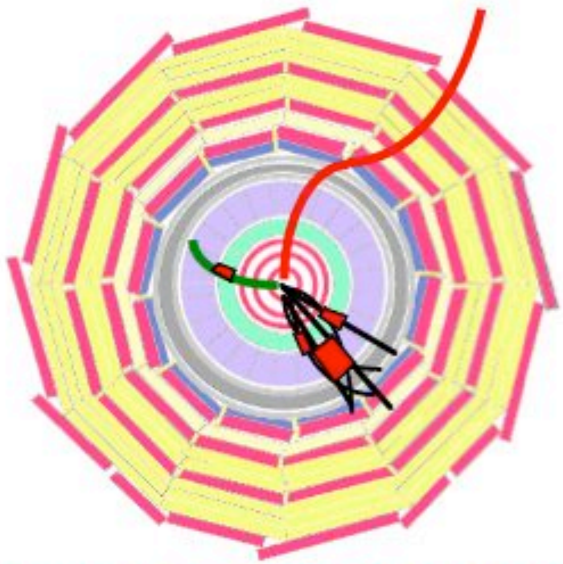
Trigger

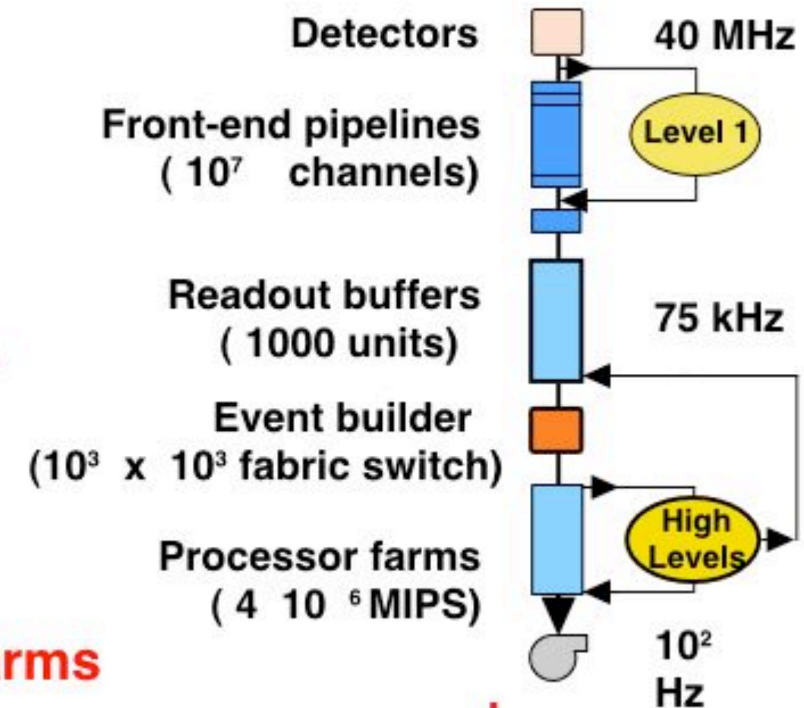
Trigger Rate vs Physics Cross Section



- Acceptable Trigger Rate << many physics cross sections

Example: CMS trigger





High level triggers. CPU farms

- Finer granularity precise measurement
- Clean particle signature (π^0-γ, isolation, ...)
- Kinematics. Effective mass cuts and topology
- Track reco and matching, b,τ-jet tagging
- Full event reconstruction and analysis

Successive improvements : background event filtering, physics selection

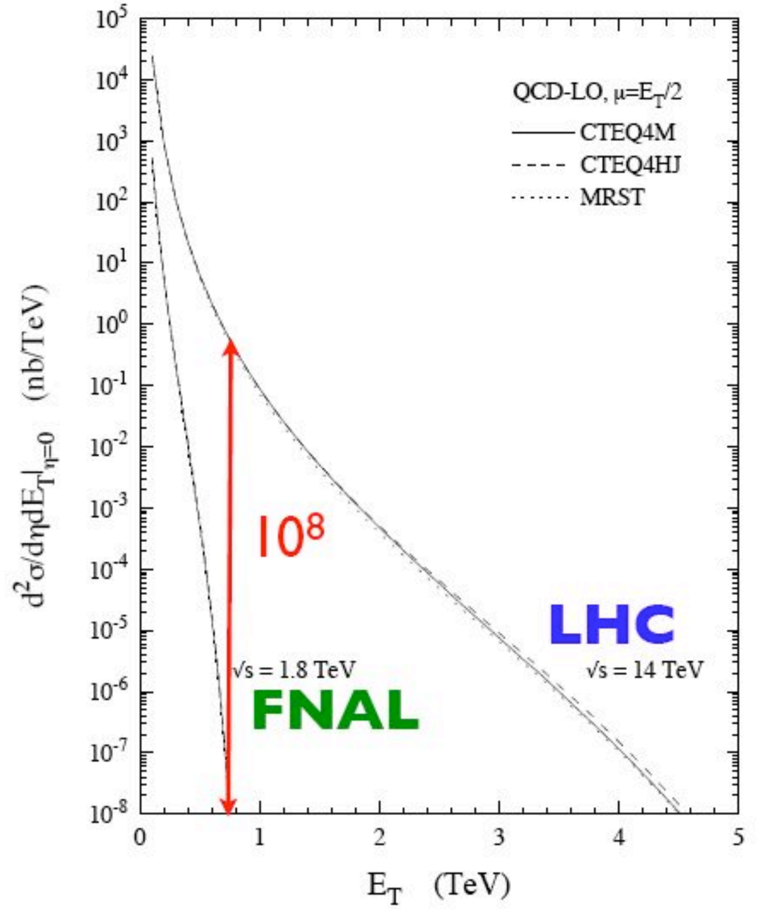
NB: Similar output rate at the Tevatron

Tevatron versus LHC Cross Sections

Cross Sections of Physics Processes (pb)

	Tevatron	LHC	Ratio
$W^{\pm}$ (80 GeV)	2600	20000	10
$t\bar{t}$ (2x172 GeV)	7	800	100
$gg \to H$ (120 GeV)	1	40	40
$\tilde{\chi}^{+}_{1}\tilde{\chi}^{2}_{0}$ (2x150 GeV)	0.1	1	10
$\tilde{q}\tilde{q}$ (2x400 GeV)	0.05	60	1000
$\tilde{g}\tilde{g}$ (2x400 GeV)	0.005	100	20000
Z' (1 TeV)	0.1	30	300

Jet Cross Section



- **Amazing increase for strongly interacting heavy particles!**
- **LHC has to trigger >10 times more selectively than Tevatron**

Are your events being triggered?

- Typically yes, if
  - events contain high p_T isolated leptons
    - e.g. top, Z, W
  - events contain very high p_T jets or very high missing E_T
    - e.g. SUSY
  - …
- Possibly no, if
  - events contain only low-momentum objects
    - E.g. two 20 GeV b-jets
      - Still triggered at Tevatron but not at LHC
  - ….
- This is the first thing you need to find out when planning an analysis
  - If not then you want to design a trigger if possible

Examples for Unprescaled Triggers

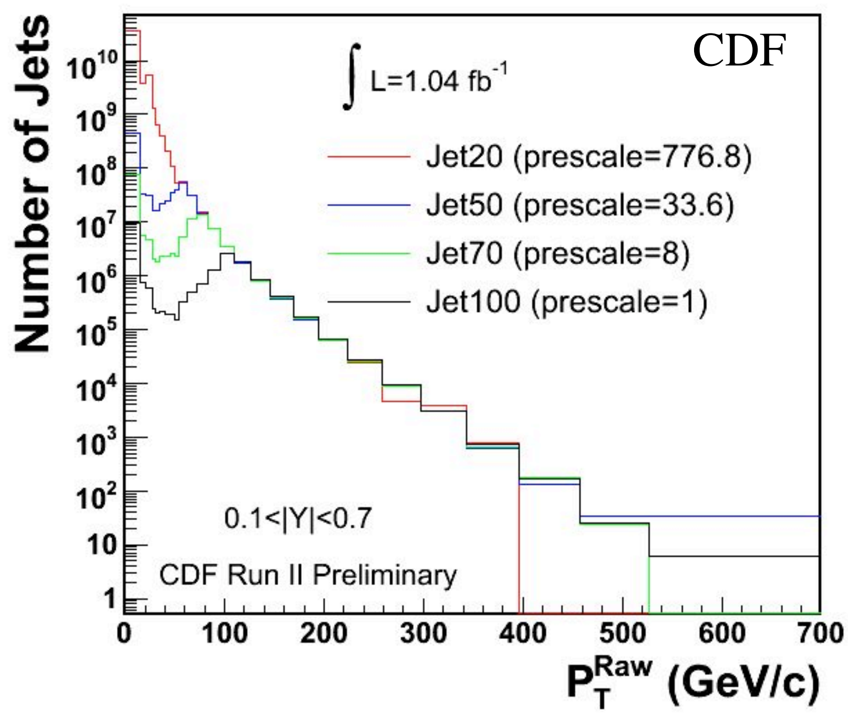
	ATLAS(*) (L=2x10^{33} cm^{-2}s^{-1})	CDF (L=3x10^{32} cm^{-2}s^{-1})
MET	> 70 GeV	> 40 GeV
Jet	> 370 GeV	> 100 GeV
Photon (iso)	> 55 GeV	> 25 GeV
Muon	iso + p_T> 20 GeV	> 20 GeV
Electron	Iso + E_T> 22 GeV	> 20 GeV
incl. dimuon	> 10 GeV	> 4 GeV

- Increasing luminosity leads to
  - Tighter cuts, smarter algorithms, prescales
  - Important to pay attention to this for your analysis!

Typical Triggers and their Usage

- Unprescaled triggers for primary physics goals, e.g.
  - Inclusive electrons, muons p_T>20 GeV:
    - W, Z, top, WH, single top, SUSY, Z',W'
  - Lepton+tau, p_T>8-25 GeV:
    - MSSM Higgs, SUSY, Z
    - Also have tau+MET: W->taunu
  - Jets, E_T>100-400 GeV
    - Jet cross section, Monojet search
    - Lepton and b-jet fake rates
  - Photons, E_T>25 GeV:
    - Photon cross sections, Jet energy scale
    - Searches (GMSB SUSY), ED's
  - Missing E_T>45-100 GeV
    - SUSY

- Prescale triggers because:
  - Not possible to keep at highest luminosity
  - But needed for monitoring
  - Prescales depend often on Luminosity
- Examples:
  - Jets at E_T>20, 50, 70 GeV
  - Inclusive leptons >8 GeV
  - Backup triggers for any threshold, e.g. Met, jet ET, etc…
    - At all trigger levels

