BERGISCHE
UNIVERSITÄT
WUPPERTAL

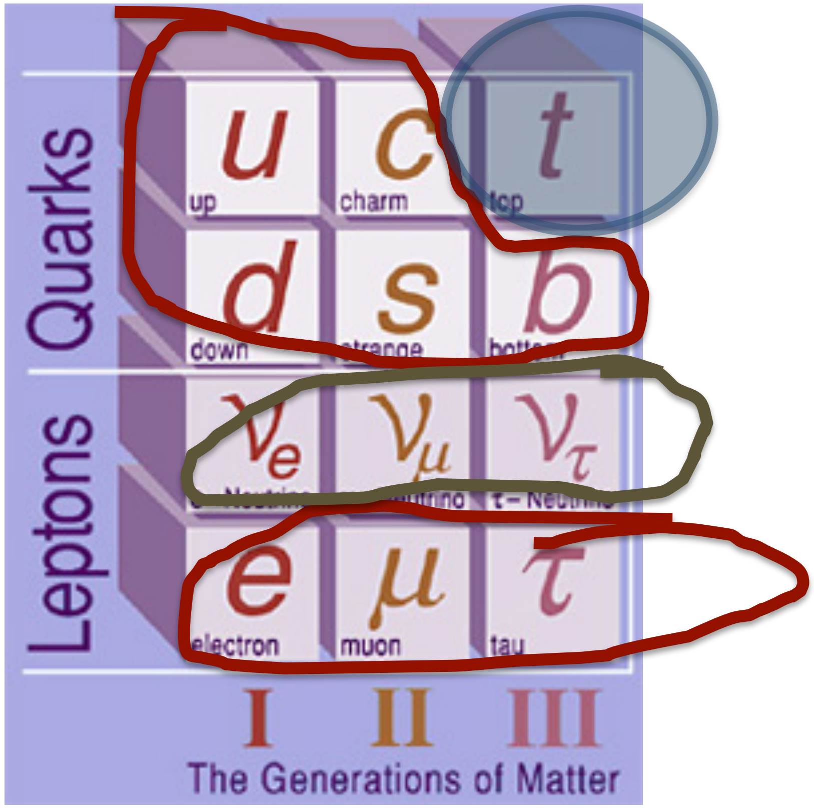
Standard Model @ Hadron Colliders
I. QCD

P.Mättig

Bergische Universität Wuppertal

Standar model pillar I: Matter

BERGISCHE UNIVERSITÄT WUPPERTAL



Unique topic for hadron colliders

Neutrinos not really testable @ hadron colliders

Most quarks/all charged leptons very deeply scrutinized

Standard Model pillar II: Forces

BERGISCHE
UNIVERSITÄT
WUPPERTAL

All interactions very precisely determined:

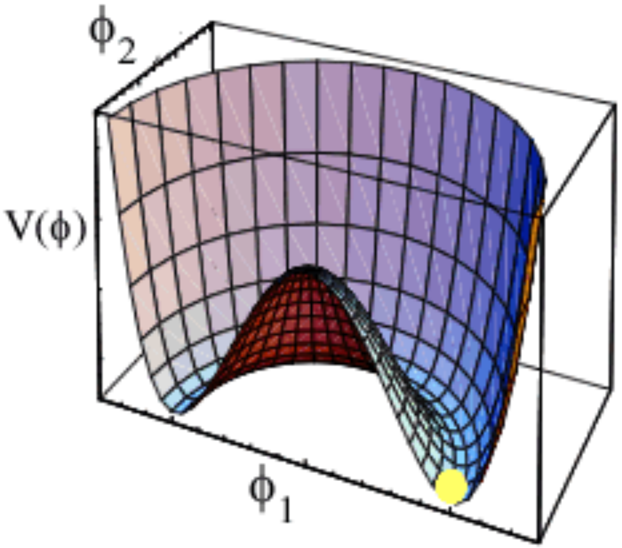
$$\begin{aligned} \alpha_s(M = M_Z) &= 0.1184(7) \\ \alpha_{em} &= 1/137.03499976(50) \\ G_F(M = m_\mu) &= 1.16639(1) \cdot 10^{-5}\ \mathrm{GeV}^{-2} \\ M_Z &= 91.1882(22)\ \mathrm{GeV} \end{aligned}$$

Dynamics well tested at energies ~ 100 GeV

e.g.: g → gg, (Z, γ) → W^+W^-, ...

Standard Model Pillar III: Higgs

BERGISCHE UNIVERSITÄT WUPPERTAL



Boson masses and fermion masses break gauge symmetries

➔Non – renormalisable theory

Standard Model way out:
Four Higgs fields
- **Three give mass to W/Z bosons**
- **one is physical with well defined properties (except mass)**

Until 20 days ago ???
THE ONLY MISSING PIECE OF THE STANDARD MODEL!

Why Standard Model @ Hadron Colliders?

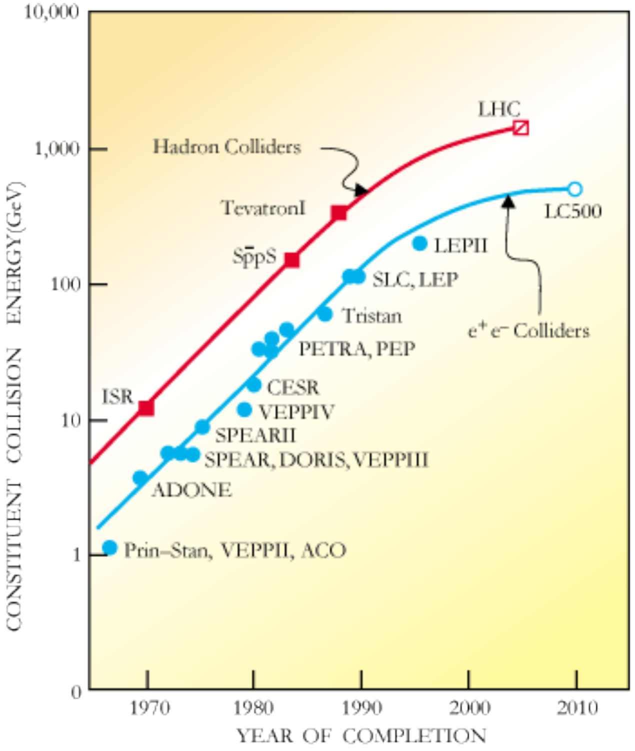
- Explore phase space not determined from first principles
- Probe at highest energies
- More statistics → Top Quark
- Scrutinize the remaining piece → Higgs Boson

Standard model: the way towards establishing ‚New Physics'?

- Standard Model processes background to ‚New Physics'
- will provide tools for searches for new phenomena
- Testing Standard Model to the extreme →
  may reveal a glimpse of ‚New Physics'

Forerunners of LHC

BERGISCHE UNIVERSITÄT WUPPERTAL

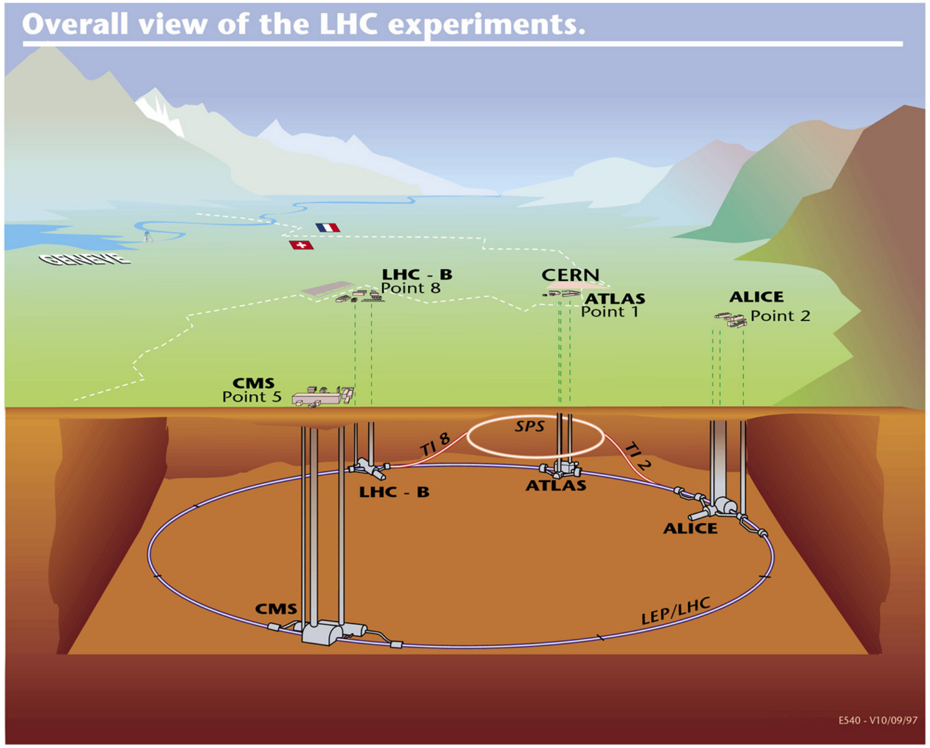


Tevatron (Fermilab): last 20 years:
Leading Proton – Antiproton collider
1.96 TeV c.m. energy

Two experiments
CDF & D0

Today's flagship LHC

BERGISCHE UNIVERSITÄT WUPPERTAL



Proton – Proton Kollisionen @ 14 TeV c.m. energy (currently 8 TeV)

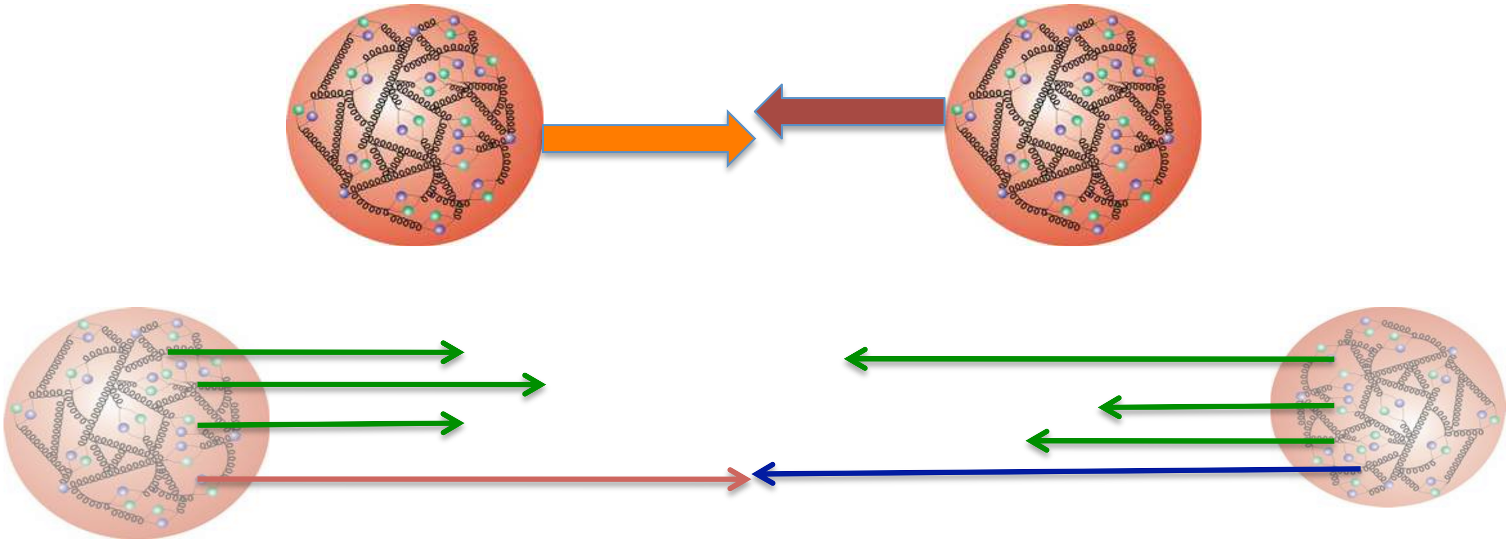
4 Experiments

Will focus on results from ATLAS and CMS

(LHCb → talk of G.Raven)

Reminder: how ‚protons' interact

BERGISCHE UNIVERSITÄT WUPPERTAL

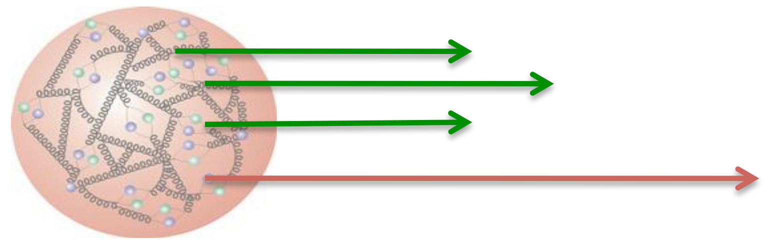


Proton scattering = scattering of quarks and gluons

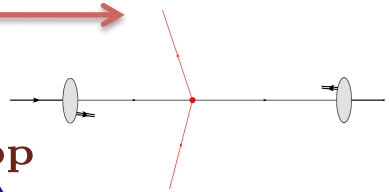
$$\sigma(pp \to YX) = \int_0^1 dx_1 \int_0^1 dx_2 \sum_f f_f(x_1) f_{\bar{f}}(x_2) \cdot \sigma(q_f(x_1 P) + \bar{q}_f(x_2 P) \to Y)$$

