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Standard Model @ Hadron Colliders I
Basics & QCD

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Pillars of the Standard Model

Peter Mättig, CERN Summer Students 2013

Standard model:
Comprehensive and precisely tested

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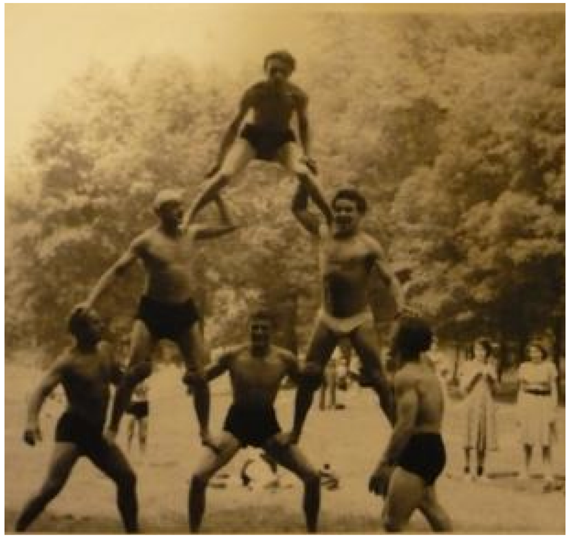
LHC Standard model 'on the shoulder of giants'



40 years of experimental scrutiny
LEP, SLC, HERA, Tevatron, PETRA, PEP, SppS, ….

Answers to questions of a century ago!

Standard model pillar I: Matter

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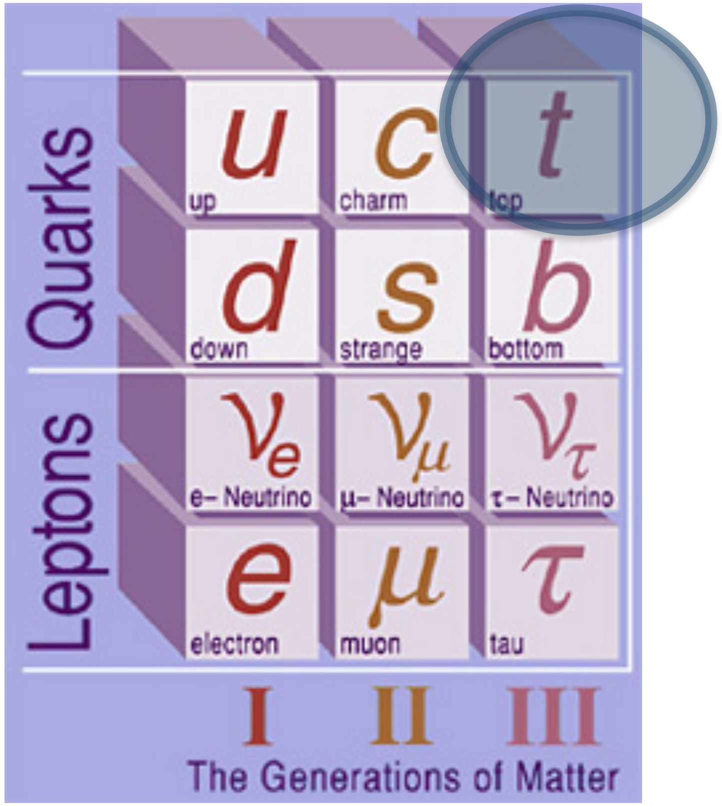
Twelve kinds of spin ½ fermions to build the world



LHC's role:

Heaviest Standard Model particle - Top Quark: unique at hadron colliders

Neutrinos not really testable @ hadron colliders

Most quarks/all charged leptons very deeply scrutinized

Standard Model pillar II: Forces

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Three interactions to hold world together

realised by three Spin 1 bosons

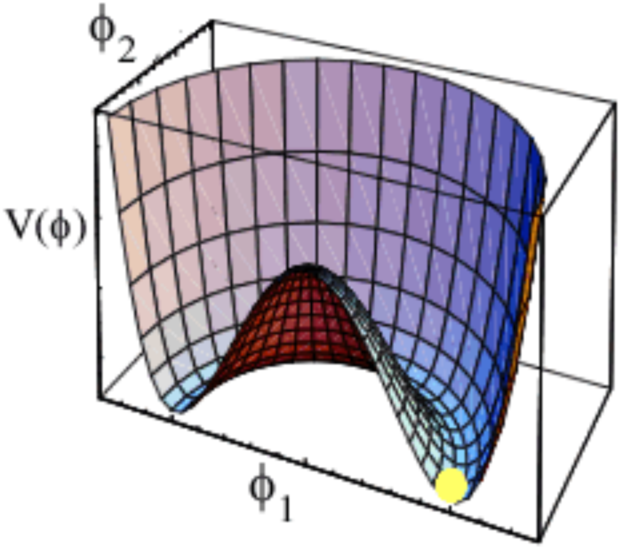
Dynamics known to a precision of 10^{-5} – 10^{-8}

LHC‘s mission:

- probe rare processes
- probe dynamics at unprecedented energies

Standard Model Pillar III: Higgs

Spin 0 particle to prevent theory from exploding



Massive Bosons and Fermions

➔Basic principles of SM violated

➔Cross section violates unitarity

SM: new elementary boson

LHC‘s mission: find it !!!!!!!

MISSION ACCOMPLISHED!!!!! (????)

LHC‘s quest: ‚New Physics‘

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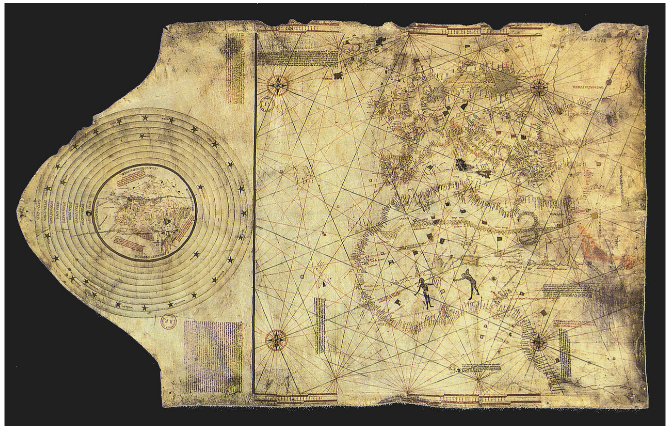

LHC entering unchartered territory

Understanding SM precondition to establish ‚New Physics‘

- **Standard Model processes background**
- **Tools**
- **Standard Model to the extreme**

Our dream for the next years

Today's Santa Maria: LHC

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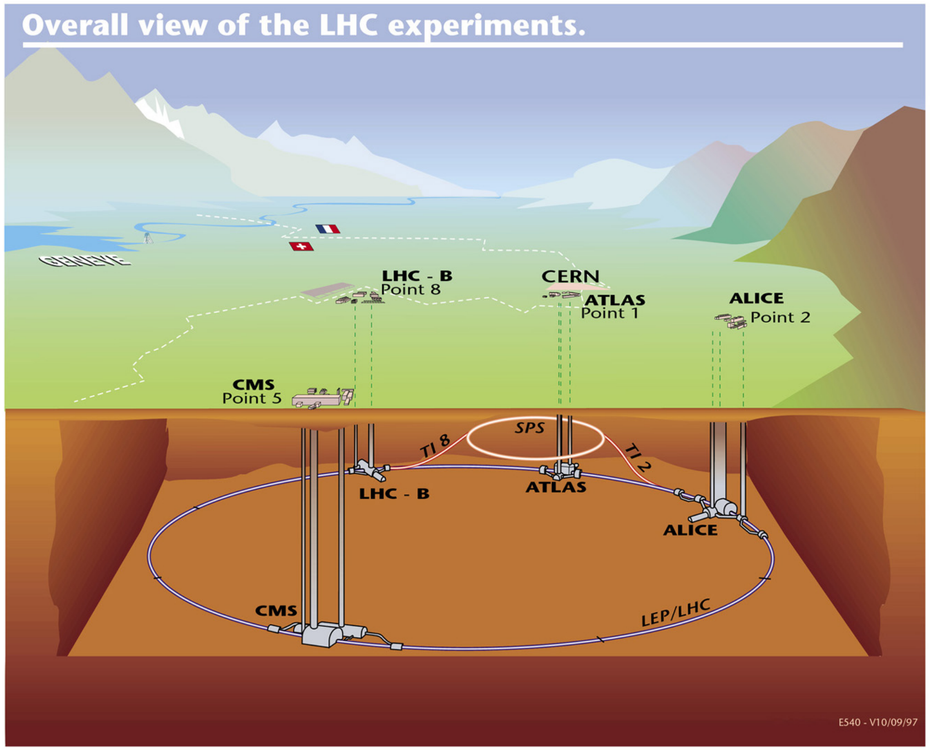
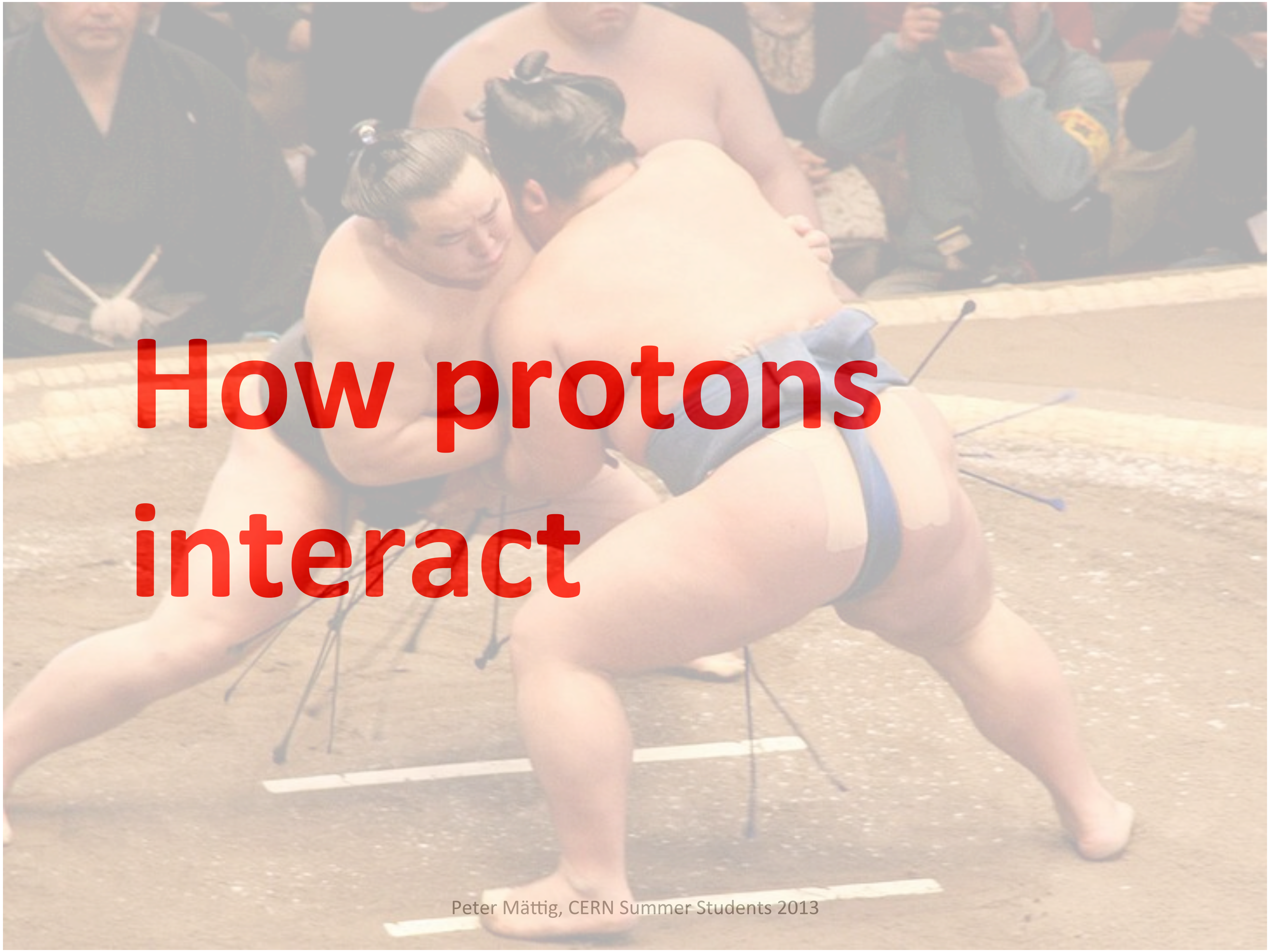


Proton – Proton Kollisionen
@ 14 TeV c.m. energy
(up to now 8 TeV)

4 Experiments

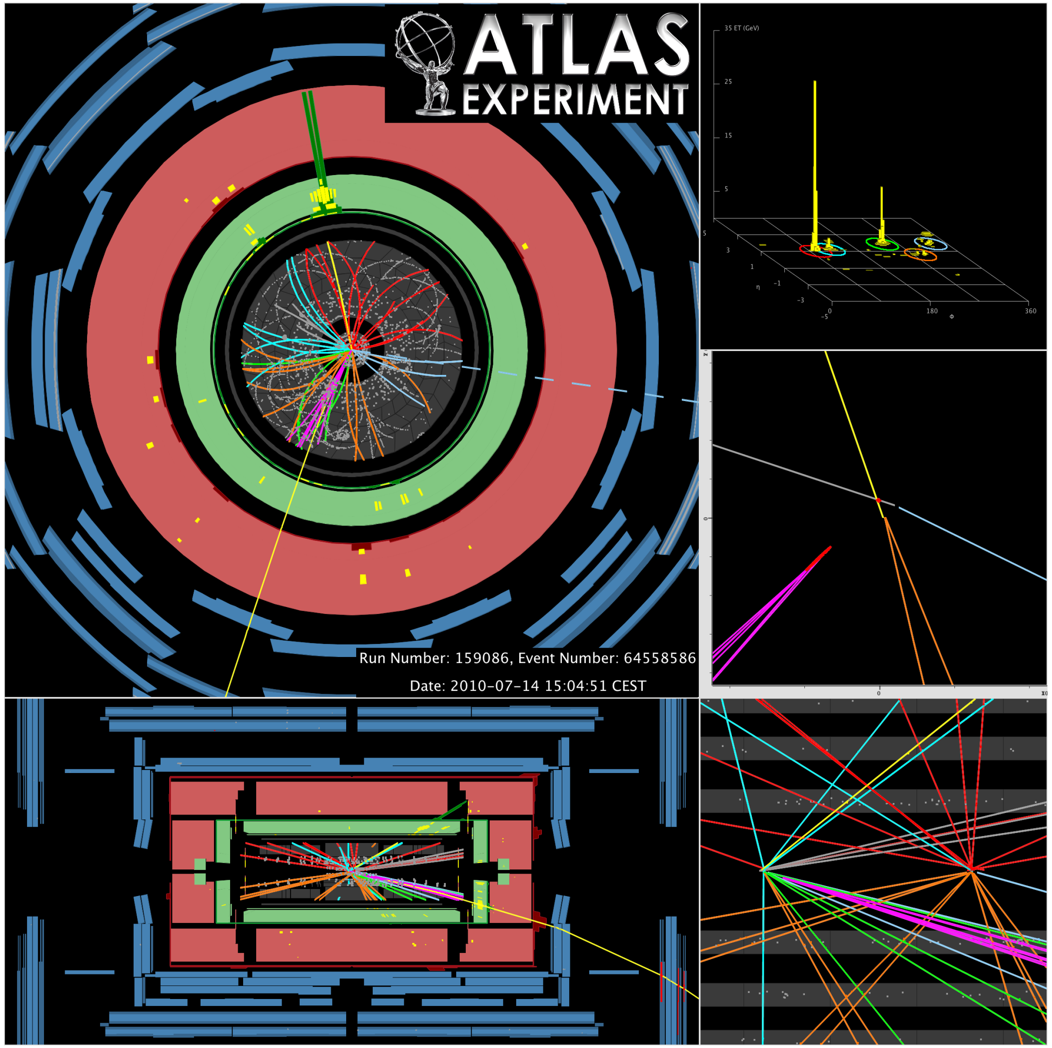
Will focus on results from
ATLAS and CMS

(LHCb ➔ talk of Tim Gershon)



How protons interact

Proton interactions: complex events

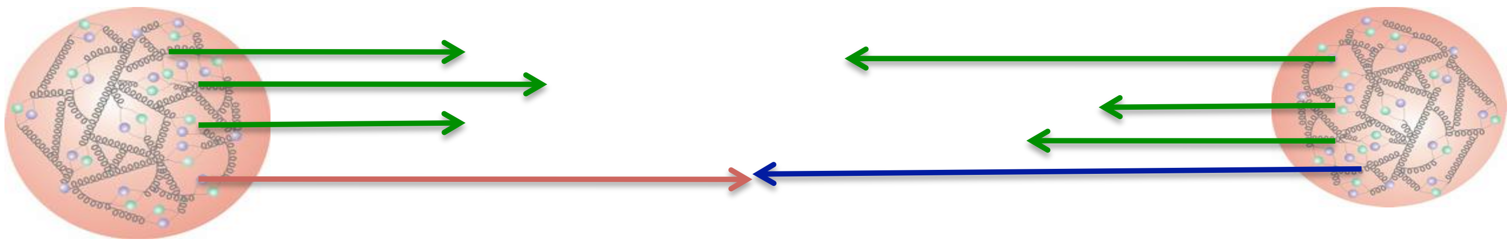


Some 1000 particles!

