MC Tuning and
recent measurements of the UE

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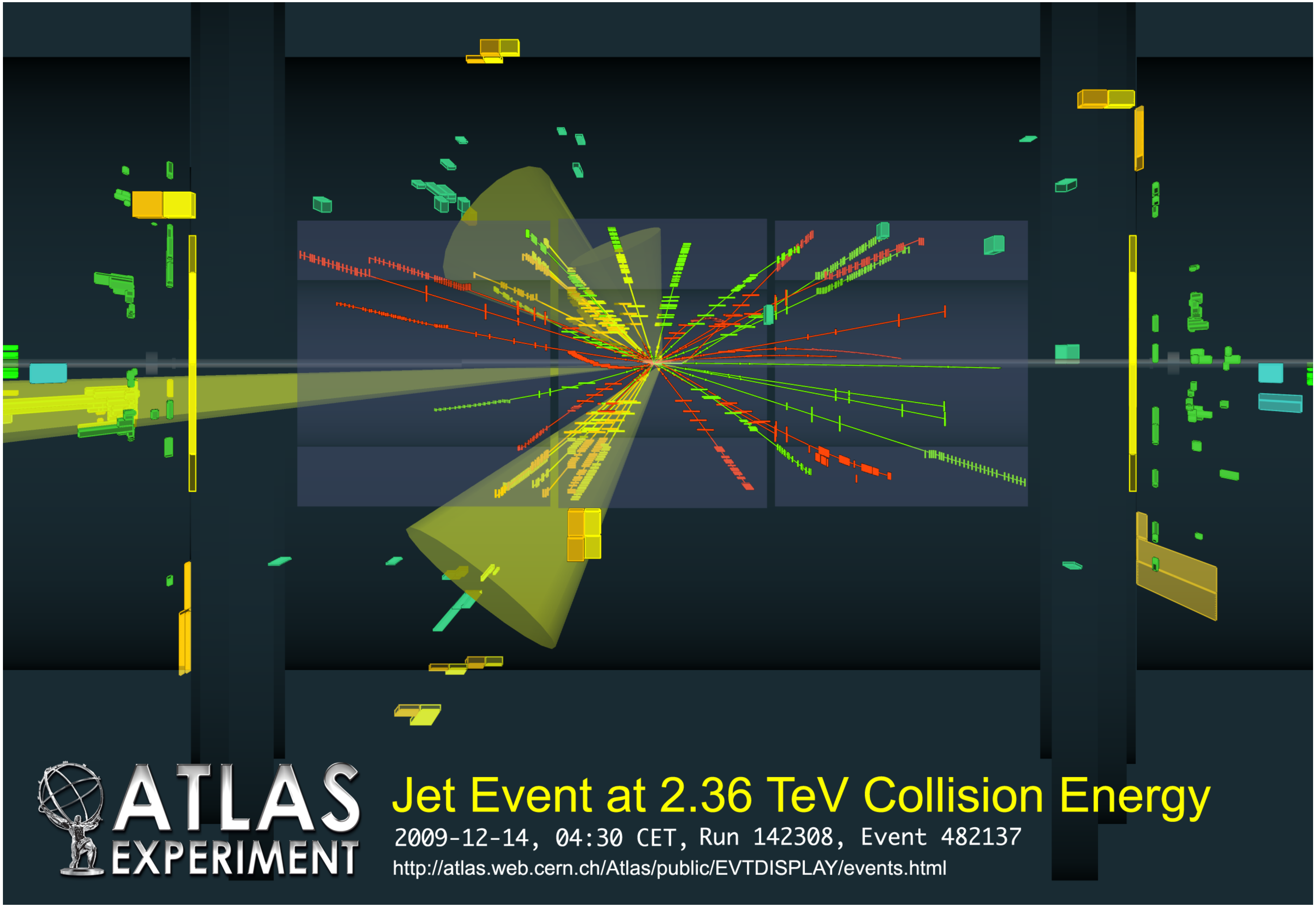
Outline

Introduction to a MC event
Automated tuning
Recent UE measurements from LHC
Tuning example from LHC
Summary

Collisions in Real Data

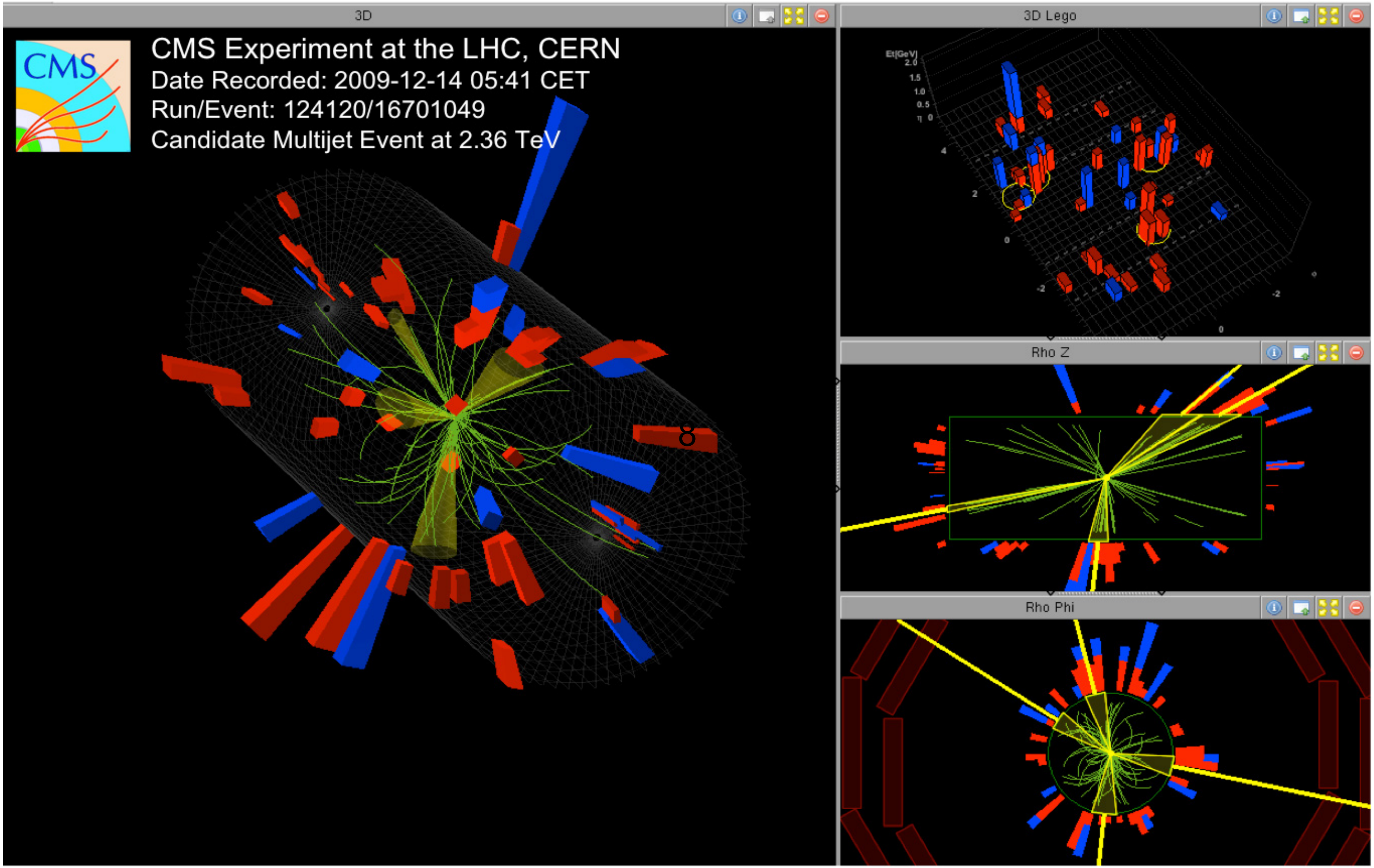
Collision in the ATLAS detector at $\sqrt{s}$ = 2.36 TeV



High particle multiplicity, different particles types (depositing energy in different parts of the detector)

Collisions in Real Data

Collision in the CMS detector at $\sqrt{s}$ = 2.36 TeV

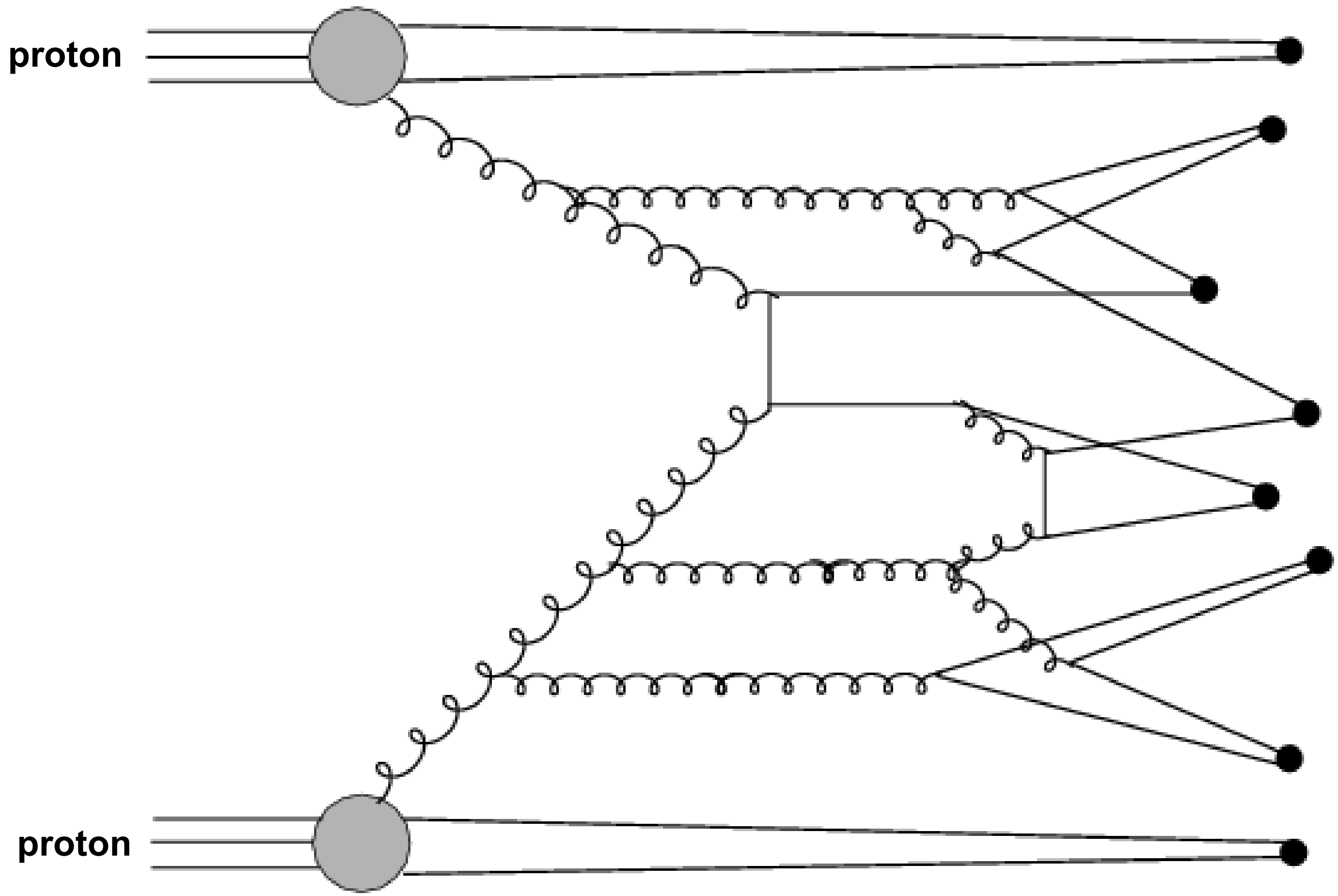


In classical mechanics not even a 3 body system is exactly calculable.
Use Monte Carlo methods to understand and simulate high energy collisions.

A Monte Carlo Event

In the Monte Carlo generator scheme, one of these events could look like this:

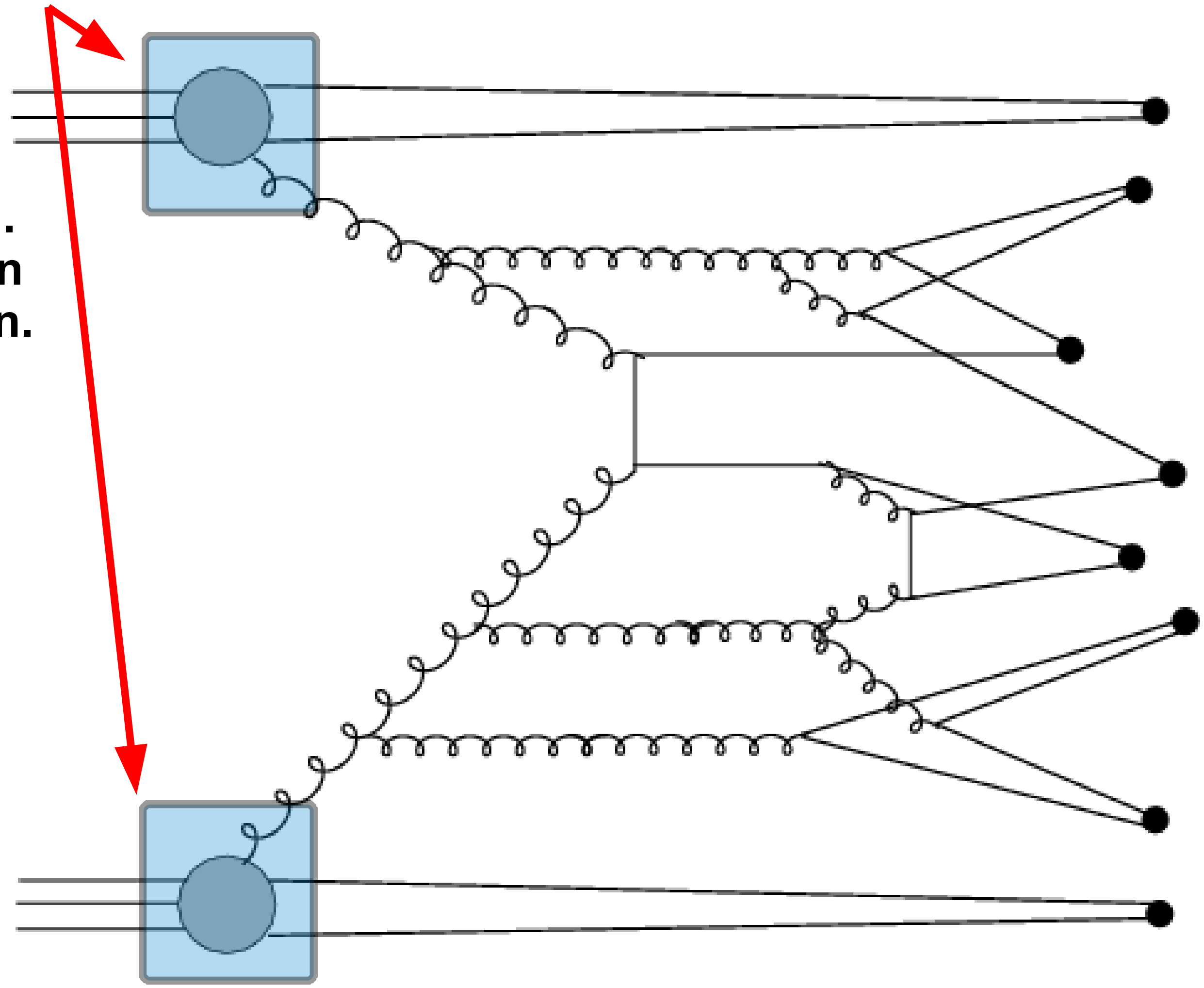
Event = PDF × (hard part × shower) × hadronisation



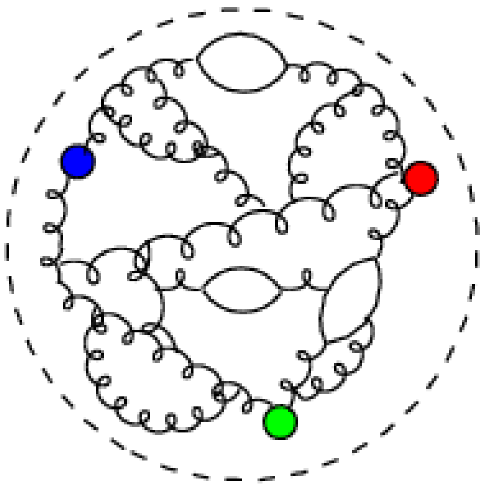
(Simple cartoon, some pieces are missing...)

A Monte Carlo Event

Event = PDF × (hard part × shower) × hadronisation



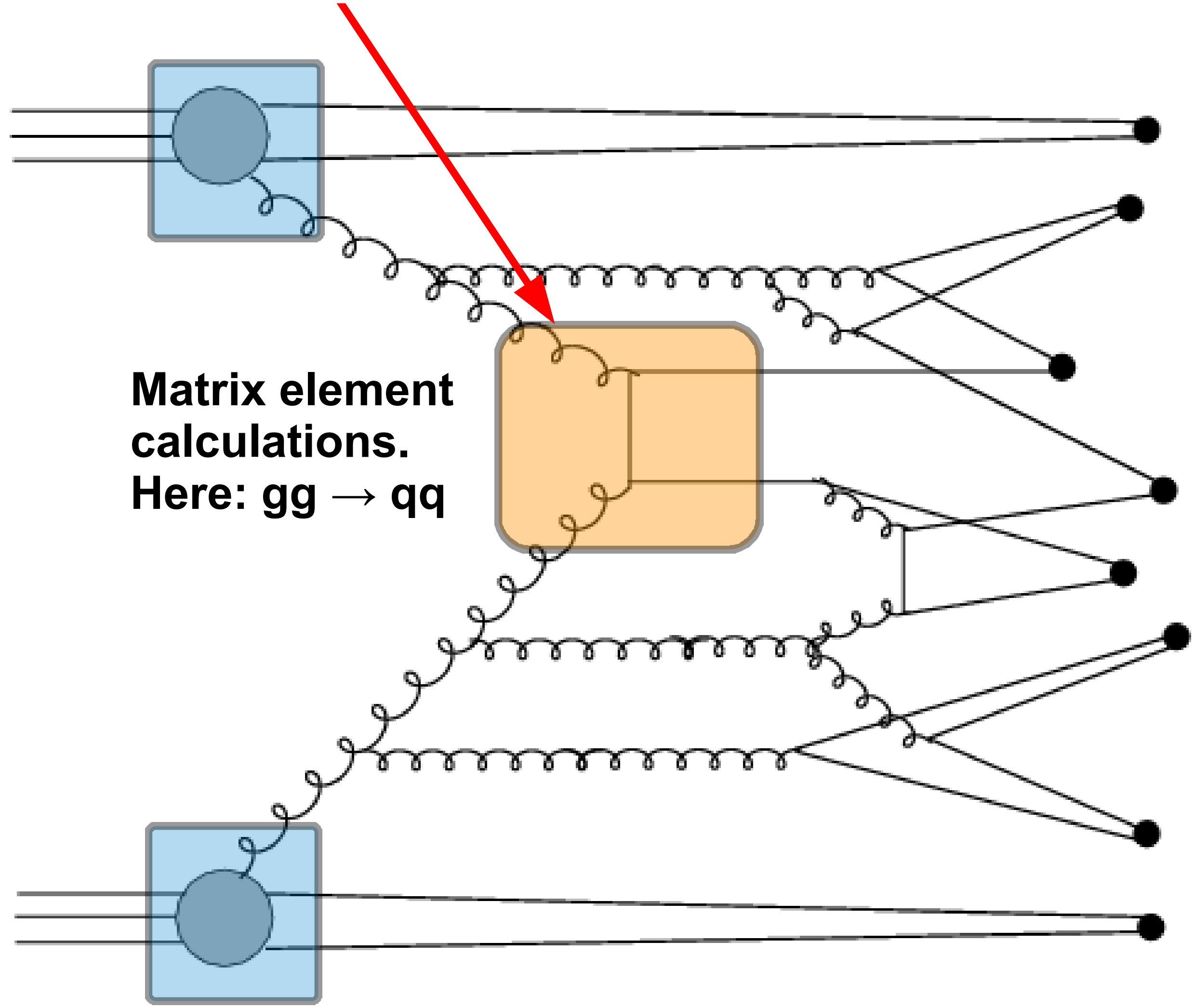
The Parton Density Function.
Parameterization of the gluon and quark densities in proton.



valence quarks
sea quarks,
gluons

A Monte Carlo Event

Event = PDF × (hard part × shower) × hadronisation



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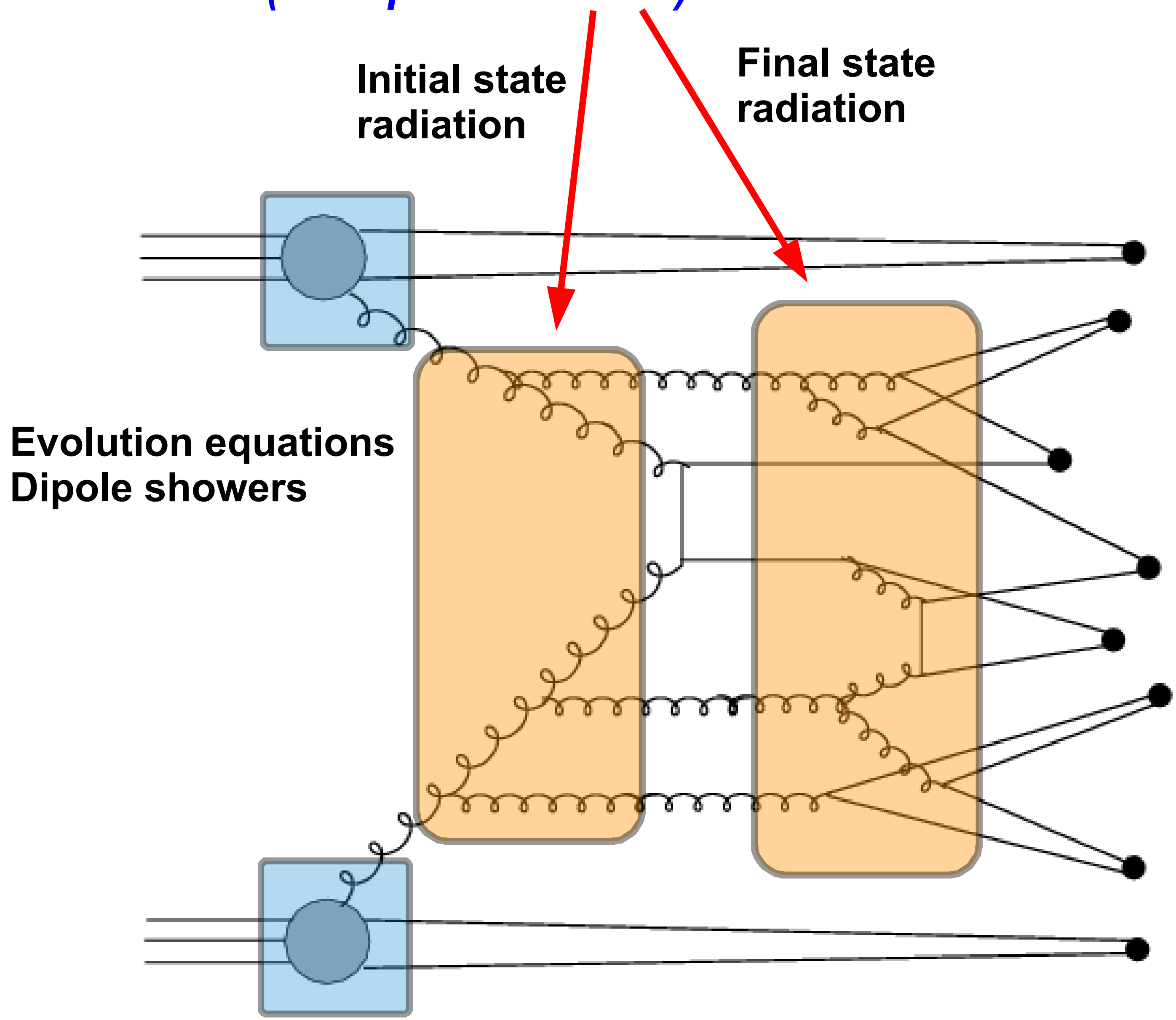

A Monte Carlo Event

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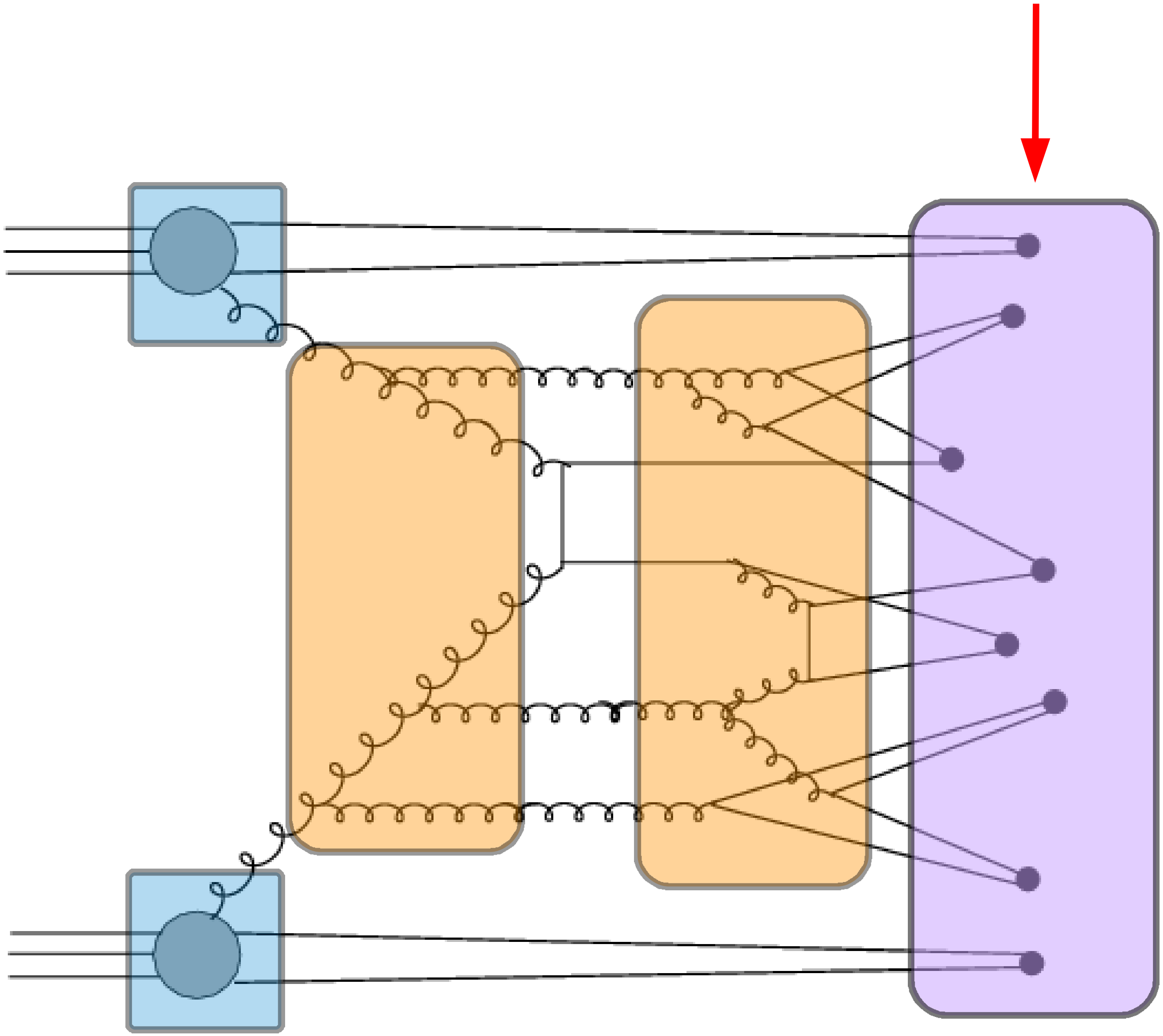