Reminder: x, M

BERGISCHE UNIVERSITÄT WUPPERTAL



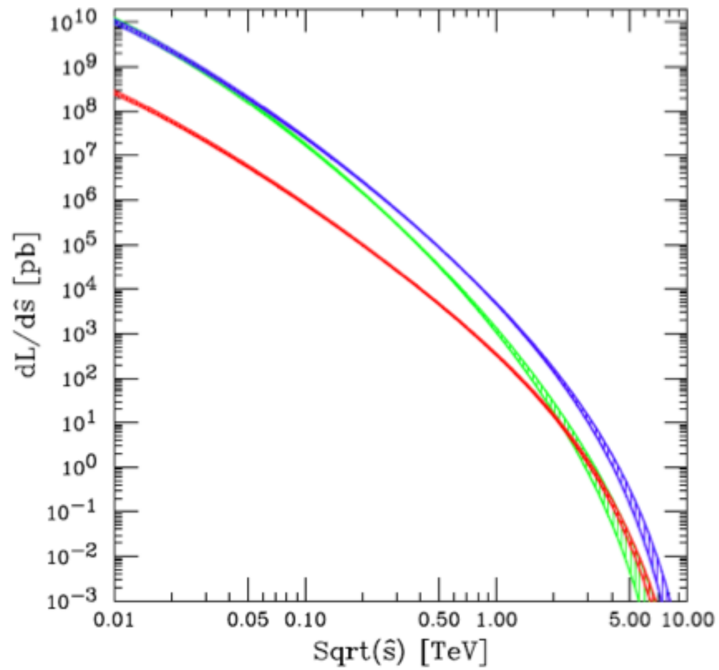
$x = E_{parton}/M_{proton}$



$$M_{scatter} = \sqrt{x_1 \cdot x_2} \cdot E_{pp}$$

‚resolution power'

for LHC: 8 TeV



I.e. high masses requires large x - values

LHC and Tevatron:
LHC has 4 (7)x higher energy,

Note for M ~ 400 – 1000 TeV: Tevatron qq – LHC gg

Some basics: rapidity

BERGISCHE UNIVERSITÄT WUPPERTAL

Rapidity a ‚natural' observable for consequtive branchings

$$\frac{d\sigma}{dy} = \text{const}$$

$$y = \frac{1}{2}\ln\left(\frac{E+p_{\|}}{E-p_{\|}}\right) = \frac{1}{2}\ln\left(\frac{E+p_{\|}}{\sqrt{m^2+p_T^2}}\right)$$

$$y \Longrightarrow y' = y + \frac{1}{2}\ln\left(\frac{1+\beta}{1-\beta}\right)$$

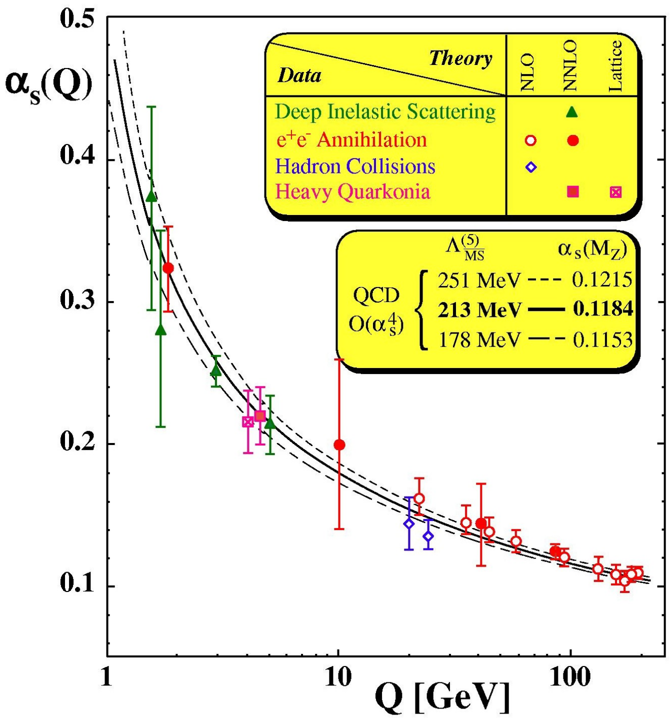
Frequently used y → η assuming massless particles ‚pseudo – rapidity'

$$\eta = \frac{1}{2}\ln\left(\tan\theta/2\right)$$

LHC a strong interaction collider

BERGISCHE UNIVERSITÄT WUPPERTAL

Remember: strong coupling rises with decreasing Q^2



Difficulty:
at around Q ~ 1 GeV
too strong to be calculable in
perturbation theory

‚too many gluons emitted'

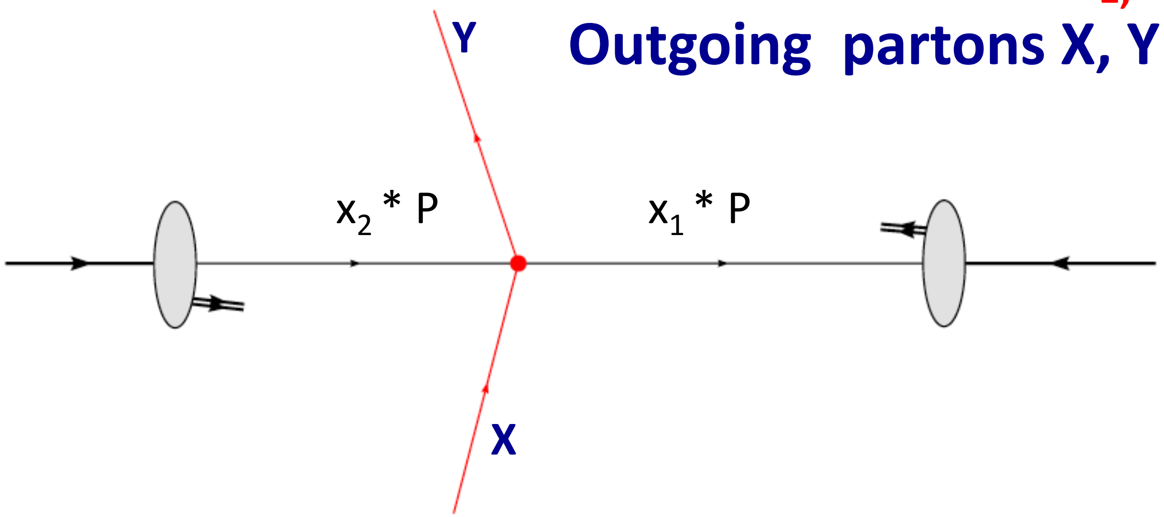
Basic limitation of theoretical description

hard scatter: two in → two out

This can be calculated:

Imcoming partons $p_{1,}$ p_2 with momenta P_1, P_2

Outgoing partons X, Y



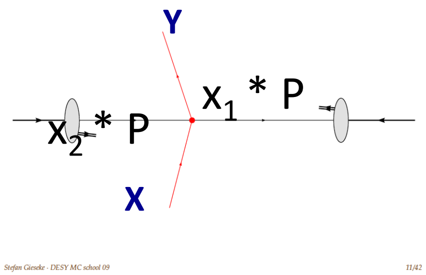
Stefan Gieseke · DESY MC school 09 11/42

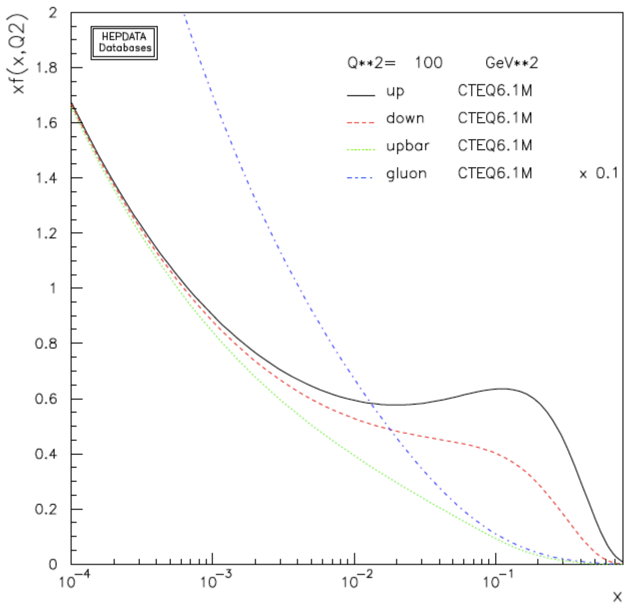
$$\sigma(\mathbf{p_1}(\mathbf{P_1}) + \mathbf{p_2}(\mathbf{P_2}) \to \mathbf{Y} + \mathbf{X} + \mathrm{Rest})$$

$$= \int_0^1 \mathbf{dx_1} \int_0^1 \mathbf{dx_2} \sum_{\mathbf{f}} \mathbf{F_f}(\mathbf{x_1}) \mathbf{F_{\bar{f}}}(\mathbf{x_2}) \sigma(\mathbf{q_1}(\mathbf{x_1 P}) + \mathbf{q_2}(\mathbf{x_2 P}) \to \mathbf{Y} + \mathbf{X} + \mathrm{Rest})$$

Parton distribution function

Parton momenta P_1, P_2 : fraction of proton momenta ➔ x_1P, x_2P
only probability distributions known





Interpolated from previous data

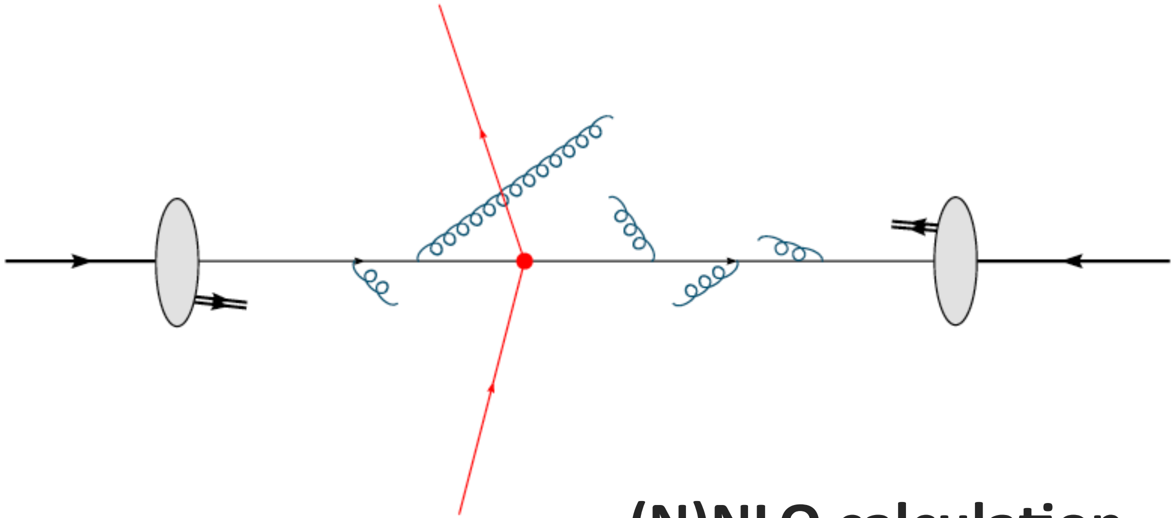
Extrapolated to LHC energies

$$\sigma(\mathbf{p_1}(\mathbf{P_1}) + \mathbf{p_2}(\mathbf{P_2}) \to \mathbf{Y} + \mathbf{X} + \mathrm{Rest})$$

$$= \int_0^1 \mathbf{dx_1} \int_0^1 \mathbf{dx_2} \sum_{\mathbf{f}} \mathbf{F_f}(\mathbf{x_1})\mathbf{F_{\bar{f}}}(\mathbf{x_2})\sigma(\mathbf{q_1}(\mathbf{x_1}\mathbf{P}) + \mathbf{q_2}(\mathbf{x_2}\mathbf{P}) \to \mathbf{Y} + \mathbf{X} + \mathrm{Rest})$$

Strong interaction: gluon radiation

BERGISCHE UNIVERSITÄT WUPPERTAL

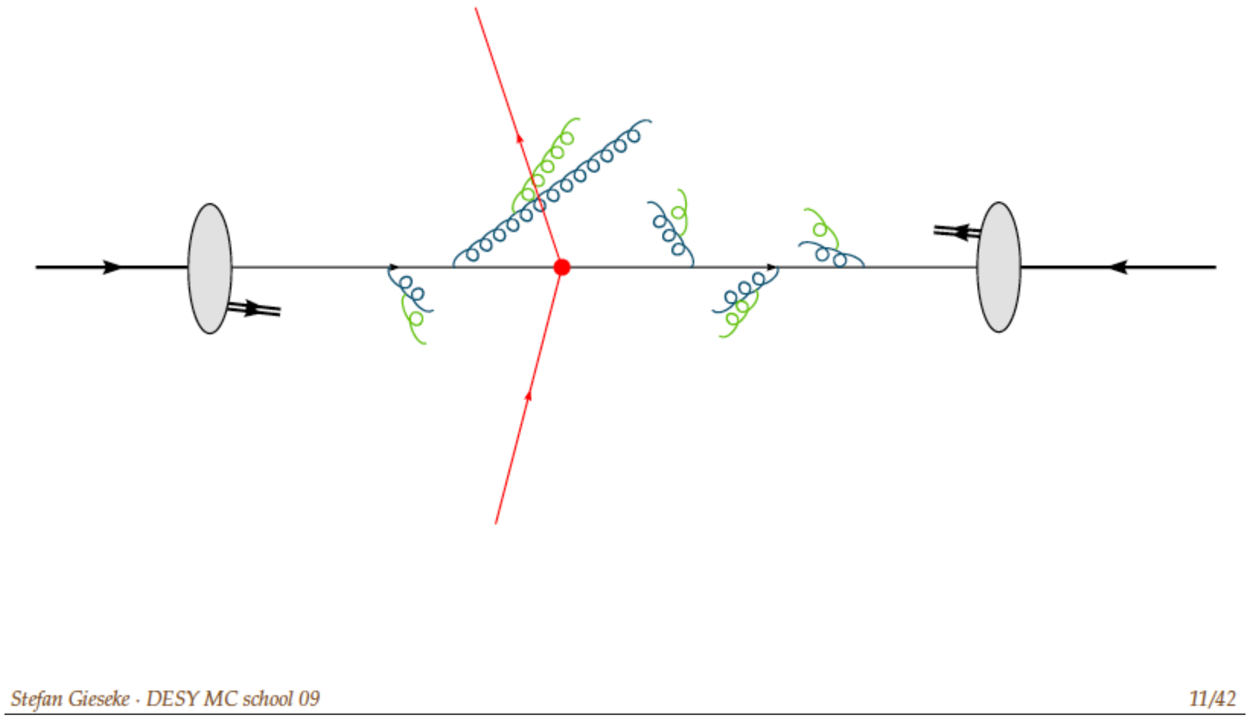


calculable (although in most cases not completely)

