QCD Studies at the LHC

Klaus Rabbertz, University of Karlsruhe, CMS

Some Search at LHC

Why my observation channel is important, unique, complimentary, the most promising ...

What to look for ...

How to select the signal events ...

What NOT to look for: QCD Background!

What are the systematic uncertainties ...

How good is the signal to noise ratio ...

Summary

Somehow the general outlay of many LHC talks ... :-)

Real Outline

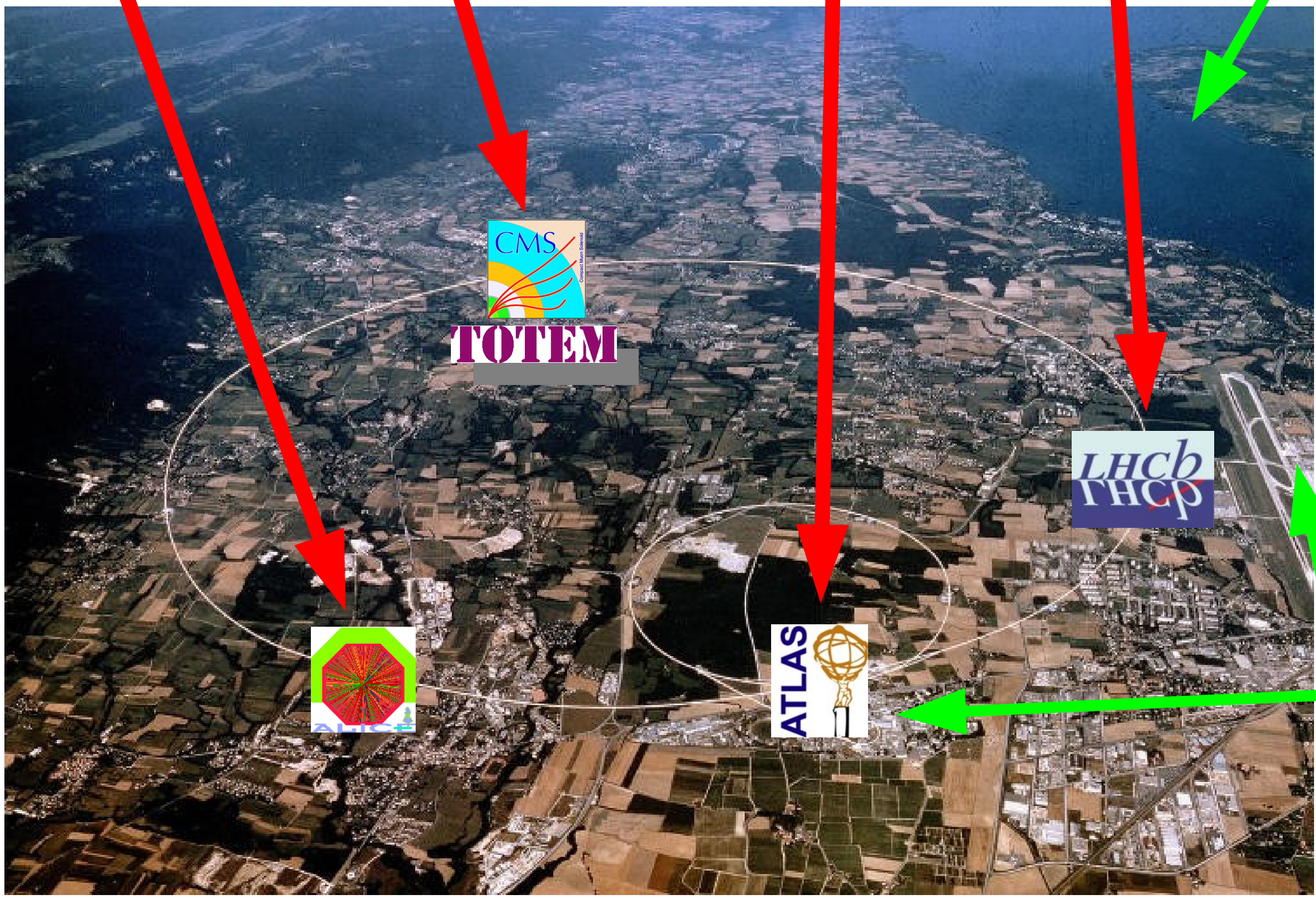
- Warming up
  - The LHC
  - The Experiments
  - Possible Commissioning Scenario
- Selected Topics (Personally biased → CMS, Start-up Physics)
  - High p_T Jet Cross Section & PDFs
  - LHC Standard Candle
  - Event Shapes (Time permitting)
- Outlook

I don't have to convince <u>this</u> audience of the importance of QCD ...

The Large Hadron Collider

Four interaction points with the experiments: **Lake Geneva**

ALICE **CMS/TOTEM** **ATLAS** **LHCb**



Geneva Airport

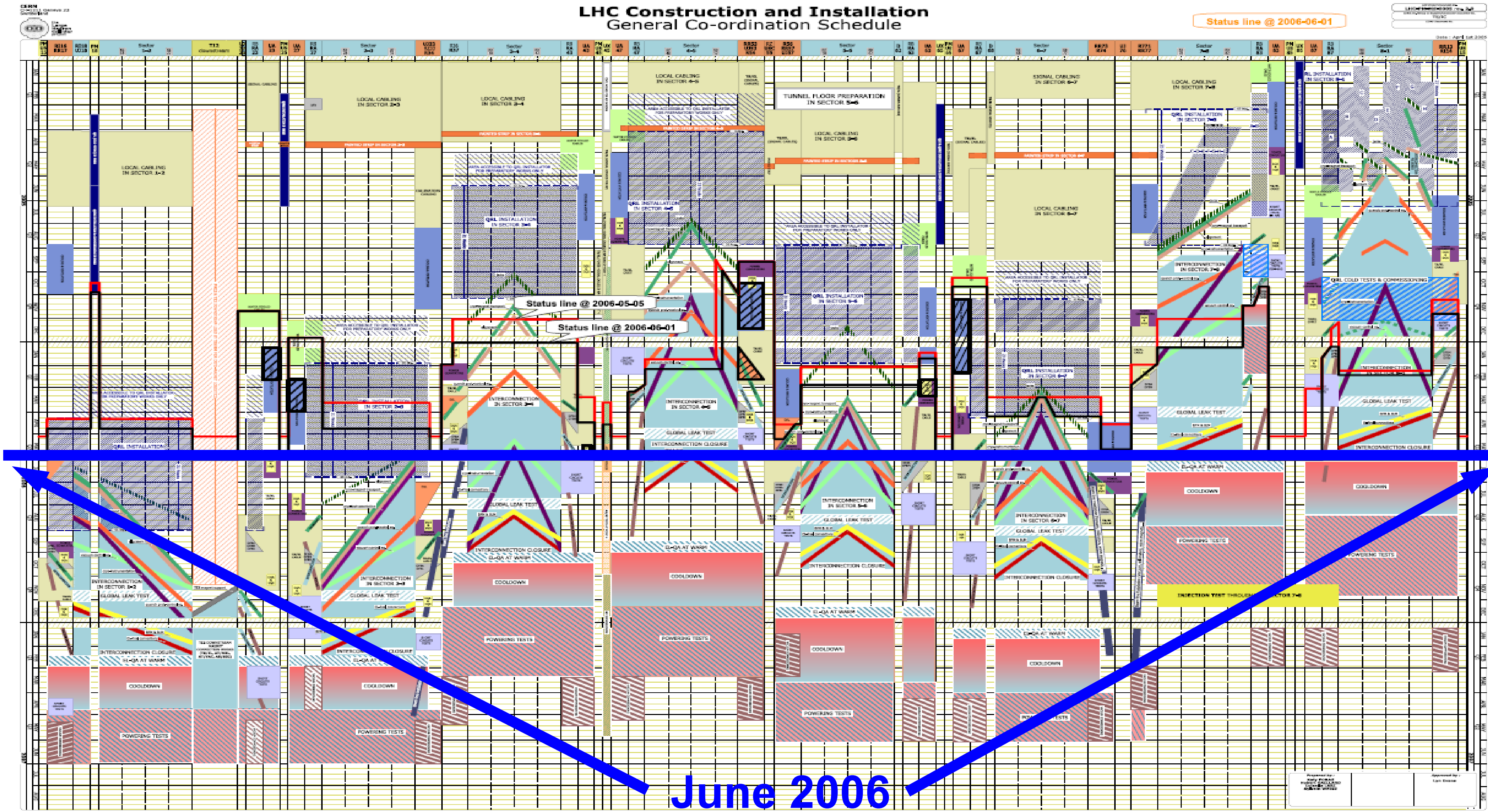
CERN Meyrin Site

LHC Design Parameters:

	pp	AA
Energy/Nucleon/TeV:	7.0	2.76
Bunch separation/ns:	25	100
Design Luminosity/$cm^{-2}m^{-1}$:	10^{34}	10^{27}
Number of bunches:	2808	592
No. of particles/bunch:	$1.15 \cdot 10^{11}$	$7.0 \cdot 10^{7}$

All pictures and schematics pp. 4 – 16 are taken from CERN or the experiments!

LHC Construction Schedule



LHC Installation (1/2)

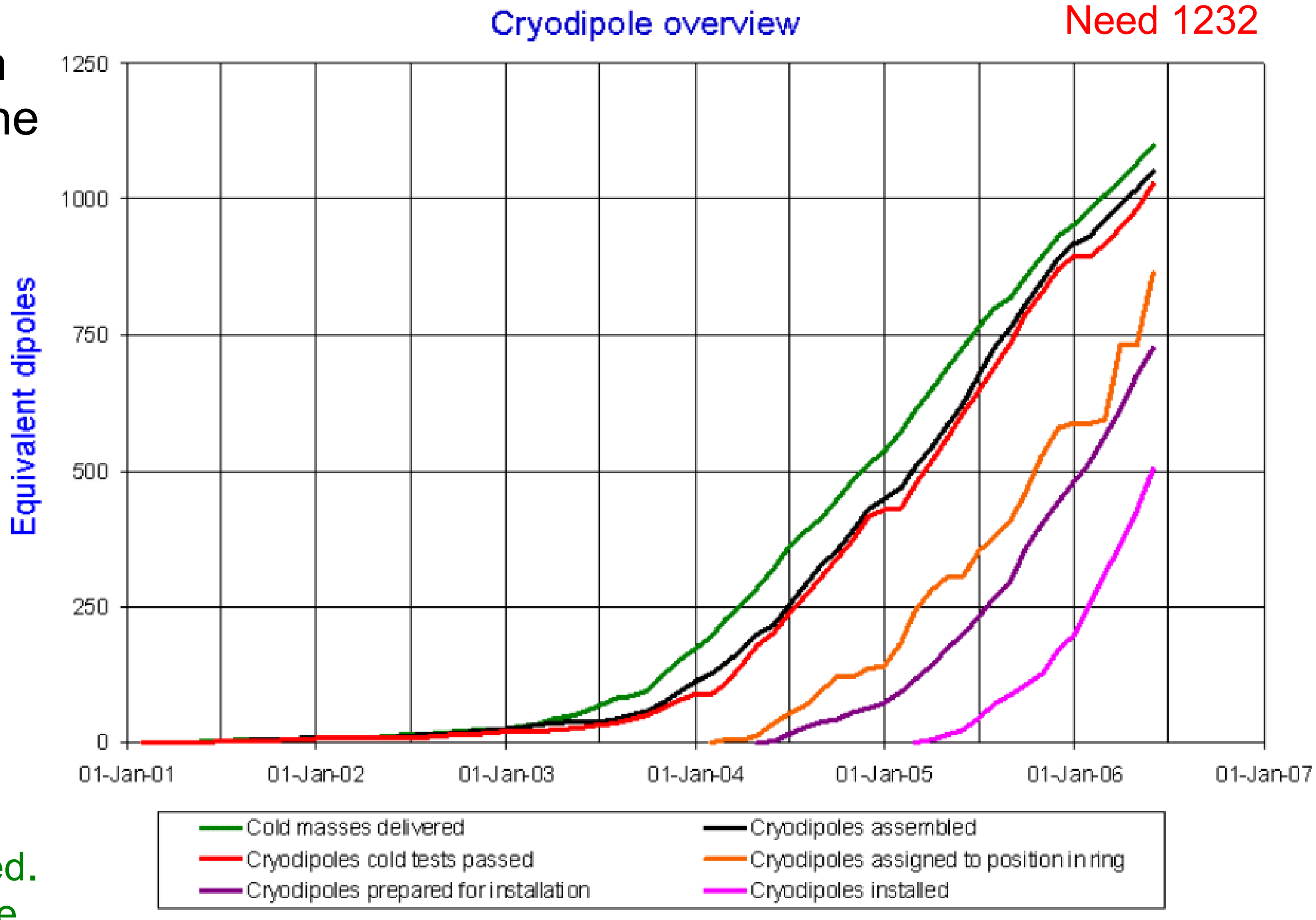
LHC Installation (2/2)