Formation of hadrons

PYTHIA:
The Lund string model

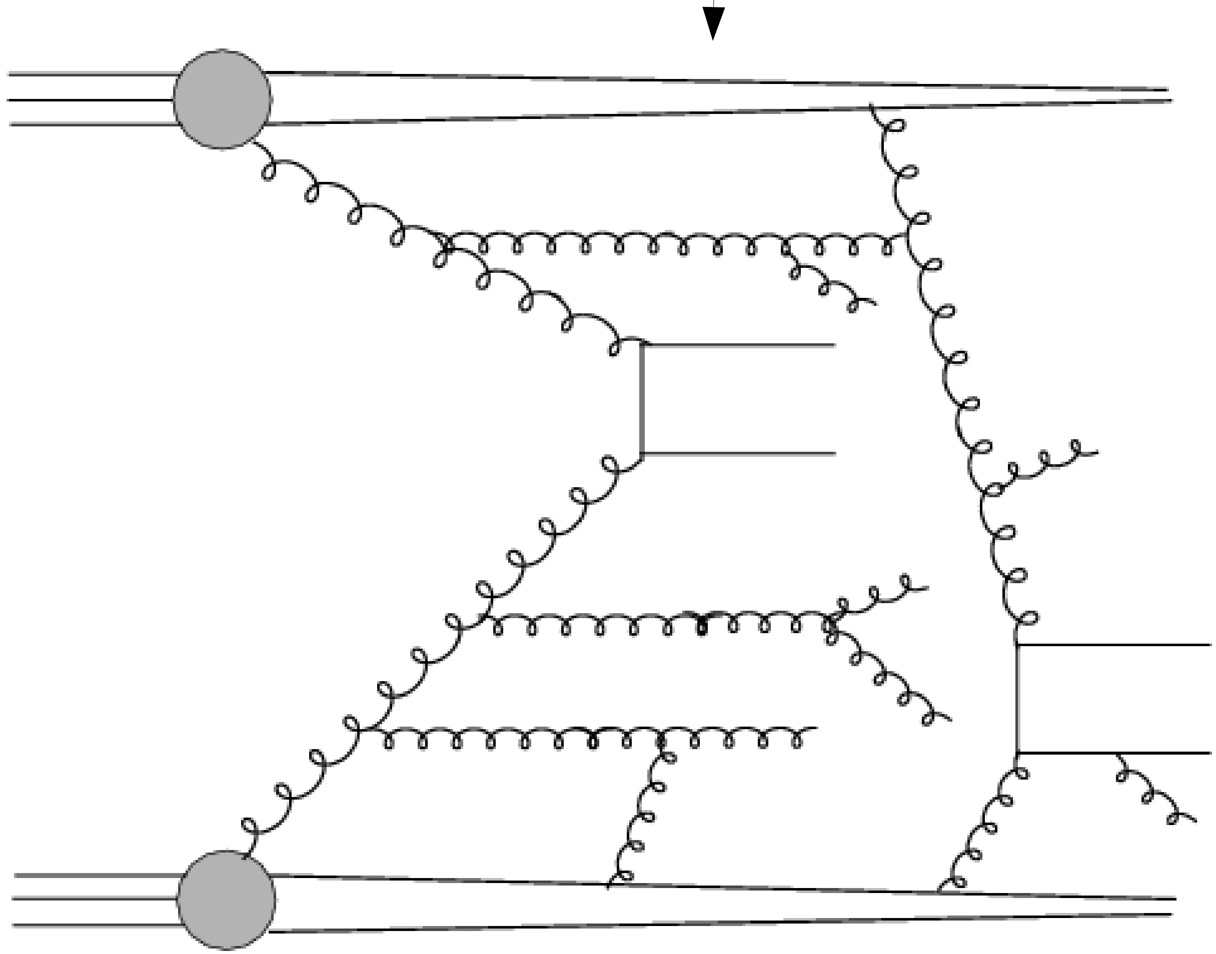
HERWIG:
Cluster fragmentation

A Monte Carlo Event

But we are not done yet. We may have several interactions within one collision:

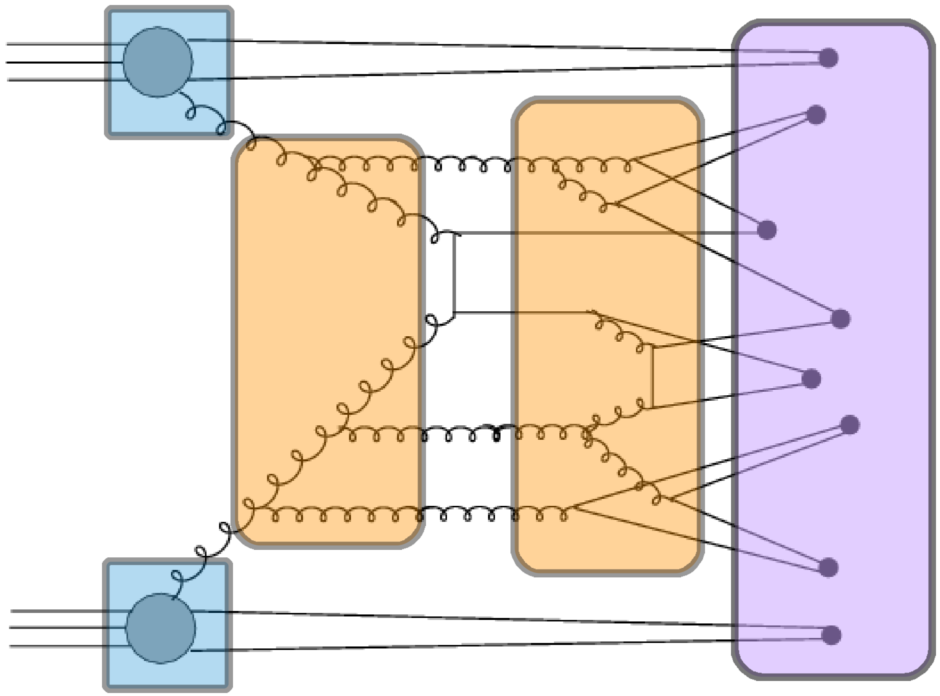
Multiple Parton Interactions

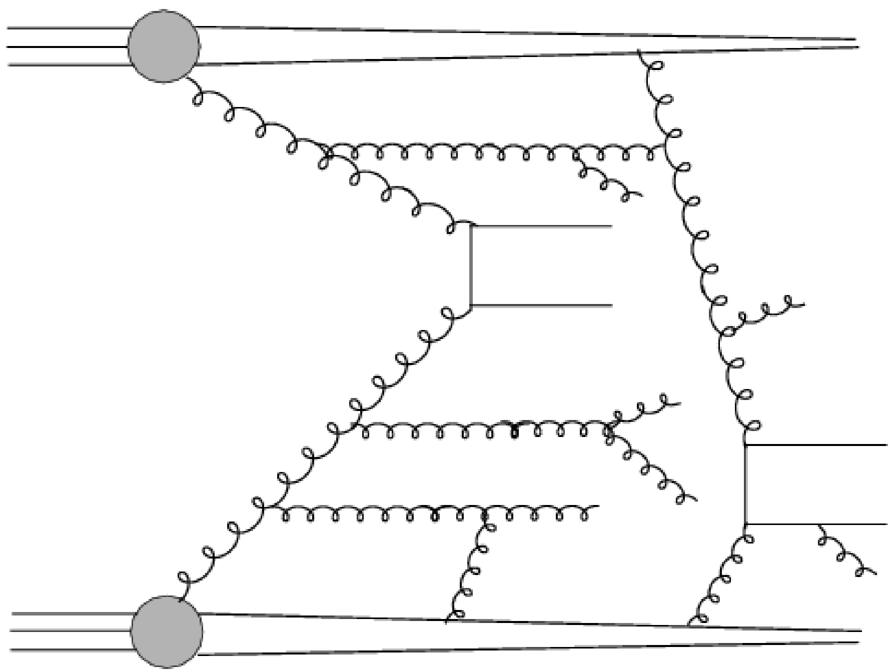
Event = PDF × (hard part × shower + MPI × shower) × hadronisation



A Monte Carlo Event

Event = PDF × (hard part × shower + MPI × shower) × hadronisation





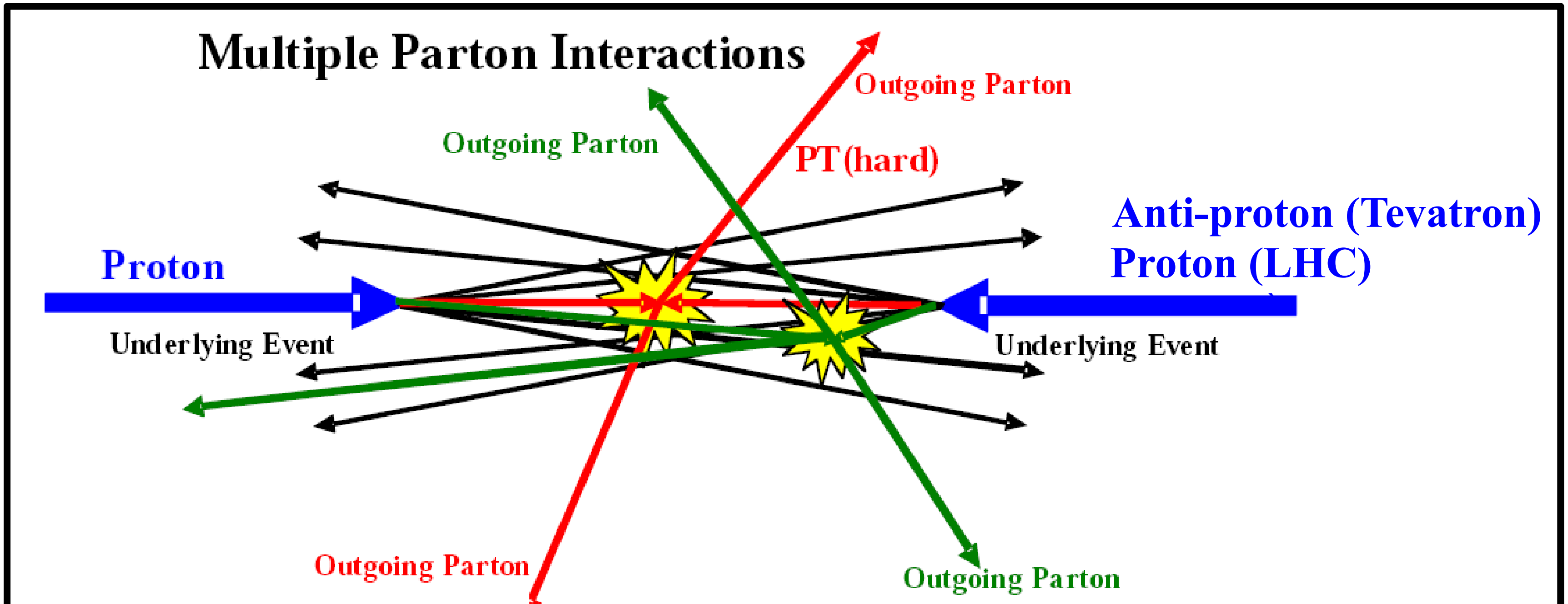
In the MC, **all the parts have free parameters** which needs to be determined by using data (LEP, HERA, TEVATRON, LHC, ...)

→ We need to fit or tune the MC parameters to data...

The Underlying Event (UE)

UE = everything except the studied LO process:

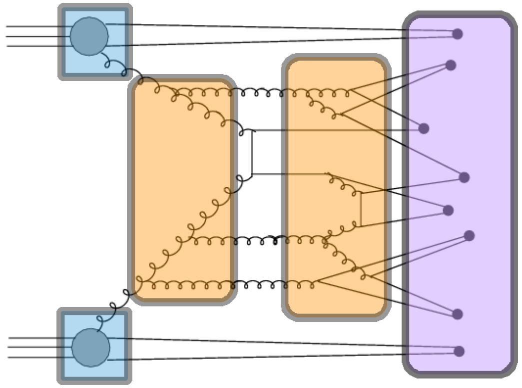
- Parton showers
- Multiple interactions:
    - Additional remnant-remnant, or parton-remnant interactions (soft or hard)
- Not pile up (= overlapping pp collisions in a triggered event. Machine dependent.)



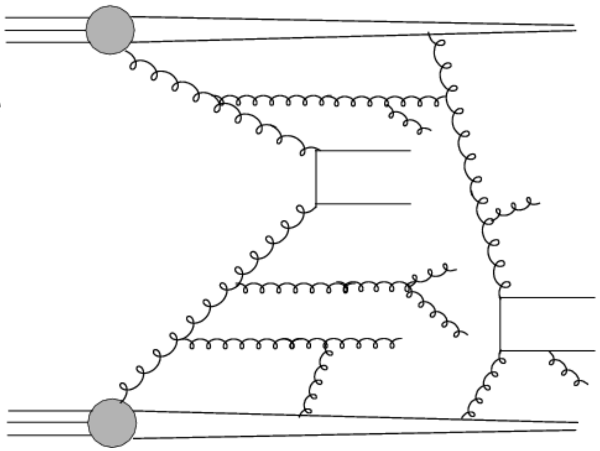
from R. Field

MC Tuning

Motivation for Tuning



- MC generators are based on phenomenological models, e.g.
  - PDFs
  - Fragmentation/hadronization models
  - MPI models
  - Parton shower and Dipole shower models



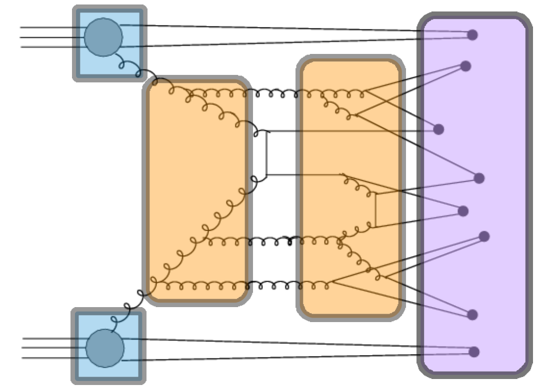
- The free parameters are not exactly theoretically calculable

- Many parameters are "non-universal" and model specific and exist only in the particular MC model.

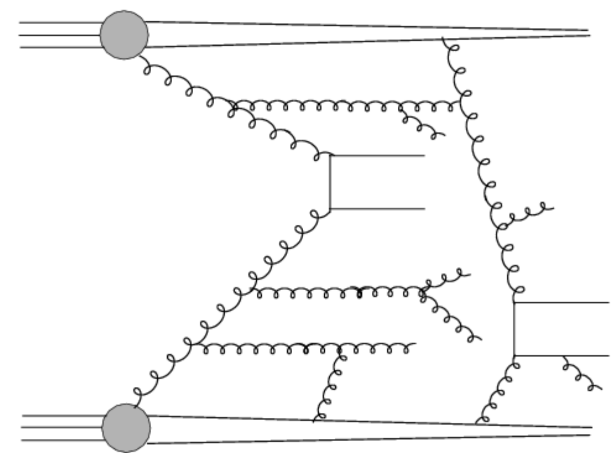
- The MC should describe (all) data as good as possible.

→ We need to tune the parameters in the generators.

Complications



- Many free parameters in the models
- Correlation between parameters
- Possible correlation between the different parts of the events.



Common stratetgy:

Tune the different parts of the event separately to data which is sensitive to the particular physics...

For example: use existing PDFs already fitted to HERA data, and tune the hadronization parameters to LEP data and the MI parameters to TEVATRON/LHC data.

Example of Parameters to Tune

- **Flavour parameters** (examples)

  Mainly parameters which gives (suppress) the **probability that quarks with a particlular flavour is produced**. Other parameters related to the fragmentation e.g. production probability and spin of mesons.

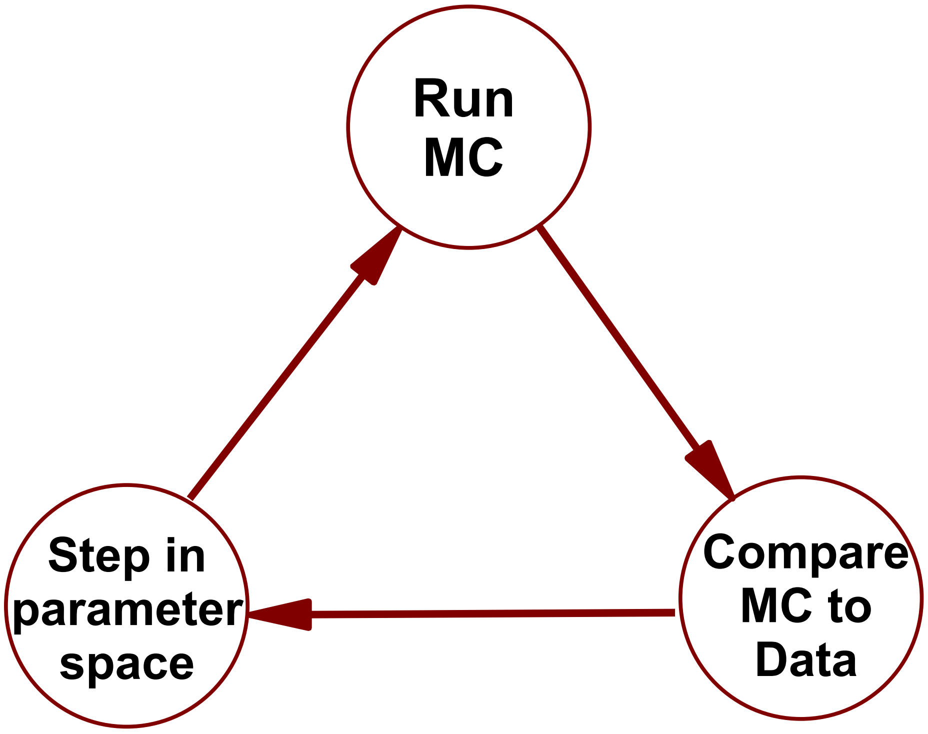
- **Fragmentation parameters** (examples)
  - **Width of Gaussian distribution for p_x and p_y of hadrons created in the hadronization**
  - **Λ_{QCD} for α_s in parton showers**
  - **Cut off parameters for parton showers.** Determines if partons will radiate or not.

- **Underlying event parameters** (examples)
  - **Parton shower parameters**
  - **Parameters determining the shape of the transverse-momentum spectra for MPI**
  - **Matter overlap for the colliding hadron (~impact parameter).**
  - **Probabilities that an additional interaction gives more gluons and how they color connected.**
  - **Parameters which determines the k_t-distribution of partons inside the proton**

The Classic Fitting Approach

...and why it doesnt work for the MC tuning.

1. **Calculate observables using Monte Carlo for a given set of parameter values**
2. **Compare to data, calculate χ^2 and feed it to a minimization program (MINUIT)**
3. **Minimization program estimates new parameter values**
4. **Iterate 1. - 3. until χ^2 is minimized**



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O(100) iterations needed to minimize χ^2,
i.e. the generator is run O(100) times, iteratively:

If one MC generator run takes 1 hour, the minimization takes O(100) hours.

One may need exclusive selections.

$\longrightarrow$

Good MC statistics. Minimization >> 100h.

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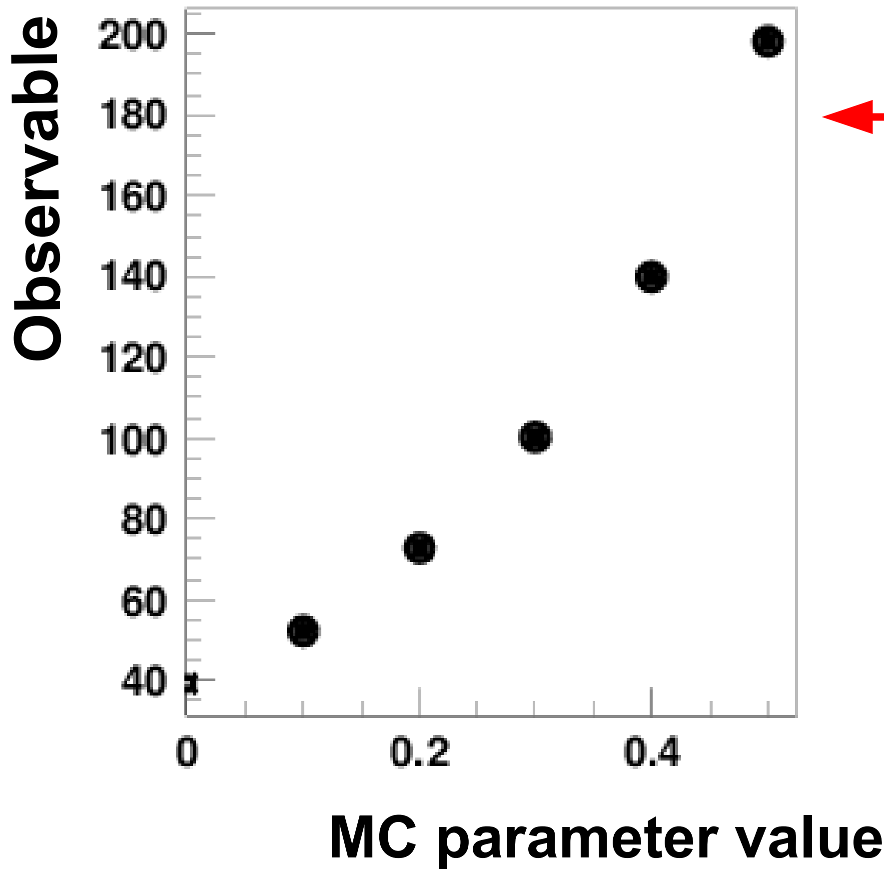
Automated Tuning Approach:

Describe parameter dependence before parameter fitting,
by using a ***grid in MC parameter space***.
The MC grid points can be calculated simultaneously.
The fitting itself then takes a few seconds.

Simplest possible example

1 parameter, 1 data observable

1. Do MC predictions in parameter space



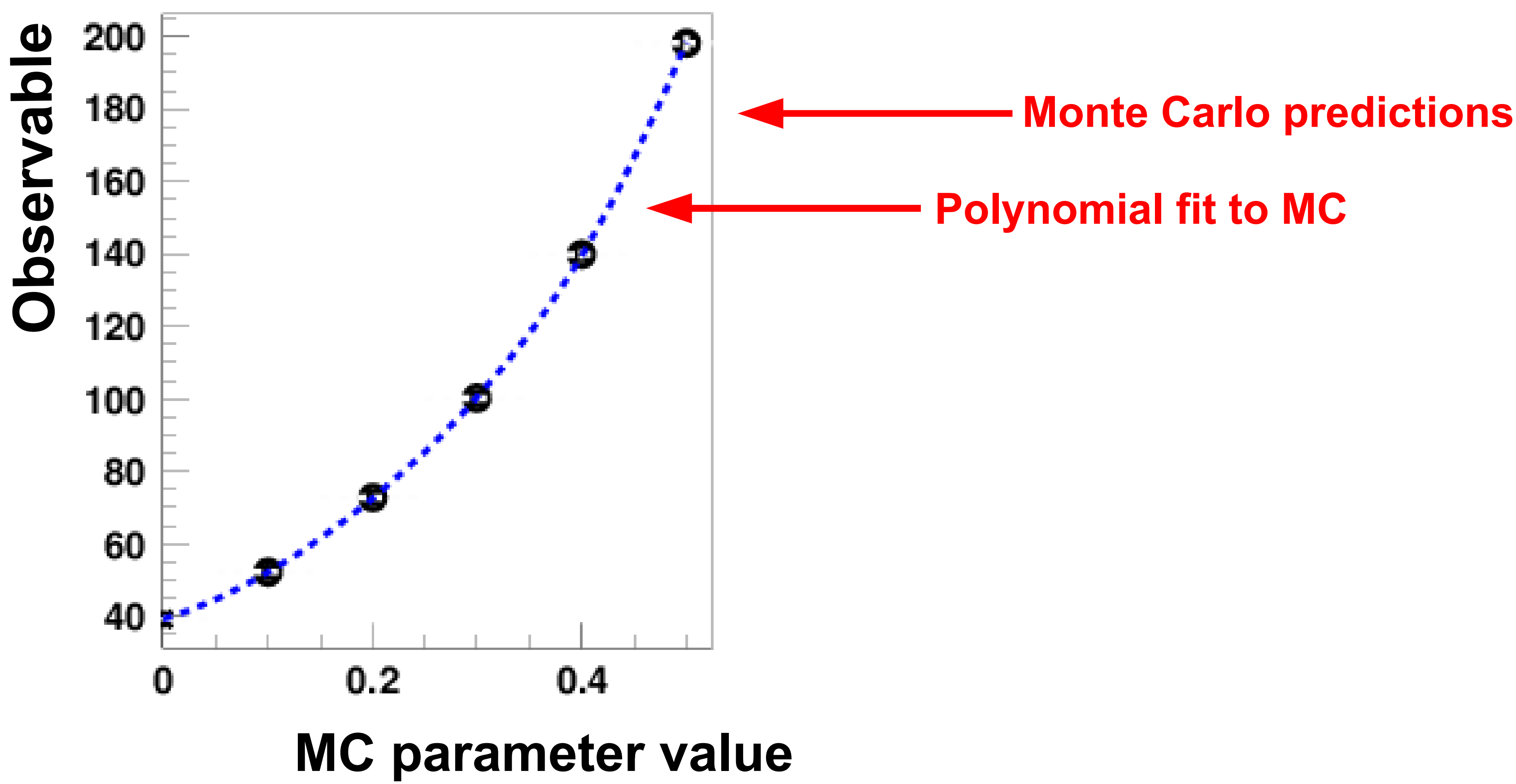
Monte Carlo predictions

Equidistant or random grid points.