Stefan Gieseke · DESY MC school 09

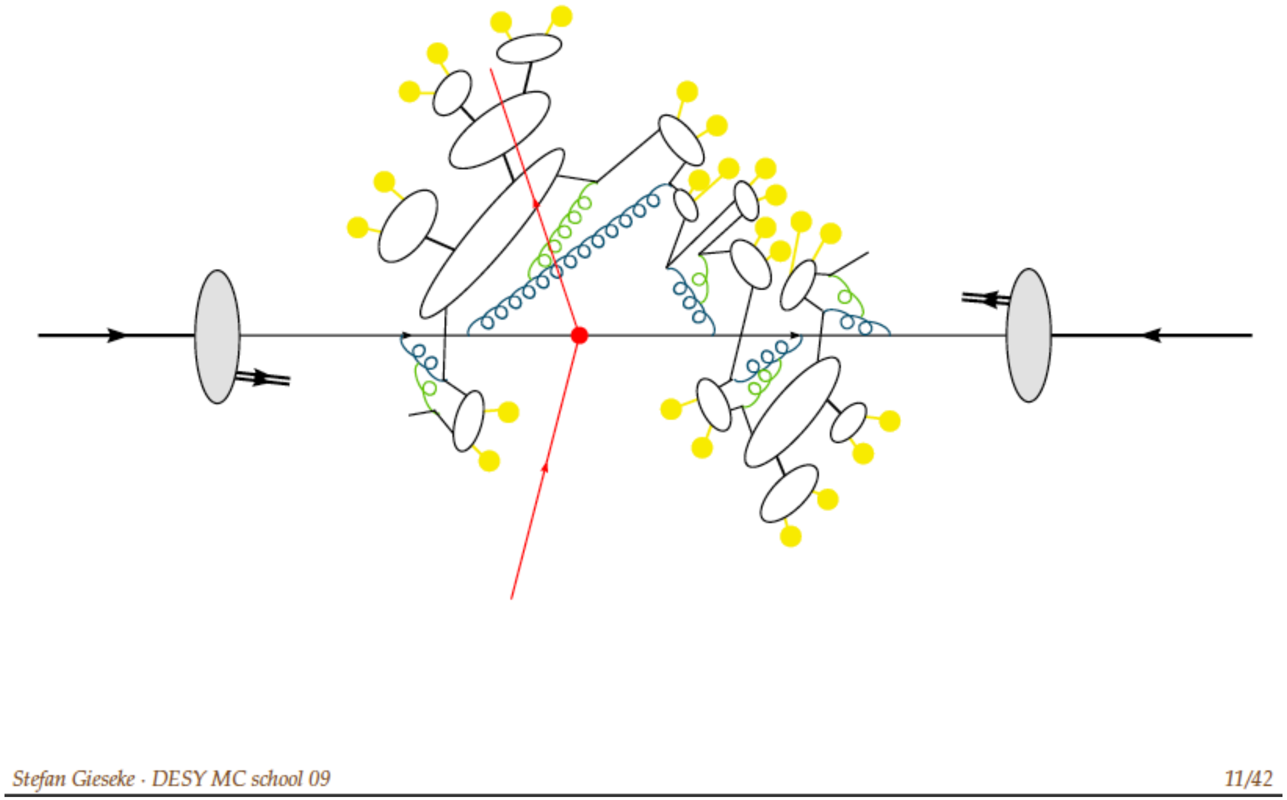
(N)NLO calculation,
i.e. full matrix element with up to two additional partons $O(\alpha_s^3)$

A parton shower



Original hard partons start to ‚shower', i.e. split in gluons and quarks

Quarks and Gluons hadronize

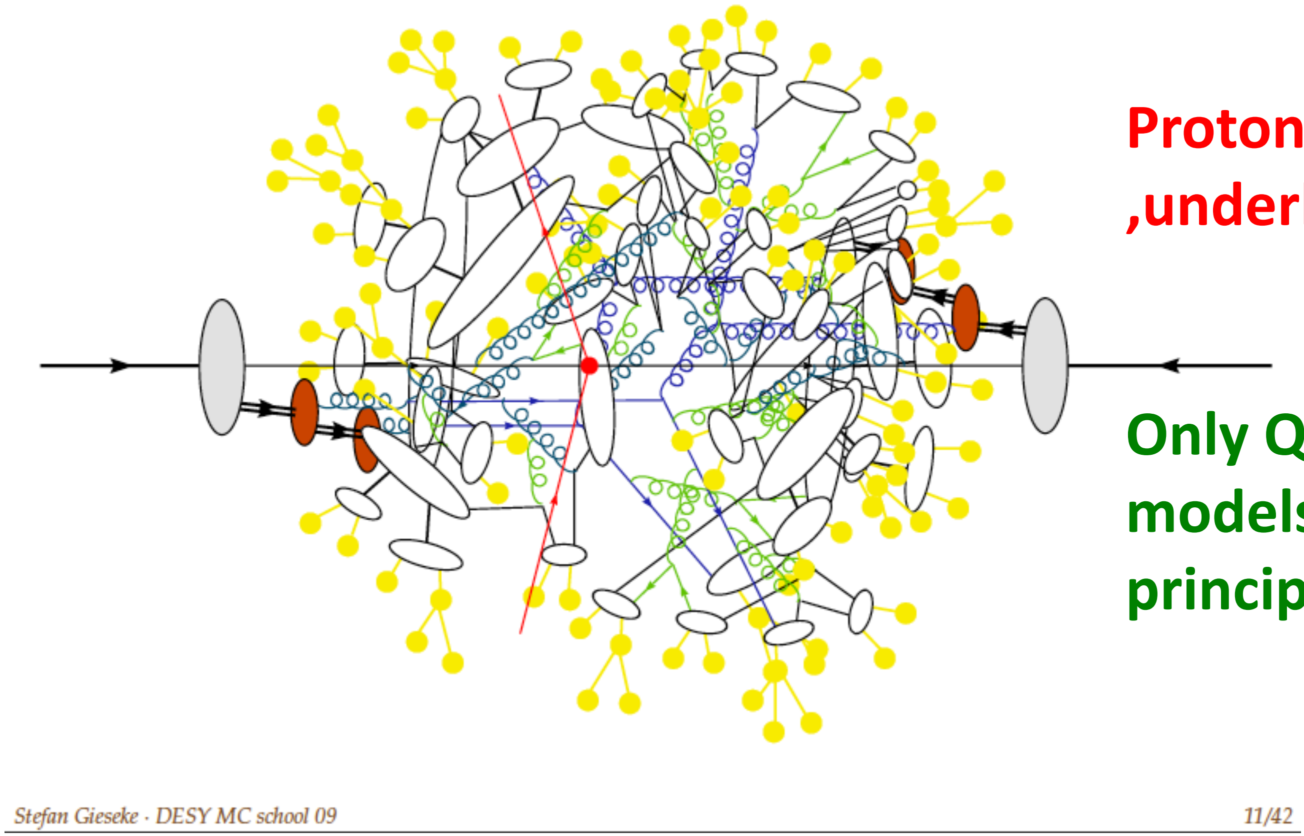


Quarks and Gluons turn into pions, kaons, protons:

hadronisation

A more comprehensive picture

BERGISCHE
UNIVERSITÄT
WUPPERTAL



Proton remnants interact: ‚underlying event‘

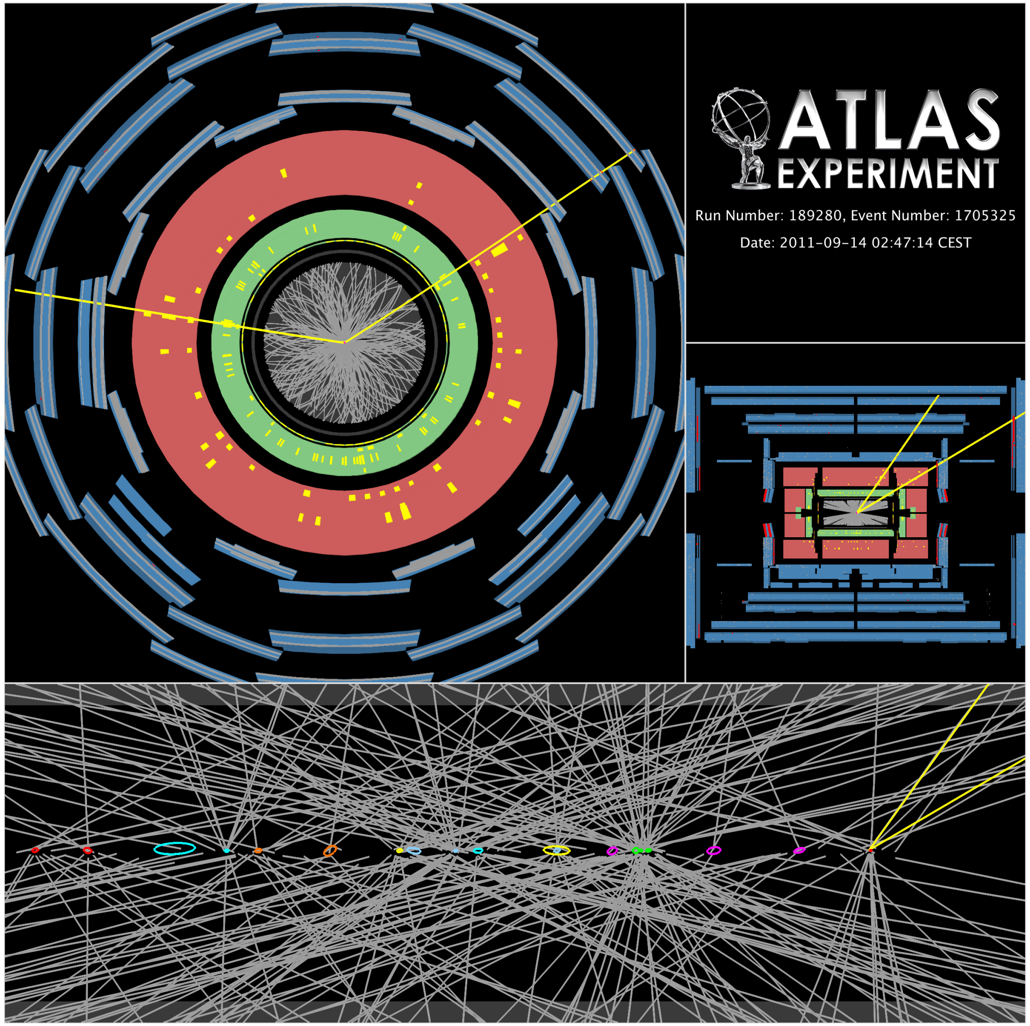
Only QCD ‚motivated‘ models – not from first principles!

$$\sigma(\mathbf{p_1}(\mathbf{P_1}) + \mathbf{p_2}(\mathbf{P_2}) \rightarrow \mathbf{Y} + \mathbf{X} + \mathrm{Rest})$$

$$= \int_0^1 \mathbf{dx_1} \int_0^1 \mathbf{dx_2} \sum_{\mathbf{f}} \mathbf{F_f}(\mathbf{x_1}) \mathbf{F_{\bar{f}}}(\mathbf{x_2}) \sigma(\mathbf{q_1}(\mathbf{x_1 P}) + \mathbf{q_2}(\mathbf{x_2 P}) \rightarrow \mathbf{Y} + \mathbf{X} + \mathbf{Rest})$$

QCD in the detector

BERGISCHE
UNIVERSITÄT
WUPPERTAL



A lot of ‚isotropic' hadron production

One bunch Xing:
Some 20 pp – interactions
‚pile – up'

Started with
qq → qq
Result: 1000 hadrons

Standard Model tests: Type I
Underlying event

BERGISCHE UNIVERSITÄT WUPPERTAL

$$\sigma(\mathbf{p_1}(\mathbf{P_1}) + \mathbf{p_2}(\mathbf{P_2}) \rightarrow \mathbf{Y} + \mathbf{X} + \mathrm{Rest})$$

$$= \int_0^1 \mathbf{dx_1} \int_0^1 \mathbf{dx_2} \sum_{\mathbf{f}} \mathbf{F_f}(\mathbf{x_1}) \mathbf{F_{\bar{f}}}(\mathbf{x_2}) \sigma(\mathbf{q_1}(\mathbf{x_1 P}) + \mathbf{q_2}(\mathbf{x_2 P}) \rightarrow \mathbf{Y} + \mathbf{X} + \mathbf{Rest})$$

Take from previous measurements

Well known process

Measure underlying event

Standard Model tests: Type II
Parton distribution function

BERGISCHE UNIVERSITÄT WUPPERTAL

$$\sigma(\mathbf{p_1}(\mathbf{P_1}) + \mathbf{p_2}(\mathbf{P_2}) \rightarrow \mathbf{Y} + \mathbf{X} + \mathrm{Rest})$$

$$= \int_0^1 \mathbf{dx_1} \int_0^1 \mathbf{dx_2} \sum_{\mathbf{f}} \mathbf{F_f}(\mathbf{x_1}) \mathbf{F_{\bar{f}}}(\mathbf{x_2}) \sigma(\mathbf{q_1}(\mathbf{x_1 P}) + \mathbf{q_2}(\mathbf{x_2 P}) \rightarrow \mathbf{Y} + \mathbf{X} + \mathrm{Rest})$$

Well known process

Take from models

Measure parton Distribution function

Standard Model tests: Type III
The hard scatter process

BERGISCHE UNIVERSITÄT WUPPERTAL

$$\sigma(\mathbf{p_1}(\mathbf{P_1}) + \mathbf{p_2}(\mathbf{P_2}) \rightarrow \mathbf{Y} + \mathbf{X} + \mathrm{Rest})$$

$$= \int_0^1 \mathbf{dx_1} \int_0^1 \mathbf{dx_2} \sum_{\mathbf{f}} \mathbf{F_f}(\mathbf{x_1}) \mathbf{F_{\bar{f}}}(\mathbf{x_2}) \sigma(\mathbf{q_1}(\mathbf{x_1 P}) + \mathbf{q_2}(\mathbf{x_2 P}) \rightarrow \mathbf{Y} + \mathbf{X} + \mathrm{Rest})$$

Take from previous measurements

Measure hard process

Take from models

In a nutshell:

BERGISCHE UNIVERSITÄT WUPPERTAL

Hard process
= (data
- pile up events from simultaneous pp – collisions
- underlying event from proton remnants)
x (transfer from jets → partons)
x (unfolding of parton energies = parton distribution fct.)

