Hard Scattering in Hadron-Hadron Collisions: Physics and Anatomy

Section 1: Introduction, Colliders and Detectors

1. Basic anatomy of a collision
2. Collider considerations
3. Detector Implications
4. Example: Top quark pair production

Course Syllabus

This mini-course will summarize how we understand the process by which hard scattering events, characterized typically by high transverse-momentum (P_T) processes, occur in energetic hadron-hadron collisions, and what effects have to be understood and taken into account in order to make robust measurements and discoveries of new phenomena. The course will focus on the 7-14 TeV proton-proton collisions produced by the Large Hadron Collider, but will use examples from experience gained at the 2 TeV proton-antiproton Tevatron Collider. The anatomy of a hard-scattering event will be dissected, and we'll discuss each element through an interplay between the theoretical and phenomenological framework and the experimental challenges.

This course is targeted at the level of a graduate student in particle physics experiment or phenomenology who already has some background in relativistic quantum field theory and the Standard Model of particle physics.

References:

Collider Physics (Updated Edition), Barger & Phillips, Westview Press (1996).

Some Introductory Comments

- **Standard approach to hadron-hadron collisions is to**
  - **Focus on high P_T process**
  - **Largely ignore most of the other effects**
    - Some of which are quite important
    - Could lead to different analysis choices
    - Largely not well documented (or understood)
- **Approach here will be to dissect a collision**
  - **Not focus as much on the theory of the hard-scattering process, ie., matrix element (ME)**
  - **More on what this process looks like "dressed up" with all the real-life effects**
  - **Challenges that must be confronted in making measurements**

Anatomy of a Collision

- **Pick apart the collision**
  - **Incoming proton (or pbar) bunches**
    - + beam halo and other garbage
  - **Assume time of interaction << timescale of any other process**
    - Treat hadron as a "bag" of free partons
  - **Two partons interact**
    - Hard scattering process
  - **Rest of hadrons "fragment" into an underlying event (UE)**
    - Caused by initial acceleration?
  - **Maybe (usually?) have one or more independent collisions (pileup)**
    - Increases low-energy particle multiplicities
    - Has effects on instrumentation

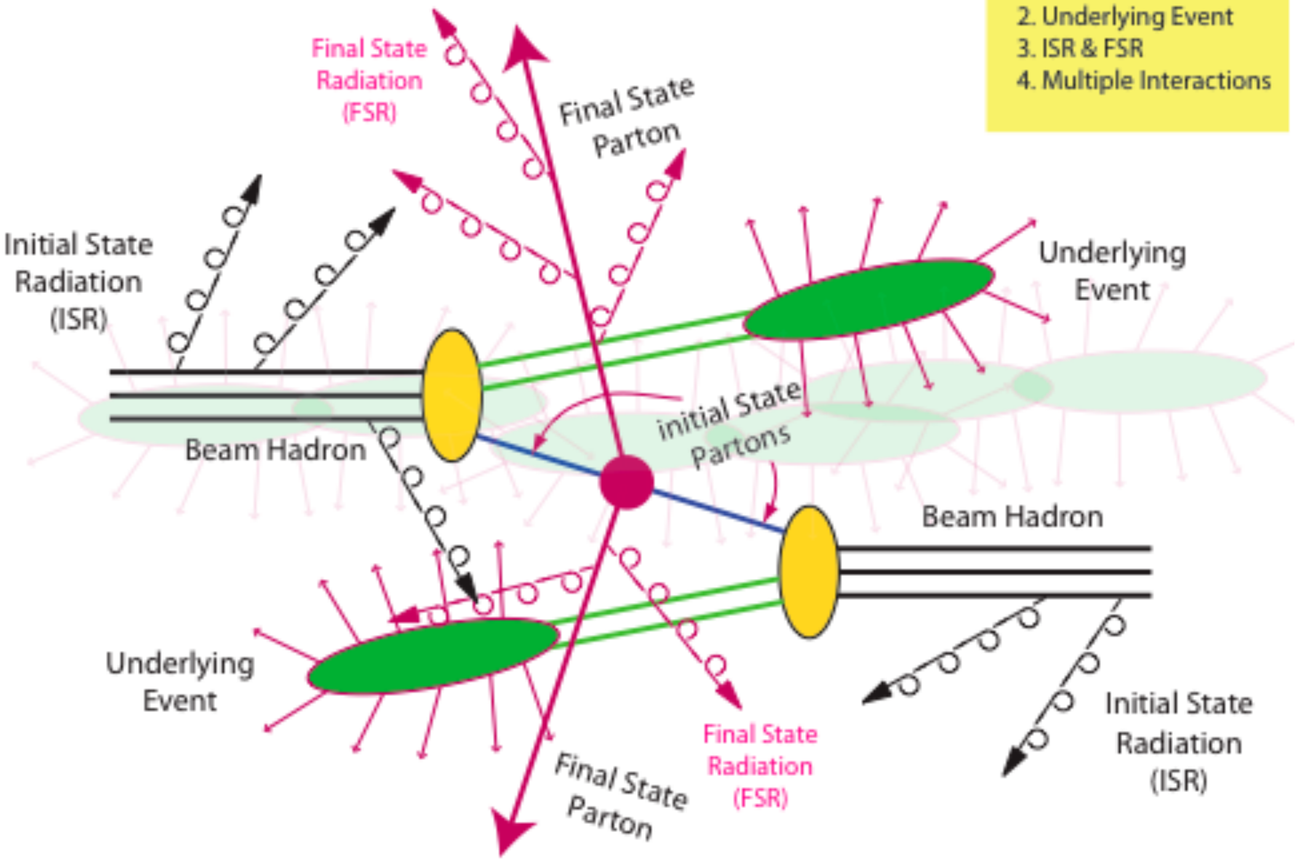
- **Acceleration process produces**
  - **Initial State Radiation (ISR)**
  - **Final State Radiation (FSR)**

