QCD and jet physics (Experiment, Part 2)

Aidan Robson

University of Glasgow

University of Glasgow | Experimental Particle Physics

The story so far

Evidence for jets

The collision of very high energy e− & e+ beams gave the opportunity to look for direct evidence for quarks

- Back-to-back collimated bunches of tracks from charged hadrons seen in the central tracking detector
- Back-to-back hadronic clusters in the calorimeter
- 1st observation of back-to-back dijet events in $e^+e^- \to \bar{q}q$ at SPEAR 1975

Gluons and 3-jet events

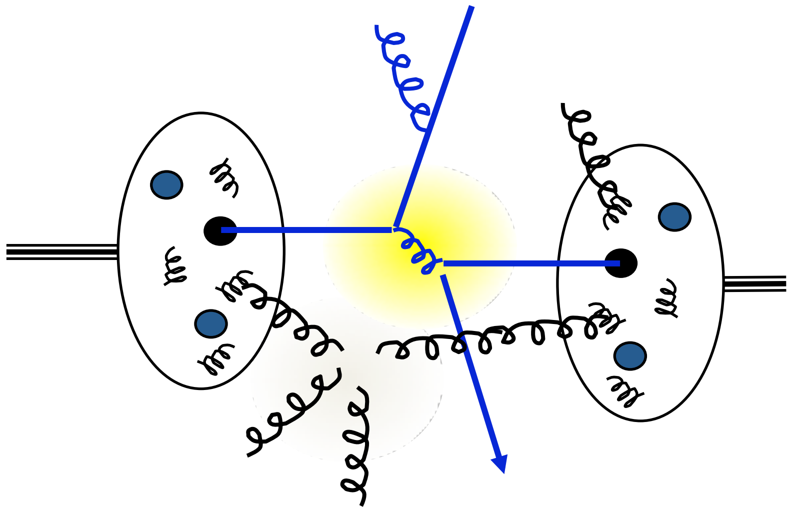
$O(\alpha_S)$ correction to $e^+e^- \to \bar{q}q$ gives events with 3 jets in the final state

- Jets are coplanar to conserve momentum
- first direct evidence for gluons by observation of 3-jet events at PETRA in 1979

Triple gluon vertex

4-jet events have been observed at LEP

- Variables were devised to highlight the non-abelian nature of QCD in contrast with abelian theories such as $[U(1)]^3$



- QCD at hadron colliders
- Soft physics
- Hadronization and jets
- Jet substructure
- Matching
- PDFs
- Dedicated calculations

Thanks to James Ferrando, Jim Pilcher, Rick Field, …

- QCD at hadron colliders
- Soft physics
- Hadronization and jets
- Jet substructure
- Matching
- PDFs
- Dedicated calculations

Track multiplicities

Jet energy scale/
Inclusive jets

W+jets
Z+b

W charge asymmetry

Z p_T

Top mass

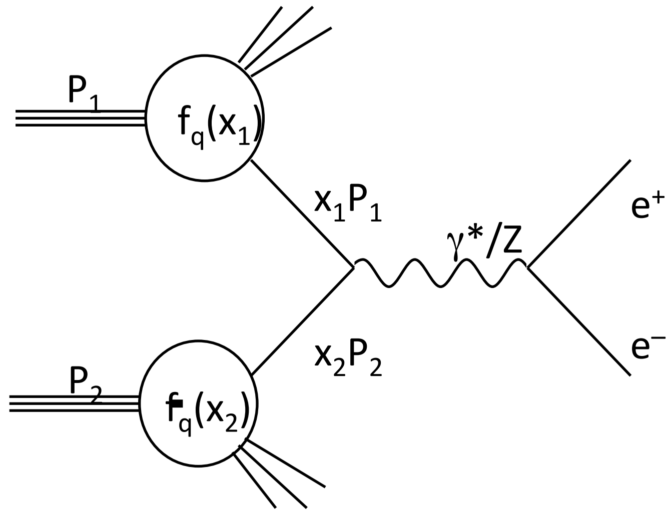
Thanks to James Ferrando, Jim Pilcher, Rick Field, …

Hard scattering

In 1971, Drell & Yan applied DIS parton-model ideas to hadron-hadron collisions. They postulated that:

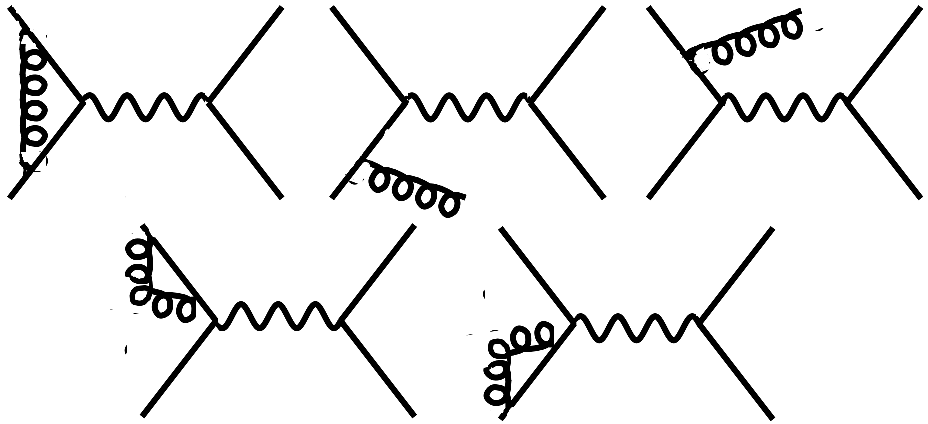
$$\sigma_{AB\to\mu^+\mu^-X} = \Sigma_{a,b}\int dx_a\, dx_b \cdot f_{a/p}(x_a)\cdot f_{b/p}(x_b)\cdot \hat{\sigma}_{ab\to\mu^+\mu^-X}$$

- $\hat{\sigma}$ is the hard scattering cross-section given by a perturbation series in α_s
- $f_{a/p}(x)$ is the parton distribution function for finding a parton a with momentum xP in a proton with momentum P.
- $f_{a/p}(x)$ are universal (process-independent) nonperturbative functions found from fitting to experimental data.



QCD factorization theorem

The quark-parton model predicts exact scaling



However, a problem arose when accounting for perturbative real and virtual gluon emission (i.e. first order in QCD, shown here for vector boson production): large logs [log($Q^2/p_{T\min}{}^2$), with $p_{T\min}$ small] from collinear-gluons spoiled the convergence of the pQCD expansion – a property of a gauge theory with point-like fermion–vector couplings.

Then in 1987 Collins & Soper proved the QCD factorization theorem: ALL the large logs are the same as in DIS structure functions (which are responsible for the logarithmic scaling violation), and can be absorbed by the DGLAP equations in the definition of the parton distribution fns:

$$\log(Q^2/p_{T\min}{}^2) = \log(Q^2/\mu_F{}^2) \cdot \log(\mu_F{}^2/p_{T\min}{}^2)$$

So at LO:

$$\sigma_{AB\to\mu^+\mu^-X} = \Sigma_{a,b} \int dx_a\, dx_b \cdot [f_{a/p}(x_a,\mu_F{}^2)\cdot f_{b/p}(x_b,\mu_F{}^2)] \cdot \hat{\sigma}_{ab\to\mu^+\mu^-X}$$

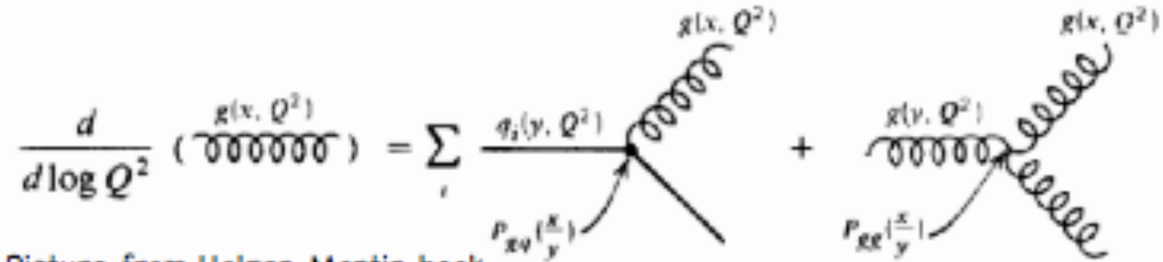
where: μ_F = factorization scale, i.e. large momentum scale (M^2, $p_T{}^2$, Q^2) that makes the scattering hard.

DGLAP evolution equations

$$\frac{\partial q_i(x,\mu^2)}{\partial \log \mu^2} = \frac{\alpha_S}{2\pi}\int_x^1 \frac{dz}{z}\left\{P_{q_iq_j}(z,\alpha_S)q_j(\frac{x}{z},\mu^2) + P_{q_ig}(z,\alpha_S)\, g(\frac{x}{z},\mu^2)\right\},$$

$$\frac{\partial g(x,\mu^2)}{\partial \log \mu^2} = \frac{\alpha_S}{2\pi}\int_x^1 \frac{dz}{z}\left\{P_{gq_j}(z,\alpha_S)q_j(\frac{x}{z},\mu^2) + P_{gg}(z,\alpha_S)g(\frac{x}{z},\mu^2)\right\}.$$

Dokshitzer
Gribov
Lipatov
Altarelli
Parisi



Picture from Halzen-Martin book

The splitting functions P_{ab} govern the splittings of the partons and have perturbative expansions:

$$P_{ab}(x,\alpha_S) = P_{ab}^{(0)}(x) + \frac{\alpha_S}{2\pi}P_{ab}^{(1)}(x) + \cdots$$

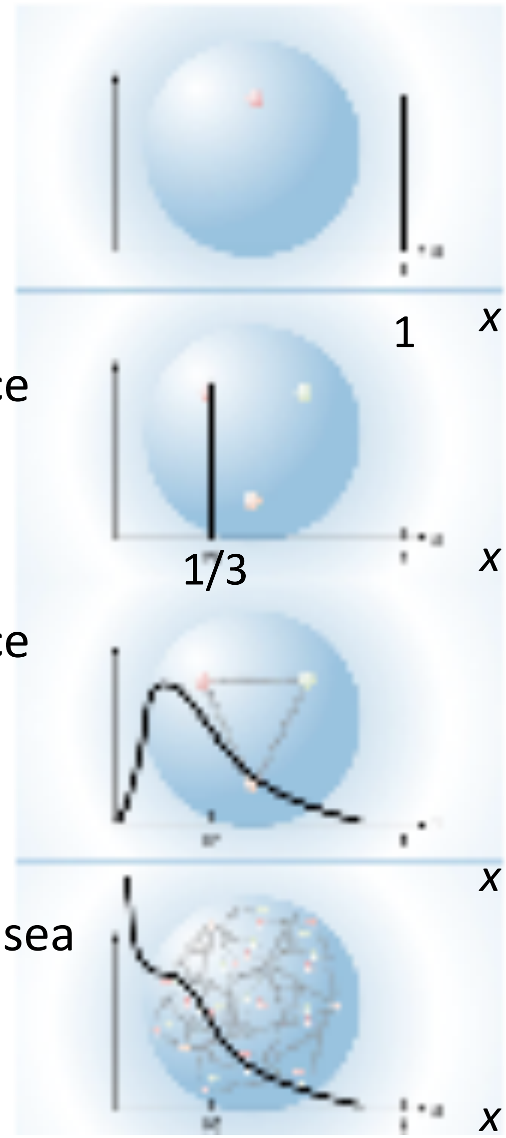
Demystifying PDFs

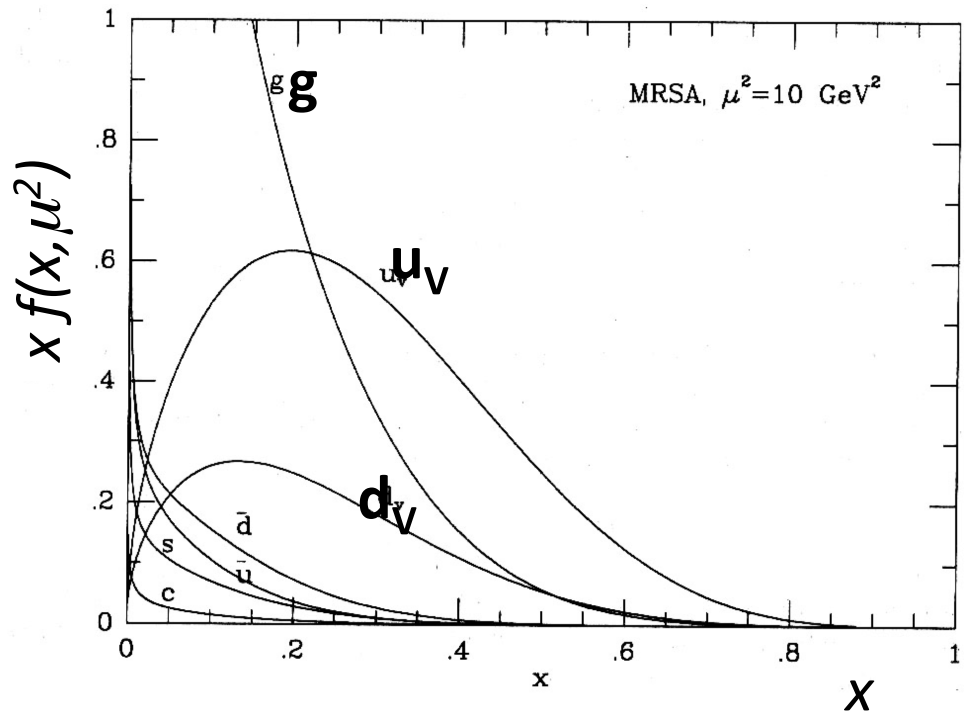
A single particle

Three valence quarks

Three valence quarks with interactions

Valence and sea quarks with interactions





Factorization and renormalization scales

Another complication comes from the fact that there are finite, process-dependent corrections to the cross section:

$$\hat{\sigma}_{ab\to X} = [\,\hat{\sigma}_0 + \alpha_S(\mu_R^2)\,\hat{\sigma}_1 + \cdots\,]_{ab\to X}$$

which have to be computed for each process. Therefore:

$$\sigma_{AB} = \int \mathrm{d}x_a \mathrm{d}x_b\, f_{a/A}(x_a, \mu_F^2)\, f_{b/B}(x_b, \mu_F^2) \times [\,\hat{\sigma}_0 + \alpha_S(\mu_R^2)\,\hat{\sigma}_1 + \cdots\,]_{ab\to X}$$

where: μ_F = ***Factorization scale***, separates short & long distance physics

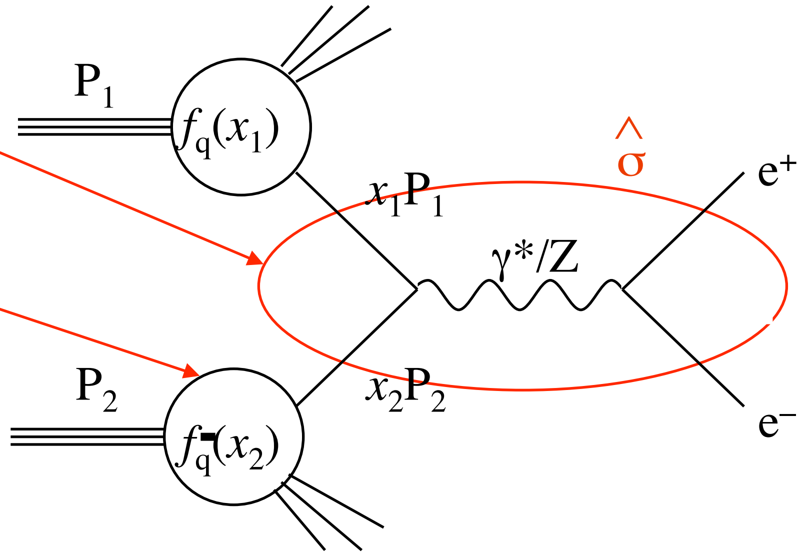
μ_R = ***Renormalization scale*** for the QCD running coupling

Note: σ is not dependent on μ_F and μ_R if it is calculated to all orders of pQCD. But if σ is computed up to a certain order, different scale choices will give different results. A sensible choice is $\mu_F = \mu_R$ = typical momentum scale of the hard-scattering process. Example: $\mu_F = \mu_R = M^2$ for Drell-Yan.

Factorization

- Part that can be calculated perturbatively with Feynman diagrams. $\hat{\sigma}(\hat{s})$

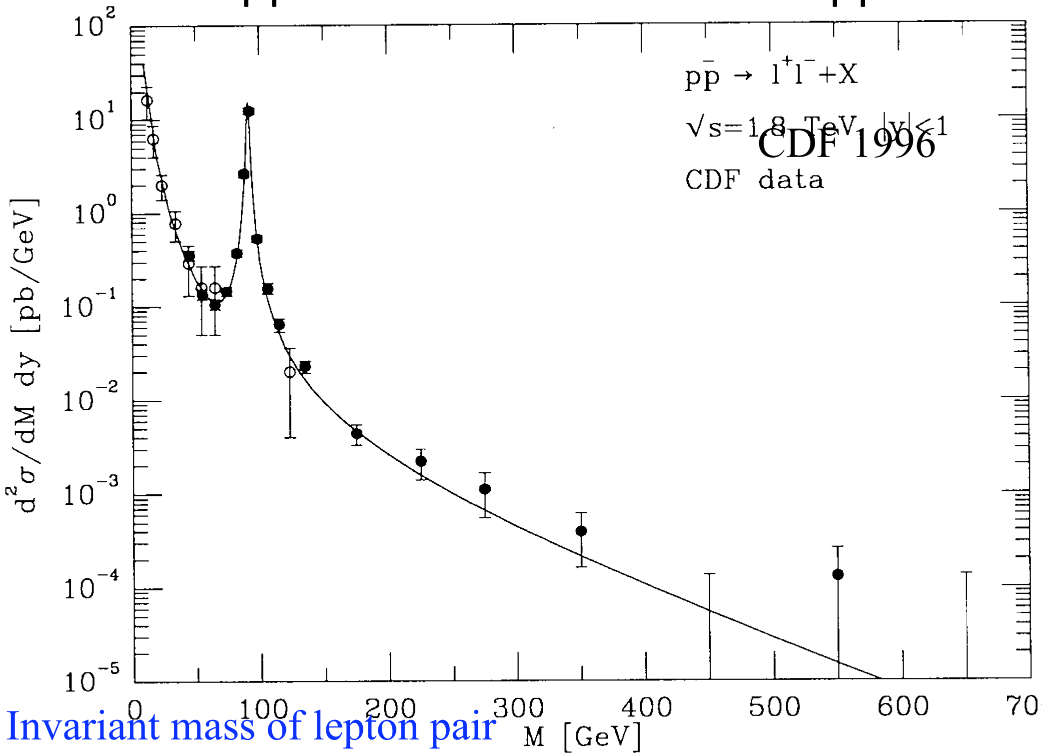
- Part that can not be calculated with perturbative theory because of low-energy gluons: Parton distribution functions. Parametrizations from experimental data: MRST, CTEQ5L,…. Phenomenological functions that give the probability of finding a parton with momentum fraction in the interval [*x*, *x*+δ*x*]



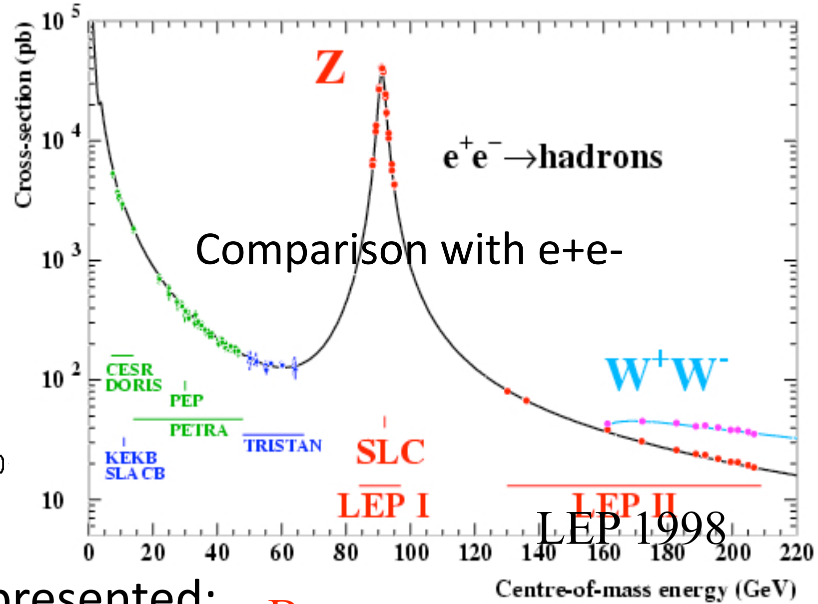
$$\sigma_X = \sum_{a,b} \int_0^1 dx_1 dx_2 \, f_a(x_1, \mu_F^2) \, f_b(x_2, \mu_F^2)$$
$$\times \; \hat{\sigma}_{ab \to X}\left(x_1, x_2, \{p_i^\mu\}; \alpha_S(\mu_R^2), \alpha(\mu_R^2), \frac{Q^2}{\mu_R^2}, \frac{Q^2}{\mu_F^2}\right)$$

Drell-Yan process

Does the approach work? Yes! First applied to the Drell-Yan process



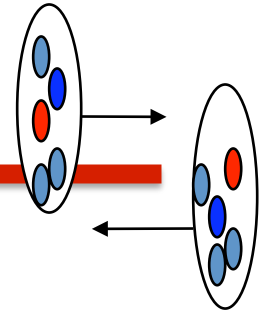
Drell-Yan
lepton pair production
$q\bar{q} \to l^+l^-$

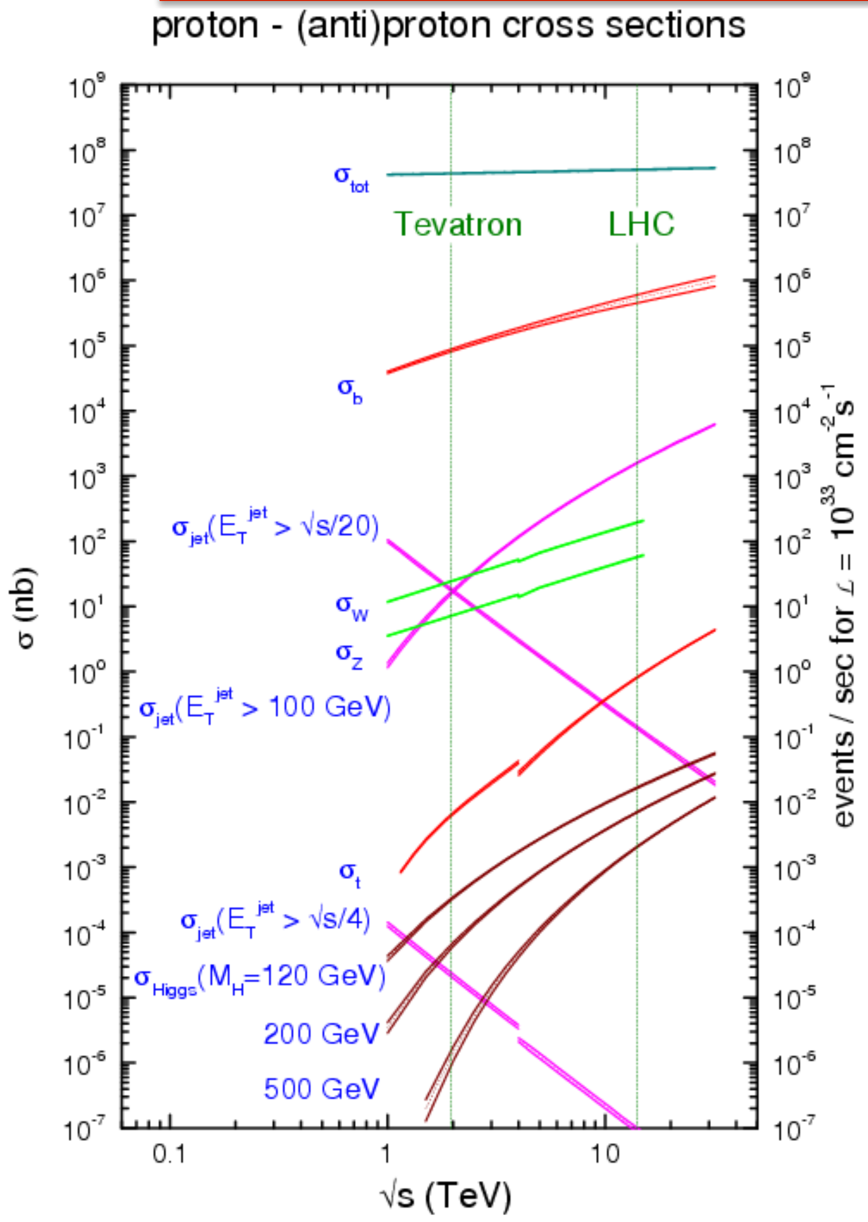


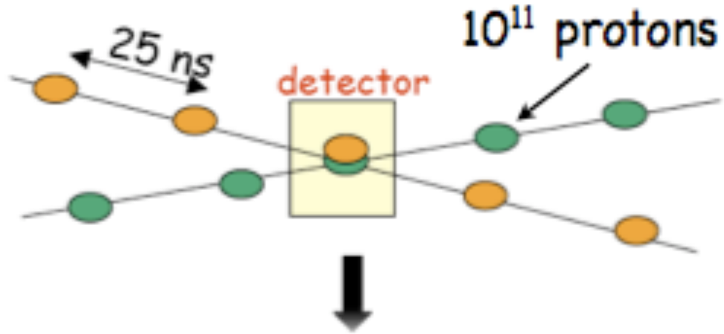
Good agreement with data was found, which represented:

- confirmation of parton model
- quantitative treatment (for the first time) of hadronic processes
- proof that Parton Distribution Functions (PDFs) are fundamental quantities
  ie can measure them in ep, then apply them to pp.

pp collisions



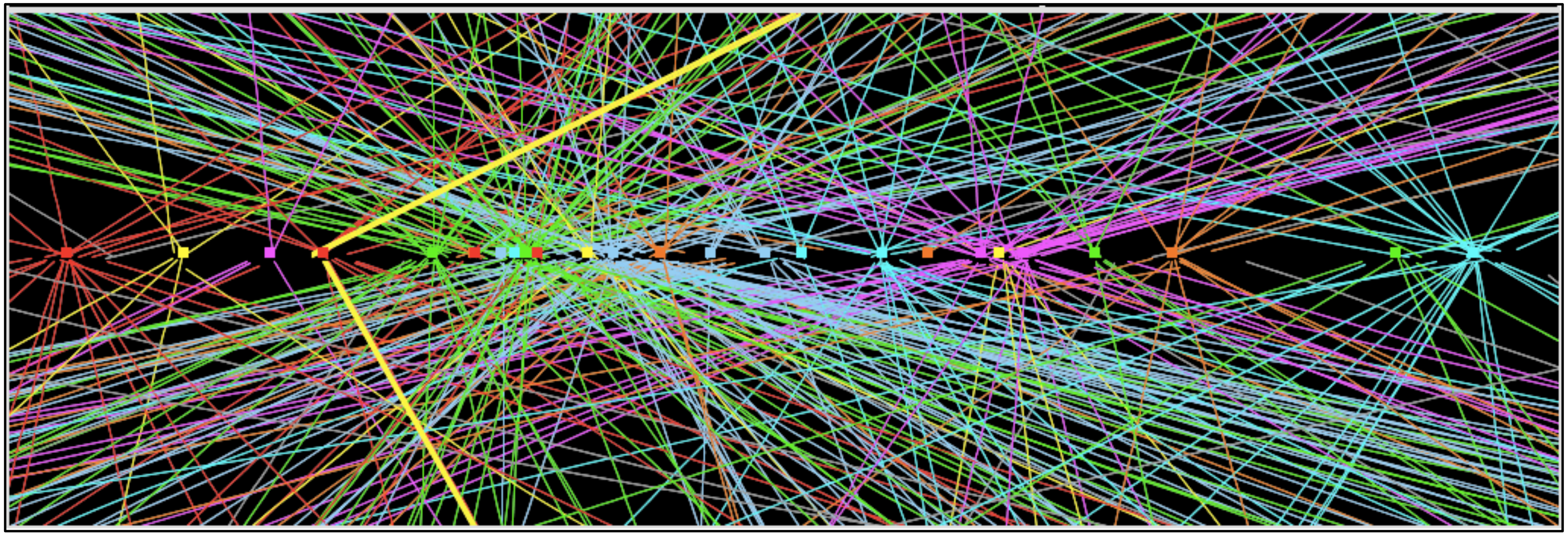




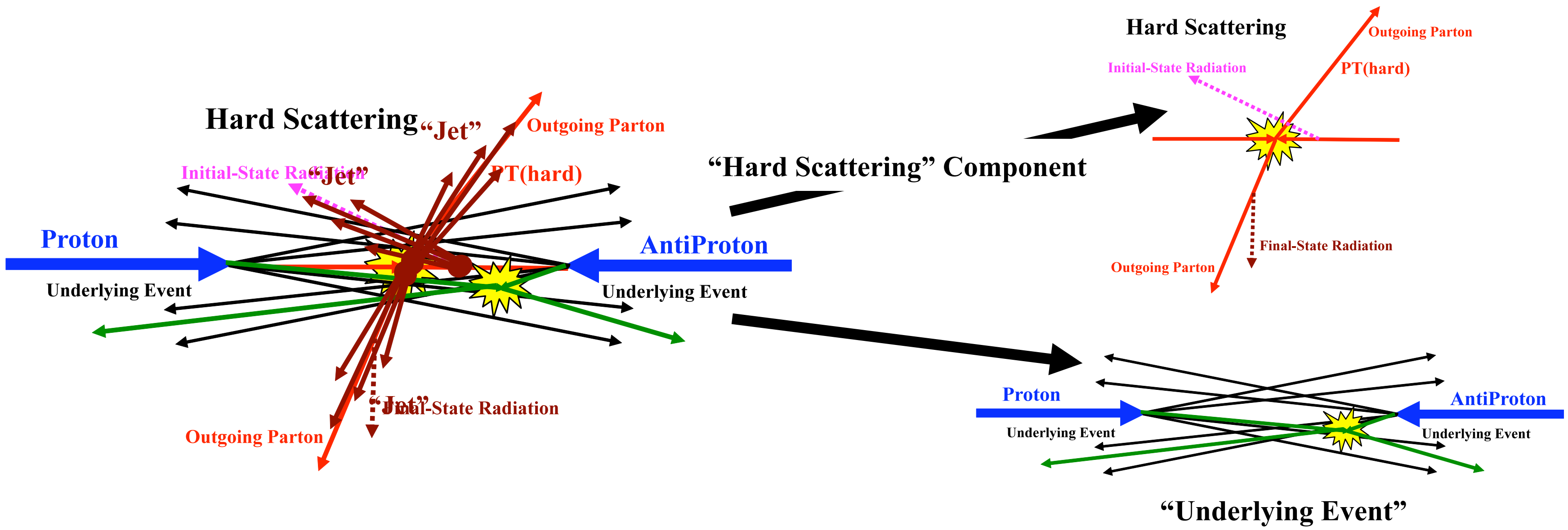
Event rate in ATLAS & CMS

$N = L\ .\ \sigma_{inel}(pp) \approx 10^{34}\text{cm}^{-2}\text{s}^{-1}\ .\ 100\text{mb}$

$\approx 10^9$ interactions/s !