Involved,
.... but with experimental knowledge feasible

Key ingredients to use data

BERGISCHE UNIVERSITÄT WUPPERTAL

- pile up events = multiple proton – proton interactions in one bunch crossing
- ‚underlying event'

- transfer function (partons → hadrons)

-Parton distribution functions

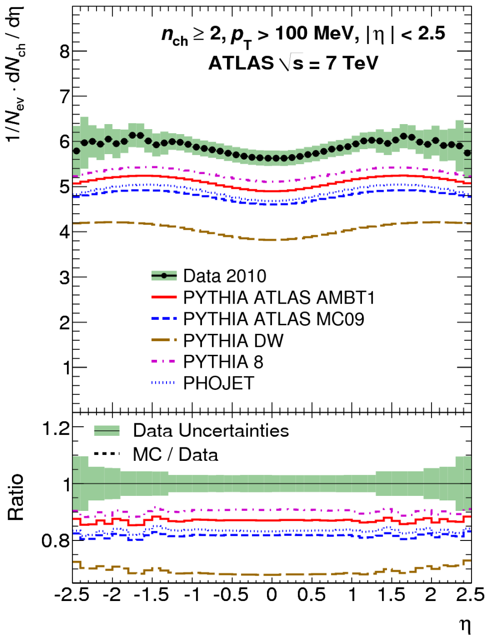
Pile up events

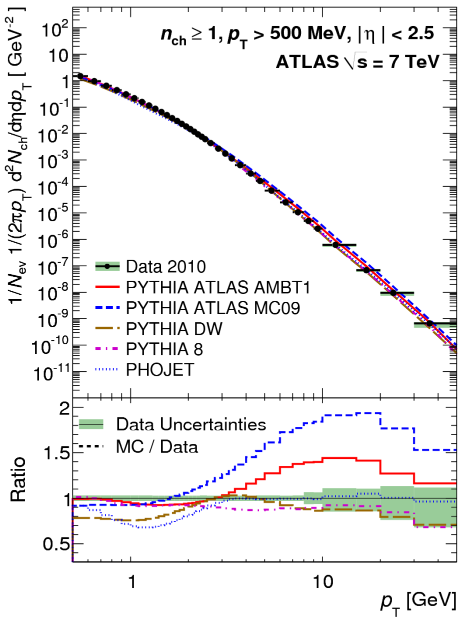
BERGISCHE
UNIVERSITÄT
WUPPERTAL

Pile – up events can be measured:

pp – interactions without trigger bias ‚minimum bias events'

At 7 TeV: 6 charged particles per |Δη| = 1, mostly low p_T

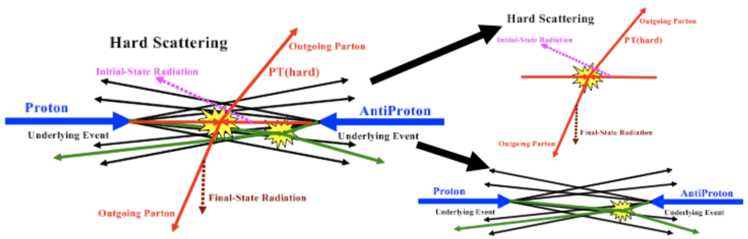


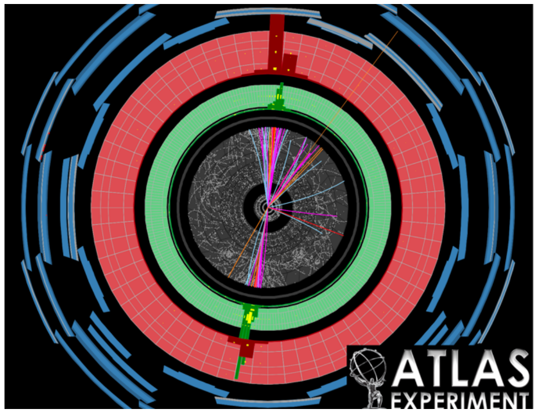


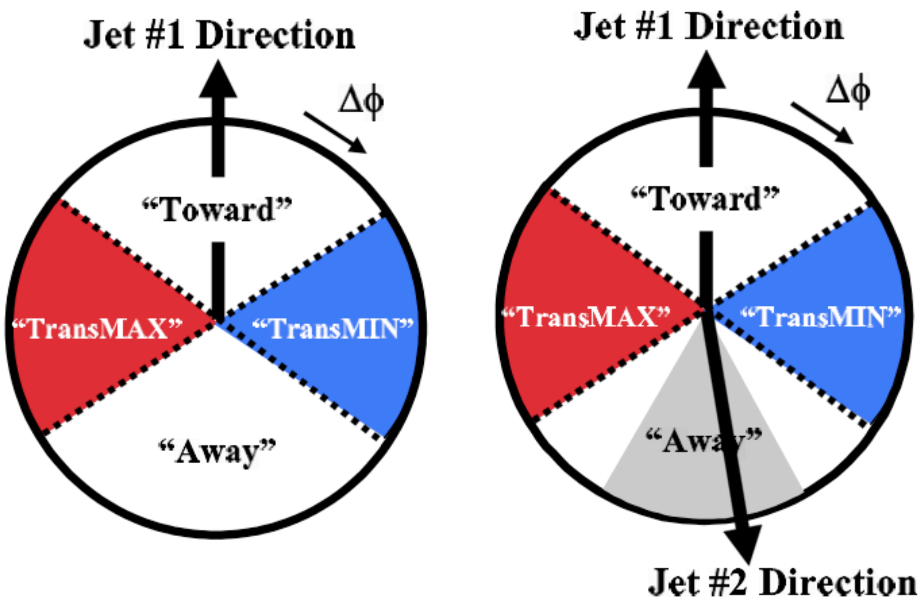
No good description by models

Note: per LHC bunch crossing ~ currently 20 of these events

Underlying events





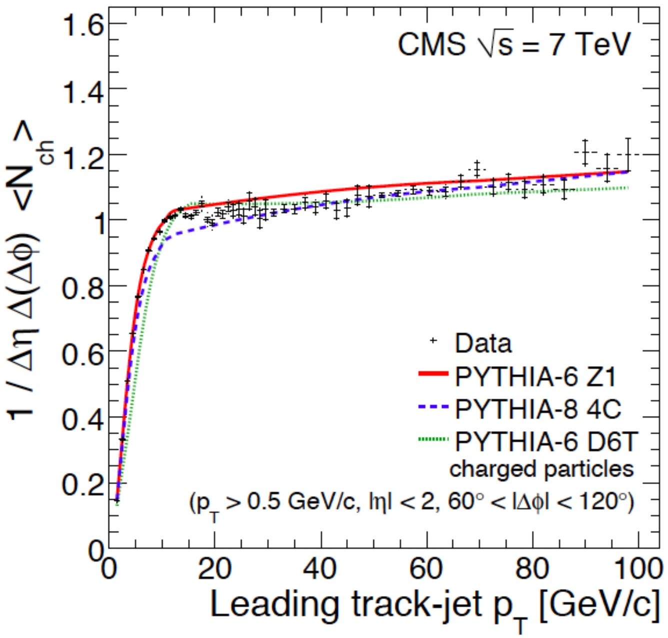


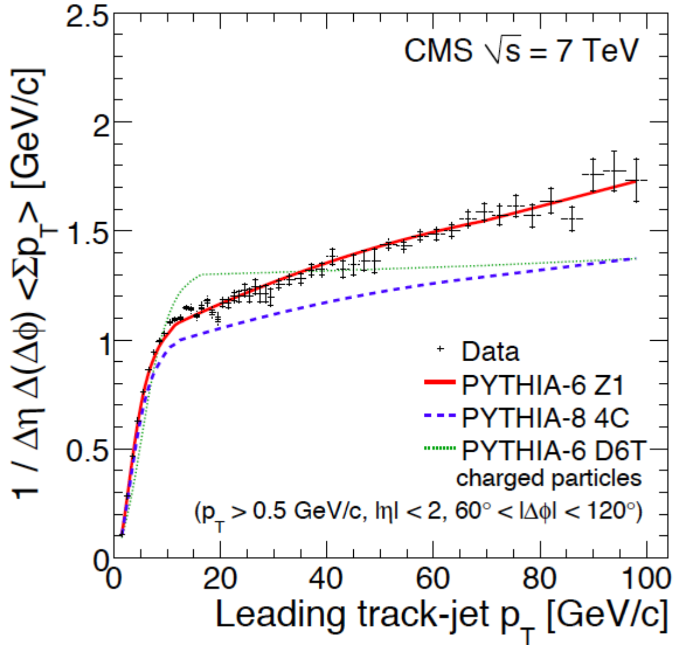
Transverse regions little affected by hard process

➔ properties like underlying event

Particle distributions in UE events

BERGISCHE UNIVERSITÄT WUPPERTAL

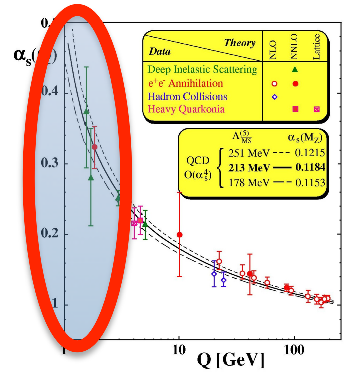




Can be reasonably described by models

Modelling ‚soft interactions‘

BERGISCHE UNIVERSITÄT WUPPERTAL

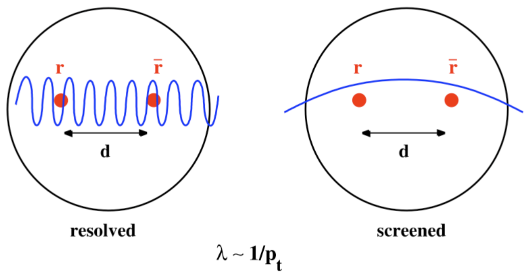


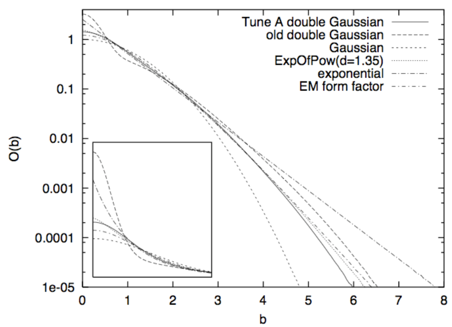
Minimum bias + underlying events:

Measured in special environment

Extrapolate to all conditions:

try to model applying several ad – hoc concepts

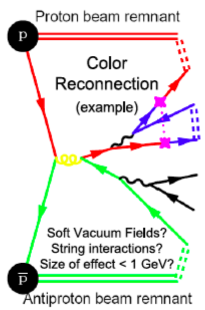




Overlap of protons

Colour screening

Colour reconnection



Challenging! Only an approximate description possible!

Parton distribution functions

BERGISCHE UNIVERSITÄT WUPPERTAL

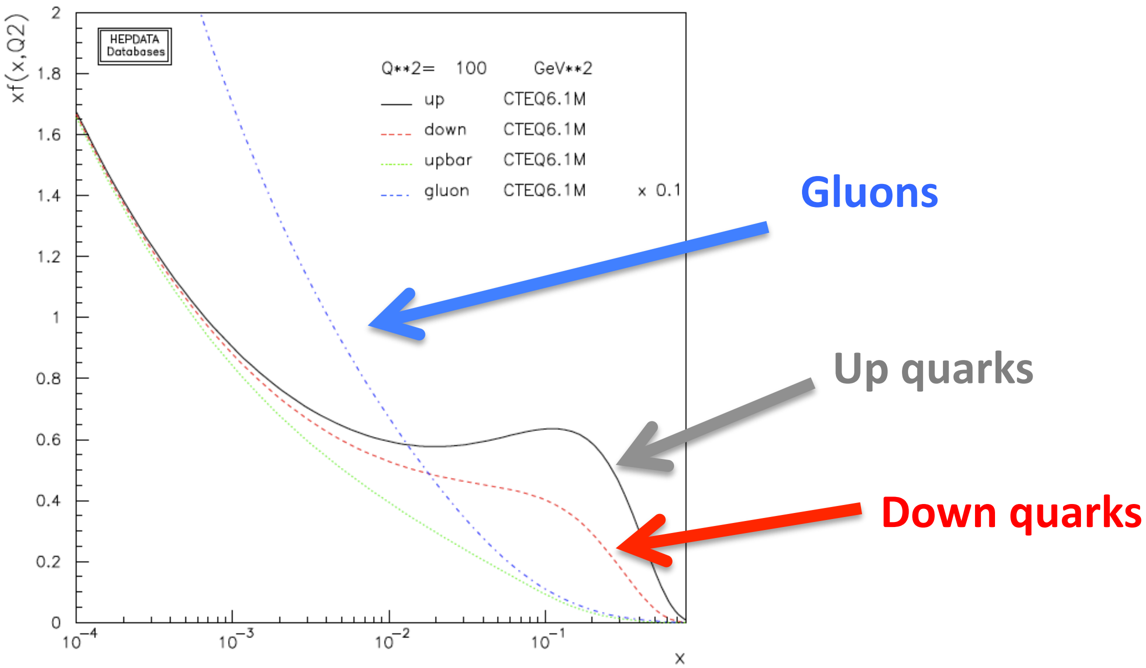
Energy fractions of different kinds of partons f in proton

$$\sigma(\mathbf{p_1}(\mathbf{P_1}) + \mathbf{p_2}(\mathbf{P_2}) \to \mathbf{Y} + \mathbf{X} + \mathrm{Rest})$$

$$= \int_0^1 \mathbf{dx_1} \int_0^1 \mathbf{dx_2} \sum_{\mathbf{f}} \mathbf{F_f}(\mathbf{x_1})\mathbf{F_{\bar{f}}}(\mathbf{x_2})\sigma(\mathbf{q_1}(\mathbf{x_1}\mathbf{P}) + \mathbf{q_2}(\mathbf{x_2}\mathbf{P}) \to \mathbf{Y} + \mathbf{X} + \mathrm{Rest})$$