- **UE characterized by**
  - **~60 particles**
  - **Average PT ~ 0.5 GeV/c**
  - **Distributed uniformly in η**

- **Multiple interactions depend on**
  - **Instantaneous luminosity and crossing rate**
    - Increases low-energy particle multiplicities
  - **Long read-out times result in "pileup" effects from one crossing to the next**

Picturing a Hard Scatter

1. Hard Scatter
2. Underlying Event
3. ISR & FSR
4. Multiple Interactions



First Look at Hard Scattering

- **We start with two partons interact**
  - **Each has momentum fraction x_1, x_2 of hadron**
    - Given by parton distribution function (PDFs)
    - Either valence (u,d) or gluons & sea quarks
  - **Cross section given by**

$$\sigma = \sum_{\substack{partons\ i \\ colour\ j}} C_{ij} \int_0^1 d\tau \int_\tau^1 \frac{dx_1}{\tau} \left[f_1(x_1) f_2(\tau / x_1) \right] \hat{\sigma}'(\tau s)$$

$\hat{\sigma}'$ *is partonic cross section*

$$\tau = x_1 x_2$$

- **"Factorize" the problem:**
  - **Subprocess cross section**
    - Summed over colours & spins
  - **Colour average factors (C_{ij})**
    - $C_{ij} = 1/9$ for quarks
    - $C_{ij} = 1/64$ for gluons
  - **Parton distribution functions (PDF)**

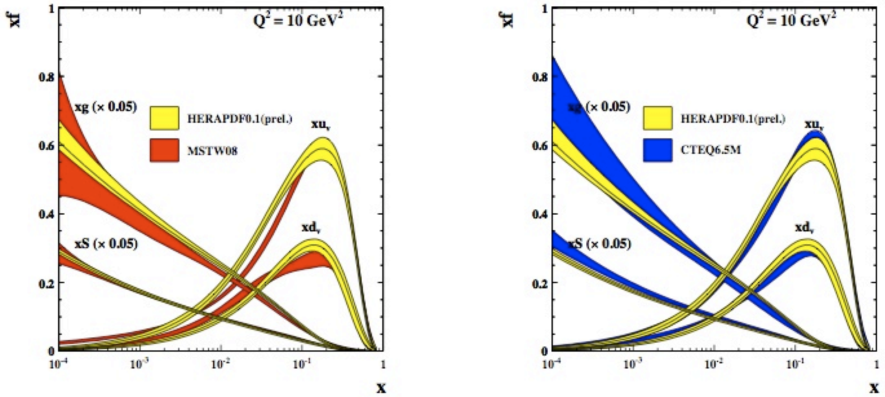


Figure 4: HERAPDF0.1 fit compared with MSTW and CTEQ fits.

C. Diaconu, hep-ex/0901.0046v1

Collider Considerations

- **Basic function is to**
  - **Create well-confined bunches of particles**
  - **Accelerate them to nominal energy**
  - **Reduce any "beam related backgrounds"**
  - **Maintain collisions till store is finished**

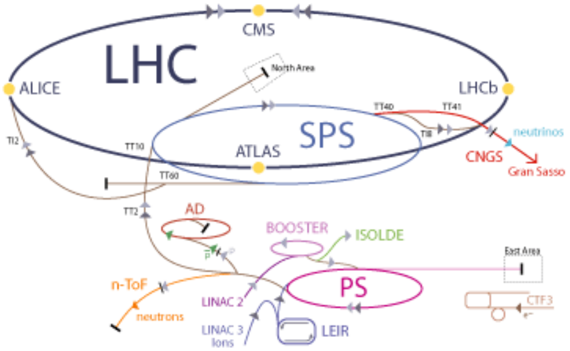
- **Figures of merit are:**
  - **Instantaneous luminosity**
  - **Beam lifetime**
  - **Low beam-related backgrounds**