Experimenters task:
find the basic structures

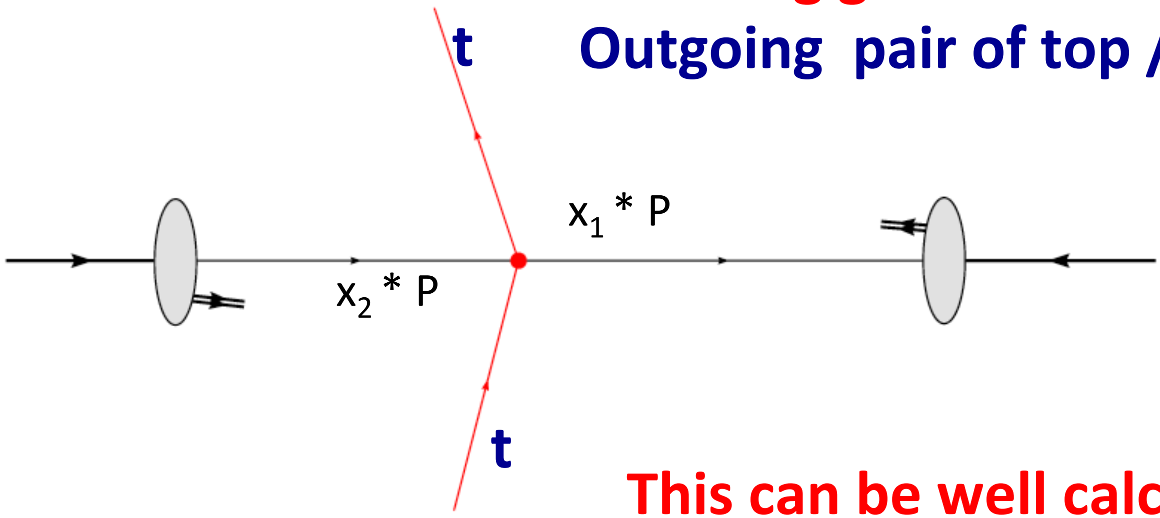
Reveals picture of space - time of 10^{-19} m

hard scatter: two in → two out
e.g. gluon-gluon → top-antitop



Incoming gluons have momenta $p_{1,}\ p_2$

Outgoing pair of top / anti-top quarks



This can be well calculated:

$$\sigma(\mathbf{g_1}(\mathbf{p_1}) + \mathbf{g_2}(\mathbf{p_2}) \rightarrow \mathbf{t\bar{t}})$$

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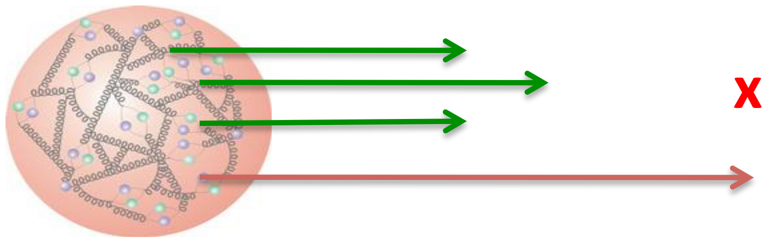
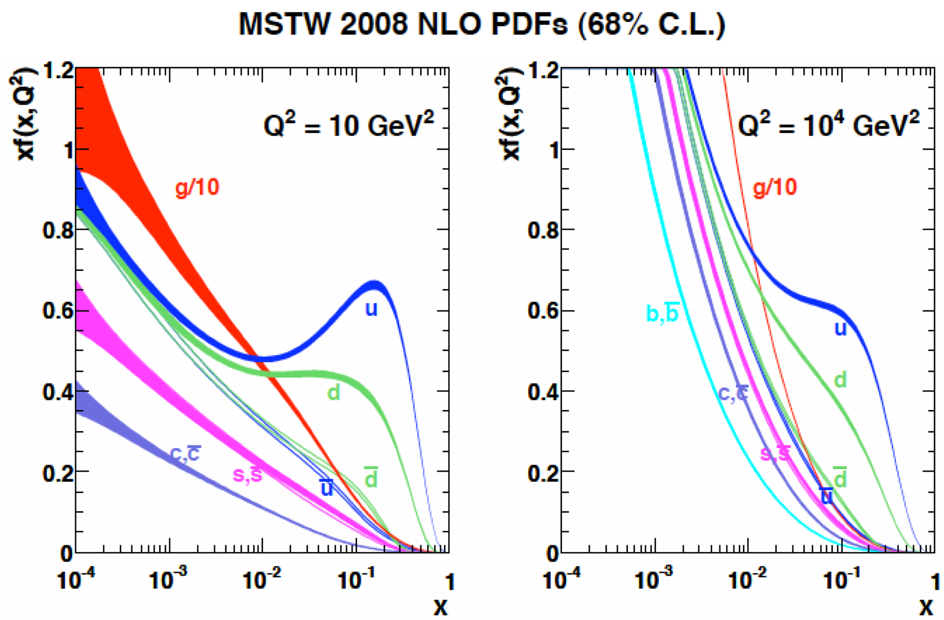
Add-on 1: Parton distribution function

Partons only take fraction of proton momentum
pdfs: probability for parton to assume fraction of proton momenta



$x = E_{parton}/E_{proton}$ for $E \rightarrow$ infinity



Allow all combinations of gluon energies to contribute

$$\int_0^1 dx_1 \int_0^1 dx_2 \sum_f F_f(x_1) F_{\bar{f}}(x_2)\, \sigma(q_1(x_1 P) + q_2(x_2 P) \rightarrow t\bar{t})$$

LHC: probing SM @ highest masses

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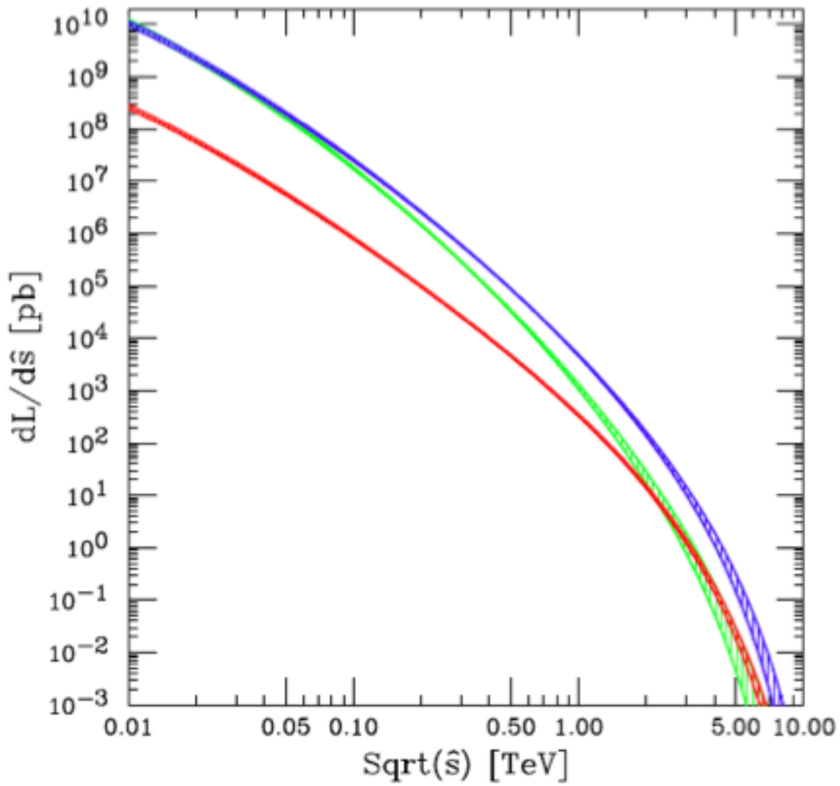
$$M_{scatter} = \sqrt{x_1 \cdot x_2} \cdot E_{pp}$$

‚resolution power'

for LHC: 8 TeV

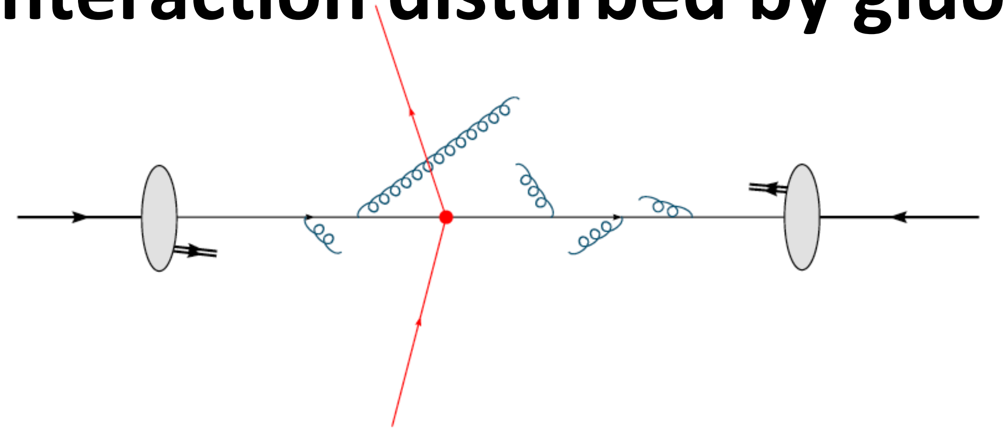
I.e. high masses requires large x - values

Low masses: mostly gluon – gluon scattering



High masses mostly quark - quark scattering

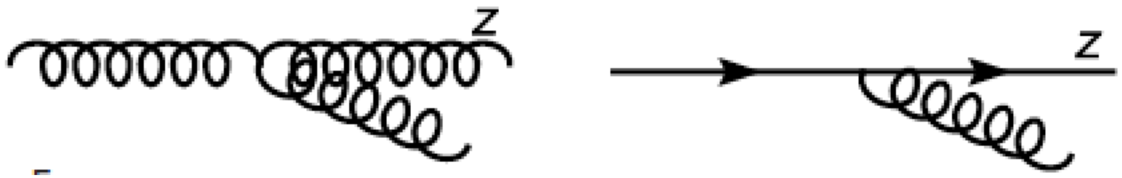
Add on 2:
Interaction disturbed by gluons



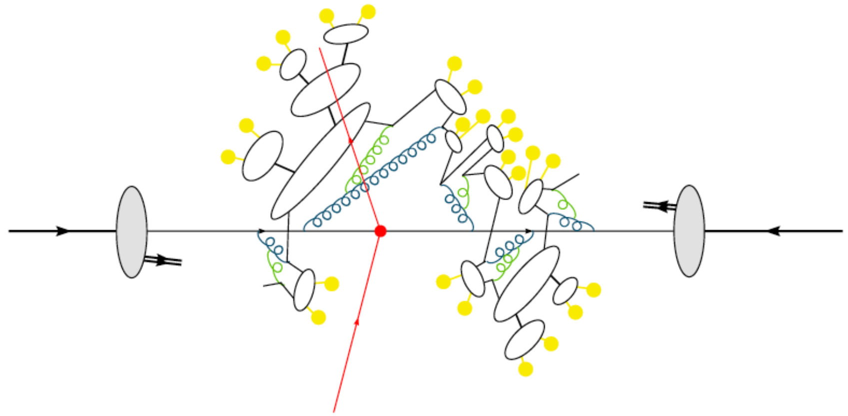
calculable (although in most cases not completely)

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

Beyond this: iterative parton splitting (Markov chain)
no interferences considered



partons turn to hadrons



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Quarks and Gluons turn into pions, kaons, protons:

hadronisation

No fundamental description

➔ model with many parameters

Colour flow of proton remnants

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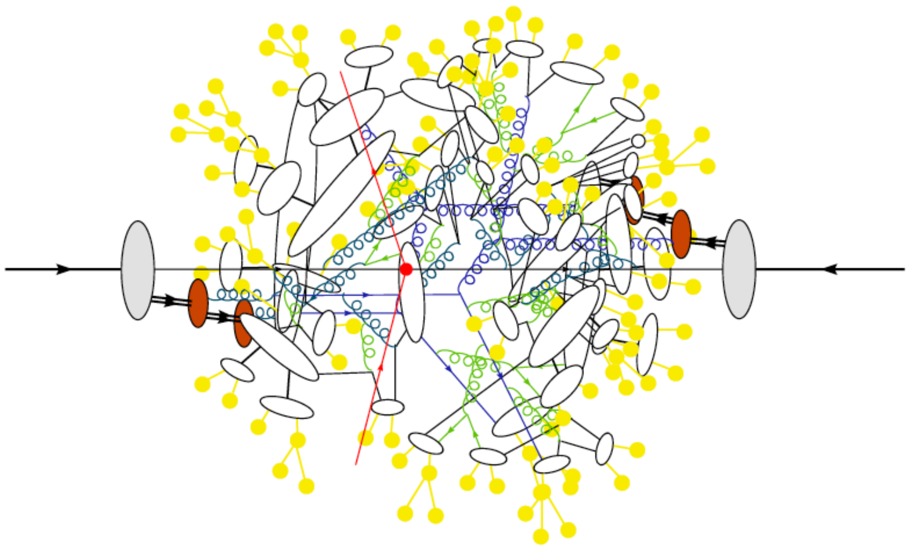

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Remainung quarks and gluons interact

‚Underlying event'

$$\int_0^1 \mathbf{dx_1} \int_0^1 \mathbf{dx_2} \sum_{\mathbf{f}} \mathbf{F_f(x_1)F_{\bar{f}}(x_2)}\sigma(\mathbf{q_1(x_1P) + q_2(x_2P) \rightarrow X + Y_{underlying}})$$

Requires multidimensional integration → Monte Carlo simulation

Several QCD generators: PYTHIA, HERWIG, SHERPA, …..

