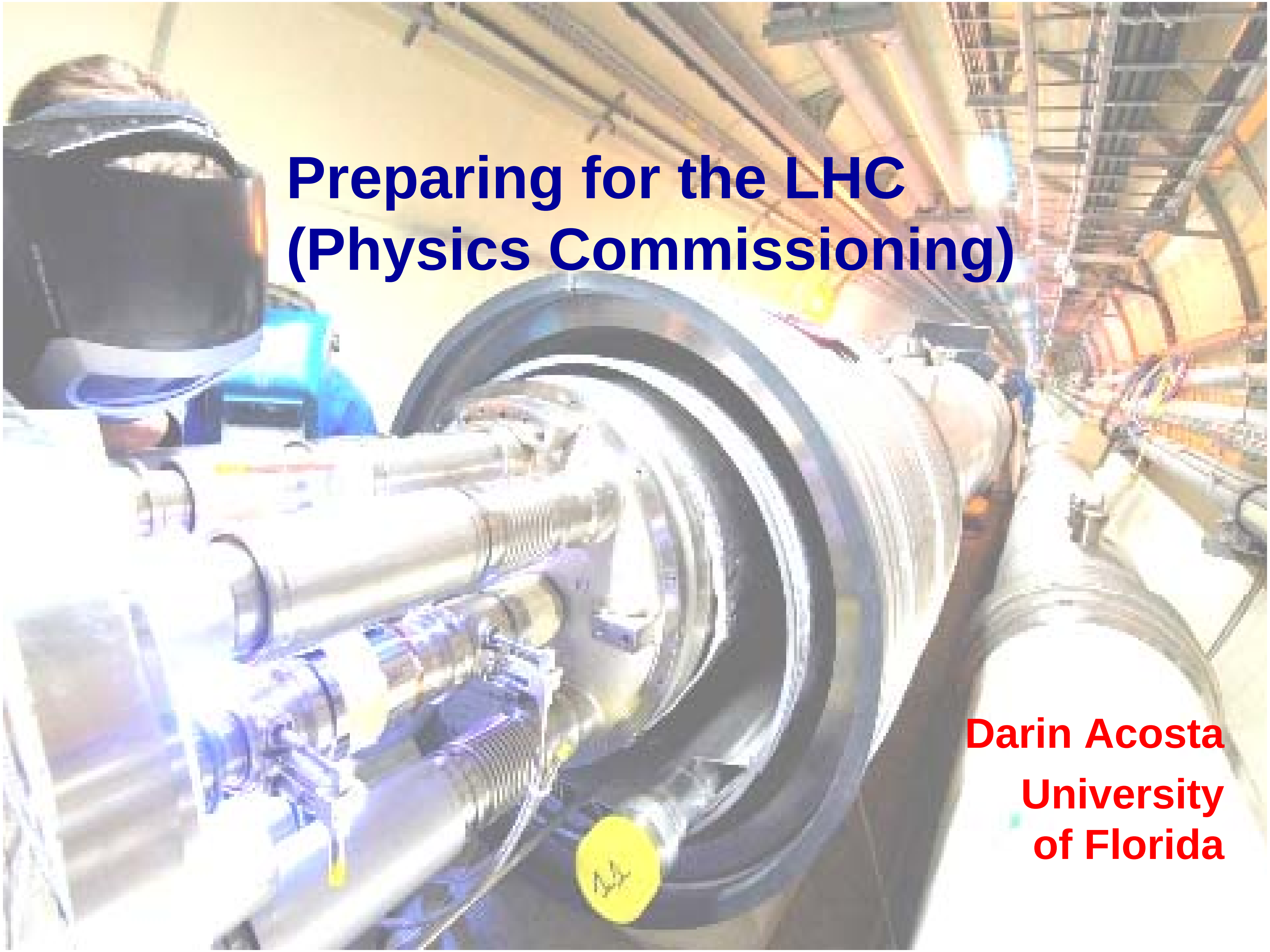


Preparing for the LHC (Physics Commissioning)

Darin Acosta

University of Florida

Outline, Cont'd

Lecture 4

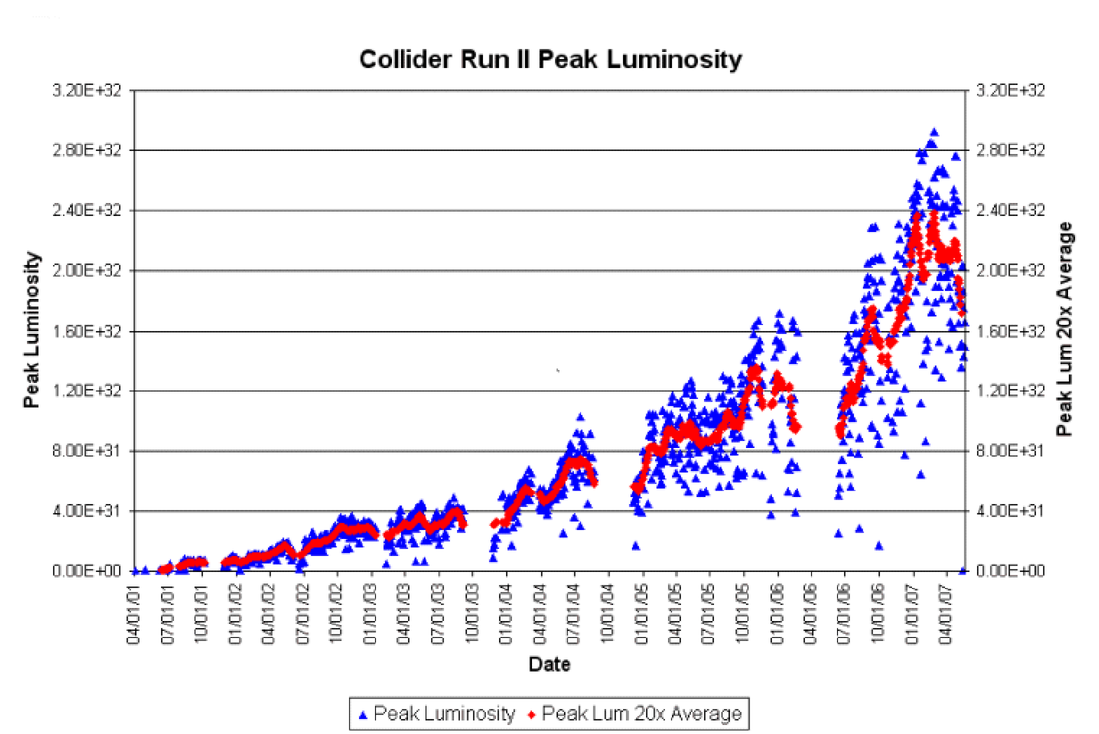
- Early LHC physics measurements – Physics Commissioning
  - Luminosity measurement
  - Impact of pile-up
  - Underlying Event
  - Dealing with instrumental issues in measurements
    - Missing Transverse Energy – catch-all of instrumental problems
    - Jet Energy scale
  - Calibrating the Standard Model backgrounds
    - e.g. QCD jet production, Electroweak measurements, Top quark measurements

First Physics Measurements – "Physics Commissioning"

Luminosity

What is Luminosity?

- ☐ Luminosity is a measure of the "brightness" of the colliding beams at a collider
- ☐ It determines the rate of collisions and, integrated over time, the total number of events in our data samples



Tevatron peak luminosity:

$\mathcal{L}$ =2.8x10^{32} cm^{-2}s^{-1}

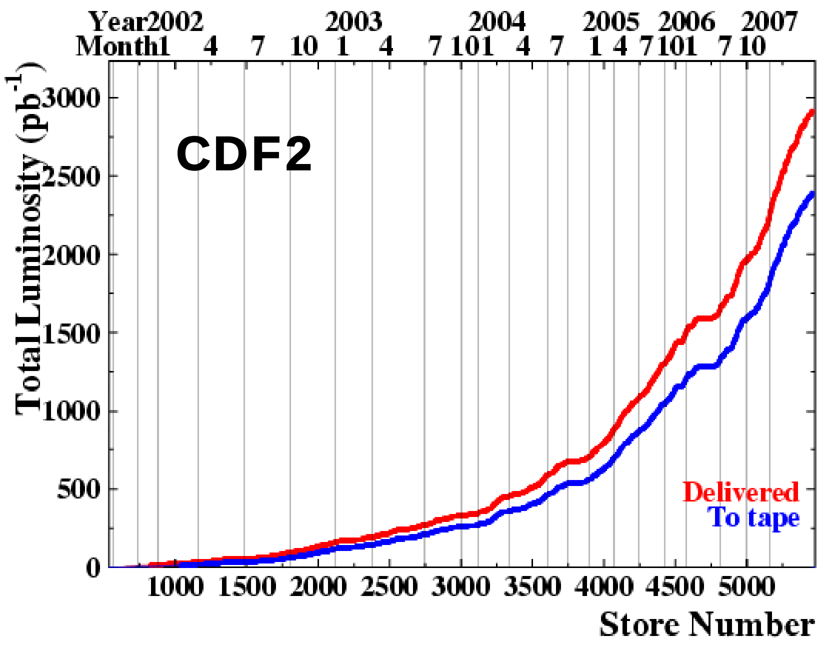
Rate=$\sigma\,\mathcal{L}$

LHC design goal:

$\mathcal{L}$ =10^{34} cm^{-2}s^{-1}

Why is luminosity important?

- You want to accumulate as much as possible to search for rare processes
  - Tevatron Run 2 integrated luminosity is nearly 3 fb^{-1}
  - Standard Model Higgs search requires several times more than that



- You need to know the denominator of your cross section measurement!

$$\sigma = \frac{N_{sel}}{\varepsilon L}$$

Luminosity from Machine Parameters

- $\mathcal{L} = (k\, N_p^{\,2} f) / (4\pi\, \sigma_x \sigma_y)$
  - f = revolution frequency
  - N_p = number of protons per bunch (assumed equal)
  - k = number of bunches (2808)
  - σ_x, σ_y = transverse sizes of the beam
- Goal is to maximize $\mathcal{L}$
  - Increase N_p as much as possible
  - Increase bunch crossing frequency
  - Decrease beam cross section
- And if we can measure these parameters, we also have a measurement of the luminosity
  - "Van der Meer scan" of stepping beams through each other to determine parameters from count rates

See lectures by
Dr. Wenninger for more
information on LHC

Luminosity – Also a Critical Analysis Ingredient

- ☐ Generally one is interested in measuring the cross section of an interesting process at a collider:

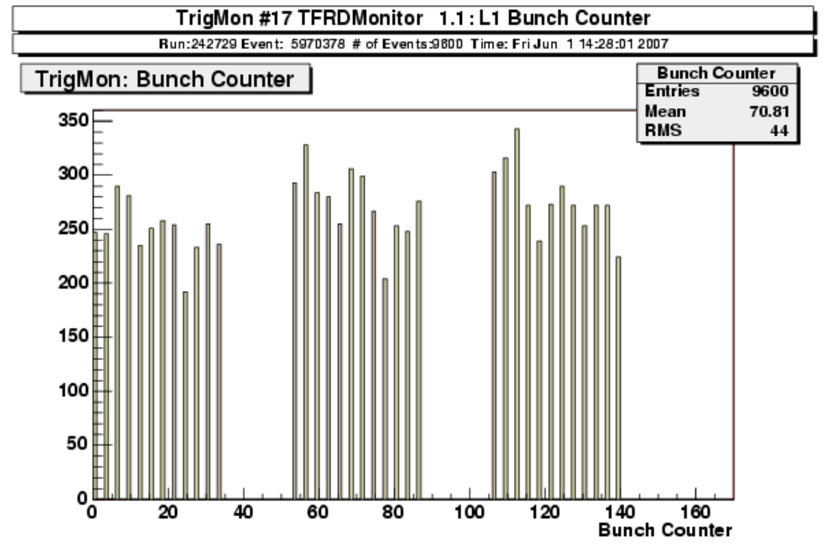
$$\sigma = \frac{N_{sel}}{\varepsilon L}$$

  - N_{sel} = number of selected interesting events
  - ε = efficiency to select those events
  - L = total integrated luminosity (cm^{-2}, or fb^{-1} = 10^{-39} cm^{-2})