LHC Dipoles

06.06.2006: Shown by R. Bailey from the

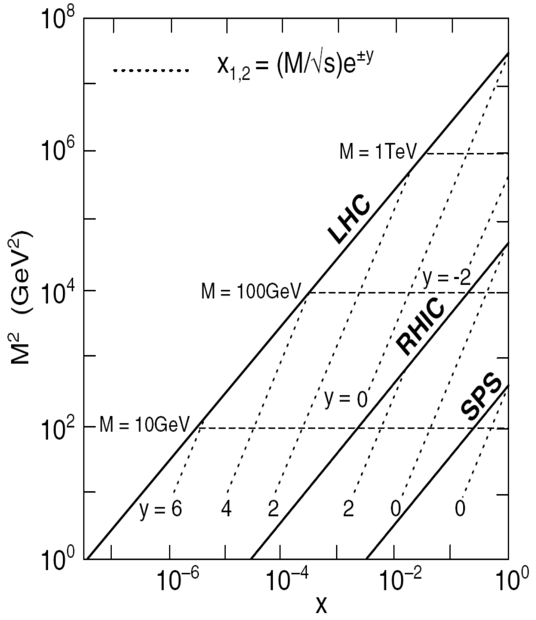
LHC Progress Dashboard

Need 1232



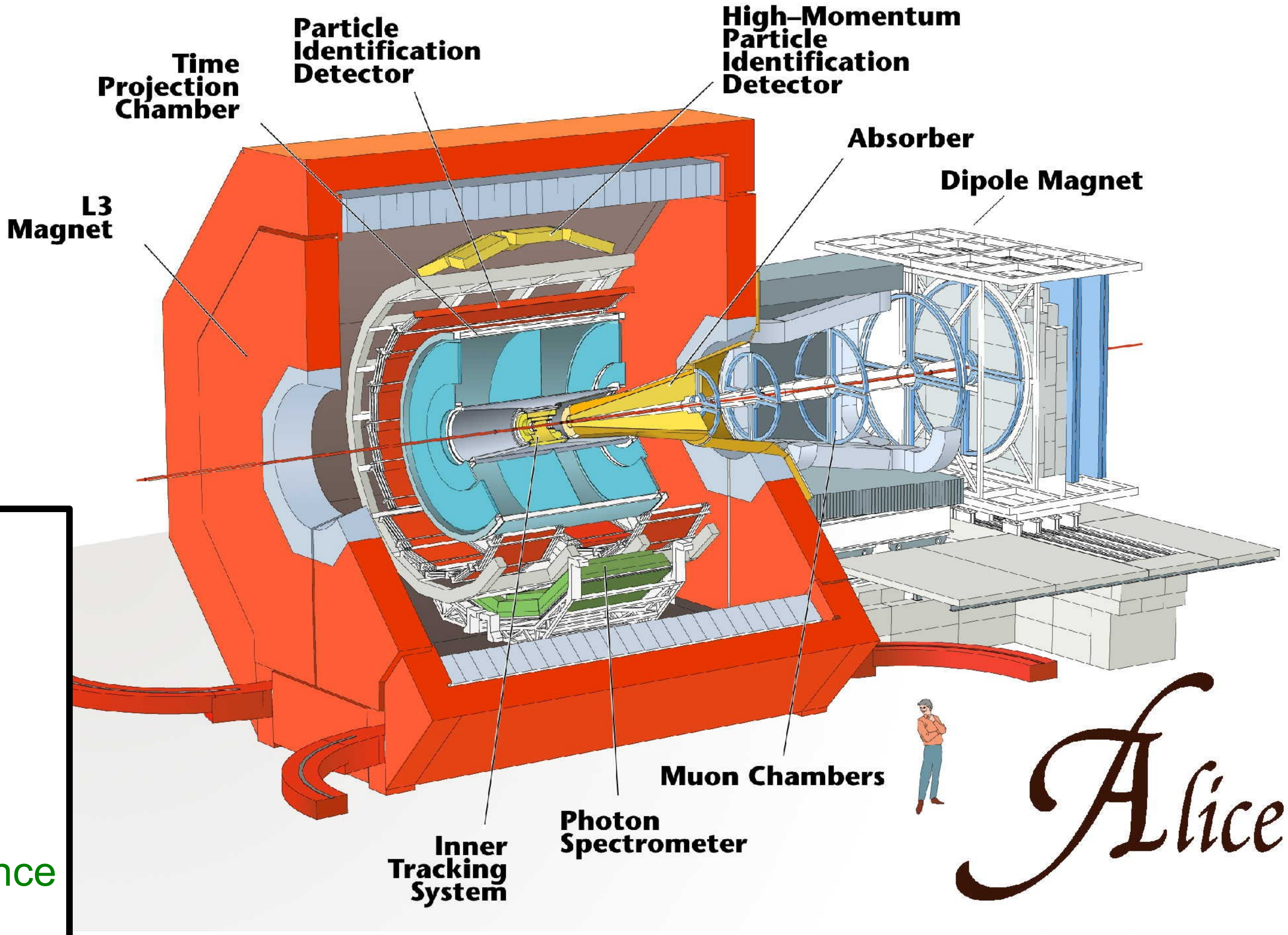
Due to problems with the cryolines in the beginning the dipole installation was delayed. Now we are just in time ...

The ALICE Detector

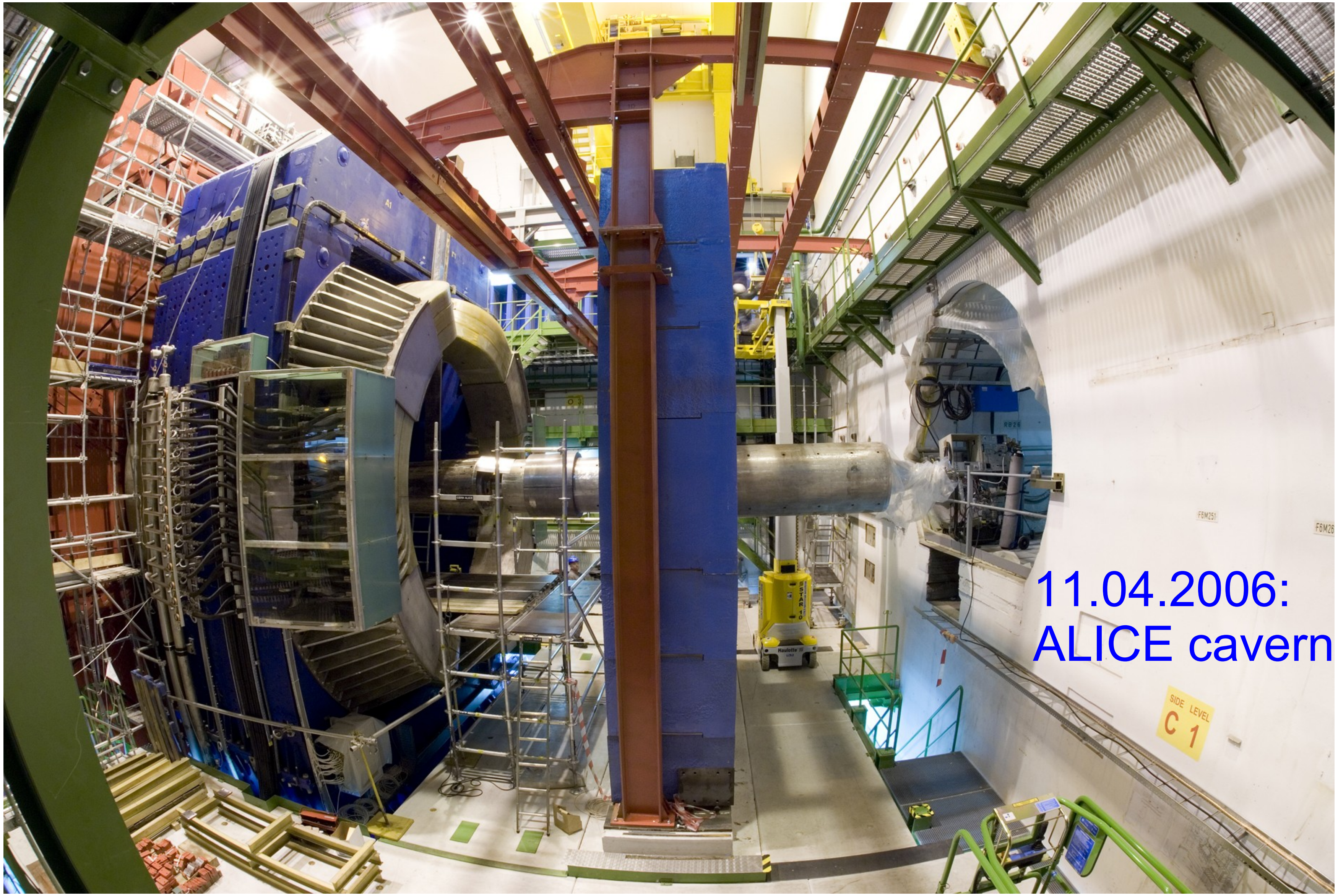


General purpose heavy-ion experiment:
Study of strongly interacting matter and the quark-gluon-plasma

For details see e.g.:
ALICE Physics Performance Report, Vol. I, 2004

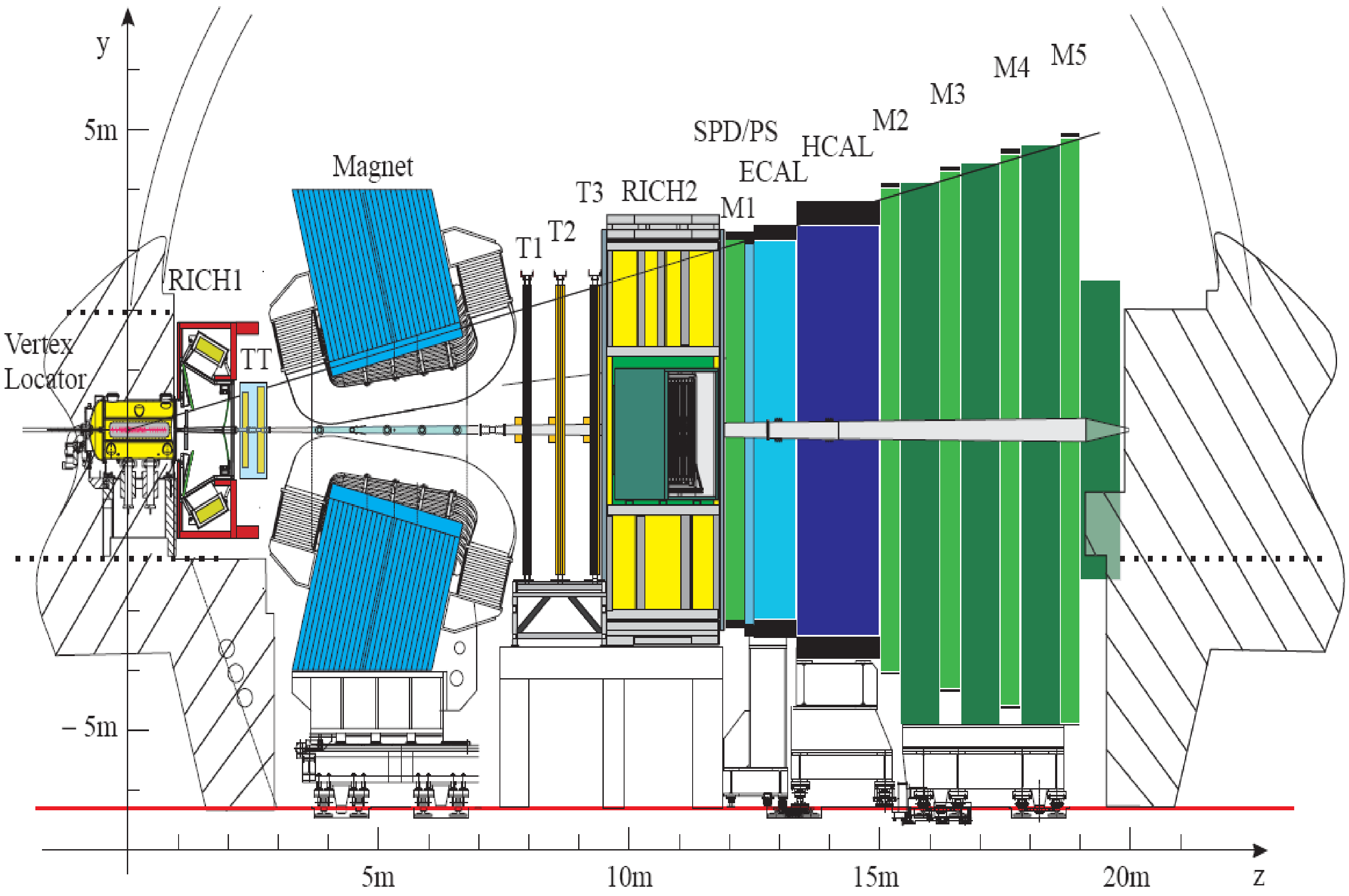


ALICE Installation



11.04.2006:
ALICE cavern

The LHCb Detector

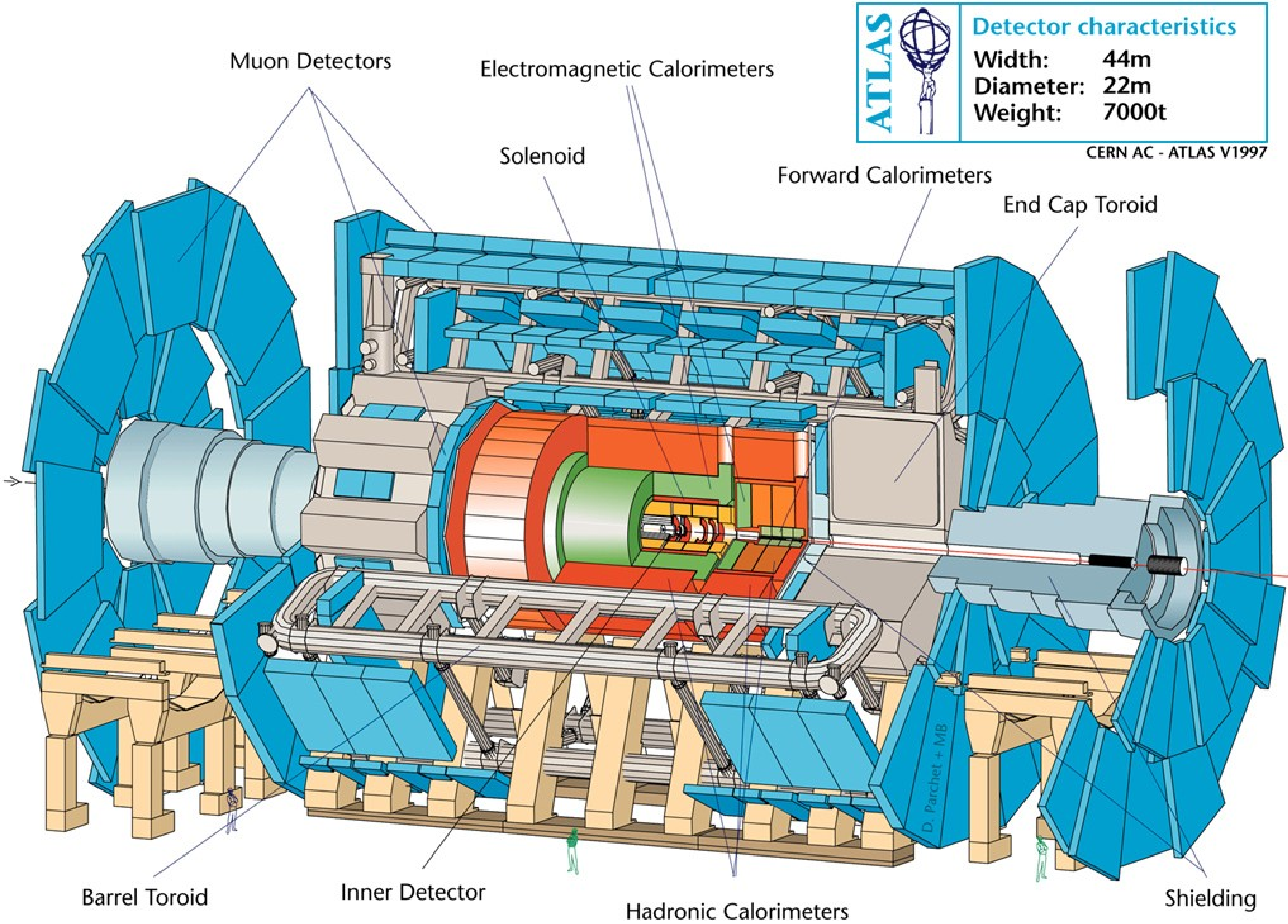


B-Physics experiment:
Study of CP violation and precision measurement of other rare phenomena in B meson decays