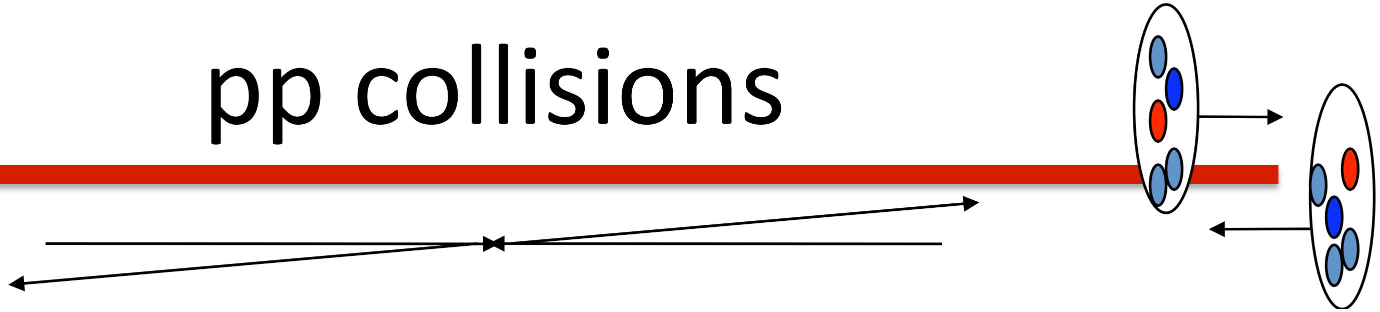


pp collisions



From Rick Field

pp collisions



Elastic scattering: p p → p p

Single diffractive scattering

Double diffractive scattering

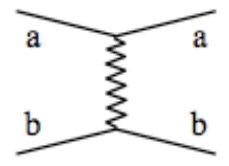
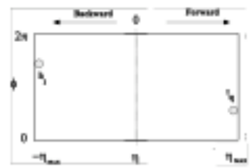
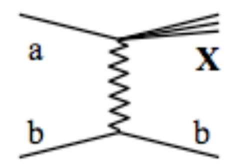
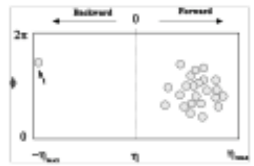
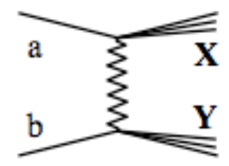
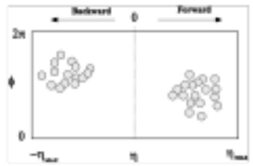
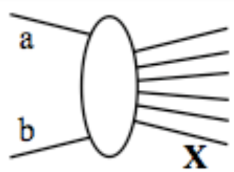
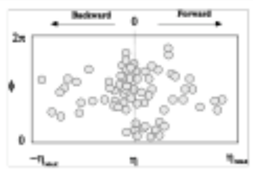
Soft scattering (aka minimum bias events)

Hard scattering

“Perturbative part”: parton-parton interaction

“Non-perturbative part”:

Parton Distribution Functions (PDF)

Process	σ (mb) at $\sqrt{s}$=14TeV	diagram	η-Φ plane
elastic	20		
single diffractive	15		
double diffractive	10		
non-diffractive	55		

Partons carry a fraction x of the proton momentum.

The “energy reach” of a hadron accelerato lower than the beam energy,

The parton-parton energy varies from an event to another and is a priori unknown

Luminosity : increase the number of tries to get a reasonable number of rare high-energy scattering events

Minimum bias

Minimum bias can be defined as INELASTIC collisions of two protons accepted by the trigger with the only requirement being some activity in the detector, i.e.
a minimal p_T threshold of ≈100 MeV (ISR-experiments, UA5, E735, CDF).
(No energy threshold ⇔ no bias).

it includes very rare high-p_T scatters and very common low p_T events
MB events occur in all collisions, and overlap with high-p_T events.

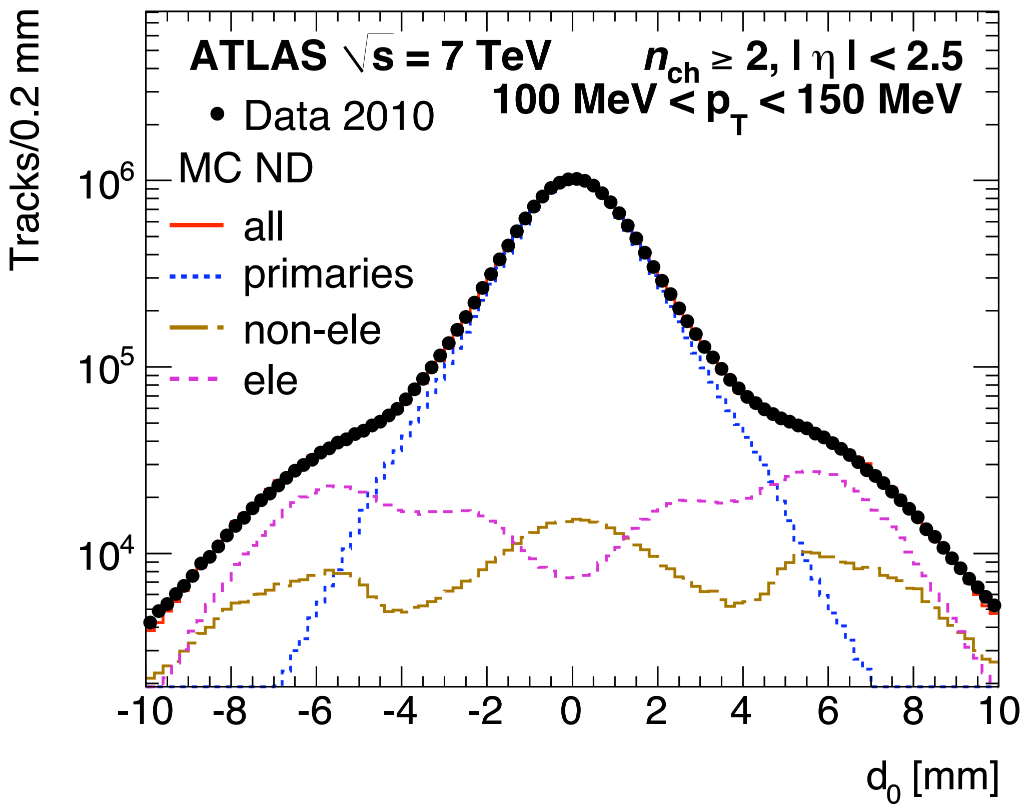
- main component of pileup -> unavoidable background for all processes!
- allows prediction of radiation levels -> detector damage and occupancy

The soft parts

It is important to know soft QCD:

- Theoretical reasons:
  - –insight of fundamental aspects of strong interactions, hadron structure, factorization of interactions
- Experimental reasons:
  - –design and understanding of detectors (radiation, occupancy...)
  - –calibration of analysis tools (jet energy, missing energy, vertexing, jet/e±/γ isolation tuning of Montecarlo generators

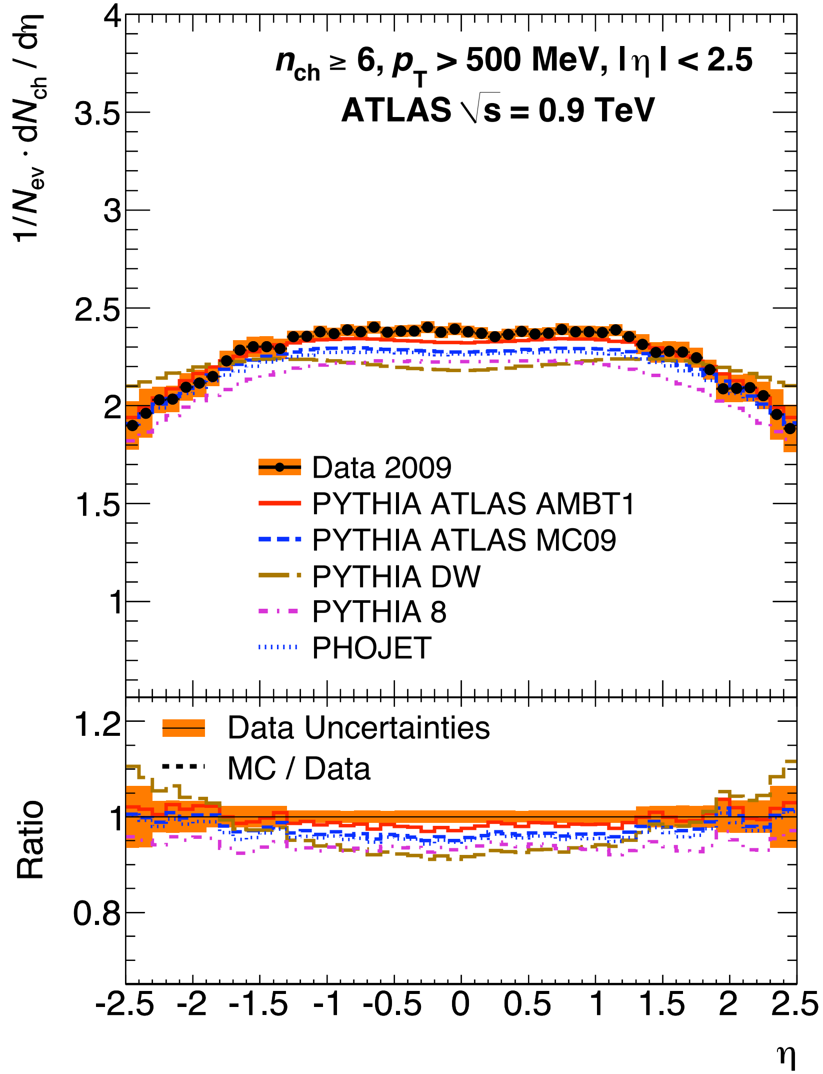
Charged particle multiplicities

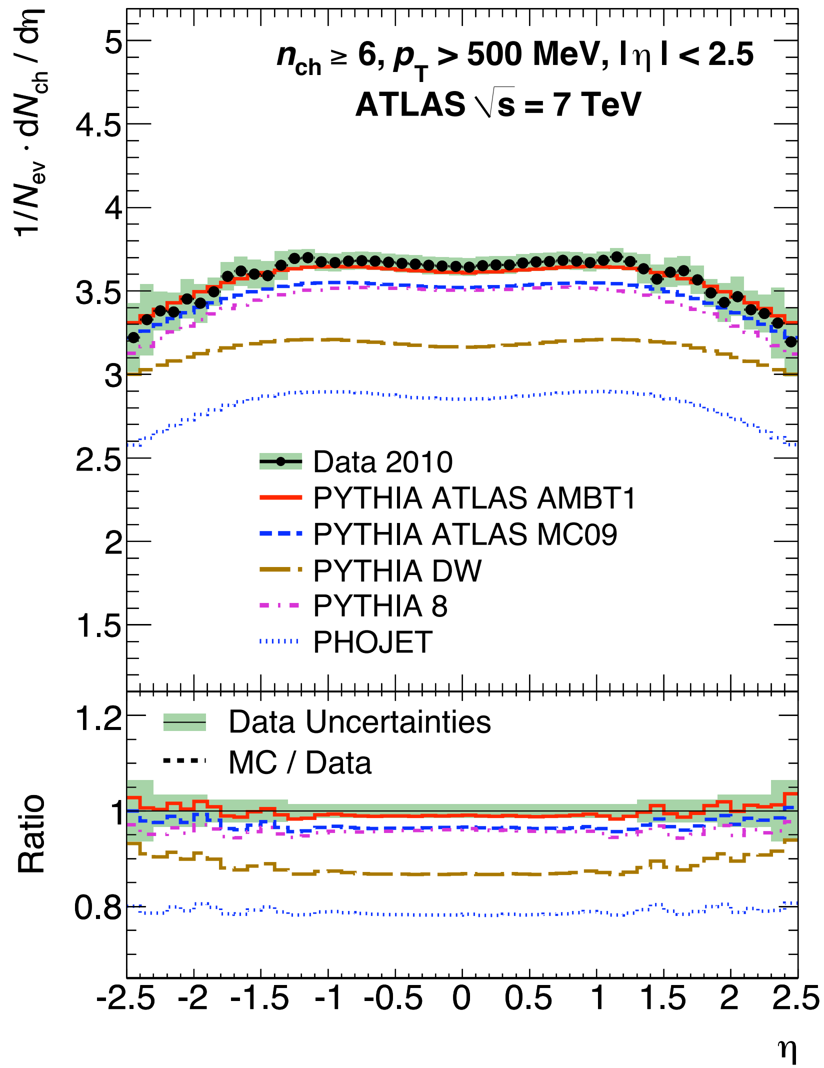


First work out which are primary tracks…

Charged particle multiplicities

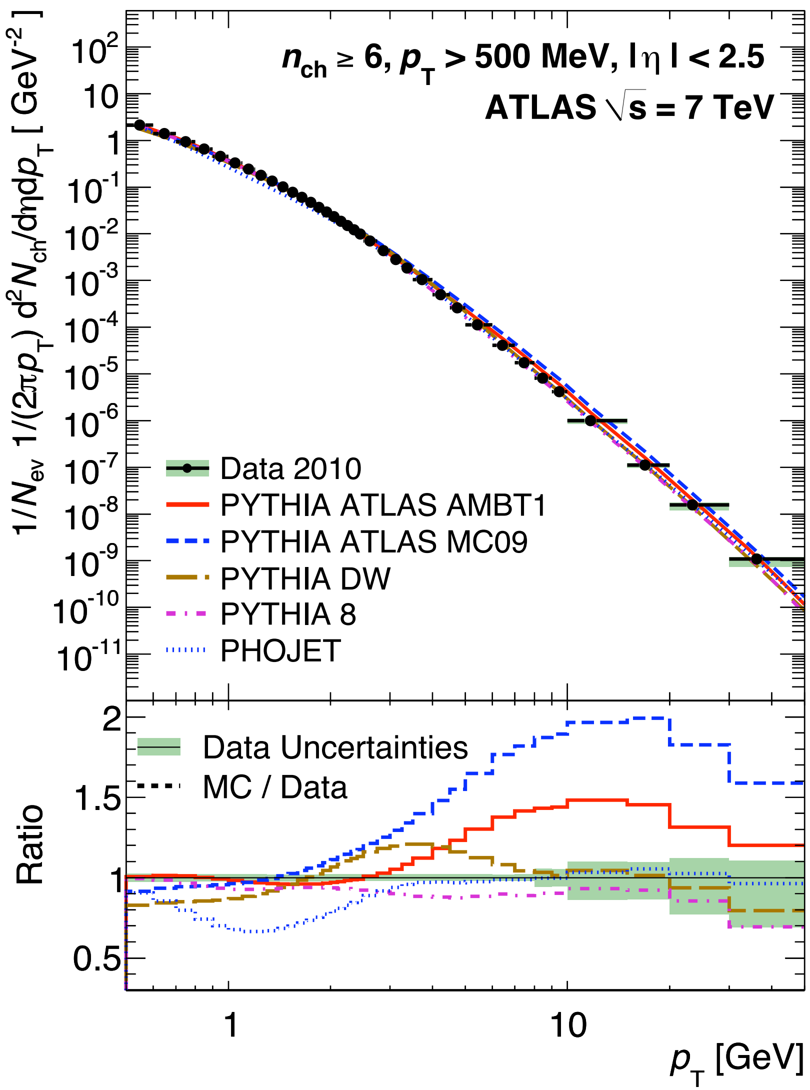
low energy 'QCD-inspired' models -> parameters in MC generators

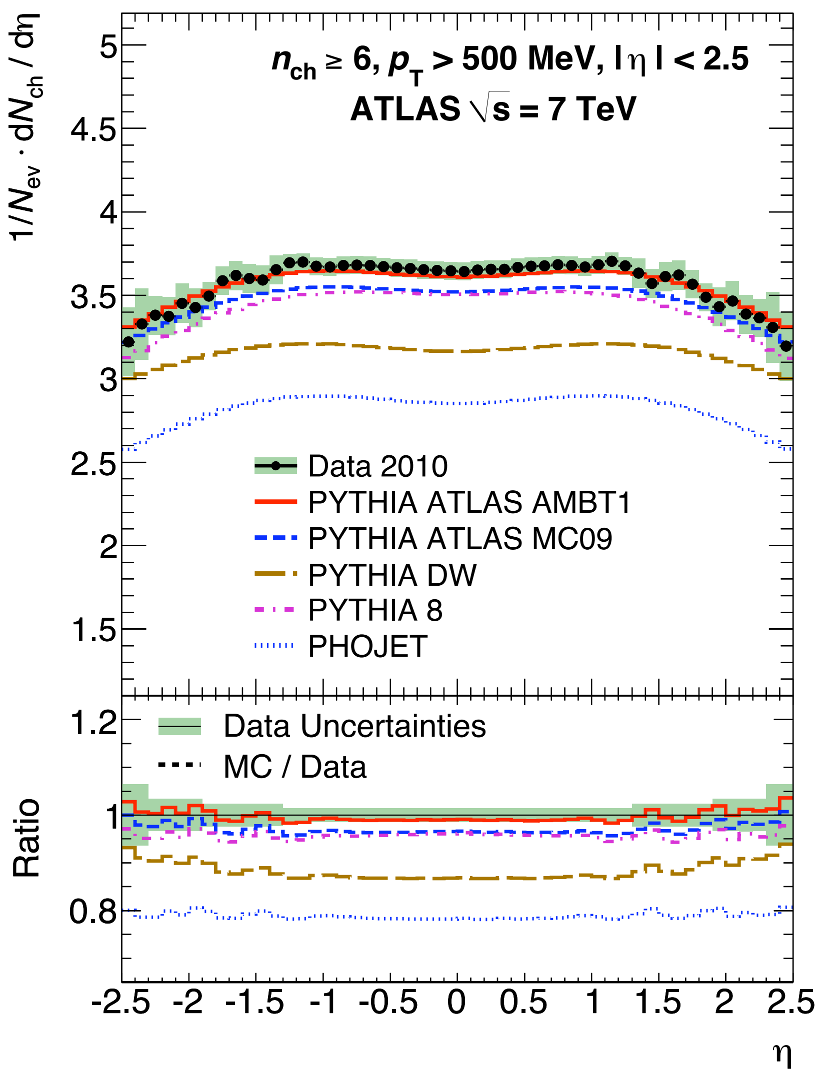




Charged particle multiplicities

low energy ‘QCD-inspired’ models -> parameters in MC generators

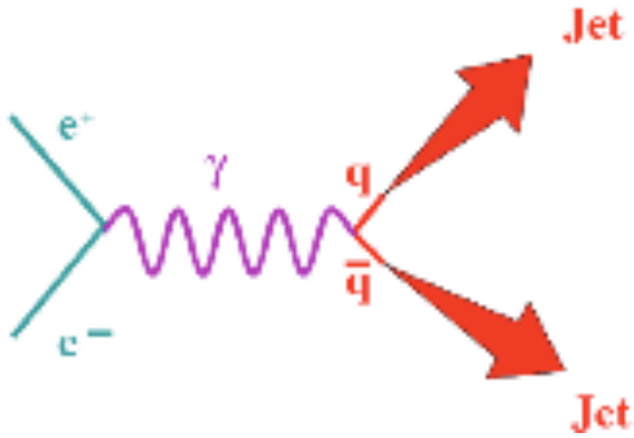




Comparison: e+e–

e+e–

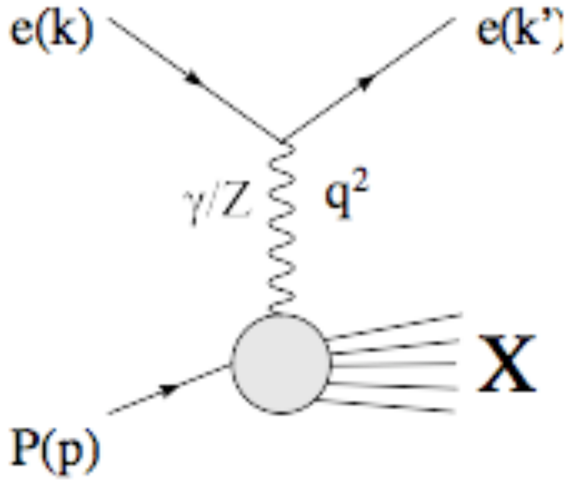
- Good for studying:
  - Photon structure
  - Jet Production/properties
  - Event shapes
- No use for:
  - Hadronic structure
  - Underlying event
- Characterise behaviour by:
  - $\sqrt{s}$
  - Jet energy



Comparison: ep

ep

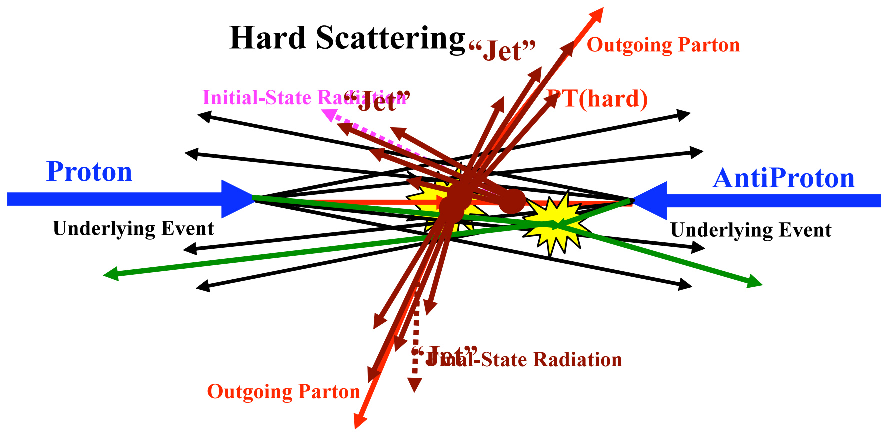
- Good for studying:
  - Hadron (proton) structure
  - Jet Production/properties
  - Event shapes
- Less good for
  - Photon structure
  - Underlying event
- Characterise behaviour by:
  - Q^2 (four momentum transfer)
  - p_T of jets



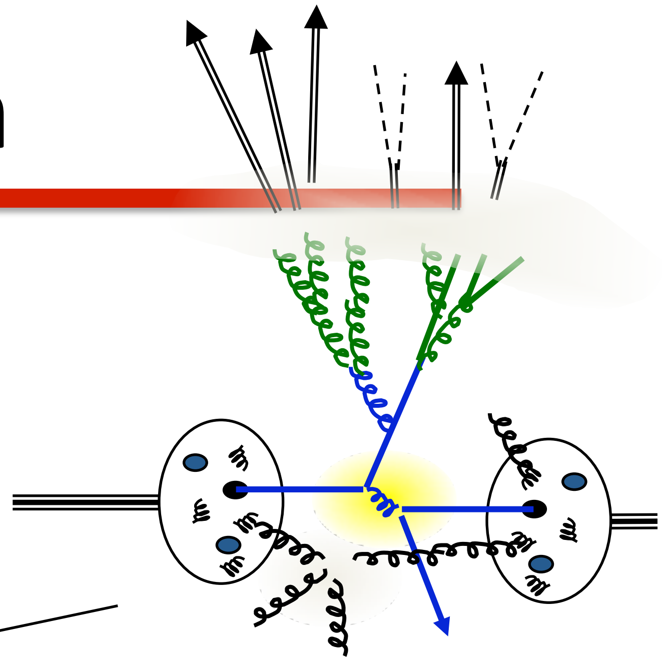
Comparison: pp

pp/p̄p

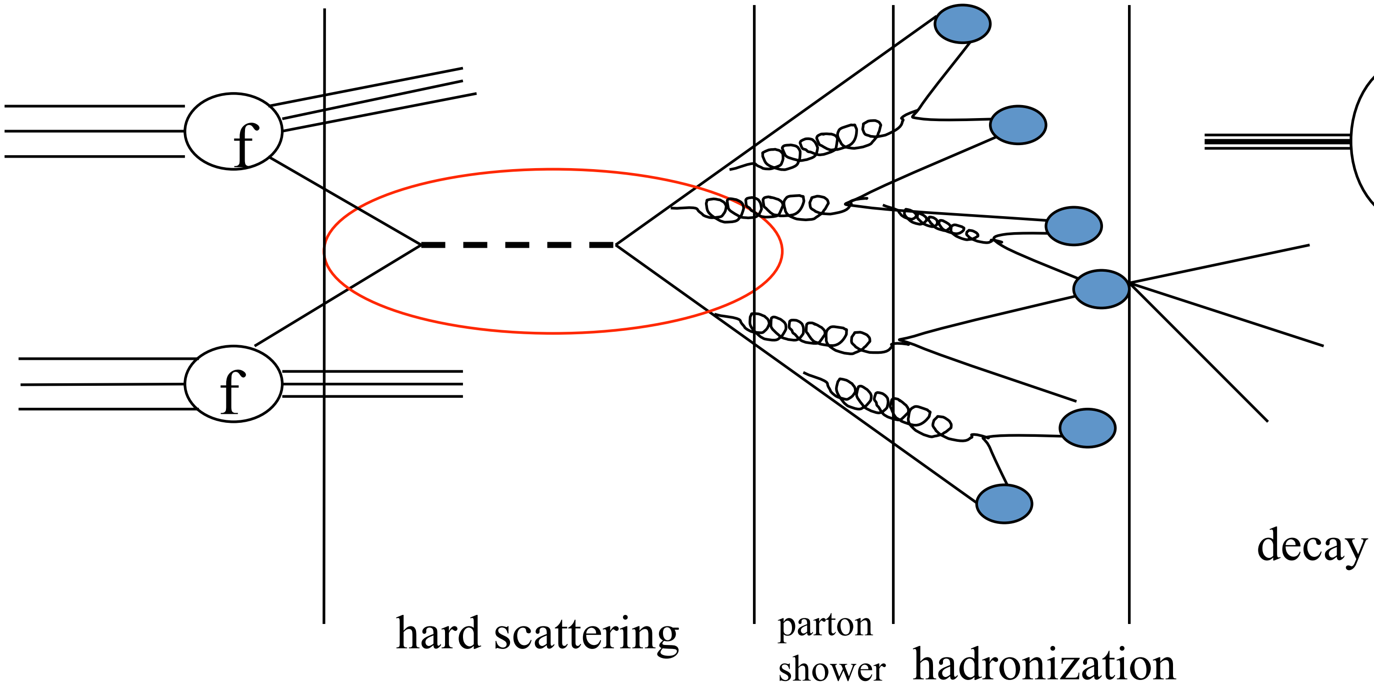
- Good for studying:
  - Jet Production/properties
  - Event shapes
  - Underlying event
  - Multiple-Parton Scattering
- Less good for
  - Hadron (proton) structure
- No use for:
  - Photon structure
- Characterise behaviour by:
  - $\sqrt{\hat{s}}$ ($\sqrt{s}$ of process products)
  - p_T of jets



Hadronization



more complicated case: hadronic final state



Parton shower and hadronization models:

- Independent fragmentation (Feynman-Field)
- String Model (Sjostrand)
- Cluster model (Webber)

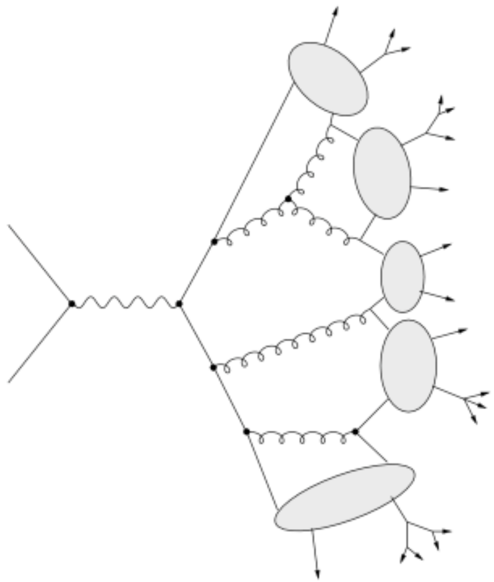
Hadronization models

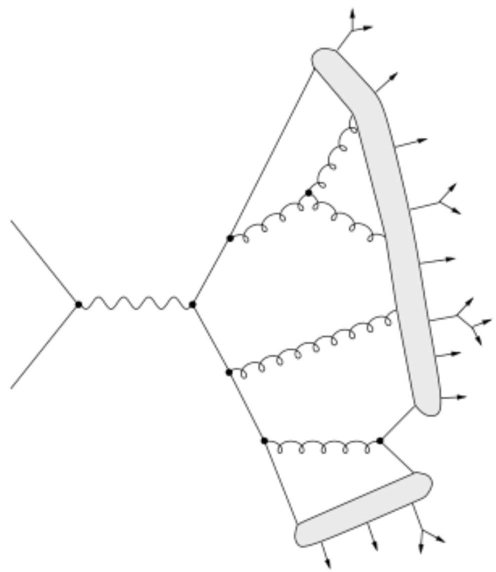
Hadronization is a long-distance process, small momentum transfer
– hadron-level energy/momentum/flavour follows parton-level

String
partons moving apart lose energy to the colour field; qq pair produce
Gluons: 'kinks on the string' – better 3-jet angular agreement than independent fragmentation

Cluster
colour-singlet clusters of partons form and decay into observed hadrons

Independent fragmentation
fragmenting quark combines with q from qq pair out of vacuum; etc until falls below threshold.
Problems with momentum scales, colour and flavour neutralisation, jets that are close in angle





Jets

Jets are ubiquitous in hard QCD processes in all environments

Qualitatively we understand what jets are: sprays of hadrons from quarks produced in hard process

A naive assumption – local hardon-parton duality (LHPD) – is that a jet corresponds to partons from the hard process

But which partons, at what stage? We can't stop QCD from producing higher order processes in real life

Quantitative comparison of data (all orders of QCD) to theory (fixed order) demands a quantitative jet definition

Jets

How to define jets?