- ☐ Can spend a lot of time determining cuts to isolate the interesting events of a particular process from a myriad of ordinary Standard Model backgrounds, and measuring, or otherwise simulating, the efficiency of those cuts and estimating systematic uncertainties
- ☐ But it is also important and necessary to measure the luminosity accurately and precisely
  - Even better to have several handles cross-checking

Processes from which to Measure Luminosity

- The luminosity measurement should provide quick feedback to the accelerator operators and to the experiment, so need good statistics on short timescales
  - e.g. to provide bunch-by-bunch luminosity →



Filled bunches @ Tevatron from CDF measurement

- Choose high cross-section processes at colliders:
  - e^+e^- : Bhabha scattering $e^+e^- \rightarrow e^+e^-$
  - ep : ep bremsstrahlung $ep \rightarrow ep\gamma$
  - pp : inelastic scattering $pp \rightarrow X$

Luminosity from total inelastic cross section

- Rate of inelastic collisions: $R = \sigma \mathcal{L}$
  - σ = inelastic cross section (cm^2, or barns)
  - $\mathcal{L}$ = instantaneous luminosity ($cm^{-2}\,s^{-1}$)
- Rate is also $R = \mu\, f_{BC}$
  - μ = average number of inelastic collisions per bunch crossing
  - f_{BC} = frequency of bunch crossings
- So experimentally, instantaneous luminosity can be measured by:
  - $\mathcal{L} = \mu\, f_{BC} / \sigma$
  - f_{BC} comes from machine design
  - σ must be measured, or otherwise calculated, from the process used to measure luminosity
  - Measure μ from your detector

Methods to measure μ: Zero Counting Method

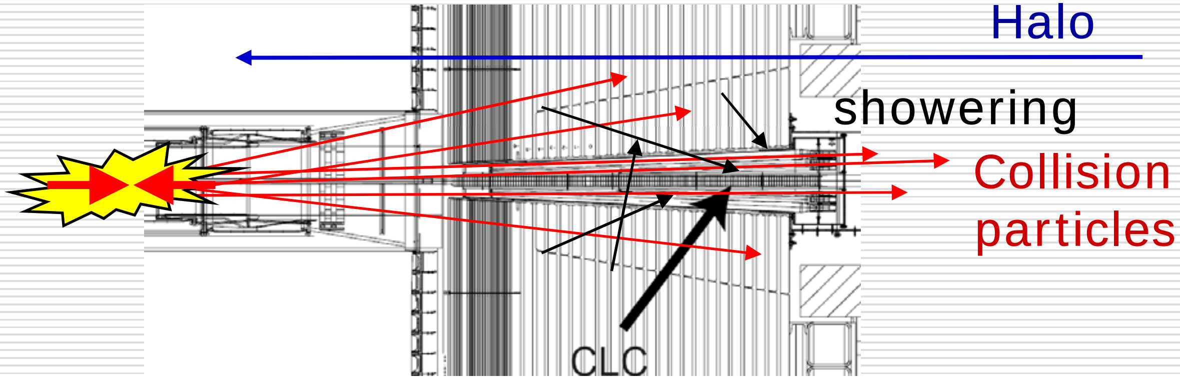
- The probability of n inelastic collisions in a given bunch crossing, given a mean number of collisions μ, is given by Poisson formula:
  - $P(n) = \exp(-\mu)\, \mu^n / n!$
- The probability of zero collisions is:
  - $P(0) = \exp(-\mu)$
- Thus, one can measure the fraction of empty bunch crossings to get μ:
  - $\mu = -\ln P(0)$
- In practice, a detector is not 100% efficient at detecting a collision due to limited angulae coverage and detection inefficiency
  - $P(0) = \exp(-\varepsilon\mu)$, ε = efficiency
- One also can have backgrounds or detector noise that can mimic a detector response from a collision
  - Trickier to deal with if cannot be removed
- Limitation:
  - "Zero starvation" at high luminosity (i.e. if $\mu \gg 1$, so that $P(0)$ is small)
  - This makes the measurement susceptible to systematic uncertainties
    - e.g. Backgrounds or noise that mimic a collision and bias μ larger, or inefficiencies that bias μ smaller, have a fractionally larger bias

Methods to measure μ: Hit/Particle counting

- Rather than try to measure the fraction of empty events, measure the number of detector elements hit (counters, towers), or better the number of collision particles, in a beam crossing
- $\mu = \langle N_H \rangle / \langle N_H^1 \rangle$
- $\langle N_H \rangle$ = measured number of hits or particles
- $\langle N_H^1 \rangle$ = number of hits, or particles, for a single collision
  - Could be measured from counting a fraction of the charged particles in a collision, for example
  - Need good separation of one collision from two, and avoid saturation of counters at high luminosity

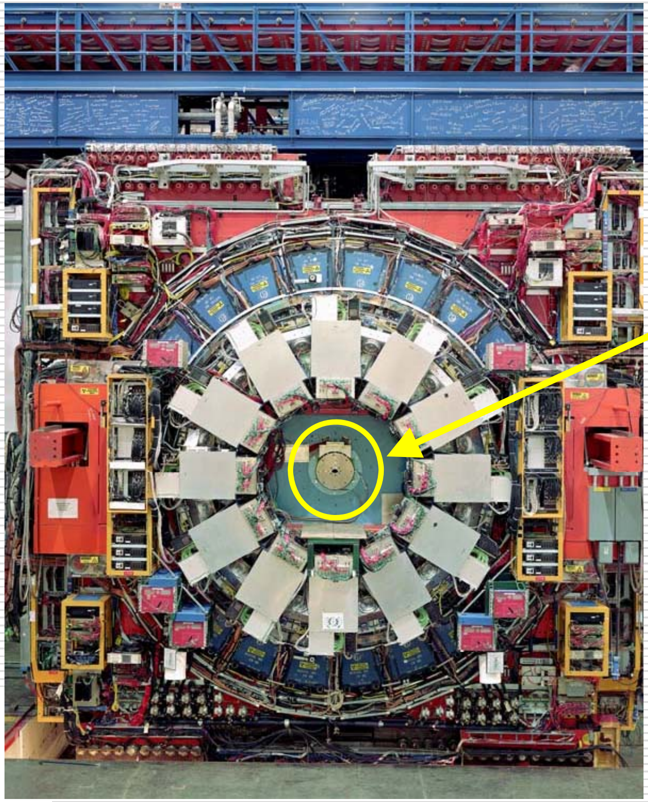
Detectors for Relative Luminosity Measurement

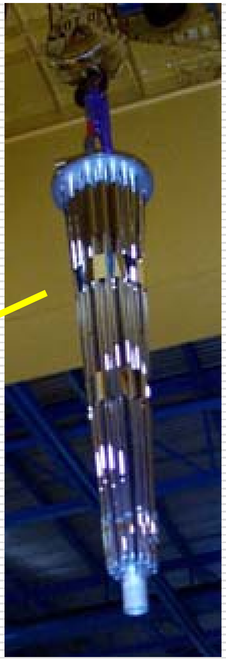
- A measurement of just about any process with any detector is sensitive to the luminosity
  - Inelastic scattering, W/Z production, J/Ψ production, …
  - Calorimeter occupancy/energy, tracking detector currents, tracks,…
- Choose a high cross section process for good statistics
- Choose high acceptance, low noise/background detector or technique to minimize <u>systematic uncertainties</u>
  - Generally means covering the forward regions of collider expt.

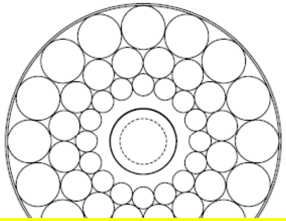


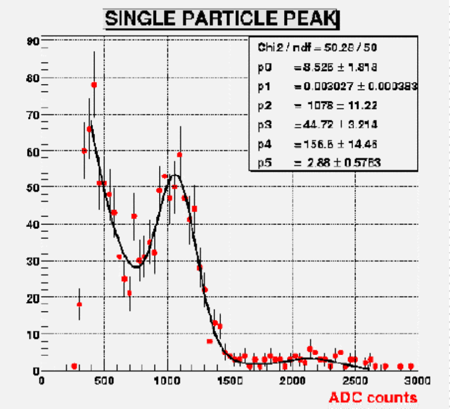
CDF Cherenkov Luminosity Counters

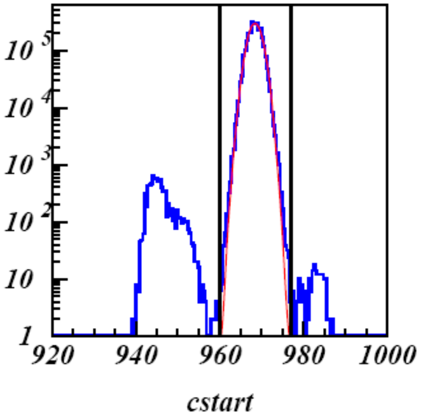
- Eta coverage: $3.7 < |\eta| < 4.7$
- Good acceptance: 60%
  - 95% of which is from hard-core inelastic collisions
- Cherenkov device :
  - Good signal:noise separation
  - Self calibrating
  - Excellent timing
  - Directionality









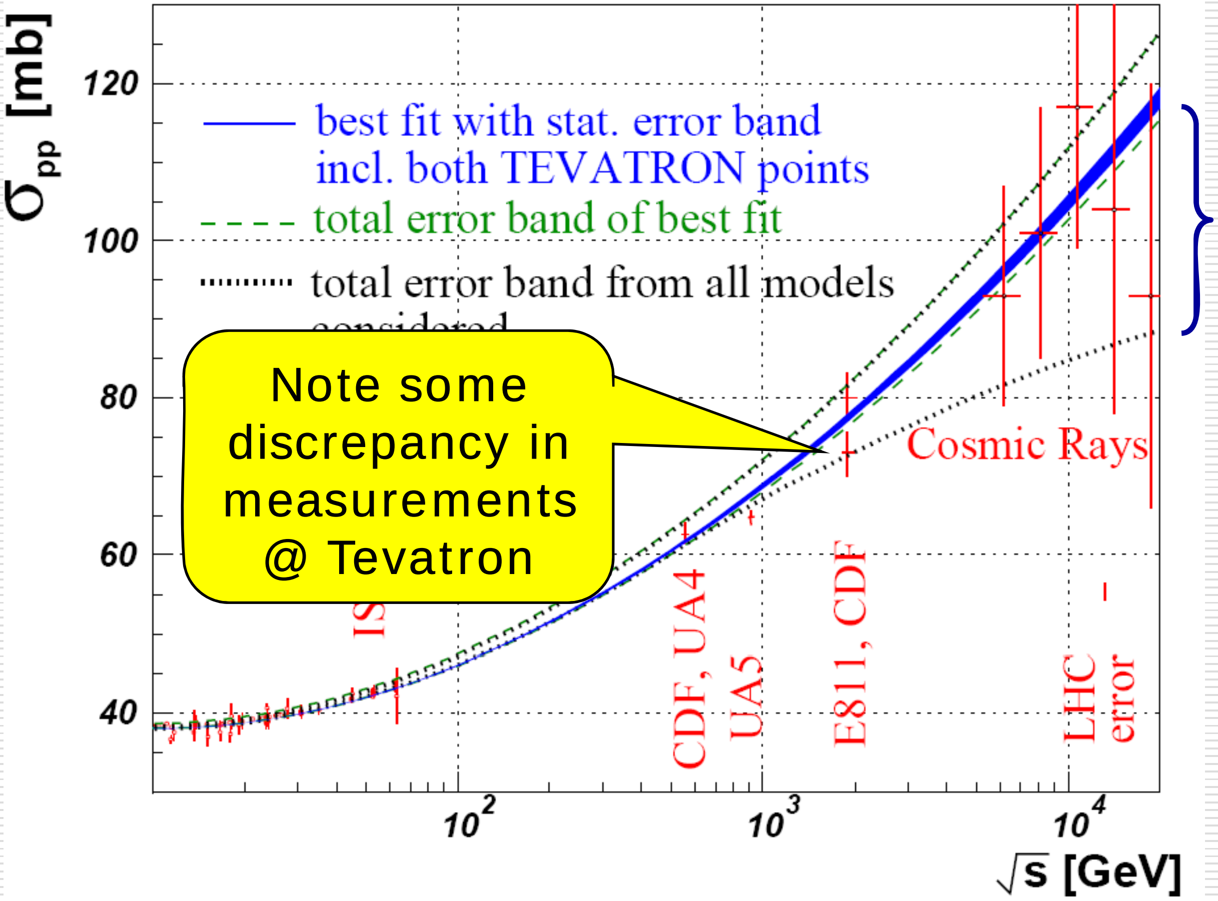


4.2% measurement uncertainty

(6% with cross-section uncertainty)

