# Proton-proton physics studies at the LHC with CMS/CASTOR

September 1, 2007

Workshop on low x physics, Helsinki

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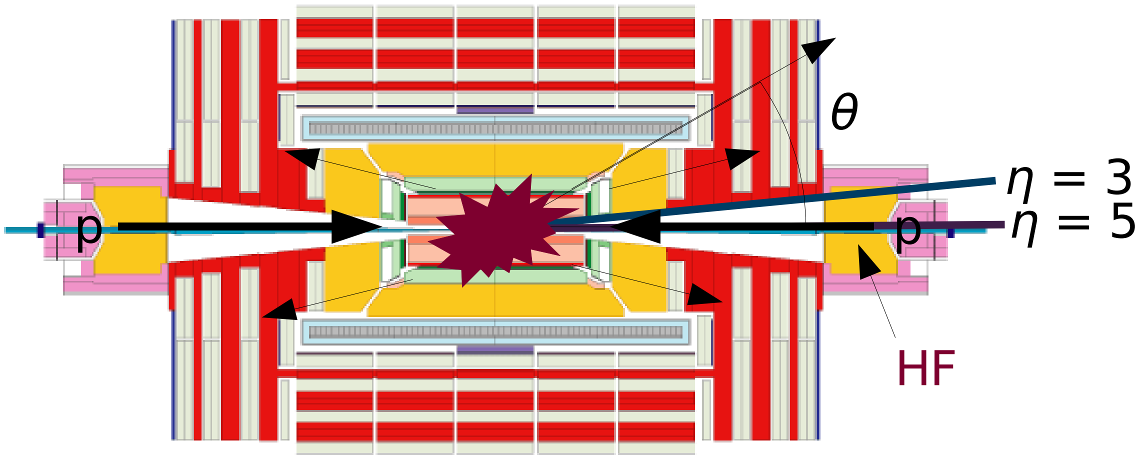
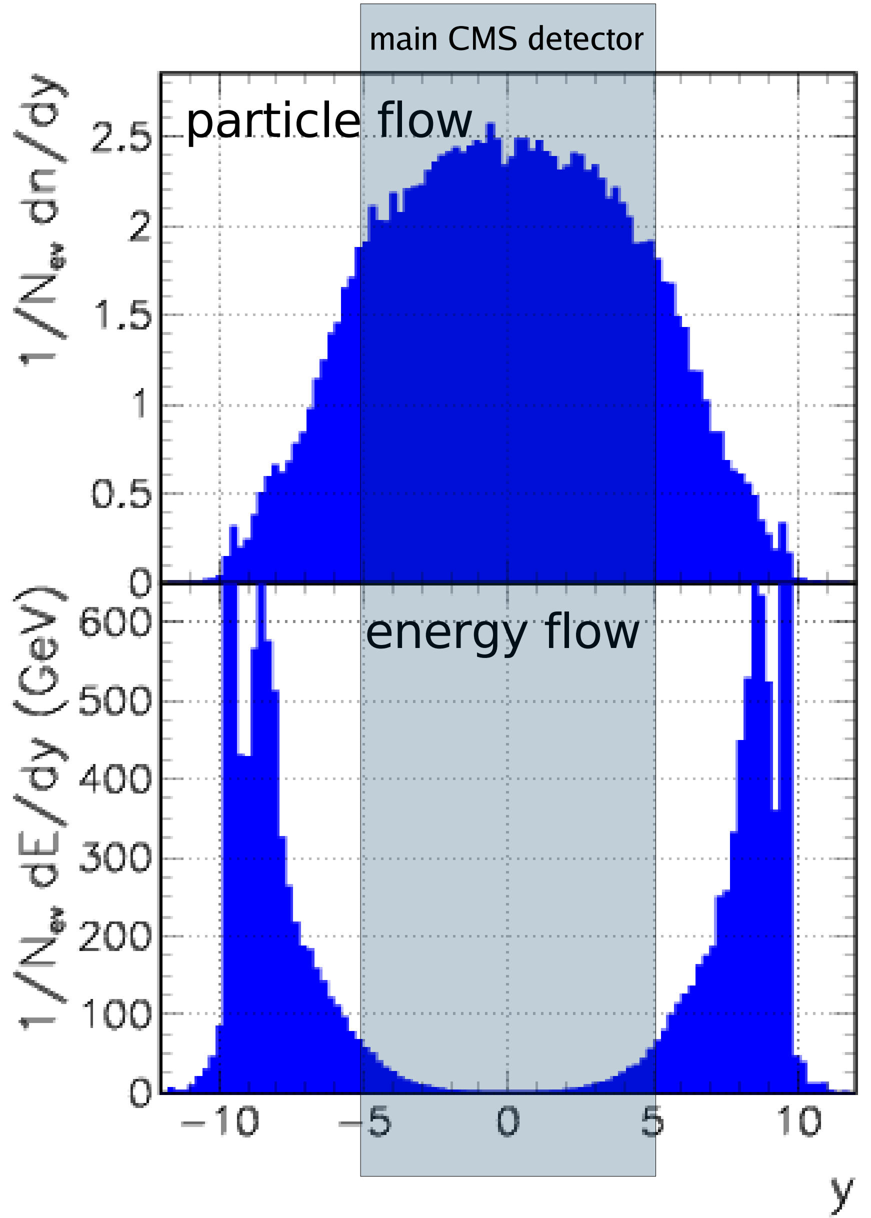
# The CMS detector




**Forward Physics:**

All processes in which particles are produced at small polar angles (i.e. large rapidities).

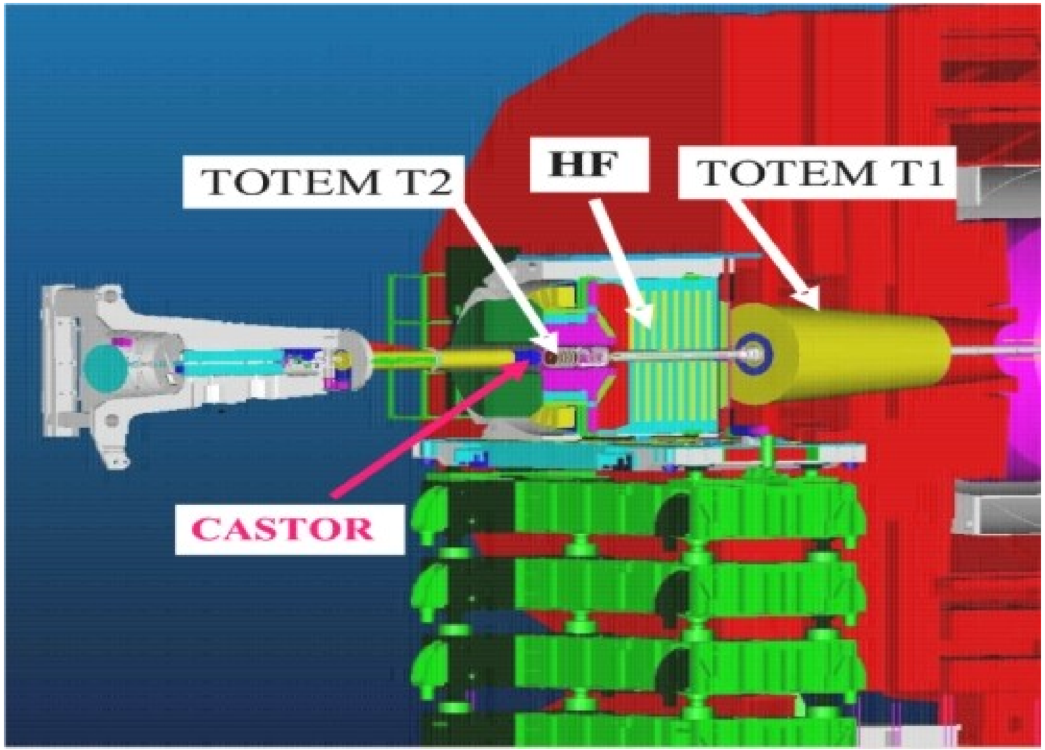
Maximal rapidity at the LHC given by:

$$y_{max} = \ln \frac{\sqrt{s}}{m} \approx 11.5$$

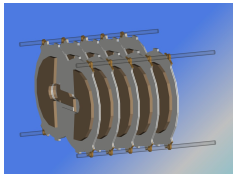
# Forward detectors at CMS

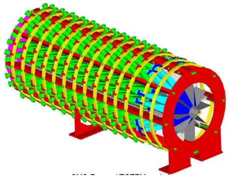
Unprecedented coverage
up to high rapidity!

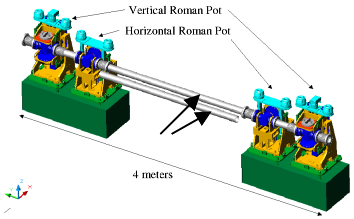
**T1** (CSC) $3.1 \leq |\eta| \leq 4.7$
**HF** $3 \leq |\eta| \leq 5$
**T2** (GEM): $5.3 \leq |\eta| \leq 6.6$
**Castor** $5.3 \leq |\eta| \leq 6.6$
**ZDC** $|\eta| > 8.5$ for neutrals

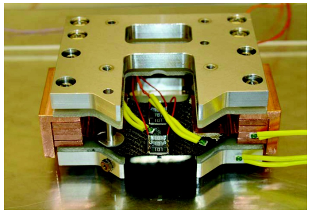



IP5





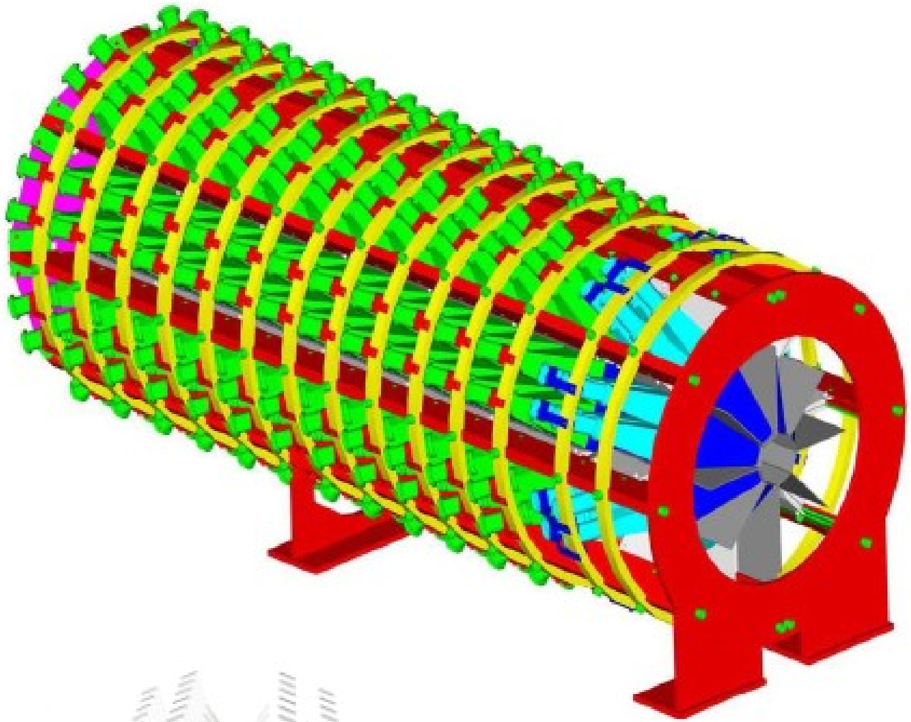


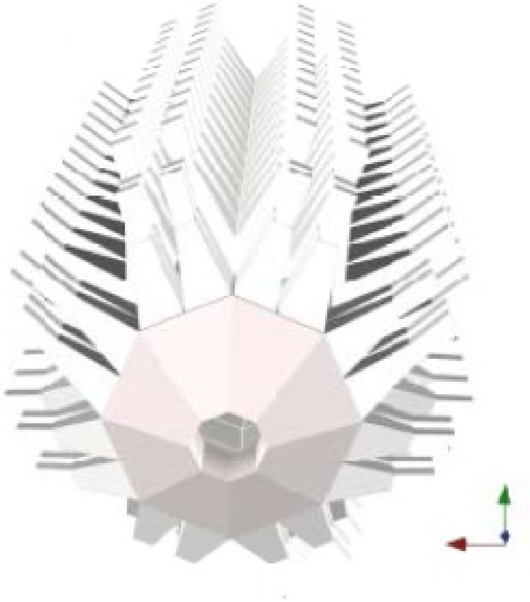



| TOTEM-T2 | CASTOR | ZDC/FwdCal | TOTEM-RP | FP420 |
|---|---|---|---|---|
| 14m | 16m | 140m | 147-(180)-220m | 420m |