Need a set of rules on how to group particles into jets

Need to define how kinematics of particles are combined to give that of the jet

Need to be able to apply algorithm for building the jet to:

- experimental data (energy deposits/tracks/combined objects)
- output particles from MC generators
- output partons from fixed order QCD calculations

Important properties for the definition to fulfil are thus:

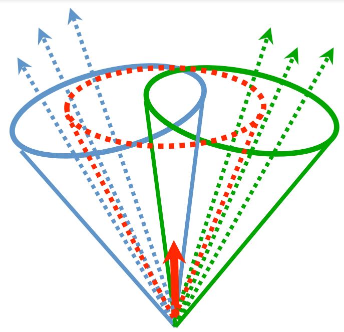
- simple to implement in an experimental analysis
- simple to implement in theoretical calculations
- defined at any order of pQCD
- give finite cross-sections at any order of pQCD
- yield a cross section that is relatively insensitive to hadronisation

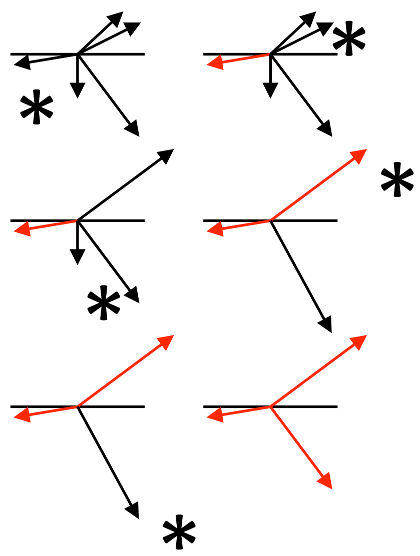
Jet algorithms

Two main classes of jet algorithms:

- Cone algorithms
  Geometric definition: collect energy flow in a cone around initiating parton
- Sequential Recombination algorithms
  iteratively combine closest pair of particles under some distance measure

–must also define the Recombination Scheme:
- four-vector addition (massive)
- Snowmass convention (massless, sum E_T, direction from E_T weighted mean)

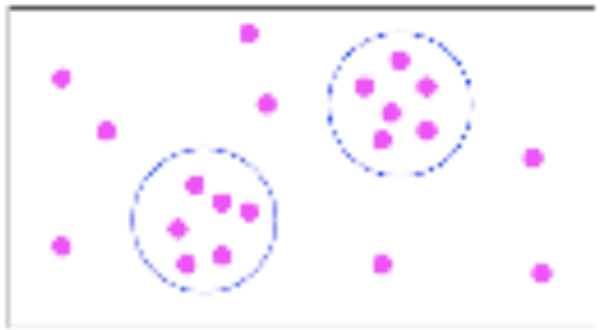




A jet has no existence independent of the jet algorithm!

Cone algorithms

Find directions of dominant energy flow = find ALL stable cones



for a cone of fixed radius *R* in the (eta,phi) plane: stable cones such that centre of cone – direction of the total momentum of its particle contents

seeded/iterative approaches
- – seed = initial particle
- – seed = midpoint between stable cones found at first step

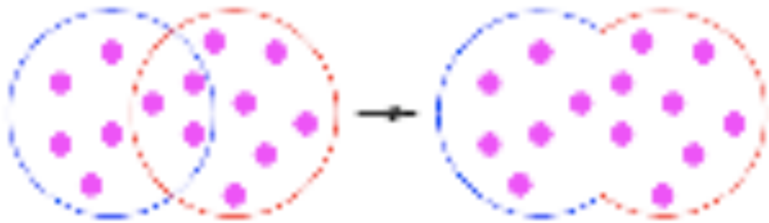
Need to deal with overlapping stable cones – 2 subclasses:

Cone algorithms

(1) cones with split/merge

p_T(shared) > f p_T (min)

p_T(shared) <= f p_T (min)



eg jetclu / midpoint

(2) cone with progressive removal

iterate from the hardest seed

remove the stable cone as a jet and start again

eg Seeded Cone

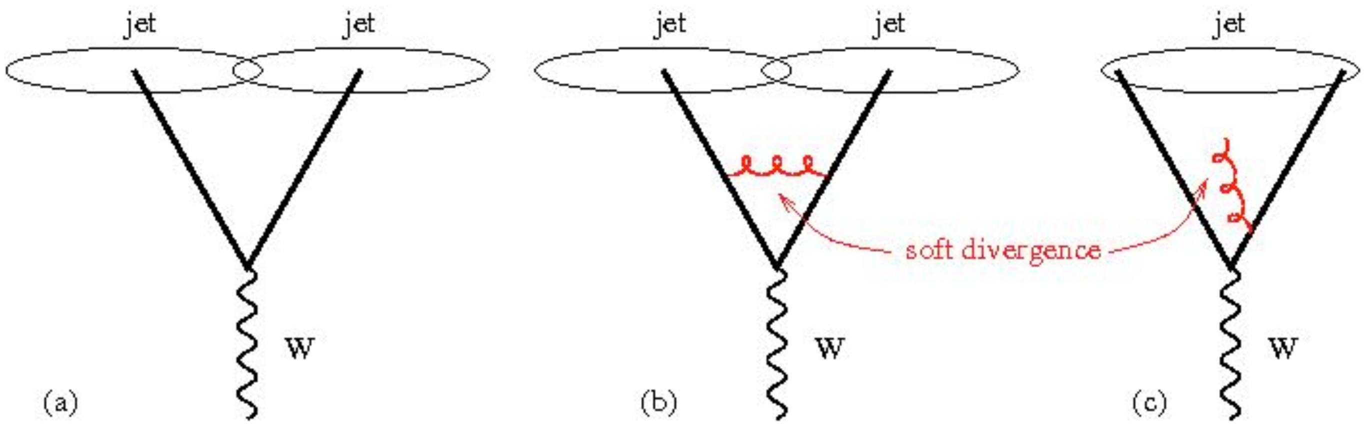
idea: ‘regular / circular’

Cone algorithms

Two things that can be disastrous for jets:

- not being Infra-red safe: Infra-red safety: jet configuration is not changed by extra emission of a very low p_T particle
- not being collinear safe: Collinear safety: jet configuration is not changed by one of the particles splitting into two particles travelling in the same direction

– because in QCD emission of FSR diverges for very low p_T and/or very small angle emissions.



IR unsafety – for an iterative cone algorithm the number of jets from W decay is changed by a soft gluon emission. Only one safe cone algorithm for practical use: Seedless Infra-red Safe Cone algorithm (SISCone)

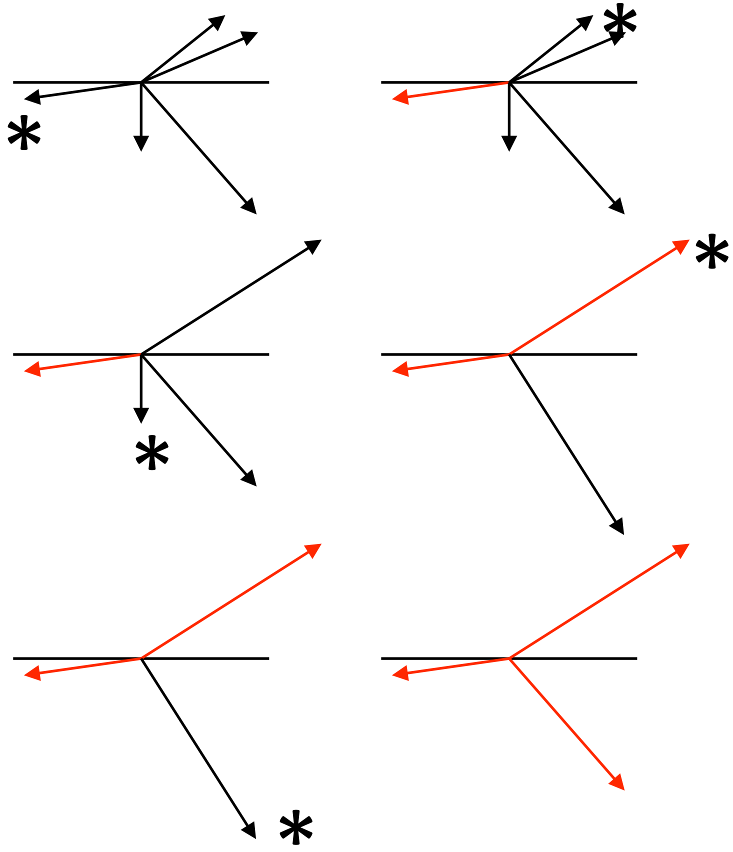
Recombination algorithms

Successive recombinations of the "closest" pairs of particles:

Distance parameter $d_{ij} = \min(k_T{}^{2p}{}_i\,,\, k_T{}^{2p}{}_j)(\Delta\varphi^2{}_{i,j} + \Delta y^2{}_{i,j})$

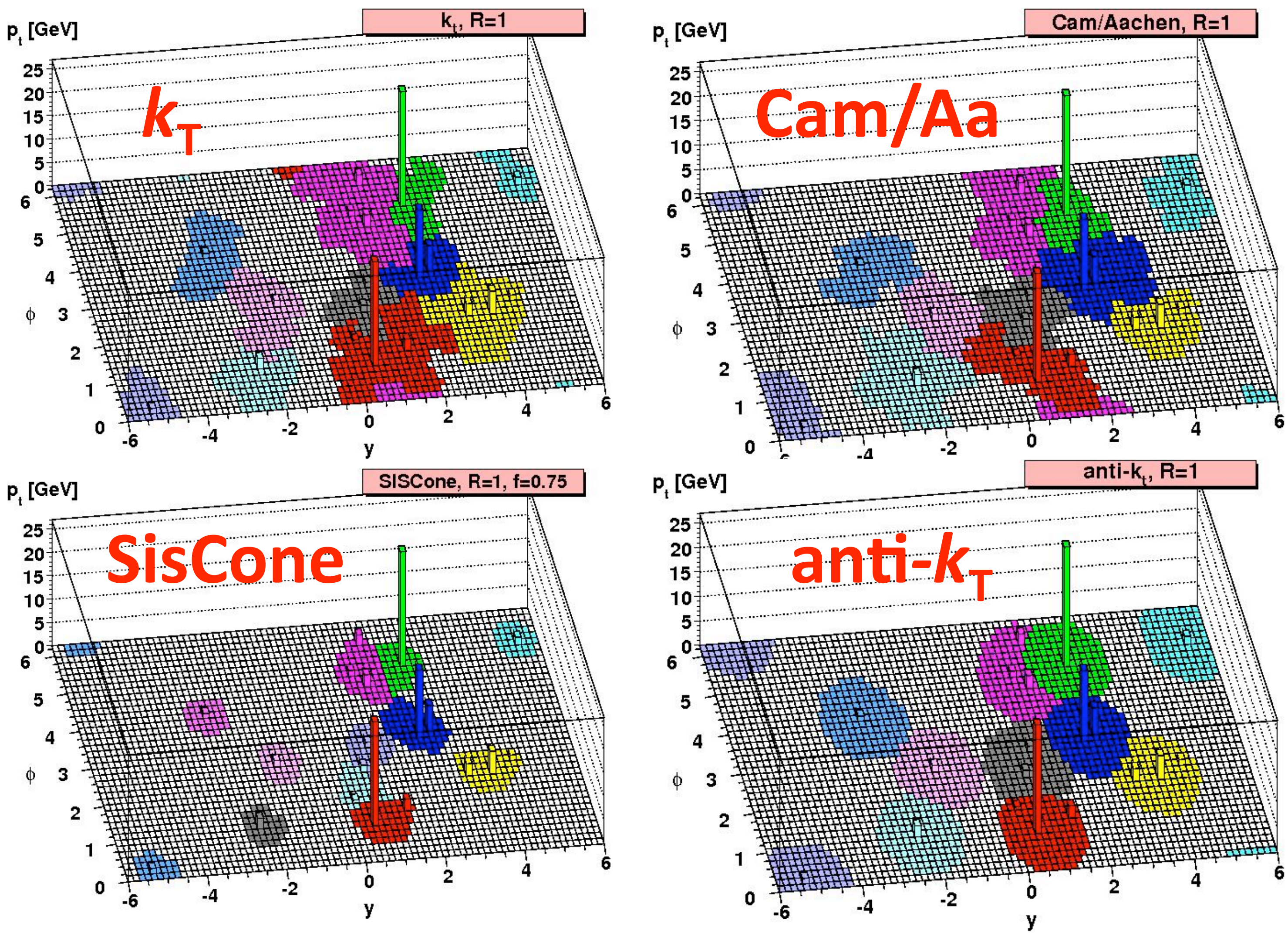
p = 1 : k_T algorithm
p = 0 : Aachen/Cambridge algorithm
p = −1 : Anti-k_T algorithm

Stop when $d$min > R (for some chosen R)



All of these algorithms are infra-red and collinear safe.

Recombination algorithms



All of these algorithms are infra-red and collinear safe.

Gavin Salam

ATLAS approach

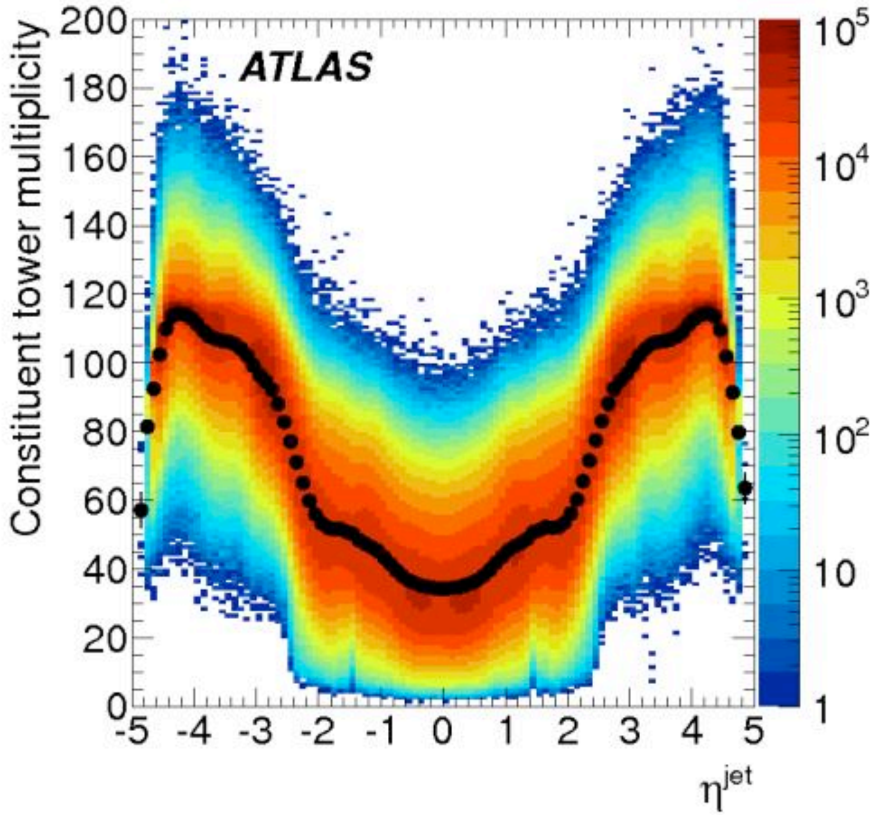
ATLAS:

- anti-k_T
- R-parameter 0.4 or 0.6
- Input to jets topological clusters ('topo-clusters') or alternatively calorimeter towers

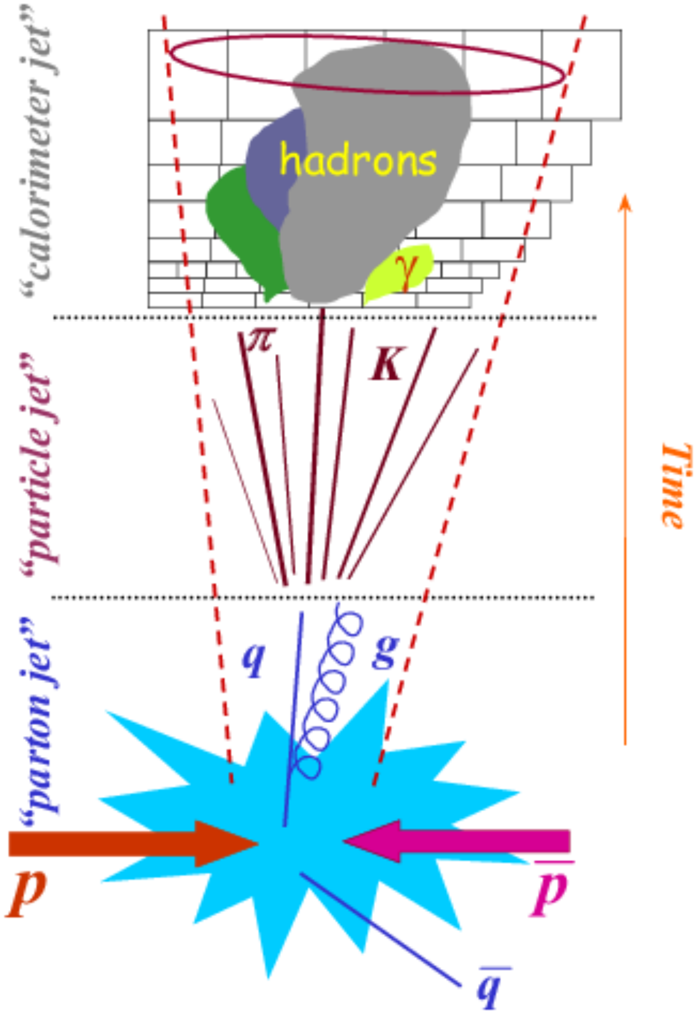
Topoclusters – follow shower development; use fine calorimeter segmentation.

Algorithm:

start from seed cell, signal-to-noise (S/N) > 4
[where noise estimated from events triggered at random bunch crossings]
iteratively include neighbouring cells having S/N>2
use local maxima (500MeV) as seeds for new iteration



Jet energy scale

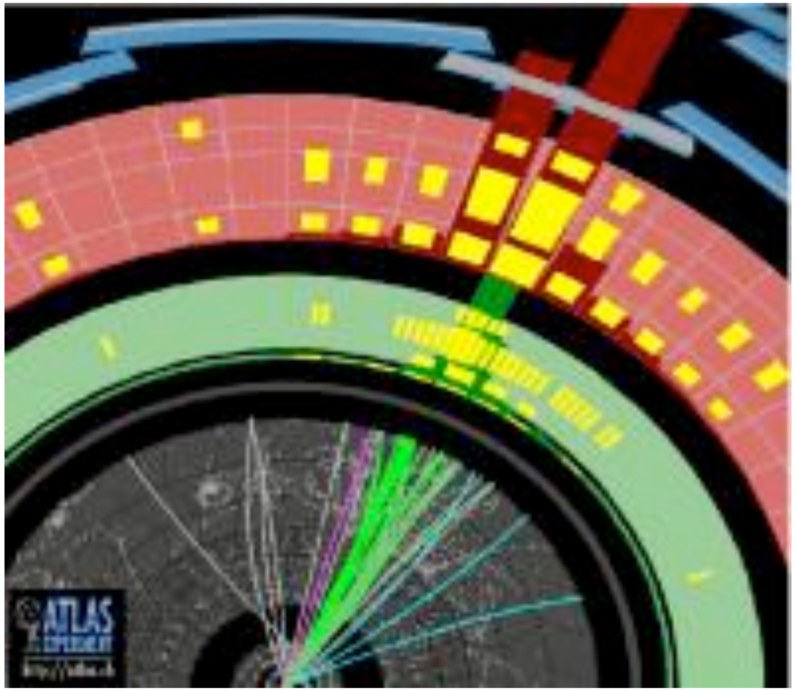


We need to go from what we measure in the calorimeter back to the parton level

Need good simulation – try to look at it in as many ways as possible – single track response, multiplicities; material from conversion mapping and EM response….

Correcting for both calorimeter effects and physics effects

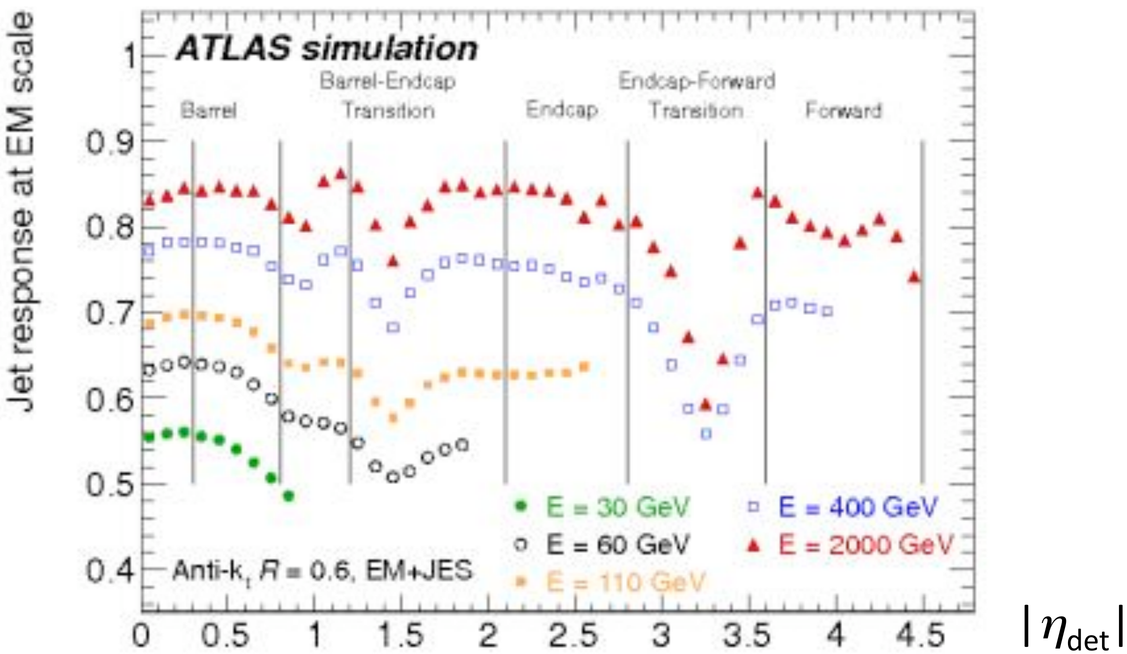
Jet energy calibration



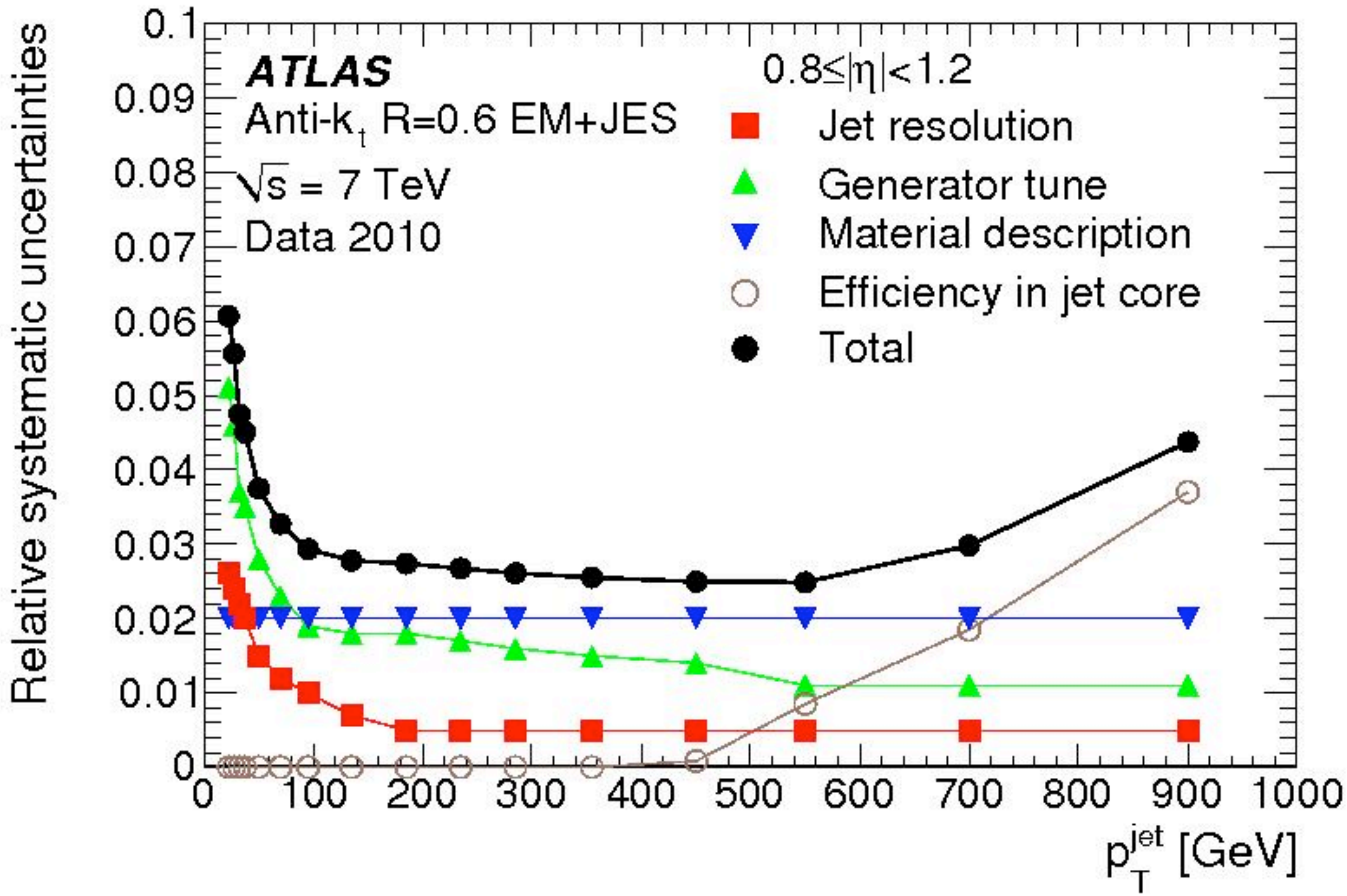
1. Calorimeter non-compensation: partial measurement of the energy deposited by hadrons.
2. Dead material: energy losses in inactive regions of the detector.
3. Leakage: energy of particles reaching outside the calorimeters.
4. Out of calorimeter jet cone: energy deposits of particles inside the truth jet entering the detector that are not included in the reconstructed jet.
5. Noise thresholds and particle reconstruction efficiency: signal losses in the calorimeter clustering and jet reconstruction.

Jet energy calibration

1. ***Pile-up correction***: The average additional energy due to additional proton-proton interactions is subtracted from the energy measured in the calorimeters using correction constants obtained from in-situ measurements.
2. ***Vertex correction***: The direction of the jet is corrected such that the jet originates from the primary vertex of the interaction instead of the geometrical centre of the detector.
3. ***Jet energy and direction correction***: The jet energy and direction as reconstructed in the calorimeters are corrected using constants derived from the comparison of the kinematic observables of reconstructed jets and those from truth jets in Monte Carlo simulation.



