Physics opportunities with forward detectors at the LHC

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Overview

Motivation

QCD description of hard exclusive processes

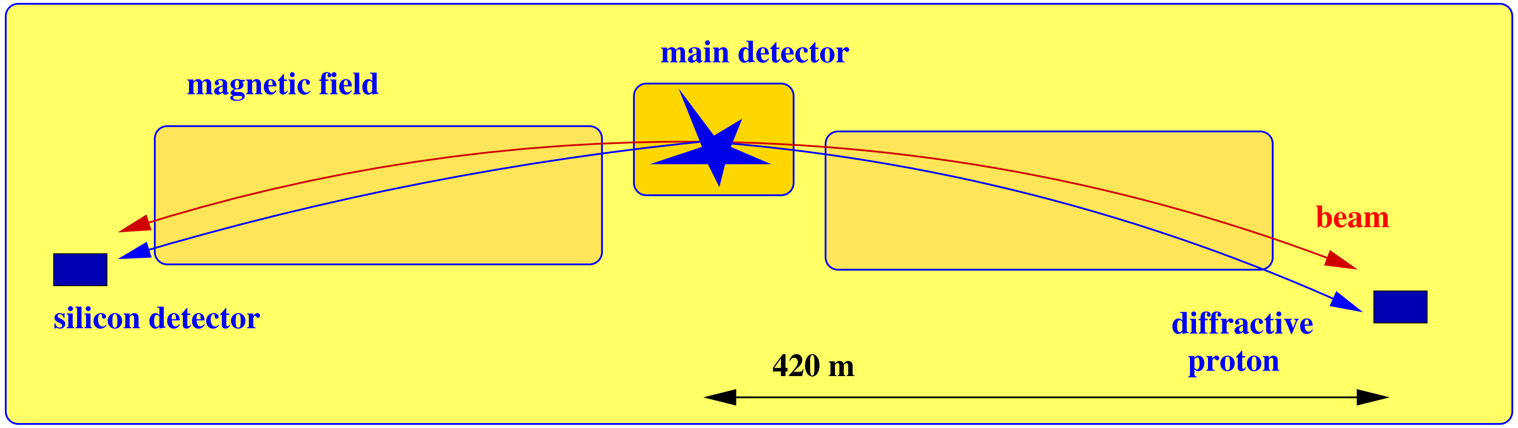
Study of SM and SUSY Higgs sector in exclusive channels

QCD measurements with forward detectors

Tests of the framework

Conclusions

Scheme of a possible experiment



Forward Proton measurement – 200-420 meters downstream

Magnetic spectrometer: small loss of proton energy $\mathcal{O}(1\%)$ $\longrightarrow$ drift of proton outside the beam

Silicon trackers – a few millimeters from the beam

Production of central large mass system measured in the main detector

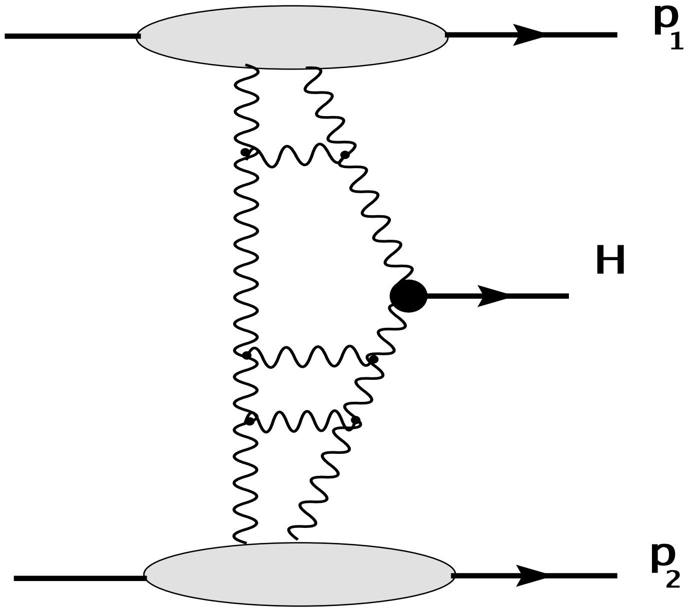
Main merits of forward detectors

$\longrightarrow$ All final state particles may be measured

$\longrightarrow$ Precise determination of kinematics and mass of the produced system, $\Delta M \sim 1$ GeV, $\Delta p_t \sim 100$ MeV

$\longrightarrow$ Extremely clean measurements, with backgrounds being substantially suppressed

$\longrightarrow$ Key process: The exclusive Higgs boson production in pp: $pp \to pHp$



$\longrightarrow$ Excellent energy resolution should be useful in determination of Higgs boson decay width and distinguishing almost degenerate Higgs boson states in some SUSY scenarios

$\longrightarrow$ Possibility to investigate quantum numbers of the produced state e.g. by observing angular correlations of the protons filtering the scalar from the pseudo-scalar: dominance of 0^{++} states

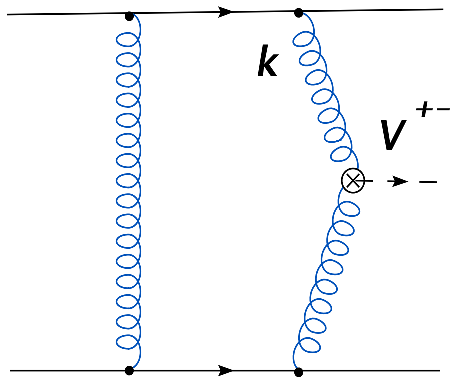
$\longrightarrow$ Very forward kinematics — detailed probe of multiple scattering at very high energies

Theory of hard exclusive diffractive production

[Khoze, Martin, Ryskin, Kaidalov]

Consider the lowest order diagram $qq \longrightarrow qHq$
Colour flow requires the exchange of at least two gluons

High energy kinematics imposes eikonal couplings γ^+ and γ^- and this leads to $k^2 \sim \boldsymbol{k}^2$



Higgs boson production vertex can be obtained in the effective theory, $m_t \longrightarrow \infty$:

$$V^{\mu\nu}(k_1, k_2) = V_0[k_1^\nu k_2^\mu - g^{\mu\nu} k_1 \cdot k_2]$$

Convolution with eikonal couplings: $V^{+-} \sim V_0 \; \boldsymbol{k_1} \cdot \boldsymbol{k_2}$

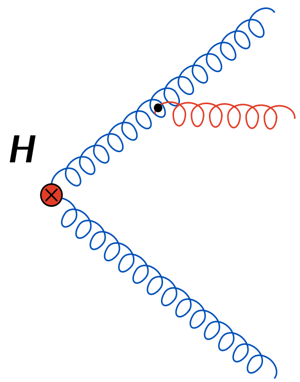
In the forward direction:

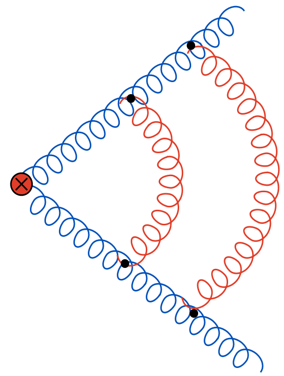
$$M \sim \int_{\mu_0} \frac{d^2k \; k^2}{k^6} \Phi_q(\boldsymbol{k}) \Phi_q(-\boldsymbol{k})$$

The lowest order result is strongly infra-red sensitive $\sim 1/\mu_0^2$

Sudakov form-factor

Beyond two-gluon exchange:
1) Higher order QCD corrections should be included
2) The gluon radiation is forbidden from the system





The gHg vertex defines the invariant mass of the gg system

Screening of radiated gluons is efficient only if $q < k$

Probability of the radiation of a single gluon

$$P_1 = \int_{k^2}^{M_H^2} \frac{dq^2}{q^2} \frac{C_A \alpha_s(q^2)}{\pi} \int_q^{M_H} \frac{d\omega}{\omega} \simeq \frac{C_A \alpha_s}{4\pi} \log^2(M_H^2/k^2)$$

Classical calculation of the Sudakov form-factor:

$$P(\text{no radiation}) \sim \exp(-A_1)$$

Equivalently – the Sudakov form factor follows from resummation of QCD virtual QCD corrections

$$S(k,\mu) = \exp\left(- \int_{k^2}^{\mu^2} \frac{dq^2}{q^2} \frac{N_c \alpha_s}{\pi} \int_q^{\mu} \frac{d\omega}{\omega} \right)$$