Instead of two top quarks:

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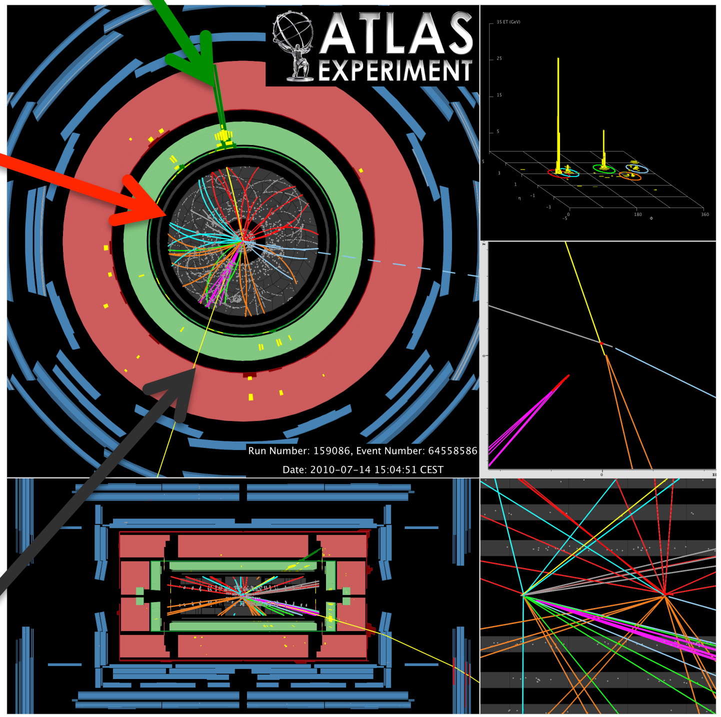
Electron

Collimated hadrons: ‘jets’



Apparent momentum imbalance: ‘Missing Energy’ due to ν

Homogeneously distributed low momentum hadrons: ‘underlying event’

Affect measurements of objects!

Many tt – events: extract physics

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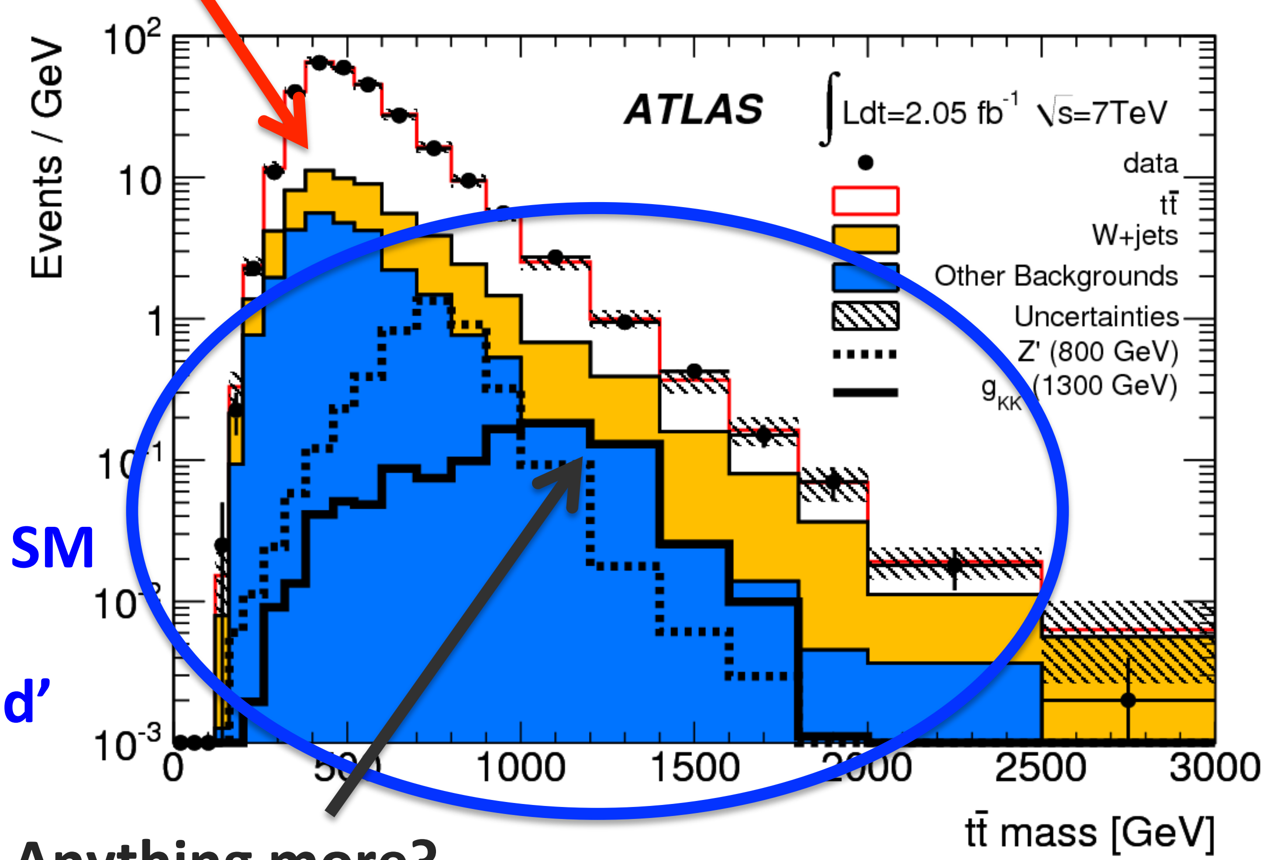
Example: measure mass of tt –system

this is what we want



Similar signatures from other SM processes 'background'

Anything more?
New physics may add structures

Standard Model tests

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

$$= \int_0^1 \mathbf{dx_1} \int_0^1 \mathbf{dx_2} \sum_{\mathbf{f}} \underbrace{\mathbf{F_f}(\mathbf{x_1})\mathbf{F_{\bar{f}}}(\mathbf{x_2})}_{\text{pdfs}} \underbrace{\sigma(\mathbf{q_1}(\mathbf{x_1}\mathbf{P}) + \mathbf{q_2}(\mathbf{x_2}\mathbf{P})}_{\text{Hard scatter}} \to \mathbf{Y} + \mathbf{X} + \underbrace{\mathrm{Rest})}_{\text{Underlying event}}$$

underlying event	parton distribution function	$\sigma(p_f(xP) + p_{f'}(x'P) \to X)$
measure	from previous measurement	from theoretical calculation
from models	**measure**	from theoretical calulation
from models	from previous measurement	**measure**

Three items only mildly related ….

but lead to uncertainties

Rapidity

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Parton collisions not in rest system→ rapidity accounts for boost

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

Typical for radiative multi-particles

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

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

Difference of rapidities Lorentz invariant

$$\mathbf{\Delta R} = \sqrt{(\mathbf{y_A}-\mathbf{y_B})^2+(\phi_\mathbf{A}-\phi_\mathbf{B})^2}$$

Separation is Lorentz invariant

For m→ 0: y → η , pseudo – rapidity'

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

Simpler to measure, but Δη not Lorentz invariant


Soft interactions
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No ‚direct' parton – parton hit

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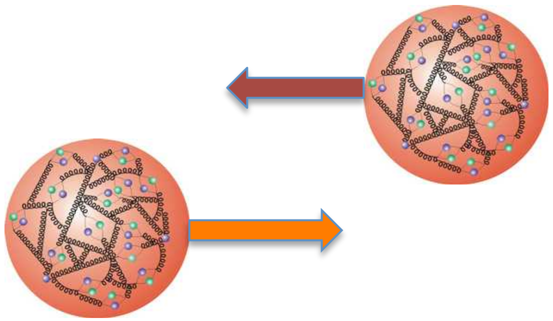
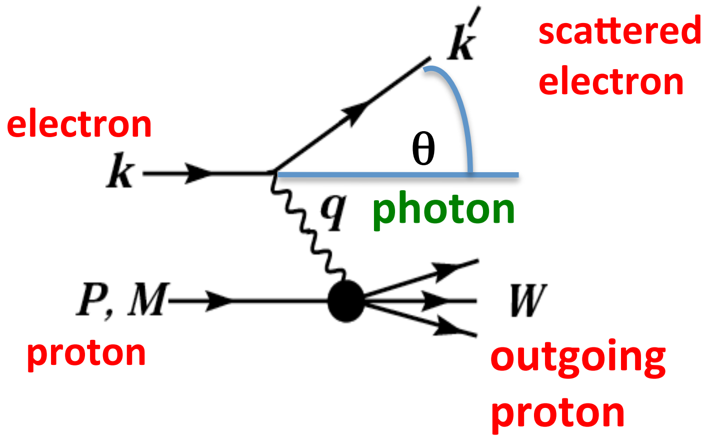
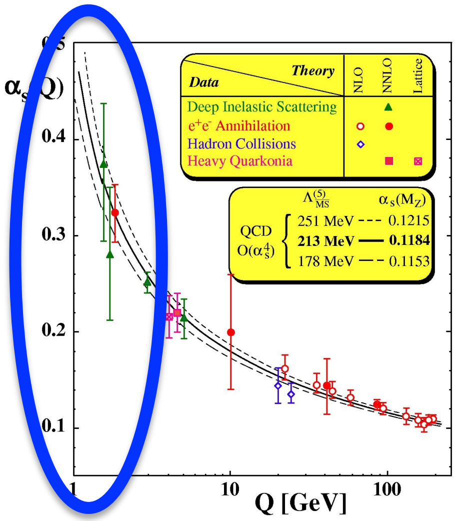


Small overlap: no hard parton interactions
Cannot be calculated from 1st principles



Partons scatter under small angle
➔ low Q^2

$$\mathbf{Q^2 = -2E_\gamma E_e + 2\tilde{p}_e \cdot \tilde{p}_\gamma}$$



low Q^2 ➔ large 'strong coupling' α_s
Calculation not feasible
build a 'reasonable' model

Examples of model concepts

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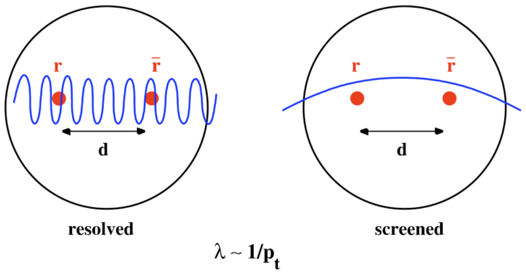
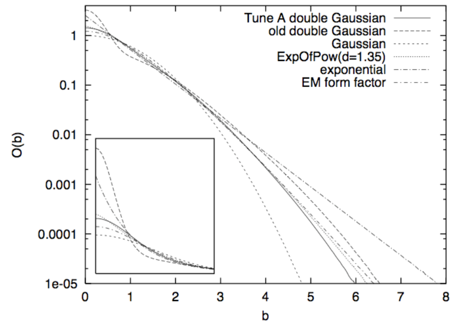
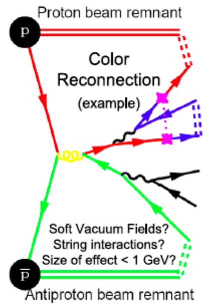






Colour screening

P_t cut -off

Overlap of protons

Colour reconnection

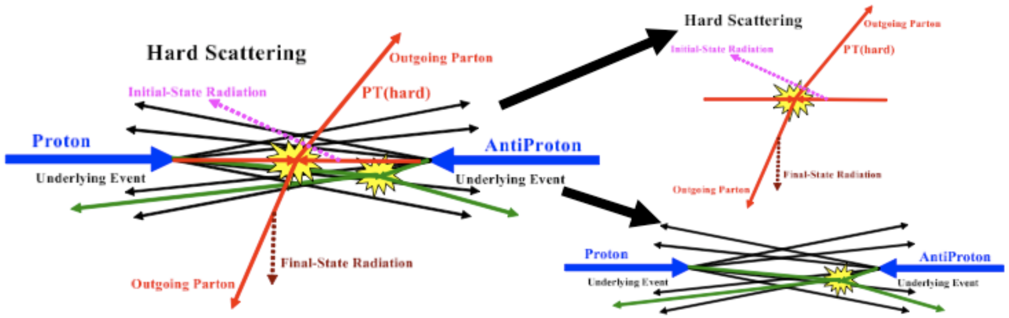
Introduces ‚free' parameters to be determined from data

Soft processes provide constraints in special conditions

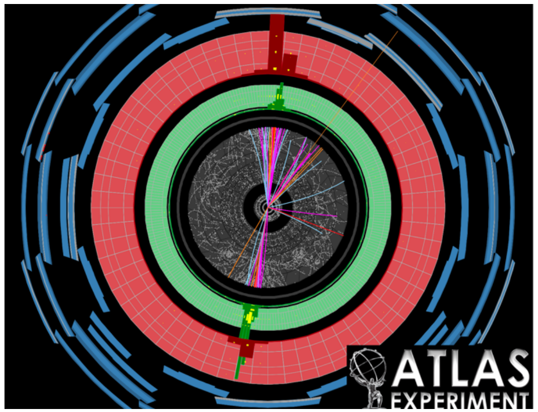
Extrapolate to all topologies (and hope it will work)

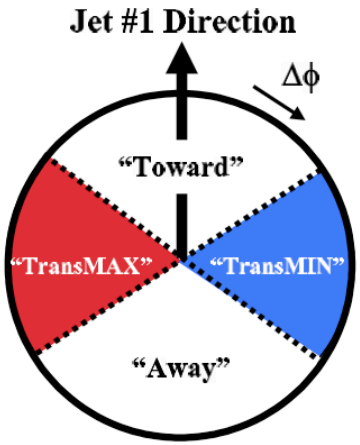
Challenging! Only an approximate description possible!