$$L = \frac{rN_1N_2}{4\pi\sigma_x\sigma_y}$$

r = crossing rate

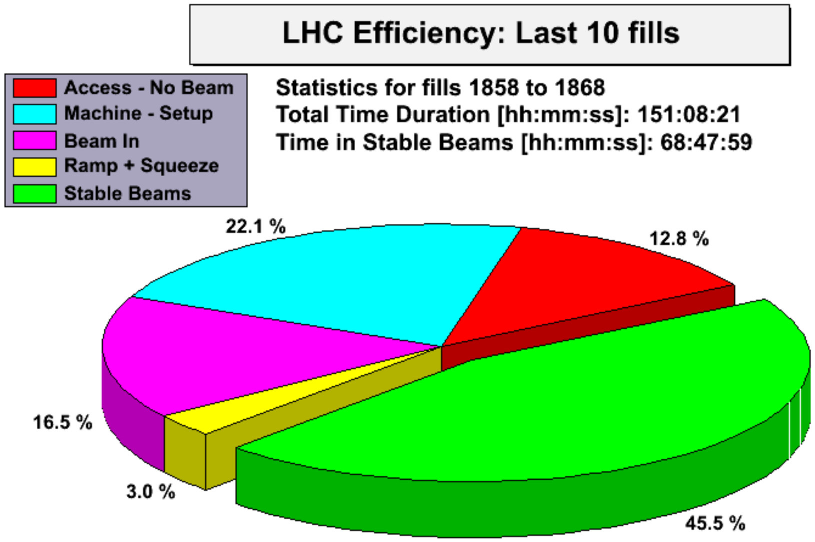
$N_{1,2}$ =# particles bunch$_{1,2}$

$\sigma_{x,y}$ = bunch profile$_{x,y}$



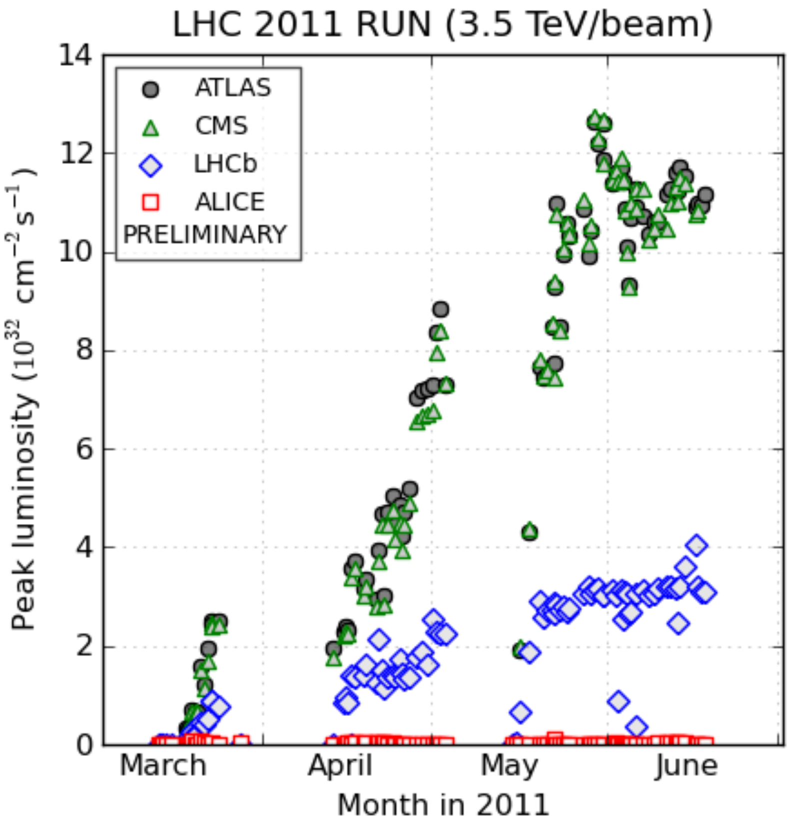
	Tevatron	LHC (Design)	LHC (Now)
Beam Energy (TeV)	0.98	7.00	3.50
Crossing Rate (MHz)	2.52	40.08	20.04
Bunches	36	2,808	1,092
Particles/Bunch - N1 (10^11)	2.50	1.15	1.25
Particles/Bunch - N2 (10^11)	0.70	1.15	1.25
Transerve size (microns)	30	17	17
L (10^33 cm-2 s-1)	0.32	10.00	10.00
Multiple Interactions/crossing	6	20-25	20-25
Beam Lifetime (hr)	15-20	15.00	15.00

Accelerator Operations



Statistics for fills 1858 to 1868
Total Time Duration [hh:mm:ss]: 151:08:21
Time in Stable Beams [hh:mm:ss]: 68:47:59

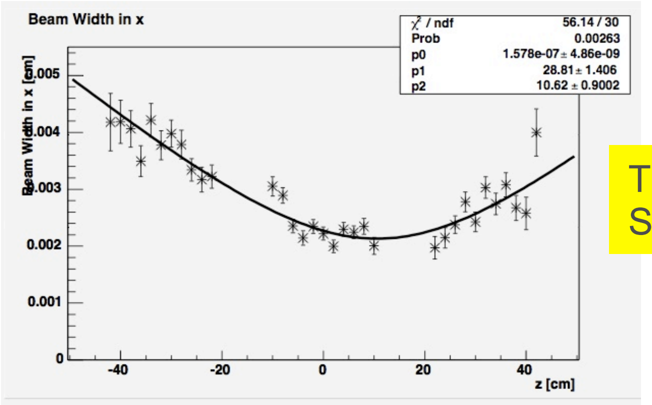
F. Zimmermann, ATLAS Week (June 2011)



(generated 2011-06-19 08:11 including fill 1880)

Luminosity Measurement & Total Cross Section

- **Luminosity measurement itself a challenge**
- **Two approaches**
  - **Collider parameters**
    - Difficult to measure beam properties with precision
    - Uncertainties at Tevatron 15-20%
  - **Collison rate at IP**
    - Detectors don't "see" total cross section
    - Have to use "tricks" to extrapolate
    - CDF/DØ have achieved precisions of no better than 6%
      - **4% from uncertainty in σ_{in}**
      - **3% from uncertainty in acceptance**