More on Sudakov form-factor

Saddle point analysis:

$$\int \frac{d^2k}{k^4} k^{4\gamma} \exp\left[\frac{-N_c \alpha_s}{4\pi} \log^2\left(\mu^2/k^2\right)\right]$$

$$k_s^2 = \mu^2 \exp\left[\frac{-2(1-\gamma)}{\bar{\alpha}_s}\right]$$

Typical virtuality $k^2 \sim 2$ GeV^2 $\longrightarrow$ Perturbative treatment makes sense

At single logarithmic accuracy:

$$T_g(\boldsymbol{k}, \mu) = \exp\left(-\int_{k^2}^{\mu^2} \frac{dq^2}{q^2} \frac{\alpha_s(q^2)}{2\pi} \int_0^{1-q/\mu} dz\, z \left[P_{gg}(z) + \sum_q P_{qg}(z)\right]\right), \qquad \mu \simeq M_H/2$$

Two Pomeron Fusion amplitude

Amplitudes to find gluon pair in the proton:

⟶ two-scale off-diagonal unintegrated gluon distributions are introduced:

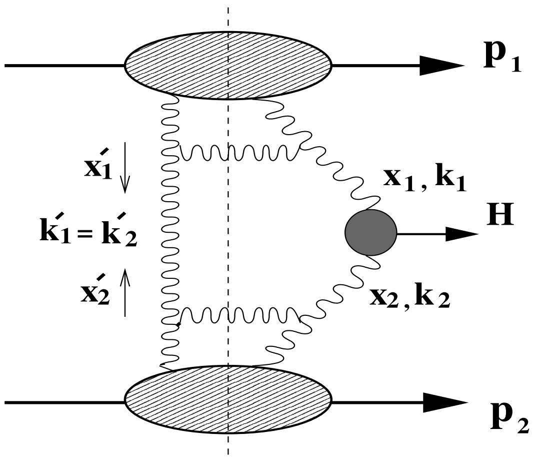
$$f_g(x, x', k, \mu), \qquad xg(x, Q^2) = \int^{Q^2} \frac{dk^2}{k^2} f_g(x, k^2, Q)$$

Sudakov form factor is naturally incorporated in f_g: **[Kimber, Martin, Ryskin]**

$$f_g(x, k^2; \mu) = Q^2 \frac{\partial}{\partial Q^2} \left[xg(x, Q^2) \cdot T_g(Q, \mu) \right]_{Q^2 = k^2}$$

$$f_g^{\rm off}(x, k^2; \mu) = R_\xi Q^2 \frac{\partial}{\partial Q^2} \left[xg(x, Q^2) \cdot \sqrt{T_g(Q, \mu)} \right]_{Q^2 = k^2}$$

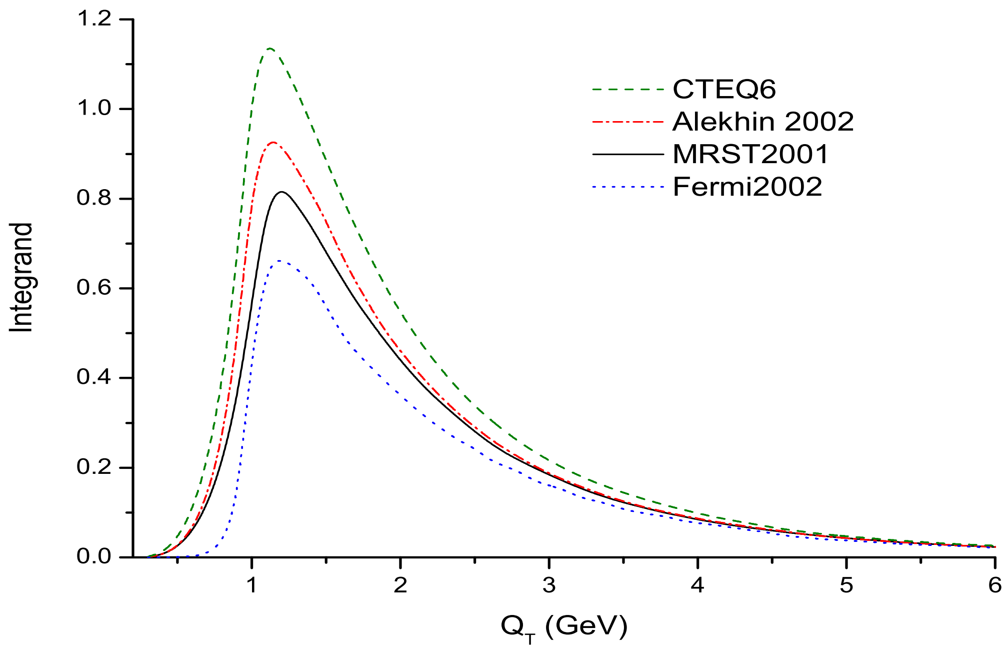
$$\text{Im}\; M_0(y) \sim \int \frac{dk^2}{k^4} f_g^{\rm off}(x_1, k^2; \mu)\, f_g^{\rm off}(x_2, k^2; \mu)$$



Behaviour of the integrand:

$$\text{Im } M_0(y) \sim \int \frac{kdk}{k^4} f_g^{\text{off}}(x_1, k^2; \mu) \, f_g^{\text{off}}(x_2, k^2; \mu)$$

[J. Forshaw]



The integrand is dominated by momenta $Q_T \sim 1 - 2$ GeV

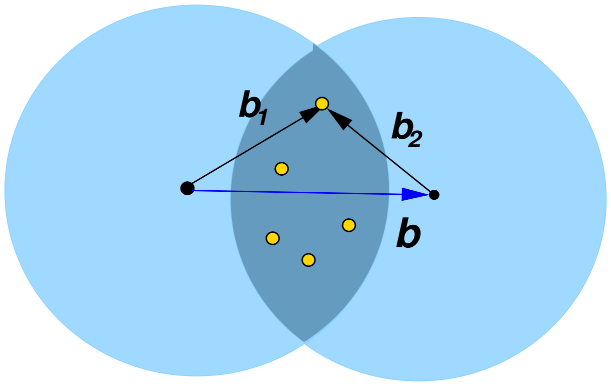
Sudakov form factor reduces the exclusive cross section by two orders of magnitude

Soft Rescattering

The exclusive character of the process may be spoiled by soft rescattering. In the standard approach one assumes that rescattering does not affect the hard matrix element describing the production

Simplest assumption: uncorrelated, independent acts of soft rescattering characterised by the amplitude

$$M_1(b) = \Omega(b)/2$$



Unitarised scattering amplitude:

$$\Omega(b)/2 - \frac{(\Omega(b)/2)^2}{2!} + \frac{(\Omega(b)/2)^3}{3!} + \ldots = 1 - \exp(-\Omega(b)/2)$$

The total cross section: $\sigma_{tot} = 2\int d^2b[1 - \exp(-\Omega(b)/2)]$

The elastic cross section $\sigma_{el} = \int d^2b[1 - \exp(-\Omega(b)/2)]^2$

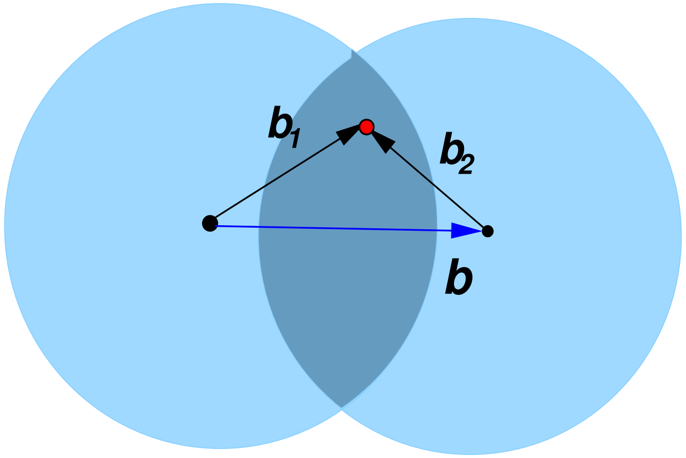
The inelastic cross section $\sigma_{inel} = \int d^2b[1 - \exp(-\Omega(b))]$

