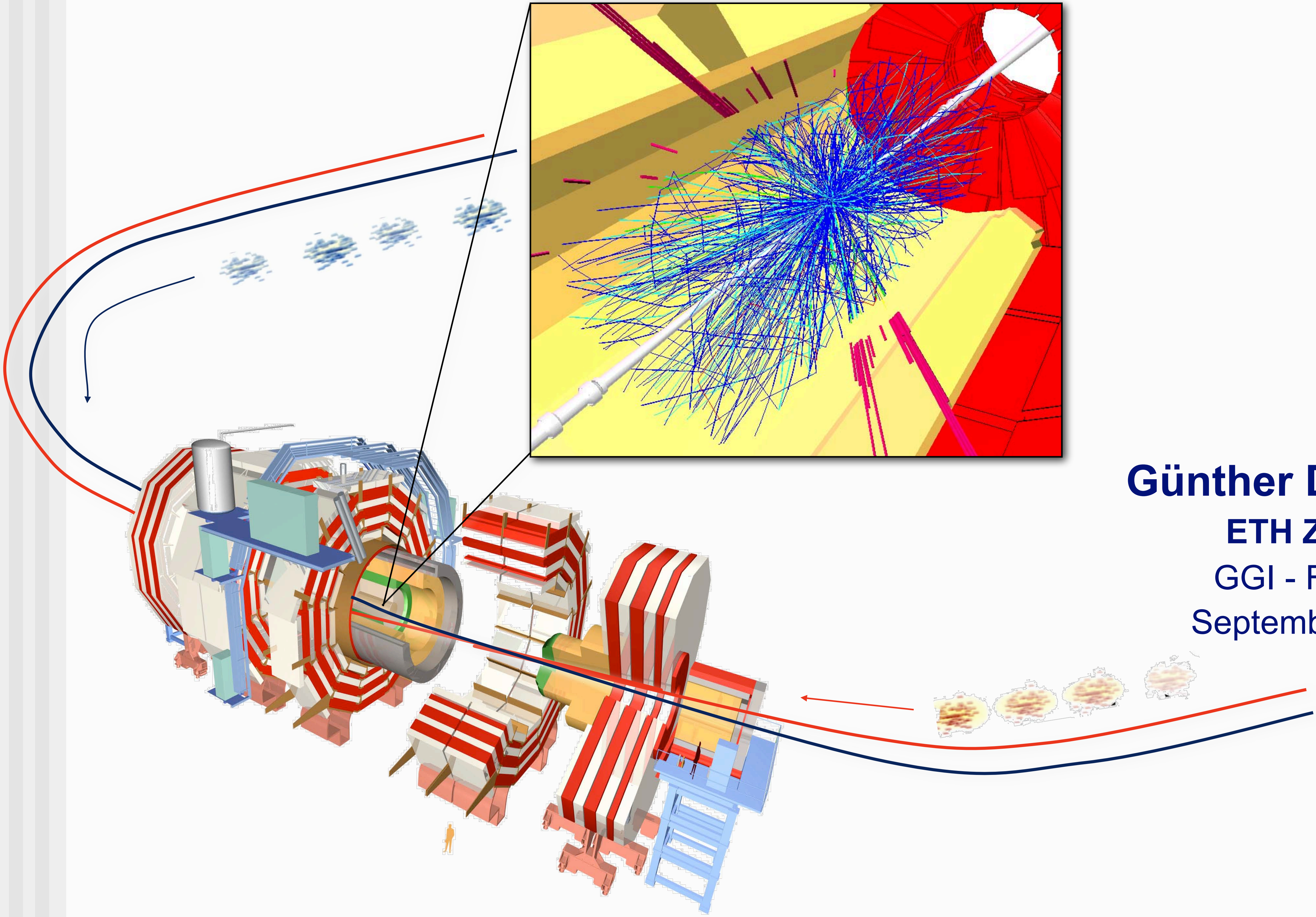
LHC Detectors : Part 3



Günther Dissertori

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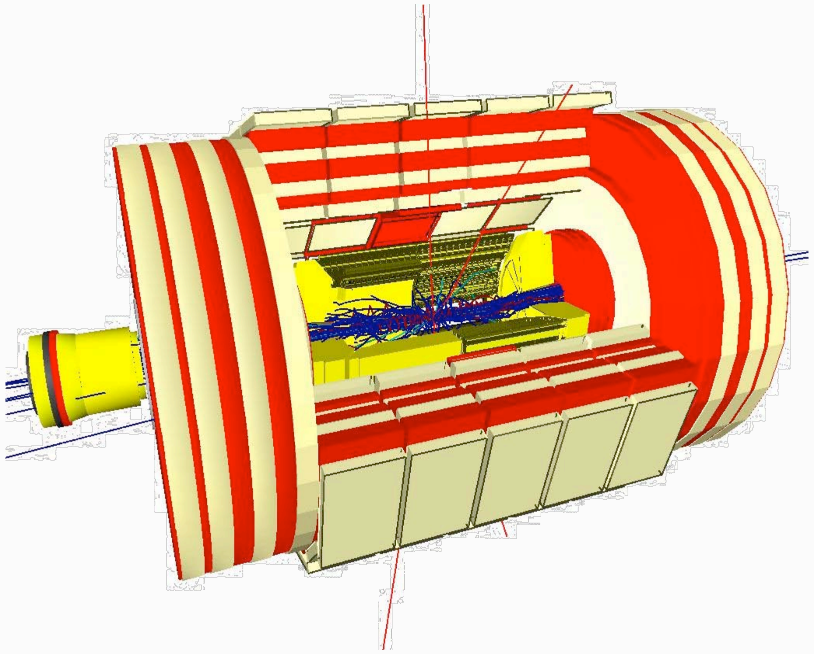
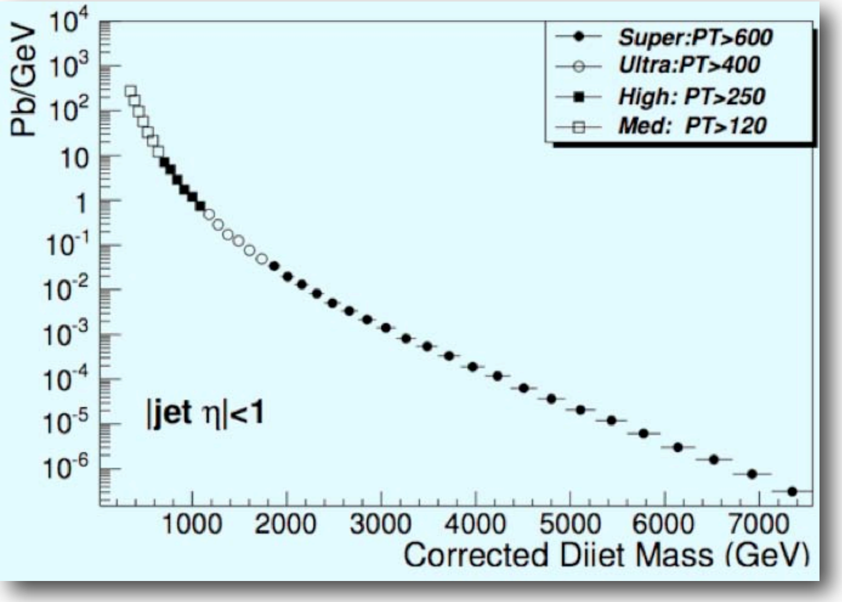
Outline

- What is measured, how and why?
  - Basic processes, rates
  - Resulting difficulties and requirements
  - Basic detector layout



- ATLAS and CMS
  - Overview
  - Construction status
  - Comparison

- Experimental issues
  - Some examples of experimental issues to be addressed
  - such as Jet Energy Calibration
  - and background estimations

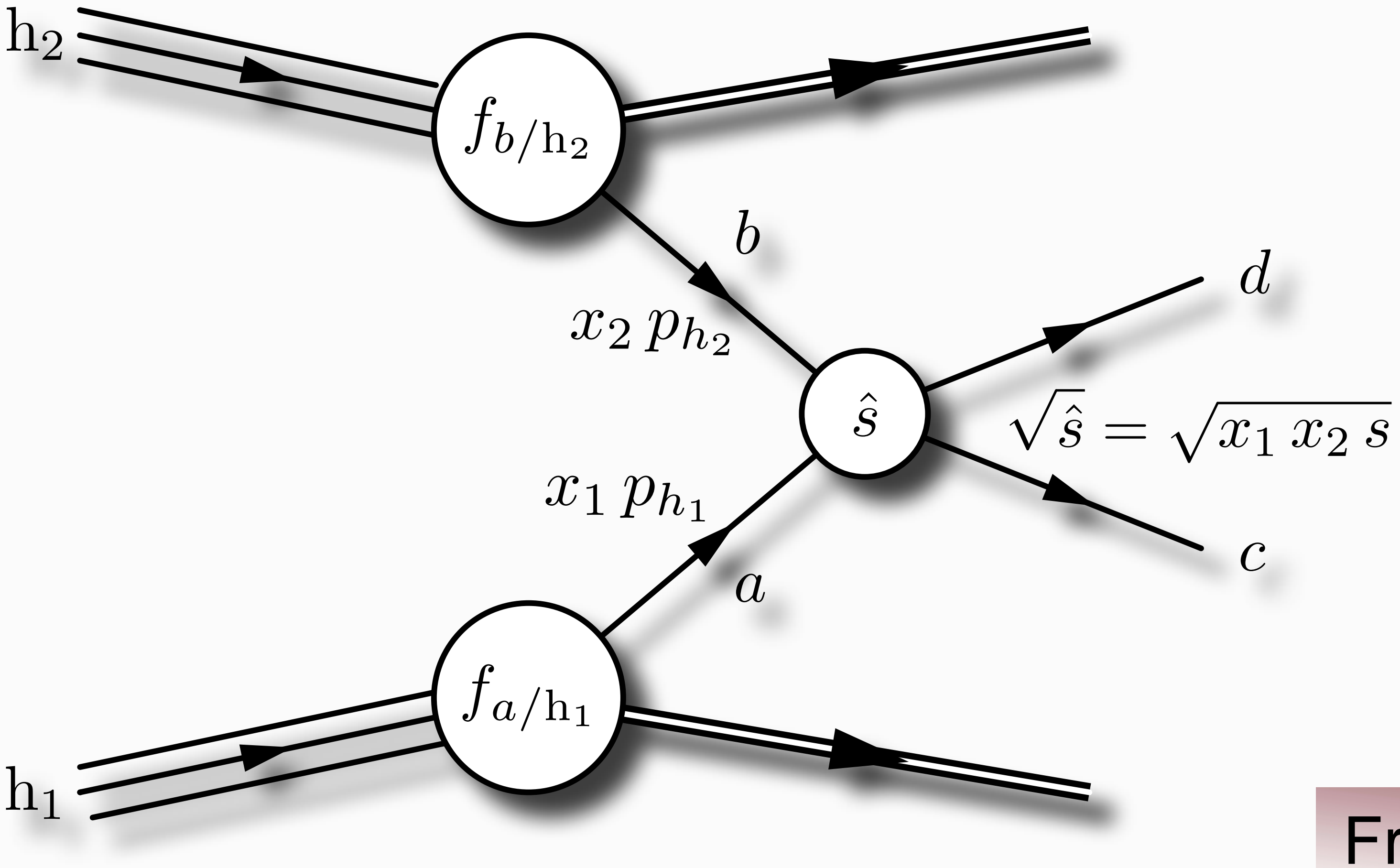


Disclaimer 1 : I concentrate on multi-purpose detector ATLAS and CMS

Disclaimer 2 : Some slides or slide content taken from seminars/lectures of other LHC colleagues, eg. K. Jakobs, O. Buchmüller, L. Dixon, M. Dittmar, D. Froidevaux, F. Gianotti

Introduction : Measurements of hard processes

The hard scattering



To produce (at central rapidity, ie. $x_1 \sim x_2$) a mass of

	LHC	TEVATRON
100 GeV	x~0.007	0.05
5 TeV	x~0.36	--

From where do we know these?

$$d\sigma(h_1 h_2 \to cd) = \int_0^1 dx_1 dx_2 \sum_{a,b} f_{a/h_1}(x_1, \mu_F^2) f_{b/h_2}(x_2, \mu_F^2) d\hat{\sigma}^{(ab\to cd)}(Q^2, \mu_F^2)$$

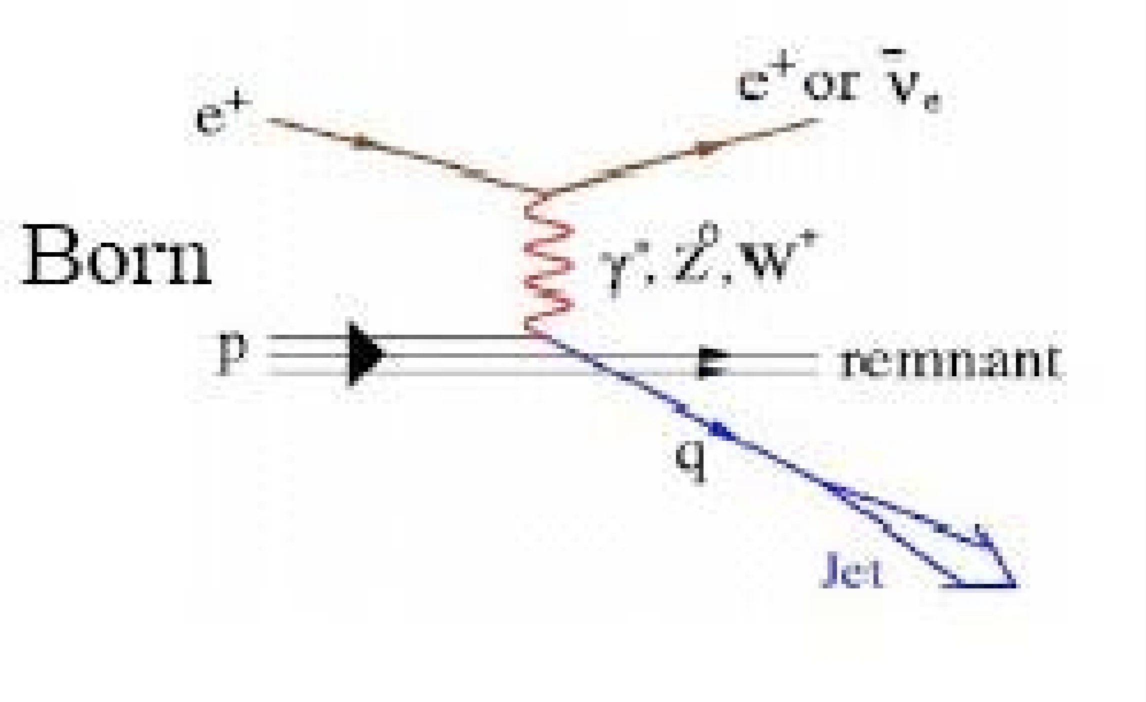
Hard Scattering = processes with large momentum transfer (Q^2)

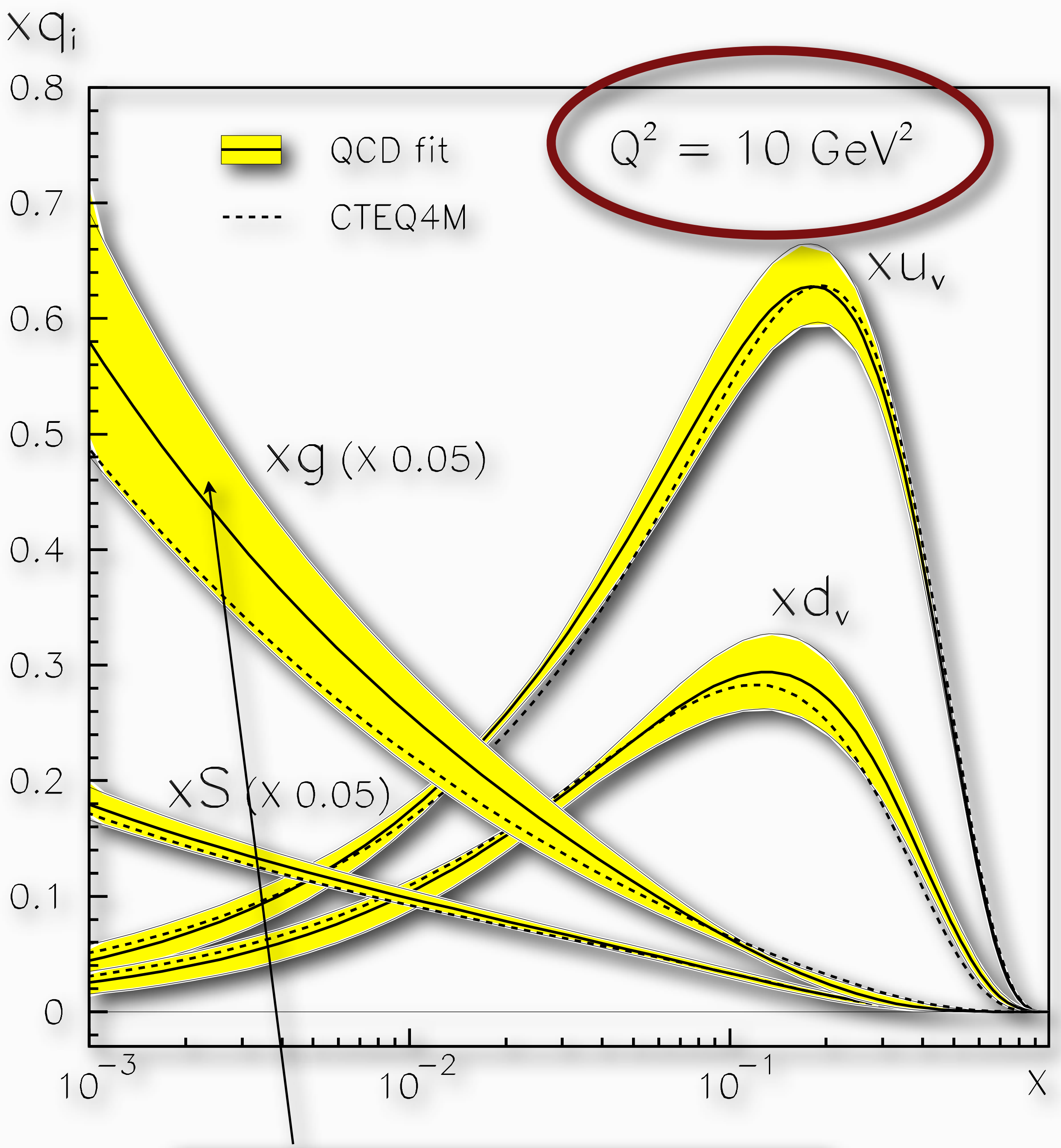
Represent only a tiny fraction of the total inelastic pp cross section (~ 70 mb)

eg. σ(pp → W+X) ~ 150 nb ~ $2 \cdot 10^{-6}\, \sigma_{tot}(pp)$

Parton Distribution functions

HERA ep accelerator, 6.3 km circumference





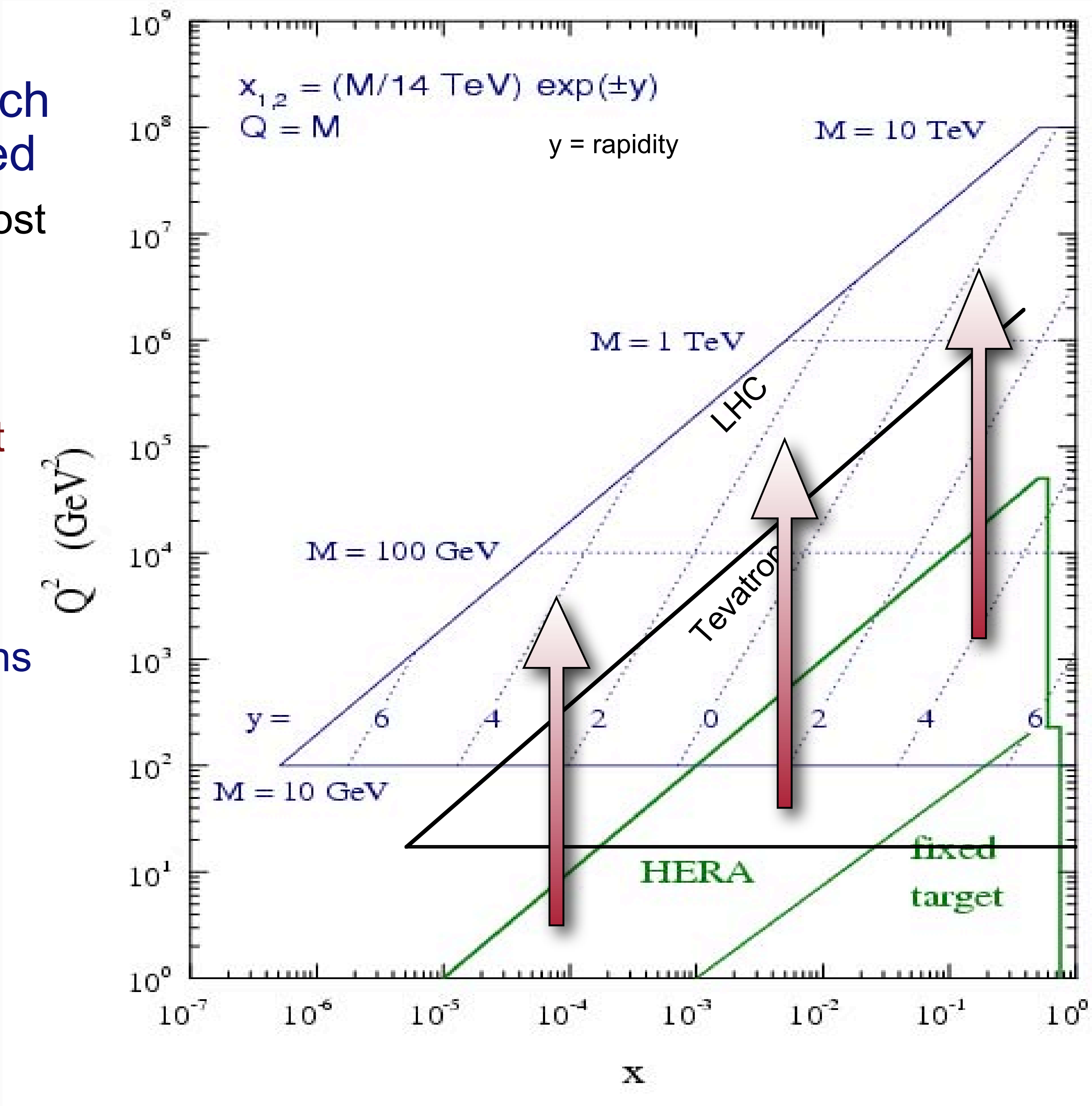
gluons dominate at low x !

Scattering of 30 GeV electrons on 900 GeV protons:
→ Test of proton structure down to 10^{-18} m

→ the LHC is a gluon-gluon collider !

Parton Distribution functions

- Kinematic regime for LHC much broader than currently explored
  - for example, HERA covers most of the relevant x range, but at much smaller values of Q^2
- Is NLO DGLAP evolution sufficient for LHC?
- Have to propagate correctly the uncertainties of PDF determinations into predictions of LHC processes
  - important when comparing to data
- Have to determine / constrain the pdfs at LHC itself
  - what are useful processes for this?



Event rates

Event production rates at $L=10^{33}\ cm^{-2}\ s^{-1}$ and statistics to tape

Process	Events/s	Evts on tape, 10 fb^{-1}
$W \to e\nu$	15	10^8
$Z \to ee$	1	10^7
$t\bar{t}$	1	10^6
Minimum bias	10^8	10^7
QCD jets $p_T > 150$ GeV/c	10^2	10^7
$b\bar{b} \to \mu X$	10^3	10^7
gluinos, m=1 TeV	0.001	10^3
Higgs, m=130 GeV	0.02	10^4

assuming 1% of trigger bandwidth

10^7 events to tape every 3 days, assuming 30% data taking efficiency, 1 PB/year/exp

statistical error negligible after few days (in most cases) !
dominated by systematic errors (detector understanding, luminosity, theory)

First Physics runs (2008, 2009, …)

- After first “good” 10 pb^{-1}
  - many jets...
  - ~20000 W, decaying to lepton + neutrinos
  - ~2500 Z, decaying into two leptons
  - ~200 semi-leptonic top-pair events
    - Measure rates, align and calibrate better

- After first “good” 100 pb^{-1}
  - W(Z)+jets rates well measurable
    - Jet calibration, MET calibration (for SUSY)
  - Inclusive leptons, di-leptons, photons, di-photon triggers (for Higgs)

- From 100 pb^{-1} to 1 fb^{-1}
  - Standard model candles
    - Top pair prod., W/Z cross sections, PDF studies, QCD studies, b-jet production
    - Do extensive MC tuning
  - Early Higgs boson search
    - $H \rightarrow \gamma\gamma$,WW,ZZ
  - Early SUSY-BSM searches
    - MET + anything, di-jet, di-leptons, di-photon, resonances….

Why SM physics?

- Interesting in its own right
  - measure (calculable) event rates, cross sections
  - establish (dis)agreement with SM, constrain SM
  - challenge theoretical calculations at high Q^2
  - demonstrate “working” experiment with well known processes
- Understanding, commissioning, calibration of detector and the software. eg. well suited : $Z \rightarrow \ell^+\ell^-$
- Backgrounds to many searches : check MC simulations
  - eg. W/Z+jets, Multi-Jets, top-pair events
- Constrain (relative) PDFs
- Alternative measurements of luminosity

Our Master Equation

Event rates (absolute, relative, differential)
Stat vs syst errors, backgrounds from data or MC?
Resolution, Energy Scale, Signal Significance

$$\sigma_{\text{meas}} = \frac{N_{\text{obs}} - N_{\text{bkg}}}{\varepsilon \quad L}$$

Proton-Proton Luminosity
uncertainty ~ 5% ? Do better?