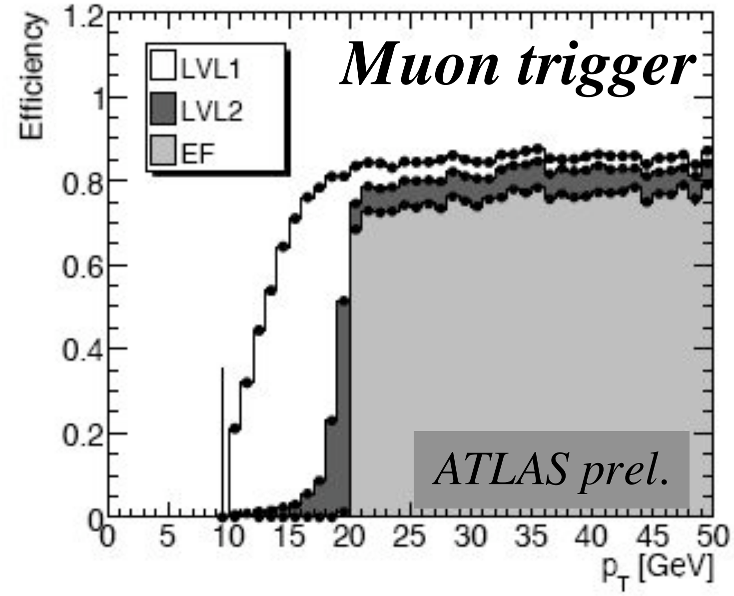


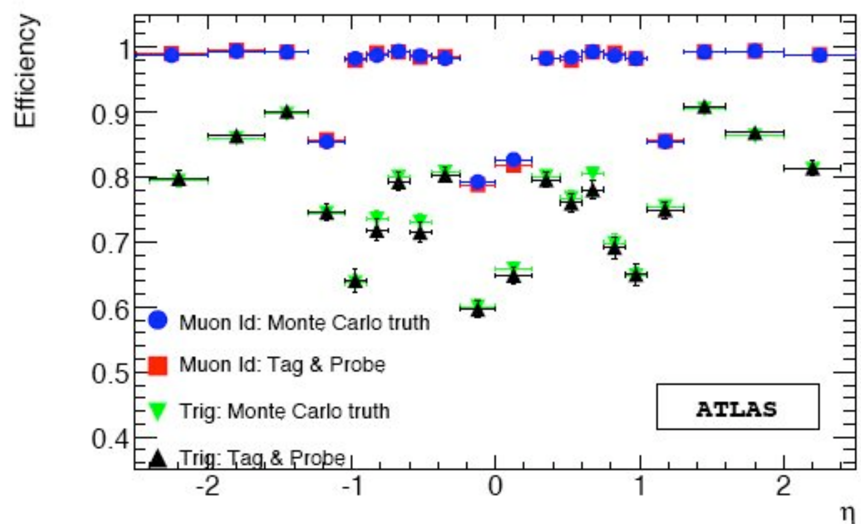
Trigger Efficiency for e's and μ's

- Can be measured using Z's with tag & probe method
  - Statistically limited

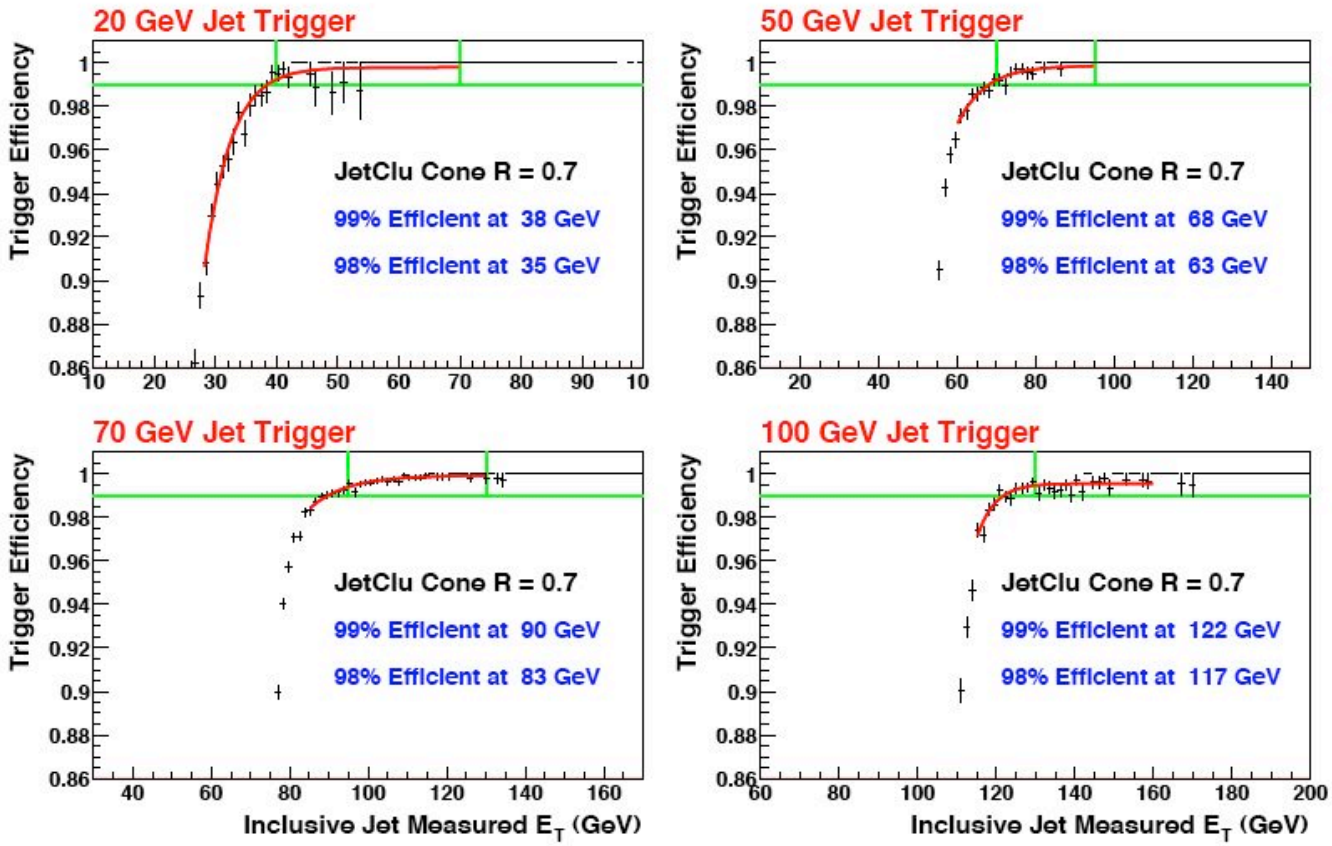
$$\varepsilon_{trig} = \frac{N_{trig}}{N_{ID}}$$

- Can also use trigger with more loose cuts to check trigger with tight cuts to map out
  - Energy dependence
    - turn-on curve decides on where you put the cut
  - Angular dependence
    - Map out uninstrumented / inefficien parts of the detectors, e.g. dead chambers
  - Run dependence
    - Temporarily masked channels (e.g. due to noise)





Jet Trigger Efficiencies



- Bootstrapping method:
  - E.g. use MinBias to measure Jet-20, use Jet-20 to measure Jet-50 efficiency … etc.
- Rule of thumb: choose analysis cut where ε>90-95%
  - Difficult to understand the exact turnon

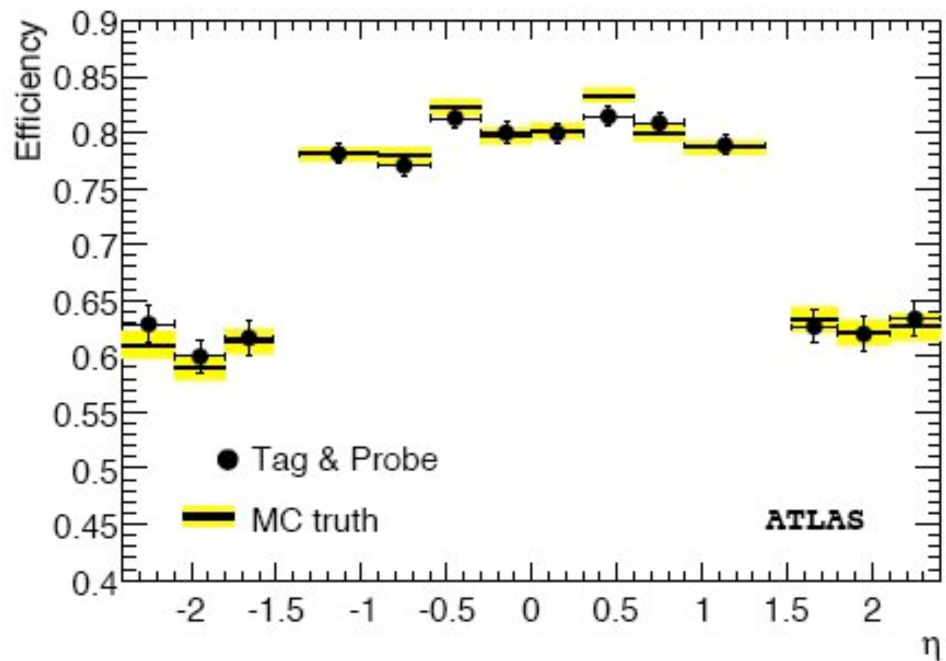
Efficiencies

Two Examples

- Electrons
- B-jets

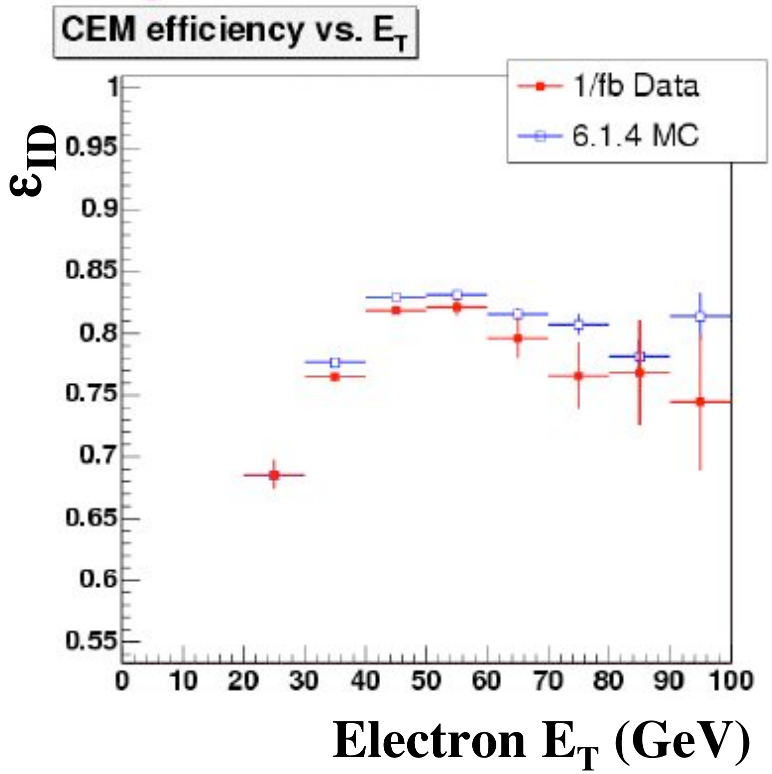
Electron Identification

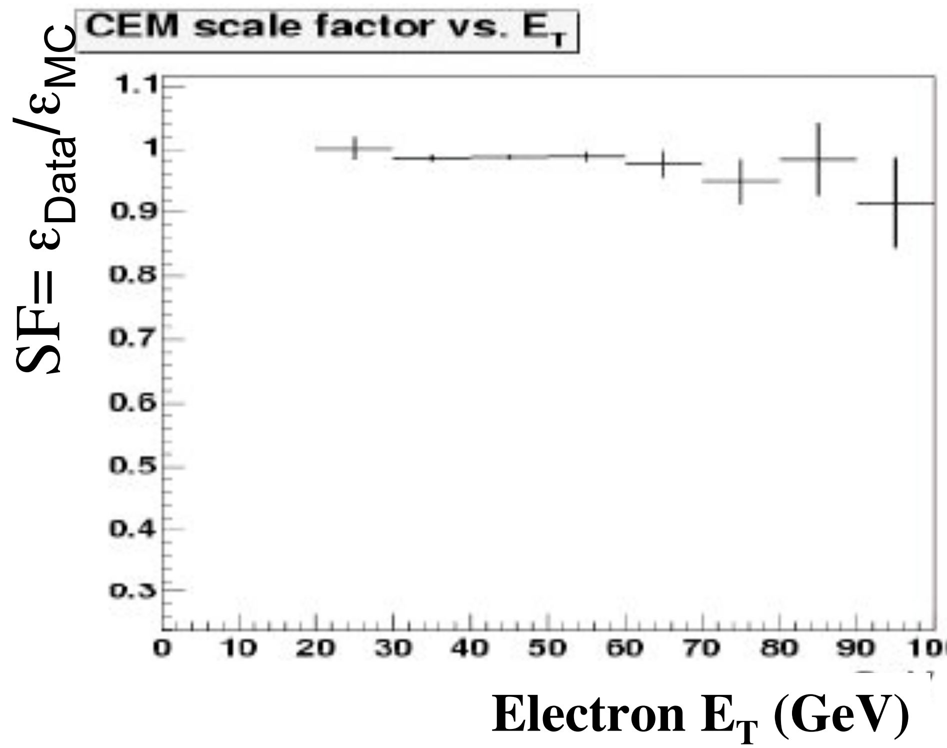
- Desire:
  - High efficiency for (isolated) electrons
  - Low misidentification of jets
- Cuts:
  - Shower shape
  - Low hadronic energy
  - Track requirement
  - Isolation
- Performance:
  - Efficiency measured from Z's using "tag and probe" method
    - See lecture by U. Bassler
  - Usually measure "scale factor":
    - SF=$\varepsilon_{Data}/\varepsilon_{MC}$ (=1 for perfect MC)
    - Easily applied to MC