Total pp Cross Section @ LHC

- ☐ Large extrapolation from Tevatron to LHC, so large uncertainty until measured



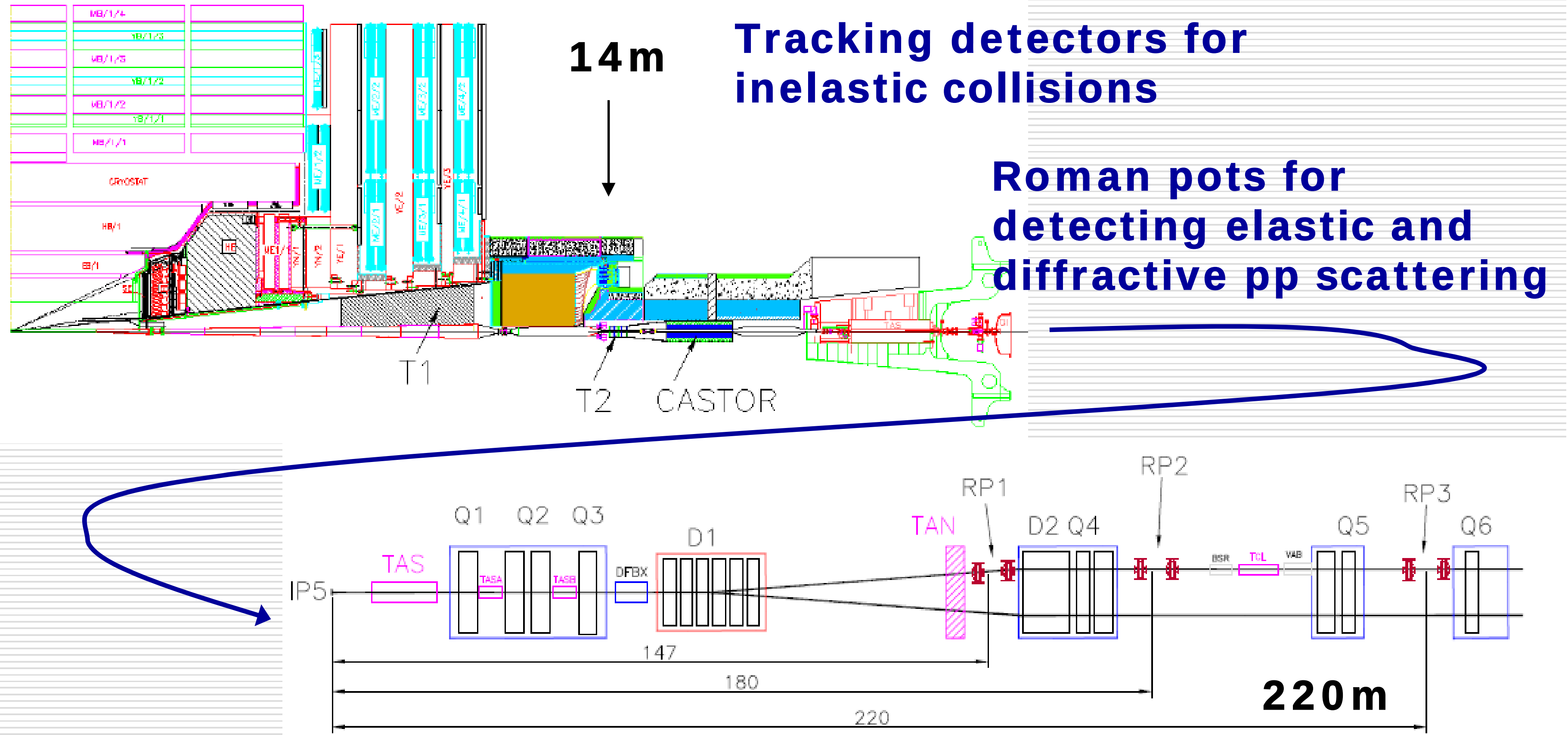
Note some discrepancy in measurements @ Tevatron

Conservatively 100±15 mb

J.Cudell et al., PRL 89, 201801 (2002)
σ=111.5±4.2

TOTEM Experiment

- ☐ Dedicated experiment @ LHC (shares P5 with CMS) devoted to measuring the total pp cross section and study elastic and diffractive dissociation

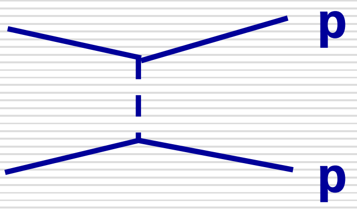


Tracking detectors for inelastic collisions

Roman pots for detecting elastic and diffractive pp scattering

Total cross section & absolute luminosity measurement from elastic scattering

- Optical Theorem: the total cross section is related to the imaginary part of the elastic scattering amplitude extrapolated to zero momentum transfer:
  - Incident flux is removed by total xsec



$$\sigma_{tot} = 4\pi \, \mathrm{Im}\left[f_{el}\left(t=0\right)\right] \qquad -t \propto \theta^2$$

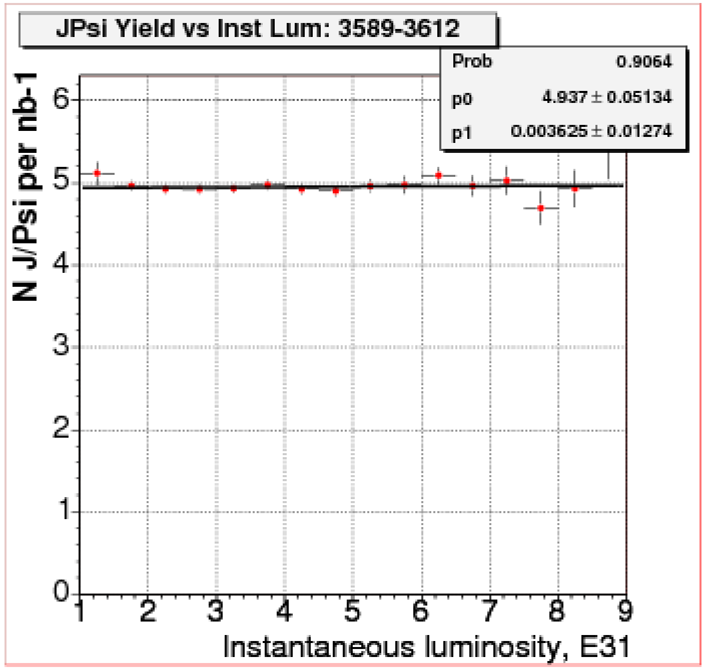
- Measure the total interaction rate R_{tot} and the elastic rate in the forward direction $(dR_{el}/dt)_{t=0}$

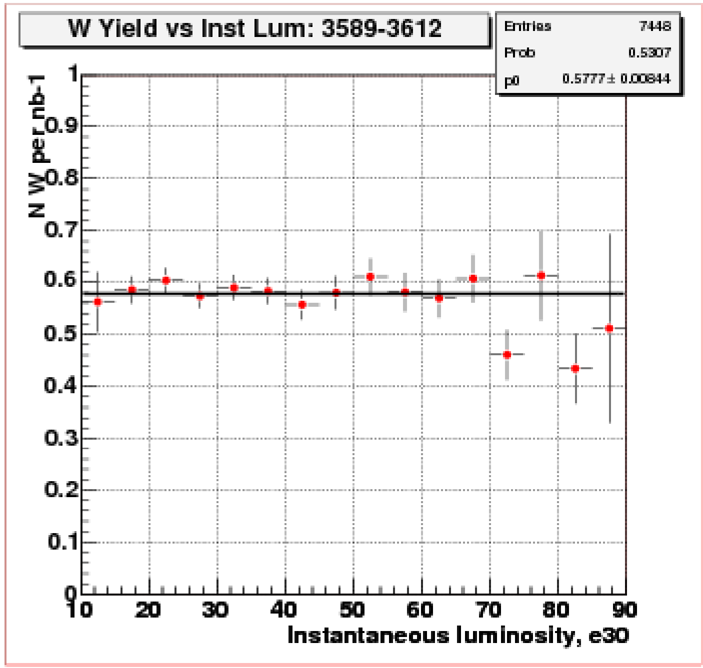
$$\sigma_{tot} = \frac{16\pi}{\left(1+\rho^2\right)} \frac{\left(dR_{el}/dt\right)_{t=0}}{R_{tot}} \qquad \rho = \left.\frac{\mathrm{Re}\left[f_{el}\left(t\right)\right]}{\mathrm{Im}\left[f_{el}\left(t\right)\right]}\right|_{t=0} \approx 0.14$$

$$L = \frac{R_{tot}}{\sigma_{tot}} = \frac{\left(1+\rho^2\right) R_{tot}^2}{16\pi \left(dR_{el}/dt\right)_{t=0}}$$

Luminosity cross-checks

- ☐ With the luminosity measurement from the experiment, useful to make cross-check with other processeses





CDF

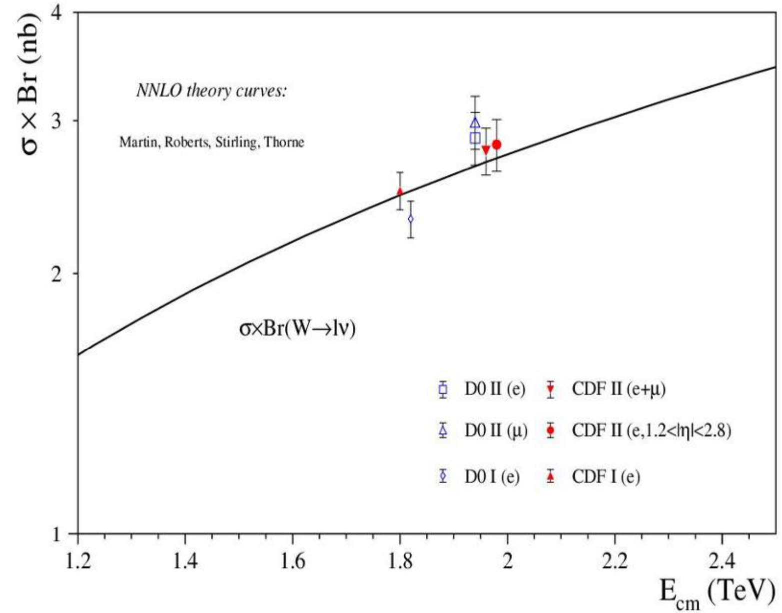
→ Pile-up conditions change

Figure 18: $J/\psi \to \mu\mu$ yield per instantaneous luminosity bin. The number of reconstructed J/ψs is flat versus luminosity.

Figure 19: $W \to e\nu$ yield per instantaneous luminosity bin. The number of reconstructed Ws is flat versus luminosity.

