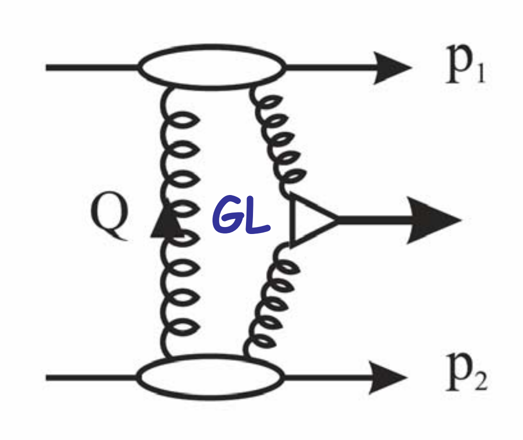
Measurement of Hard and Soft Diffraction at the LHC

Towards a DESY LOI

Henri Kowalski



Final state can be fully *controlled* by measurement
→ high measurement precision

Predominant production of *neutral, scalar states*
→ sensitive to new physics

X-sections for new physics in low x region depend on *Gluon Luminosity* which is precisely determined through measurement of *QCD jet-jet* reaction at LHC and HERA data input

Byproduct: Clean QCD measurements in new, non-trivial, regions

New Physics in Diffraction?

J. Ellis,
HERA-LHC
Workshop

Higher symmetries (e.g. Supersymmetry) lead to existence of *several* scalar, neutral, *Higgs states*, H, h, A . . . . Higgs Hunter Guide, Gunnion, Haber, Kane, Dawson 1990

In MSSM *Higgs x-section* are likely to be much *enhanced* as compared to Standard Model (tanβ large because $M_{Higgs} > 115$ GeV)

In MSSM there are *many ways* to generate *CP violation* ⇒
CP violation is *highly probable* ⇒ all *three* neutral Higgs bosons have *similar masses* ~120 GeV

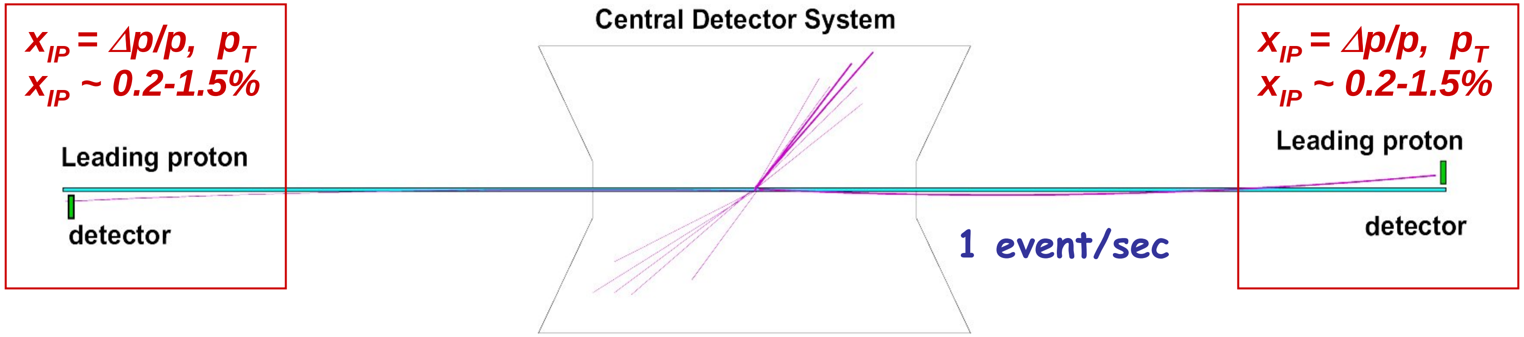
can ONLY be RESOLVED in DIFFRACTION

Ellis, Lee, Pilaftisis Phys Rev D, 70, 075010, (2004) , hep-ph/0502251

Correlation between *transverse momenta* of the tagged *protons* give a handle on the CP-violation in the Higgs sector

Khoze, Martin, Ryskin, hep-ph 040178

Hard Diffractive Reactions

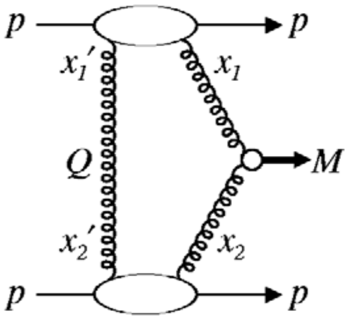


low *x QCD* reactions:

pp => pp + $g_{Jet}\, g_{Jet}$ $\sigma \sim$ 1 nb for $E_T > 20$ GeV , M(jj) ~ 50 GeV

$\sigma \sim 0.5$ pb for $E_T > 60$ GeV , M(jj) ~ 200 GeV

$|\eta_{JET}| < 2$ KMR Eur. Phys J. C23, p 311



$\sigma^{Diff} = \hat{\sigma} \cdot L \Longleftrightarrow$

σ^{Diff} = hard X-section × Gluon Luminosity

factorization !!!

$$M^2 \frac{\partial L}{\partial y \partial M^2} = S^2 O$$

$$\frac{d\hat{\sigma}}{dt} \approx \frac{9}{4} \frac{\pi \alpha_s^2}{E_T^4}$$

$$\hat{\sigma}_{Higgs} \propto \Gamma_{Higgs}$$

gg ⇒ Jet+Jet

gg ⇒ Higgs

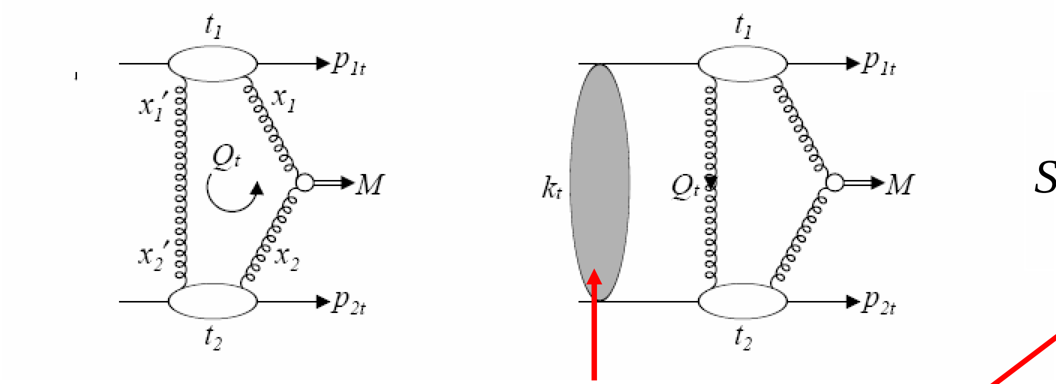
$$O^{exclusive} = \left(\frac{\pi}{(N_c^2 - 1)b} \int \frac{dQ_t^2}{Q_t^4} f_g(x_1, x_1', t, Q_t, \mu)\, f_g(x_2, x_2', t, Q_t, \mu) \right)^2$$

f_g - un. gluon densities

pp => pp + Higgs $\sigma \sim$ O(3) fb ~ O(100) fb *(MSSM)*

High LHC Luminosity Optics required

Survival Probability S^2



Soft Elastic Opacity

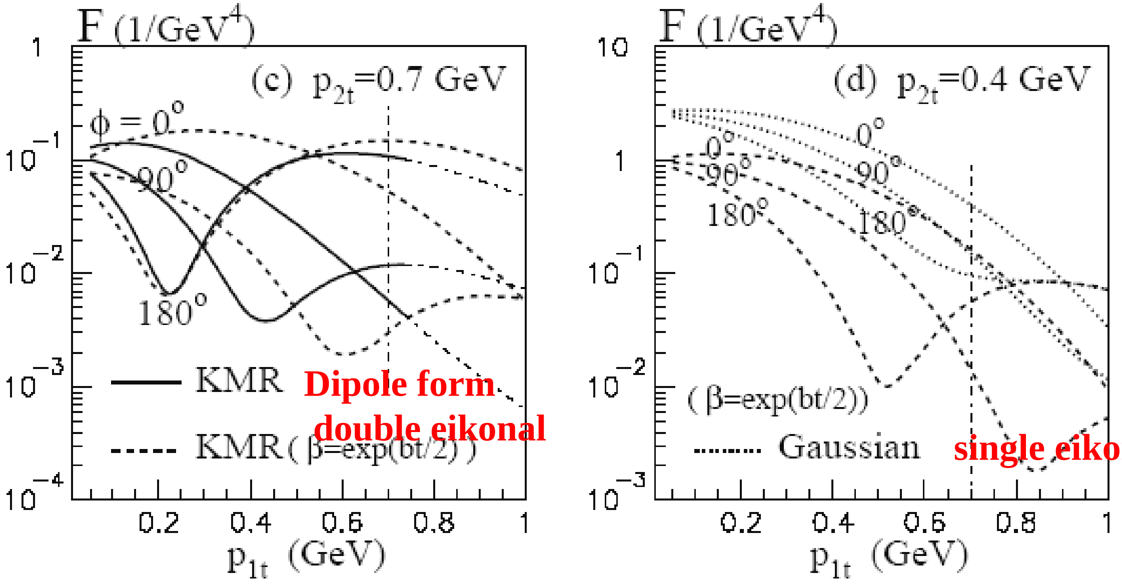
$$S^2 = \frac{\int M^2(s,b)\boxed{e^{-\Omega(s,b)}}d^2b}{\int M^2(s,b)d^2b}$$

$$F(\vec{p}_{1t},\vec{p}_{2t}) = \frac{\beta^2(t_1)\beta^2(t_2)}{<S^2>\pi^2/b_0^2}S^2(\vec{p}_{1t},\vec{p}_{2t})$$

t – distributions at LHC

Effects of soft proton absorption modulate the hard *t* - distributions

t-measurement will allow to disentangle the effects of soft absorption from hard behavior