Transverse Beam Size at CDF

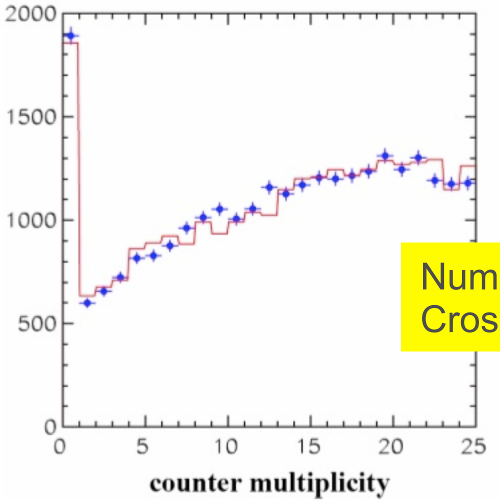


Fig. 3. Data vs Monte Carlo simulation comparison of the multiplicity of the luminosity counters at D0 using the final non-diffractive fraction. The points represent the data and the solid line the Monte Carlo. The plot corresponds to an instantaneous luminosity of 1.3 x 10^{31} $cm^{-2}s^{-1}$.

Number of "empty" Crossings at D0

$$\mu \times r = \sigma_{in} \times L$$

$\mu = \langle \text{interactions /crossing} \rangle$

σ_{in} = inelastic cross section

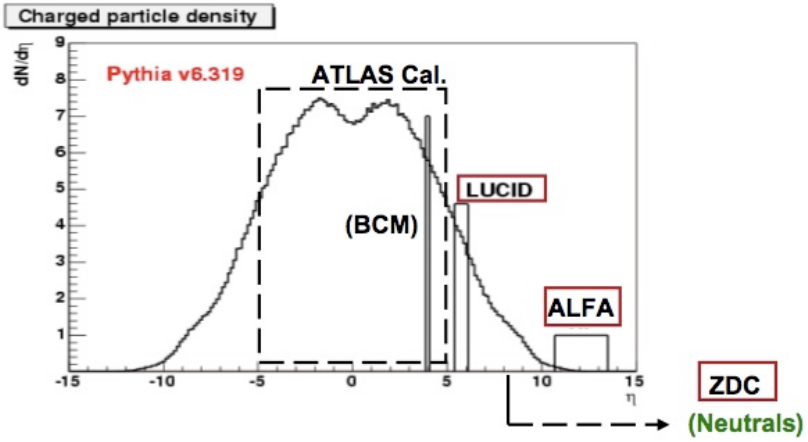
$\approx e^{-\mu}$, where

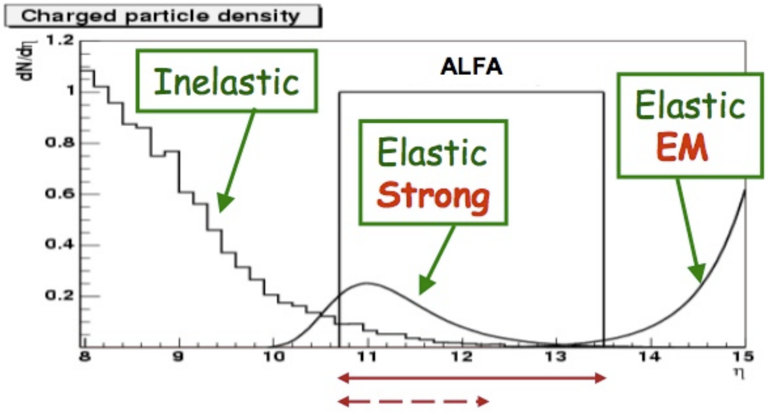
$\mu = \#$ collisions/crossing

v. Papadimitriou, Nucl.Instrum.Meth.A598:14-18,2009.

ATLAS Luminosity (Expected)

- **High instantaneous luminosity creates challenges**
  - **Empty bunches will be rare**
  - **Need to actively count number of interactions**
  - **Using LUCID detector to monitor**
    - 17 m from interaction
  - **Also measuring elastic scattering with ALPHA (Roman Pots)**
    - 240 m from IP
    - Use optical theorem to relate to total cross section
    - Calibrate LUCID
- **Expected uncertainties of 15-20% initially**
  - **Have achieved ~11% initially**
  - **Uncertainty on integrated luminosity is ~3.4%**