Various measurements at M^2_1
theoretical evolution to $(M^2)_2$

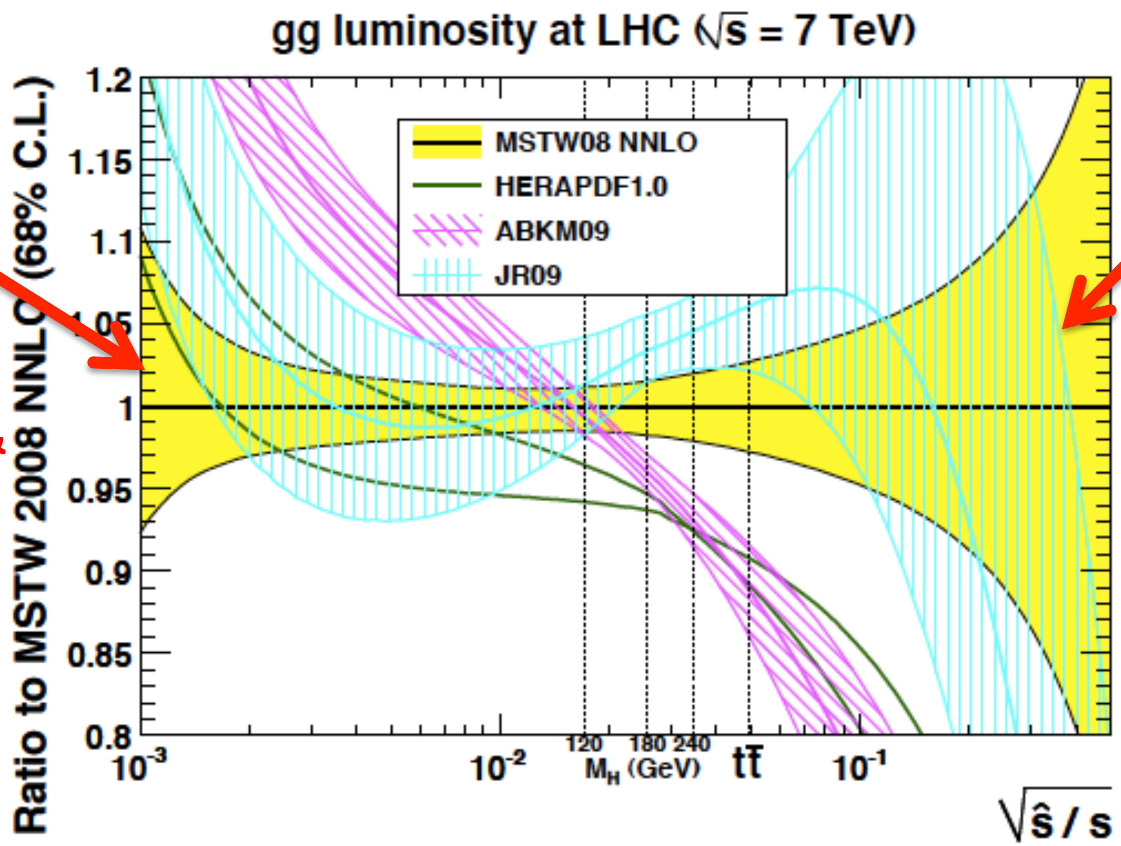
Just one of several pdf parametrisations



Significant uncertainties

BERGISCHE
UNIVERSITÄT
WUPPERTAL

G.Watt

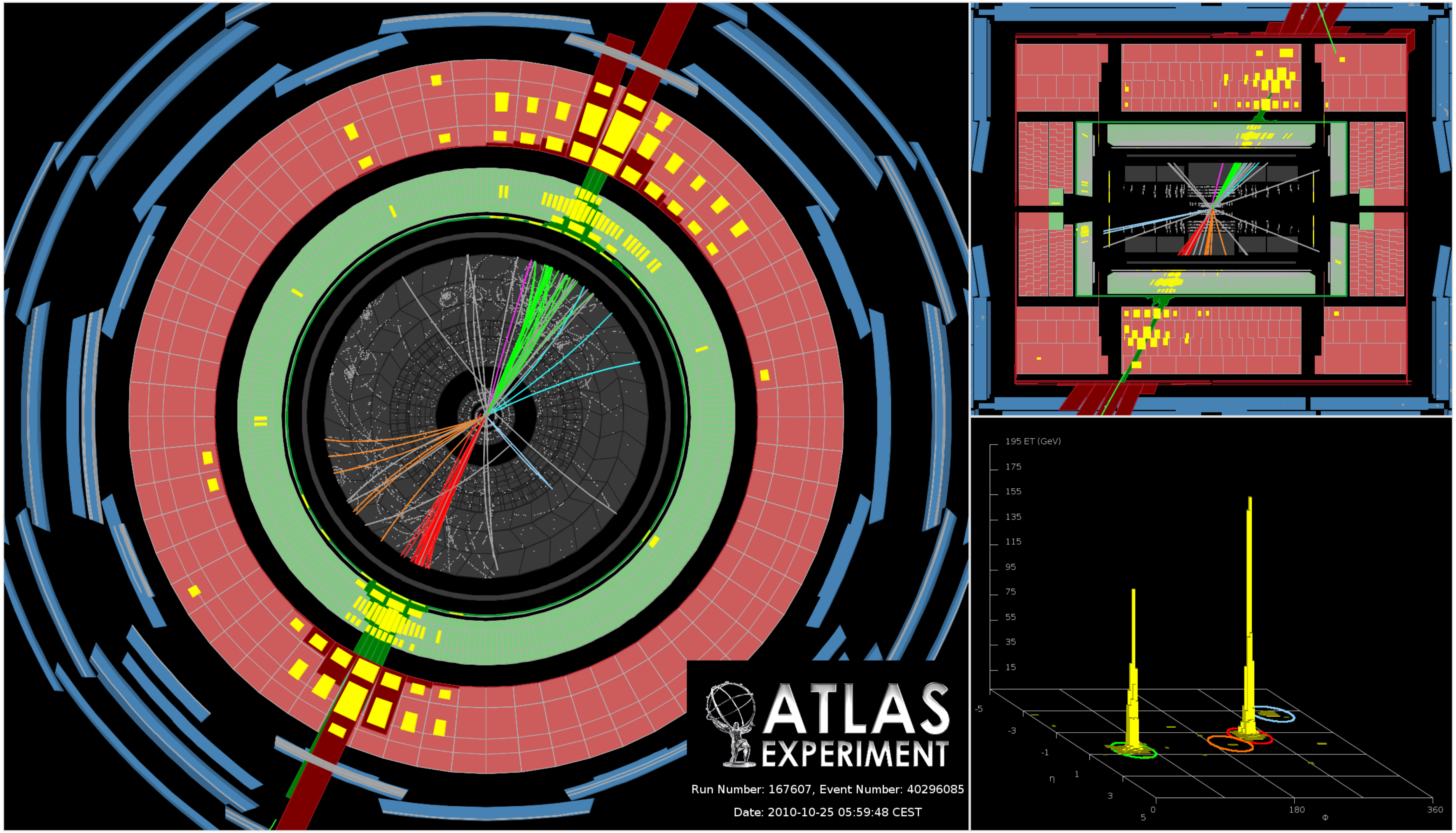


low x:
many gluons
➔ Theoretical & experimental uncertainties

High x:
few gluons
➔ Large uncertainty

LHC will allow some self - calibration

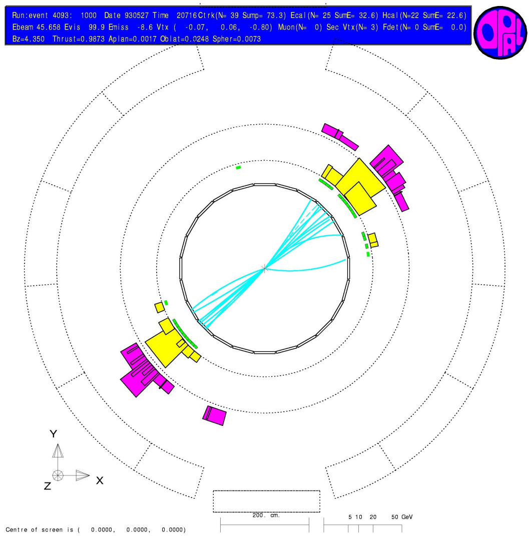
Hard interaction: Jets



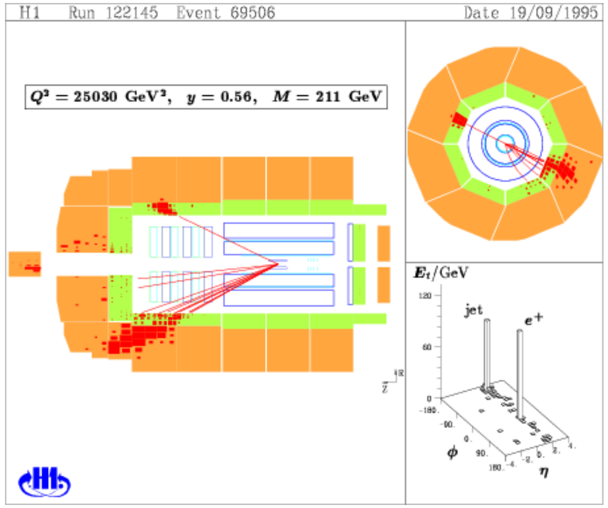
Jets are universal

BERGISCHE
UNIVERSITÄT
WUPPERTAL

$e^+ e^-$ collisions



e p collisions

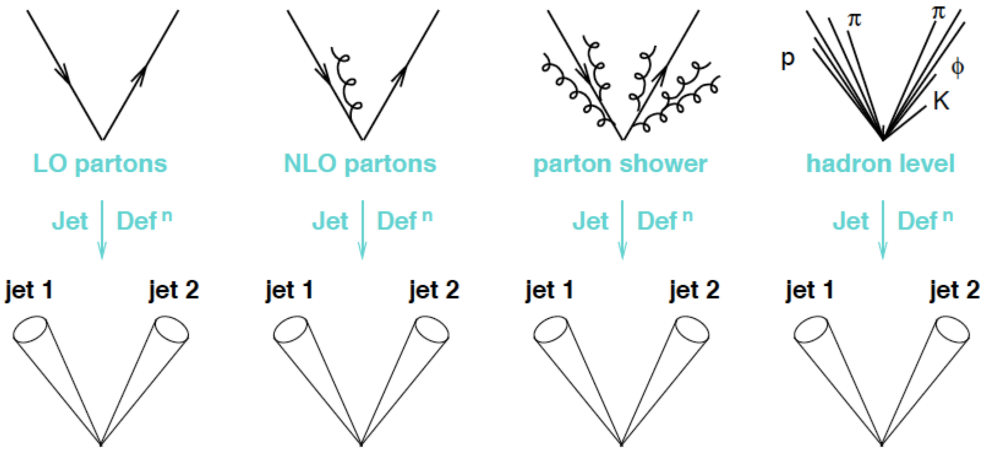


Jets: representative of quarks and gluons

- ➔ stringent test of theory
- ➔ experimenal challenge: extract partons from 1000 hadrons
- ➔ experimentally attainable
  direction and energy + (sometimes) parton flavour

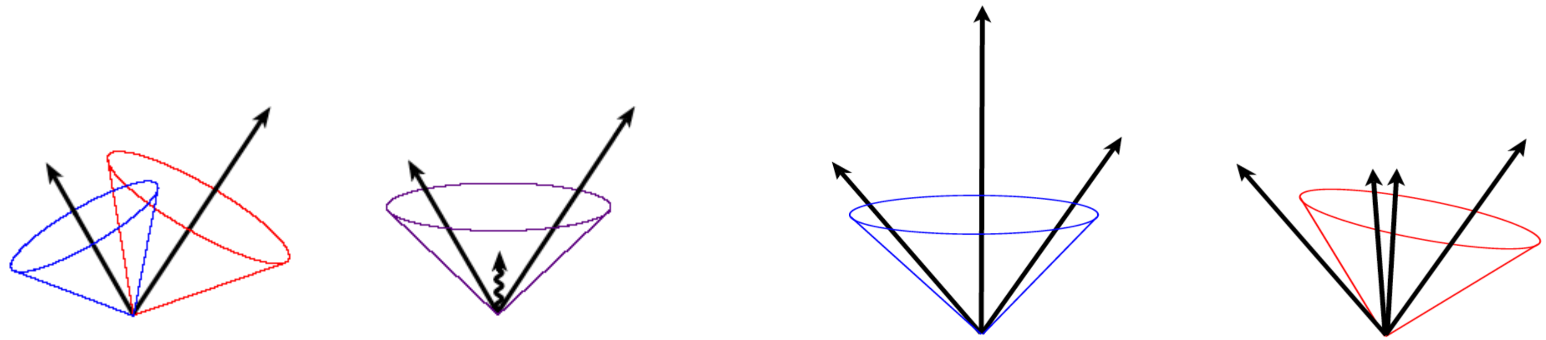
How to find a jet ?

BERGISCHE UNIVERSITÄT WUPPERTAL



Unambiguous connection to underlying partons → Comparison to theory

Not so straight – forward: example cone – jet finder



Sequential jet finder

BERGISCHE UNIVERSITÄT WUPPERTAL

‚Reverse evolution of event'

1 Select one particle (e.g. most energetic)

2 Find ‚most similar' particle, (e.g. smallest angle, p_t)

3 Is combination smaller than predefined ‚cut off' value (e.g. maximum angle, maximum mass ....)

IF YES:

4 Combine to a new ‚pseudo – particle' (e.g. sum 4 – momenta)

5 Go to 2

IF NO:

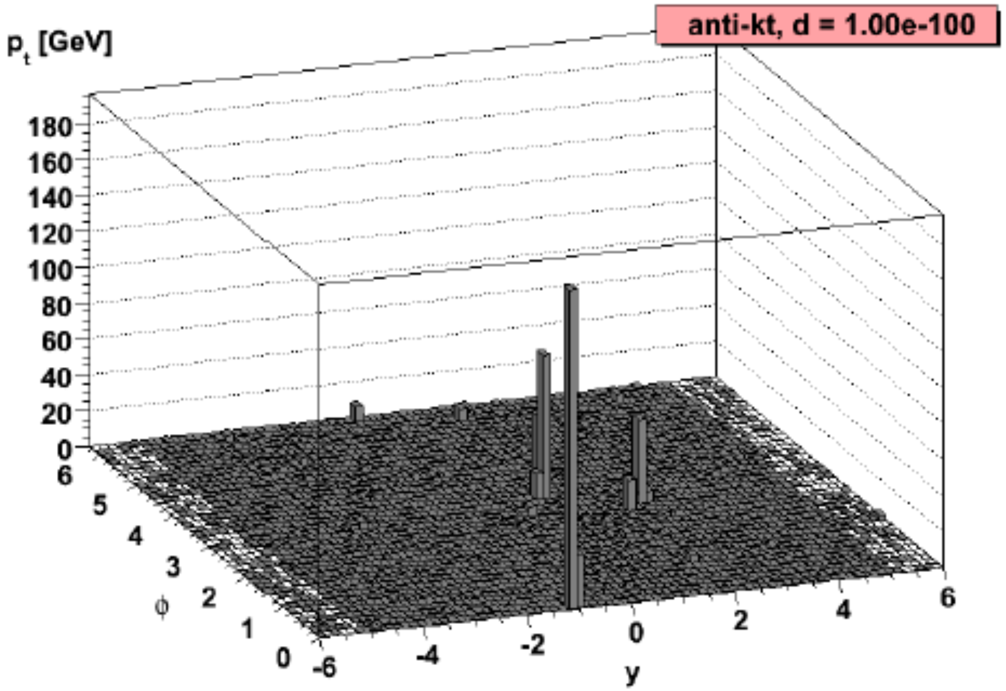
4 Jet found: sum of all associated particles

