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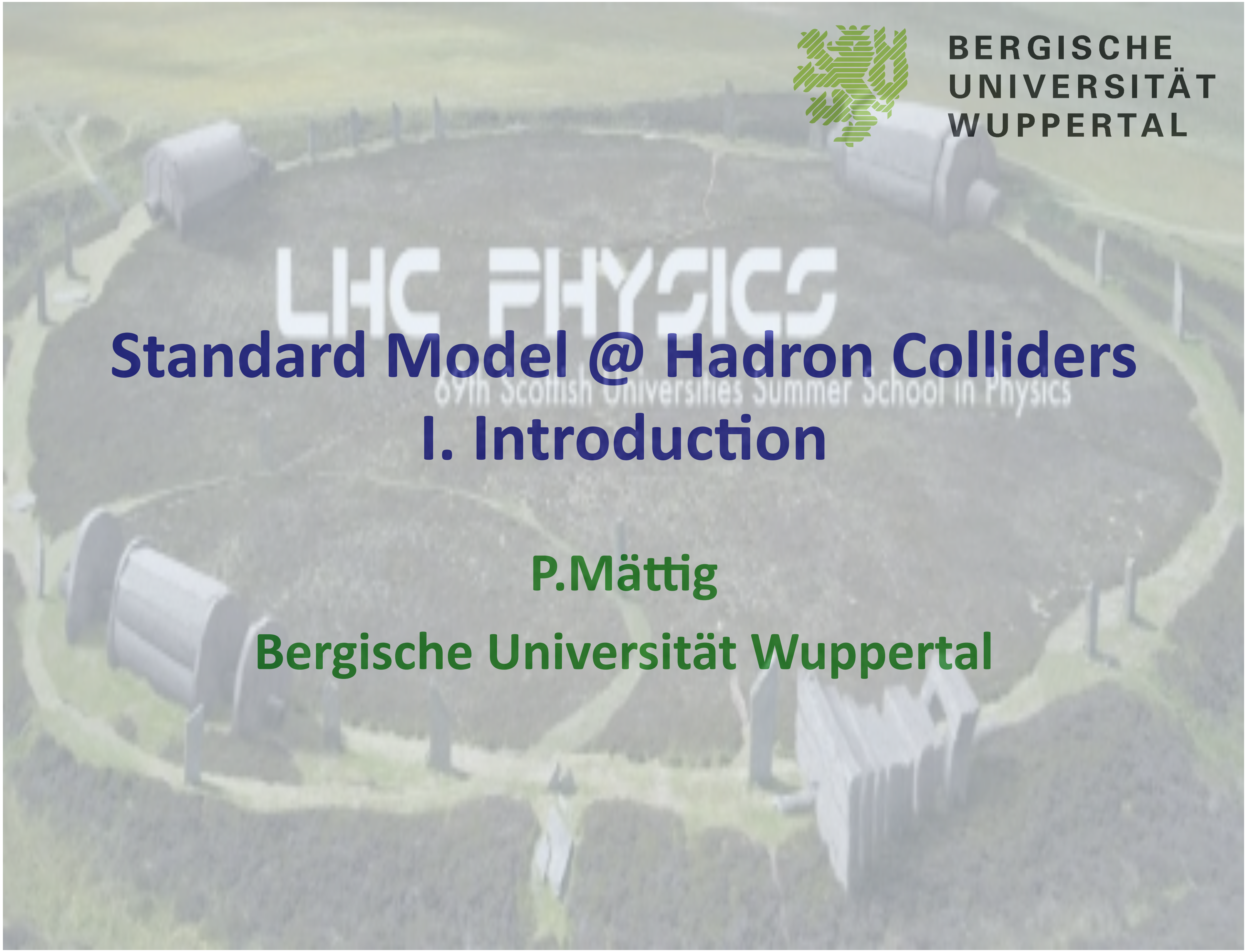
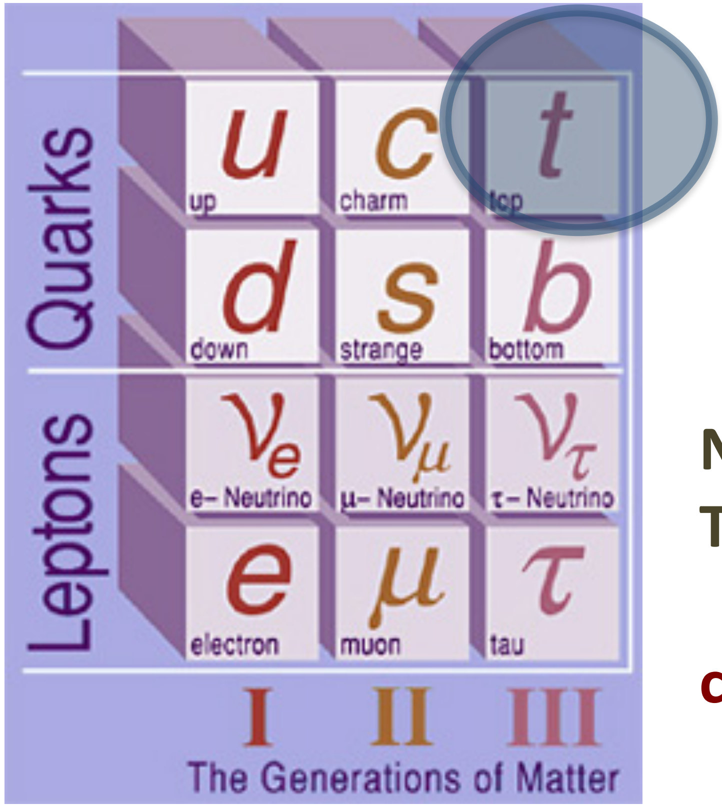


Standard Model @ Hadron Colliders
I. Introduction

P.Mättig

Bergische Universität Wuppertal

Standard model pillar I: Matter



Unique topic for hadron colliders
Experiments just started

‚light' quarks intensive studies via hadrons

Neutrinos tiny masses
Transition matrix to be measured

charged leptons deeply scrutinized

Standard Model pillar II: Forces

Strength of all interactions very precisely known

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

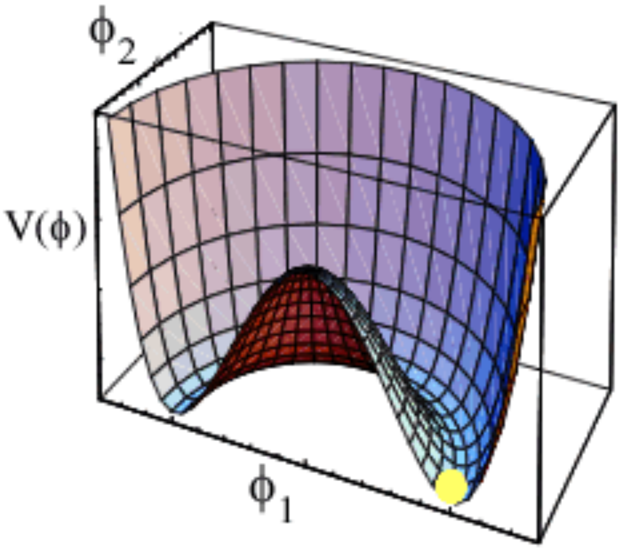
Dynamics of interactions well tested at energies ~ 100 GeV

LHC: still true at several TeV?

Standard Model Pillar III: Higgs

Evidently this could only have been (re)found by someone working at a Scottish university ..... and likes to walk in the Highlands!

Standard Model Pillar III: Higgs



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)

FOUND ???

(Almost) All parameters of the Standard Model known

LHC (currently) the only place to study mechanism

➔ see Bill Murray‘s lecture

Why Standard Model @ Hadron Colliders?

- Explore phase space not determined from first principles
- Probe at highest energies
- Scutinize Top Quark
- Explore the ‚Higgs (?)‘ boson (or alternative EWSB mechanisms)

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‘

Experimental Standard Model

1. Experimental environment for SM Tests @ proton colliders
2. Some basics of pp collisions
3. Soft QCD processes
4. Hard parton scattering – Jet production
5. Hard parton scattering – Structure of jets
6. QCD aspects of W/Z production
7. Electroweak measurements: W – mass & W/Z self coupling
8. The top quark: production
9. The top quark: properties

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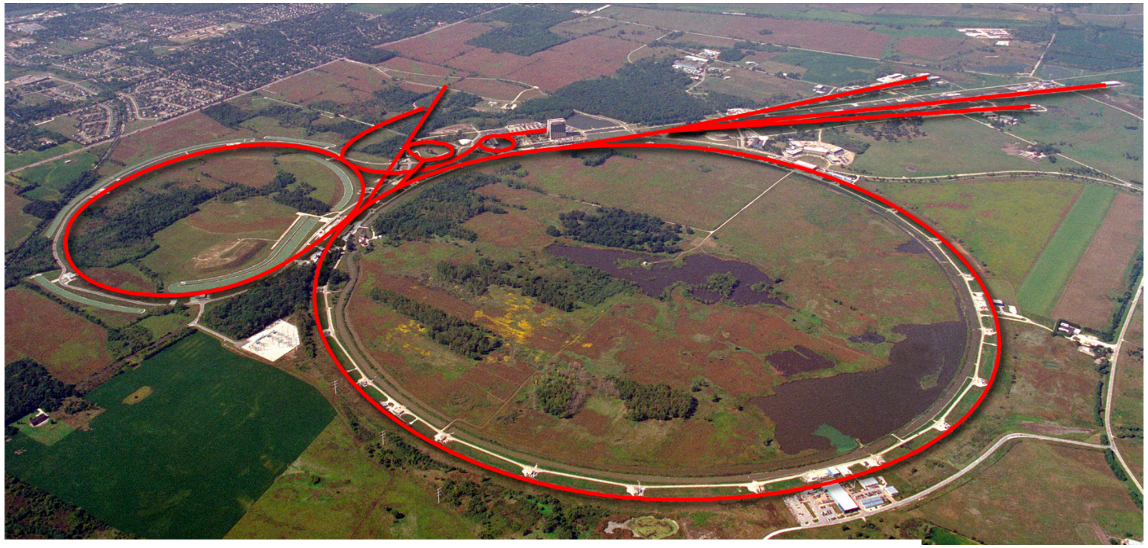
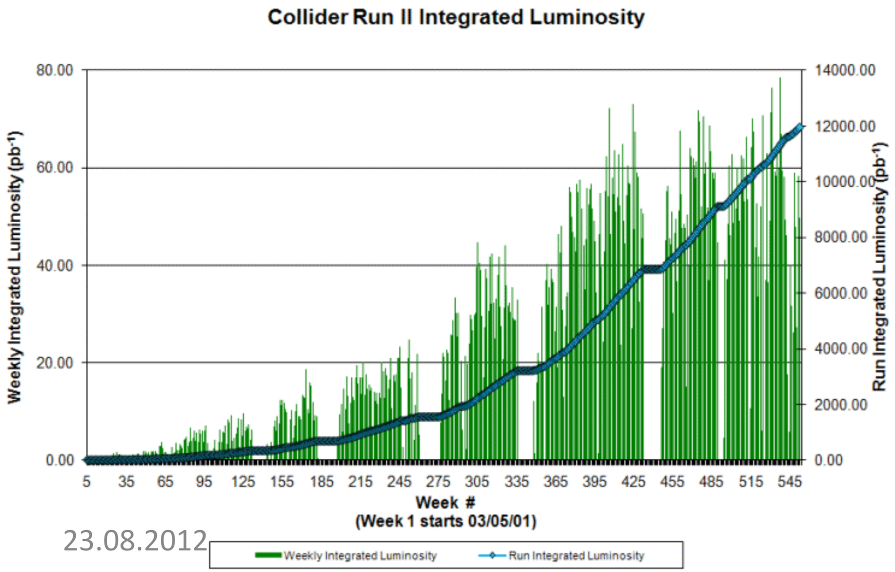
Standard Model @ Hadron Colliders
I. Experimental Environment

Yesterday‘s flagship Tevatron



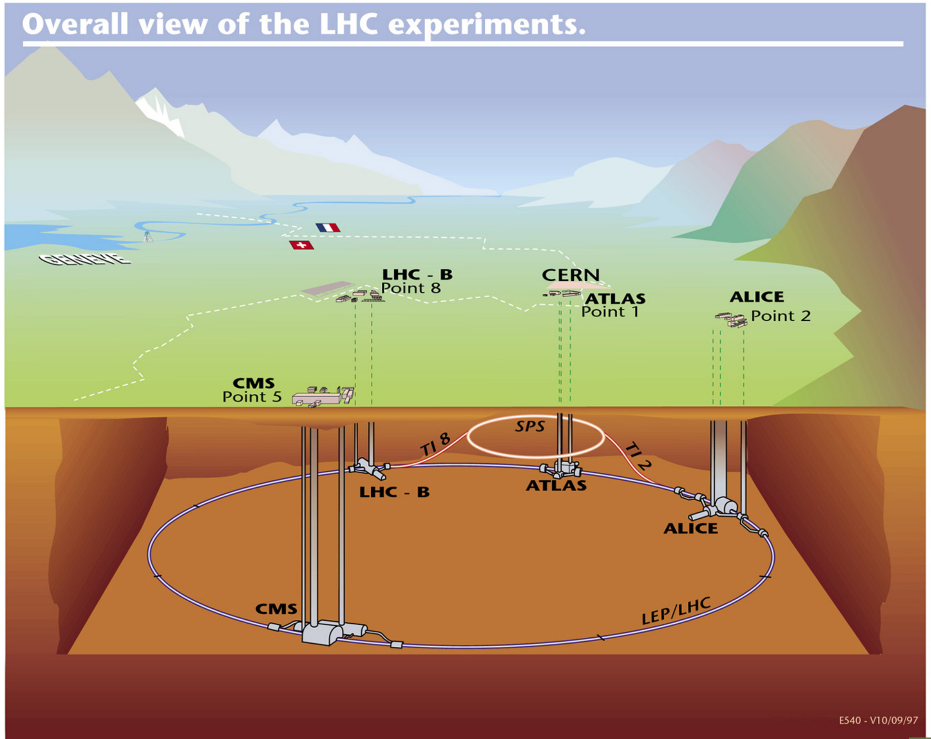


Proton – Antiproton Collisions
@ 2 TeV c.m. energy

2 Experiments (CDF & D0)

Each collected 10 fb^{-1}

Today‘s flagship LHC



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

Will focus on ATLAS and CMS

ALICE: quark – gluon plasma
LHCb: bottom physics

Note: difference to Gaelic LHC
too lazy to dig???
but they love symmetry!