For details see e.g.:
LHCb Technical Design Report, Vol. 9, 2003

LHCb Installation

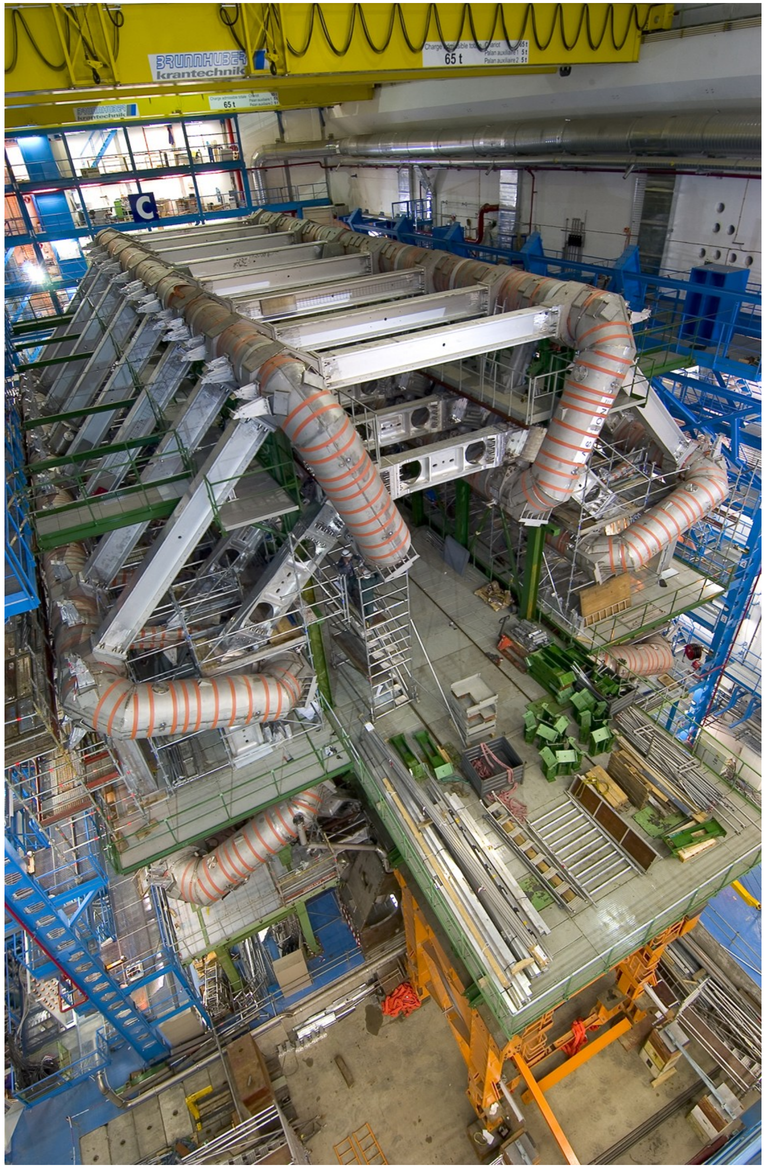
The ATLAS Detector



General purpose
pp collider experiment:
Searches for Higgs bosons, other new particles (SUSY, ...) and new phenomena;
Precision measurement of SM parameters like top and W masses, ...;
Heavy ion program.