Luminosity from Standard Candles (W, Z)

- The W boson cross section has been measured to 7% at the Tevatron, and agrees very well with NNLO theory
  - 6% of this uncertainty comes from the luminosity measurement, and only 3.5% from the W measurement itself
- Thus, it may be appropriate to choose such a process to ultimately normalize the luminosity
  - But sacrifices W/Z cross section measurements at the LHC, and measurements of the proton parton densities
  - Also, it may take some time before all systematic uncertainties of this measurement are fully understood
    - CDF publication came 5 years after Run 2 start

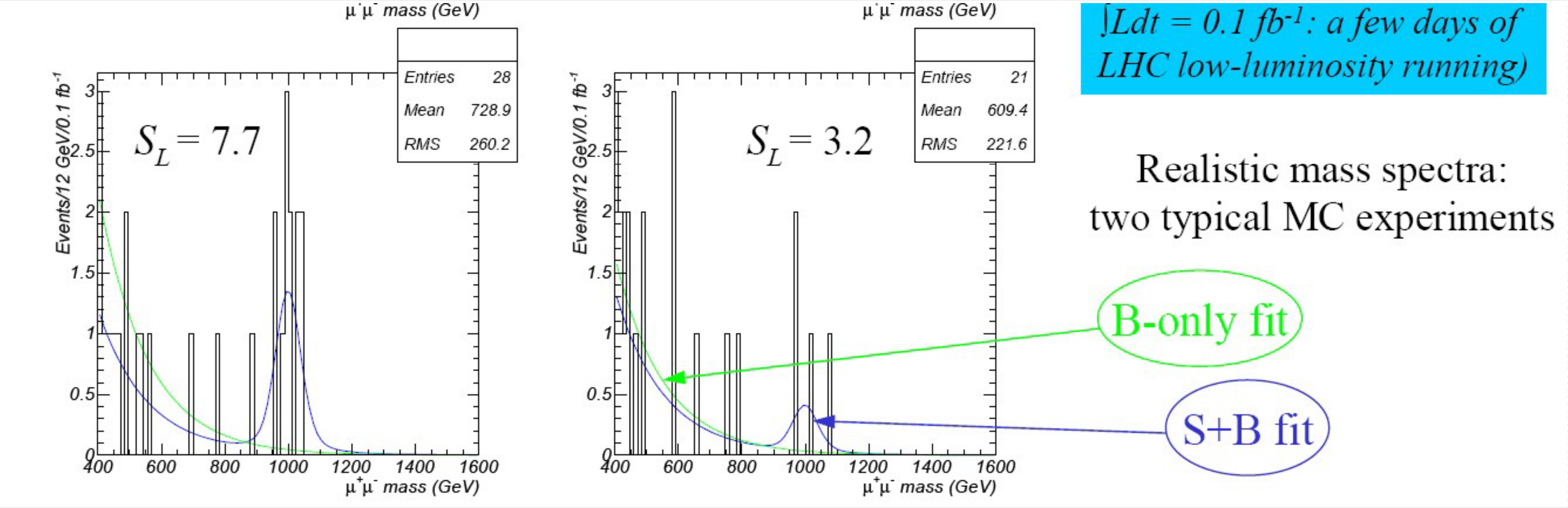


Or skip cross sections, measure relative rates

- Previous example shows that one can usually quote smaller experimental errors by measuring ratios
  - For example, at LHC, perhaps $\sigma(pp \rightarrow H \rightarrow ZZ \rightarrow 4\mu)$ / $\sigma(pp \rightarrow Z \rightarrow \mu\mu)$
- Luminosity will cancel in the ratio
- Many common systematic uncertainties cancel as well
  - e.g. muon reconstruction efficiency (partly)
- Moreover, for new physics searches, generally can set stronger limits (because of smaller systematic uncertainties) by not doing a "dead reckoning" counting experiment
  - i.e. instead of setting an upper limit based on the number of observed candidates and the estimated number of background candidates, let the background float →

Z′→μμ Search Strategy

- Fit mass distribution to expected resonance and background <u>shapes</u>
- Extract significance of excess, and measured mass



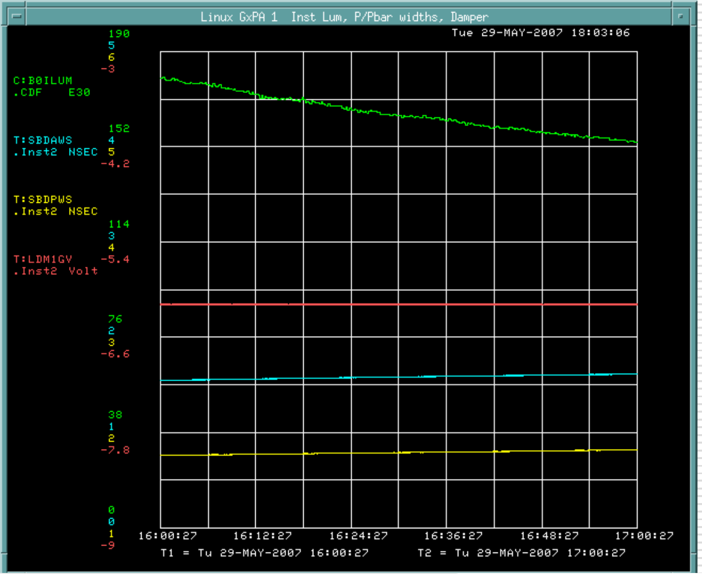
$\int Ldt = 0.1\ fb^{-1}$: a few days of LHC low-luminosity running)

Realistic mass spectra:
two typical MC experiments

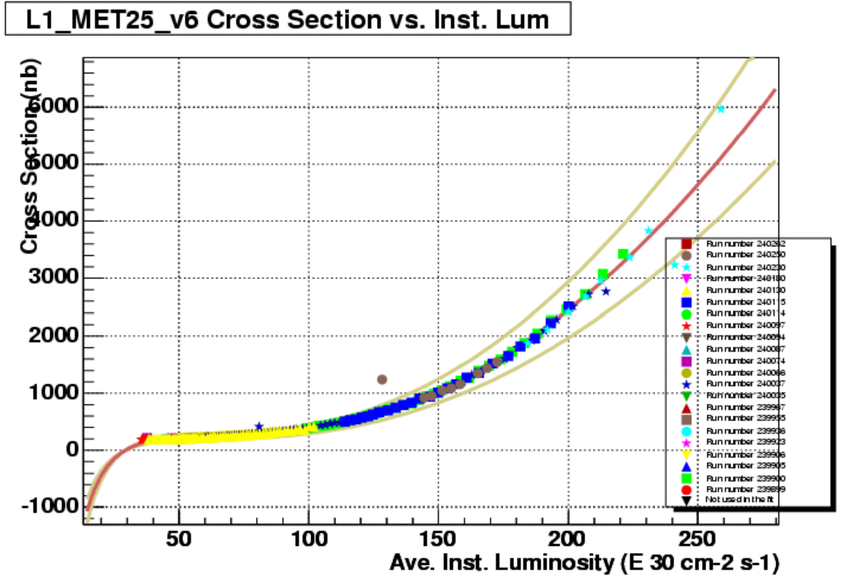
- Better than trying to estimate absolutely the background in a mass window for the signal

Finally, where to report luminosity information ?

- ☐ To the accelerator group for monitoring feedback →
  - Aiming for 1 Hz refresh rate



- ☐ Data quality monitoring
  - Online cross sections →
  - Conditions for detectors



- ☐ Into database for use in analyses
  - Tools to calculate integrated luminosity for given datasets

What is μ at the LHC anyway? (Pile-up Issues)

- ☐ Take total inelastic cross section (hard-core scattering plus diffractive scattering) to be about 80 mb
- ☐ In-time pile-up:
  - Time indistinguishable from collision of interesting signal process

$$\mu = \sigma L \Delta t \frac{N_{\text{tot}}}{N_{\text{filled}}}$$

$$= \left(80\times10^{-3}\times10^{-24}\ \text{cm}^2\right)\times\left(2\times10^{33}\ \text{cm}^{-2}s^{-1}\right)\times\left(25\times10^{-9}\ \text{s}\right)\times\frac{3564}{2808}$$

⇒

$$\mu = 5.1 \quad \text{for } L = 2\times10^{33}$$

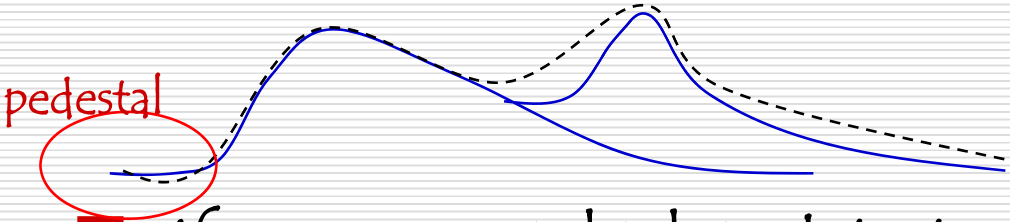
$$\mu = 25 \quad \text{for } L = 10^{34}$$

3.5
17.5
without diffraction

- ☐ In addition, pile-up from collisions in bunch crossings just before and just after the signal collision also can affect detector signals
  - Pulses come before or after those from signal process BX

Out-of-time pile-up

- Pulses on same electronic channel:

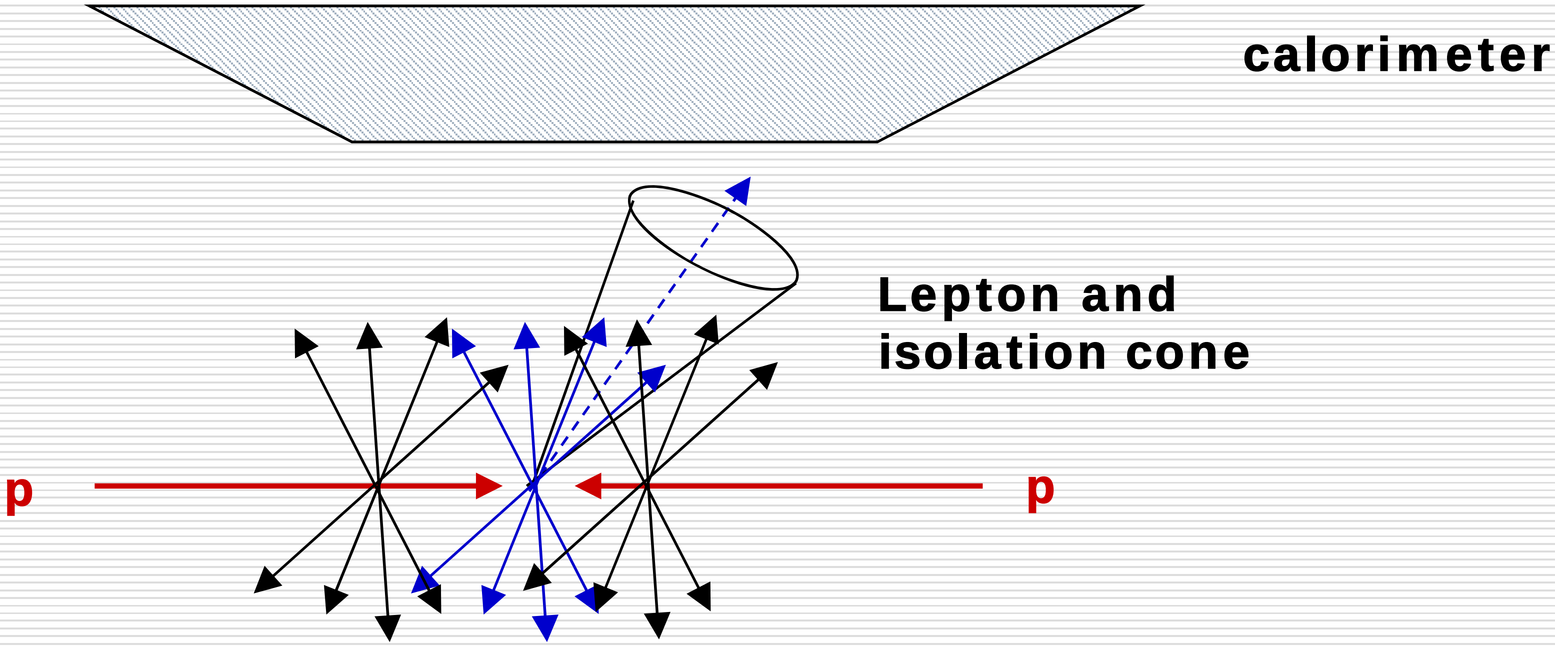


- If occupancy is high in detector (e.g. tracking and calorimeters), can affect measurement of pulse
- Ways to combat:
  - Good granularity of detectors
  - Good time resolution from detectors/electronics
  - Dynamic pedestal subtraction (sample signal before main pulse)
  - Use shape of pulse to determine if pile-up occurred, correct or remove
- For pulses on different channels:
  - If good time resolution, cut out signals not consistent with signal BX

Effect of pile-up on analyses

- If not otherwise removed electronically (not possible for in-time pile-up), adds energy and tracks to the recorded event
  - Adds underlying energy to jets (should be subtracted)
  - Adds underlying energy around otherwise isolated leptons (decreases isolation efficiency)
  - Worsens the resolution on missing transverse energy
  - Complicates calorimeter calibration
- Should be included into Monte Carlo simulations of detector performance
- Good tracking capability → reconstruct separate vertices for different collisions
  - Use vertex of signal lepton to determine which vertex, or make choice that highest P_T vertex is signal
  - Base isolation on tracks emanating from same signal vertex, not calorimeter energy