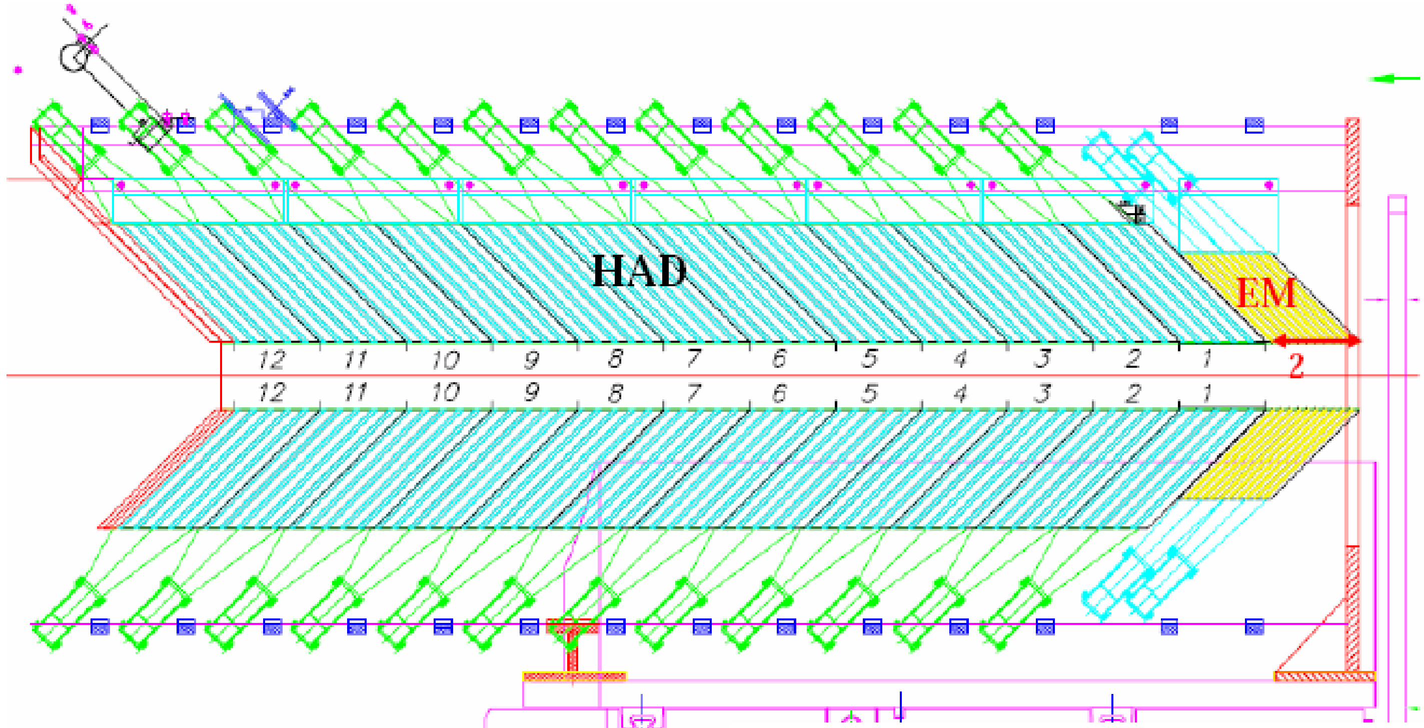
# The CASTOR calorimeter

- extends the coverage in forward direction to $5.2 < \eta < 6.6$ → enhances the hermiticity of CMS!
- 14.37 m from the interaction point
- octogonal cylinder with inner radius 3.7cm, outer radius 14cm and total depth 10.5 $\lambda_I$
- signal collection through Čerenkov photons transmitted to PMTs through aircore lightguides
- W absorber & quartz plates sandwich, with 45° inclination with respect to the beam axis
- electromagnetic and hadronic sections
- 16-fold segmentation in $\varphi$
  14-fold segmentation in $z$
  no segmentation in $\eta$
- staged construction: 1 CASTOR in 2008, maybe a second CASTOR in 2009





# CASTOR specifications

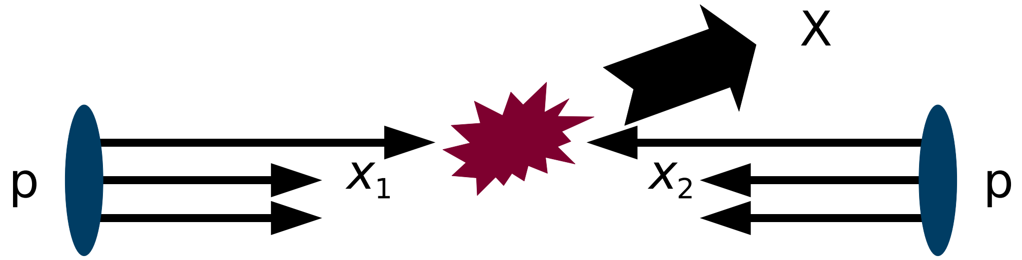



- hadronic section
  - absorber: tungsten plates of 10mm thickness
  - active material: fused silica plates of 4mm thickness
  - 5 tungsten-quartz sandwiches form 1 reading unit
  - total interaction length (2+12 r.u.) 10.3 $\lambda_I$
- electromagnetic section
  - absorber: tungsten plates of 5mm thickness
  - active material: fused silica plates of 2mm thickness
  - 5 tungsten-quartz sandwiches form 1 reading unit
  - total radiation length (2 reading units) =20.12 $X_0$

# Low x

How to get interesting physics at small polar angles?

**1. parton-parton scattering: qq → X**



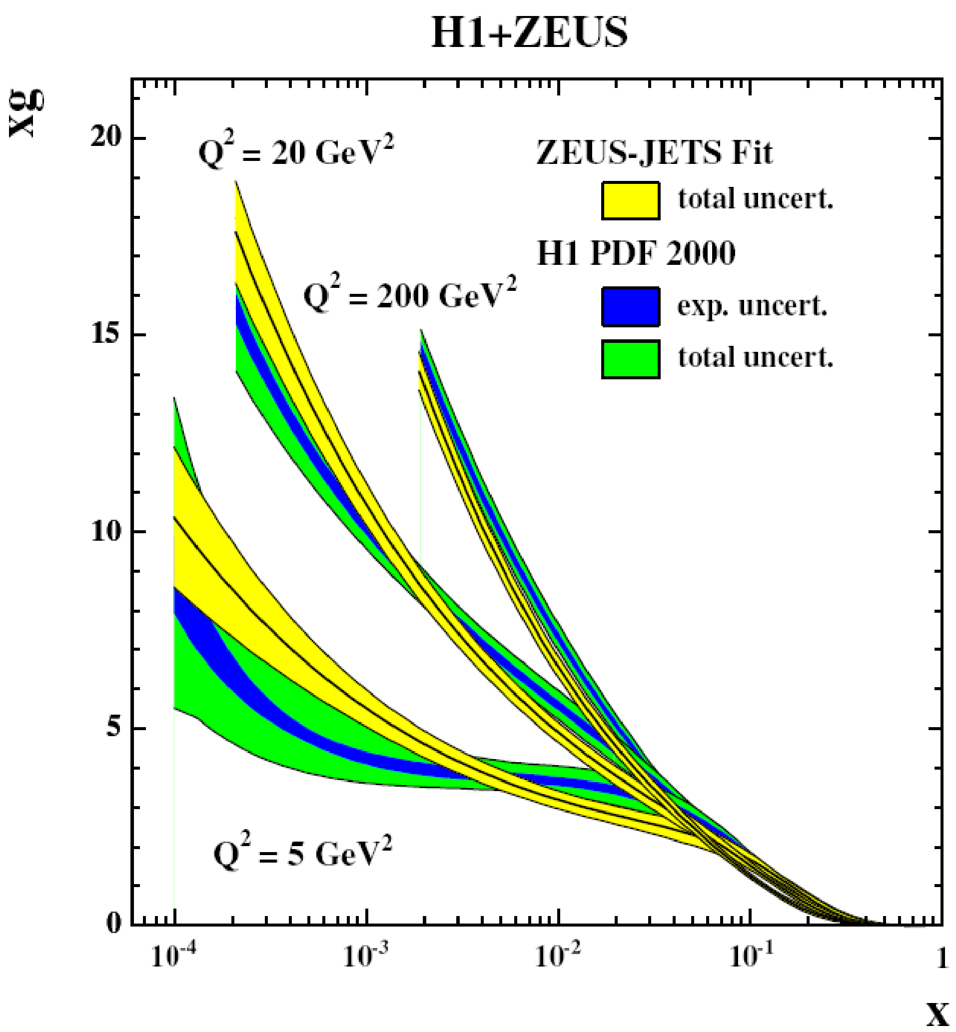

- X can be jets, Drell-Yan pairs, prompt photons, heavy quark pairs, ...
- X goes forward if $x_2 \ll x_1$ → access to low-$x_{\text{Bjorken}}$ proton structure:

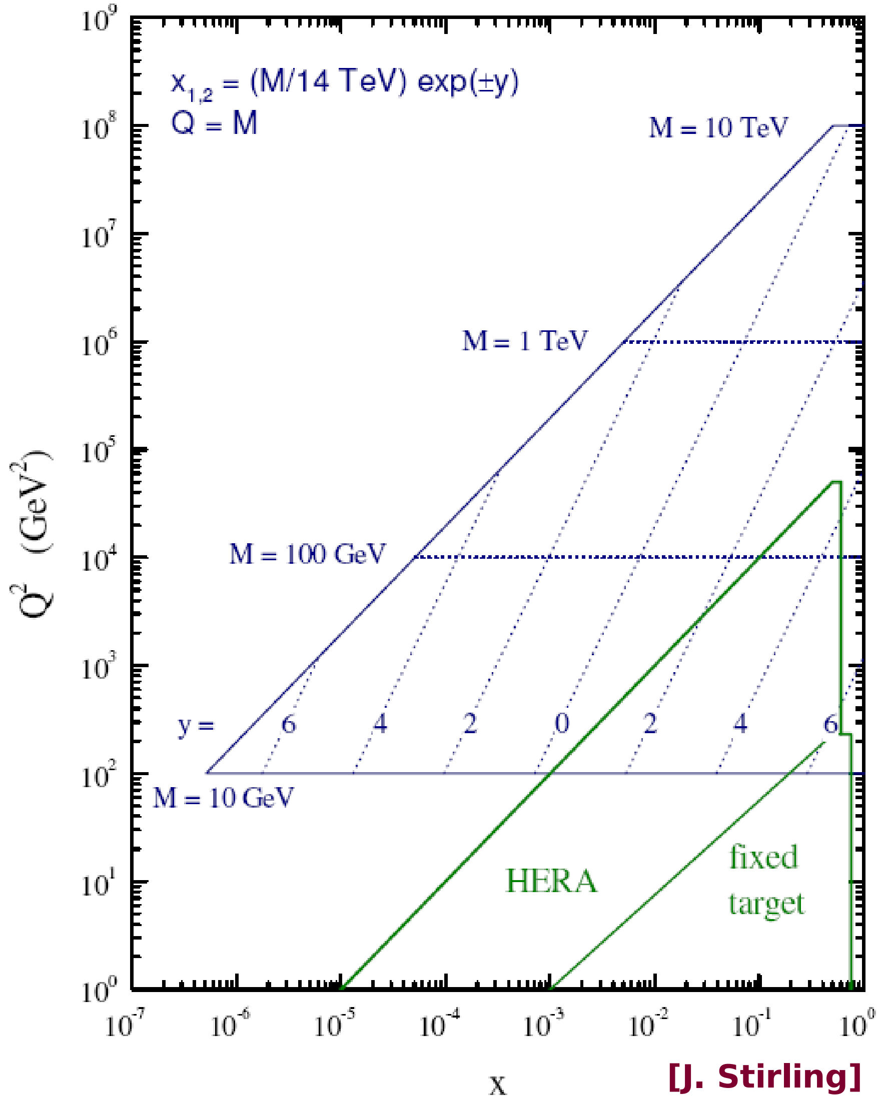
$$x_{Bj} = \frac{Q}{\sqrt{s}} e^{-\eta}, \qquad Q = p_T, M, \ldots$$