For details see e.g.:
ATLAS Technical Design Report, Vol. II, 1999

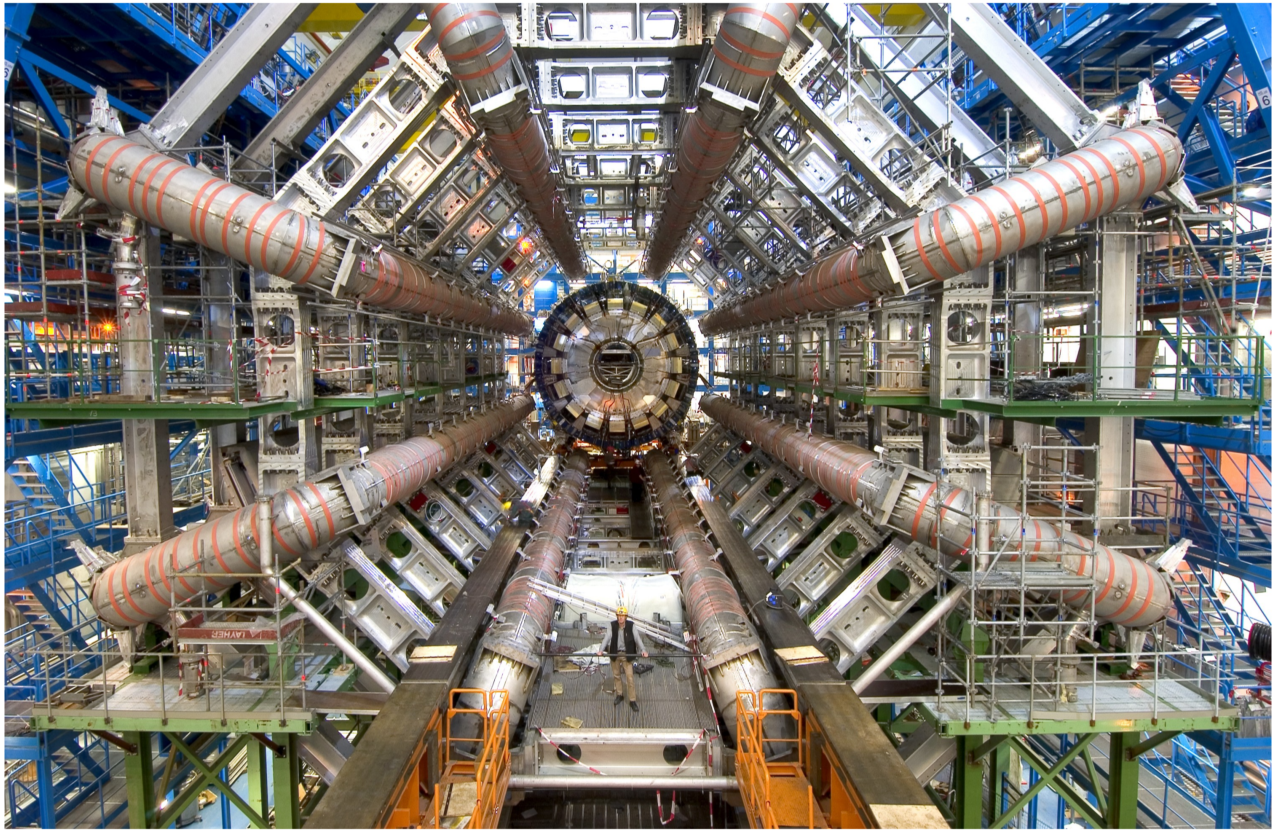
ATLAS Installation



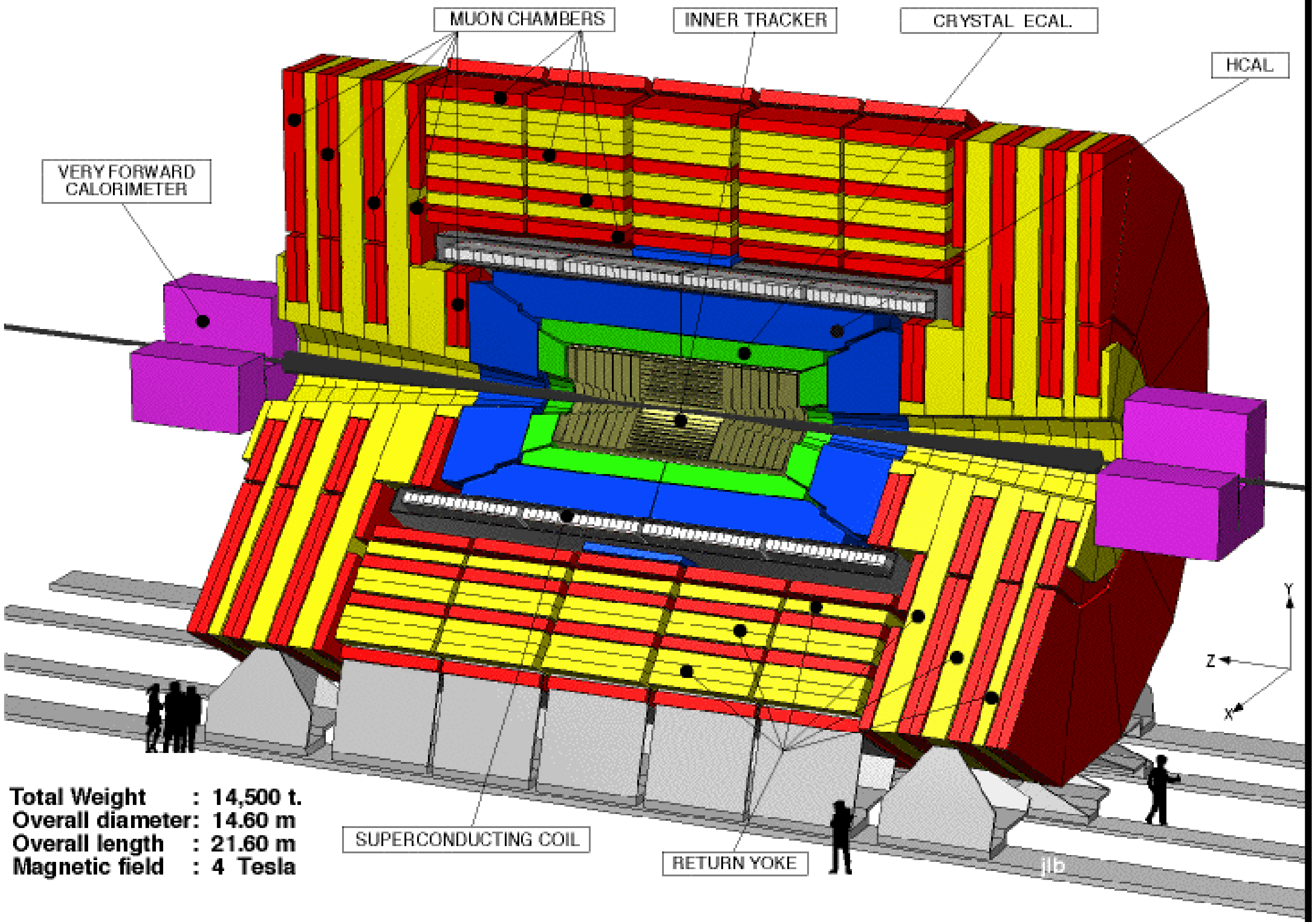
23.09.2005

ATLAS cavern with last toroid coil installed

04.11.2005



The CMS Detector



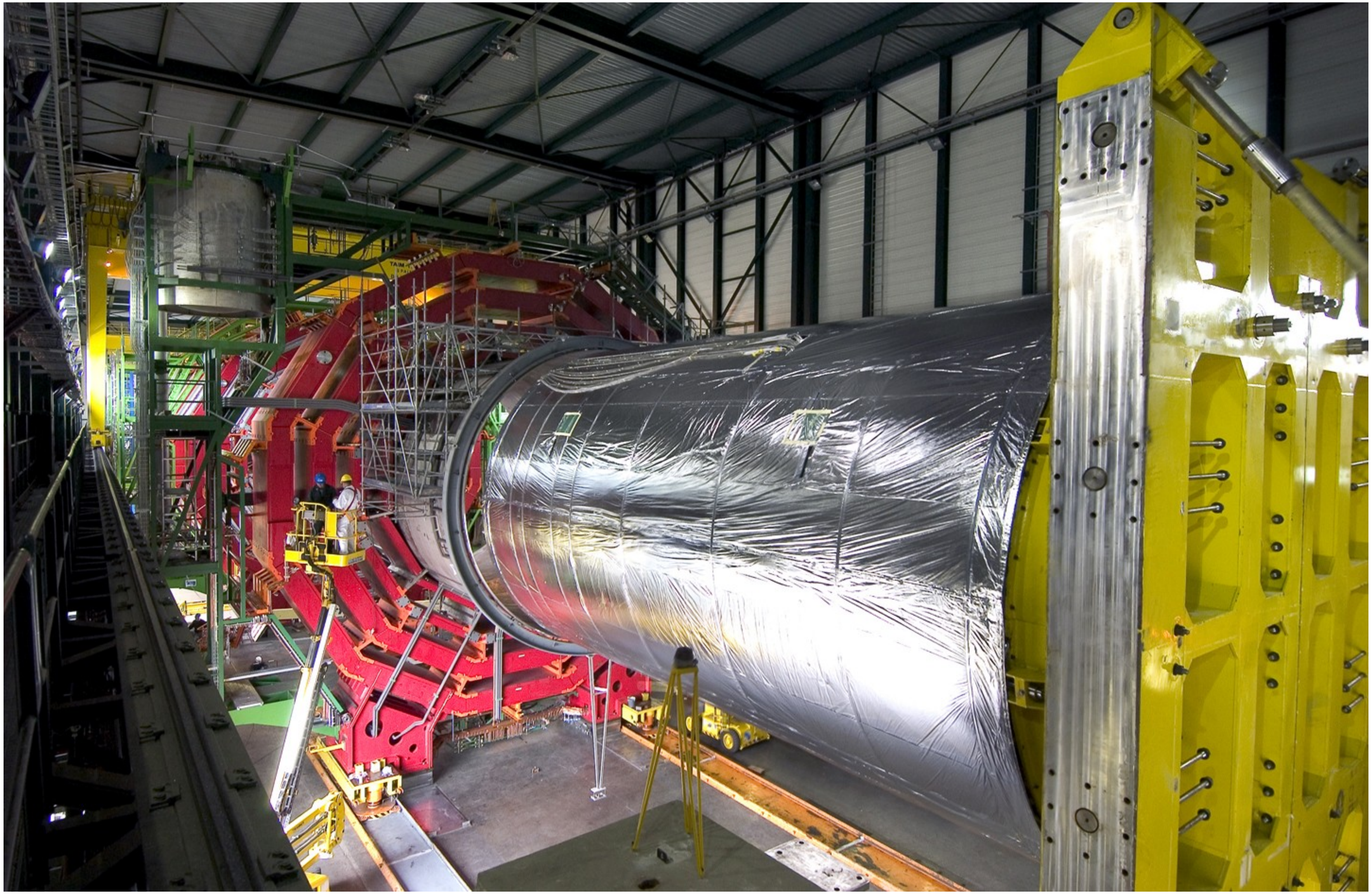
General purpose pp collider experiment:
Searches for Higgs bosons, other new particles (SUSY,...) and new phenomena;
Precision measurement of SM parameters like top and W masses, ...;
Heavy ion program.

Plus TOTEM:
Total cross section, elastic pp scattering, diffractive dissociation

For details see e.g.:
CMS Physics Technical Design Report, Vol. I, 2005; Vol. II to be released soon;
TOTEM Technical Design Report, 2004; a common note with CMS is in preparation.

CMS Installation

12.05.2006: Insertion of CMS tracker for magnet test and cosmic challenge (in surface hall)



Note: In 2007, CMS will start without the pixel detectors and the endcap elm. calorimeter.

LHC Commissioning (1/2)

2007 Pilot run scenario (LHC-OP-BPC-0001 rev 1):

Beam energy (TeV)	6.0, 6.5 or 7.0	6.0, 6.5 or 7.0	6.0, 6.5 or 7.0
Number of bunches (per beam)	43	43	156
β^* in IP 1, 2, 5, 8 (m)	18,10,18,10	2,10,2,10	2,10,2,10
Crossing Angle (μR)	0	0	0
Transverse emittance (μm)	3.75	3.75	3.75
Bunch spacing (μs)	2.025	2.025	0.525
Bunch Intensity	$1\ 10^{10}$	$4\ 10^{10}$	$4\ 10^{10}$
Luminosity in IP 1 & 5 ($cm^{-2}\ s^{-1}$)	$\sim 3\ 10^{28}$	$\sim 5\ 10^{30}$	$\sim 2\ 10^{31}$
Luminosity in IP 2 ($cm^{-2}\ s^{-1}$)	$\sim 6\ 10^{28}$	$\sim 1\ 10^{30}$	$\sim 4\ 10^{30}$

Dedicated runs for TOTEM or with heavy ions have to fit in

- Not very probable to happen in 2007

LHC Commissioning (2/2)

- CMS interpretation (CMS Physics TDR Vol. I):

	Pilot Run 2007	1st Physics Run 2008
Bunch separation/ns:	2025 → 525	75 → 25
Number of bunches:	43 → 156	936 → 2808
No. of particles/bunch:	10^{10} → $4•10^{10}$	$4•10^{10}$
Luminosity/$cm^{-2}m^{-1}$:	$3•10^{29}$ → $2•10^{31}$, 10^{32}	10^{32} → $2•10^{33}$

- CMS assumptions on integrated luminosity:
  - Pilot run 2007: 1/fb
  - Low luminosity phase: 10 – 30 /fb
  - High luminosity phase: 100 – 300 /fb

HERALHC

- Many more details can be found in the talks of the current HERALHC workshop at CERN:

  http://indico.cern.ch/conferenceDisplay.py?confId=186

Tuesday 06 June 2006

14:00	introduction to the workshop, prospects and the future (30') (Slides)	A. De Roeck (*CERN*)
14:30	status of LHC machine (30') (Slides)	Roger Bailey (CERN)
15:00	Status and startup for physics with CMS (30') (Slides)	Maria Spiropulu (CERN)
15:30	Status and startup for physics with ATLAS (30') (Slides)	Marina Cobal (Udine)
16:00	Coffee break	
16:20	Status and startup for physics with ALICE (30') (Slides)	Jean Piere Revol (CERN)
16:50	Status and startup for physics with LHCb (20') (Slides)	Giovanni Passaleva (*Firenze*)
17:10	Diffraction with TOTEM (20')	Risto Orava (*Helsinki*)
17:30	HERA program until 2007 (45') (Slides)	Elisabetta Gallo (*INFN Firenze/DESY*)
18:15	ep program at LHC (30') (Slides)	Emmanuelle Perez (*Saclay/DESY*)

Selected Topics

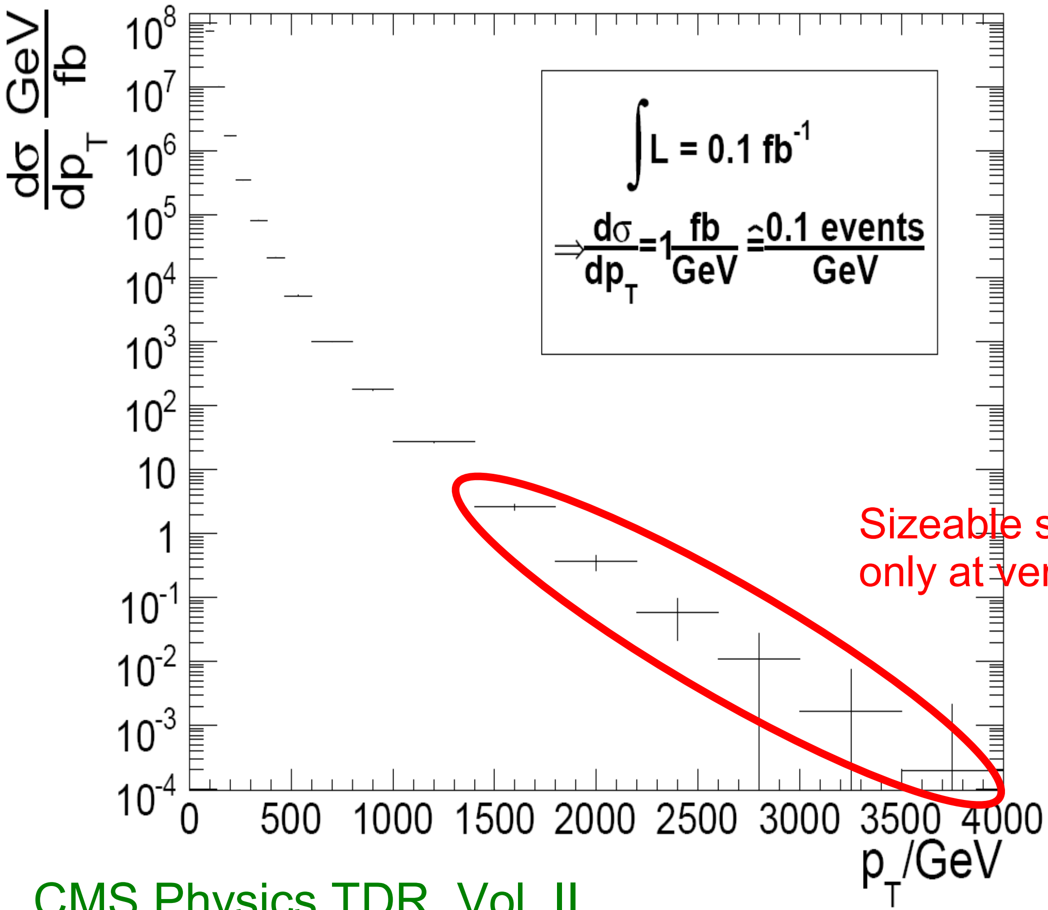
- Concentrate on start-up physics probably possible in 2007, hence:
  - Neither heavy ions, nor forward physics with TOTEM
  - No ECAL in CMS endcaps, no pixel detectors
  - No Higgs :-) ?
- But see the informative talks from D. d´Enterria on Monday: “... from RHIC to LHC”, or from Chr. Weiss on “GPDs ... at LHC” on Tuesday

High p_T Jets

- Statistically, no problem even with only a pilot run in 2007 (up to ≈ 1.5 TeV in p_T)
- Important to study the detector behaviour
- Improve understanding and estimates of QCD background to other processes
- Useful to measure the jet cross sections (ok)
- Improve on PDFs, especially the gluon at high x (not so simple)
- Extract running of strong coupling in new p_T range (slope decreases)
- Precisely determine the strong coupling (curr. rel. uncertainty ≈ 2%, HERA goal: 1%; probably not competitive with inclusive jets, but with jet rates ? To be investigated ...)

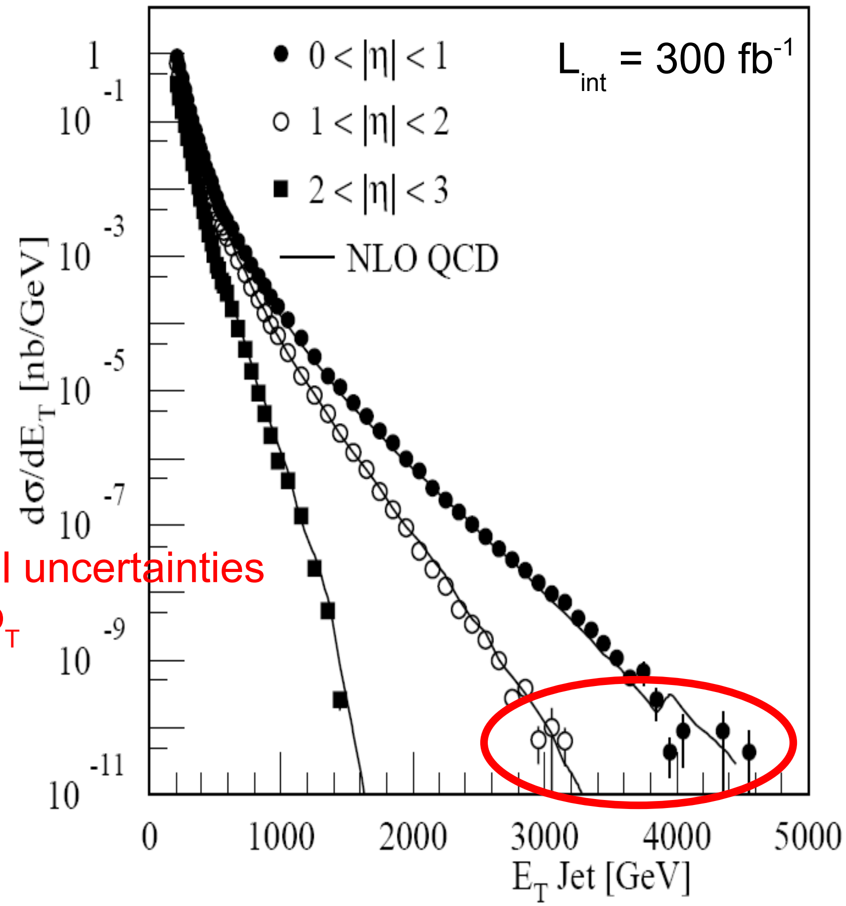
Statistical Uncertainties

Est. statistical uncertainty for L_{int} = 0.1 fb^{-1}
(Pythia LO high p_T event cross section, all rap.)