The outstanding LHC performance

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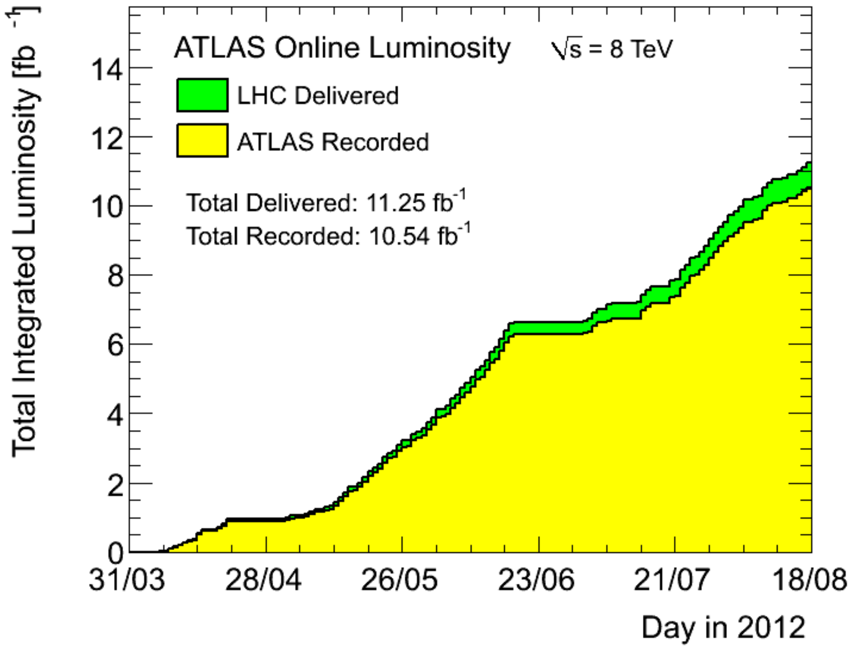
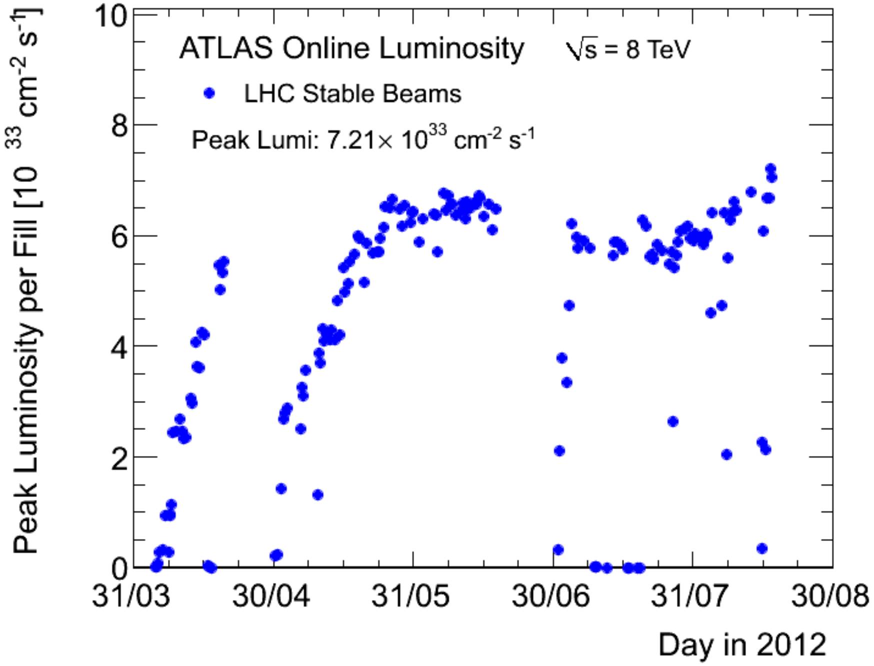
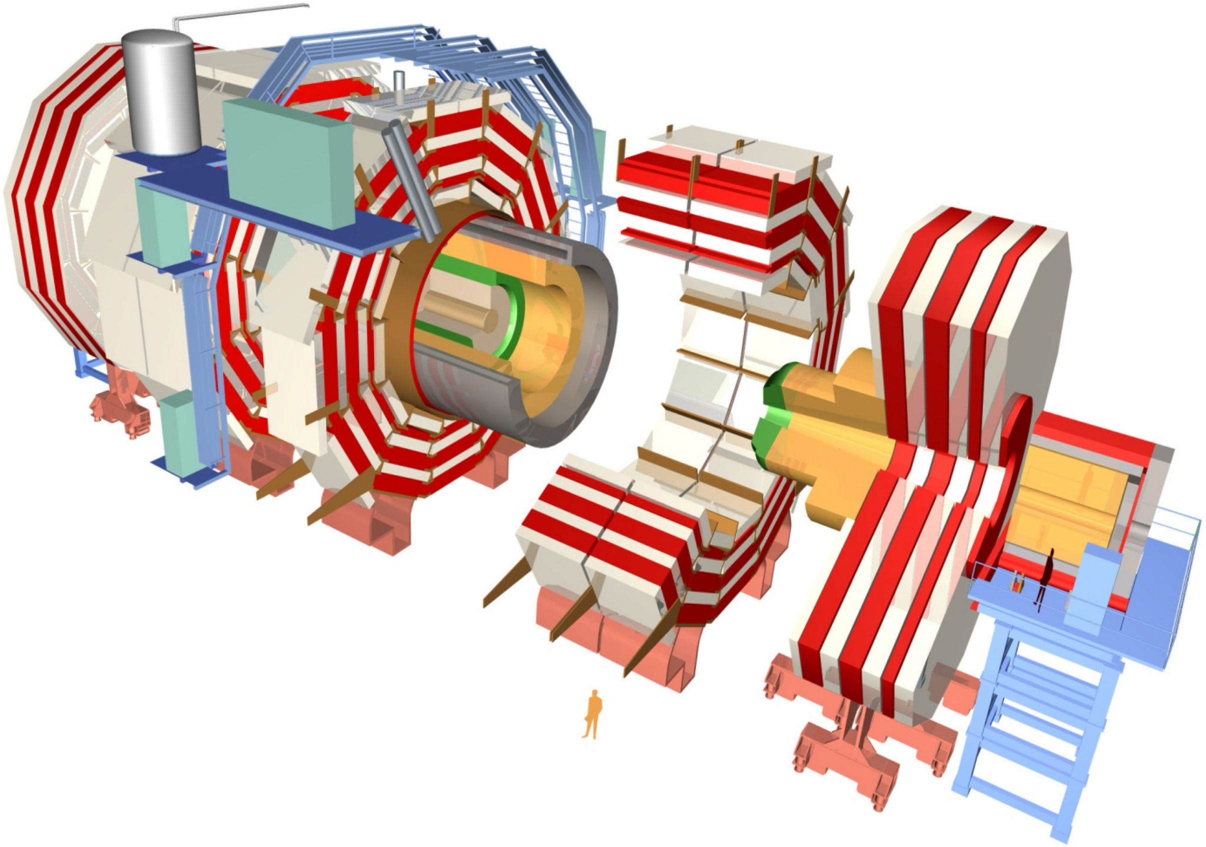




CMS = Compact Muon Solenoid

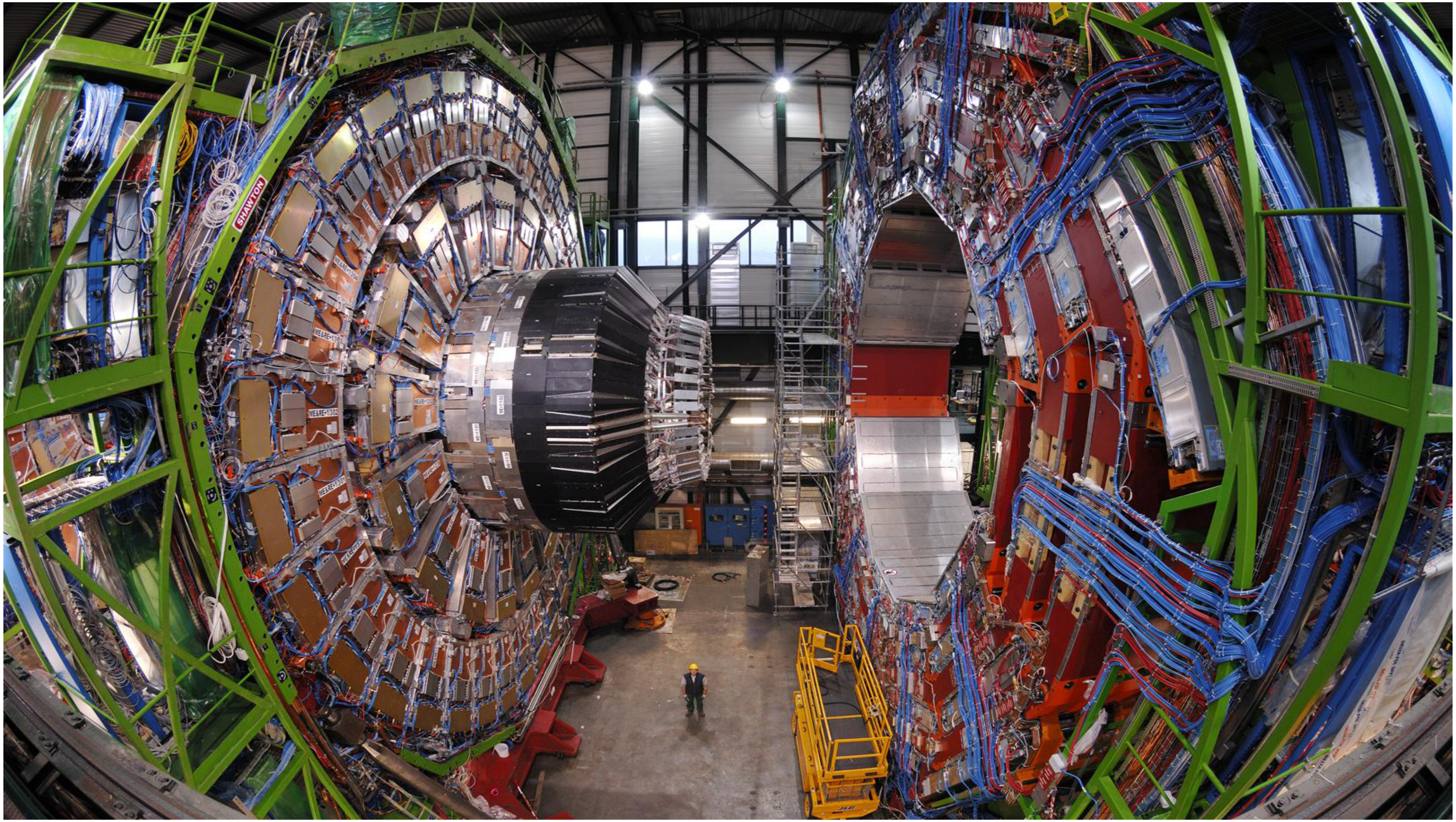


21.6 m long
14.6 m diameter
12 500 tons

3275 authors

Hermetic up to $|\theta| = 0.014$ rad

CMS



ATLAS

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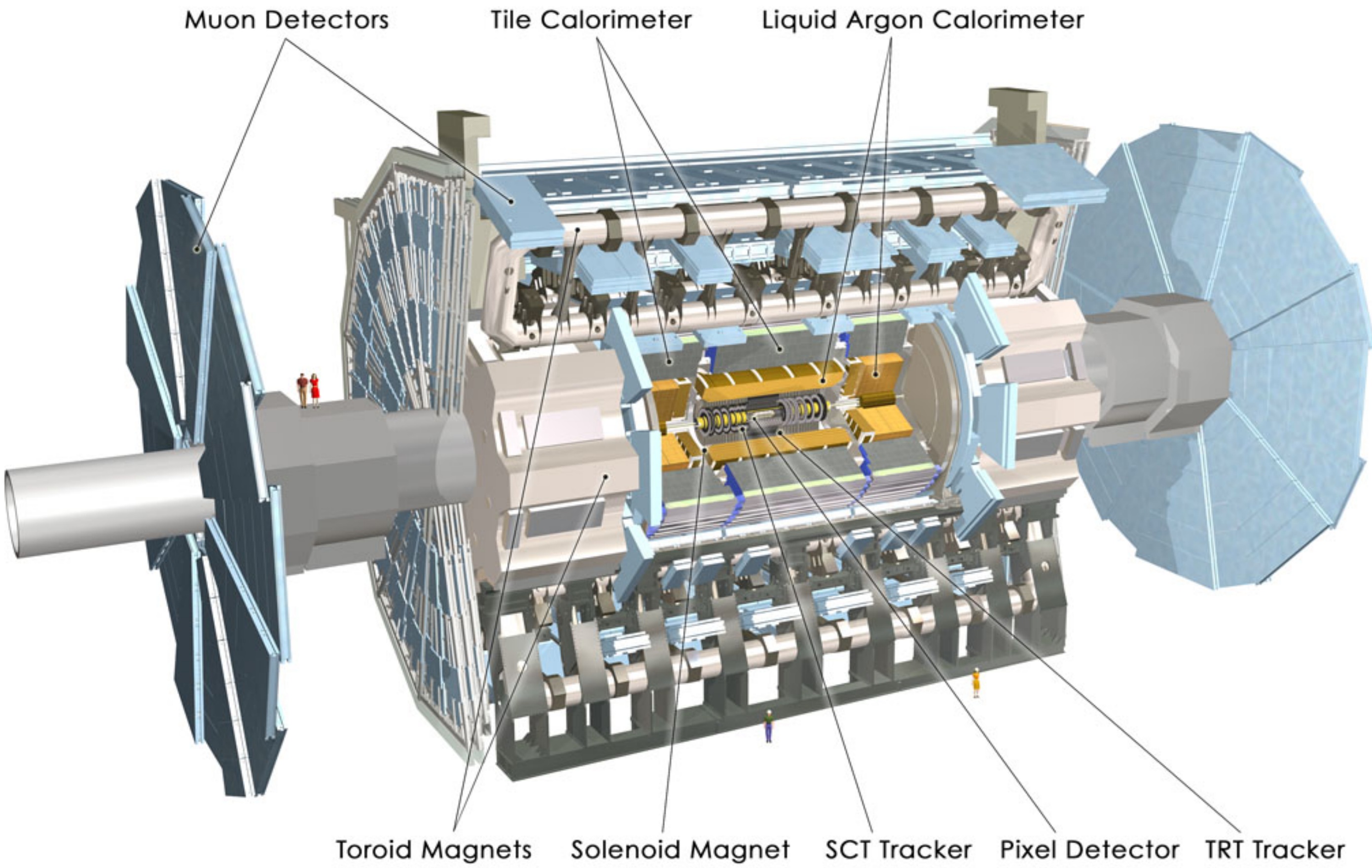


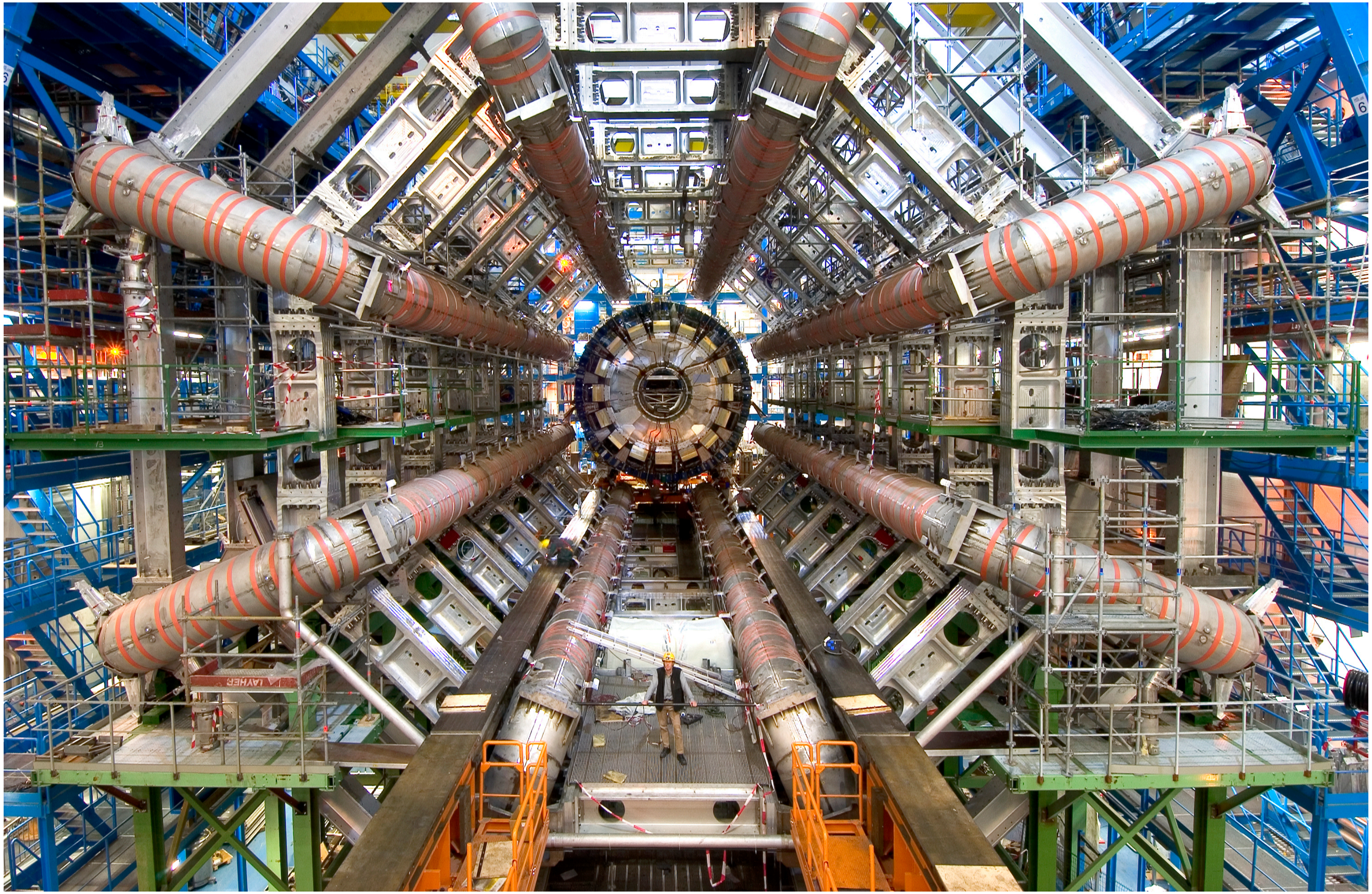
45 m long
25 m wide
25 m high
7 000 tons