	CDF	ATLAS
Loose cuts	85%	88%
Tight cuts	60-80%	~65%

Electron ID "Scale Factor"

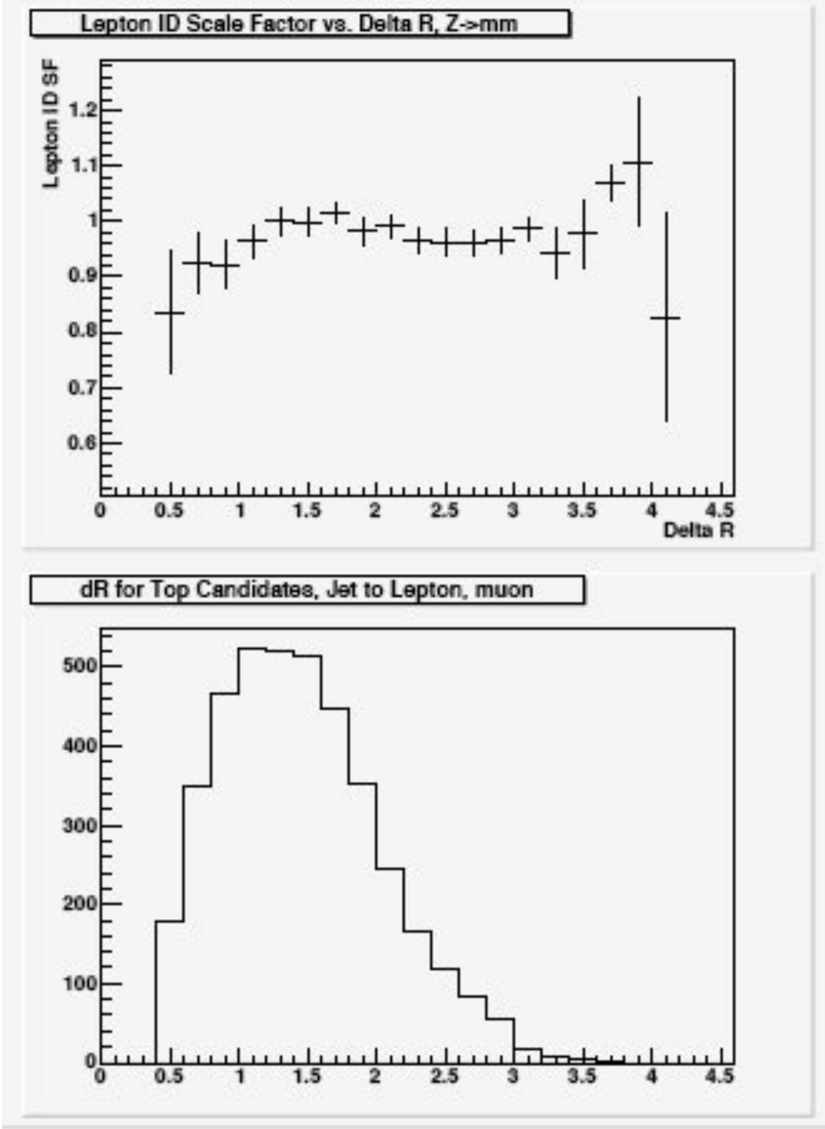




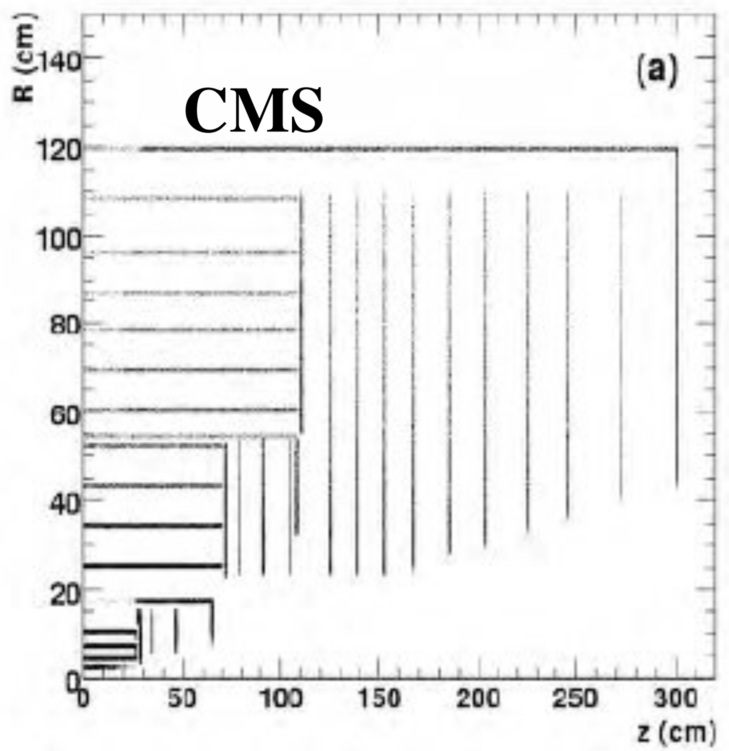
- Efficiency can generally depend on lots of variables
  - Mostly the Monte Carlo knows about dependence
- Determine "Scale Factor" = $\varepsilon_{Data}/\varepsilon_{MC}$
  - Apply this to MC
  - Residual dependence on quantities must be checked though

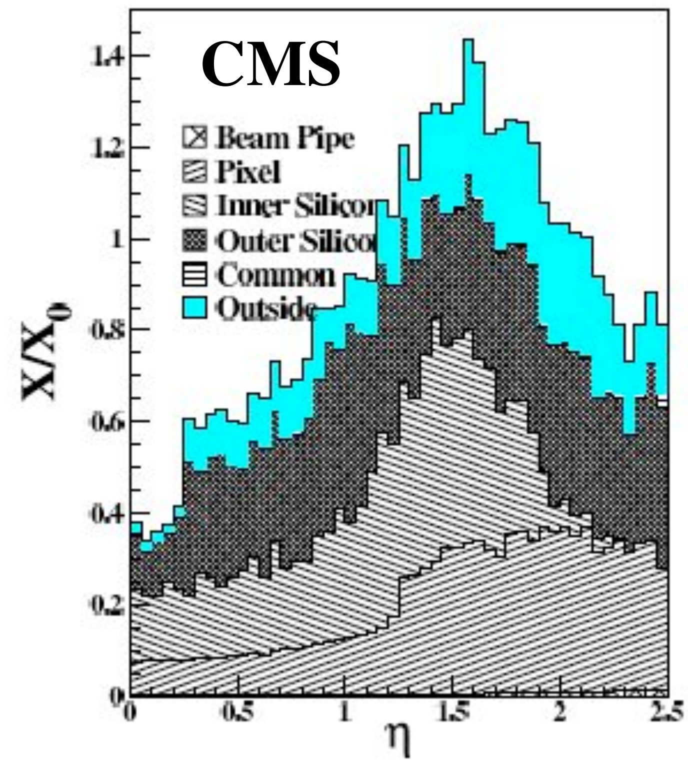
Beware of Environment

- Efficiency of e.g. isolation cut depends on environment
  - Number of jets in the event
- Check for dependence on distance to closest jet



Material in Tracker

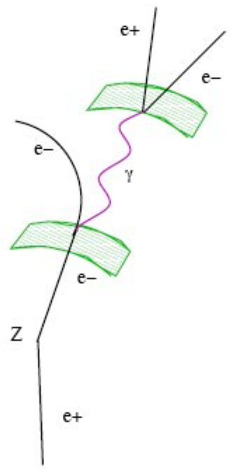


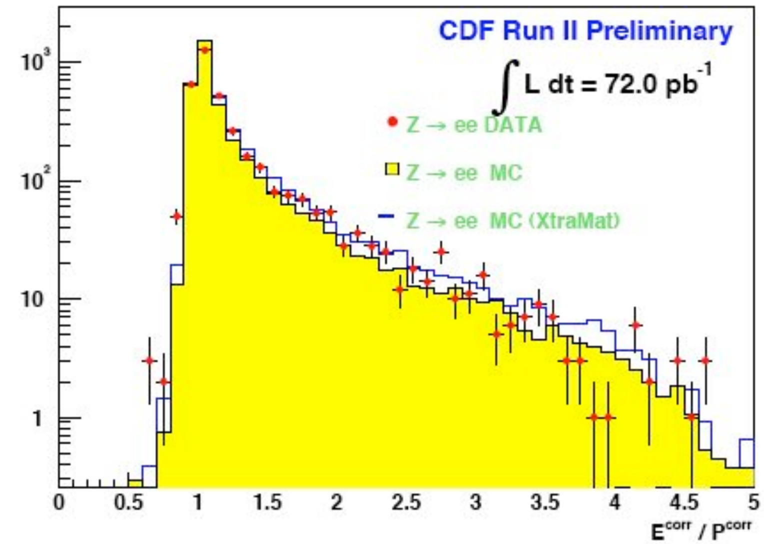


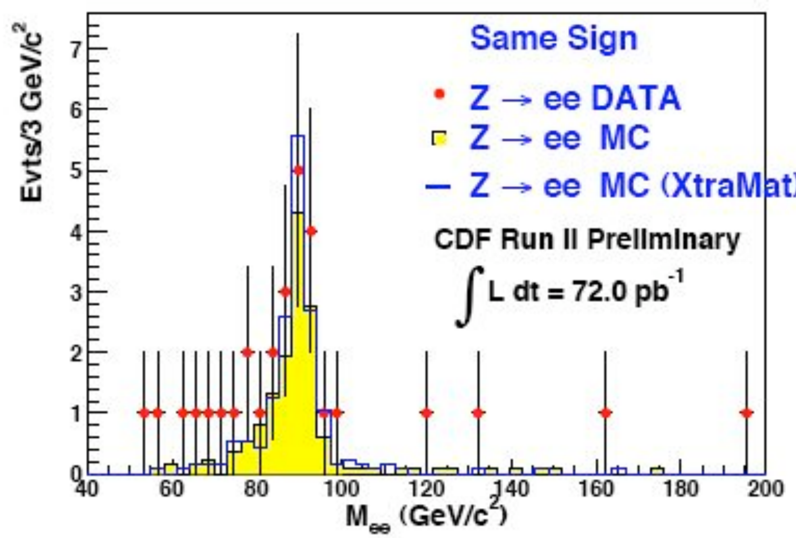
- Silicon detectors at hadron colliders constitute significant amounts of material, e.g. for R<0.4m
  - CDF: ~20% X_0
  - ATLAS: ~20-90% X_0
  - CMS: ~20-80%

Effects of Material on Analysis

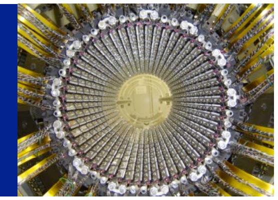
- Causes difficulties for electron/photon identification:
  - Bremsstrahlung
  - Photon conversions
- Constrained with data:
  - Photon conversions
  - E/p distribution
  - Number of $e^{\pm}e^{\pm}$ events



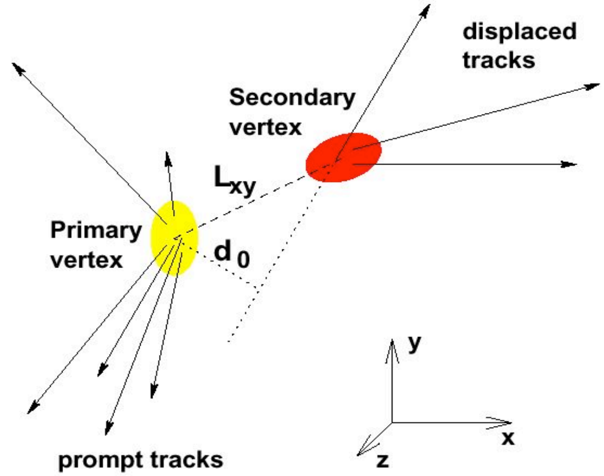


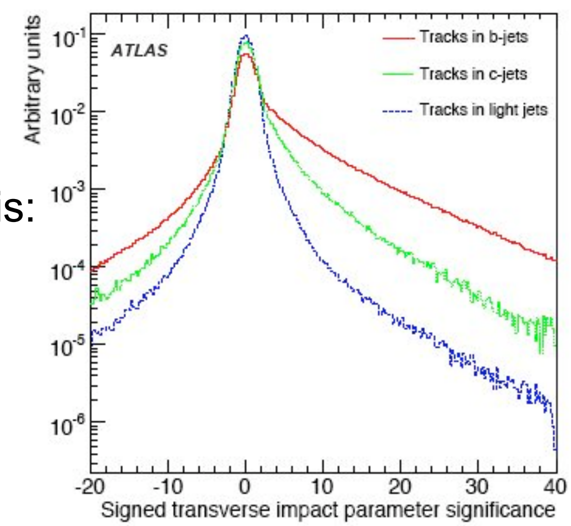


Finding the b-jets



- Exploit large lifetime of the b-hadron
  - B-hadron flies before it decays: $d=c\tau$
    - Lifetime τ =1.5 ps^{-1}
    - $d=c\tau$ = 460 μm
    - Can be resolved with silicon detector resolution
- Procedure "Secondary Vertex":
  - reconstruct primary vertex:
    - resolution ~ 30 μm
  - Search tracks inconsistent with prim. vtx (large d_0):
    - Candidates for secondary vertex
    - See whether those intersect at one point
  - Require distance of secondary from primary vertex
    - Form L_{xy}: transverse decay distance projected onto jet axis:
      - $L_{xy}>0$: b-tag along the jet direction => real b-tag or mistag
      - $L_{xy}<0$: b-tag opposite to jet direction => mistag!
    - Significance: e.g. δL_{xy} / L_{xy} >7.5
- More sophisticated techniques exist
  - Neural networks, likelihoods, etc.