Dipole form double eikonal

single eikonal

Khoze Martin Ryskin

t – distributions at LHC

with the cross-sections of the O(1) nb and $L \sim 1\ \mathrm{nb}^{-1}\,\mathrm{s}^{-1}$ =>
O(10^7) events/year are expected.

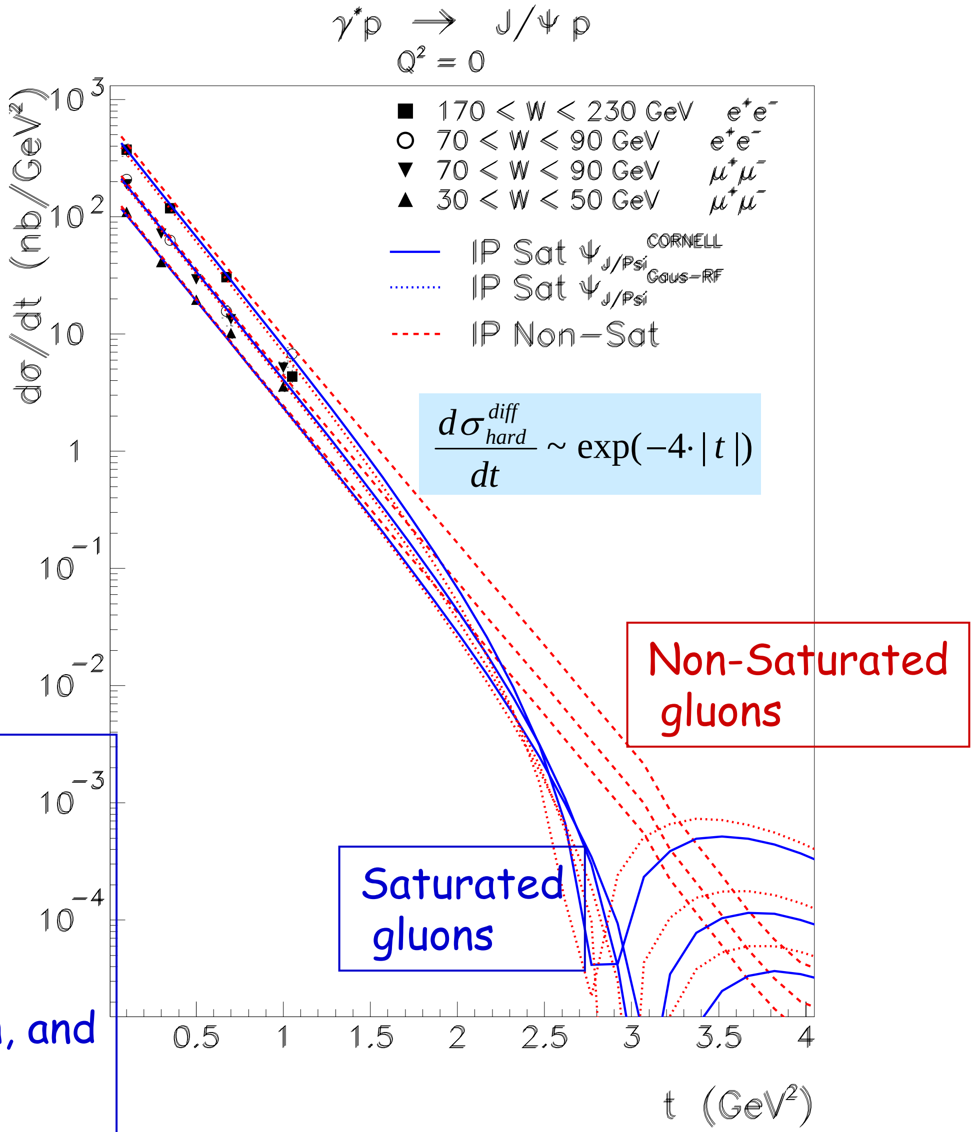
For hard diffraction this allows to follow the *t* – distribution to
$t_{max} \sim 4\ \mathrm{GeV}^2$

For soft diffraction $t_{max} \sim 2\ \mathrm{GeV}^2$

t-distribution of hard processes should be sensitive to the evolution and/or saturation effects

see:
Al Mueller dipole evolution, BK equation, and the impact parameter saturation model for HERA data