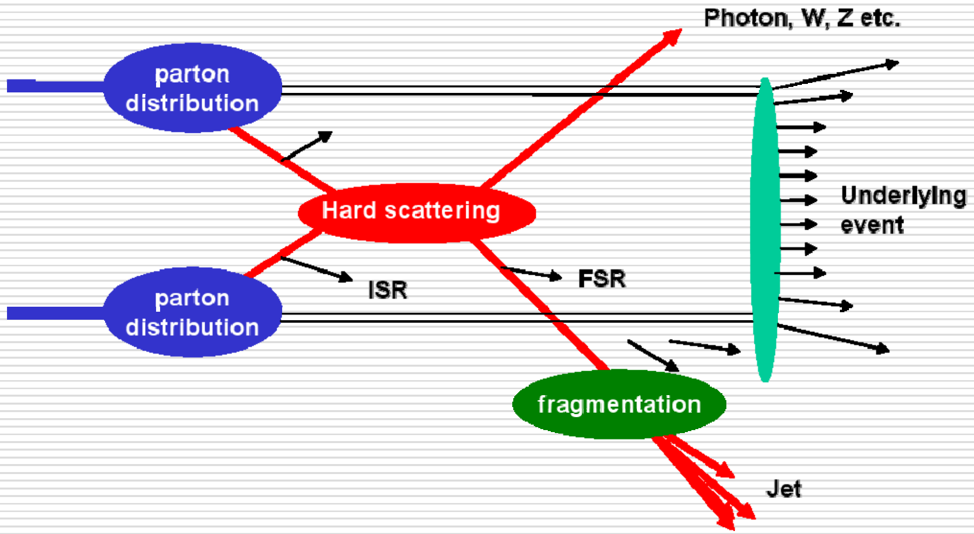
Several Pile-up collisions



n.b. interesting to know what to do for Super-LHC, with L=10^{35} and 50 ns bunch spacing → 350 inelastic proton collisions in one BX!

The "Underlying Event"

- The non-perturbative soft QCD energy flow surrounding a hard 2→2 parton scattering in pp collisions
  - Proton remnants
  - Higher-order QCD terms to 2→2 scattering (initial state radiation, final state radiation)

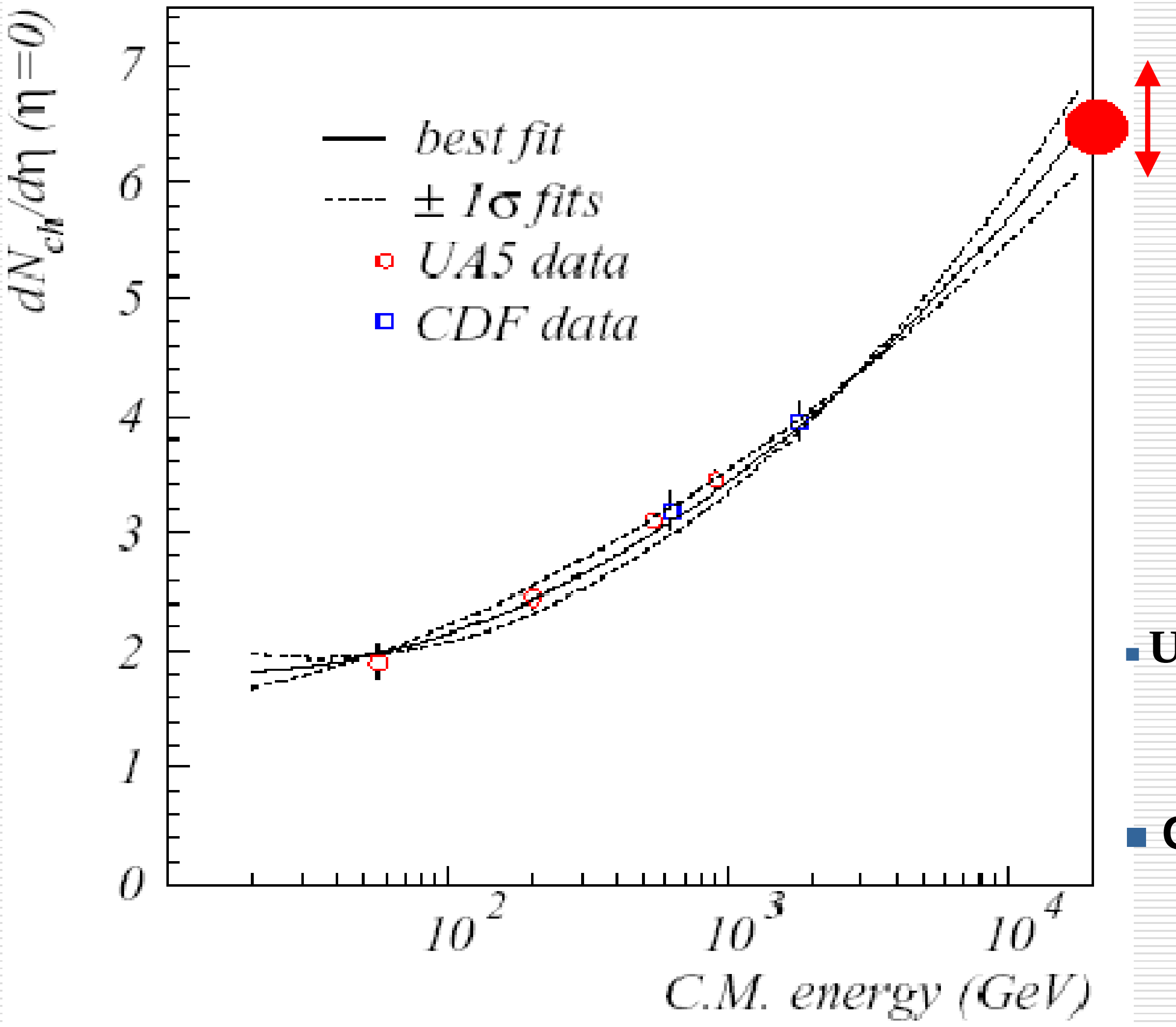


- Experimentally, effects are similar to pile-up

U.E. and Minimum Bias Events, Measurables

- In fact, without the hard scattering, you just have the underlying event, i.e. a "minimum bias" collision
- The measurable parameters of either are:
  - Charged particle density
  - Charged particle momentum density
  - Total energy density (calorimeter measurements)
- It's actually fairly uncertain at the LHC, though it affects the conditions of every physics signal
  - So it is important to pin down early
- Since physics is non-perturbative, only have models of this in event generators like Pythia, Herwig

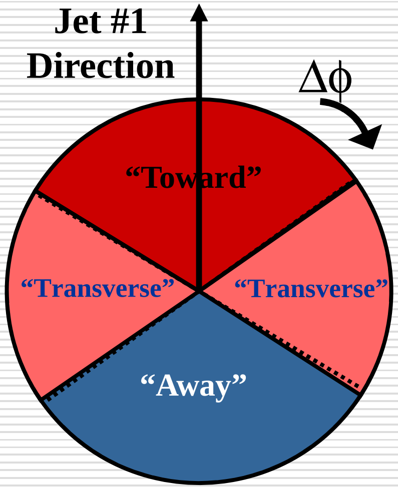
Minimum bias charged particle density

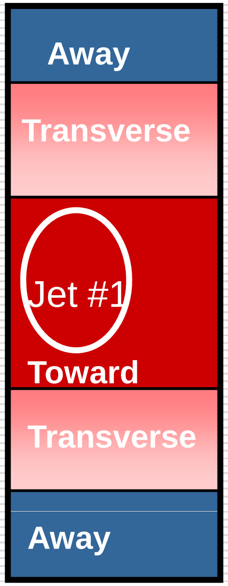


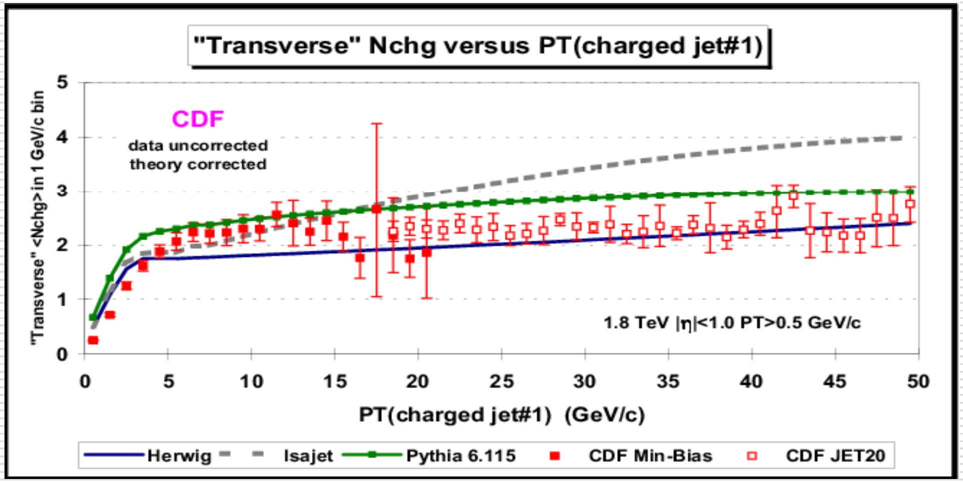
- **UA5 at $\sqrt{s}$ = 53, 200, 546, 900 GeV**
  [Z. Phys. C 33 (1986) 1]
- **CDF at $\sqrt{s}$ = 630, 1800 GeV**
  [PRD 41 (1989) 2330]

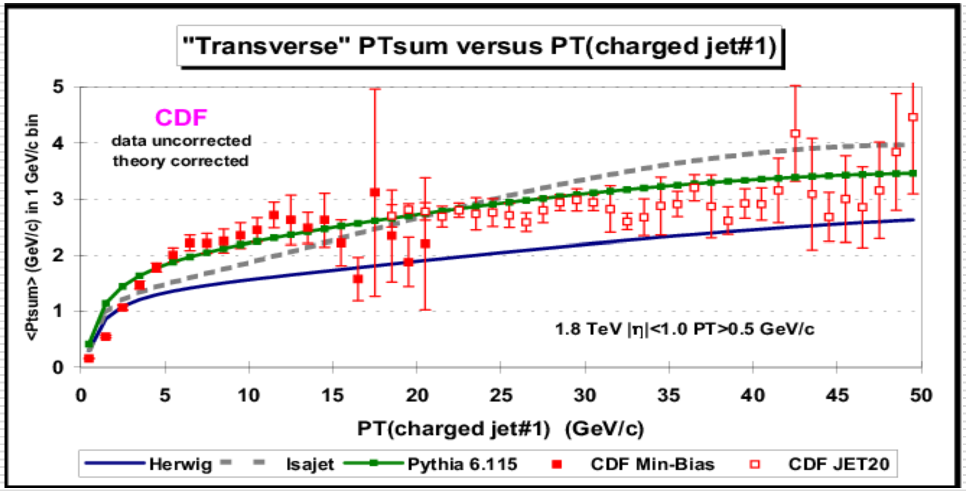
Ways to Measure U.E.