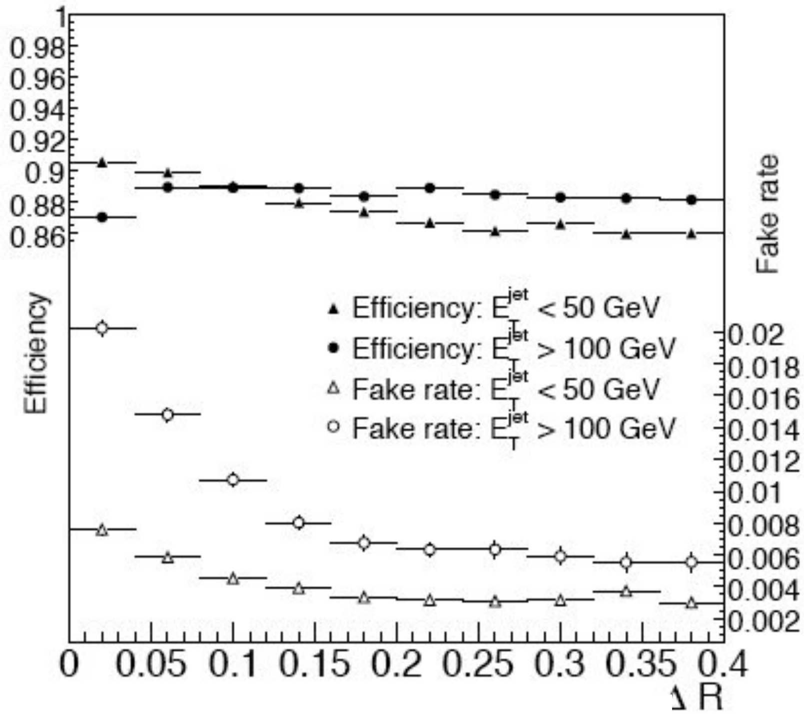




B-tagging relies on tracking in Jets

- Finding "soft" tracks inside jets is tough!
  - Difficult pattern recognition in dense environment
- Trade-off of efficiency and fake rate
- Difficult to measure in data
  - Only method I know is "track embedding"
  - Embed a MC track into data and check if one can find it

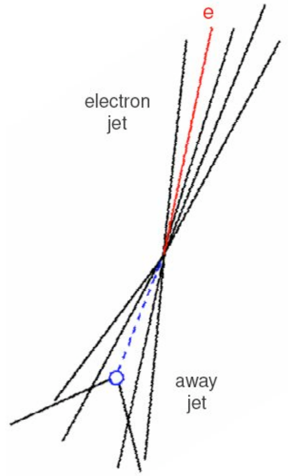
ATLAS

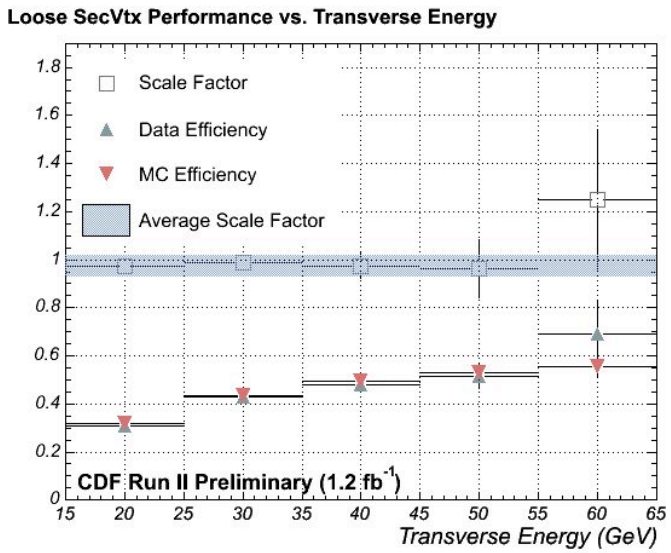


Distance to closest jet

Characterize the B-tagger: Efficiency

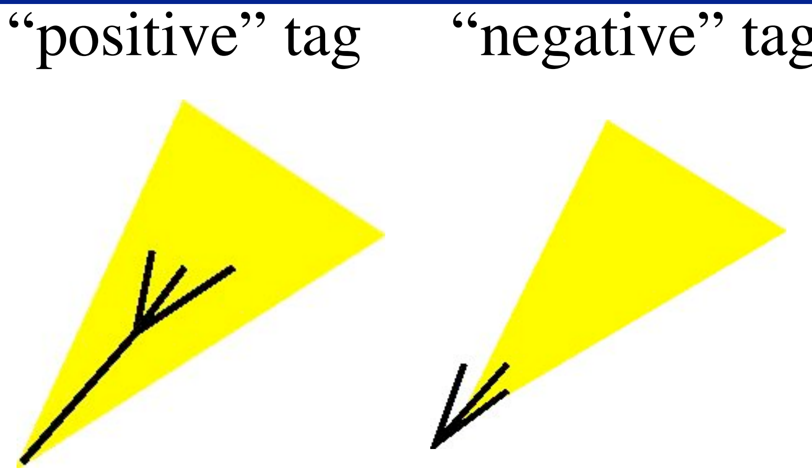
- Efficiency of tagging a true b-jet
  - Use Data sample enriched in b-jets
  - Select jets with electron or muons
    - From semi-leptonic b-decay
    - And b-jet on the opposite side
  - Measure efficiency in data and MC
    - Determine Scale Factor
  - Can also measure it in top events
    - Particularly at LHC ("top factory")

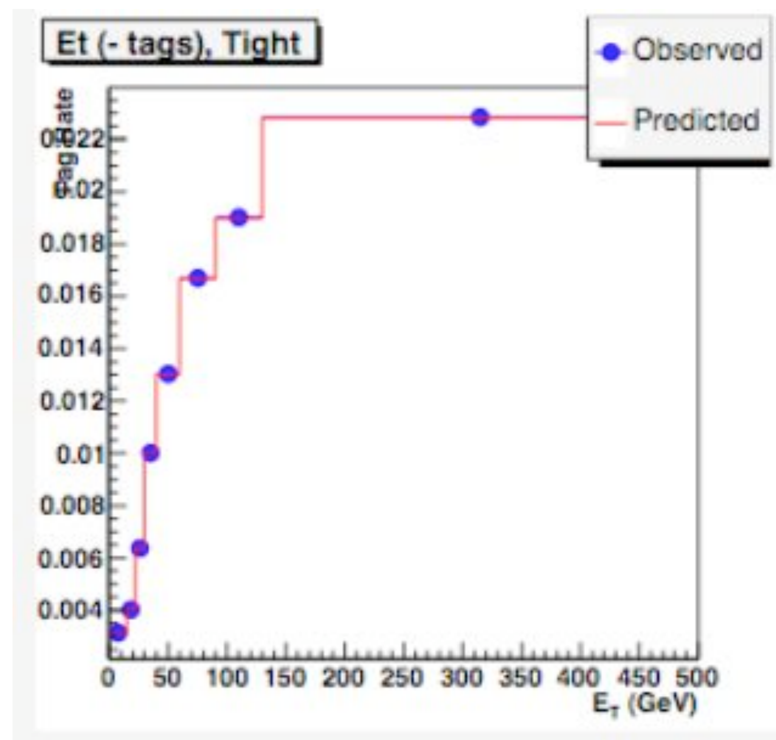




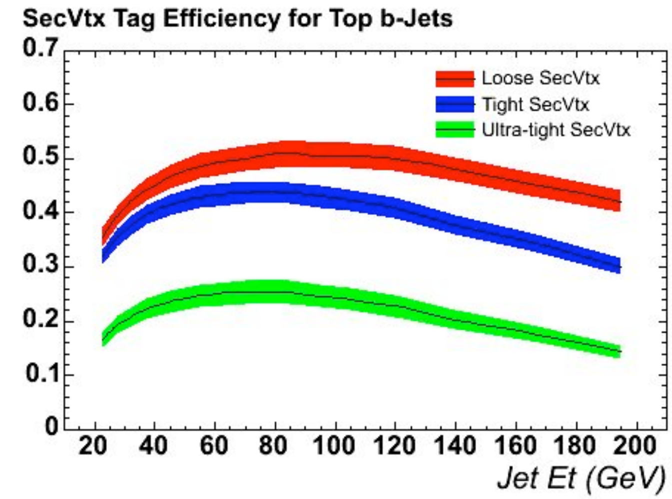
Characterize the B-tagger: Mistag rate

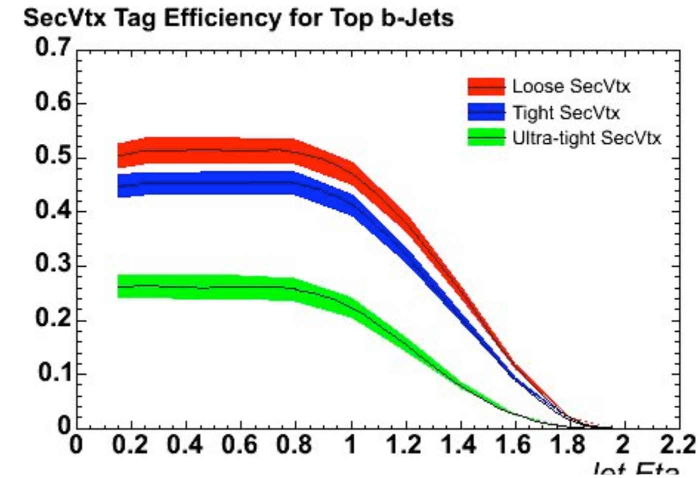
- Mistag rate measurement:
  - Probability of light quarks to be misidentified
  - Use “negative” tags: $L_{xy}<0$
    - Can only arise due to misreconstruction
  - Need to correct to positive L_{xy}
    - Material interactions, conversions etc …
- Determine rate as function of all sorts of variables
  - Apply this to data jets to obtain background