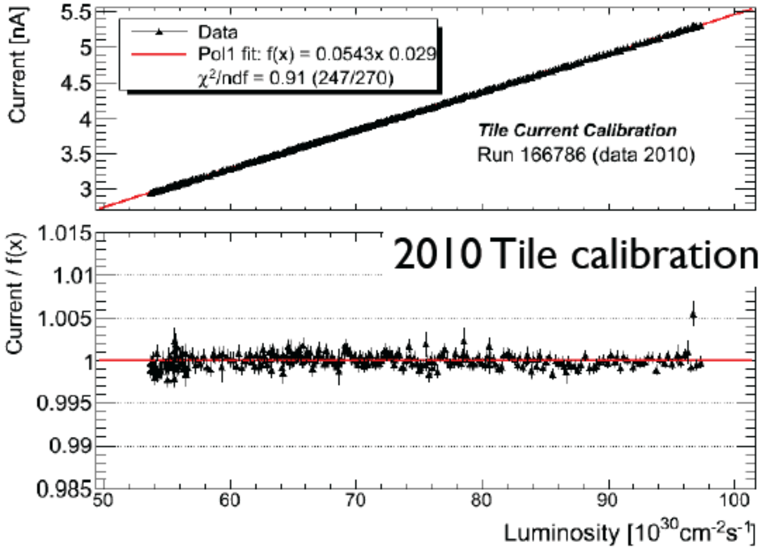


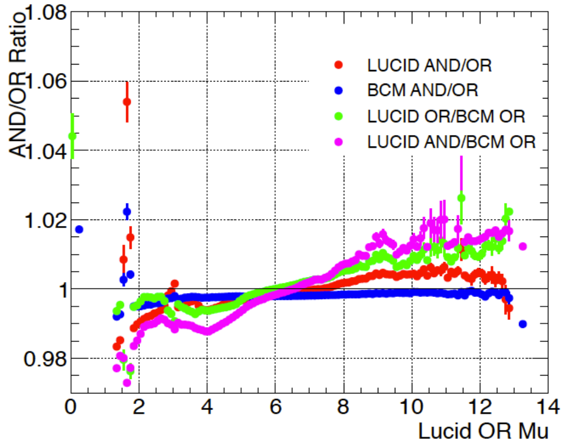
http://indico.carXiv:1101.2185v1ern.ch/contributionDisplay.py?contribId=97&sessionId=7&confId=9499

See arXiv:1101.2185v1

ATLAS Luminosity (Now)

- Realized that can use raw calorimeter signals to measure rate of events
  - Allows for several other measurements for event counting
  - Can cross-calibrate LUCID and BCM
- Result for 2010 data
  - 3.4% uncertainty
  - For 2011, more challenging because of "bunch trains"

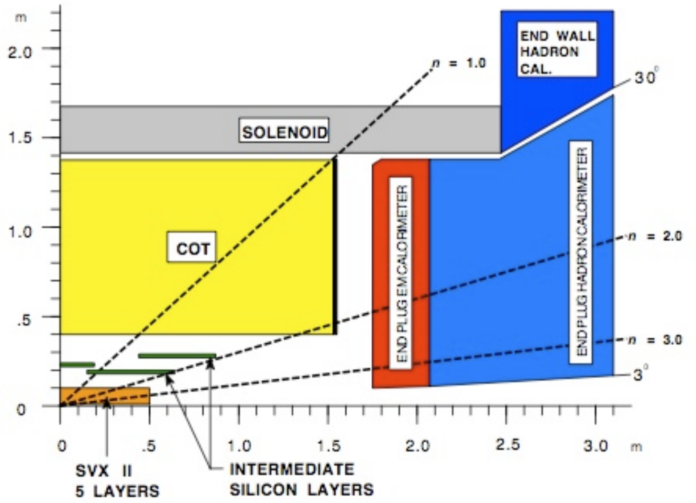




See arXiv:1101.2185v1

Detector Implications

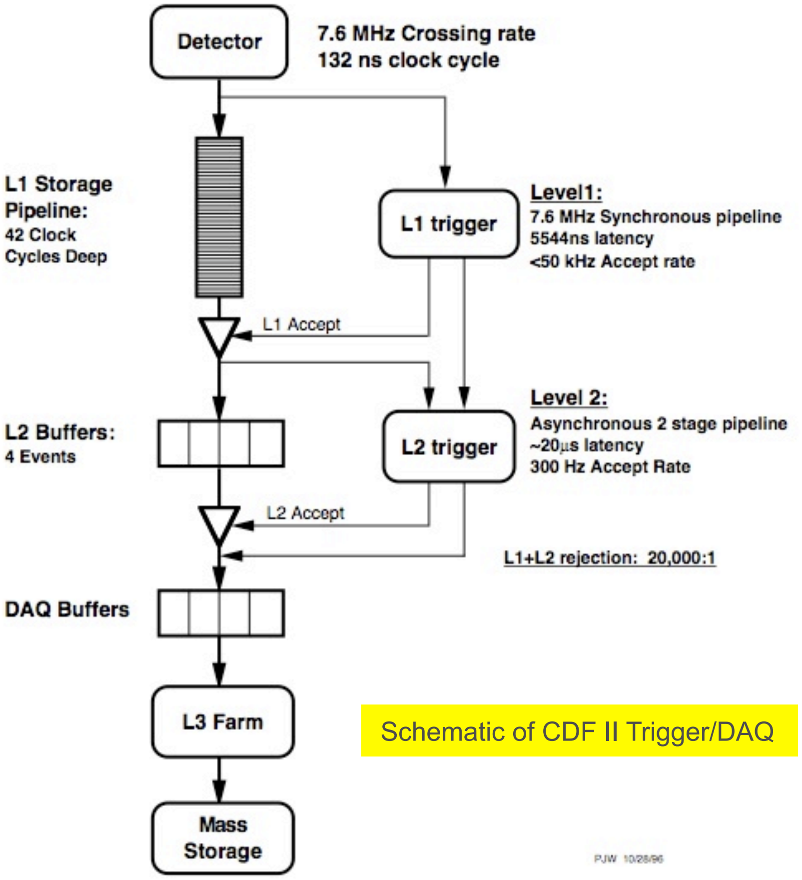
- **Role of detector is to**
  - **Examine every collision (or as many as possible)**
  - **Decide on which ones are interesting enough to store for physics**
    - Keep some data for monitoring and calibration
  - **Record characteristics of events with appropriate resolution**
- **Key elements are:**
  - **Sensors for charged and neutral particles (including readout)**
    - Measurement of charged particle momentum (sets inner detector scale)
    - Sufficient depth of calorimetry to contain EM and hadronic showers
    - Muon particle ID and momentum analysis
  - **Creates a "standard" general-purpose detector configuration**