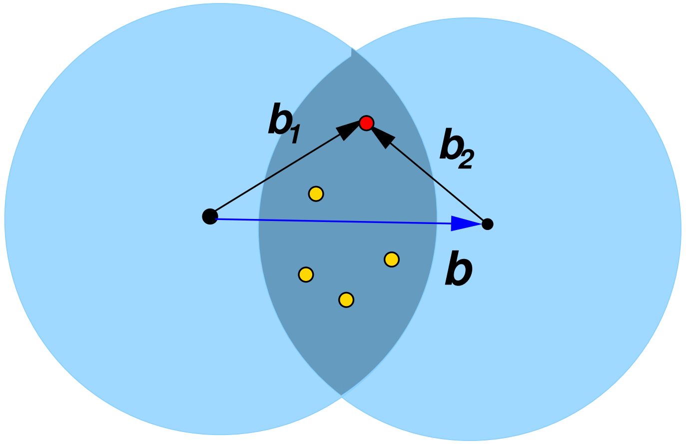
Soft gap survival

Soft rescattering corrections to a hard exclusive scattering process $\longrightarrow$ opacity $\Omega(b)$

Independence of hard production and rescattering is assumed

$$M_{corr}(b) = M_{hard}(b)[1-\Omega(b)/2+(\Omega(b)/2)^2/2!-(\Omega(b)/2)^2/3!+\ldots] = M_0(b)\,\exp(-\Omega(b)/2)$$





Amplitude of matter distribution in the proton

$$S(b_1) \sim \exp(-b_1^2/R^2), \qquad R^2 \sim 8\ \mathrm{GeV}^{-2}$$

$$M_{\mathrm{hard}}(b) \;\sim\; M_0 \int d^2b_1\; S(\boldsymbol{b}_1)\, S(\boldsymbol{b}_1 - \boldsymbol{b})$$

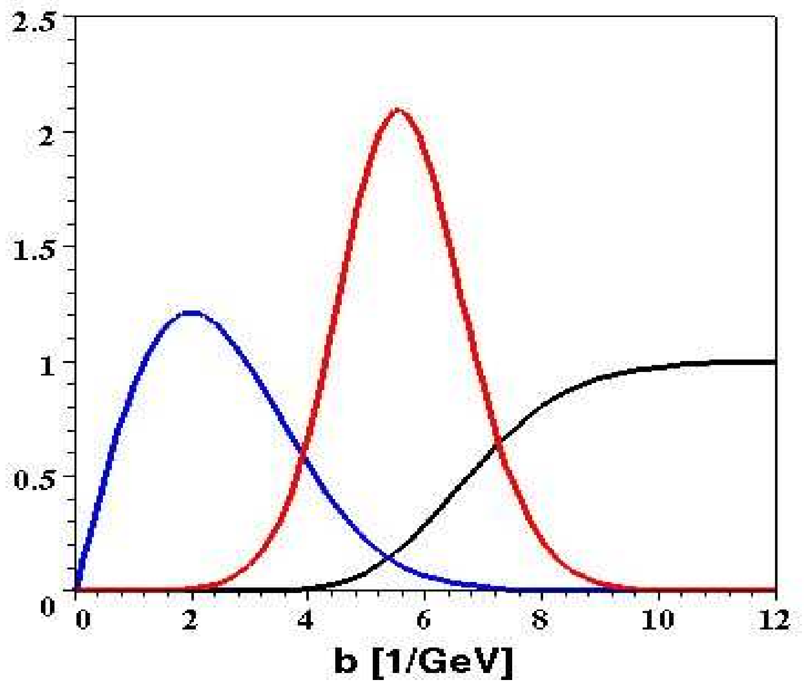
$$\sigma_{\mathrm{excl}} \;=\; \int d^2b \int d^2b_1\, |M_0\; S(\boldsymbol{b}_1)\, S(\boldsymbol{b}_1 - \boldsymbol{b})\,|^2\, \exp(-\Omega(b))$$

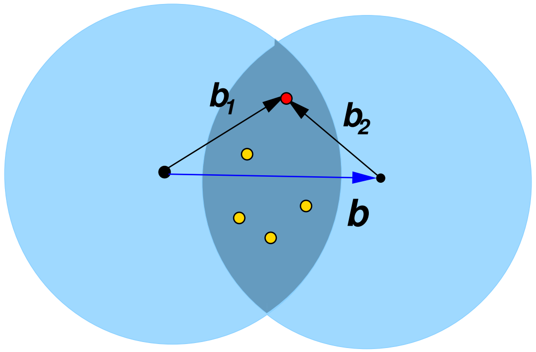
Impact parameter profile of exclusive process

Gap survival factor: $$S^2 = \frac{\int b\, db\ \exp(-\Omega(b))\, |M_{\rm hard}(b)|^2}{\int b\, db\, |M_{\rm hard}(b)|^2}$$

Exclusive Production = Hard matrix element × Amplitude of no rescattering

Production profile (red) for LHC is magnified by factor of 100





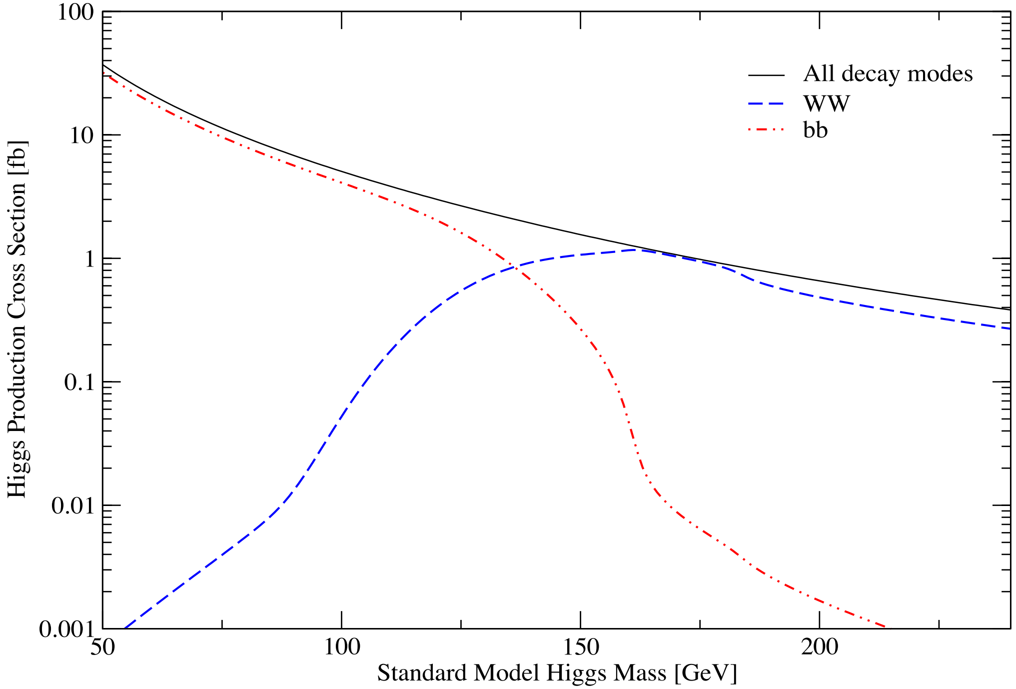
Production dominated by $b \simeq 1$ fm and $b_1 \simeq 0.5$ fm

Two-channel eikonal model of gap survival is used that incorporates low-mass diffractive intermediate states. Typically: $S^2 \simeq 0.03$ for exclusive processes at the LHC

Higgs boson detection channels

Main detection channels for the SM Higgs boson in exclusive processes: $b\bar{b}$ and (virtual) W^+W^-

Exclusive Higgs boson cross sections fall into $\mathcal{O}(1\ \text{fb})$ range

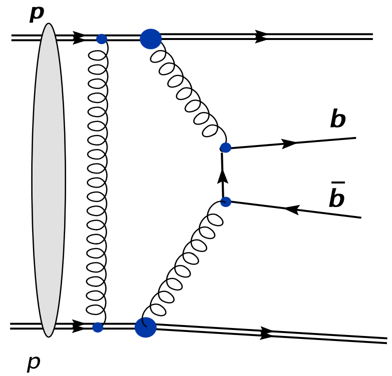


[B. Cox et al., hep-ph/0505240]