Simplest possible example

1 parameter, 1 data cross-section

2. Determine polynomial using SVD

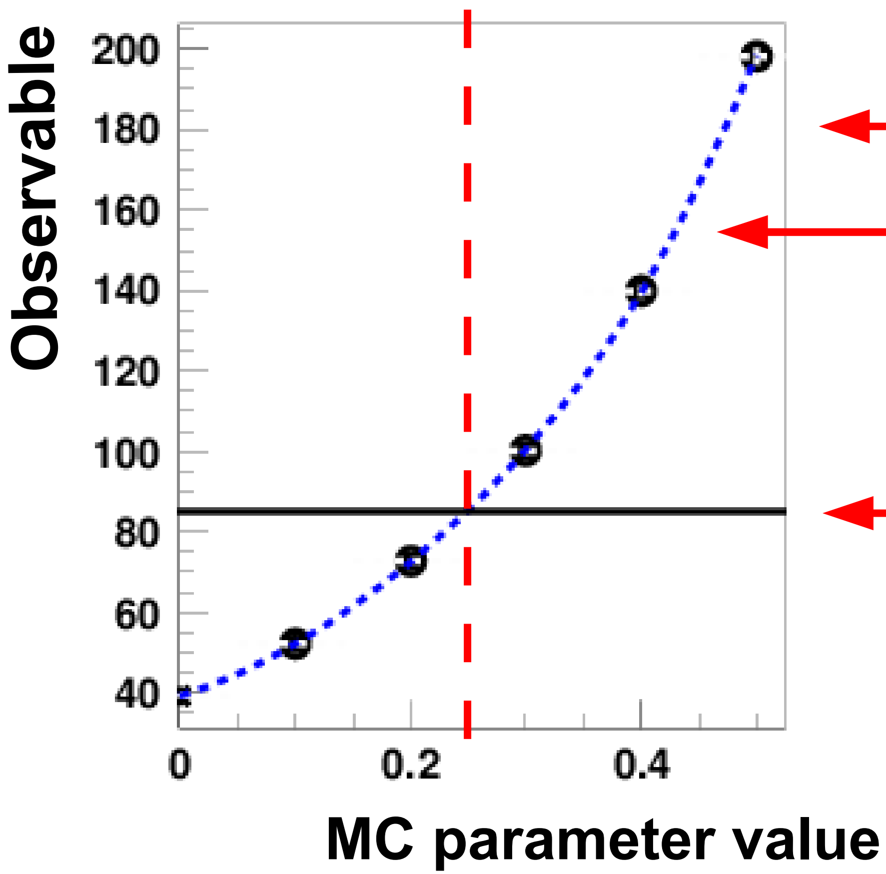


Automated Tuning – Simple Example

Simplest possible example

1 parameter, 1 data cross-section

3. Minimize Chi2 to data using the polynomial



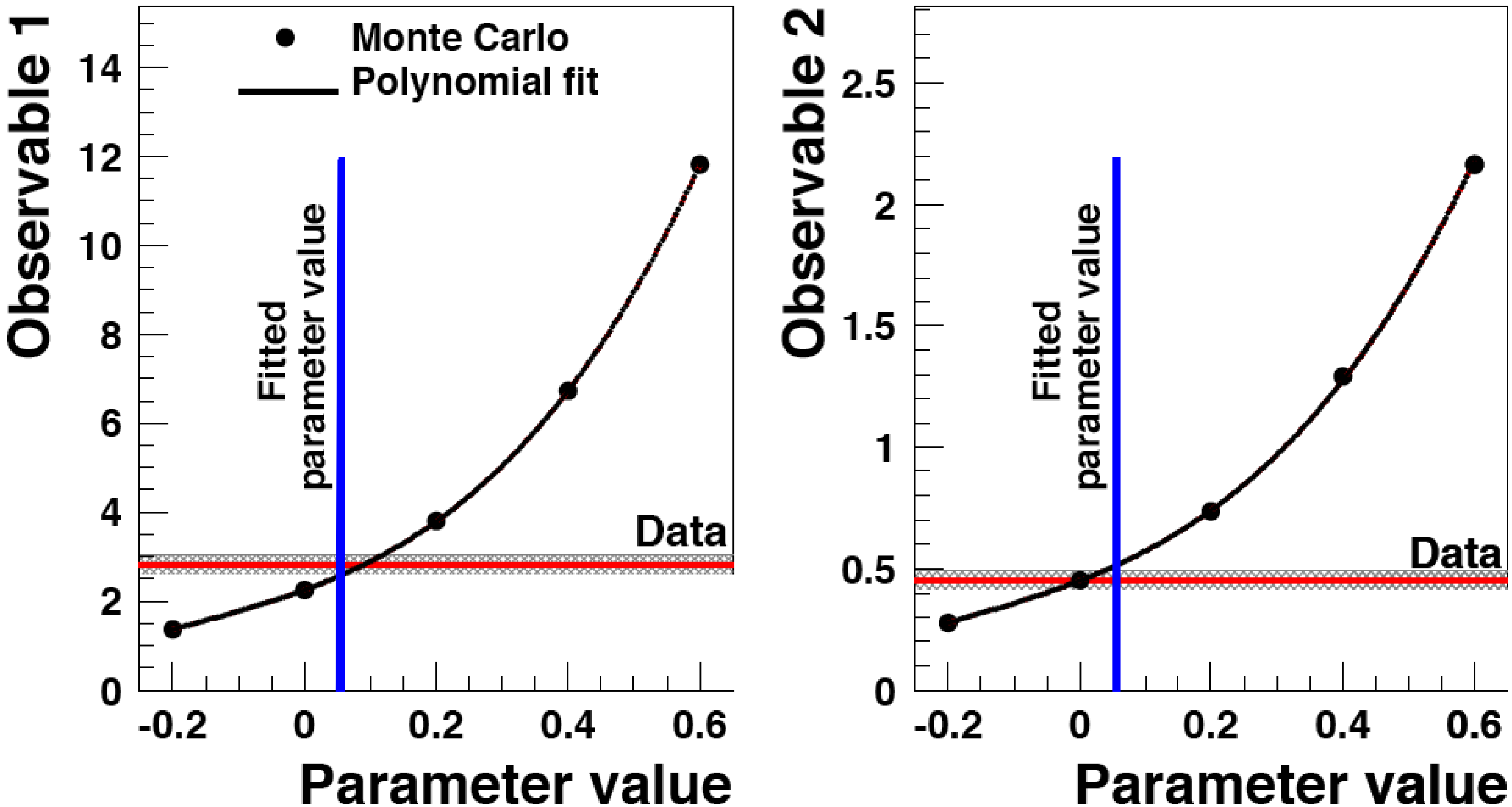
Monte Carlo predictions

Polynomial fit to MC

Fit polynomial to data cross-section

2 observables

If 2 observables (e.g. two data points in the same measurement):



...same thing, but we need two polynomials and minimum not that obvious.

Note the importance of including the error of the data in the fit. We do not need to be perfect, just good enough.

Automated Tuning

- **The method was suggested for LEP 14 years ago:**
  "Tuning and test of fragmentation models based on identified particles and precision event shape data.", *Z.Phys.C73:11-60,1996*

Implemented in the programs:

- **PROFESSOR:** **Extensively used for MC tuning within the experiments at LHC.**
  Used for tuning of HERWIG++ and PYTHIA.
  `[Buckley et al, Eur.Phys.J.C65:331-357,2010]`

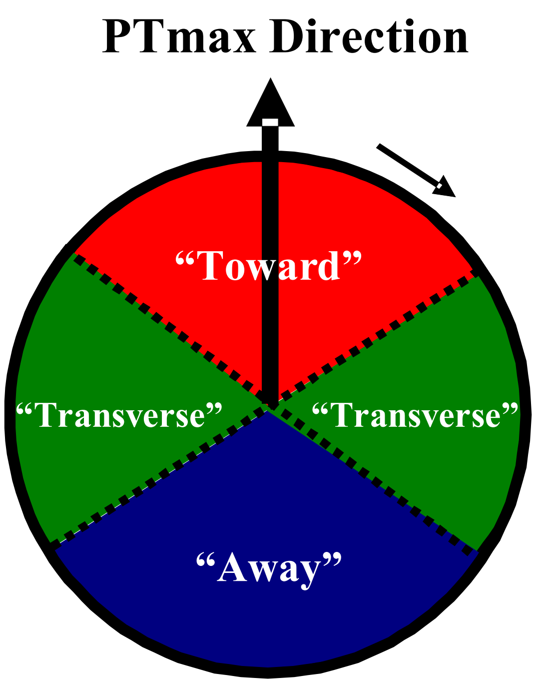
- **PROFFIT:** **Used at DESY to fit unintegrated PDFs to HERA data.**
  Emphasis on complete error treatment as in other PDF fits (a la CTEQ).
  Has also been used for tuning for fragmentation parameters to HERA data.
  `[Bachetta, AK, et al, Eur.Phys.J.C70:503, 2010]`

Measurements of the UE

The Classic UE Measurement

General idea: Measure the energy flow and particle multiplicity transverse to the hard object(s) produced in the sub-process.

This may be a jet or particle pair in Drell-Yan or simply just a particle with a high transverse energy.



- In the toward and away region the UE signal may be washed away by the hard activity (e.g. the high pt jet).
- High activity also in away region due to momentum balance.
- Transverse region expected to be more sensitive to MI and UE

Measured at the TEVATRON, LHC and HERA.

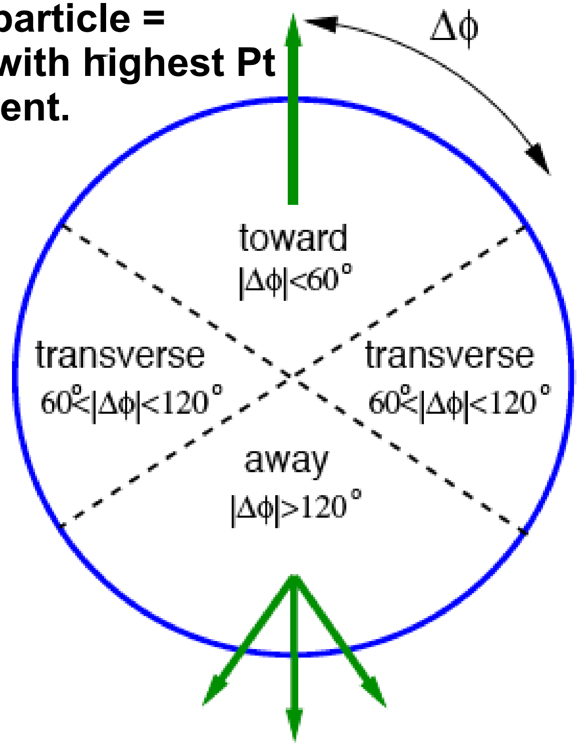
Recent measurements from ATLAS

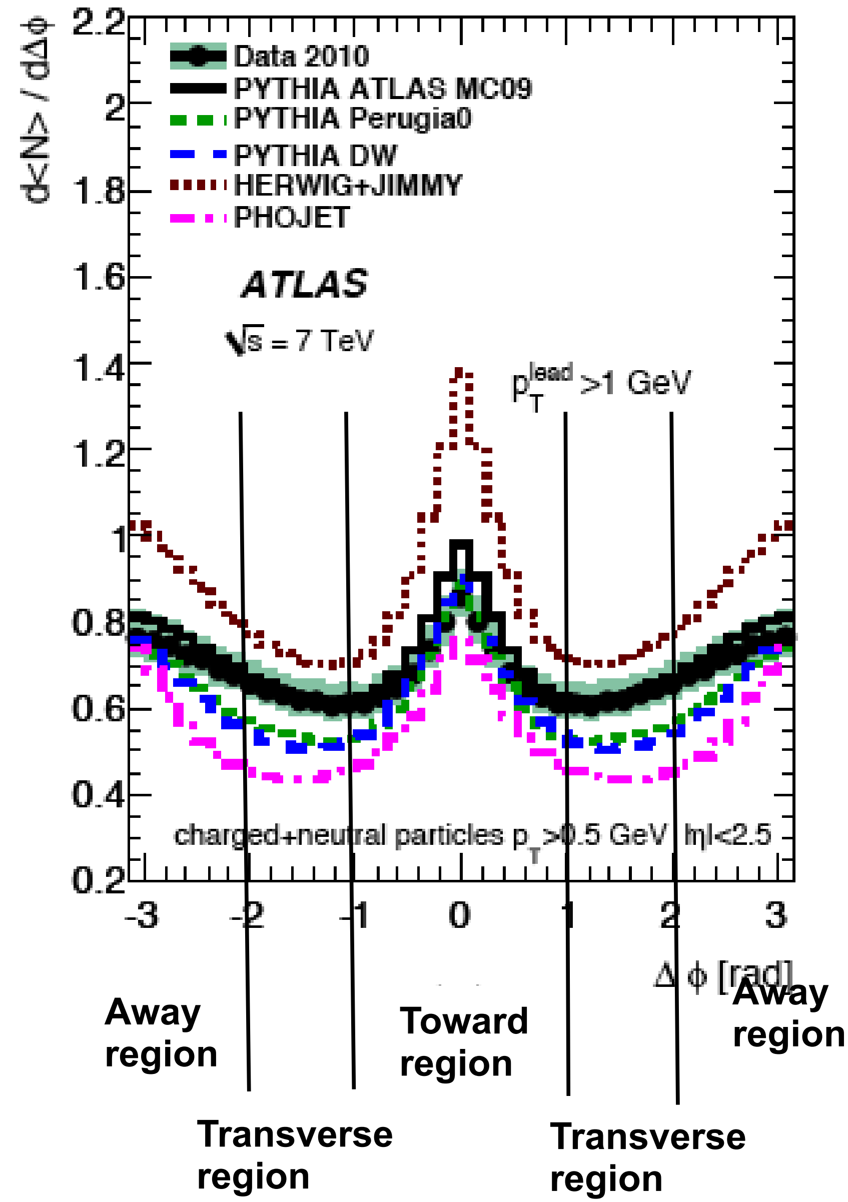
[arXiv:1103.1816v1 submitted to EPJC]

Select collisions where the leading particle has a Pt>1 GeV.

Measure the activity in the event with respect to this particle.

leading particle = particle with highest Pt in the event.

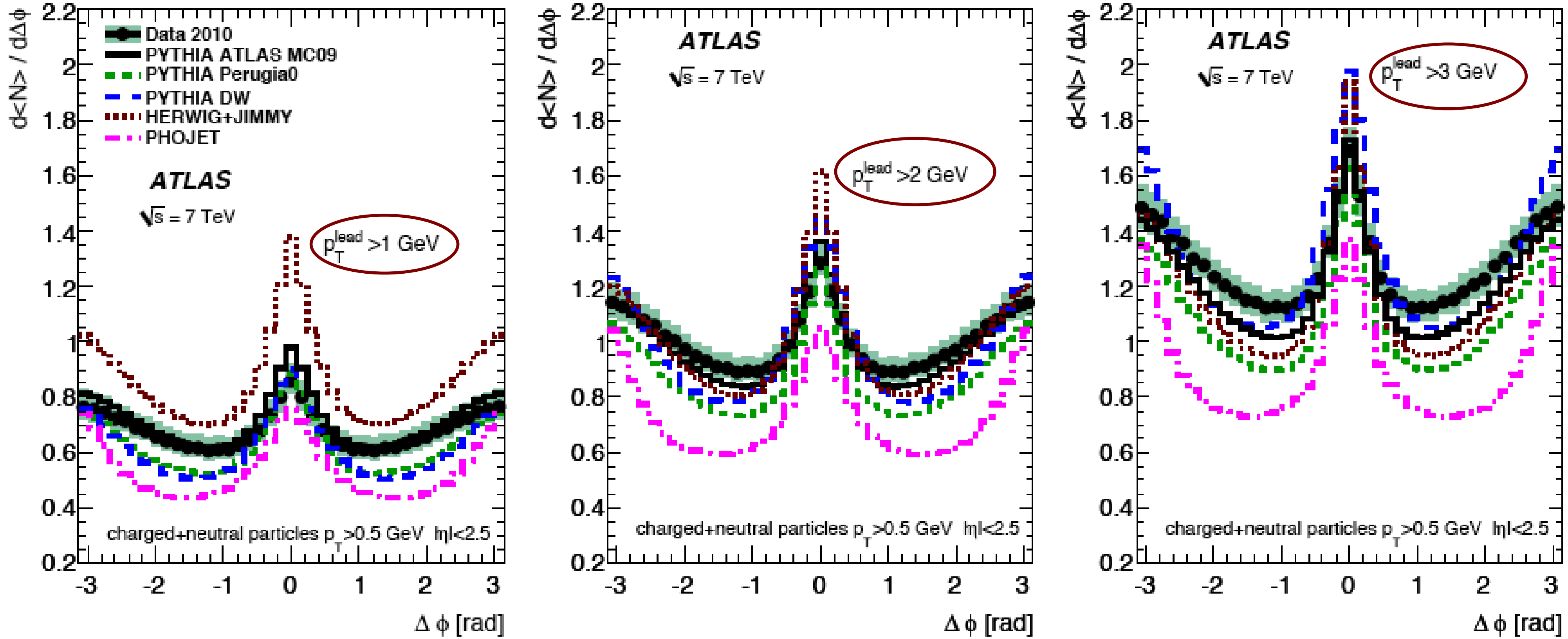




- **High activity (particle multplicity) in the region around the leading particle**
- **Large activity in the opposite region to to the leading particle. Momentum conservation.**
- **Lowest activity transverse to the leading particle. Measure the underlying event here.**

Recent measurements from ATLAS

Mesurement repeated for different Pt requirements of the leading particle:



- **The hardness of the reaction effect the whole underlying event structure. Higher leading Pt ⟶ More activity all over the event and a more focused activity around the leading particle.**

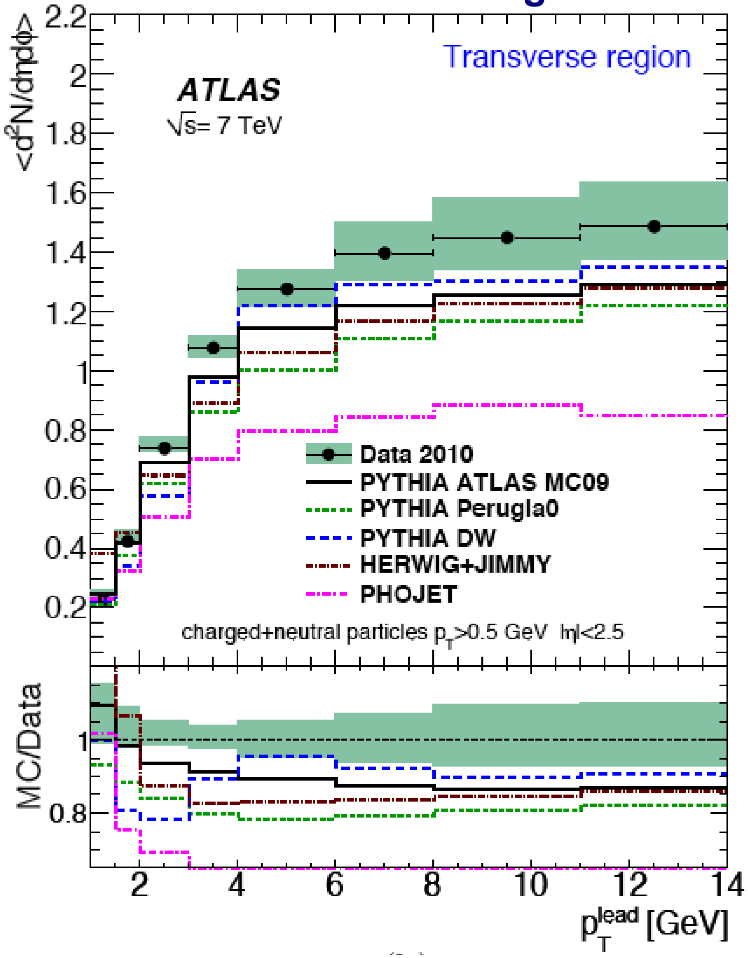
MC-data comparison:

- **The MC that was tuned to other data do not describe this data.**
- **No MC describes the details of the data.**
- **High discriminating power. We should use the data to improve the models.**

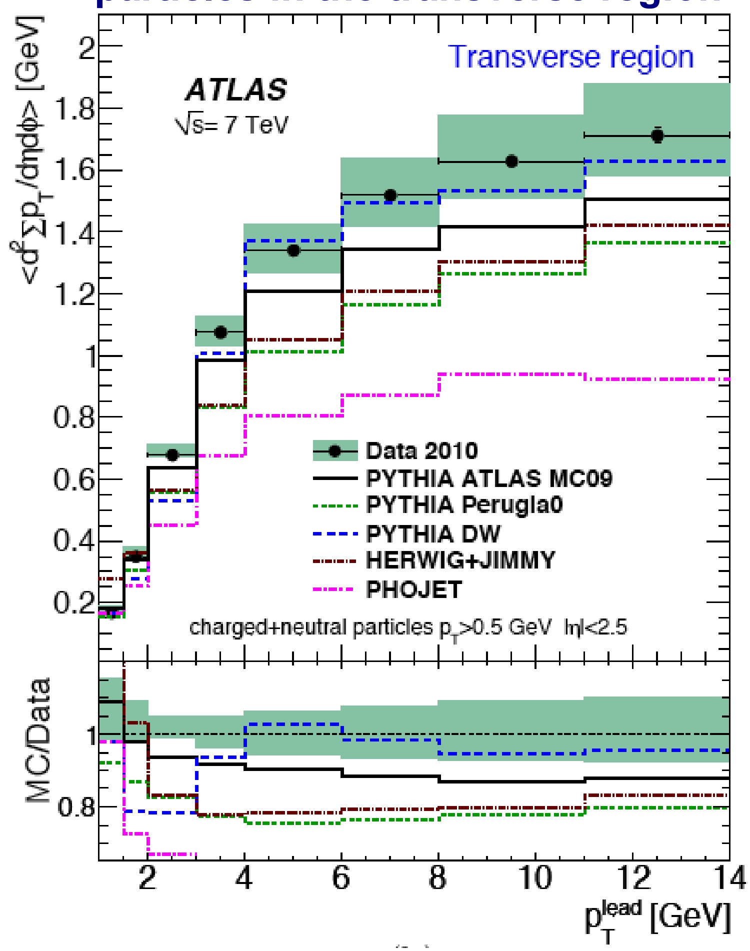
Recent measurements from ATLAS

A typical UE measurement a la Tevatron: Look at activity in the transverse regions:

Average particle multiplicity in the transverse region



Average transverse momenta of particles in the transverse region

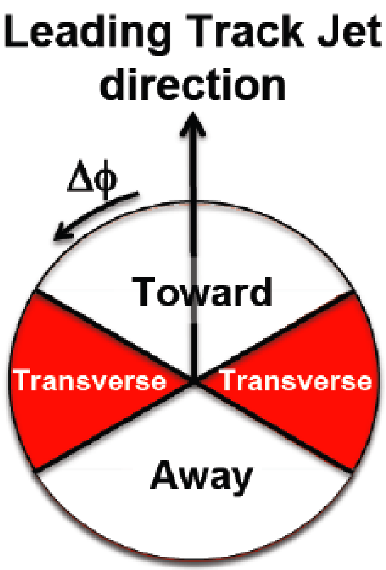


- **The particle multiplicity in the UE increases when the hardness of the reaction increases. (This we already learned from the last slide.)**

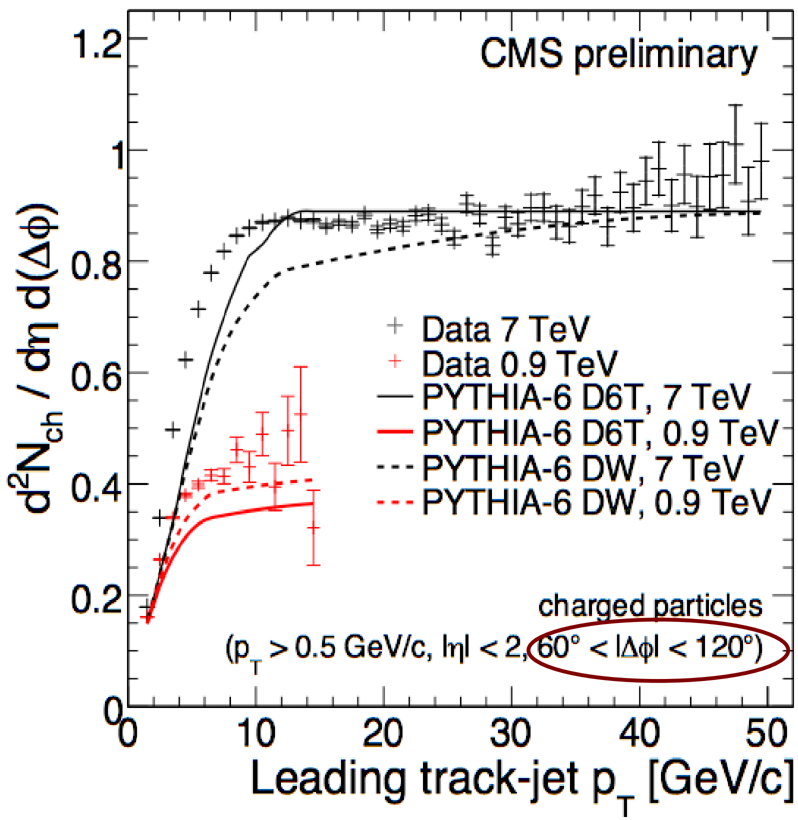
- **Pt in the UE also increases with p_t-lead.**
- **Again: we do not understand what is in the UE. No single MC describes all the data...**

Recent measurement from CMS [CMS-QCD-10-010]

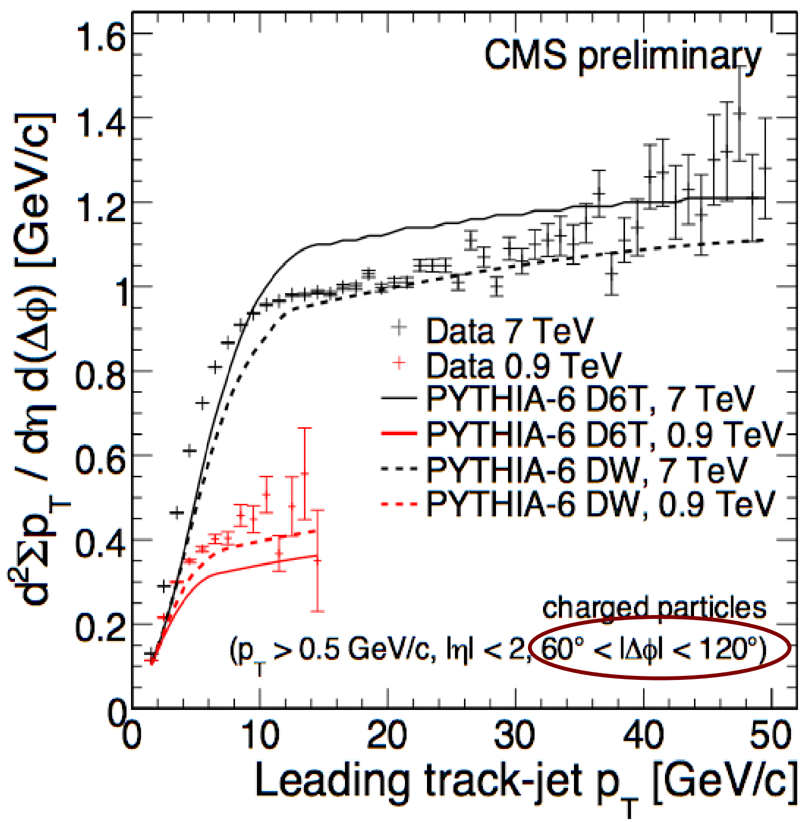
Similar measurement from CMS. Using a (track-) jet to define the reference axis.