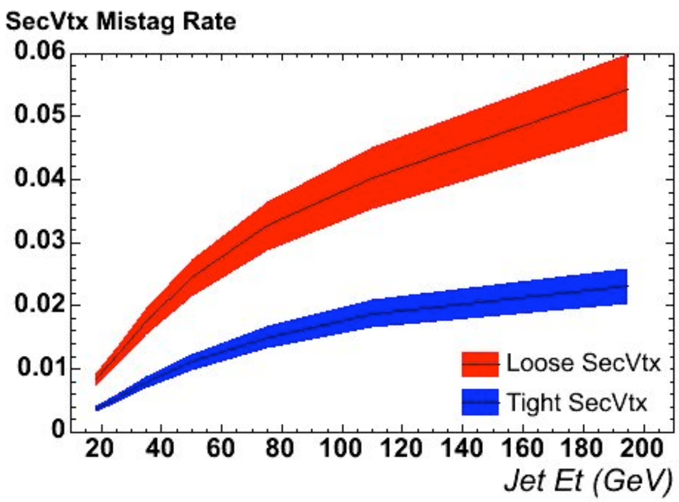


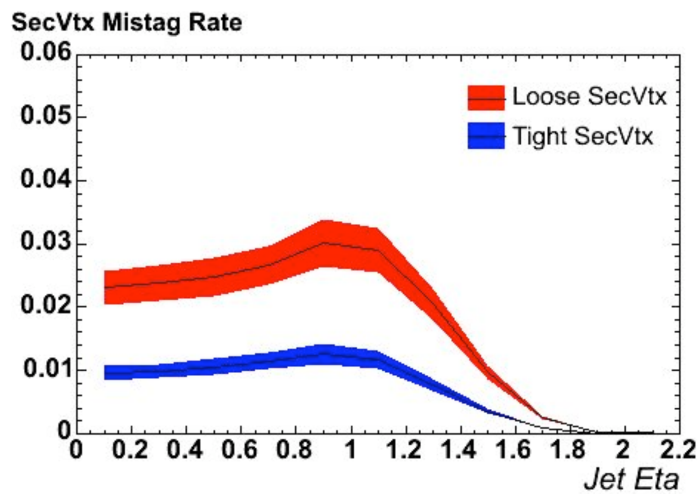


Final Performance



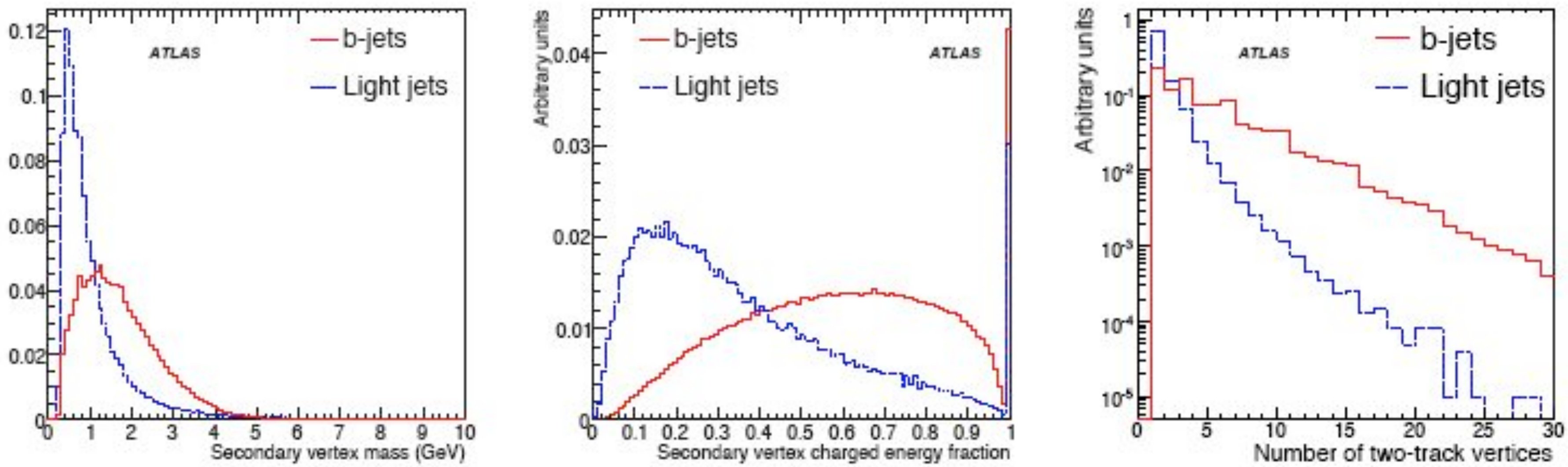




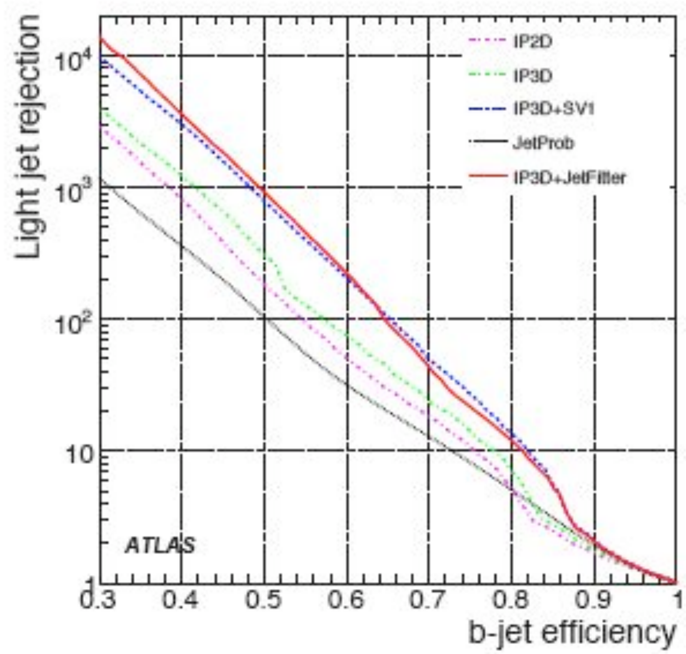


- Choose your operating point depending on analysis
  - Acceptance gain vs background rejection

Improving B-tagging

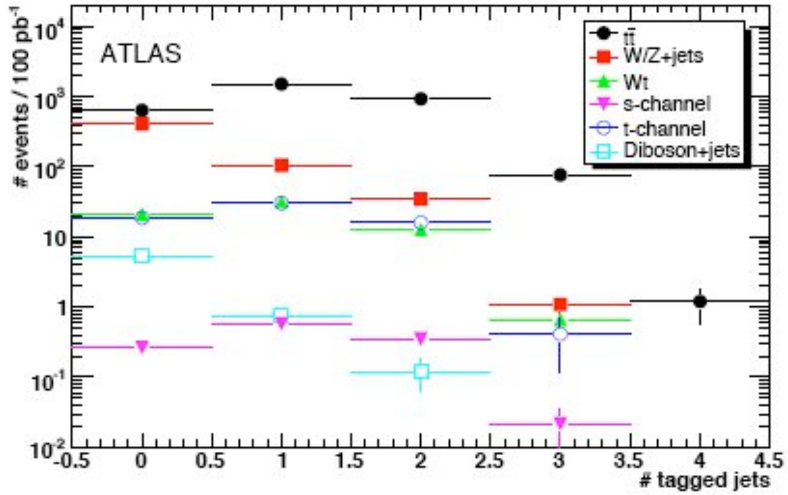


- Use more variables to achieve higher efficiency / higher purity
  - Build likelihood or Neural Network to combine the information
- E.g. for 50% efficiency
  - Mistag rate 0.1%



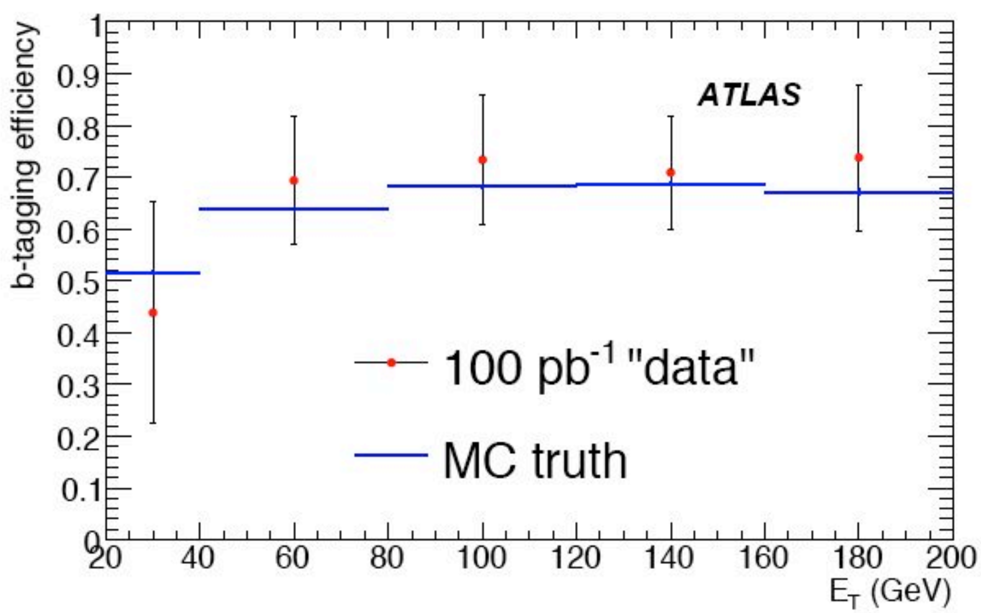
Measure b-tag Efficiency in top

- At LHC high purity of top events
  - Ntop(0-tag)$\propto (1-\varepsilon_b)^2$
  - Ntop(1-tag)$\propto 2\varepsilon_b(1-\varepsilon_b)$
  - Ntop(2-tag)$\propto \varepsilon_b^2$



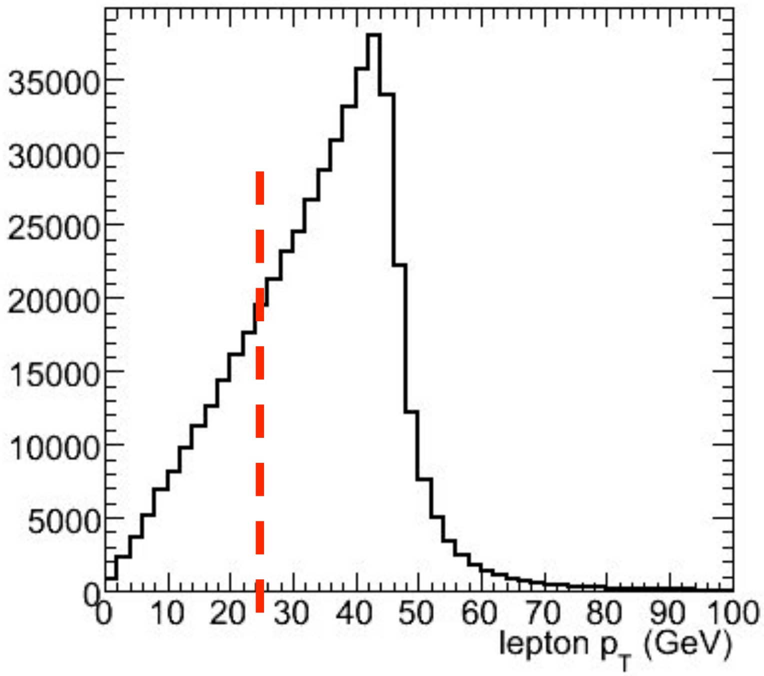
- => Solve for ε_b

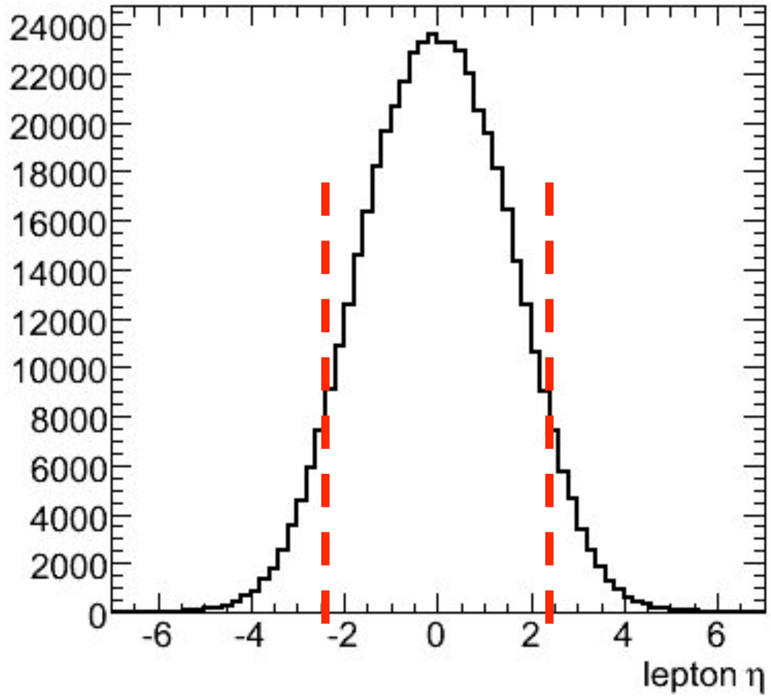
- Backgrounds are complicating this simple picture
  - But it is doable!