Jet energy scale



Uncertainties / Validation

Uncertainties

Calorimeter response (extrapolation from single-particle)

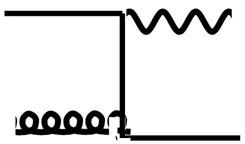
Calorimeter cell noise thresholds

Additional detector material

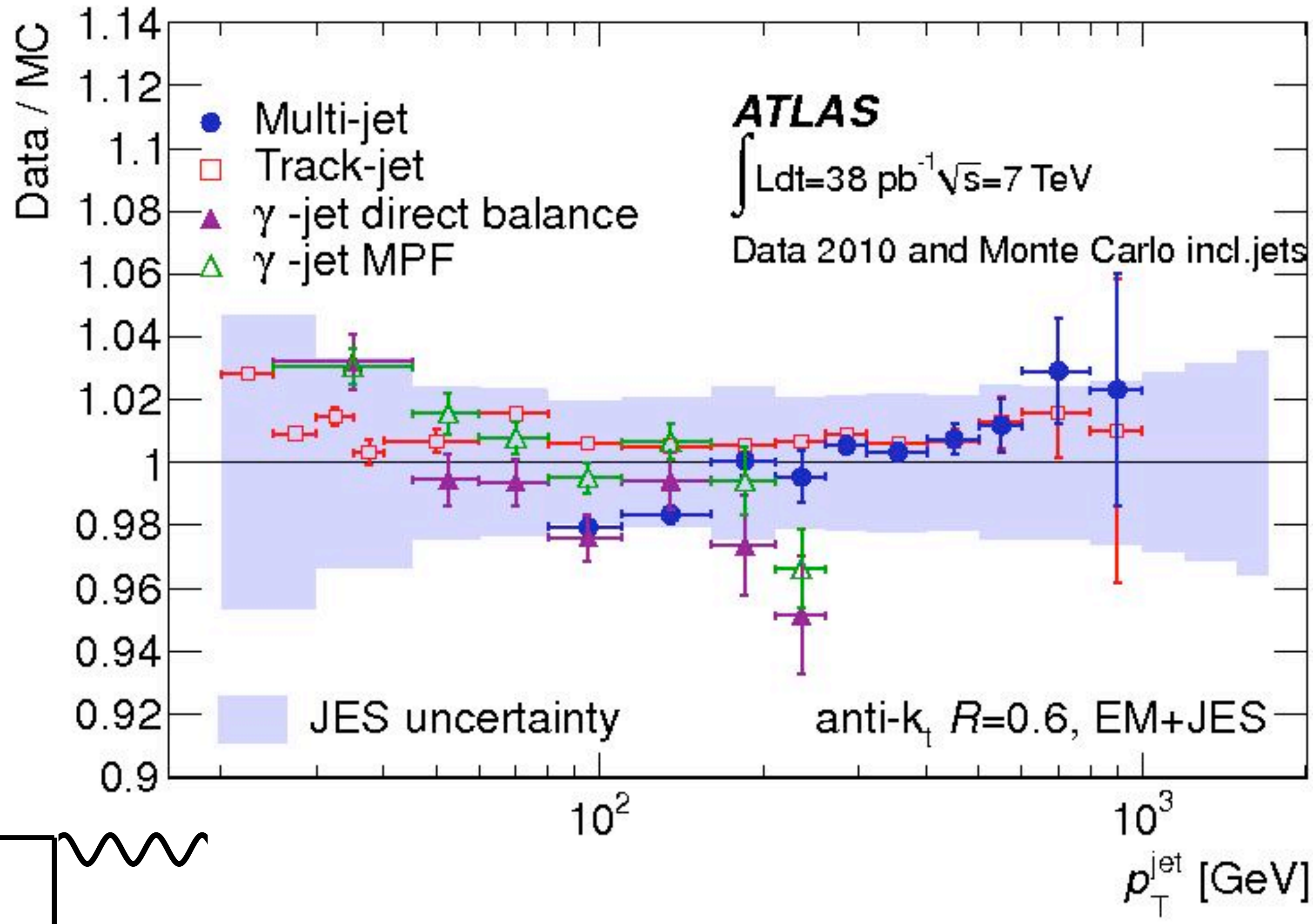
Generator event modeling

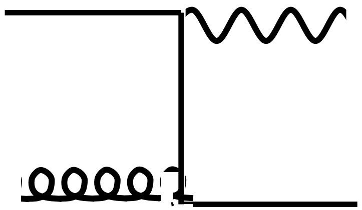
Validation

1. Comparison to the momentum carried by tracks associated with a jet
2. Direct pT balance between a photon and a jet
3. Photon p_T balance to hadronic recoil
4. Balance between a high-p_T jet and low-p_T jet system



In-situ techniques





Refinements

Global event variables

Next step: use other variables correlated with jet energy response

Remove remaining dependence without changing average energy

-> reduce spread, ie improve resolution

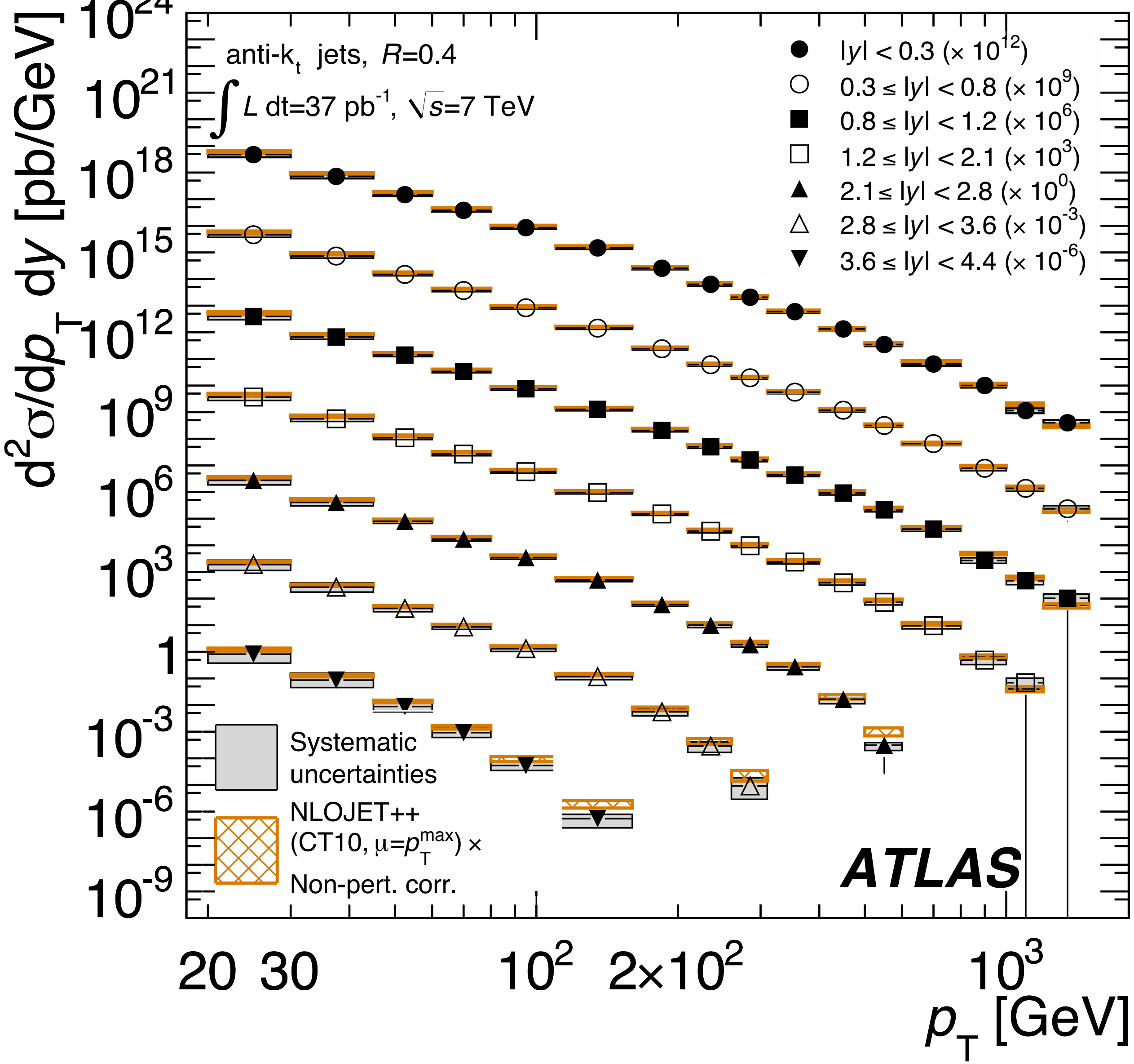
$|\eta|$ region	Corr 1	Corr 2	Corr 3	Corr 4
$|\eta| < 1.2$	$f_{\mathtt{Tile0}}$	$f_{\mathtt{LAr3}}$	f_{PS}	width
$1.2 \leq |\eta| < 1.4$	$f_{\mathtt{Tile0}}$			width
$1.4 \leq |\eta| < 1.7$	$f_{\mathtt{Tile0}}$	$f_{\mathtt{HEC0}}$		width
$1.7 \leq |\eta| < 3.0$		$f_{\mathtt{HEC0}}$		width
$3.0 \leq |\eta| < 3.2$		$f_{\mathtt{LAr3}}$		width
$3.2 \leq |\eta| < 3.4$		$f_{\mathtt{LAr3}}$		
$3.4 \leq |\eta| < 3.5$		$f_{\mathtt{LAr3}}$		width
$3.5 \leq |\eta| < 3.8$	$f_{\mathtt{PCal1}}$			width
$3.8 \leq |\eta| < 4.5$	$f_{\mathtt{PCal1}}$			

Table 13: Sequence of corrections in the GS calibration scheme in each $|\eta|$ region.

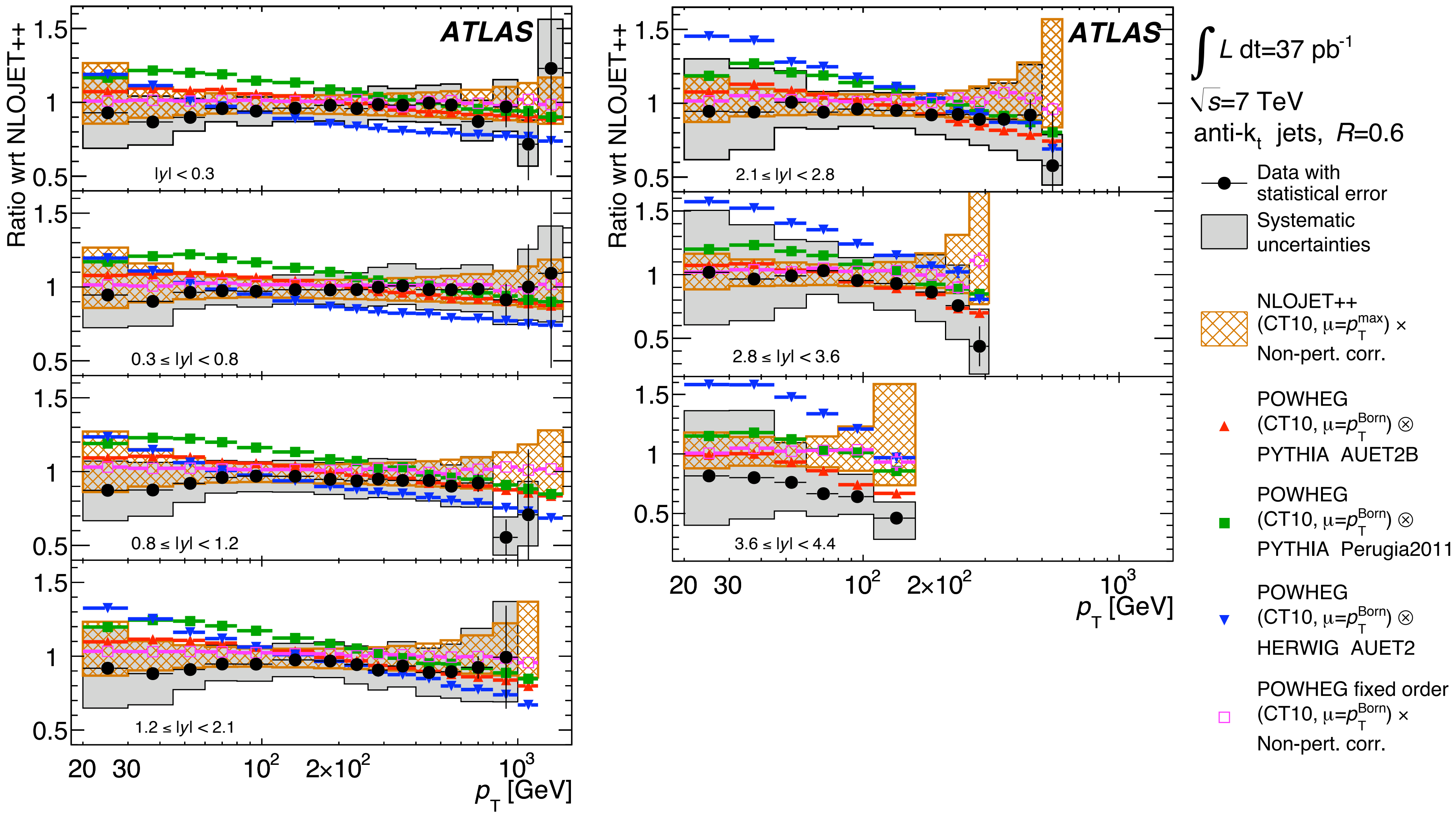
Cell energy weighting

Weight differently the cell deposits from EM / Had showers

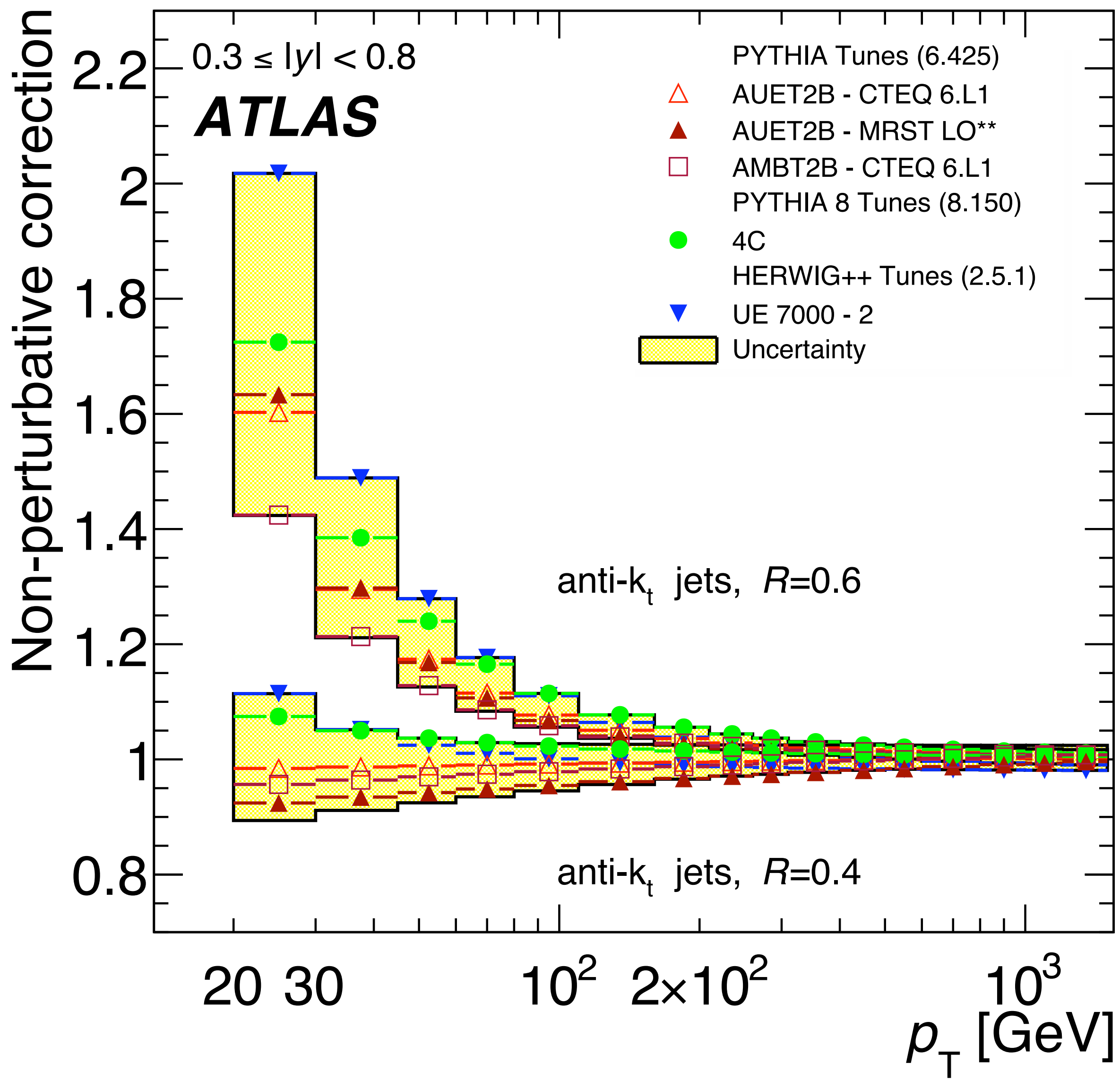
Inclusive jets



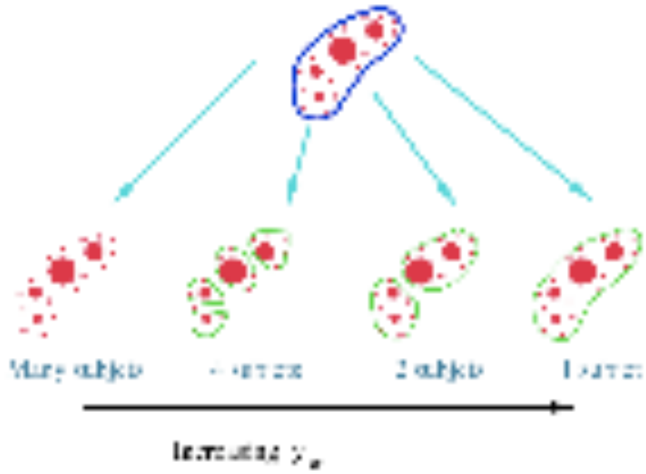
Inclusive jets



Inclusive jets



Jet substructure



Jet substructure is now a very fashionable research field at the LHC:

- Fertile testing ground for QCD
- Important tool for New Physics searches

Jet substructure can also be used in searches
– a popular approach is subjet/filtering

- Cluster all particles in the event with an inclusive jet definition
- Take each jet, and cluster only its constituents with another jet definition yielding a set of subjets of the original jet
- Keep the n_{subjet} subjets of a jet according to a chosen criteria and throw away the rest of the constituent of the original jet (the filter)
- Replace original jet with the merged subjets

Substructure and searches

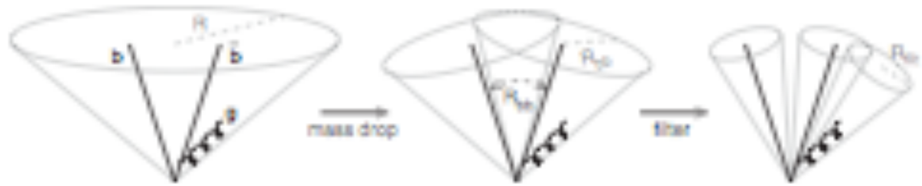
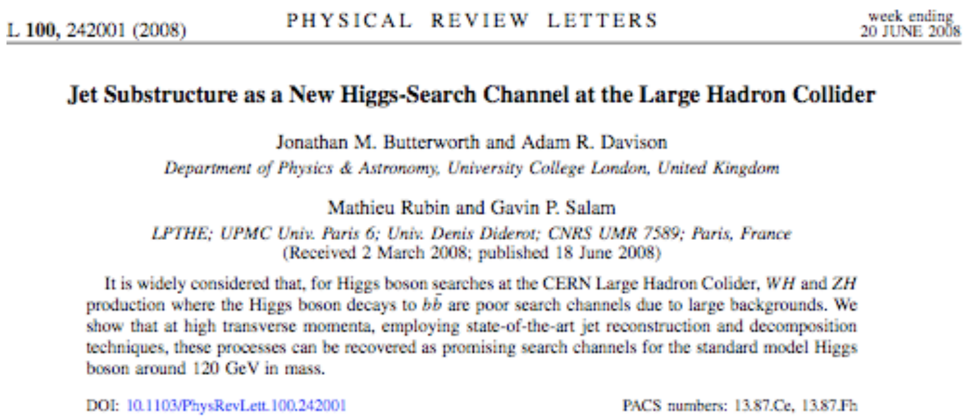


FIG. 1. The three stages of our jet analysis: starting from a hard massive jet on angular scale R, one identifies the Higgs neighborhood within it by undoing the clustering (effectively shrinking the jet radius) until the jet splits into two subjets each with a significantly lower mass; within this region, one then further reduces the radius to R_{filt} and takes the three hardest subjets, so as to filter away UE contamination while retaining hard perturbative radiation from the Higgs decay products.



L 100, 242001 (2008) PHYSICAL REVIEW LETTERS week ending 20 JUNE 2008

Jet Substructure as a New Higgs-Search Channel at the Large Hadron Collider

Jonathan M. Butterworth and Adam R. Davison
Department of Physics & Astronomy, University College London, United Kingdom

Mathieu Rubin and Gavin P. Salam
LPTHE; UPMC Univ. Paris 6; Univ. Denis Diderot; CNRS UMR 7589; Paris, France

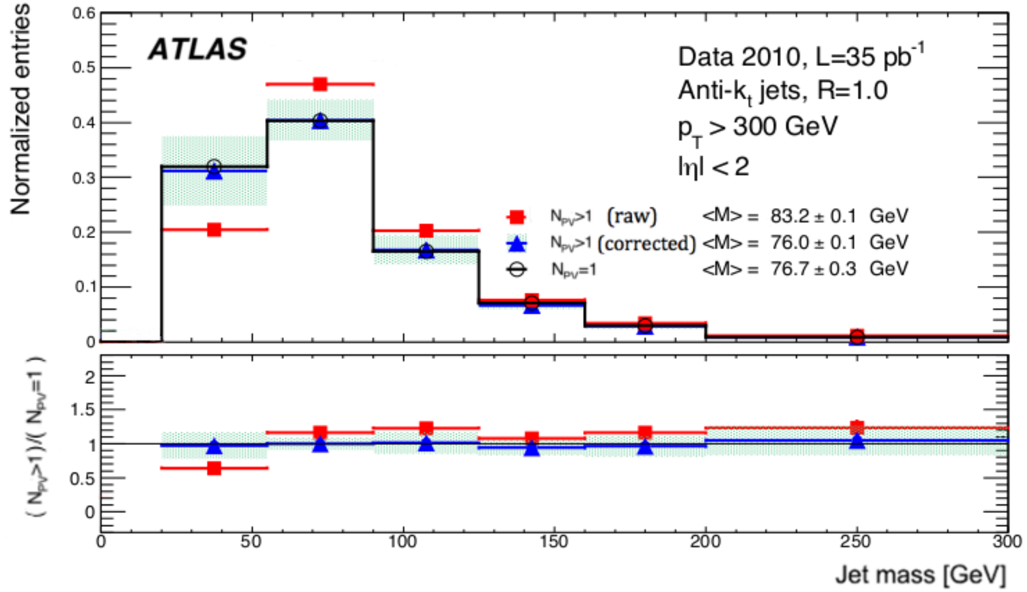
(Received 2 March 2008; published 18 June 2008)

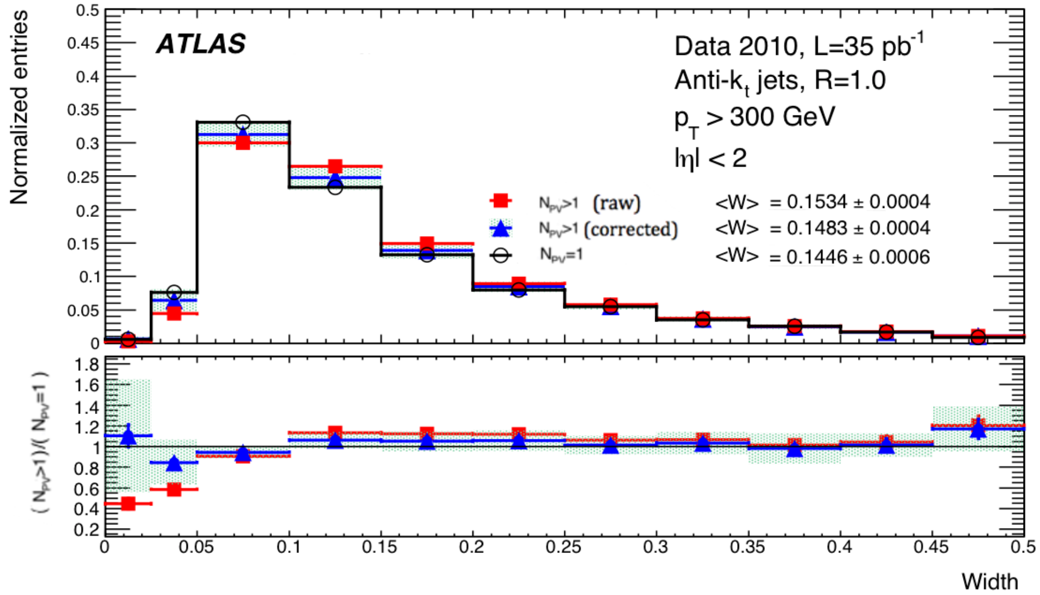
It is widely considered that, for Higgs boson searches at the CERN Large Hadron Colider, WH and ZH production where the Higgs boson decays to $b\bar{b}$ are poor search channels due to large backgrounds. We show that at high transverse momenta, employing state-of-the-art jet reconstruction and decomposition techniques, these processes can be recovered as promising search channels for the standard model Higgs boson around 120 GeV in mass.

DOI: 10.1103/PhysRevLett.100.242001 PACS numbers: 13.87.Ce, 13.87.Fh

Most celebrated example is Phys. Rev. Lett. 100, 242001
Used to search for boosted H → $b\bar{b}$ decays
Try to remove UE and identify subjets for: $b\bar{b}$, g
Significantly improves *M* resolution and background rejection

Substructure first steps



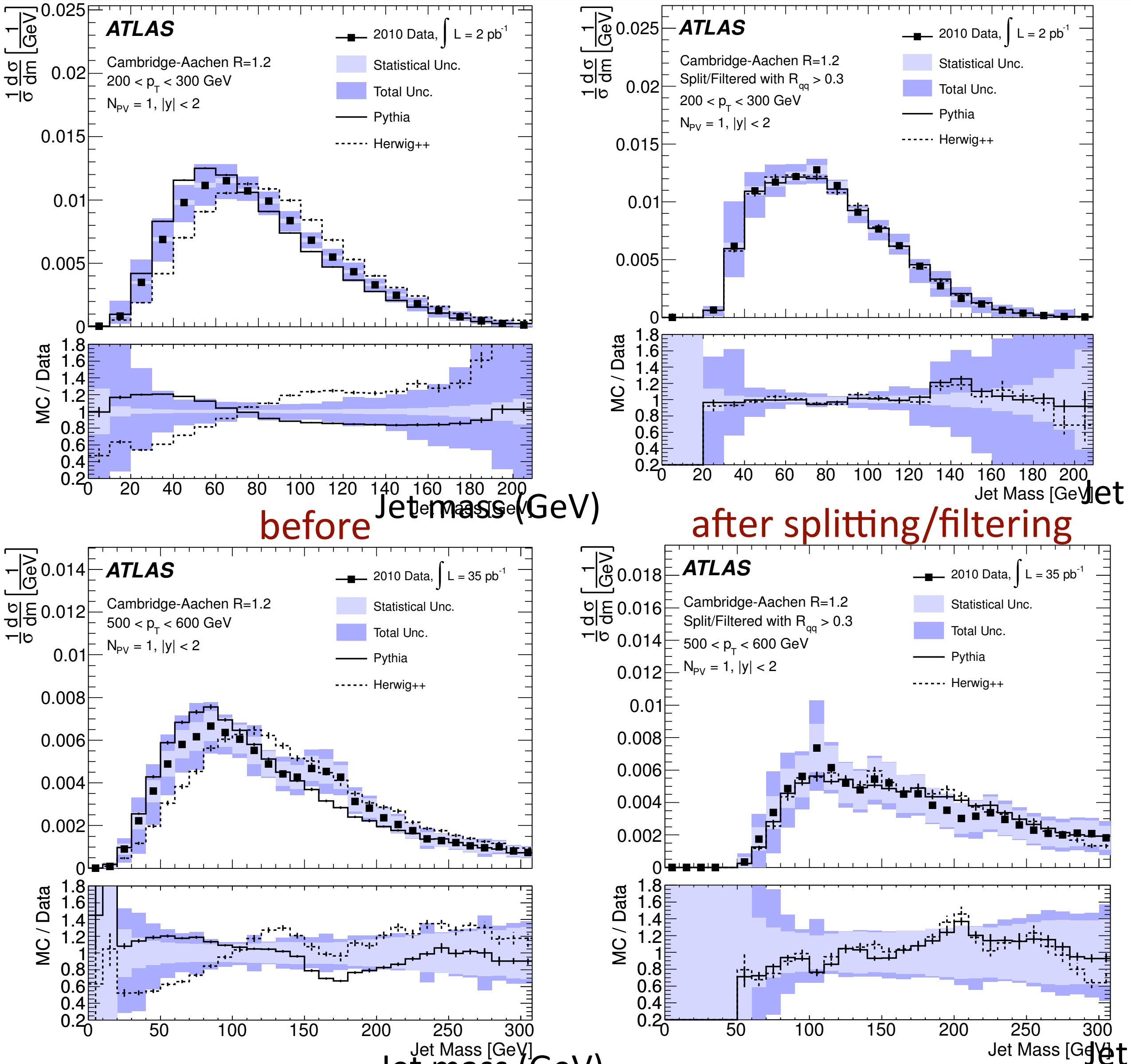


First step:
measure light-quark properties
–can they be modeled?
–vulnerable to pileup??