For $\mathcal{L} = 30\ \text{fb}^{-1}$ at LHC and $M_H < 150$ GeV 5–10 Higgs boson events in the detector are expected in $b\bar{b}$ or W^+W^- channels with low background

Backgrounds

Main source irreducible of background for exclusive $H \to bb$: direct exclusive $b\bar{b}$ production via $pp \to ppb\bar{b}$



If both protons scatter in the forward direction — no J_z may be transfered to the produced state

The $J_z = 0$ rule: at the leading order and for massless quarks $\sigma(gg^{J_z=0} \to q\bar{q}) = 0.$

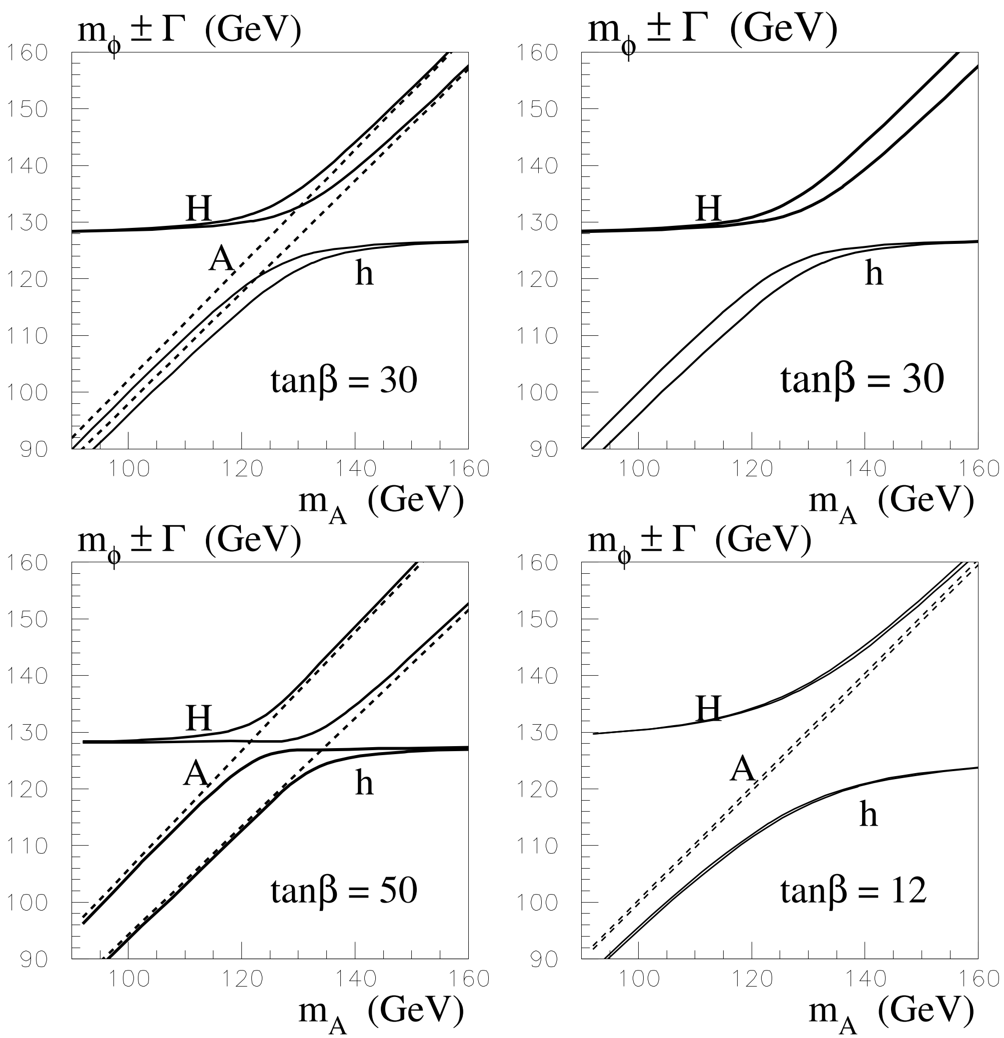
NLO, non-zero quark mass and p_t $\longrightarrow$ small cross sections: $\mathcal{O}(m_b^2/M_H^2)$ and $\mathcal{O}(p_t^2/k_t^2)$

Detailed calculation including experimental resolution $\longrightarrow$ signal to background ratio ~ 1

A more complex composition of the background processes ($\gamma\gamma$ and gg) is found for the WW channel but $S > B$ for $M_H < 150$ GeV and $5 - 10$ clean events are expected in this mass range

Supersymmetric Higgs bosons searches

Three neutral Higgs bosons in MSSM: scalar h, H and pseudo-scalar A



$M_A \simeq 150$ GeV $\longrightarrow$ "decoupling scenario"

h — very similar to SM Higgs and H at may be hard to measure in inclusive measurements

$130 < m_A < 170$ and $\tan\beta \simeq 4 - 6$ — a more reliable measurement should be possible in diffractive channel than in the exclusive channel

"Intense coupling scenario" — approximate degeneracy of the Higgs boson states

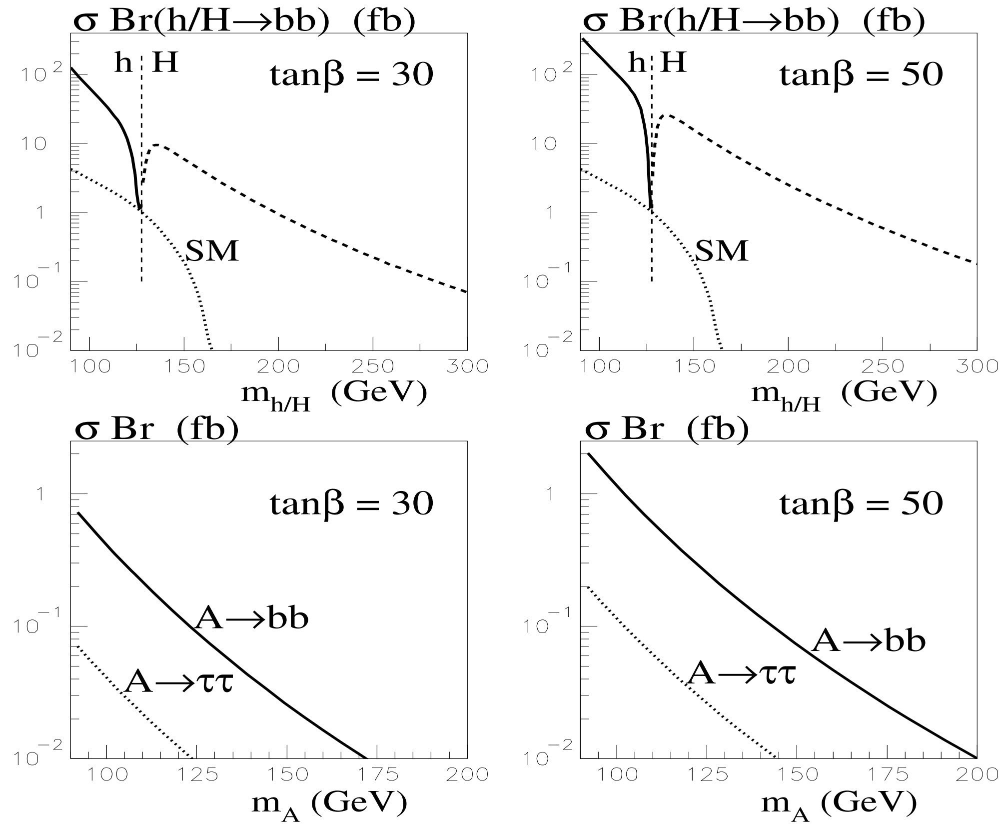
"Intense coupling regime": large $\tan\beta$ and three bosons have similar masses — difficult to resolve them in inclusive measurements.