Experimental issues : Triggers, reconstruction, isolation cuts, low-p_T jets (jet veto)

Theoretical issues : p_T distributions at NLO + resummation;
differential calculations for detectable acceptance.

$$\sigma_{\text{theo}} = PDF(x_1, x_2, Q^2) \otimes \hat{\sigma}_{\text{hard}}$$

constrain, define uncertainties

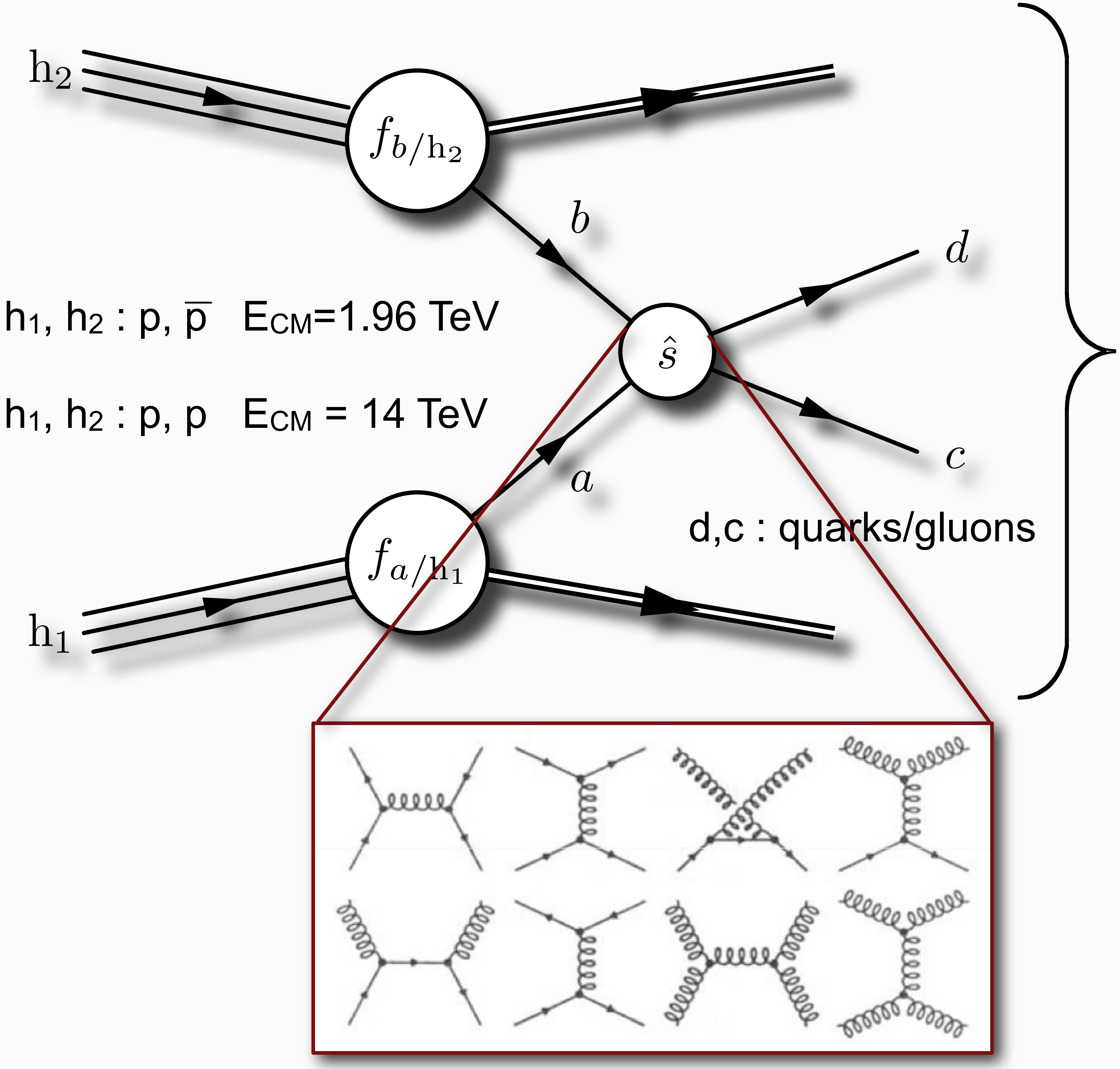
HO calculations,
implement in MC

Goal : test SM (in)consistency : $\sigma_{\text{exp}} \pm \Delta_{\text{exp}} \overset{?}{=} \sigma_{\text{SM}} \pm \Delta_{\text{th}}$

Jets

JET production at hadron colliders

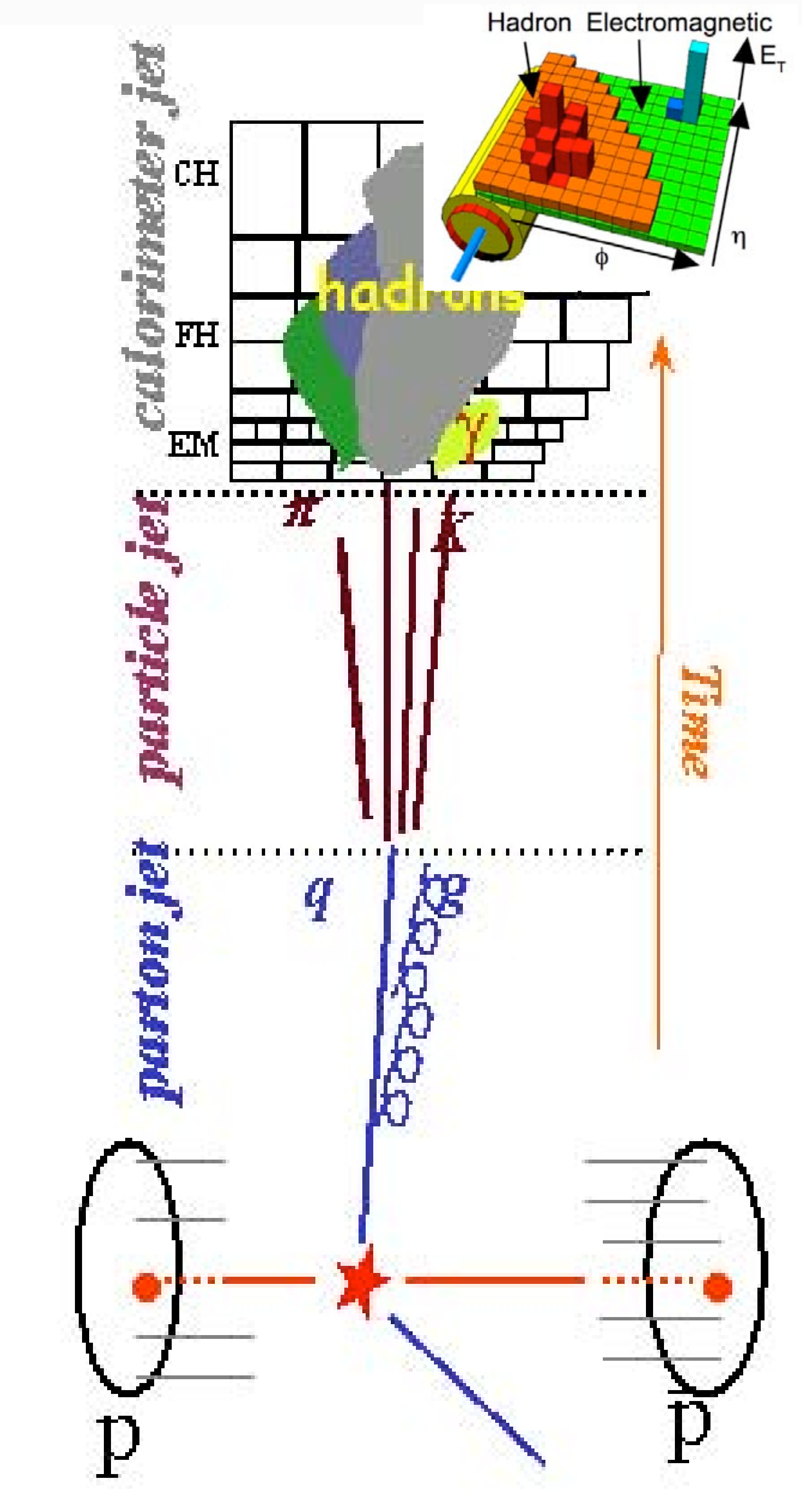
- at the Tevatron, or in the future at the LHC



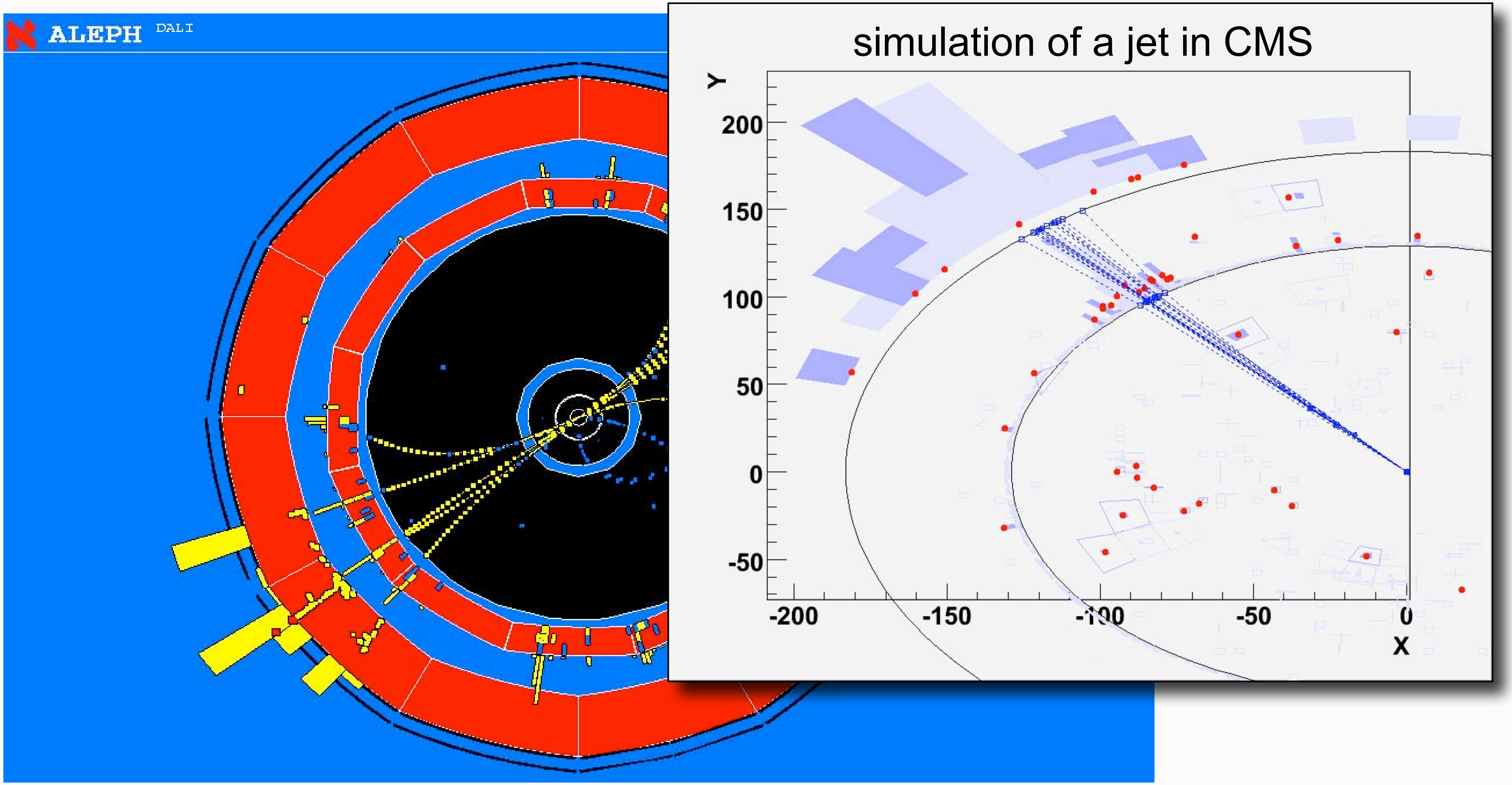
h_1, h_2 : p, $\bar{p}$ E_{CM}=1.96 TeV

h_1, h_2 : p, p E_{CM} = 14 TeV

d,c : quarks/gluons



What is a jet?



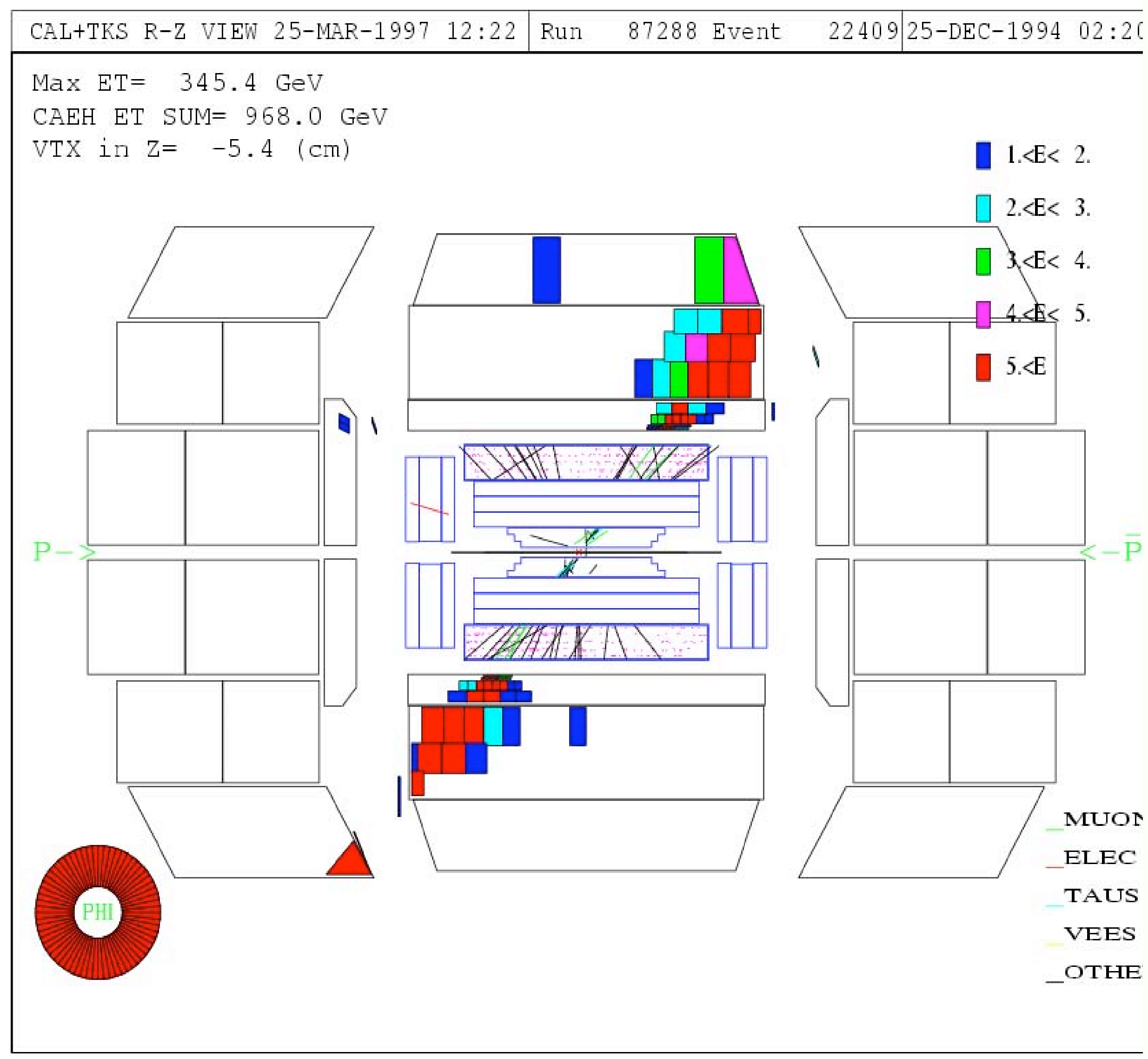
> *"cluster/spray of particles (tracks, calorimeter deposits) or flow of energy in a restricted angular region"*

- clear : need some algorithmic definition

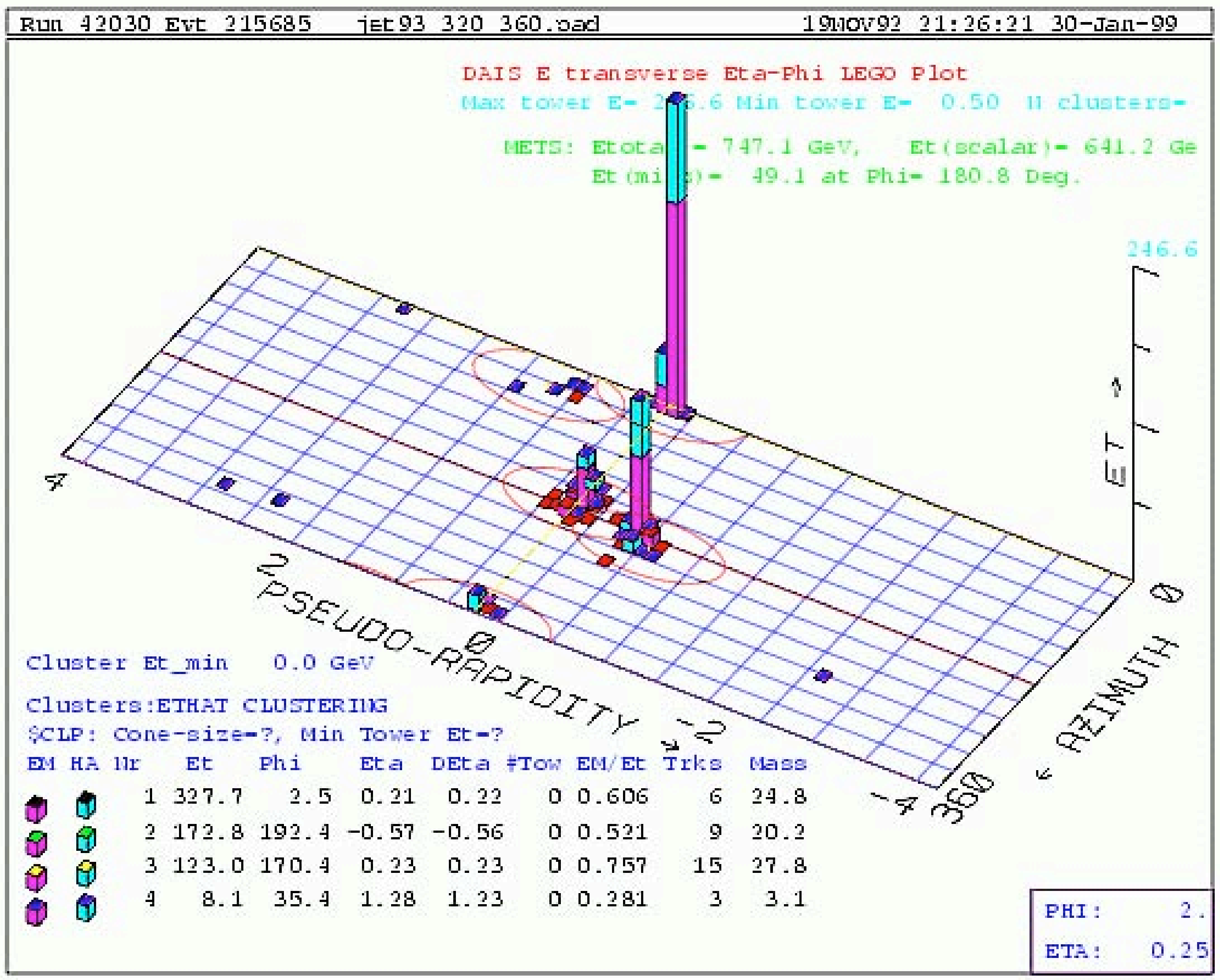
A short digression: Jet Algorithms

Jets in Hadron Collider Detectors

Jets in DØ CDF



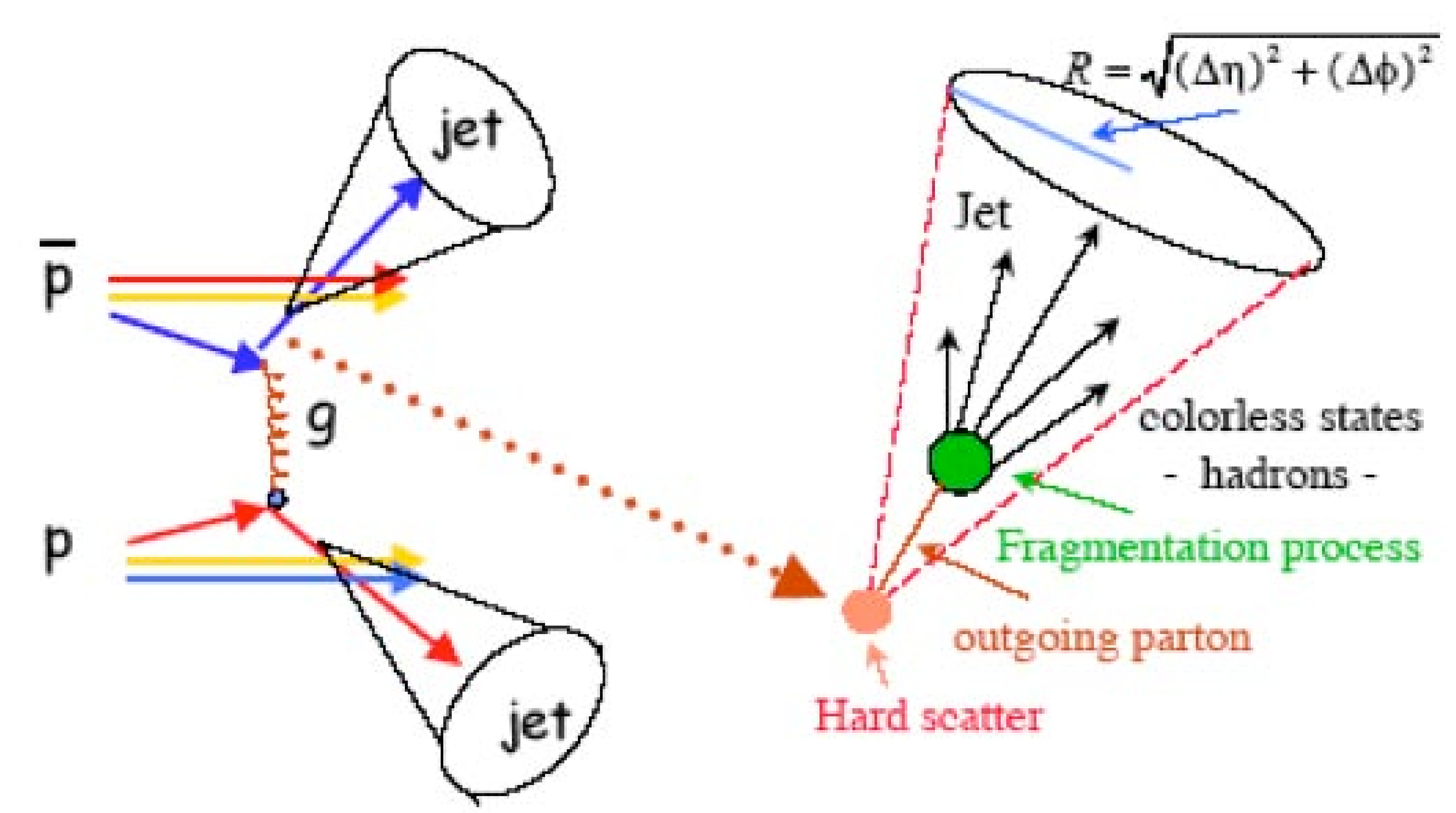
```
CAL+TKS R-Z VIEW 25-MAR-1997 12:22 | Run    87288 Event    22409 | 25-DEC-1994 02:2
Max ET=   345.4 GeV
CAEH ET SUM= 968.0 GeV
VTX in Z=   -5.4 (cm)
```



```
Run 42030 Evt 215685    jet93 320 360.pad            19NOV92 21:26:21 30-Jan-99
DAIS E transverse Eta-Phi LEGO Plot
Max tower E= 2 6.6 Min tower E=  0.50  N clusters=
METS: Etota  = 747.1 GeV,    Et(scalar)= 641.2 Ge
      Et(mi  )=  49.1 at Phi= 180.8 Deg.
Cluster Et_min   0.0 GeV
Clusters:ETHAT CLUSTERING
$CLP: Cone-size=?, Min Tower Et=?
EM HA Nr    Et    Phi    Eta   DEta #Tow EM/Et Trks   Mass
       1 327.7    2.5   0.21   0.22    0 0.606    6   24.8
       2 172.8  192.4  -0.57  -0.56    0 0.521    9   20.2
       3 123.0  170.4   0.23   0.23    0 0.757   15   27.8
       4   8.1   35.4   1.28   1.23    0 0.281    3    3.1
PHI:     2.
ETA:   0.25
```

- Introducing a cone prescription seems “natural”...
- But how to make it more quantitative?
  - don’t want people “guessing” at whether there are 2,3, ... jets

Cones...

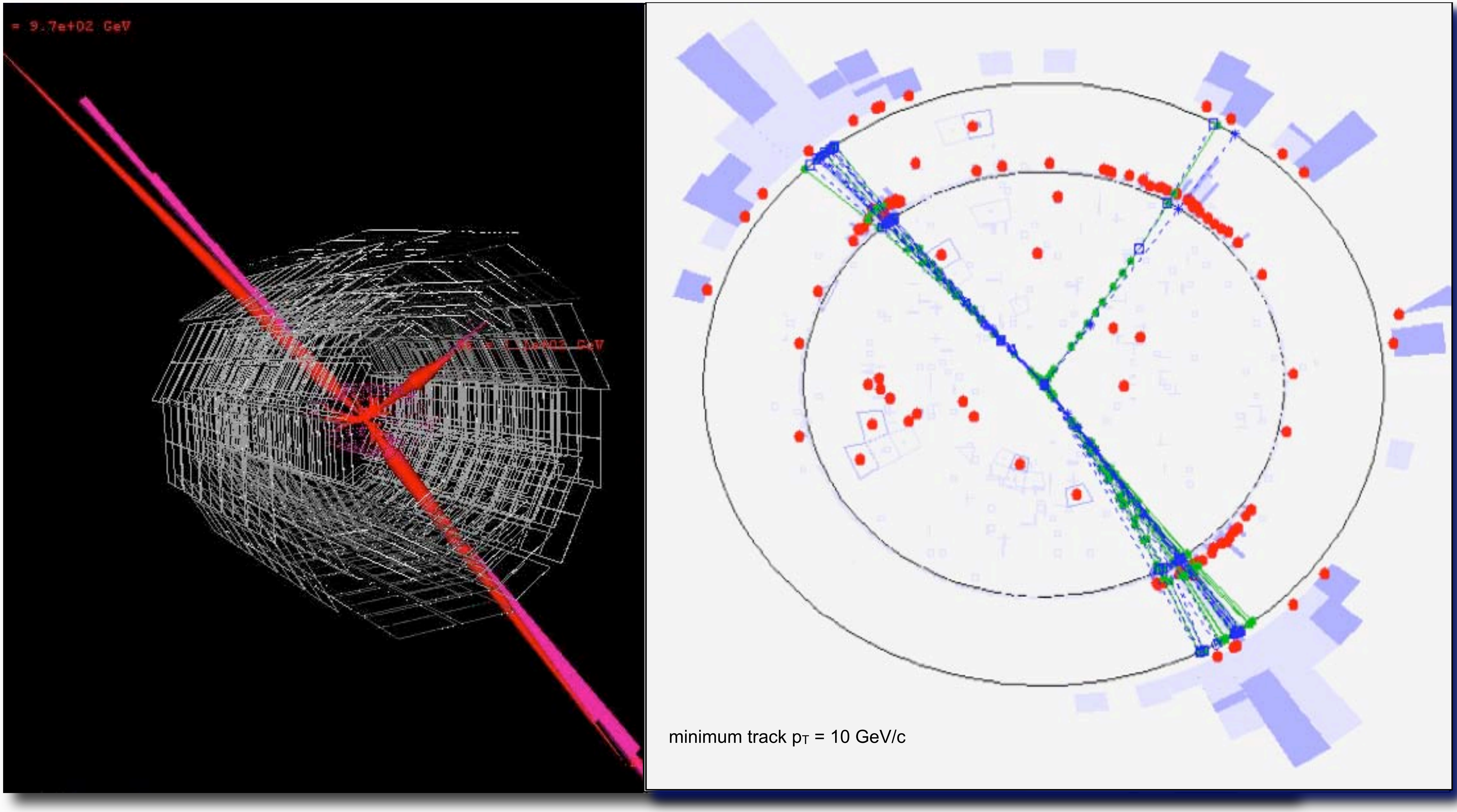


The natural (?) definition of a jet in a hadron collider environment

from J. Huston, CTEQ summer school 2004

Jets in Hadron Collider Detectors

(simulated) Jets in CMS



Requirements

- Applicable at all levels
  - partons, stable particles
    - for theoretical calculations
  - measured objects (calorimeter objects, tracks, etc)
  - and always find the same jet

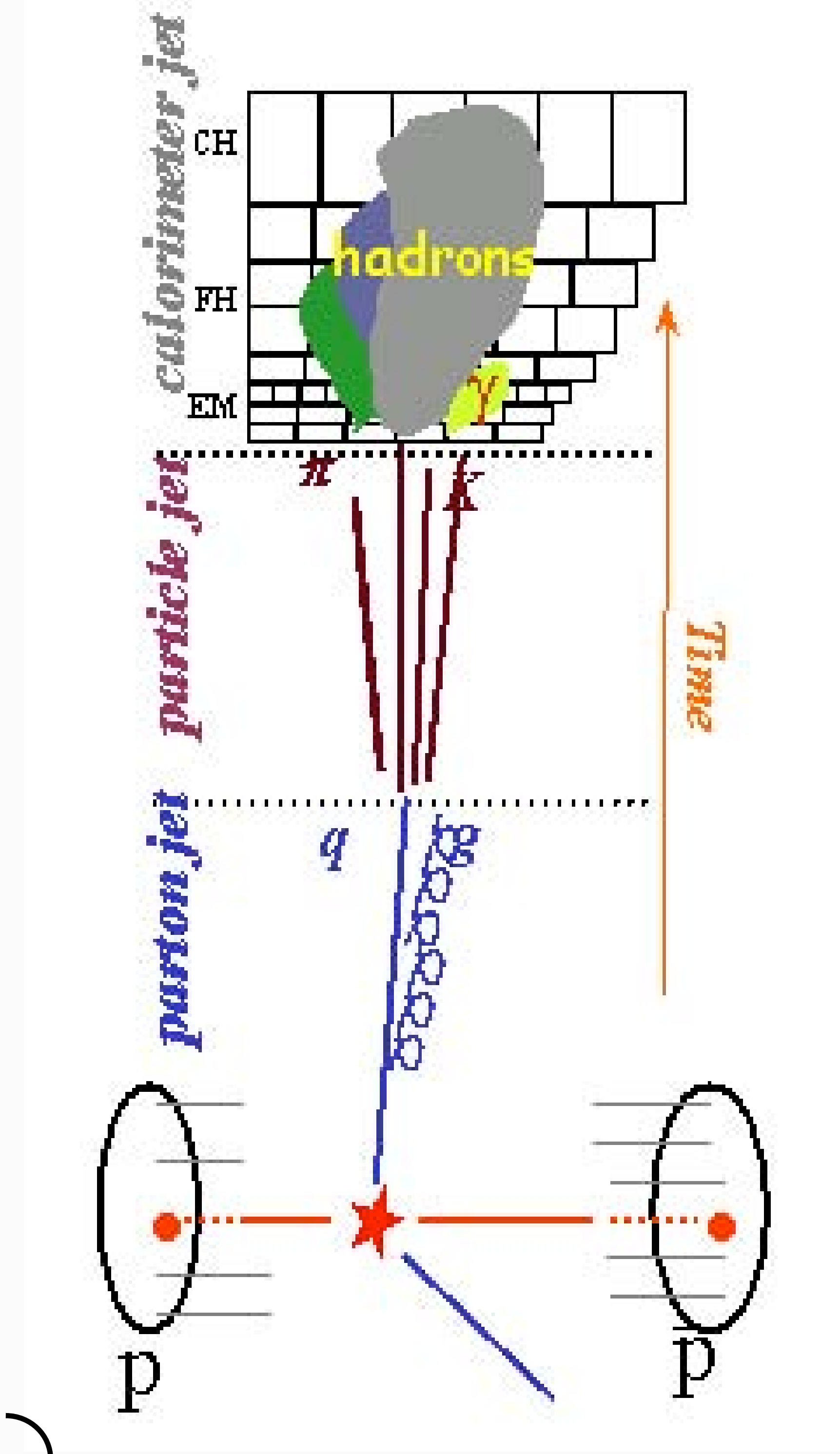
- Independent of the very details of the detector
  - example : granularity of the calorimeter, energy response,...

- Easy to implement !