Substructure first results

200<p_T<300

500<p_T<600



before

after splitting/filtering

Jet mass (GeV)

Jet mass (GeV)

Jet mass (GeV)

Jet mass (GeV)

W+jets

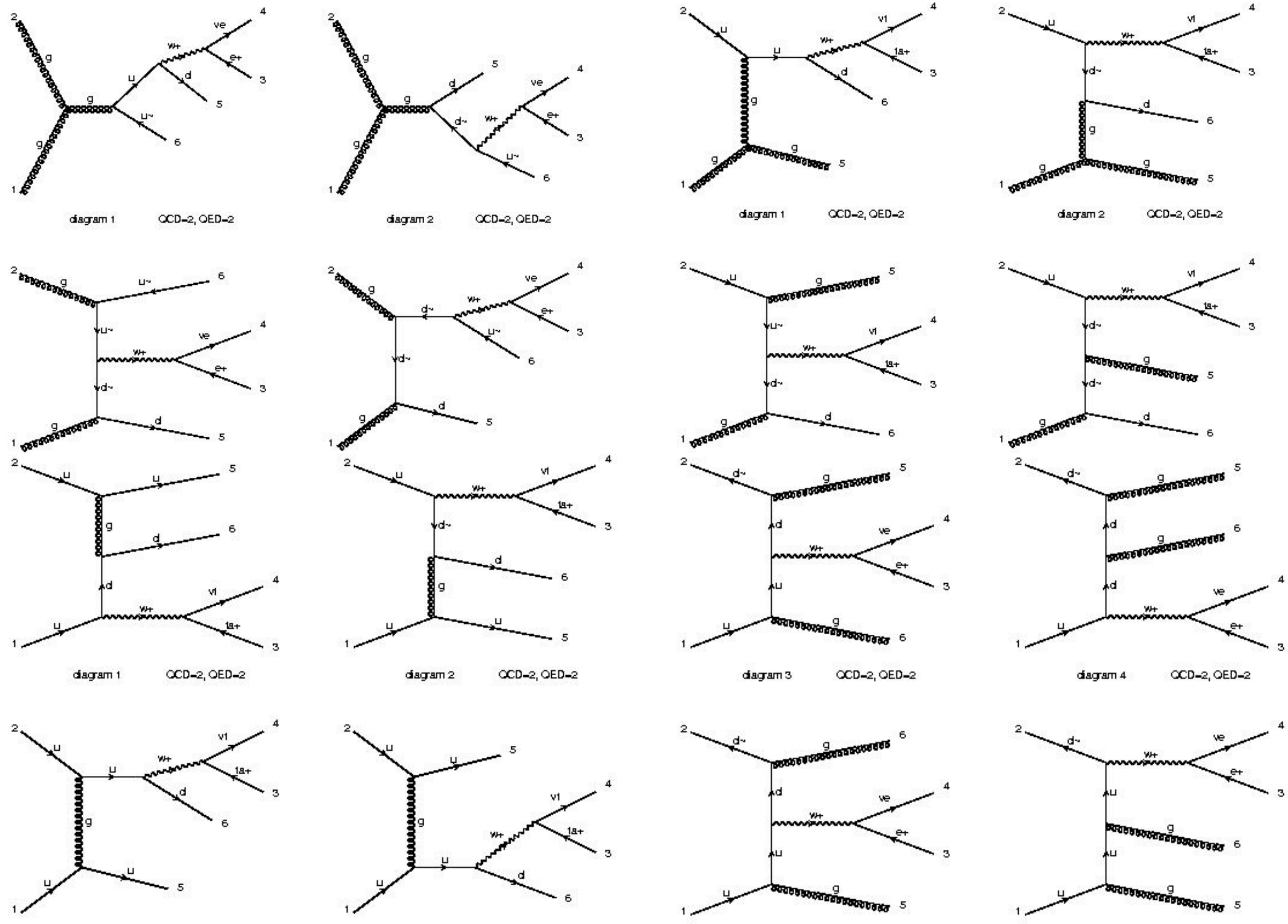
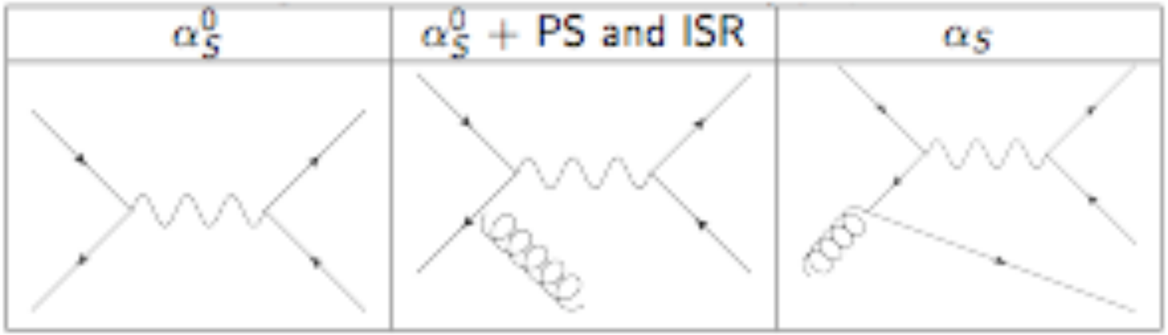


diagram 1 QCD=2, QED=2
diagram 2 QCD=2, QED=2
diagram 1 QCD=2, QED=2
diagram 2 QCD=2, QED=2
diagram 1 QCD=2, QED=2
diagram 2 QCD=2, QED=2
diagram 3 QCD=2, QED=2
diagram 4 QCD=2, QED=2

Matching

So how do we include higher-order contributions in our MC?
Consider adding next order in α_S terms Z/γ^* production:



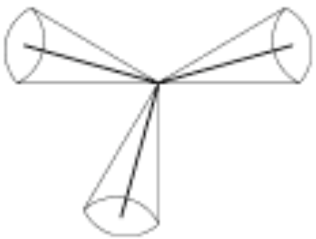
Middle diagram also in the α_S terms. we need something to ensure no double counting between ISR/FSR/showering and new ME terms
→ use matching or vetoing.

Alpgen uses MLM matching, which works as follows (for n=0,1,...*N* jets):

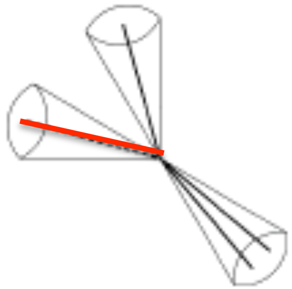
- choose a jet measure, y (with scale Q=f(y)), and a jet separation, y_0
- calculate the cross-section for all processes, σ(X)+njets, with $\alpha_S(Q_0)$
- generate event with n-jets (use $y_{cut} < y_0$)
- cluster the partons, using y
- run parton-shower (Herwig or Pythia)
- do complete jet finding using y_0
- match the original ME partons to the jets and reject if not matched
- generate more events

David Erikkson

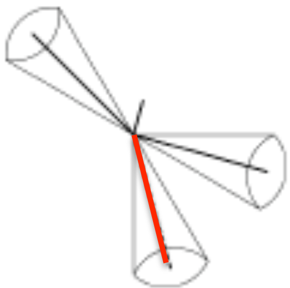
Matching



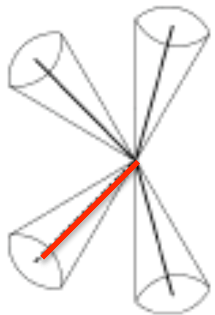
- 3 jets with ME partons
- Matched



- 2 jets with ME partons
- 1 jet from parton shower
- Not matched



- 2 jets with ME partons
- 1 jet from parton shower
- Not matched



- 3 jets with ME partons
- 1 jet from parton shower
- Not matched

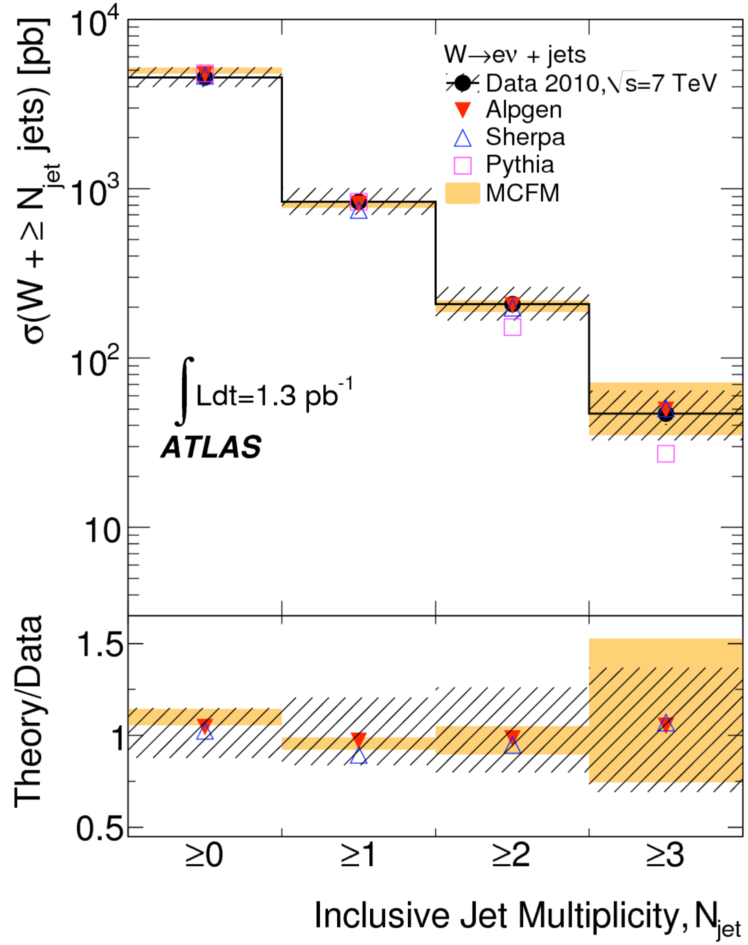
David Erikkson

Matching

This would leave us with no events with *N* + 1 jets, so we run the highest multiplicity samples in inclusive mode:

- same procedure as lower multiplicity samples
- at matching stage, keep events with extra jets so long as extra jets are softer that ME jets

Alpgen and Sherpa are much better than Pythia at describing jet multiplicity distributions in W + jet events.



- The matching procedures described so far produce results that are good to next-to-leading log (NLL)
- Proper NLO calculations must incorporate real and virtual corrections and also handle matching effects just as the multi-leg generators do.
- Two main MC codes:
  - MC@NLO
  - POWHEG (Positive Weight Hardest Emission Generator)
  - in development aMC@NLO (automated)

MC@NLO / Powheg

A simplified description of the ***MC@NLO*** method:

- Construct NLO matrix elements (MEs) for numerical integration
- Construct a counter distribution that compensates for double counting from the parton shower (PS)
- Generate events from both with PS (some will have negative weights)
- Summing the weights gives the expected number of events

(counter-terms are specific to the PS choice.)

The ***Powheg*** method in a nutshell:

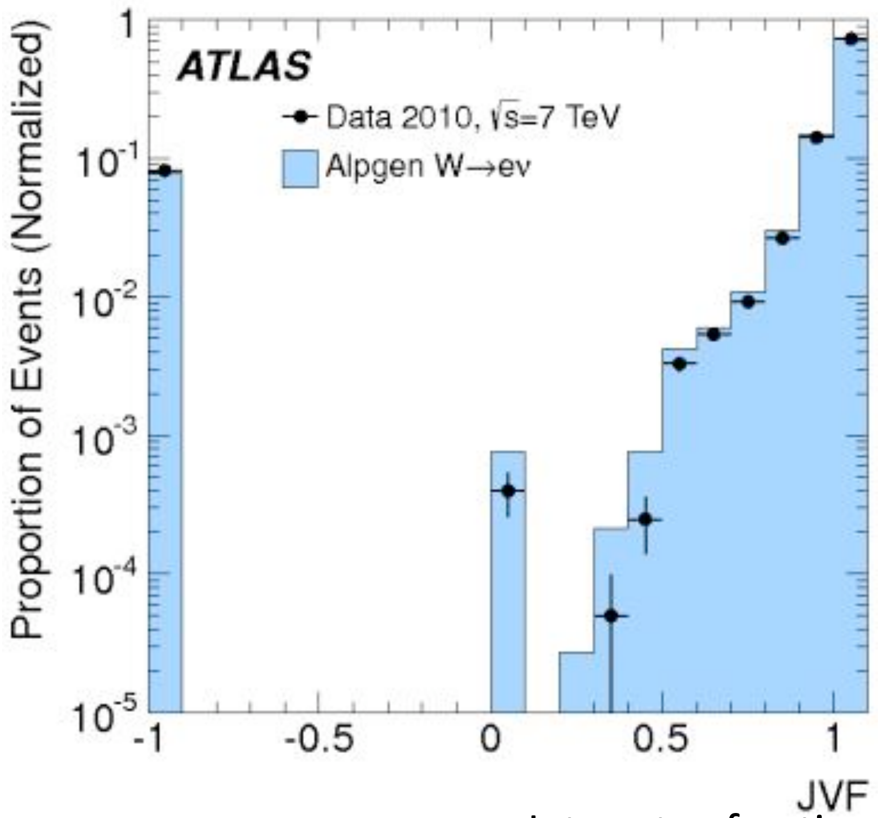
- Take NLO Matrix Elements
- Run the normal parton shower (p_T ordered) or...
- veto any emissions in the parton shower with p_T greater than those of the ME partons.

The method gives formally NLO accuracy for infra-red finite observables.

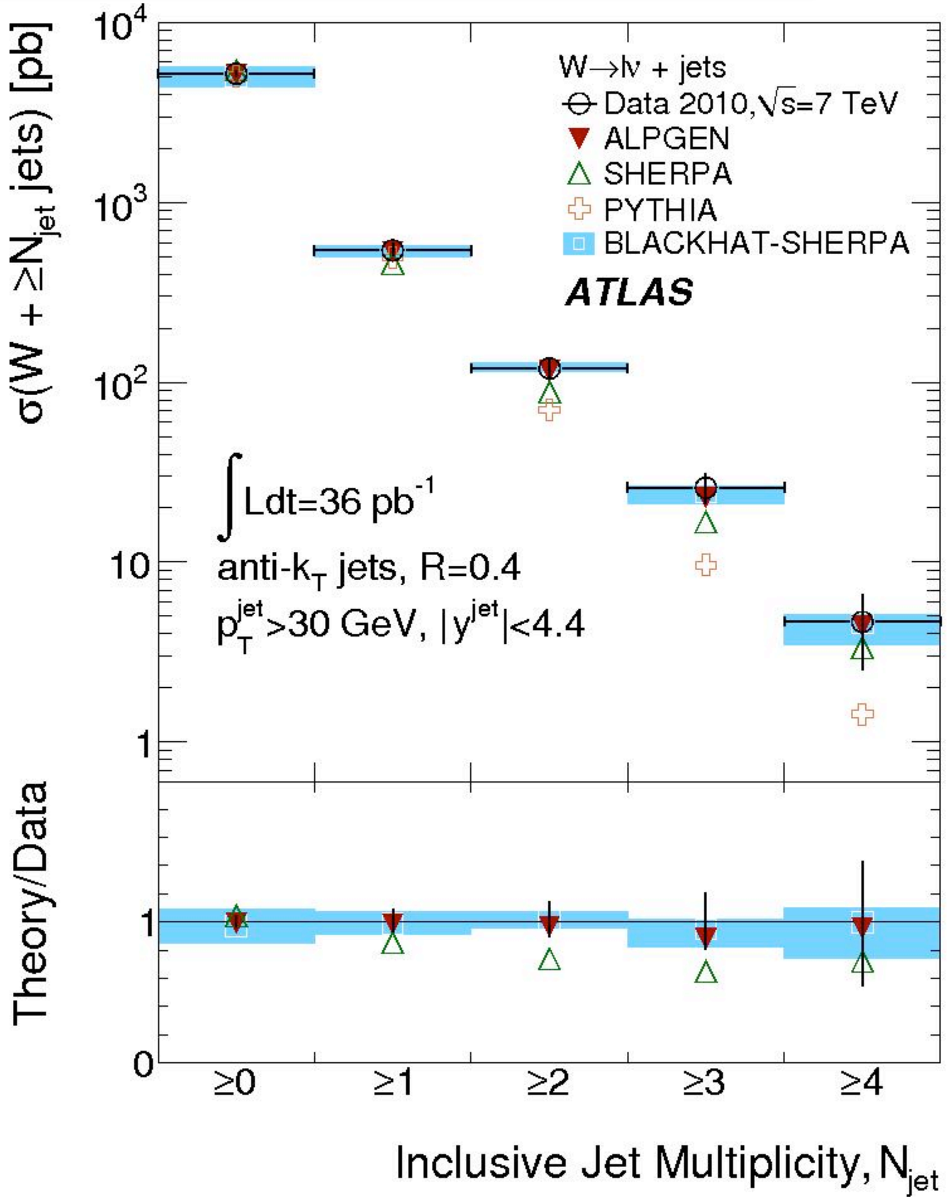
NLO MCs available processes

Process	POWHEG			MC@NLO	
	POWHEG-BOX	HERWIG++	SHERPA	MC@NLO	aMC@NLO
e+e− → jj	x	√	√	√	x
DIS	x	√	√	√	x
pp → H (GF)	√	√	√	√	x
pp → V+H	√	√	√	√	x
pp → VV	x	√	√	√	x
VBF	x	√	in prep	x	x
pp → QQ	√	x	√	√	x
pp → QQ+j	√	x	√	x	x
single top	√	x	√	√	x
pp → V+j	√	x	in prep	x	x
pp → V+jj	in prep	x	in prep	x	x
pp → H+j(GF)	x	x	in prep	x	x
pp → H+tt	√	x	x	x	√
pp → WWjj	√	x	x	x	x
pp → V+bb	√	x	in prep	x	√
diphotons	?	√	in prep	x	x
dijets	√	x	in prep	x	x

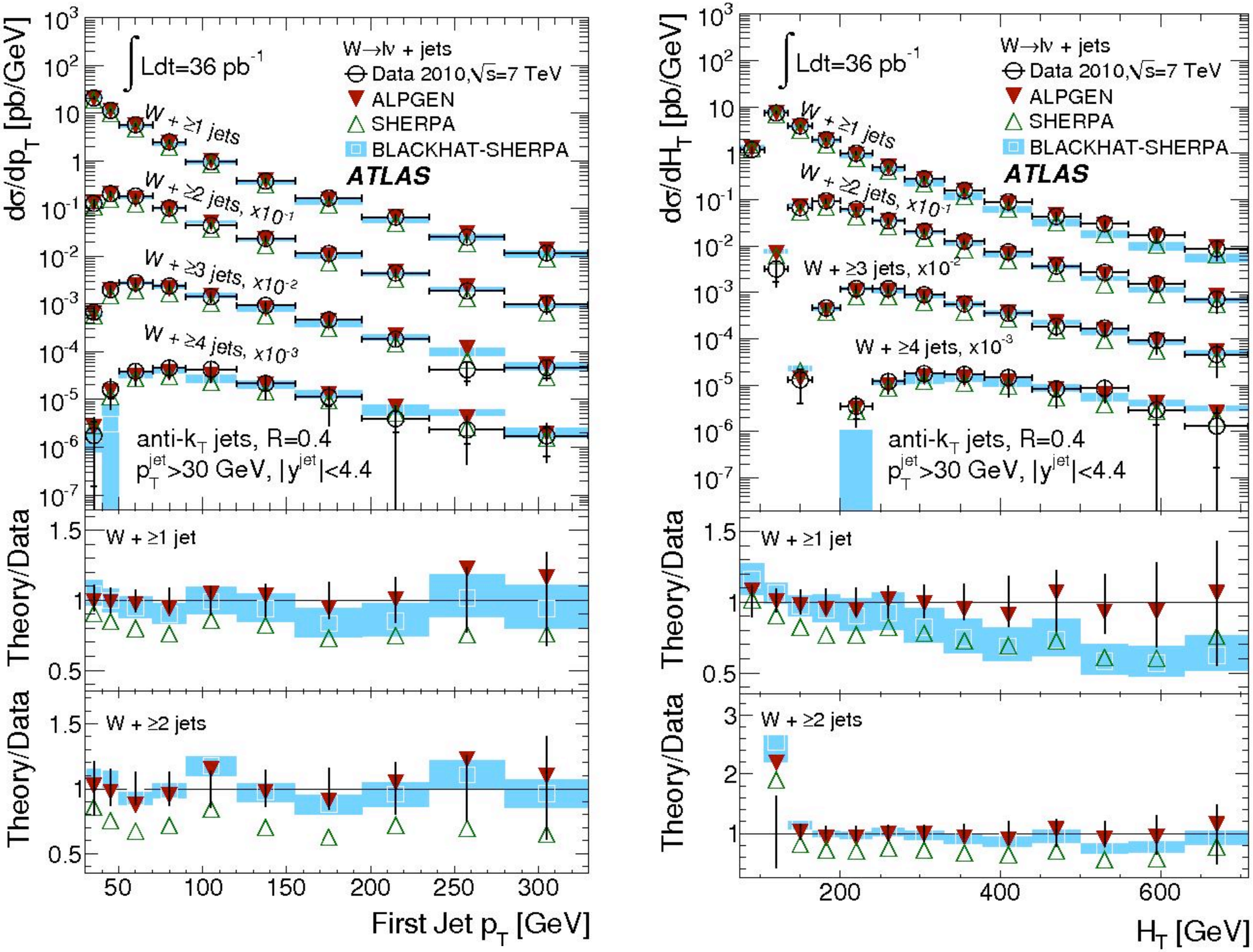
W+jets



Jet-vertex fraction

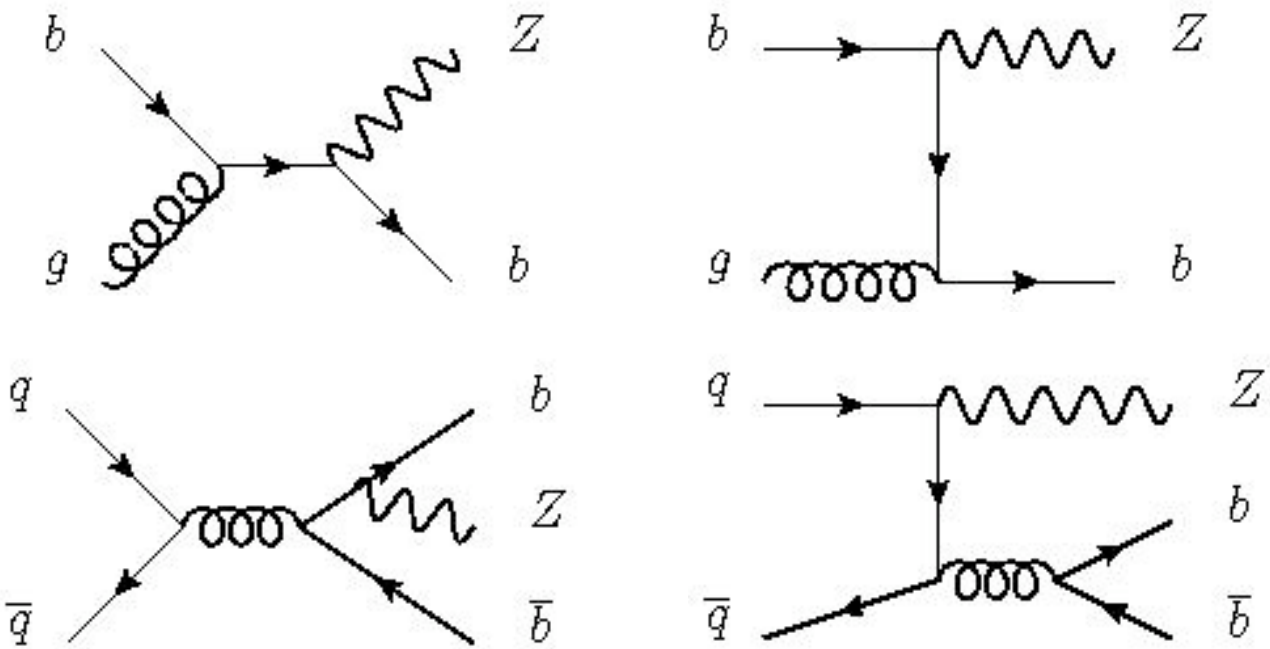


W+jets

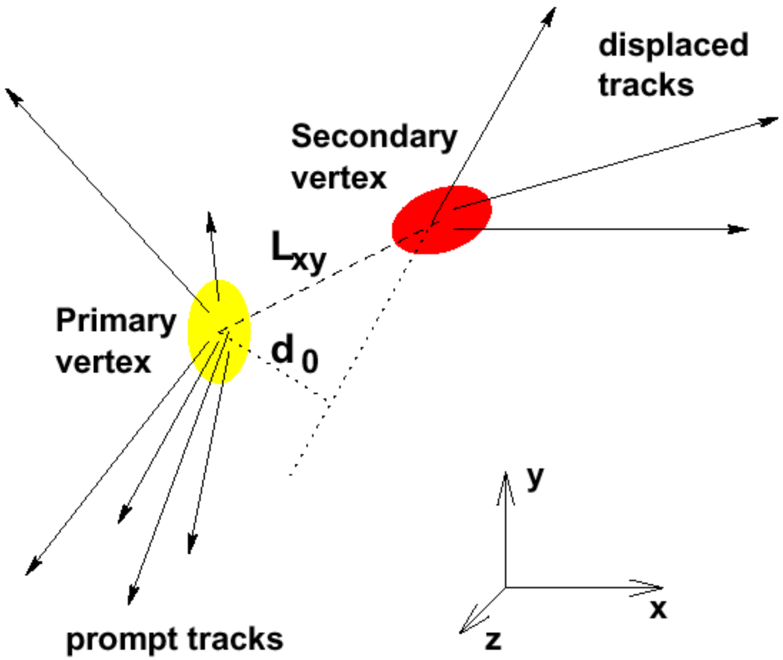


∫Ldt=36 pb⁻¹
W→lν + jets
Data 2010,√s=7 TeV
ALPGEN
SHERPA
BLACKHAT-SHERPA
ATLAS
W + ≥1 jets
W + ≥2 jets, x10⁻¹
W + ≥3 jets, x10⁻²
W + ≥4 jets, x10⁻³
anti-k_T jets, R=0.4
p_T^jet>30 GeV, |y^jet|<4.4
dσ/dp_T [pb/GeV]
dσ/dH_T [pb/GeV]
Theory/Data
W + ≥1 jet
W + ≥2 jets
First Jet p_T [GeV]
H_T [GeV]