Scalars are strongly coupled to gluons $\longrightarrow$ easy to measure in diffractive channel

$$M_A = 130 \text{ GeV}, \qquad \tan\beta = 50, \qquad \mathcal{L} = 30 \text{ fb}^{-1}$$

	S	B
$M_h = 124.4$ GeV	71	3
$M_H = 135.5$ GeV	124	2
$M_A = 130$ GeV	1	2

Central exclusive diffractive production



Higgs in CP violating SUSY

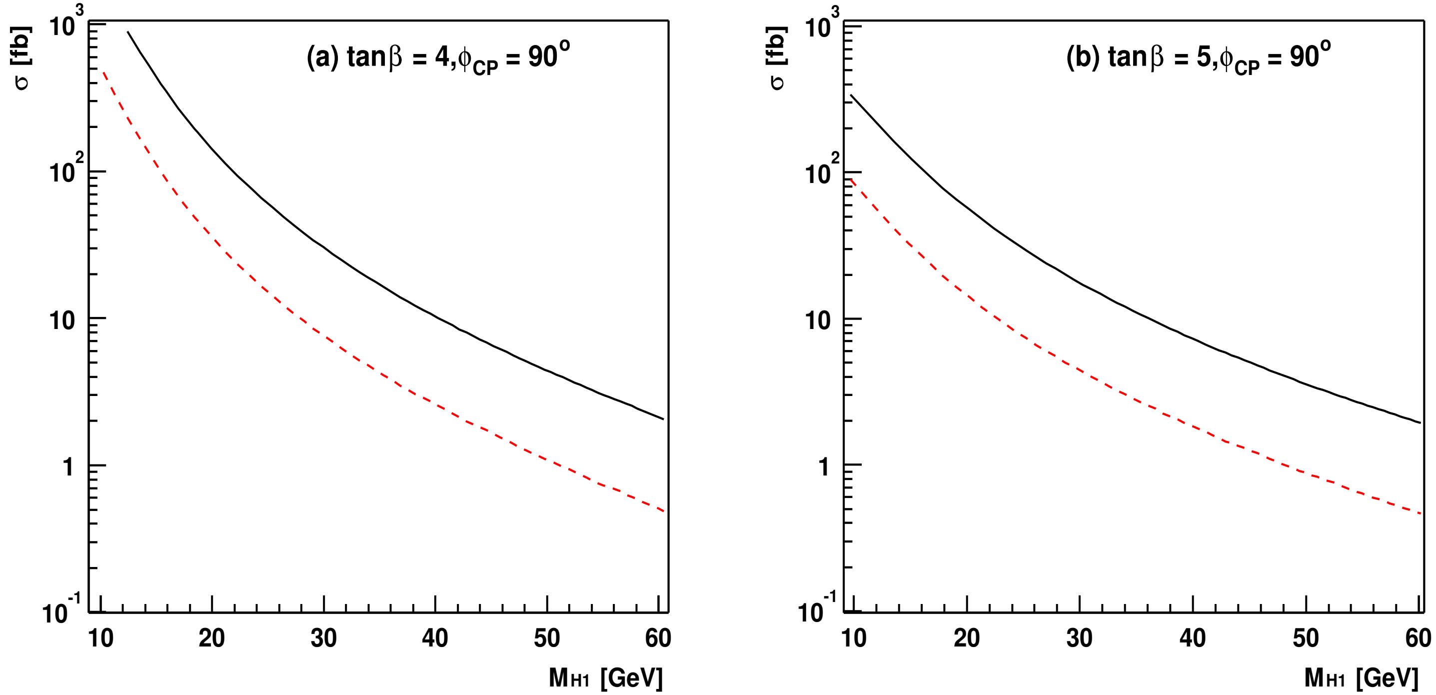
Soft SUSY breaking terms $\longrightarrow$ sizable CP violating effects beyond CKM phase

H, h and A Higgs states mix to give H_1, H_2, and H_3 Higgs states without definite CP

$M_{\rm SUSY} = 0.5$ TeV, $\Phi_{\rm CP} = 90^o$, $\tan\beta = 4(5)$

In this scenario (which is not excluded by present constraints) the lightest Higgs boson H_1 may be as light as $M_{H_1} \simeq 50$ GeV

Exclusive production cross sections $\sigma \sim 5$ fb **[Cox, Forshaw, Lee, Monk, Pilaftsis]**



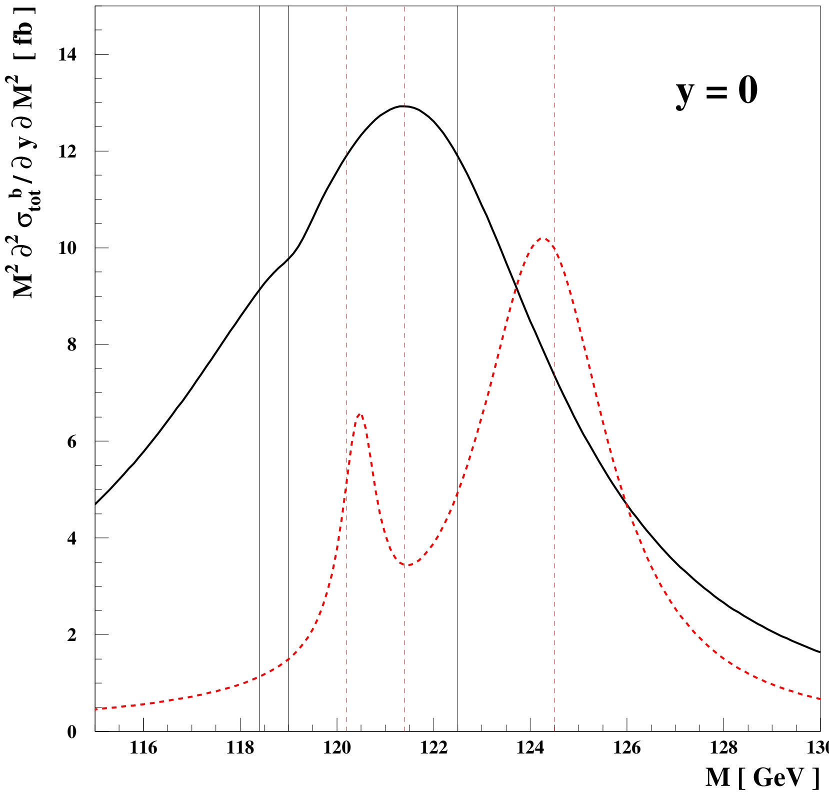
Tri-mixing CPX SUSY scenario

[Ellis, Lee, Pilaftsis]

Tri-mixing scenario: with $\tan\beta \simeq 50$, $M_{\rm SUSY} = 0.5$ TeV, $M_{H^\pm} \simeq 155$ GeV

H_i are nearly degenerate, $M_{H_i} \simeq 120$ GeV

CPX phase -90^o (-10^o)

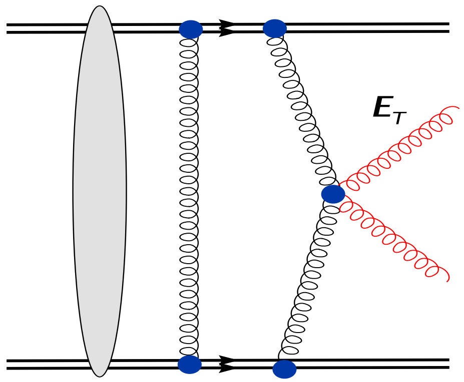


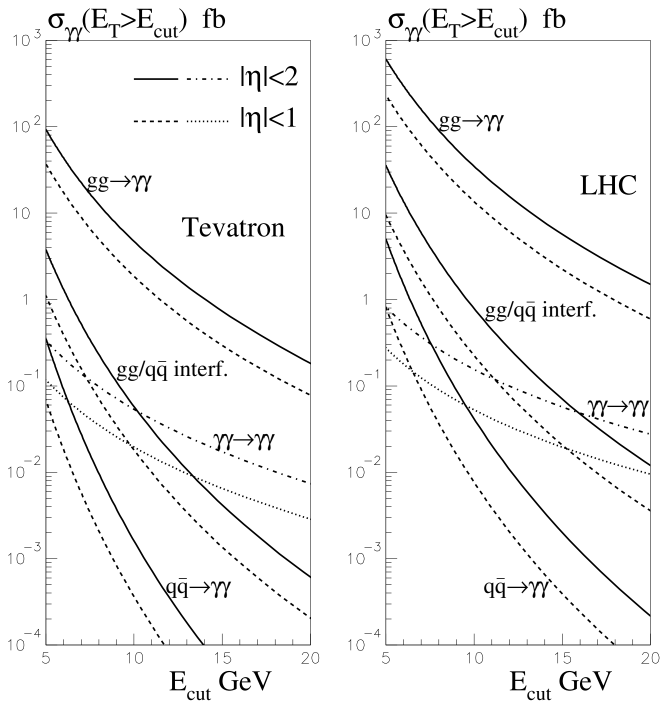
$$M^2 \frac{d\sigma}{dy\,dM^2}(pp \to pp + H \to pp + b\bar{b})$$