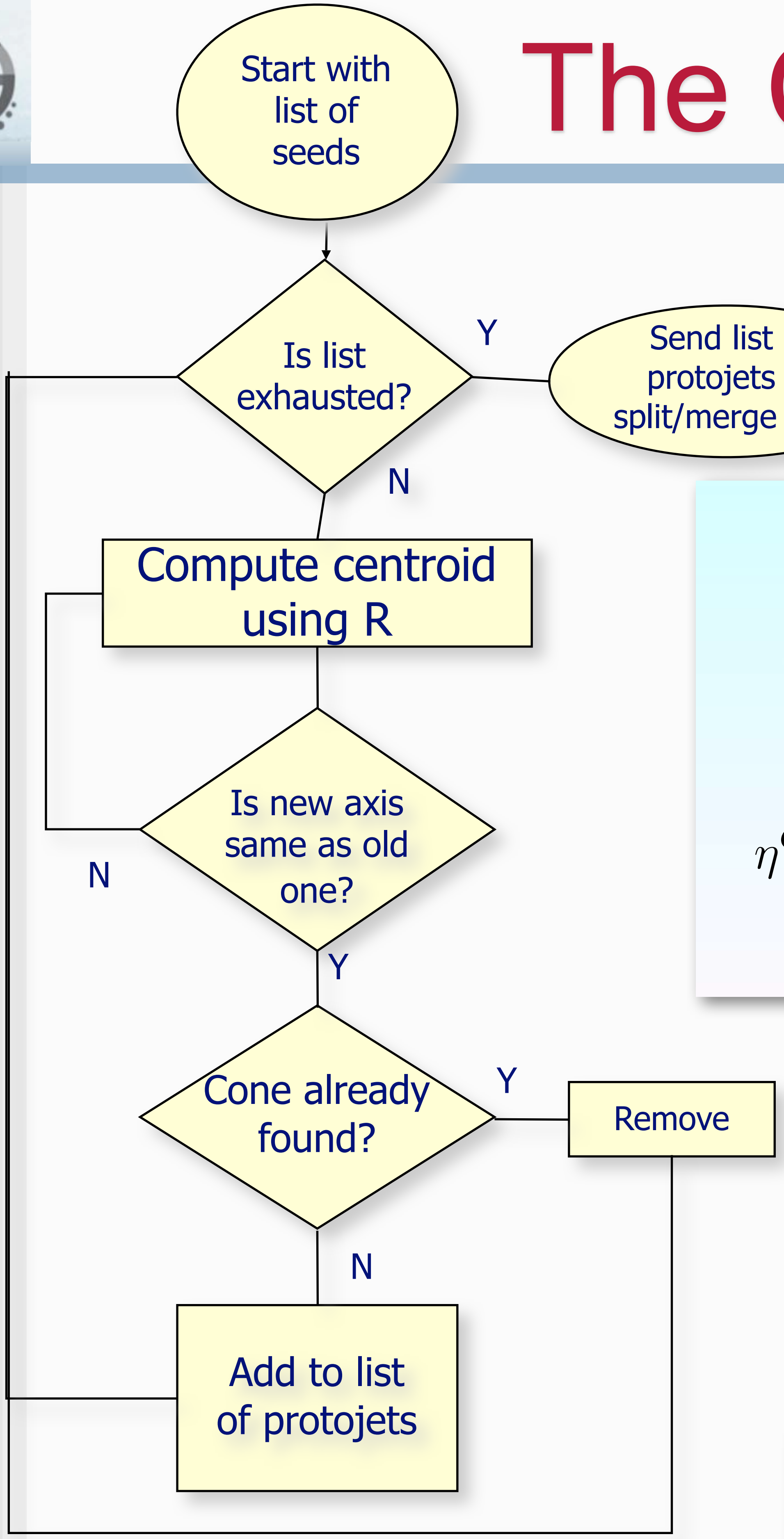
- Close correspondence between

$P_{\text{parton}} \Longleftrightarrow P_{\text{jet}}$

Energy
Momentum
angle



The CONE algorithm



Start with list of seeds

Is list exhausted?

Y

Send list of protojets to split/merge algo

N

Compute centroid using R

Is new axis same as old one?

N

Y

Cone already found?

Y

Remove

N

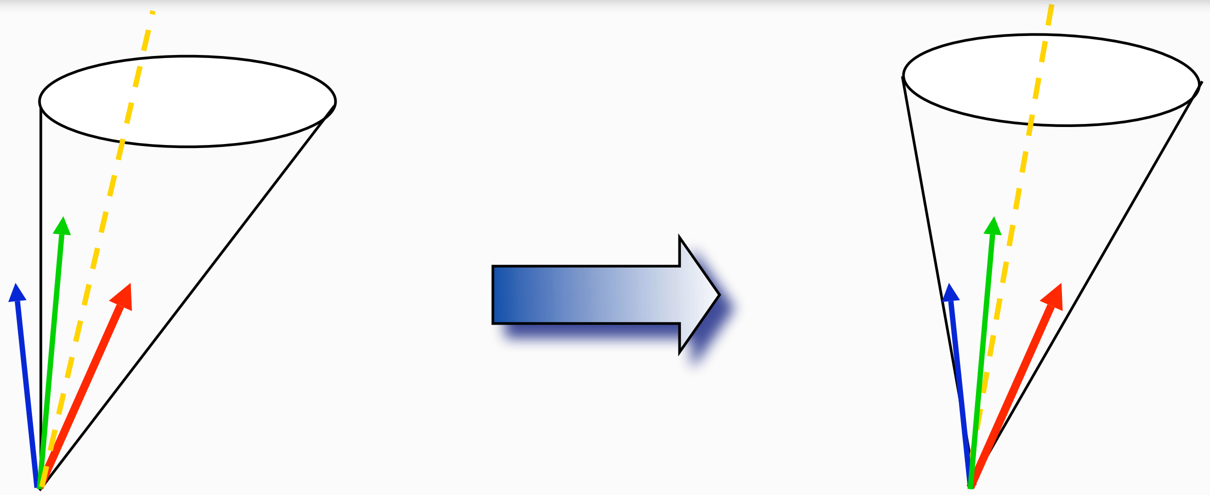
Add to list of protojets

Seeds: for example, energy deposits with transverse energy ($E_T = E \sin\theta$) > 2 GeV in a tower of the calorimeter

Centroid (one possible def) :

$$i \in C \quad : \quad \sqrt{(\eta^i - \eta^C)^2 + (\Phi^i - \Phi^C)^2} \leq R \quad \text{cone radius}$$

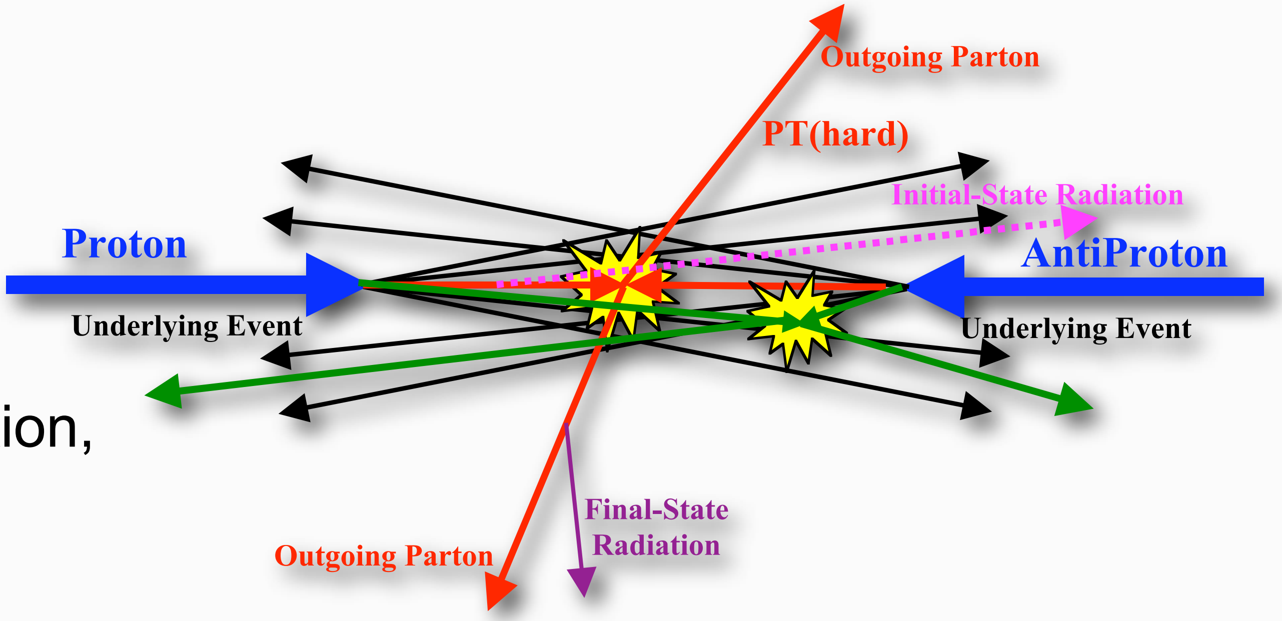
$$\eta^C = \frac{1}{E_T^C} \sum_{i \in C} E_T^i \eta^i \quad ; \quad \Phi^C = \frac{1}{E_T^C} \sum_{i \in C} E_T^i \Phi^i \quad ; \quad E_T^C = \sum_{i \in C} E_T^i$$



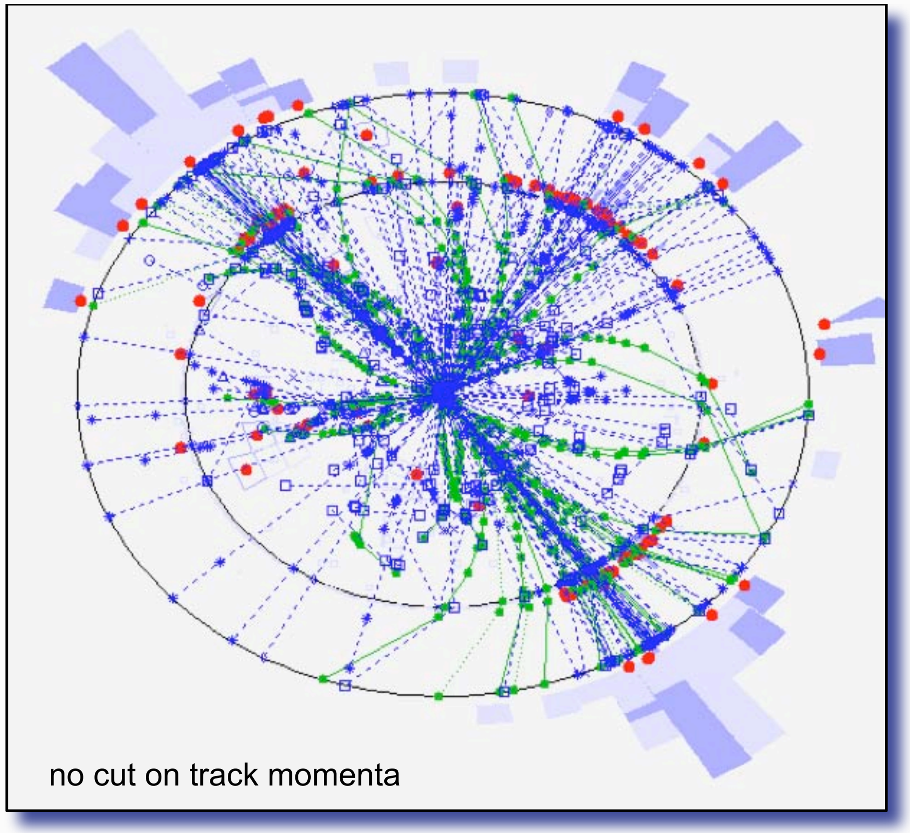
Also : new seedless cone algorithm and k_T algorithm (not cone based) !

Further difficulties

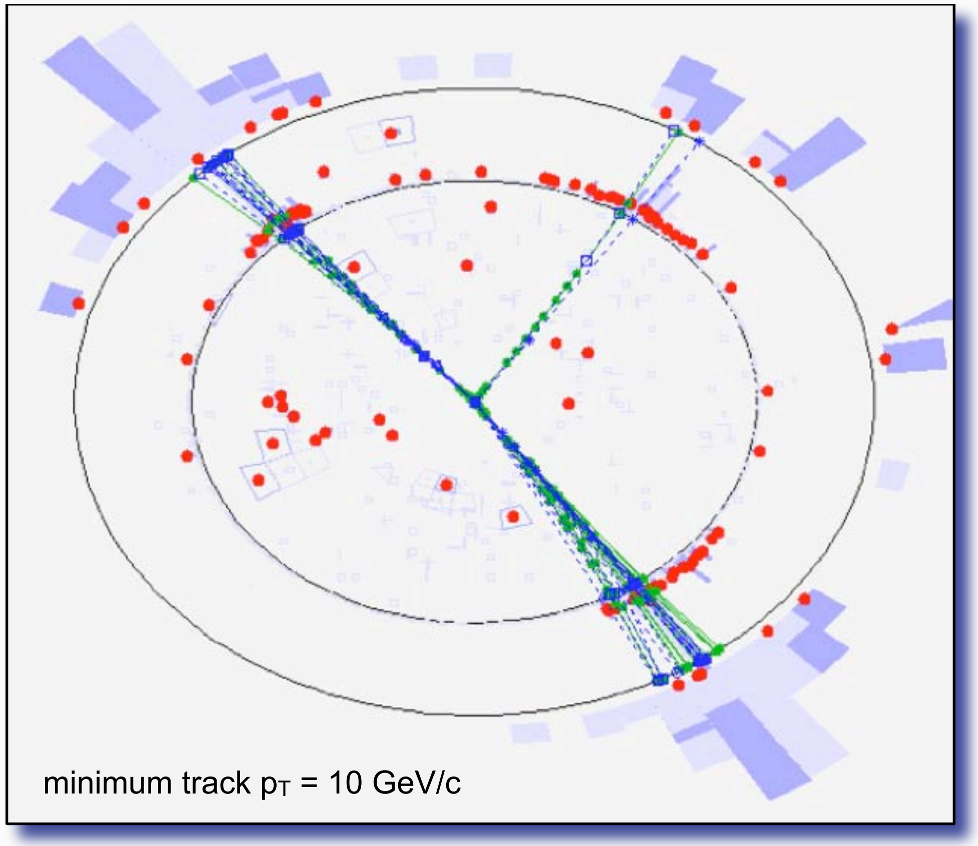
- Pile Up : many additional soft proton-proton interactions
  - up to 20 at highest LHC luminosity
- Underlying event
  - beam-beam remnants, initial state radiation, multiple parton interactions
  - gives additional energy in the event



- All this additional energy has nothing to do with jet energies
  - **have to subtract it**



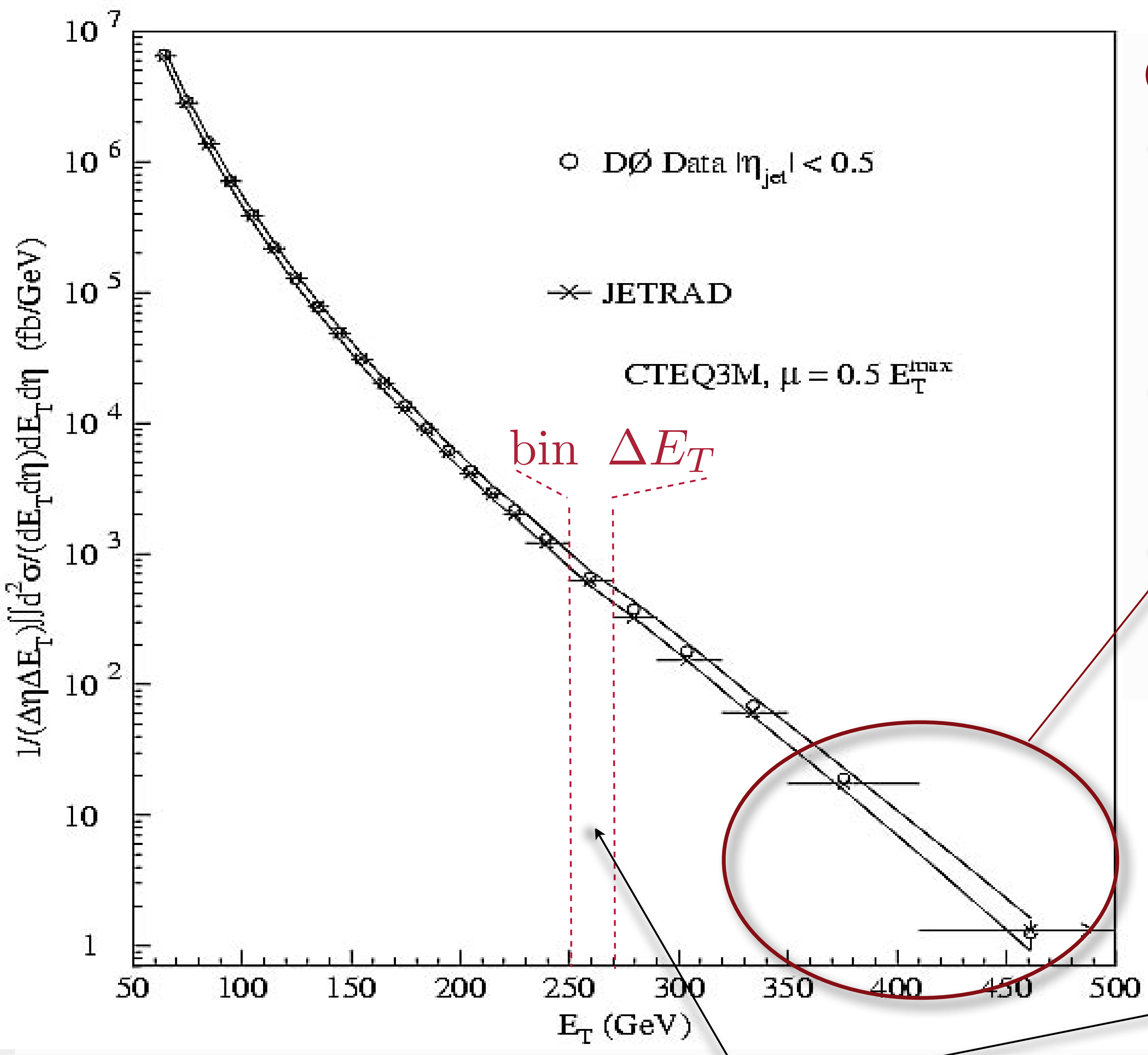
no cut on track momenta



minimum track p_T = 10 GeV/c

End of the digression

What do we have to measure?



Goal

- measure cross section inclusively for jets that are produced with a certain transverse energy E_T, within a certain rapidity range
- Test of perturbative QCD, over many orders of magnitude!
- Look at very high energy tail, new physics could show up there in form of excess (eg. sub-structure of quarks?)

can be calculated in pert. QCD

$$\left\langle \frac{d^2\sigma}{dE_T d\eta} \right\rangle = \frac{N}{\Delta E_T \Delta\eta\, \epsilon\, \mathcal{L}}$$

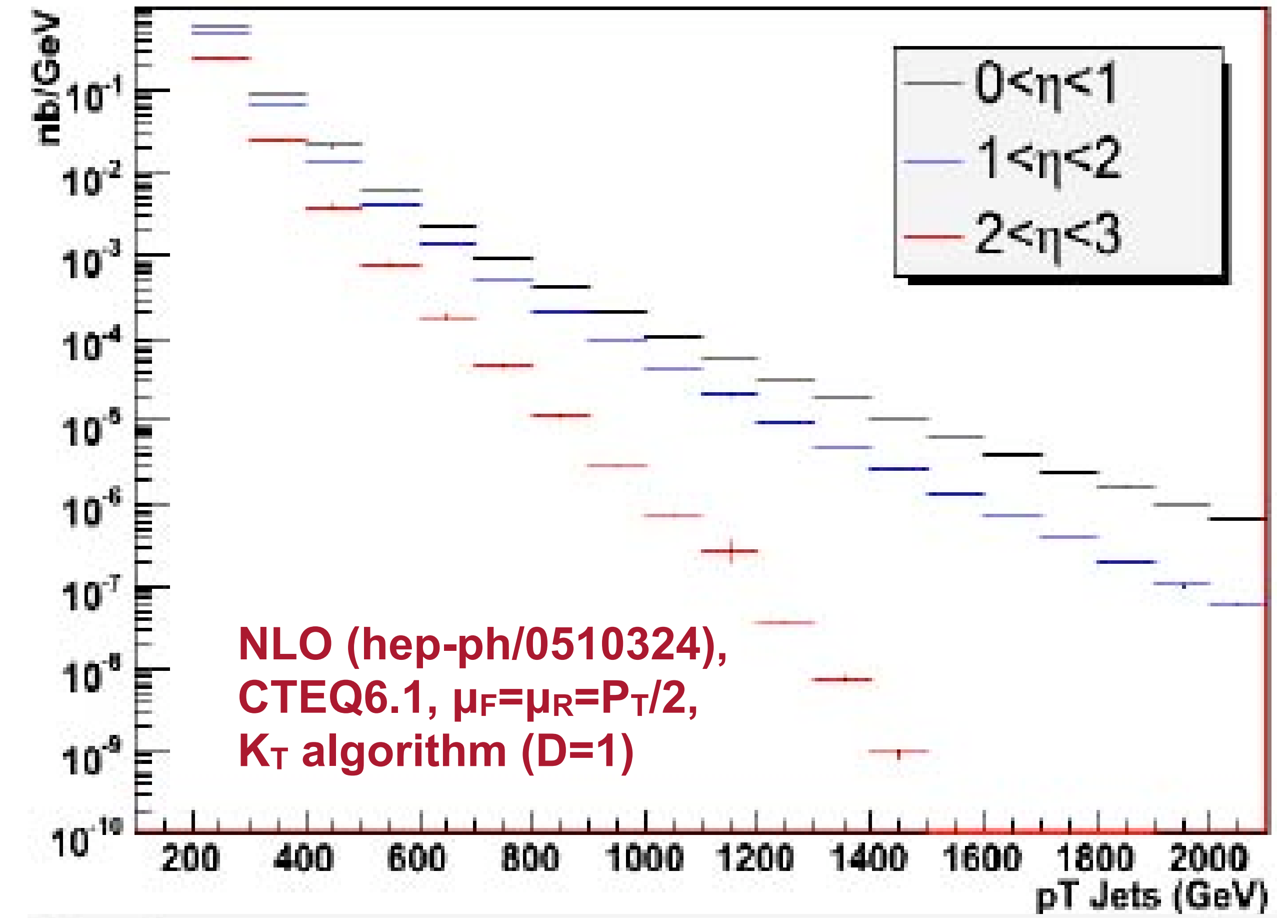
- count number of events, N, in this bin
- for a certain range in rapidity (angle) $\Delta\eta$

efficiency to reconstruct jets

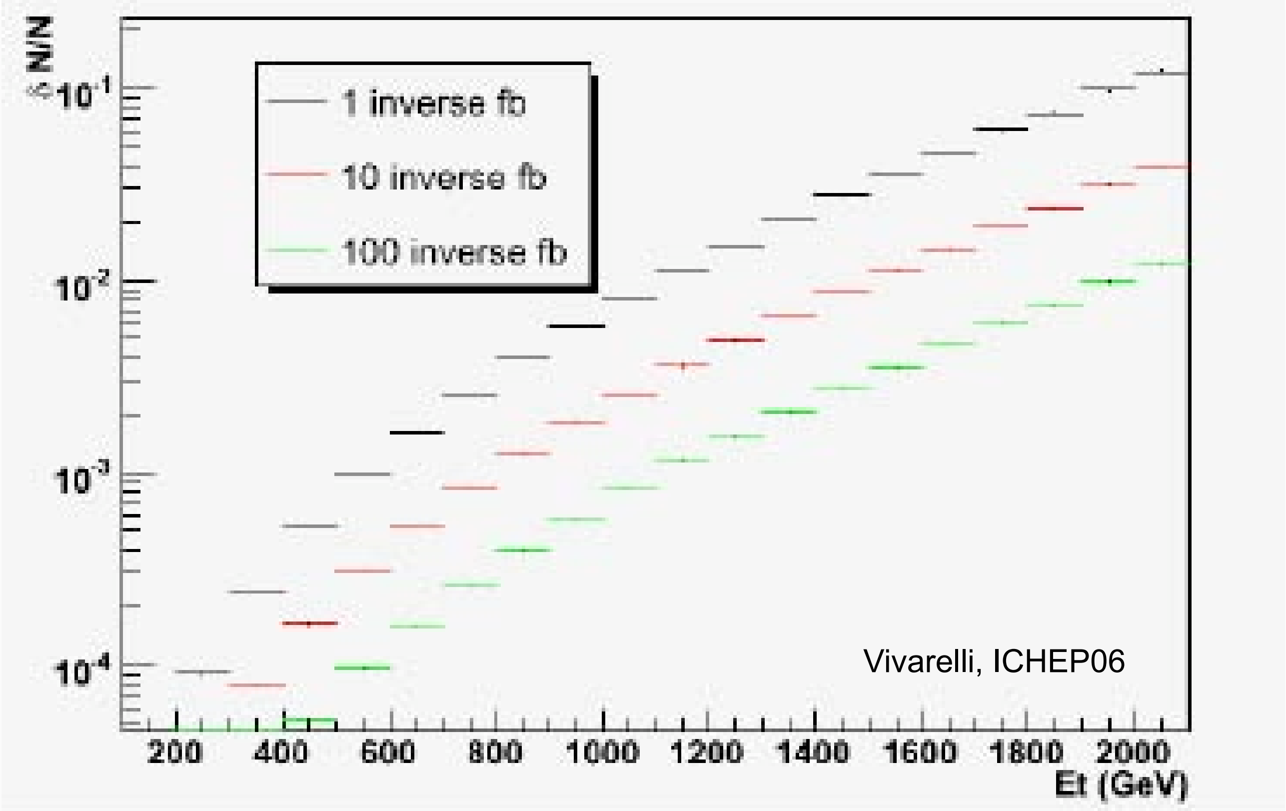
integrated luminosity

Inclusive Jet cross section at the LHC

- After MB studies, jets will be the first objects seen and measured
- Enormous cross section, so statistical errors quickly negligible
  - 1% at p_T=1 TeV for 1 fb^{-1} (central)
  - 10% for $3 < \eta < 5$
- Steeply falling cross section : energy scale knowledge most relevant



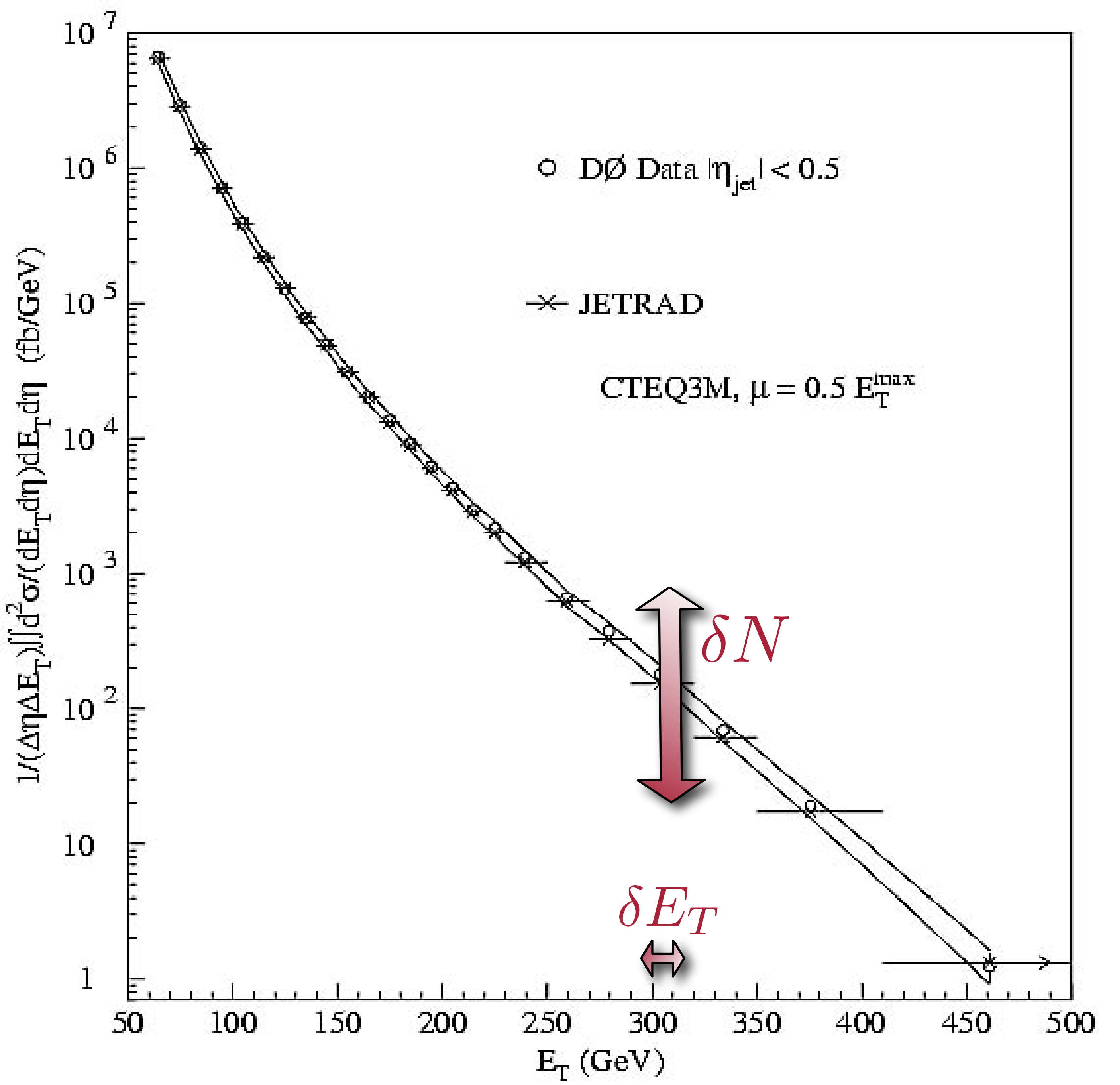
NLO (hep-ph/0510324), CTEQ6.1, $\mu_F=\mu_R=P_T/2$, K_T algorithm (D=1)



Vivarelli, ICHEP06

Problem 1 : Energy scale

- Question : how well do we know the energy calibration?
- Critical because of very steeply falling spectrum!