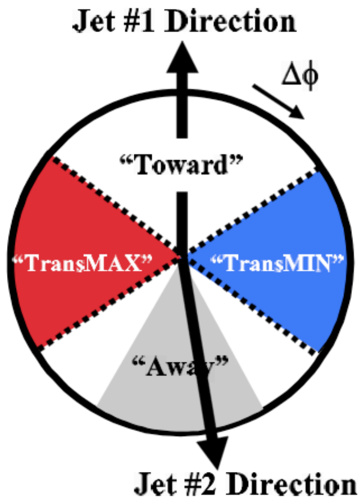
Separating underlying events



Hard interactions +
soft contributions

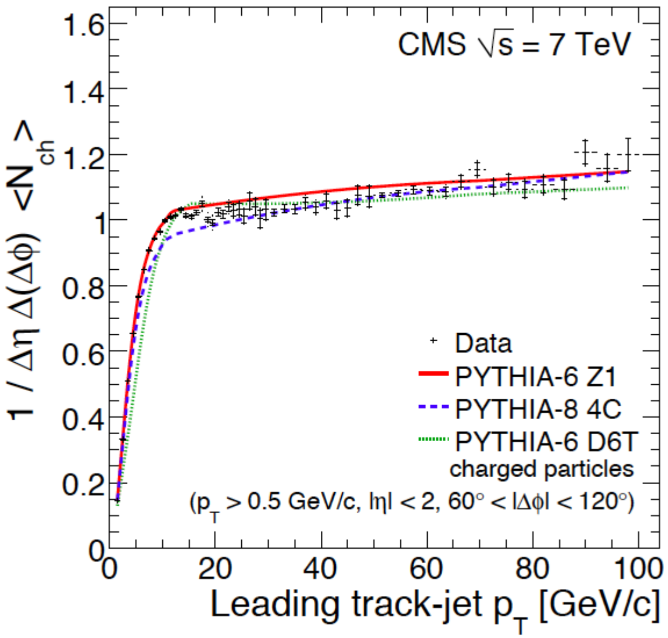


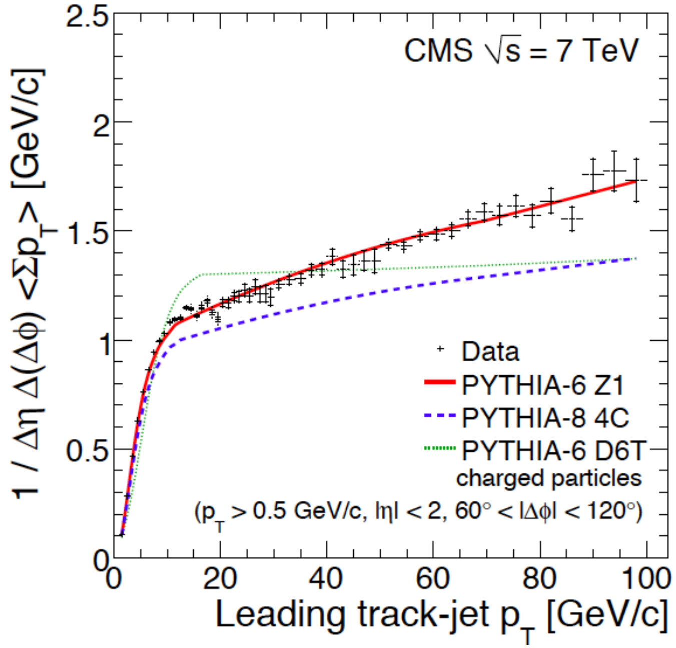




Transverse regions little affected by hard process
➔ properties like underlying event

Particles in underlying events





Can be reasonably described by models

99,999% of all LHC events: soft

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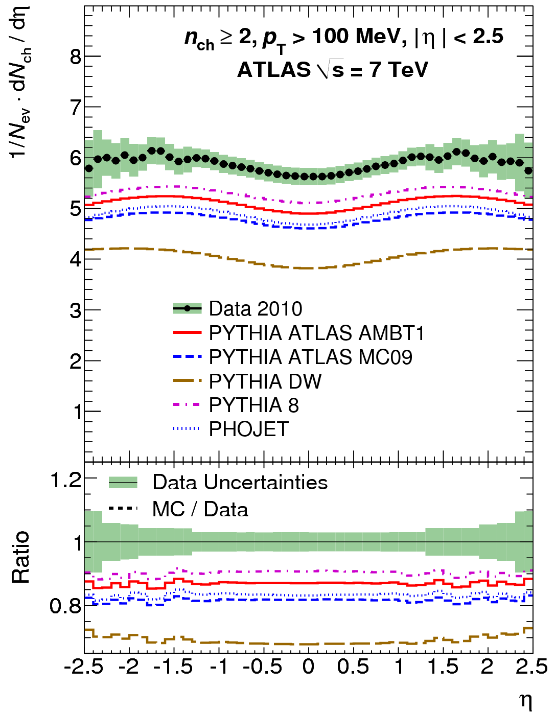
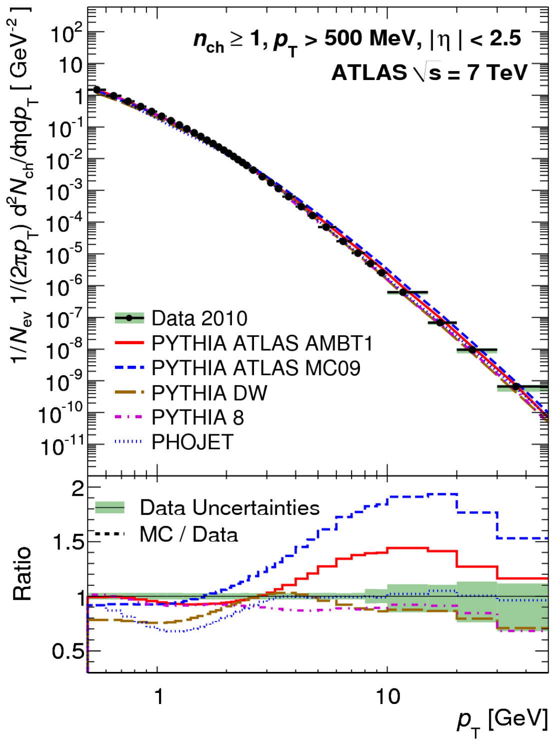
Measure pile – ups:

no trigger bias
‚minimum bias events'

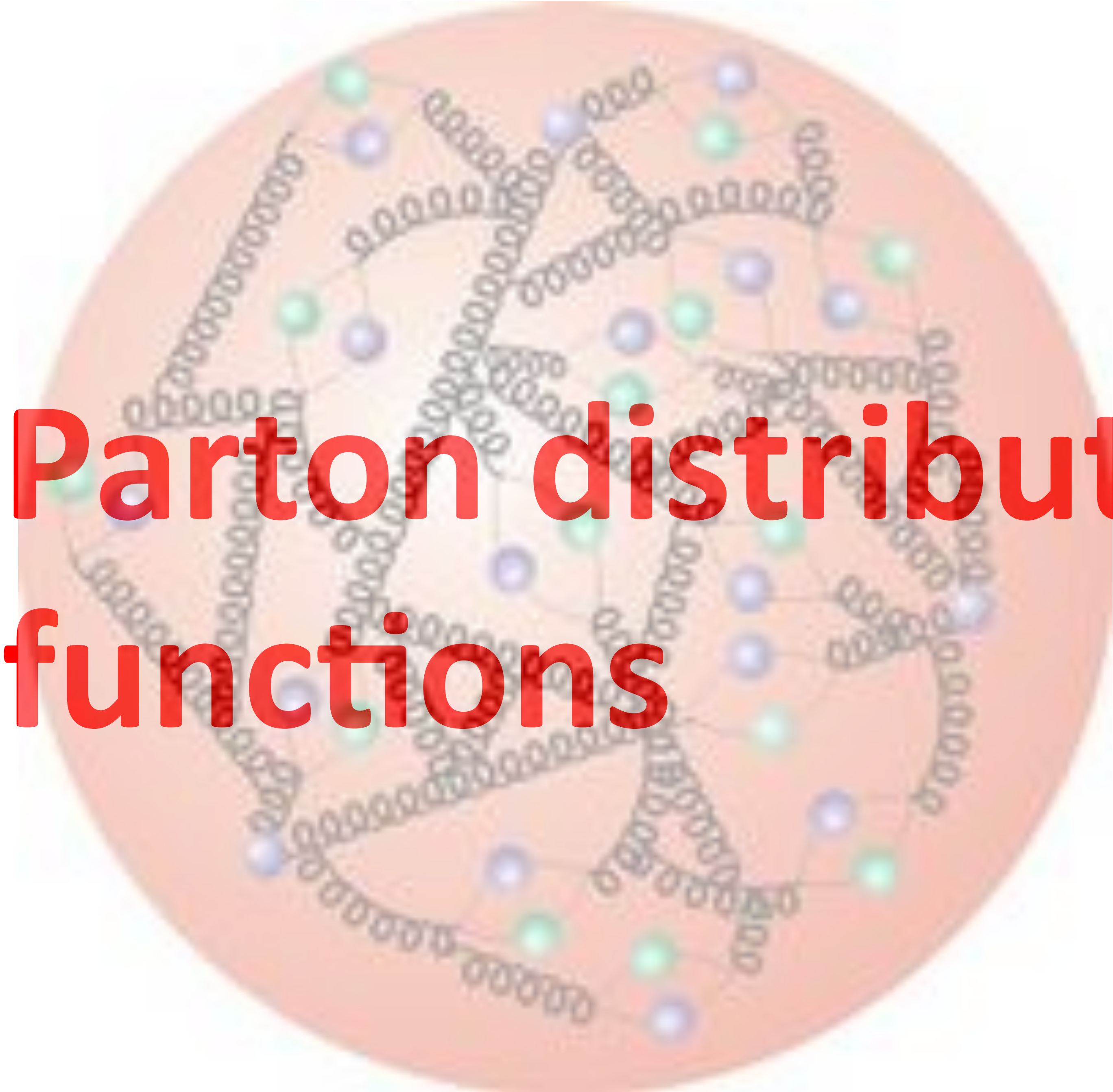
At 7 TeV: 6 charged particles per |Δη| = 1, mostly low p_T





Model parameters have to be adjusted
Note: per LHC bunch crossing ~ currently 30 of these events

Parton distribution functions



Parton distribution functions

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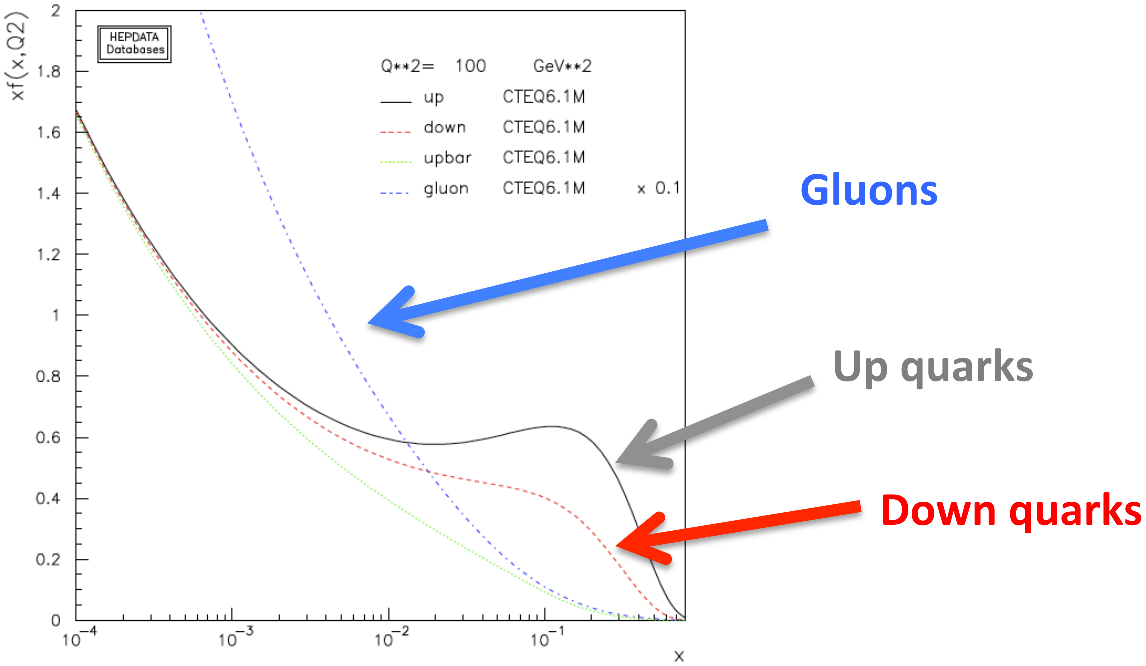
Energy fractions of different kinds of partons f in proton

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

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

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

Just one of several pdf parametrisations



Significant uncertainties

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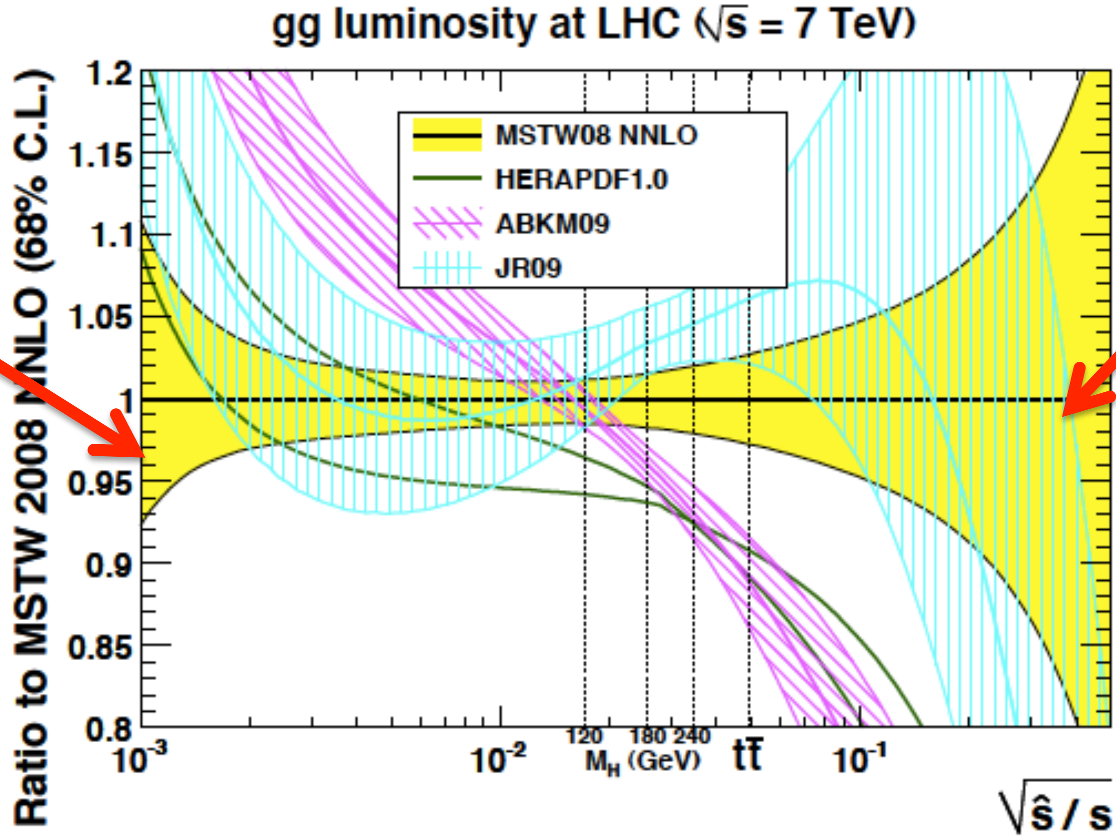
G.Watt

low x:
many gluons
➔ Theoretical & experimental uncertainties



High x:
few gluons
➔ Large uncertainty

LHC processes sensitive to pdfs:
Specific processes will allow to disentangle contributions
➔ some self – calibration of pdfs