2890 authors

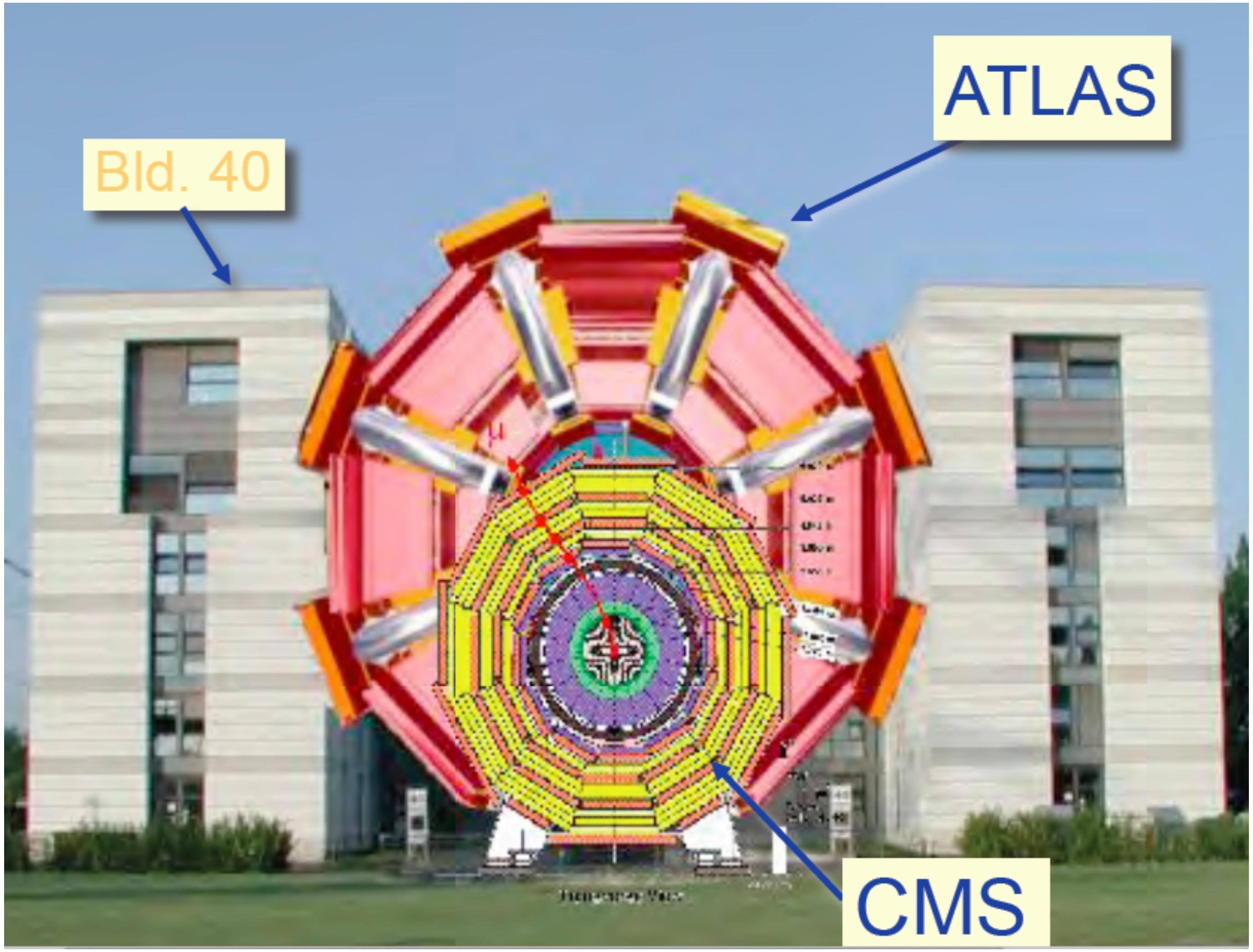
Hermetic up to $|\theta| = 0.015$

Largest particle detector ever .... but would float in water

ATLAS



Biggggg & sophisticated



Inner Tracker

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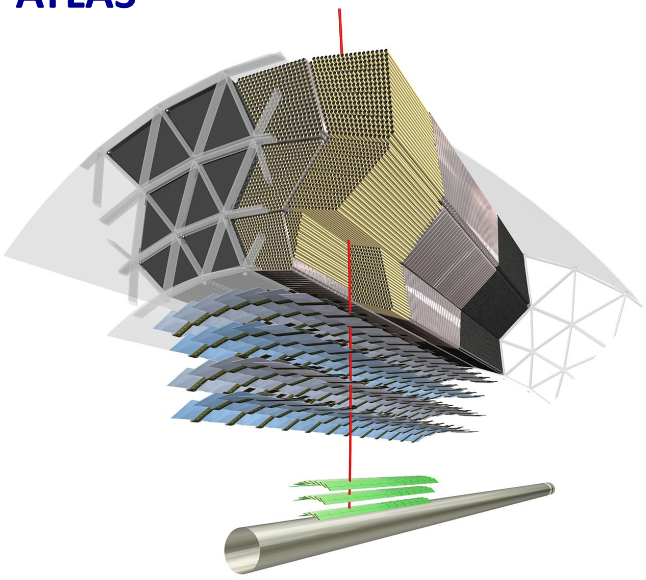
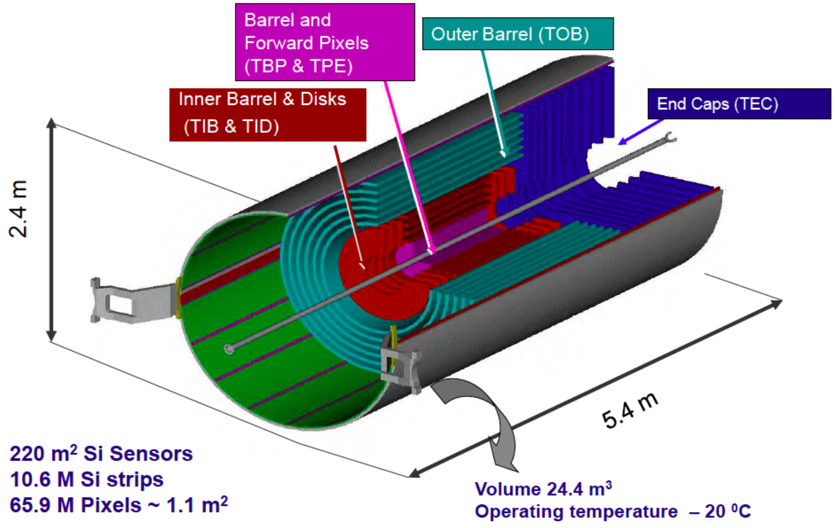
ATLAS



The CMS Inner Tracker (all Si)



220 m^2 Si Sensors
10.6 M Si strips
65.9 M Pixels ~ 1.1 m^2

Volume 24.4 m^3
Operating temperature – 20 ^{0}C

Inner part: Silicon, outer TRT
Magnetic field: 2 Tesla
Radii: 50 - 107 mm
# of measurements: 11 Silicon
+ 35 straws

All silicon
Magnetic field: 4 Tesla
Radii: 44 - 110
# of measurements: 17 Silicon

Momentum resolution

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Curvature k = 1/R

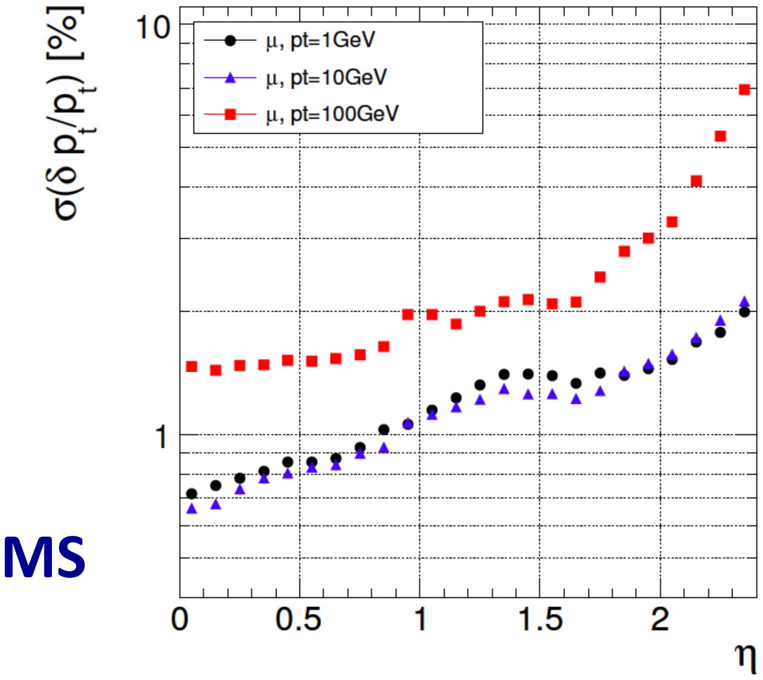
$$\frac{\delta \mathrm{k_{res}}}{\mathrm{k}} = \frac{\mathrm{p_{xy}}}{0.3 \cdot \mathrm{B}} \frac{\delta_{\mathrm{point}}}{\mathrm{L}^2} \sqrt{\frac{720}{\mathrm{N_{point}} + 4}}$$

Resolution is
- linear with 1/magnetic field
- quadratic in projected length of track
- linear in pT

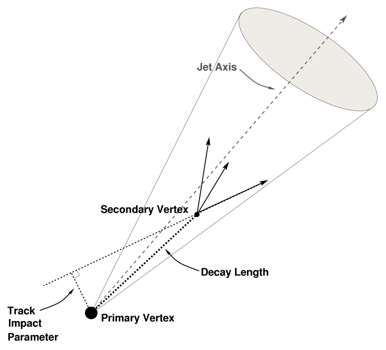
In addition multiple scattering (low p_T)
➔ reduce material!

$$\frac{\sigma(p_T)}{p_T} = a \oplus b \cdot p_T$$

Equal at ~ 45 GeV/90 GeV for ATLAS/CMS

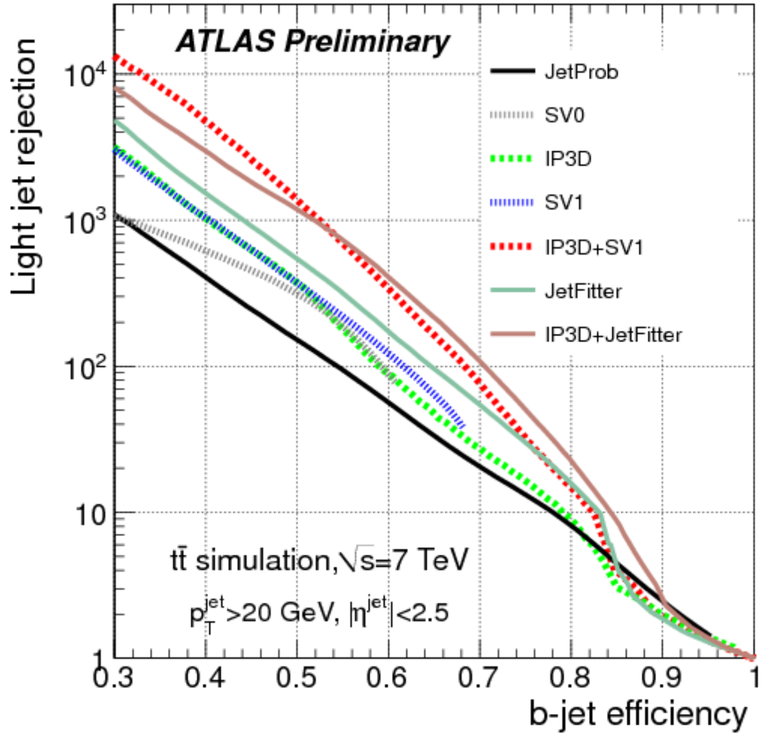


Impact parameter resolution



Simplified: 2 measurements at r_1, r_2 same precision σ

$$\sigma(\mathbf{d_0}) = \sigma^2 \frac{\mathbf{r_1^2 + r_2^2}}{(\mathbf{r_2 - r_1})^2}$$



Plus multiple scattering term

$$\sigma(\mathbf{d_0}) = \mathbf{c/p_T} \oplus \mathbf{d}$$

- **Close as possible to IP**
- **Long lever arm**
- **High precision**

Little material before measurement

Calorimeter system

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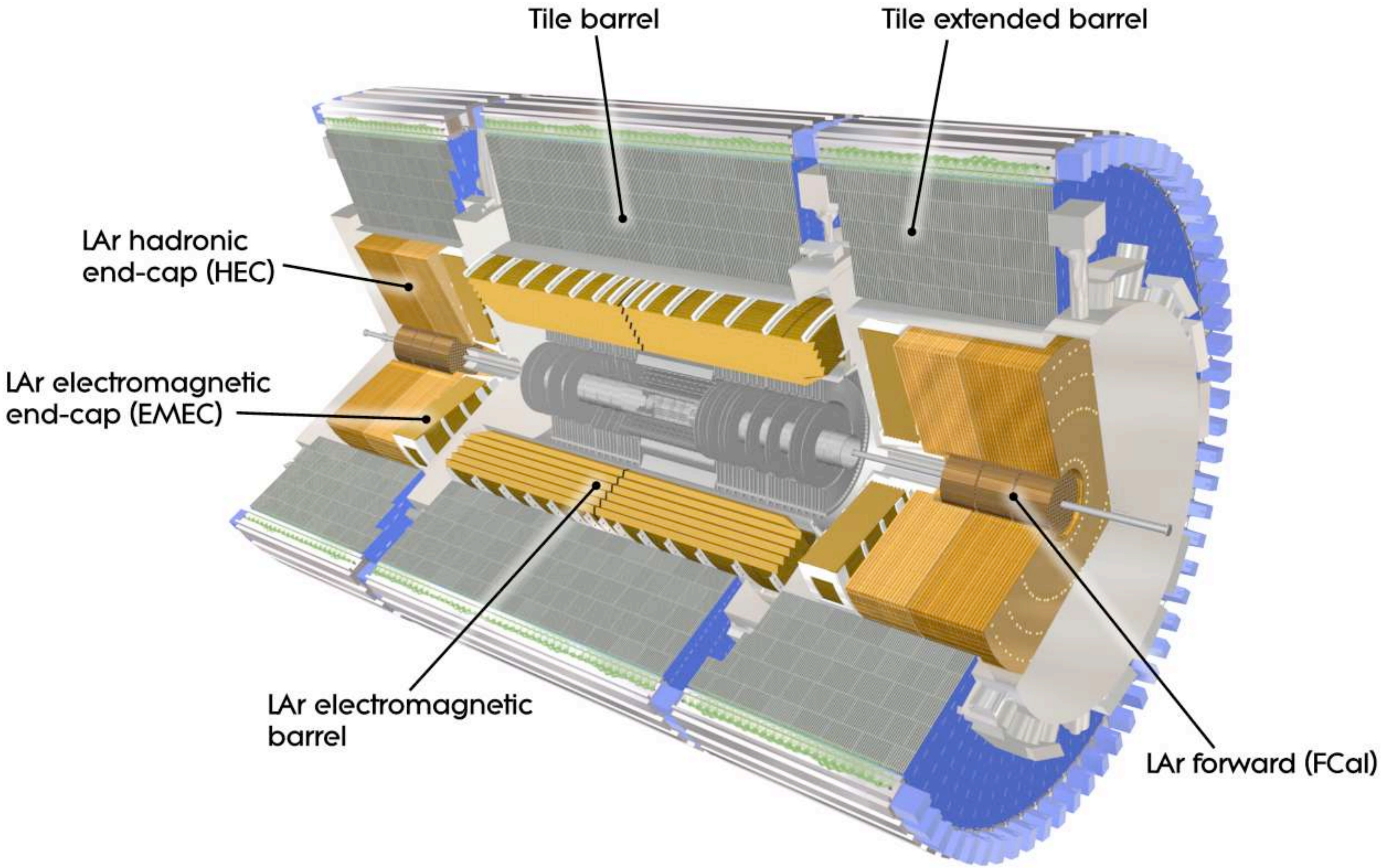