- **Trigger and DAQ:**
  - **Trigger system for making decisions**
  - **DAQ system to create digital record of each triggered event**
  - **Control system (for sensors & DAQ)**
  - **Monitoring system**

Trigger/DAQ System

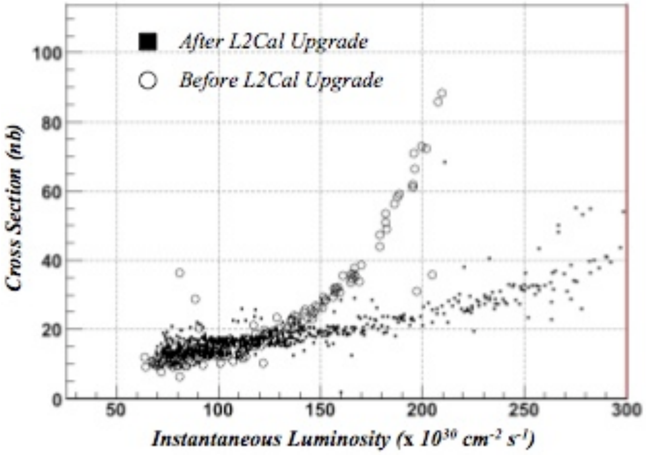
- **Triggering strategy has become standard**
  - **Organize into "levels"**
    - Each level has more information, and greater flexibility
    - Rejection between 10-1000 per level
  - **Allows increasing time/ candidate collision**
    - Level 1: 6 μs
      - **Rejection of >150**
    - Level 2: 20 μs
      - **Rejection of >180**
    - Level 3: Semi-infinite
      - **Rejection of > 5-10**



Schematic of CDF II Trigger/DAQ

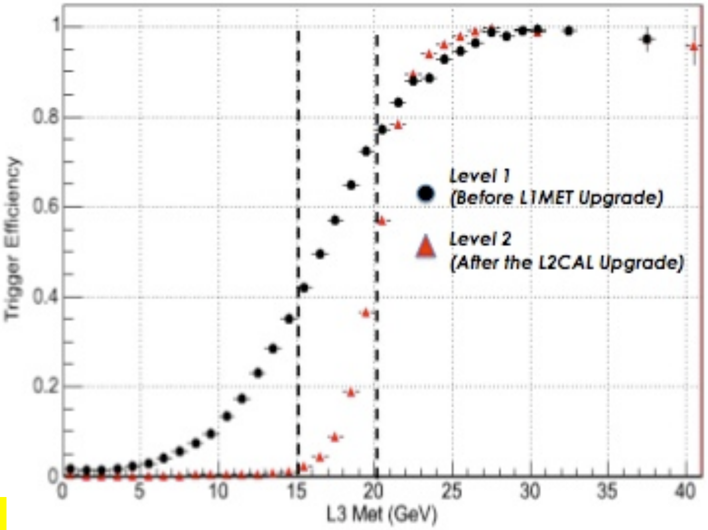
Think "Trigger!"

- **In CDF, have > 420 internal notes with "trigger" in title**
  - **Active area of ongoing development**
  - **Increasing sophistication & improved performance**
    - Reduce luminosity growth
    - Improve capability
  - **Have to understand this part of the experiment very well!**



A. Canepa et al., physics-in.dett/0810.3738

- **Example:**
  - **CDF Jet/Met trigger limited by resolution**
    - Least count in trigger 0.5 GeV
    - Meant that trigger σ grew with L
  - **Recent upgrade to use "full" resolution at 0.125 GeV**



Detector Acceptance & Efficiency

- **Detectors designed with specific physics processes in mind**
  - **Break these down into**
    - Total transverse energy
    - Charged leptons (e, μ, τ)
    - Jets (quarks & gluons)
    - Missing transverse energy
  - **Huh? But aren't we supposed to be discovering stuff?**
    - Hope is that by focusing in detection and triggering of "basic elements", one will have a broad enough menu that new phenomena will be recorded
    - Doesn't seem like a bad idea
      - **But creates practical challenges**
      - **Very large "trigger" menus**

- **Helpful to separate detector effects out:**
  - **Acceptance: Fraction of events of a given process "contained" within the detector**
  - **Efficiency: Fraction of contained events/objects ultimately passing some set of criteria ("cuts")**
  - **Resolution: Accuracy of measurements of specific event-related quantities**

- **Warning: Not a strict convention on how these terms used!!**
  - **Always make sure you define what you mean**