Explicit CP violation measurement should be possible in $\tau\bar{\tau}$ decay channels

Exclusive di-jets and di-photons at LHC

[Khoze, Martin, Ryskin]





Universality of the "scalar luminosity function" — calibration before exclusive Higgs measurement

Comfortably high rates, especially for di-jets:

$\sigma \sim 1$ nb for $E_T > 20$ GeV,

$\sigma \sim 0.5$ pb for $E_T > 60$ GeV, $|\eta| < 1$

For di-photons: $\sigma \sim 0.1$ pb for $E_T < 8$ GeV and $|\eta| < 2$

Precise measurements of protons' $p_t \longrightarrow$ possibility to study proton structure in the transverse plane

Excellent environment to study properties of gluonic jets

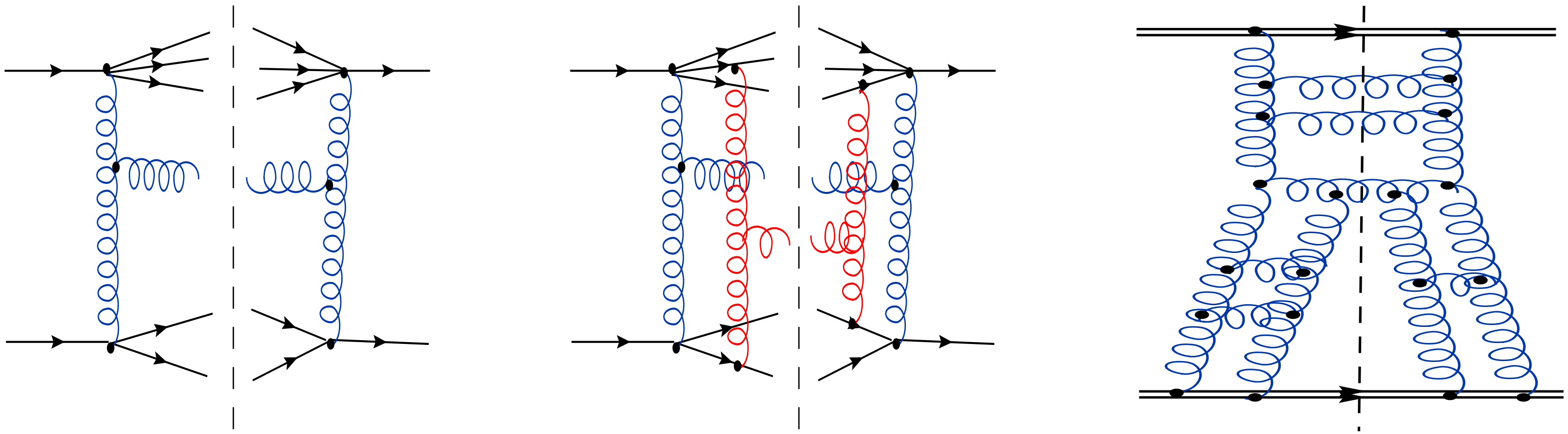
Multiple scattering and exclusive production

Multiple scattering: multiple production of mini-jets with sizable E_T, pedestals in particle distributions and modified jet shapes may produce backgrounds that interfere in analyzes of hard physics

From theory side: multiple pp scattering at the LHC is poorly understood

Descriptions of exclusive processes and of multiple scattering rely on the same core formalism in QCD

Optical theorem $$\sigma(s)_{tot} \propto \sum_X |M(pp(s) \to X)|^2 \propto \text{Im}\, M(s, t=0)$$



Combined measurements of hard exclusive processes, multiple scattering observables and diffractive processes would provide excellent input and constraint for theoretical QCD framework

$\longrightarrow$ better understanding of the event structure

Transverse imaging of the proton

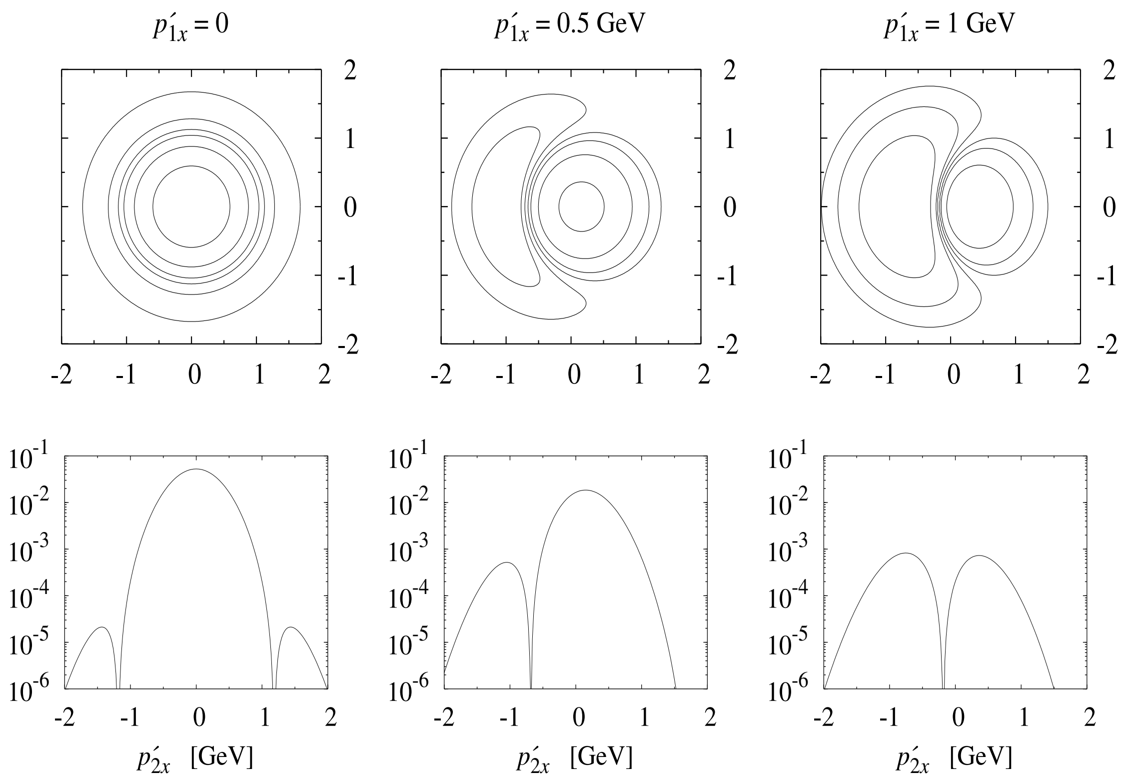
[Franfurt, Hyde-Wright, Strikman, Weiss]