Calorimeter: electromagnetic

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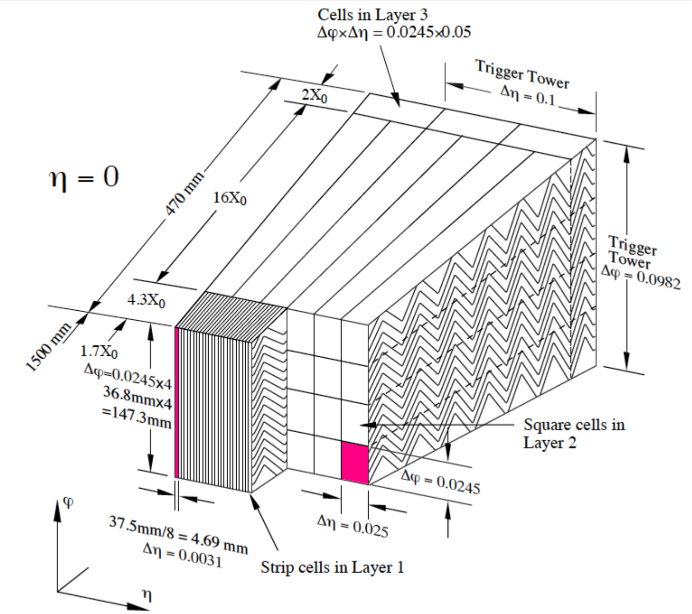
ATLAS



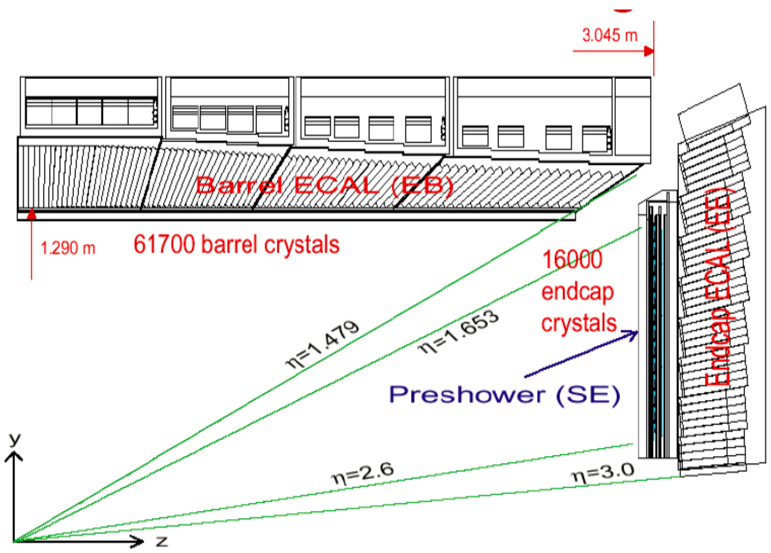
Outside magnetic field

Liquid – argon sampling

Granularity: 0.025x0.025

Longitudinal segementation

CMS



Inside magnetic field

Crystals $PbWO_4$

Granularity: 0.017 x 0.017

Energy resolution

$$\frac{\sigma(E)}{E} = \frac{0.1}{\sqrt{E}} \oplus 0.002$$

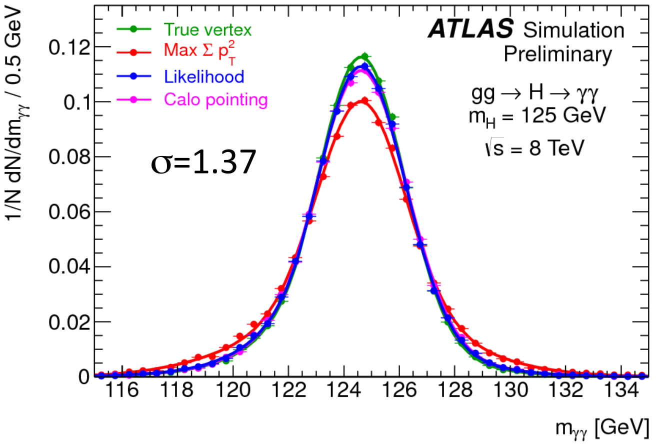
$$\frac{\sigma(E)}{E} = \frac{0.028}{\sqrt{E}} \oplus \frac{0.12}{E} \oplus 0.003$$

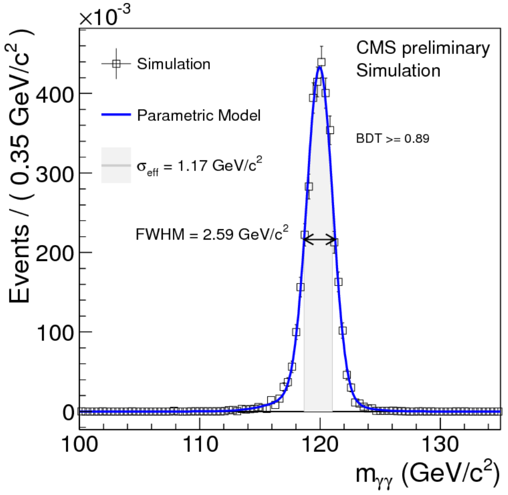
Note: assumes no material in front

Reality: 2-4 X_0 (ATLAS) magnet! **0.6 X_0 (CMS)**

Very high resolution for electromagnetic interaction

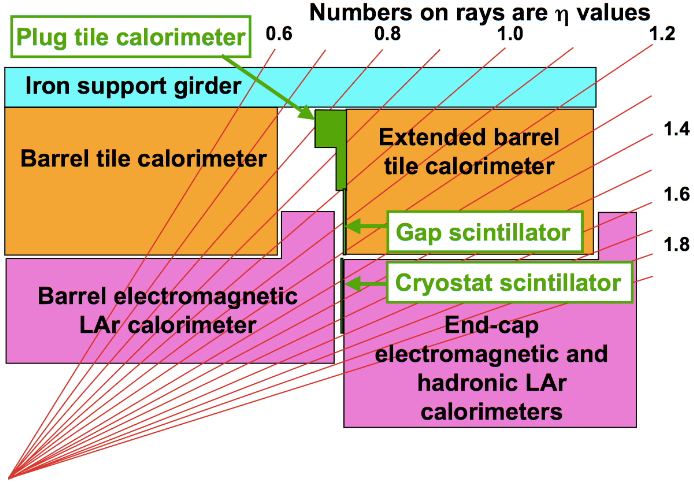
Importance of directional information





Calorimeter: hadronic

ATLAS



Outside magnetic field

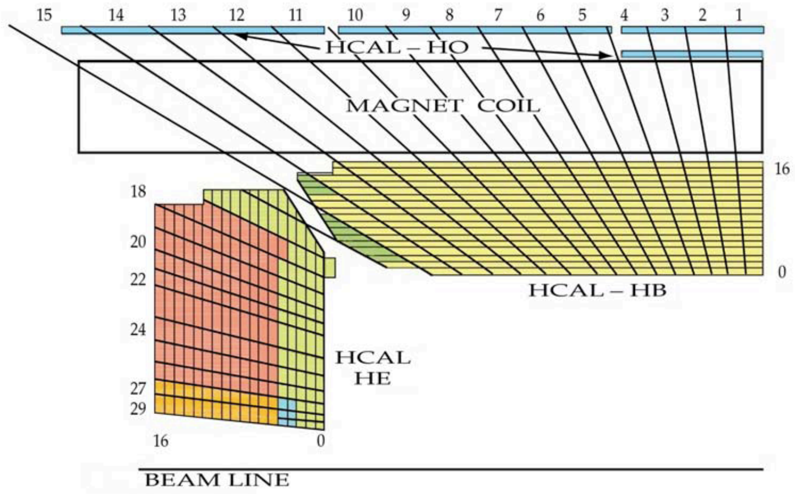
Sampling Iron-Scintillator

fwd: Cu or W + LAr

Granularity: 0.1 x 0.1

$$\frac{\sigma(\mathrm{E})}{\mathrm{E}} = \frac{0.45}{\sqrt{\mathrm{E}}} \oplus 0.013$$

CMS



Inside magnetic field

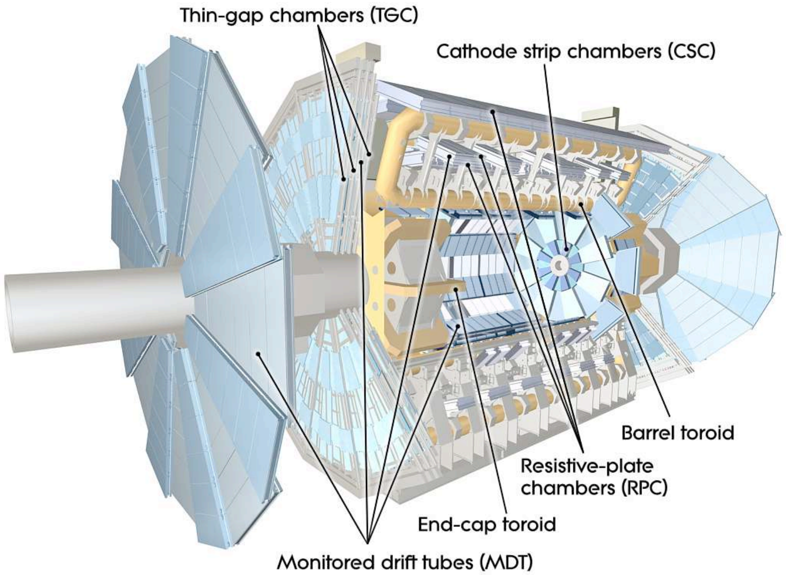
Sampling Brass-Scintillator

Granularity: 0.087 x 0.087

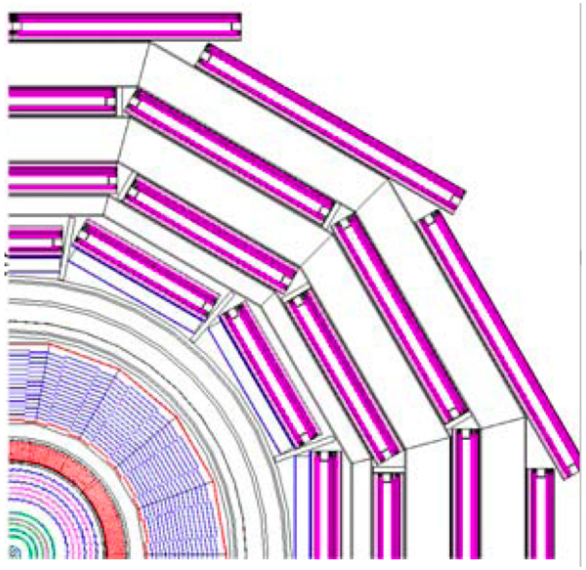
$$\frac{\sigma(\mathrm{E})}{\mathrm{E}} = \frac{1}{\sqrt{\mathrm{E}}}$$

Muon chambers

ATLAS



CMS



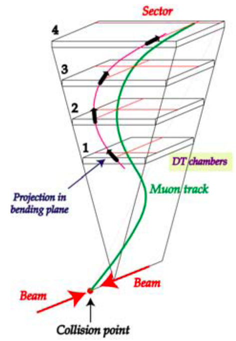
In strong toroidal magnets

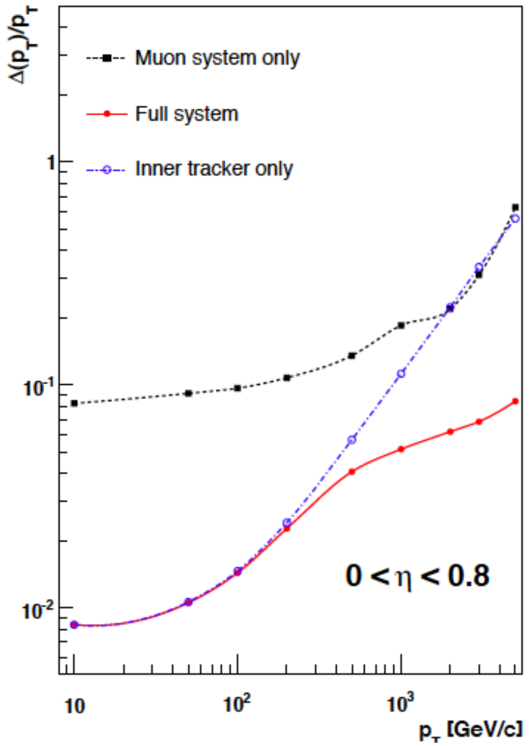
In iron return yoke

Both fast trigger chambers & precision chambers
Gaseous detectors and high sophisticated alignment system

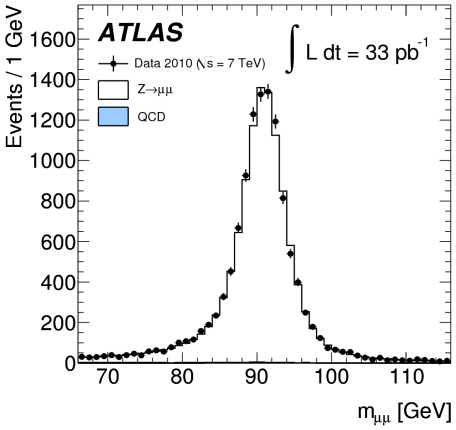
Muon momentum resolution

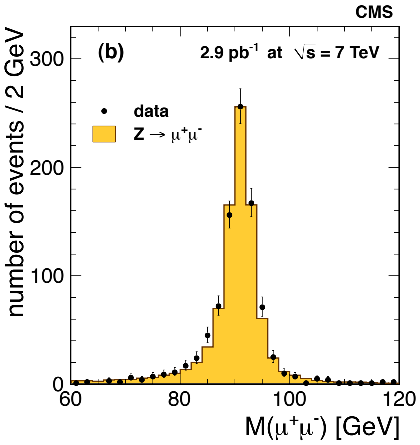
Stand – alone track finding/fitting in μ chambers
ATLAS: 3-4% (central) CMS: 10% resolution



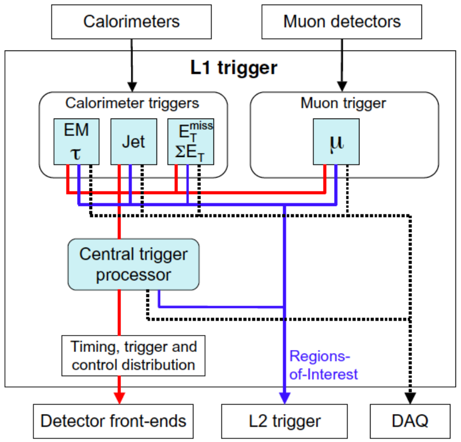


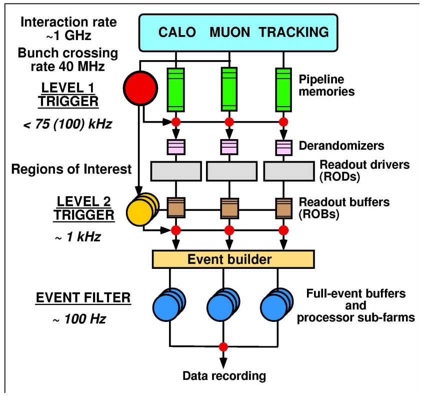
Identification & best resolution: combine ID & μ - chambers



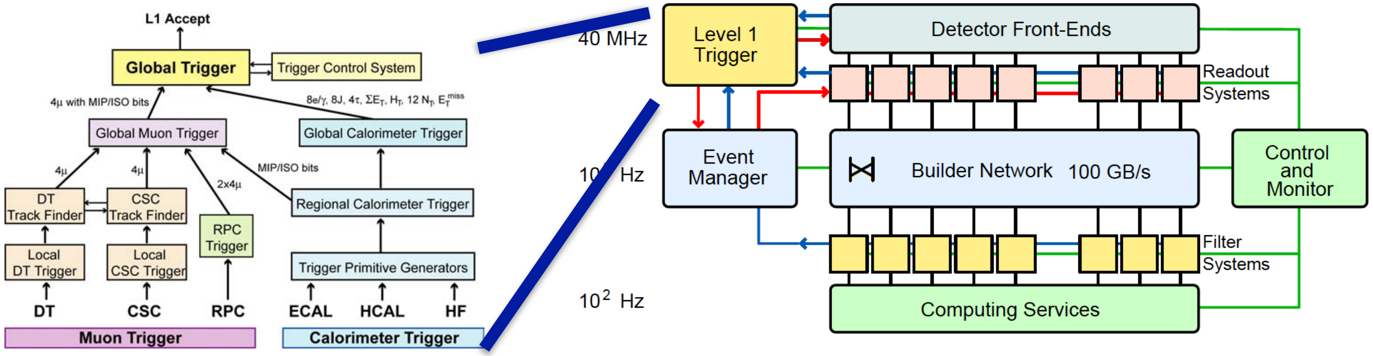


Trigger + DAQ





ATLAS:
‚region of interest‘



CMS:
Early merging of all regions no L2

L1 Trigger based on μ chamber & calorimeter
~ 200 – 400 Hz stored on disk

Comparing the ATLAS-CMS lay-out

	ATLAS ≡ A Toroidal LHC ApparatuS	CMS ≡ Compact Muon Solenoid
MAGNET (S)	Air-core toroids + solenoid in inner cavity (4 magnets) Calorimeters in field-free region	Solenoid Only 1 magnet Calorimeters inside field
TRACKER	Si pixels+ strips TRT → particle identification B=2T $\sigma/p_T \sim 3.8\text{x}10^{-4}\, p_T \oplus 0.015$	Si pixels + strips No particle identification B=4T $\sigma/p_T \sim 1.5\text{x}10^{-4}\, p_T \oplus 0.005$
EM CALO	Pb-liquid argon $\sigma/E \sim 10\%/\sqrt{E}$ uniform longitudinal segmentation	$PbWO_4$ crystals $\sigma/E \sim 2\text{-}5\%/\sqrt{E}$ no longitudinal segm.
HAD CALO	Fe-scint. + Cu-liquid argon (10 λ) $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$	Cu-scint. (> 5.8 λ +catcher) $\sigma/E \sim 100\%/\sqrt{E} \oplus 0.05$
MUON	Air → $\sigma/p_T \sim 10$ % at 1 TeV standalone (~ 7% combined with tracker)	Fe → $\sigma/p_T \sim 15\text{-}30\%$ at 1 TeV standalone (5% with tracker)