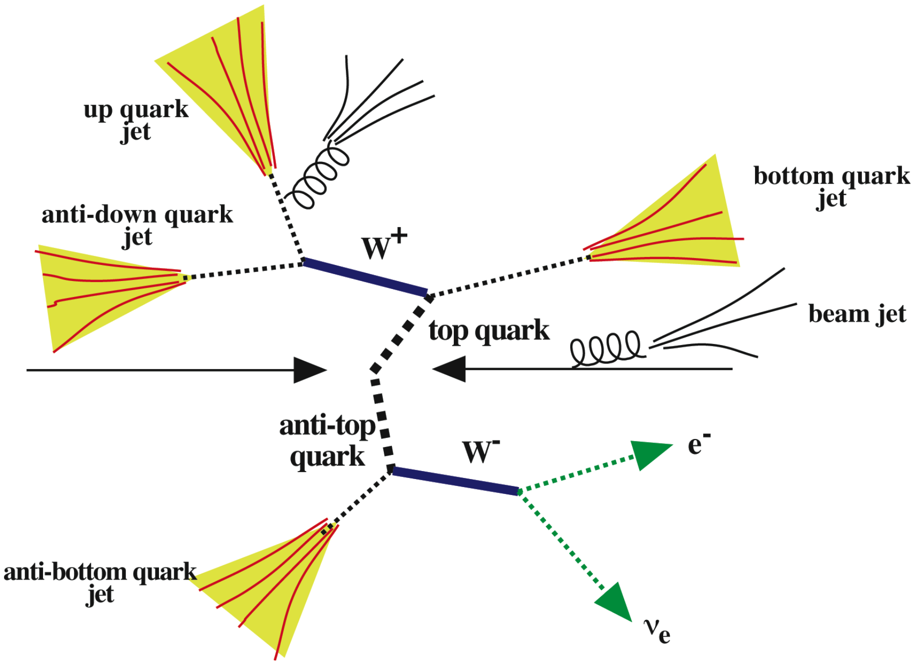
Example: Top Quark Production

- **Good tutorial:**
  - **High P_T process**
  - **Produces ≥ 6 objects in final state**
    - Exercises entire detector
  - **Large source at LHC**

$$\sigma_{t\bar{t}} \cong 830\ pb \left(\sqrt{s} = 14\ TeV\right)$$
$$\Rightarrow r_{t\bar{t}} \cong \sigma_{t\bar{t}} \times L \times \varepsilon_{acc\times eff}$$
$$= \left(8.3\times10^{-34}\right)\left(1.0\times10^{32}\right)\left(4\times10^{-2}\right)$$
$$= 3.3\times10^{-3}\ \mathrm{s}^{-1} = 1.2/hour$$

  - **Very good SM calibration source**
    - Lepton ID efficiencies
    - Missing Et
    - Jet Energy Scales
    - B tagging efficiencies

- **Biggest problem is difficulty of correctly constructing final state**
  - **Tagging b's reduces this problem**
    - Also reduces the rate of candidate events



Acceptance x Efficiency

- **Have to decide channel to focus on**
  - **Semi-leptonic channel is favourite "whipping boy"**
  - **Require**
    - One W to decay leptonically (e/μ required in final state)
      - **Charged lepton with $<P_T>\sim$ 50 GeV/c**
      - **Neutrino with energy $<P_T>\sim$ 50 GeV/c**
      - **This also accepts some W->τν**
    - One W to decay hadronically
      - **2 jets with average $<P_T>\sim$ 50 GeV/c**
    - Two b jets
      - **Maybe require jets, maybe tagged?**
      - **On average, a little harder…**
  - **Estimate BR = (2/9)x(2/3)x2=8/27=30%**
    - But need to run full MC! Why?

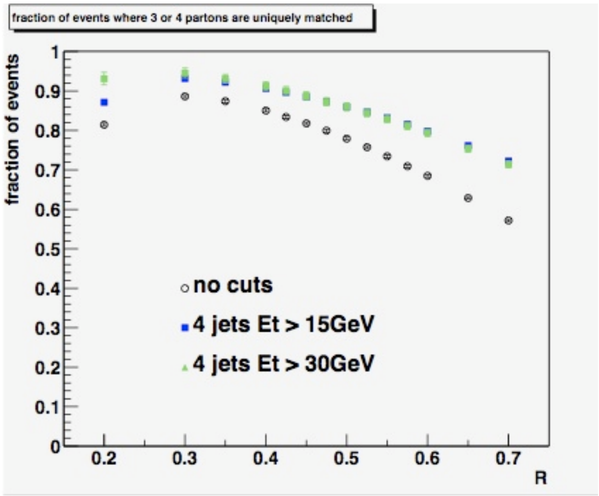
- **Have to decide on trigger:**
  - **Inclusive e or μ**
    - $P_T > 20\text{-}25$ GeV/c
    - $|\eta| < 1.5$
  - **Acceptance ~ 85%**
  - **Efficiency ~ 90-95%**

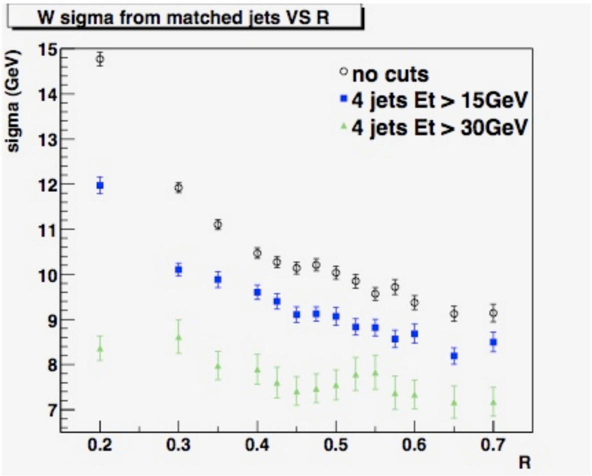
L1/L2/L3 Inclusive Lepton trigger

- **Offline selection requirements**
  - **Lepton ID**
  - **Missing $E_T > 25$**
  - **3-4 jets**
    - E_T>20 GeV
    - $|\eta| < 2.4$
  - **B tagging?**
    - Single b-tag efficiency around 50%

How Are These Chosen?

