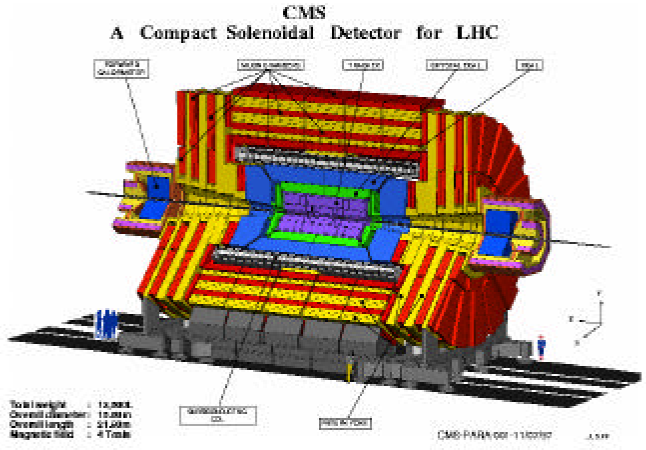
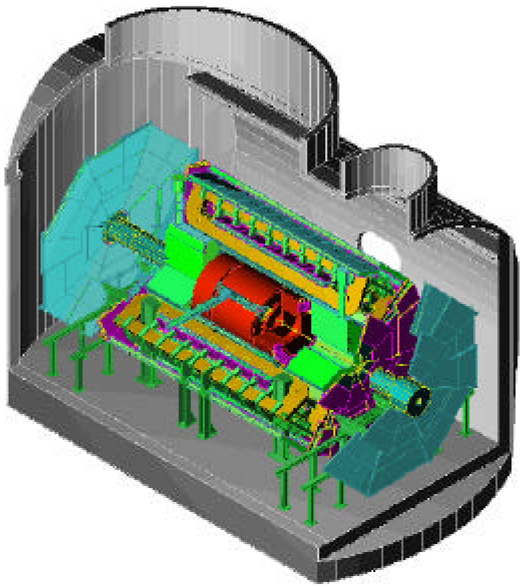
QCD at LHC





Stefan Tapprogge

HIP Helsinki

IPPP Workshop on
'Multiparticle Production in QCD jets'

Durham, December 12-15, 2001

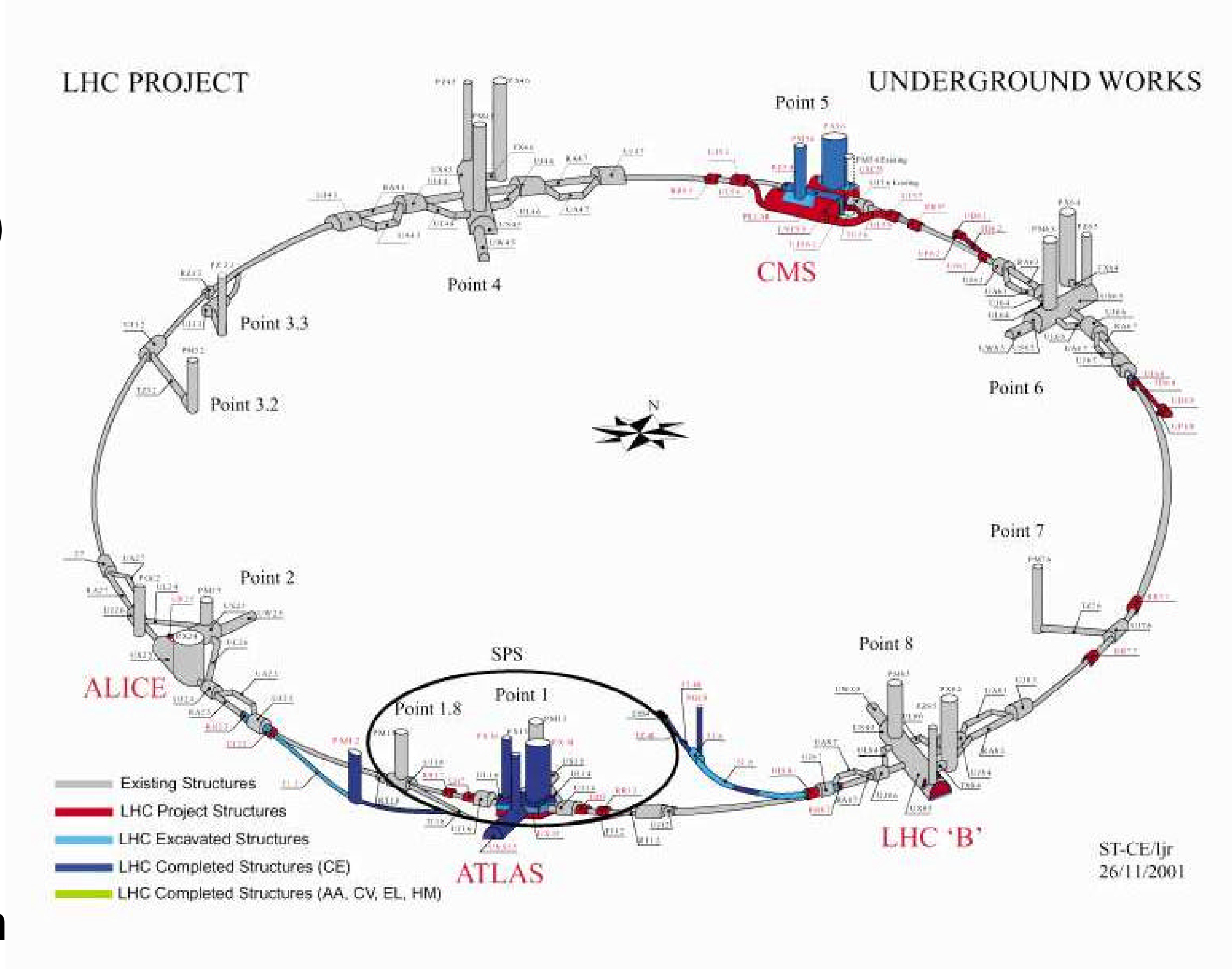
A story in two episodes ...

- Episode I: 'The baseline'
  - The LHC, ATLAS and CMS
  - QCD at the LHC: why, what and how?
  - Physics topics
    - Jets: partons and α_s determination
    - Drell-Yan and W/Z: partons
    - Direct Photons: partons and α_s determination
    - BFKL signatures
- Episode II: 'Beyond the baseline'
  - Forward Physics
  - The TOTEM experiment
  - Physics topics
    - Exclusive (and non-exclusive) central production
    - Two photon physics
    - Forward production of hard probes
  - Scenarios for LHC upgrades
  - Outlook

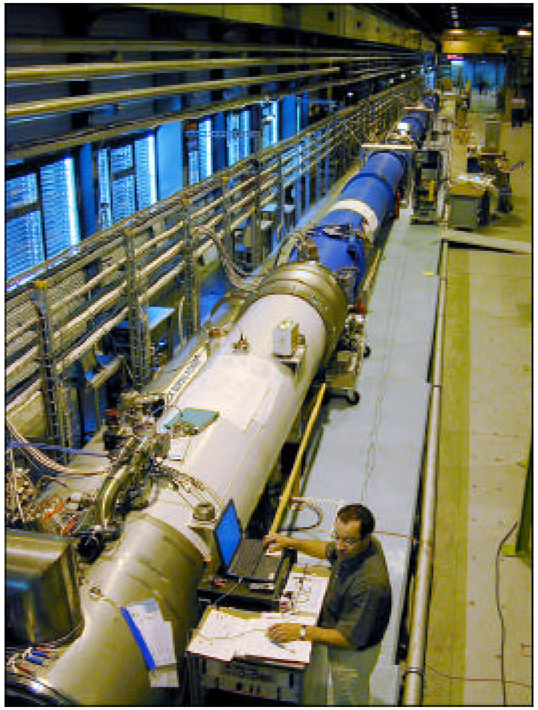
The LHC and its parameters

- **pp collisions @ $\sqrt{s}$ = 14 TeV**
  - ➲ 1104 dipoles with B = 8.3 T (NbTi @ 1.9 K)
- **25 ns bunch spacing**
  - ➲ 2835 bunches (10^{11}p/bunch)
- **L_{design} = $10^{34}cm^{-2}s^{-1}$**

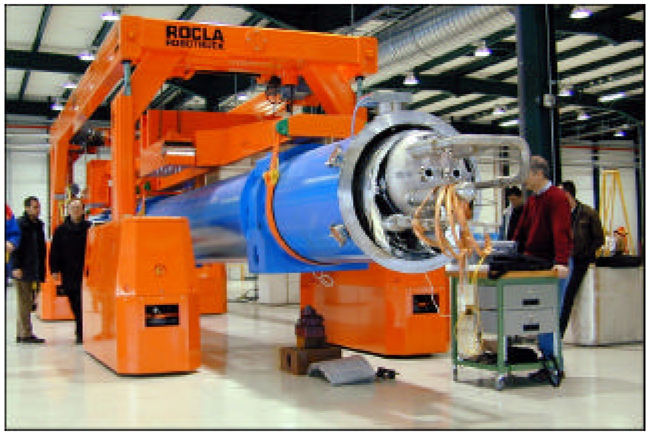
  ($\rightarrow$ 100 fb^{-1} / year)
  - ➲ 23 inelastic events / bunch crossing



The LHC: making it real



String 2 / Pre-series LHC dipole



ATLAS main /electronics cavern (UX15/USA15)

Present LHC schedule

- As of January 2001 (watch this space for updates ... !)

- Apr.-Sep. 2004 sector test with pilot beam
- Feb. 2006 first beam
- Apr. 2006 first collisions

  luminosity of $5\text{-}10 * 10^{32}\ cm^{-2}\ s^{-1}$

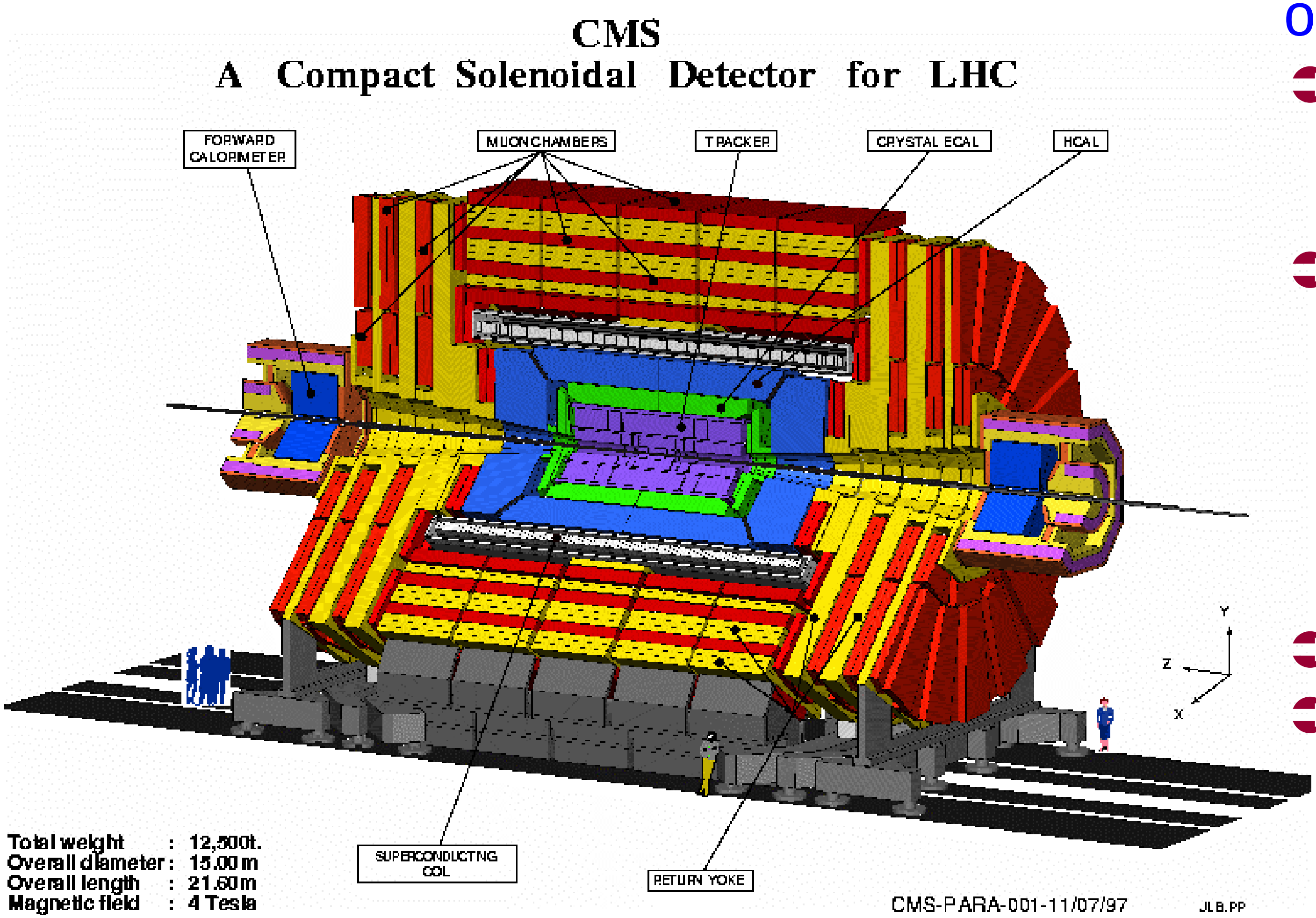
- May-July 2006 shutdown
- Aug. 06 - Feb. 07 physics run

  luminosity of $2 * 10^{33}\ cm^{-2}\ s^{-1}$

  leading to $L_{integrated} = 10\ fb^{-1}$

- Mar. 07 - Apr. 07 heavy ion run

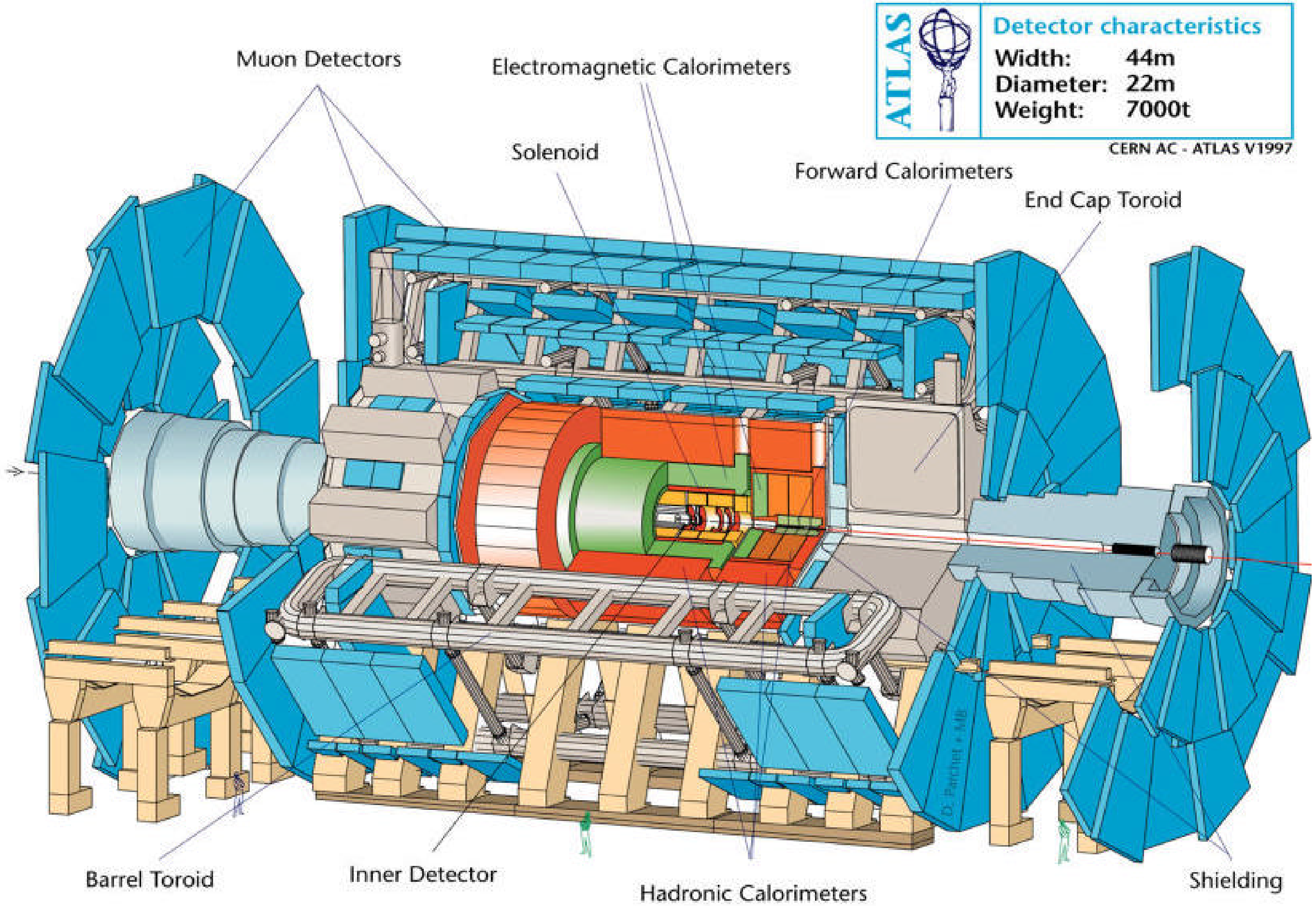
The CMS experiment



From inside out:

- Tracking
  - Silicon pixel
  - Silicon strip
- calorimeters
  - $PbWO_4$ crystals for e.m. part
  - Scintillator based for hadr. part
- 4T solenoid
- return yoke instrumented with muon chambers

The ATLAS experiment



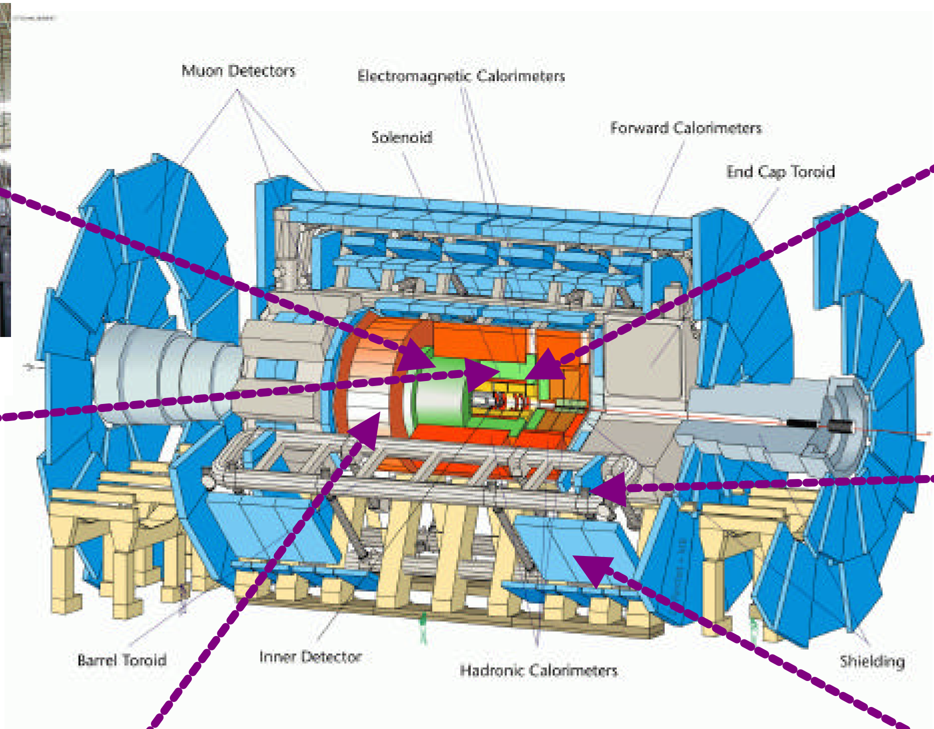
- not shown
  - **trigger and data acquisition**
  - **software (offline reconstruction)**

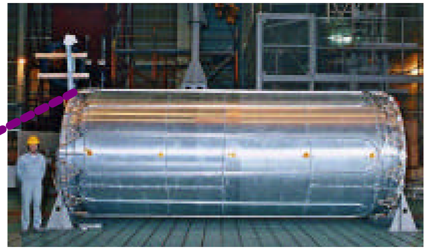
From inside out:

- Inner Detector
  - Silicon pixel and strip
  - Transition radiation tracker (TRT)
- 2T solenoid
- e.m. and hadronic calorimeters
  - LAr and scintillator tile based
- air core toroids and muon detectors