$$\frac{d^2\sigma}{dE_T d\eta} \approx \text{const} \cdot E_T{}^{-6}$$

relative uncertainties

$$\frac{\delta N}{N} \approx 6 \cdot \frac{\delta E_T}{E_T}$$

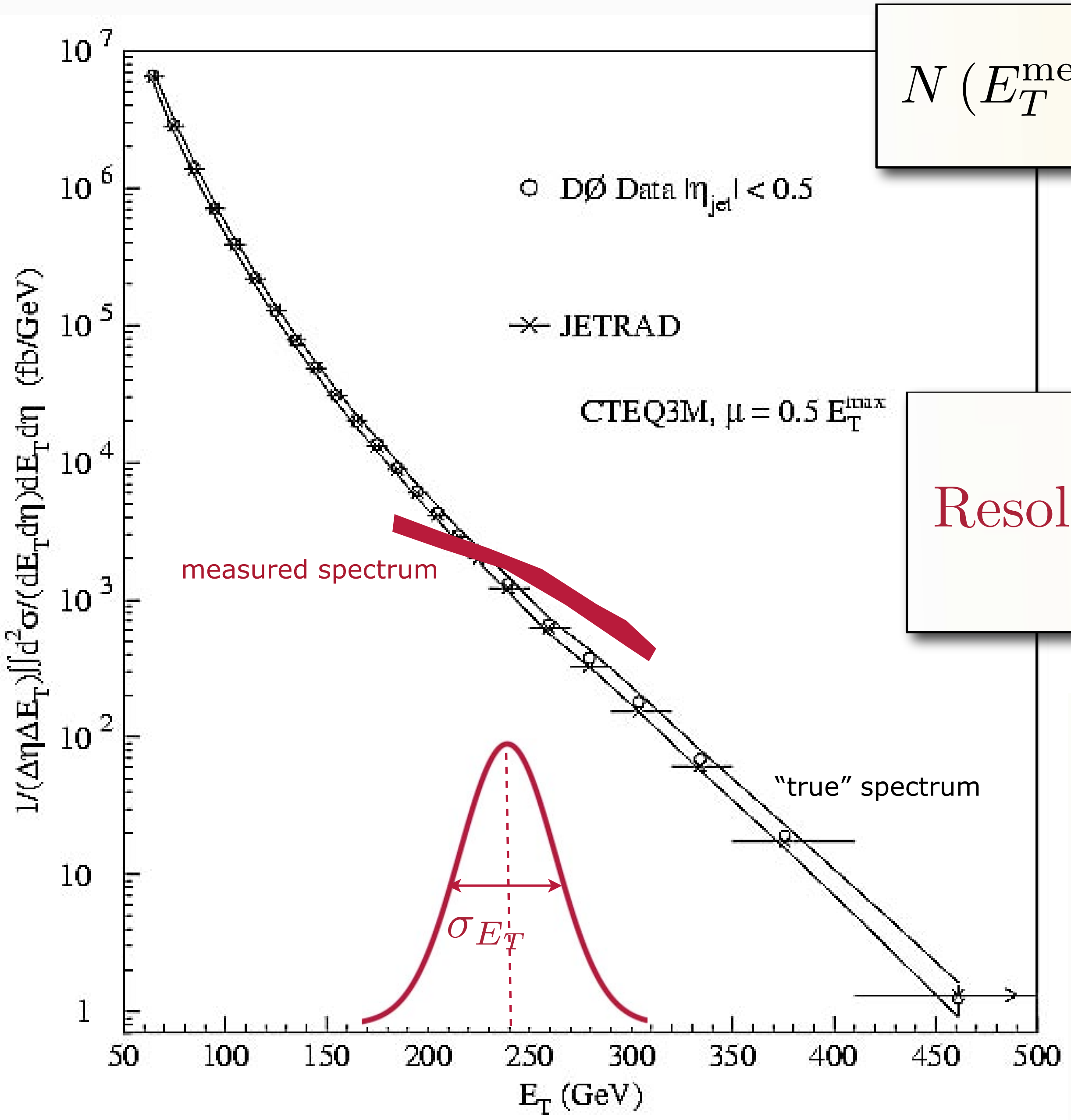
so beware:

eg. an uncertainty of **5%** on absolute energy scale (calibration)

➜ an uncertainty of **30%** (!) on the measured cross section

Problem 2 : Energy resolution

- The energy resolution can distorts the spectrum
- Again : Critical because of very steeply falling spectrum!



$$N\left(E_T^{\mathrm{meas}}\right) = \int_0^\infty N\left(E_T^{\mathrm{true}}\right) \cdot \mathrm{Resol}\left(E_T^{\mathrm{meas}}, E_T^{\mathrm{true}}\right) \mathrm{d}E_T^{\mathrm{true}}$$

eg. Gaussian resolution function

$$\mathrm{Resol}\left(E_T^{\mathrm{meas}}, E_T^{\mathrm{true}}\right) \propto \exp\left[-\frac{\left(E_T^{\mathrm{meas}} - E_T^{\mathrm{true}}\right)^2}{\sigma_{E_T}^2}\right]$$

so beware:

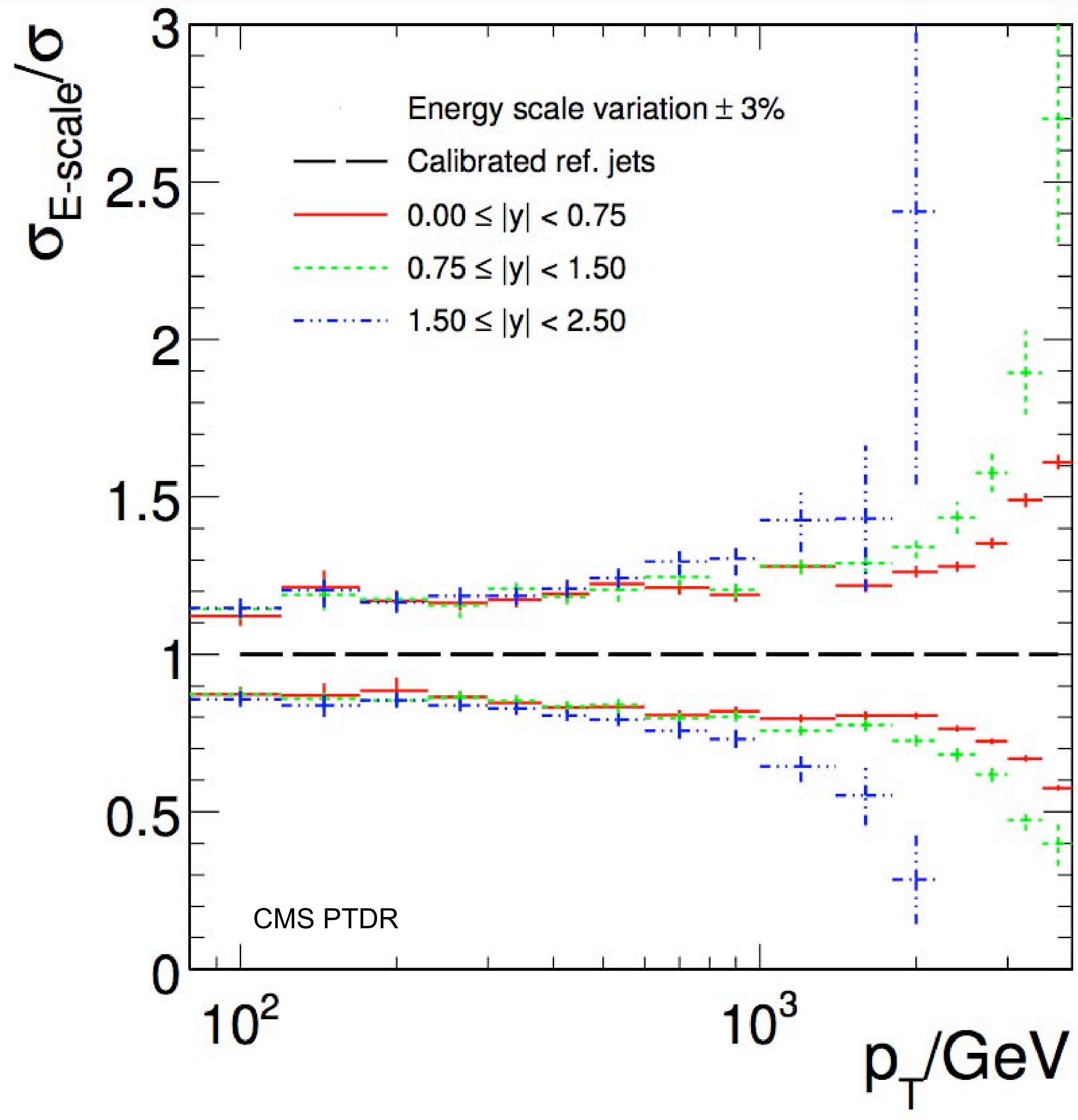
A bad energy resolution can distort the true spectrum

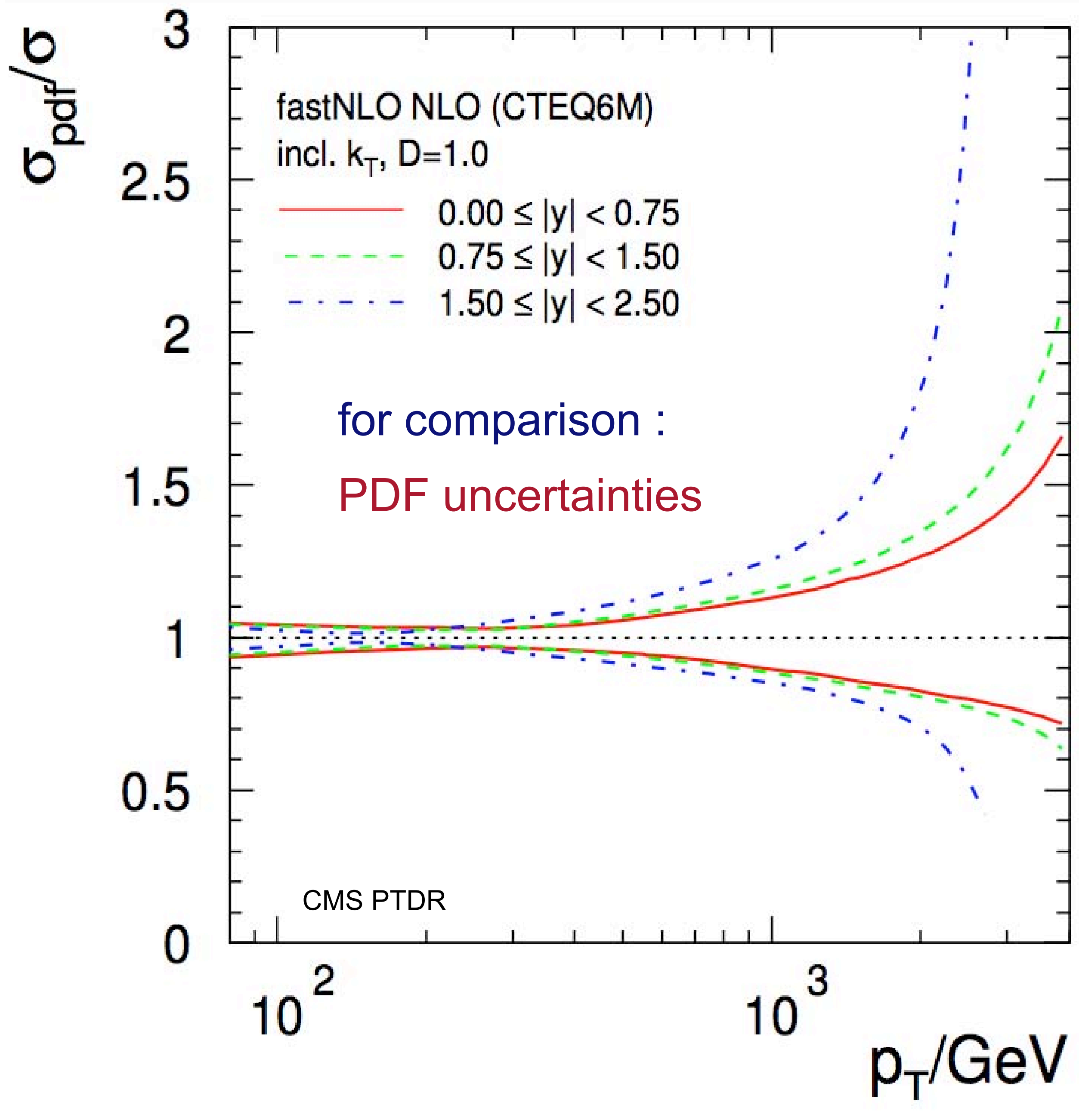
➜ have to determine the energy resolution

➜ have to "unfold" the measured spectrum

➜ problem is minimized if bin width ~ σ_{E_T}

Inclusive Jets : Systematics





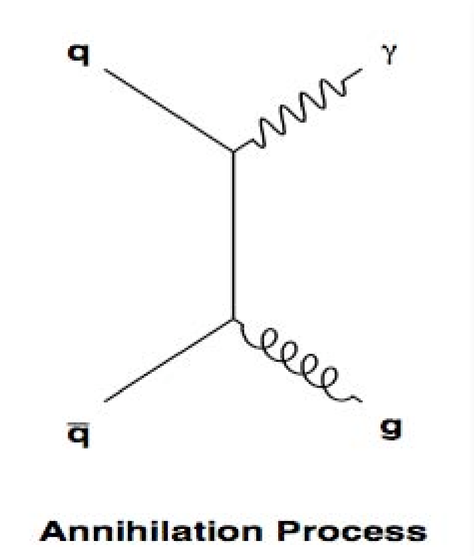
for comparison :

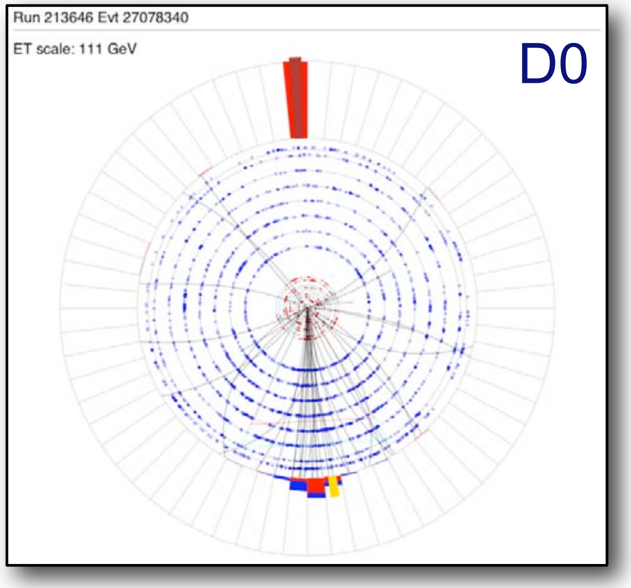
PDF uncertainties

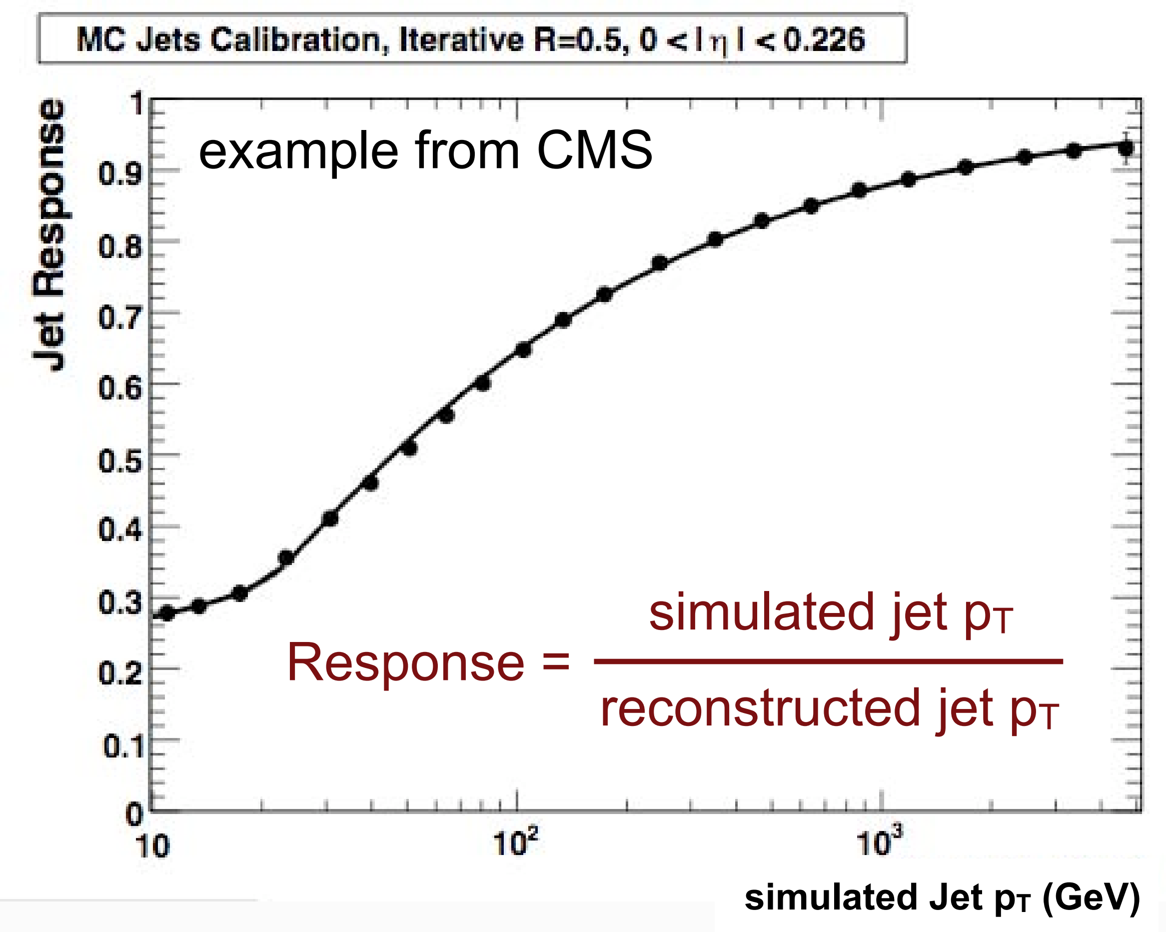
- a **5% jet energy scale** uncertainty (which is more realistic at start-up) gives a **30% error** on the cross section!
- Control in-situ with : photon/Z+jets and W➔ JJ in top decays
- Other sources : jet corrections (det ➔ had ➔ part), UE subtraction

Jet+Photon and Jet Energy Scale (JES)

- Jet calibration using p_T **balance** in Jet+Photon events
  - Selection : isolated photons, no high-p_T secondary jet, photon and jet well separated in transverse plane
  - Statistical error well below 1% after 10 fb^{-1}



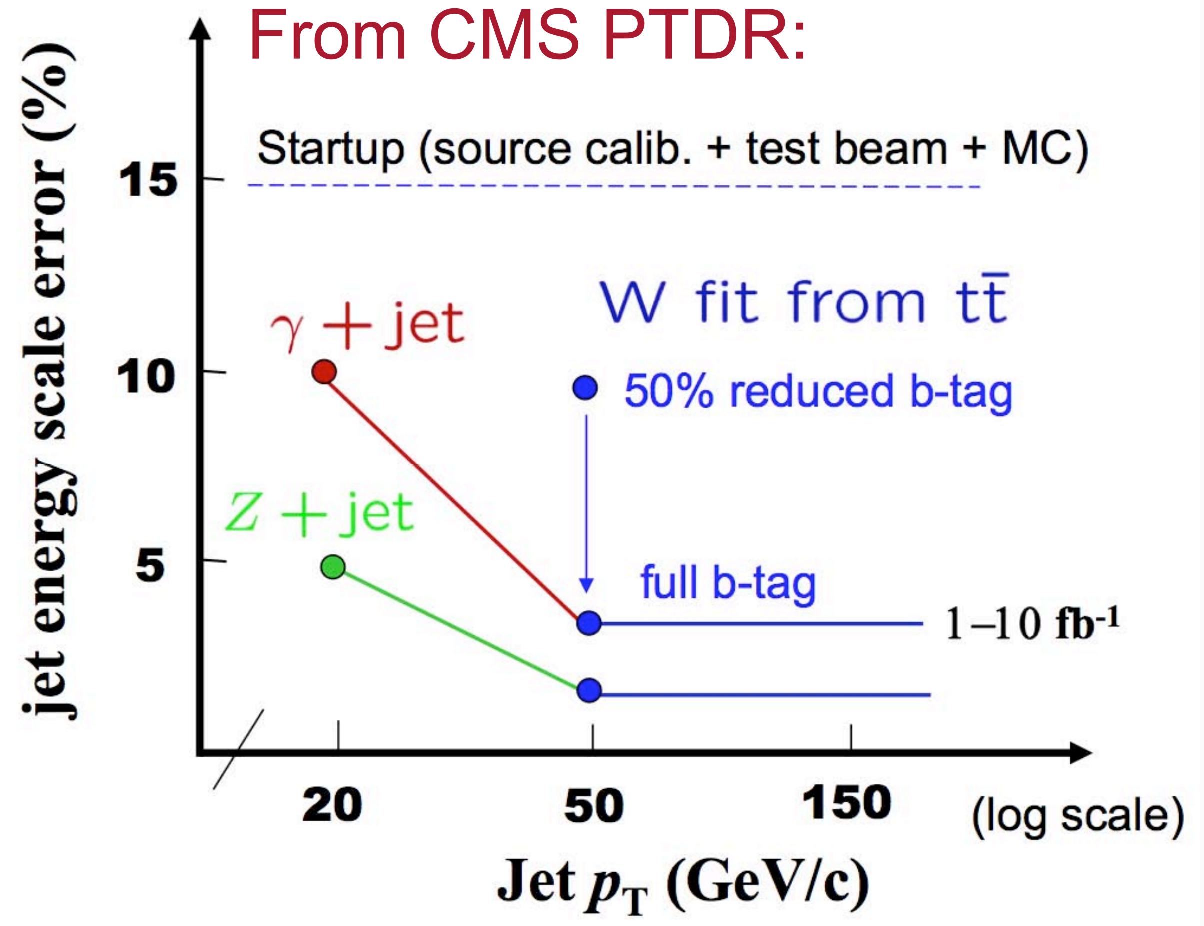




example from CMS

$$\text{Response} = \frac{\text{simulated jet } p_T}{\text{reconstructed jet } p_T}$$

From CMS PTDR:

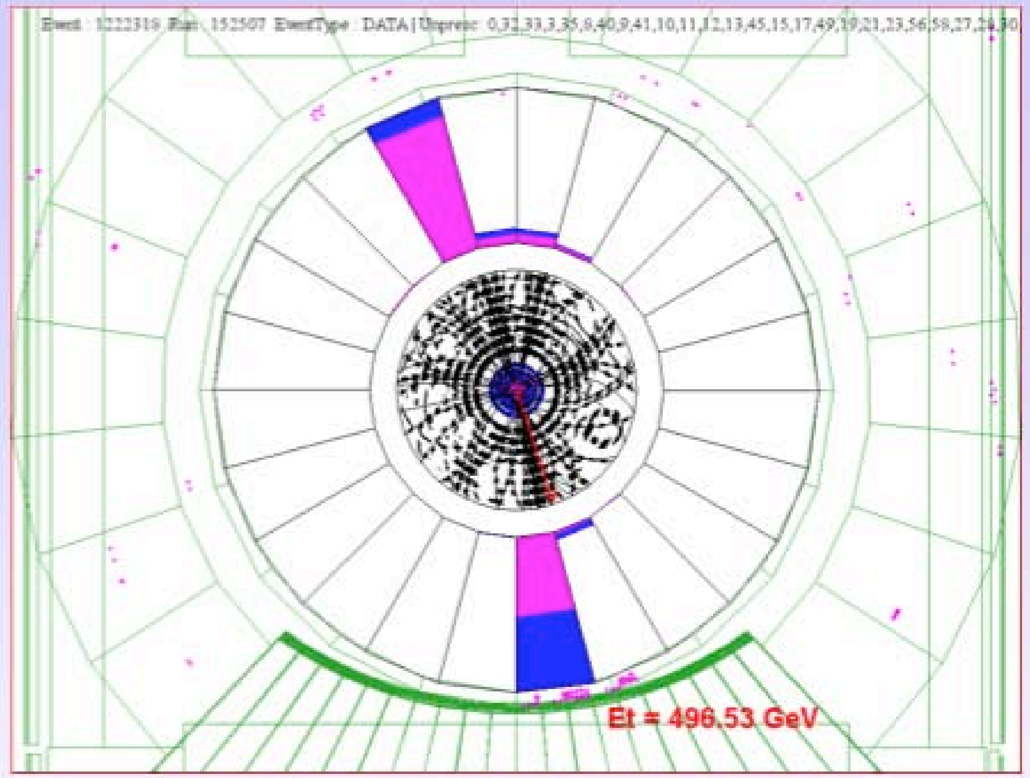


Currently:
“monolithic” MC-corrections, i.e.
one-step correction from calorimeter-level to particle level
(inverse of response function)

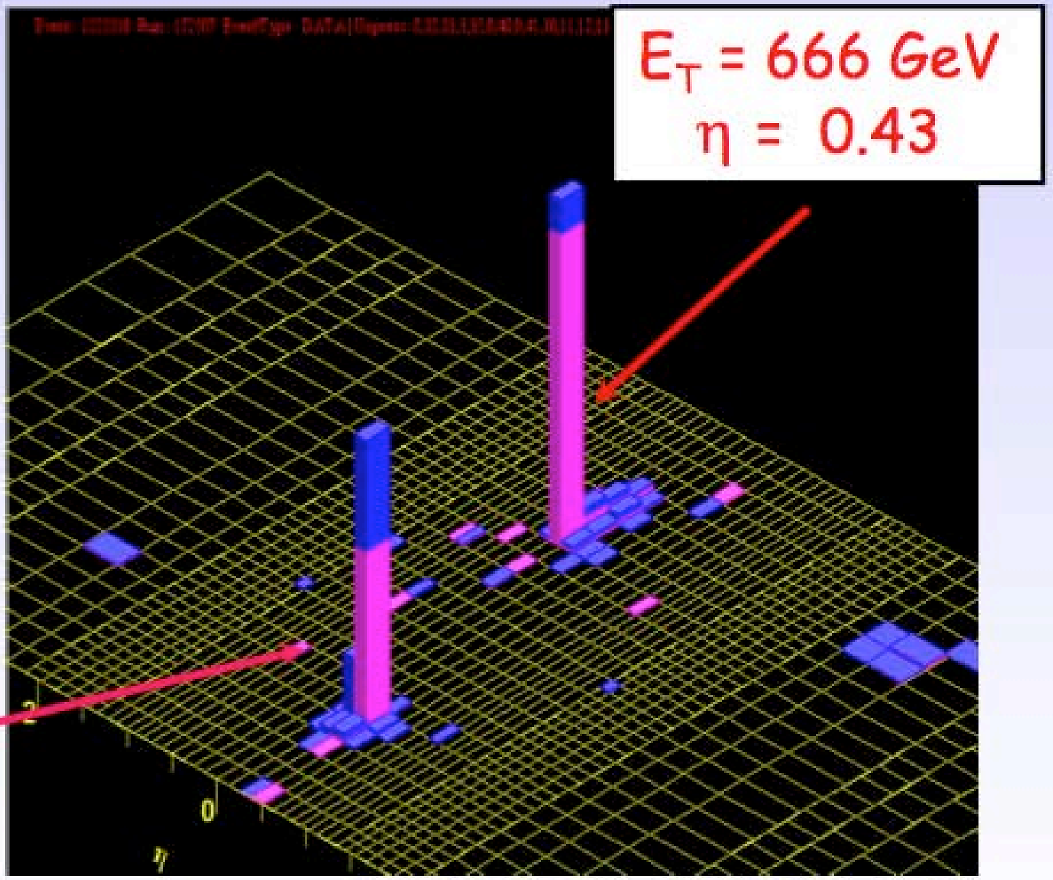
Di-Jets

A two jet event at the Tevatron (CDF)

Dijet Mass = 1364 GeV/c^2



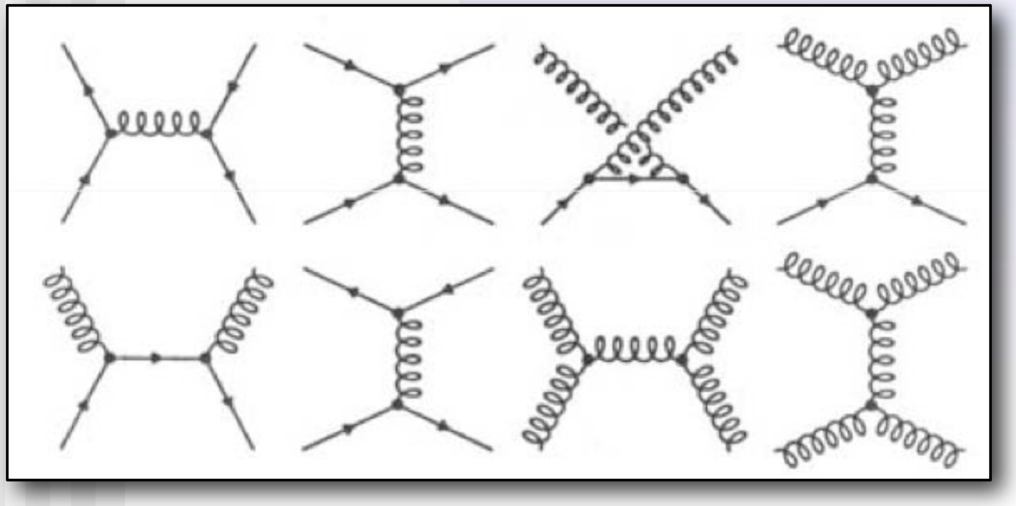
CDF (ϕ-r view)