CMS Physics TDR, Vol. II

Est. statistical uncertainty for L_{int} = 300 fb^{-1}
(Pythia LO high E_T jet cross section, hadrons)



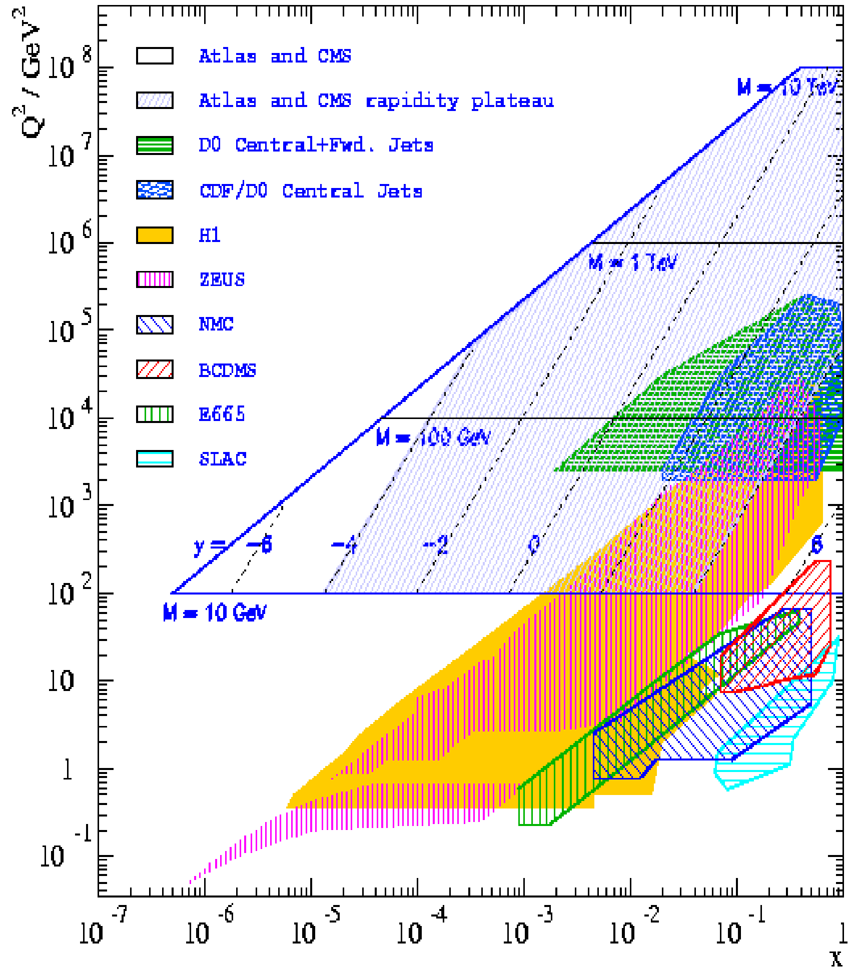
Sizeable statistical uncertainties only at very high p_T

ATLAS Physics TDR, Vol. II

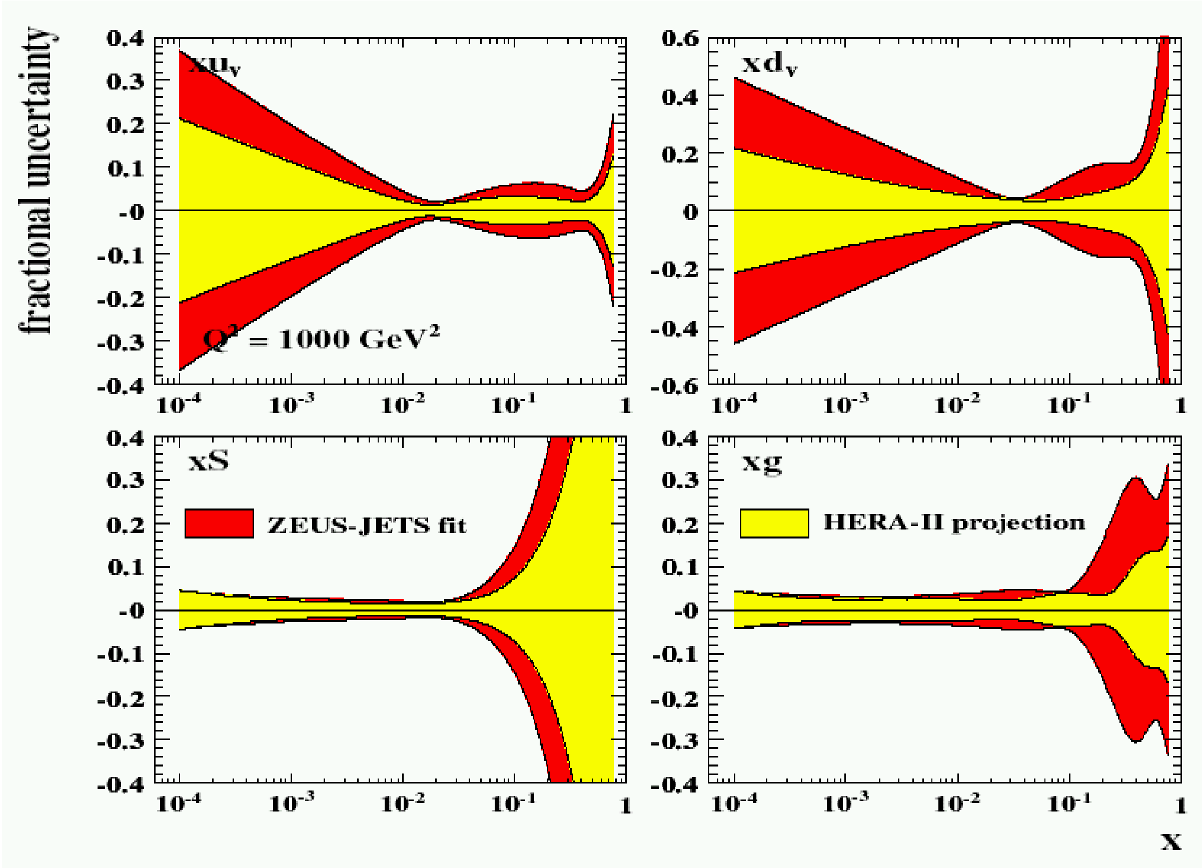
Knowledge on PDFs

- Much insight has been gained, especially due to HERA, more to come from HERA II, see talk from D. Saxon on Monday

Kinematic reach of LHC

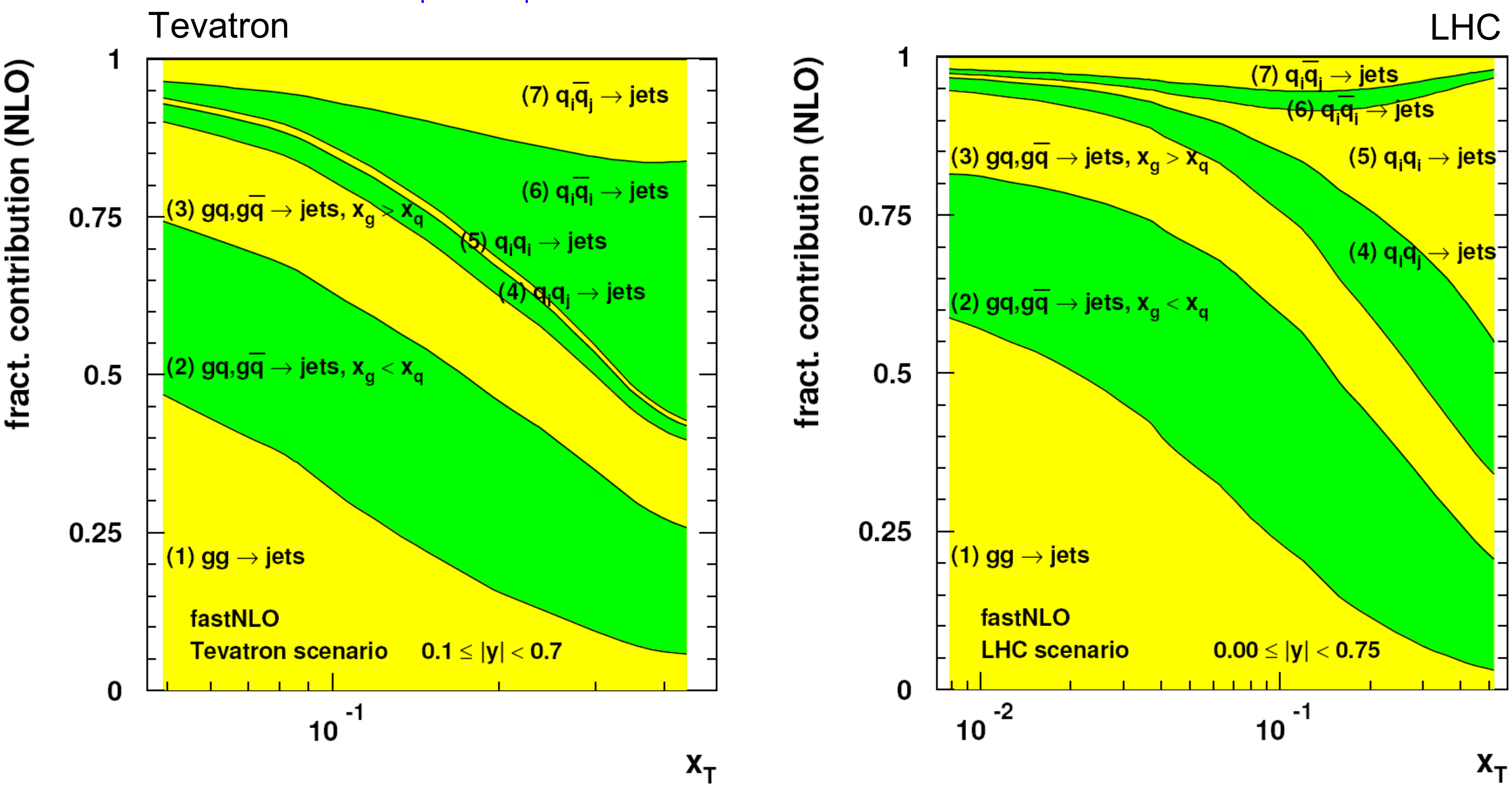


Prospected reduction in uncertainty on PDF fits from ZEUS (F2 + jets) for HERA II



Subprocess Decompositions

Decomposition of high p_T jet cross sections into partonic subprocesses depending on $x_T = 2p_T/\sqrt{s}$ in central rapity region



Recent Progress

- One of the most important developments in the last years are the error PDF sets, e.g. from the CTEQ group
- But their evaluation and especially PDF fits require:
  - Availability of reasonably fast theory calculations
  - Often needed: Repeated computation of same cross section
- Sometimes NLO predictions can be computed fast, but some are very slow, esp. for jets
- New procedure for fast repeated computations of NLO cross sections: Project fastNLO (T.Kluge, M.Wobisch, KR)
  - Useable for any observable in hadron-induced processes (hh,DIS,...)
  - Does not include theor. calculation itself, here: NLOJET++ (Zoltan Nagy)
- No computation time saved at first run, repetition with e.g. another PDF set takes only milliseconds
- Involves one single approximation with quantifiable precision

PDF Approximation

- Introduce set of discrete $x^{(i)}$ with $x^{(n)} < .. < x^{(i)} < .. < x^{(0)} = 1$
- Around each $x^{(i)}$ define eigen function $E^{(i)}(x)$ with:

  $E^{(i)}(x^{(i)}) = 1$, $E^{(i)}(x^{(j)}) = 0$ $(i \neq j)$, $\Sigma_i E^{(i)}(x) = 1$ for all x

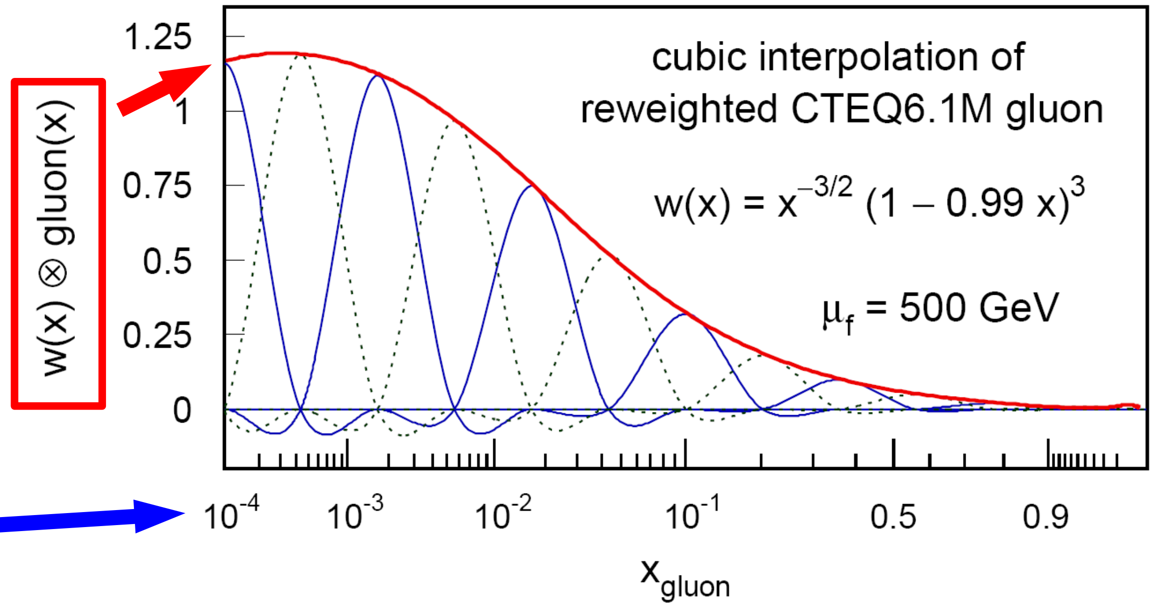
- Express PDF f(x) by lin. combination of eigen functions with coefficients given by PDF values **at discrete points:**

  $f(x) = \sum_i f(x^{(i)}) E^{(i)}(x)$ => Integration only over $E^{(i)}(x)$, not f(x)!