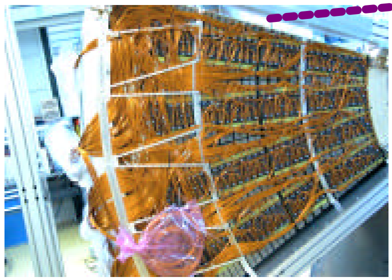
ATLAS: towards reality …

LAr Calorimeter Cryostat

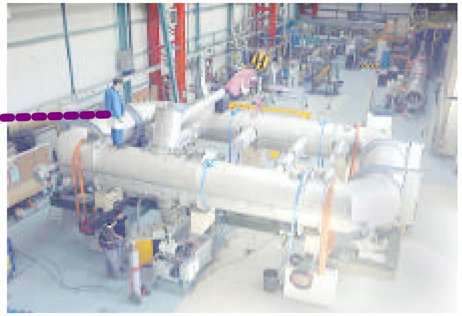




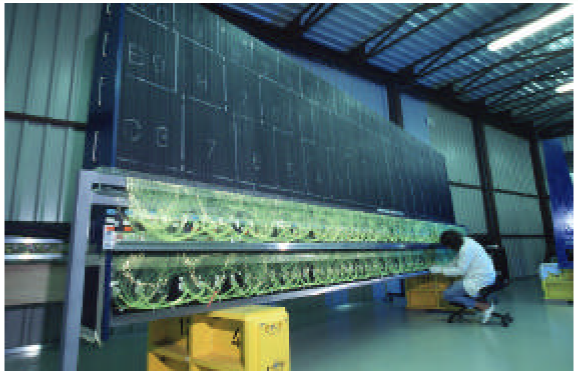
Solenoid magnet



LAr e.m. barrel module



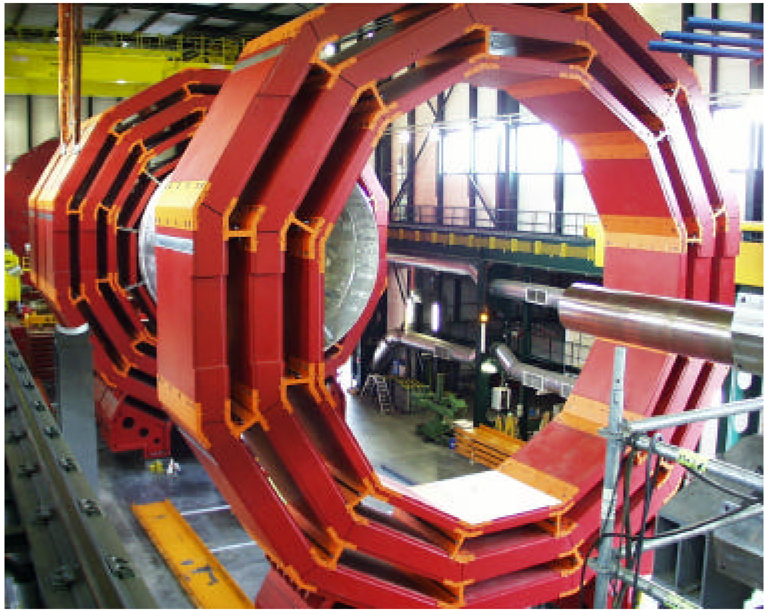
Barrel toroid prototype



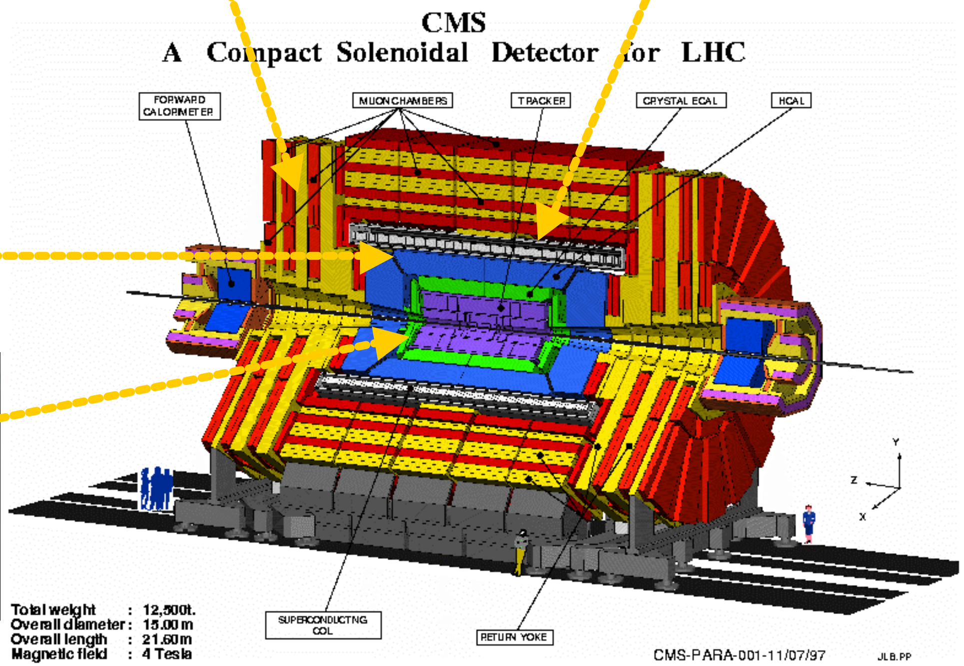
Tile Calorimeter Module(s)

MDT chamber assembly

CMS: towards reality …



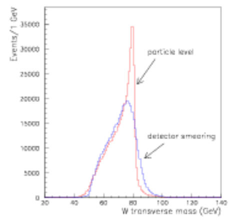
Coil winding machine for solenoid



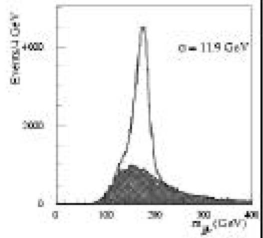
CMS HCAL half barrel (absorbers)

The LHC physics programme

- Precision measurements
  - ➲ m_W to 15 MeV, m_{top} to 1.5 GeV
  - ➲ TGC, $\sin^2 \theta_l^{eff}$, ...
- Higgs physics
  - ➲ discovery(SM): full mass range
    - ❍ mostly several channels
  - ➲ determine properties
    - ❍ mass, width, B.R., spin (?)
  - ➲ A,H and $H^{\pm}$ can not be discovered over full parameter space
- Physics beyond the SM
  - ➲ SUSY: $\tilde{q}$, $\tilde{g}$ up to 2.5 TeV
  - ➲ W'(Z') bosons up to 4.5(6) TeV
  - ➲ compositeness up to 40 TeV

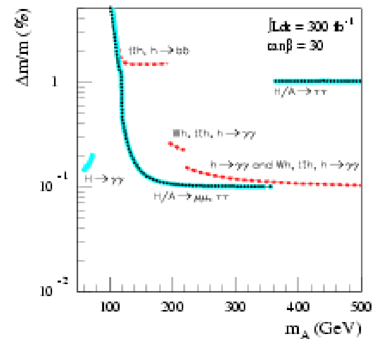


Δm_W

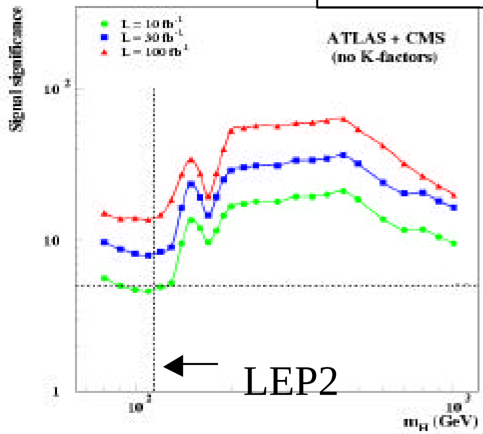


Δm_{top}

SM Higgs

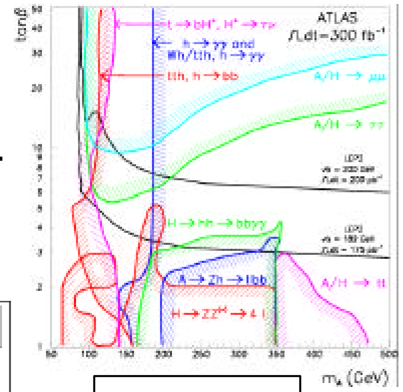


Δm_H

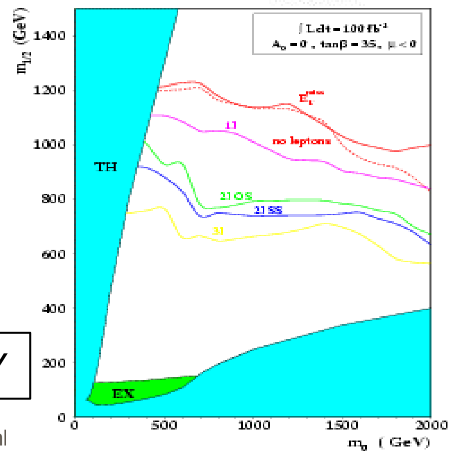


5σ

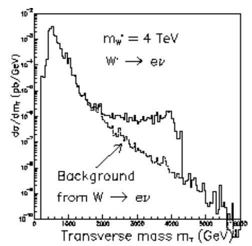
LEP2



MSSM Higgs



SUSY



W'

Signatures in ATLAS/CMS

- Detectors have been optimized for high p_T signatures
  - Needed for Higgs discovery and measurement
  - Search for new physics beyond the Standard Model
- precision measurement of **e, g, m, t, b-jets**:
  - tracking: $|\eta| < 2.5$
  - fine granularity calorimeters: $|\eta| < 2.5$
  - muon system: $|\eta| < 2.7$
- measurement of **jets, missing transverse energy**
  - calorimeter coverage extended up to $|\eta| < 5$
- ingredients for precision measurements
  - knowledge of the **energy scale**
    - for leptons (electrons and muons): aim is 0.1%
    - for jets (b-quark jets and light quark jets) aim is 1%
  - knowledge of the **absolute luminosity**
    - normalize to parton-parton luminosity ? (e.g. W production)

ATLAS and CMS performance

	ATLAS	CMS
MAGNET (S)	Air-core toroids + solenoid in inner cavity Calorimeters outside field 4 magnets	Solenoid Calorimeters inside field 1 magnet
TRACKER	Si pixel + strips TRD $\rightarrow$ particle identification B=2T $\sigma/p_T \sim 5\times10^{-4}\, p_T \oplus 0.01$	Si pixel + strips No particle identification B=4T $\sigma/p_T \sim 1.5\times10^{-4}\, p_T \oplus 0.005$
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-scintillator + Cu-liquid argon (10 λ) $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$	Cu-scint. (> 5.8 λ + catcher) $\sigma/E \sim 65\%/\sqrt{E} \oplus 0.05$
MUON	Air $\rightarrow$ $\sigma/p_T \sim 7$ % at 1 TeV standalone	Fe $\rightarrow$ $\sigma/p_T \sim 5\%$ at 1 TeV combining with tracker

QCD at the LHC: Why?

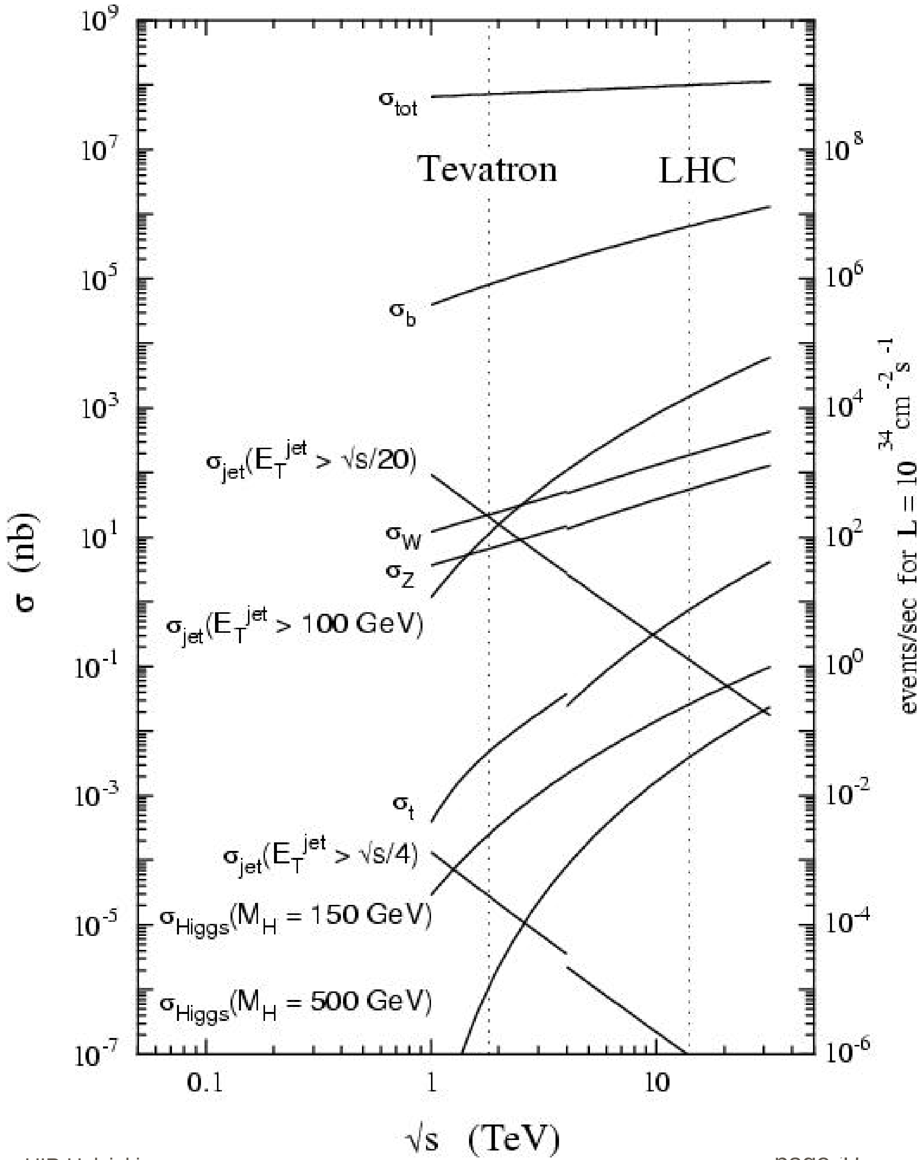
- QCD is one of the least well tested parts of the Standard Model
  - interest ‘per se’ (new phenomena at energy frontier?)
  - precision measurements of QCD observables
    - strong coupling constant α_s, parton distribution functions
      - and all the other ‘tests of QCD’ ...
- Knowledge of background (and signal) processes essential for searches and precision measurements
  - QCD controls production of (almost) everything
  - higher order corrections difficult to calculate
  - improve modelling of Monte Carlo generators
  - Quantify (and improve) uncertainties due to knowledge of parton distribution functions

QCD at the LHC: What?

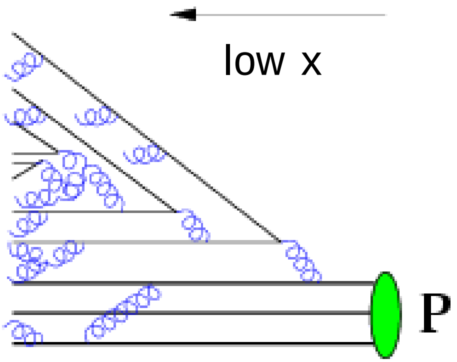
- the strong coupling constant (up to O(TeV) ?)
  - using jet production (jet shape), photon-to-jet ratio, ...
- parton densities of the proton
  - small $x_{Bjorken}$ values (for large Q^2 !)
- Study QCD dynamics in new kinematic regions
  - BFKL signatures
- structure of minimum bias events
  - Understand jet production at small E_T values (jet veto!)
- diffractive scattering
  - LHC as a Pomeron-Pomeron collider with $\sqrt{s}$ = O(TeV)
- exclusive production of central states
  - precise (model independent) mass measurements
- heavy ion collisions (not discussed here)
  - ➲ Including p-A, understand nuclear structure

QCD at the LHC: How?

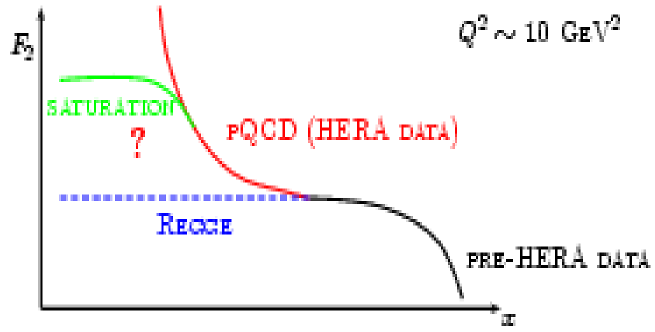
- High p_T signatures
  - jets
  - photons
  - W/Z bosons and Drell-Yan
    - electrons, muons
  - heavy flavour production
    - b-quark jets, (B-hadron studies)
- other signatures
  - minimum bias events
  - leading protons
    - elastic/diffractive scattering
  - rapidity gaps
    - tools for new physics searches
  - event multiplicity
- huge range of cross-sections
  - need for efficient online selection (trigger)

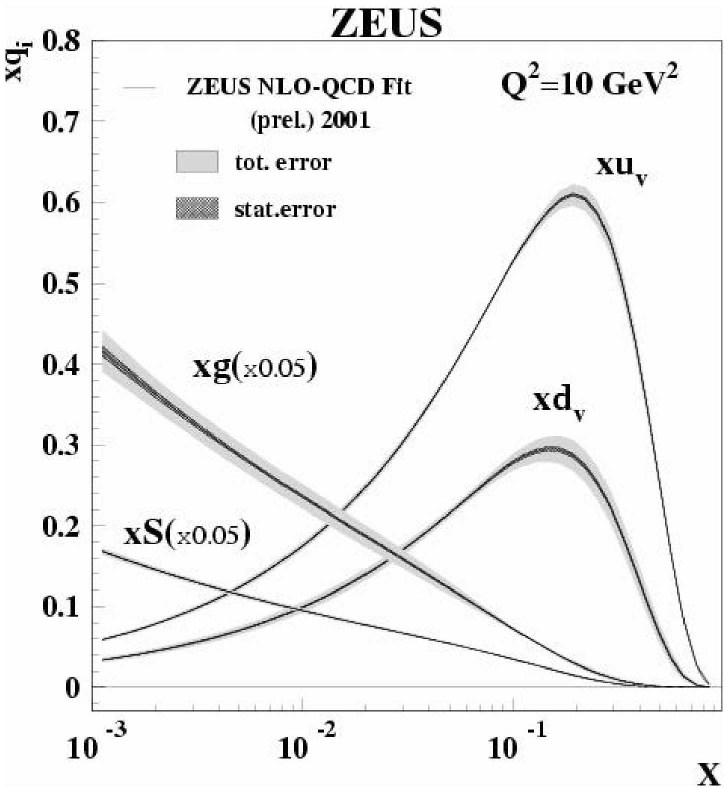


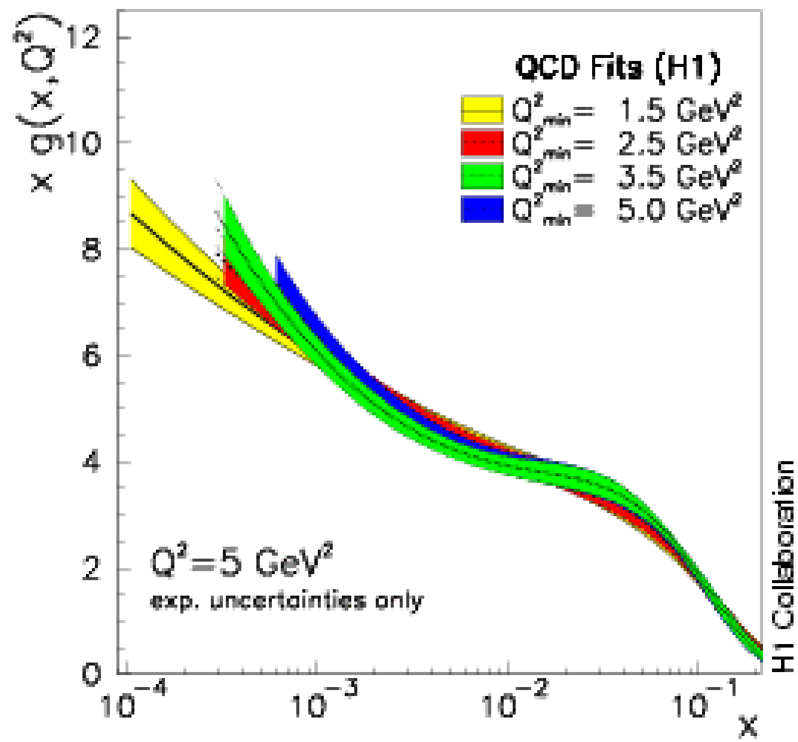
Proton structure from HERA



- QCD dynamics at low x?
  - ➲ Rise of the gluon density cannot continue for ever
    - Saturation, parton-parton recombination