→ at LHC (for $Q \gtrsim 1$ GeV and $\eta = 8$): $x_{\text{Bjorken}} \gtrsim 10^{-8}$

→ $x_{\text{Bjorken}}$ decreases by factor 10 for each 2 units in rapidity

# Proton structure at low x




[J. Stirling]

→ strong rise of $F_2(x,Q^2)$ at low $x$ observed at HERA

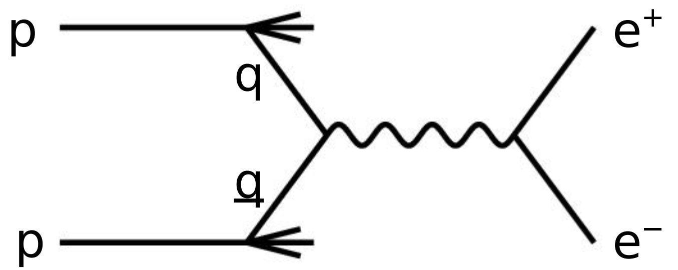
→ extrapolation to LHC?

# Forward Drell-Yan pairs

- Kinematics of pp → $e^+e^-X$:

$$M^2 = s x^+ x^- \qquad x^\pm = \frac{M}{\sqrt{s}} \exp^{\pm y}$$

$$x_F = \frac{p_z^+ + p_z^-}{\sqrt{s}/2} = x^+ - x^-$$



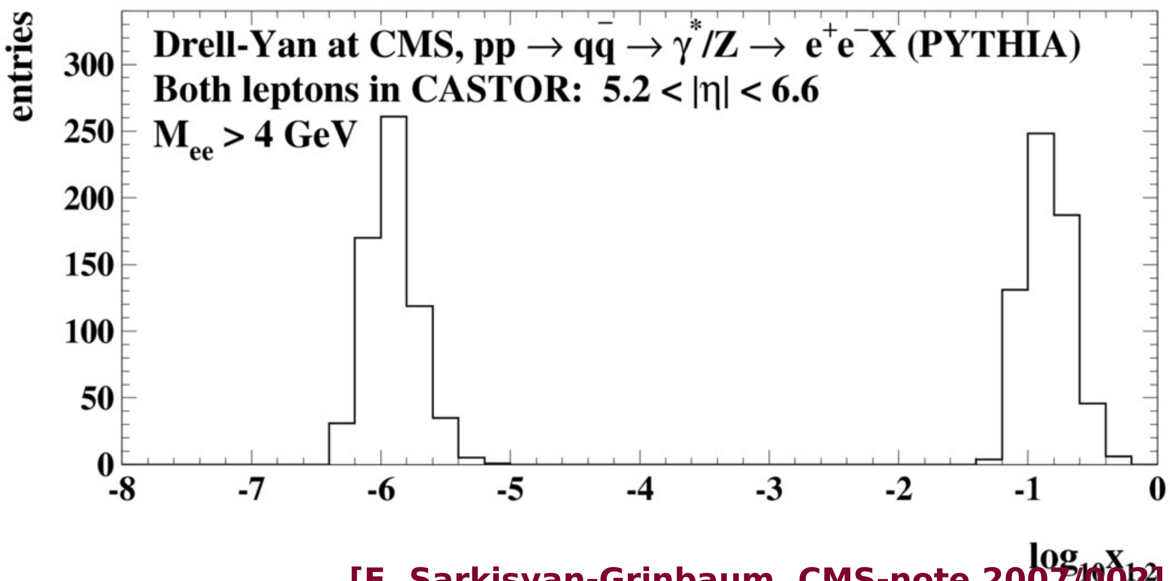

→ asymmetric $x_{Bj}$ values ($x^- \ll x^+$) will boost the leptons to large rapidity

→ pdf known at high $x^+$ ⇒ constrain pdf at low $x^-$

- CASTOR acceptance:

→ low mass DY in CASTOR probes the proton down to $x_{Bj} = 10^{-6} – 10^{-7}$

→ constraint of global parton density fits!



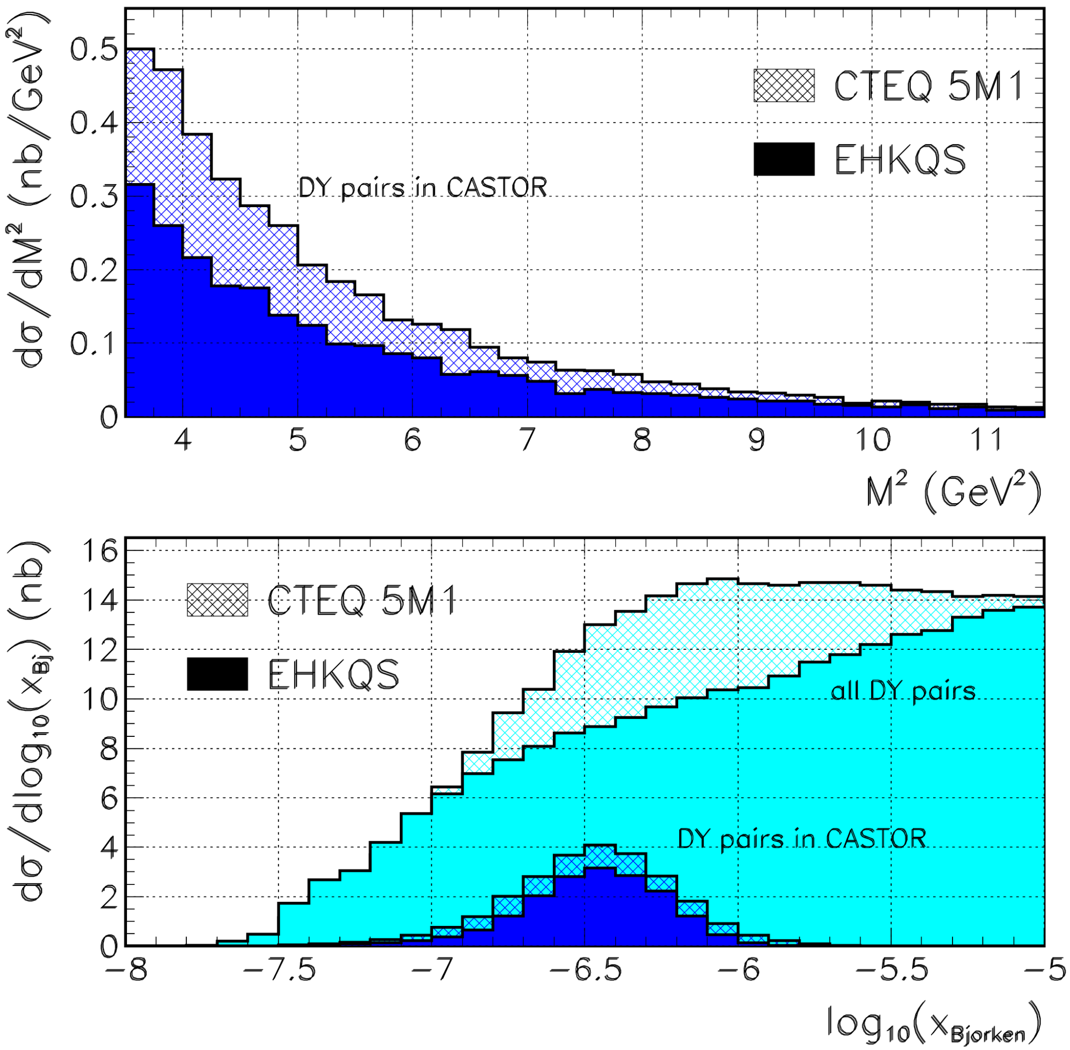

[E. Sarkisyan-Grinbaum, CMS-note 2007/002]

Rise of $F_2$ tamed by saturation?

- CTEQ 5M1: standard, "non-saturated" pdf
- EHKQS: "saturated" pdf with nonlinear terms in gluon evolution

**[A. Dainese et al., HERA-LHC Workshop proc.]**

→ Saturation effects cause a 30% decrease in the DY cross section!

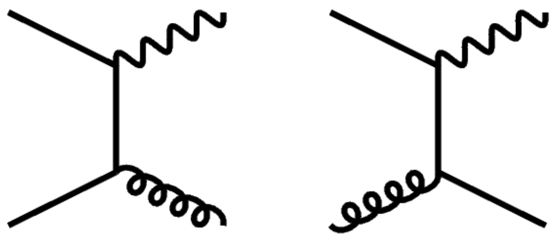



**[PVM, CMS-note 2007/002]**

Event yield: ~2 million events/$fb^{-1}$ in CASTOR

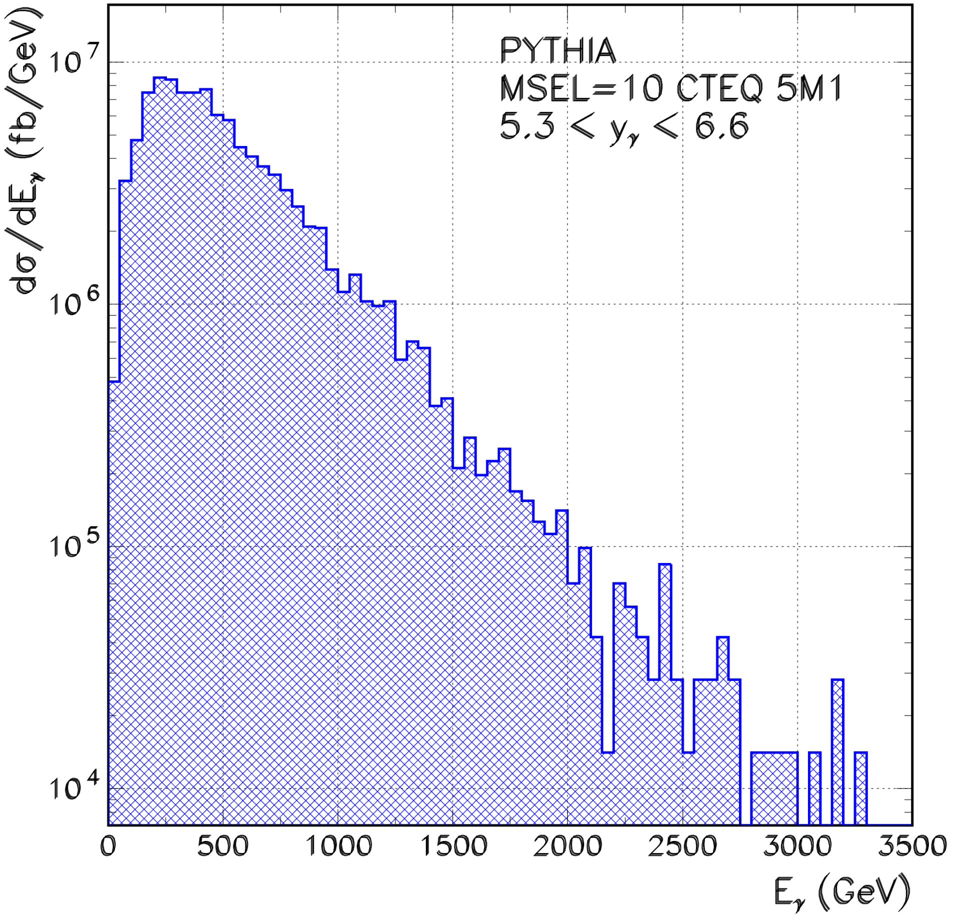
# Prompt γ

- Forward prompt photons are mainly produced through



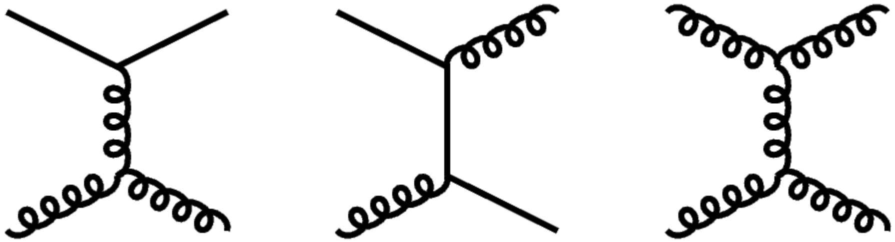
qq → gγ    qg → qγ

- Large imbalance in fractional momenta of incoming partons boosts photons forward
  ➔ access to low x with prompt photons in CASTOR