Forward detectors may measure $\boldsymbol{p}_1$, $\boldsymbol{p}_2$ of scattered protons in hard exclusive production

$$\frac{d^4\sigma(pp \to ppA)}{d^2p_1\, d^2p_2}$$

Contour plots of $\boldsymbol{p}_2$ dependence and

distributions for parallel momenta $\boldsymbol{p}_1$ and $\boldsymbol{p}_2$



Differential $\boldsymbol{p}_i$ distributions may be used to probe

⟶ (in)dependence of production and rescattering mechanisms

⟶ (energy dependent) matter distribution in the proton in transverse space

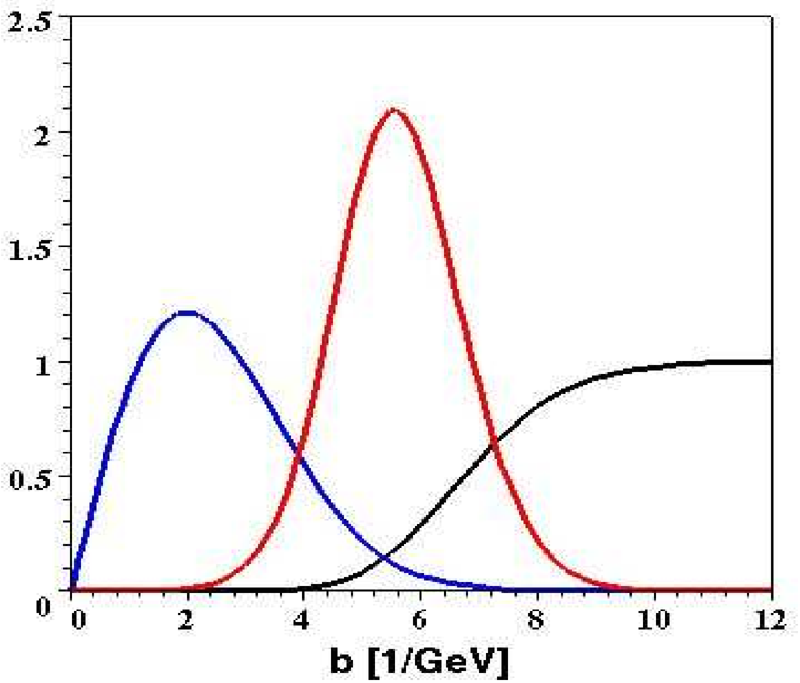
⟶ Unique possibility to probe directly S-matrix instead of T-matrix

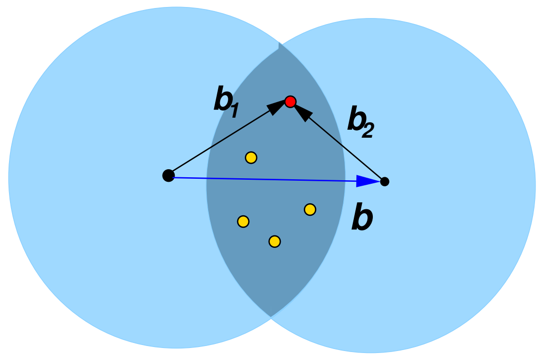
S-matrix and hard exclusive production

Gap survival factor: $$S^2 = \frac{\int b\,db\ \exp(-\Omega(b))\,|M_{\rm hard}(b)|^2}{\int b\,db\ |M_{\rm hard}(b)|^2}$$

Exclusive Production = Hard matrix element $\times$ Amplitude of no rescattering

Production profile (red) for LHC is magnified by factor of 100





The b profile depends strongly on details of the pp S-matrix $\longrightarrow$ so do the p_t distributions of the scattered protons

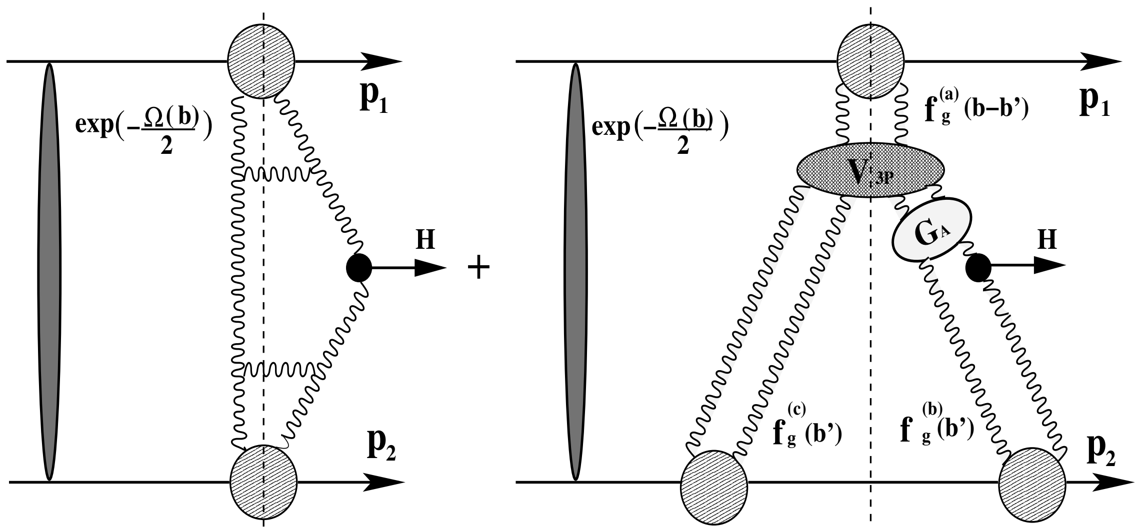
Uncertainties in hard exclusive production estimates

Basis of QCD calculations: hard production subprocess × soft rescattering

Hard production part — perturbative QCD — under good theoretical control

Soft rescattering — phenomenological, constrained by total, elastic and diffractive cross sections

⟶ Uncertainties: T vs S-matrix, extrapolations to the LHC energy, QCD rescattering within the hard part, possible breaking of factorisation between hard and soft part

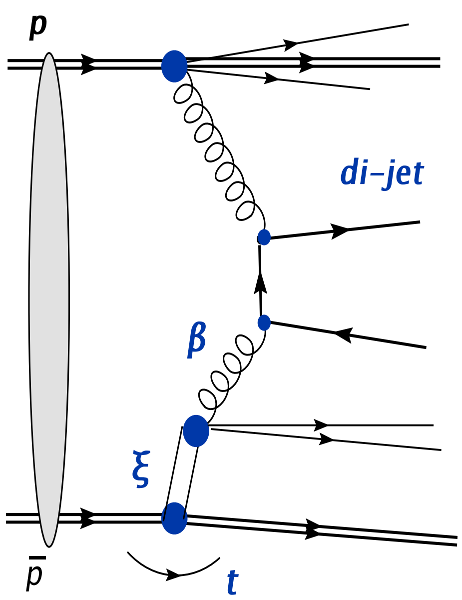


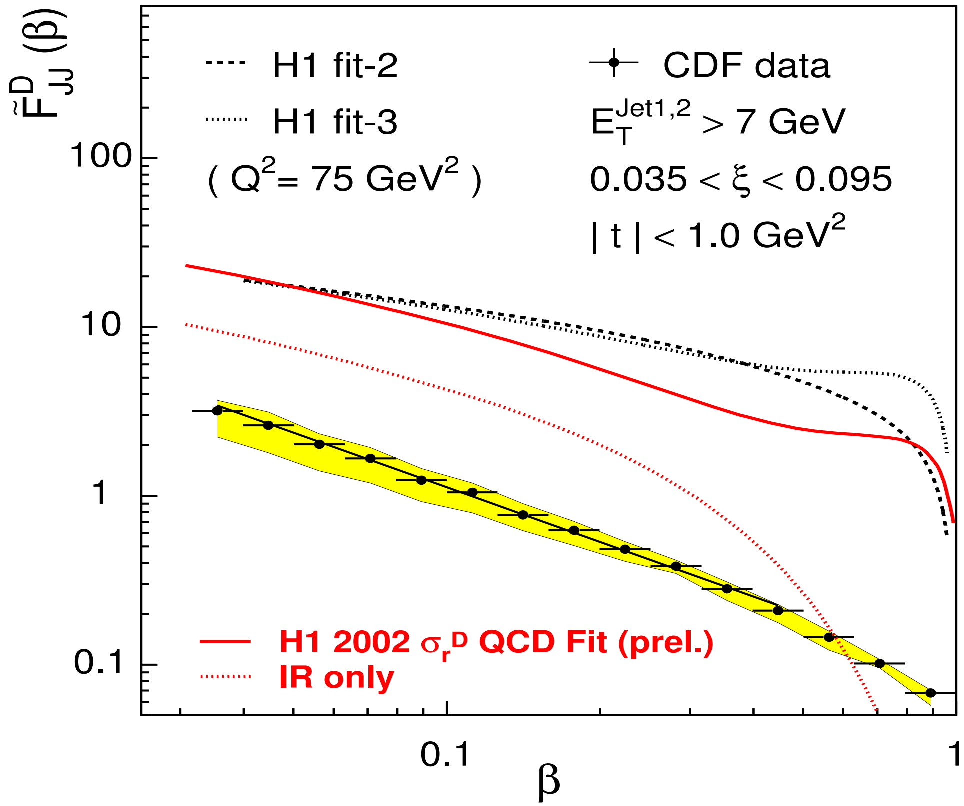
[Bartels, Bondarenko, Kutak, LM]