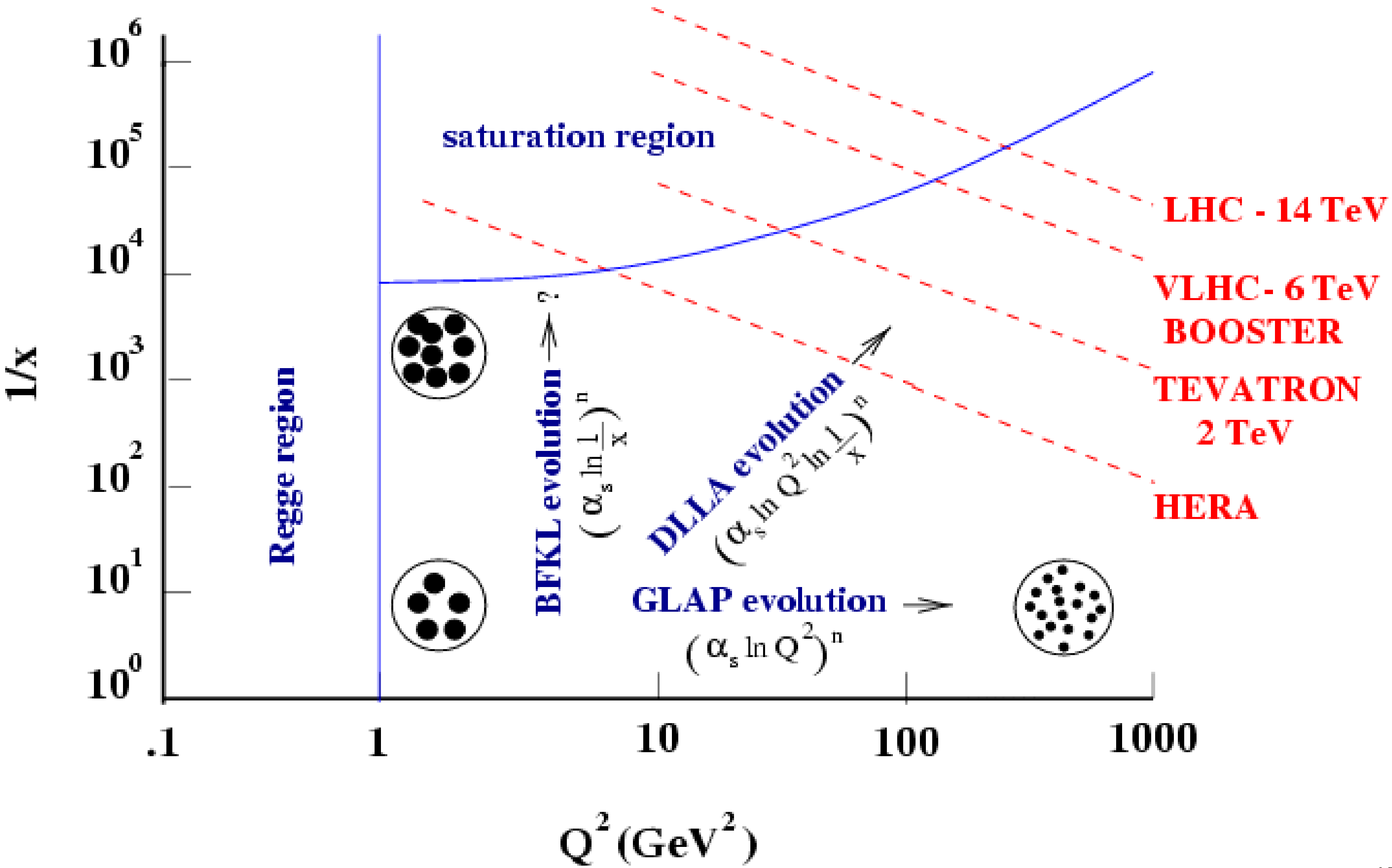






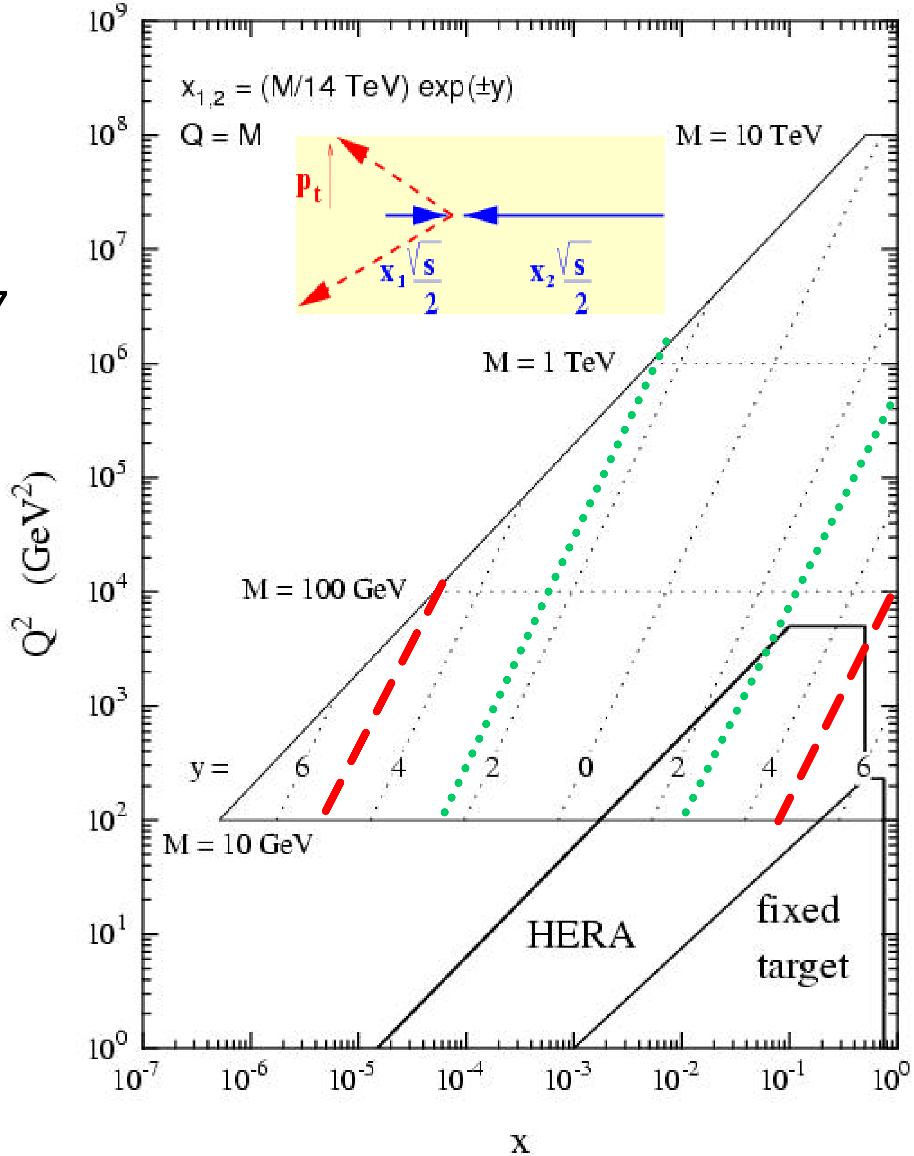
Partons in the proton

Ellis, Sterling & Webber "QCD and Collider Physics"



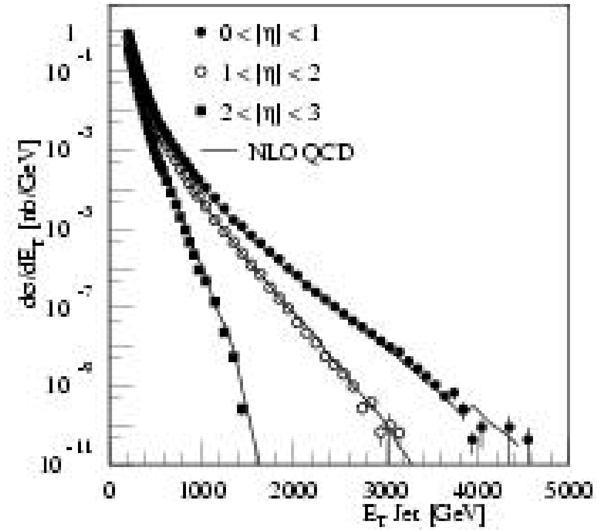
Parton Kinematics at the LHC

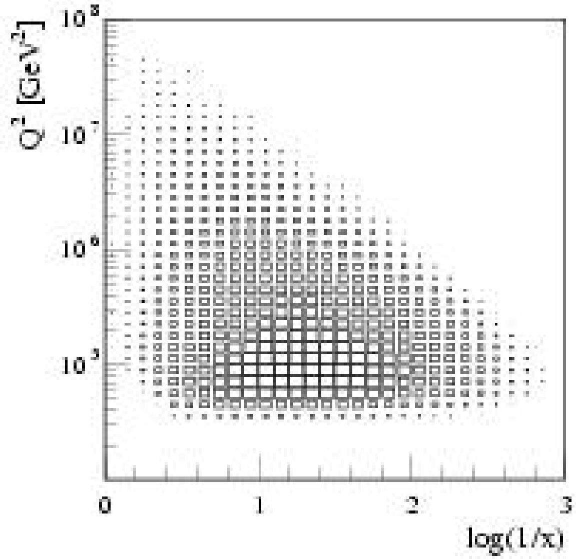
- Proton structure at LHC
  - highest Q^2 values (10^8 GeV^2)
    - with reach to small x
  - e.g. production of W/Z bosons ($Q^2 \approx 10^4$ GeV^2): $5*10^{-4} < x < 0.07$
- Wide range of signatures
    - W/Z, Drell-Yan, jets, g, ...
  - Different sensitivity to quark and to gluon distributions
- Important: pdf's with errors!
  - To move away from comparing different parametrisations
- Extension of rapidity coverage beyond **2.5** (**5**) ?
  - To access really low x values
    - Needs small M !
  - See Episode II



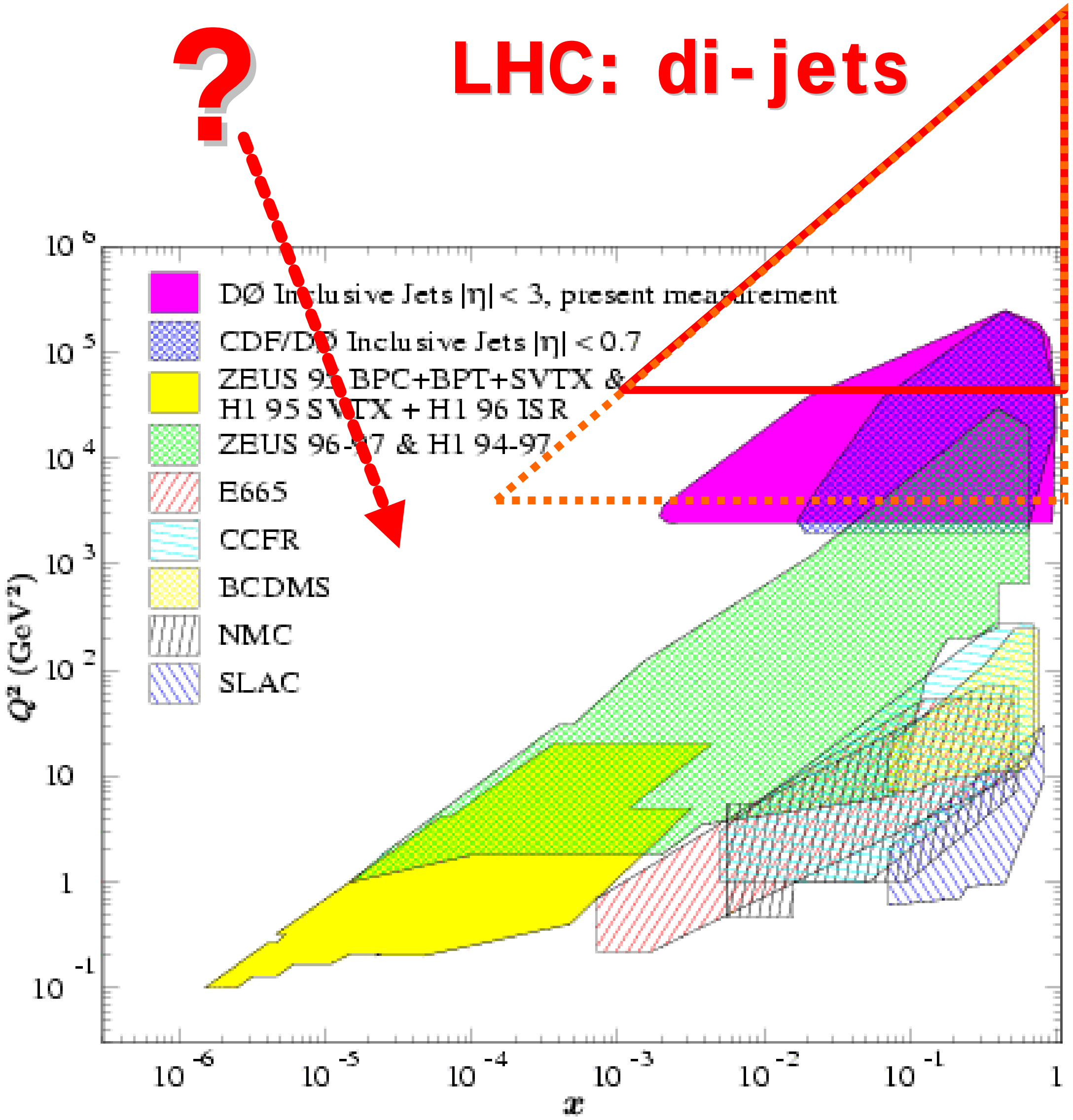
Jets and partons

- Access to smallest scales (highest E_T)
  - due to large cross-section (wrt to γ,...)
- uncertainties
  - how to best define a jet
    - CONE vs. k_T algorithm(s)
      - e.g. usage for jet shape measurements
  - energy scale for jets
    - e.m. and hadronic showers components
    - extrapolation to highest E_T necessary
      - limited reach in E_T of in-situ calibration
  - effects of the underlying event (low E_T)
- parton densities from jet production
  - access to largest kinematic range
    - due to largest cross-sections
  - very high Q^2 possible
  - BUT: mixture between quarks and gluons

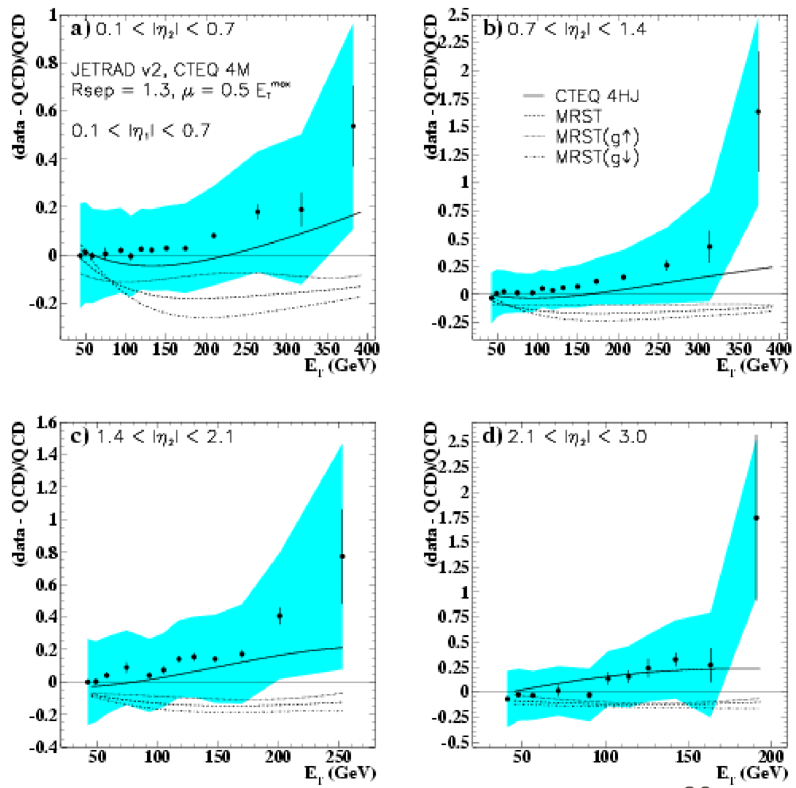




Tevatron results: di-jet production

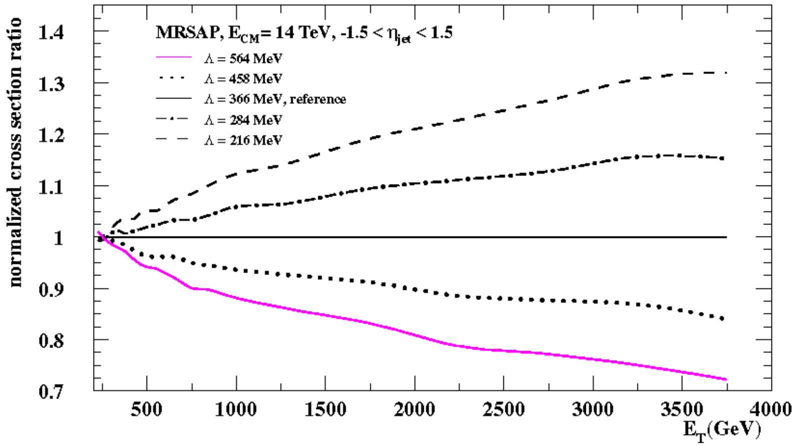


- LHC will cover the region down to $x_{Bjorken} \approx 10^{-4}$
  - ➲ large Q^2 values: $Q^2 > 10^3 GeV^2$
- CDF di-jet results:

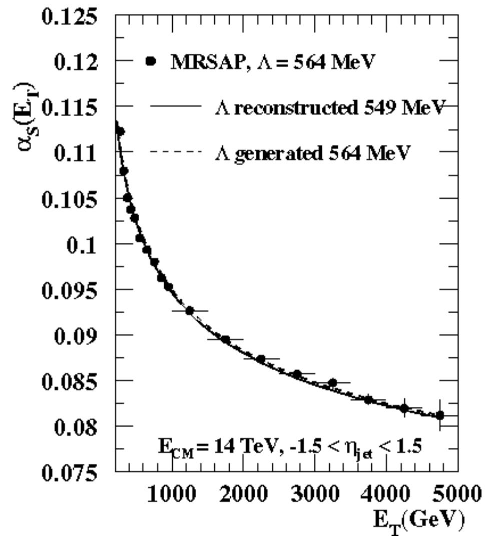


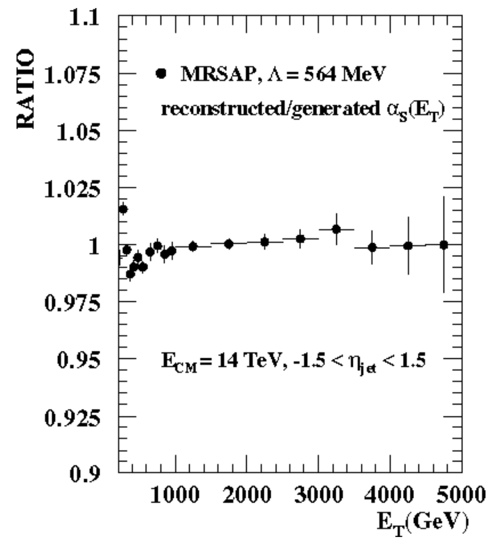
α_s determination using jets

- Study the variation in the shape of the inclusive jet cross-section
- $\sigma_{norm}(E_T) = d^2\sigma/dE_T d\eta \,/\sigma_{jettot}$
  - Shows dependence on Λ_{QCD} value



- Parameterise the normalised cross-section as
  - $\sigma_{norm} = a(E_T) + b(E_T)\, \alpha_s(E_T)$
- Determine the coefficients a and b using NLO calculations
  - will depend on parton distributions
- Unfold $\alpha_s(E_T)$ from a ‘measured’ cross-section
  - See plots on the right for consistency check

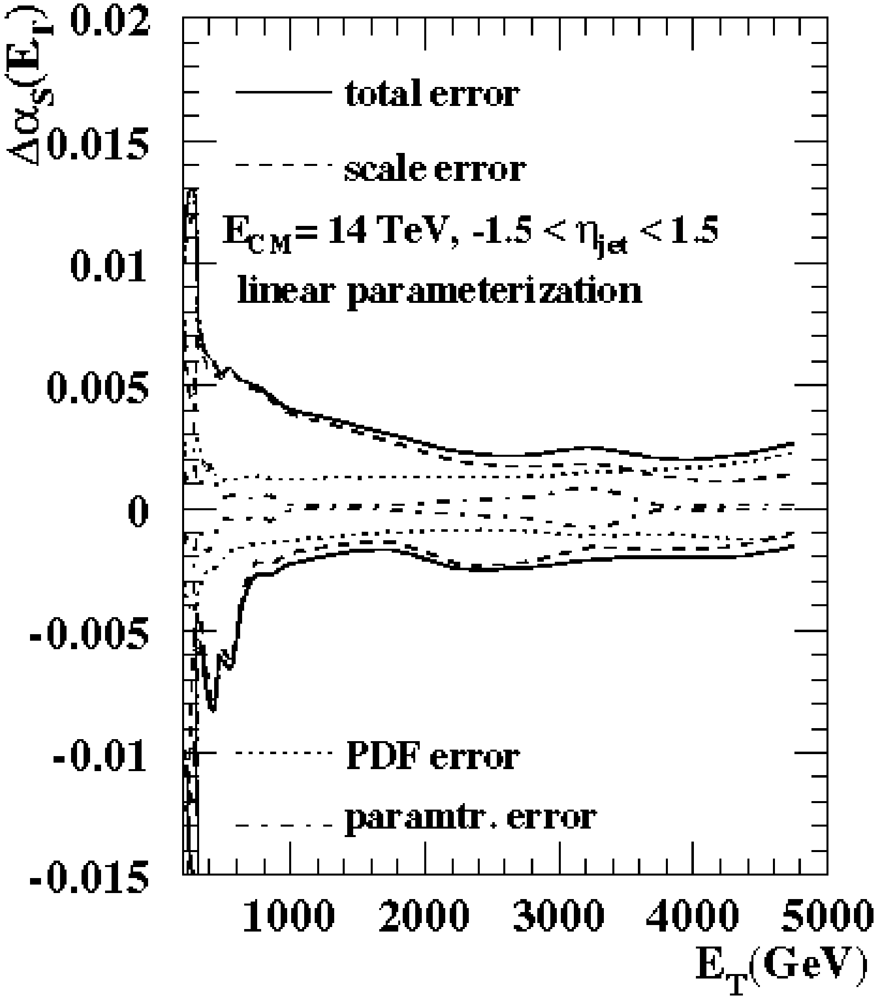




H. Stenzel, ATL-PHYS-2001-003

α_s determination using jets

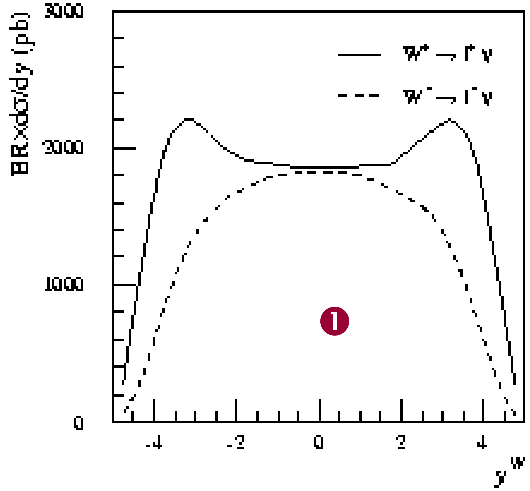
- Extraction of $\alpha_S(E_T)$
  - expected accuracy in total: about 10%
    - Dominant sources: missing higher order corrections
    - Pdf and parametrisation uncertainties: about 3 %
  - Should allow to check on "running" of α_S up to O(TeV)
  - experimental errors not yet taken into account
    - Jet energy scale knowledge etc.
- Reduce dependence on pdf's
  - By making a combined fit of pdf's and α_S ?