Standard jet finding at LHC: ‚Anti – kt‘

$$d_{ij} = \min(p_{ti}^{-2}, p_{tj}^{-2}) \frac{\Delta R_{ij}^2}{R^2}$$

© Gavin Salam

$$\Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$



Select hard particles as ‚seeds‘ for jets: favoured by $\min(p_t^2)$

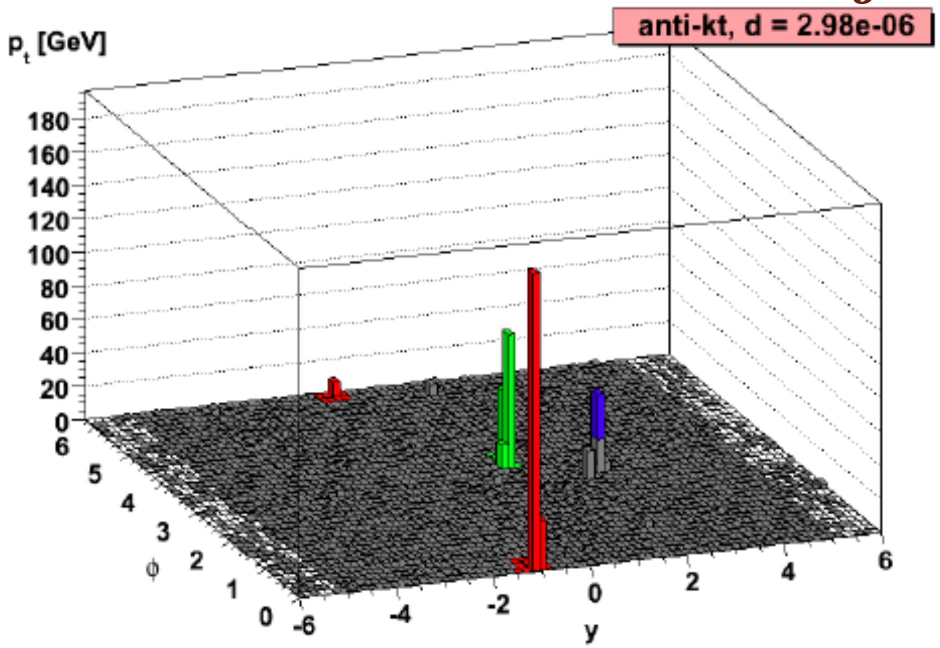
Hard particles separated in space are disctinct seeds: large ΔR_{ij}

‚cut off‘ given by d_{ij} (steered by R)

Standard jet finding at LHC: ‚Anti – kt'

$$d_{ij} = \min(p_{ti}^{-2}, p_{tj}^{-2}) \frac{\Delta R_{ij}^2}{R^2}$$

$$\Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$



Gradual d_{ij} increase:

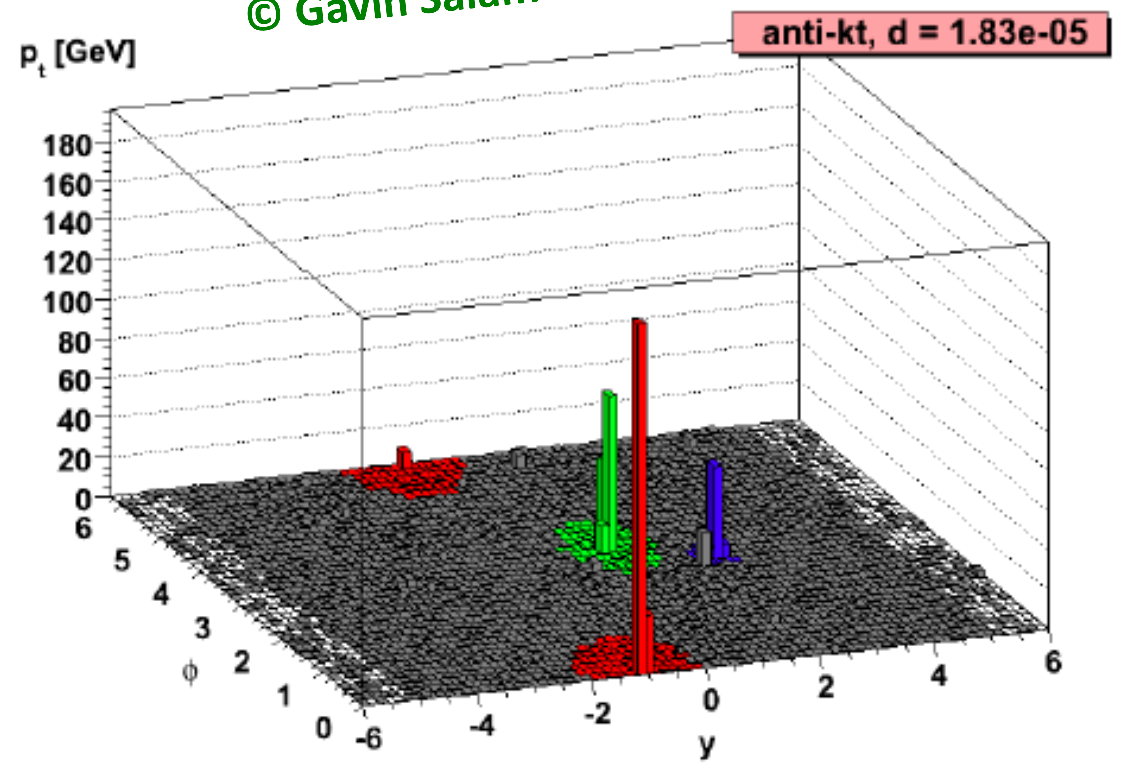
Associate close by particles: mostly soft ones in neighbourhood

(if no hard ones close by)

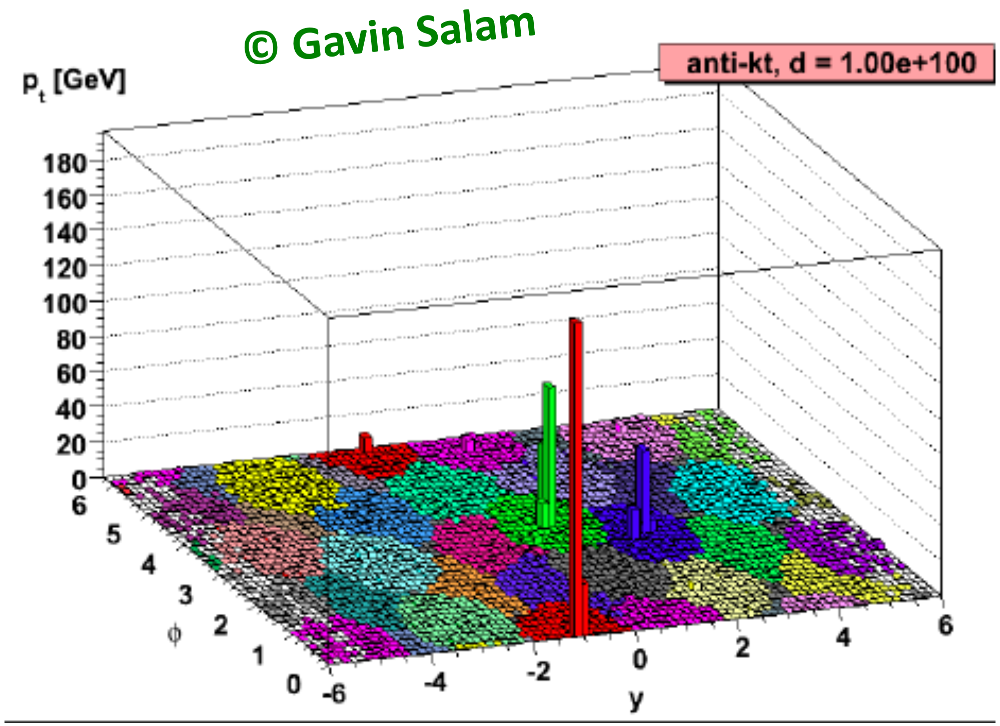
Standard jet finding at LHC: ‚Anti – kt‘

Intermediate step: emerging jet cones

© Gavin Salam



The final jets



All particles assigned to jets

Close to circular in space good for experimental corrections

Note: special treatment of particles close to beam

Physics from Jet measurements @ hadron - colliders

BERGISCHE UNIVERSITÄT WUPPERTAL

- crucial for understanding background
- tests of QCD predictions at highest reachable energies (inclusive jets, jj – masses, multi – jets)
- will help sorting out parton distribution functions
- tests of physics beyond SM

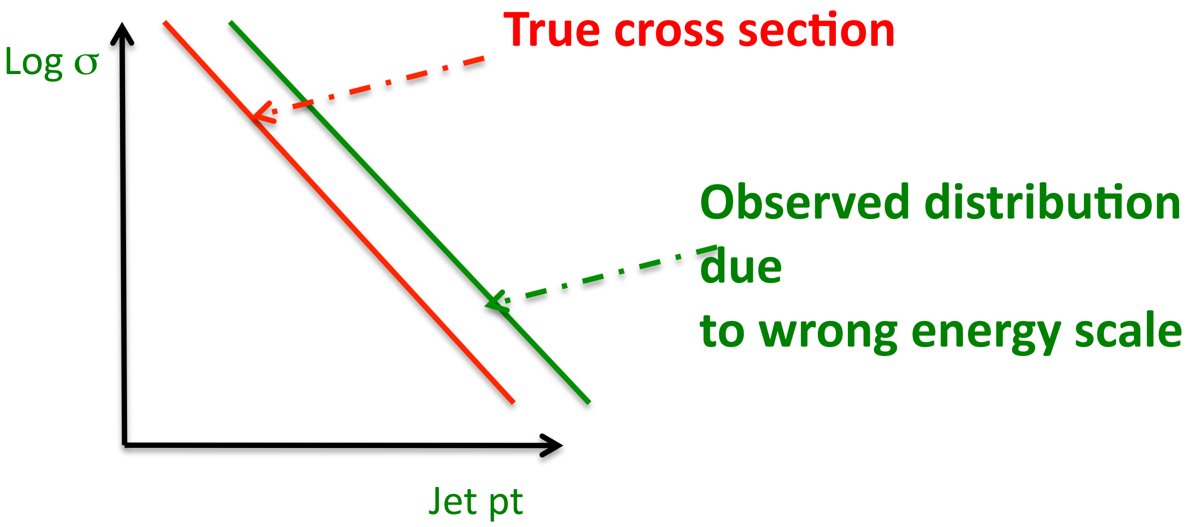
The experimental challenge I

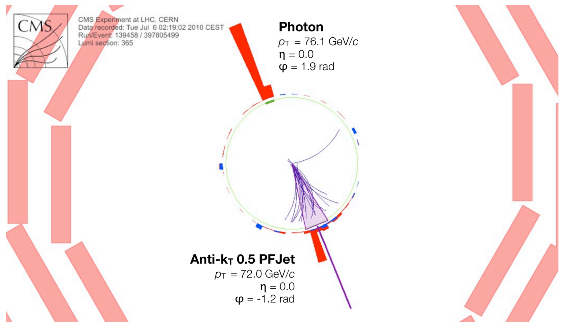
BERGISCHE UNIVERSITÄT WUPPERTAL

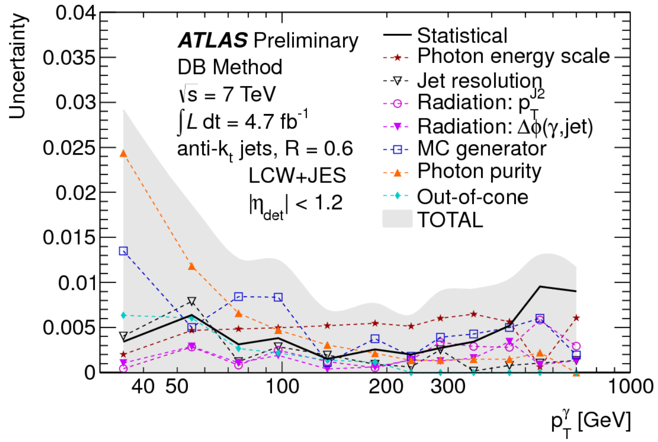
Steeply falling cross section ➔ sensitivity to energy scale

Jet energy determined from calorimeter (+ tracking information)

Sophisticated calibration procedure





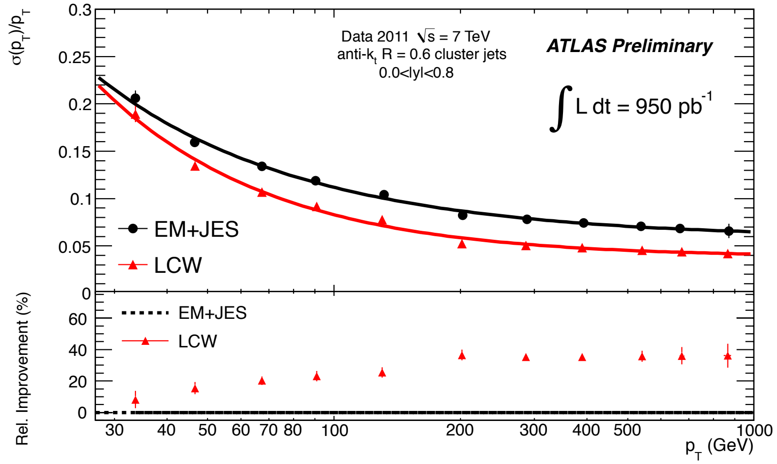


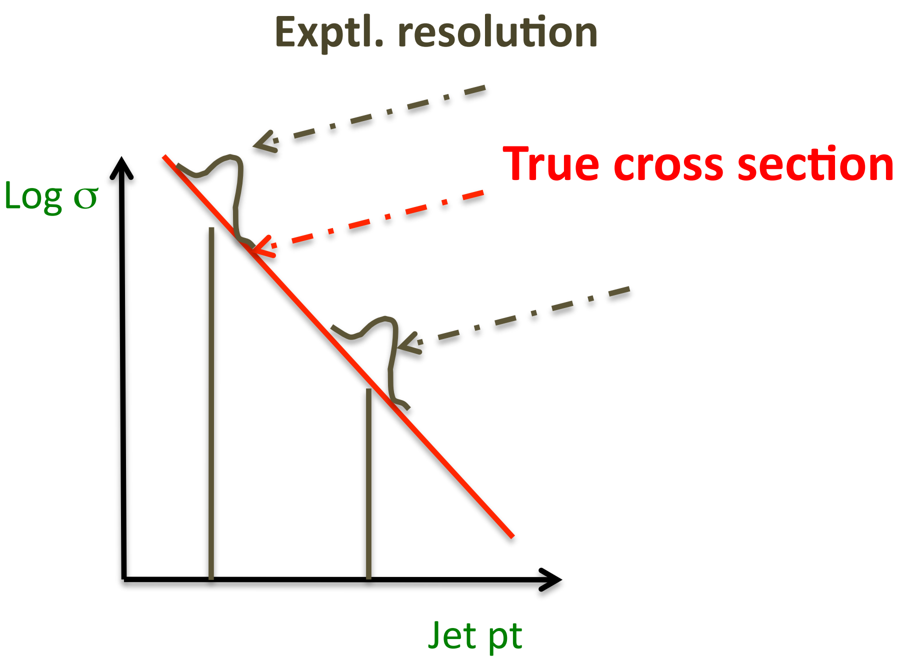
Use γ + jet events:
Jet energy scale known to 1 – 3%!