Parton jets
'hard' QCD

Hard interaction: Jets

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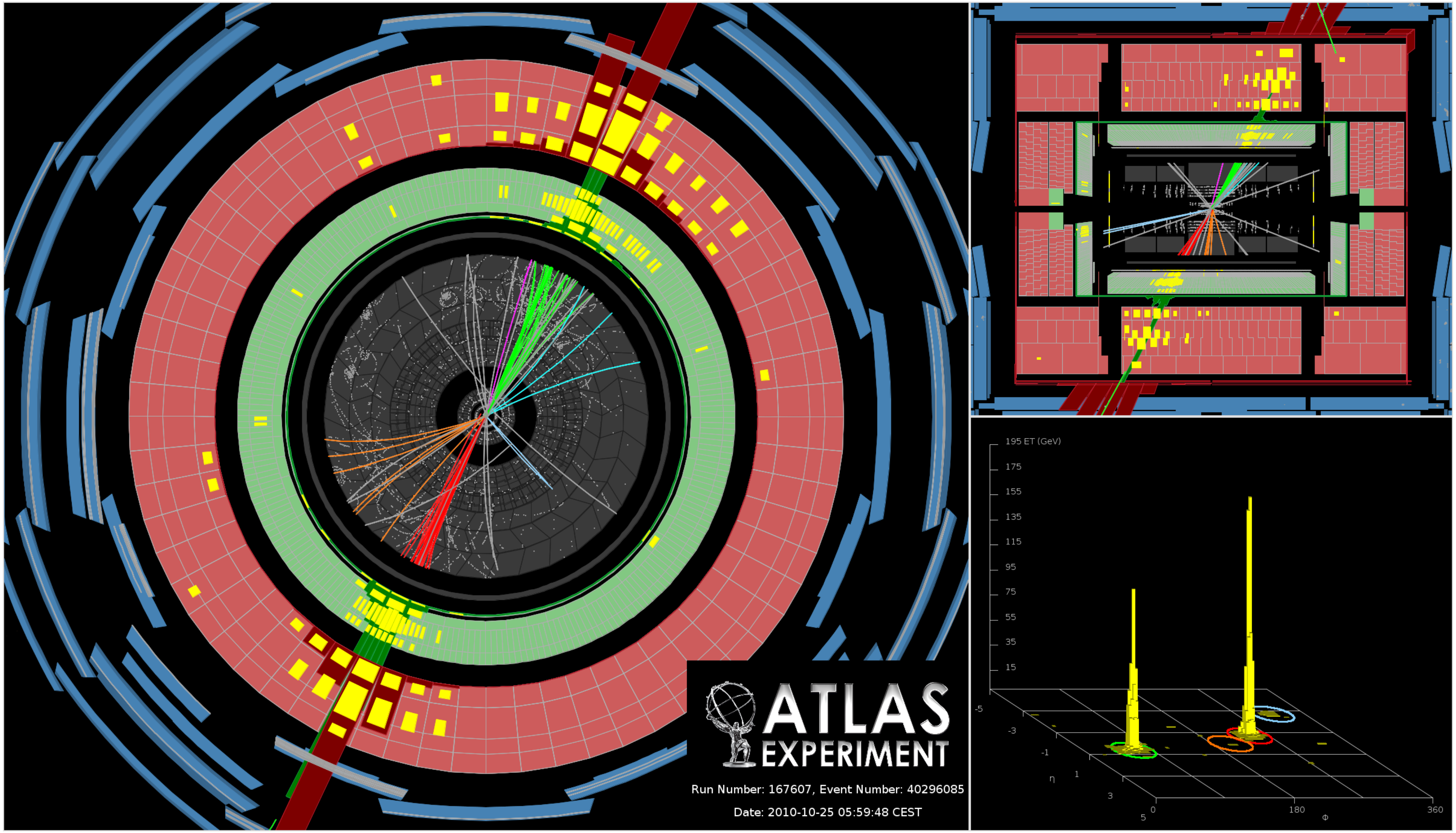

Jets are universal

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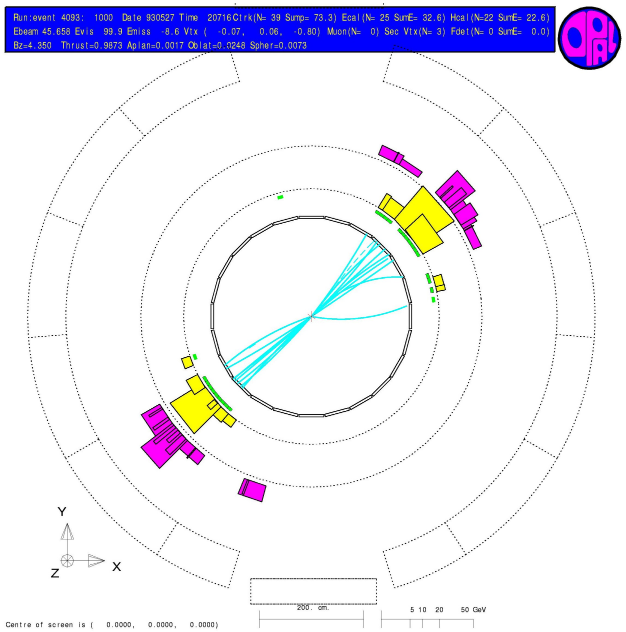
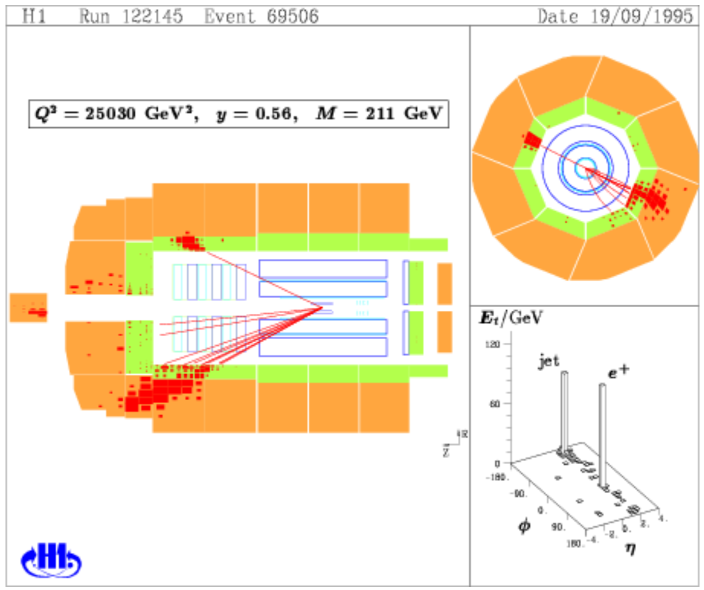
$e^+ e^-$ collisions



e p collisions



Jets: bundles of hadrons

➔ **representative of quarks and gluons**

➔ **direction, energy + (sometimes) parton flavour measurable**

➔ **direct QCD tests possible**

➔ **Experimental challenge: extract jets from 1000 particles**

Jets are even more universal

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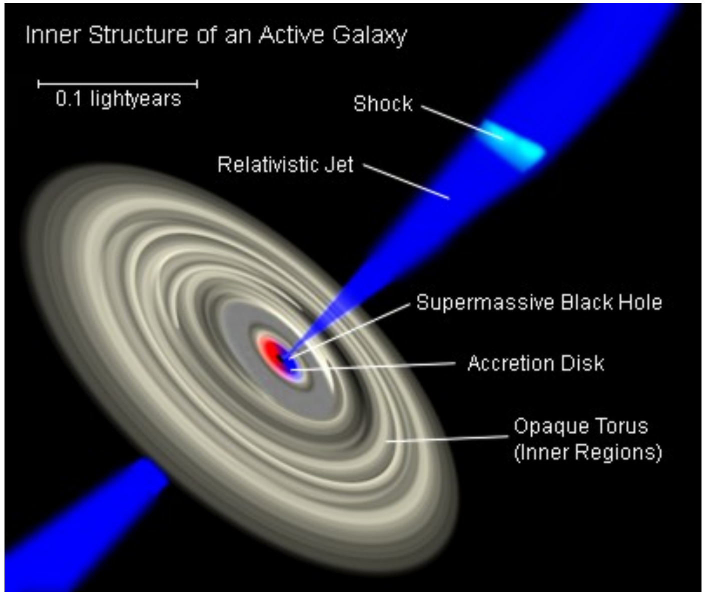

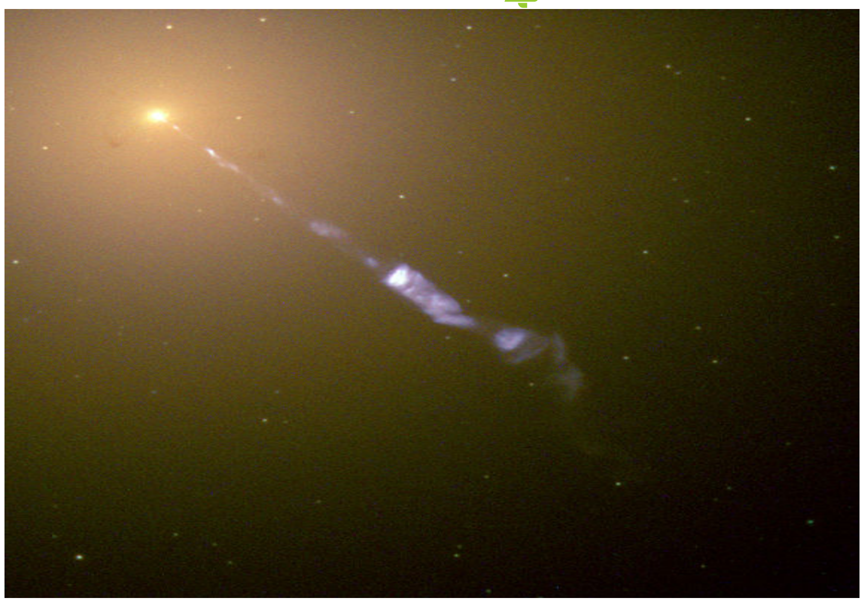

How to find a jet ?

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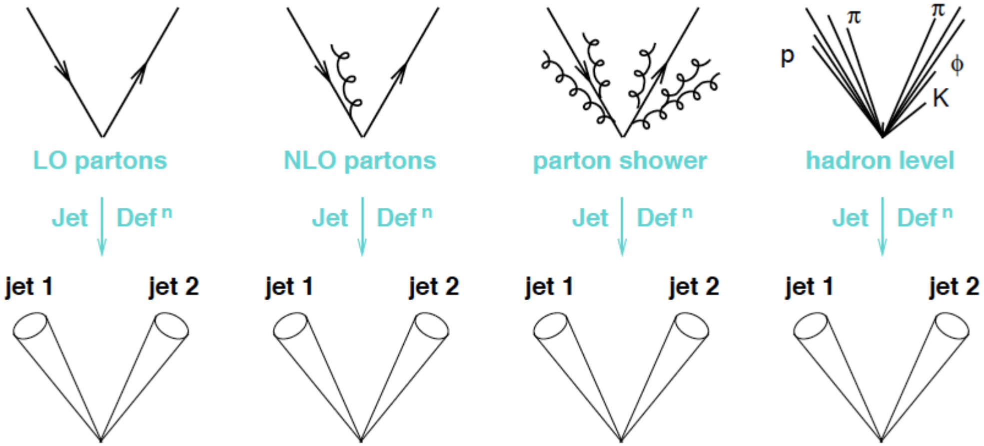
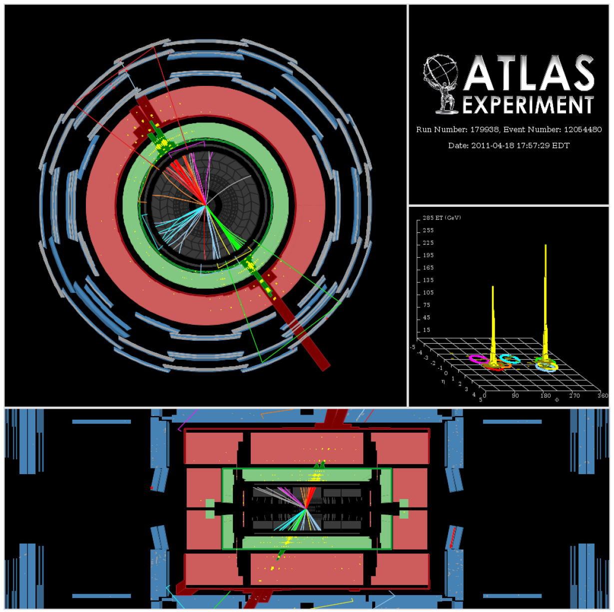


Unambiguous connection to underlying partons ➔ Comparison to theory



Anyway ..... how many jets?
'broadness' of jets arbitrary
➔ jet multiplicity depends on choice
➔ defined according to physics

Predefine how broad a jet should be!

Sequential jet finder

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‚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

➔ Start next 'jet'

Standard jet finding at LHC: ‚Anti – kt‘

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

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

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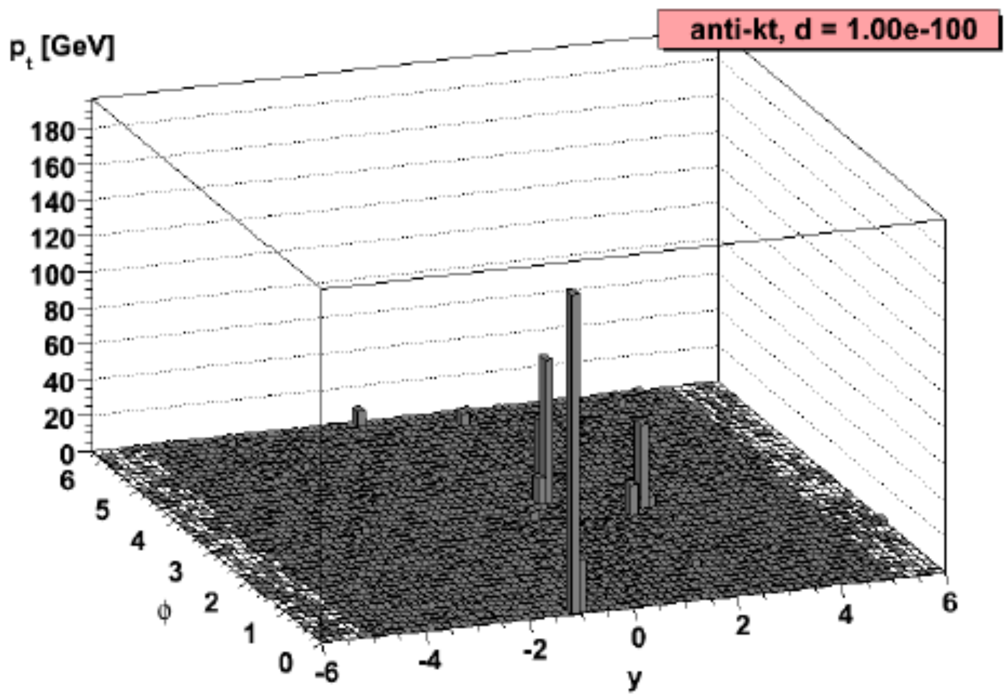

Select hard particles as ‚seeds‘ for jets: favoured by $\min(p_t^2)$

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'