Acceptance of kinematic cuts

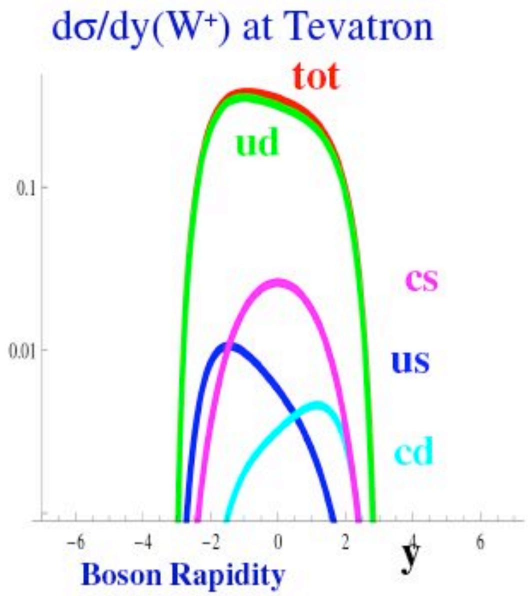
Acceptance of Kinematic Cuts: Z's

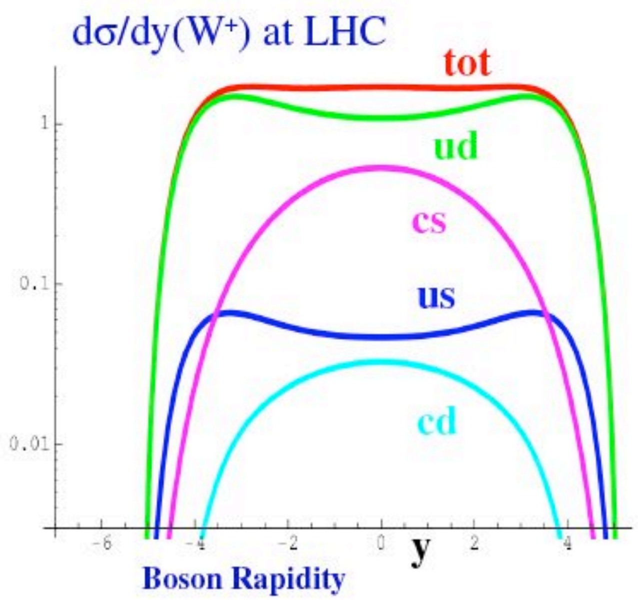


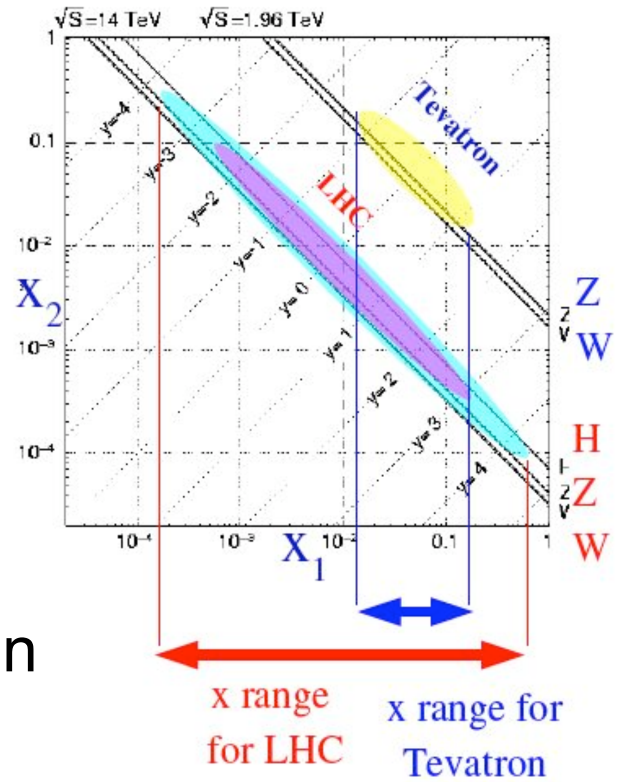


- Some events are kinematically outside your measurement range
- E.g. at Tevatron: 63% of the events fail either p_T or η cut
  - Need to understand how certain these 63% are
  - Best to make acceptance as large as possible
    - Results in smaller uncertainties on extrapolation

Parton Distribution Functions



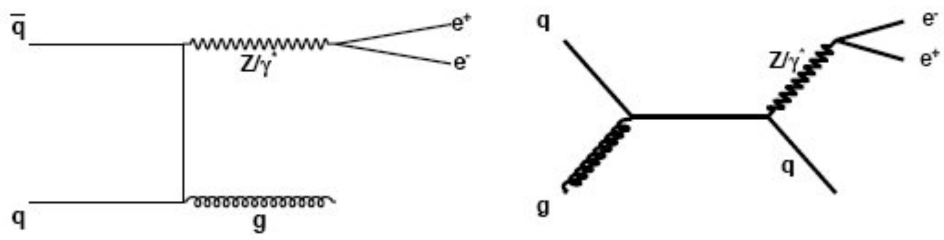


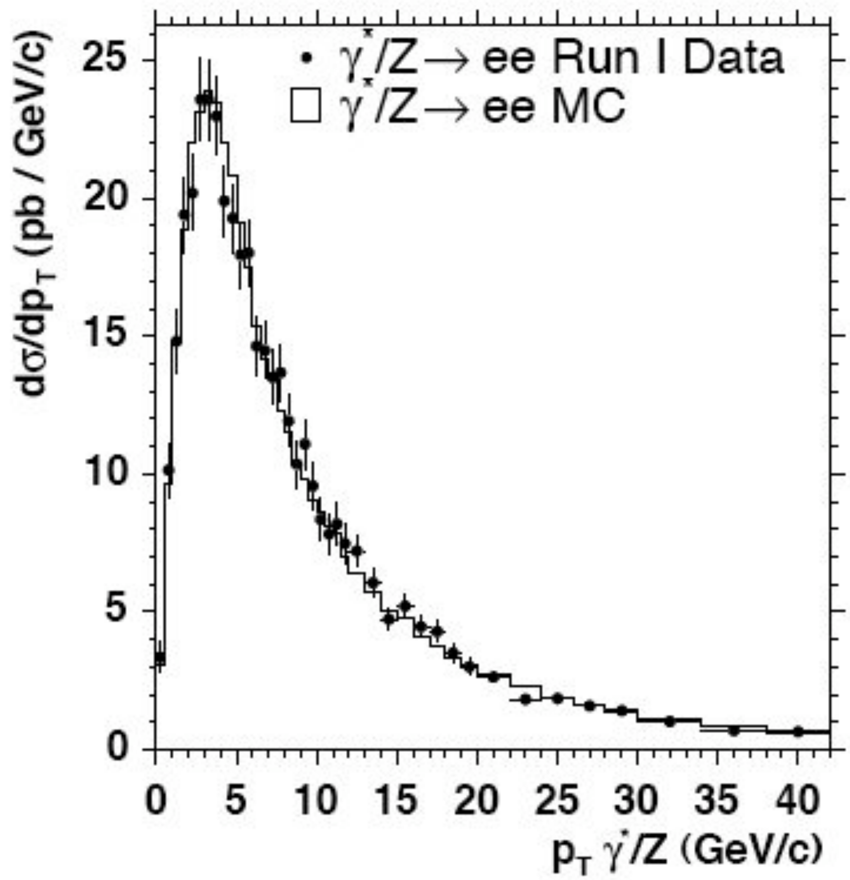


- Acceptance sensitive to parton distribution functions
  - At LHC charm quark density plays significant role but not well constrained
  - Typical uncertainties on charm pdf: ~10%
- Can result in relatively large systematic uncertainties

QCD Modeling of Process

- Kinematics affected by p_T of Z boson
  - Determined by soft and hard QCD radiation
    - tune MC to describe data
- Limitations of Leading Order Monte Carlo
  - Compare to NNLO calculation



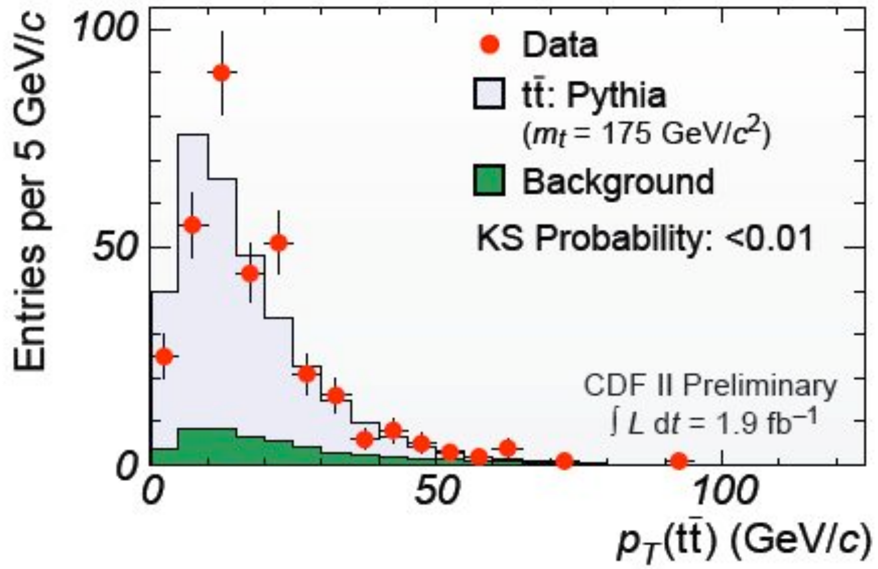


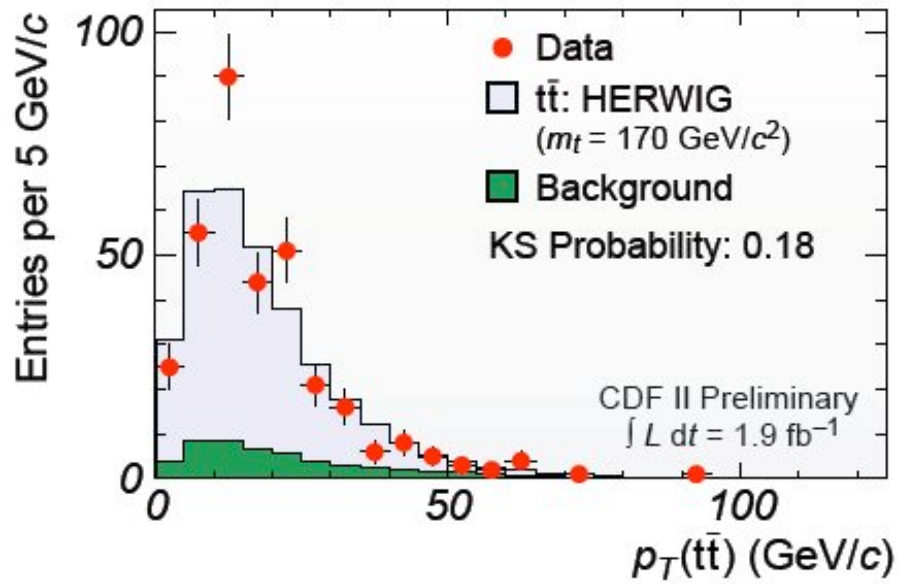
CDF TABLE XII: Central acceptance values for our candidate samples based on $d\sigma/dy$ distributions obtained from both NNLO and PYTHIA simulation.