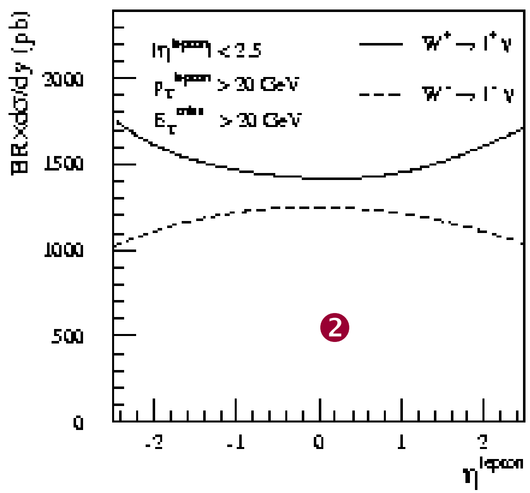


H. Stenzel, ATL-PHYS-2001-003

Drell-Yan and W/Z Physics

- Final states with electrons or muons
  - clean signature (and large cross section)
    - but for electrons
      - background from jets
        (esp. in case of W production)
- features of W production
  - different rapidity distribution for W^+/W^- bosons (❶)
    - still visible in pseudo-rapidity of the charged lepton from W decay (❷)
    - use to determine parton densities (quarks)
  - use W's for parton-parton luminosity?
  - Measure W p_T distrib. (needed for m_W)



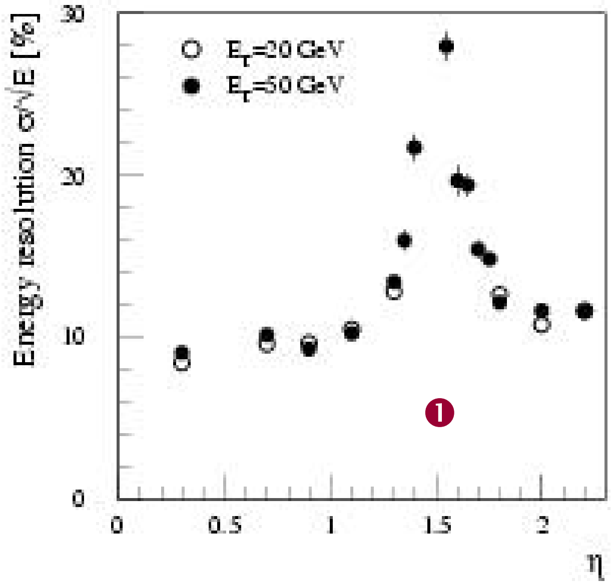


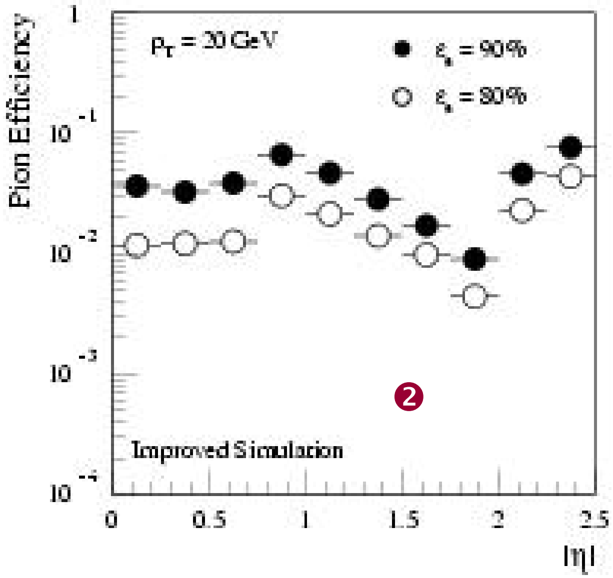
❶ Rapidity distribution of $W^{+/-}$ bosons

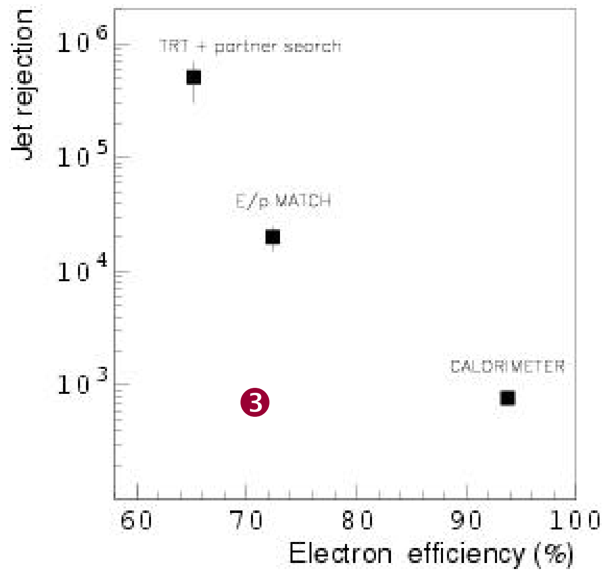
❶ Pseudo-rapidity distribution of leptons from $W^{+/-}$

Detector Performance for Electrons

❶ electron energy resolution vs. η (E_T = 20 and 50 GeV)
❷ π efficiency vs. $|\eta|$ for two electron efficiencies (TRT)
❸ jet rejection vs. electron efficiency (E_T = 20 GeV)



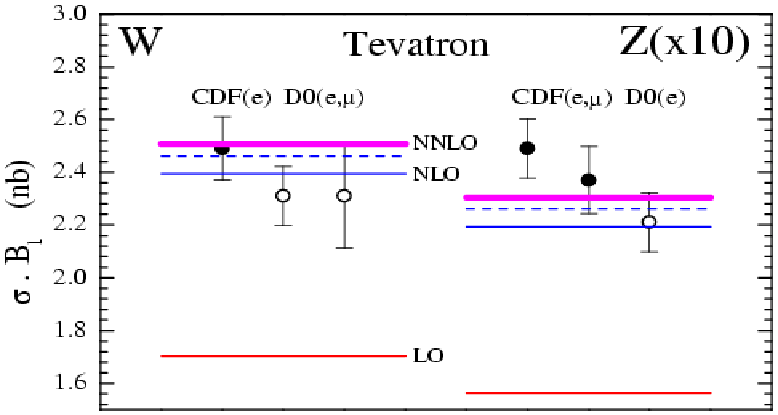


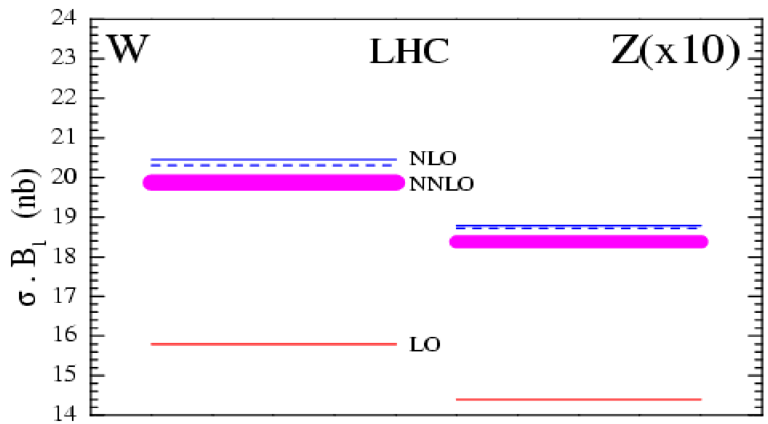


- Aim: electro-magnetic scale to be known to 0.1%, using e.g.
  - ➲ high energy: $Z \rightarrow e^+e^-$ and E/p ratio of electrons
  - ➲ low energy: $J/\Psi \rightarrow e^+e^-$ and $\Upsilon \rightarrow e^+e^-$

W/Z cross-section expectations

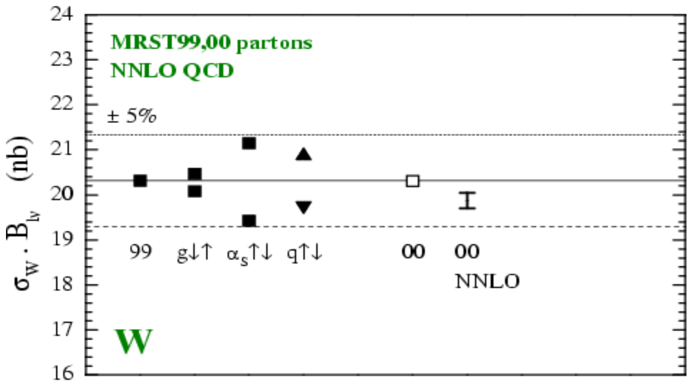
- A.D. Martin, R.G. Roberts, W.J. Stirling, R.S. Thorne in Eur. Phys. J. C18, 117 (2000)

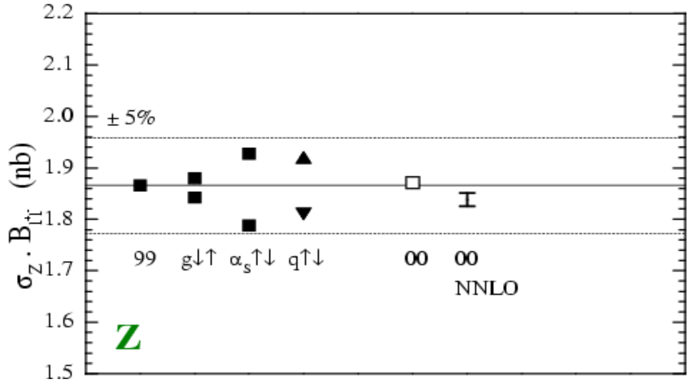




- A.D. Martin, R.G. Roberts, W.J. Stirling, R.S. Thorne in Eur. Phys. J. C14, 133 (2000)

W and Z Cross Sections: LHC

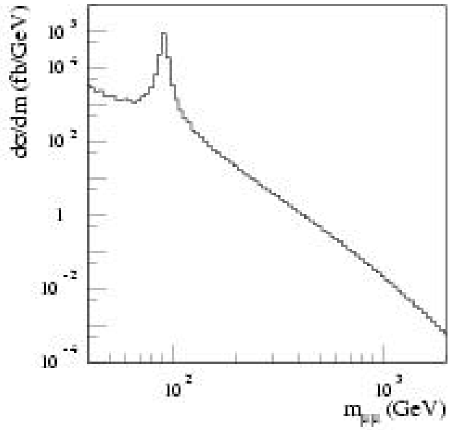


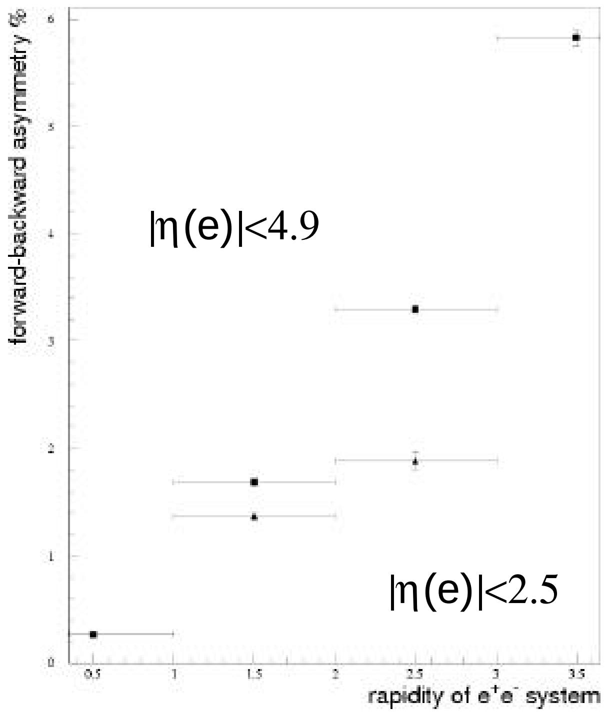


- Clear need for NLO
- NNLO corrections smaller than NLO
  - ➲ NLO due to soft gluon emission
- $\sigma_{W/Z}$ known to 4% for LHC
  - ➲ Dominating uncertainties due to α_s knowledge and q densities

$\sin^2\theta_{eff}^{lep}$ from A_{FB} in $Z \to e^+e^-$

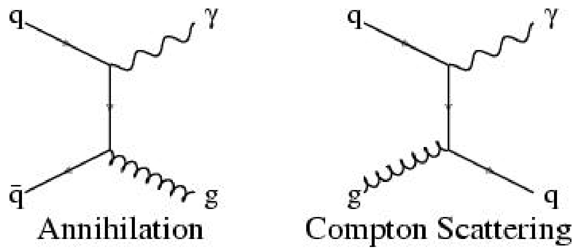
- Forward-backward asymmetry in Z decays
  - LEP: $\sin^2\theta_{eff}^{lep}$ to $2.3*10^{-4}$ accuracy
  - Determine $\sin^2\theta_{eff}^{lep}$ at LHC?
    - Large number of Z being produced
- Size of the asymmetry increases with increasing rapidity of the Z
  - Gain in sensitivity if forward ($|\eta|>2.5$) electron tagging possible (modest rejection against jets: $\approx$ 50 - 100)
    - In combination with Z mass constraint and a well defined (central) electron
  - Statistical accuracy of $1.4*10^{-4}$ possible
  - Needs precise knowledge of quark/anti-quark densities
    - $|\eta|<2.5$: $5*10^{-4} < x < 0.07$
    - $|\eta|<4.9$: $4*10^{-5} < x < 0.8$

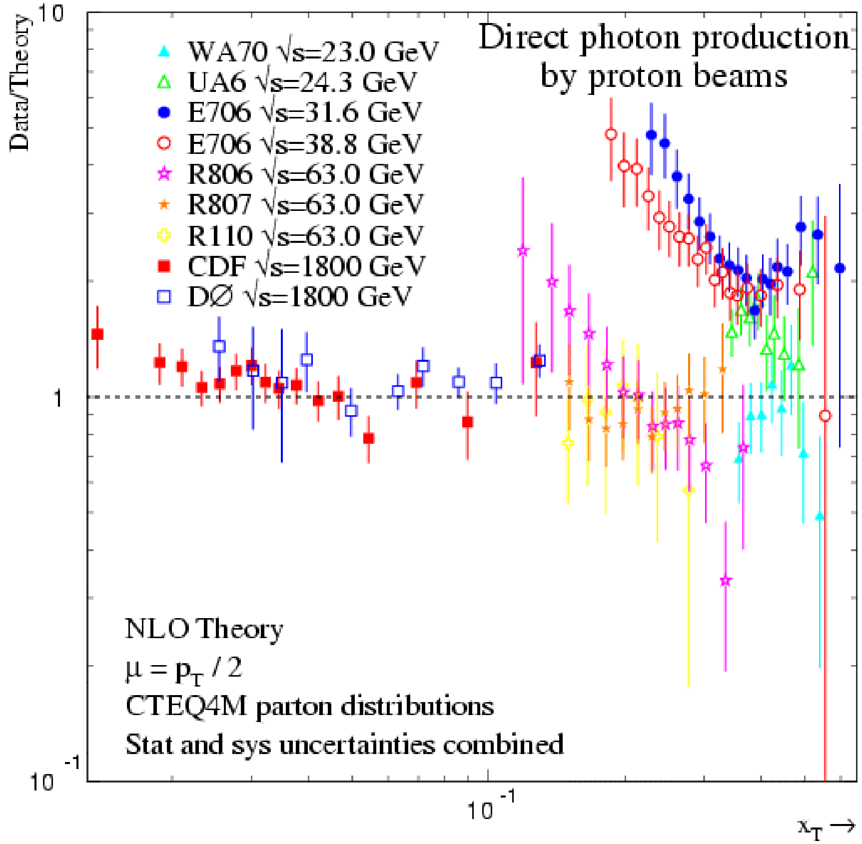




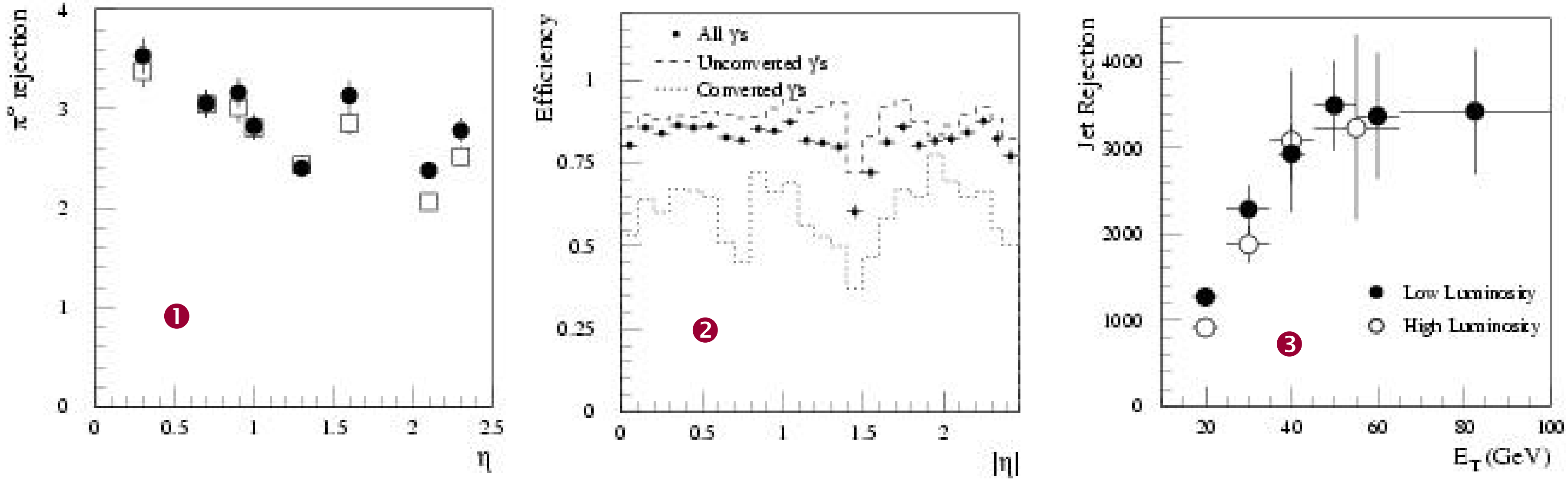
Direct Photon production

- LO: direct access to g distribution
  - two partonic processes contribute
    - cf. π^0 production (via fragmentation)
- Caveat: γ's are produced as well via fragmentation
  - all partonic processes contribute
- Apply isolation criteria
  - Needed experimentally to improve S:B ratio
  - Suppress the fragmentation contribution
    - Being essentially a collinear process
- Fixed target data and Tevatron data
  - as a function of **x_T = 2 p_T/Ös**
  - Disagreement between data and theory (NLO)
    - Needs to be understood!