- Look in regions transverse to jets in dijet events
  - Only slow growth with scale of hard scattering



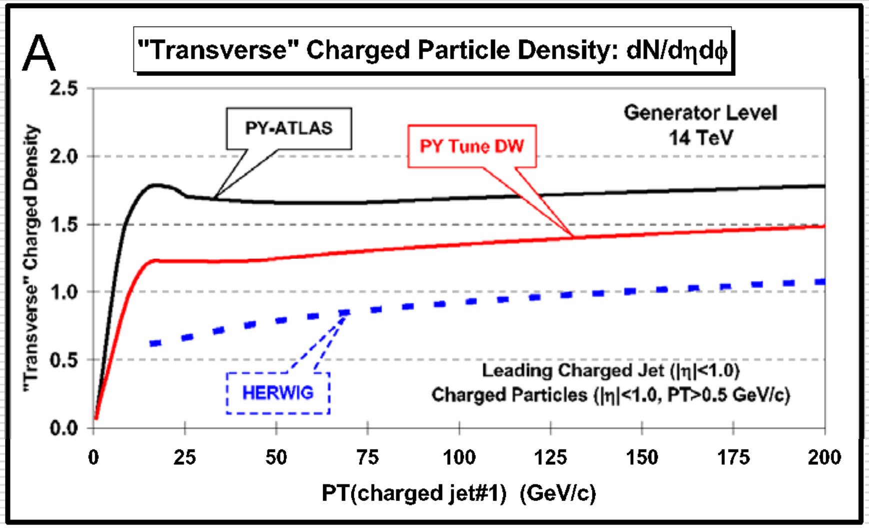


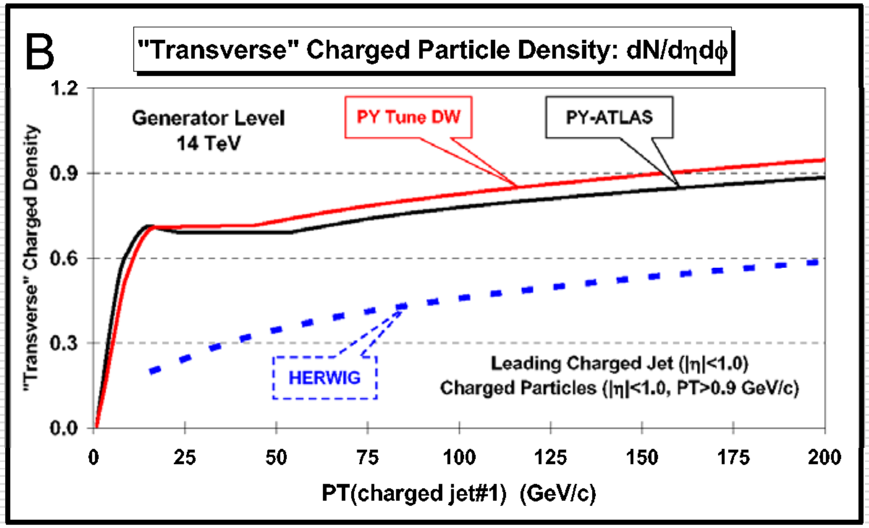




R.Field et al., PRD 65 (2003) 092002

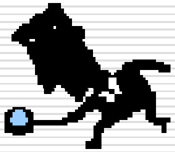
Different "Tunes" in Generators @ LHC scale





- Differences in model tunes more prominent the lower in track P_T you go
- Don't need a lot of integrated luminosity, just track reconstruction working efficiently

Missing Transverse Energy



Missing E_T

- Many signatures of new physics involve particles that are invisible to the detector
  - Lightest Supersymmetric Particles (LSP) in MSSM scenarios
  - Extra dimensions (energy escaping into the bulk)
- Leads to observed momentum imbalance
- Longitudinal momentum not well measured in hadron colliders
  - Particles escape down forward beampipe region (namely p remnant)
- Measure imbalance in transverse plane only

$$MET_x = -\sum_i E_i \sin\theta_i \cos\phi_i$$

$$MET_y = -\sum_i E_i \sin\theta_i \sin\phi_i$$

$$|MET| = \sqrt{MET_x^{\,2} + MET_y^{\,2}}$$

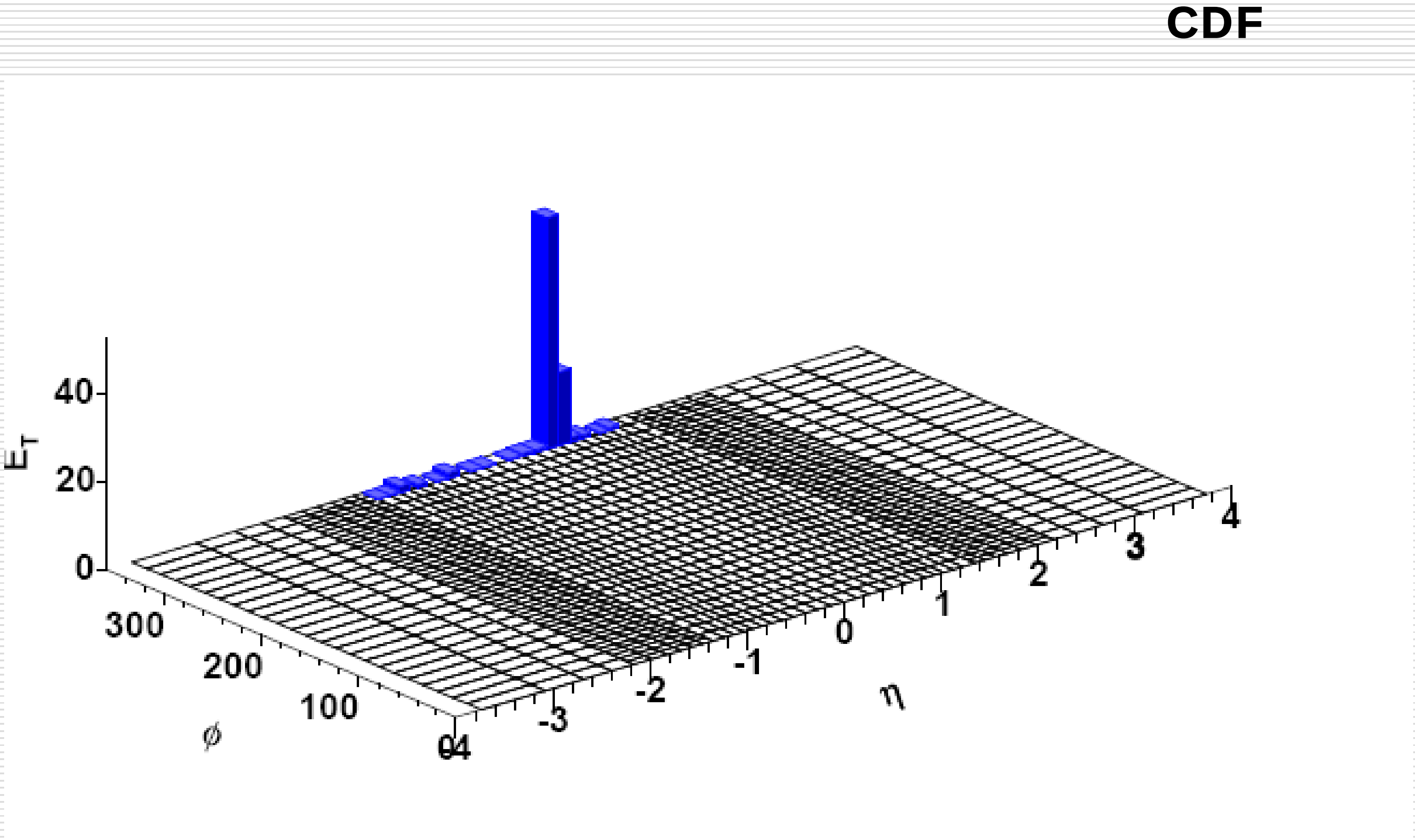
Sum runs over all calorimeter towers, or more generally, over all "particles"

Problems with Missing E_T

- Many instrumental issues can mimic momentum imbalance!
  - Dead towers
  - Cracks
  - Noise
  - Miscalibration
  - Jet energy mismeasurement
  - Non-collision backgrounds (cosmic rays, beam halo muons)
  - Beam gas collisions, beam wall collisions, collisions not at nominal vertex (satellite bunches)
  - Offset of beam or detector from nominal z axis
  - Muons (MIPs), for calorimeter-only Missing E_T
- Basically a catch-all of any problems (good DQM tool)

Could be considered the "garbage can" dataset!

Beam Halo with bremsstrahlung as seen by calorimeter



Missing E_T "Cleaning"

- Tight timing cuts on calorimeter deposits
  - Remove out-of-time particles (cosmics, beam halo) and noise
- Noise suppression algorithms
- Pattern recognition/reconstruction algorithms
  - Remove cosmic muons, beam halo muons
- Event topology
  - Charged particle vertex requirement
  - Jet requirement
  - Charged particle energy fraction of event
  - Electromagnetic energy fraction
    - Also removes cosmics, halo, …

EEMF, ECHGF

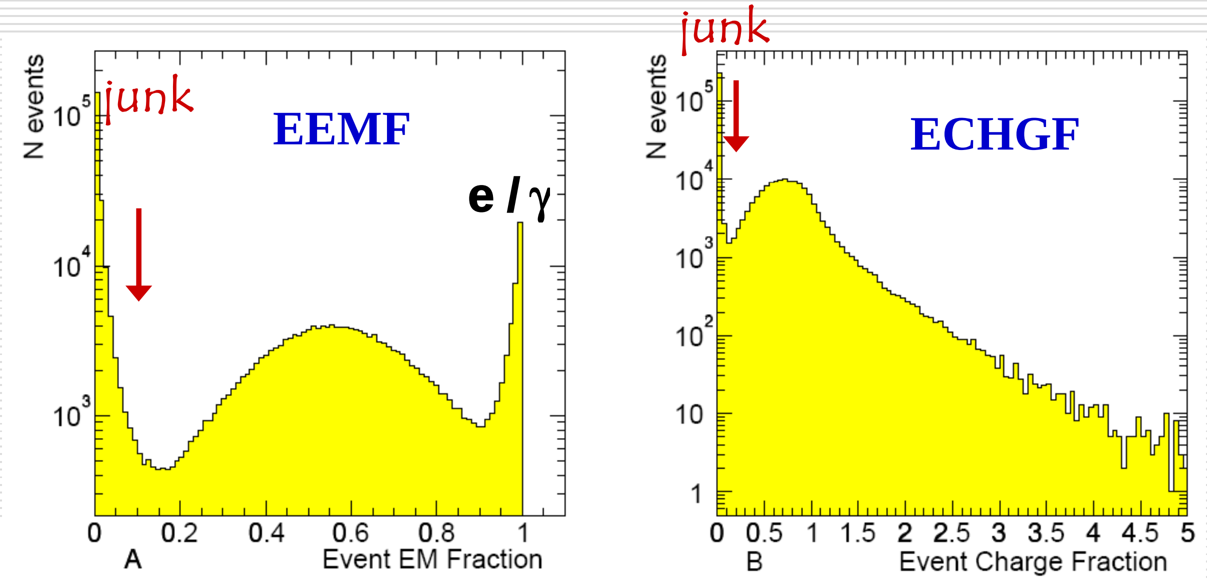
$$\mathrm{EEMF} = \frac{\sum_{j=1}^{N_{jet}} E_T^j \times EMF_j}{\sum_{j=1}^{N_{jet}} E_T^j}$$

$$EMF_j = \text{Jet EM fraction}$$

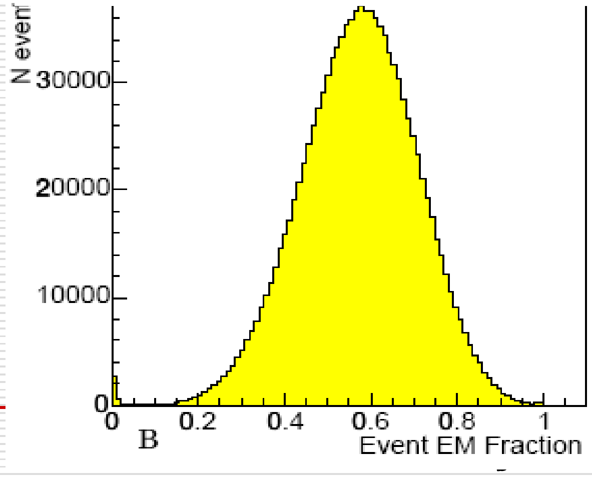
$$\mathrm{ECHGF} = \frac{1}{N_{jet}} \sum_{j=1}^{N_{jet}} \frac{\sum_{i=1}^{N_{trks}} P_T^{i,j}}{E_T^j}$$

Examples from CDF data

- ☐ MET dataset:

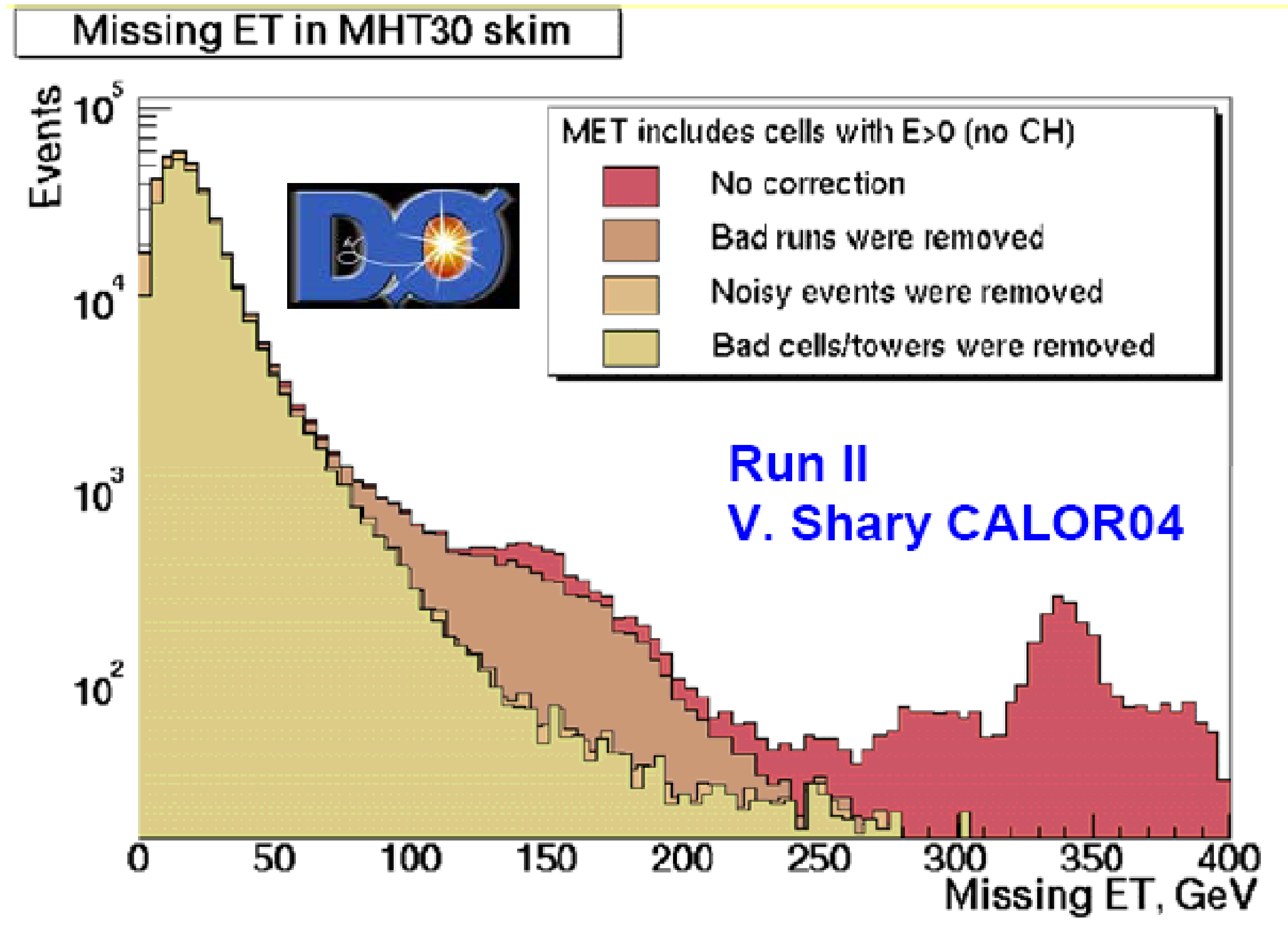


- ☐ Jet data:

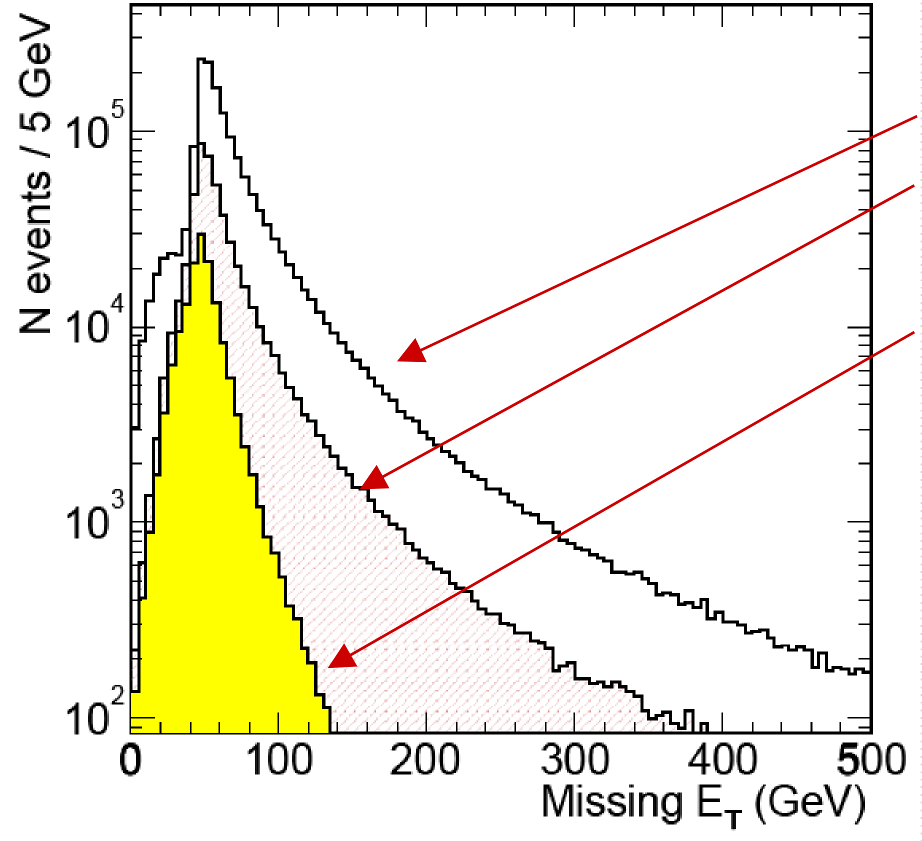


D. Tsybychev, Fermilab-thesis-2004-58

Effect of MET Clean-up (DO, Run 2)



Effect of MET Clean-up (CDF, Run 2)



- After good run selection from DQM
- After a vertex requirement in tracking detectors
- After remaining preselection cuts
  - Event EM fraction > 0.1
  - Event charged fraction > 0.1
  - At least one central jet E_T > 10 GeV
  - Total calorimeter energy < $\sqrt{s}$

n.b. Tevatron Run 2 started March 2001
First paper on pure MET dataset published 2005
Search for Scalar Leptoquark Pairs Decaying to $\nu\nu qq$ in pp Collisions at $\sqrt{s}$ =1.96 TeV

Missing E_T corrections

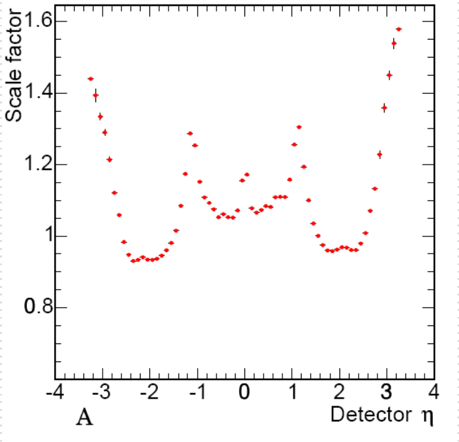
- Can replace MIP deposit in calorimeter with actual measured momentum of reconstructed muons
- Can replace calorimeter cells corresponding to jets with corrected jet energies
  - For example:

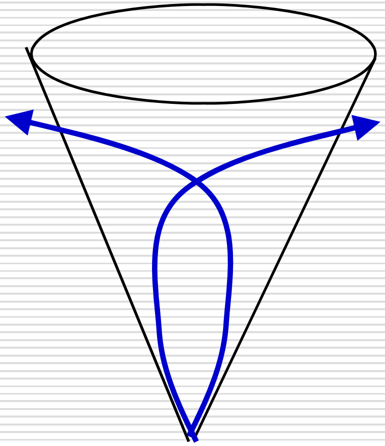
$$MET_x = -\sum_{i \in \text{unclustered}} E_i \sin\theta_i \cos\phi_i - \sum_{j \in \text{jets}} E_{x,j} - \sum_{k \in \text{muons}} E_{x,k}$$

  - "Unclustered" is everything except the jets and muons

Jet Energy Corrections (Jet Calibration)

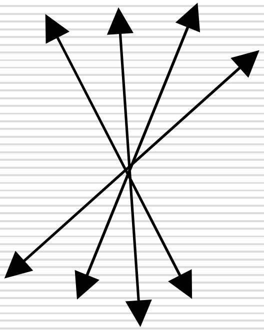
- Various physical effects cause measured jet energies not to agree with parton energies:
  - Neutrinos and muons (MIPs) in jets, different calorimeter response to different particles at low energy
  - Calorimeter response in different fiducial regions
    - effect of cracks, etc.
  - Energy falling outside cone
    - Finite cone size (or whatever you jet definition is)
    - Tracks bending outside cone
  - Detector noise
  - Pile-up



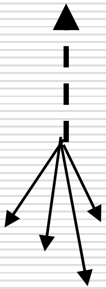


Data-driven ways to calibrate jet energies

- Dijet balancing
  - Trigger jet selected to be in well measured region, well above Jet E_T trigger threshold (to avoid energy bias)
  - Study momentum balance with probe jet

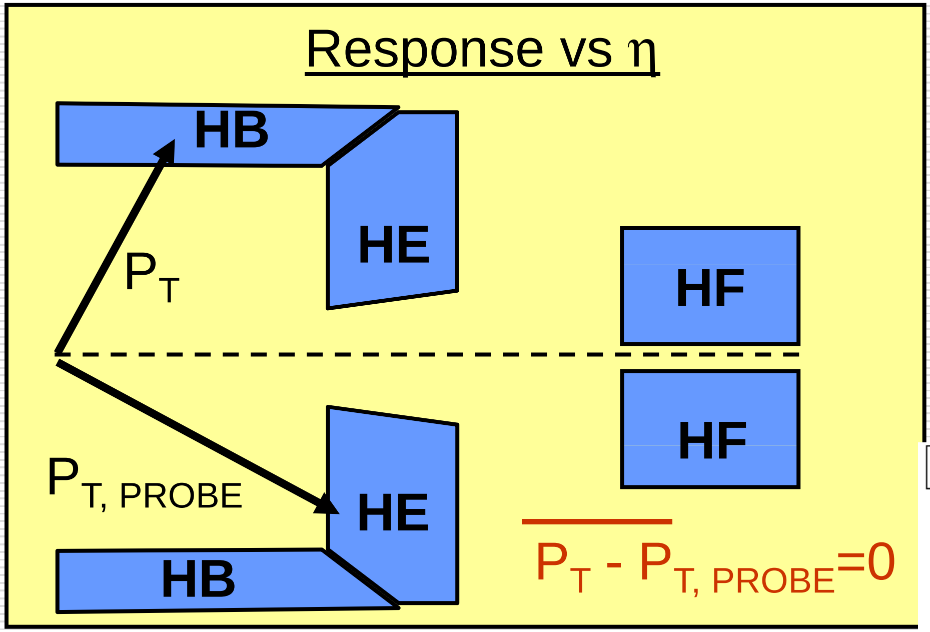


- Photon/Z+jet balancing
  - Since EM calorimeter will be well calibrated for electron and photon measurements (and muons for Z^0 decay), select events with back-to-back photon and jet in transverse plane