Z+b


b
Z
g
b
b
Z
g
b
q
b
Z
$\overline{q}$
$\overline{b}$
q
Z
b
$\overline{q}$
$\overline{b}$

b-tagging



Secondary vertex-finding algorithm

Attempt to fit tracks to decay vertex

Jet probability

Compares track impact parameters to measured resolution functions

Neural network filters

n_{tracks} in secondary vertex

p_T fraction carried by those tracks

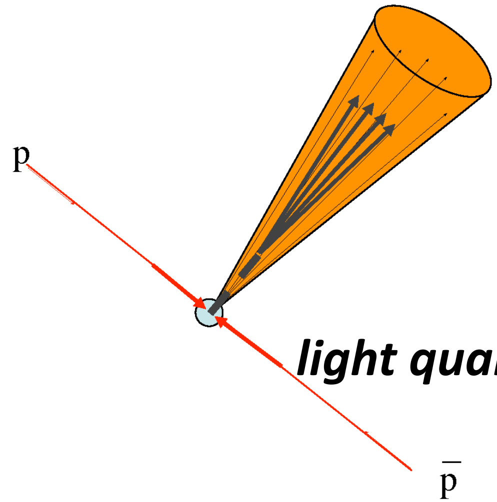
goodness of vertex fit

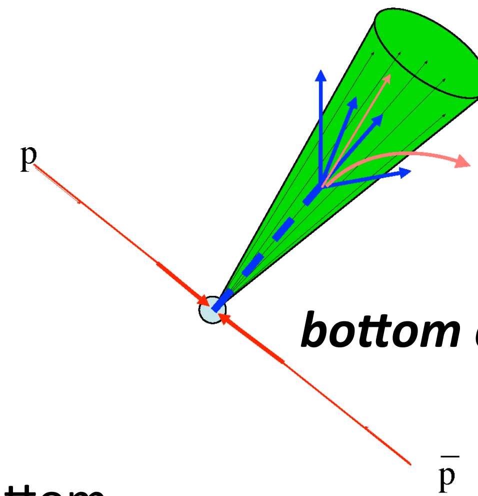
vertex mass

transverse decay length & significance

…

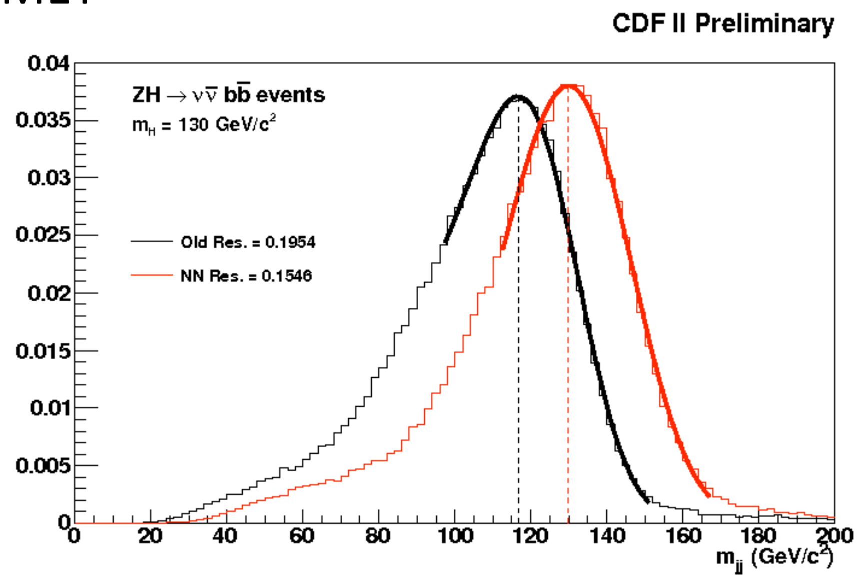
Jet resolution improvements…



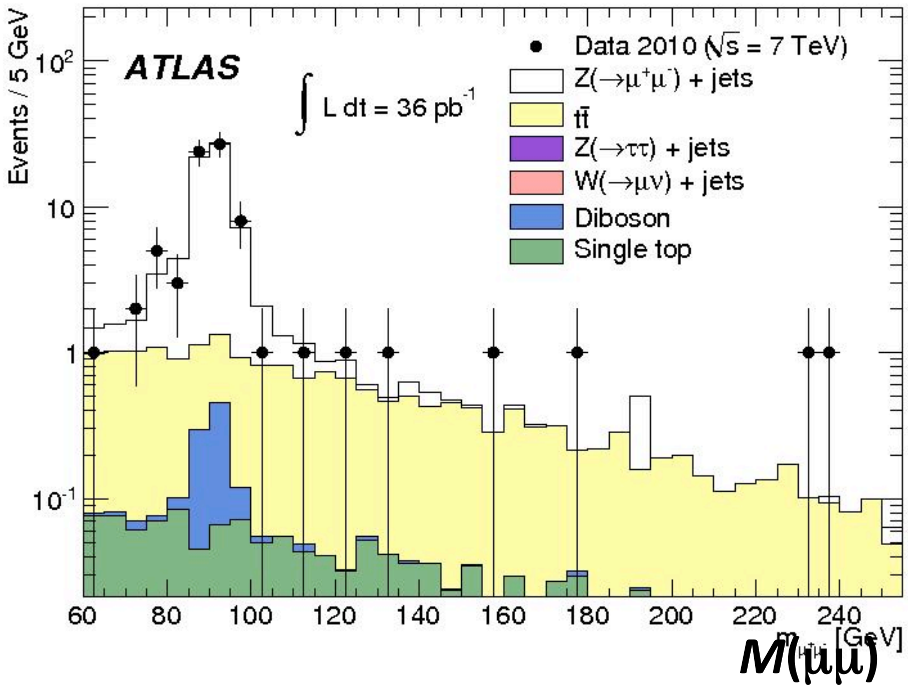


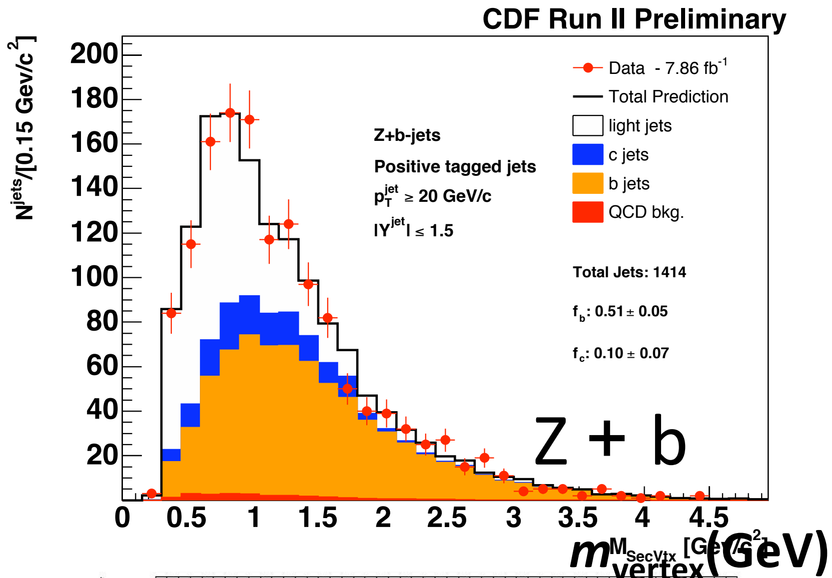
Specialized jet energy scale corrections for bottom quark jets improve dijet invariant mass and MET measurements

- Neural network correlates all jet-related variables and returns most probable jet energy based on bottom quark hypothesis – better signal/background separation

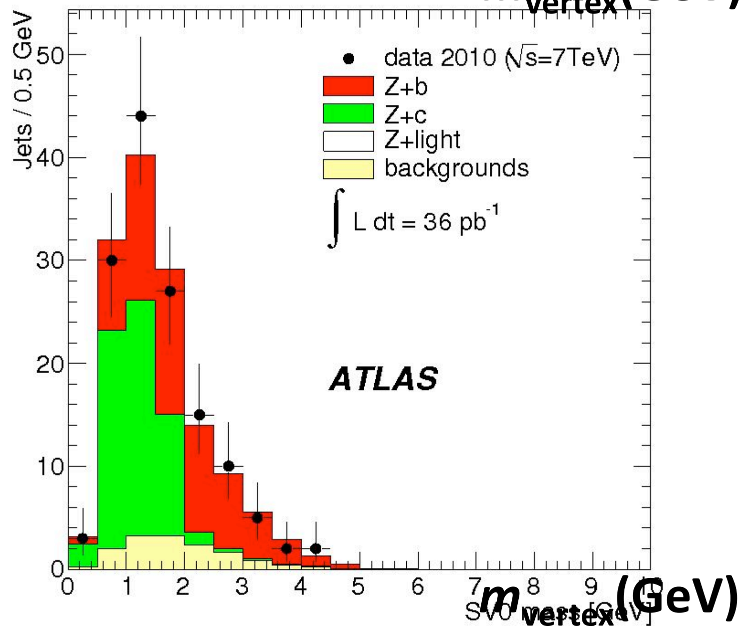


Z+b



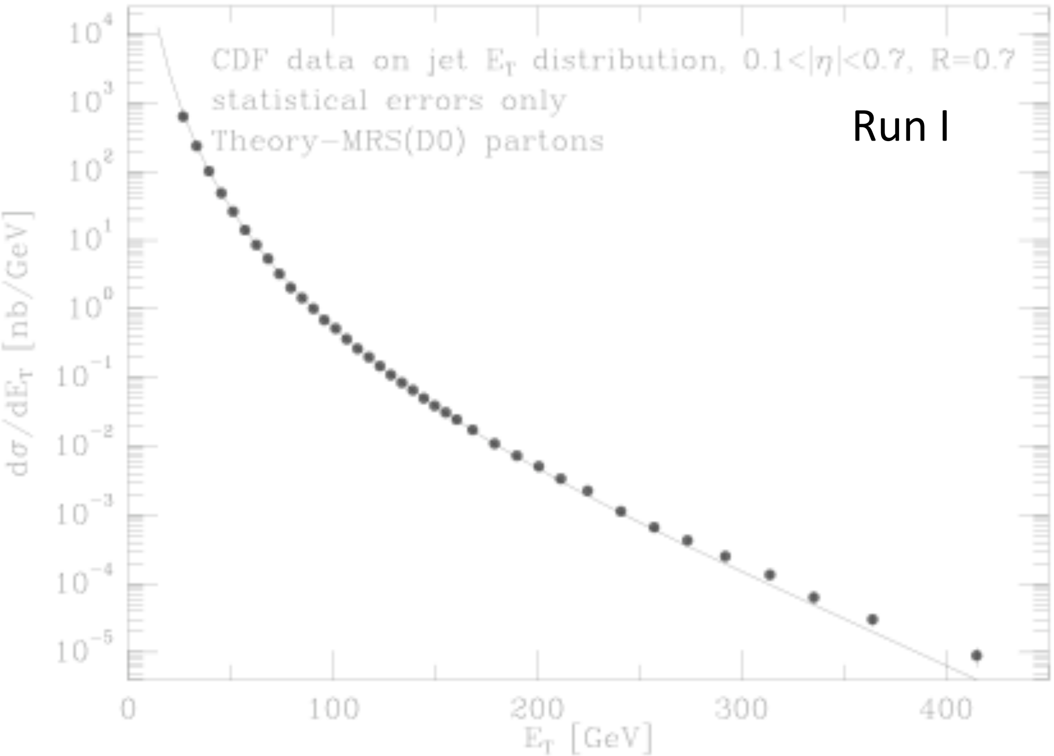


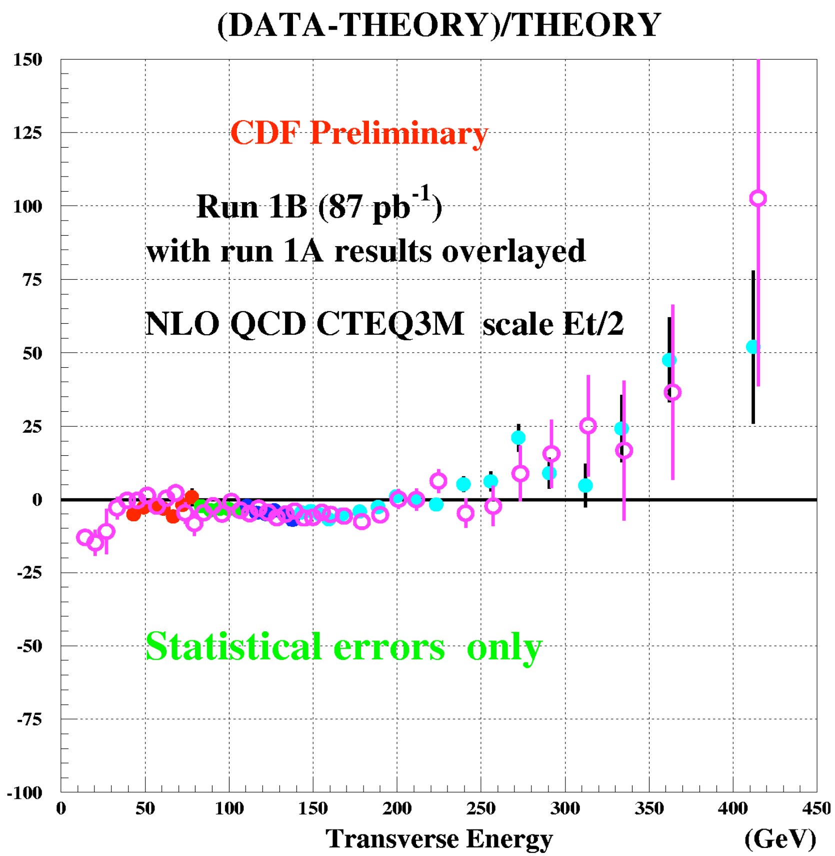
flavour decompositions



Now return to PDFs…

Inclusive jet production





Excitement over excess at high E_T?

PDF determination

DGLAP evolution tells us how the PDFs change as a function of Q^2 , but not as a function of x. Need to assume a functional form:

- Parametrise PDFs in x at some low starting scale Q^2_0 ~ 1−7 GeV^2 :

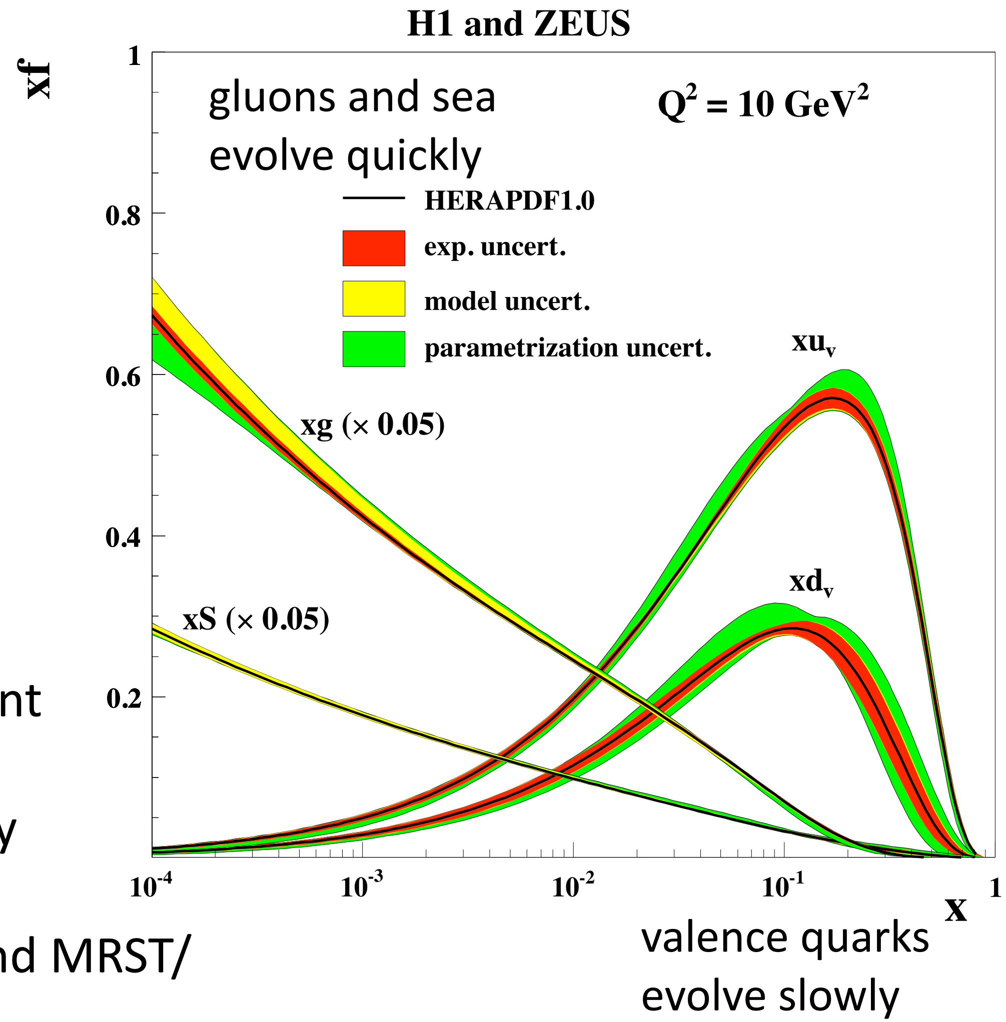
  $x f(x) = A x^b (1 - x)^c P(x)$

  [b controls low-x shape, c controls high-x shape;
  $P(x)$ is a polynomial function in x $(1 + d\sqrt{x} + ex)$]
- Evolve PDFs with Q^2 using DGLAP equations
- Convolve PDFs with coefficient functions to predict structure functions
- Apply constraints with Sum rules

Done by theorists (CTEQ, MRST/MSTW, ABKM, JR, NNPDF) and experimental collaborations (H1, ZEUS, ATLAS - soon)

ZEUS global fit:

input data μ-induced F_2 from BCDMS,NMC,E665
Deuterium-target data from NMC,E665
NMC data on F_2^D / F_2^P
CCFR xF3 data ($0.1 < x < 0.65$)
ZEUS 96-97 NC cross-sections



Parametrise PDFs at $Q^2_0 = 7 GeV^2$

$xf(x) = Ax^b(1 - x)^c (1 + ex)$

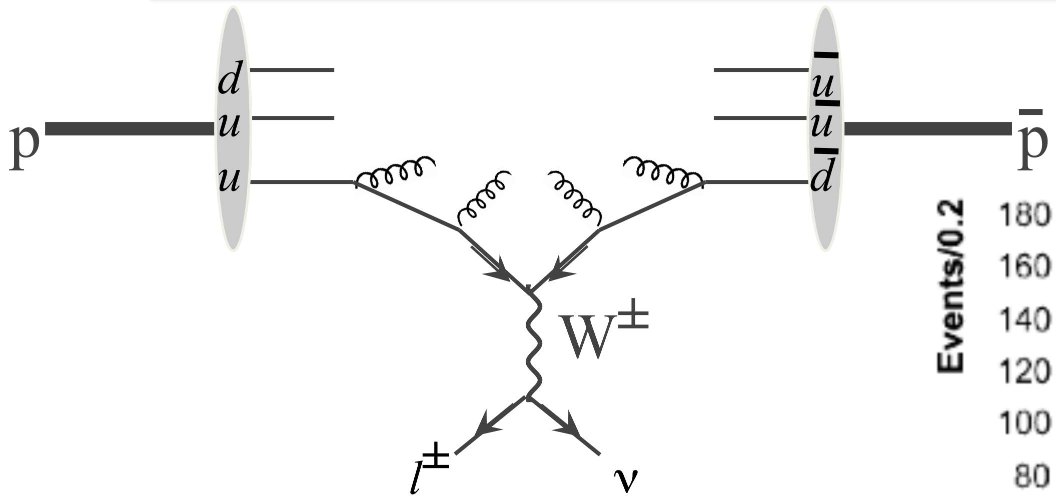
make assumptions about s and c content

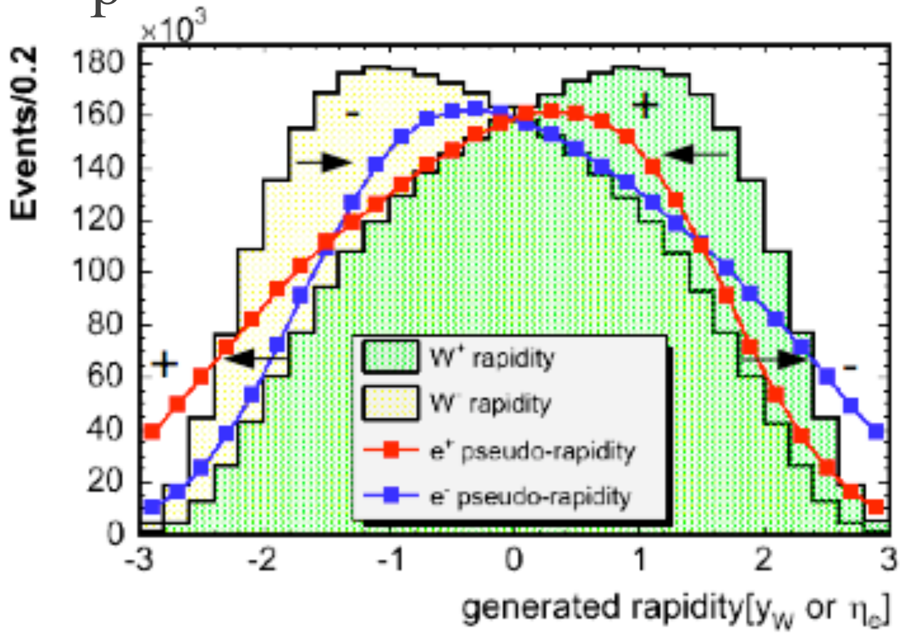
e=0 for xg

All assumptions are varied in uncertainty determination

Good agreement between ZEUS PDFs and MRST/MSTW and CTEQ

W charge asymmetry



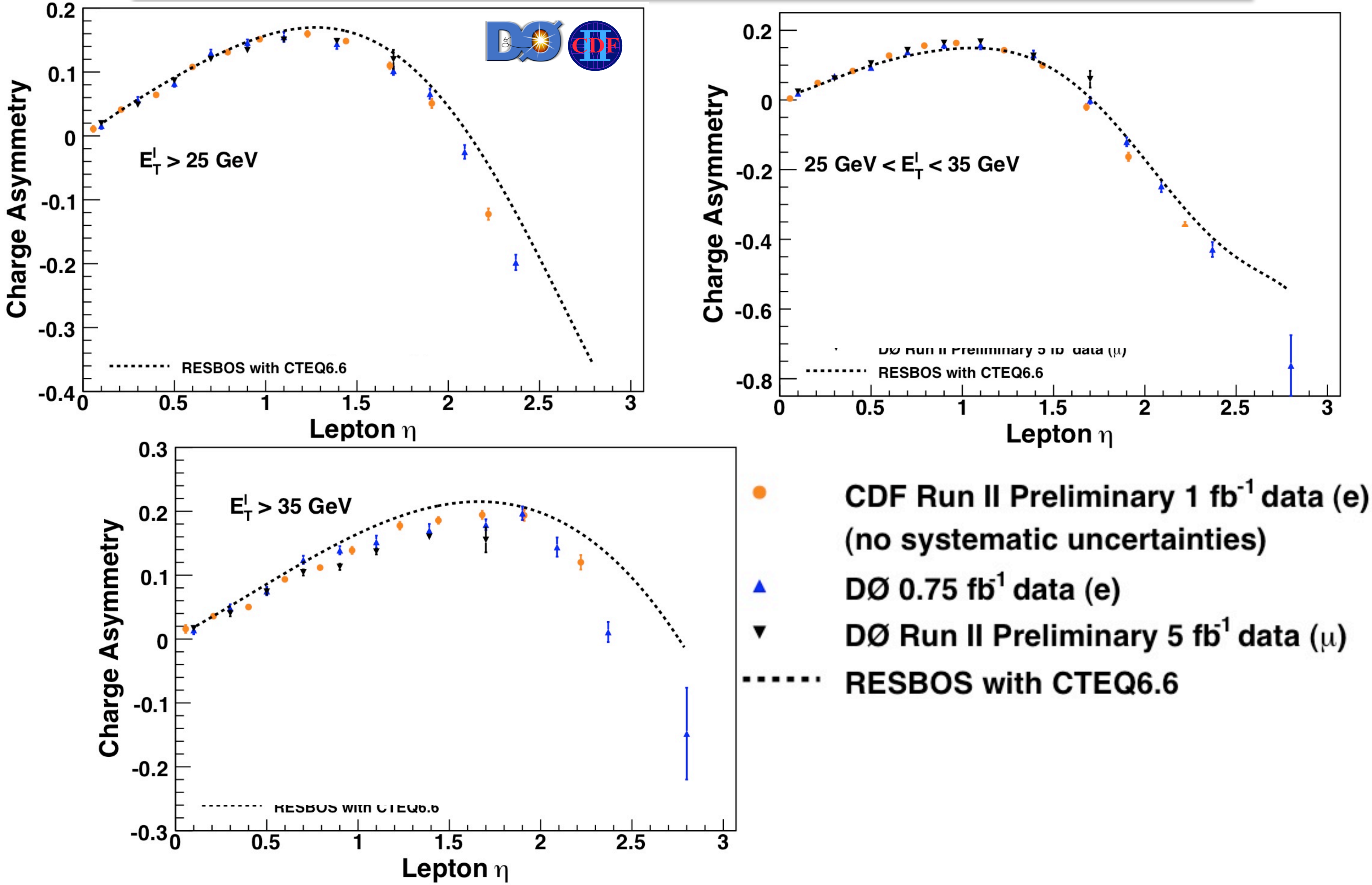


$$A_W(y) \equiv \frac{d\sigma(W^+)/dy - d\sigma(W^-)/dy}{d\sigma(W^+)/dy + d\sigma(W^-)/dy}$$

$$A_\ell(\eta) \equiv \frac{d\sigma(\ell^+)/d\eta - d\sigma(\ell^-)/d\eta}{d\sigma(\ell^+)/d\eta + d\sigma(\ell^-)/d\eta} = A(y_W) \otimes (V\!-\!A) \sim \frac{d(x)}{u(x)}$$

Run 1 measurement resulted in d quark increased by 30% at Q^2=(20GeV)^2

W charge asymmetry



Quantifying PDF uncertainties

- PDFs are parameterised fits to DIS/fixed target DY/Tevatron data

  $xf_a(x,Q_0) = A_0 x^{A1} \cdot (1-x)^{A2} \cdot e^{A3x} \cdot (1+A_4 x)^{A5}$ (CTEQ)

  where *a* are combinations of u,d,g,$\bar{u}$,$\bar{d}$

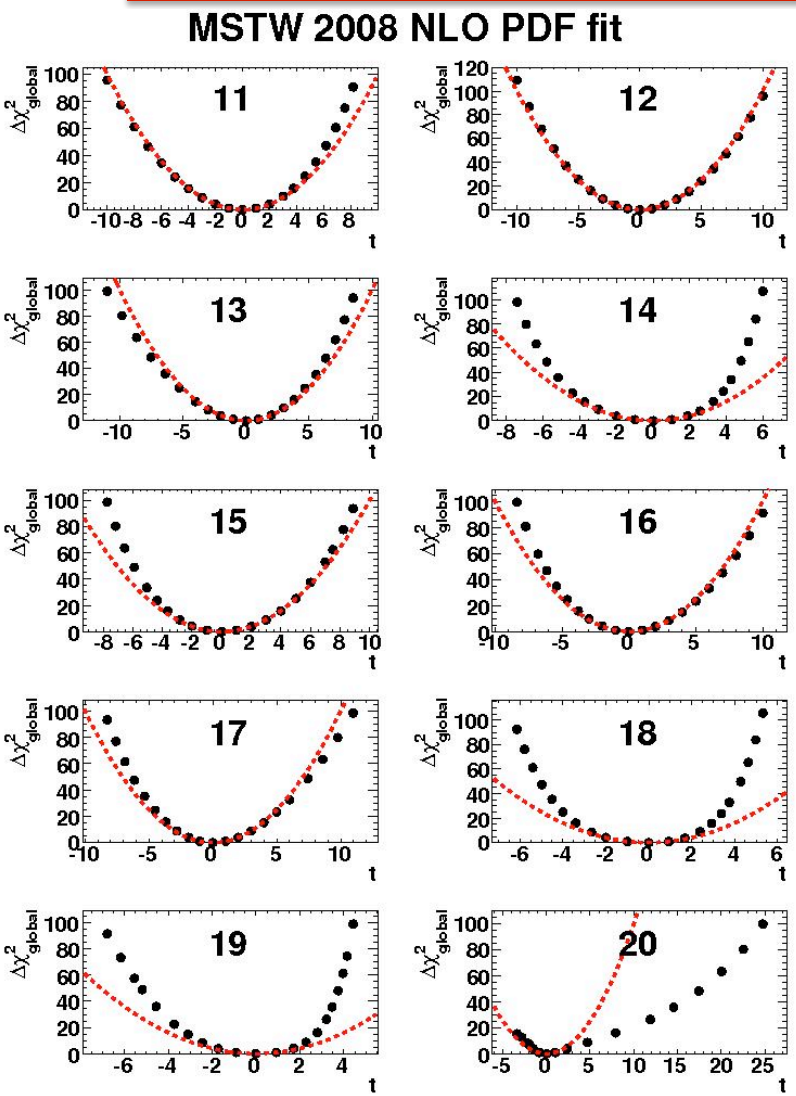
  $\Rightarrow$ 30 total parameters of which 10 fixed

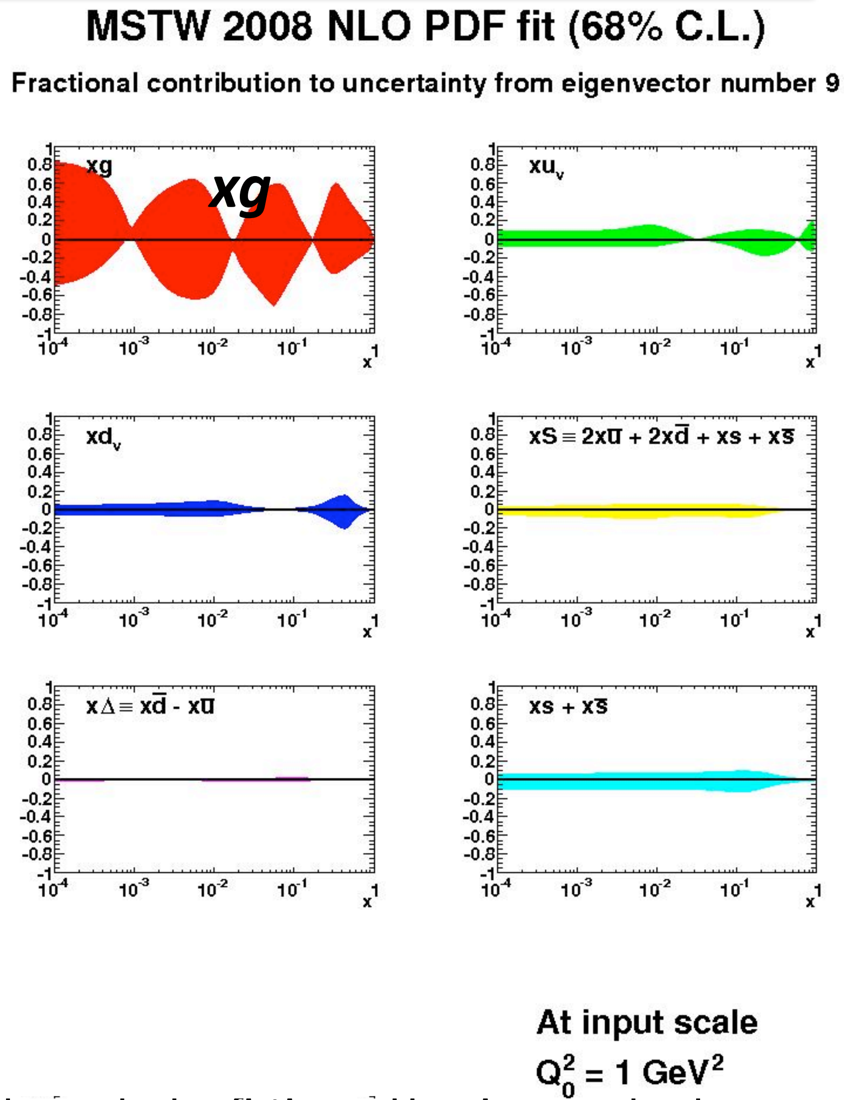
- Parameters determined at low scale Q_0=1.3GeV and evolved

- Eigenvectors formed in A_i space (20 for CTEQ, 15 for MRST)

- 'Error' PDF sets provided for each eigenvector at $\Delta\chi^2$=100(CTEQ) or 50(MRST) from best fit.