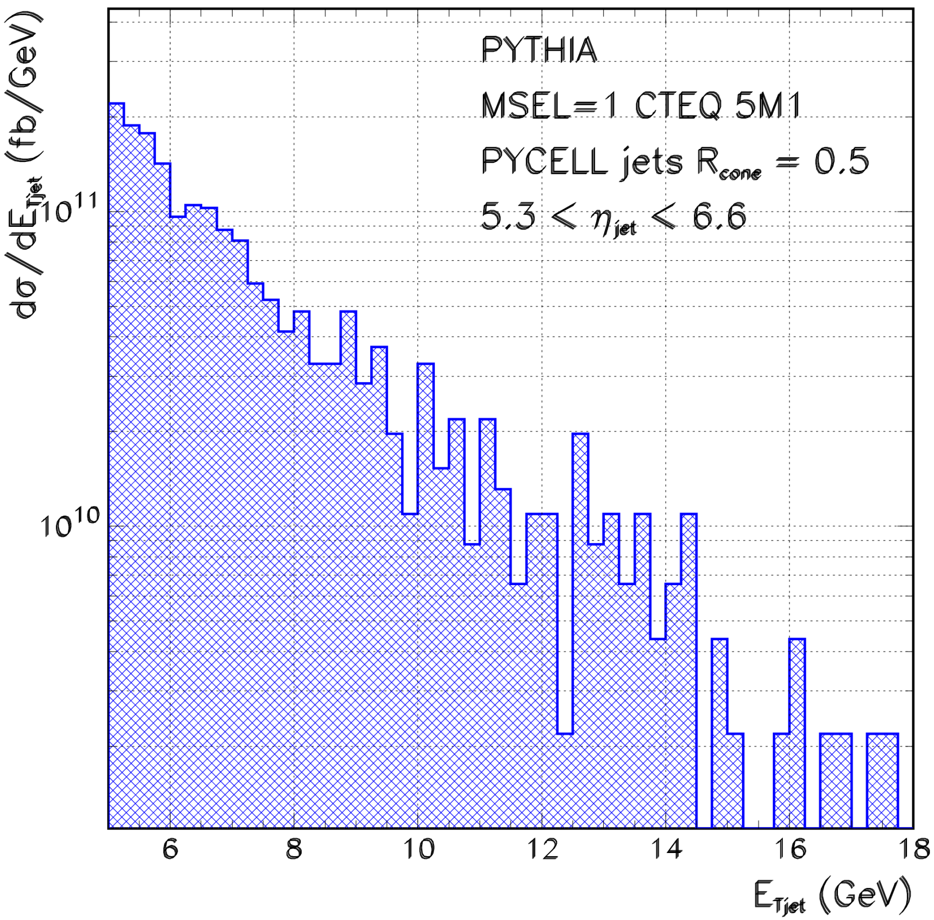
# Forward jets

- Forward jets are mainly produced through



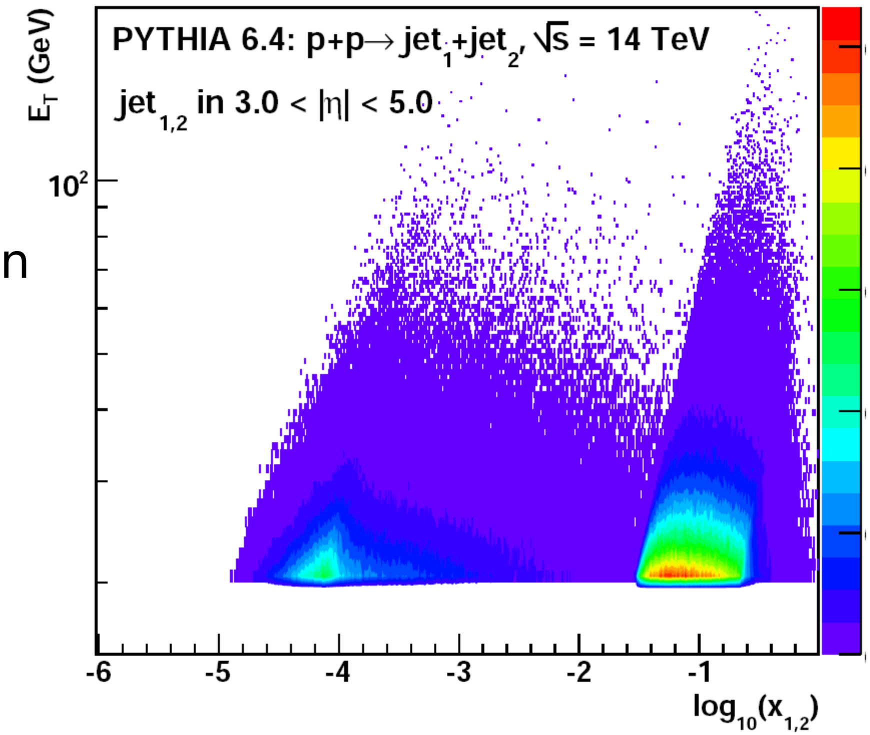
qg → qg                    gg → gg

- Large imbalance in fractional momenta of incoming partons boosts jets forward
  - → access to low x with jets in CASTOR

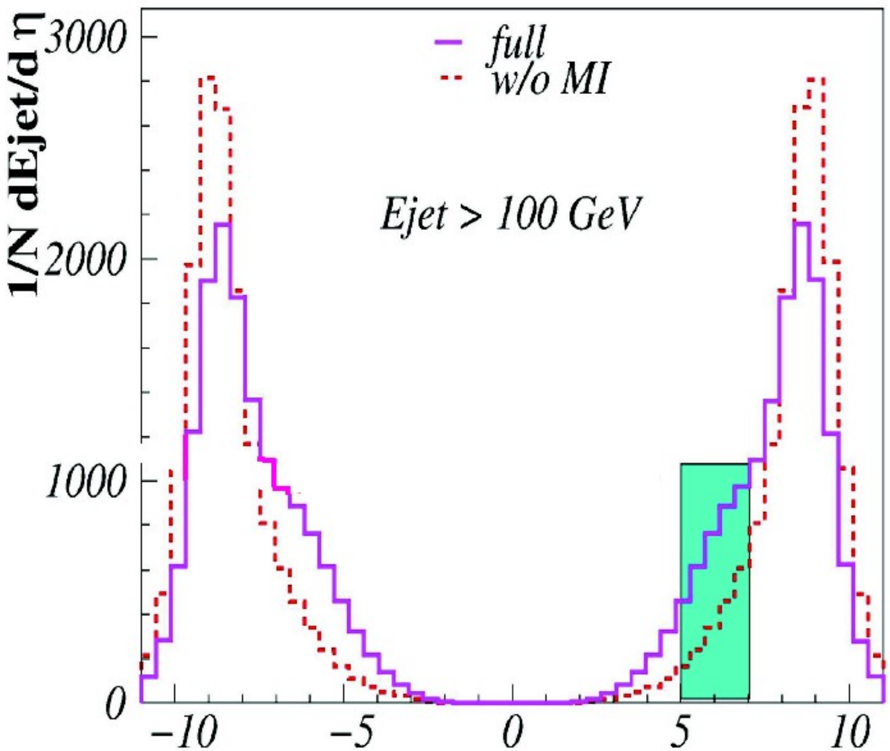


# Single inclusive forward jets

- Single inclusive forward jets probe the low-x structure of the proton
  - → saturation will reduce the jet cross section




[D. d'Enterria, CMS-note 2007/002]

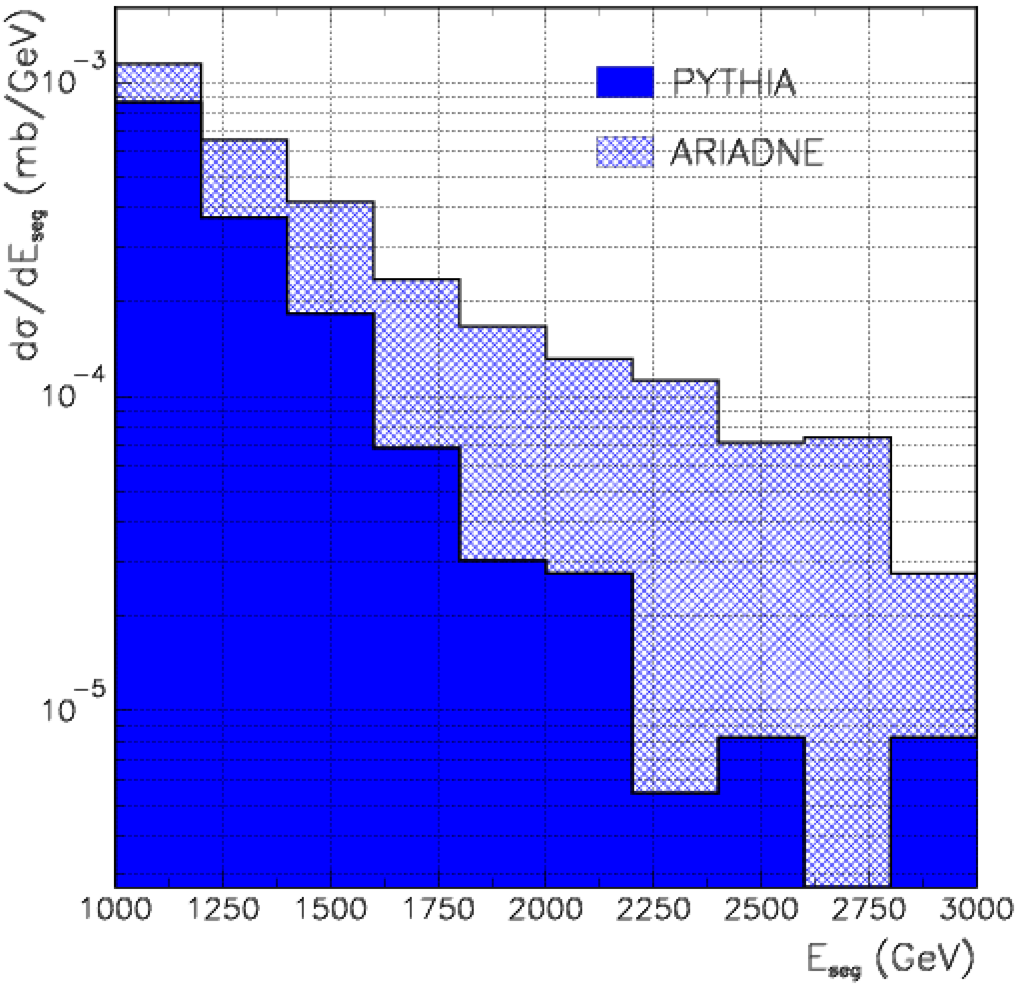



[M. Deak]

- Depending on the multiple interaction ansatz more or less energy is taken from the beam remnants
  - → M.I. will increase the jet energy