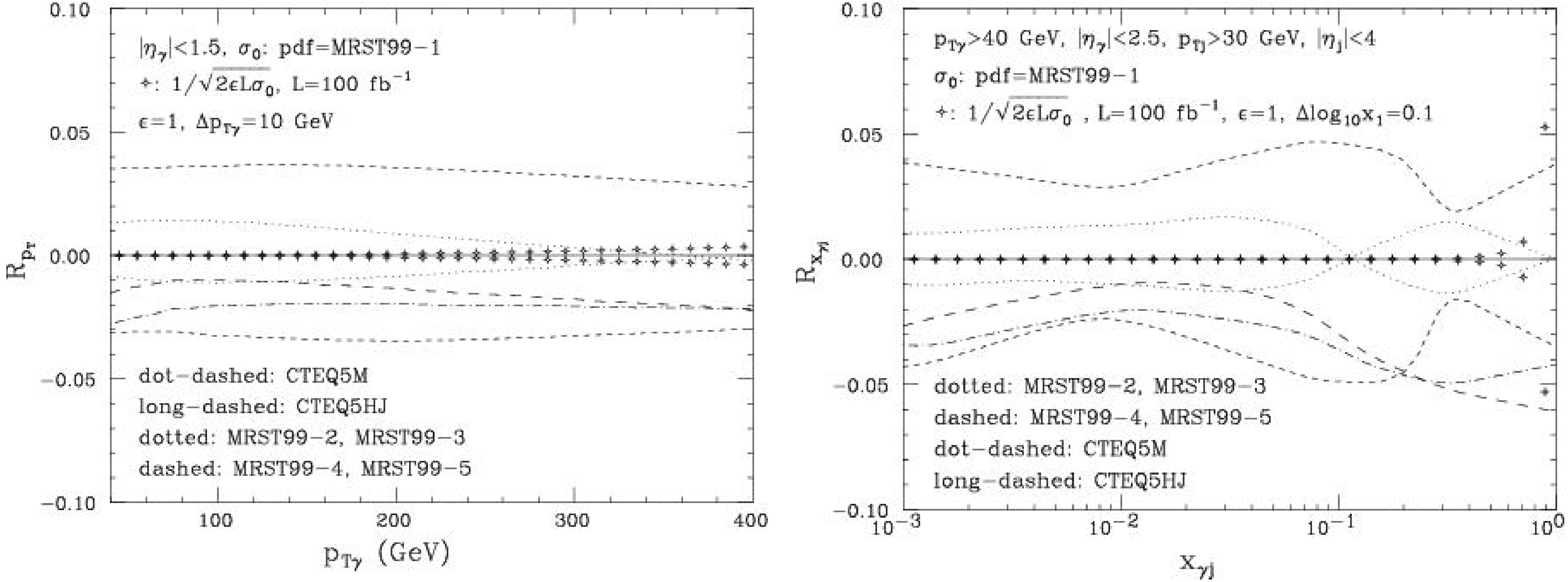
Detector Performance for Photons



- ❶ Rejection against π^0's (for $E_T(\gamma)$ = 50 GeV and 90% eff.)
  - ➲ Without (●) and with (□) electronic and pile-up noise (design luminosity)
- ❷ Photon reconstruction efficiency vs. η (low luminosity)
  - ➲ for unconverted and converted photons (from $H \to \gamma\gamma$)
- ❸ Jet rejection vs. photon E_T
  - ➲ for the photon efficiency shown in ❷
  - ➲ Ratio of inclusive photon cross-section to inclusive jet cross-section is about 10^{-3} (for p_T > 40 GeV)

Sensitivity on parton distributions

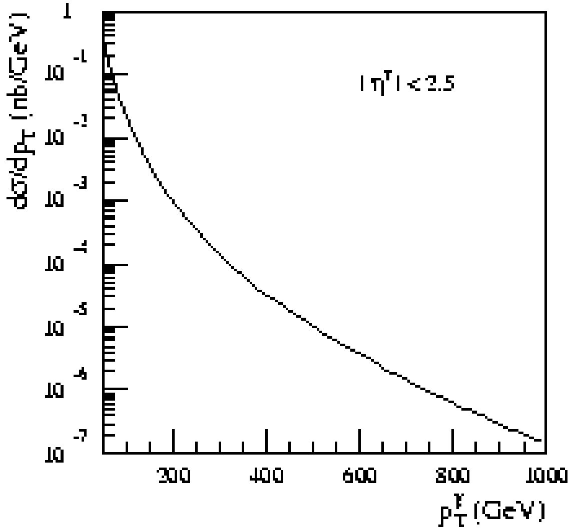
S. Frixione, W. Vogelsang (proceedings Les Houches 1999)



- Isolated photon (photon + jet) cross-section vs. $p_{T\gamma}$ ($x_{\gamma j}$)
  - $R = (\sigma_0 - \sigma)/(\sigma_0 + \sigma)$ and $x_{\gamma j} = (p_{T\gamma}\exp(\eta_\gamma) + p_{Tj}\exp(\eta_j))/\sqrt{s}$
- Statistics for 100 fb^{-1} offer potential to distinguish various pdf sets available today (better constraints when using γ + jet production)
  - $p_{T\gamma}$ gives no information on the shape of the gluon distribution
  - $x_{\gamma j}$ should allow direct unfolding from the data

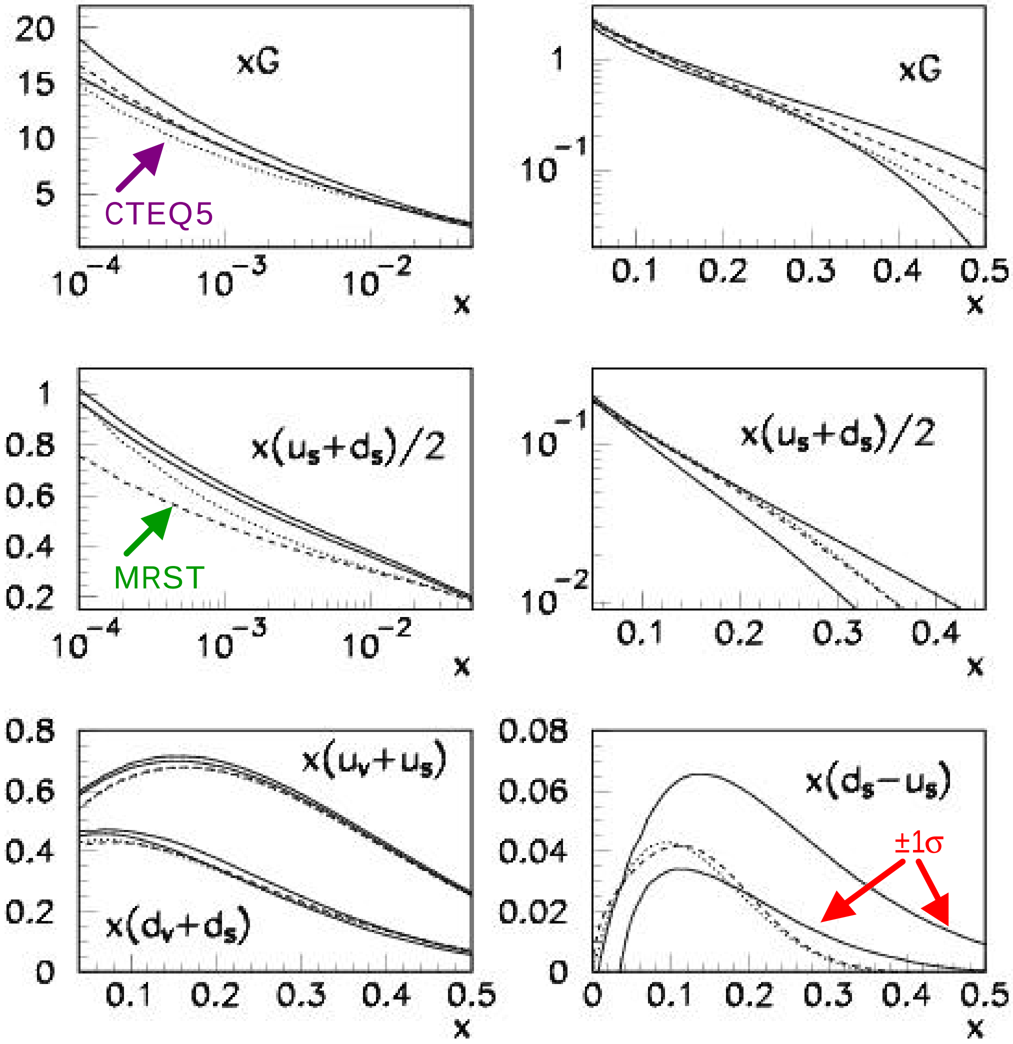
Direct Photon Production at LHC

- Cross-section for single photon production
  - Huge statistics expected, e.g. **$2*10^4$** events with $p_T(\gamma)$ > 500 GeV
    - for 1 year at low luminosity
  - Kinematics
    - $x_{min} = 2E_T^{min}/\sqrt{s}\, e^{-\eta(max)}$
    - $x_{max} = 2E_T^{max}/\sqrt{s}\, e^{\eta(max)}$
  - With $|\eta|<2.5$
    - $E_T >$ 40 GeV: $x > 5*10^{-4}$
    - $E_T <$ 500 GeV: $x < 0.2$



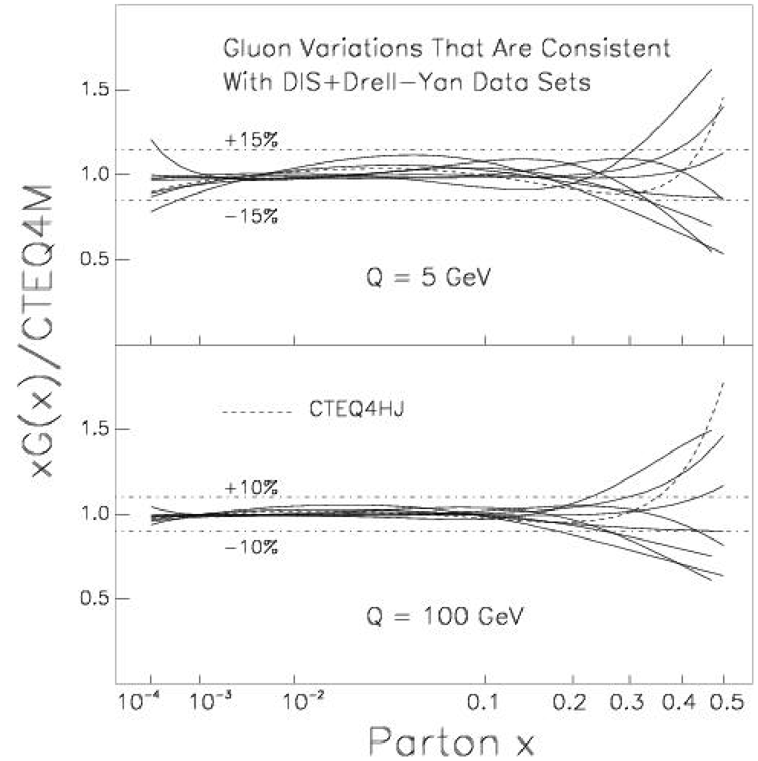
- Determination of the strong coupling constant
  - Exploratory study by S. Frixione (CERN SM Workshop 1999):
  - $\aleph(p_T) = (d\sigma_j/dp_{Tj}) \;/\; (d\sigma_\gamma/dp_{T\gamma})$
    - ratio $\aleph$ of the single-inclusive jet cross-section to the single inclusive photon cross-section
  - Proportional to α_s (at leading order), dependencies on the parton distributions cancel to first order

PDF's with uncertainties



S. Alekhin, Phys.Rev.D63, 094022, 2001

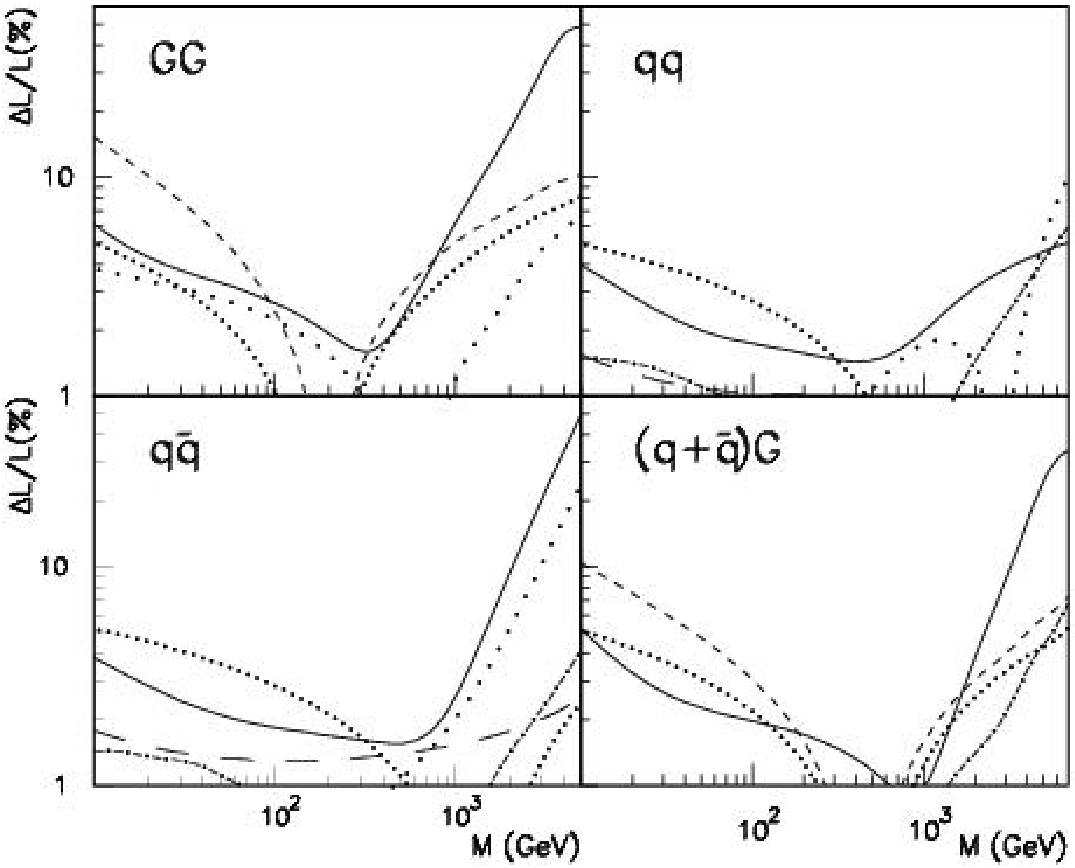
J. Huston et al., Phys.Rev.D58, 114034, 1998



- Many more groups are working to quantify the uncertainties
  - A.D. Martin, R.G. Roberts, W.J. Stirling, R.S. Thorne
  - W. Giele, S. Keller
  - W.K. Tung, J. Pumplin

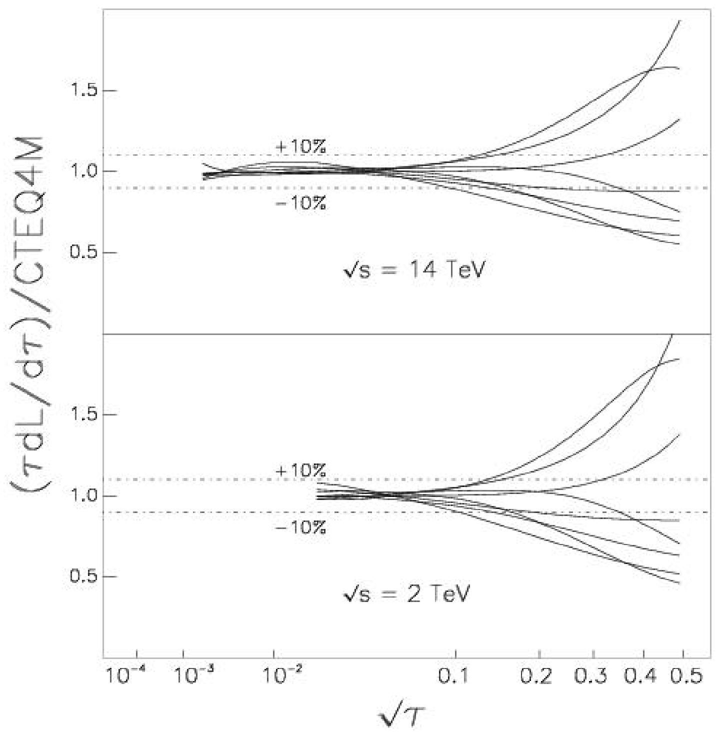
Parton-parton luminosity

$$L_{ij}(M) = \frac{1}{s}\int_{\tau}^{1}\frac{dx}{x}q_i(x,M^2)q_j(\tau/x,M^2)$$



S. Alekhin, Phys.Rev.D63, 094022, 2001

J. Huston et al., Phys.Rev.D58, 114034, 1998



- Uncertainty to produce a system of mass M / $\sqrt{(\tau s)}$
  - Known to better than 10% in most regions
    - E.g. the ones relevant for Higgs production

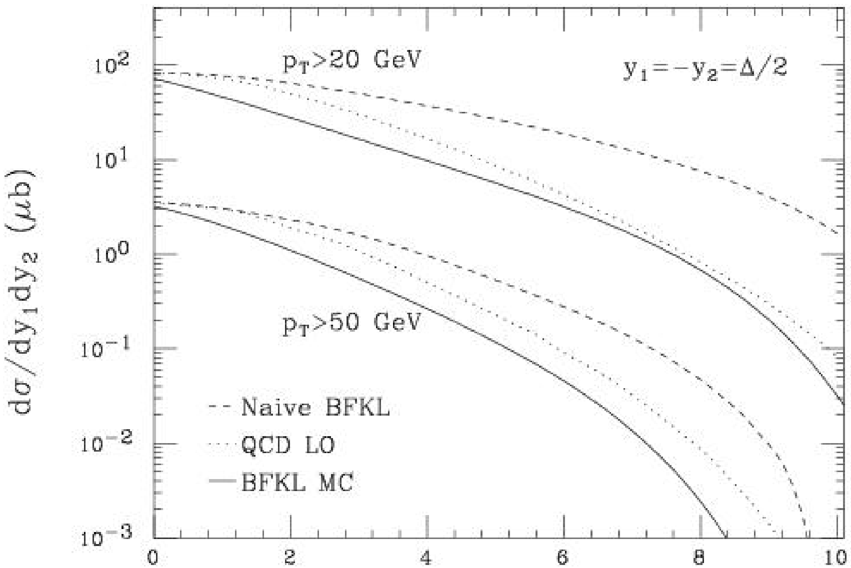
Pertubative QCD & parton evolution

- DGLAP: summation of $\log(Q^2)^n$ terms
  - ➲ Determines Q2 evolution of F_2
- BFKL: summation of $\log(1/x)^n$ terms
  - ➲ Determines x dependence of F_2
    - BFKL Kernel at leading order → $xg(x) \sim x^{-0.5}$
    - BUT: large NLO corrections → $xg(x) \sim x^{-0.2}$
- CCFM: evolution in two scales

- How to detect the presence of BFKL effects (and more, e.g. saturation)?
    - Inclusive measurements (e.g. F_2) not conclusive
  - ➲ Study more exclusive processes
    - Di-jet production at large rapidity separation
      - "Mueller-Navelet jets"
    - $d^2\sigma/d\Delta y/d\Delta\phi(pp \rightarrow j+X+j)$, where $\Delta y=\Delta y(j_1,j_2)$ and $\Delta\phi=\Delta\phi(j_1,j_2)$

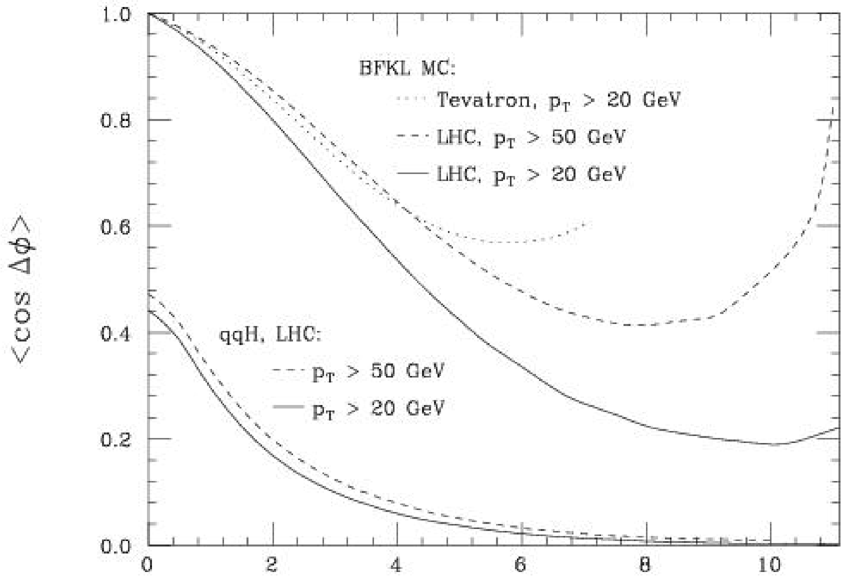
BFKL signatures using di-jets

- Large effect in hard subprocess cross-section is reduced due to folding with parton densities



- Study azimuthal de-correlation between the two jets

L.H. Orr and W.J. Stirling, Phys. Lett. B436, 372 (1998)



- LHC detectors (baseline design) offer a range of $-5 < y < 5$
  - Experimental issue: how low in E_T can one trigger such events?
    - Forward energy/jet trigger will be available up to $|\eta|=5$
  - Other processes: W+jet+jet, bb+bb (trigger restricted to $|\eta|<2.5$)
    - Use of Z+jet+jet might allow access to larger y (one loose electron $|\eta|<5$ – cf. $\sin^2\theta_{eff}^{lep}$)

End of Episode I

- CMS and ATLAS have been optimized for high p_T signatures for discovery physics
  - Will allow precise QCD related measurements without additional resources
  - A detailed understanding of QCD will be of utmost importance for discovery and measurements of new physics
    - Do not want to rely on Monte Carlo modelling of physics processes!
- LHC will study the strong interaction in an as yet uncovered kinematical region
  - Strong coupling constant up to scales of O(TeV)
  - Partonic structure of the proton at very large Q^2 and low x
  - And many more related publications (cf. Tevatron results)
- But this is not the end of the story
  - In order to exploit the new energy frontier at its most, an extension of the general purpose 4p detectors is necessary
  - Stay tuned for Episode II of the saga on “QCD at LHC” ...