For more info see: http://hepforge.cedar.ac.uk/fastnlo
(T.Kluge,M.Wobisch,KR)

Similar project: NLO-GRID
(D.Clements, C.Gwenlan,
C.Buttar, G.Salam, T.Carli,
A.Cooper-Sarkar, M.Sutton)

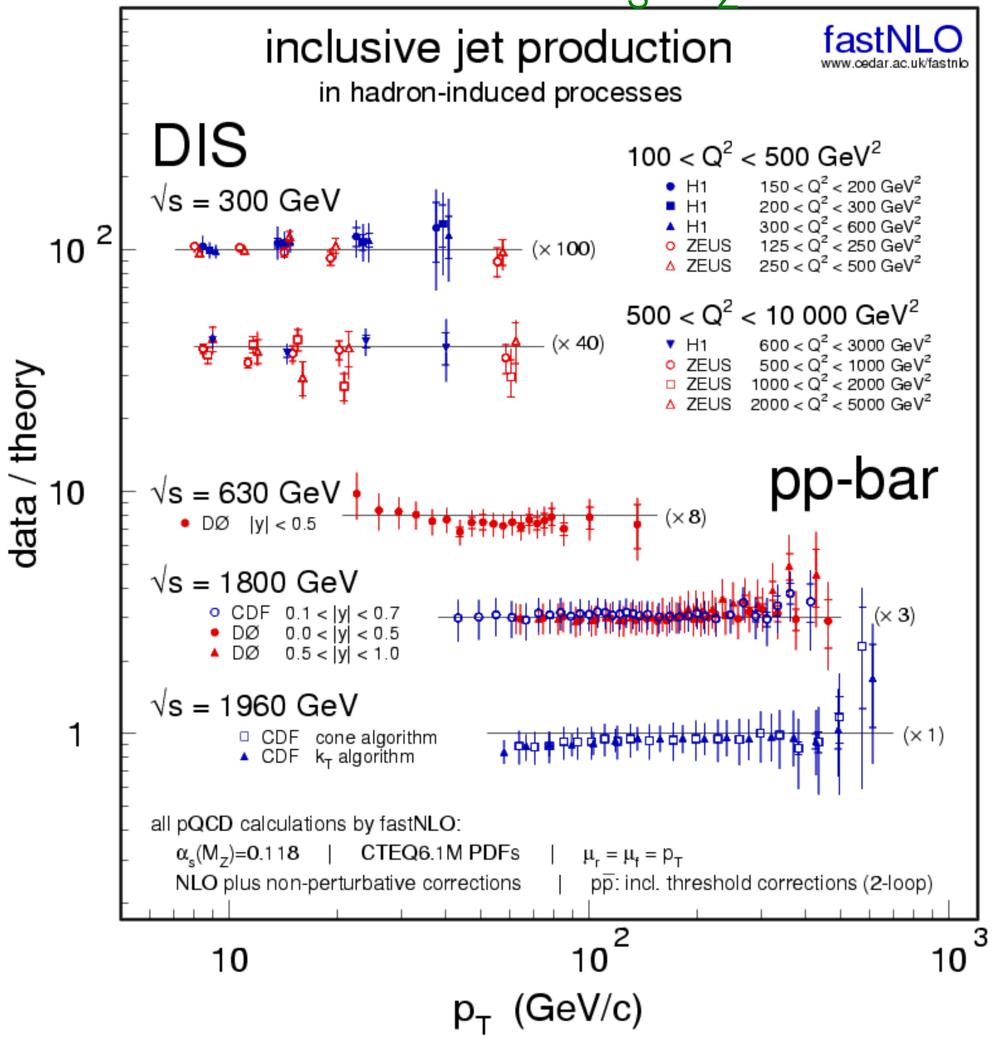
Equidistant binning in: $\sqrt{\log(1/x)}$



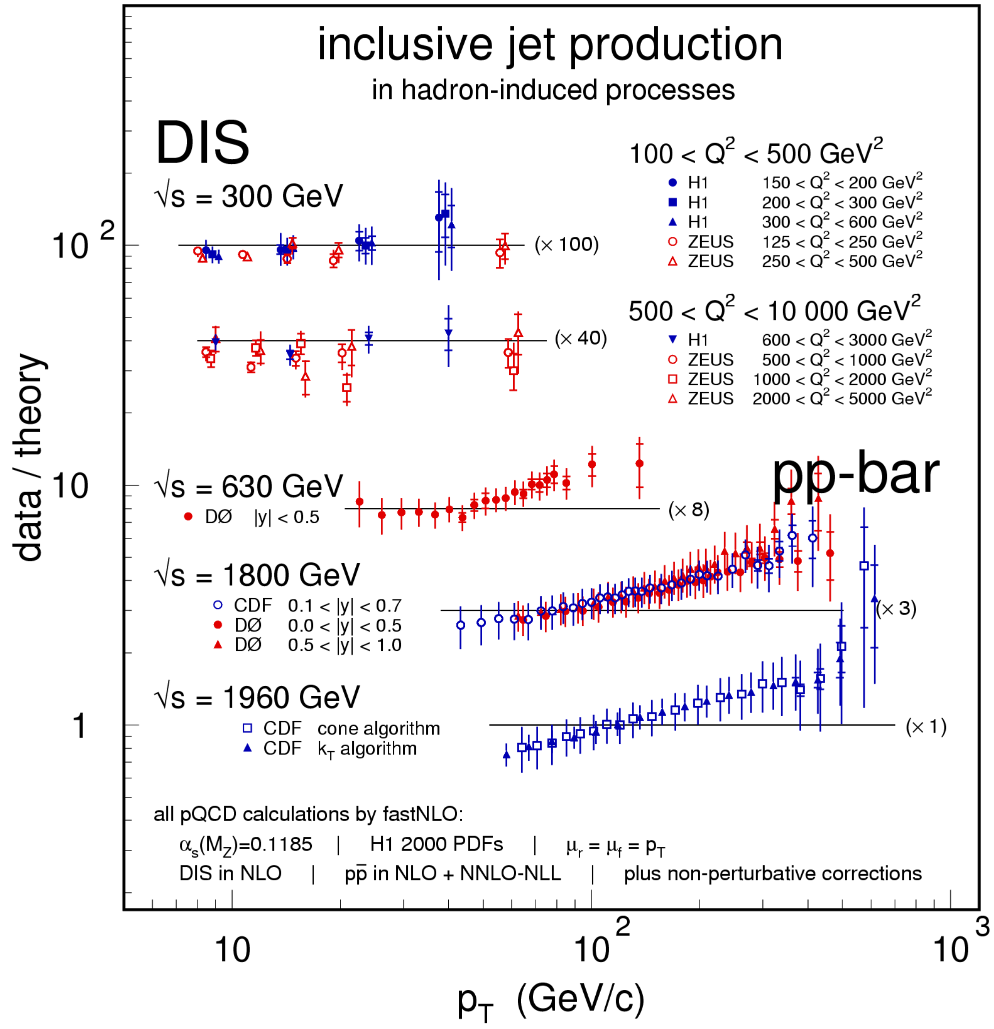
fastNLO Application

No jet data used for PDF fits

CTEQ6.1 PDFs, $\alpha_s(M_Z)= 0.118$

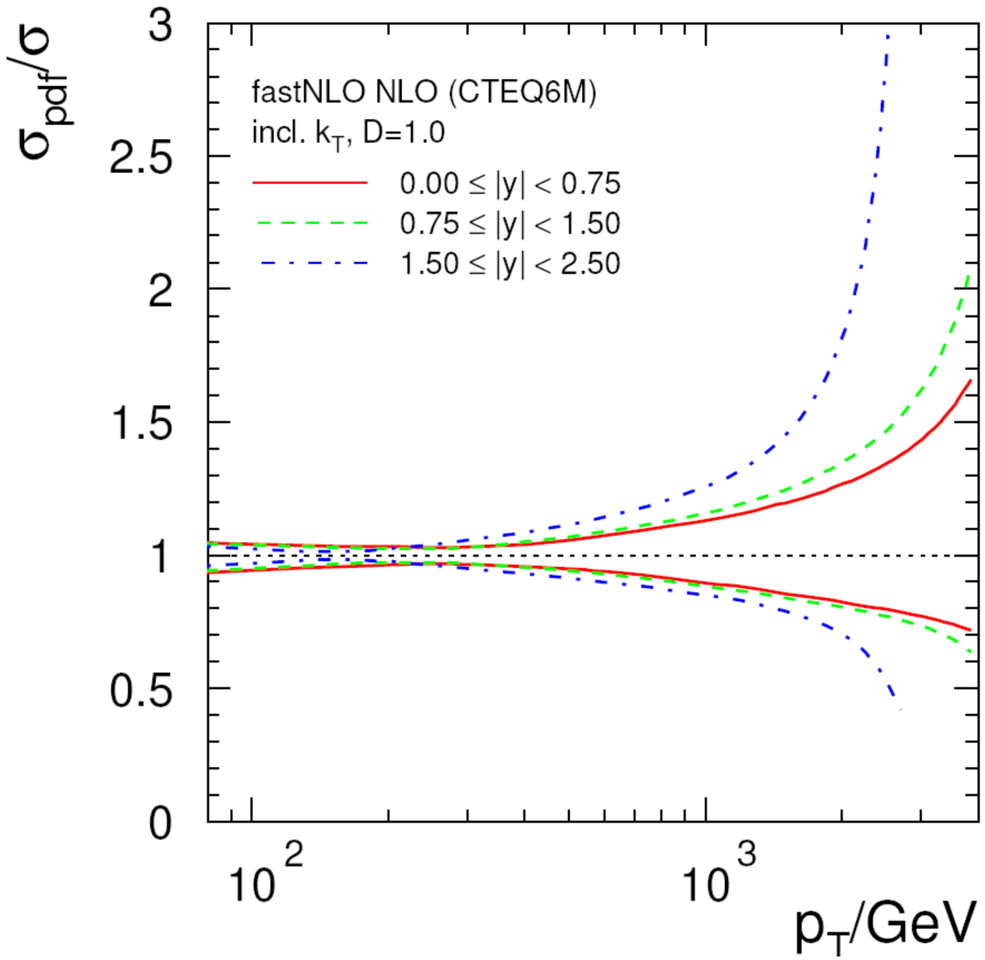


H1 2000 PDFs, $\alpha_s(M_Z) = 0.118$

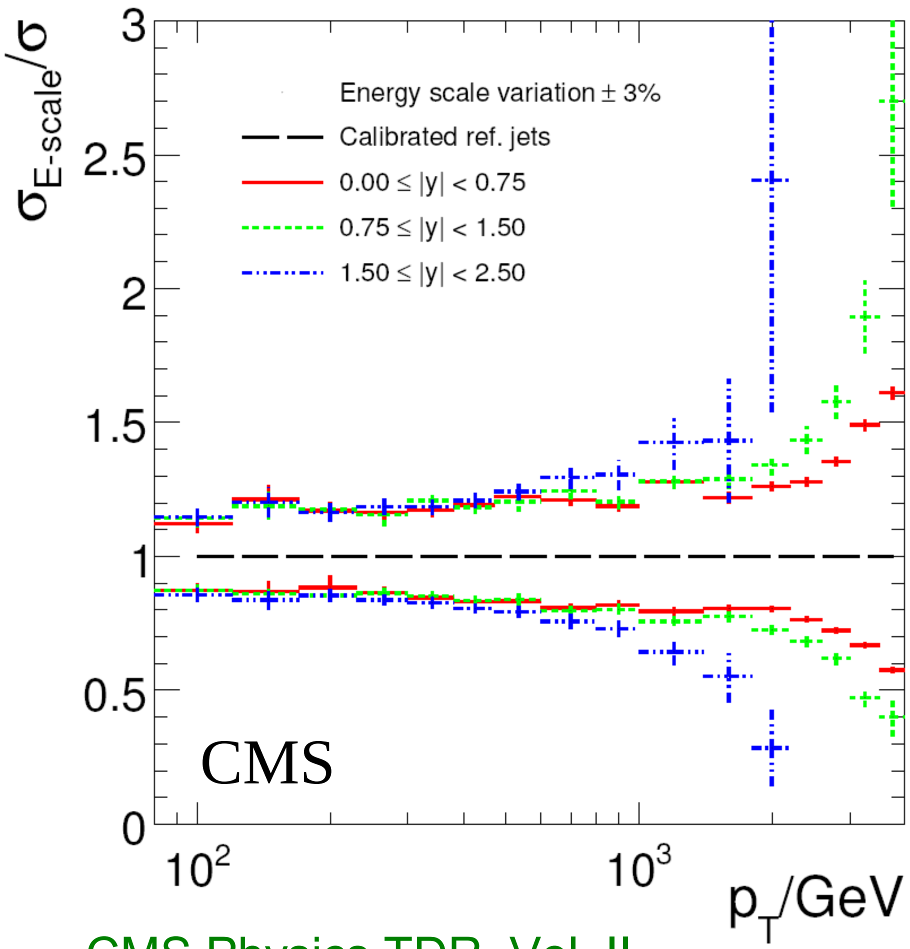


Dominant Uncertainties at high p_T

PDF uncertainty on high p_T jet cross section acc. to evaluation of the 40 CTEQ6 error PDFs



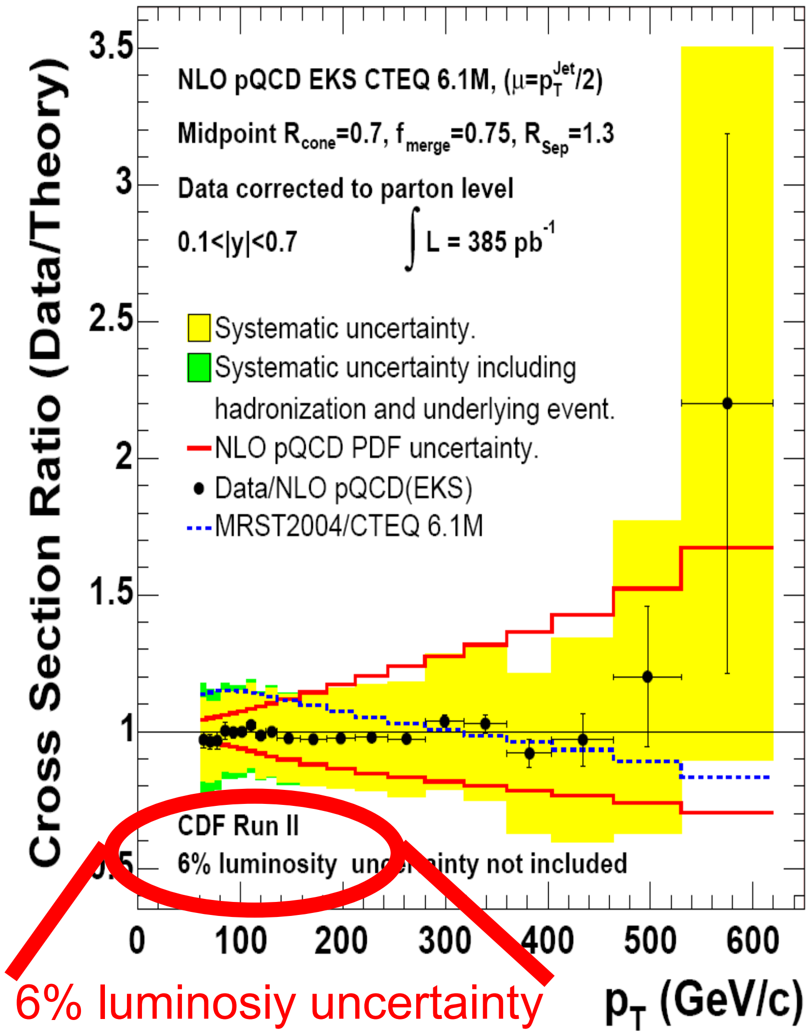
E scale uncertainty on high p_T jet cross section as derived from full CMS detector simulation