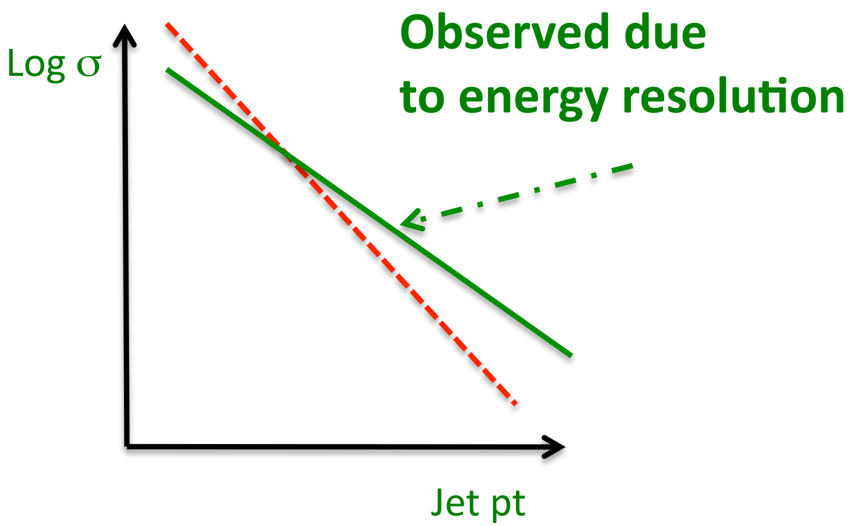
The experimental challenge II

BERGISCHE UNIVERSITÄT WUPPERTAL

sensitivity to energy resolution

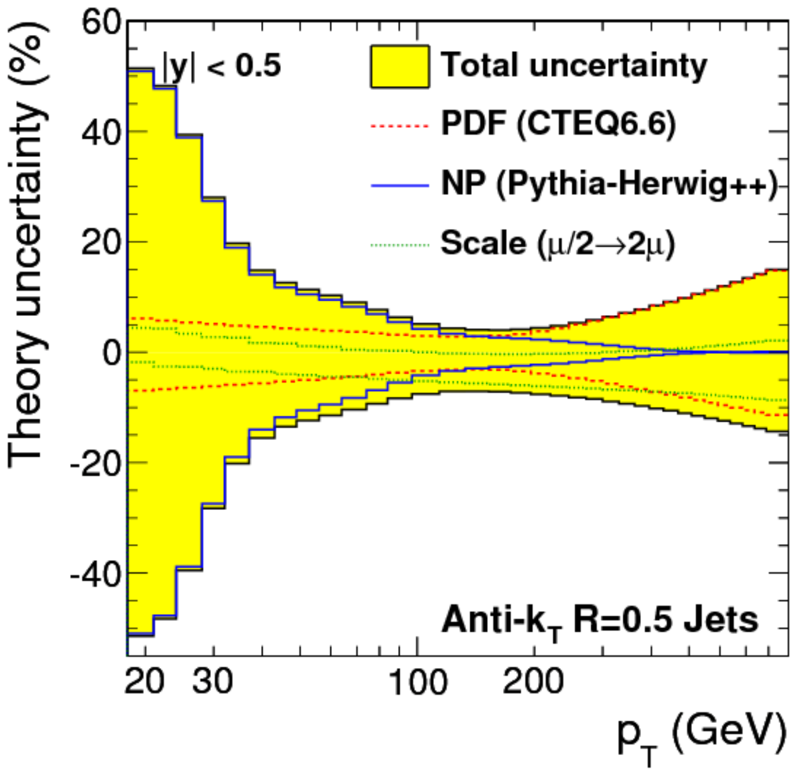






Uncertainties: summary

BERGISCHE UNIVERSITÄT WUPPERTAL



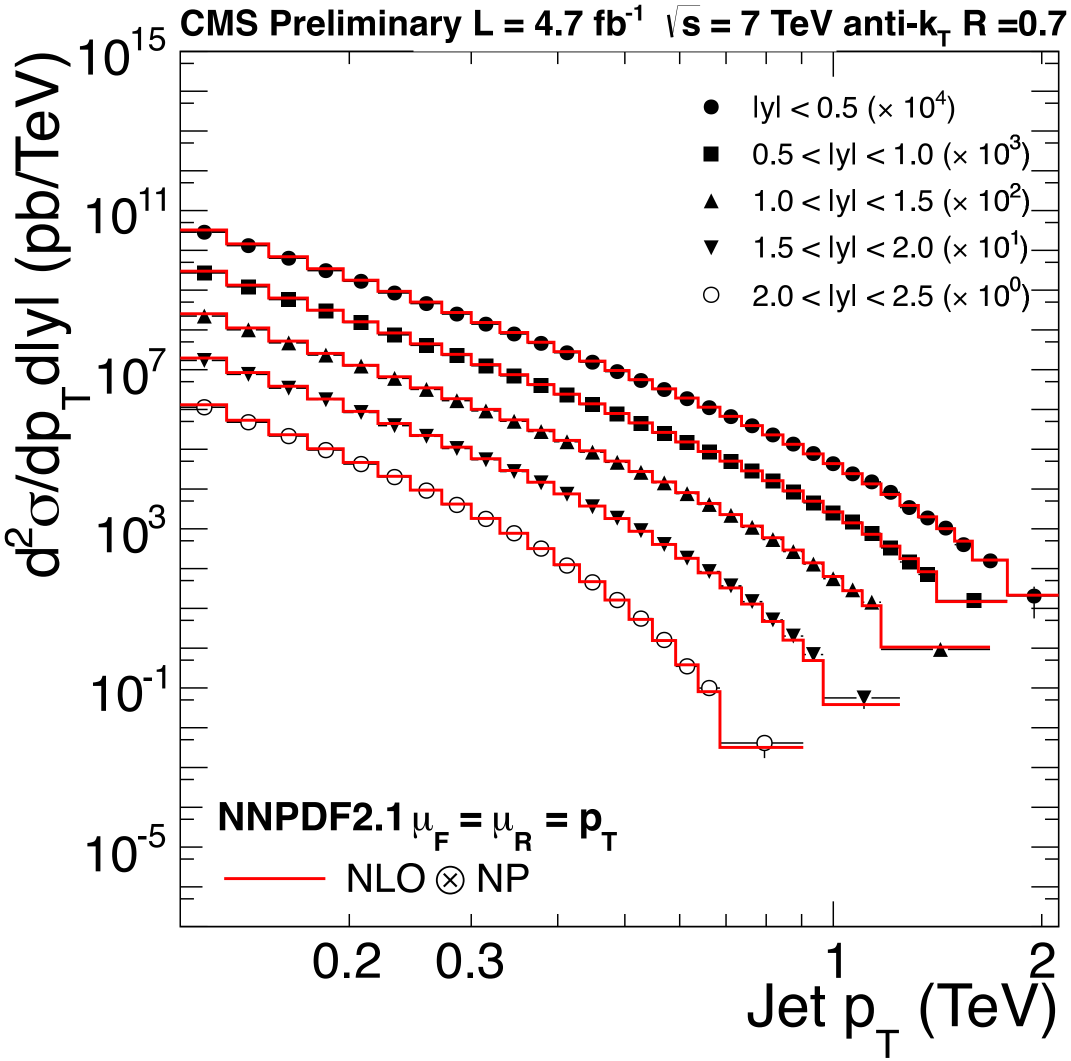
Experimental uncertainties dominate at low p_T

pdf/theoretical uncertainties dominate at high p_T

Note: loss of control of uncertainties for p_T < 20 GeV

Jet cross sections in rapidity and pT

BERGISCHE UNIVERSITÄT WUPPERTAL

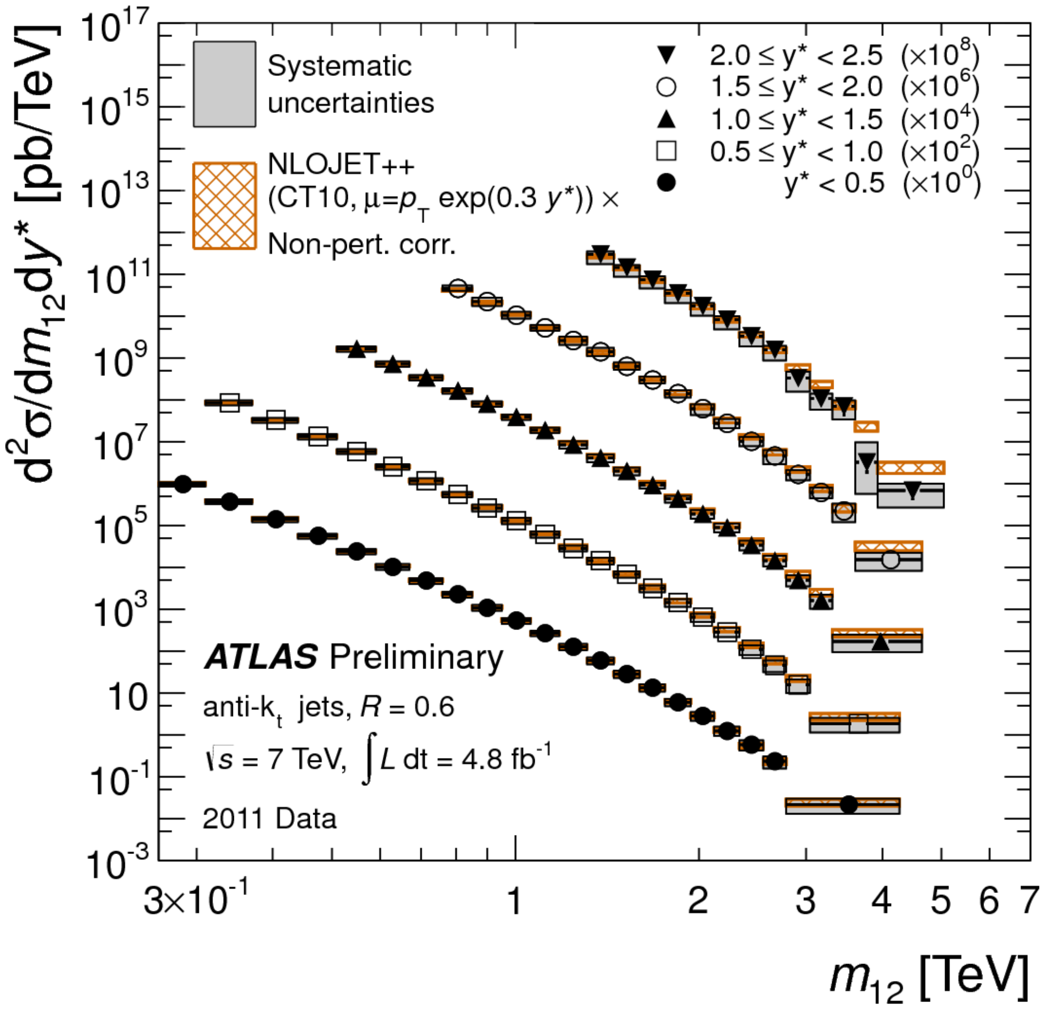


Excellent agreement theory <-> data

over huge range in phase space

jet – jet mass

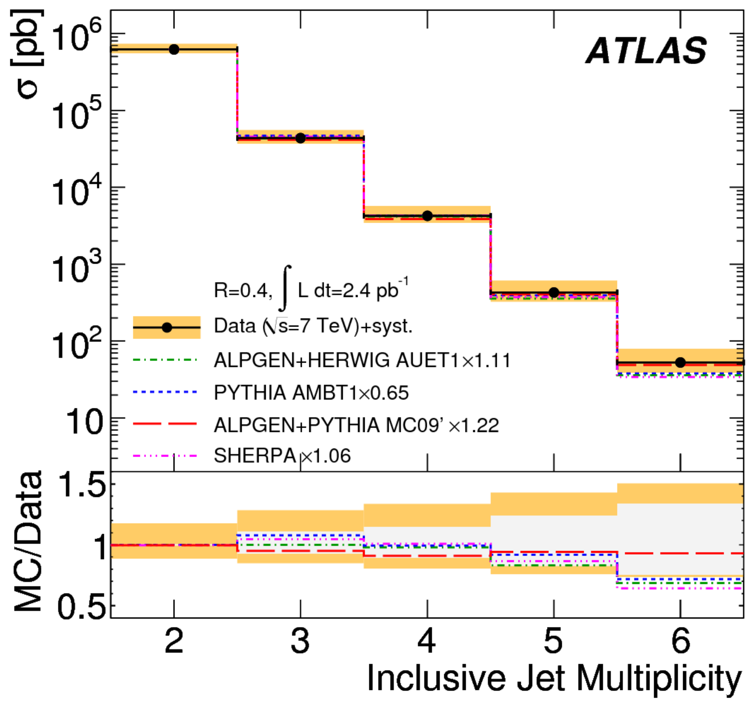
BERGISCHE UNIVERSITÄT WUPPERTAL

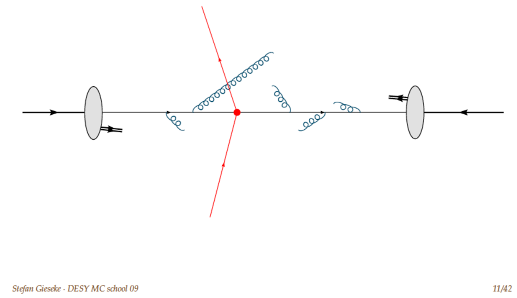


Excellent agreement theory <-> data

Probing masses up to 5 TeV!