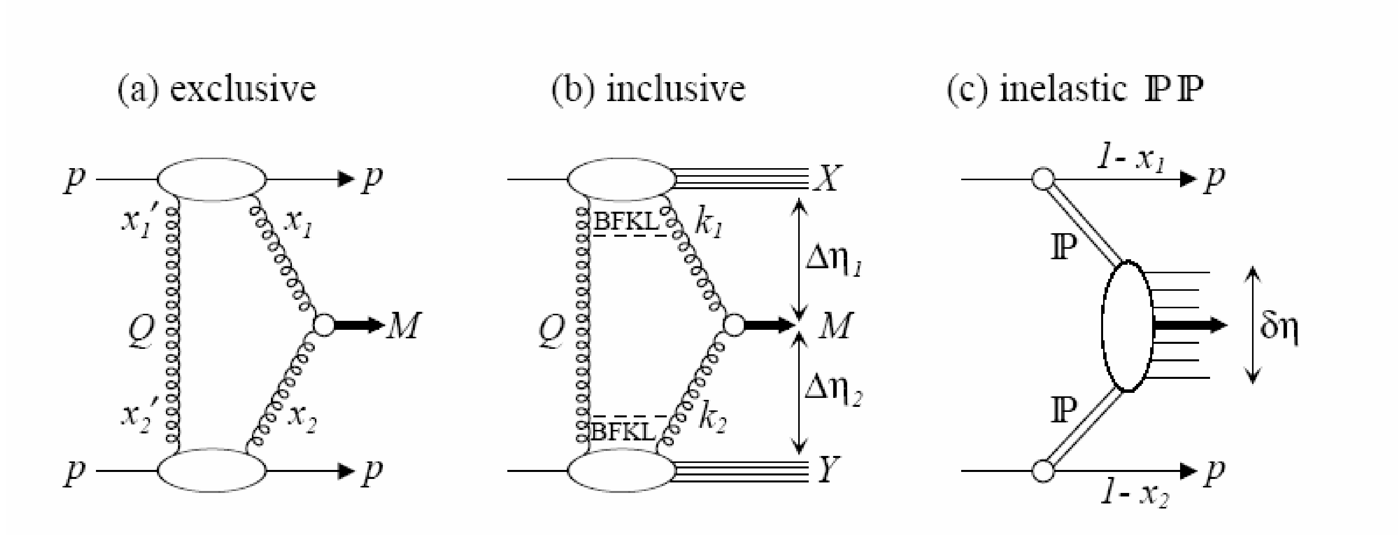
t – distributions at HERA



$$\frac{d\sigma^{diff}_{hard}}{dt} \sim \exp(-4\cdot|t|)$$

Non-Saturated gluons

Saturated gluons



diff X-Sections

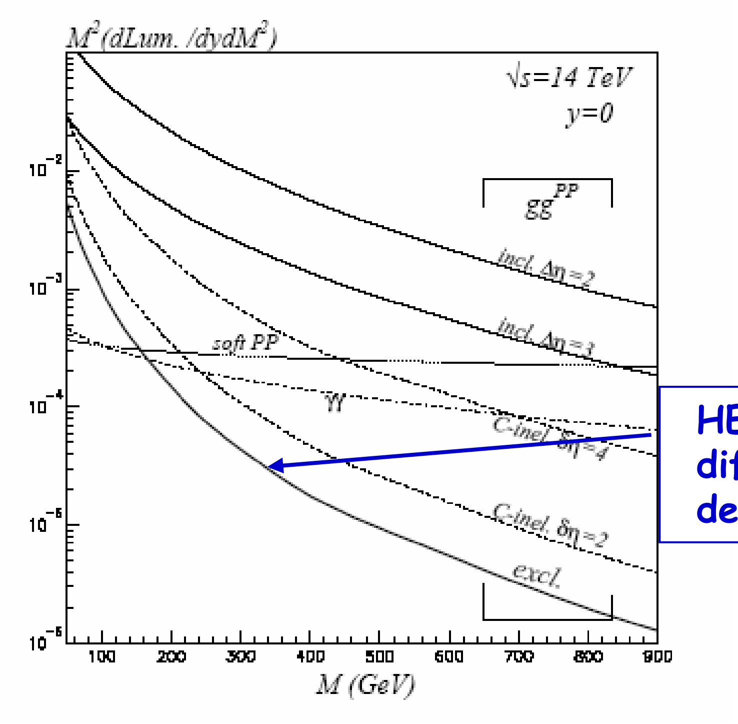
$$\sigma = L \cdot \hat{\sigma}$$

$$M^2 \frac{\partial L}{\partial y \partial M^2} = LS^2$$

gg ->Jet+Jet

$$\frac{d\hat{\sigma}}{dt} \approx \frac{9}{4} \frac{\pi \alpha_s^2}{E_T^4}$$

Gluon Luminosity -KMR



HERA Data & Exclusive Jet-Jet diffractive cross-sections determine Gluon Luminosity

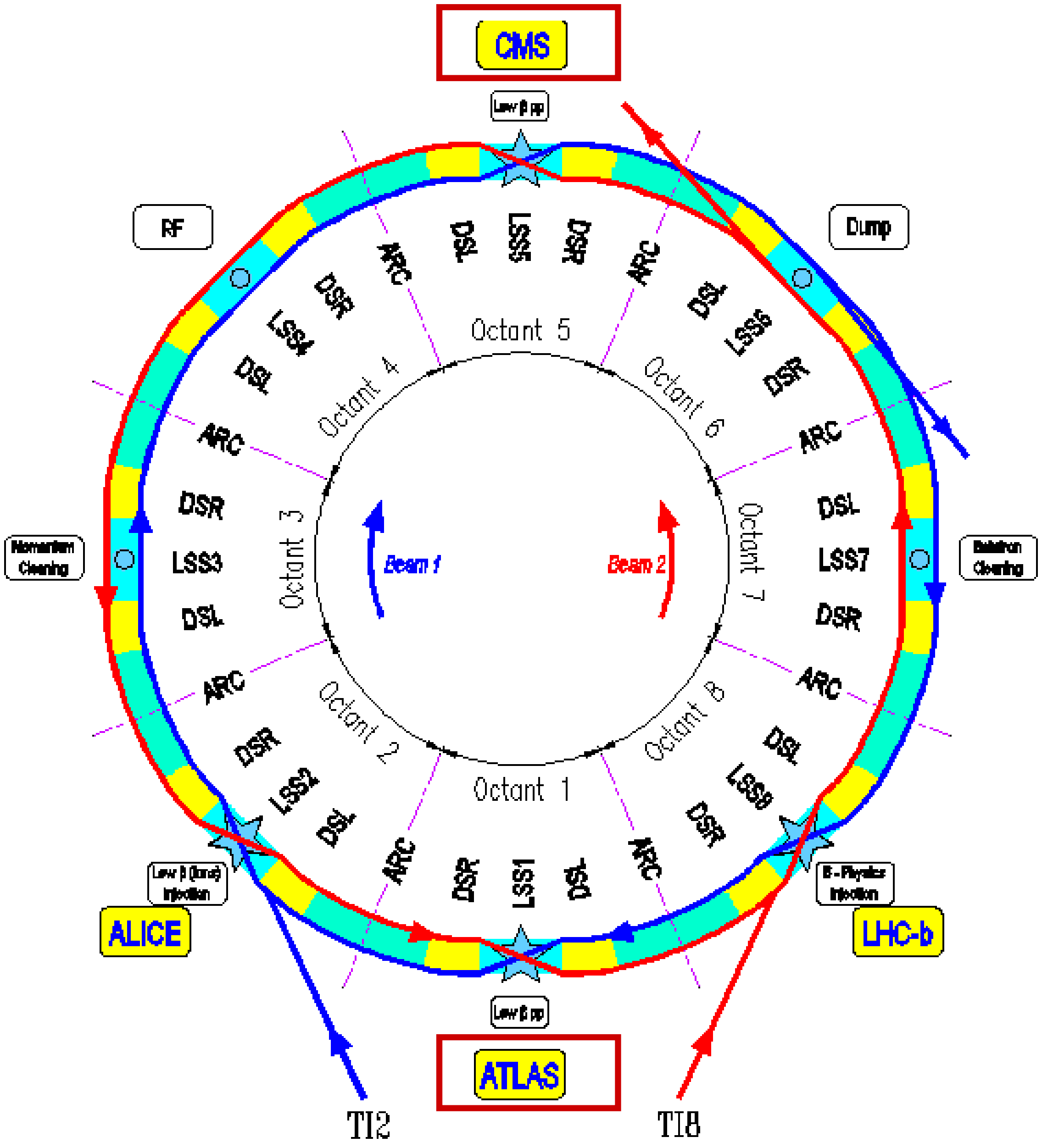
Challenge of Diffractive DPE Measurement at high luminosity

- acceptance
- calibration and alignment
- stability of measurement conditions
- high resolution in x_{IP}
- backgrounds
- multiple events

→

Specially designed forward detectors

x_{IP} - 0.2 — 1.5 % t - 0 — O(10) GeV^2



LHC parameters

Length	**26.6 km**
Nr. of bunches	**2808**
Nr. of particle/bunch	**1.15 10^{11}**
Frequency	**40 MHz**
Inter-bunch distance	**25 nsec**

Maximal Luminosity - 10^{34} cm^{-2} s^{-1}

Coasted Beam Optics

x - transverse deviation from the beam position

x' - transverse angular deviation

Transport Matrix
(from text books)

$$\begin{pmatrix} x \\ x' \\ \xi \end{pmatrix} = \begin{pmatrix} \sqrt{\frac{\beta}{\beta_0}}(\cos\Psi + \alpha_0 \sin\Psi) & \sqrt{\beta\beta_0}\sin\Psi & \mathrm{D} \\ \frac{(\alpha_0 - \alpha)\cos\Psi - (1+\alpha_0\alpha)\sin\Psi}{\sqrt{\beta\beta_0}} & \sqrt{\frac{\beta_0}{\beta}}(\cos\Psi - \sin\Psi) & \mathrm{D}' \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x_0 + 0 \\ x'_0 + \theta \\ \xi_0 - x_{IP} \end{pmatrix}$$

observation point

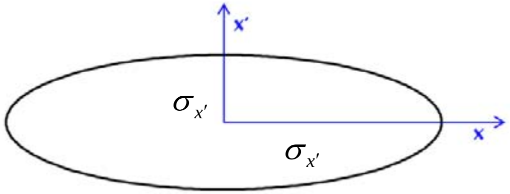
interaction point

e.g. P.Schmueser in CERN 94-01

β-amplitude function, Ψ-phases, D-dispersion can be obtained from the LHC Optic Webpage

Coasted beam optics is considerably easier to handle than ray tracking in MAD

x, x' are moving on
Phase Ellipse



$$\alpha \neq 0 \qquad \sigma_x = \sqrt{\varepsilon\beta_x} \qquad \sigma_{x'} = \sqrt{\frac{\varepsilon(1+\alpha_x^2)}{\beta_x}}$$

LHC High Luminosity Optics

Interaction point

$\beta_x = \beta_y = 0.55\,\mathrm{m}$ $\varepsilon_N = 3.75\,\mu\mathrm{rad}\cdot\mathrm{m}$

$\sigma_x = \sigma_y = \sqrt{\varepsilon\beta} = 16.6\,\mu\mathrm{m}$ $\varepsilon = \varepsilon_N / \gamma$

$\sigma_{x'} = \sigma_{y'} = \sqrt{\dfrac{\varepsilon(1+\alpha^2)}{\beta}} = 30.2\,\mu\mathrm{rad}$ => $p_T \sim 200\,\mathrm{MeV}$