Average particle multiplicity in the transverse region

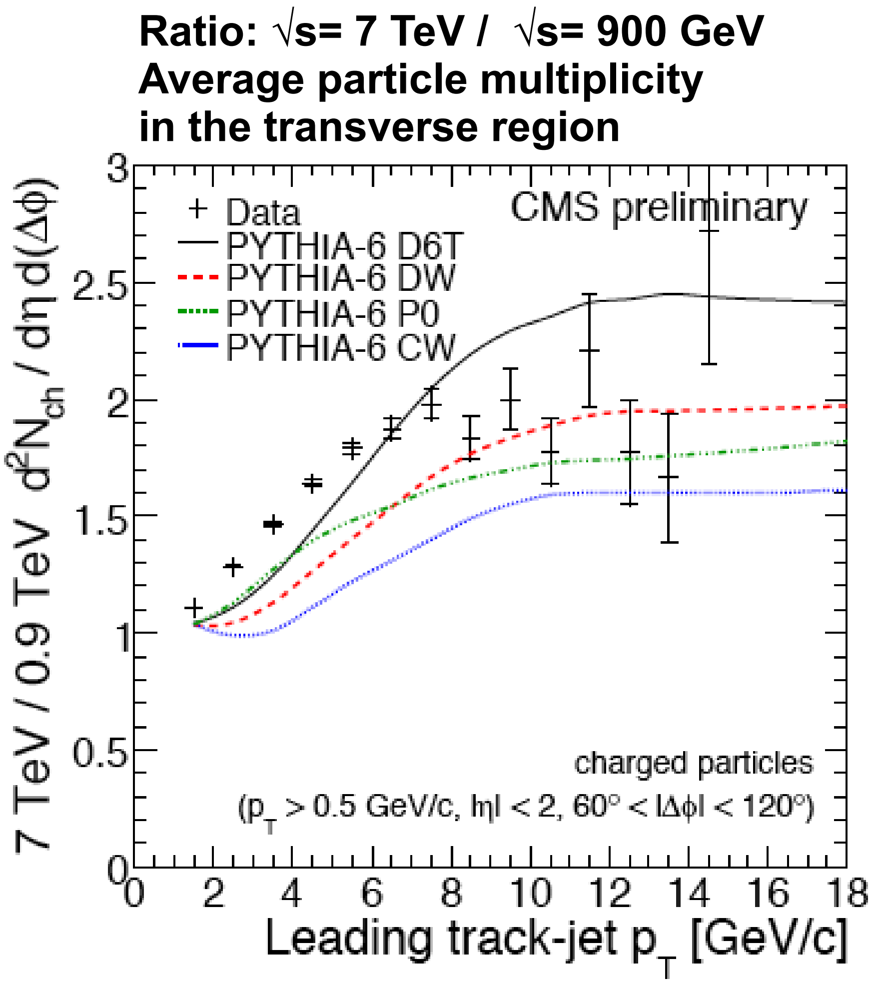


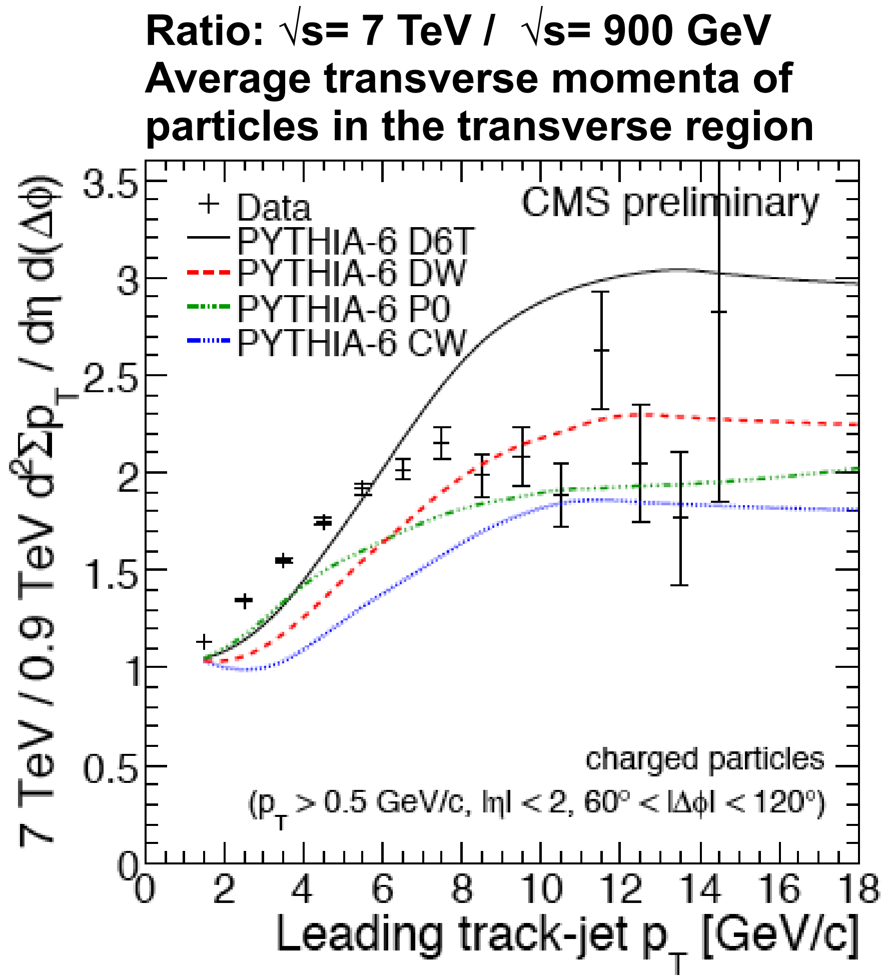
Average transverse momenta of particles in the transverse region



- **The UE depends also on the center of mass energy of the collision.**
- **MC unsatisfactory description of the data.**

Recent measurement from CMS





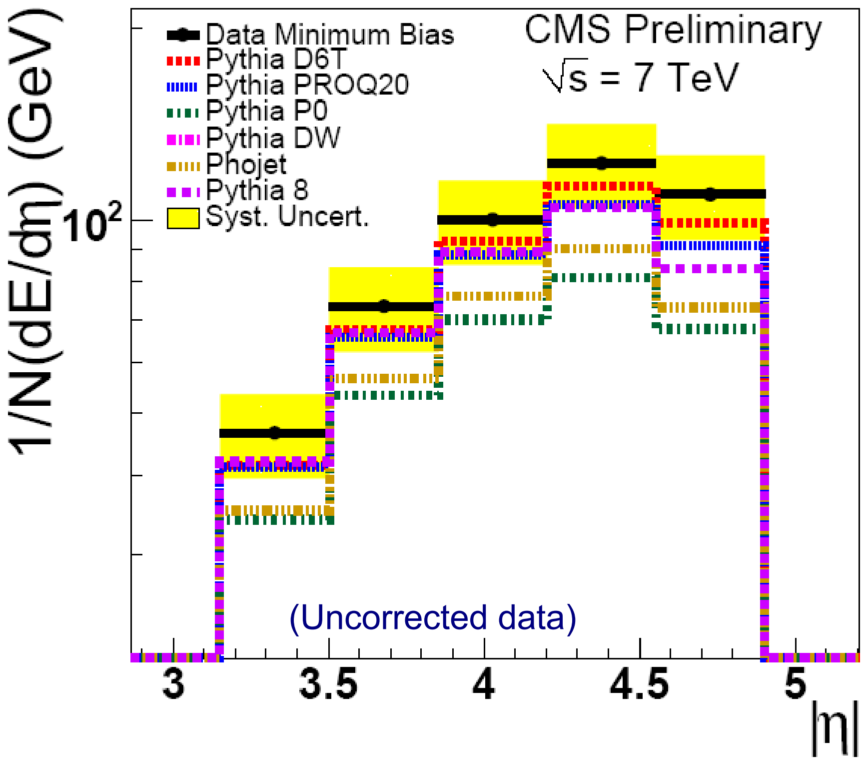
- **The increase of the UE with center of mass energy depends on the hardness of the reaction.**
- **None of the tested Pythia models can describe this behaviour.**

Alternative measurement (CMS)

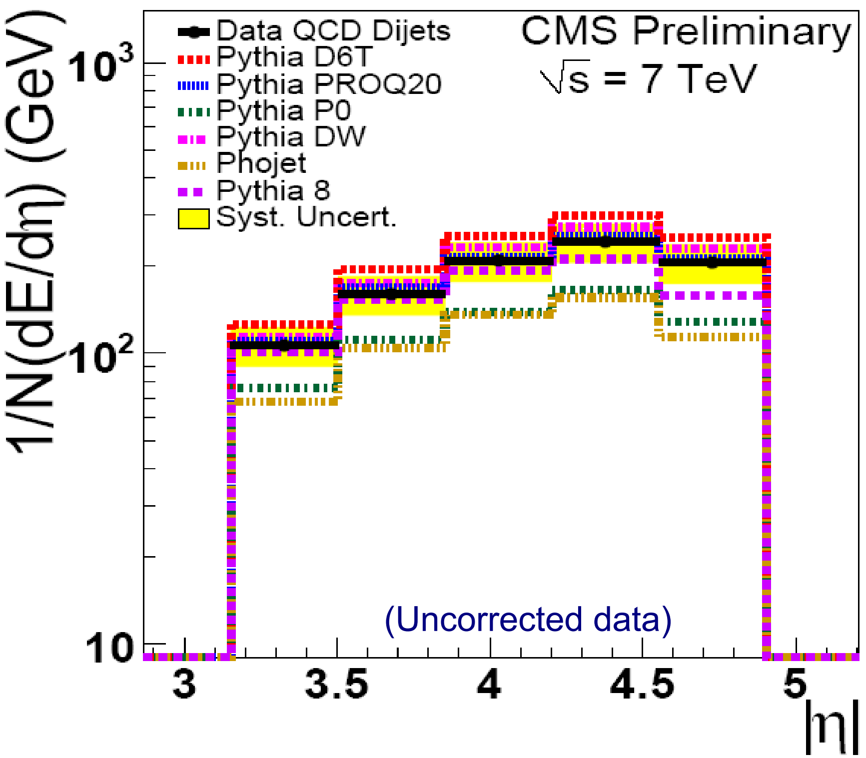
- There are many alternative measurements that can teach us about the UE and the MC models. Just one example...

- Energy flow in the forward region (= close to the beam direction) for Minimum Bias events and Di-jet events.

Minimum Bias Data



Central Di-jets Data



- Yet another example of that none of the existing MC models/tunes can describes all data. Which MC that “works” depends on the hardness of reaction.
  --> Sensitivity to the parameters and models.

Tuning example –

Recent tune from ATLAS where they used the here presented (prelim.) ATLAS data to perform a MC tune.

Tuning example – Recent tuning from ATLAS

ATLAS has improved the description of the data by the MC by tuning MC parameters.
First tune done to √s=7 TeV data.

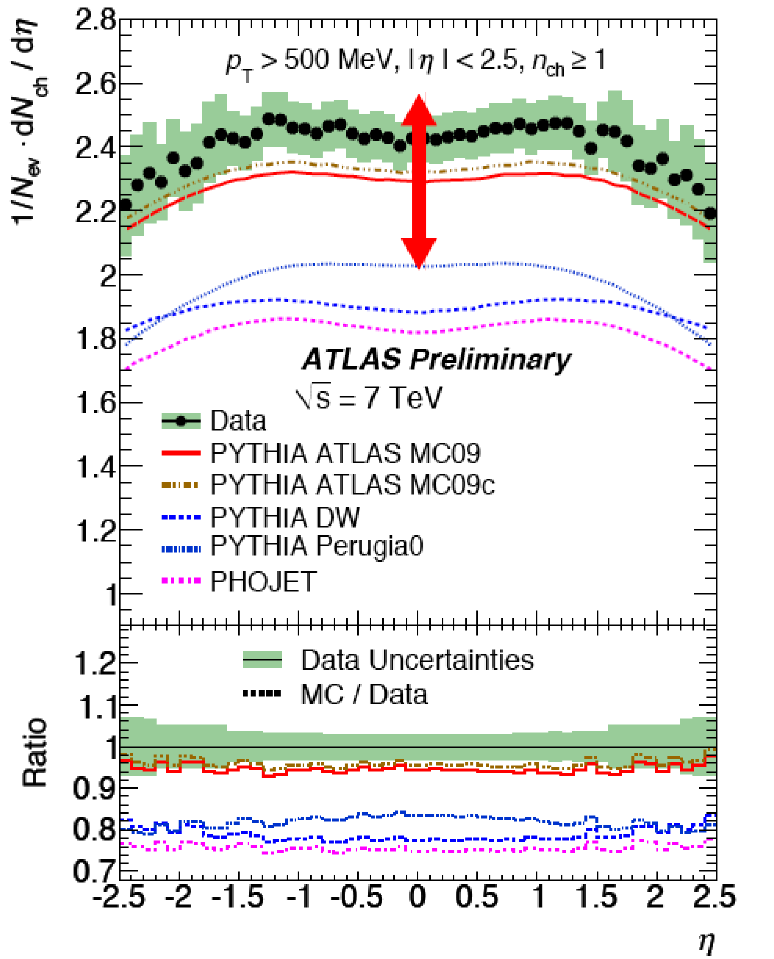
- **Regulatization cut-off in 2 → 2 scatterings in MI:**

Dependence on center of mass energy.

$$p_T^{min}(E_{CM}) = \boxed{p_T^{min}(E_{ref})} \cdot \left(\frac{E_{CM}}{E_{ref}}\right)^{\boxed{\alpha}}$$

tuned parameters

p_T^{min} **lower** → **more activity**



Slide adapted from talk by J. Katzy
(LHC forum DESY January 2011)
and M. Warsinsky
(Helmholtz Alliance Yearly Meeting December 2011)

*Tuning example – Recent tuning from ATLAS**

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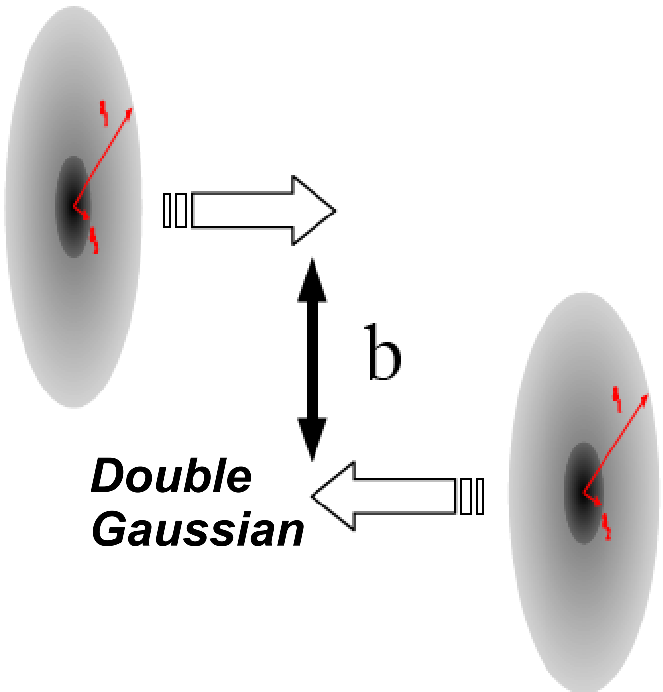
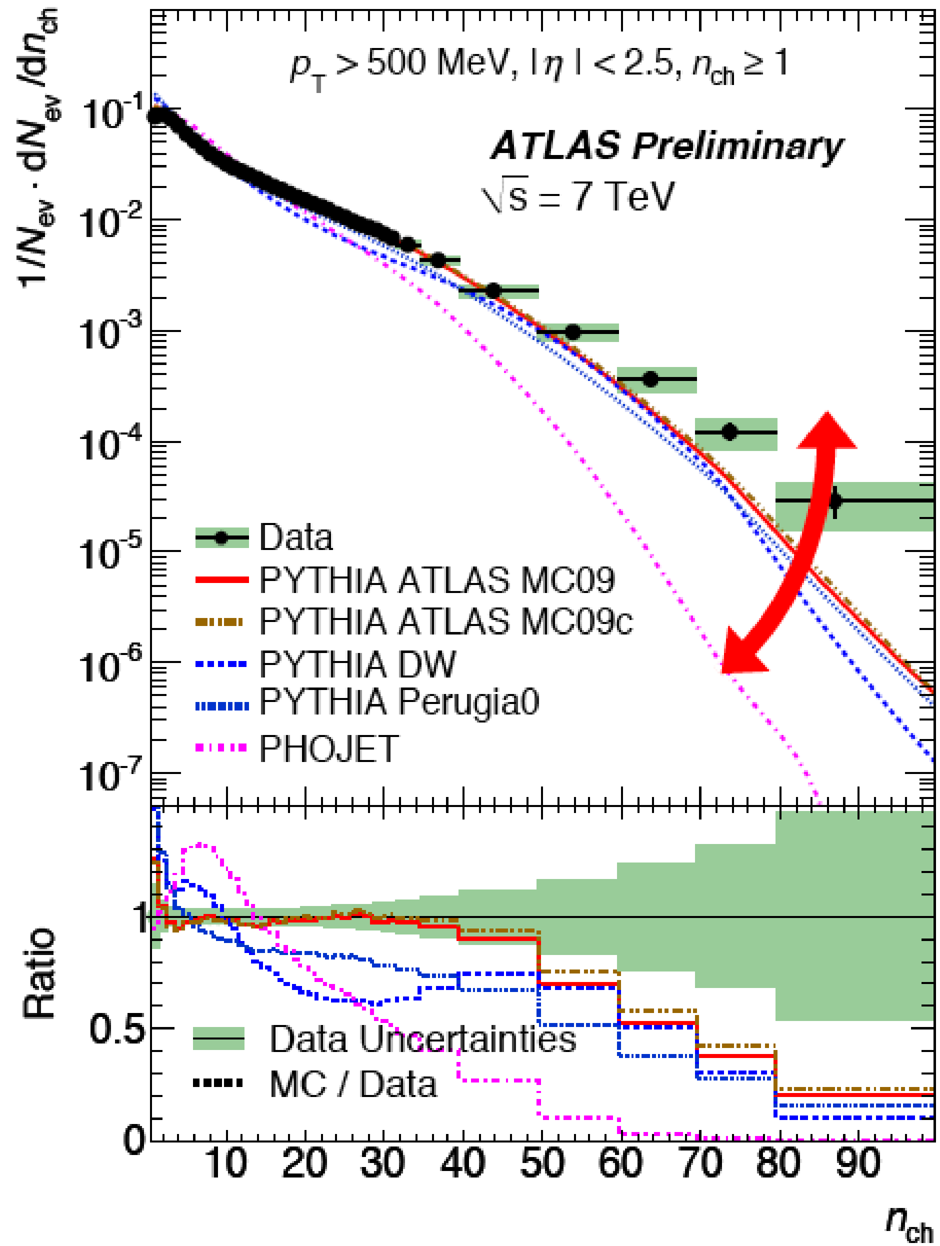
- **Matter overlap (central or peripheral collisions):**



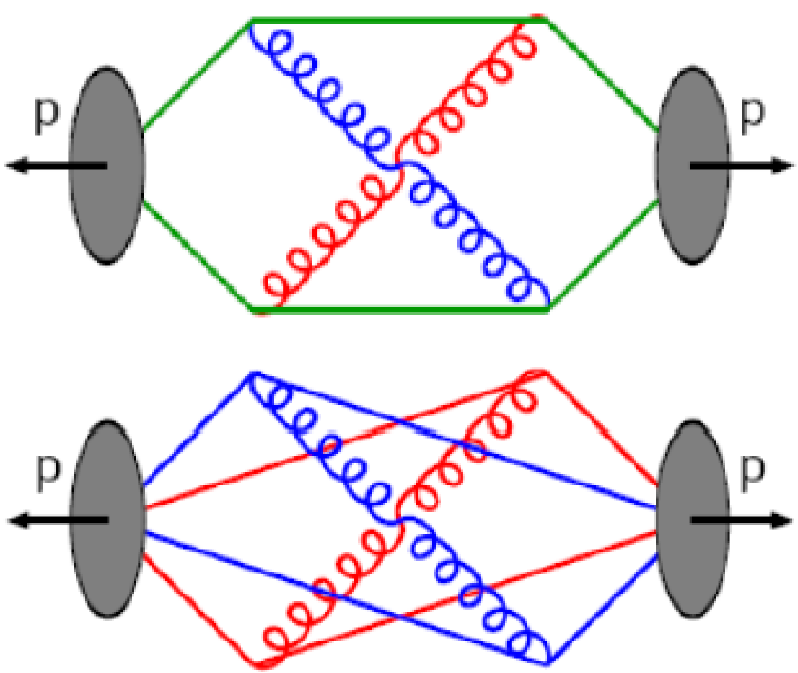


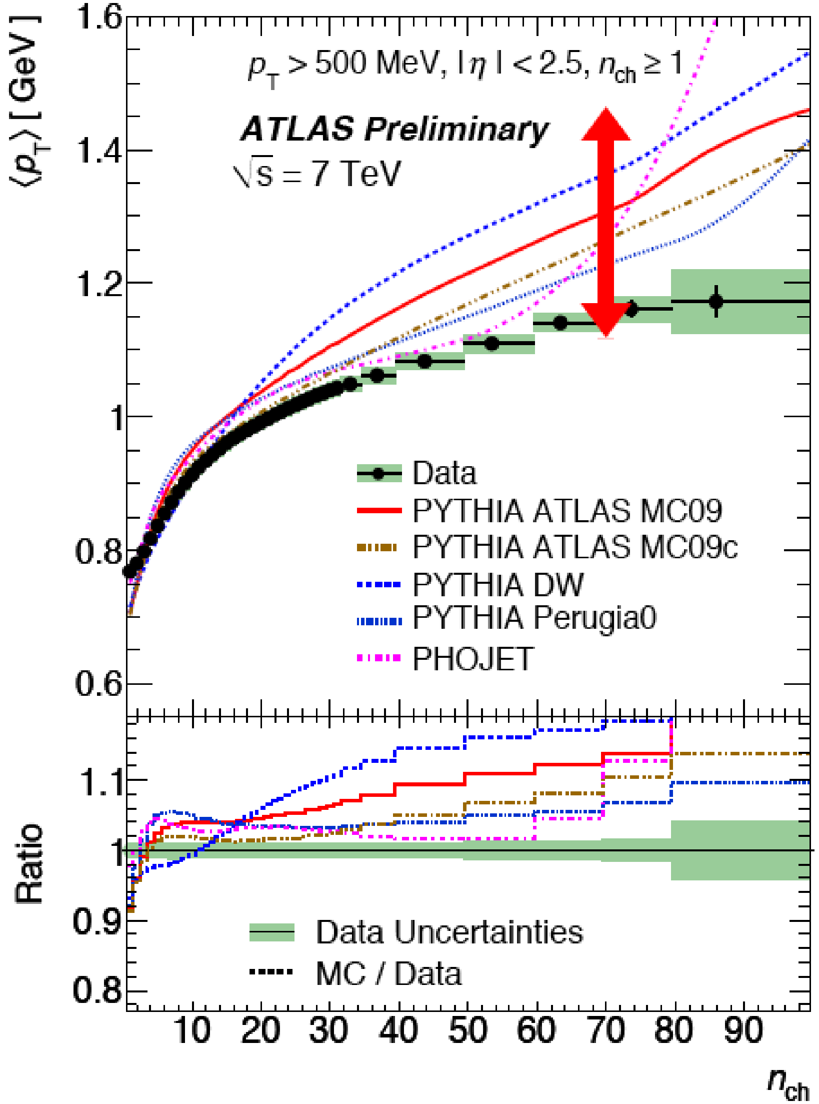
→ **Varying the matter overlap affects the high multiplicity tail.**

Tuning example – Recent tuning from ATLAS

• **Tune the color reconnection strength and suppression of fast moving string pieces.**

Probability for MI to produce 2 gluons with color strings to closest neighbor.