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

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

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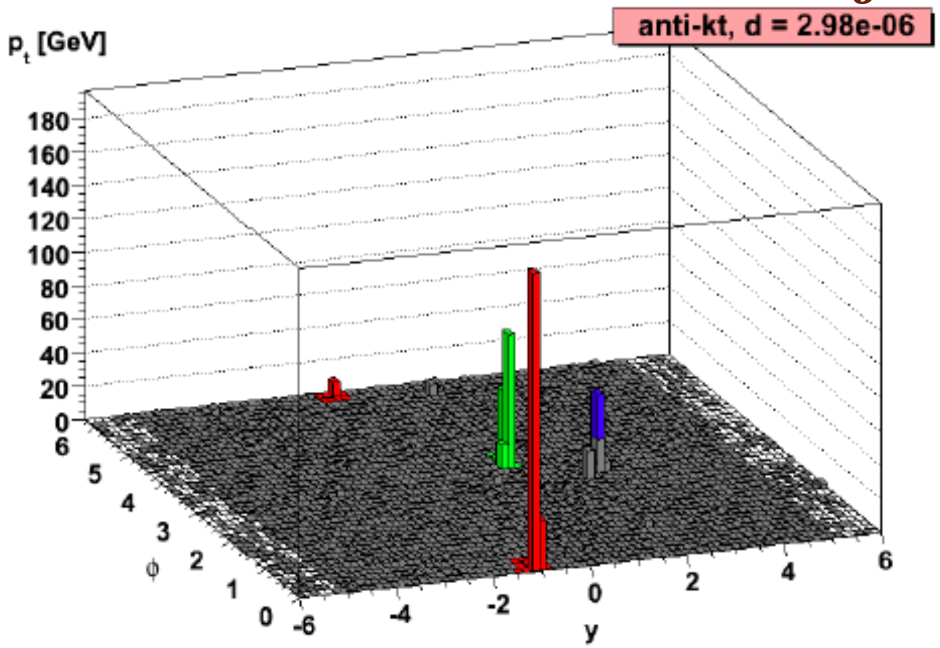

Gradual d_{ij} increase:

Associate close by particles:
mostly soft ones in
neighbourhood

(if no hard ones close by)

The final jets

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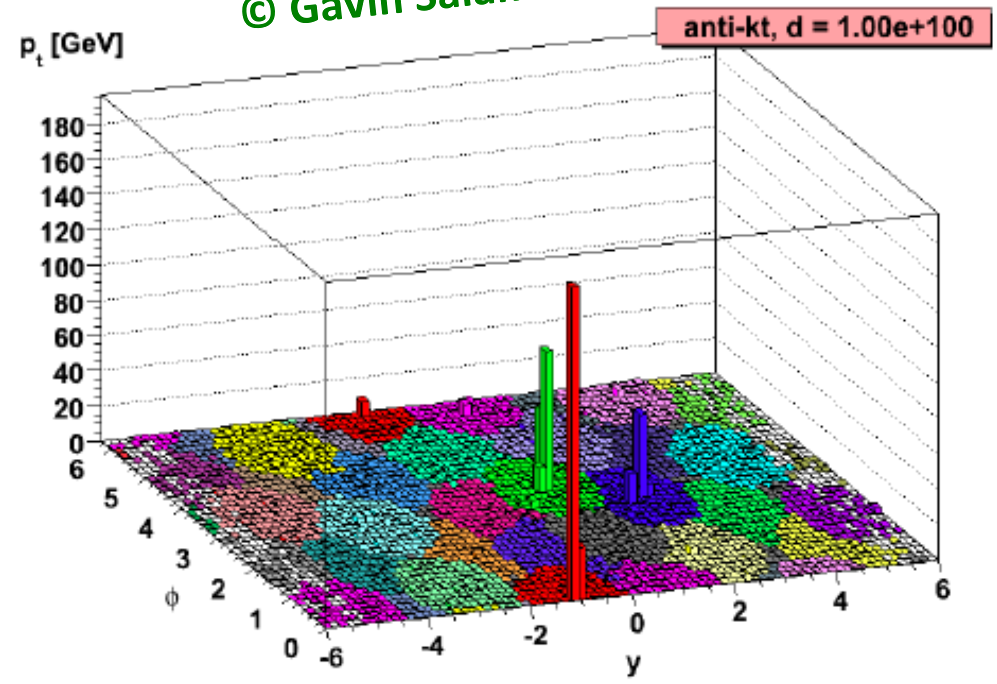

All particles assigned to jets

Close to circular in space good for experimental corrections

Note: special treatment of particles close to beam

Typical $\Delta R \approx$ 0.4 – 0.6

Probing the strong force

The key test: jet cross section

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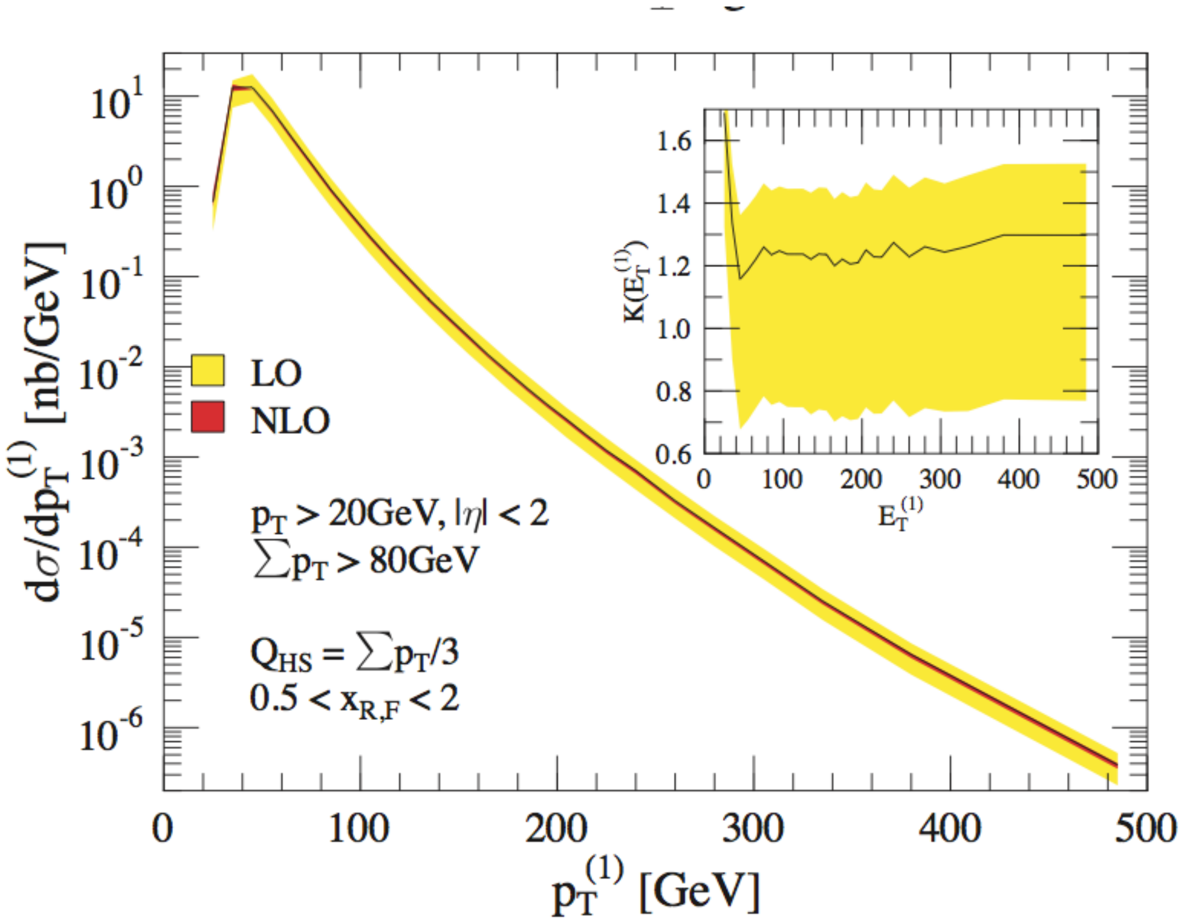
Calculated to Next-to-leading order (NLO)



Steeply falling

7 orders of magnitude for modest 500 GeV

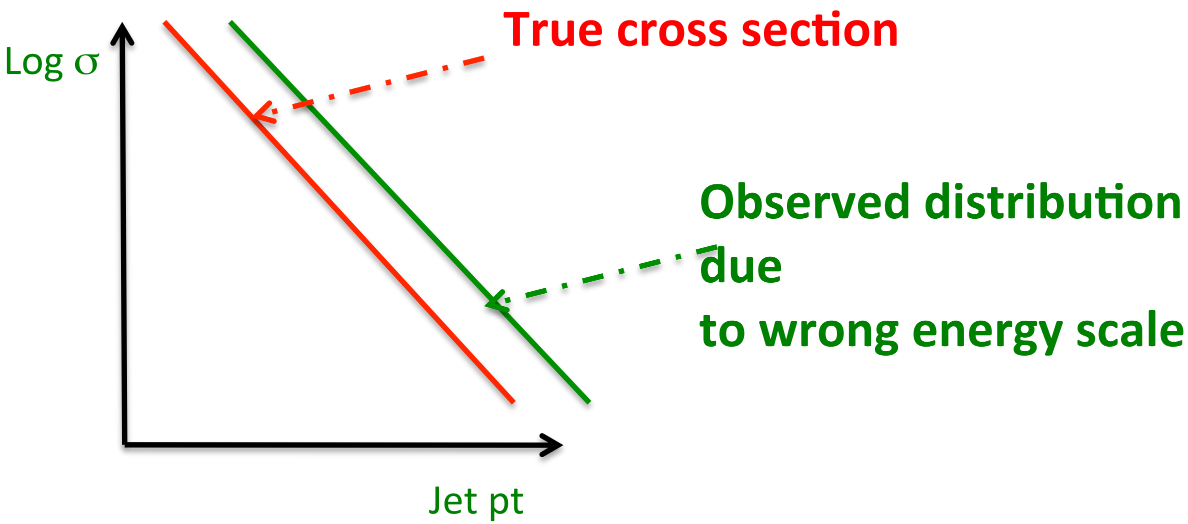
➔ Significant tests require high experimental precision

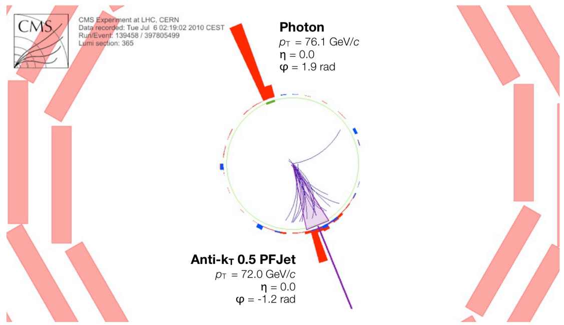
The experimental challenge I

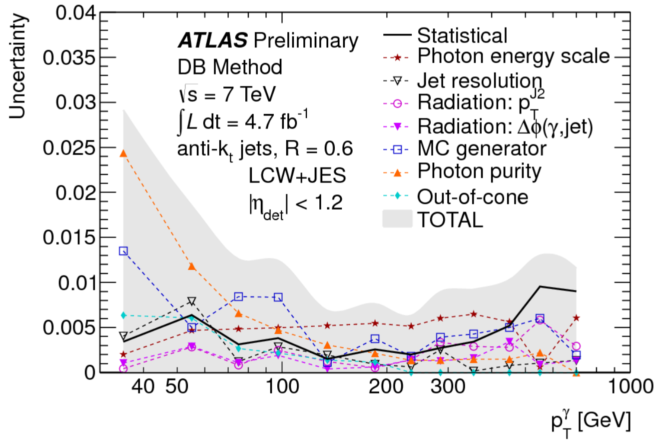
Energy scale uncertainty magnified by steep slope

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

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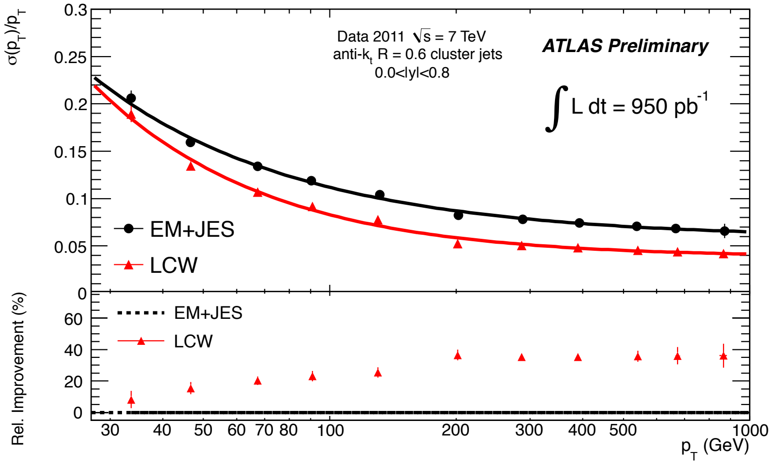
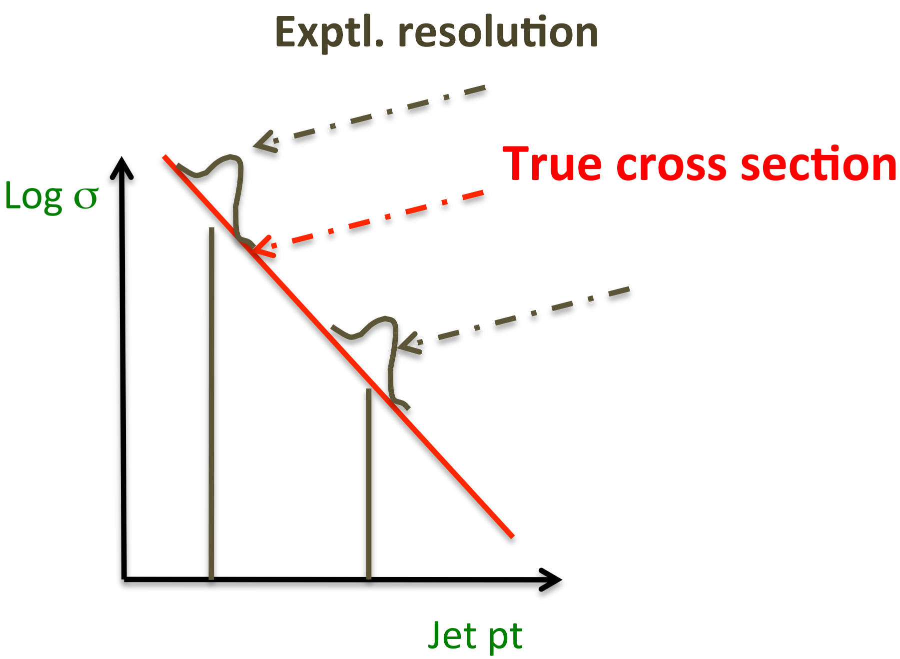
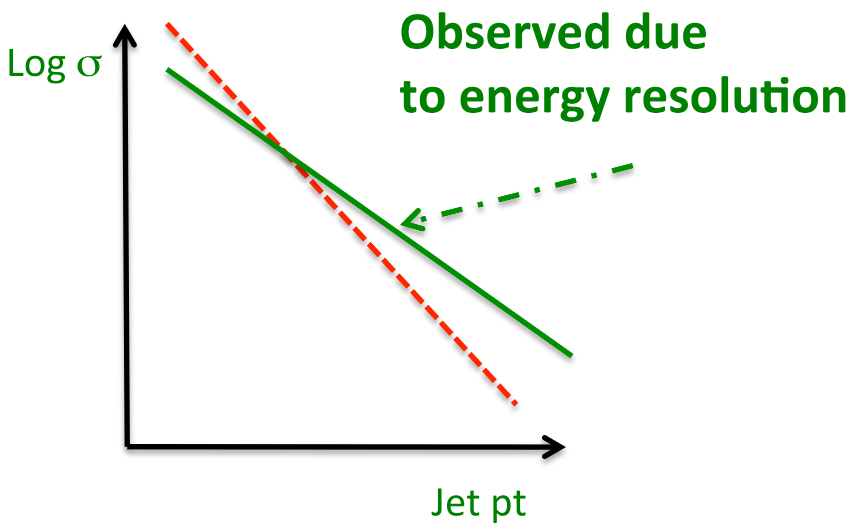
sensitivity to energy resolution