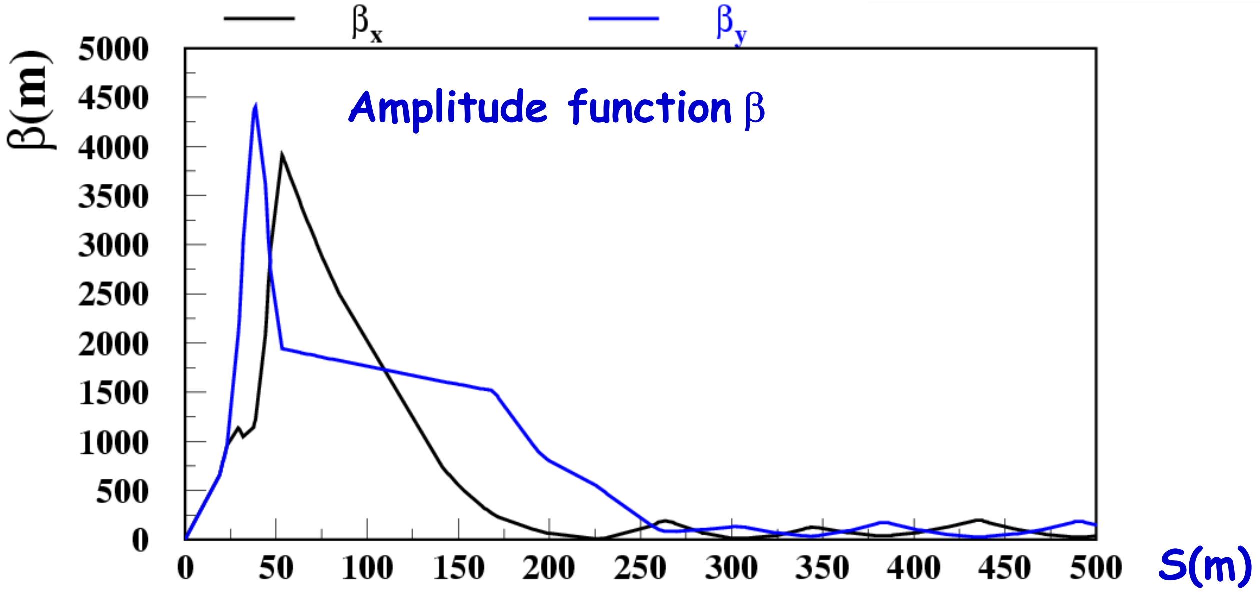
420 m point

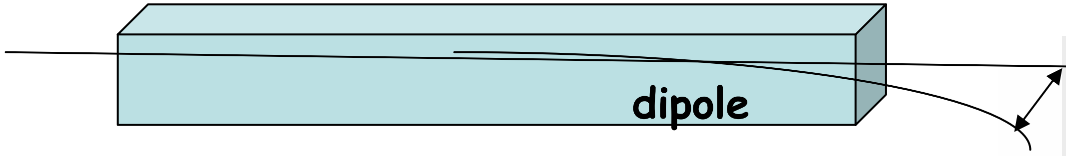
$\beta_x = 130\,\mathrm{m}$ $\beta_y = 50\,\mathrm{m}$

$\sigma_x = 250\,\mu\mathrm{m}$ $\sigma_y = 160\,\mu\mathrm{m}$

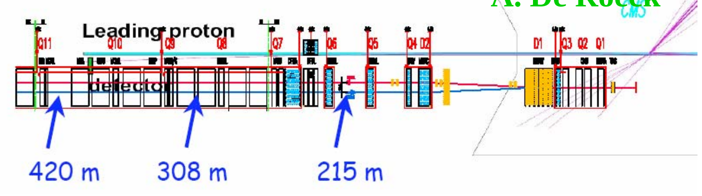
$\sigma_{x'} = 4.5\,\mu\mathrm{rad}$ $\sigma_{y'} = 4.5\,\mu\mathrm{rad}$

LHC HL Optics: transverse deviations are magnified, angular deviations are diminished