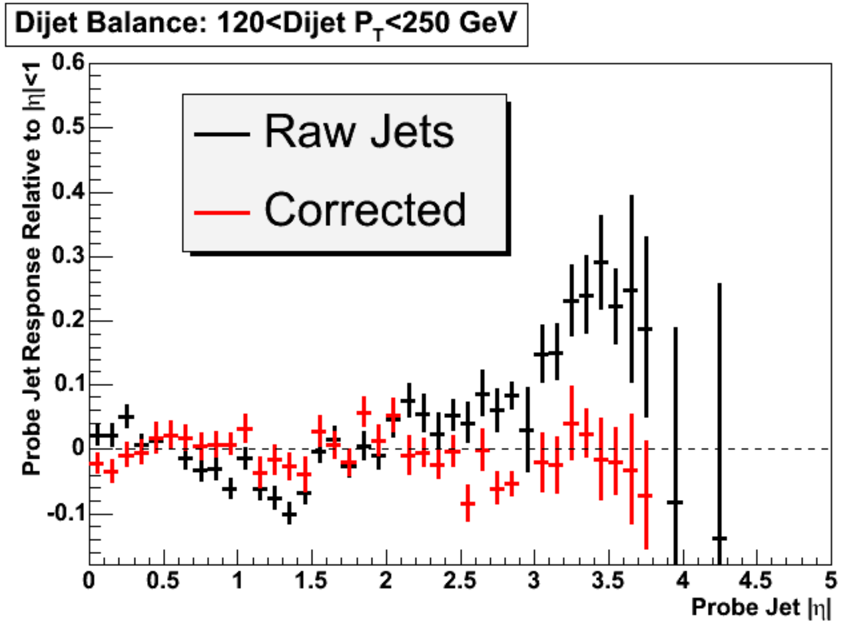


- W mass constraint in hadronic W decays in top quark pair production (overall jet energy scale)
  - Top pairs will be copiously produced at LHC
  - Isolate and use kinematic mass constraint on two jets from W decay

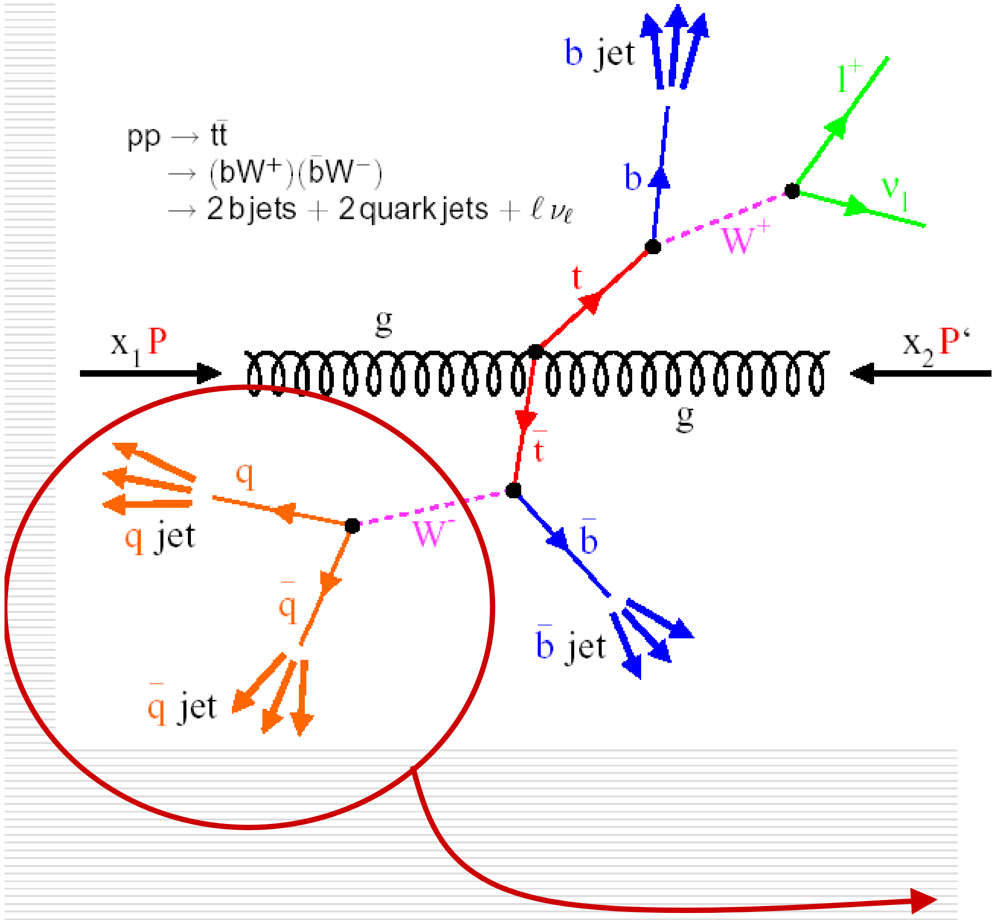
DiJet Balancing



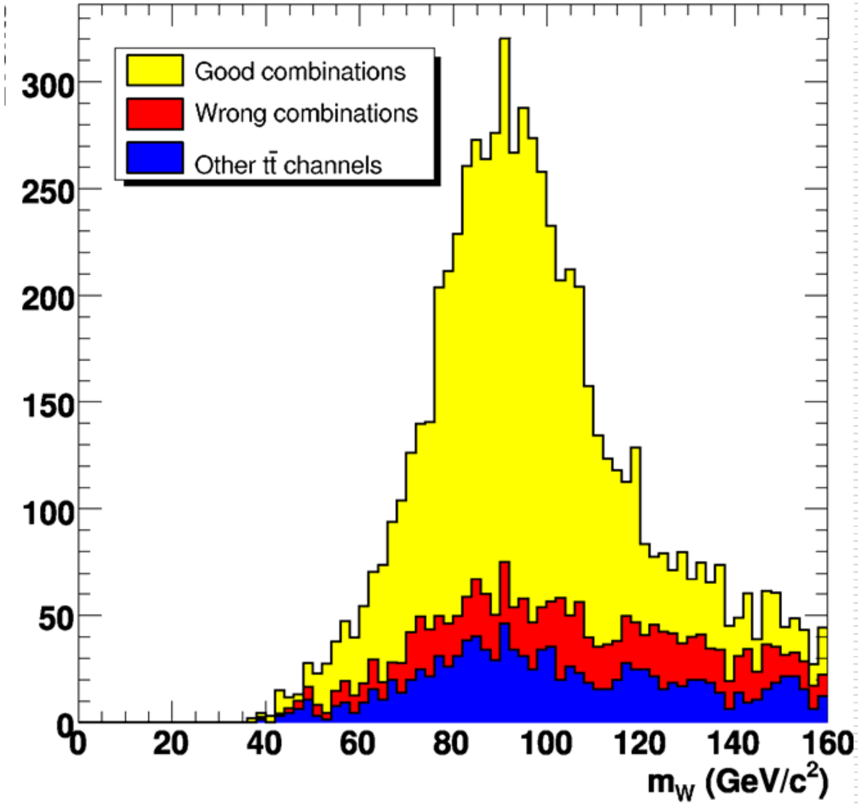
- CMS MC study
- (but technique used since UA2 experiment)



W mass constraint in Top Events

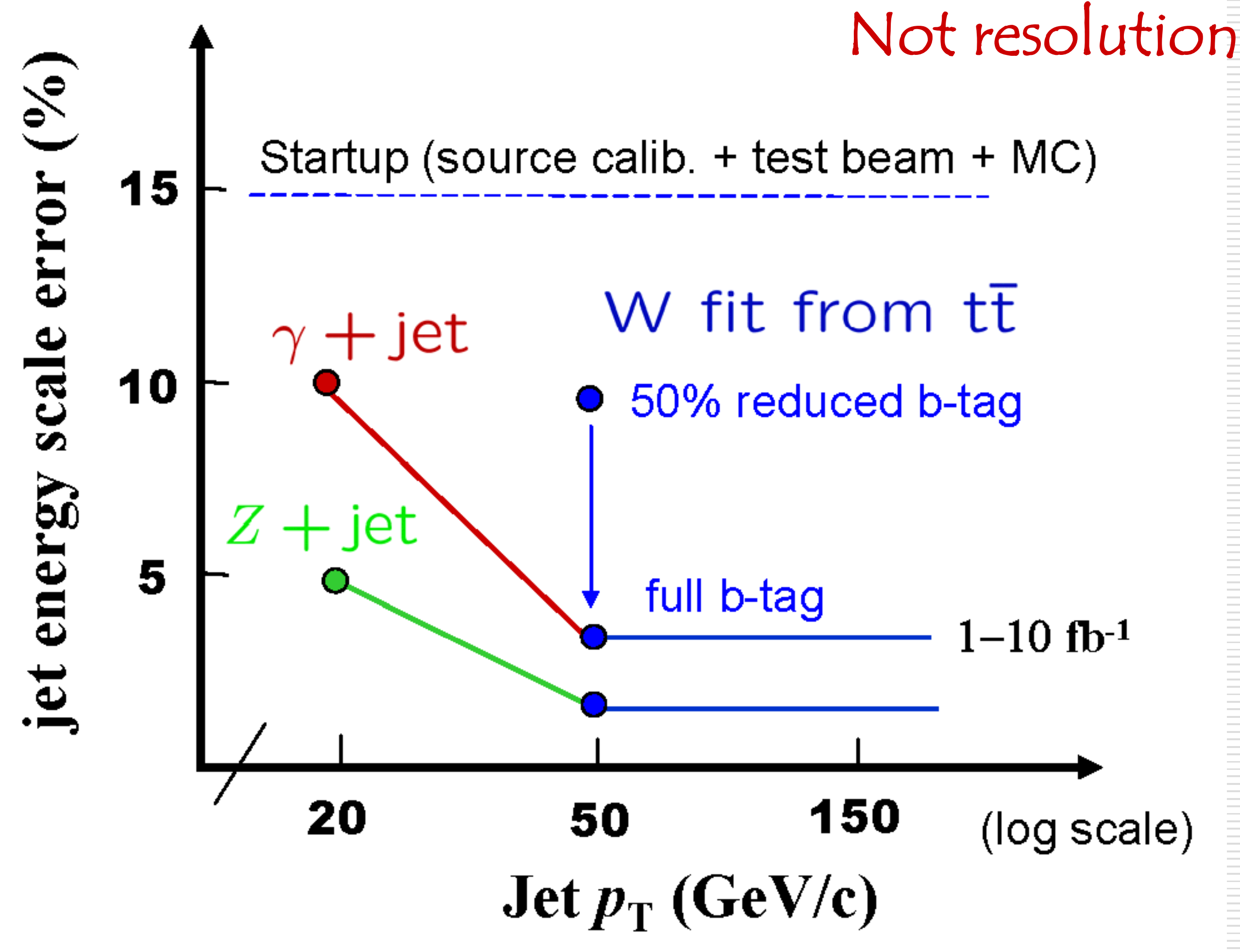


$$pp \rightarrow t\bar{t} \rightarrow (bW^+)(\bar{b}W^-) \rightarrow 2\,\text{bjets} + 2\,\text{quarkjets} + \ell\,\nu_\ell$$



Jet Energy Scale Uncertainty (CMS estimate)

Not resolution



- Aiming to achieve 3% JES uncertainty for E_T>50 GeV with 1–10 fb^{-1}

Tying it all Together

- Armed with a commissioned, calibrated, aligned detector, and with data cleaned and corrected for basic physics objects, go after measurements of Standard Model processes
  - "Calibration" of the backgrounds for new particle searches
- For example
  - QCD multi-jet production
  - Z/W+jets production
  - Top pair production
  - Diboson production (Z,W,γ) + (Z,W,γ)

Final Remarks

- Many things not covered, e.g.
  - Grounding issues (commissioning)
  - Measurements, and uncertainties of, partons density functions
- Commissioning is a big job
  - These are the most complex experiments ever built
- Don't expect it to happen overnight – patience and perseverance
- Assume nothing, check everything
- But do it well, and your experiment will pay big dividends for years to come in analyses
  - Guaranteed to be a most exciting time in this field starting now!
- Go forth and make a discovery!
    - Just don't forget to leave the water running ☺

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Some Further Reading

- CMS Physics Technical Design Report, Vols.1 & 2
  - CERN/LHCC 2006-001 – Detector Performance
  - CERN/LHCC 2006-021 – Physics Performance
    - http://cmsdoc.cern.ch/cms/cpt/tdr/
- ATLAS Physics Technical Design Report, Vols. 1 & 2
  - CERN/LHCC 1999-14 – Detector Performance
  - CERN/LHCC 1999-15 – Physics Performance
    - http://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/TDR/access.html

Credits

- ATLAS
- CDF
- CMS
- D0
- Angela Acosta
- Christoph Amelung
- Paolo Bartalini
- Victor Blobel
- Adolf Bornheim
- Rick Cavanaugh
- Sergio Cittolin
- Pawel De Barbaro
- Jorgen D'Hondt
- Domenico Giordano
- Rob Harris
- Khristian Kotov
- Marcus Stoye
- Slawek Tkaczyk
- Dmitri Tsybychev
- Jim Virdee