Acceptance	NNLO Calc.	PYTHIA	Difference (%)
$A_{W\to\mu\nu}$	0.1970	0.1967	+0.15
$A_{W\to e\nu}$	0.2397	0.2395	+0.08
$A_{Z\to\mu\mu}$	0.1392	0.1387	+0.36
$A_{Z\to ee}$	0.3182	0.3185	-0.09
$A_{Z\to\mu\mu}/A_{W\to\mu\nu}$	0.7066	0.7054	+0.17
$A_{Z\to ee}/A_{W\to e\nu}$	1.3272	1.3299	-0.20

MC Modeling of top

- Use different MC generators
  - Pythia
  - Herwig
  - Alpgen
  - MC @ NLO
  - …
- Different tunes
  - Underlying event
  - Initial/final state QCD radiation
  - …
- Make many plots
  - Check if data are modelled well

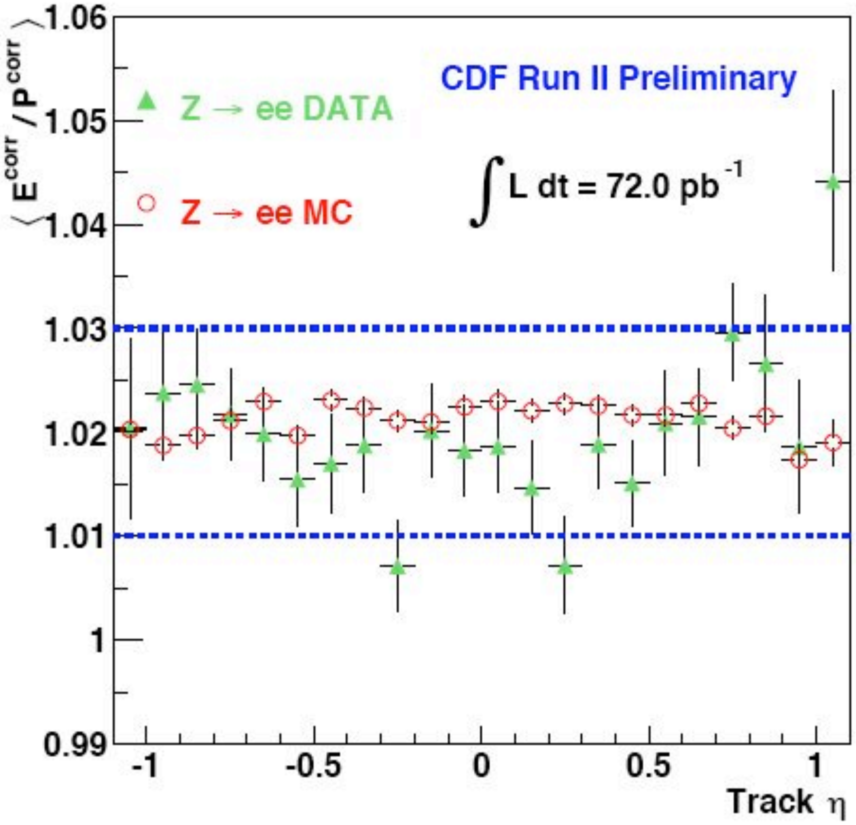


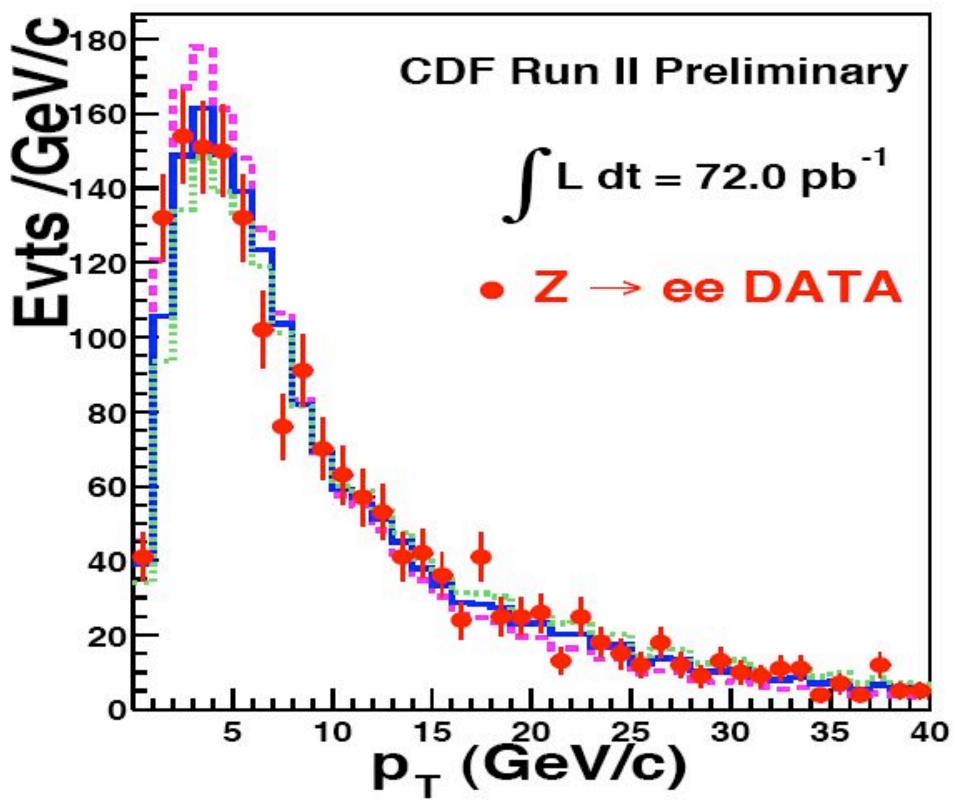


Systematic uncertainties

- This will likely be >90% of the work
- **Systematic errors cover our lack of knowledge**
  - need to be determined on every aspect of measurement by varying assumptions *within sensible reasoning*
  - Thus there is no "correct way":
    - But there are good ways and bad ways
    - You will need to develop a feeling and discuss with colleagues / conveners / theorists
    - There is a lot of room for creativity here!
- What's better? Overestimate or underestimate
  - Find New Physics:
    - it's fine to be generous with the systematics
    - You want to be really sure you found new physics and not that "Pythia doesn't work"
  - Precision measurement
    - Need to make best effort to neither overestimate nor underestimate!

Examples for Systematic Errors





- Mostly driven by comparison of data and MC
  - Systematic uncertainty determined by (dis)agreement and statistical uncertainties on data

Systematic Uncertainties: Z and top

Z cross section (not all systematics)

source	variation	ΔA_Z	$\Delta A_Z / A_Z$
E_T^e scale	1% variation	0.03%	0.3%
E_T^e resolution	2% extra smearing	0.02%	0.2%
p_T^e scale	1% variation	0.01%	0.1%
p_T modelling		0.01%	0.1%
Material	5.5 % X_0	0.54%	4.7%
PDFs	reweighting of y	0.34%	2.9%
overall		0.64%	5.5%

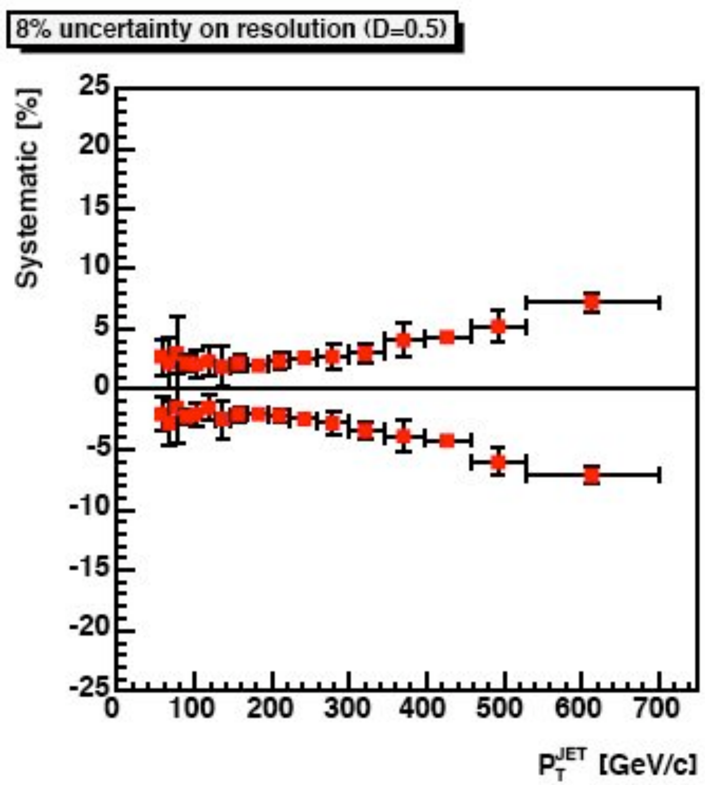
top cross section

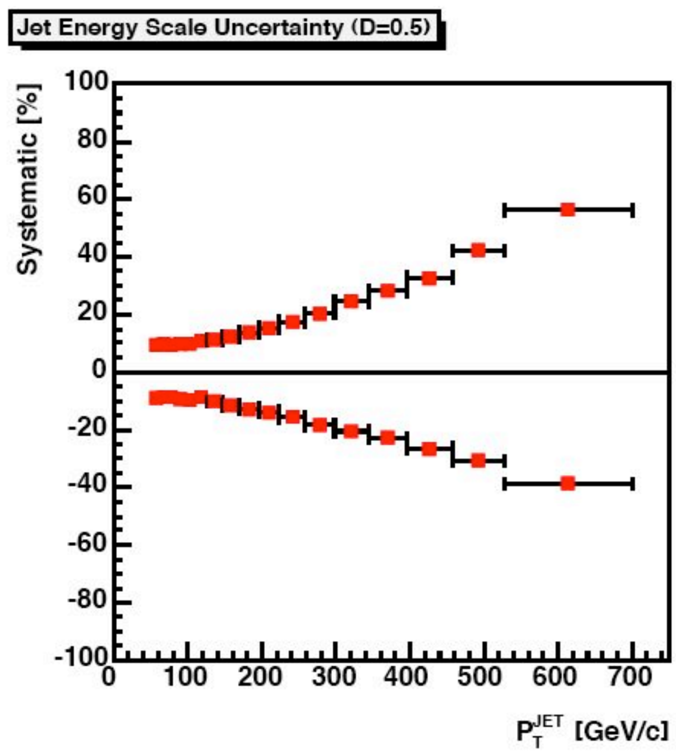
<table>
<tr><th>Systematic</th><th>Inclusive (Tight)</th><th>Double (Loose)</th></tr>
<tr><td>Lepton ID</td><td colspan="2">1.8</td></tr>
<tr><td>ISR</td><td>0.5</td><td>0.2</td></tr>
<tr><td>FSR</td><td>0.6</td><td>0.6</td></tr>
<tr><td>PDFs</td><td colspan="2">0.9</td></tr>
<tr><td>Pythia vs. Herwig</td><td>2.2</td><td>1.1</td></tr>
<tr><td>Luminosity</td><td colspan="2">6.2</td></tr>
<tr><td>JES</td><td>6.1</td><td>4.1</td></tr>
<tr><td>b-Tagging</td><td>5.8</td><td>12.1</td></tr>
<tr><td>c-Tagging</td><td>1.1</td><td>2.1</td></tr>
<tr><td>l-Tagging</td><td>0.3</td><td>0.7</td></tr>
<tr><td>Non-W</td><td>1.7</td><td>1.3</td></tr>
<tr><td>W+HF Fractions</td><td>3.3</td><td>2.0</td></tr>
<tr><td>Mistag Matrix</td><td>1.0</td><td>0.3</td></tr>
<tr><td>Total</td><td>11.5</td><td>14.8</td></tr>
</table>

- Relative importance and evaluation methods of systematic uncertainties are very, very analysis dependent

Systematic Uncertainties: Jets

Jet cross section





- For Jet Cross Section the Jet Energy Scale (JES) uncertainty is dominant systematic error
  - 3% uncertainty on JES results in up to 60% uncertainty on cross section

Final Result: Z cross section

- Now we have everything to calculate the final cross section

TABLE XXXVII: Summary of the input parameters to the $\gamma^*/Z \to \ell\ell$ cross section calculations for the electron and muon candidate samples.