$$x = D_x \frac{\Delta p}{p}$$

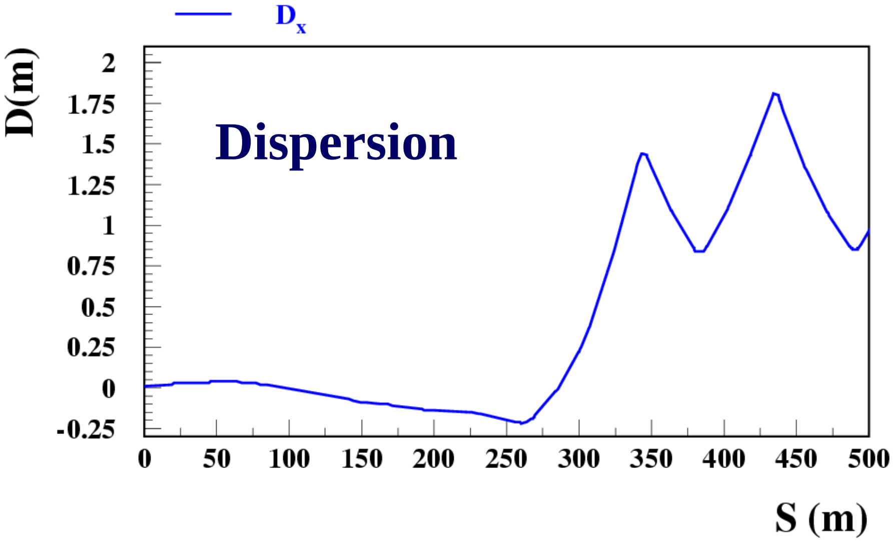


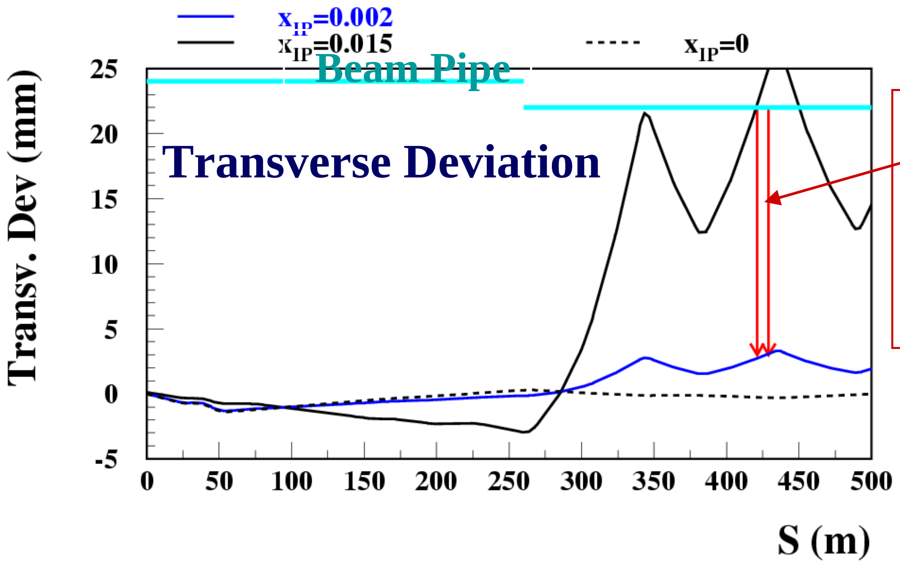
picture from
A. De Roeck

At 420 m

$$\frac{\Delta p}{p} = 0.01 \quad \Rightarrow \quad x = 1.5\,\text{cm}$$

$$\frac{\Delta p}{p} = 0.001 \quad \Rightarrow \quad x = 1.5\,\text{mm}$$





Detector

closest
approach
12 σ ~3mm

acceptance
x_{IP} ~ 0.2 - 1.5 %
t from 0 to ~10 GeV^2

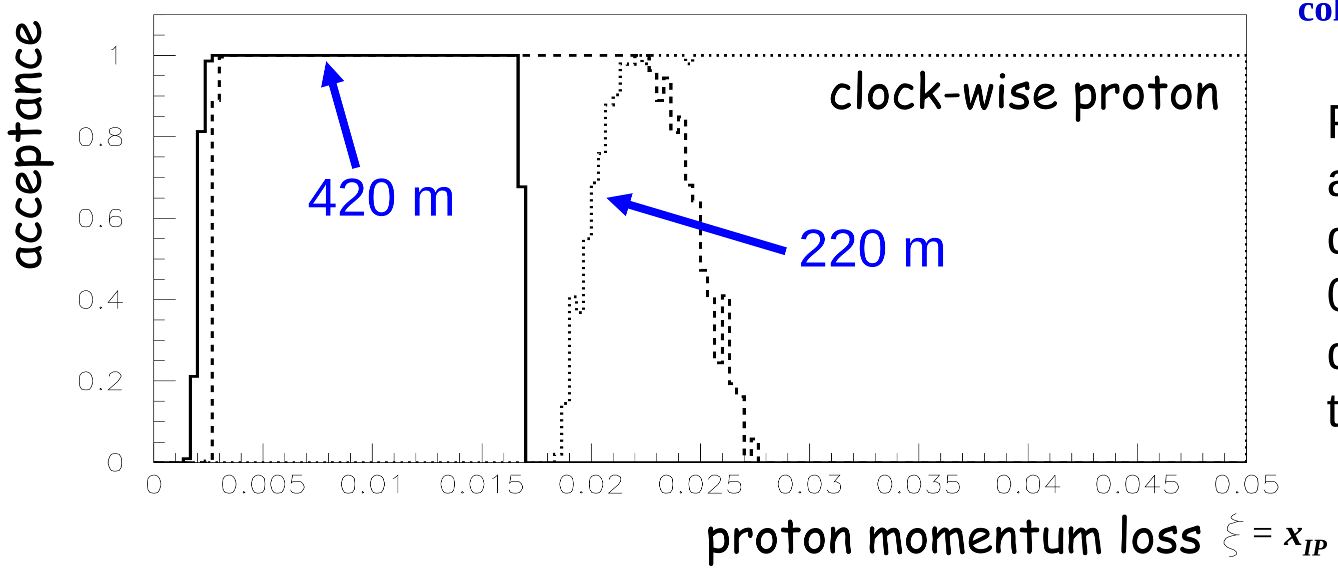
deflection of protons
due to main magnets

⇒ stability against
beam tuning effects

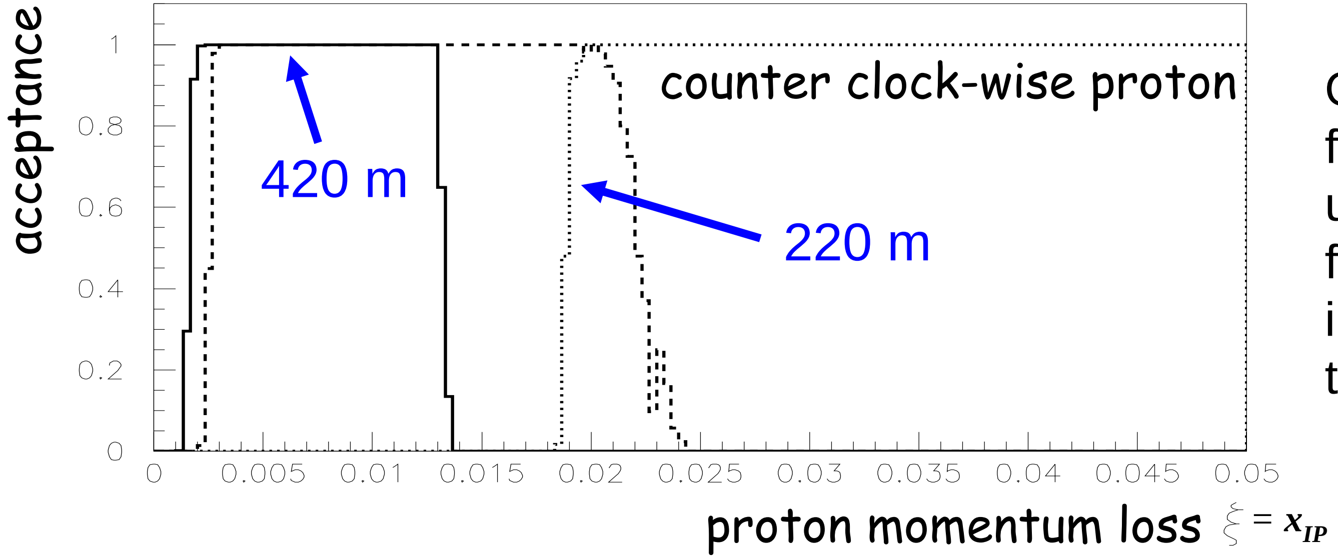
Leading proton acceptance ($\beta^* = 0.5$ m)

March 2003

from the talk of
K. Österberg, Manchester
for the TOTEM
collaboration



Proton acceptance down to x_{IP} = 0.2 % if detectors in the cold region



Only proton info from detectors up to 220 m from IP arrive in time for L1 trigger decision

Reconstruction of Kinematic Variables

Transport Matrix
(from text books)

$$\begin{pmatrix} x \\ x' \\ \xi \end{pmatrix} = \begin{pmatrix} \sqrt{\frac{\beta}{\beta_0}}(\cos\Psi+\alpha_0\sin\Psi) & \sqrt{\beta\beta_0}\sin\Psi & \mathrm{D} \\ \frac{(\alpha_0-\alpha)\cos\Psi-(1+\alpha_0\alpha)\sin\Psi}{\sqrt{\beta\beta_0}} & \sqrt{\frac{\beta_0}{\beta}}(\cos\Psi-\sin\Psi) & \mathrm{D}' \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x_0+0 \\ x_0'+\theta \\ \xi_0-x_{IP} \end{pmatrix}$$

observation point
3-measured

Real mapping should be computed with MAD

interaction point
2-unknown

Calibration using events with reconstructed x_{IP1} and x_{IP2} in CD, e.g *DPE* with σ ~ O(1) μb

$$x_{IP1} = \frac{M}{\sqrt{s}}e^{y} \qquad x_{IP2} = \frac{M}{\sqrt{s}}e^{-y}$$

Exploit t = 0 peak for alignment

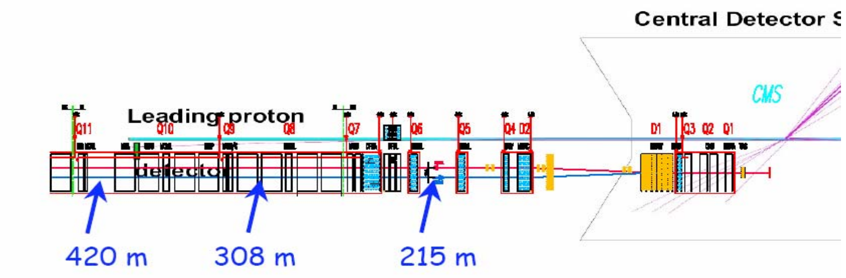
$$\chi^2_{calib} = \frac{\theta_x^2}{\sigma_{\theta_x}^2} + \frac{(x_{IP}-x_{IP}^{CD})^2}{\sigma^2_{x_{IP}-x_{IP}^{CD}}}$$

Minimize χ^2

$$\chi^2 = (x_i - x_i(\theta_x, x_{IP}) \cdot c_{ij}^{-1} \cdot (x_j - x_j(\theta_x, x_{IP}))$$

H1 experience with VFPS - Real evaluation should take into account nonlinearities and correlations between the vertical and horizontal planes due to sextupoles and higher order magnets (Pierre van Mechelen)

420 m Detectors



Missing dipole in the lattice – 14 m space. With a bypass ~8 m space remains for warm detectors sitting in Roman Pots

detector resolution should be better than the beam spread at 420 m

$$\sigma_x \approx 250\ \mu\text{m} \qquad \sigma_y \approx 160\ \mu\text{m}$$

$$\sigma_{x',y'} \approx 4.5\ \mu\text{rad}$$

angular measurement can be performed with silicon detectors spaced 8 m apart, with ~10 μm resolution. Size of the detectors: ~30 mm * 20 mm

alignment with physics reactions (much easier than at HERA, high statistics)

simple estimate of the proton momentum resolution:

$$\Delta x_{IP} / x_{IP} \sim 8\% \quad \text{for} \quad x_{IP} \approx 0.002 \qquad \sigma_x / 3mm$$

$$\Delta x_{IP} / x_{IP} \sim 1.5\% \quad \text{for} \quad x_{IP} \approx 0.01 \qquad \sigma_x / 15mm$$

$$\Delta p_T \sim 200\ \text{MeV}$$

LHC No Pileup Measurement Scenarios
at full luminosity

The *no pileup* situation allows to apply rapidity gap, primary single vertex and energy matching requirements to select diffractive events.