$E_T = 666$ GeV
$\eta = 0.43$

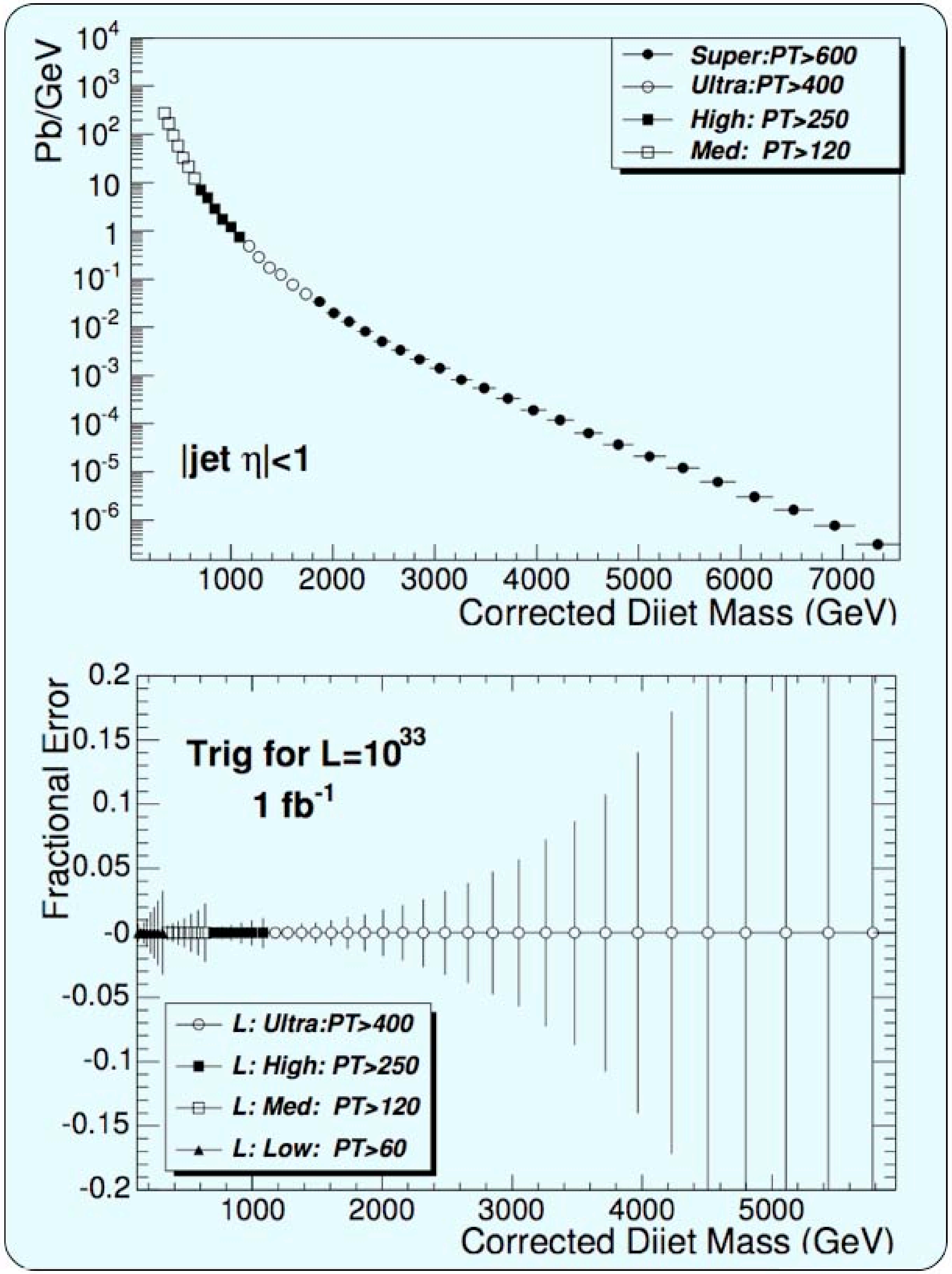
$E_T = 633$ GeV
$\eta = -0.19$

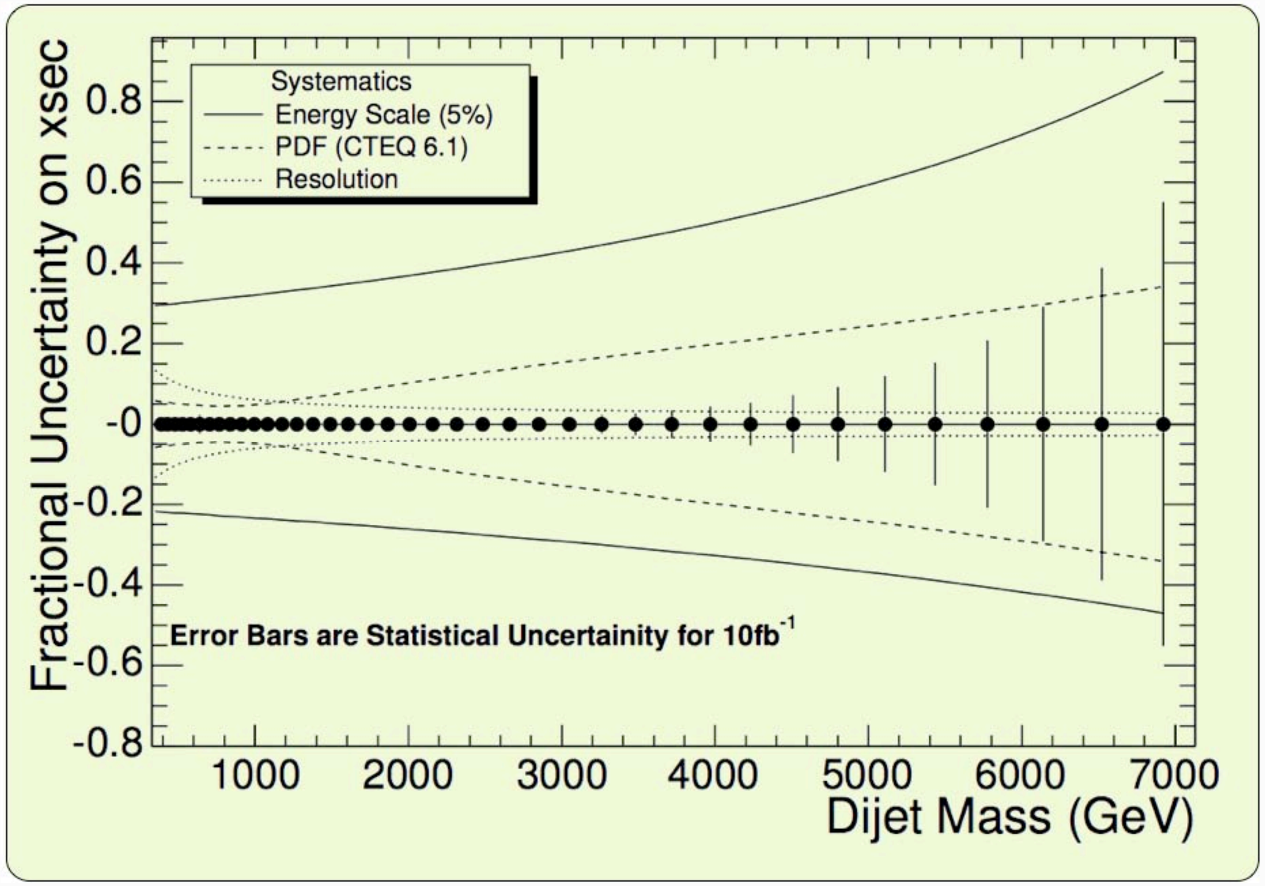
K. Jakobs, CSS07

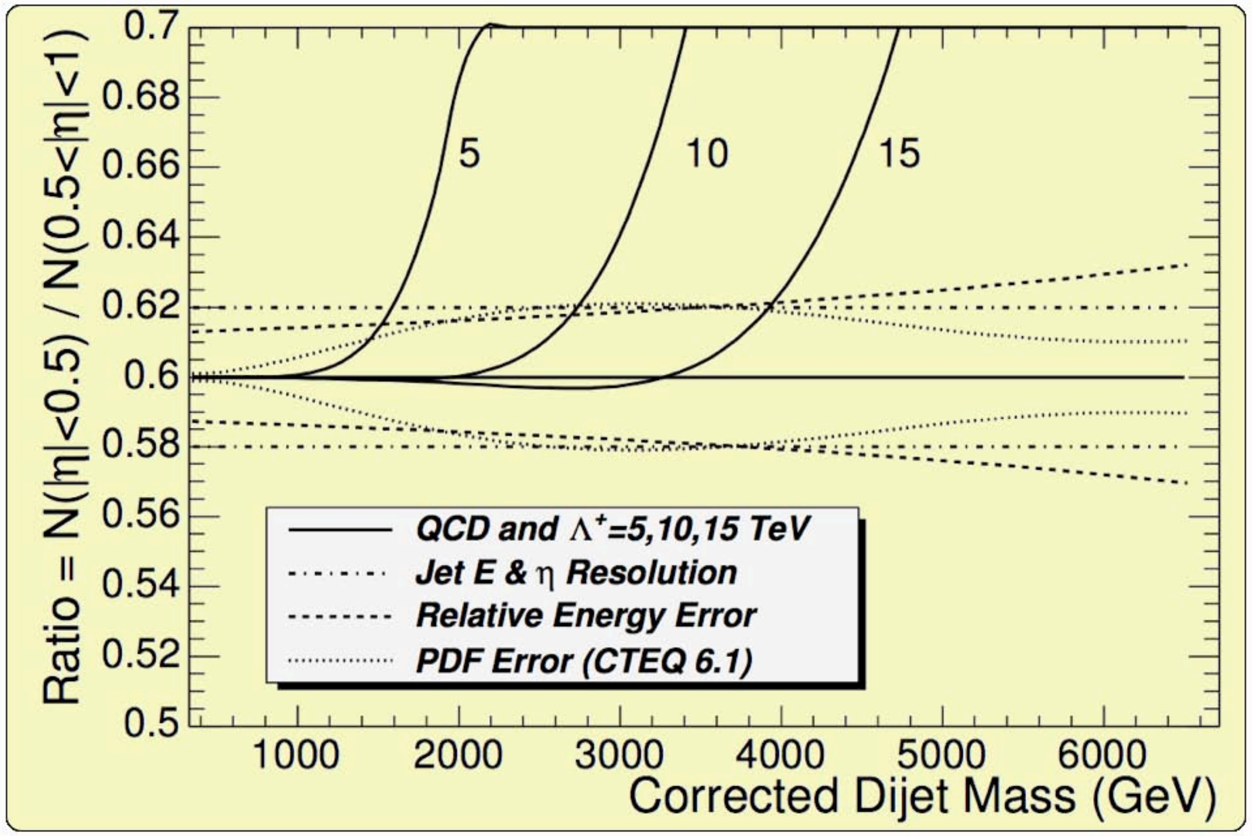


Goal : Measure cross section as function of invariant mass of the two jets.
Test QCD predictions and kook for resonances at high invariant mass.

Di-Jets (CMS PDTR)





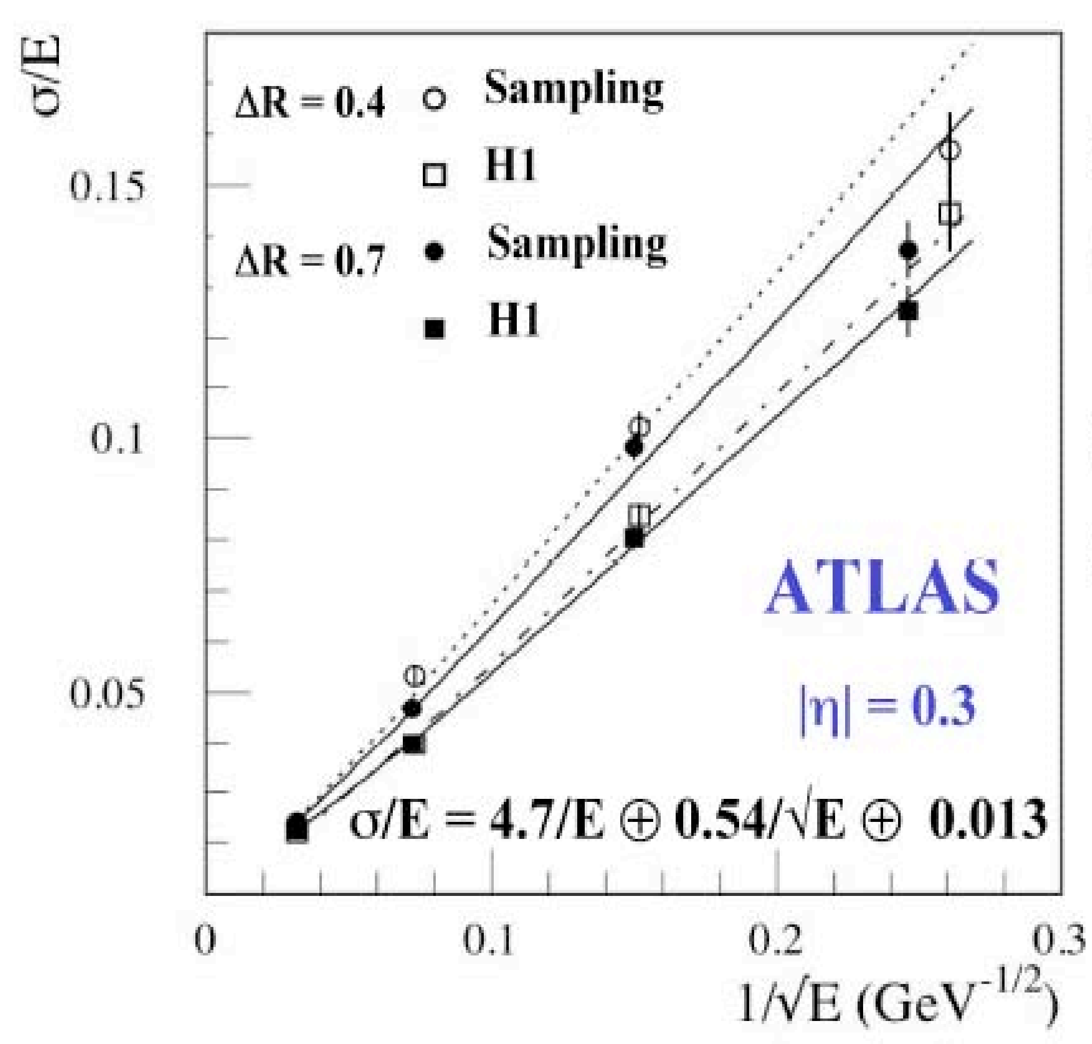


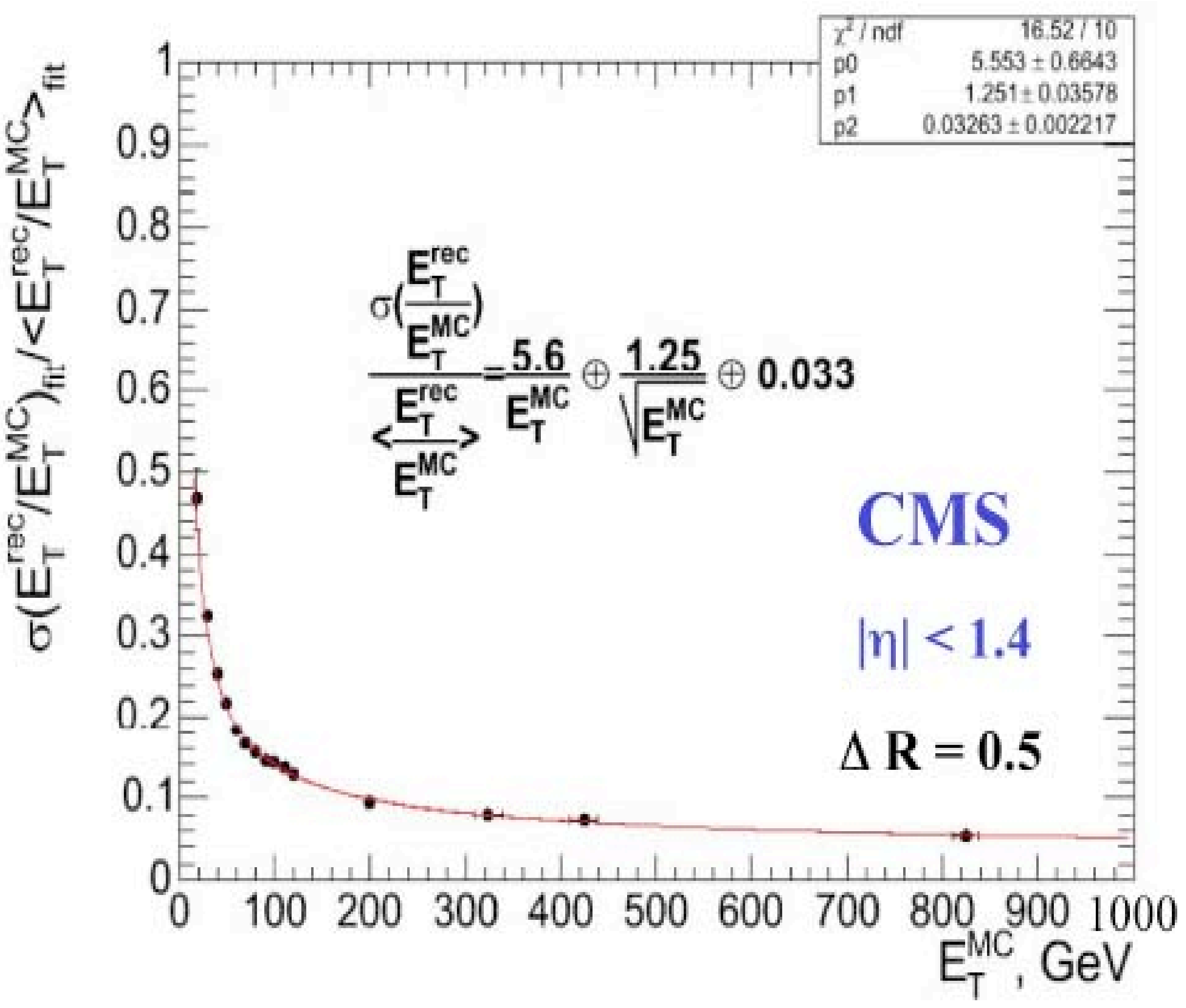
Note : Ratio of cross-section central / forward !

Comparison ATLAS - CMS

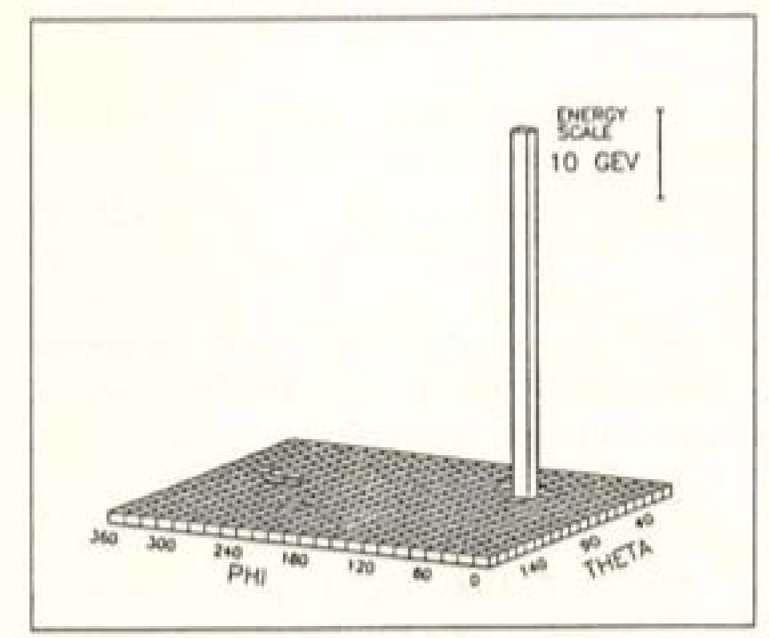
Biggest difference in performance perhaps for hadronic calo

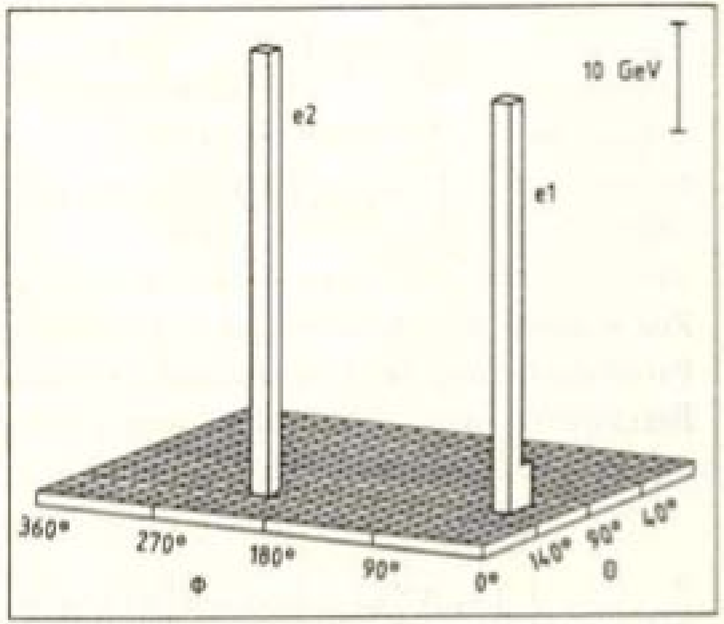
Jets at 1000 GeV ATLAS ~ 2%
energy resolution CMS ~ 5%
energy resolution,
but expect sizeable improvement
using tracks (especially at lower E)





W and Z production

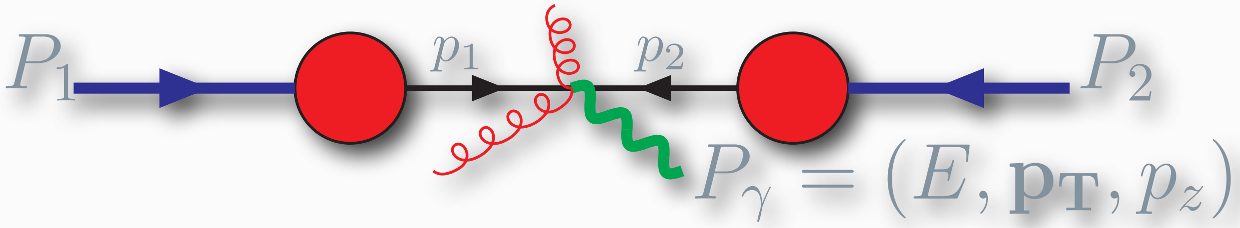


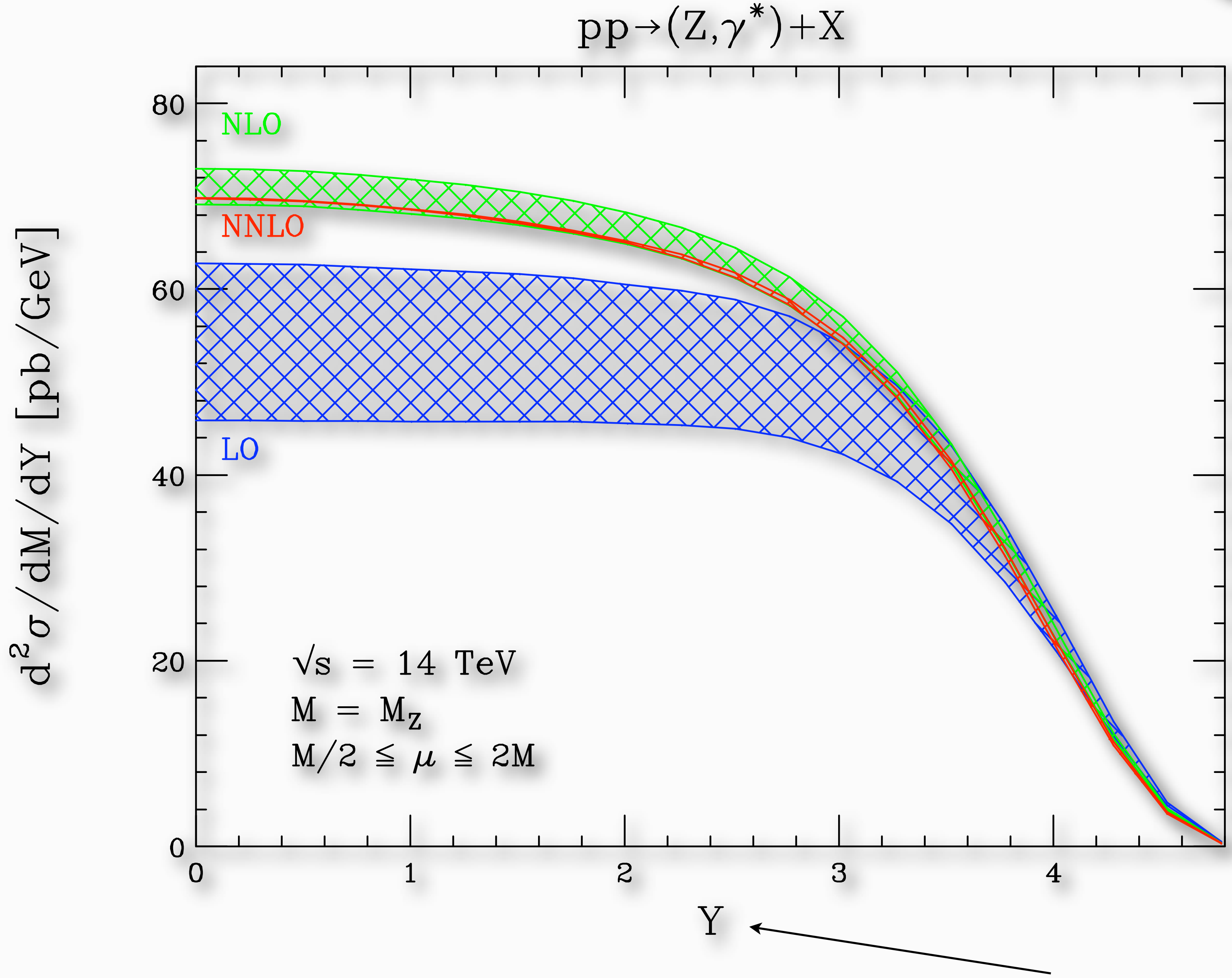


... one of the first W and Z's in UA1/2

Predictions

- Probably best known cross section at LHC, NNLO, differentially
- a well suited normalization process





small NNLO scale uncertainty:

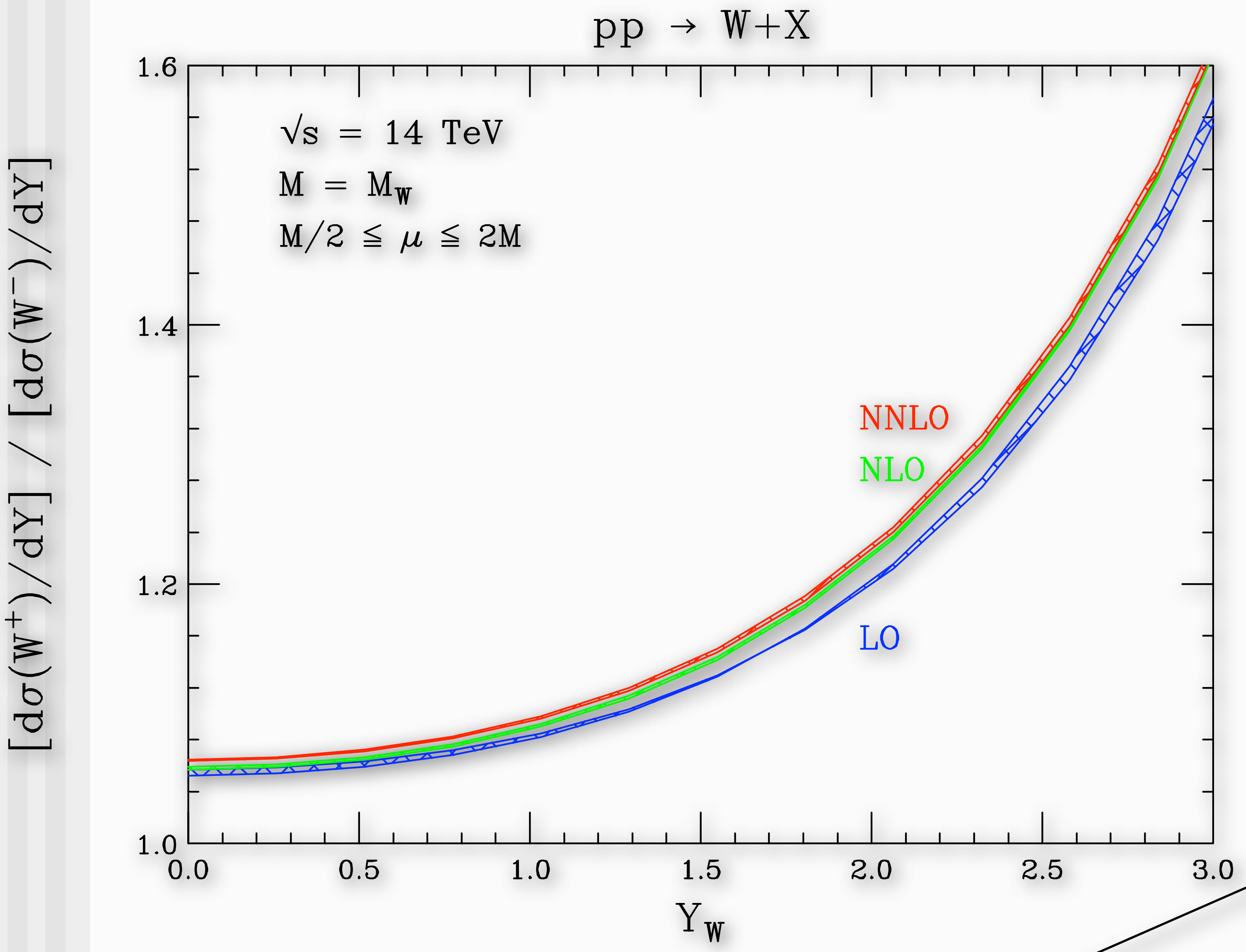
LO : 25% - 30%
NLO : 6%
NNLO : 0.1 % (Y=0) -
1% (Y<3) -
3% (Y ~ 4)

shape stabilizes at NNLO

Anastasiou, Dixon, Petriello, Melnikov : differential in W/Z rapidity
Petriello, Melnikov : fully differential in lepton momenta

Predictions

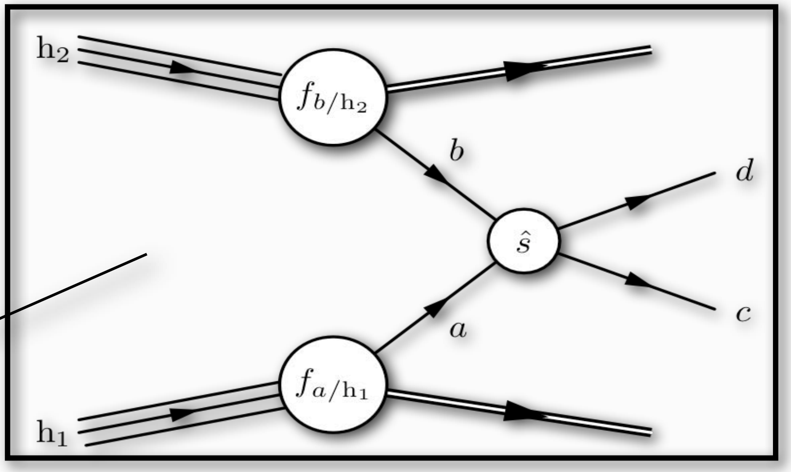
similarly for W^+/W^- : very small
NNLO scale uncertainty: 0.5 - 0.7 %



However :
dominant uncertainty for **absolute** W and Z cross section:

PDFs : 4 - 5 %

remember:

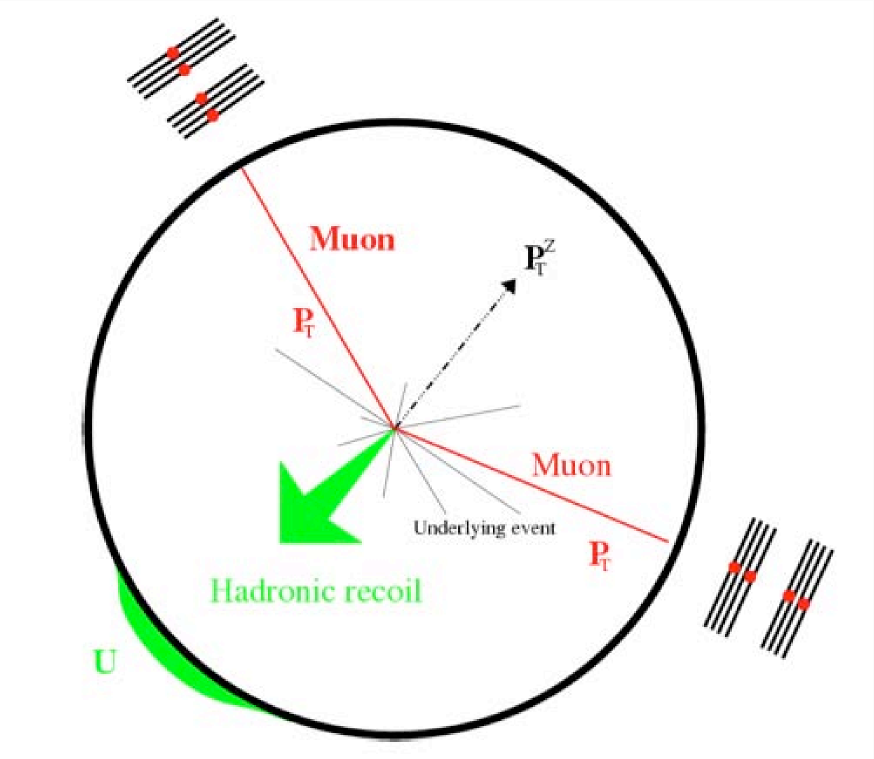


$$d\sigma(h_1h_2 \to cd) = \int_0^1 dx_1 dx_2 \sum_{a,b} f_{a/h_1}(x_1,\mu_F^2) f_{b/h_2}(x_2,\mu_F^2) d\hat{\sigma}^{(ab\to cd)}(Q^2,\mu_F^2)$$

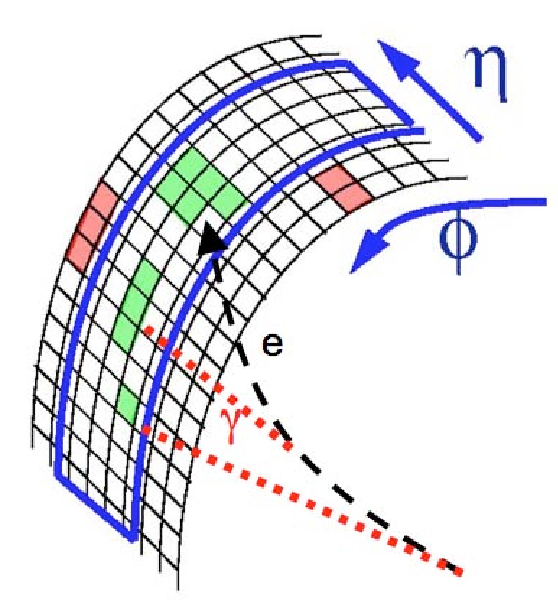
so : if we measure precisely this, can we constrain this?

known precisely up to NNLO

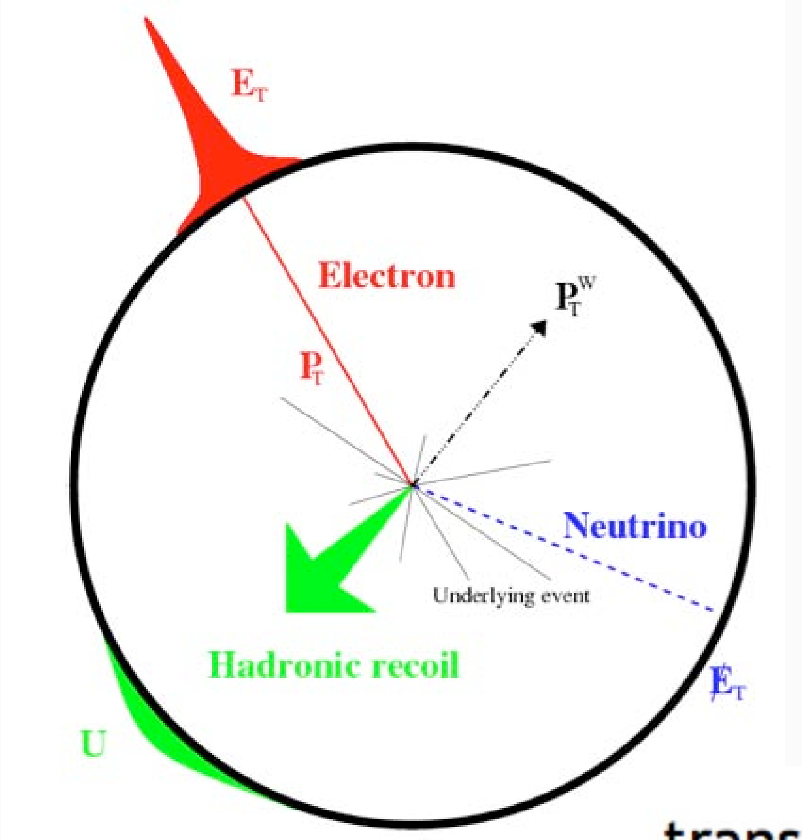
Experimental signature



Z: pair of charged leptons
- high-p_T
- isolated
- opposite charge
- ~70 < m_{ll}< ~110 GeV



Example: electron reconstruction
- isolated cluster in EM calorimeter
- p_T > 20 GeV
- shower shape consistent with expectation from electrons
- matching charged track



W: single charged leptons
- high-p_T
- isolated
- $E_{T,miss}$ (from neutrino)

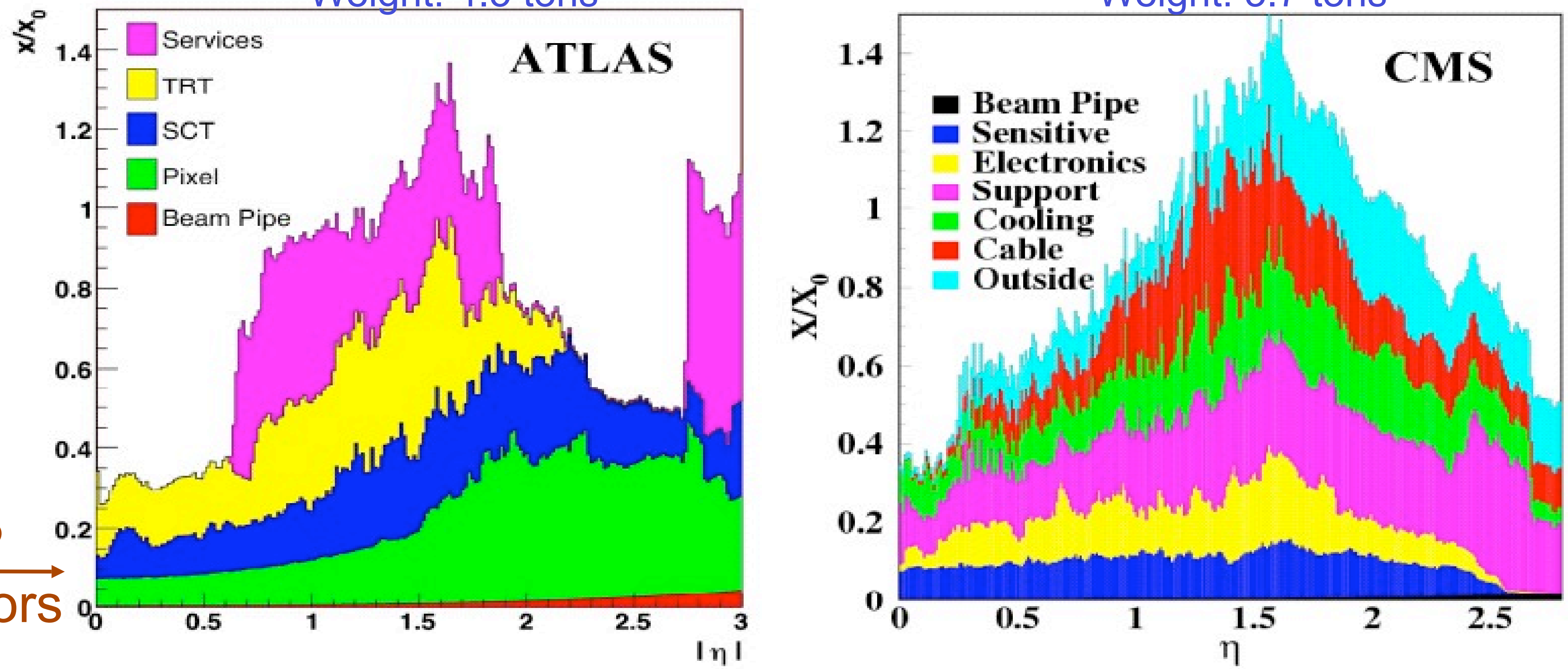
transverse mass: $M_W^T = \sqrt{2 \cdot P_T^l \cdot P_T^\nu \cdot \left(1 - \cos \Delta\phi^{l,\nu}\right)}$

ATLAS/CMS : from design to reality

Amount of material in ATLAS and CMS inner trackers

Weight: 4.5 tons

Weight: 3.7 tons



LEP detectors

- Active sensors and mechanics account each only for ~ 10% of material budget
- Need to bring 70 kW power into tracker and to remove similar amount of heat
- Very distributed set of heat sources and power-hungry electronics inside volume:

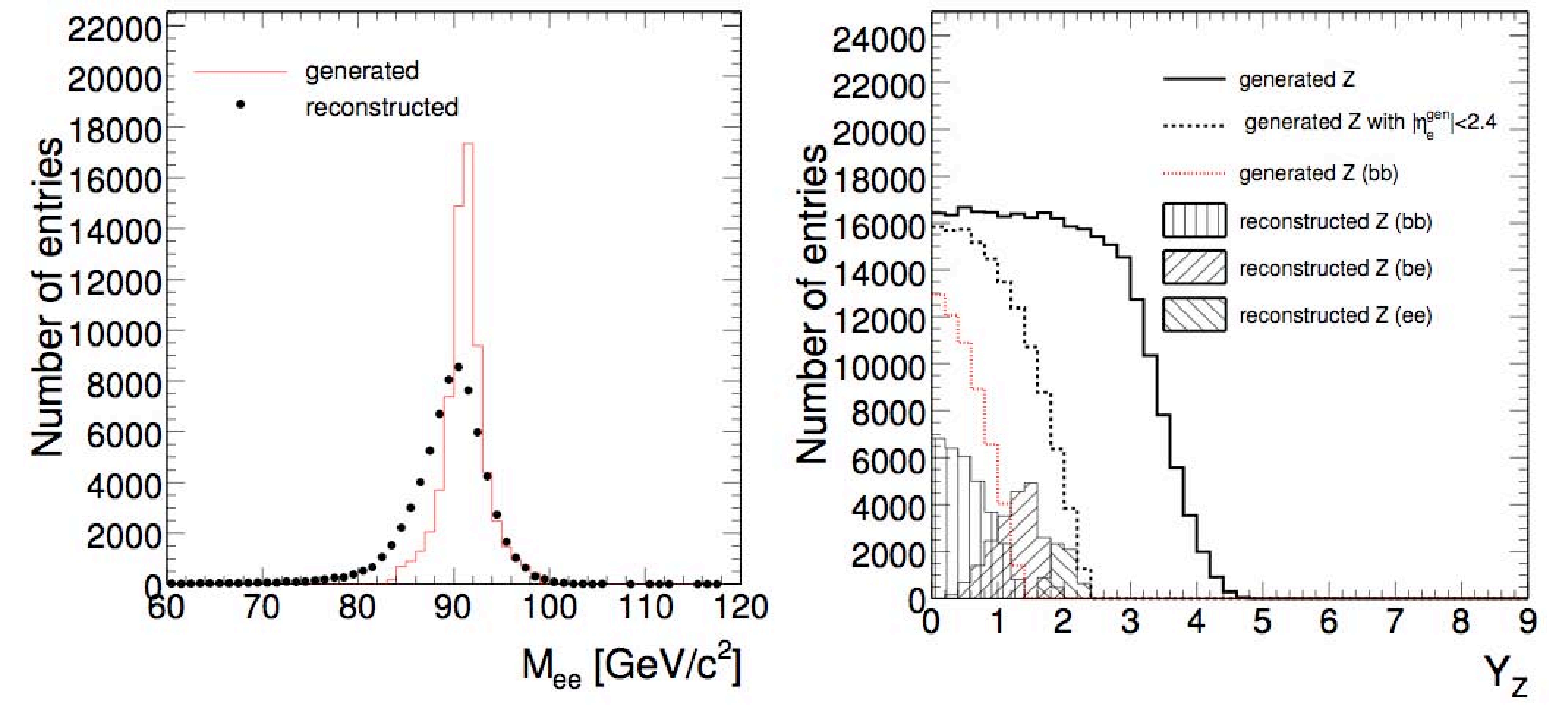
this has led to complex layout of services, most of which not at all understood at the time of the TDRs

- Material increased by ~ factor 2 from 1994 (approval) to now (end constr.)
- Electrons lose between 25% and 70% of their energy before reaching EM calo
- Between 20% and 65% of photons convert into e^+e^- pair before EM calo
- Need to know material to ~ 1% X_0 for precision measurement of m_W (< 10 MeV)!

Experimental Z/W counting

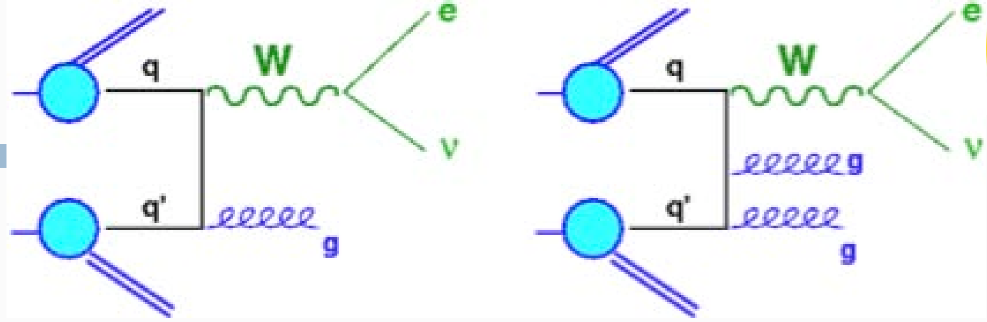
- Example of selection from CMS (simulation studies)
  - Z : 2 isolated leptons, p_T>20 GeV, $|\eta| < 2.5$, W : 1 isolated lepton + MET
  - Studied : electrons, muons.
  - Difficult issue : MET (=neutrino reconstruction)

CMS PTDR, G.D., Dittmar, Ehlers, Holzner

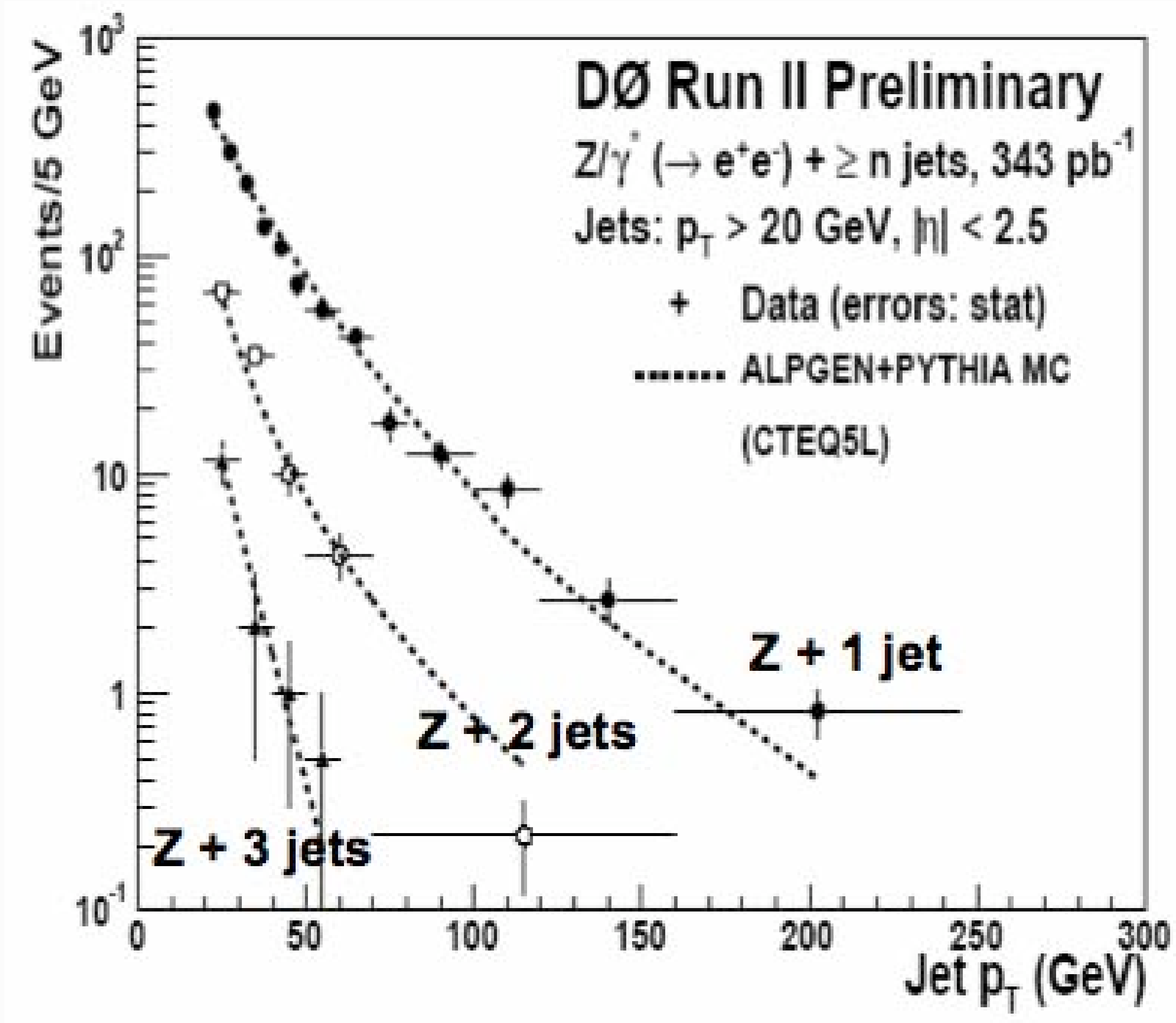


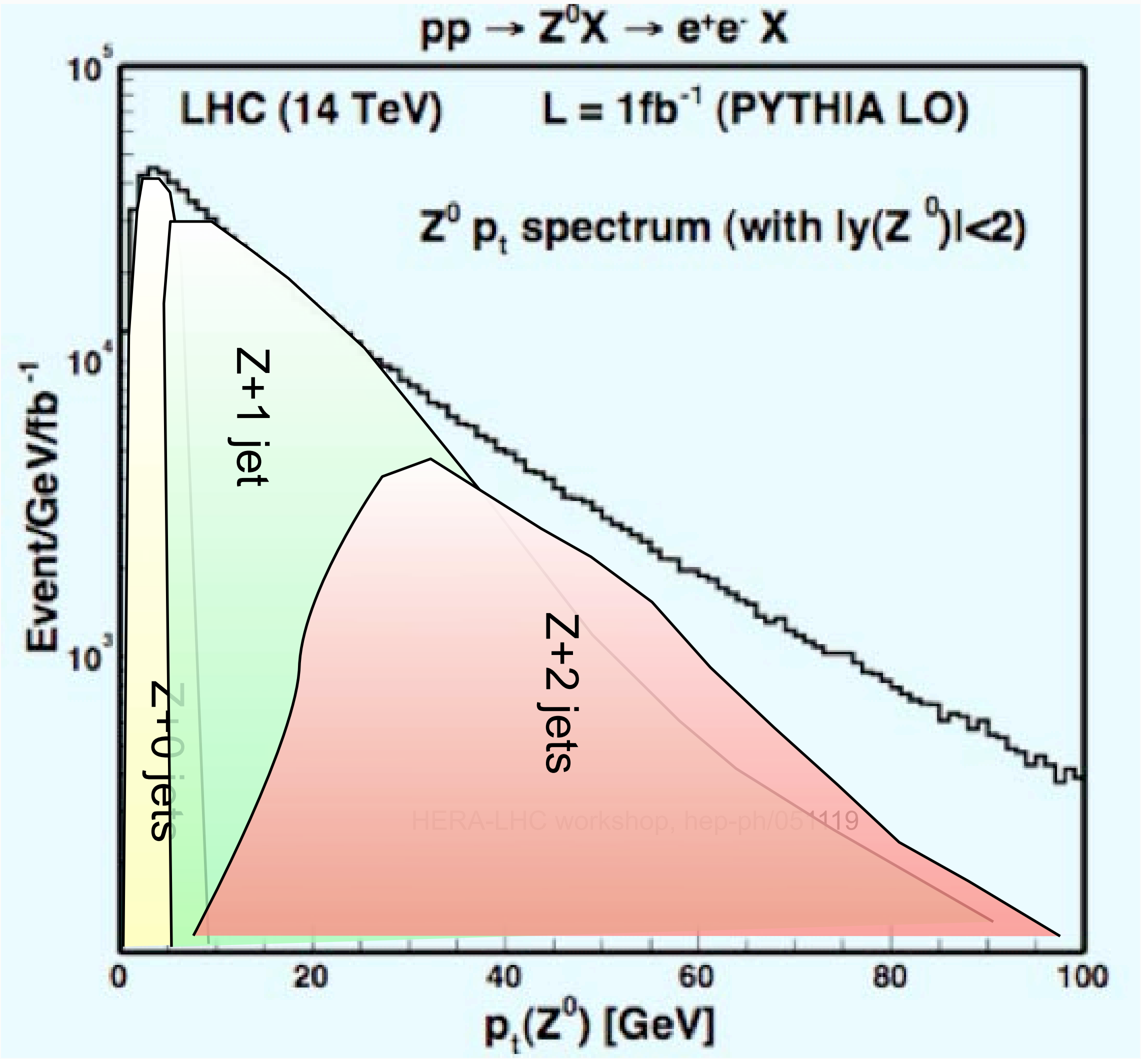
Experimental Z counting precision of 1 - 2 % appears feasible, even after 1. year

W/Z + jets

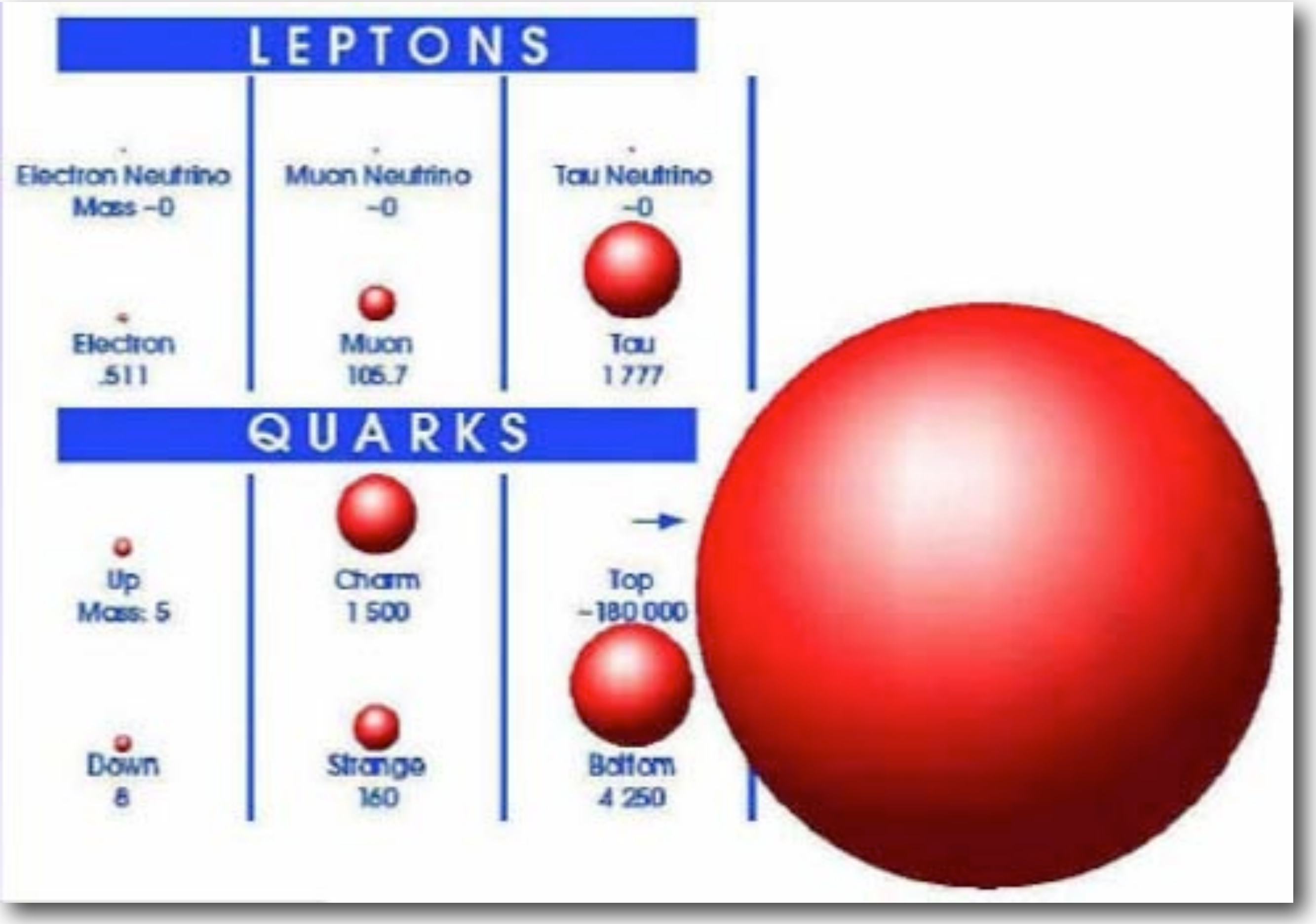


- Extremely important background for many searches
  - in particular for SUSY searches in the “jets+lepton+E_{Tmiss}” channel
- Remember : Jet scale uncertainty extremely important (xsec as function of jet p_T), also here
  - can expect some 30 % uncertainty from that. Probably less in case of rate measurements.
- Should also have a more “inclusive” look at it : Measuring the Z p_T can be done with a relative precision at the per-cent level (leptons (!) again), will be invaluable for checking predictions and tuning MCs

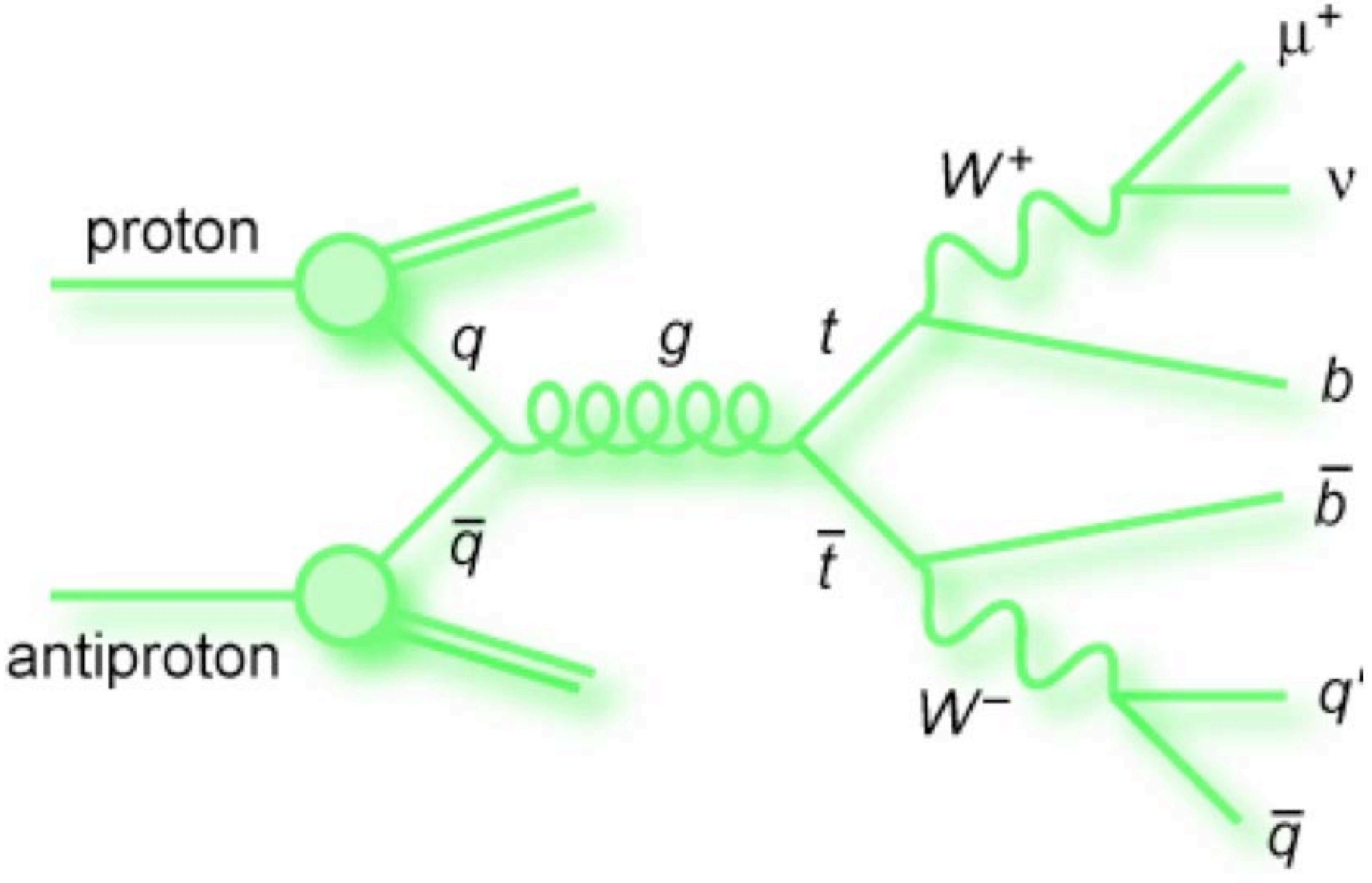




Top production



Top as a “Tool”