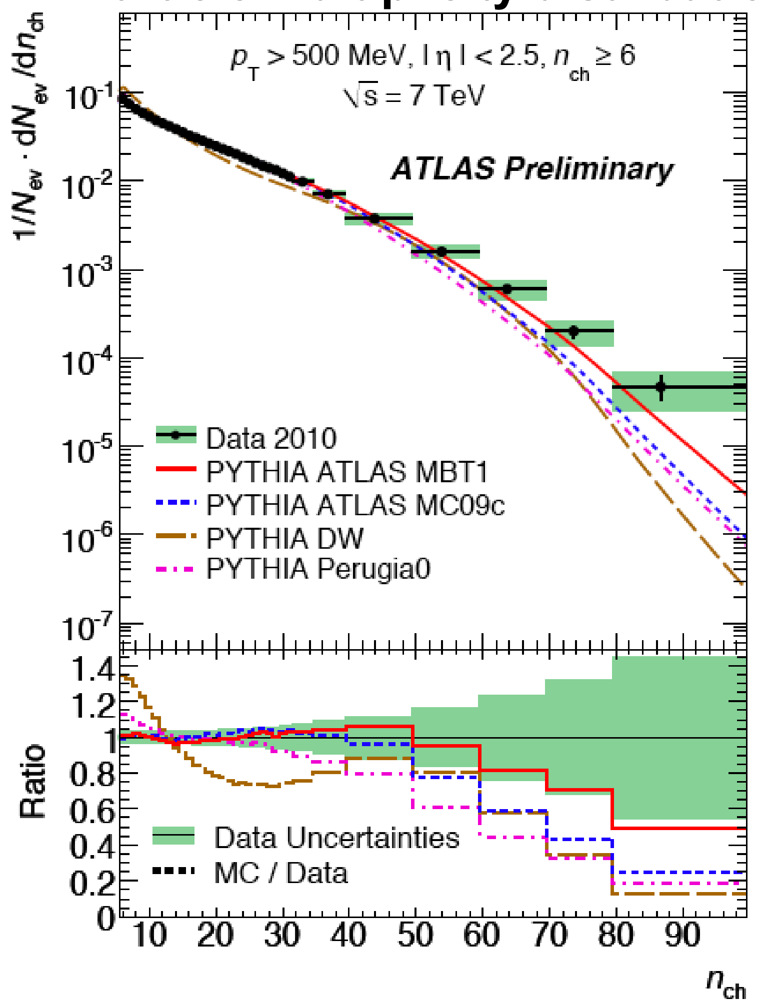




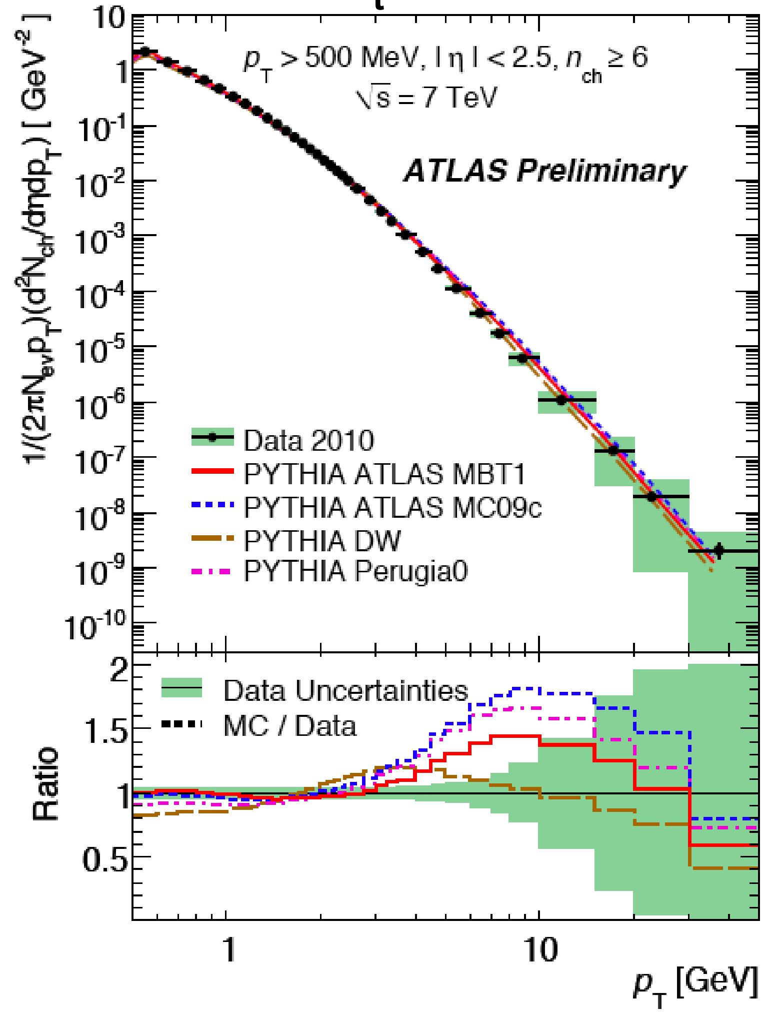
Tuning example – Recent tuning from ATLAS

Tune result (5 parameters):

Particle multiplicity distribution



Particle P_t distribution

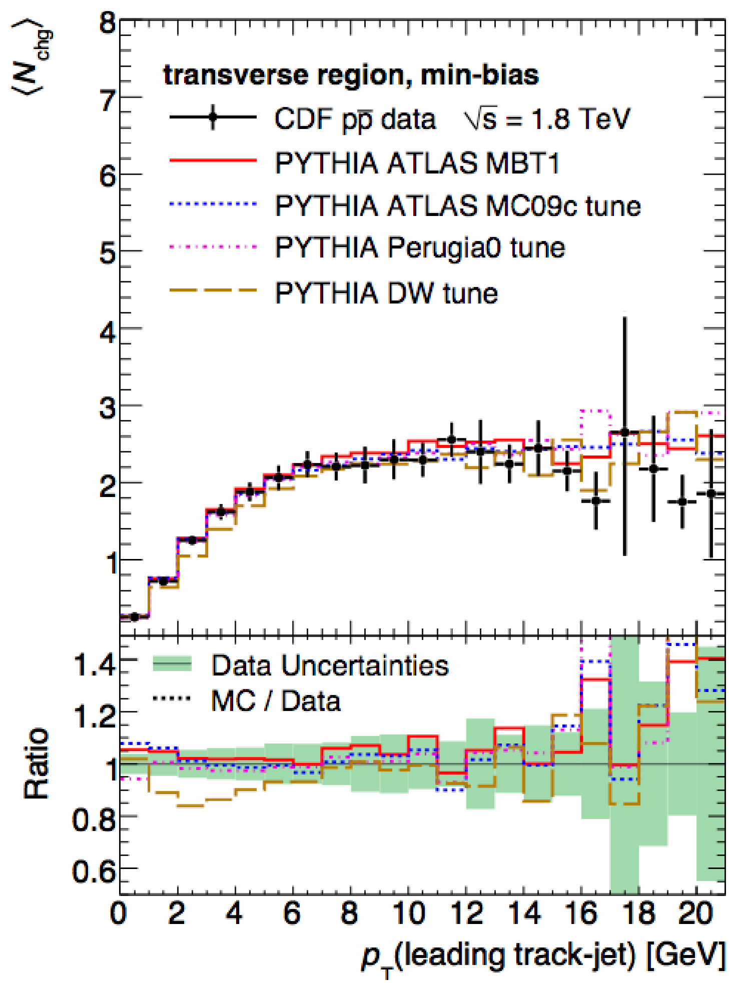


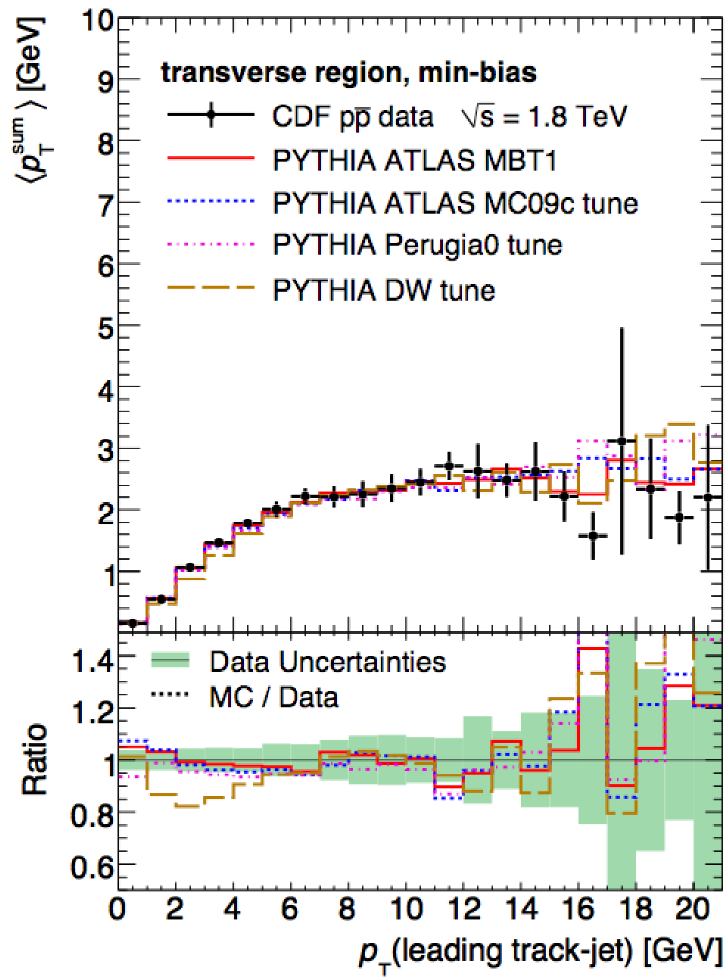
- **Very good description at low N and Pt.**
- **Improved description of data at high N and Pt.**
- **But data still not understood...**

Tuning example – Recent tuning from ATLAS

The challenge is of course to not destroy the description of other data.
(We need a proper model with enough universality / correct energy dependencies.)

ATLAS tune compared to UE data from the Tevatron at √s=1.8 TeV





- **Very good description of the Tevatron data.**

Quick overview of other tunes

Different Tunes

The Pythia6 Tunes from Rick Field

- Manual tunes to Tevatron data, recently also active tuning to LHC data.

The PROFESSOR Tune of Pythia

- Tune flavour and fragmentation to LEP data.
- Tune the UE parameters to TEVATRON data.

The Perugia Tunes, by the Pythia author (Skands) et al, arXiv:1005.3457v2

- A set of complete tunes of MC parameters including Final State Radiation, Hadronisation, Initial state radiation, MPI, Beam remnants, Color Reconnections.

Herwig++ Tuning activities

- Determination of the 2 free MPI parameters to TEVATRON data
- Tune the hadronization to LEP data, and color reconnection to ATLAS data

Sherpa, Pythia 8, and other Mcs tuning.

The ATLAS Tune(s): Use PROFESSOR for PYTHIA tuning within the ATLAS experiment.

CMS specific tunes within short.

Quick overview of Pythia tunes

Just to give you a feeling how active this area of QCD has been the last years...

Screenshot from
P.Skand, Phys.Rev.D82:074018,2010
(Good publication if want to know more about tuning.)

100+: Q^2-ordered shower and "old" underlying-event model

MSTP(5)	Name		Description	Date
1st generation: Rick Field's CDF tunes and a few more				
100	A	:	Rick Field's CDF Tune A	(Oct 2002)
101	AW	:	Rick Field's CDF Tune AW	(Apr 2006)
102	BW	:	Rick Field's CDF Tune BW	(Apr 2006)
103	DW	:	Rick Field's CDF Tune DW	(Apr 2006)
104	DWT	:	As DW but with the old default ECM-scaling	(Apr 2006)
105	QW	:	Rick Field's CDF Tune QW using CTEQ6.1M	
106	ATLAS-DC2	:	Arthur Moraes' (old) ATLAS tune ("Rome")	
107	ACR	:	Tune A modified with new CR model	(Mar 2007)
108	D6	:	Rick Field's CDF Tune D6 using CTEQ6L1	
109	D6T	:	Rick Field's CDF Tune D6T using CTEQ6L1	
2nd generation: The same, but with Professor's LEP parameters				
110	A-Pro	:	Tune A, but with Professor's LEP parameters	(Oct 2008)
111	AW-Pro	:	Tune AW, but with Professor's LEP parameters	(Oct 2008)
112	BW-Pro	:	Tune BW, but with Professor's LEP parameters	(Oct 2008)
113	DW-Pro	:	Tune DW, but with Professor's LEP parameters	(Oct 2008)
114	DWT-Pro	:	Tune DWT, but with Professor's LEP parameters	(Oct 2008)
115	QW-Pro	:	Tune QW, but with Professor's LEP parameters	(Oct 2008)
116	ATLAS-DC2-Pro	:	ATLAS-DC2/Rome, but with Professor's LEP parameters	(Oct 2008)
117	ACR-Pro	:	Tune ACR, but with Professor's LEP parameters	(Oct 2008)
118	D6-Pro	:	Tune D6, but with Professor's LEP parameters	(Oct 2008)
119	D6T-Pro	:	Tune D6T, but with Professor's LEP parameters	(Oct 2008)
3rd generation: Complete Q2-ordered Tune by Professor				
129	Pro-Q2O	:	Professor Q2-ordered tune	(Feb 2009)

200+: Intermediate and hybrid models

MSTP(5)	Name		Description	Date
200	IM 1	:	Intermediate model: new UE, Q2-ord. showers, new CR	
201	APT	:	Tune A w. pT-ordered FSR	(Mar 2007)
211	APT-Pro	:	Tune APT, with LEP tune from Professor	(Oct 2008)
221	Perugia APT	:	"Perugia" update of APT-Pro	(Feb 2009)
226	Perugia APT6	:	"Perugia" update of APT-Pro w. CTEQ6L1	(Feb 2009)

Tunes to/with
- different data
- different parameters
- different models
- different assumptions
- different tuning methods

Quick ov

Just to give you a feeling how active this area of QCD has been the last years...

Screenshot from
P.Skand, Phys.Rev.D82:074018,2010
(Good publication if want to know more about tuning.)

300+: $p_\perp^2$-ordered shower and interleaved underlying-event model

MSTP(5)	Name		Description	Date
1st generation: Sandhoff-Skands CDF Min-Bias tunes and a few more				
300	S0	:	Sandhoff-Skands Tune using the S0 CR model	(Apr 2006)
301	S1	:	Sandhoff-Skands Tune using the S1 CR model	(Apr 2006)
302	S2	:	Sandhoff-Skands Tune using the S2 CR model	(Apr 2006)
303	S0A	:	S0 with "Tune A" UE energy scaling	(Apr 2006)
304	NOCR	:	"best try" without CR	(Apr 2006)
305	Old	:	Original (primitive) CR model	(Aug 2004)
306	ATLAS-CSC	:	Arthur Moraes' $p_\perp$-ordered ATLAS tune w. CTEQ6L1	
2nd generation : The same, but with Professor's LEP parameters				
310	S0-Pro	:	S0, but with Professor's LEP parameters	(Oct 2008)
311	S1-Pro	:	S1, but with Professor's LEP parameters	(Oct 2008)
312	S2-Pro	:	S2, but with Professor's LEP parameters	(Oct 2008)
313	S0A-Pro	:	S0A, but with Professor's LEP parameters	(Oct 2008)
314	NOCR-Pro	:	NOCR, but with Professor's LEP parameters	(Oct 2008)
315	Old-Pro	:	Old, but with Professor's LEP parameters	(Oct 2008)
3rd generation : The Perugia, Professor and ATLAS MC09 pT-ordered Tunes				
320	Perugia 0	:	"Perugia" update of S0-Pro	(Feb 2009)
321	Perugia HARD	:	More ISR, More FSR, Less MPI, Less BR, Less HAD	(Feb 2009)
322	Perugia SOFT	:	Less ISR, Less FSR, More MPI, More BR, More HAD	(Feb 2009)
323	Perugia 3	:	Alternative to Perugia 0, with different ISR/MPI balance & different scaling to LHC & RHIC	(Feb 2009)
324	Perugia NOCR	:	"Perugia" update of NOCR-Pro	(Feb 2009)
325	Perugia *	:	"Perugia" Tune w. (external) MRSTLO* PDFs	(Feb 2009)
326	Perugia 6	:	"Perugia" Tune w. (external) CTEQ6L1 PDFs	(Feb 2009)
327	Perugia 2010	:	Perugia 0 with more FSR off ISR and more strangeness	(Mar 2010)
328	Perugia K	:	Perugia 2010 with a "K" factor on the MPI cross sections	(Mar 2010)
329	Pro-pT0	:	Professor pT-ordered tune w. S0 CR model	(Feb 2009)
330	MC09	:	ATLAS MC09 tune with (external) LO* PDFs	(2009)
335	Pro-pT*	:	Professor Tune with (external) LO* PDFs	(Mar 2009)
336	Pro-pT6	:	Professor Tune with (external) CTEQ6L1 PDFs	(Mar 2009)
339	Pro-pT**	:	Professor Tune with (external) LO** PDFs	(Mar 2009)

Tunes to/with
- different data
- different parameters
- different models
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Quick ov

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(Good publication if want to know more about tuning.)

List is not complete – more tunes to LHC data have been made and are coming still in progress. Not only because we are confused and desperately keep tuning, but:

- **New measurements are coming.**
- **The different MC generators are developing.**

300+: $p_\perp^2$-ordered shower and interleaved underlying-event model

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Tunes to/with
- different data
- different parameters
- different models
- different assumptions
- different tuning methods

Summary – what we learned...

I hope that you learnt:

- **How a typical UE measurement is done:**
  Transverse region to leading objects.....

- **Why we tune:**
  The MC models are complex with a lot of free parameters...

- **What we tune:**
  Hadronization, flavours, showers, MPI,...

- **What automated tuning is:**
  The MC parameter dependence is determined analytically before the actual fit is performed.

- **Roughly what different tunes mean, and that there are a lot on the market.**
  Tunes to different data, different models and assumptions, with emphasis on different parts of the MC. Different MC.

- **Experimentally and theoretically the UE is a very hot topic, because we do not understand all the data. Exciting times...**

Thank you for your attention!

Back up

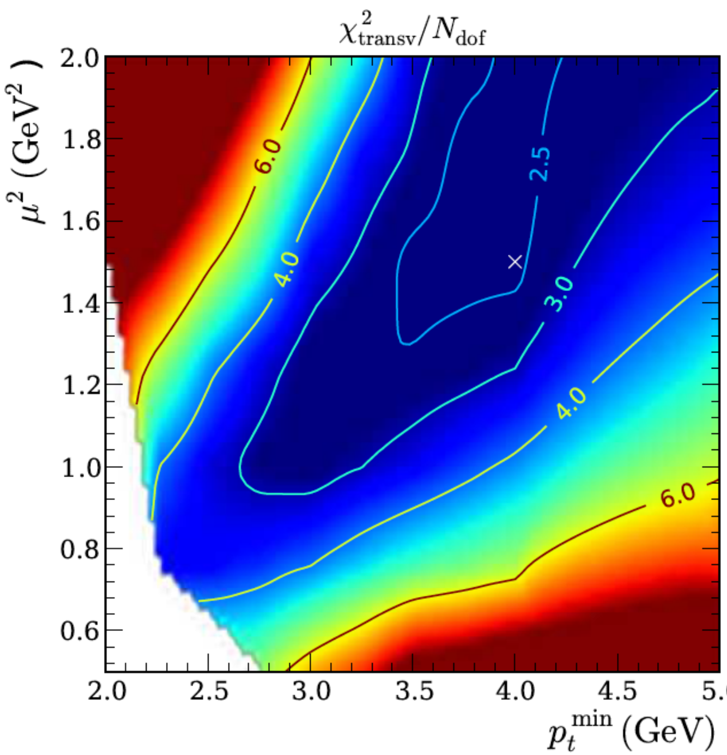
Tuning in HERWIG++

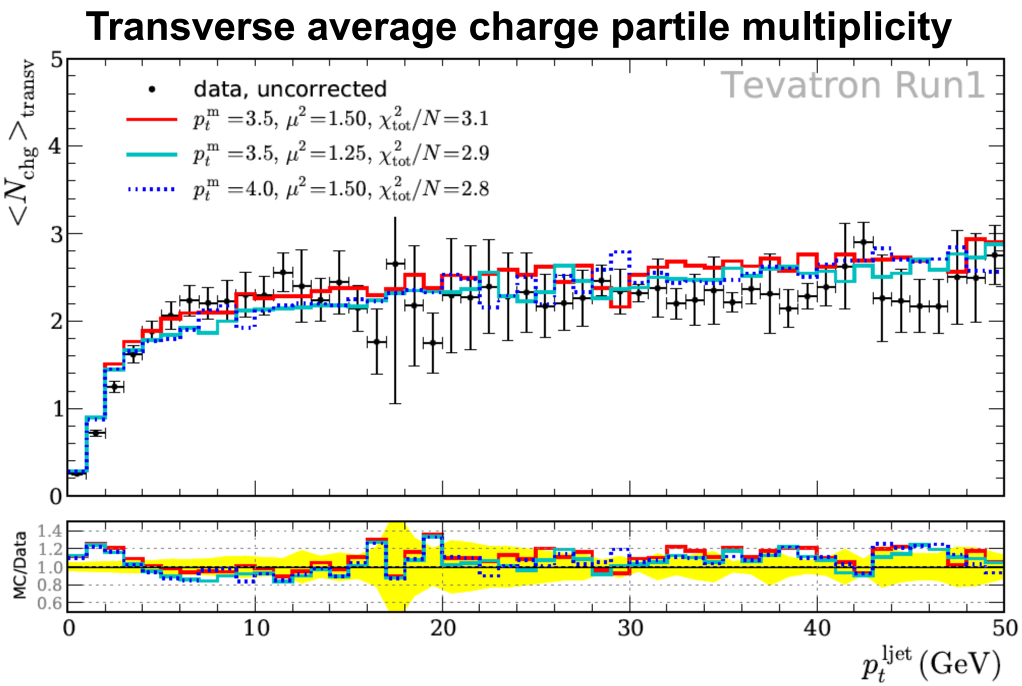
Tuning in HERWIG

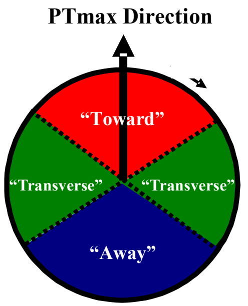
- MI model in HERWIG++, two parameters to tune:
  - μ^2 – determines how the colliding particles overlap (impact parameter dependence)
  - p_t^{min} – p_t-cut off for multiple hard interactions

Use simple but effective "tune" (perfect for 2 free parameters): χ^2 scans

Data from the "classic" UE - jet measurement from the TEVATRON.



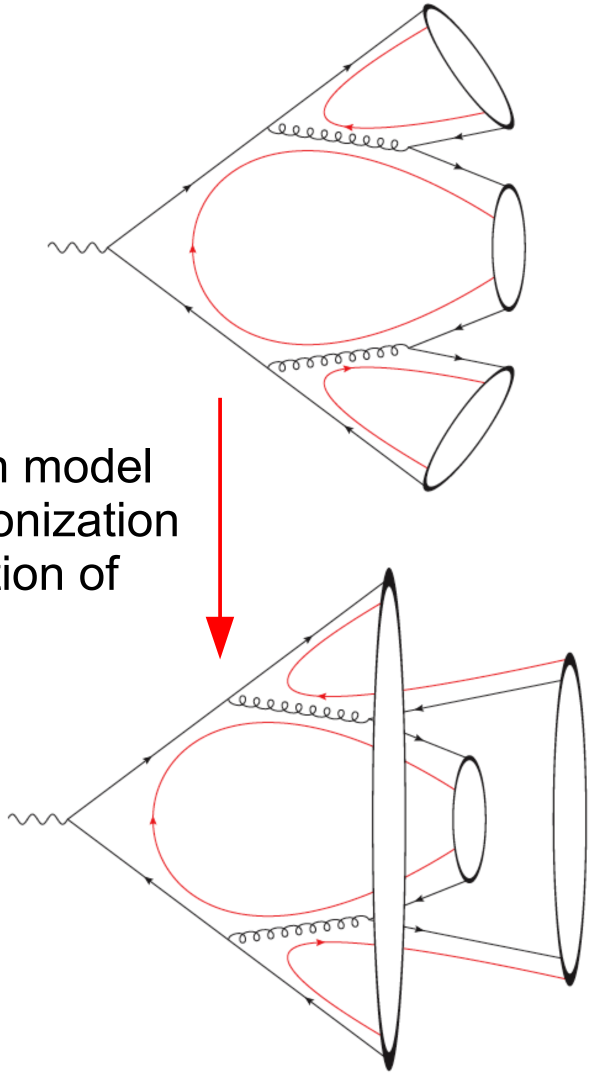




Tuning in HERWIG

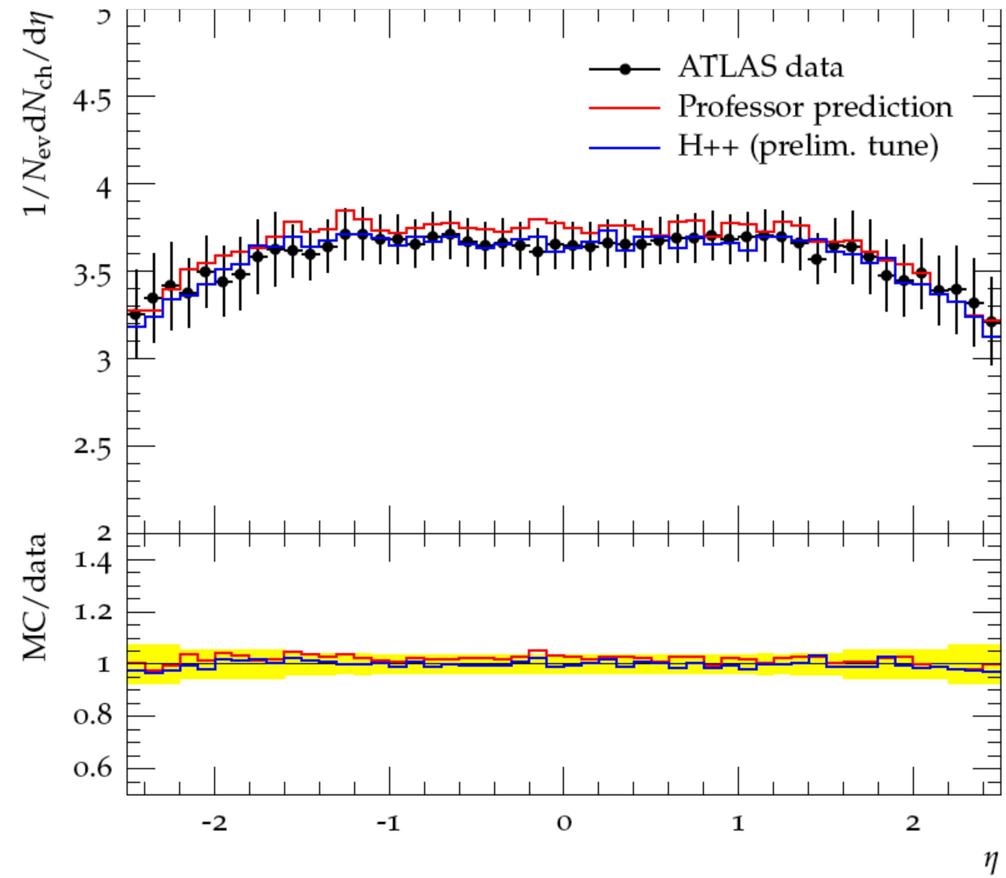
- Tuning of several parton shower and hadronization parameters model to LEP data, by using PROFESSOR.