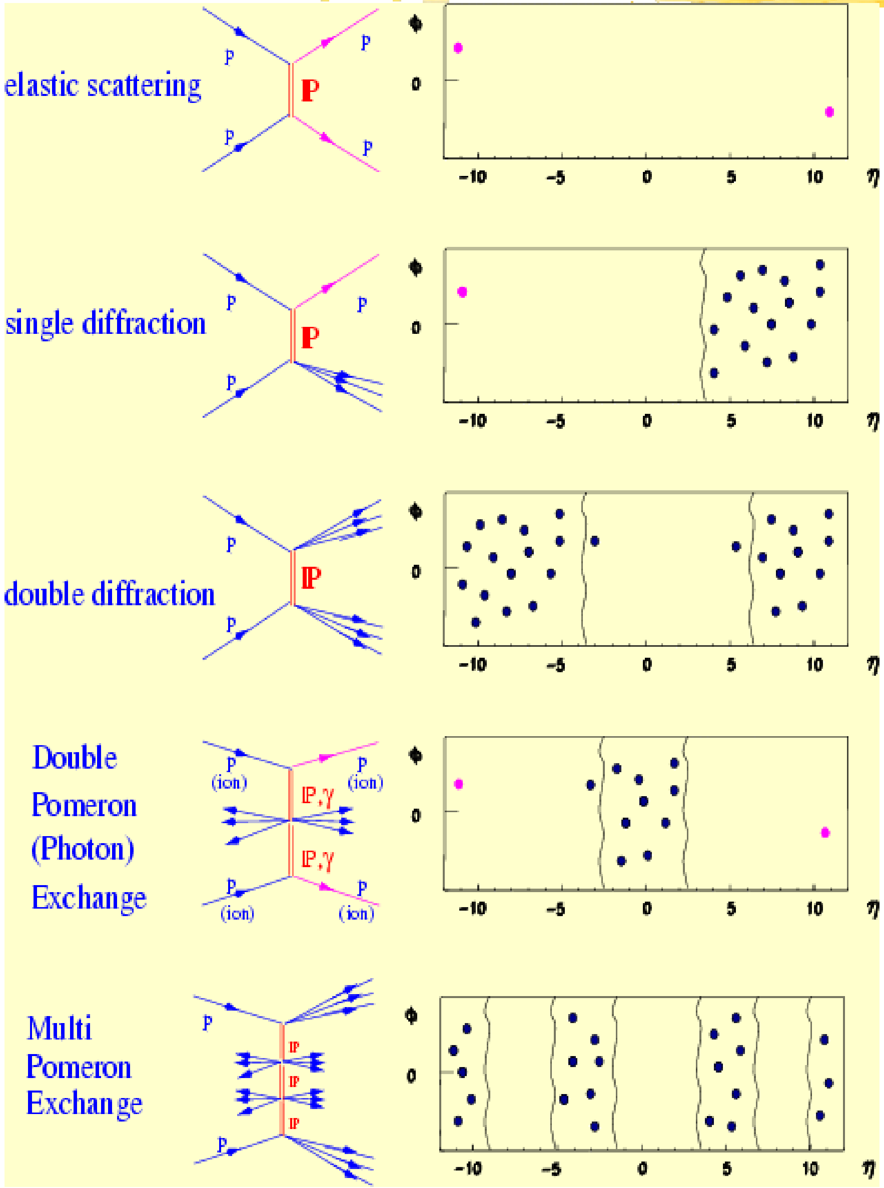
Episode II: 'Beyond the baseline'

- CMS and ATLAS have been designed and optimized for discovery physics
  - high p_T signatures in central region ($|\eta|<5$)
- Is there anything else that should / can be done at LHC?
  - YES: Forward Physics
    - Not covered by the baseline design of ATLAS and CMS
    - Diffractive processes contribute to a large part of σ_{tot}
  - Signatures:
    - leading protons, extended coverage for rapidity gaps, particle detection beyond $|\eta| = 5$
  - Integration with central detector mandatory for optimal exploitation
- Dedicated experiment foreseen: TOTEM

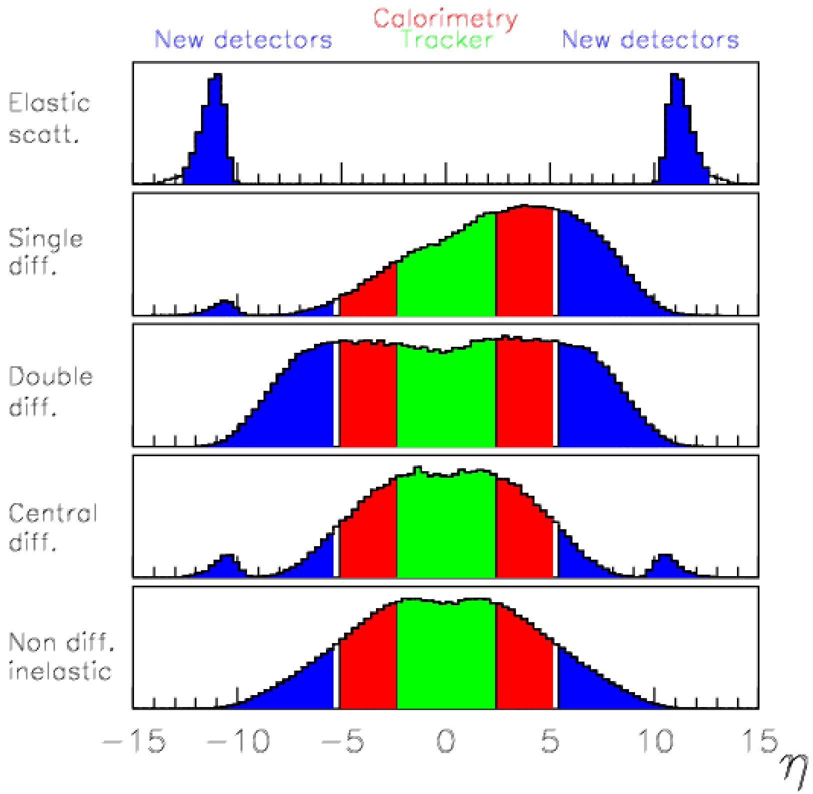
Forward Physics Measurements

- total cross-section
- elastic scattering
  - $d\sigma/d|t|$, $\sigma_{el}/\sigma_{total}$, ρ parameter
- diffractive scattering (single, central, double)
  - differential cross-sections
    - e.g. $d^2\sigma/dtdM_X$ for single diffraction
- minimum bias event structure
- properties of rapidity gaps
  - survival probability, ...
  - rapidity gaps as tools for new physics
- hard diffractive scattering
  - combine e.g. leading proton with high p_T jets
- exclusive production ($pp \to p + X + p$)
  - Of Higgs boson, SUSY particles, ...
  - Measure missing mass precisely ?

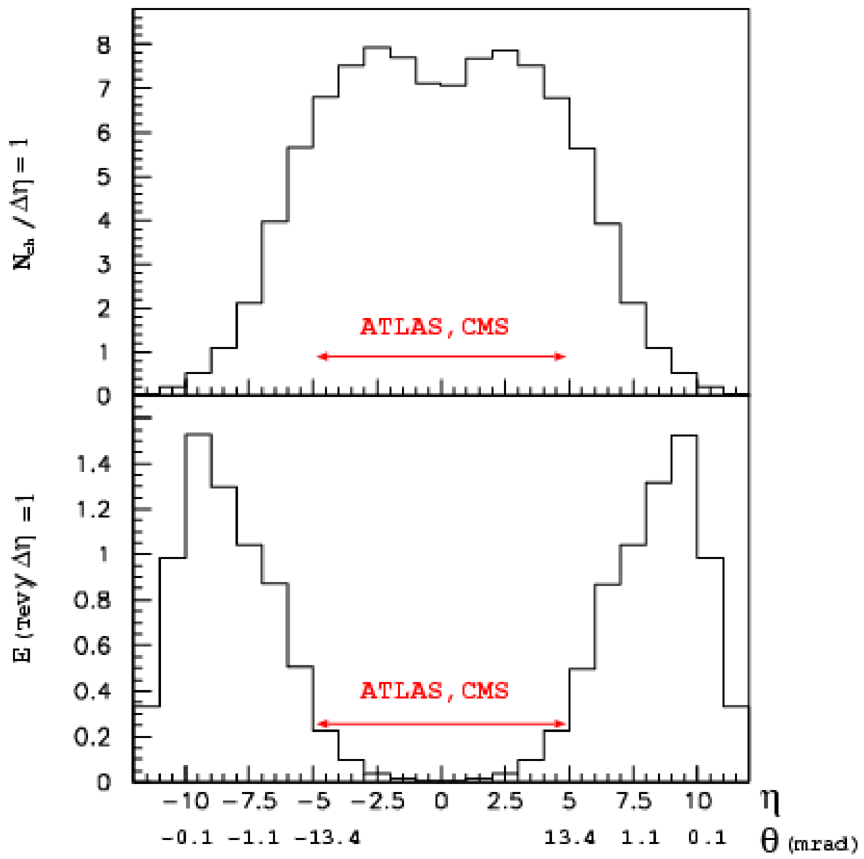
Diffractive processes / signatures

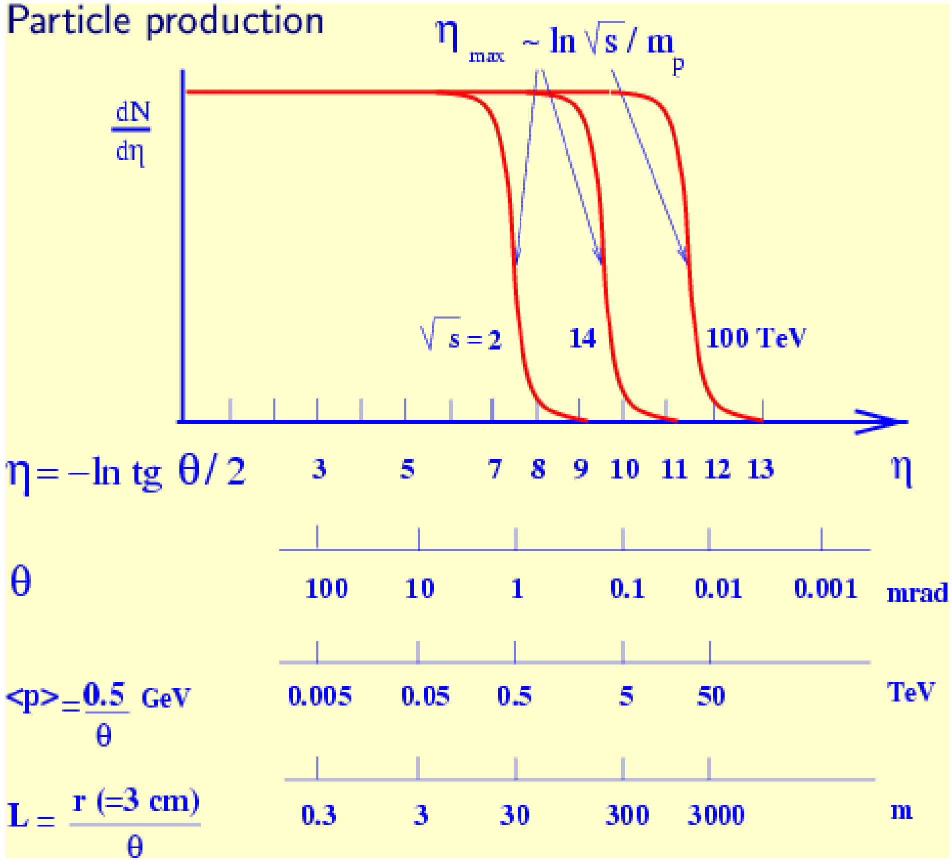


- Leading protons
- Rapidity gaps



Particle production at Ös = 14 TeV

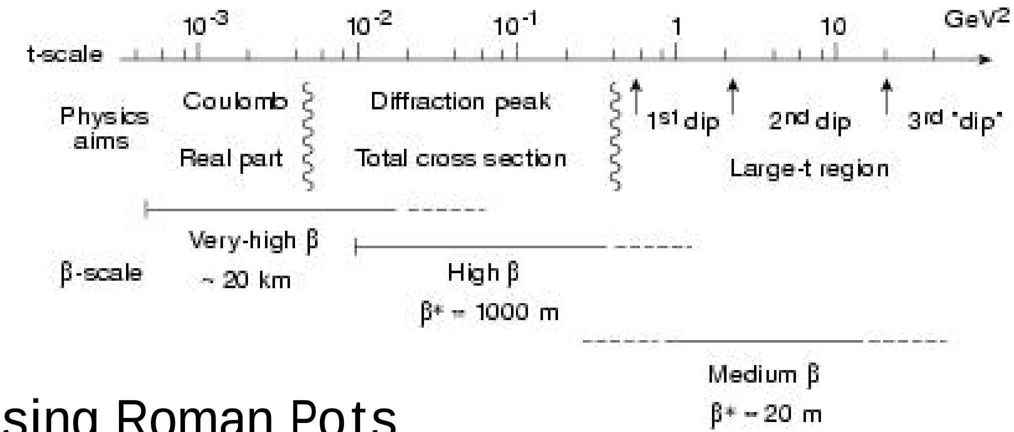




- Forward direction (|η|>5)
  - few particles produced, however with large energies
  - Small transverse momenta correspond to large energies

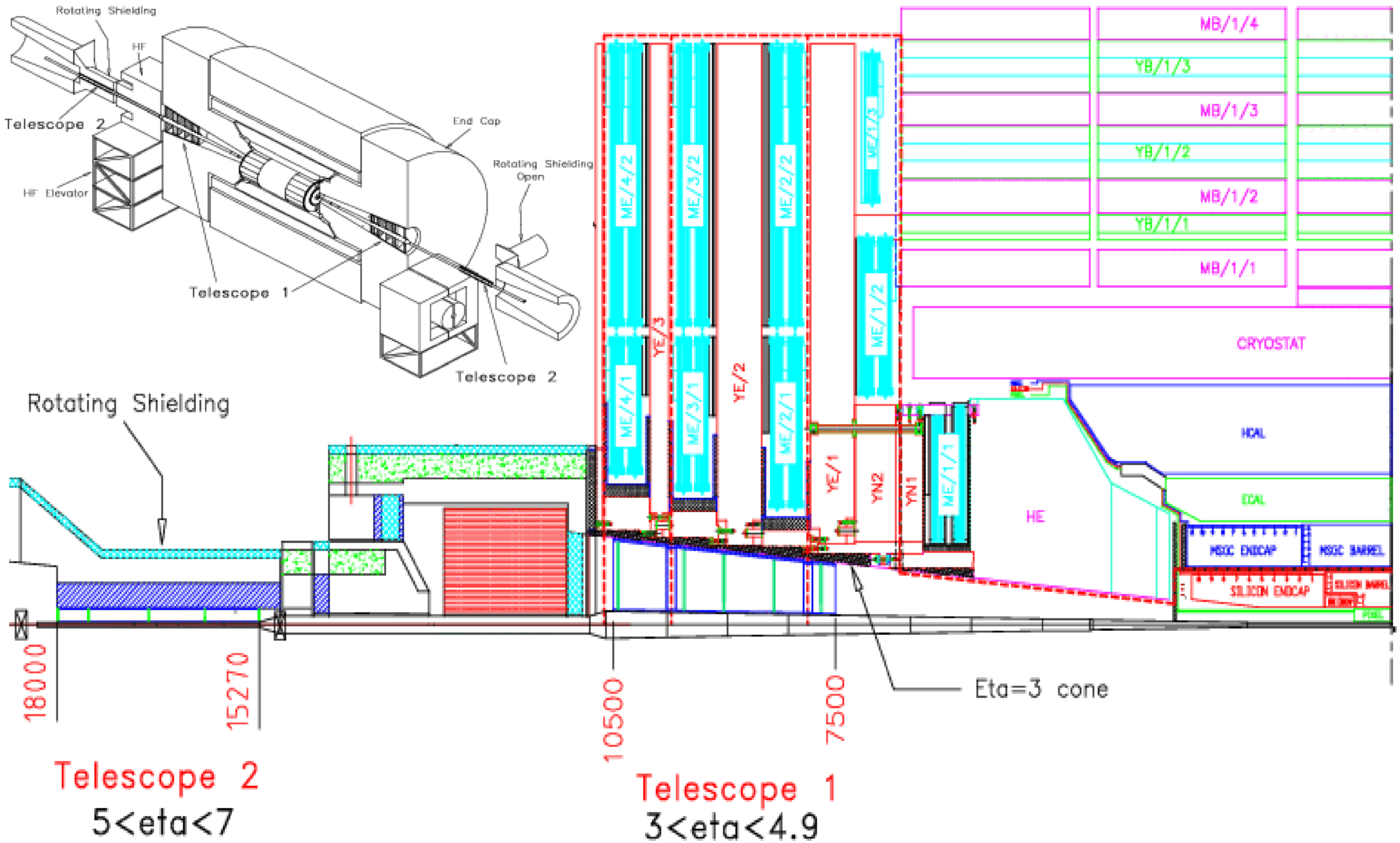
The TOTEM experiment

- Technical Proposal submitted in
  - approved to work towards Technical Design Report
  - To be installed in IP5 (CMS)
- Physics aims
  - Precise measurement of σ_{tot} ($\Delta\sigma$ = 1 mb promised)
  - Elastic scattering pp → pp
    - small –t needed for σ_{tot} !
    - dedicated machine optics
  - Inclusive diffraction pp → p X

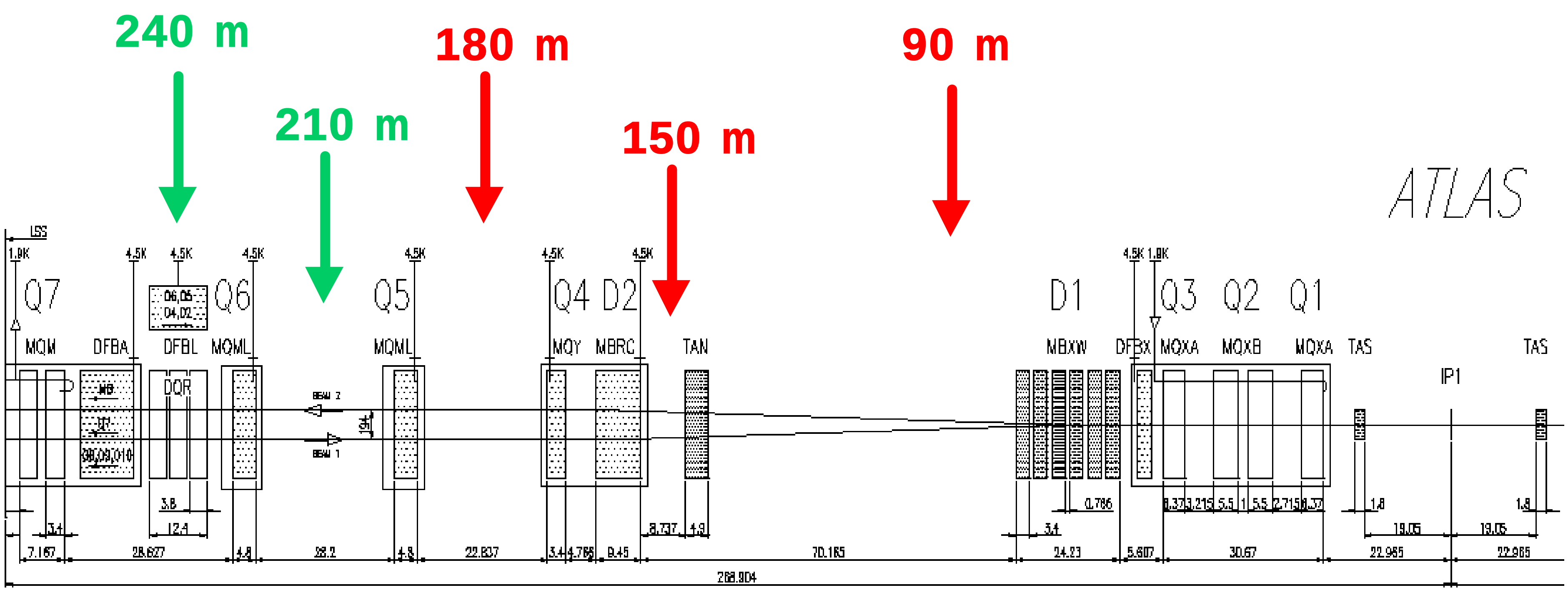


- Detector components
  - Leading proton detection using Roman Pots
  - Inelastic events using telescopes covering 3 < |η| < 7
- Most measurements to be performed in (short) dedicated runs with high β* optics
  - How to profit during normal LHC running?