Tag and Lepton study tool

Missing E_T study tool

b-tag study tool

Light quark: jet energy scale from M_W constraint

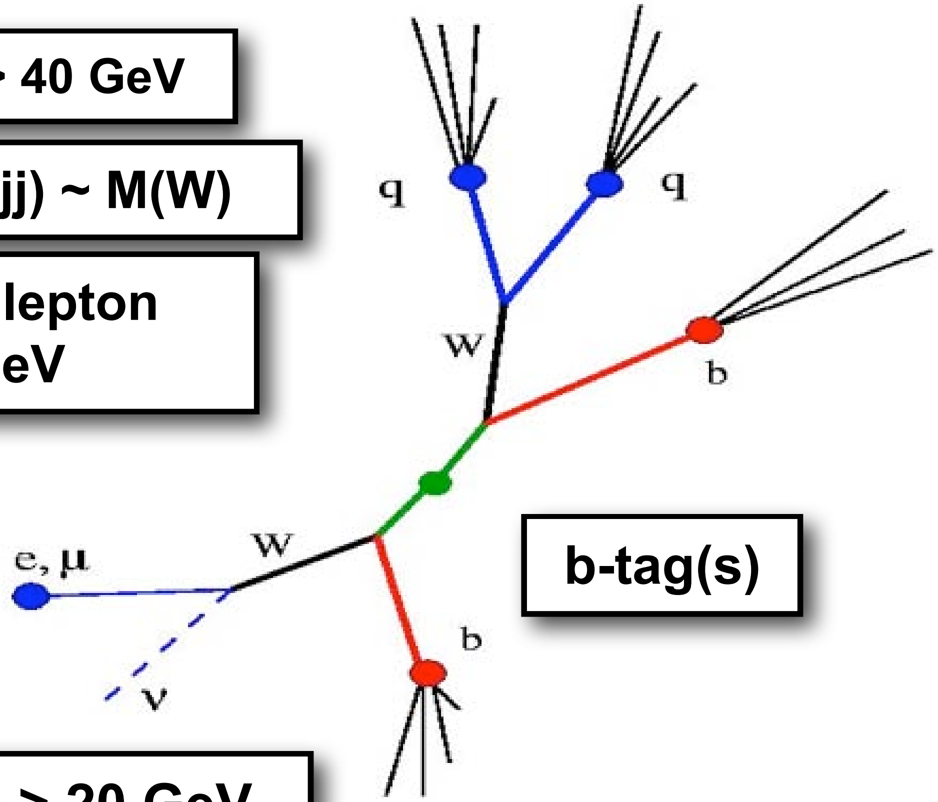
b quark: jet energy scale from M_{top} constraint

Top identification

4 jets p_T> 40 GeV

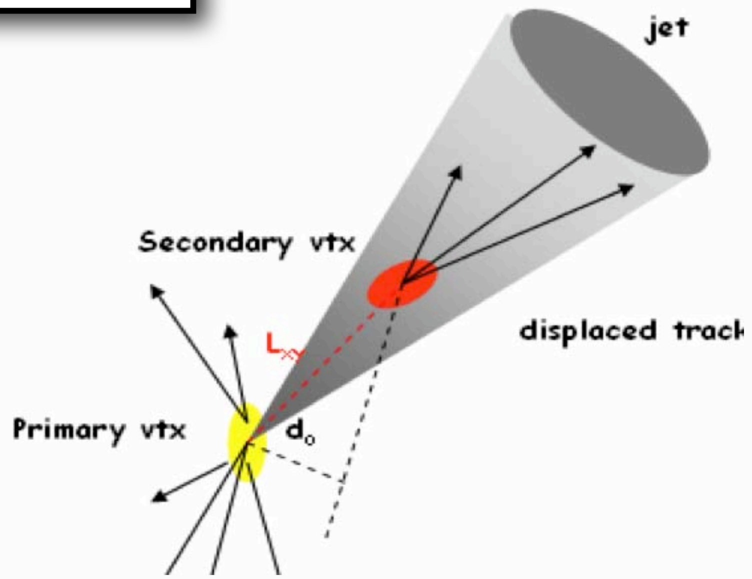
2 jets M(jj) ~ M(W)

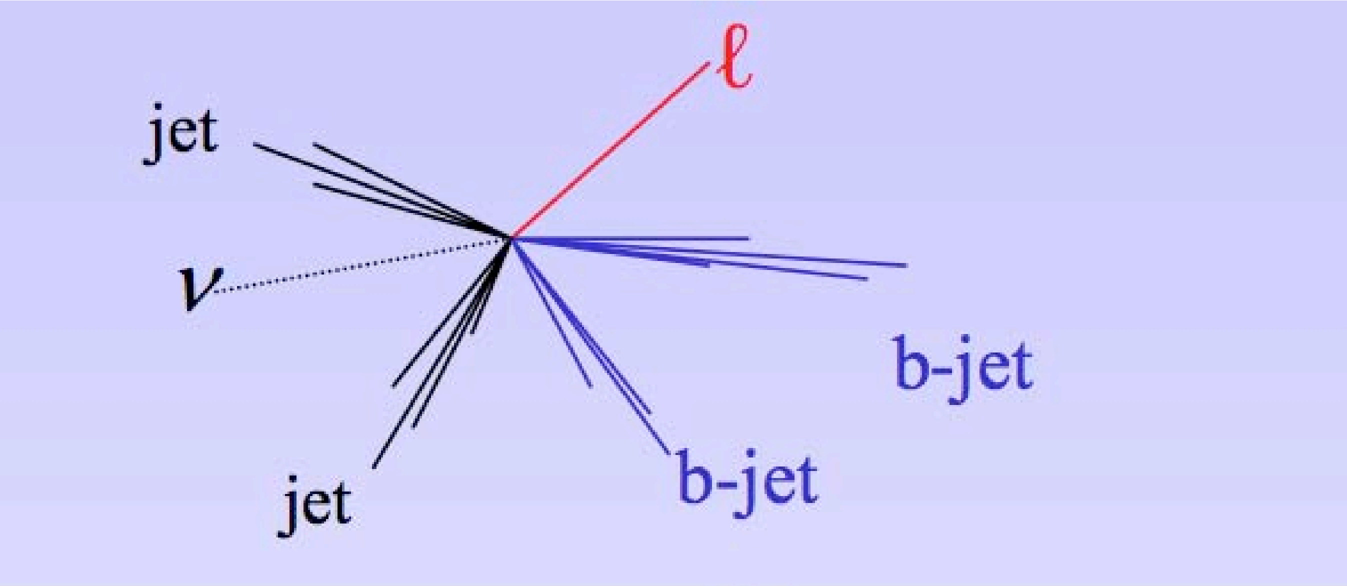
Isolated lepton p_T> 20 GeV

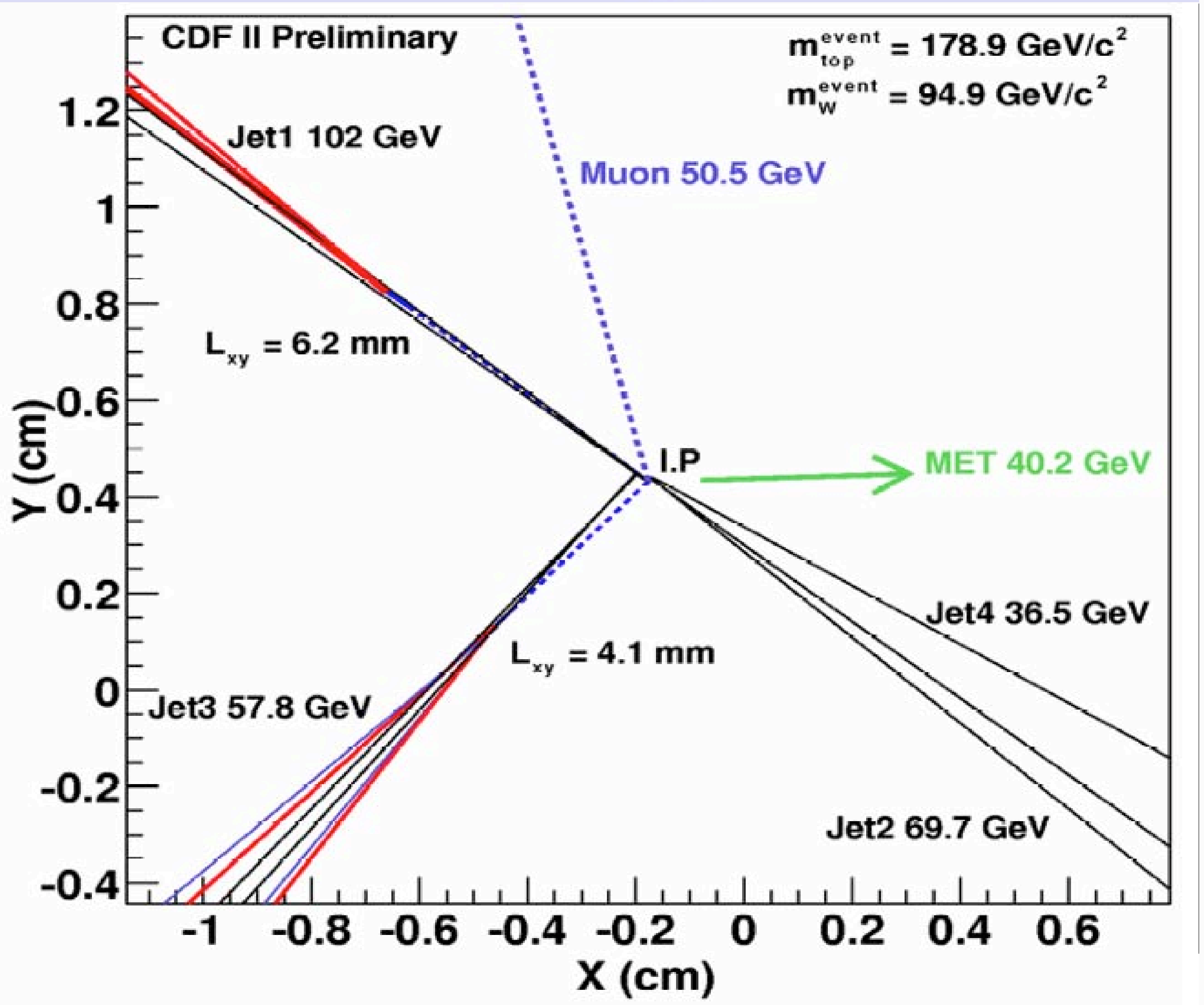


b-tag(s)

E_T^{miss} > 20 GeV







b-tagging important:
Need excellent Silicon Vertex and Pixel Detectors

Top Production (example : semi-leptonic case)

See the top immediately with simple selection :
Missing E_T, 1 lepton, ≥4 jets ,
even without b-tag (!),
cut on hadronic W mass

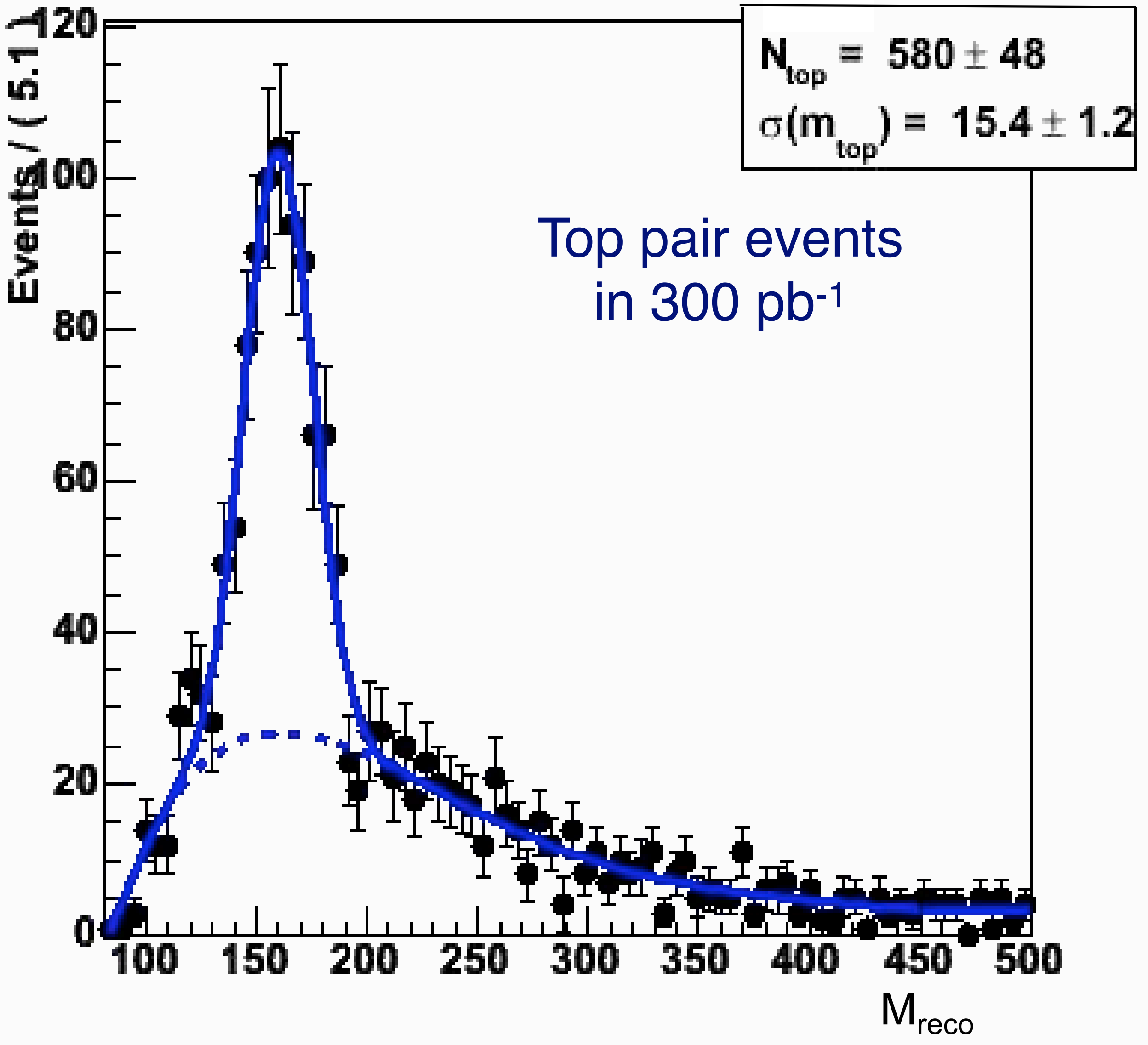
Example (ATLAS study):
- Observe it with 30 pb^{-1}
- σ(tt) to 20 % with 100 pb^{-1}
- M(t) to 7-10 GeV

Once b-tagging is understood:
Very high S/B achievable ~ 27 !

Backgrounds :
W+4j, Wbb+2j(3j) (minor here)

relevant also for single-top

Atlas FullSim Preliminary



Top pair events in 300 pb^{-1}

Study the top quark properties
mass, charge, spin, couplings, production and decay,
ΔM_{top} ~ 1 GeV ?

important background for searches

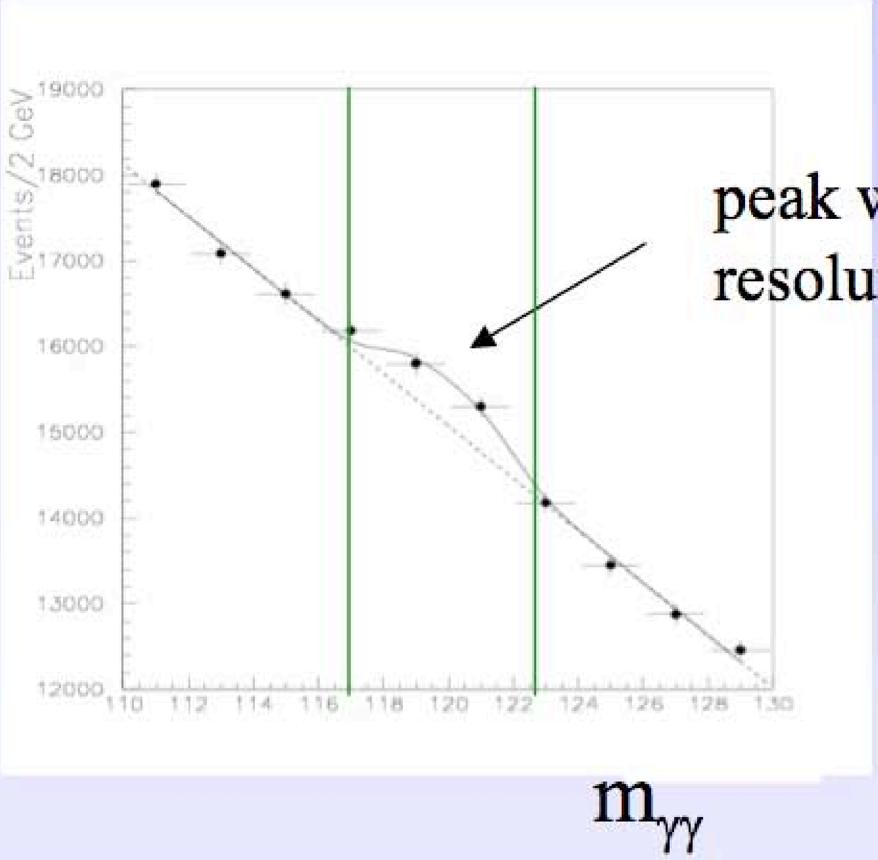
Jet energy scale from W→jet jet,

commission b-tagging

General remarks on searches for new physics

How to claim discovery

Suppose a new narrow particle $X \rightarrow \gamma\gamma$ is produced:



peak width due to detector resolution

Signal significance:

$$S = \frac{N_S}{\sqrt{N_B}}$$

N_S= number of signal events
N_B= number of background events

} in peak region

$\sqrt{N_B} \equiv$ error on number of background events, for large numbers
otherwise: use Poisson statistics

S > 5 : signal is larger than 5 times error on background.
Gaussian probability that background fluctuates up by more than 5σ : 10^{-7} → discovery

Signal Significance : Issues

- Detector resolution (eg. mass resolution σ_m)

If σ_m increases by e.g. a factor of two, then need to enlarge peak region by a factor of two to keep the same number of signal events

→ N_B increases by ~ 2 (assuming background flat)

$\Rightarrow$ **$S = N_S/\sqrt{N_B}$ decreases by $\sqrt{2}$**

$$\boxed{\Rightarrow S \sim 1/\sqrt{\sigma_m}}$$

"A detector with better resolution has larger probability to find a signal"

<u>Note</u>: only valid if $\Gamma_H \ll \sigma_m$. If Higgs is broad detector resolution is not relevant.

$m_H = 100$ GeV → $\Gamma_H \sim 0.001$ GeV

$m_H = 200$ GeV → $\Gamma_H \sim 1$ GeV

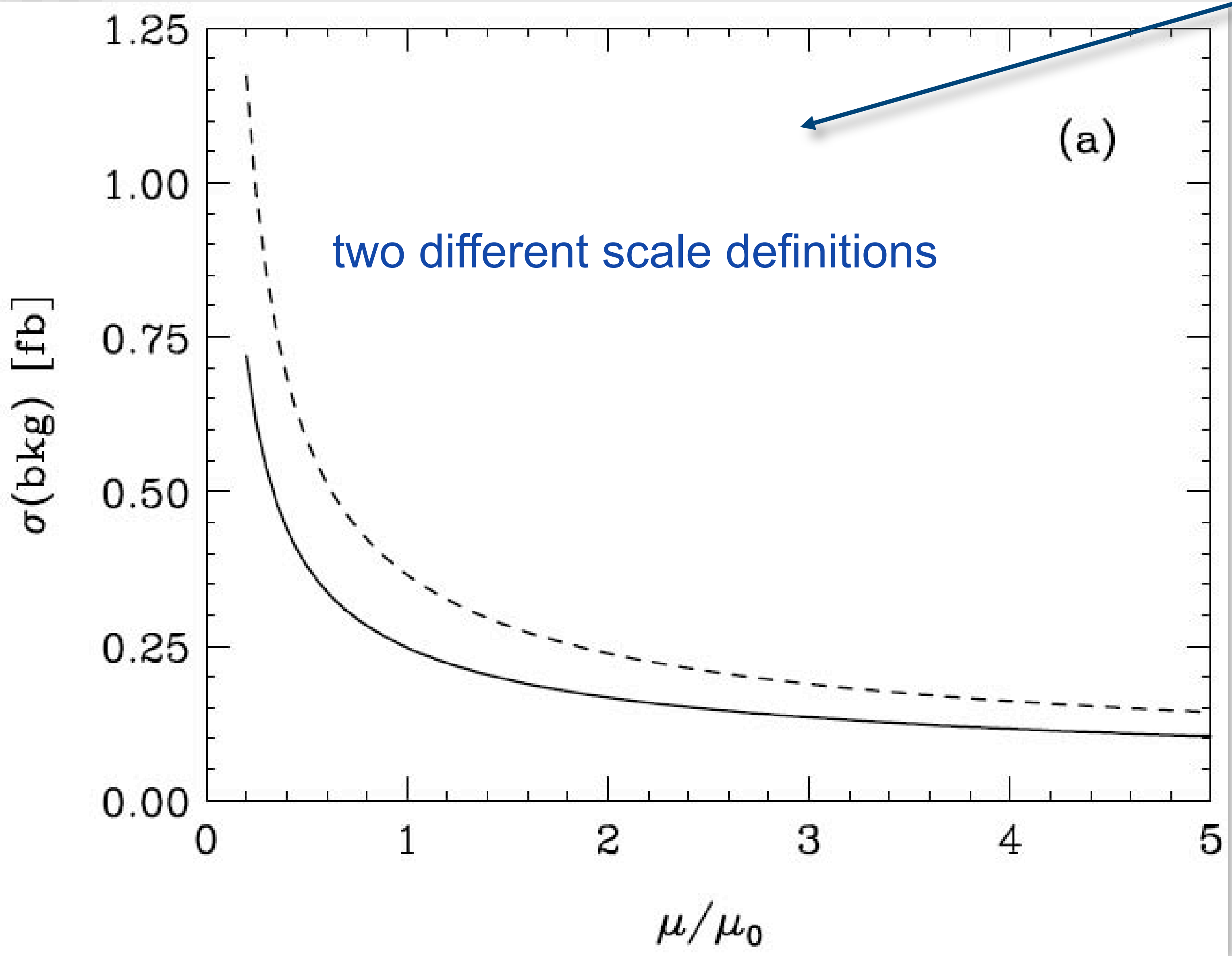
$m_H = 600$ GeV → $\Gamma_H \sim 100$ GeV $\qquad \Gamma_H \sim m_H^3$

- Luminosity

$$\left.\begin{aligned} N_S &\sim L \\ N_B &\sim L \end{aligned}\right\} \qquad \boxed{\Rightarrow S \sim \sqrt{L}}$$

Background extrapolation

Backgrounds to $H \to WW \to \ell\nu\ell\nu$: WW, $t\bar{t}$ for gluon fusion, $t\bar{t}j$ for qqH



two different scale definitions

40-50% scale uncertainty at LO

Idea of extrapolation:

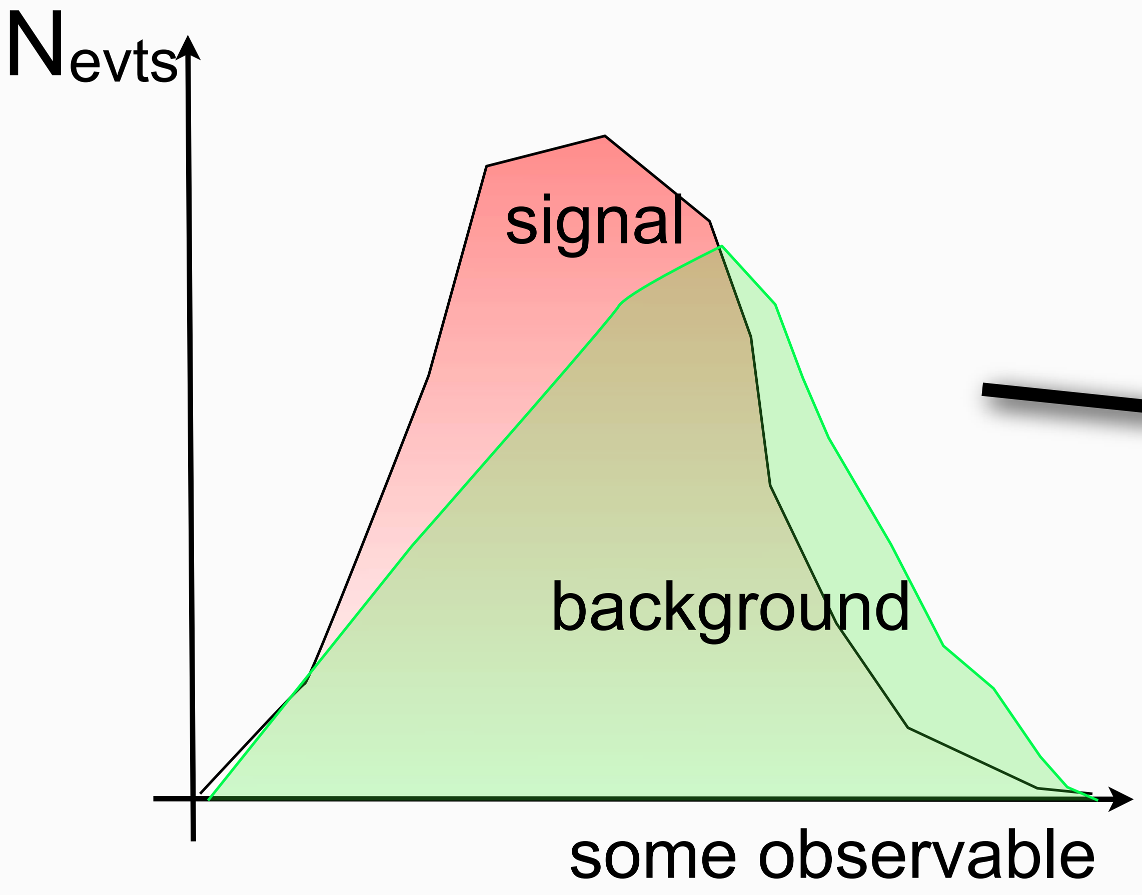
Kauer et al.

$$\sigma_{bkg} \approx \underbrace{\left(\frac{\sigma_{bkg,\,\mathrm{LO}}}{\sigma_{ref,\,\mathrm{LO}}}\right)}_{\text{low theoret. uncertainty}} \cdot \underbrace{\sigma_{ref}}_{\text{low experim. uncertainty}}$$

$\sigma_{\mathbf{bkg}}$: background with cuts optimized for finding signal

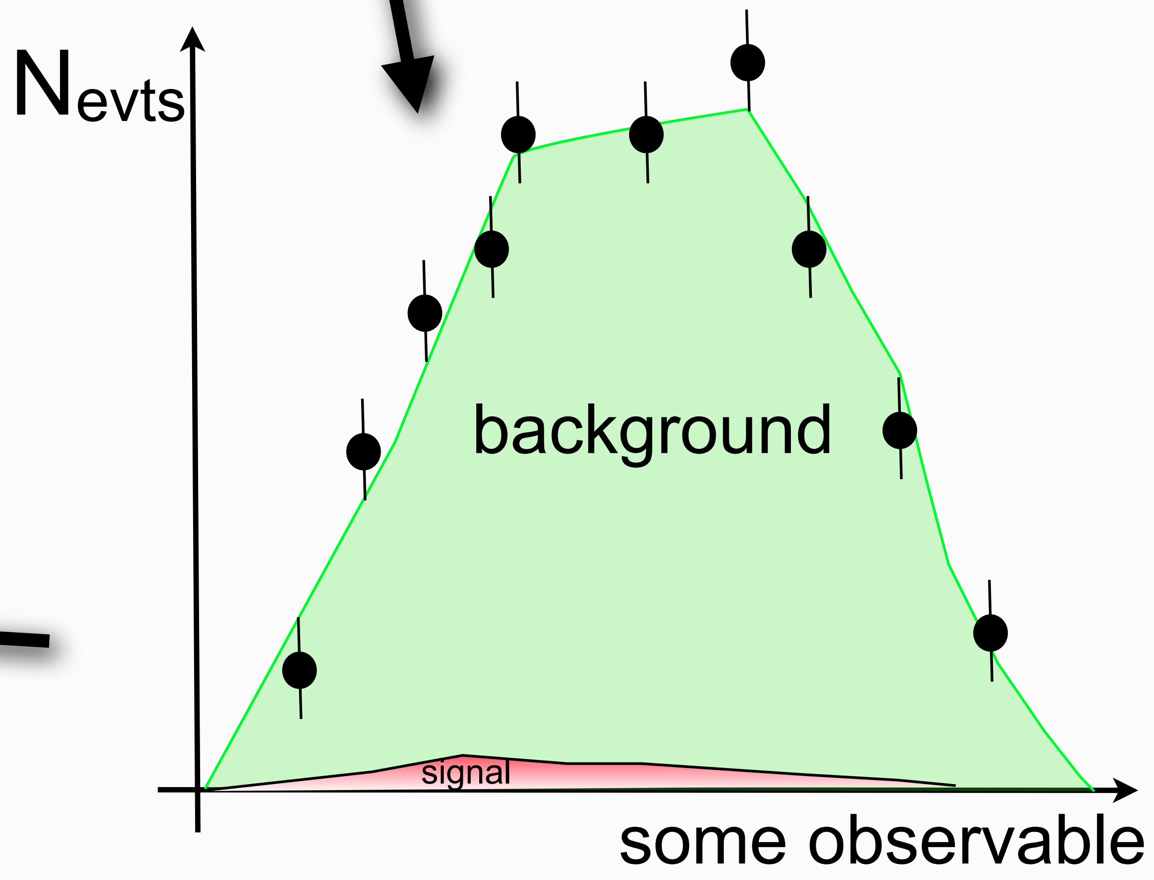
$\sigma_{\mathbf{ref}}$: background with cuts to enrich background (eg. revert the cuts above)

Background extrapolation



invert cuts :
from signal enhancement to background enhancement

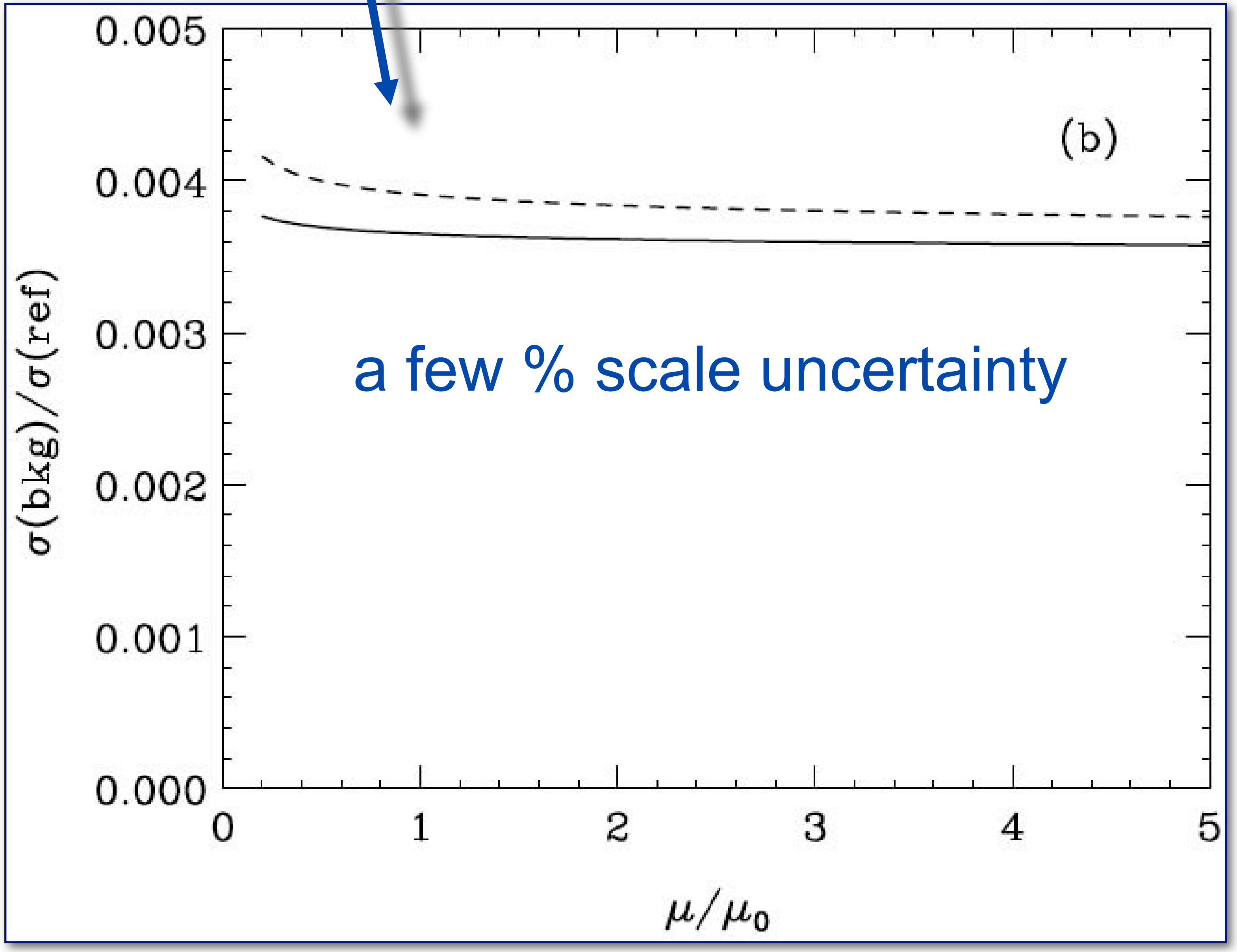
use data to
normalize background



theory :
use theory to compute change in background when inverting cuts

Background extrapolation...

$$\sigma_{bkg} \approx \underbrace{\left(\frac{\sigma_{bkg,\,\mathrm{LO}}}{\sigma_{ref,\,\mathrm{LO}}}\right)}_{\text{low theoret. uncertainty}} \cdot \underbrace{\sigma_{ref}}_{\text{low experim. uncertainty}}$$



a few % scale uncertainty

Reference selection :

- like signal, but
- no central jet veto
- no lepton pair cuts
- require b-tag

This enriches the data sample in pure bckg (SM processes), with high statistics.