- After that the Color reconnection model, has been tuned to ATLAS data.



Color reconnection model in the cluster hadronization allows for reformation of clusters.

Charge particle multiplicity as a function of η (7 TeV, N_{ch}>5)



Manual and Automatic Tuning

The Manual Tuning Approach (a la Rick Field)

“Armed with a good understanding of the underlying model and using only the generator itself as a tool ... “ *Skands, arXiv:1005.3457v2*

Change parameters in the models until the MC curve looks close to the data points.

Obvious Drawbacks:

- There is a limit on how many plots we can look on and keep in mind at the same time.

- It is hard to see what is good. If the errors of the data and MC are small even what looks good may be a bad agreement (high Chi2).
  Fastly falling distribution needs to be viewed in both lin and log scale... (or better create ratio plots.)

- Biggest limitation: time and manpower

Anyway, it is much better than just using the default parameters, and Rick Field and his PYTHIA tunes have improved the description of the data and our understanding of the UE significantly.

Rick Field Tunes of Pythia 6

Very many tunes... to different data... and with different parameters kept fixed.

Parameter	Tune B	Tune A
MSTP(81)	1	1
MSTP(82)	4	4
PARP(82)	1.9 GeV	2.0 GeV
PARP(83)	0.5	
PARP(84)	0.4	
PARP(85)	1.0	
PARP(86)	1.0	
PARP(89)	1.8 Te	
PARP(90)	0.25	
PARP(67)	1.0	

Parameter	Tune A	Tune A25	Tune A50
MSTP(81)	1	1	1
MSTP(82)			
PARP(82)			
PARP(83)			

Parameter	Tune H(6.418)	Tune DWT	Tune D6T
PDF	CTEQ5L	CTEQ5L	CTEQ6L
MSTP(81)	1	1	1
		4	4

Parameter	Tune AW	Tune DW	Tune D6
PDF	CTEQ5L	CTEQ5L	CTEQ6L
MSTP(81)	1	1	1
MSTP(82)	4	4	4
PARP(82)	2.0 GeV	1.9 GeV	1.8 GeV
PARP(83)	0.5	0.5	0.5
PARP(84)	0.4	0.4	0.4
PARP(85)	0.9	1.0	1.0
PARP(86)	0.95	1.0	1.0
PARP(89)	1.8 TeV	1.8 TeV	1.8 TeV
PARP(90)	0.25	0.25	0.25
PARP(62)	1.25	1.25	1.25
PARP(64)	0.2	0.2	0.2
PARP(67)	4.0	2.5	2.5
MSTP(91)	1	1	1
PARP(91)	2.1	2.1	2.1
PARP(93)	15.0	15.0	15.0

Parameter	Tune DW	Tune AW
MSTP(81)	1	1
MSTP(82)	4	4
PARP(82)	1.9 GeV	2.0 GeV
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PARP(85)	1.0	0.9
PARP(86)	1.0	0.95
PARP(89)	1.8 TeV	1.8 TeV
PARP(90)	0.25	0.25
PARP(62)	1.25	1.25
PARP(64)	0.2	0.2
PARP(67)	2.5	4.0
MSTP(91)	1	1
PARP(91)	2.1	2.1
PARP(93)	15.0	15.0

Automated Tuning

1. Build up a grid in parameter – observable space using Monte Carlo.

   If you have a CPU farm (or use the *GRID*) this ultimately
   takes the time of running the MC generator once.

Automated Tuning

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2. Fit polynomials to the Monte Carlo grid.

$$\sigma_{\text{poly}} = A + \sum_{1}^{N} B_i \cdot p_i + \sum_{1}^{N} C_i \cdot p_i^2 + \sum_{i=1}^{N} \sum_{j=i+1}^{N} D_{ij} \cdot p_i p_j + H.O.$$

A, B, C **and** D **are determined by fitting the polynomial to the parameter grid.**

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Takes care of correlation between parameters

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Step 1. and 2. are done for each data point in the measurement.

Automated Tuning

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A, B, C and D are determined by fitting the polynomial to the parameter grid.

Step 1. and 2. are done for each data point in the measurement.

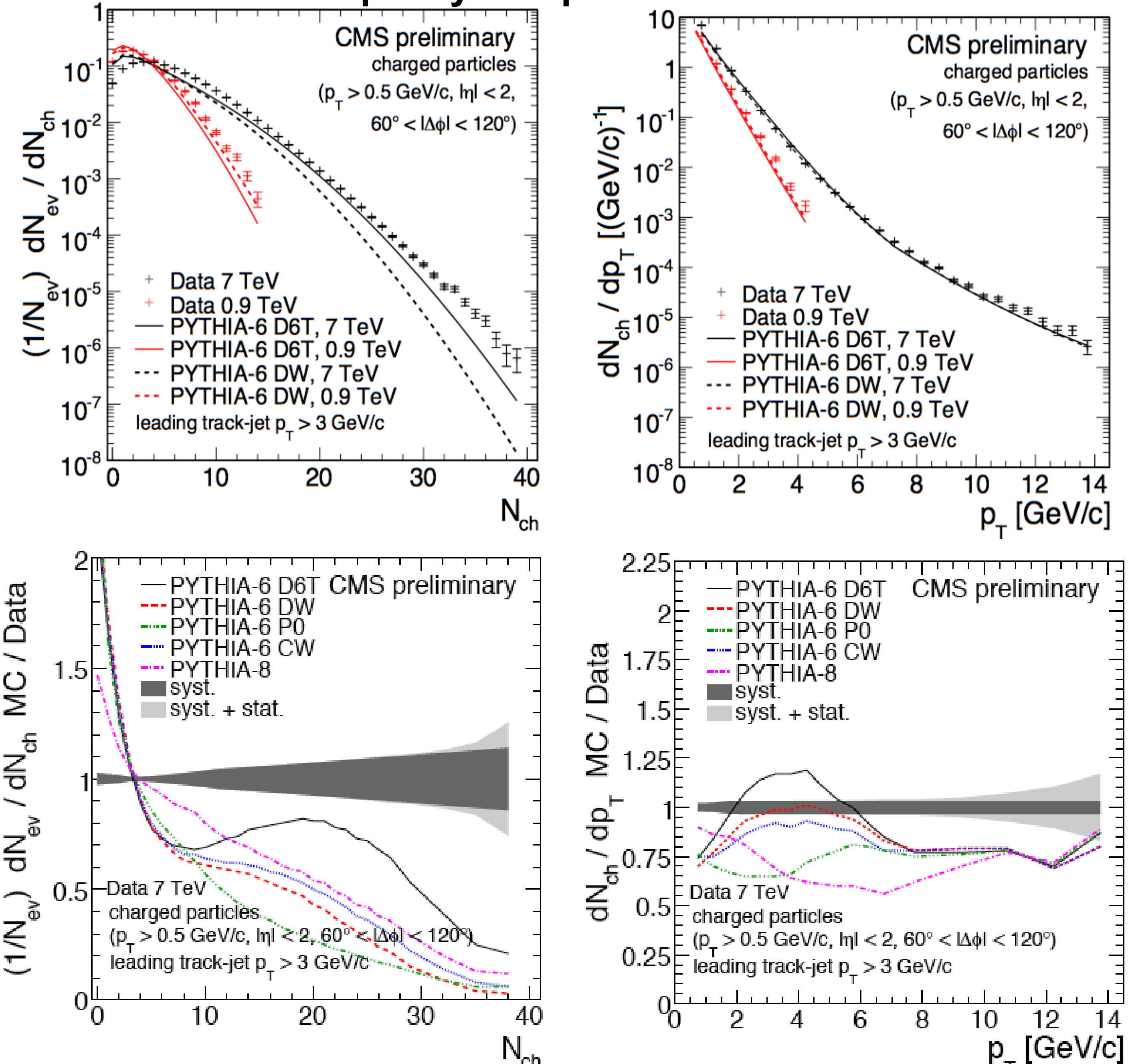
3. Determine MC parameters, p_i, by fitting all the polynomials to data simultaneously

Also this takes only a few seconds.

Measurements

Recent measurement from CMS

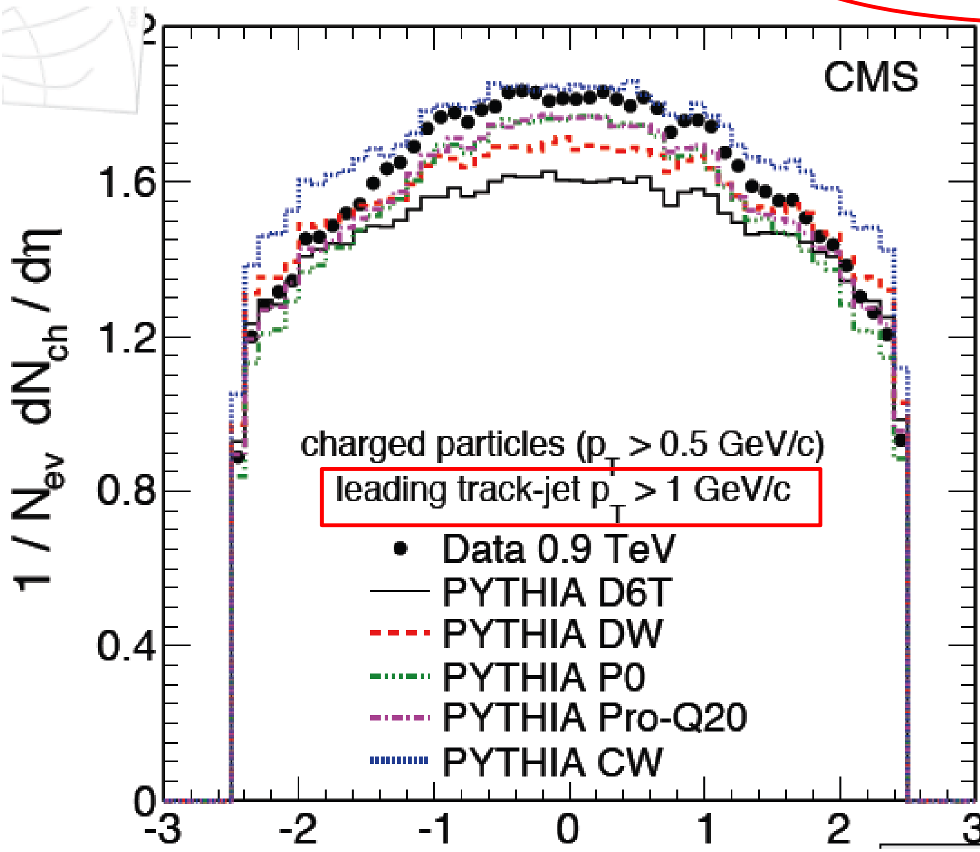
Particle multiplicity and particle transverse momenta

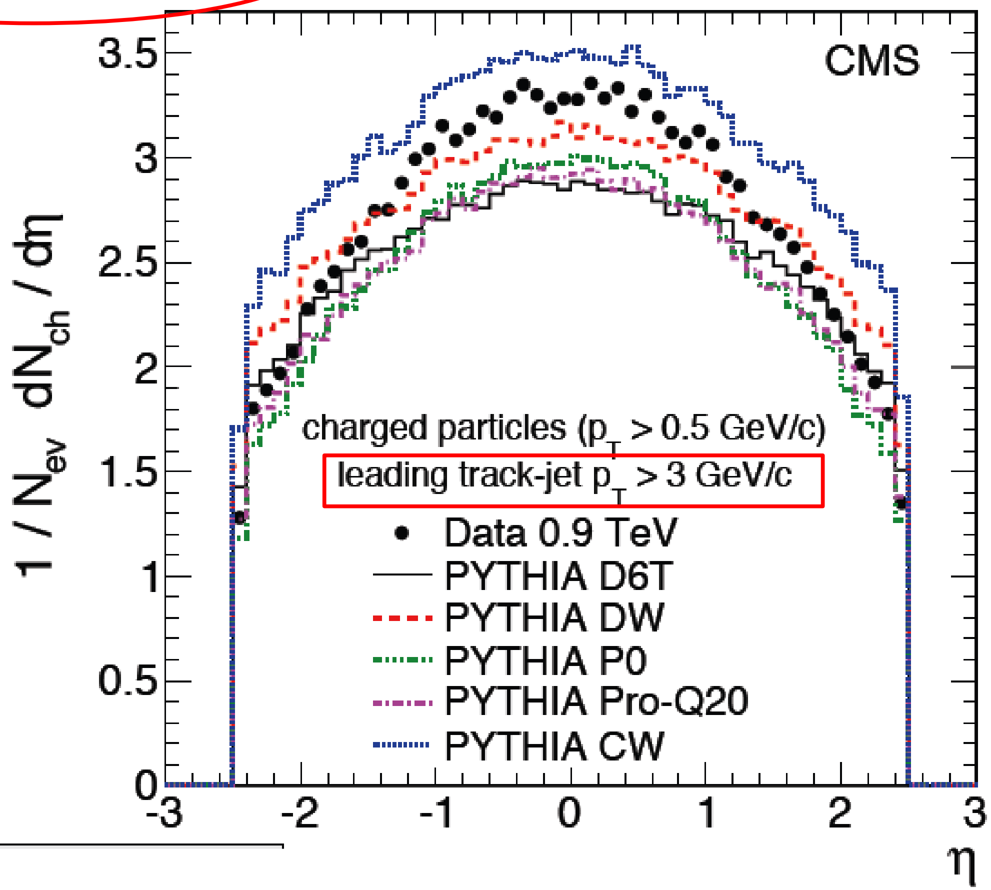


LHC Measurements

Inclusive measurement: Charge particle multiplicity as a function of rapidity.

$\sqrt{s} = 900\ \mathrm{GeV}$



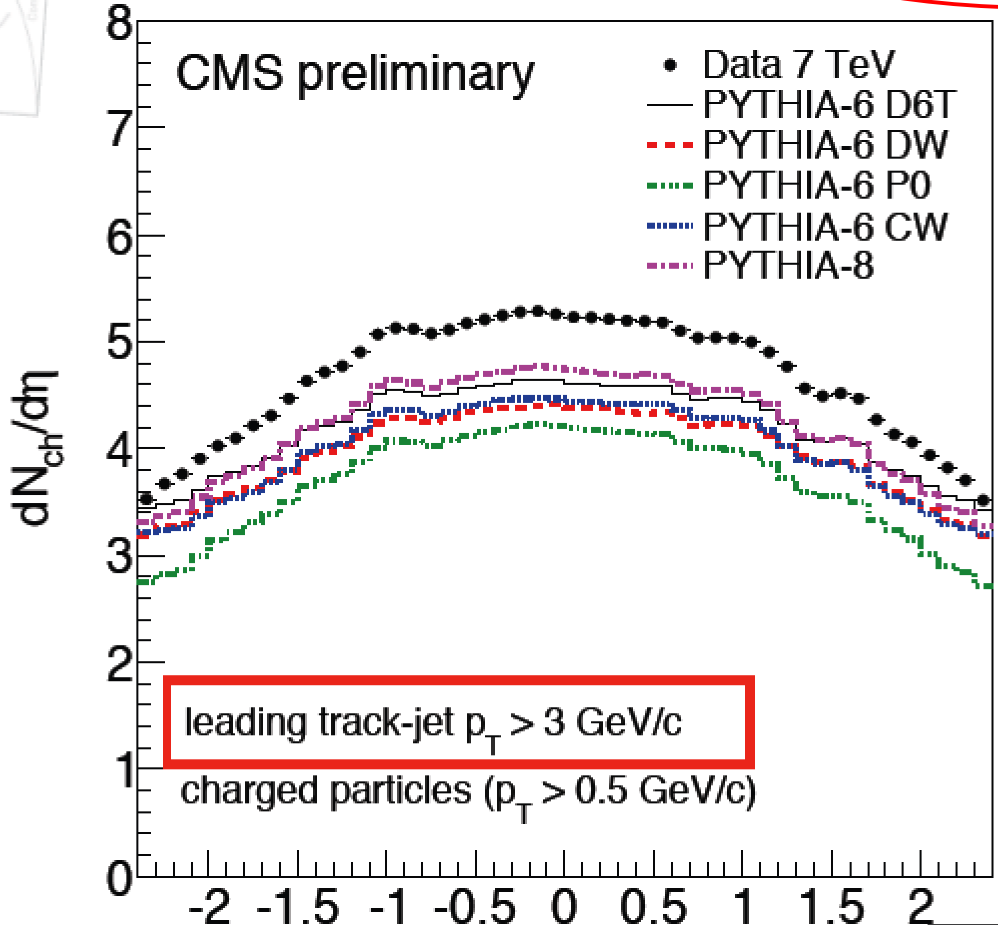


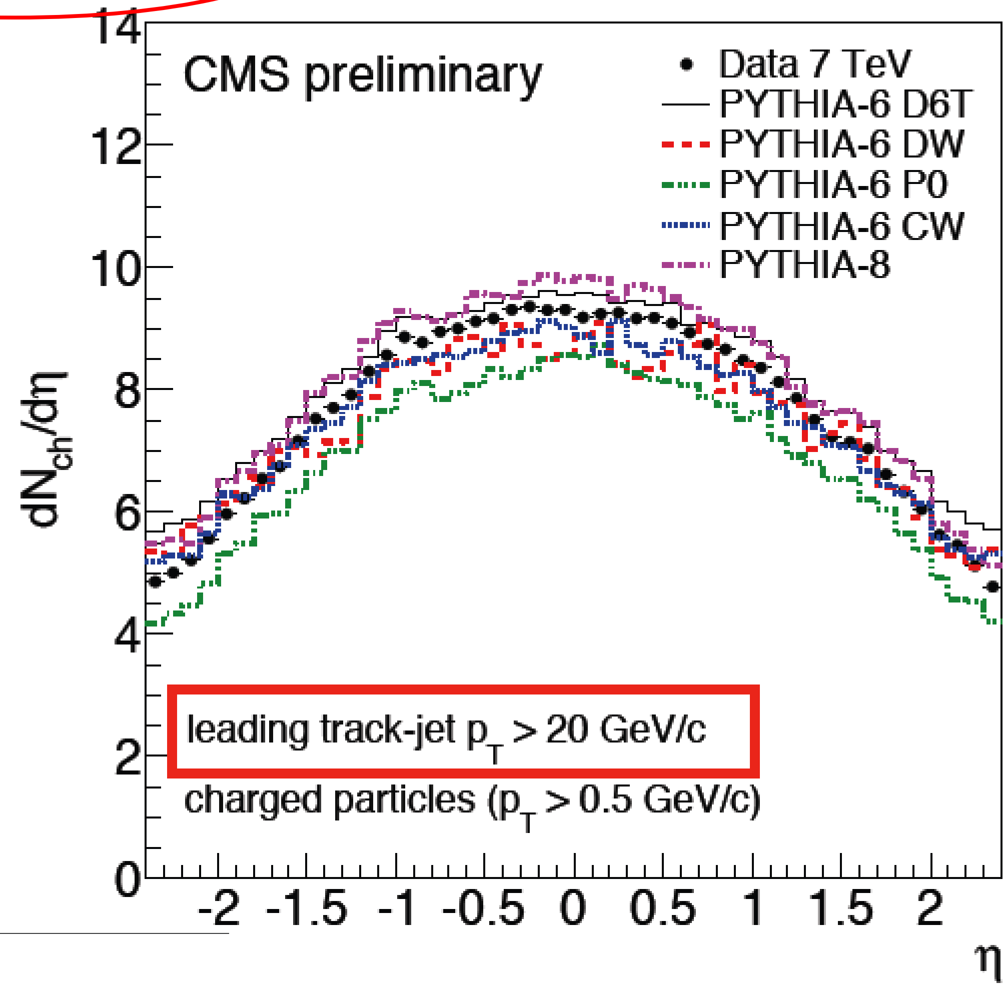
- **Available tunes do not describe the data.**
- **Dependency on “trigger” energy / hardness.**

LHC Measurements

Inclusive measurement: Charge particle multiplicity as a function of rapidity.

$$\sqrt{s} = 7\ \mathrm{TeV}$$

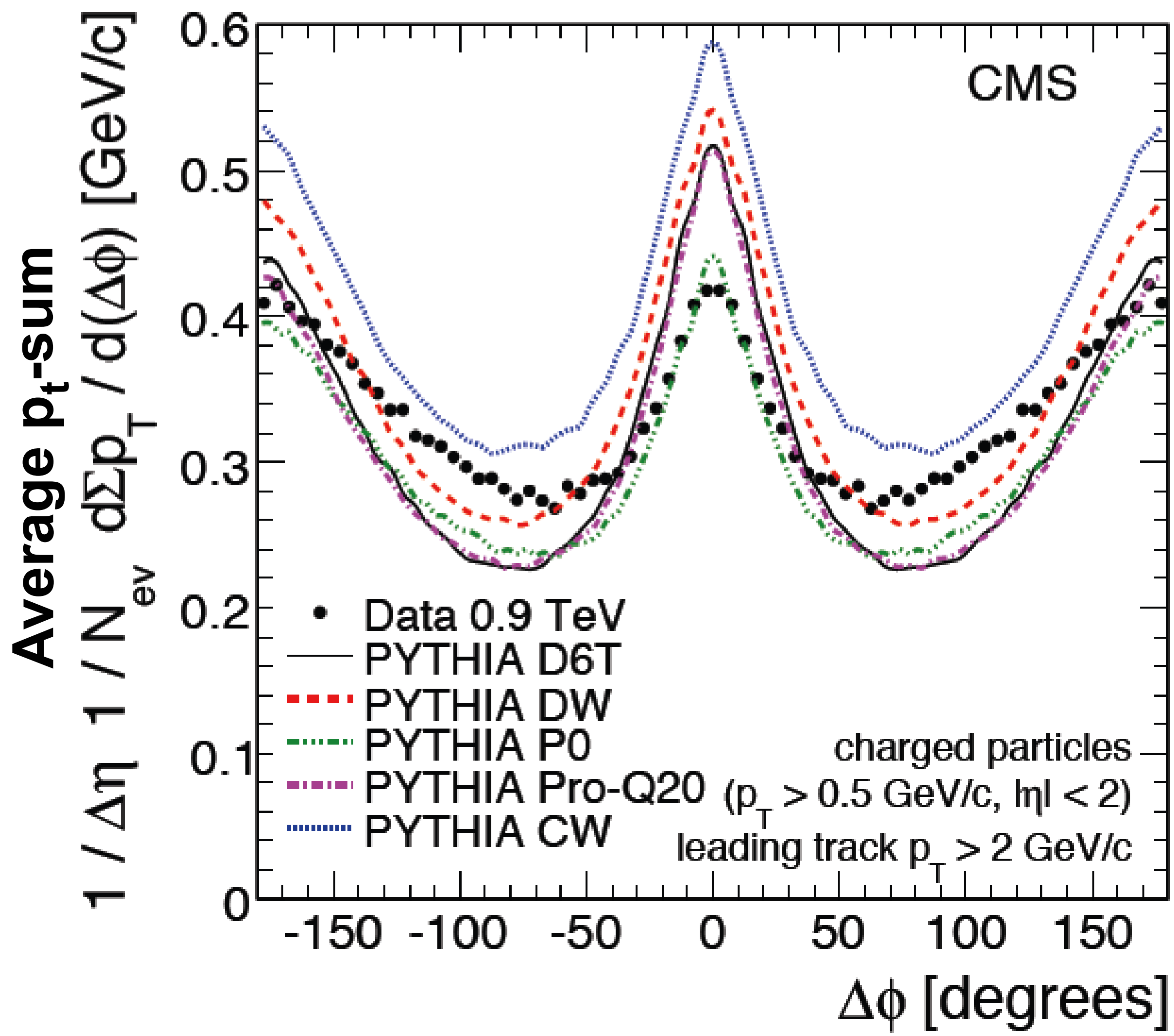




- **At 7 TeV the picture change somewhat, but still not ok for low p_t-jet events.**
- **In high p_t-jet events the data is described if we pick the "correct" tune.**

LHC Measurements

More discrimiating variable: Azimuthal differenence between particles.



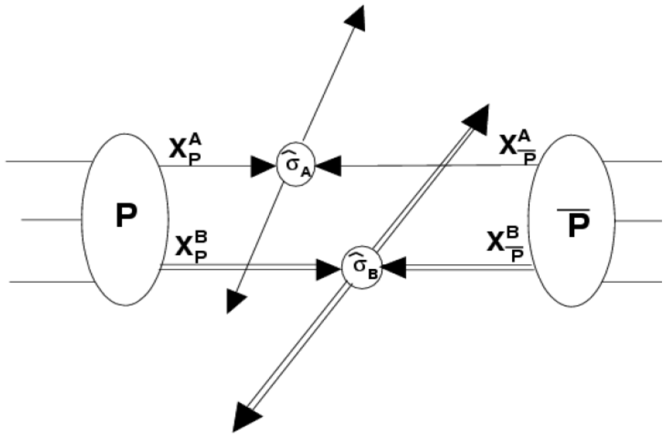
• **Worse description... Shape of not understood!**

Conclusion from Data-MC comparisons

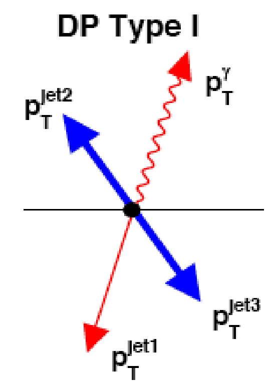
- No available PYTHIA tune describes all data
- Energy dependencies!
  The UE depends on the collision c.o.m energy.
  The UE depends on the “hardness” of the reaction (high vs low p_t jet events)
- Positive point of view:
  We have a lot of new data to, which sensitive to the MPI and UE.
- Most tunes focused on old PYTHIA6 (fortran), but we also have the new PYTHIA8 (c++) and HERWIG++.
- The data keep coming in at LHC...

→ The UE and MPI is hotter than ever! A lot of work still to do.