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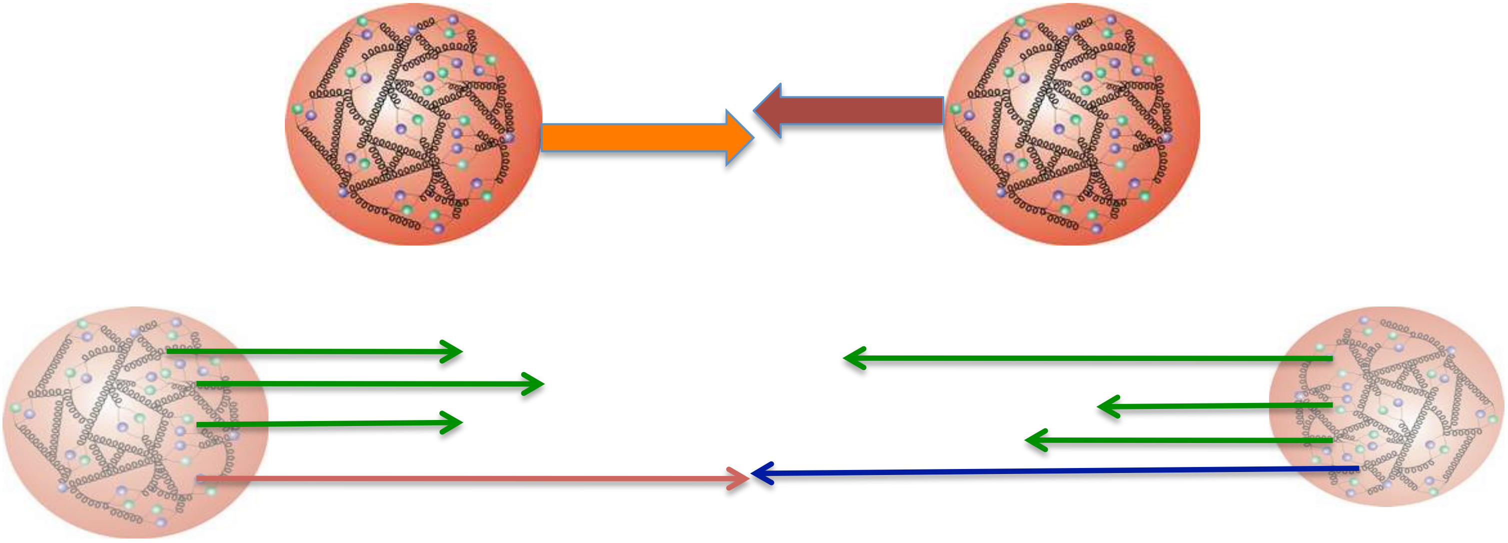
Standard Model @ Hadron Colliders

II. Some basics of pp - physics

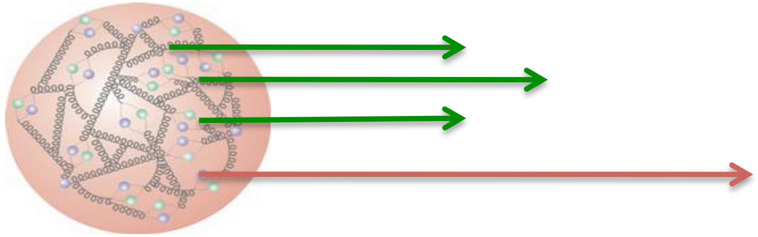
Reminder: how ‚protons‘ interact

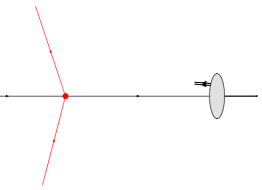


Proton scattering = scattering of quarks and gluons

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

Reminder: x, M





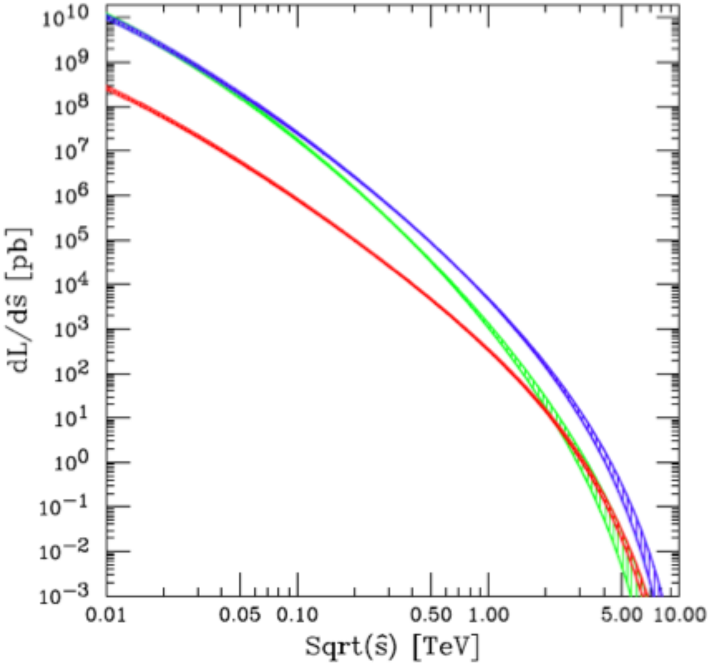
Stefan Gieseke - DESY MC school 09

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

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

‚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

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Rapidity a ‚natural' observable for consequtive branchings

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

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

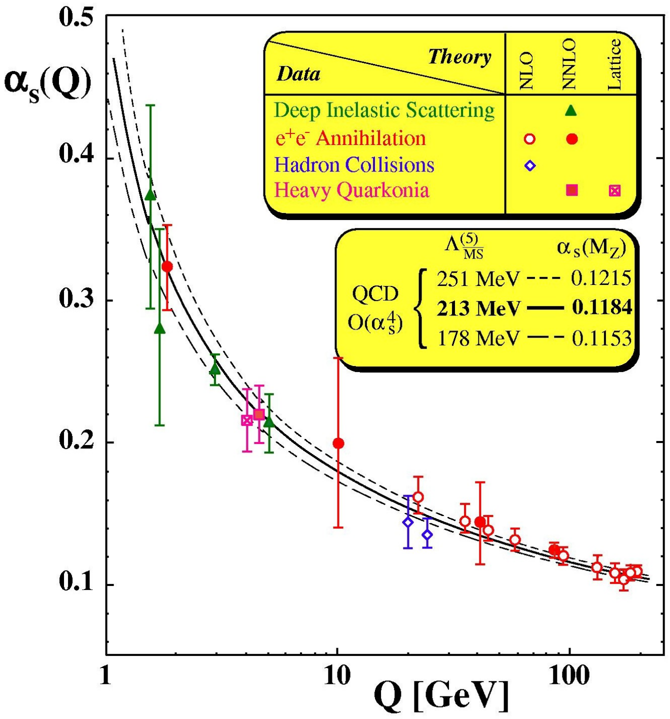
$$y \Longrightarrow y' = y + \frac{1}{2}\ln\left(\frac{1+\beta}{1-\beta}\right)$$

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

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

LHC a strong interaction collider

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‘

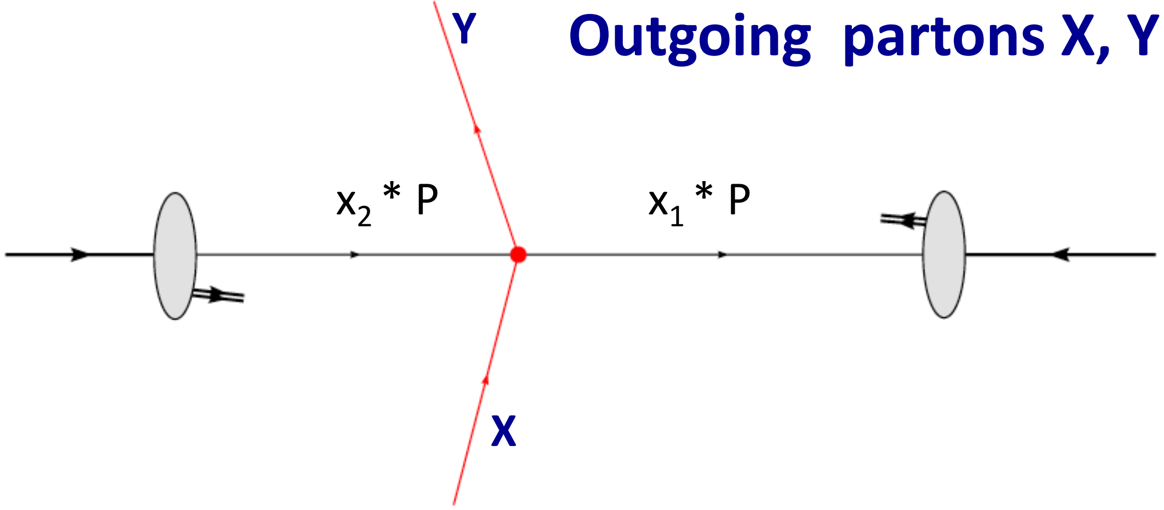
Basic limitation of theoretical description

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



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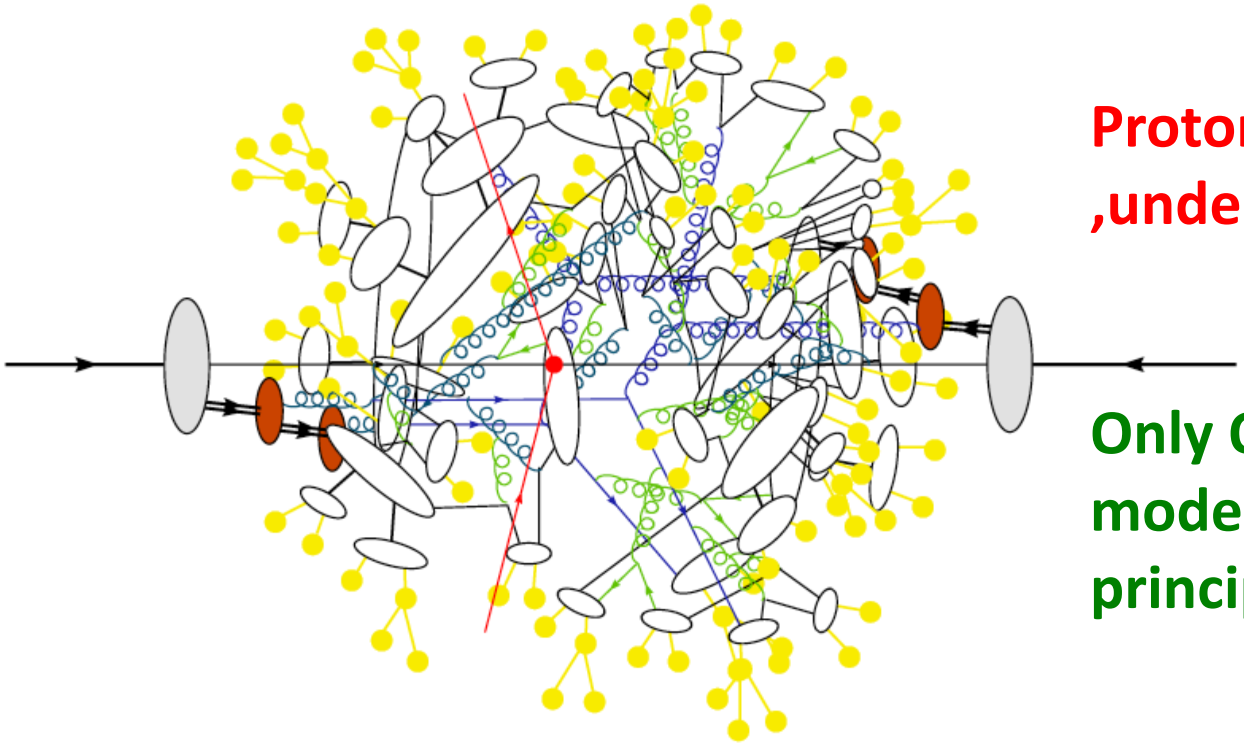
$$\sigma(\mathbf{p_1}(\mathbf{P_1}) + \mathbf{p_2}(\mathbf{P_2}) \to \mathbf{Y} + \mathbf{X} + \mathrm{Rest})$$

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

A more comprehensive picture



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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

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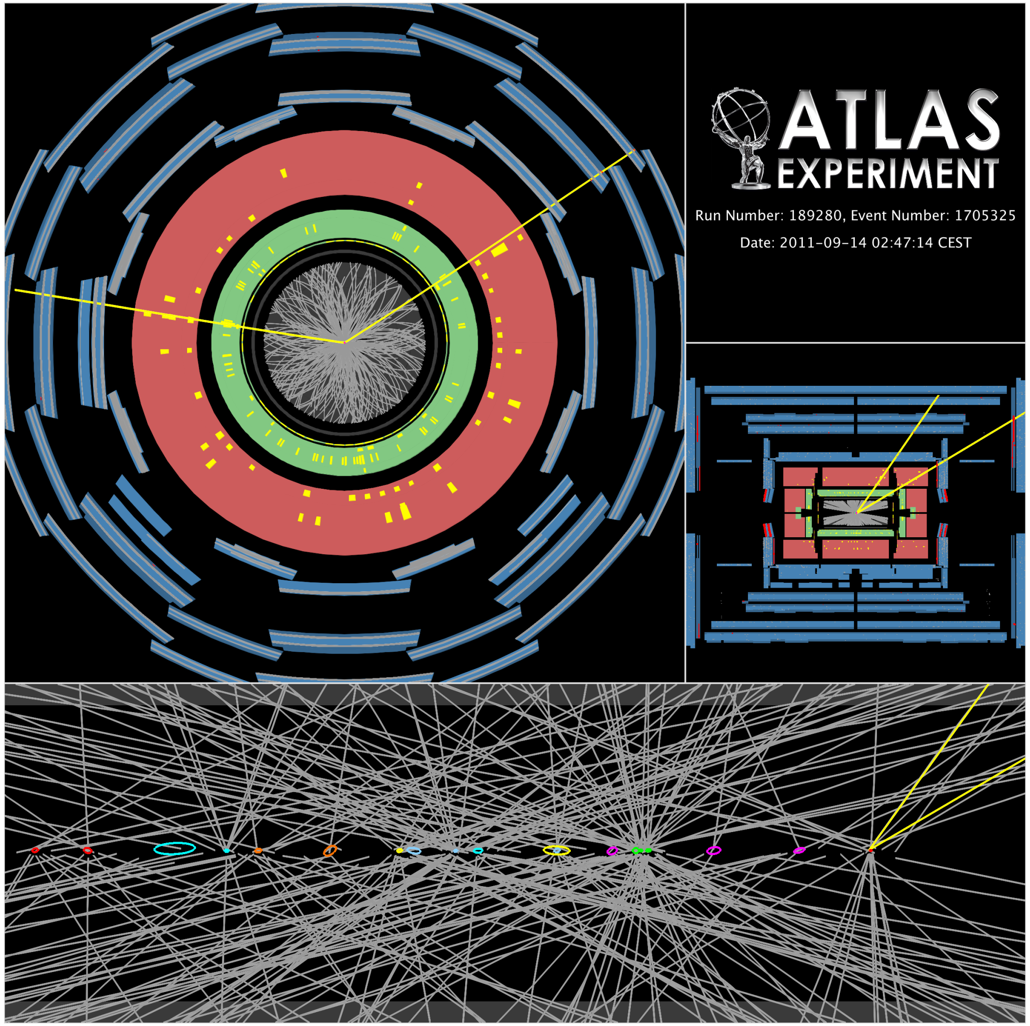