# Forward jets and BFKL dynamics

- Different approaches for parton showers result in different signatures i the final state:
  - DGLAP (as in standard PYTHIA) use $k_T$ ordered QCD cascades
    → few forward jets with high $p_T$
  - CDM (as in PYTHIA+ARIADNE) has no ordering in $k_T$
    → produces more high $p_T$ forward jets (mimics BFKL)
- Look for large and collimated energy deposits in CASTOR
  - doubling of cross section for jets with $E > 1000$ GeV ($p_T \gtrsim 5$ GeV)
- Studies of multiple jets and correlatior between central and forward jets will give information on fixed order ME calculations and PS

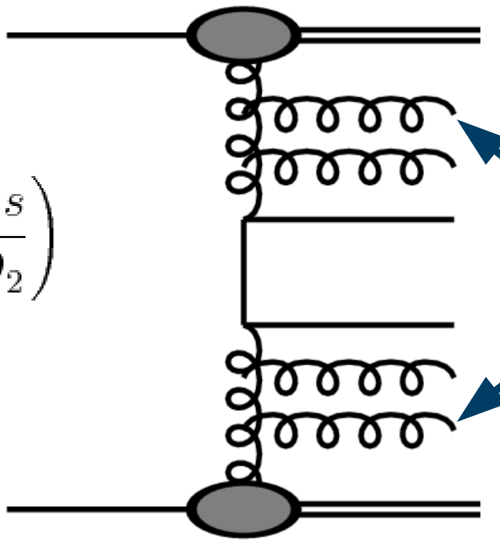


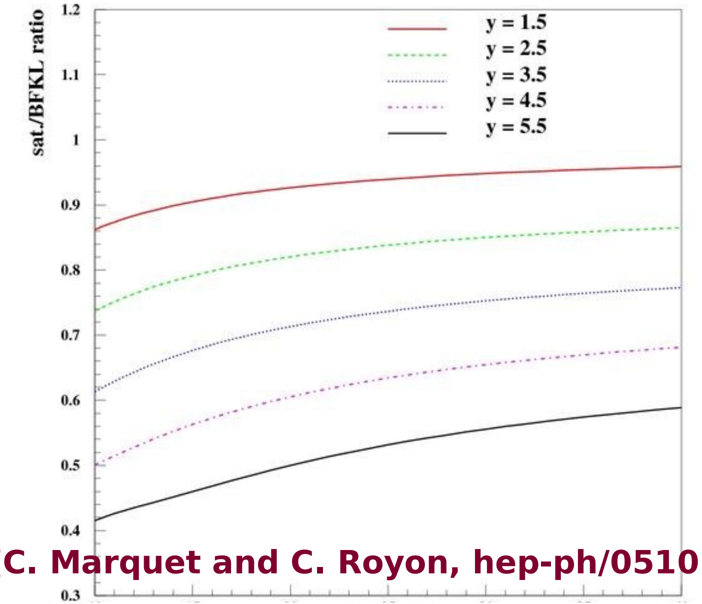

Energy deposited in 1 CASTOR $\varphi$-sector

## Jets at large Δη

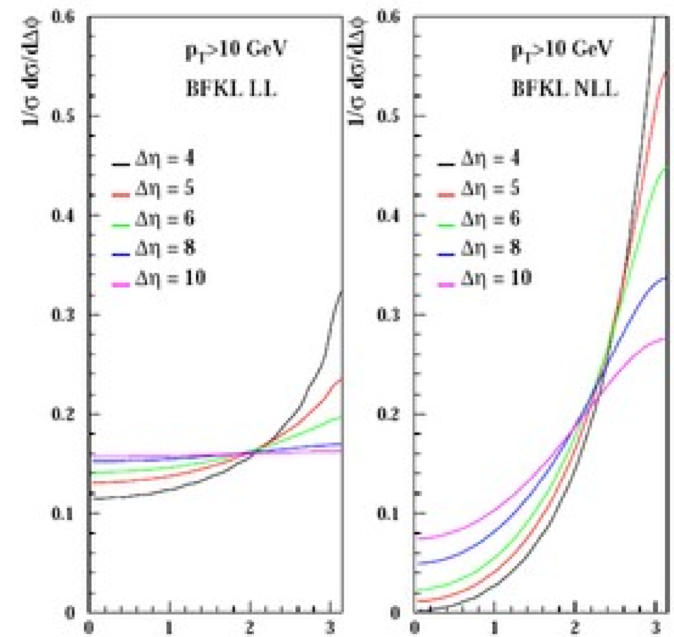
$$\Delta y = \log\left(\frac{x_1 x_2 s}{Q_1 Q_2}\right)$$

$$Q_i \approx E_{T,i}$$




[C. Marquet and C. Royon, hep-ph/0510266]




[C. Royon, HERA-LHC workshop, following A. Sabio Vera and F. Schwenssen, hep-ph/0702158 and hep/ph0602250]

- Large rapidity separation enhances phase space for BFKL
- BFKL predicts de-correlations in azimuthal angles from jets for increasing $\Delta\eta$
- Low x saturation effects in BFKL ladder?
  → biggest reduction for largest rapidity separations

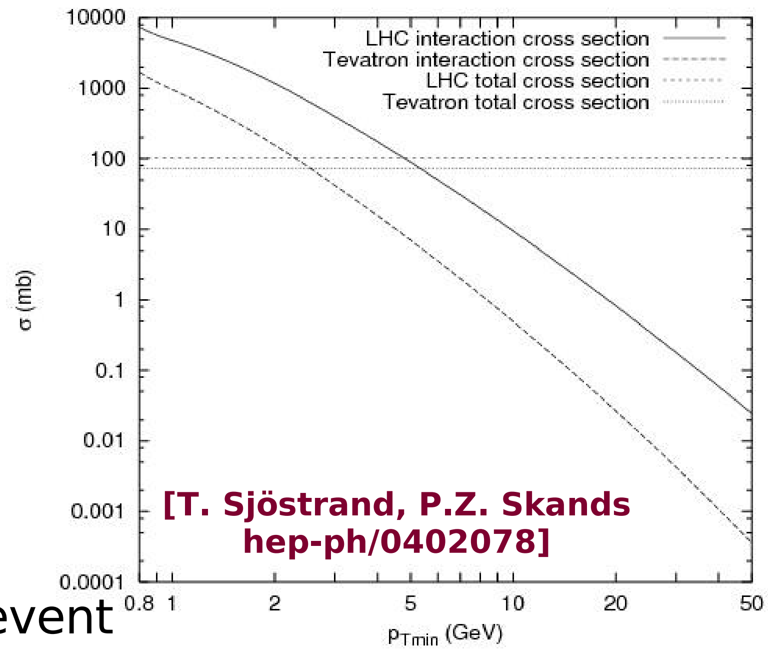
## 2. Multiple interactions/underlying events

- Basic partonic cross section

$$\sigma_{hard}(p^2_{\perp min}) = \int_{p^2_{\perp min}} \frac{d\sigma(p^2_\perp)}{dp^2_\perp} dp^2_\perp$$

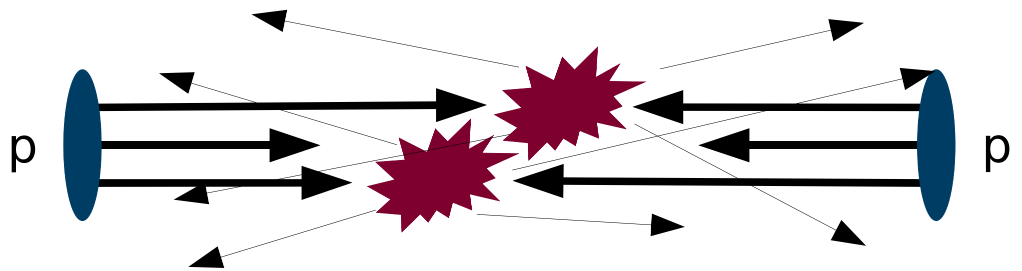
→ diverges faster than $1/p^4_{\perp min}$ as $p_{\perp min} \to 0$

→ eventually exceeds $\sigma_{tot}$(even for $p_{\perp min} > \Lambda_{QCD}$).




[T. Sjöstrand, P.Z. Skands hep-ph/0402078]

- Consequence: Multiple parton interactions per event



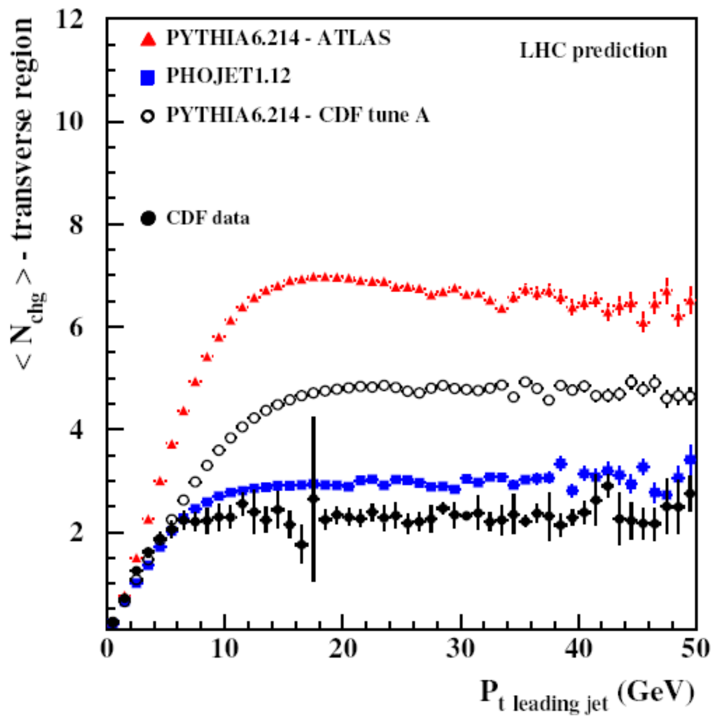

→ higher particle multiplicity (additional energy offset in jet profiles)

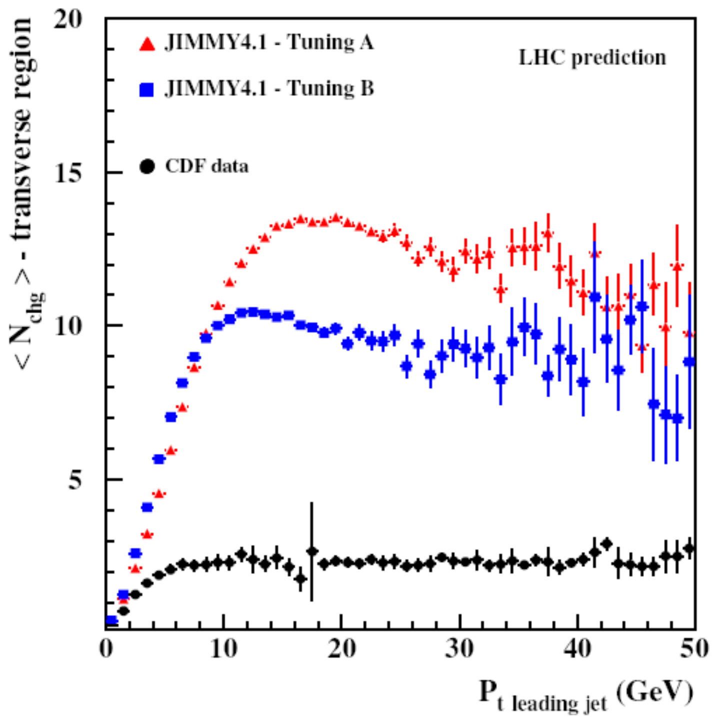
→ long distance correlations in rapidity (need to cover forward region!)