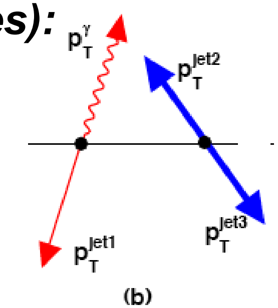
D0 – Double Parton Interactions in γ + 3-jet Events

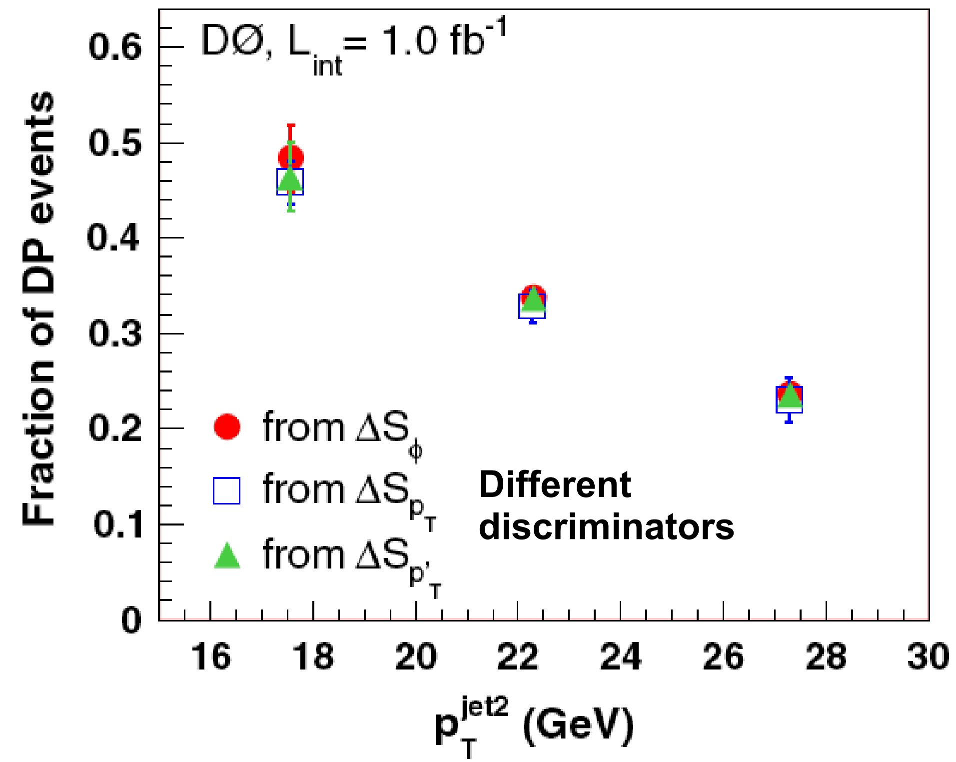


Analyse events with 3 jets and a photons.



Not to be confused with Double Proton Interactions (2 vertices):

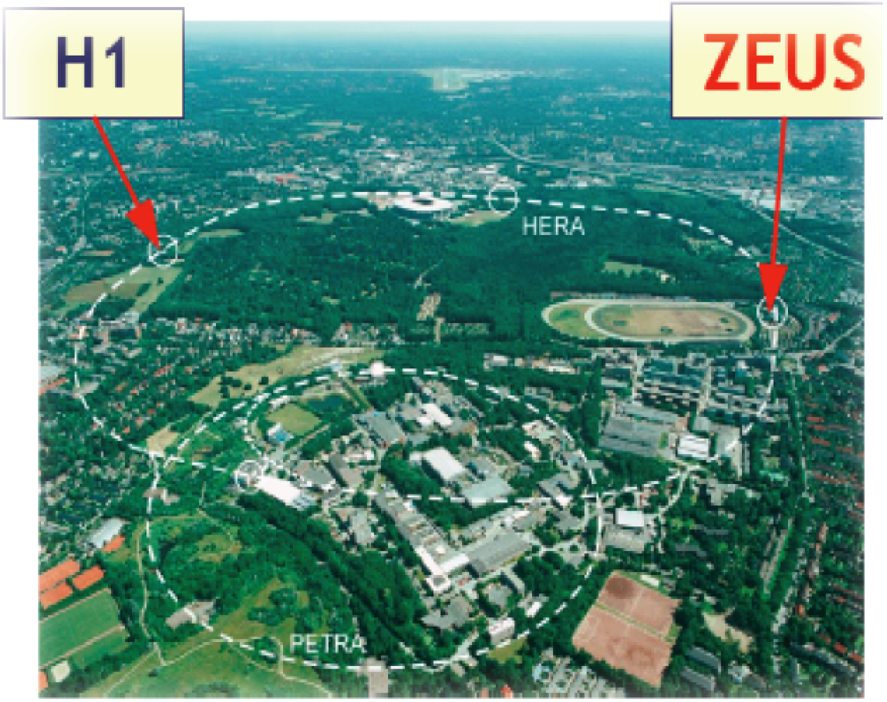




- **At low $p_{t,jet}$ every second event has 2 partonic interactions.**

MPI at HERA (if time)

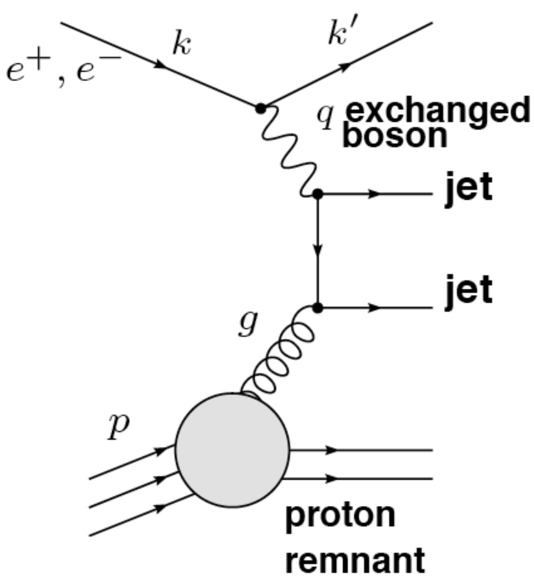
HERA Physics - Reminder



HERA: ep-collider at DESY

15 years operation (1992-2007)
Almost 0.5 pb^{-1}/experiment

H1 and ZEUS:
general purpose collider experiments

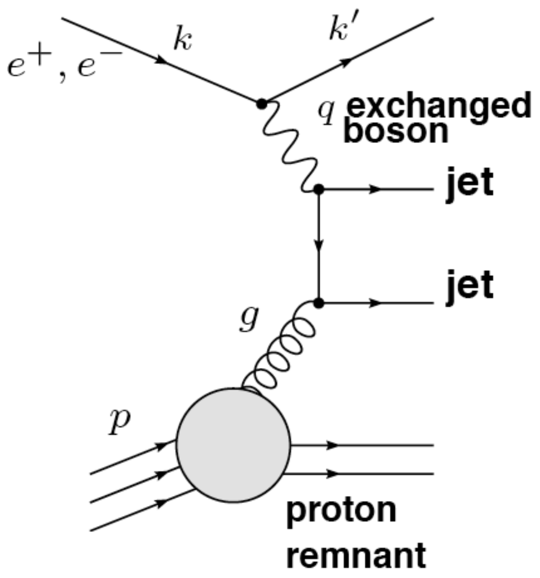


Virtuality of exchanged boson: $Q^2 = -(k-k')^2$

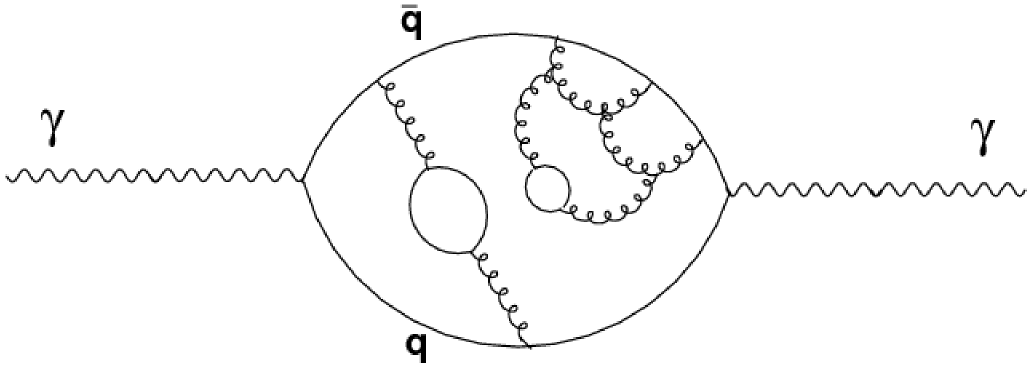
MULTIPLE INTERACTIONS AT ep-COLLIDERS?

The Hadronic Stucture of the Photon

MULTIPLE INTERACTIONS AT ep-COLLIDERS?



The exchanged photon may fluctuate into a quark-anti quark pair, which spans a hadronic-like substructure.



The Hadronic Stucture of the Photon

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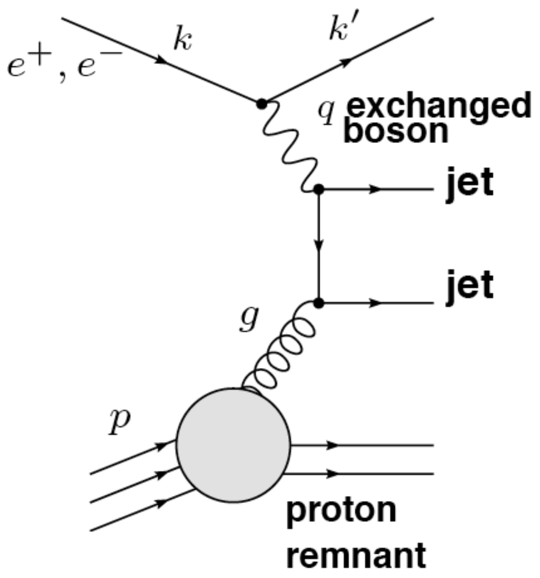

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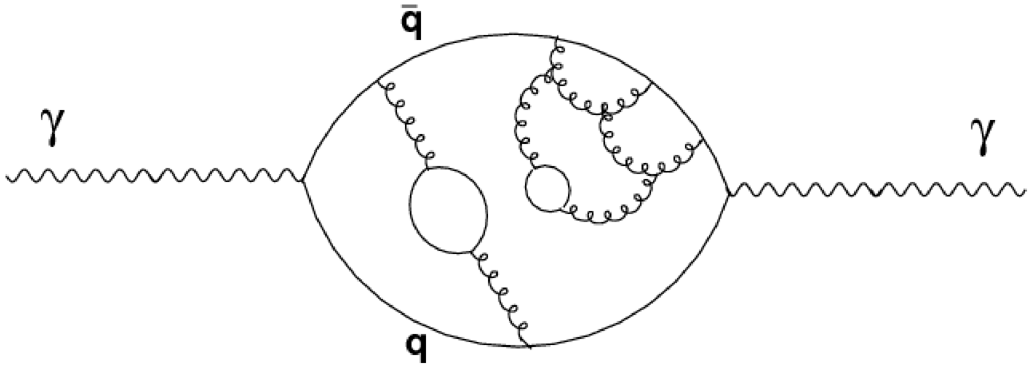


Low photon virtuality Q^2 ► More long lived photon ►Large resolved component

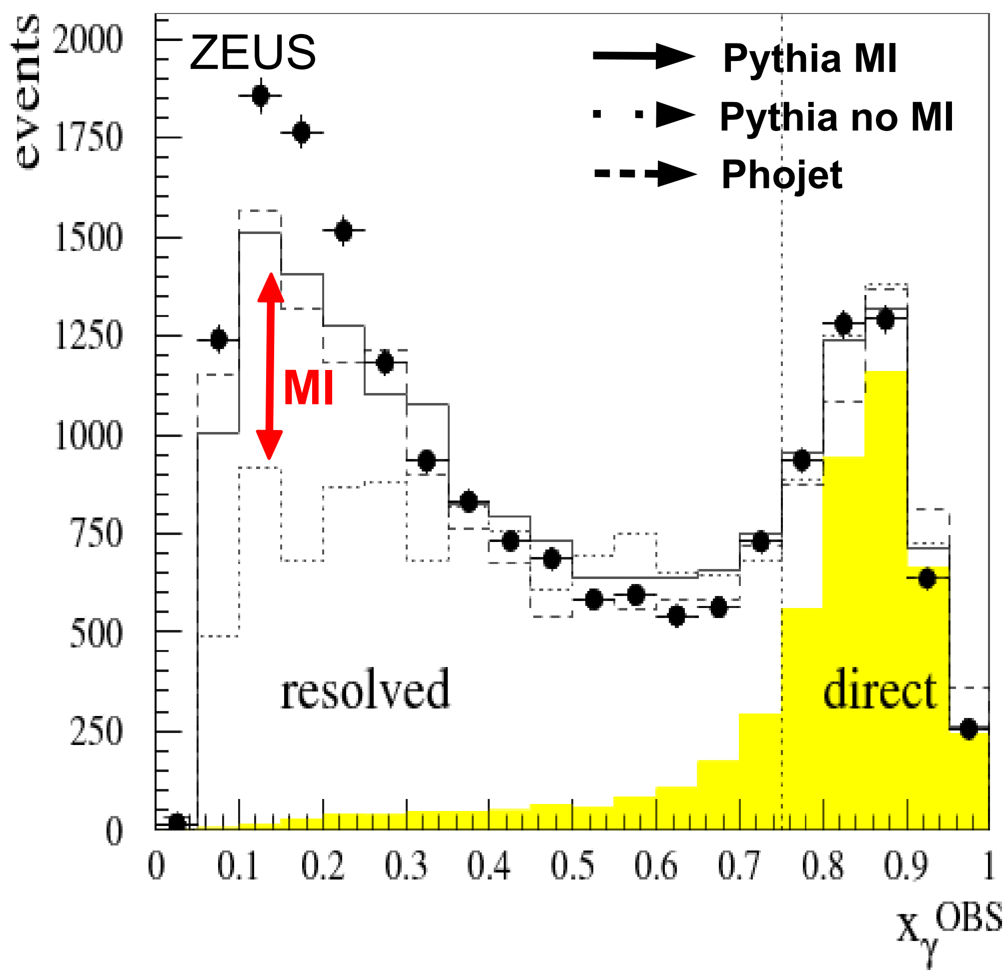
Can expect remnant-remnant interactions to take place for measurements at low Q^2

Measurement performed at $Q^2 \approx 0\ \mathrm{GeV}^2$
(Called photoproduction – almost real photon.)

Large resolved photon component.

MI studies at HERA > 10 years ago

Di-jets in photoproduction



<u>Fractional momentum of photon carried by the struck parton, x_γ :</u>

Handle to separate resolved/direct photon

Low x_γ

→

Photon has larger substructure photon

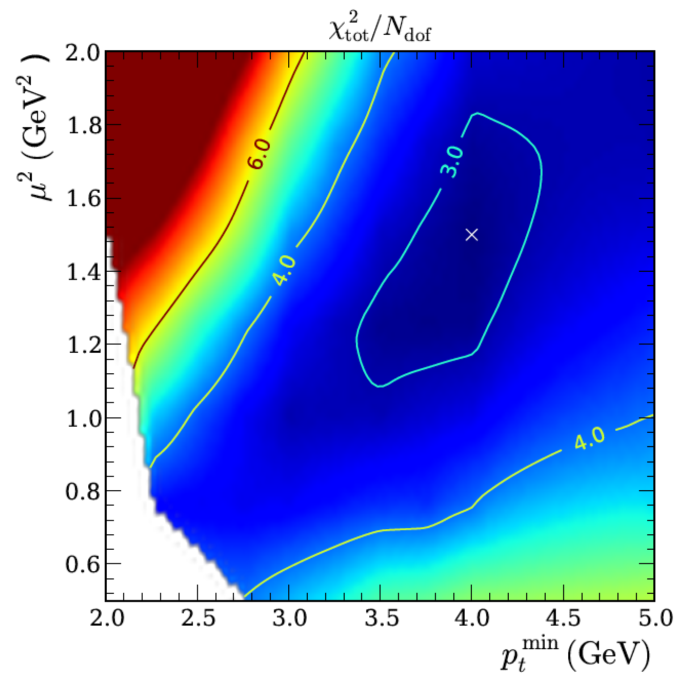
→

Remnant-remnant interactions

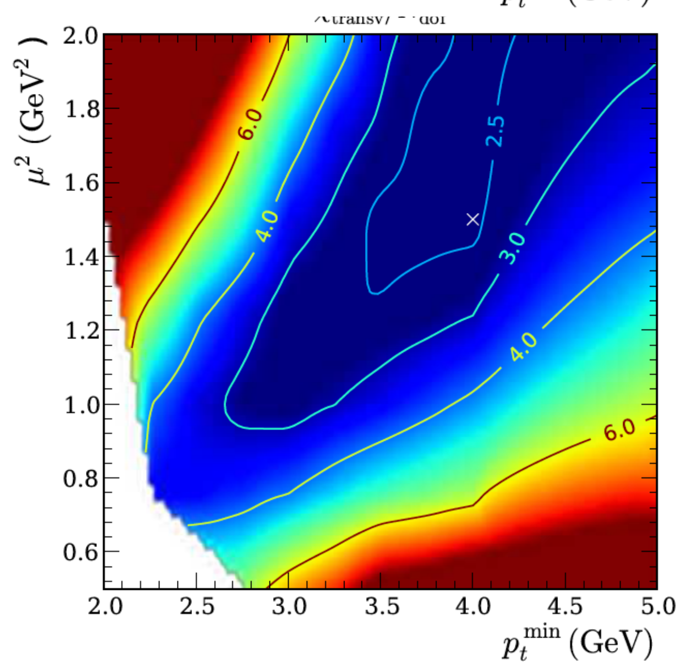
ZEUS Collaboration (J. Breitweg et al.), Eur.Phys.J.C1:109-122,1998

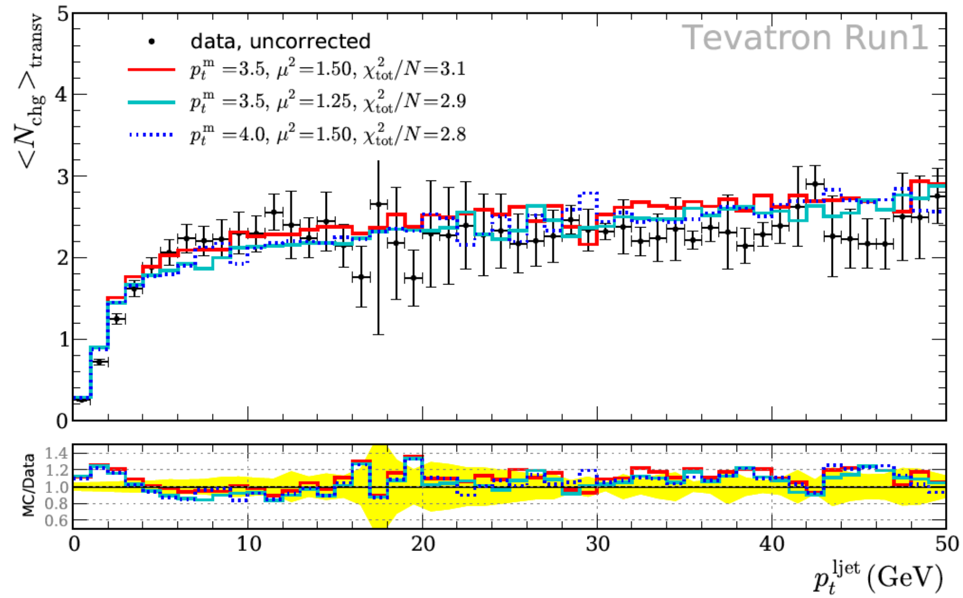
Tuning in HERWIG

- χ^2 for Rick's Run1 Jet analysis for **all** regions

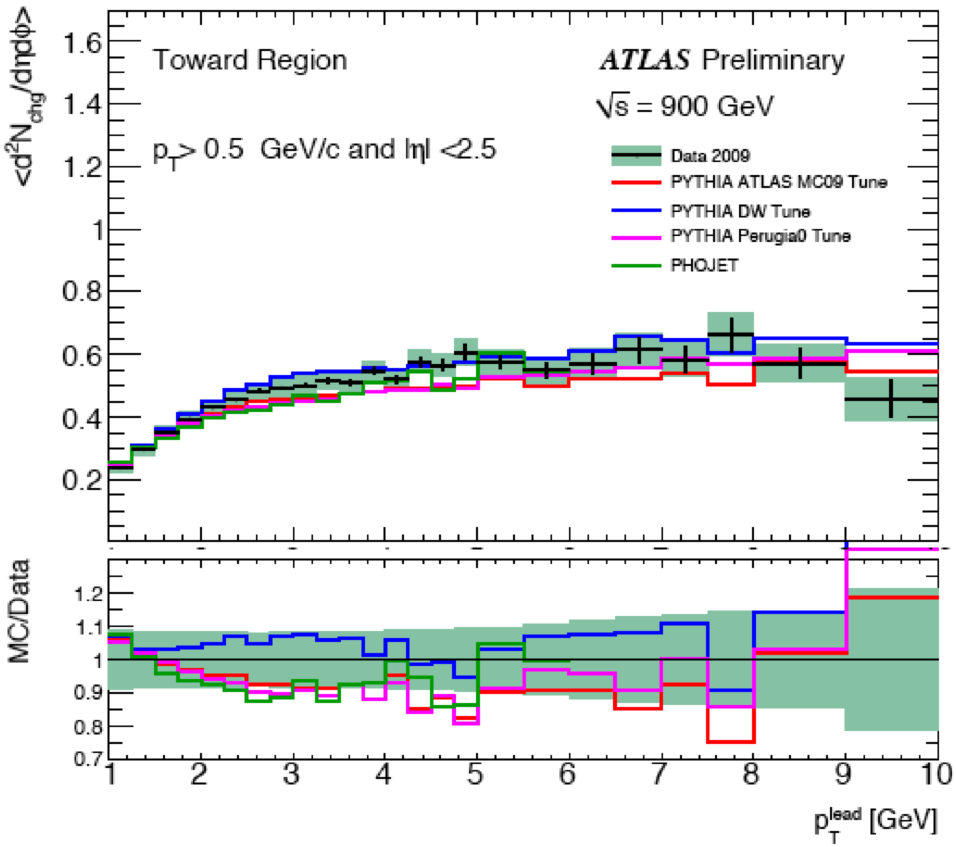


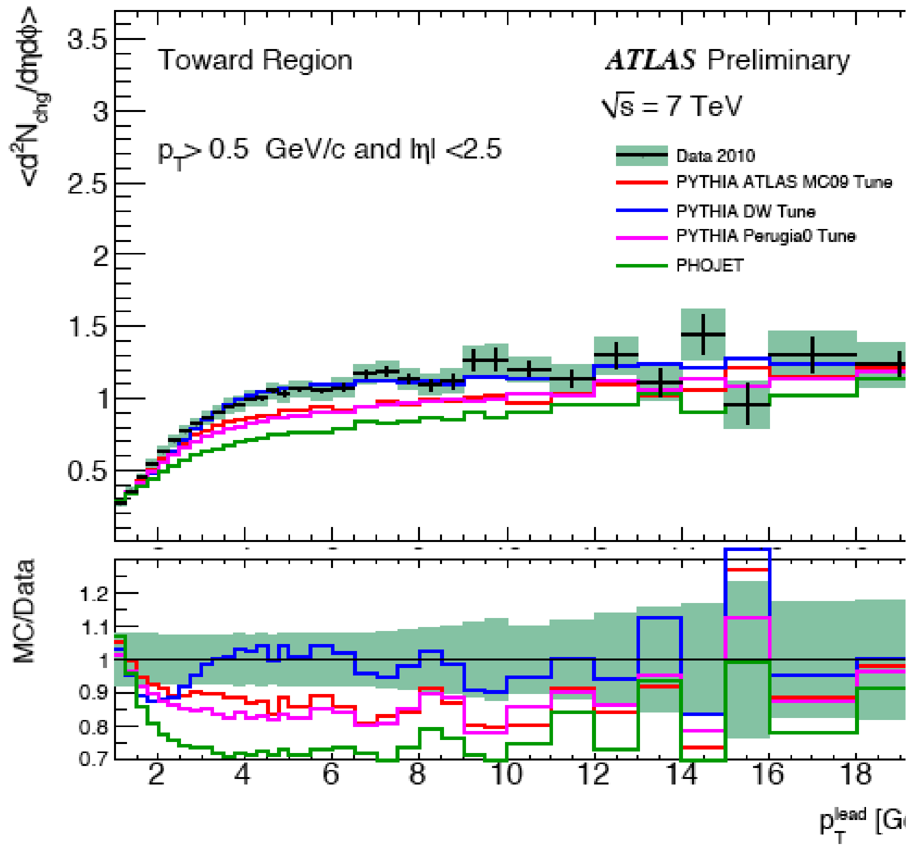
- χ^2 for Rick's Run1 Jet analysis for **all** regions
- only the transverse region