Uncertainties: summary

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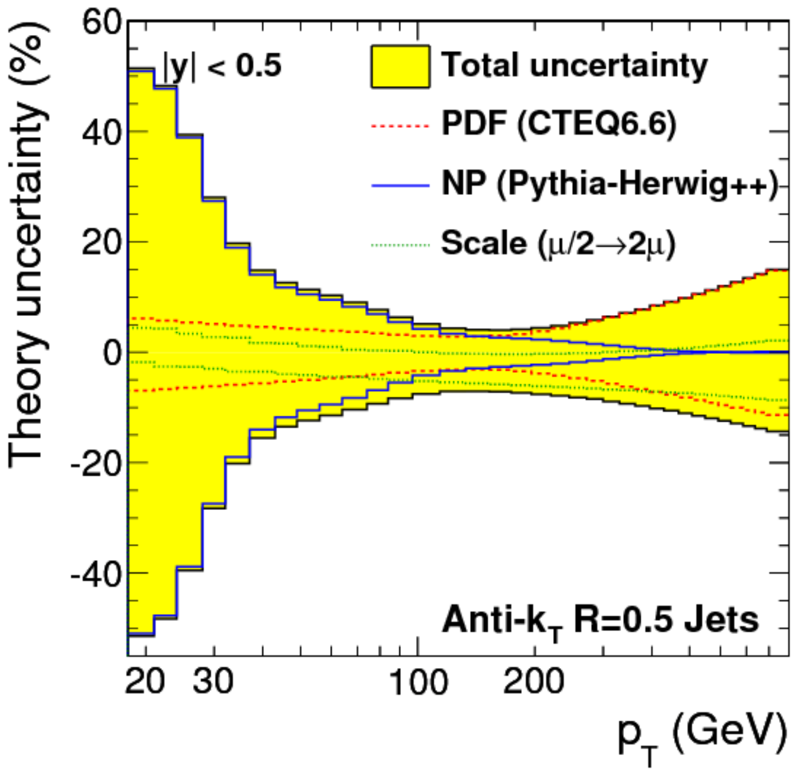
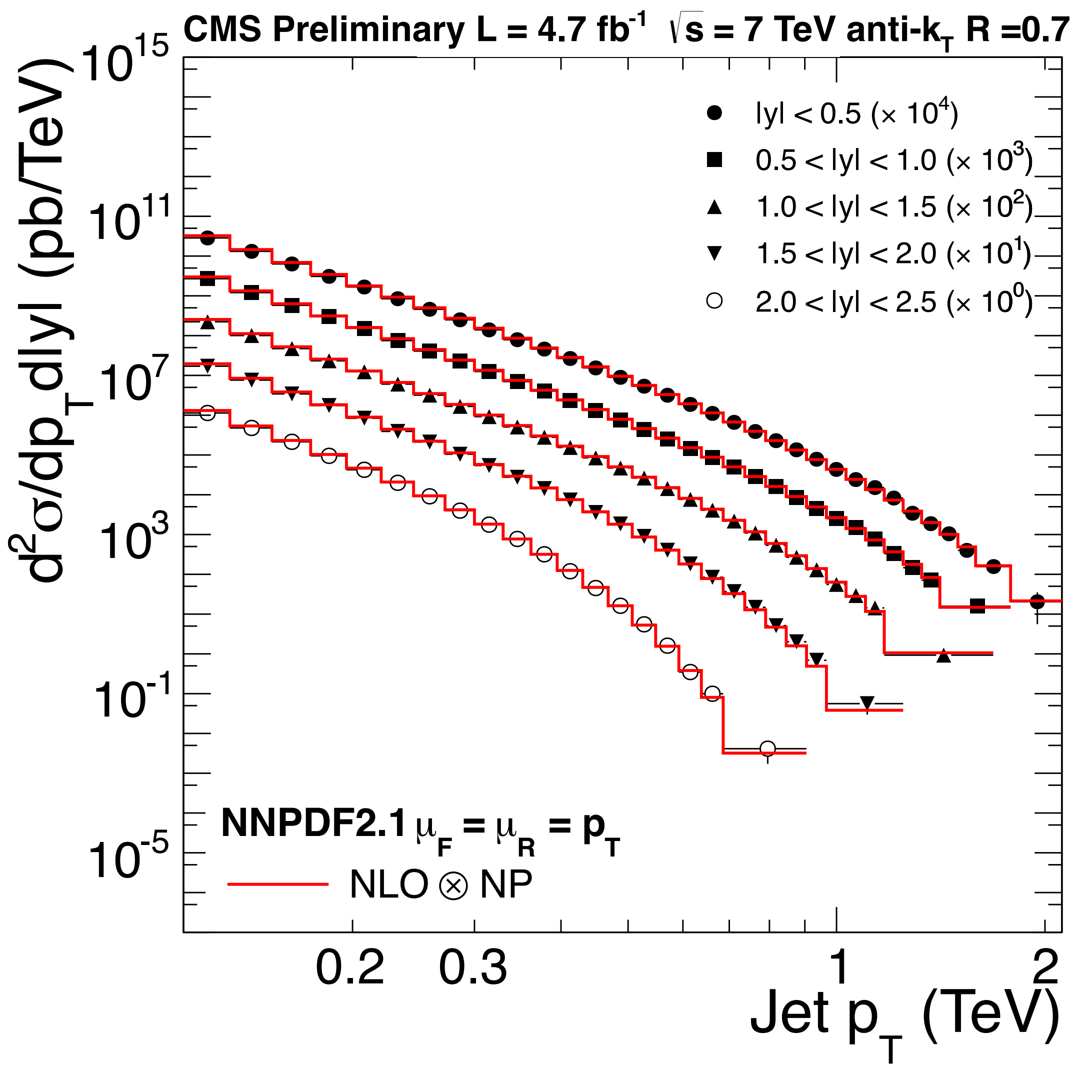


Experimental uncertainties dominate at low p_T

pdf/theoretical uncertainties dominate at high p_T

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

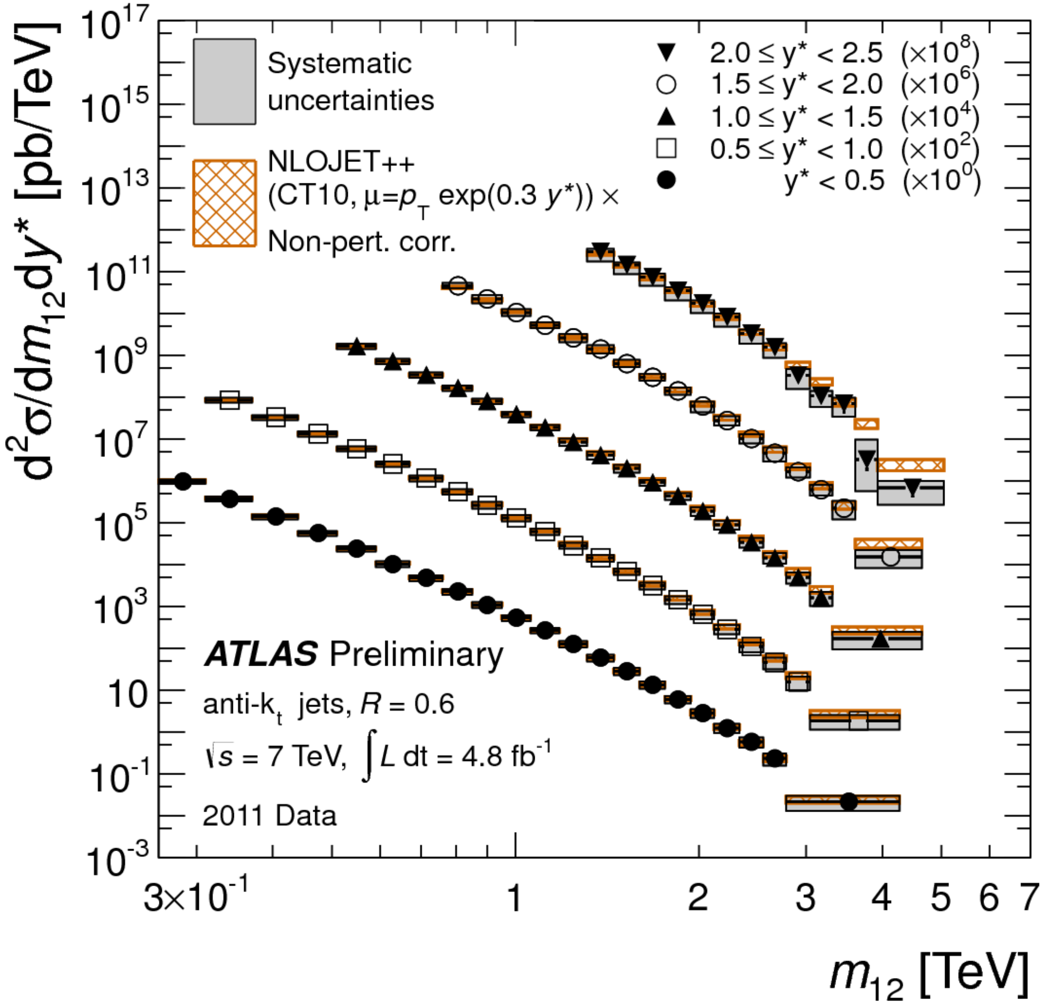
Jet cross sections in rapidity and pT



Excellent agreement theory <-> data

over huge range in phase space

jet – jet mass



Excellent agreement theory <-> data

Probing masses up to 5 TeV!

QCD effects: number of jets

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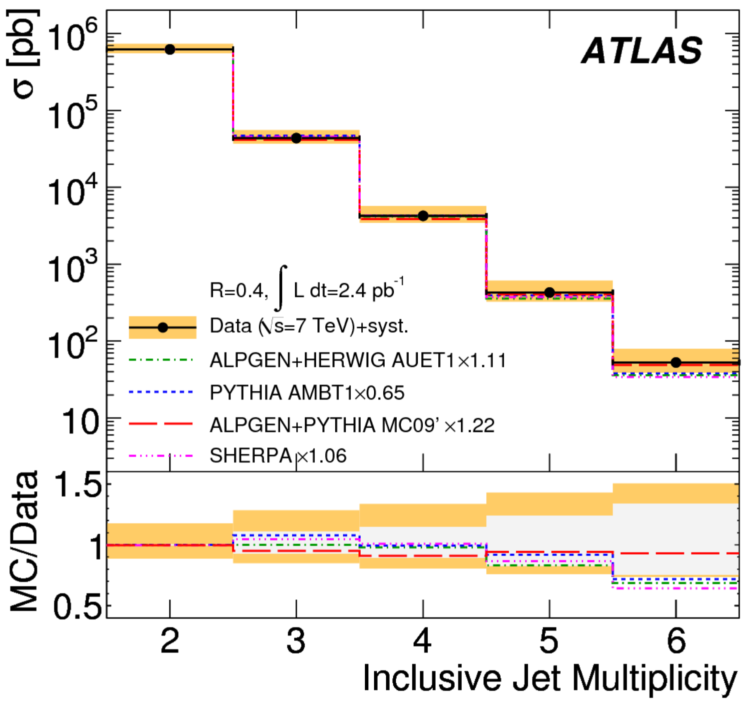

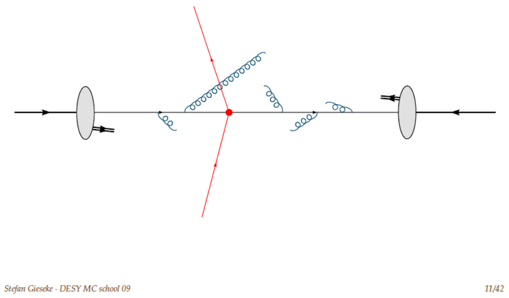

Even though not exact matrix element: Good agreement on jet multiplicity

Determining the strong coupling α_s

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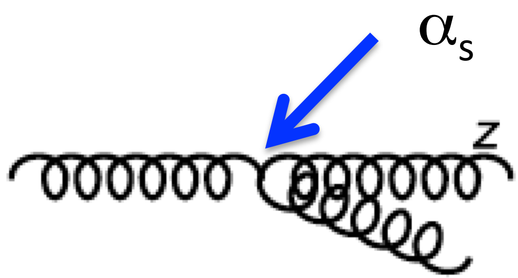
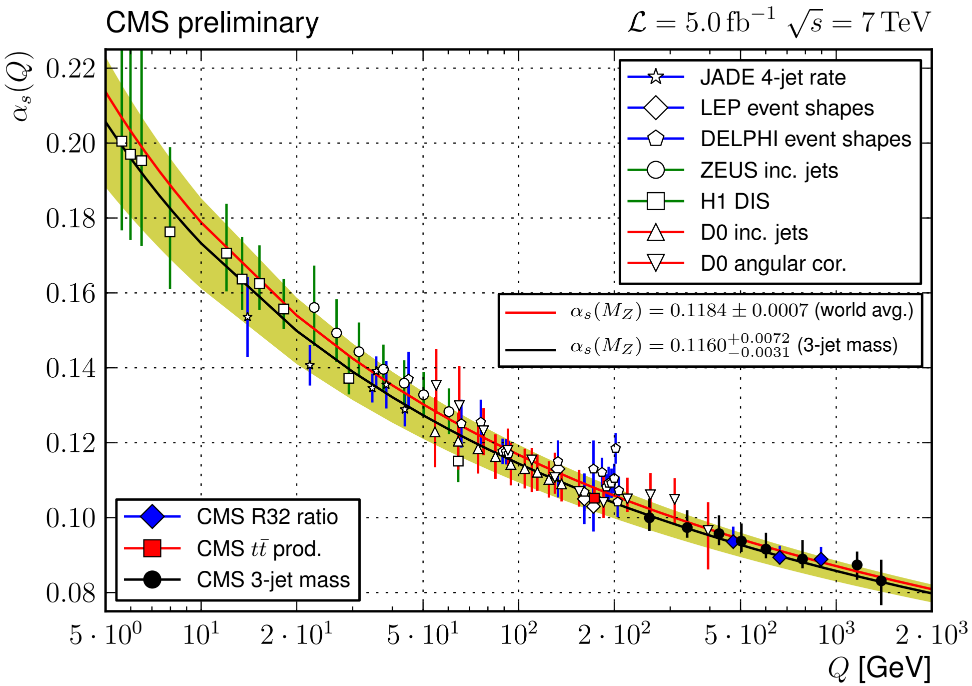


Measures of α_s :
Three – jet fraction
Jet mass



$$\alpha_{\mathbf{s}}^{\mathbf{world}} = 0.1184 \pm 0.0007$$

$$\alpha_{\mathbf{s}}^{\mathbf{LHC}} = 0.1160^{+0.0072}_{-0.0031}$$

Single value less precise, but huge energy range

Energy dependence of α_s clearly visible

Measuring jet evolution

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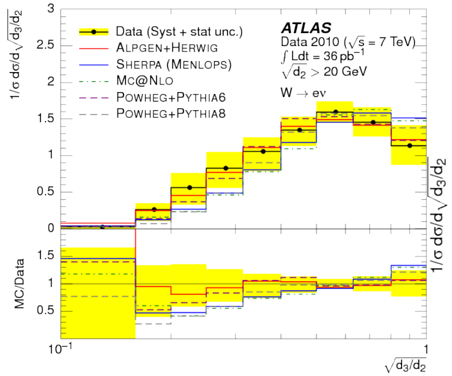
our view of jet evolution:

- **Sequential radiation of gluons**
- **Leading to finer granularities**

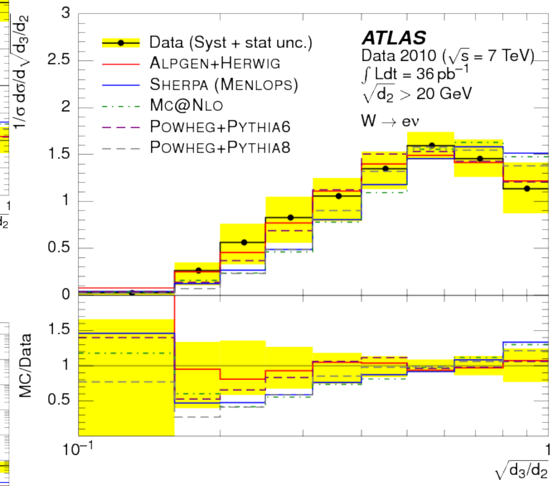
Mimicked in models –
how good are these models?