Warnings…

- Always try to be as independent from the Monte Carlo as possible!
  - eg. find a “Standard Model candle” for calibration
  - Obtain backgrounds from the data whenever possible
    - Easy if we have mass peak (from sidebands)
    - More difficult in case of excess in high-energy tails, in particular in relation to MET or high-E_T jets
  - Study carefully the validity of a Monte Carlo, and what it is exactly based on
    - eg. LO 2-to-2 process + parton shower, or 2-to-n + parton shower, or NLO+parton shower, or …
- Worry in particular about systematic errors in your search analysis when S/B << 1 !!
    - be careful with calculation of significance

Signal Significance : Issues

- as significance (number of 'sigmas') one usually sees the definition ($\sigma_{stat}(\text{background}) = \sqrt{n_b}$ for large enough statistics)

$$S = n_\sigma = \frac{n_s}{\sqrt{n_b}}$$

- Adding a relative systematic uncertainty ***f***, $\sigma_{syst}(n_b) = f\, n_b$, in quadrature to the statistical uncertainty, this becomes:

$$\tilde{n}_\sigma = \frac{n_s}{\sqrt{n_b + f^2 n_b^2}}$$

Signal Significance : Issues

- this can be rewritten as

$$\tilde{n}_\sigma = n_\sigma \cdot \left[1 + \left(\frac{f \cdot n_\sigma}{n_s / n_b}\right)^2\right]^{-\frac{1}{2}}$$

- limiting cases:

$$n_s / n_b << f \cdot n_\sigma \quad \Rightarrow \quad \tilde{n}_\sigma \approx \frac{n_s / n_b}{f}$$

dominated by systematics

$$n_s / n_b >> f \cdot n_\sigma \quad \Rightarrow \quad \tilde{n}_\sigma \approx n_\sigma$$

dominated by statistics

Signal Significance : Issues

- a concrete example (10% background uncertainty)

n_s	n_b	n_s/n_b	n_σ	$\tilde{n}_\sigma$
50	100	0.5	5	**3.5**
500	10000	0.05	5	**0.5**

- in the second case, more luminosity will not improve the significance!
  (unless more data help to better understand the background)

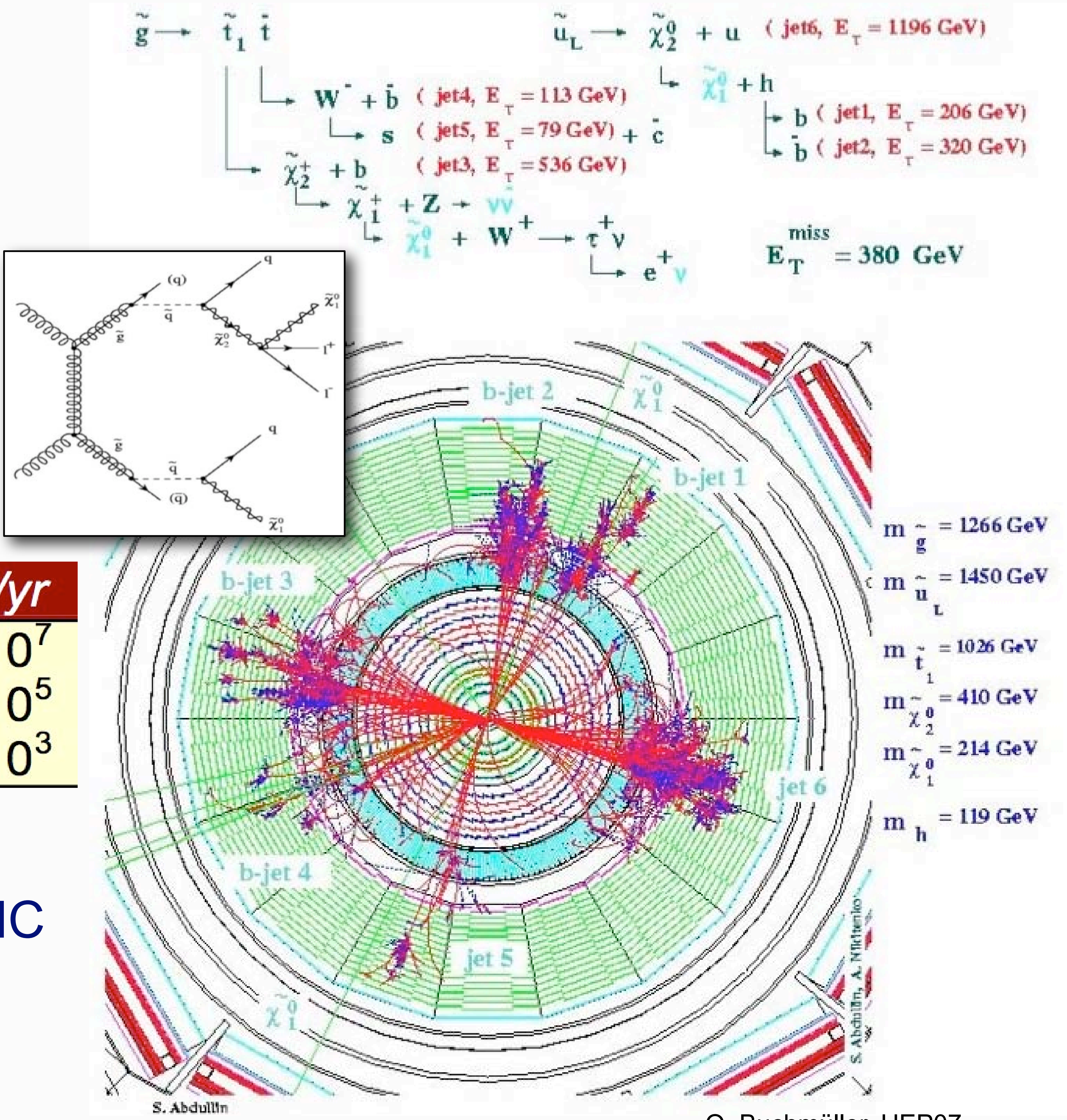
SUSY and Missing E_T

SUSY signatures

- Many hard jets
- Large missing energy
  - 2 LSPs
  - Many neutrinos
- Many leptons
- ie. : Spectacular

M_{sp}(GeV)	σ (pb)	Evts/yr
500	100	10^6-10^7
1000	1	10^4-10^5
2000	0.01	10^2-10^3

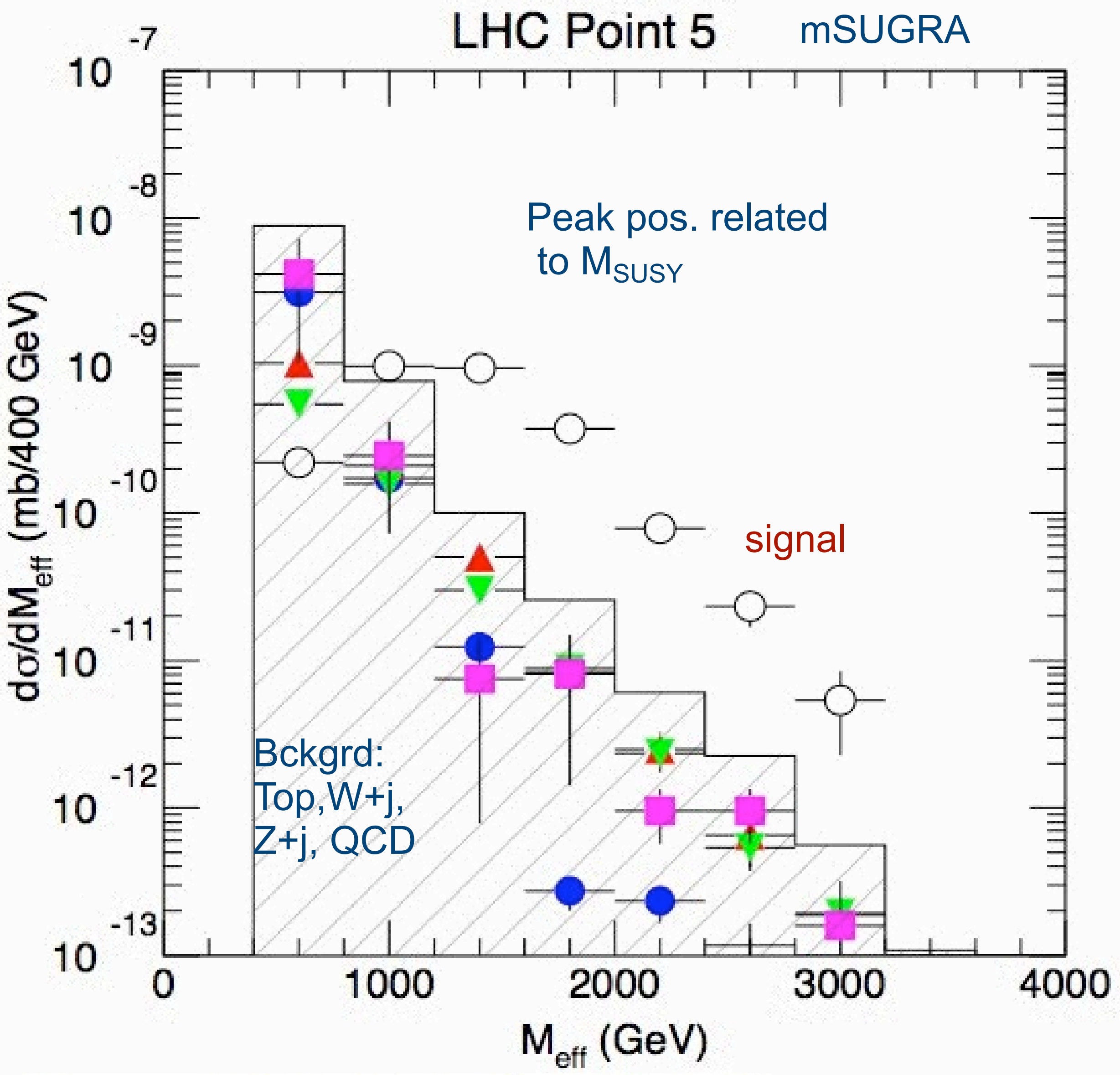
- for low masses the LHC becomes a real SUSY factory



O. Buchmüller, HEP07

Seems easy, but....

- Relies on
  - good reconstruction and understanding of
    - multi-jet backgrounds
    - Missing transverse Energy

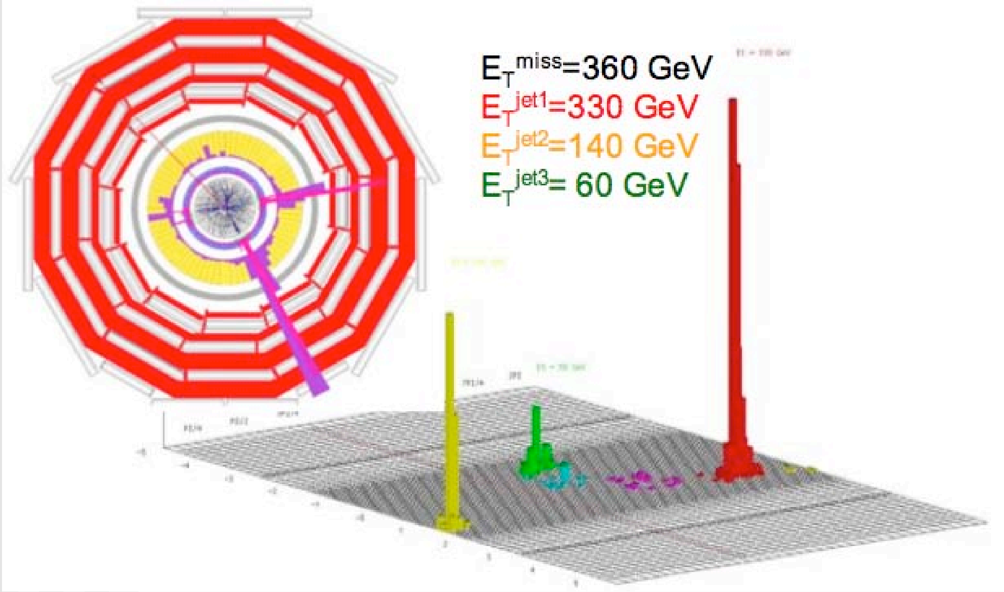


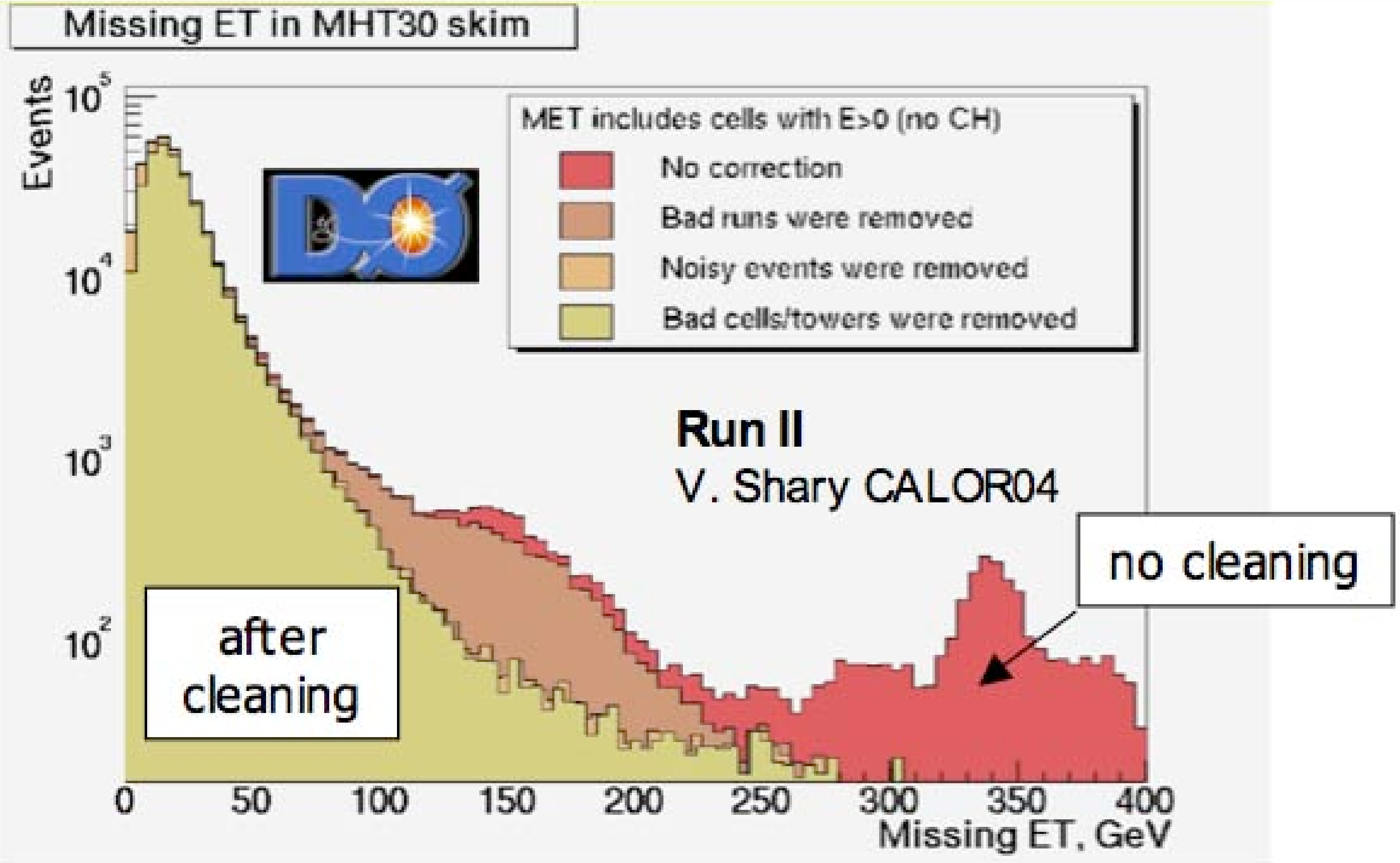
$$M_{eff} = E_T^{miss} + P_T^1 + P_T^2 + P_T^3 + P_T^4$$

- Typical selection
  - $N_{jet} > 4$
  - E_T>100,50,50,50 GeV
  - $E_{T,miss}$ > 100 GeV
- Warning
  - For description of multi-jet backgrounds a simple Parton-shower MC is not good enough
  - Have to combine with matrix elements, eg. ALPGEN

Seems easy, but....

- Relies on
  - good reconstruction and understanding of
    - multi-jet backgrounds
    - Missing transverse Energy



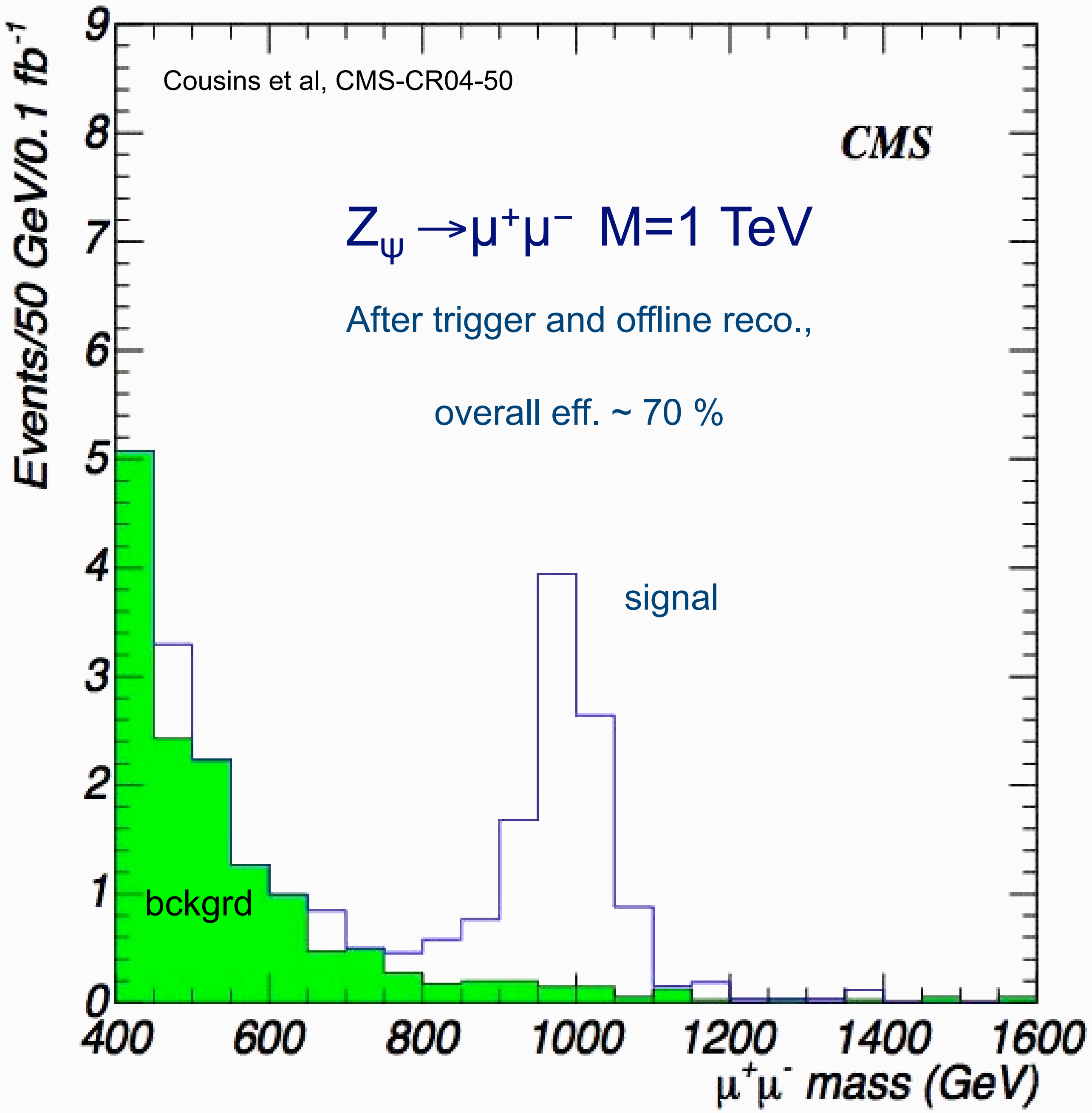


$E_{T,miss}$ is a very tricky variable to measure. Mis-measurements can easily fake “signals”.
Have to fight backgrounds, noise, use control samples, eg. Z+jets

Other discoveries

The easy case: a Z' (or similar)

- Z' : generic for new heavy gauge bosons
  - GUT, dynamical EWSB, little Higgs, …
  - Clear signature
  - low background, mainly Drell-Yan
- One of main issues
  - early control of lepton reconstruction, eg.
  - alignment effects reduce sensitivity by ~ 50 % in the early days (< 100 pb^{-1})
- Similar ATLAS study for $Z' \rightarrow e^+e^-$
  - In SSM, SM-like couplings
  - ~1.5 fb^{-1} needed for discovery up to 2 TeV
  - $Z \rightarrow \ell\ell$ +jet and DY needed to get E-calibration and understand lepton eff.

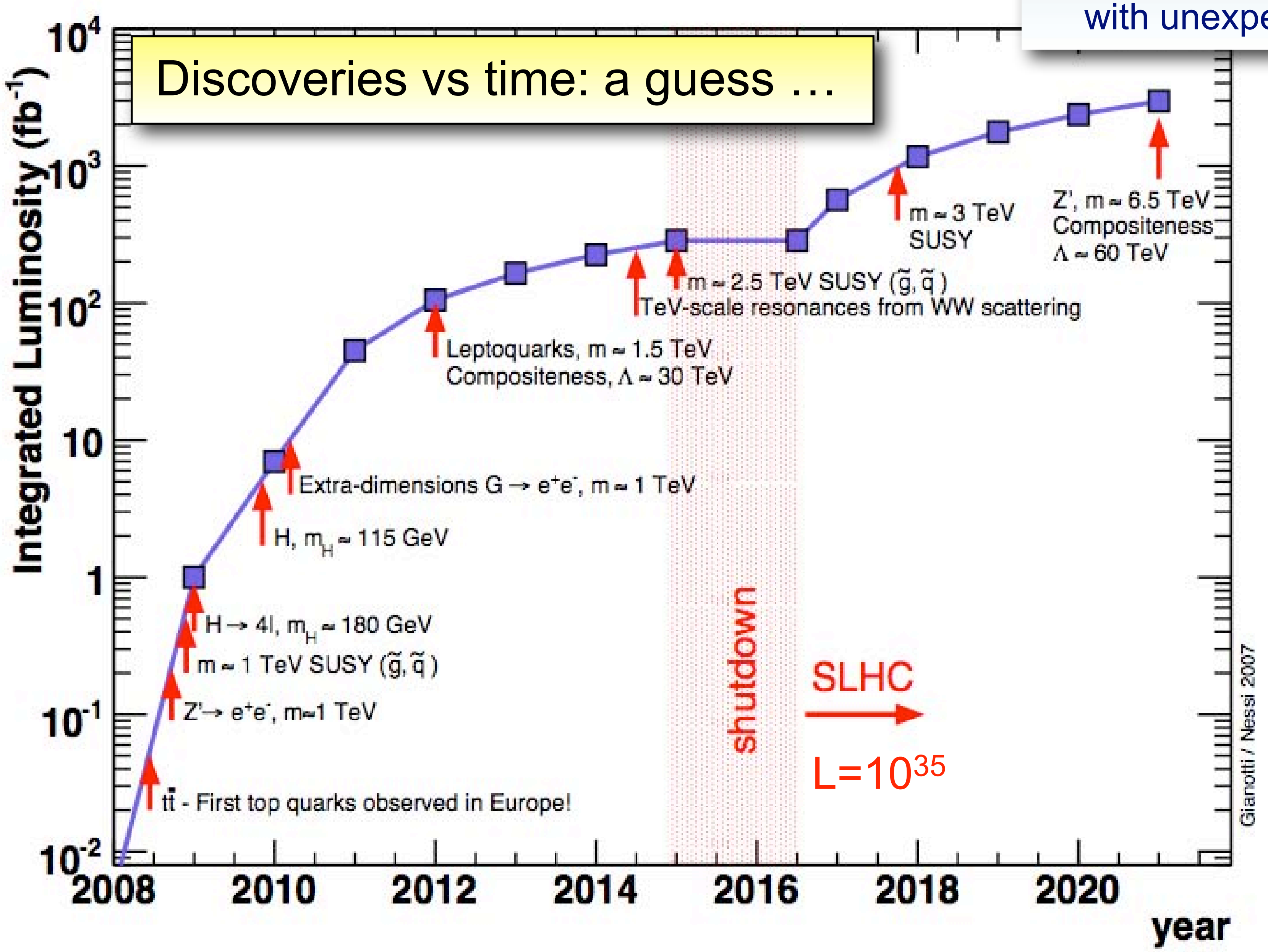


What LHC could discover (besides Higgs and SUSY)

Excited quarks q*→ γ q: up to m ≈ 6 TeV
Leptoquarks: up to m ≈ 1.5 TeV
Monopoles pp → γ γ pp: up to m ≈ 20 TeV
Compositeness: up to Λ ≈ 40 TeV
Z' → ll, jj: up to m ≈ 5 TeV
W' → l ν : up to m ≈ 6 TeV
etc.... etc….

Large number of scenarios studied
Main conclusions:
⇒ LHC direct discovery reach up to m ~ 5-6 TeV

⇒ demonstrated detector sensitivity to many signatures → robustness, ability to cope with unexpected scenarios



Discoveries vs time: a guess …

F. Gianotti

Summary of Part 3

“The only place where success comes before work is the dictionary”

Summary

- SM physics at the LHC:
  we will have to re-discover the SM before going to other discoveries

- Test the SM at an unprecedented energy scale
  - lots of highly exciting and interesting physics
    - Jets, Ws and Zs, tops, ...

- These are also important tools to
  - understand, study, calibrate and improve the detector performance
  - constrain physics input (pdfs, underlying event)
  - necessary input for all other measurements

- We are getting ready now to be able to perform all these measurements and run these tools as early as possible, once the data start flowing in....

Conclusions

- Prospects for discoveries are very good

- At the LHC we have
  - large cross sections
  - spectacular signals
    - for many new signals

- But
  - have to understand the detector first
  - as well as the SM backgrounds
  - Thus : be careful not to claim discovery too early
  - but also not too late ... ;-)

- In any case, extremely exiting years are ahead of us!