ATLAS UE Measurement



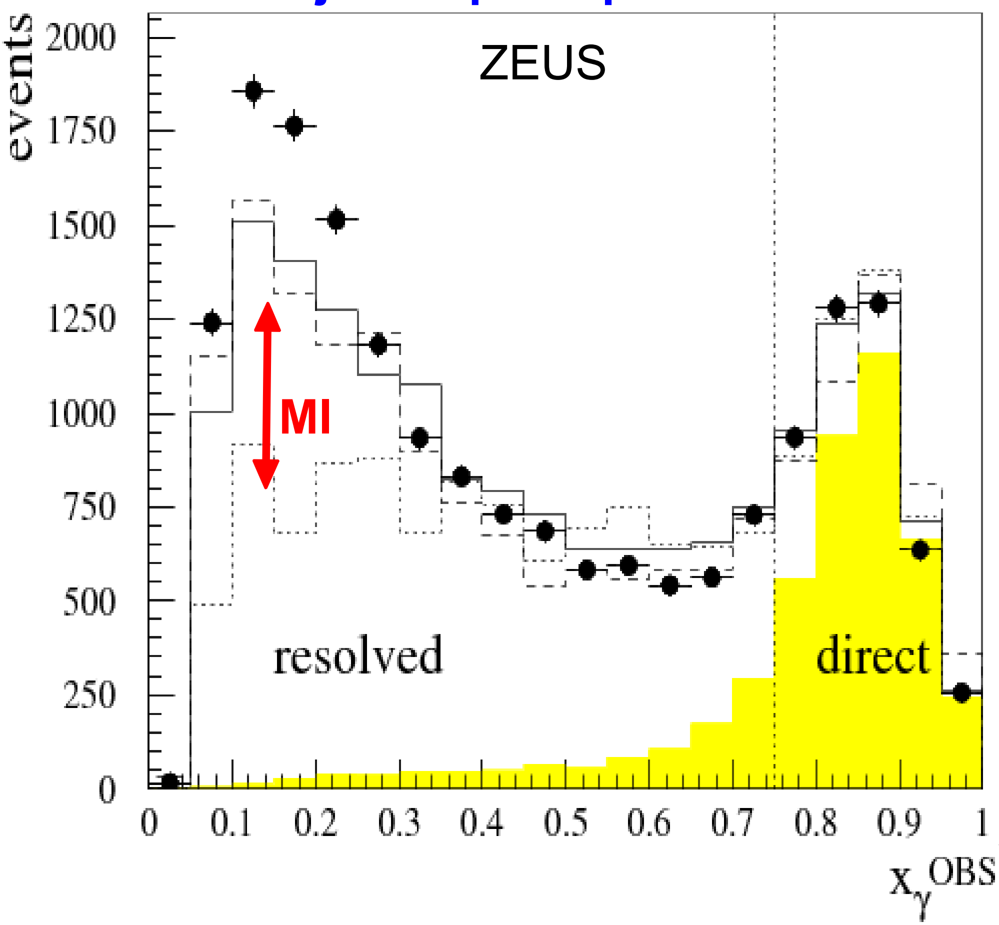


MI studies at HERA > 10 years ago

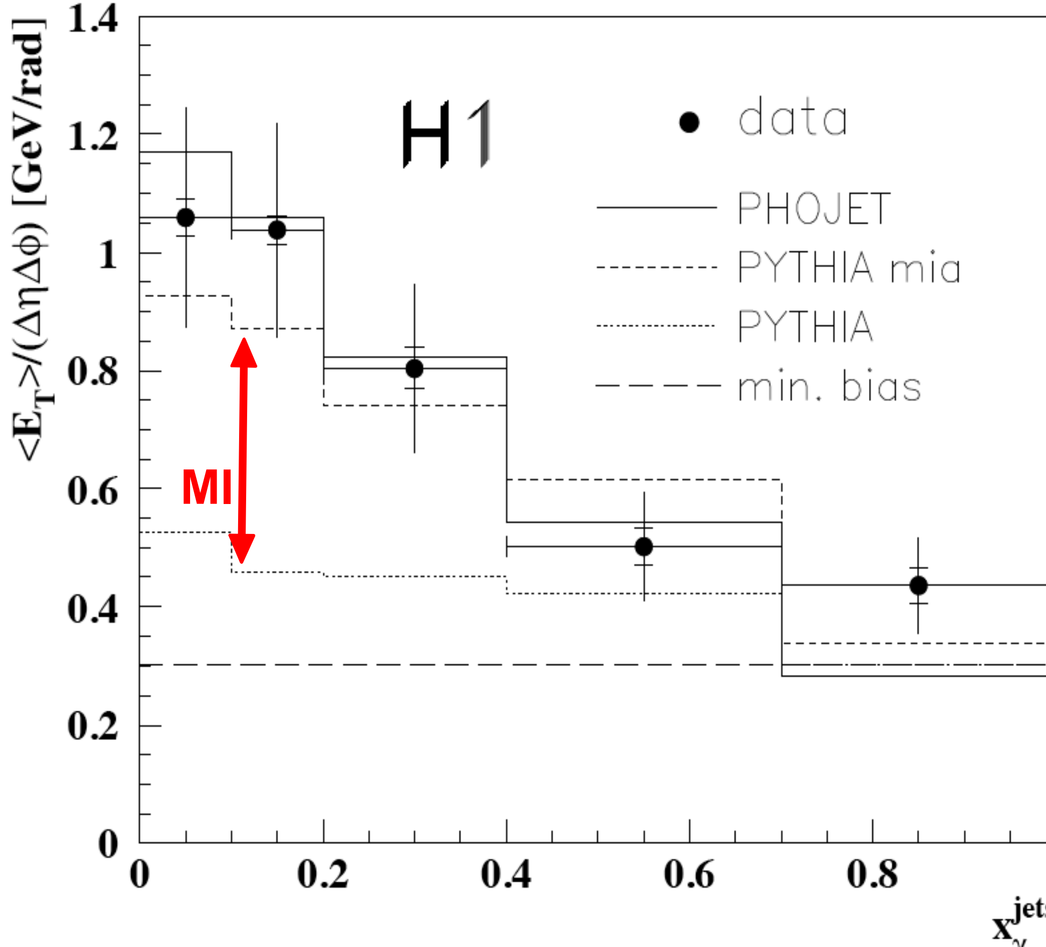
ZEUS Collaboration (J. Breitweg et al.), Eur.Phys.J.C1:109-122,1998

H1 Collaboration (S. Aid et al.), Z.Phys.C70:17-30,1996

Di-jets in photoproduction



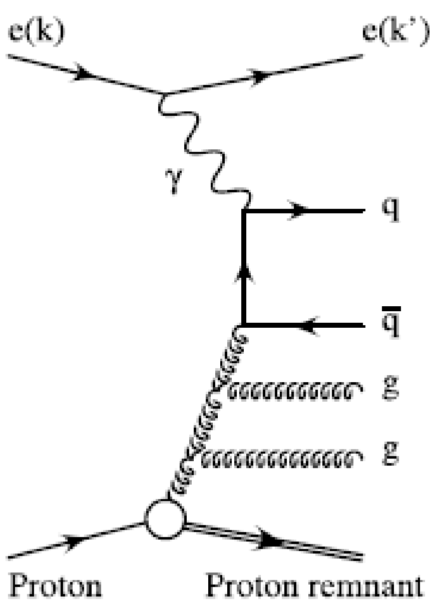
Energy flow in photoproduction, outside the two jet with highest Pt.

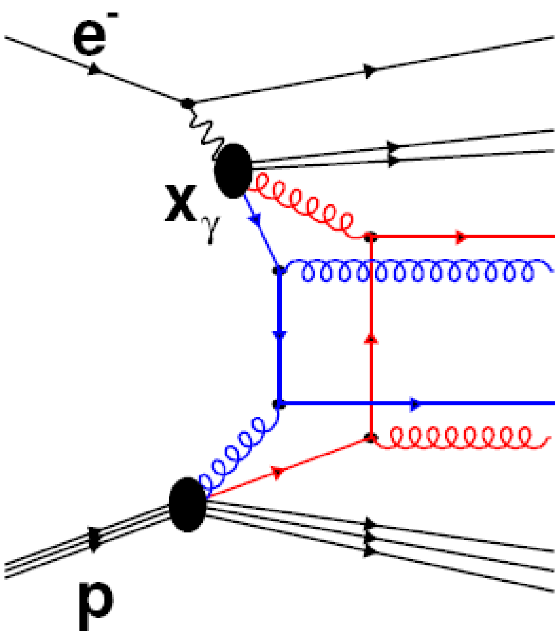


Resolved photon → Remnant-remnant interactions

Multijets in Photoproduction

- Measure 3- and 4-jet final state ➞ Tool to study higher order α_s reactions in photoproduction:
  - Fixed order calculations
  - QCD models with PS
  - Multiple interactions





Kinematic Range

- $0.2 < y < 0.85$
- $Q^2 < 1.0 \text{ GeV}^2$

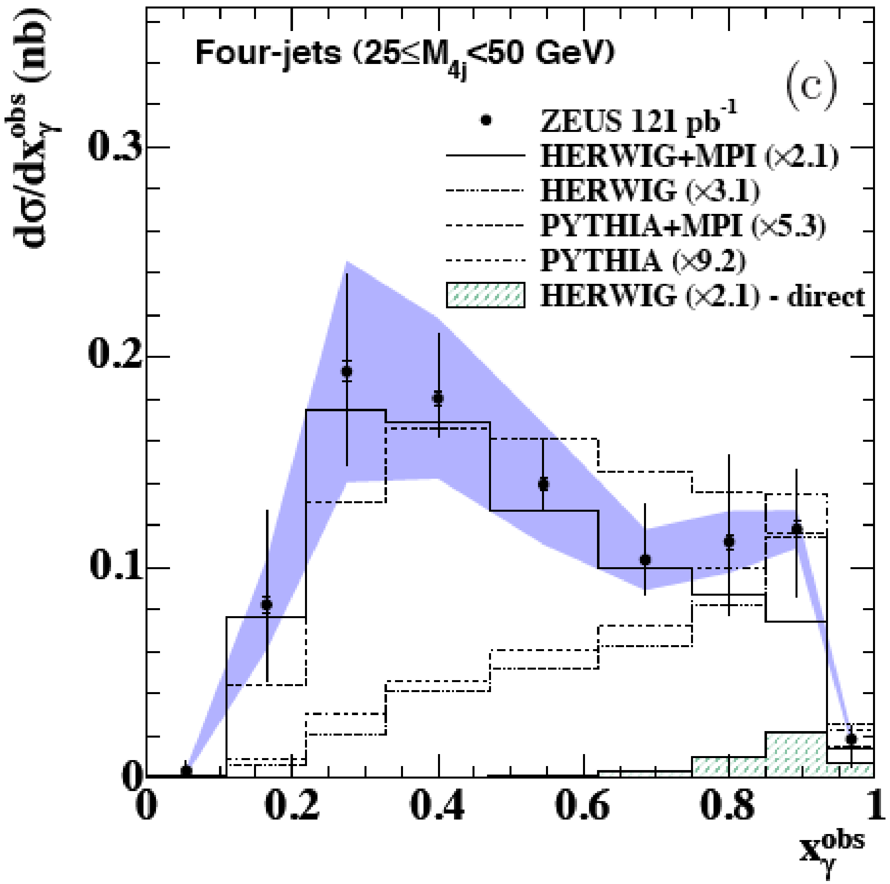
3-, 4-Jet Selection

- $E_T^{jet_{1,2,3,4}} > 6 \text{ GeV}$
- $|\eta^{jet}| < 2.4$

Jets defined by the inclusive kt-algorithm

"Three- and four-jet final states in photoproduction at HERA", *Nucl.Phys.B792:1-47,2008, ZEUS Collaboration*

4-jet cross-section in Photoproduction at HERA



- x_γ
- **Large contribution from MPI...**

Different Tunes

- Strategy
  - Tune fragmentation to LEP data
  - Tune UE to LHC data

Example of parameters:

PARJ(21) σ_q – width of Gaussian for px and py of primary hadrons

PARJ(41) a

PARJ(42) b parameters in the Lund fragmentation function

PARJ(47) r_b – interpolation between Bowler and Lund fragmentation. (1=pure Bowler shape)

PARJ(81) Λ_{QCD} for α_s in parton showers

PARJ(82) Invariant mass cut-off for PS. Partons below this value do not radiate.

Error treatment

- **The integration uncertainties are propagated to the polynomial. A co-variance matrix for the coefficients are calculated.**

- **The CTEQ χ^2 calculation** (*Phys.Rev.D65:014012,200, Stump et al*) **is used to take the correlated data uncertainties in the data into consideration.**

  In the fit of the PDF parameters to the data the uncorrelated and the different correlated uncertainties can be treated separately according to:

$$\chi^2 = \sum \frac{(X_{\mathrm{Data}} - X_{\mathrm{Polynomial}})^2}{\alpha^2} - \Sigma_j \Sigma_{j'} B_j (A^{-1})_{jj'} B_{j'}$$

$\alpha^2 =$ **Sum of uncorrelated errors (data and polynomial)**

$\Sigma_j \Sigma_{j'} B_j (A^{-1})_{jj'} B_{j'} =$ **Term defined by the correlated systematic errors**

(See Phys.Rev.D65:014012,200, Stump et al for details.)

PROFFIT

• **The whole machinery is implemented in the program PROFFIT.**
(Bacchetta, Jung, Knutsson, Kutak, DESY 10-013, arXiv:1001:4675)

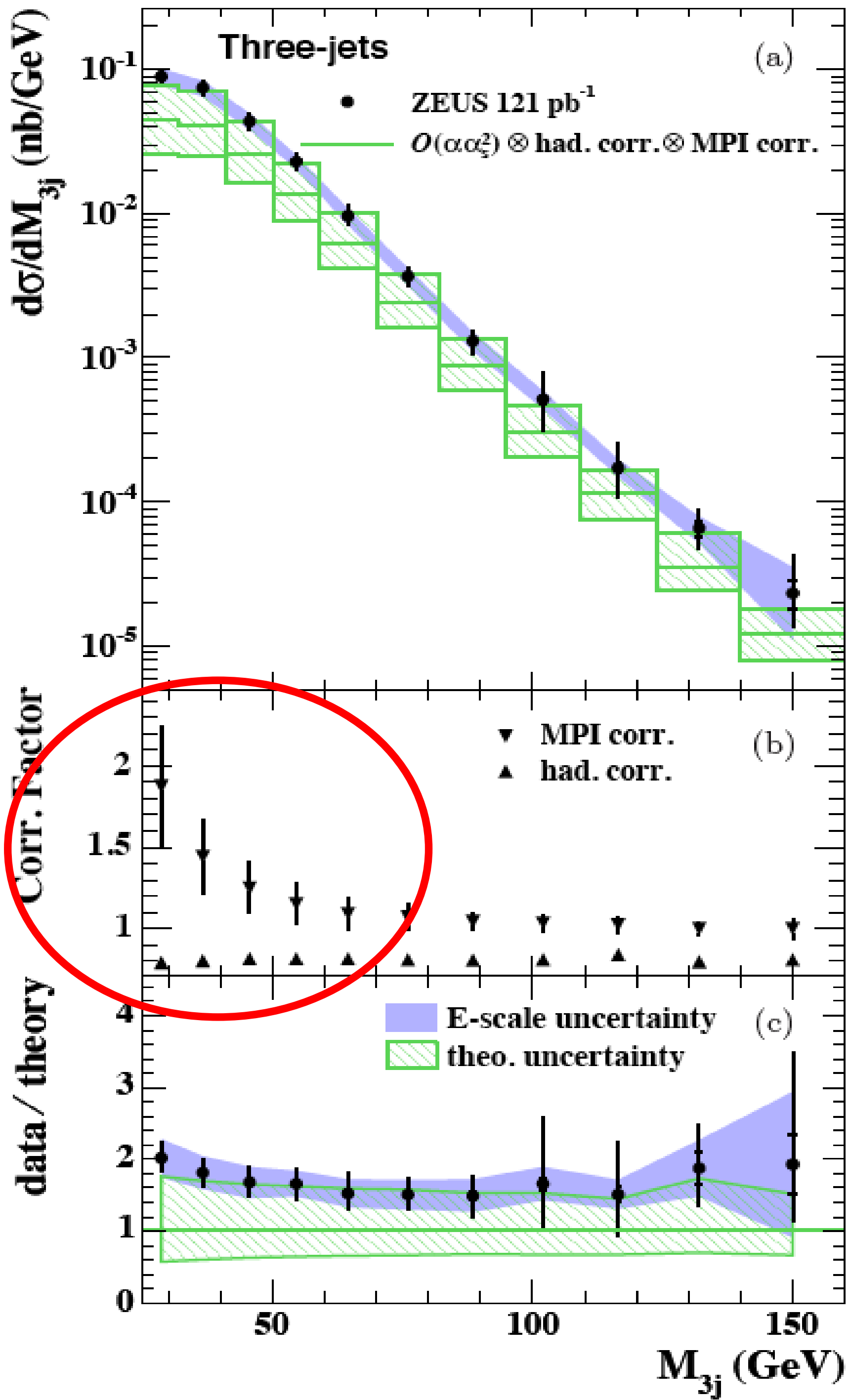
• **Official release soon available on HEPFORGE.**
(However contact me if you are interested.)

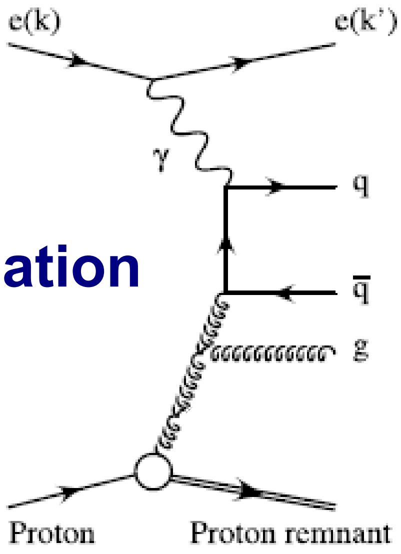
<u>Other applications:</u>

• **Also used to tune PYTHIA hadronization parameters to HERA data.**
(see http://indico.cern.ch/conferenceOtherViews.py?view=standard&confId=74601)

• **Similar approach use by the program PROFFESSOR. Used for LHC and LEP tunes of UE and hadronization MC parameters.**

Multijets in Photoproduction





LO Comparison to $O(\alpha\alpha_s^2)$ calculation

(only for 3 jets)

- Hadronization corrections
  - → Constant
- MI corrections
  - → Increasing with lower mass
  - → Necessary in order to describe data
- Data described within the fairly large theoretical uncertainties

The fitting method

Former fitting method: Based on running the generator in an **iterative procedure** in parameter space.

→ **Time consuming for exclusive final states. A high statistics MC run can take more than 24h, and ~100 iterations needed to find minimum.**

New Approach: Describe **parameter dependence** **before parameter fitting**, by building up a ***MC grid in parameter space***.
The grid points can be calculated simultaneously.
(In best case it takes the time of running the MC once.)

Parametrize the parameter space with a polynomial.

A fit takes only a few seconds.

→ Very fast to remake fit for different kinematic ranges, starting values, fitting algorithms, error treatments, etc.

Multiparton Interactions

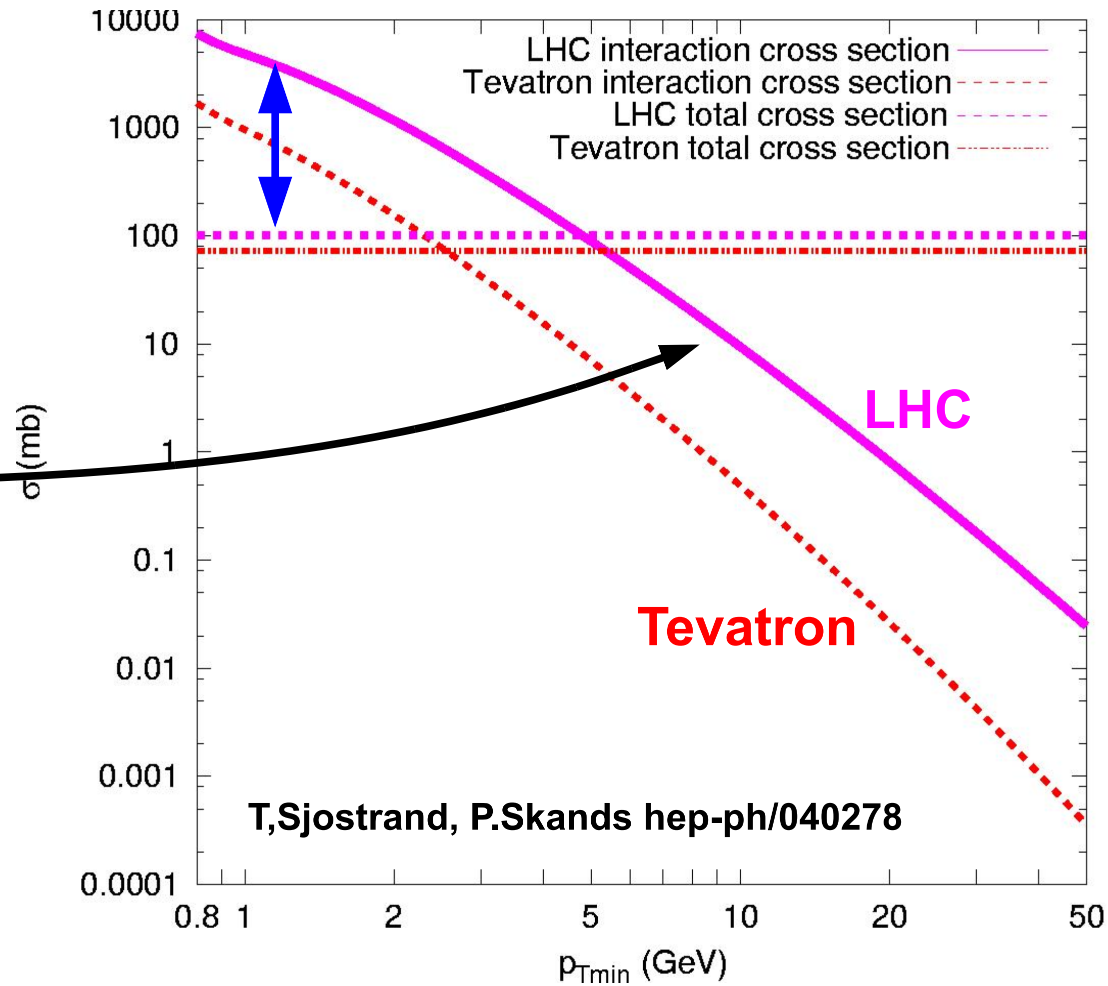
Theoretical motivation

partonic interaction cross-section:

$$\frac{d\sigma_{\rm int}}{dp_T^2} \propto \frac{\alpha_s^2(p_T^2)}{p_T^4}$$

Integrate + cut-off = $p_{T,\min}$

$$\sigma(p_{T,\min}) \propto \frac{1}{p_{T,\min}^2}$$



Interaction x-section > Total x-section

Suggests multiple parton interaction

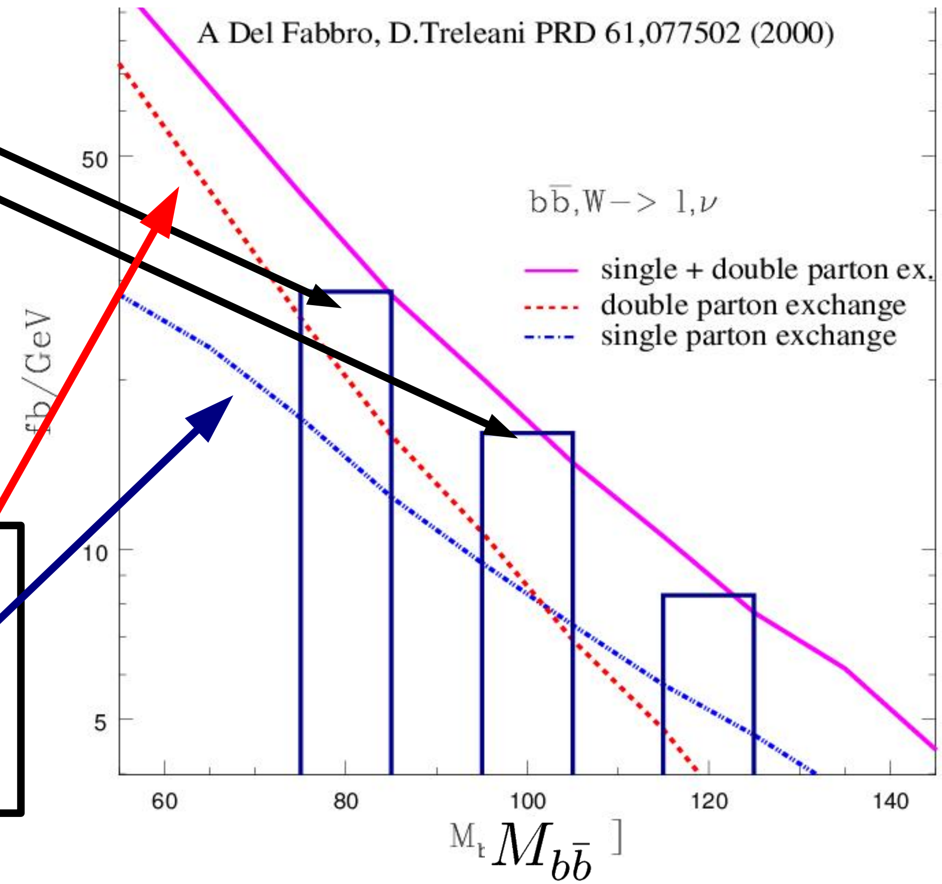
$$< n >= \sigma_{\rm int}/\sigma_{\rm tot}$$

Multiparton Interactions

MPI must be understood for high precision measurements

For example: MPI can be background to Higgs production.

$$p + p \rightarrow W + H + X$$
$$H \rightarrow b\bar{b}$$



$$p + p \rightarrow W + b\bar{b} + X$$

Double parton exch.

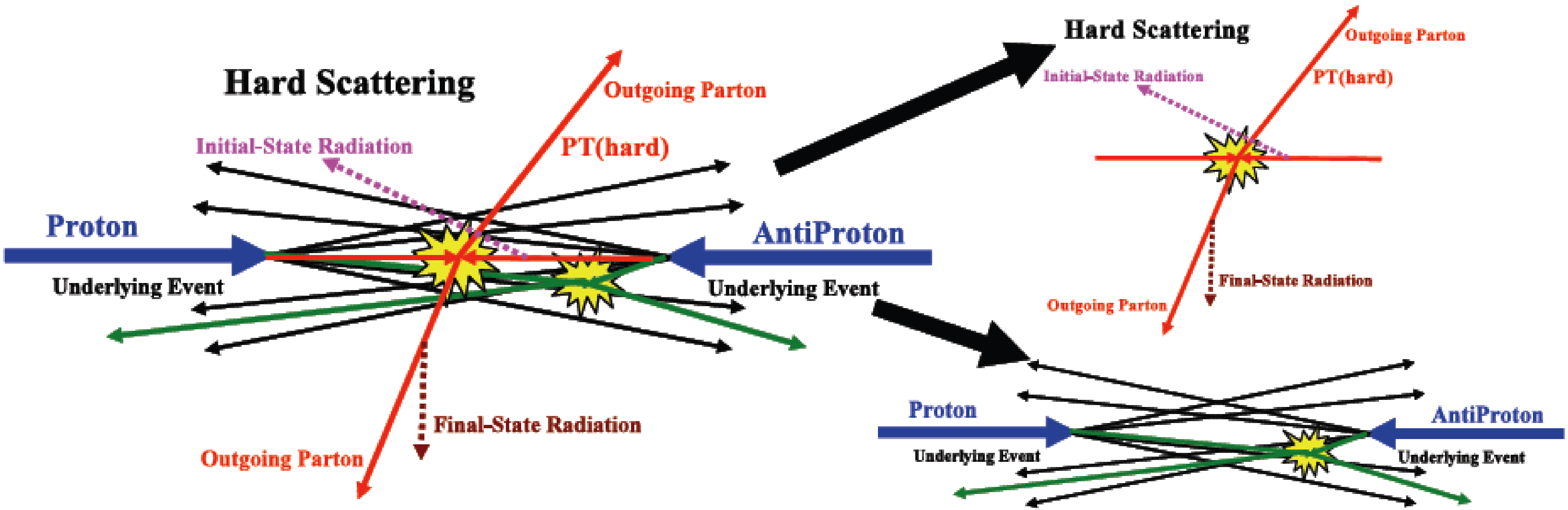
Single parton exch.

Total contribution > Higgs signal

The Underlying Event (UE)

UE = everything except the studied LO process:

- Parton showers
- Multiple interactions:
  - Additional remnant-remnant, or parton-remnant, interactions (soft or hard)



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