CMS Physics TDR, Vol. II

Tevatron Results

- CDF hep-ex/0512062:
  - Dom. uncertainty: Jet energy scale ±3% → 10% at low p_T up to 60% at high p_T
  - Energy resolution, unfolding and luminosity: Below 10% each
  - UE: -22% up to -4%
  - Hadr.: +13% up to +3.5%
- D0 hep-ex/0012046 (Run I, new Run II results only preliminary):
  - Dom. uncertainty: Jet energy scale 15% at low p_T up to 30% at high p_T



6% luminosiy uncertainty not included

Standard Candle (1/2)

- Absolute scale of high p_T jet cross section uncertain by 6% due to luminosity measurement
- Investigate processes like pp → W + X and pp → Z + X as "Standard Candles" (CMS Physics TDR, Vol. II):
  - Well measurable in case of subsequent leptonic decays W → lν resp. Z→ l^+l^- with l = e or μ
  - High cross sections above 10nb (1nb) expected in fiducial volume of CMS for W → lν (Z→ l^+l^-) channel
  - W channel more difficult, but more statistics available
  - Most dangerous background from QCD events with decay leptons, tractable with isolation criteria against jets
  - Like high p_T jets very useful for detector, jet calibration (Z + jets, also γ + jets)
  - Acceptance uncertainty is at 2-3% level already at start-up (nevermind the PDF!)

Standard Candle (2/2)

- Measures directly the quark and anti-quarks densities in the proton via

$$\int_{q,\bar{q}\ partons} dx_1 dx_2 \sigma_{q\bar{q}\to W,Z} \times L_{pp} \times PDF(x_1, x_2, Q^2)$$

- Theoretically well understood, BUT global rate uncertain to about 6 - 7% because of PDF uncertainties
- Clever combination (rates) of cross sections can be determined much more precise since uncertainties cancel
- Would be interesting to try combined fit with high p_T jets
- Drell-Yan could add even more information on PDFs into common fit procedure (Calculation in NNLO exists)

Event Shapes (1/2)

Event Shapes have been used since a long time with great success in e^+e^- scattering.

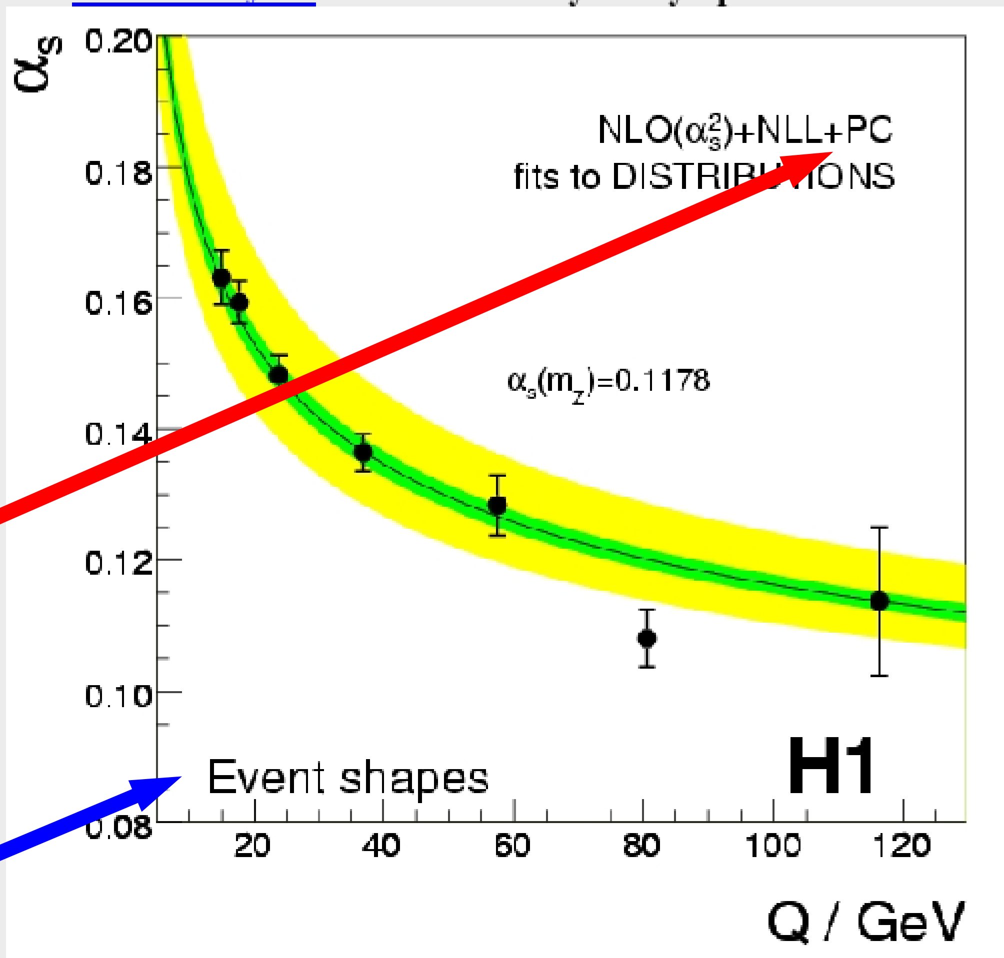
Since about ten years similarly applied in ep collisions, latest results from H1, ZEUS:
hep-ex/060432v2
Eur.Phys.J.C46:343,2006
Eur.Phys.J.C27:531,2003

Power Corrections as alternative method for MC hadronization corrections

H1 exhibits them even on their www start page!

H1 Collaboration at DESY, Notkestr.85, D-22607 Hamburg, Germany

David Gross, David Politzer and Frank Wilczek awarded the 2004 Nobel Prize in Physics for the discovery of asymptotic freedom



Twenty years ago, David Gross, David Politzer and Frank Wilczek discovered **asymptotic freedom** in the theory of the strong interactions. Measurements published by **H1** in the year 2005 beautifully illustrate this effect: the strong coupling a_s is seen to decrease as the hard scale at which it is measured, Q, increases.

Event Shapes (2/2)

ZEUS: Compatible results for event shape distributions, but less favourable of power correction concept

Shift of PT distribution by power corr.: (see papers by Dokshitzer, Webber, Dasgupta, Salam, Zanderighi, ...)

$$\frac{1}{\sigma_{\rm tot}}\frac{d\sigma(F)}{dF} = \frac{1}{\sigma_{\rm tot}}\frac{d\sigma^{\rm pert}(F-\mathcal{P})}{dF}$$

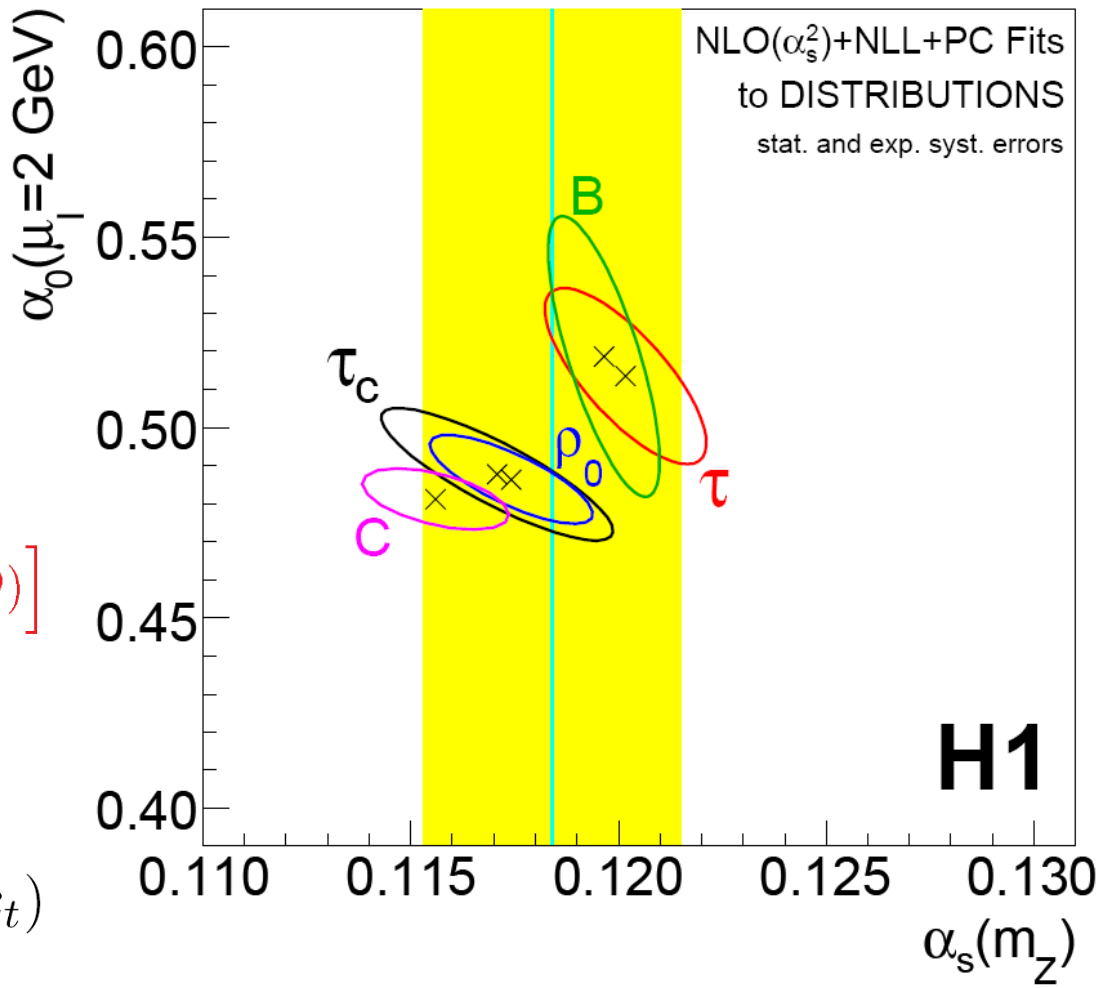
$$\mathcal{P} = a_F \frac{4C_F}{\pi\, p}\mathcal{M}'\left(\frac{\mu_I}{Q}\right)^p$$

$$\left[\overline{\alpha}_{p-1}(\mu_I) - \alpha_s(Q) - \frac{\beta_0}{2\pi}\left(\ln\frac{Q}{\mu_I} + \frac{K}{\beta_0} + \frac{1}{p}\right)\alpha_s^2(Q)\right]$$

Averaged coupling up to infrared matching scale μ_I :

$$\alpha_0(\mu_I) \equiv \int_0^{\mu_I}\frac{dk_t}{\mu_I}\alpha_s(k_t)$$

H1 common fits of strong coupling and non-perturbative α_0 parameter for five different event shape distributions



Event Shapes in pp?

- Suggestion from theory to look for event shapes in pp collisions as well (e.g. directly global transverse thrust): (A. Banfi, G. Salam, G. Zanderighi: hep-ph/0605332, hep-ph/0407287)

$$T_{\perp,g} \equiv \max_{\vec{n}_\perp} \frac{\sum_i |\vec{p}_{\perp i} \cdot \vec{n}_\perp|}{\sum_i |\vec{p}_{\perp i}|}, \qquad \tau_{\perp,g} \equiv 1 - T_{\perp,g}$$

- Needs to include emissions in complete phase space, problematic with limited detector acceptance
- Two alternative definitions exist with either addition of a global recoil term or exponentially suppressed forward terms
- Can be used to study jet hadronization and underlying event properties

Outlook

- The LHC start-up phase will probably be rather painful ...
- And also the experiments will have a hard time getting things up and running (and keeping it there)
- In any case I talked about a **near future facility!**
- QCD will be among the first topics to be studied with real data
- Already with just a pilot run a rich field of results with jets, W and Z production, Drell-Yan can be expected
- The connecting point of all these are the parton densities
- Very interesting times lie ahead and maybe some surprises with “standard” physics ... even without an early Higgs

Thank you!