TOTEM telescopes T1/T2 & CMS

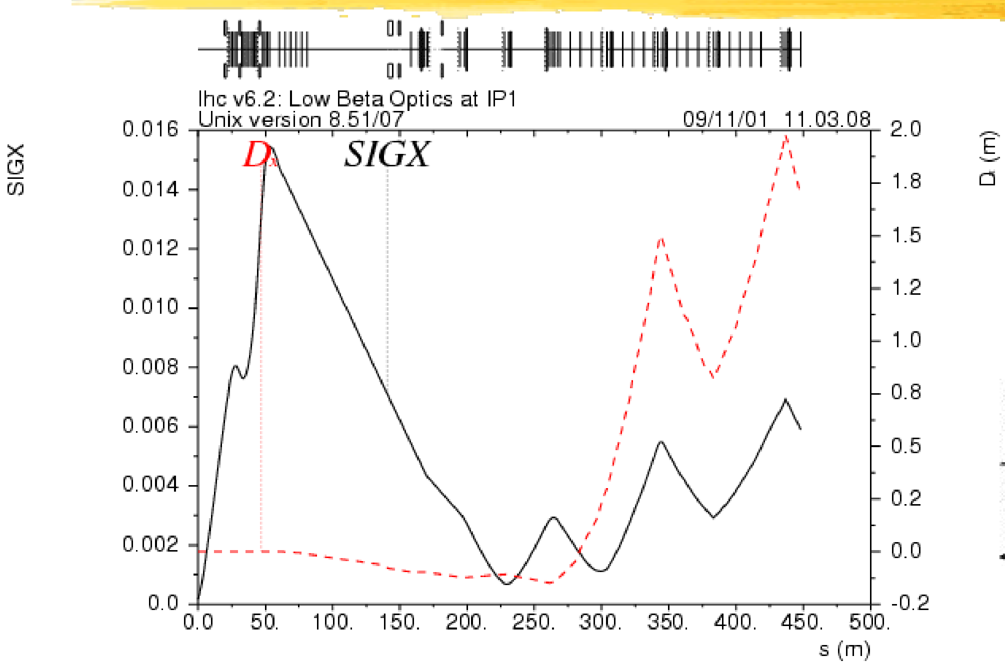


LHC optics layout (Version 6.3)



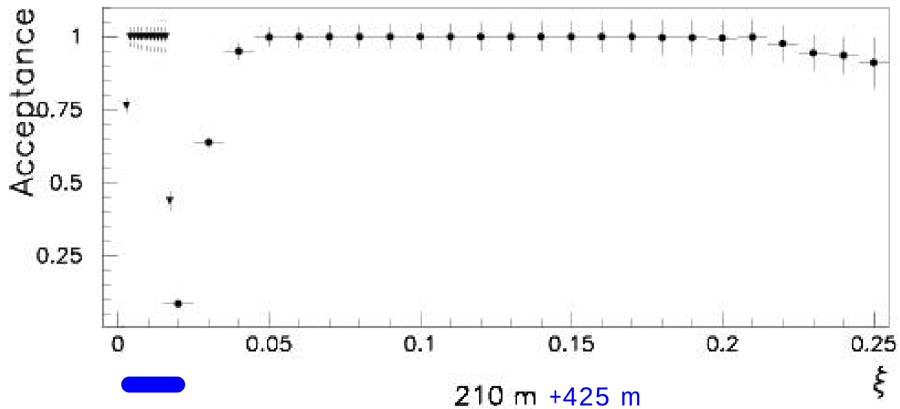
- Positions previously inside cryostats in the insertion are now available as warm space (easier to instrument)
  - Between Q5 and Q6 between Q6 and Q7
  - TOTEM (TP) positions (for IP5 – CMS)

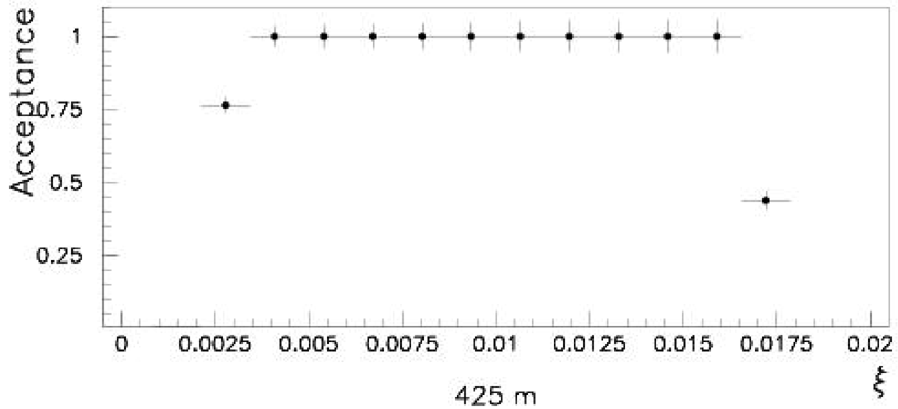
Leading proton acceptance



- Nominal optics (low β^*)
  - Small beam size between 200 and 250 m from IP
  - Large dispersion (D_x) at more than 300 m from IP
    - $\Delta x = \xi D_x$ (deviation from nominal beam position)
      - ξ: momentum loss of p

- Acceptance within insertion limited to values of $\xi > 0.03$
  - For smaller values need to go into the arc (400 m)
  - Needs further study

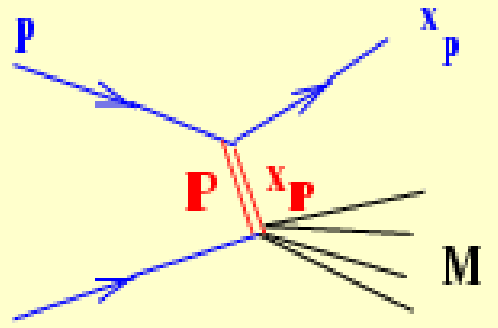


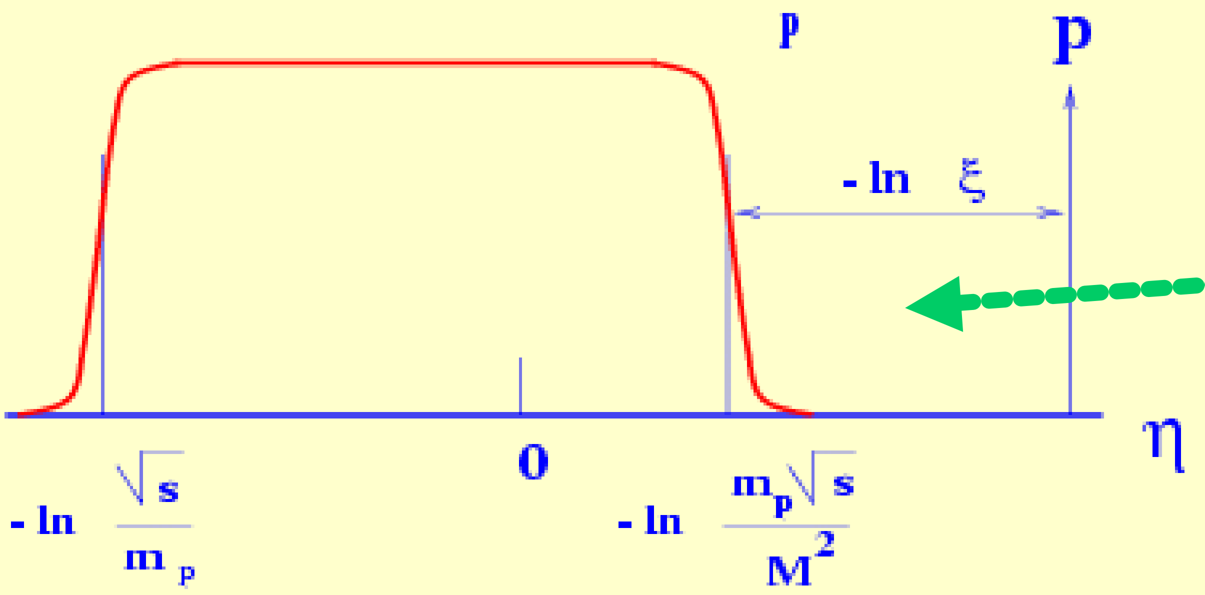


Kinematics in (Single) Diffraction

Diffraction:

$$x_{I\!P} = 1 - x_p = \xi = \frac{M^2}{s}$$





$$\frac{d^2\sigma_{sd}}{d\xi\, dt} = \frac{A}{\xi} b e^{-bt}$$

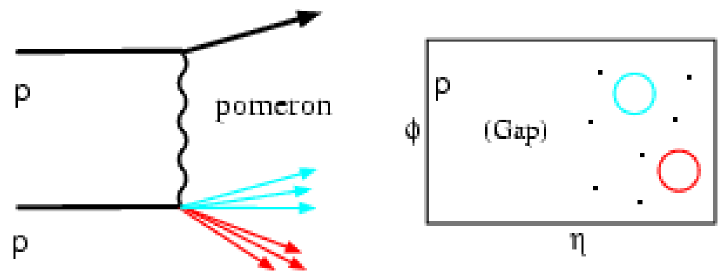
$b \sim 10\ \mathrm{GeV}^{-2}$

$t \sim \theta^2 p^2$

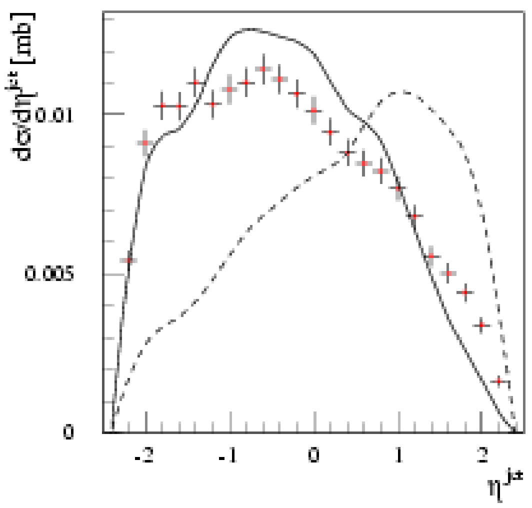
- Mass of the diffractive system depends on momentum loss ξ of p
- Size of rapidity gap related to momentum loss ξ of the proton
- Dh = - ln x

(Hard) Diffractive Scattering

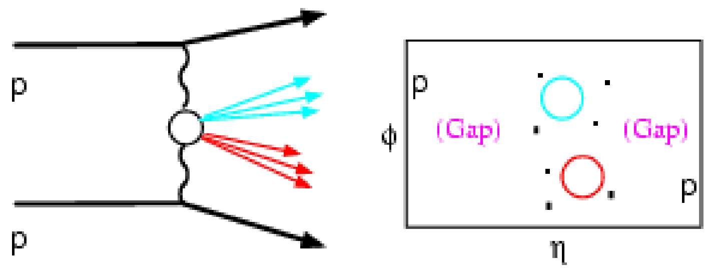
- QCD and diffraction
  - how are they related?
  - wealth of data from HERA and Tevatron



- signatures (for selection)
  - rapidity gap or leading proton
  - + hard scattering (jets, W/Z, ...)
    - smaller transverse momenta than in genuine pp collisions
    - probing partonic structure

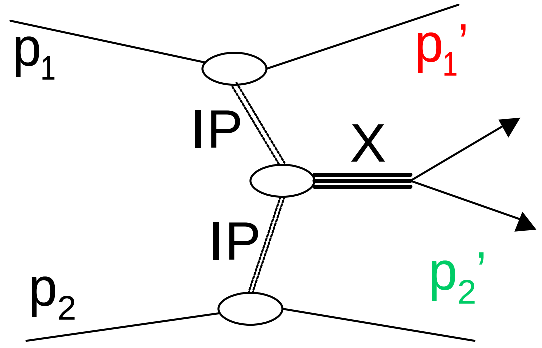


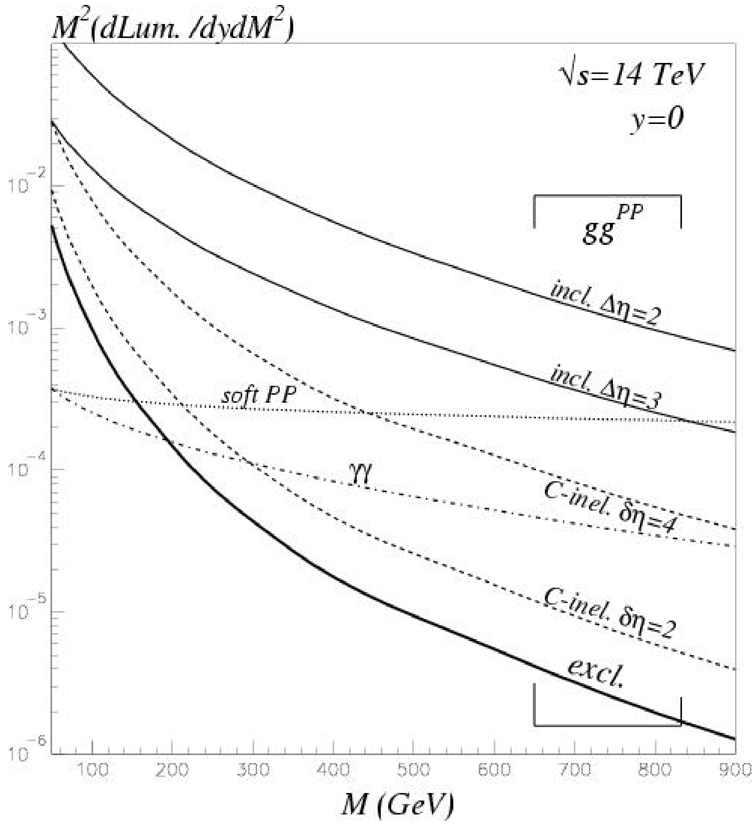
- central diffraction
  - LHC as a Pomeron-Pomeron collider with √s up to O(TeV)
    - gluon jet factory



Exclusive central production

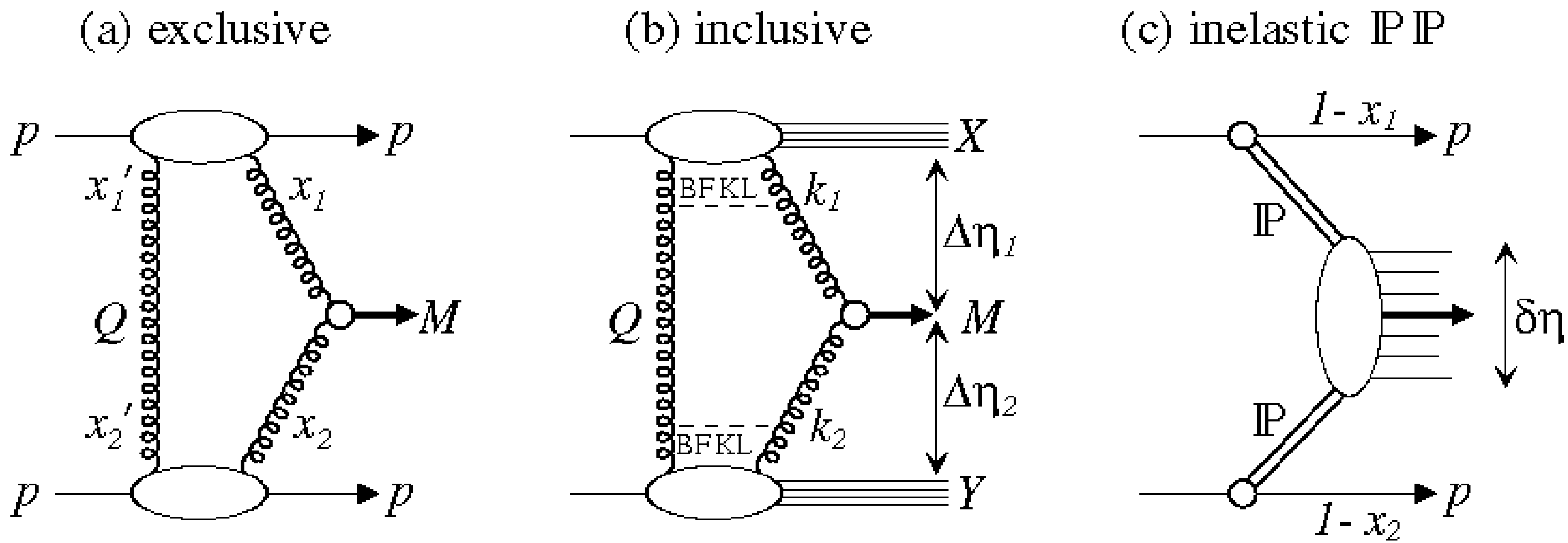
- The basic idea
  - Mass of system X determined from the two measured protons
    - $MM^2 = x_1 x_2 s$
      - E.g.: MM = 140 GeV $\rightarrow \xi = 10^{-2}$





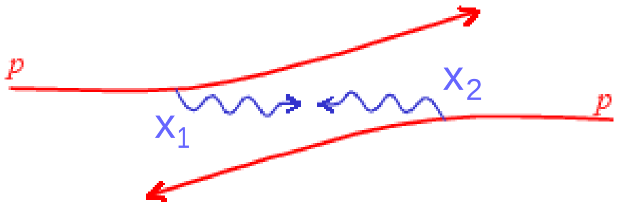
  - V.A. Khoze, A.D. Martin, M.G. Ryskin
    - hep-ph/0111078
- Factorize cross-section into
  - Luminosity for pp → p + gg + p
  - Sub-process cross-section gg → X
- Examples for cross-sections
  - Higgs (M_H=120 GeV) σ(pp → p+H+p) = 3 fb
    - S:B ratio > 15 (ΔM/250 MeV)
  - $t\bar{t}$ production
    - Near threshold: σ(pp → p+tt+p) = 0.1 fb
  - sparticle production ($M_{sparticle}$ = 250 GeV)
    - Near threshold: σ(pp → p+gg+p) = 0.15 fb
      σ(pp → p+qq+p) = 0.04 fb

Exclusive / non-exclusive production

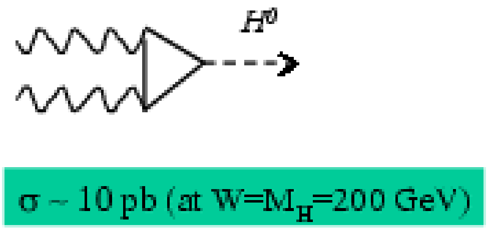


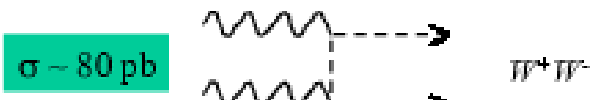
- Truly exclusive production would allow to reconstruct the mass M from the two scattered protons
  - ➲ Need a precise measurement of the scattered p momentum
- Inclusive (inelastic Pom-Pom) does no longer give this kinematic reconstruction
  - ➲ production of additional particles (besides central system)
    - ❍ either down the beampipe or in the central detector

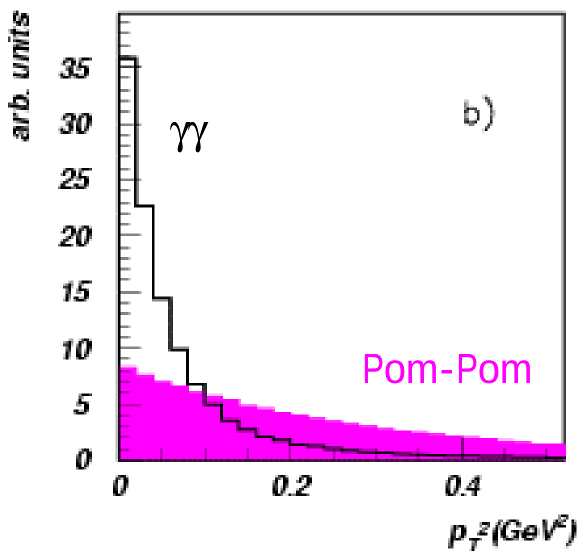
Two photon physics at LHC

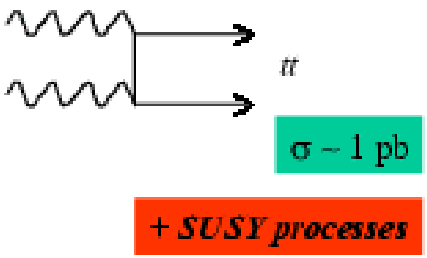


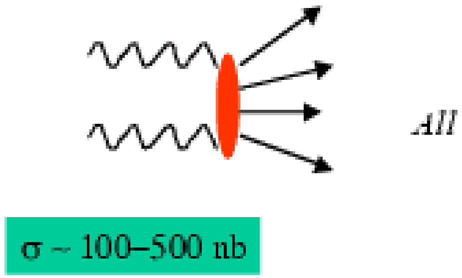
- Tagging (one or) both protons
  - K. Piotrzkowski, Phys.Rev.D63, 071502, 2001
  - Produce system X via two photon fusion with a mass W given by $W^2 = x_1 x_2 s$
  - Distinguish $\gamma\gamma$ processes from Pom-Pom via the p_T of the produced system



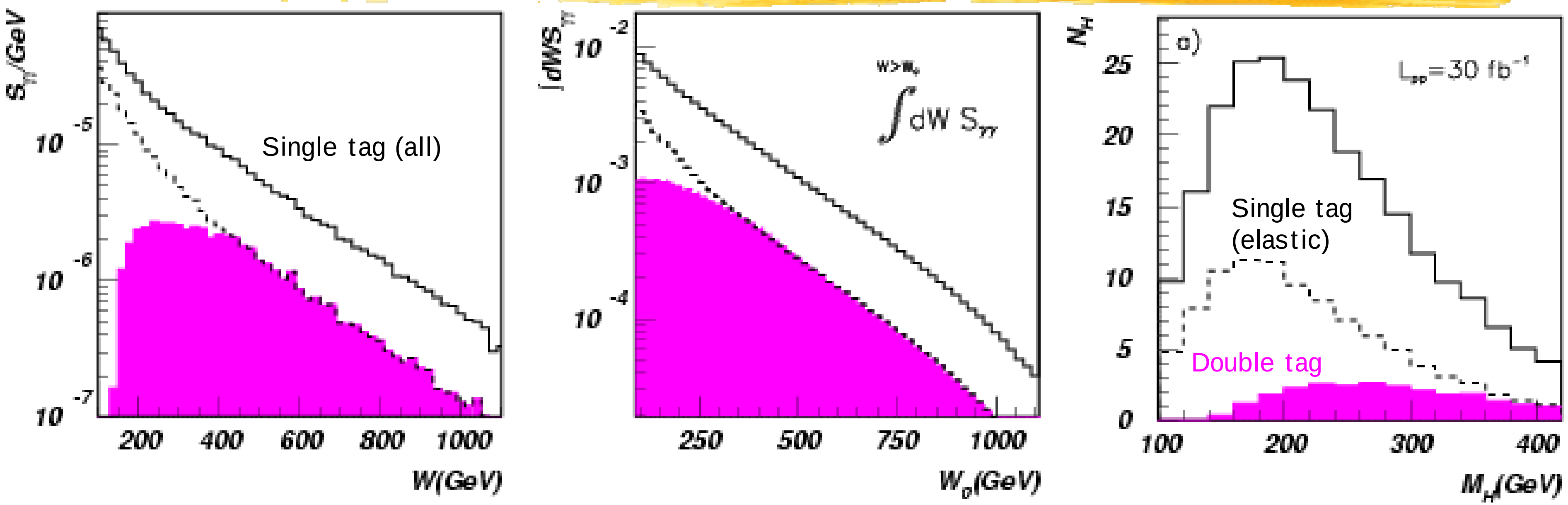






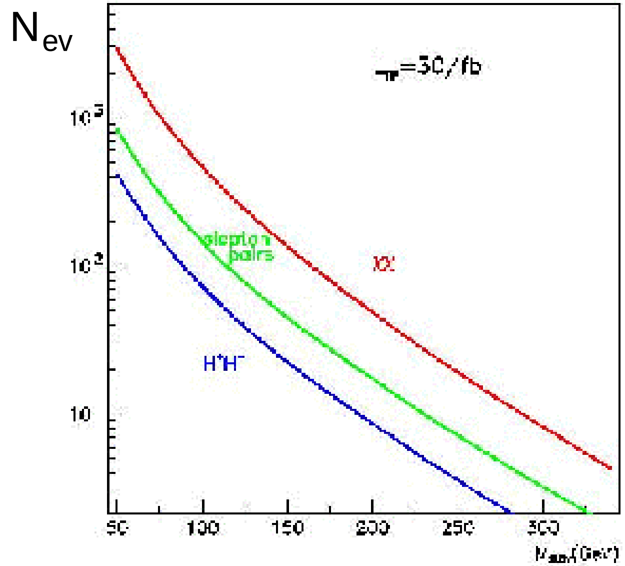


Two photon physics at LHC (cont'd)