⟶ Crude estimate of the gap survival uncertainty — factor of 2 – 4

Check – single diffraction at the Tevatron

$$\text{CDF}: \qquad p\bar{p} \to \bar{p} + \text{gap} + jj + X$$

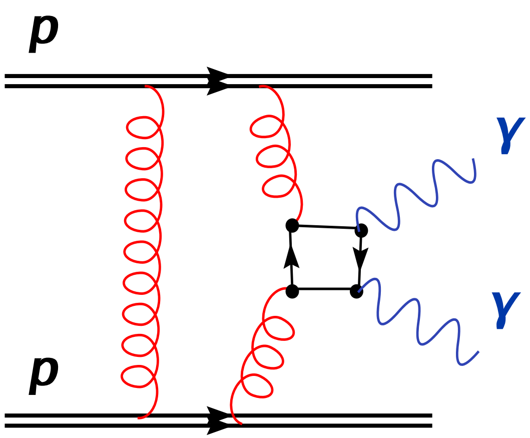




Breaking of hard diffractive factorisation

Gap survival: $S^2 \simeq 0.1$ in accordance with theoretical predictions — mind however uncertainty coming from uncertainties in HERA fits of diffractive PDF

Exclusive di-photons at the Tevatron

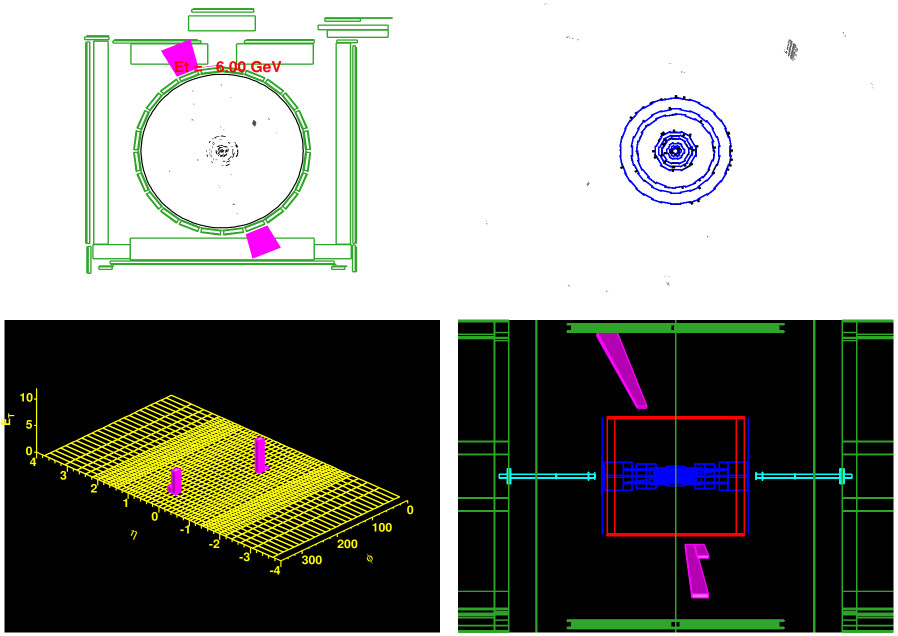


Cuts: $E_t > 5$ GeV, $\eta < 1$

Prediction: $\sigma = 0.04$ pb with uncertainty factor $3 - 5$

CDF measurement (2006): 3 events
$\longrightarrow \sigma = 0.14^{+0.14}_{-0.03} \pm 0.03$ pb

Expected background: $0^{+0.2}_{-0}$ events $\longrightarrow 3.3\sigma$ significance

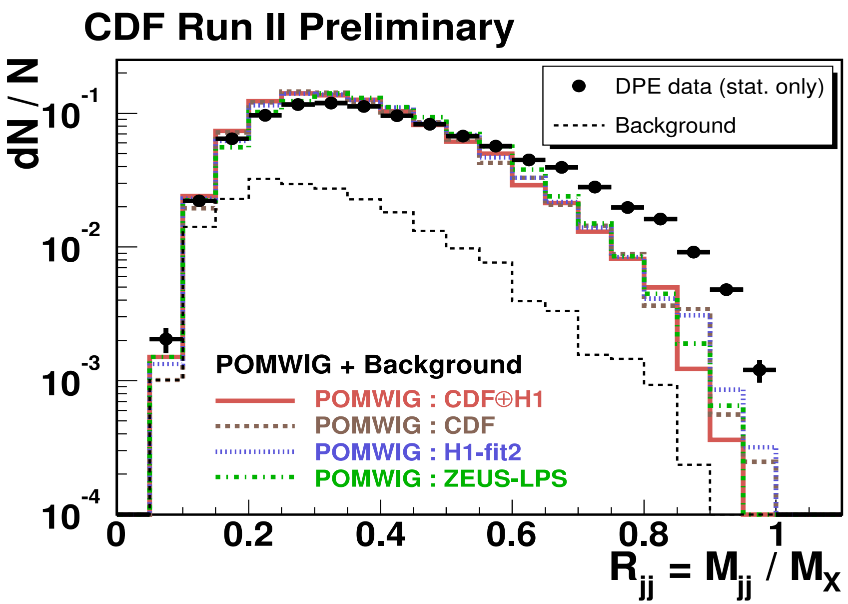


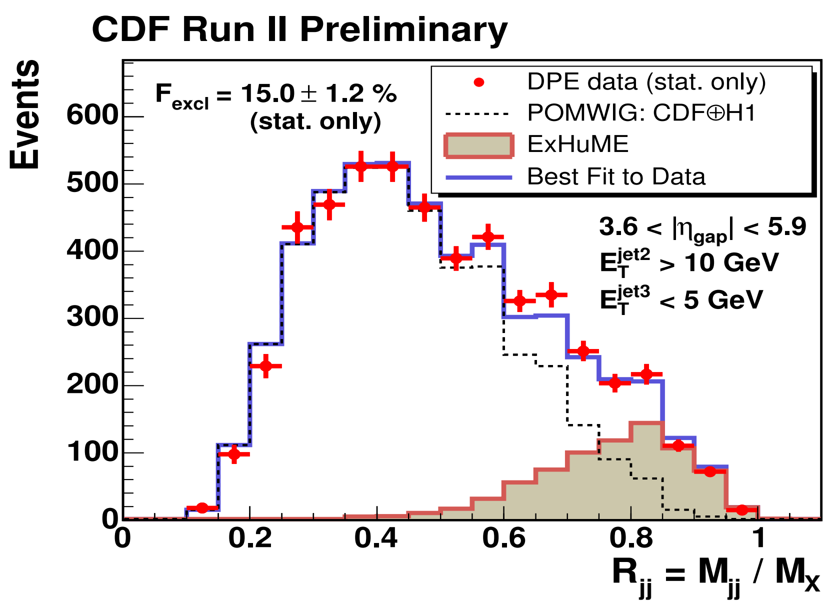
Exclusive di-jets at CDF

CDF Roman Pot Spectrometer allows for anti-proton tagging while proton escapes the detection

No activity at the proton side $3.6 < \eta < 5.9$

Excess was found over expectations from diffractive, proto-dissociative di-jet production at larger $R_{jj} = M_{jj}/M_X$ (CDF, 2006)





Excess at large R_{jj} – in agreement with QCD predictions for exclusive di-jets

Relative suppression of heavy quark jets at $R_{jj} \sim 1$ ($J_z = 0$ rule)

Summary

- Very forward proton detectors are complementary to central detectors at the LHC and enhance their discovery potential

- Main advantages of using forward detectors

  $\longrightarrow$ background suppression and 0^{++} filtering

  $\longrightarrow$ very high energy resolution

  $\longrightarrow$ access to fine details of the production mechanism

- Forward detectors are a powerful tool that may provide insight into details of new physics (e.g. SM and SUSY Higgs sector)

- Useful for more conventional studies of QCD: proton structure, rapidity gap physics, hard diffraction, two-photon physics, gluonic jets etc.

- Uncertainties of theoretical predictions remain sizable, success is not guaranteed, there are technical difficulties etc.: $\longrightarrow$ clearly — we may feel challenged

Back-up

Exclusive di-jets at CDF

QCD Monte-Carlo ExHuME based on Durham model gives correct shapes but slightly overestimates the data