Backup Slides

Partonic Subprocesses

- Don't want to deal with 13 X 13 PDFs
- For hh → jets **seven** relevant partonic subprocesses

$$\begin{array}{llcll}
1) & gg & \Rightarrow & \text{jets} & \propto H_1(x_1, x_2) \\
2) & qg, \bar{q}g & \Rightarrow & \text{jets} & \propto H_2(x_1, x_2) \\
3) & gq, g\bar{q} & \Rightarrow & \text{jets} & \propto H_3(x_1, x_2) \\
4) & q_i q_j, \bar{q}_i \bar{q}_j & \Rightarrow & \text{jets} & \propto H_4(x_1, x_2) \\
5) & q_i q_i, \bar{q}_i \bar{q}_i & \Rightarrow & \text{jets} & \propto H_5(x_1, x_2) \\
6) & q_i \bar{q}_i, \bar{q}_i q_i & \Rightarrow & \text{jets} & \propto H_6(x_1, x_2) \\
7) & q_i \bar{q}_j, \bar{q}_i q_j & \Rightarrow & \text{jets} & \propto H_7(x_1, x_2)
\end{array}$$

- Need only seven linear combinations H_i of PDFs

Symmetries

- In addition, symmetries can be exploited:

$$
\begin{aligned}
H_n(x_1, x_2) &= H_n(x_2, x_1) \quad \text{for} \quad n = 1, 4, 5, 6, 7 \\
H_2(x_1, x_2) &= H_3(x_2, x_1)
\end{aligned}
$$

- For hadron anti-hadron collisions, replace:

$$
\begin{aligned}
H_4(x_1, x_2) &\leftrightarrow H_7(x_1, x_2) \\
H_5(x_1, x_2) &\leftrightarrow H_6(x_1, x_2)
\end{aligned}
$$

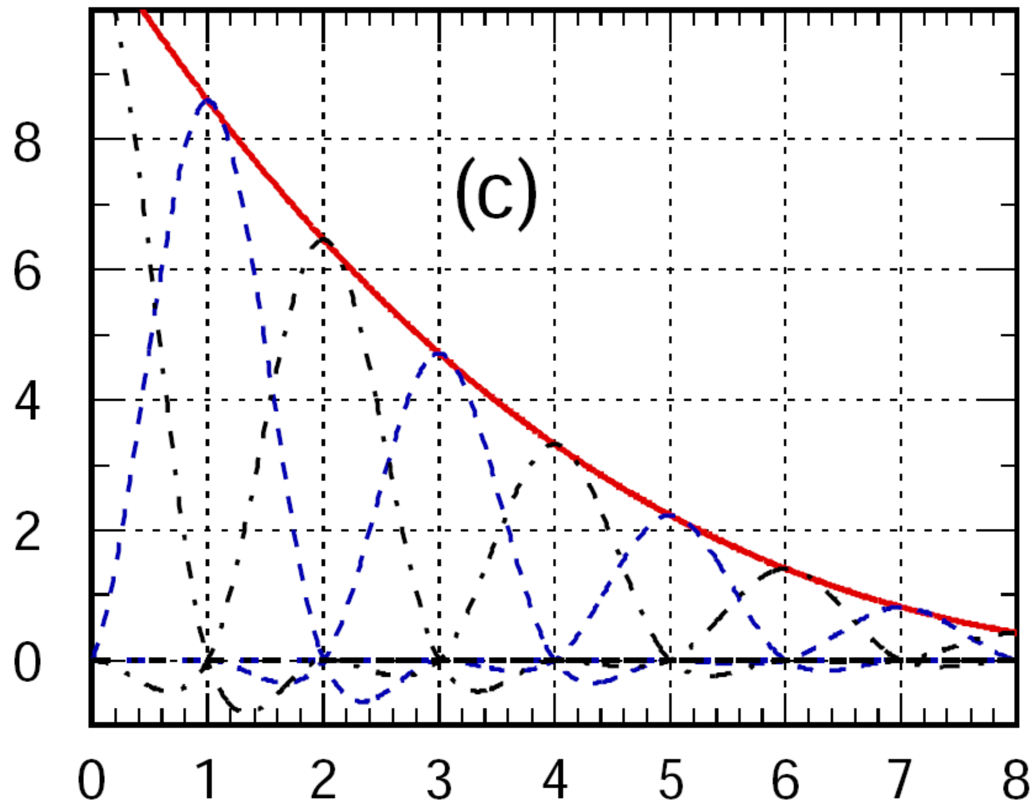
- Minimize required table size and computing time!

Actual Usage

Our actual interpolation is:

- Two-dimensional (x_1,x_2)
- Cubic, linear at the edges
- Spaced in x with points ~ $\sqrt{\log(1/x)}$

Cubic interpolation functions



Example use case:

D0 incl. jets (hep-ex/0011036)

No. of bins in rap. y:	5
No. of bins in p_T:	24 – 8
Total no. of bins:	90
No. of events (NLO):	49G
CPU time for first run:	> 4000h
Table size (10 x bins, 4 scal.):	5.5MB
Reading of table:	O(1s)
Execution time/PDF set:	< O(0.01s)
Stat. precision, y bins 1-3:	**0.1 - 0.3%**
y bins 4,5:	**0.2 - 1.0%**

(Depending on used PC!)

Jet cross sections in hadron-hadron collisions

General cross section formula:

$$\sigma_{hh} = \sum_n \alpha_s^n(\mu_r) \sum_{flavour\, i} \sum_{flavour\, j} c_{i,j,n}(\mu_r, \mu_f) \times f_i(x_1, \mu_f) \times f_j(x_2, \mu_f)$$

which depends on:

- Strong coupling constant α_s to the power of n
- Perturbative coefficients $c_{i,j,n}$
- Parton density functions (PDFs) of the hadrons $f_i(x)$, $f_j(x)$
- Renormalization scale μ_r, factorization scale μ_f
- Momentum fractions x

➔ Standard procedure: Integration over phase space in (x_1,x_2) (usually MC method) => Dependency on PDFs!

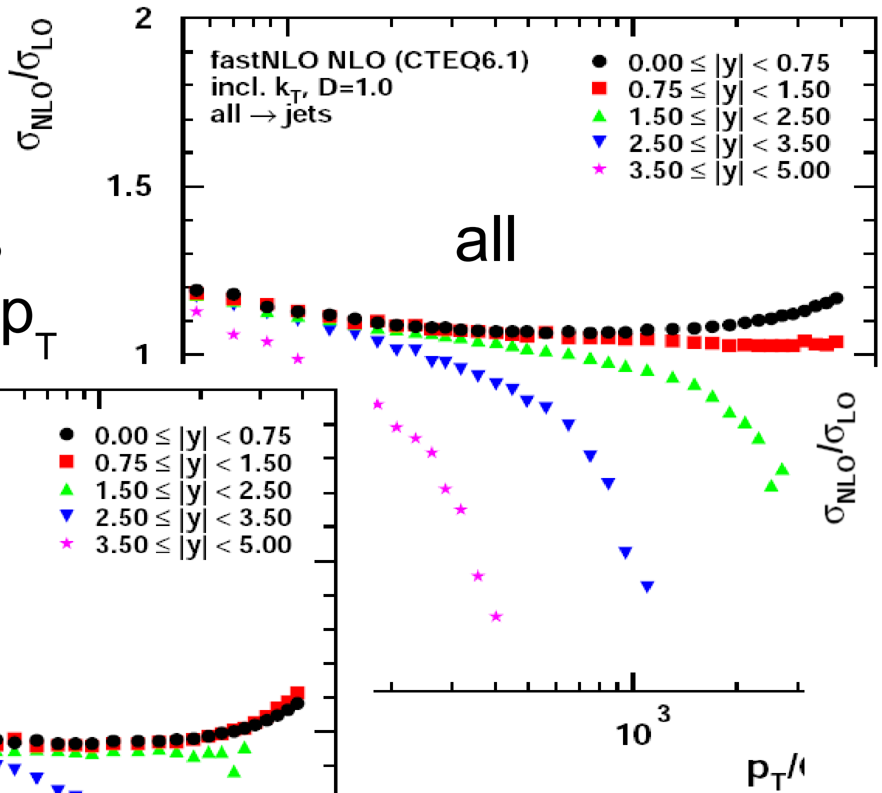
➔ New: Interpolation between fixed support points in x for PDFs => Evaluation a posteriori possible

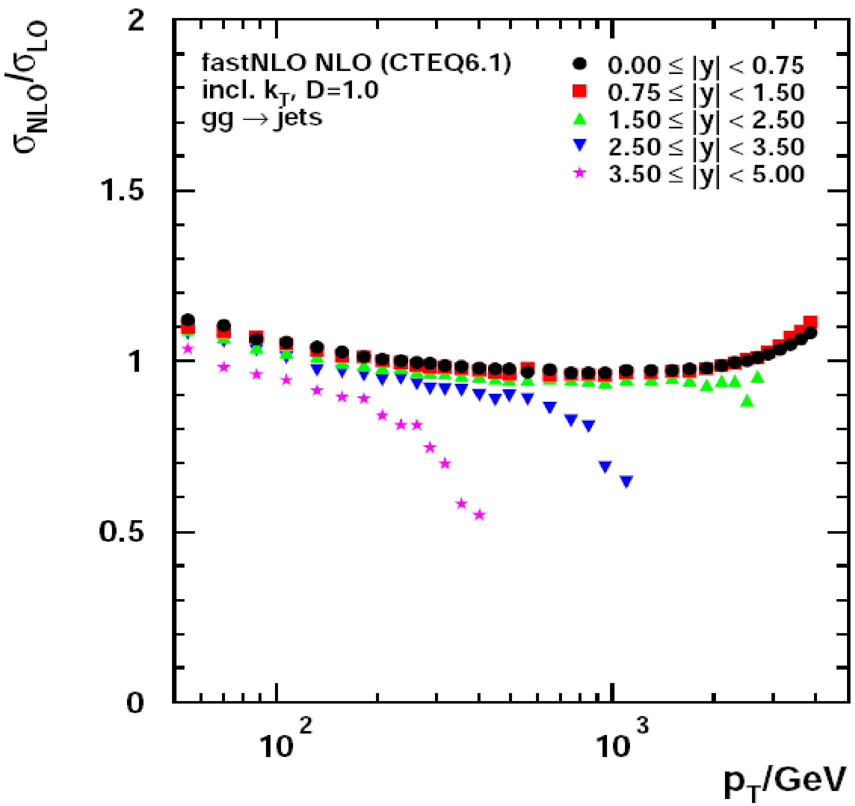
K Factors

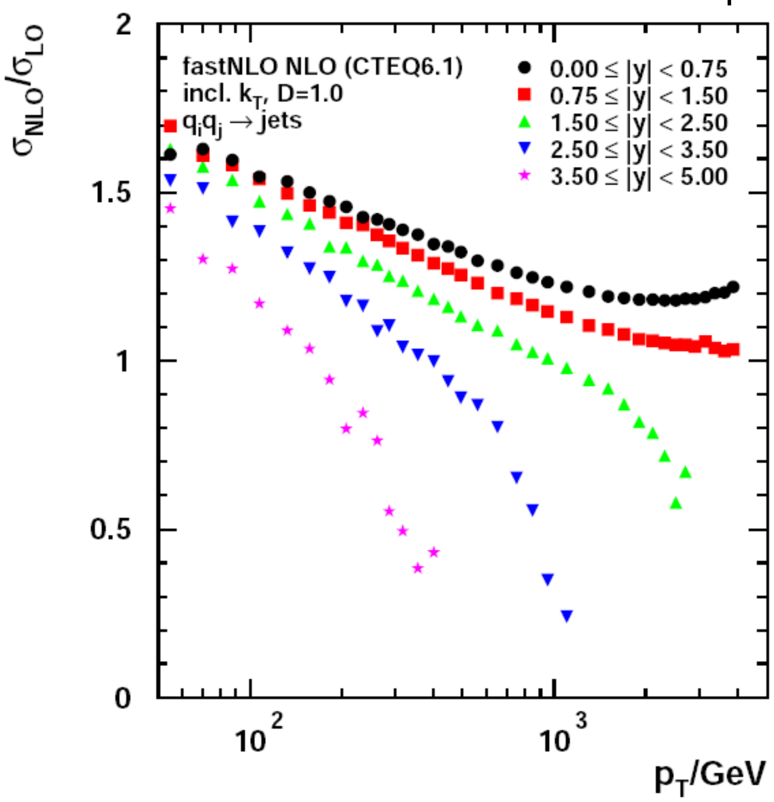
gg subprocess dominant at low p_T

all

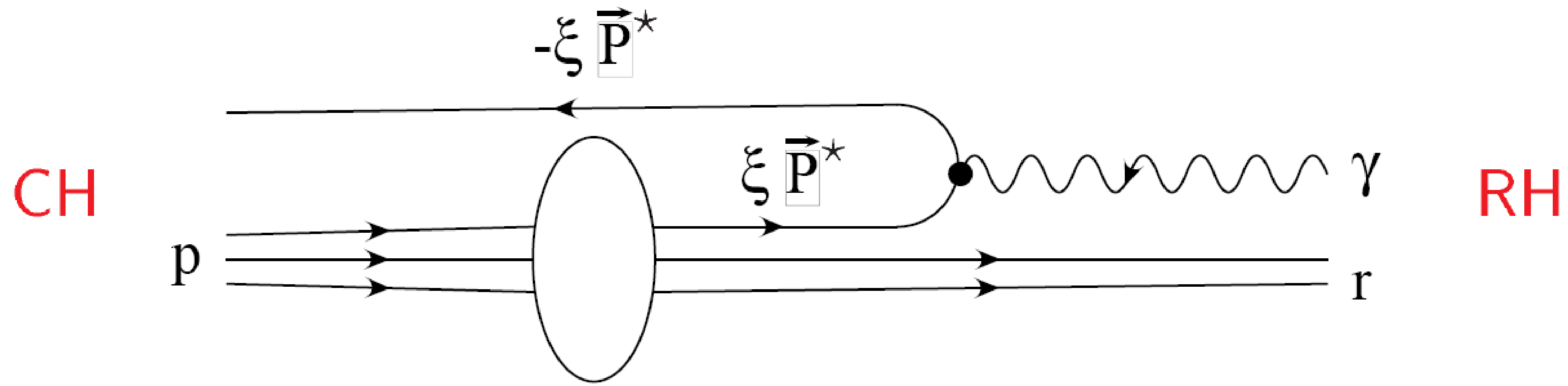
$q_i q_j$ subprocess dominant at high p_T







Event shapes in Breit frame



Example: Thrust

$$\tau := 1 - \frac{\sum\limits_{i \in \mathrm{CH}} |\vec{p_i}^{\star} \cdot \vec{n}|}{\sum\limits_{i \in \mathrm{CH}} |\vec{p_i}^{\star}|} = 1 - \frac{\sum\limits_{i \in \mathrm{CH}} |p^{\star}_{li}|}{P^{\star}}$$