A lot of ‚isotropic‘ hadron production

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

Started with
qq → qq
Result: 1000 hadrons

Standard Model tests: Type I
Underlying event

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

$$= \int_0^1 \mathbf{dx_1} \int_0^1 \mathbf{dx_2} \underbrace{\sum_{\mathbf{f}} \mathbf{F_f}(\mathbf{x_1})\mathbf{F_{\bar{f}}}(\mathbf{x_2})}_{\text{Take from previous measurements}} \underbrace{\sigma(\mathbf{q_1}(\mathbf{x_1 P}) + \mathbf{q_2}(\mathbf{x_2 P})}_{\text{Well known process}} \rightarrow \mathbf{Y} + \mathbf{X} + \mathbf{Rest})$$

Measure underlying event

Standard Model tests: Type II
Parton distribution function

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

$$= \int_0^1 \mathbf{dx_1}\int_0^1 \mathbf{dx_2}\sum_{\mathbf{f}}\mathbf{F_f}(\mathbf{x_1})\mathbf{F_{\bar f}}(\mathbf{x_2})\underbrace{\sigma(\mathbf{q_1}(\mathbf{x_1P})+\mathbf{q_2}(\mathbf{x_2P})\to \mathbf{Y}+\mathbf{X}}_{\text{Well known process}}\underbrace{+\mathrm{Rest})}_{\text{Take from models}}$$

Measure parton
Distribution function

Standard Model tests: Type III
The hard scatter process

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

$$=\int_0^1 \mathbf{dx_1}\int_0^1 \mathbf{dx_2}\underbrace{\sum_{\mathbf{f}}\mathbf{F_f}(\mathbf{x_1})\mathbf{F_{\bar f}}(\mathbf{x_2})}_{\text{Take from previous measurements}}\underset{\substack{\uparrow\\ \text{Measure hard process}}}{\sigma(\mathbf{q_1}(\mathbf{x_1P})+\mathbf{q_2}(\mathbf{x_2P})}\rightarrow \mathbf{Y}+\underbrace{\mathbf{X}+\mathrm{Rest})}_{\text{Take from models}}$$

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Standard Model @ Hadron Colliders
III. Soft QCD interactions

Measure underlying events

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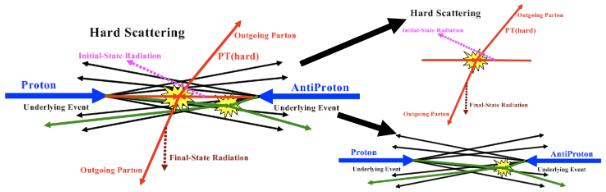
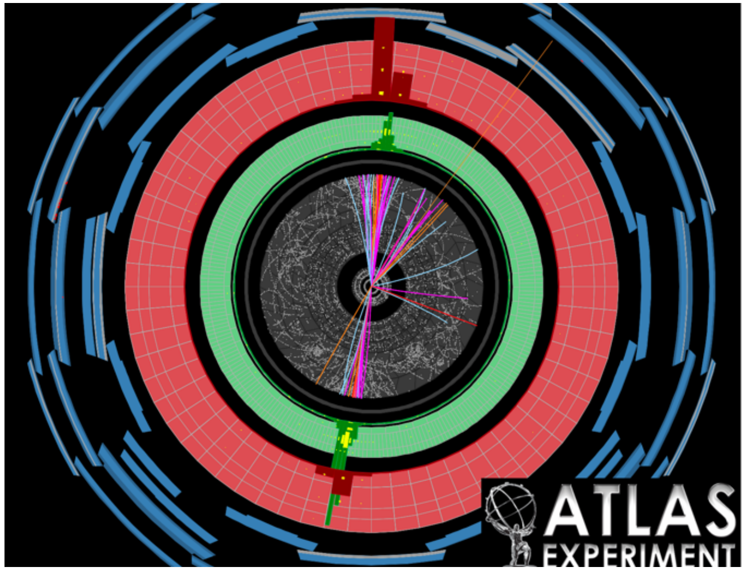
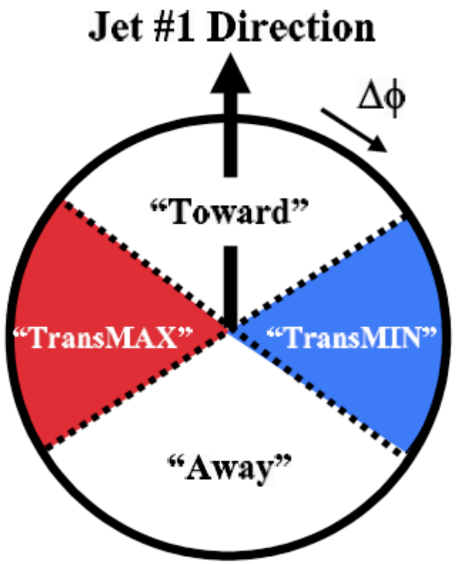
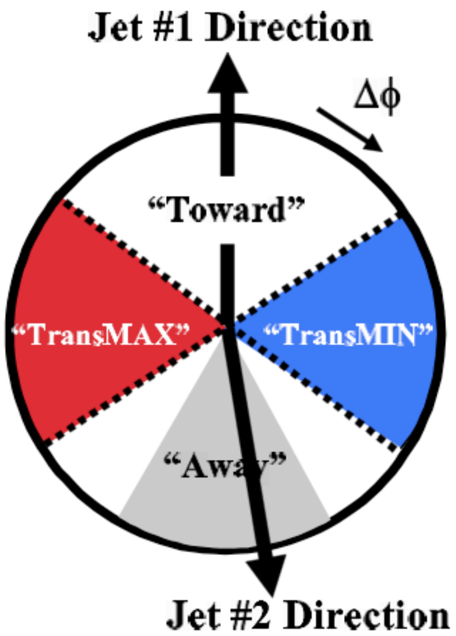


Basic idea: find region not affected by hard scatter







Select 2 back-to-back jets in plane transverse to beam

→ define four quadrants

→ assume transverse quadrants little affected by jets

Particle distributions in UE events

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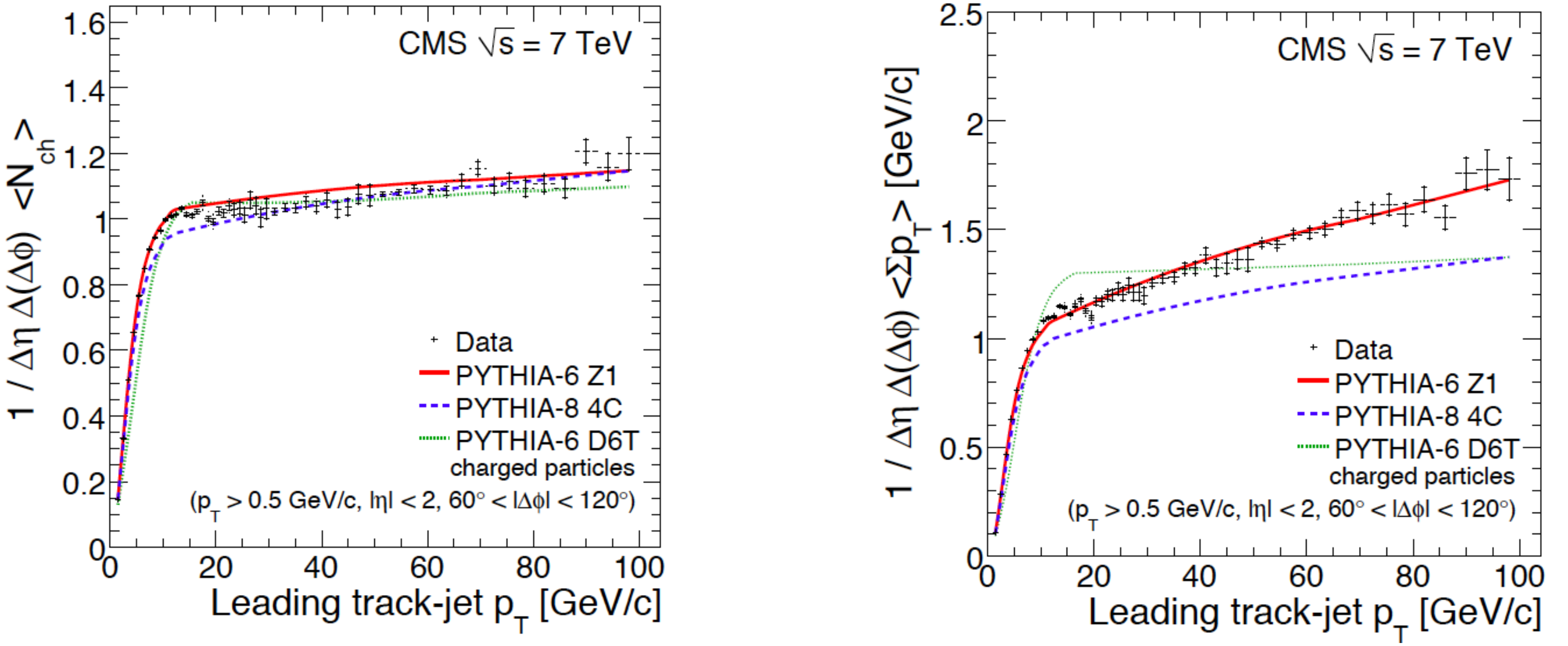
Note: only possible if no pile – up events (low luminosity)

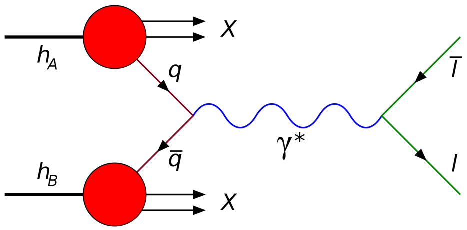


Ideally: flat with jet p_T

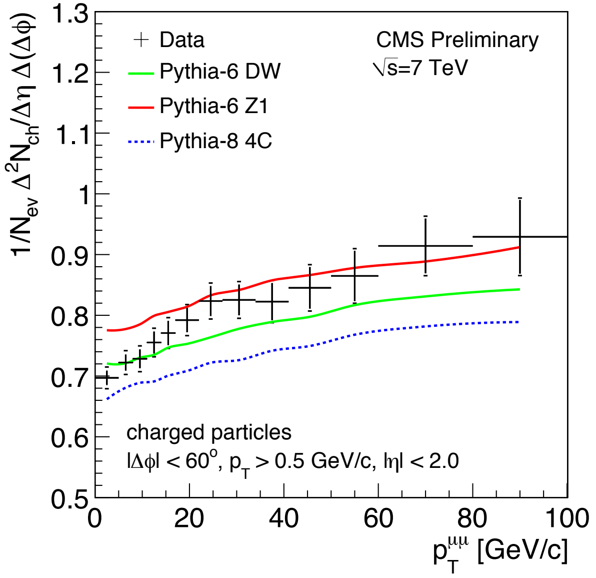
➔ cross talk from hard jets?

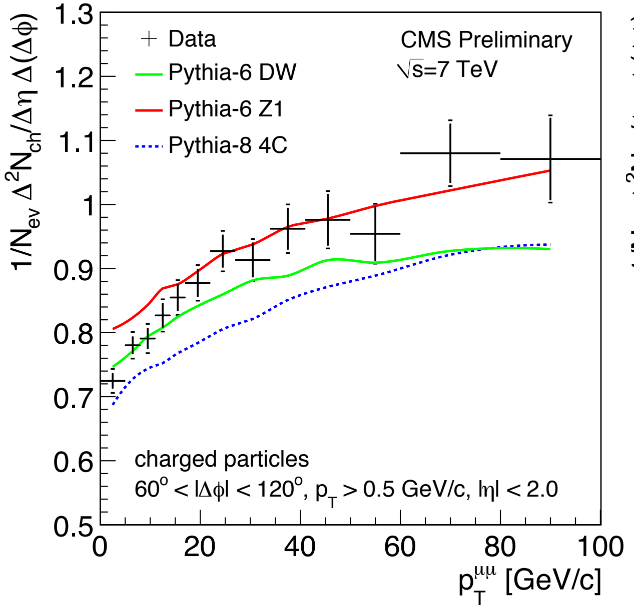
Can be reasonably described by models

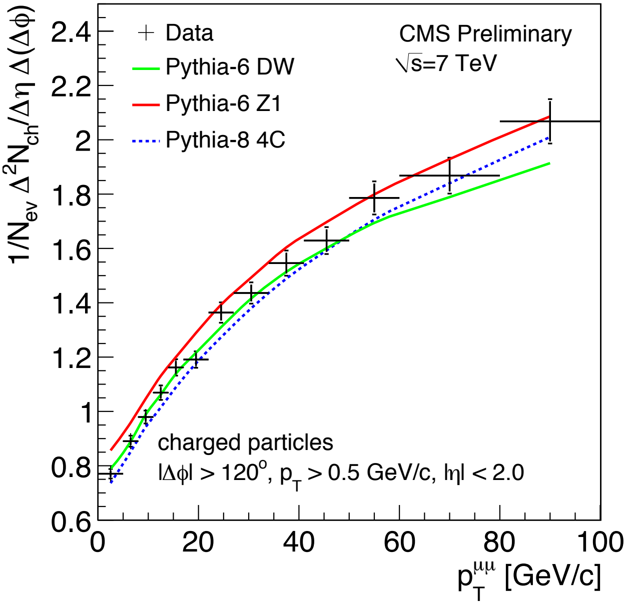
UE in Drell – Yan events



Particle flow in pp →$\mu^+\mu^-$ events
Colour – neutral ➔ no X-talk







But: colour flow different from most LHC processes

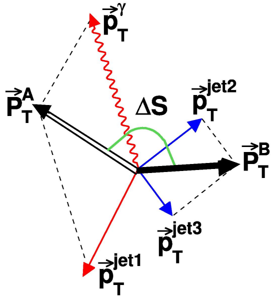
➔ measurements to test and constrain models

Will a precise and consistent modelling ever be possible?