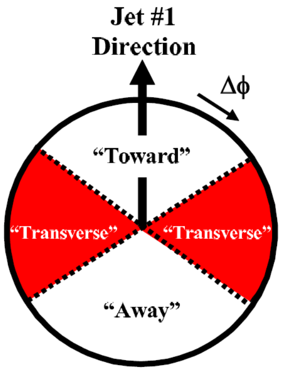
→ additional hard interactions may fake a discovery signal !
(e.g. pp → W H X with H → b<u>b</u> vs. pp → W b<u>b</u> X)

# Multiple interactions: MC tuning

LHC prediction for average multiplicity transverse to the leading jet:



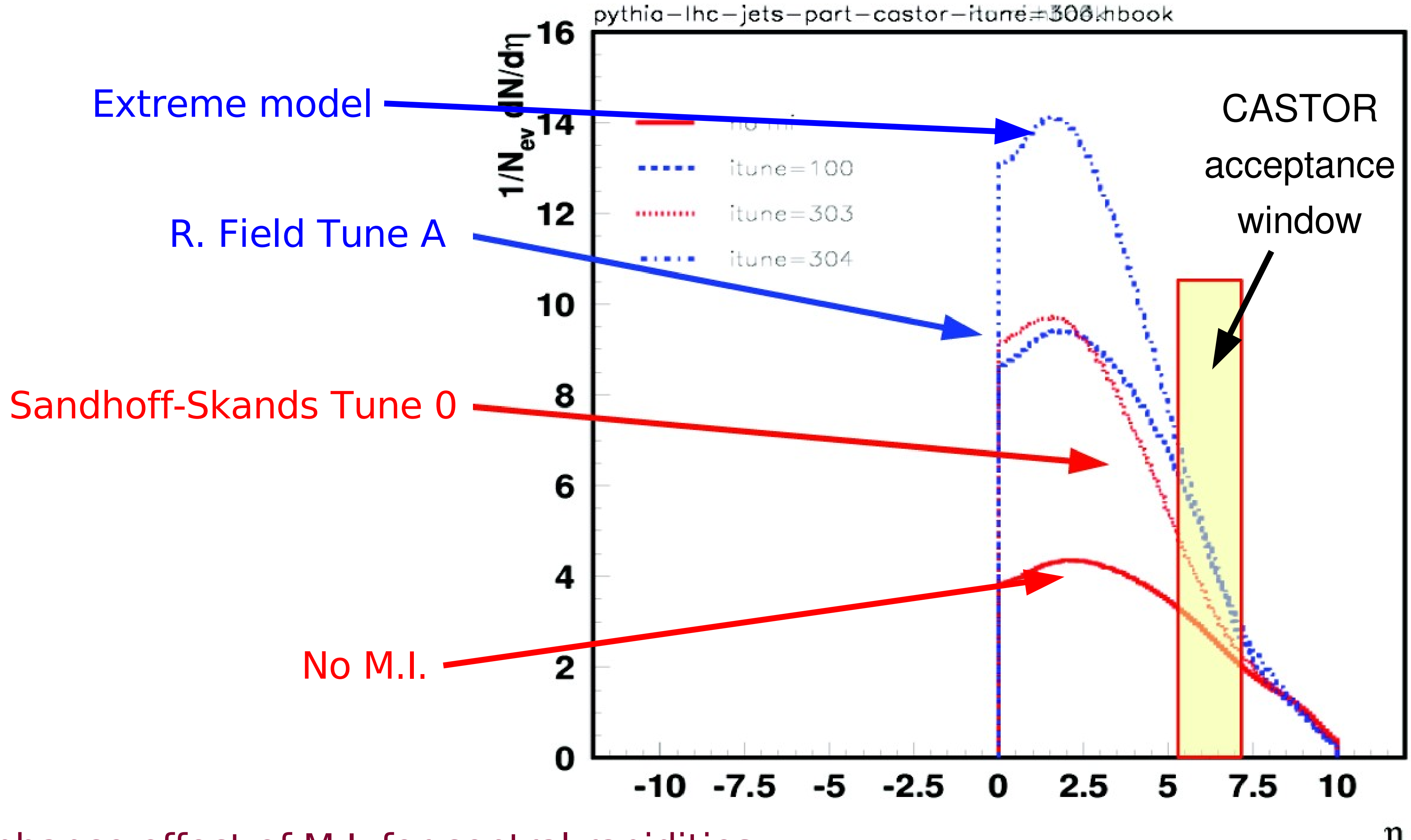




**[C. Buttar et al., HERA-LHC Workshop proc.]**

→ huge differences for the different generators and tunes

→ better understanding of multiple interactions is needed for MC tuning!

## Effect of M.I. on particle flow vs. rapidity:

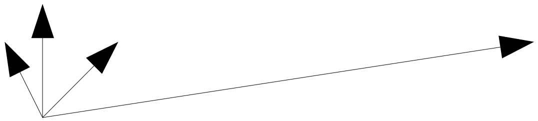



[H. Jung]

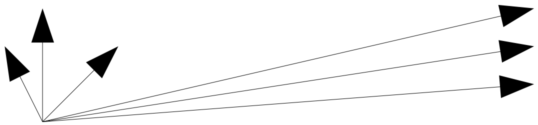
→ Enhance effect of M.I. for central rapidities by condition on forward region?

# Central-forward correlations

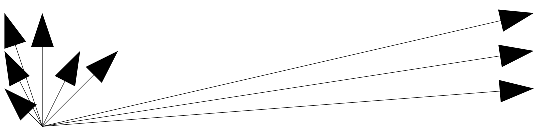
central forward

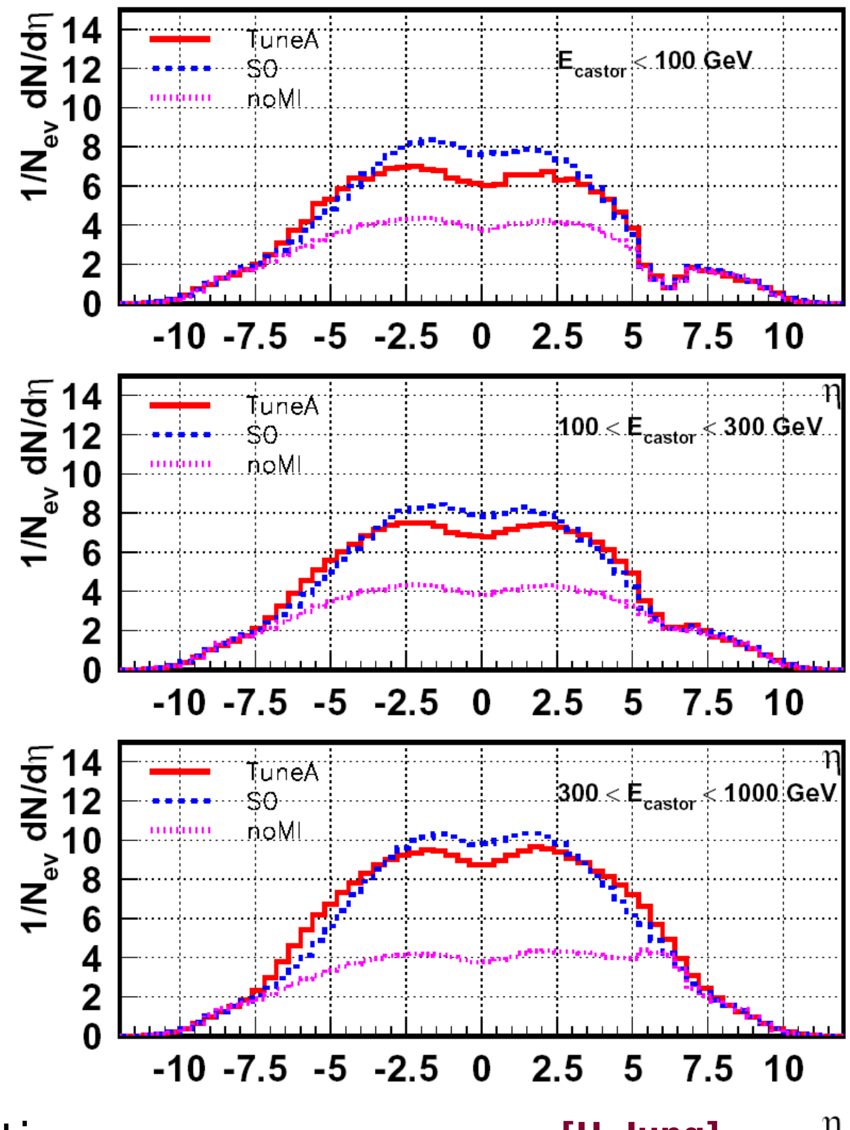



no correlation



long rang correlations





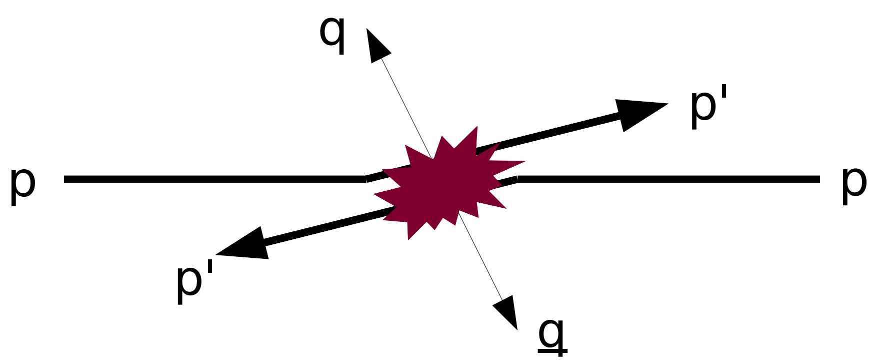

[H. Jung]

→ forward condition uncovers long range correlations

→ discriminative power for different M.I. tunes

## 3. Hard diffractive scattering

- One or both protons survive hard interaction (yielding jets, heavy quarks, ...)

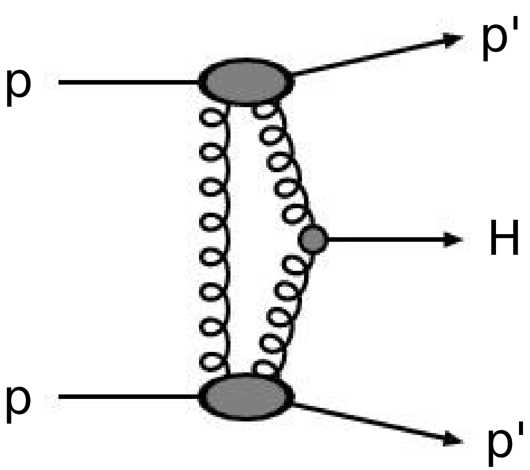



→ diffraction (including soft diffraction) makes up 25% of $\sigma_{tot}$!