⟹ Excellent conditions for selecting and investigating diffractive reactions with high cross-sections, e.g *hard QCD DPE*

inclusive and single diffractive events with σ = 70 mb produce,

at $\mathcal{L} = 10^{34}\ s^{-1}\ cm^{-2}$ => ~ 20 events per bunch crossing (no-pileup impossible)

$\mathcal{L} = 10^{33}$ => ~ 2 events per bunch
probability of no-pileup ~ 15%
effective $\mathcal{L} \sim 1.5{*}10^{32}$ or $0.15\ nb^{-1}\ s^{-1}$

$\mathcal{L} = 4{*}10^{33}$ => ~ 8 events per bunch
probability of no-pileup ~ 0.03%
effective $\mathcal{L} \sim 1{*}10^{30}$

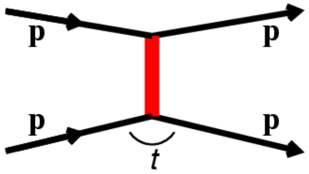
Effective Luminosity under no-pileup conditions ~ O(5) fb^{-1}

Background Reactions

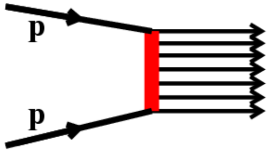
Main limits on the beam lifetime at LHC is due to strong interactions $\sigma_{tot} \sim$ O(100) mb

$$(L = 10^{34}\ \text{cm}^{-2}\ \text{sec}^{-1}) \cdot (\sigma = 100 \cdot 10^{-3} \cdot 10^{-24}\ \text{cm}^{2}) = 10^{9}\ \text{events/sec}$$

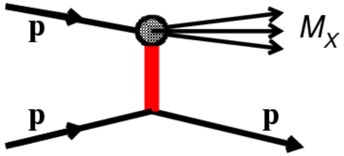
Beam lifetime $2808 \cdot 1.15 \cdot 10^{11} / (2 \cdot 10^{9} \cdot 3600) \sim$ O(40) hours



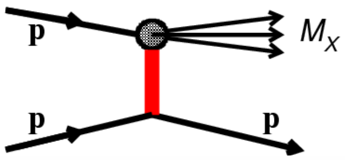
Elastic scattering – $\sigma_{el} \sim O(30)$ mb small angular and momentum deviations. Protons stay inside the acceptance of the ring



Inclusive scattering – $\sigma_{inc} \sim O(50)$ mb - most of the outgoing particles have low momentum and large emission angle. All of them will be either seen in the central detector or captured by the TAN and TAS absorbers.



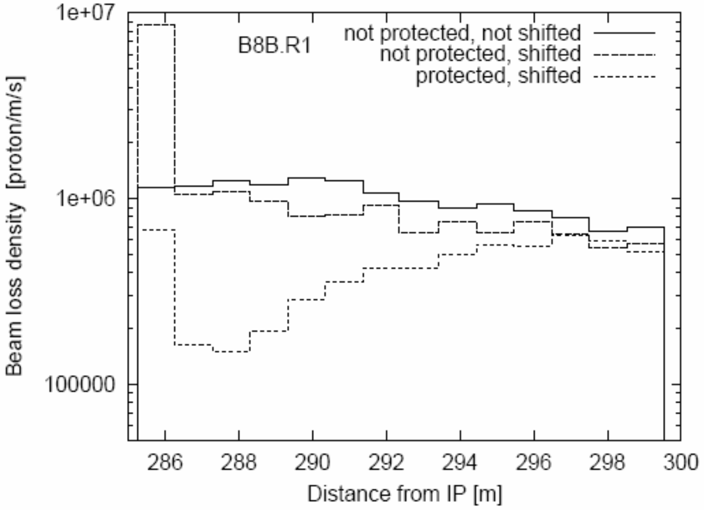
Proton dissociation – $\sigma_{el} \sim 2\ O(10)$ mb for $x_{IP} \sim 1 - 30\ \%$
Main source of the machine background. Leads to a rate of $O(10^{8})$ forward protons/sec. Attention!!! It is above the magnet quench limit of 8 10^{6} protons/m/sec

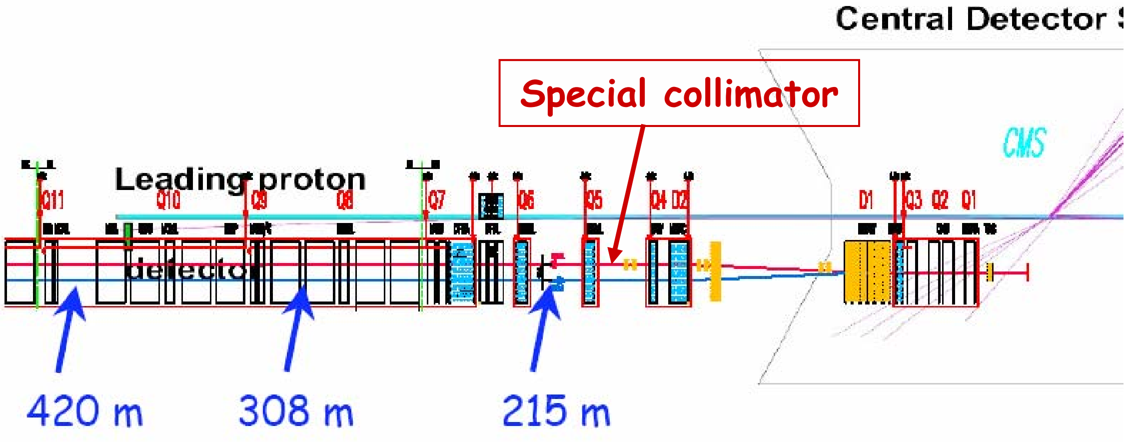


Machine background from proton dissociation reactions

LHC Project Note 240, 208

I. Baishev, J.B. Jeanneret, G.R. Stevenson



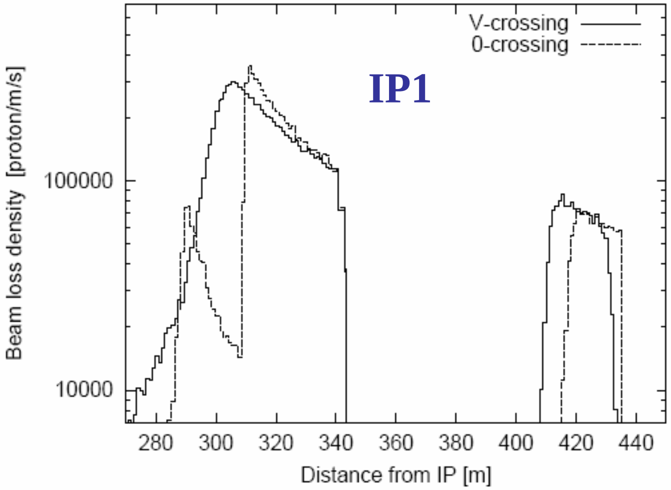


Special collimator

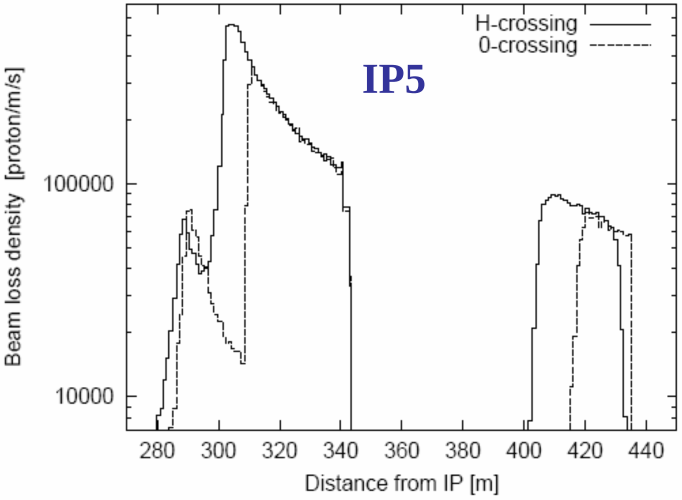
420 m

308 m

215 m

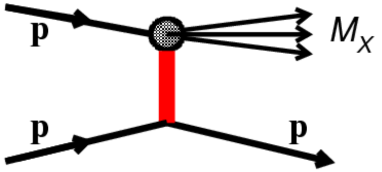


IP1



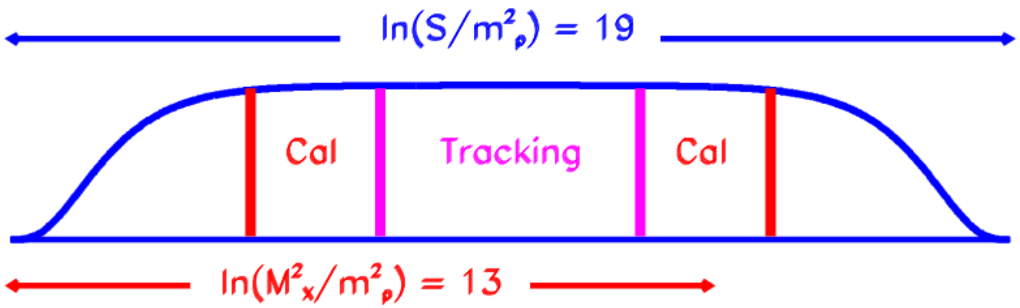
IP5

Physics background from proton dissociation reactions



420 m detector sees protons with x_{IP} ~ *0.2 – 1.5 %* and σ_{dis} ~ 3 mb ~
At luminosity of 10^{34} s^{-1} cm^2 there will be ~3 10^7 protons/sec
~ *1 proton per bunch crossing*

However, these protons are produced in a *soft interaction* together with a particle cloud of a mass M_X ~ *700 - 1700 GeV*. Such a large mass cannot escape undetected in the central detector.