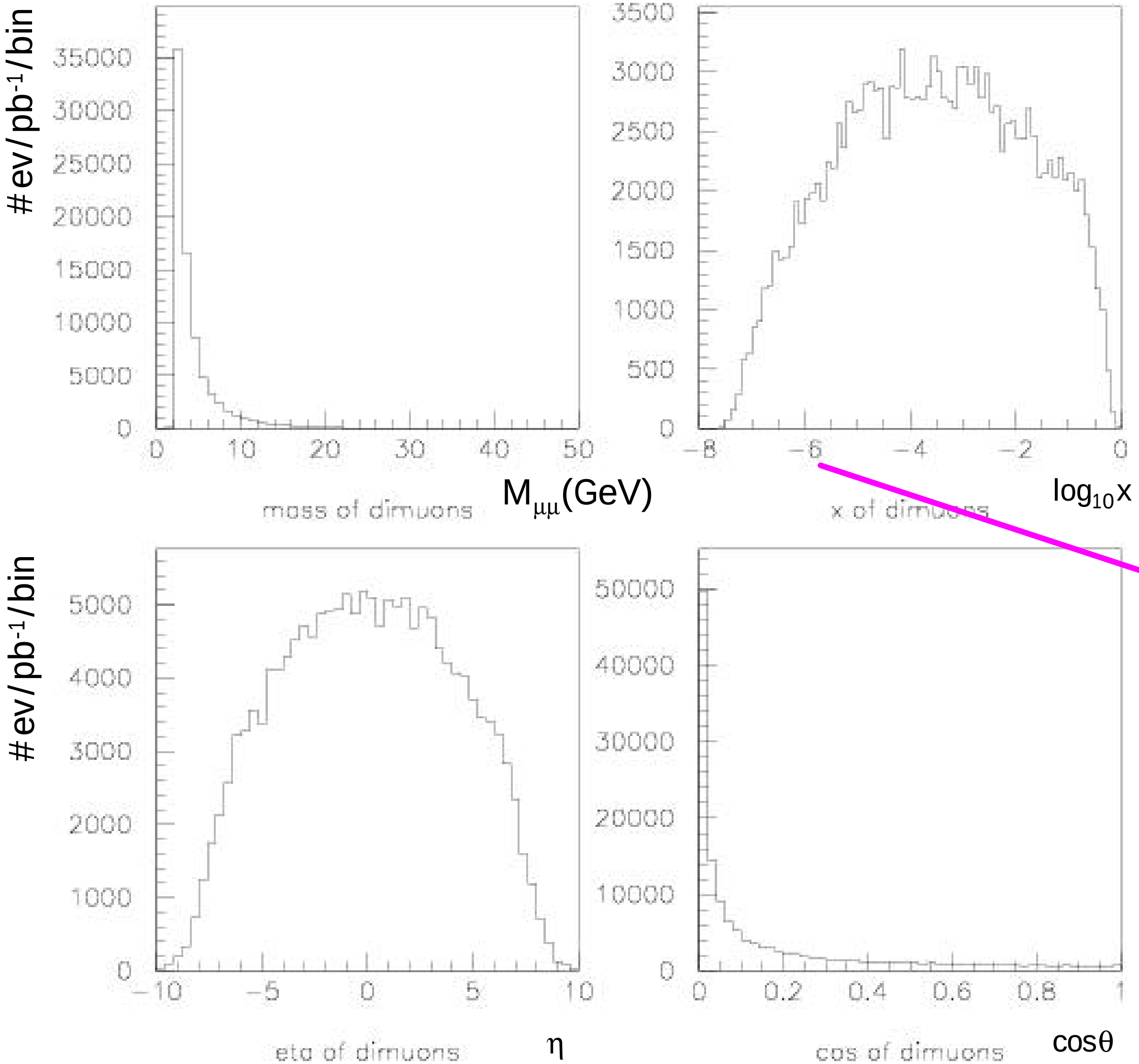


➲ K. Piotrzkowski, Phys.Rev.D63, 071502, 2001

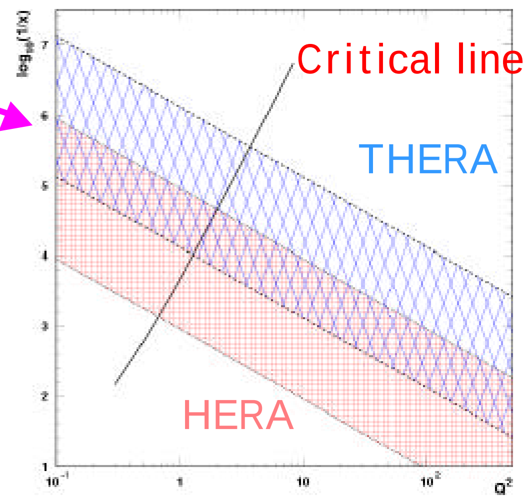
- Relative luminosity $S_{\gamma\gamma} = L_{\gamma\gamma} / L_{pp}$
  - ➲ Cuts used: 0.01 < $_{x1,2}$ < 0.1 and $Q^2 < 2$ GeV^2
- Expected number of events
  - ➲ >2000 double tagged W+W- for 30 fb-1
  - ➲ $t\bar{t}$ pairs: 2/fb
    - ❍ Cross-section depends on ($\gamma t\bar{t}$ coupling)^4



Low mass Drell-Yan production

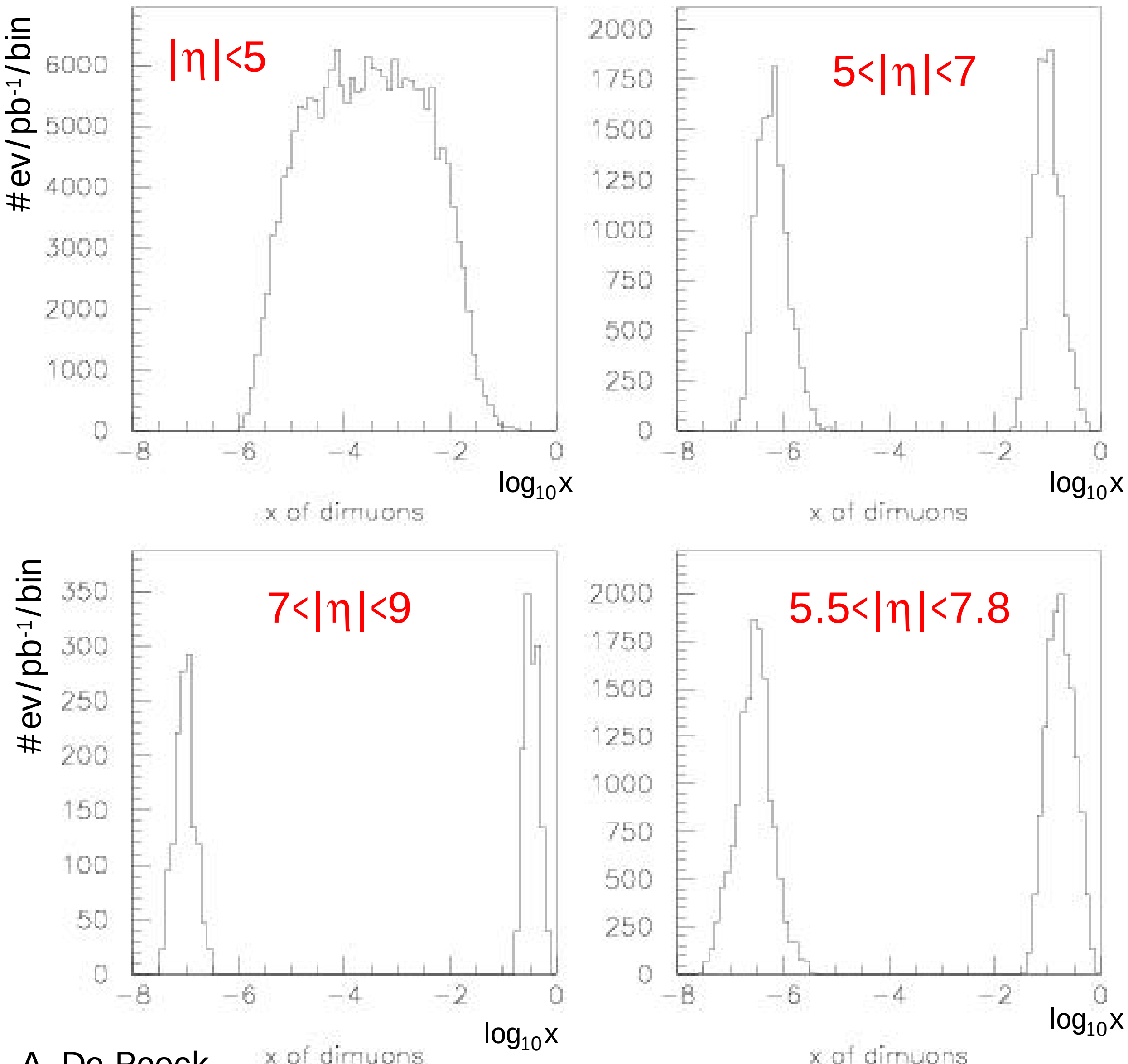


- A. de Roeck
- Kinematic properties using PYTHIA
  - MRST(LO)
  - $M_{\mu\mu}^2 > 4$ GeV^2
- Backgrounds?
  - μ from b or π/K decays?
- Low enough x values?



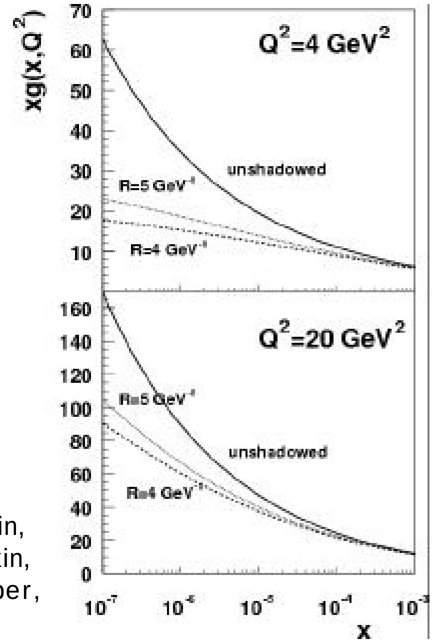
- saturation model of Golec-Biernat / Wuesthoff

Low mass Drell-Yan (cont'd)



A. De Roeck

- Experimental challenge
  - How to identify and measure muons at |η|>5?
  - Necessary to access region of parton saturation



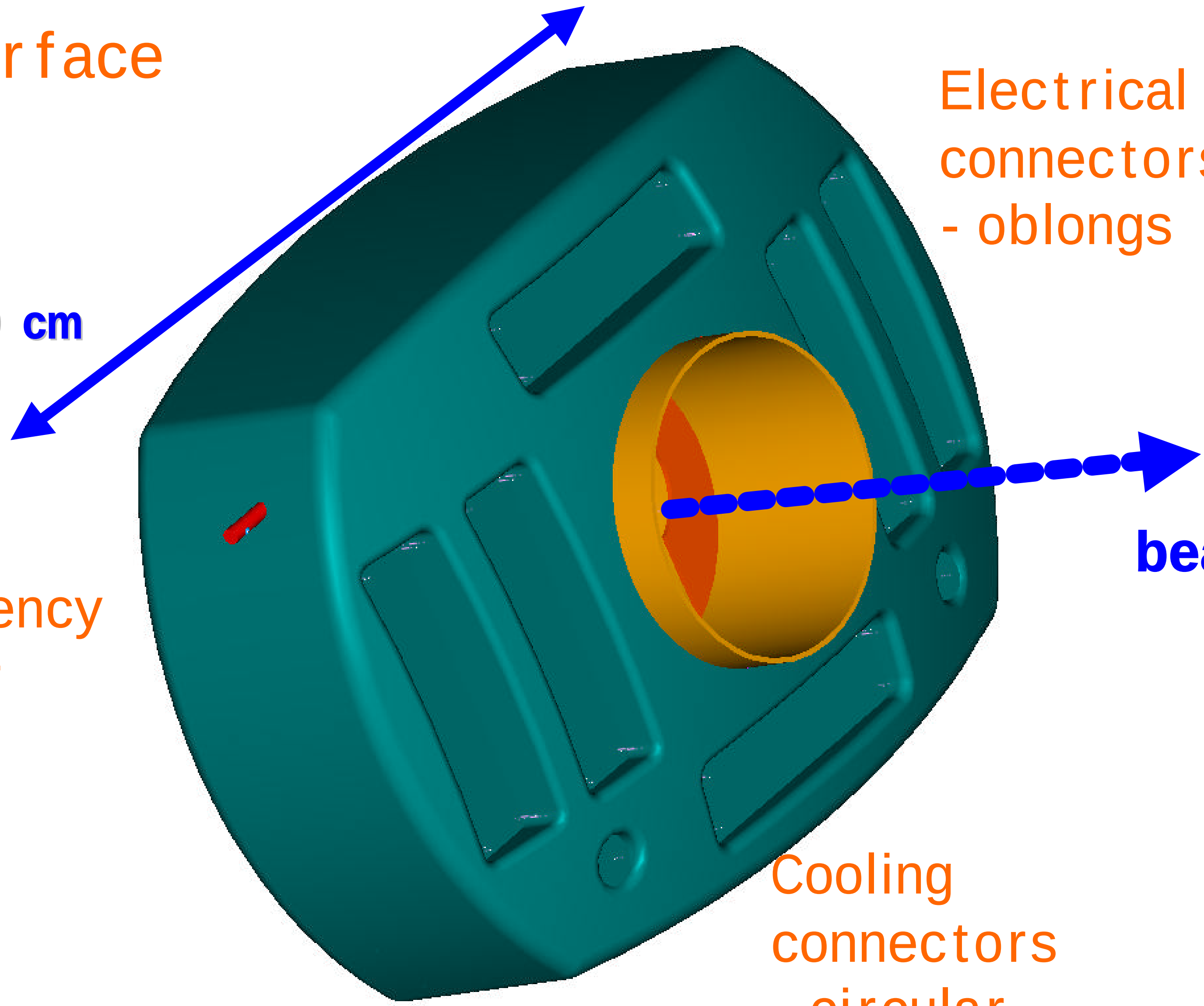
A.D.Martin, M.G. Ryskin, M.A. Kimber,

Hep-ph/0101348 (2001)

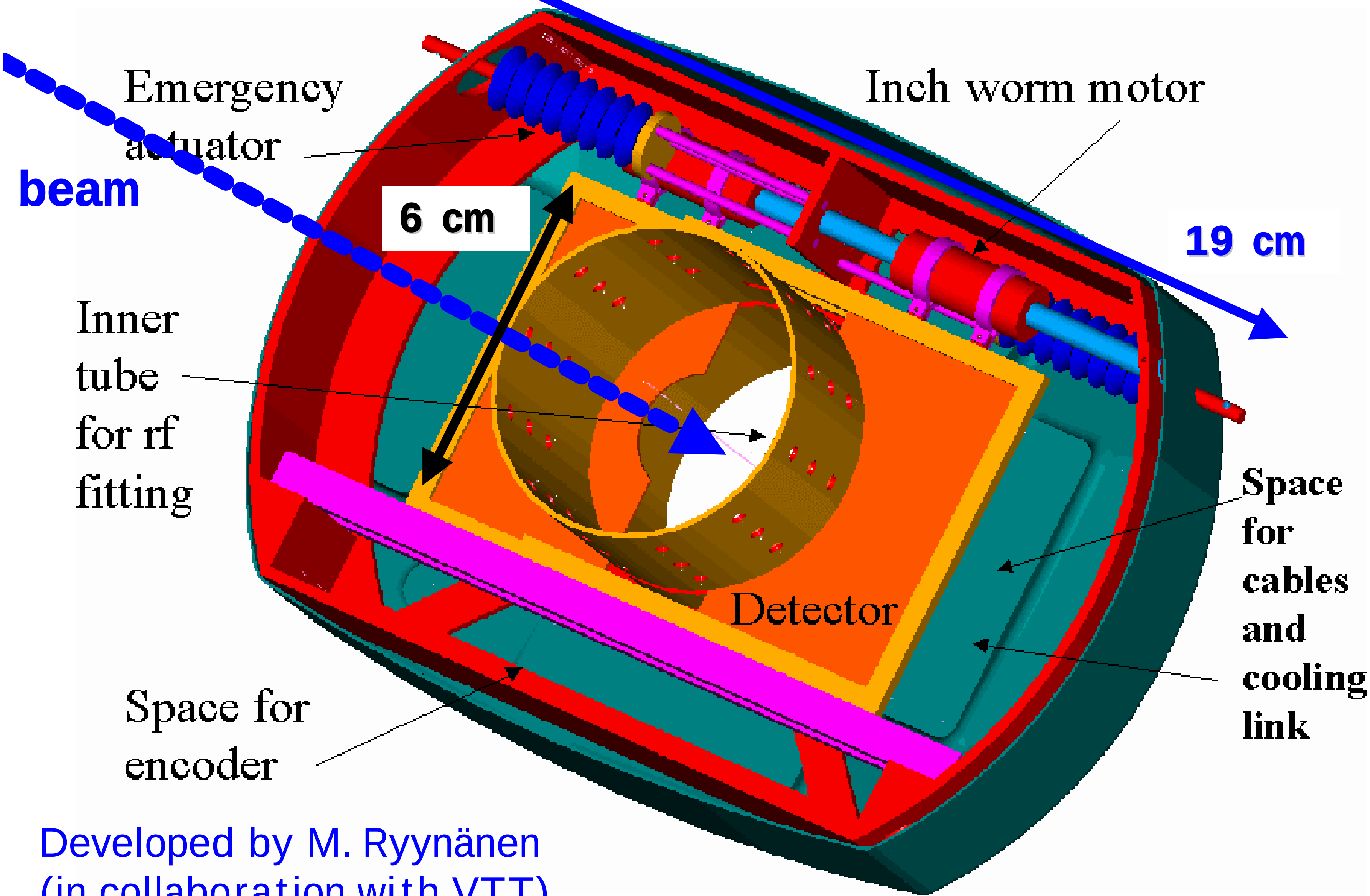
Conceptual design of a μstation

- Basic principle: measurement inside beam pipe
    - minimise effects of particle interactions in material
    - allow for closest approach of fiducial sensor area to beam
  - ➲ need to comply with LHC machine requirements
    - vacuum compatibility, additional impedance (RF) contribution, ...
  - ➲ need to operate in high radiation environment
- Major features of the μstation design
  - ➲ compact, lightweight device integrated with beam pipe
  - ➲ careful choice of all material to be used (vacuum!)
  - ➲ precision movement of sensor planes
  - ➲ reliability of operation (access is difficult)
  - ➲ Si based sensor (strip or pixel technology)

Sketch of the design of a μstation



Sketch of the design of a μstation



Developed by M. Ryynänen
(in collaboration with VTT)

Running at lower Ös energies

- LHC machine
  - $\sqrt{s}$ = 8 TeV possible without modifications
  - $\sqrt{s}$ = 2 TeV possible in principle
- Physics interest
  - $\sigma_{tot}(pp)$, compare to $\sigma_{tot}(p\bar{p})$
  - Compare W, Z, jet (etc.) production in pp to $p\bar{p}$
    - $\bar{q}$ is valence quark for $\bar{p}$
  - Study energy dependence of di-jet production at large rapidities (BFKL dynamics?)
  - Study energy dependence of rapidity gap processes
    - Diffractive phenomena
- Tevatron has done this already: 630 vs. 1800 GeV

Scenario(s) for upgrade of LHC

- luminosity upgrade (SLHC scenario)
  - increase proton intensity in bunches
  - new focusing quadrupoles (larger aperture, lower β^*)
  - reduce bunch spacing: 12.5 ns
  - ➲ all together: $L = 5 * 10^{34} - 10^{35}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$
    - part of it should be achievable with present machine design
- energy upgrade ?
  - ➲ present technology: $B_{dipole} \leq 11$ T $\Rightarrow \sqrt{s} \leq 18$ TeV
    - LHC dipole design ($B \leq 9$ T) $\Rightarrow \sqrt{s} \leq 15$ TeV
      - first industrial pre-series dipole reached 9 T without quench
    - synchrotron radiation will become problematic
      - beam screening capabilities limit to field less than 10.5 T?
    - optimisation and R&D need to be done
  - ➲ to see impact on physics potential: study $\sqrt{s} = 28$ TeV

Physics Impact of Upgrade

- SLHC scenario
  - mass reach increases by about **20% - 30%** (“for free”)
  - however, to fully benefit from increased statistics
    - e.g. for Higgs and SUSY precision measurements
  - a fully functional detector needed
    - with the planned ATLAS/CMS performance, e.g. for lepton-ID, b-tagging
  - Needs R&D effort to start soon, major upgrade would be for the tracking detectors
- larger center-of-mass energy
  - preferred option if nature has chosen a ‘heavy’ mode for new physics
  - feasibility of significant ‘jump’ in energy unclear
  - ATLAS and CMS would retain their capabilities

Outlook

- QCD is a challenging and interesting topic at the LHC
  - Not always given the necessary attention
    - So far, but will definitely change once the first data arrives
- Precision measurements at the highest energies
  - measurements of **parton densities** from a variety of processes (partially very clean signatures):
    - jet production at highest E_T $\Rightarrow$ parton densities (quarks and gluons)
    - direct photon production $\Rightarrow$ parton densities (gluons)
    - Drell-Yan, W and Z production $\Rightarrow$ parton densities (quarks)
  - measurement of α_s over a wide range of scales (up to O(TeV))
    - from jet rates (and/or jet shapes, σ(photon)/σ(jet), ... ?)
  - In order to reach really low x values (10^{-6} – 10^{-5}), a coherent extension in the forward region (beyond $|\eta|=5$) is **mandatory**
- Need to increase the awareness in the LHC experimental community
  - In order to get a forward extension of at least one experiment!
  - To fully exploit the physics potential of the LHC