→ tool to study (perturbative) QCD and the structure of hadrons

- Diffractive Higgs production pp -> p H p

→ particularly clean channel for the study (or discovery) of the Higgs boson



# Rapidity gaps

- Diffractive production of jets:

  pp → p jet jet p

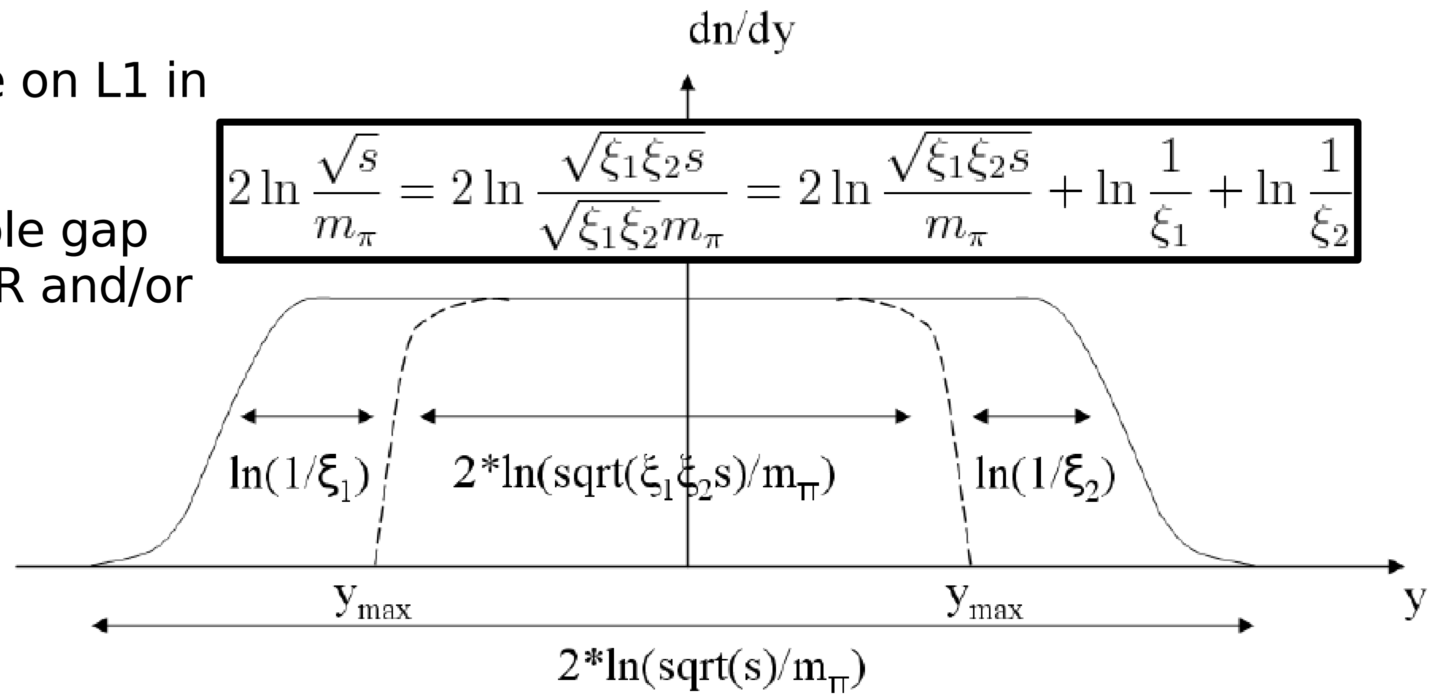
- Trigger study by Monika Grothe et al.:
  - → possible to trigger on $E_T$>40 GeV dijets with proton tag in L1 trigger

- No proton tags available on L1 in 2008
  - → need for single/double gap triggers with CASTOR and/or HF

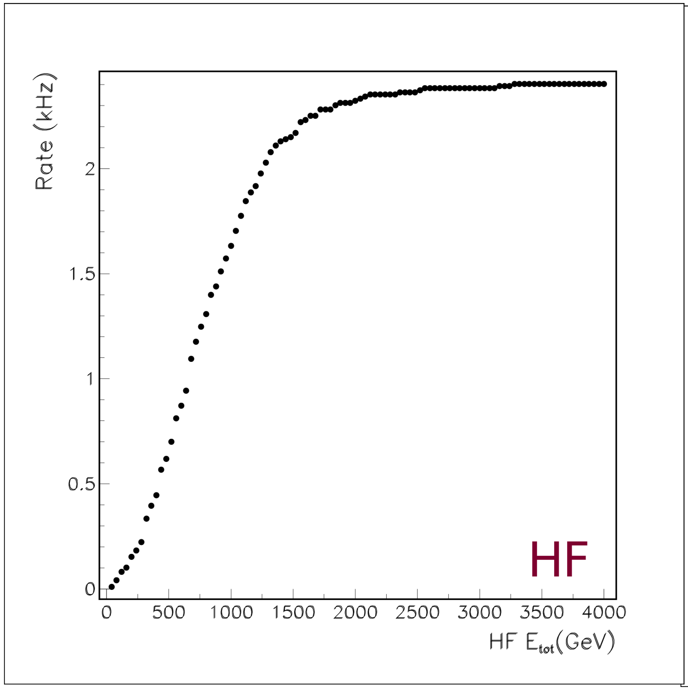
| $y_{max}$ | $\xi_{max}$ | $M_{max}$ for double gaps |
|---|---|---|
| 3.0 | 0.0002 | 3 GeV |
| 5.0 | 0.0015 | 20 GeV |
| 5.2 | 0.0018 | 25 GeV |
| 6.6 | 0.0074 | 100 GeV |
| 8.0 | 0.0302 | 420 GeV |

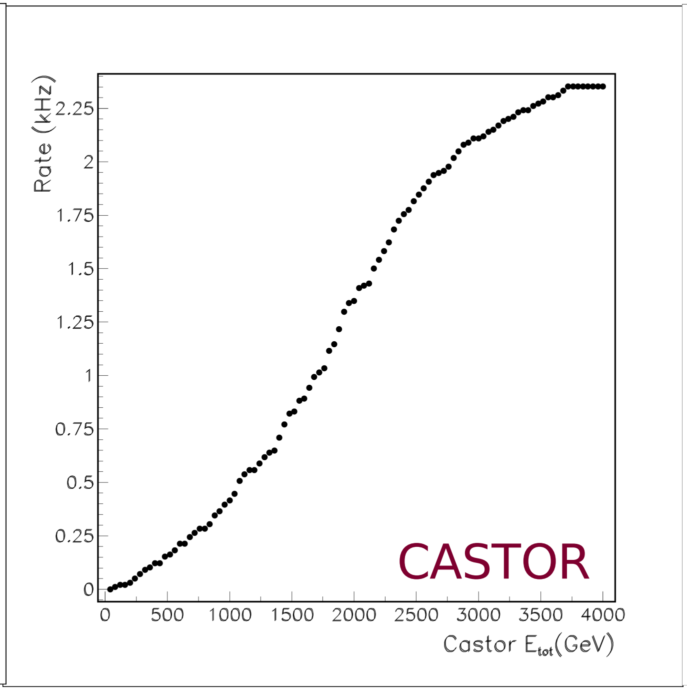
⇒ not many inclusive jet events with double gaps including HF !

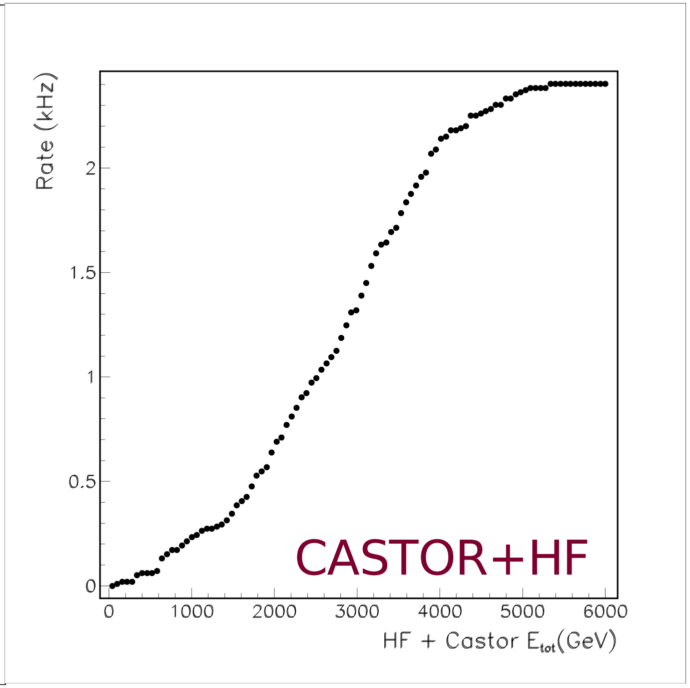
$$2\ln\frac{\sqrt{s}}{m_\pi} = 2\ln\frac{\sqrt{\xi_1\xi_2 s}}{\sqrt{\xi_1\xi_2}m_\pi} = 2\ln\frac{\sqrt{\xi_1\xi_2 s}}{m_\pi} + \ln\frac{1}{\xi_1} + \ln\frac{1}{\xi_2}$$



# Hard diffraction: dijet+gap rate



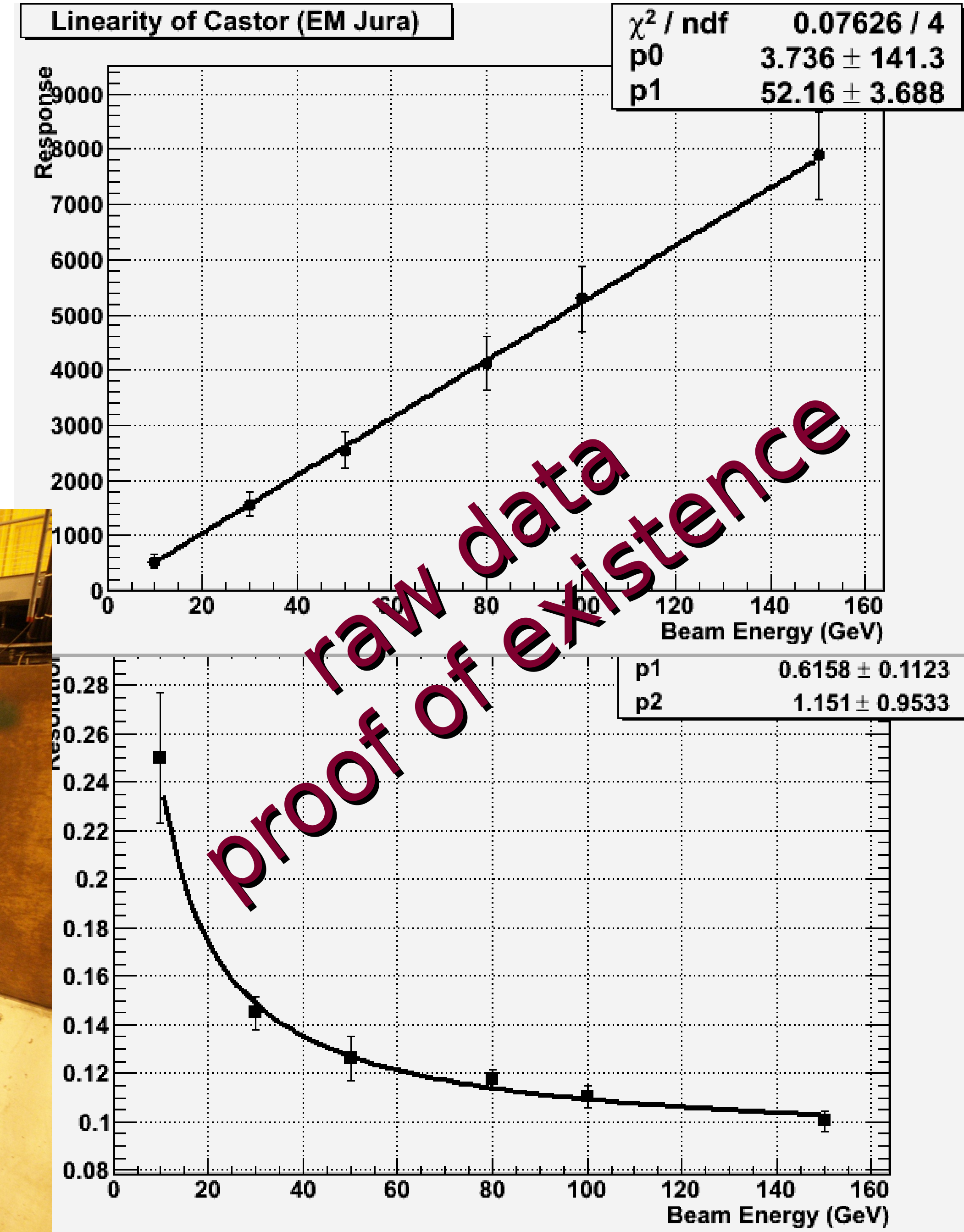




- L1 condition:
  (2 jets with $|\eta| < 2.5$ and $E_T > 40$ GeV) and ($E_{tot}$(single sided HF/CASTOR) $< E_0$)
- HLT strategies to be studied
  additional conditions on central jets (same as for proton-tagged events)

# CASTOR test beam results

One full octant (2x (2 em + 12 had) reading units) assembled and tested in beam (Aug 20-Sep 3)