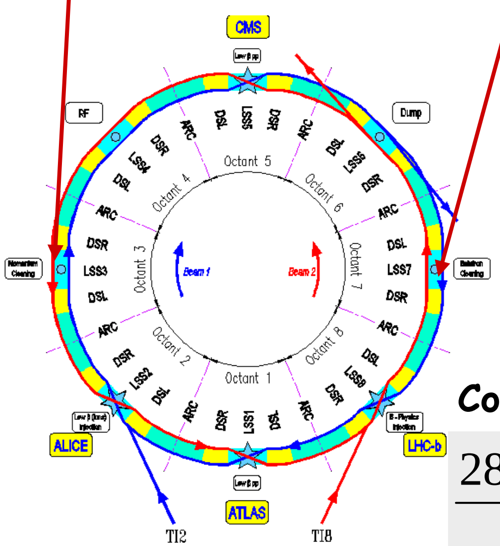
Beam Halo background from beam-beam tune shift

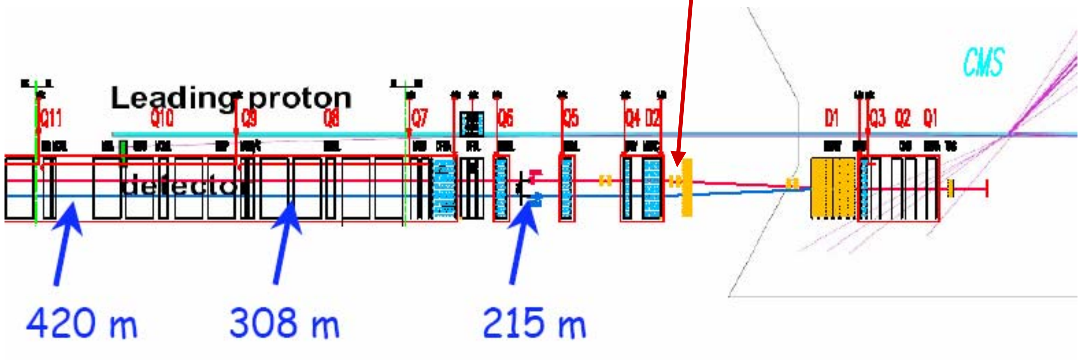
In bunch-bunch collision the particle of one bunch see the other bunch as a nonlinear lens.
Focusing properties are changing => protons of large amplitude
are getting out of tune after many crossings

Estimate of the proton loss: # protons / beam lifetime (40h)

Primary and secondary collimators
beam scratched to 6 and 7 σ

New tertiary collimators





Collimator cleaning inefficiency after 10 σ ~ 4 10^{-4}

$$\frac{2808\cdot 1.15\cdot 10^{11}\cdot 0.63\cdot 4\cdot 10^{-4}}{40\cdot 3600}=0.5\cdot 10^{6}\ \text{protons/sec}$$

<u>1 beam halo proton per ~80 bunches at the top luminosity</u>
Presumably even considerably smaller in the 420m region,
in the shadow of the incoming collimator, after D2 (R. Assmann)

Background Estimation

Example:

$pp \Rightarrow pp + g_{Jet}\, g_{Jet}$ $\sigma \sim 1$ nb for $E_T > 20$ GeV, $M(jj) \sim 50$ GeV

Signature:

2 forward protons + 2 central jets at $|\eta| < 2$ + 2 rapidity gaps at $2 < |\eta| < 5$

Background:

non-diffractive jet production: $\sigma \sim 10^4$ nb at the same E_T and $M(jj)$
+ 2 accidental beam halo protons or 2 single diff. dissociation protons

Background suppressed by:

rapidity gaps $\sim \exp(-\lambda\Delta y) \sim 0.06\%$ for $\lambda = 1.7$ and $\Delta y = 3$
matching of energies between the forward proton and CD - O(1/10)

no second vertex - O(1/100) (for s. d.)
probability to have accidental beam halo proton - O(1/80)

Background / Signal ratio = $(0.006/800)^2 * 10^4 \sim O(10^{-6})$

Higgs Search at full luminosity

Problem: Single Diffractive Dissociation (no rapidity gap rejection)

However, *SDD properties* will be *known* with high precision *from* background studies of the *QCD reactions* and comparison of Monte-Carlos with data

SDD characterized by low-p_T particle production, low particle multiplicity and - one side rapidity gaps

⇨ reject events with ≥ 2 SDD protons,

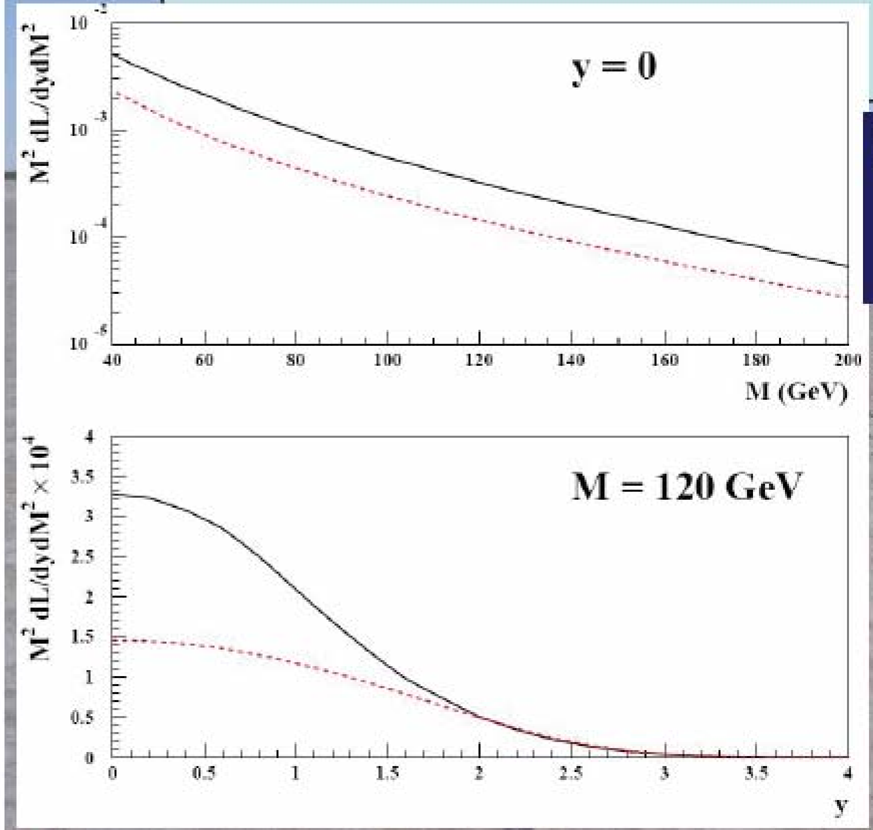
⇨ $P(n<2) \sim 45\%$ at $L = 10^{34}\ \mathrm{cm}^{-2}\ \mathrm{sec}^{-1}$

High resolution in the Higgs region for diffractive protons (~1.5% instead of ~8% and known M_{Higgs})

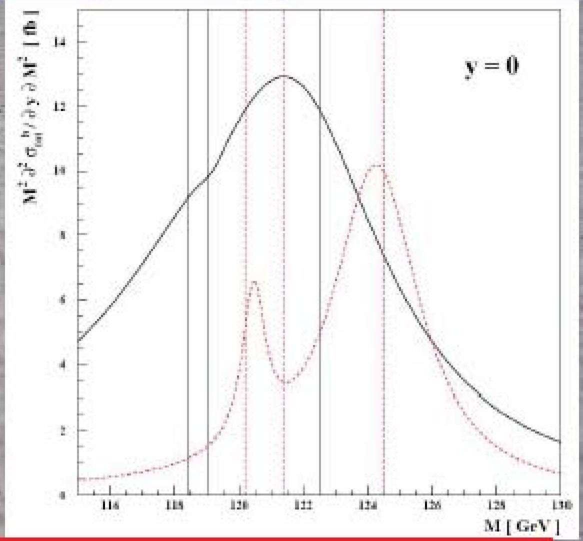
Background / Signal ratio = $(1/80\times30)^2 * 10^4 \sim 2\times10^{-3}$