Double parton interactions

Use photon as a probe

Select events with (2) 3 jets

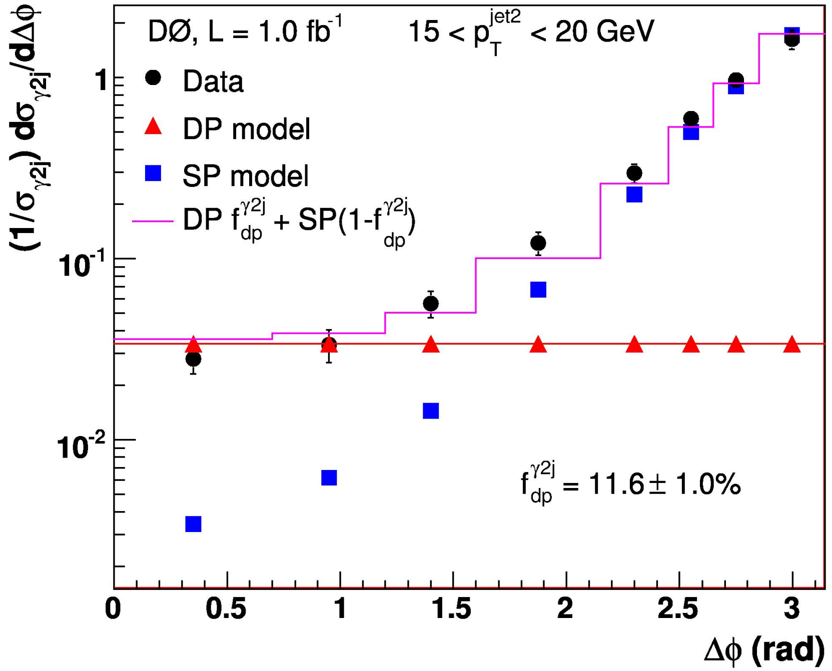


Combine

a. γ + hardest jet

b. 2 other jets

➔ Δϕ between momenta



QCD bremsstrahlung: correlation

Dble parton interaction: flat

Data show correlations but also a flat contribution

Comparison with models: ~ 10% double parton interactions

➔ Additional constraints on models

Pile up: the prize of high luminosity

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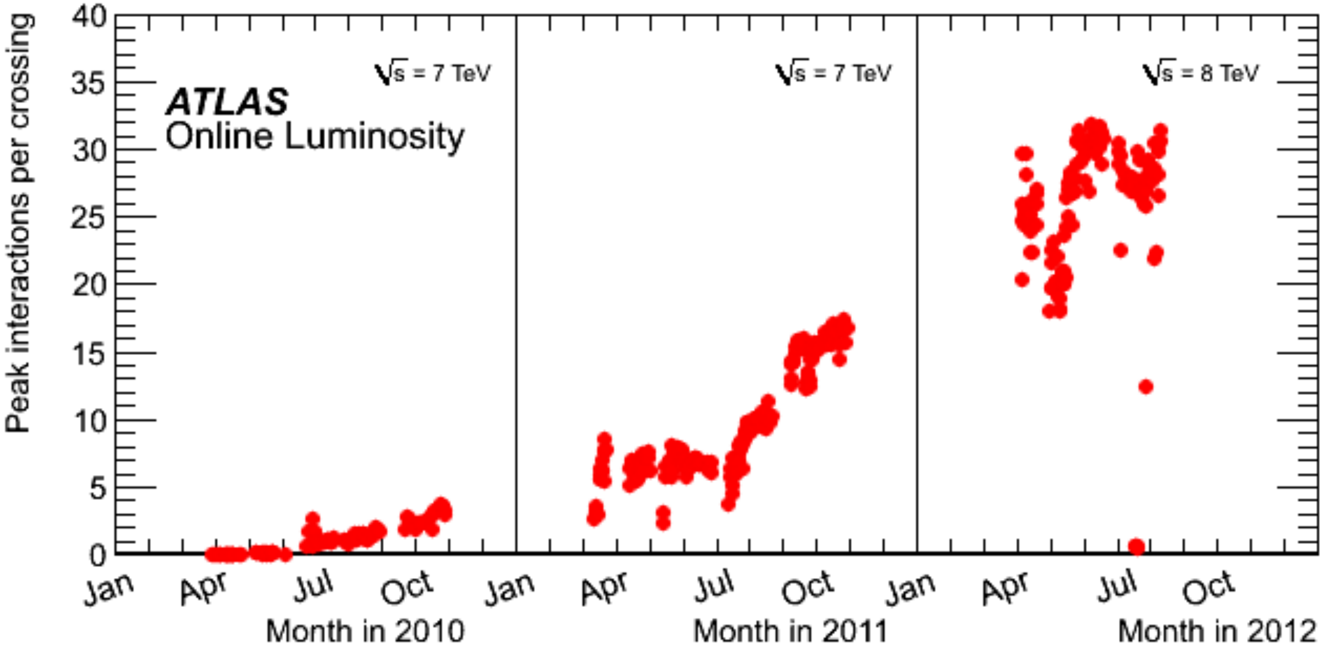


Number of interactions/bunch Xing:

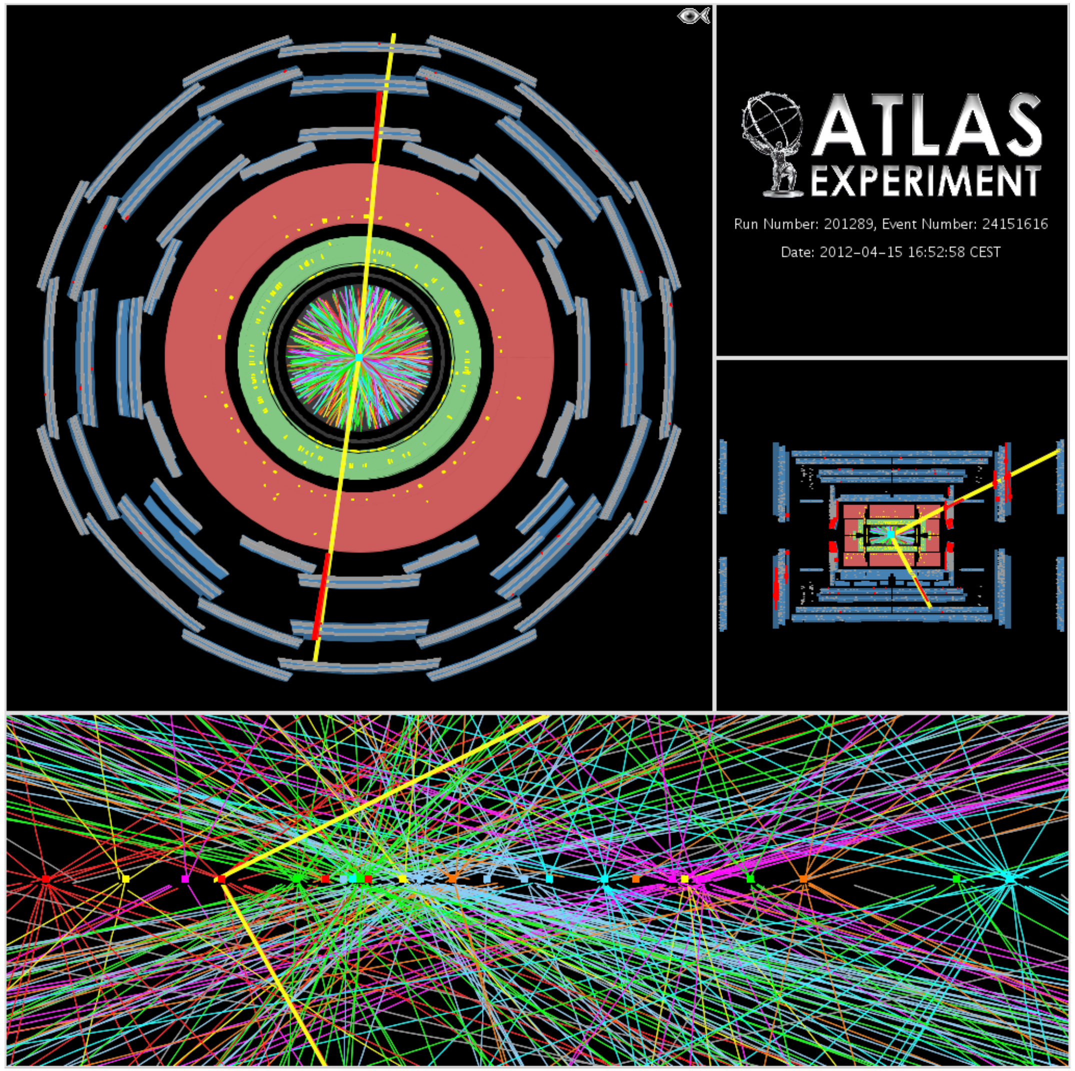
- linear with luminosity

- slowly increasing with energy

- proportional 1/bunch Xing distance

currently: 50 nsec, future: 25 nsec

Pile up: the price of luminosity



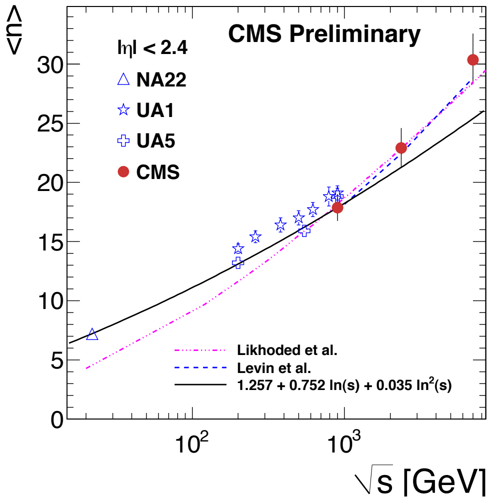
Z^0 with 25 reconstructed vertices

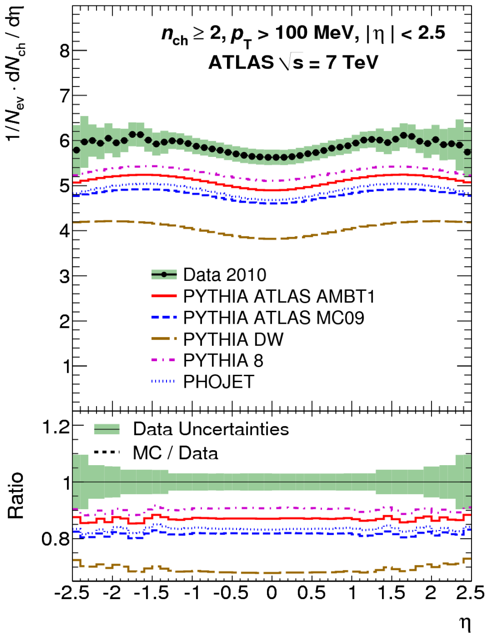
Pile up events: multiplicity

Pile – up events can be measured:

pp – interactions without trigger bias ‚minimum bias events‘

At 7 TeV: 6 charged particles per $|\Delta\eta|$ = 1, mostly low p_T



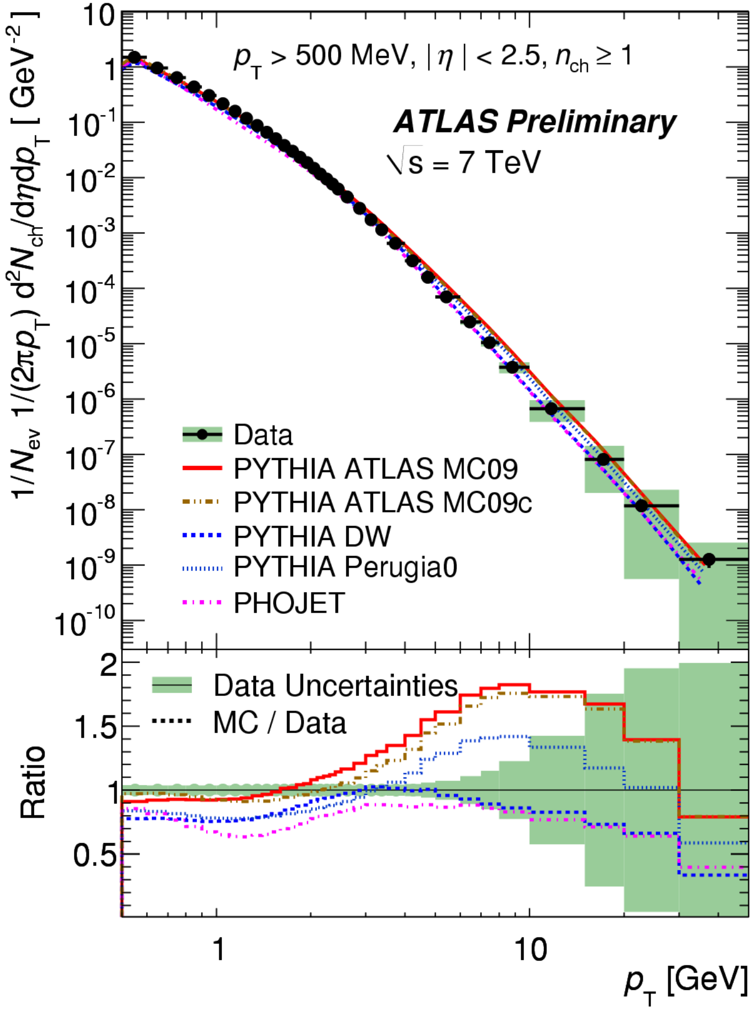


Models have deficiencies

Rather isotropically distributed

30 pile – up events ➔ 1000 charged particles in tracker volume

Minimum Bias events: pT



Most particles low transverse momentum

➔

isotropic contribution to hard processes

‚noise‘ of ~ 20 - 30 GeV/bunch Xing

Significant effect on object reconstruction

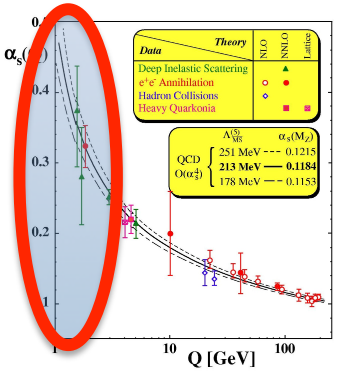
Modelling ‚soft interactions‘

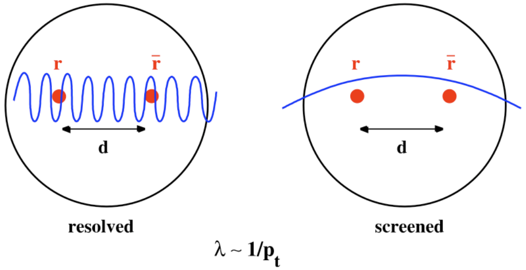
Minimum bias + underlying events:

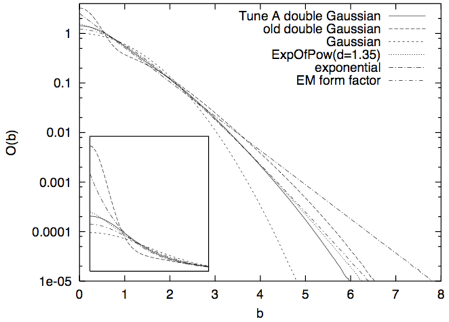
Measured in special environment

Extrapolate to all conditions:

try to model applying several ad – hoc concepts

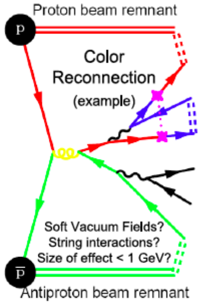






Overlap of protons

Colour screening



Colour reconnection

Challenging! Only an approximate description possible!

Parton distribution functions

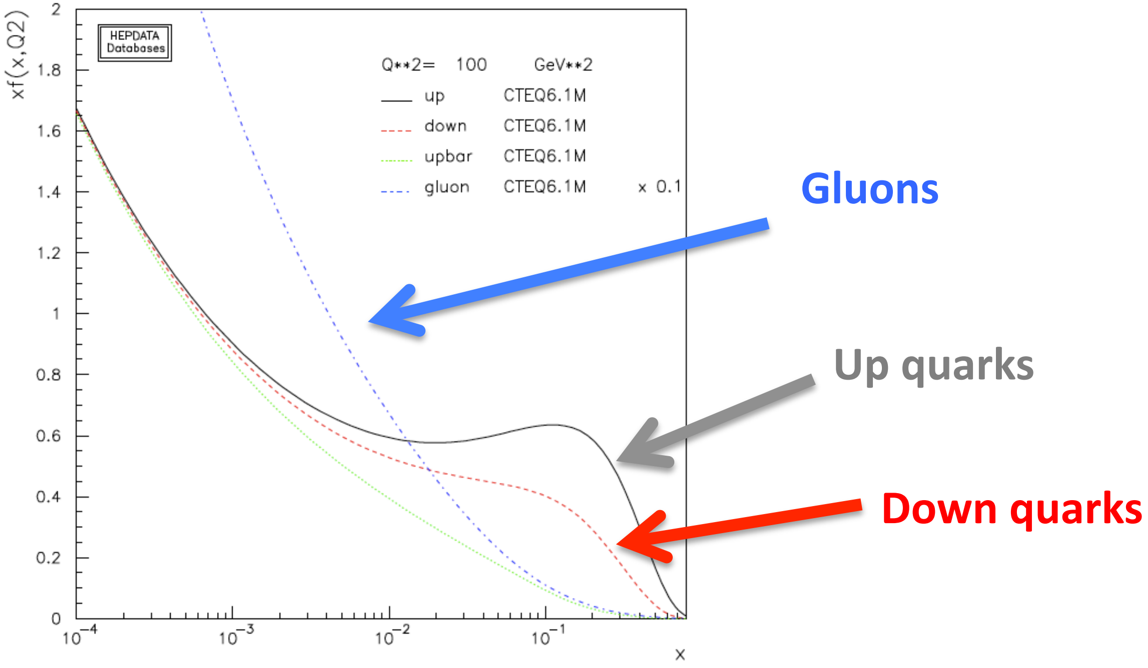
Energy fractions of different kinds of partons f in proton