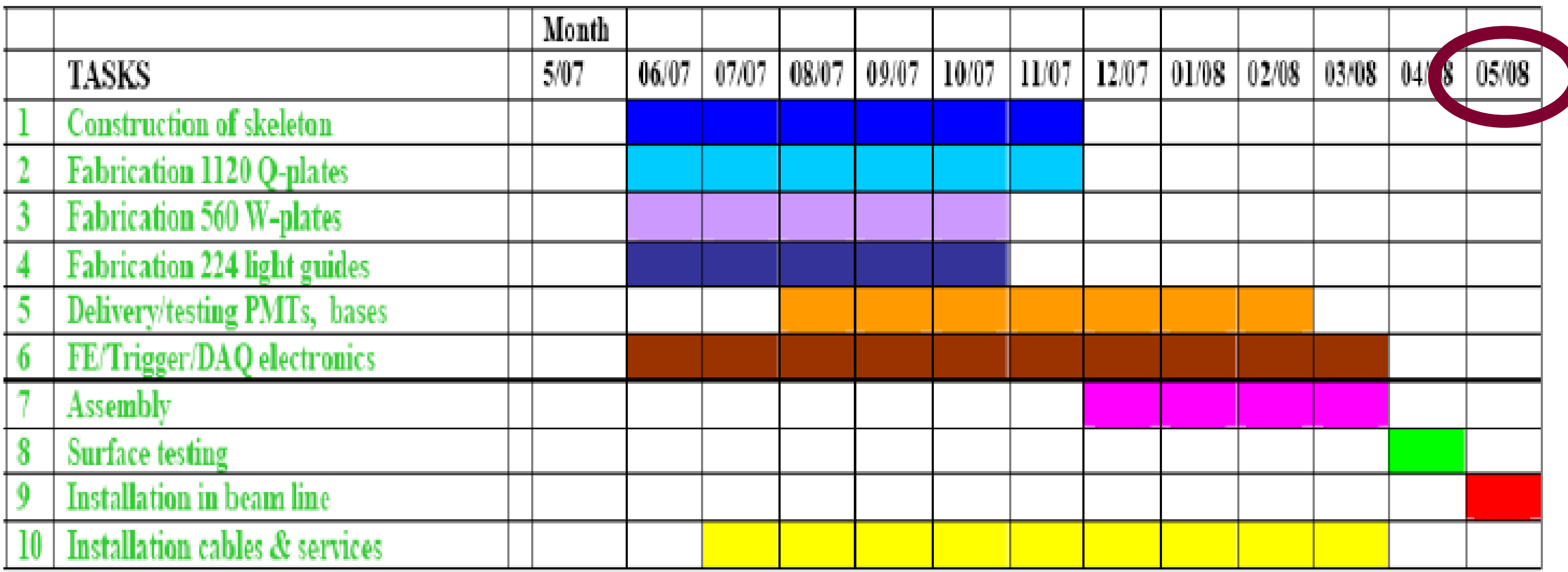
Testing different options for photomultipliers, electronics, ...




raw data
proof of existence

# Timeline

Construction & Implementation Schedule for one Calorimeter (LCAL) v1.2 (150507)



## Groups currently contributing to the project:

| | |
|---|---|
| • Athens | Design, MC sim's, funding; Project coordination |
| • Antwerp | PMTs, "electronics", funding; Electronics coordination |
| • CERN | Beam tests; SW-Physics coordination |
| • CuKurova | PMT testing |
| • DESY | FEA calculations, construction pre-prototype |
| • JINR Dubna | Design, technical manpower; Technical coordination |
| • INR, Moscow | Light guides & 2mm Q-plates, funding |
| • ITEP, Moscow | Laser/LED calibration system |
| • Northeastern | Readout devices, construction pre-prototype, funding |
| • U Iowa, ++ | Applied for NSF-MRI grant |

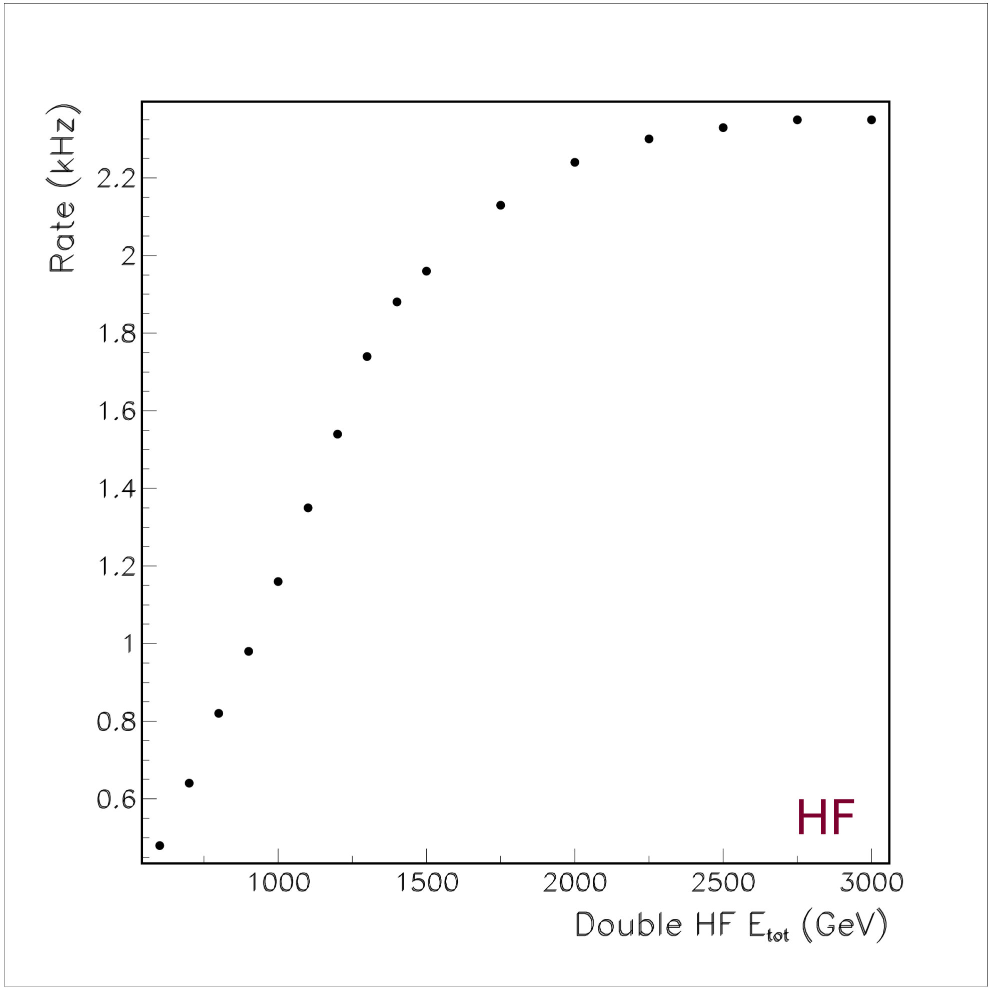
# Conclusion

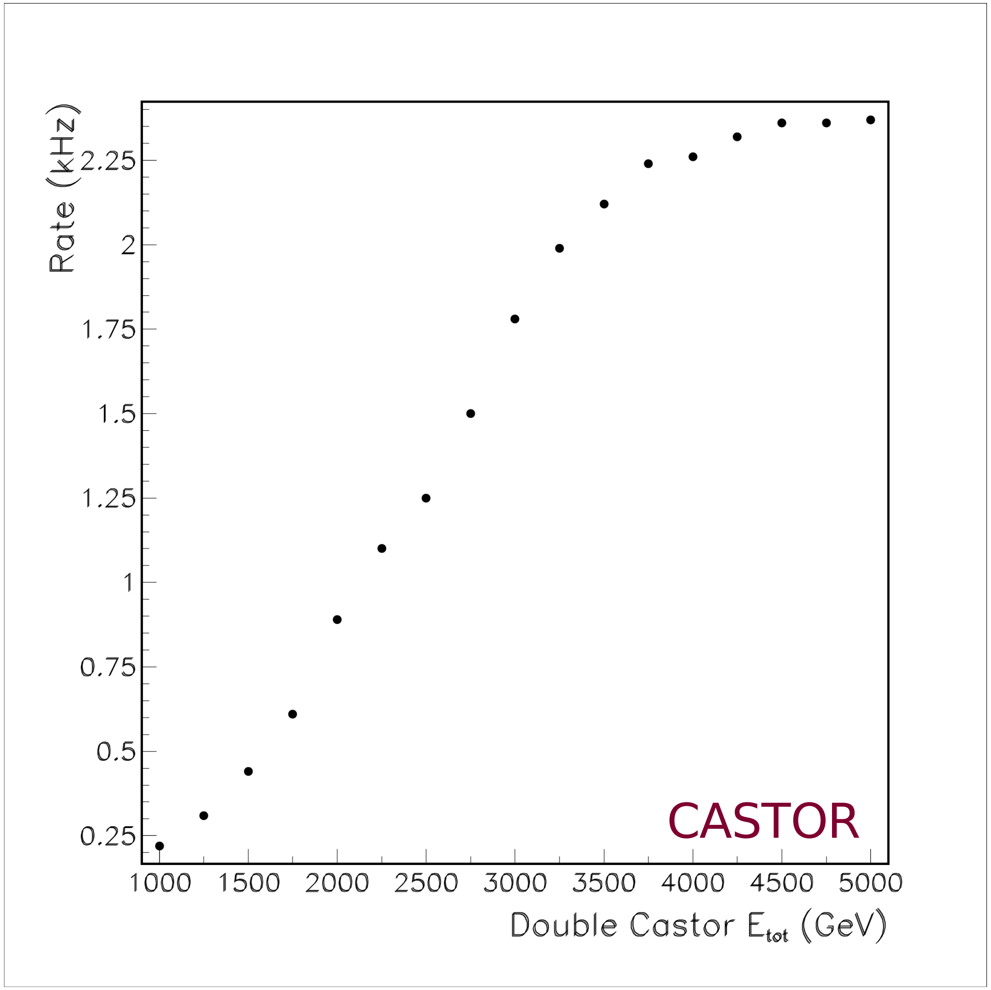
- CASTOR is a real, funded and accepted project
- CASTOR will cover pseudorapidities between 5.2 and 6.6
- It provides unprecedented and unique opportunities to study low x, multiple interactions and diffraction at the LHC:
  - $e^+e^-$ pairs from Drell-Yan, $Z^0$, J/ψ, ...
  - Prompt photons
  - Forward jets (+central jets or $W^{\pm}/Z^0$)
  - Forward/central particle and jet correlations
  - Dijets at large $\Delta\eta$, rapidity gaps between jets
  - Hard diffraction (large rapidity gaps)
- If you want a particular measurement to be made, using calorimeter coverage between 5.2 and 6.6, please let us know!
- Many thanks to:

  Hannes Jung, Kerstin Borras, Monika Grothe, Apostolos Panagiotou, ...
  for information and discussions.

# Backup

# Hard diffraction: gap+dijet+gap rate

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HLT strategies to be studied

additional conditions on central jets (same as for proton-tagged events)

# Background estimates

Non-diffractive background surviving the rapidity gap cut
(energy smearing over cut is not considered)

- CASTOR only

| Cut (GeV) | Non-diff | Single-diff ($\xi < 0.002$) | % bg |
|---|---|---|---|
| 0 | 638 | 4545 | 12.2 |
| 50 | 1842 | 4550 | 28.8 |
| 100 | 3509 | 4550 | 43.5 |
| 150 | 5559 | 4550 | 55.0 |
| 200 | 7836 | 4550 | 63.3 |

- CASTOR + ZDC ($E_{ZDC} < 50$ GeV)

| Cut (GeV) | Non-diff | Single-diff ($\xi < 0.002$) | % bg |
|---|---|---|---|
| 0 | 141 | 4545 | 3.0 |
| 50 | 430 | 4550 | 8.6 |
| 100 | 781 | 4550 | 14.7 |
| 150 | 1263 | 4550 | 22.1 |
| 200 | 1789 | 4550 | 28.2 |

Question:
- what background level is acceptable?
- how large is the systematic error due to the correction for background?

Studies will continue...

Note: particles below the Čerenkov threshold are invisible anyway!