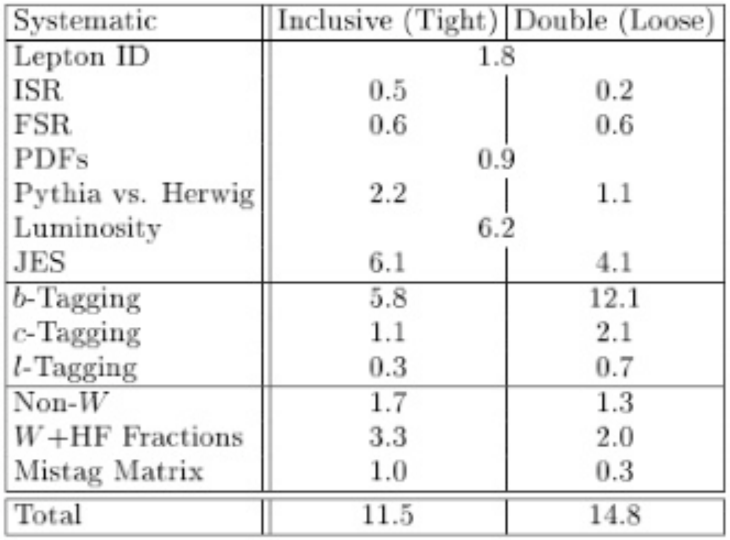
- **Study acceptance**
  - **Learn that top quark production ~ "central"**
  - **Primary backgrounds (W+bb+jets) more distributed in η**
  - **Lepton ID and jet reconstruction limiting factors**
- **Maximize efficiency**
  - **Requires S/N studies**
  - **Look at different algorithms for event reconstruction**
  - **Need to be systematic**
    - But recognize that one has to make compromises





Results with B-Tagging

- Most accurate top quark cross section
  - Lepton+jets
  - SECVTX b-tagging
- Strategy
  - Use MC to determine overall acceptance
  - Measure trigger efficiency with W->lν
  - Measure lepton ID efficiency with Z->ll
  - Measure b-tagging efficiency in data
  - Estimate systematic uncertainties



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

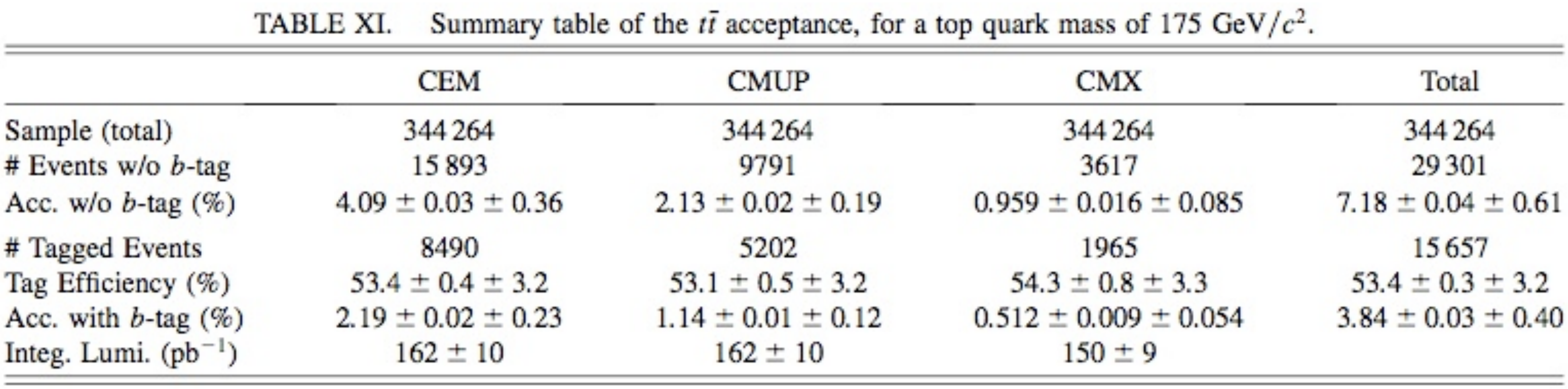


TABLE XI. Summary table of the $t\bar{t}$ acceptance, for a top quark mass of 175 GeV/c^2.

	CEM	CMUP	CMX	Total
Sample (total)	344 264	344 264	344 264	344 264
# Events w/o b-tag	15 893	9791	3617	29 301
Acc. w/o b-tag (%)	4.09 ± 0.03 ± 0.36	2.13 ± 0.02 ± 0.19	0.959 ± 0.016 ± 0.085	7.18 ± 0.04 ± 0.61
# Tagged Events	8490	5202	1965	15 657
Tag Efficiency (%)	53.4 ± 0.4 ± 3.2	53.1 ± 0.5 ± 3.2	54.3 ± 0.8 ± 3.3	53.4 ± 0.3 ± 3.2
Acc. with b-tag (%)	2.19 ± 0.02 ± 0.23	1.14 ± 0.01 ± 0.12	0.512 ± 0.009 ± 0.054	3.84 ± 0.03 ± 0.40
Integ. Lumi. (pb^{-1})	162 ± 10	162 ± 10	150 ± 9	

D. Acosta et al., PRD 71, 052003 (2005)