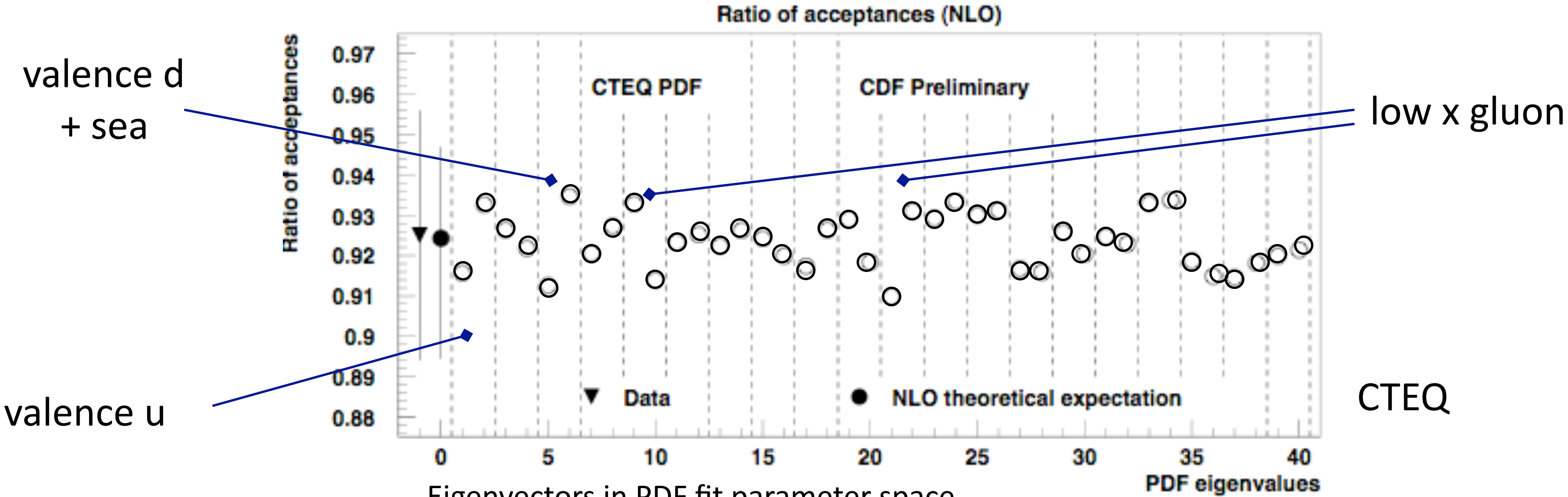
PDF eigenvectors





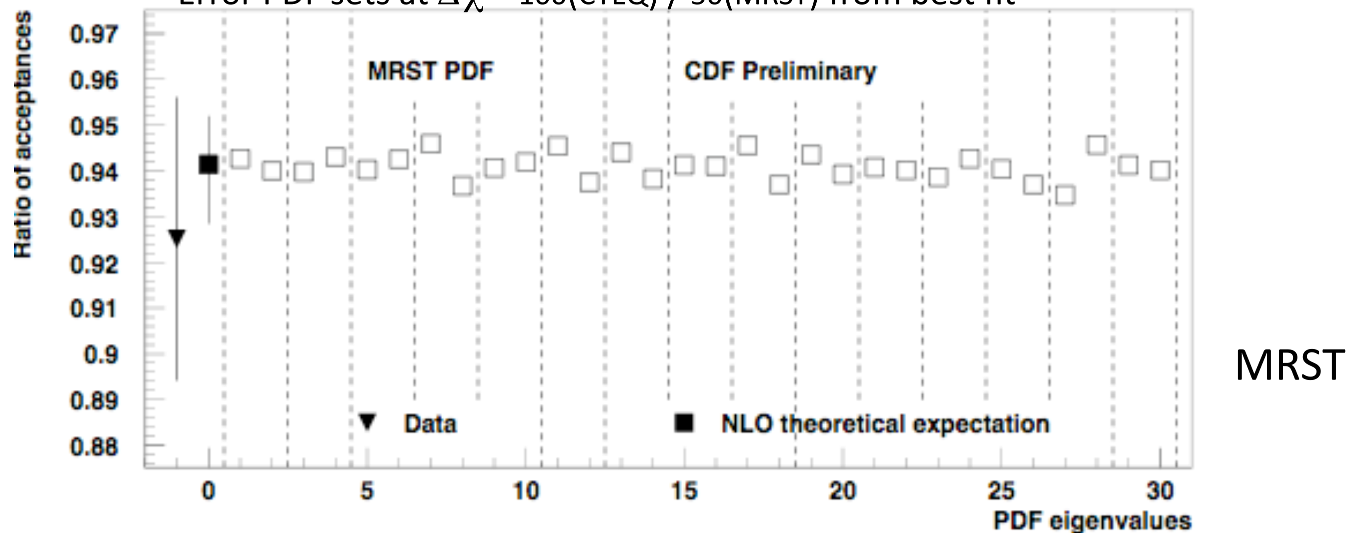
Propagation of experimental uncertainties through the fitting – Hessian method

MRST: 20 'eigenvectors' ; a χ^2 tolerance is chosen ; 'error' PDF sets generated with those fits



Eigenvectors in PDF fit parameter space

Error PDF sets at $\Delta\chi^2$=100(CTEQ) / 50(MRST) from best fit



Cross-section measurement

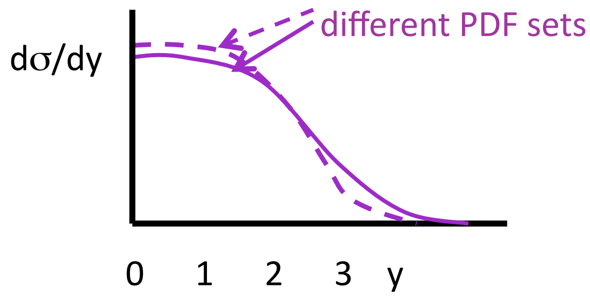
Counting experiments:

$$\sigma \cdot Br(\text{channel}) = \frac{N_{candidates} - N_{background}}{\varepsilon A \cdot \int L\,dt}$$

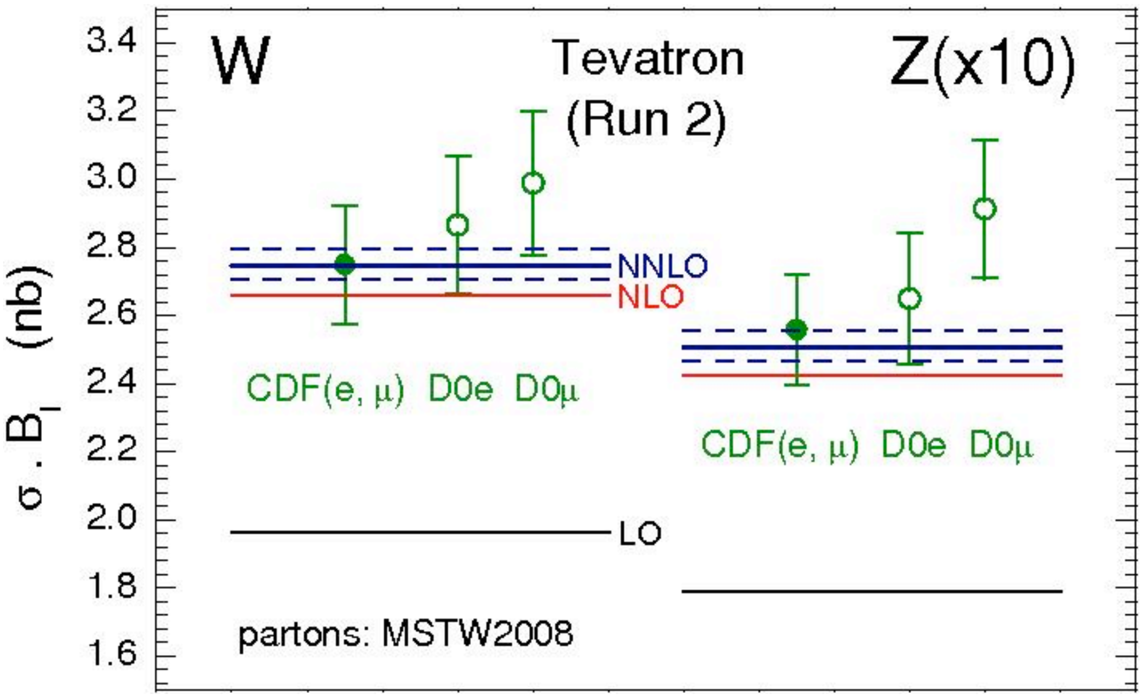
- Choose some event selection criteria, count $N_{candidates}$, estimate $N_{background}$
- Determine acceptance A - the fraction of events kinematically/geometrically detectable.
- Determine efficiency ε - the fraction of the kinematically/geometrically detectable events that passes the further selection criteria.
- Determine total integrated luminosity of the sample, $\int L\,dt$

Gross quantities eg acceptance, energy spectra: OK to ask simulation necessary eg irreducible backgrounds

Details of response, particle ID: perhaps not OK? – measure in data



pQCD and Tevatron W/Z



Effect of higher-order corrections: smaller uncertainty

NLO +25%

NNLO +5%

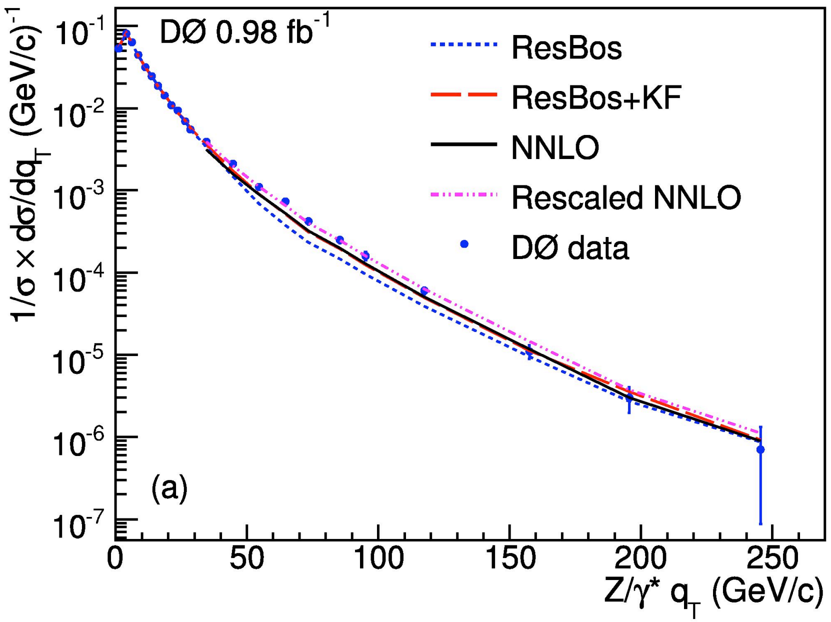
$O(\alpha_s^3)$ correction presumably smaller than 5%

- small theoretical error since $x \approx M_W/\sqrt{s} \approx 0.1$, values well-constrained by HERA measurements

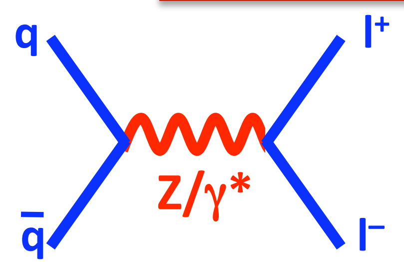
Inclusion of p_T

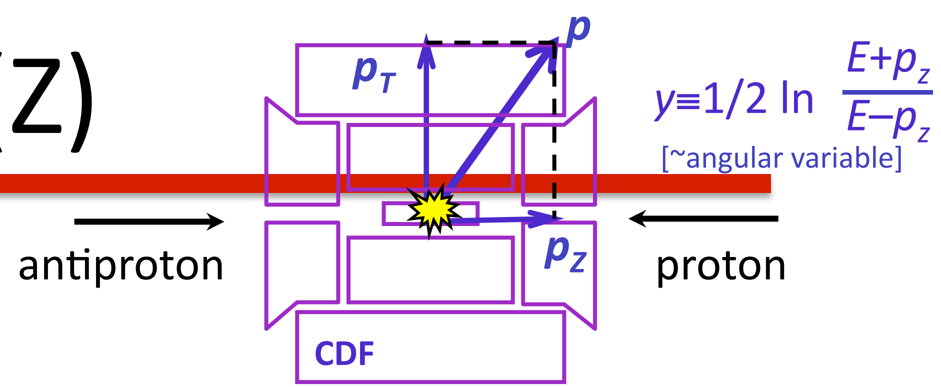
The non-perturbative Fermi motion of q,g in the colliding hadrons can't be responsible for the p_T spectra, since $k_T \approx \Lambda_{QCD}$
(Gaussian $\langle k_T \rangle \approx 700$ MeV measured in fixed target DY lepton pairs)

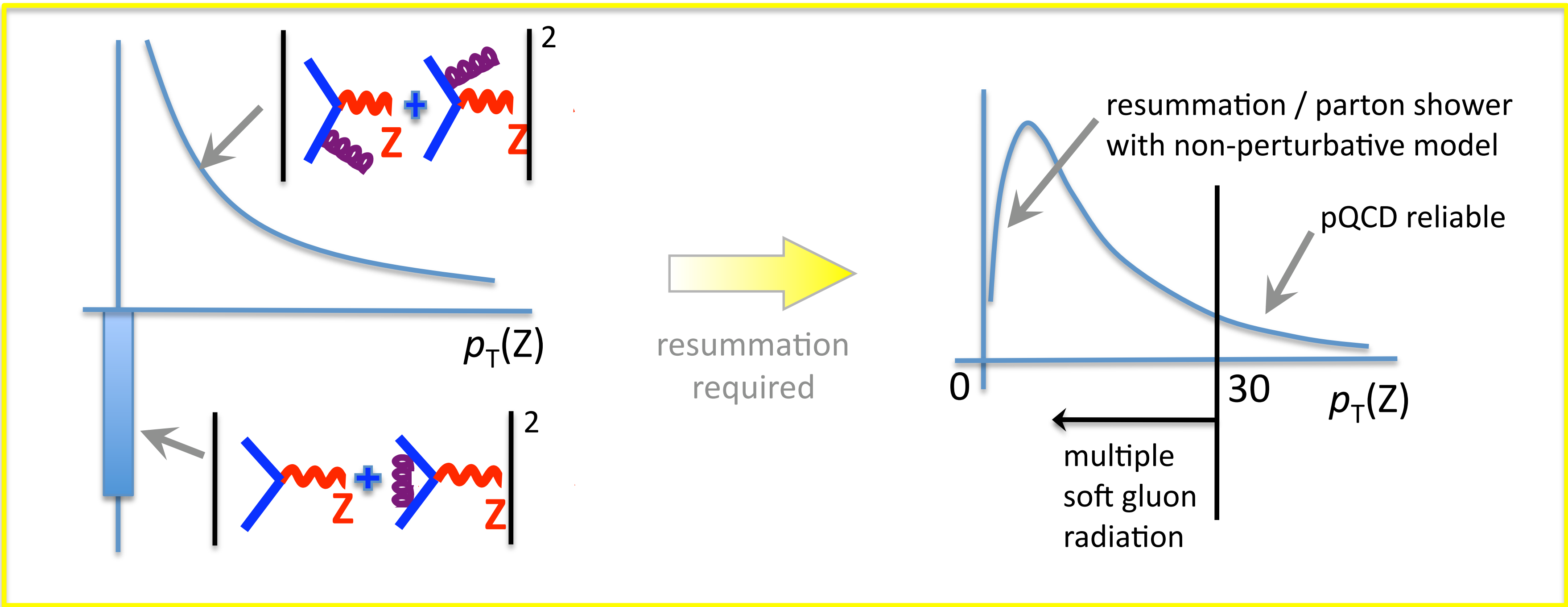
The hard, power-law p_T tail of the data must be attributed to hard emission of one or more partons



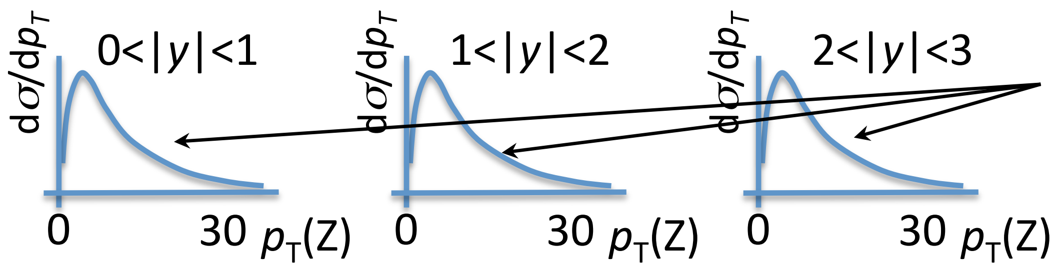
$p_T(Z)$







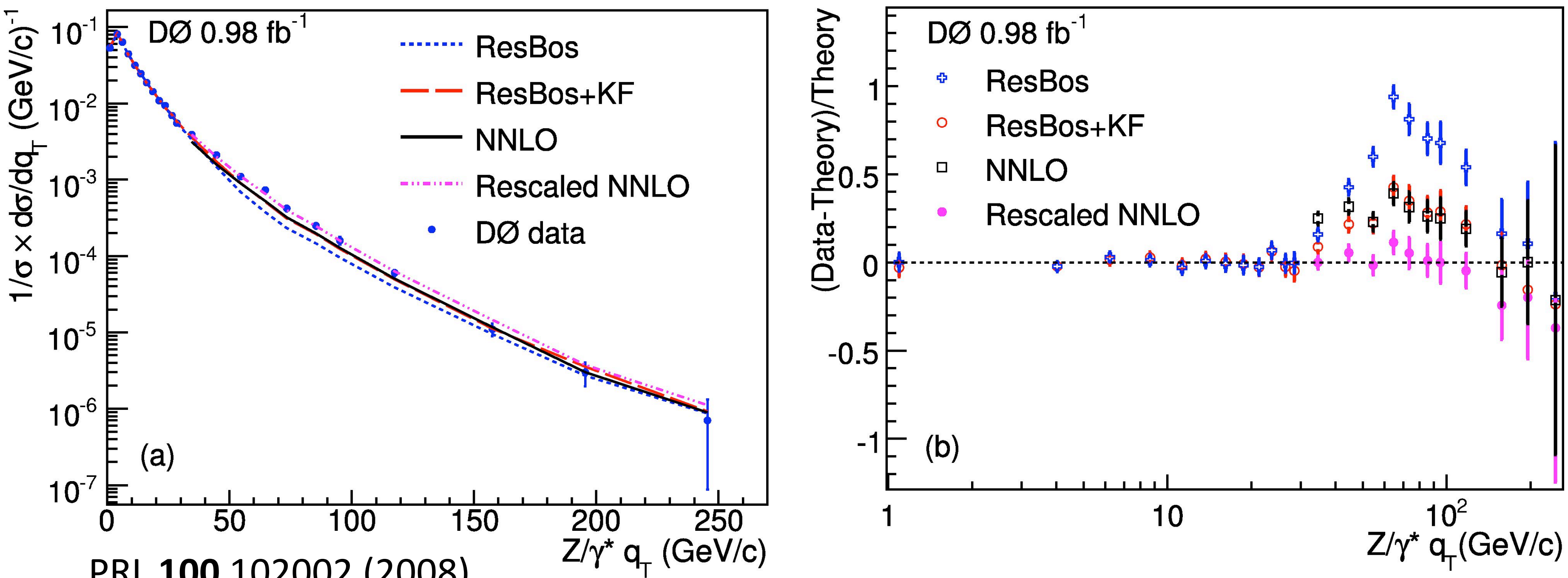
event generator tuning



distribution different for different y?

Earlier $p_T(Z)$

Electron channel:



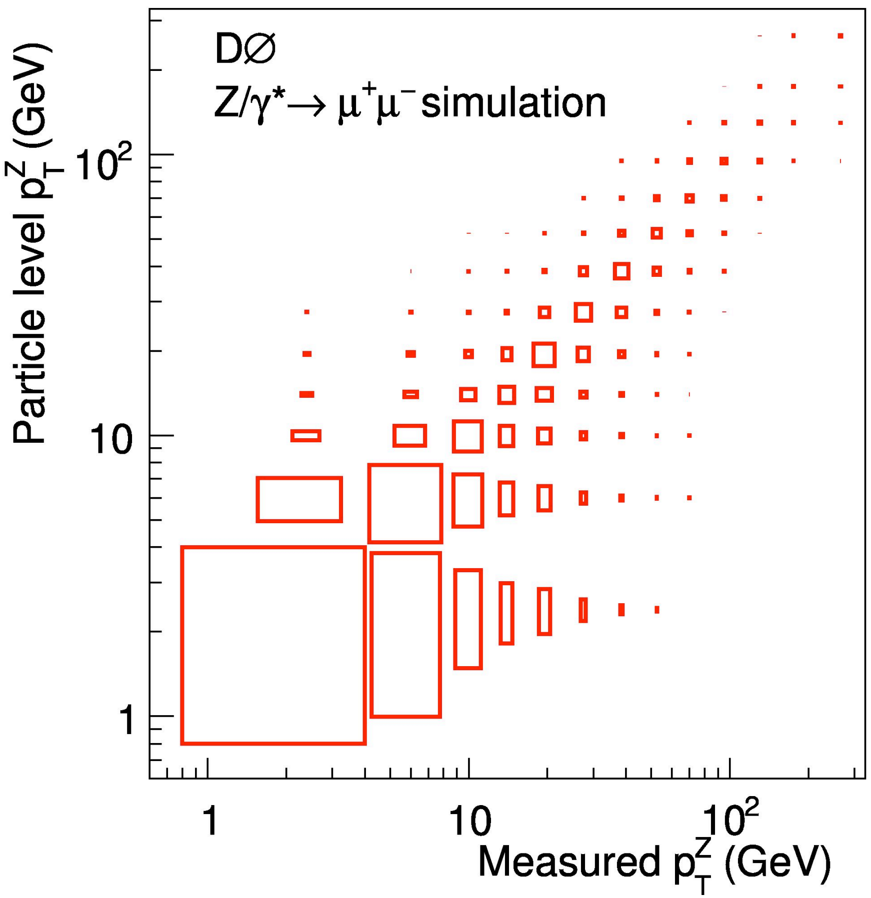
PRL **100** 102002 (2008)

Compare 4 models:
- Resbos with default parameters
- Resbos with additional NLO–NNLO K-factor
- NNLO (Melnikov and Petriello)
- NNLO rescaled at to data at 30GeV/*c*

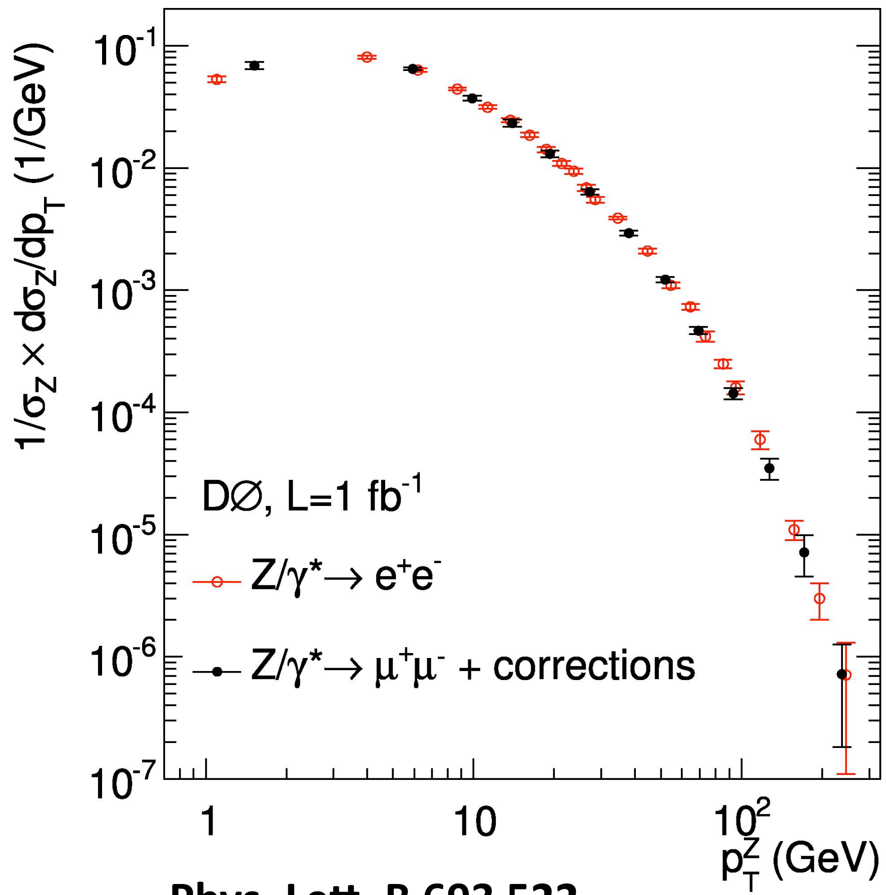
RESBOS event generator implements NLO QCD and CSS resummation

$p_T(Z)$

Measurement in muon channel
Presented at the level of particles entering the detector to avoid model-dependent corrections

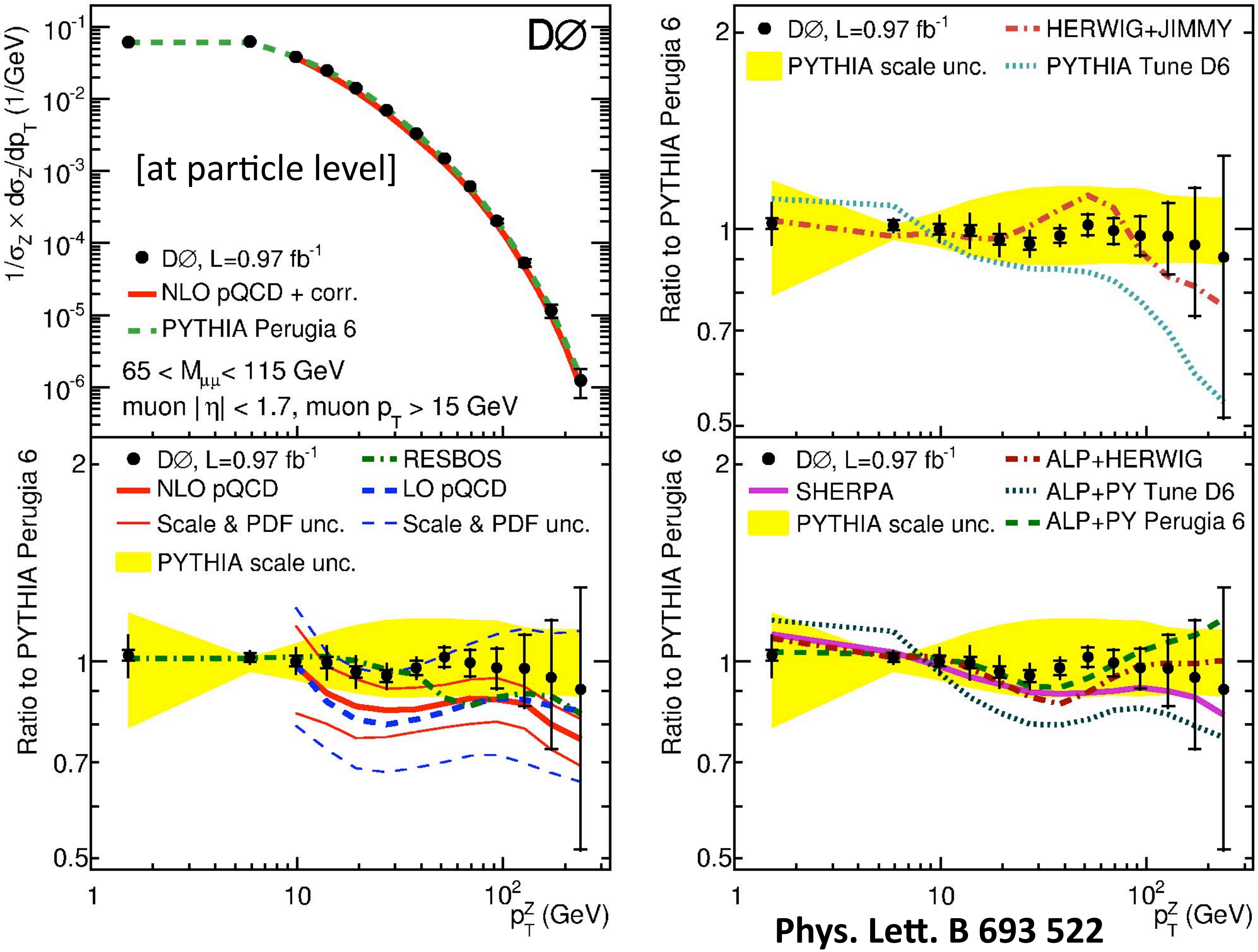


However for comparison with previous measurement, correct to 4π and for mass window:

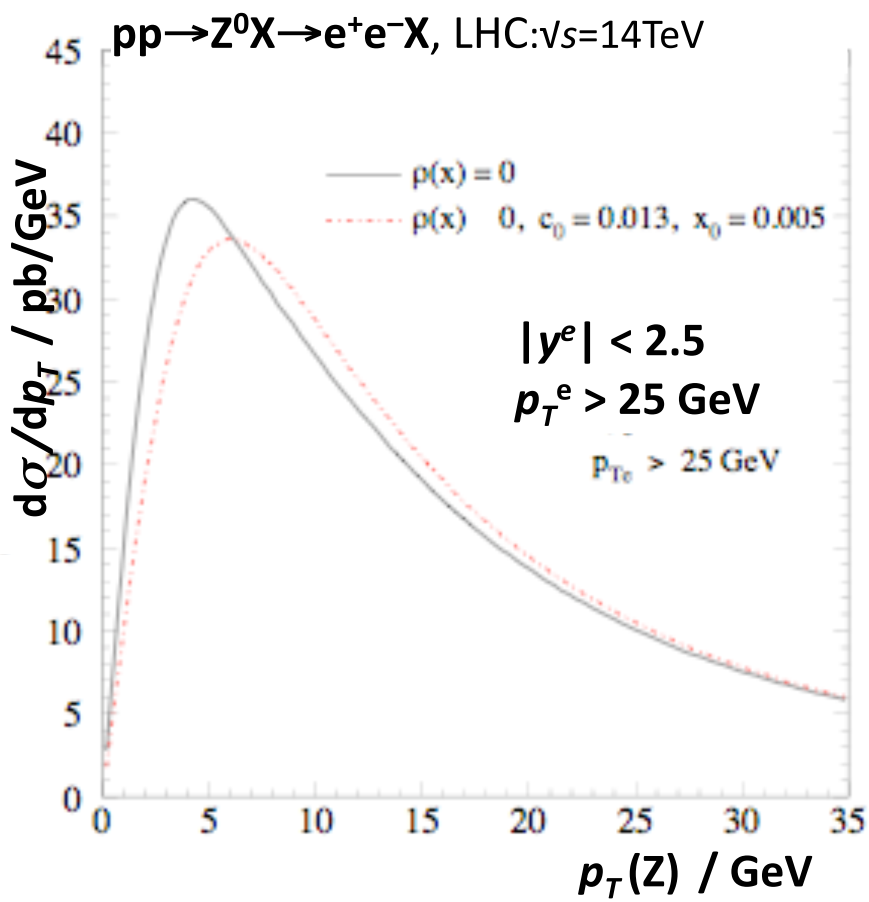


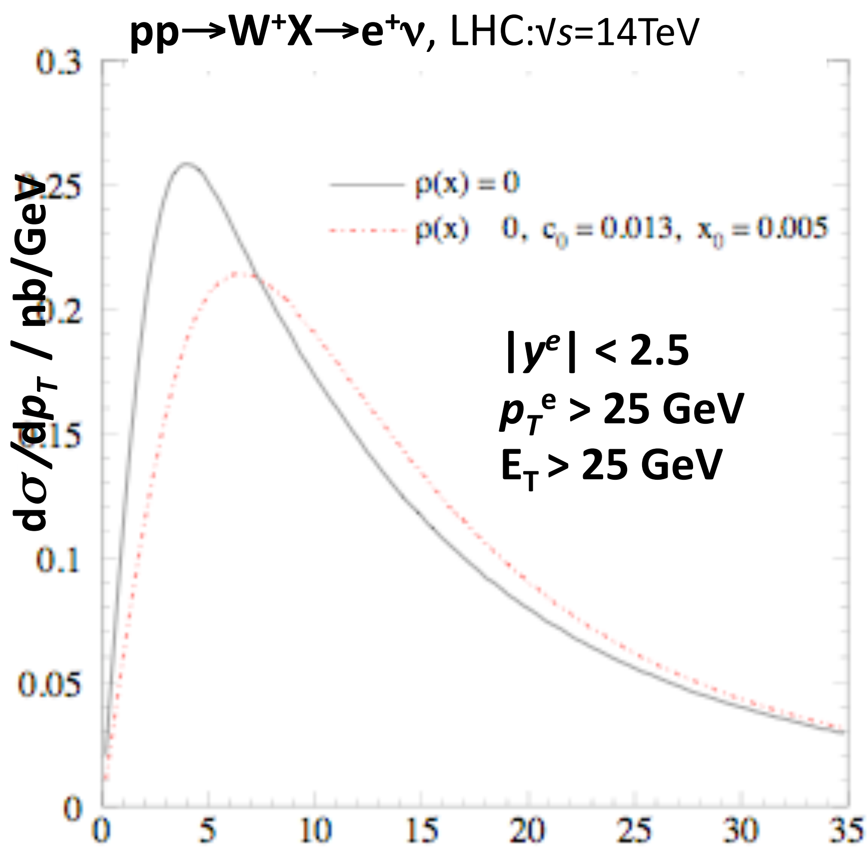
Phys. Lett. B 693 522

$p_T(Z)$

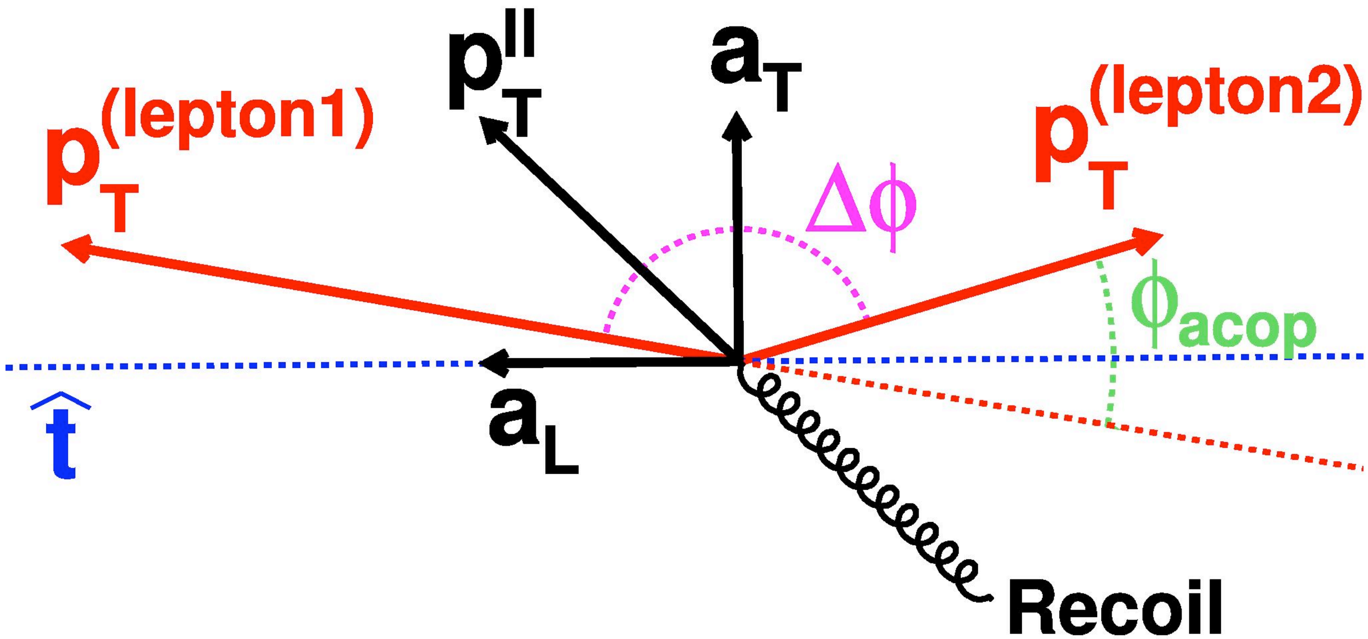


Phys. Lett. B 693 522


pp→Z⁰X→e⁺e⁻X, LHC:√s=14TeV
dσ/dp_T / pb/GeV
p_T(Z) / GeV
ρ(x) = 0
ρ(x) 0, c₀ = 0.013, x₀ = 0.005
|y^e| < 2.5
p_T^e > 25 GeV
p_Te > 25 GeV


pp→W⁺X→e⁺ν, LHC:√s=14TeV
dσ/dp_T / nb/GeV
ρ(x) = 0
ρ(x) 0, c₀ = 0.013, x₀ = 0.005
|y^e| < 2.5
p_T^e > 25 GeV
E_T > 25 GeV

ϕ^*_η

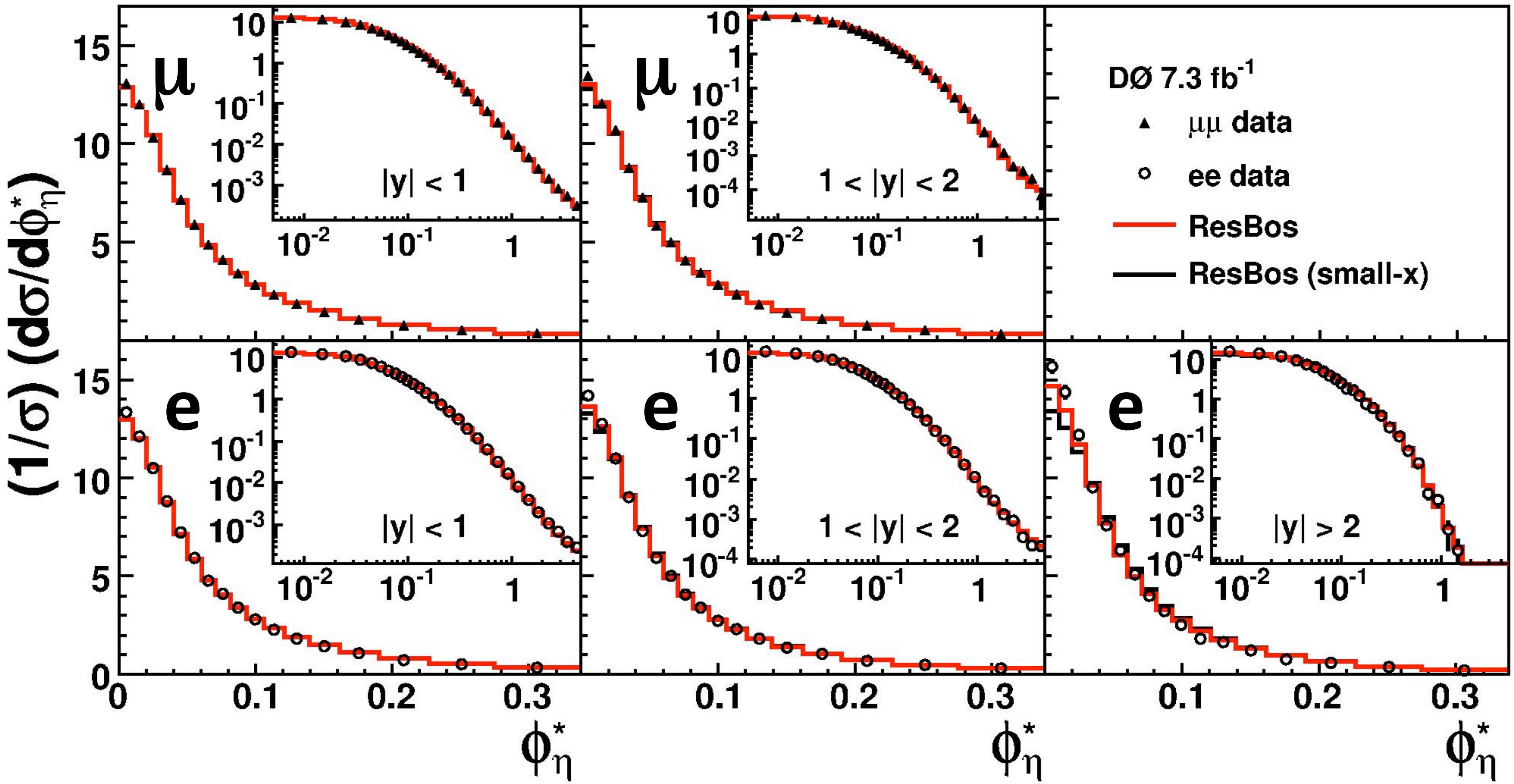


a_T : component of p_T(ll) transverse to dilepton thrust axis.
Less susceptible than p_T(ll) to detector effects

Best variable: $\phi^*_\eta = \tan(\phi_{acop}/2)\sin(\theta^*_\eta)$ – highly correlated with a_T/m_{ll}

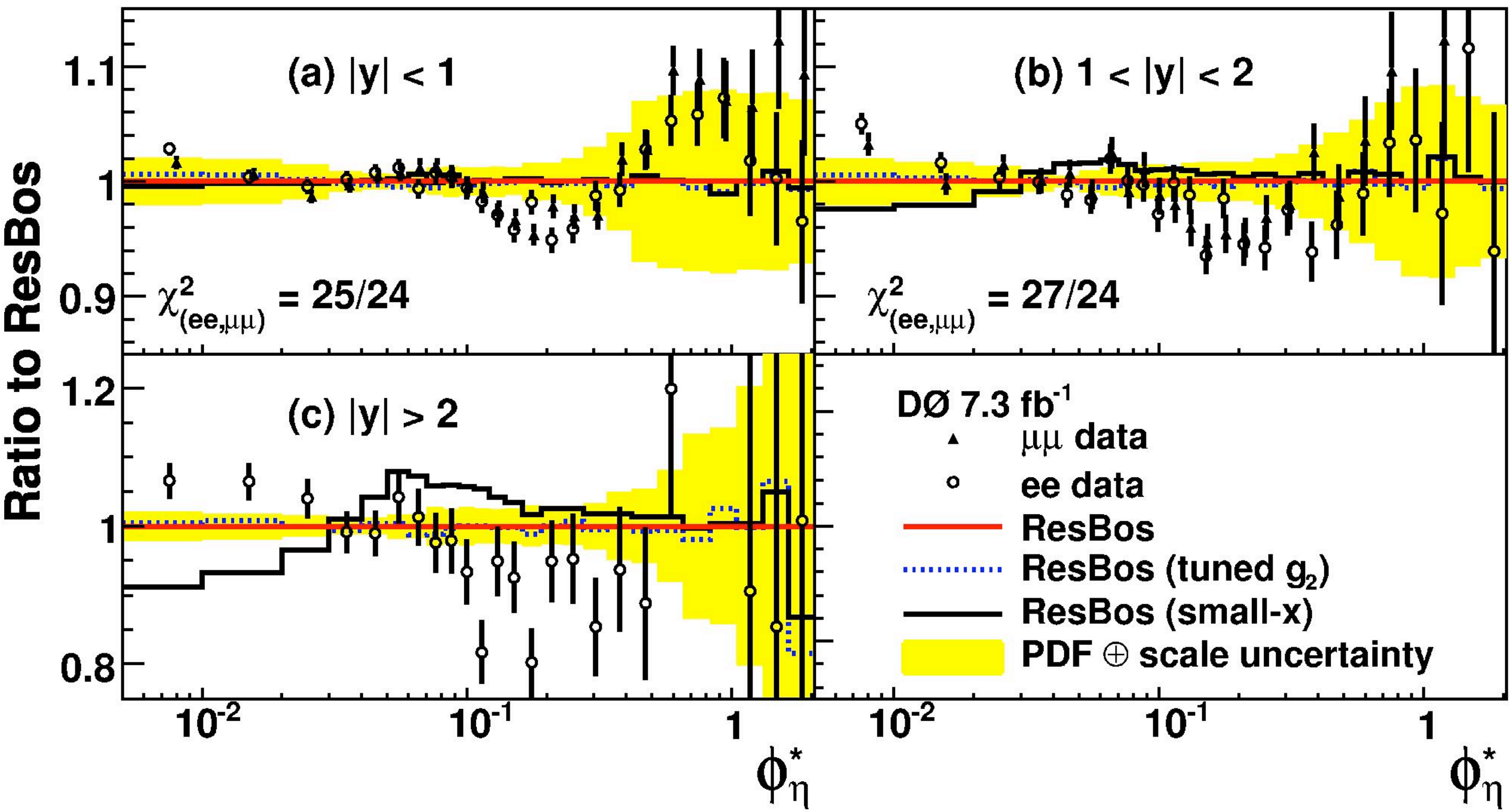
(θ^*_η measures scattering angle of leptons wrt beam, in rest frame of dilepton system)

ϕ^*_η



arXiv:1010.0262

ϕ^*_η

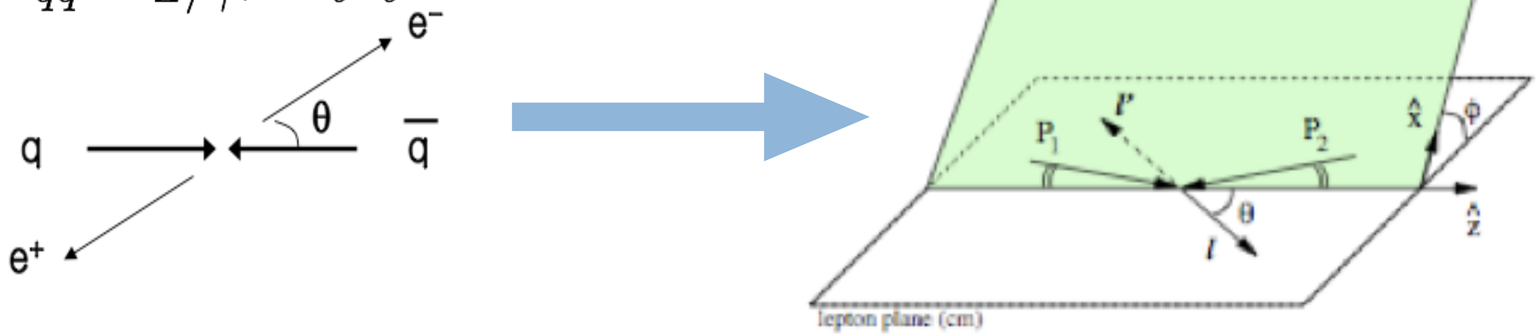


arXiv:1010.0262

Drell-Yan angular coefficients

$q\bar{q} \to Z/\gamma* \to \ell^+\ell^-$

Rest frame of dilepton system



$$\frac{d\sigma}{dP_T^2 dy d\cos\theta d\phi} \propto (1+\cos^2\theta)$$ → *LO term*

$$+ \frac{1}{2}A_0(1-3\cos^2\theta)$$ → *$\cos^2\theta$: higher order term*

$$+ A_1 \sin 2\theta \cos\phi + \frac{1}{2}A_2 \sin^2\theta \cos 2\phi + A_3 \sin\theta \cos\phi$$ → *(θ, ϕ) terms*

$$+ A_4 \cos\theta$$ → *LO term : determine A_{fb}*

$$+ A_5 \sin^2\theta \sin 2\phi + A_6 \sin 2\theta \sin\phi + A_7 \sin\theta \sin\phi$$ → *very small terms*

Integrate over all ϕ ,

$$\frac{d\sigma}{d\cos\theta} \propto (1+\cos^2\theta) + \frac{1}{2}A_0(1-3\cos^2\theta) + A_4\cos\theta$$

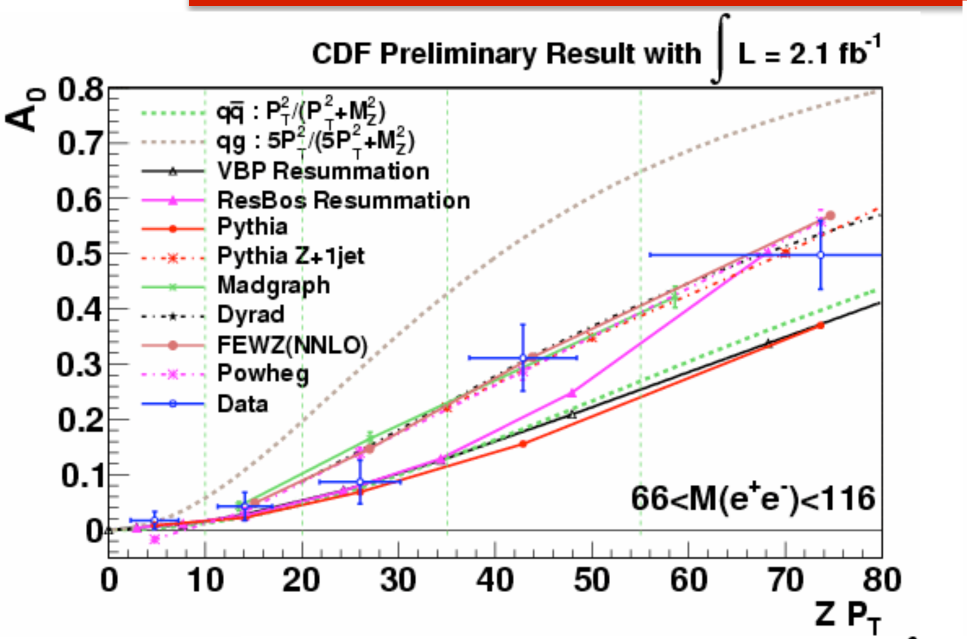
measure as function of p_T

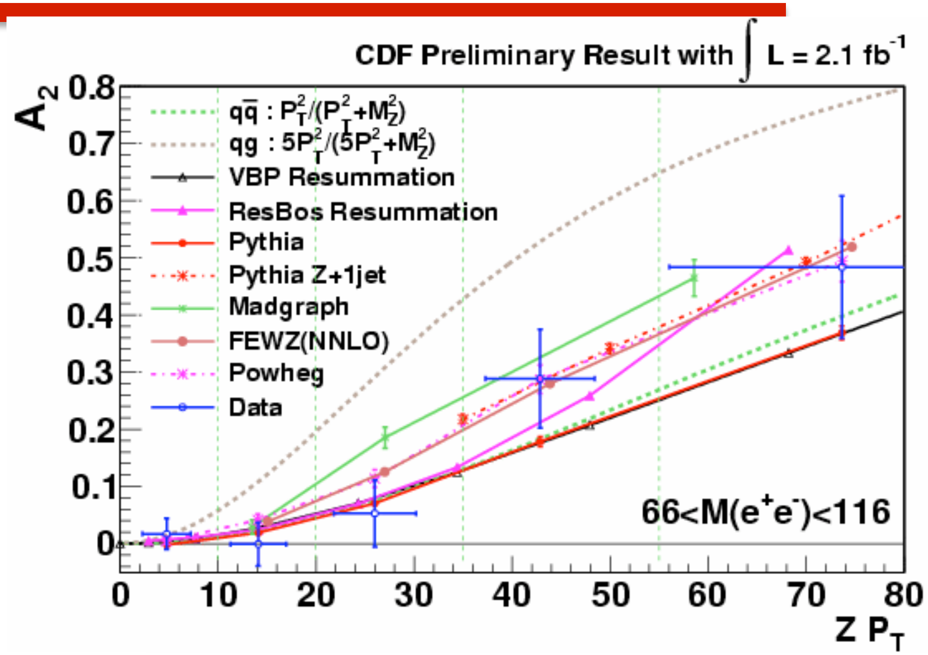
Integrate over all $\cos\theta$,

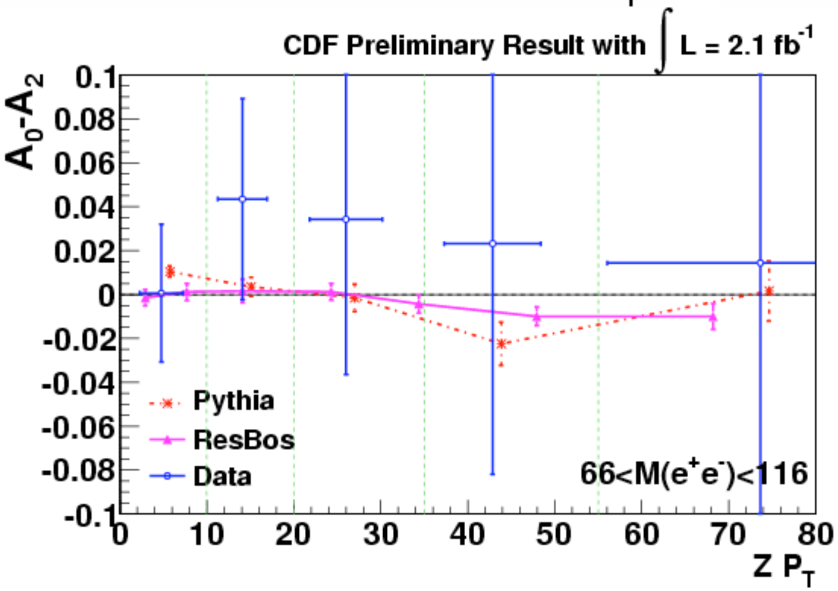
$$\frac{d\sigma}{d\phi} \propto 1 + \frac{3\pi A_3}{16}\cos\phi + \frac{A_2}{4}\cos 2\phi + \frac{3\pi A_7}{16}\sin\phi + \frac{A_5}{4}\sin 2\phi$$

($\frac{3\pi A_7}{16}\sin\phi$ =0, $\frac{A_5}{4}\sin 2\phi$ =0)

Drell-Yan angular coefficients





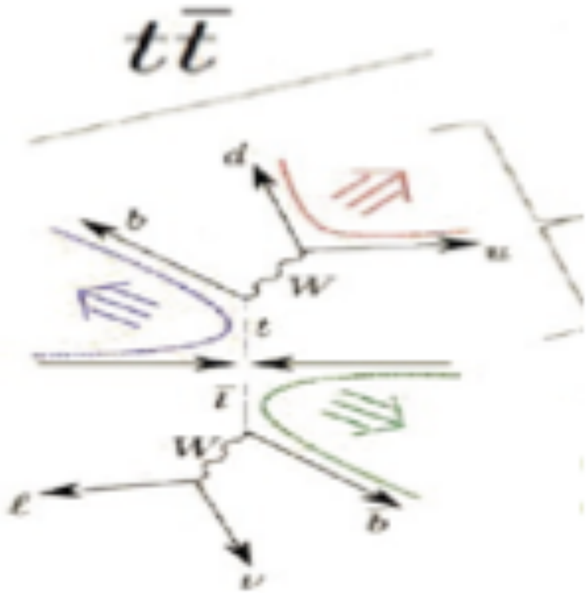


A2=A0 at LO
'Lam-Tung' relation
True only for spin-1 gluons,
strongly broken for scalar gluons

Top mass

- Confinement
  Top mass can't be defined like, eg, electron mass
  Any colored particle is not an asymptotic state: confined on a timescale ~10^{-23}s
- Decay
  top decays too quickly to hadronize: $\tau \sim 10^{-24}$s
  but its decay products hadronize: $t \rightarrow bW \rightarrow bjj$,
  and b is color-connected to the rest of the event

- Produce in hadron collision: ISR and underlying event
- Mass depends on QCD renormalization scheme

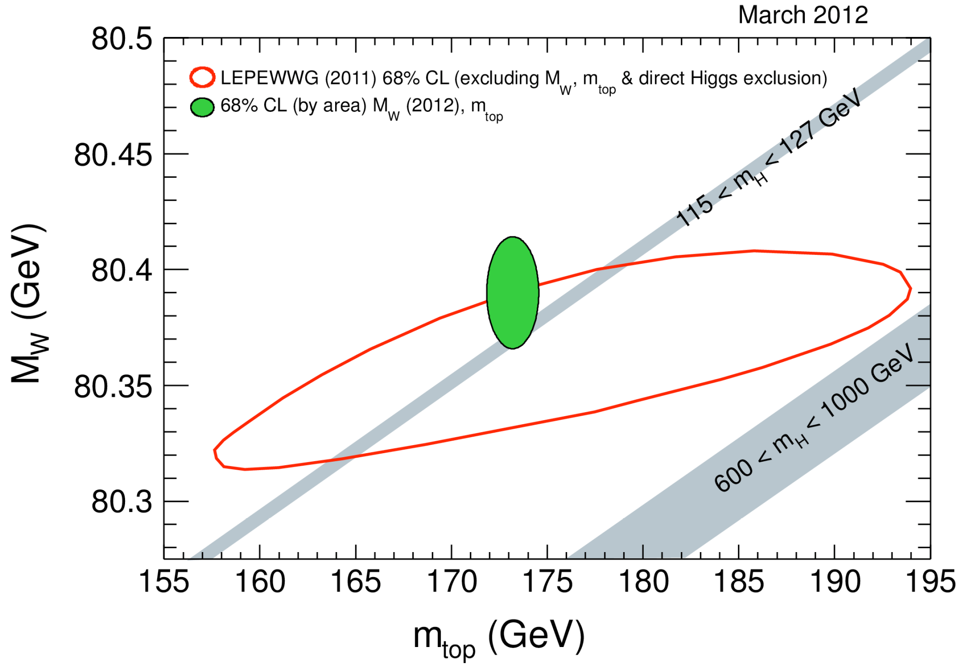


Top mass

Parameter to LL parton shower generators?
Moreover, what's the meaning of the input to the MC generators e.g. Pythia, Herwig?
Common heavy quark mass definitions

Pole mass ie $p^2=m^2$ – top as free parton – unphysical

$$\longrightarrow \;=\; \frac{i}{\not{p} - m + i\epsilon}$$



$\overline{\text{MS}}$ running mass (short distance mass)– the divergences are subtracted; It is the most commonly used subtraction scheme $\overline{\text{MS}} = m - \delta m$

What is measured experimentally? Pole mass –no, parton shower does not evolve the top perturbatively to infinitely long distance; stops at some scale Q_0
Conclusion: top mass is scheme-dependent MC generator parameter.
It is connected to the pole mass:

$$M_{pole} = M_{exp} \pm 1.\ \text{(exp)} + (2\pm 1\text{(scheme)})\ \text{GeV}/c^2$$

More info about this discussion (M. Seymour):
http://agenda.hep.manchester.ac.uk/getFile.py/access?resId=0&materialId=slides&confId=2498

George Velev

- QCD at hadron colliders
- Soft physics
- Hadronization and jets
- Jet substructure
- Matching
- PDFs
- Dedicated calculations

Track multiplicities

Jet energy scale/
Inclusive jets

W+jets
Z+b

W charge asymmetry

Z p_T

Top mass