Effective Luminosity for diffractive Higgs search
O(100) fb^{-1}

Effective Luminosity: Double-Diffractive Higgs production



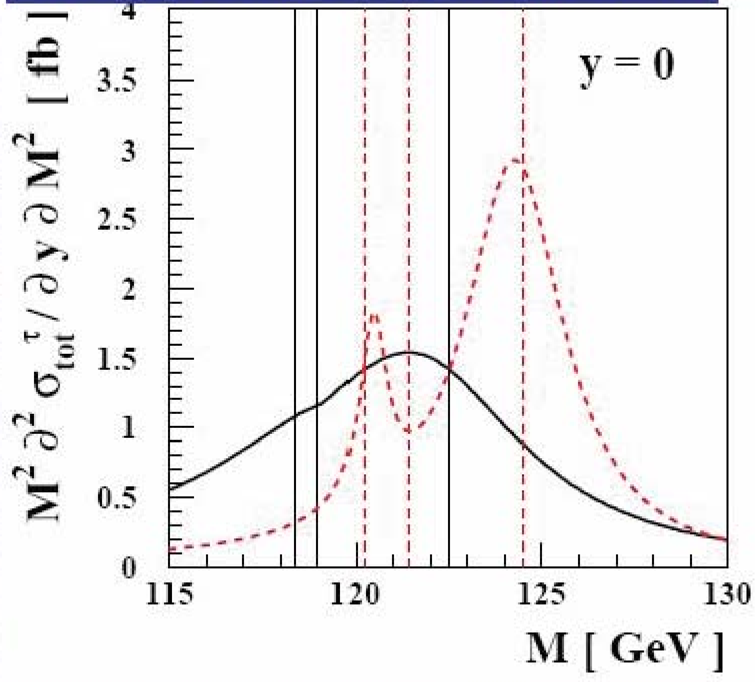
Cross section in CP-violating scenario: three-way mixing tan β = 50, $m_{H^\pm}$ = 155 GeV



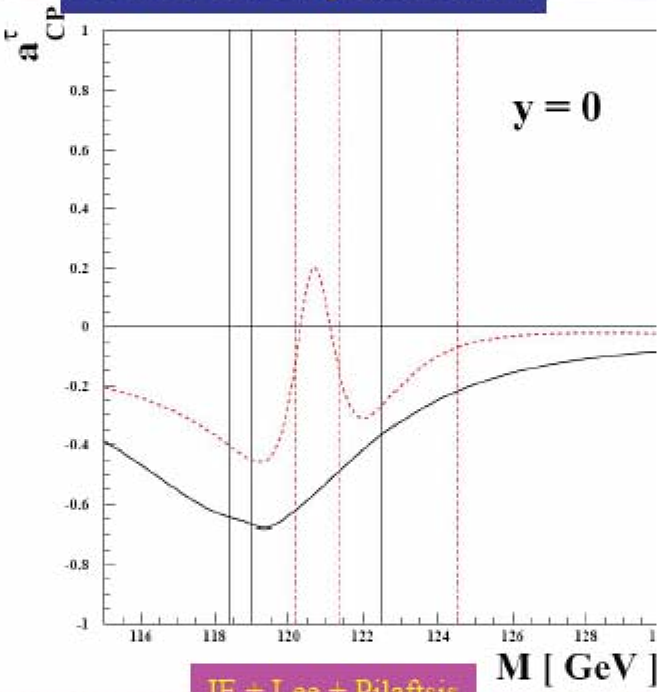
Can hope to measure line-shape using forward proton measurements?

Cross Section, CP-Violating Asymmetry for $H_i \rightarrow \tau^+\tau^-$

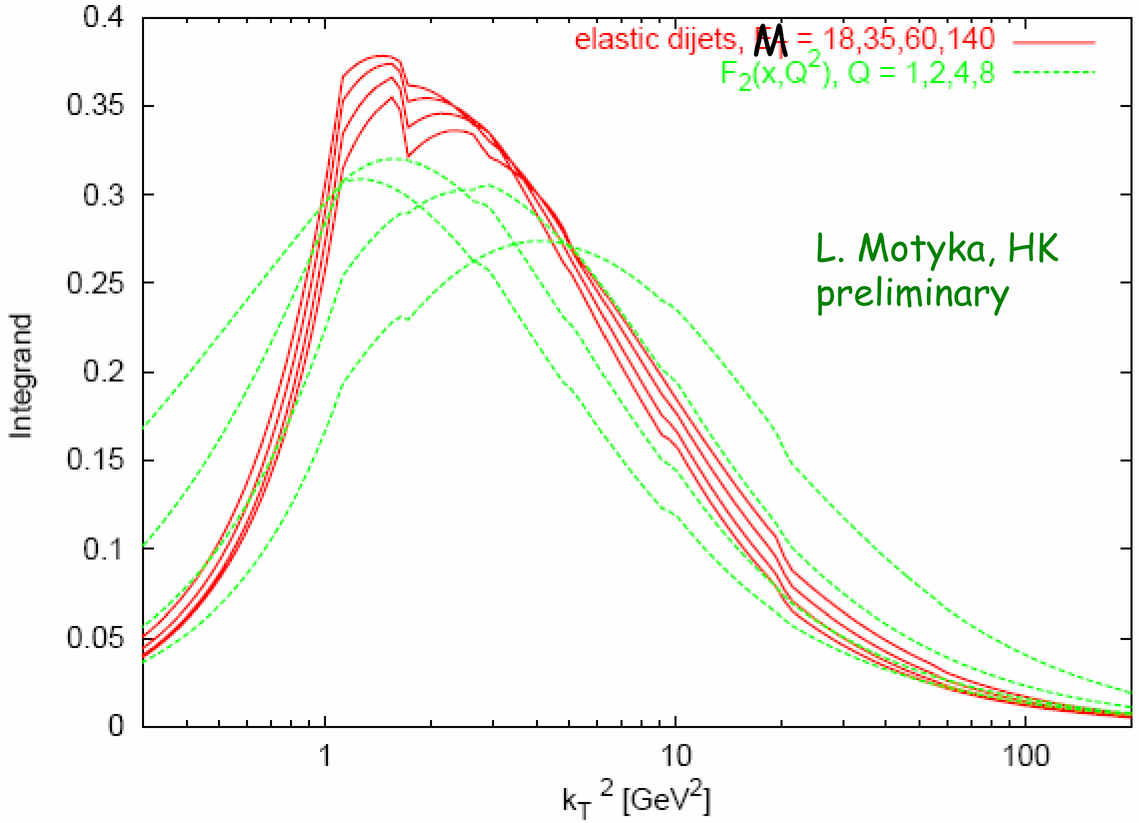
Cross section peaks not at poles …



… nor are asymmetries



JE + Lee + Pilaftsis



L. Motyka, HK
preliminary

$$M^2 \frac{\partial L}{\partial y \partial M^2} = S^2 L$$

$$L^{exclusive} = \left(\frac{\pi}{(N_c^2 - 1)b} \int \frac{dQ_t^2}{Q_t^4} f_g(x_1, x_1', t, Q_t, \mu) f_g(x_2, x_2', t, Q_t, \mu) \right)^2$$

SUMMARY

420m counters

- **acceptance**

  x^{IP} ~ 0.2 – 1.5 % t from 0 to ~10 GeV^2
  deflection of protons into 420m detectors due to main magnets (dipoles)
  stability against beam tuning effects

- **calibration and alignment**

  relatively easy due to high hard QCD DPE X-sections and
  distinct forward peak

- **resolution**

  $\Delta x_{IP}/x_{IP} \sim 1.5\ \%$ in Higgs mass region

- **backgrounds**

  $O(10^{-6})$ in no-pileup scenario and $O(2\times10^{-3})$ for pileup events

→

SUMMARY

420m counters

Unique possibility to explore new physics

pp -> pp jet+jet - $O(10^7)$ events under no pileup conditions are expected
Events are fully contained in the detector → high measurement precision
→ understanding of Gluon Luminosity → reliable Higgs expectations

Luminosity for DPE Higgs measurements $O(100)$ fb^{-1}
Higgs x-sections could reach $O(100)$ fb

⟹

Investigations of CP structure of the Higgs sector
-no other detector can do it- new window into physics

Diffractive LHC ~ pure Gluon Collider => investigations of properties of the gluon cloud in the new region

⟹

Gluon Cloud is a fundamental QCD object - SOLVE QCD!!!!