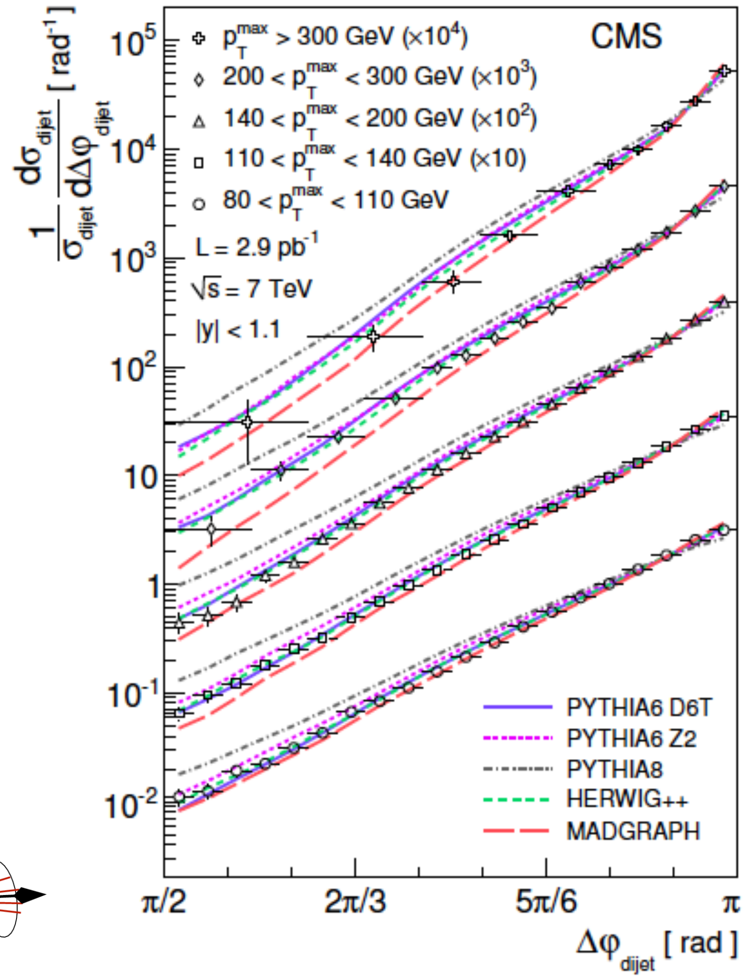
QCD effects: number of jets

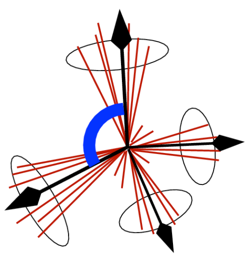


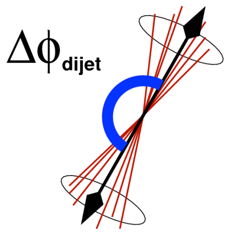


Even though not exact matrix element: Good agreement on jet multiplicity

The effects of gluon radiation



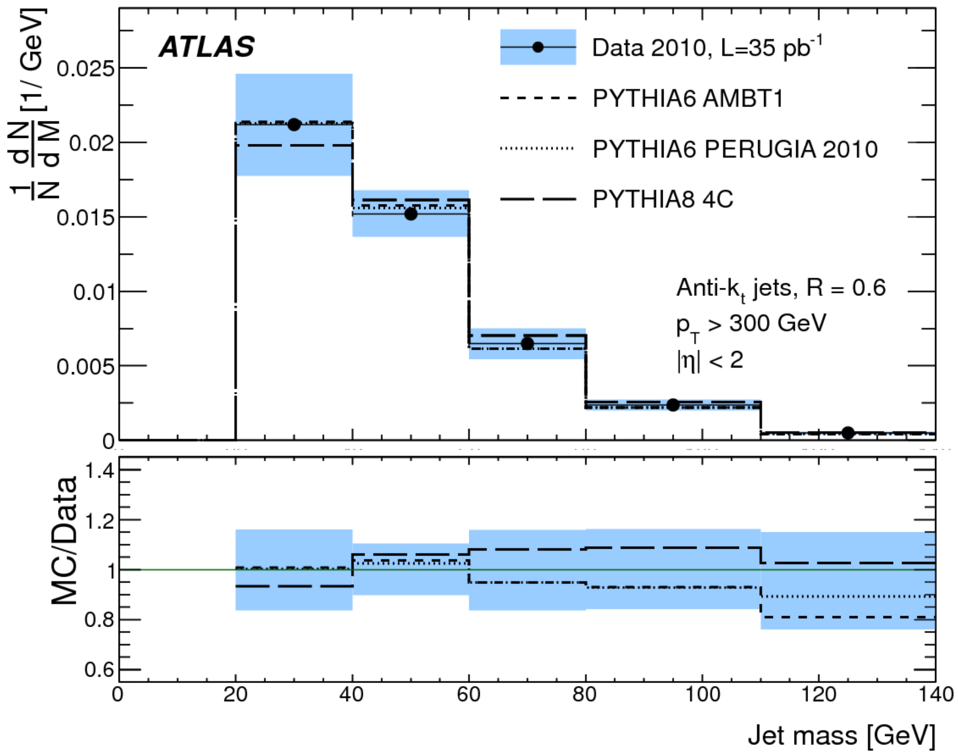




Azimuthal angle between leading, i.e. highest pT jets

High p_T Jets

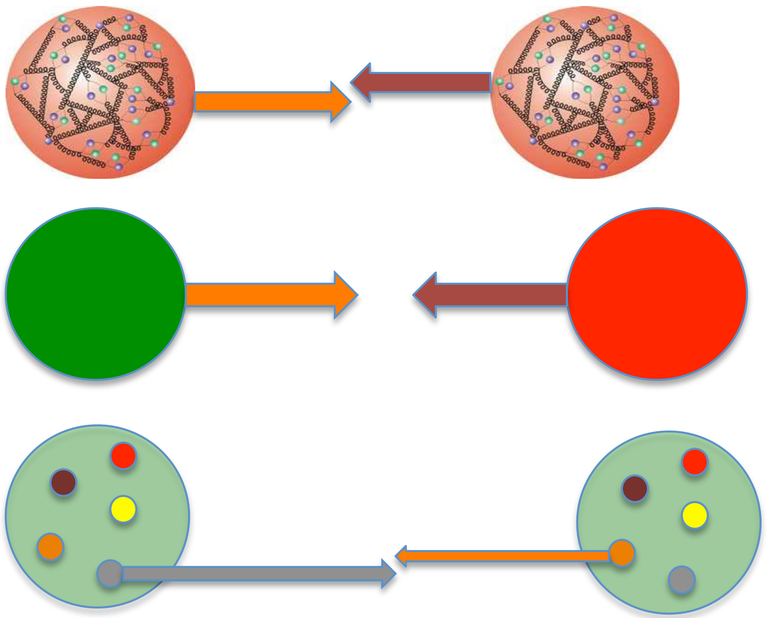
High p_T jets: important to explore TeV scale physics
May be due to boosted objects → substructure
Important: does QCD describe the structure of boosted jets?



Measure mass of high p_T jet:

Good agreement with expectation found

Testing high pT – jets = search for BSM:
Are partons composite?



pp – interaction

qq – interaction

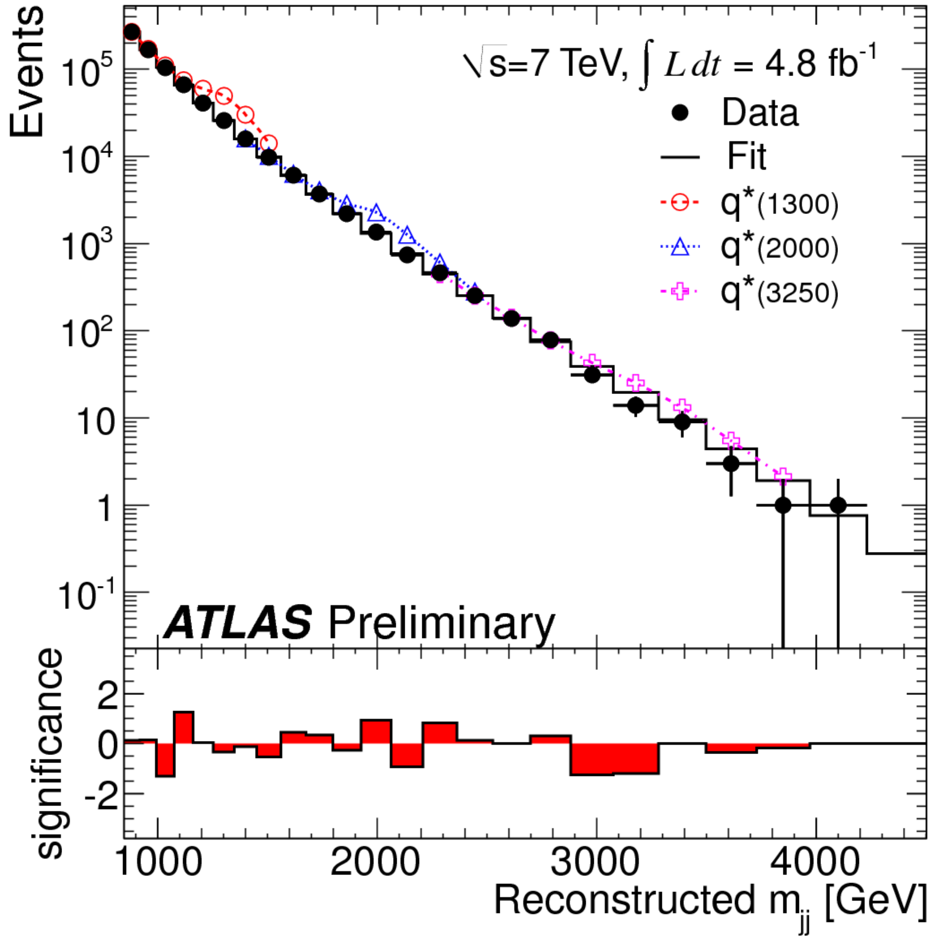
interaction of quark constituents ????

$$\mathcal{L}_{CI} = \frac{g^2}{\mathbf{\Lambda^2}}\eta_{LL}(\bar{\psi}_L\gamma^\mu\psi_L)(\bar{\psi}_L\gamma_\mu\psi_L) + (RR, LR)$$

$$\sigma_{ff} = |\mathcal{M}_{SM}|^2 + \mathbf{2}\frac{\mathbf{1}}{\mathbf{\Lambda^2}}\mathcal{RE}(\mathcal{M}_{\mathbf{SM}}\cdot\mathcal{M}_{\mathbf{CI}}) + \frac{1}{\Lambda^4}|\mathcal{M}_{CI}|^2$$

Jets and BSM: Search for di – jet resonances

BERGISCHE UNIVERSITÄT WUPPERTAL



An excited quark ?

$q^* \rightarrow q + g$

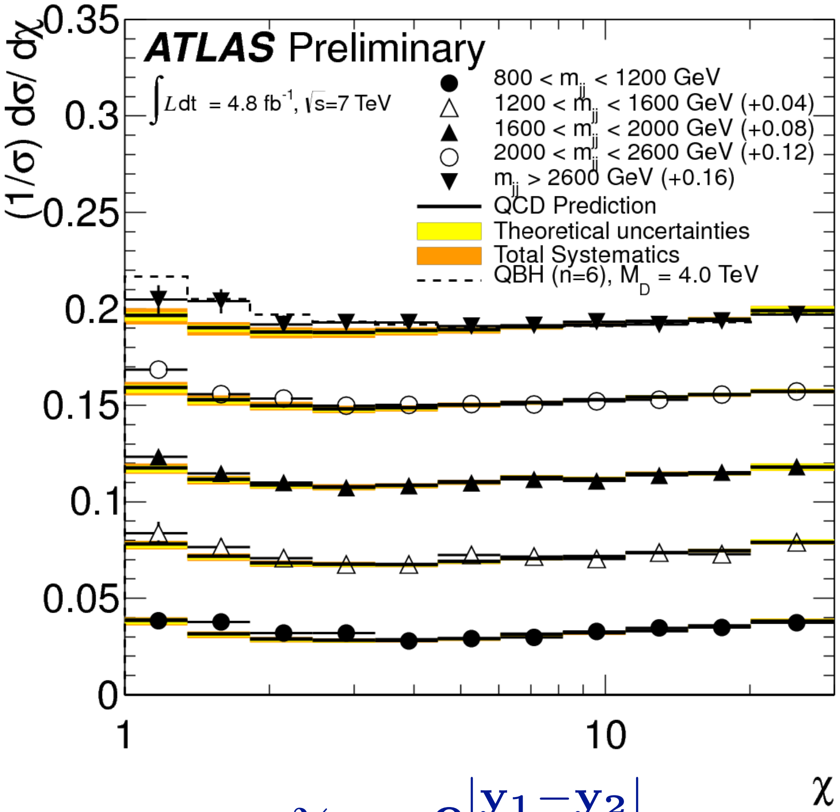
(Remember excited atom, nucleus ....)

Would be strong signal for compositeness

Search for resonance: enhancement

Are quarks composite ?

BERGISCHE UNIVERSITÄT WUPPERTAL



$$\chi = e^{|y_1 - y_2|}$$

Compositeness

➔ modify angular distribution

continous change with higher jet – jet mass

No deviation from SM observed: Λ > 7.8 TeV

Note: results applicable to other exotic models: black – holes, colour octet quarks, ...

Strong interactions at core of pp –interactions

- Multihadron events (soft interactions) measured
- Jet cross sections agree with predictions over a wide range
- Probing Multi - TeV range: no sign for physics Beyond Standard Model