Measure, at which d_{ij} jet is split into two, three, …..
I.e. reverse jet finding

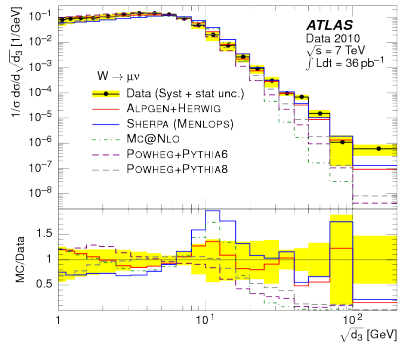
Into 2 jets ….



Ratio 2/3 jets split



Into 3 jets ….



Very good agreement …. at least for some models

High p_T Jets

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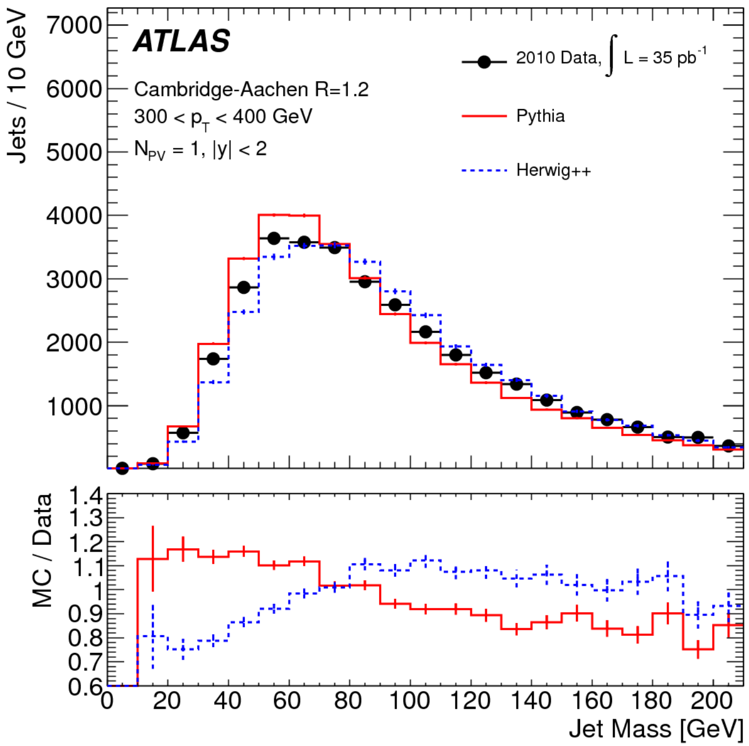
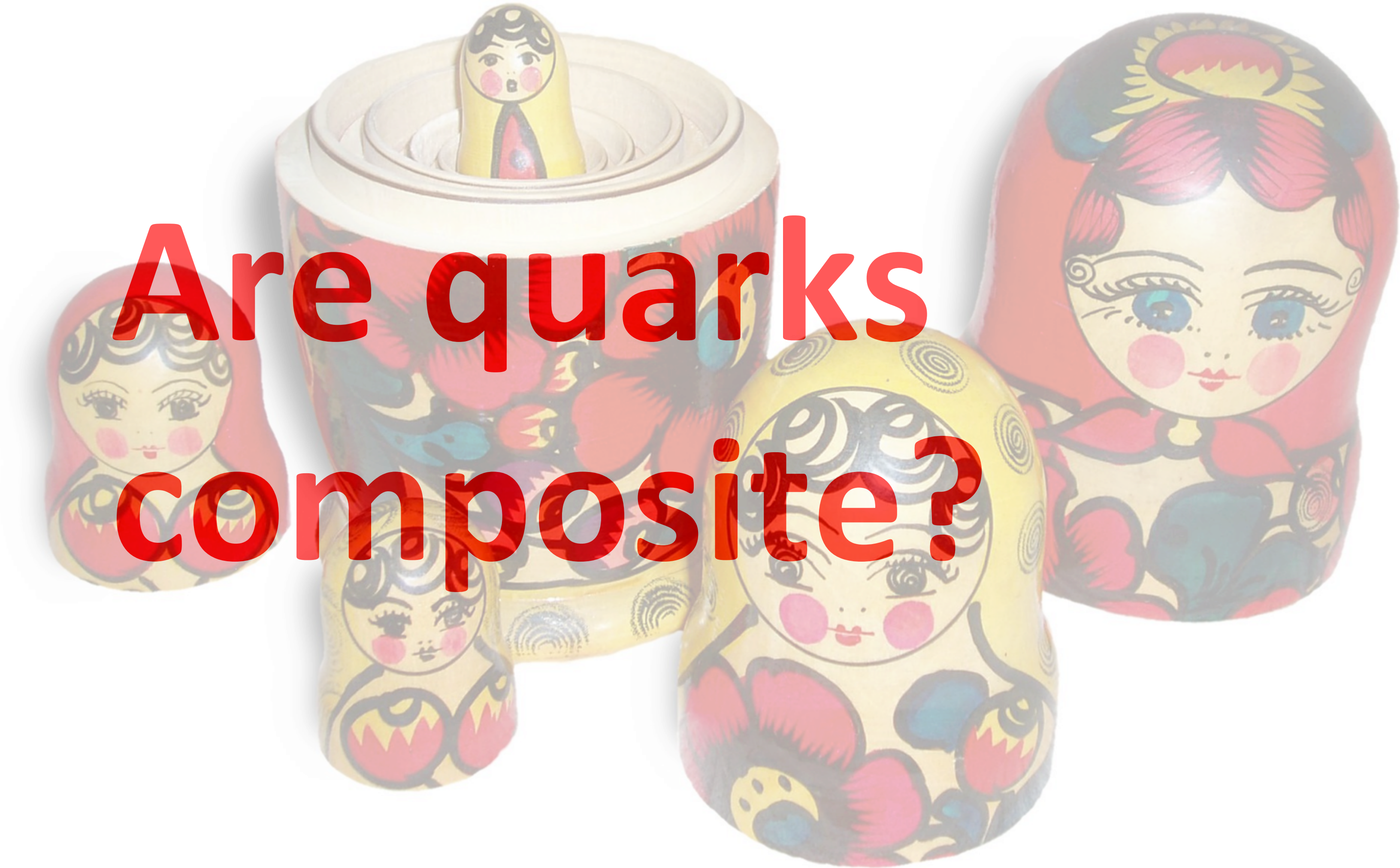
High p_T jets: important to explore TeV scale physics
May be due to boosted objects ➔ substructure
Important: does QCD describe the structure of boosted jets?



Measure mass of high p_T jet:

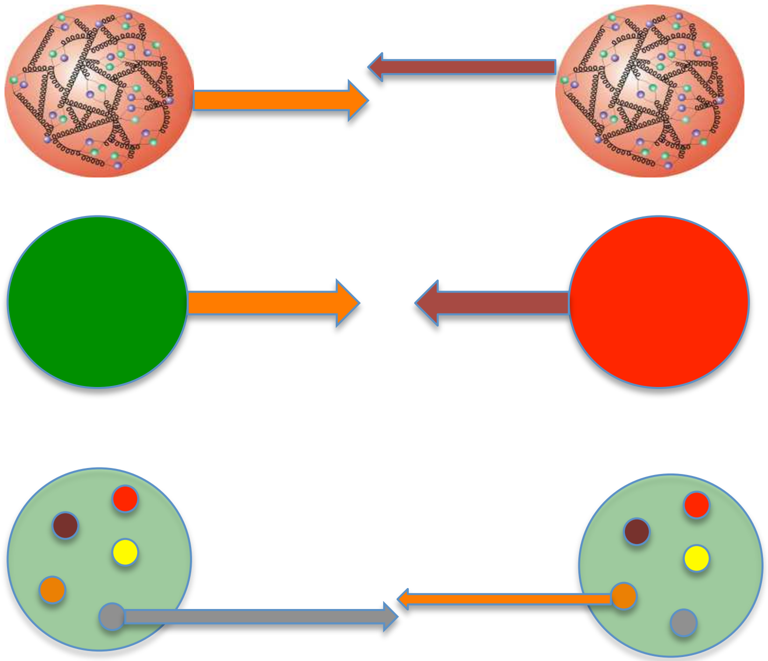
Globally:
agreement with expectation
..... But details differ!

Are quarks composite?



Are partons composite?

Rutherford all over again ....



pp – interaction @ Q ≈ 0.1 GeV

qq – interaction @ Q ≈ 10 GeV

interaction of subconstituents ?
@ Q ≈ 1000 GeV ?

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

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

Jets and BSM: Search for di – jet resonances

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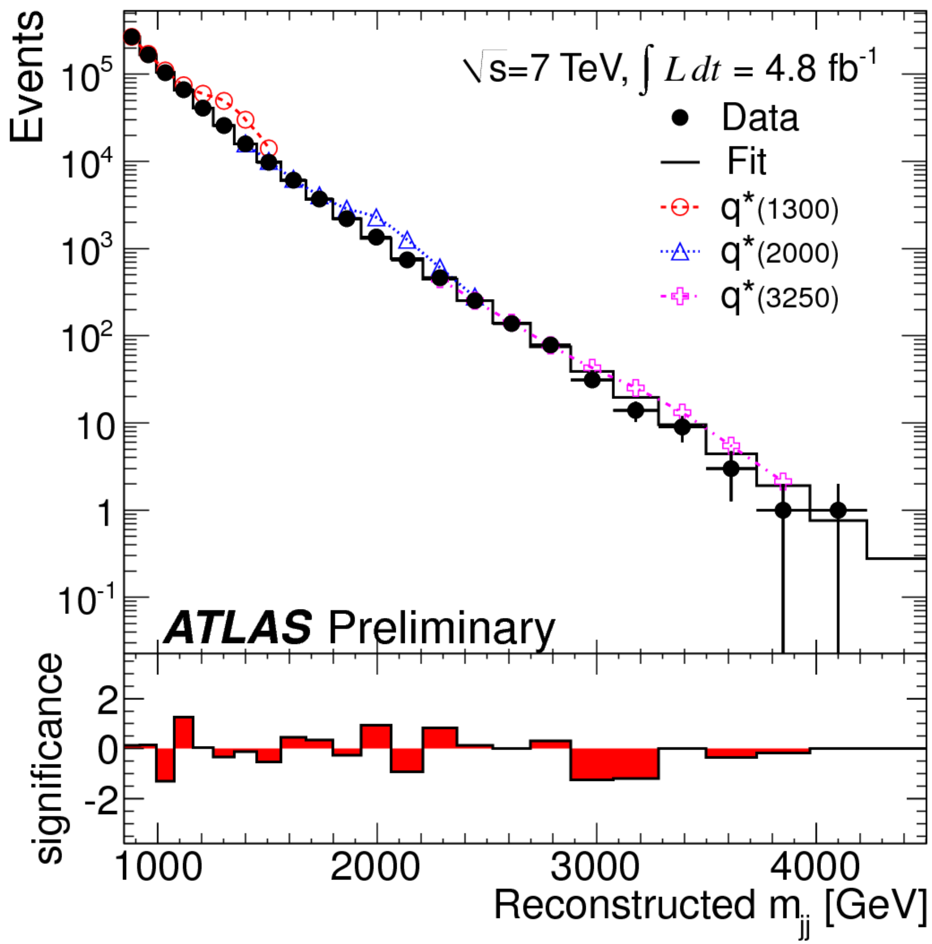

An excited quark ?

$q^* \rightarrow q + g$

(Remember excited atom, nucleus ....)

Would be strong signal for compositeness

Search for resonance: enhancement

Are quarks composite ?

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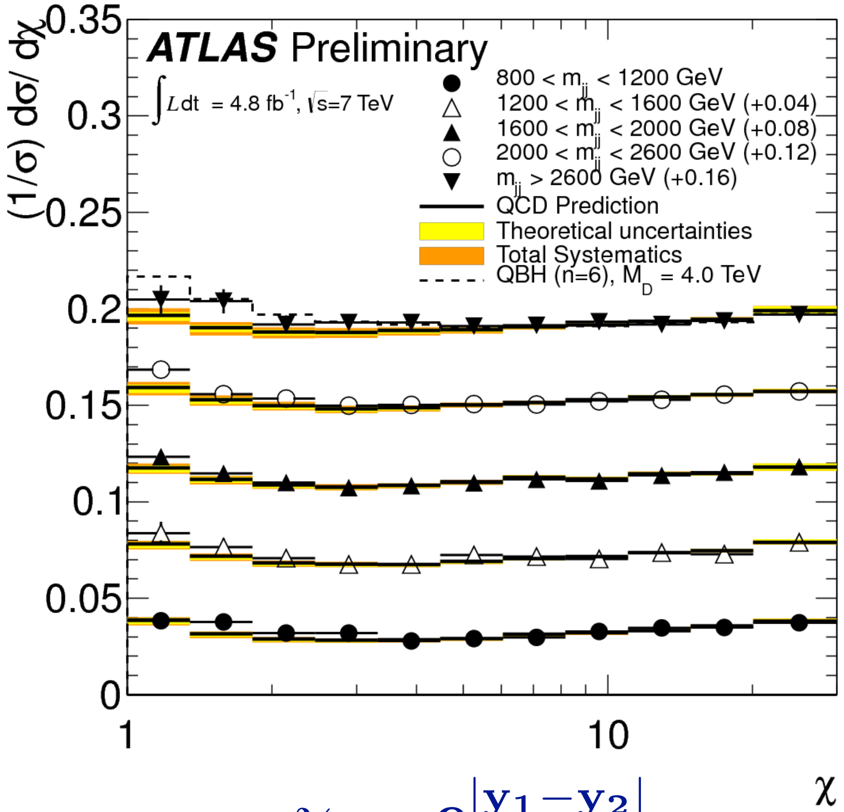

$$\chi = e^{|y_1 - y_2|}$$

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