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

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

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

Just one of several pdf parametrisations



Gluons

Up quarks

Down quarks

Significant uncertainties

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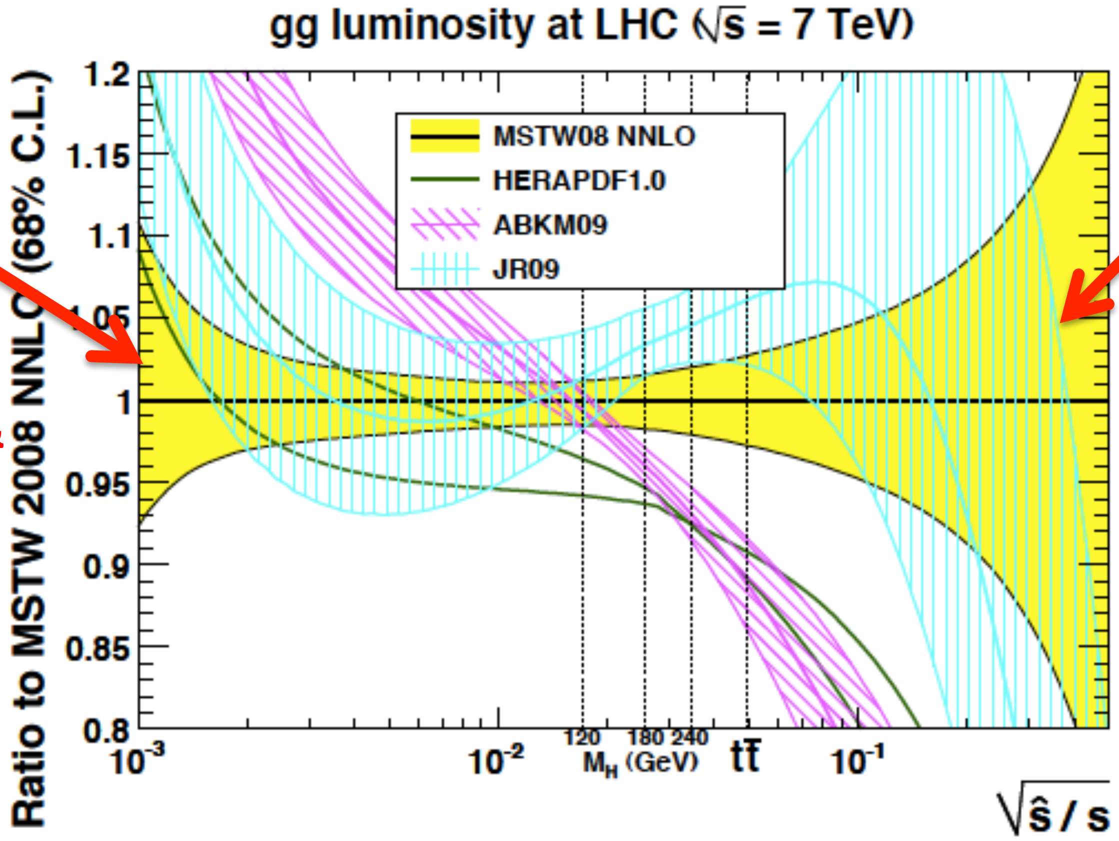
G.Watt



low x:
many gluons
➔ Theoretical &
experimental
uncertainties

High x:
few gluons
➔ Large
uncertainty

LHC will allow some self - calibration

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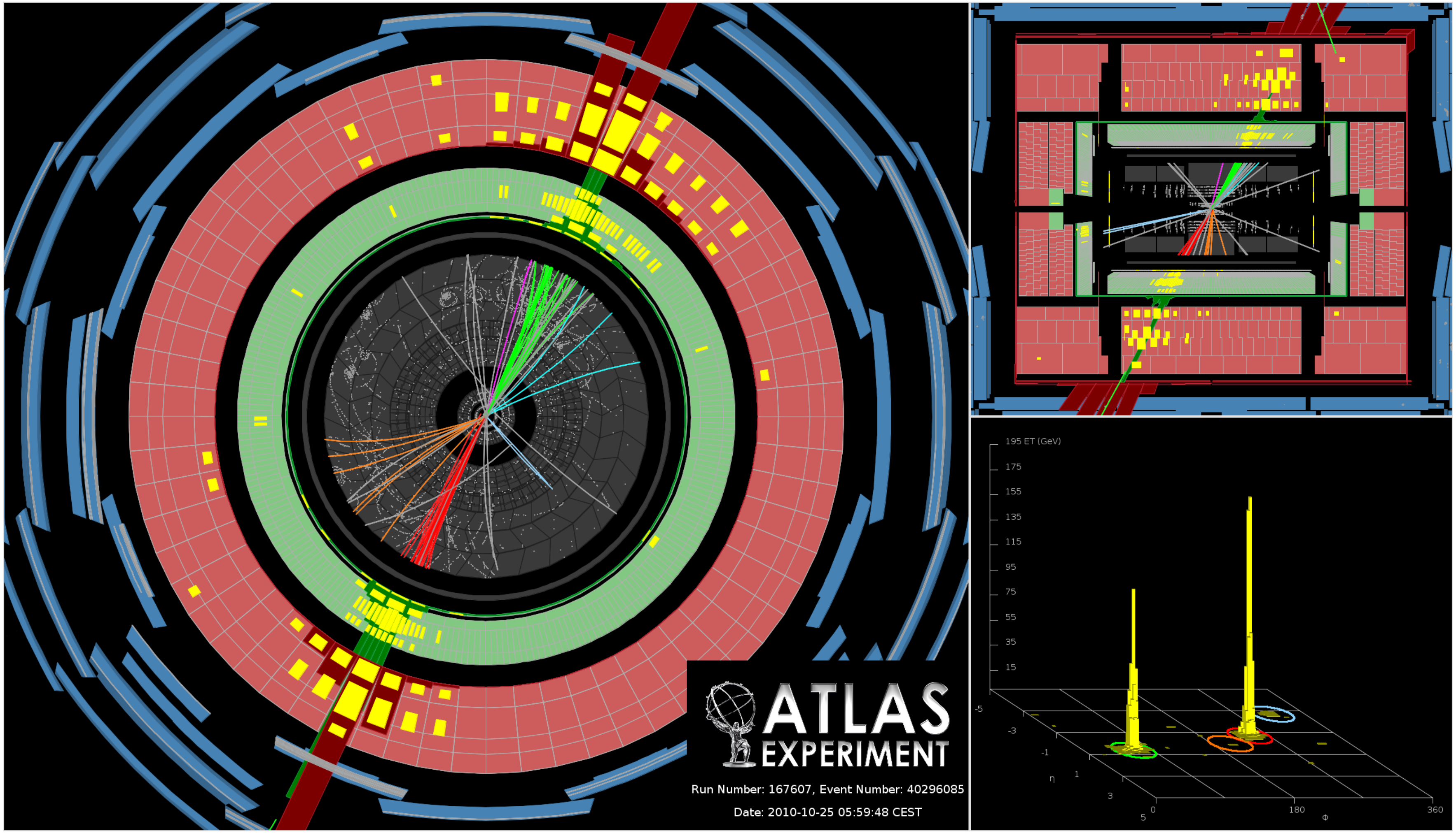
Standard Model @ Hadron Colliders
IV. Hard QCD interactions - Jets

Hard interaction: Jets



Run Number: 167607, Event Number: 40296085

Date: 2010-10-25 05:59:48 CEST

Jets are universal

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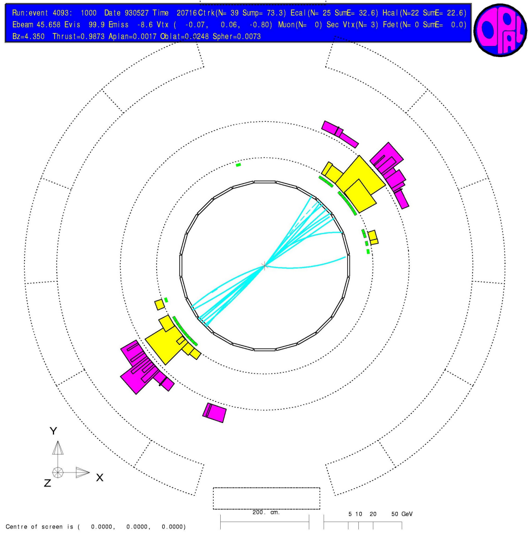
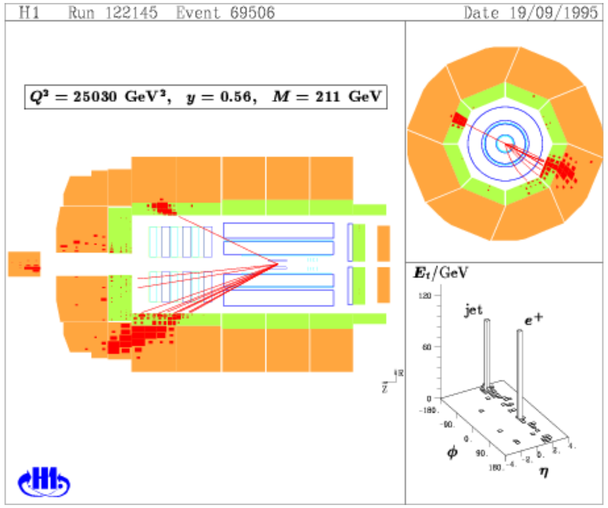
$e^+ e^-$ collisions



e p collisions

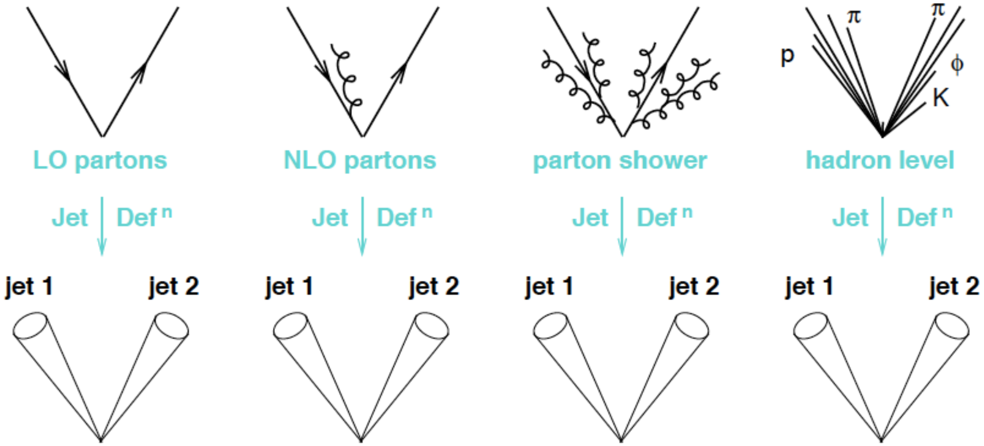


Jets: representative of quarks and gluons

- ➔ stringent test of theory
- ➔ experimenal challenge: extract partons from 1000 hadrons
- ➔ experimentally attainable

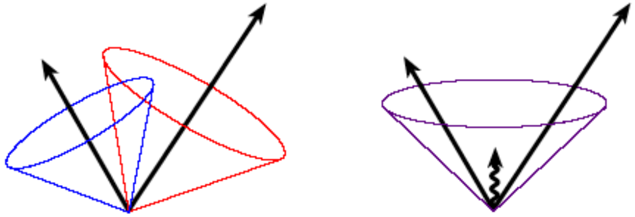
  direction and energy + (sometimes) parton flavour

How to find a jet ?

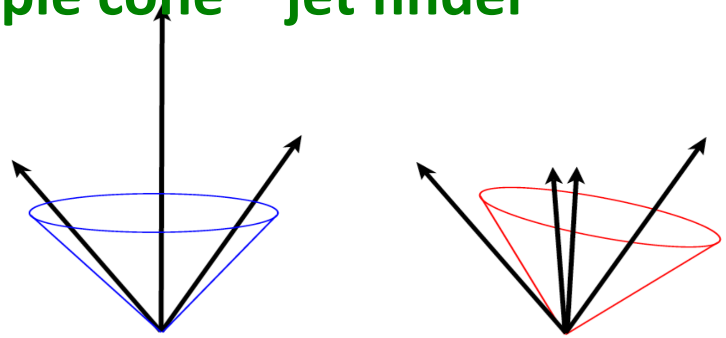


Unambiguous connection to underlying partons ➔ Comparison to theory

Not so straight – forward: example cone – jet finder



Low momentum ‚infrared' particle changes jets



Two ‚collinear' particles change jets

Sequential jet finder

‚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

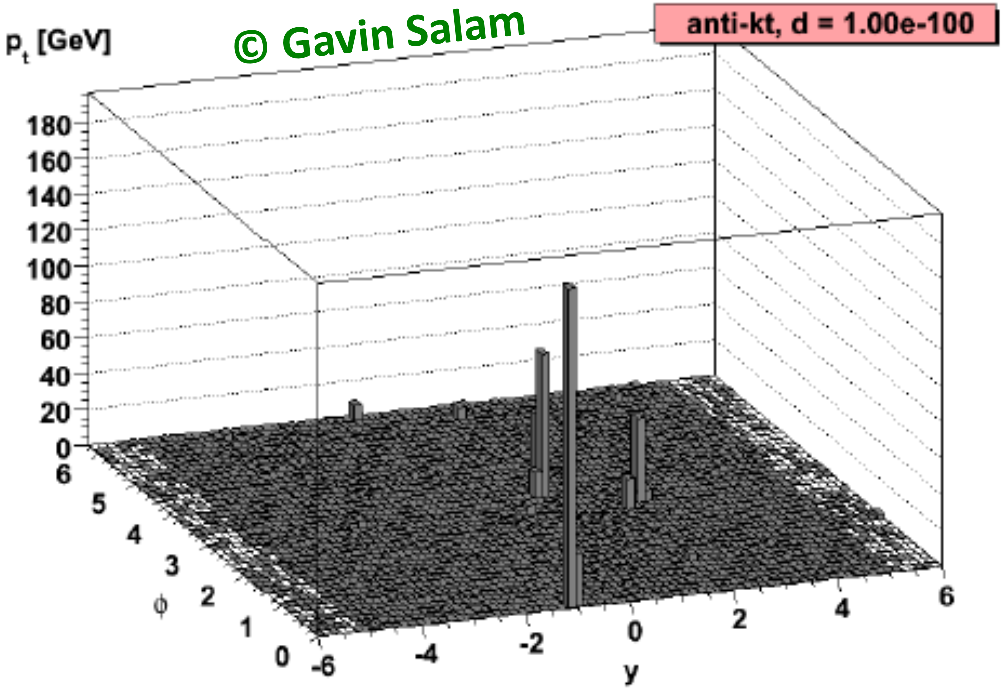
IF NO:

4 Jet found: sum of all associated particles

Favoured jet finding at LHC: ‚Anti – kt‘

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

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



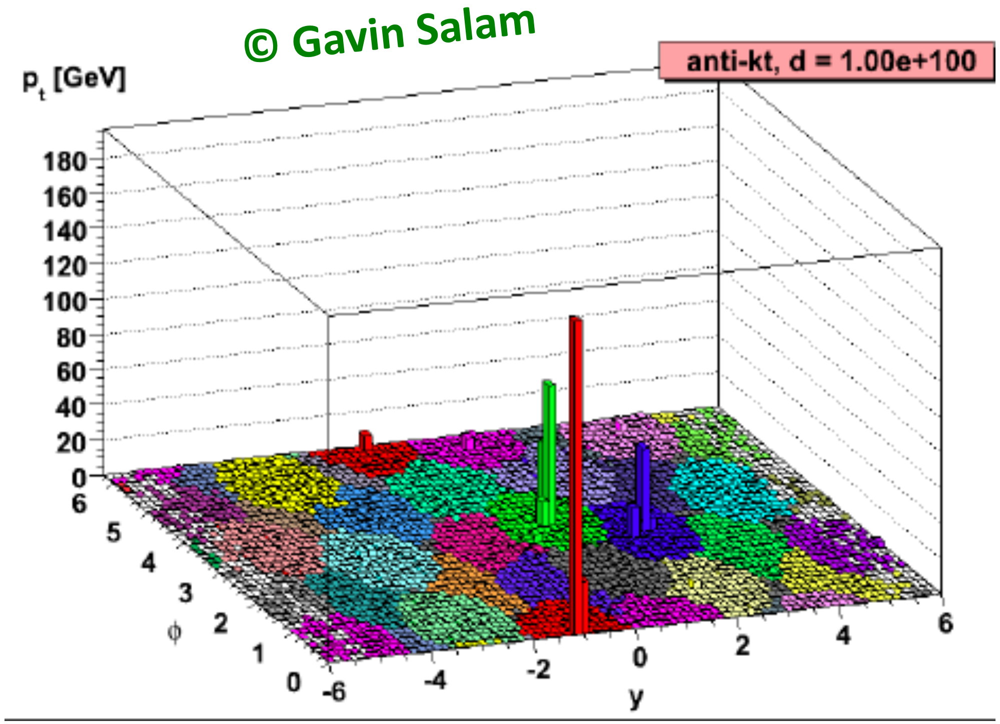
Infrared + collinear safe

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

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

Low p_t, close by particles assigned to seeds

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

In a nutshell:

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