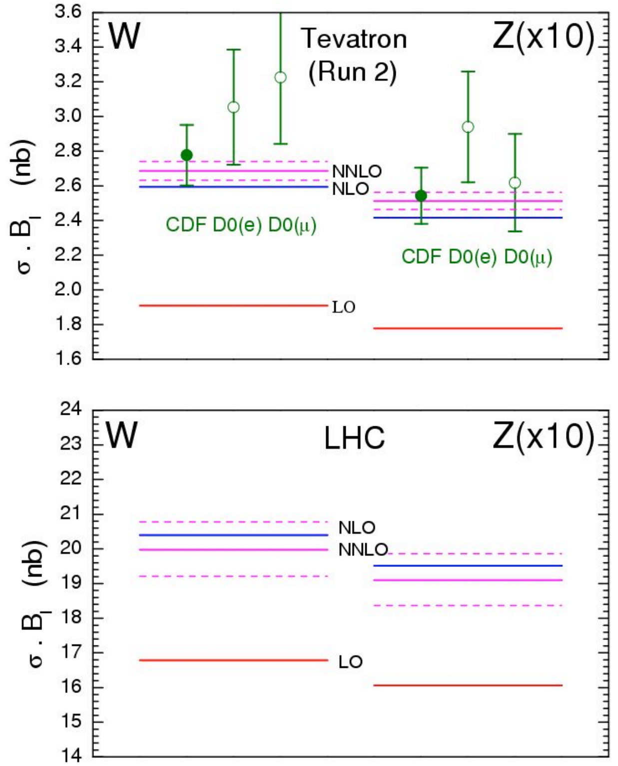
	$\gamma^*/Z \to ee$	$\gamma^*/Z \to \mu\mu$
N_Z^{obs}	4242	1785
N_Z^{bck}	62 ± 18	13 ± 13
A_Z	$0.3182\ ^{+0.0039}_{-0.0041}$	$0.1392\ ^{+0.0027}_{-0.0033}$
ϵ_Z	0.713 ± 0.012	0.713 ± 0.015
$\int \mathcal{L}dt$ (pb^{-1})	72.0 ± 4.3	72.0 ± 4.3

$$\sigma_{\gamma^*/Z} \cdot Br(\gamma^*/Z \to ee) = 255.8 \pm 3.9(stat.) \pm {}^{5.5}_{5.4}(syst.) \pm 15.3(lum.)\ \text{pb}$$

Measurement gets quickly systematically limited

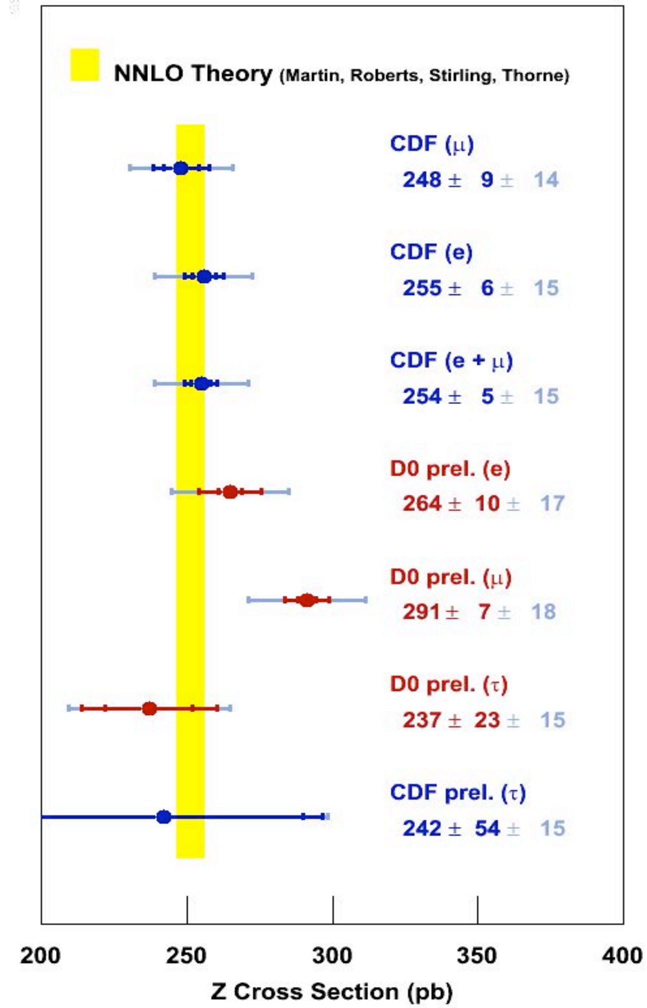
Comparison to Theory

- Experimental uncertainty: ~2%
- Luminosity uncertainty: ~6%
- Theoretical uncertainty: ~2%



partons: MRST2002
NNLO evolution: Moch, Vermaseren, Vogt
NNLO W,Z corrections: van Neerven et al. with Harlander, Kilgore corrections

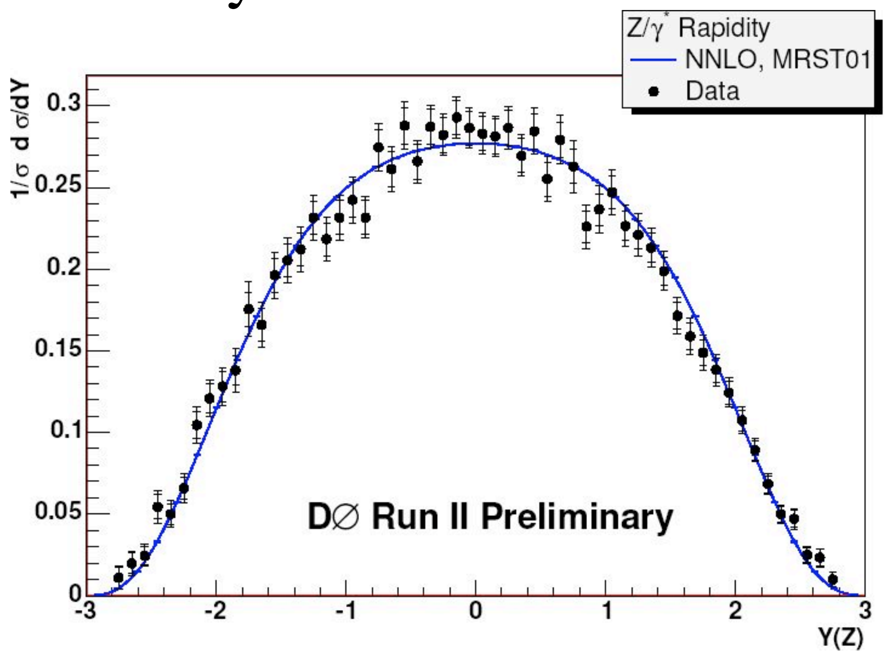
$\sigma_{Th,NNLO}$=251.3±5.0pb
(Martin, Roberts, Stirling, Thorne)

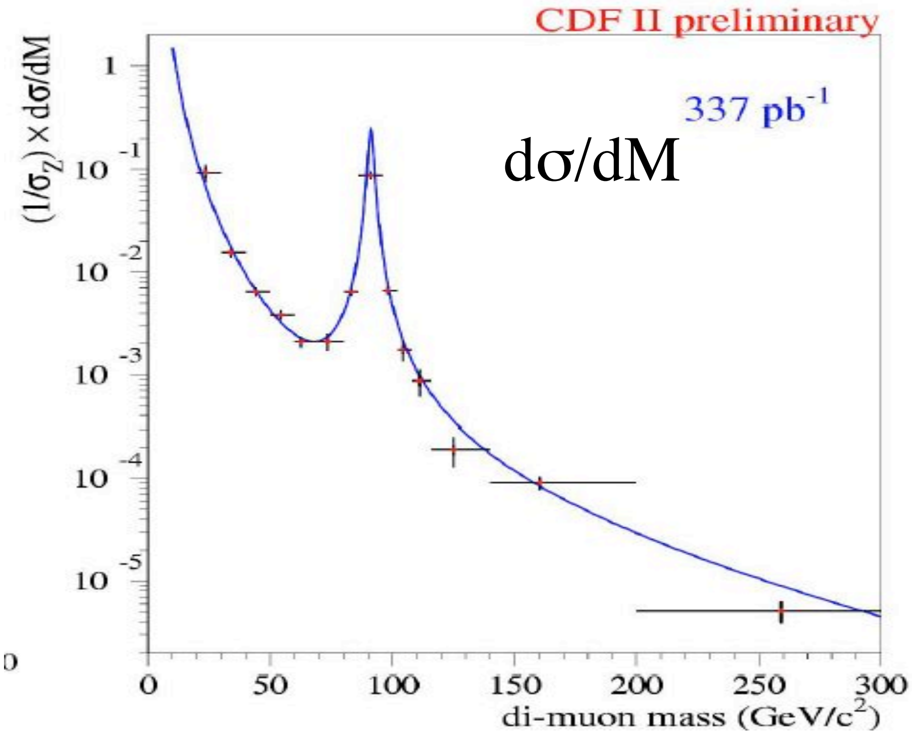


- Can use these processes to normalize luminosity absolutely
  - However, theory uncertainty larger at LHC and theorists don't agree (yet)

More Differential σ(Z) Measurements

dσ/dy



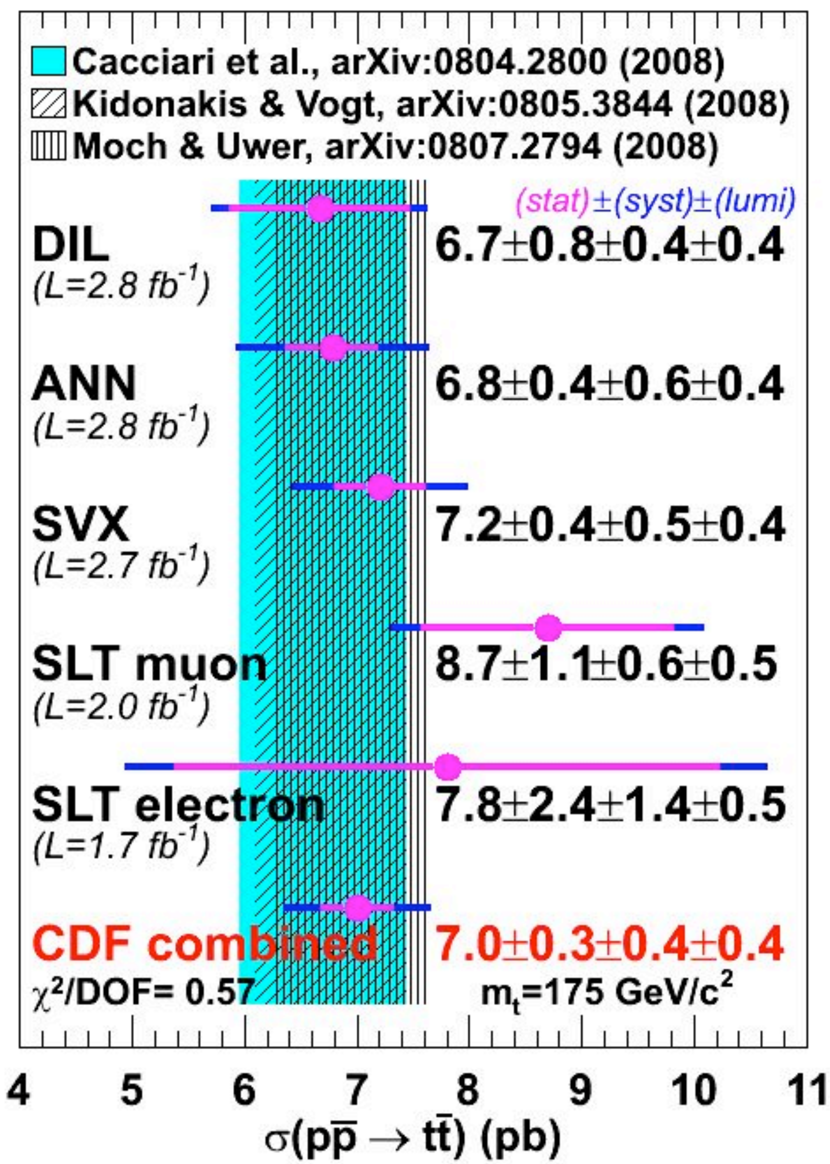


dσ/dM

Differential measurements in principle very similar

But now need to understand all efficiencies as function of y or mass

Final Results: Top Cross Section



- **Tevatron**
  - Measured using many different techniques
  - Good agreement
    - between all measurements
    - between data and theory
  - Precision: ~9%
- **LHC:**
  - Cross section ~100 times larger
  - Measurement will be one of the first milestones (already with 10 pb^{-1})
    - Test prediction
    - demonstrate good understanding of detector
  - Expected precision
    - ~4% with 100 pb^{-1}

Conclusions of 1st Lecture

- Cross section measurements require
  - Selection cuts
    - Optimized to have large acceptance, low backgrounds and small systematic uncertainties
  - Luminosity measurement
    - Several methods of varying precision
  - Trigger
    - Complex and critical: what we don't trigger you cannot analyze!
  - Acceptance/efficiency has many subcomponents
    - Estimate of systematic uncertainties associated with each
    - Dependence on theory assumptions and detector simulation particularly critical
    - Minimize extrapolations to unmeasured phase space
  - Background estimate
    - See final lecture
- Systematic uncertainties are really a lot of work