Yellow report chapter 5 : Central Exclusive Production

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- ‘Final’ version of CEP chapter 5 in latest draft report: 57 pages and 5 sections:

  - Section 1 - Introduction.
  - Section 2 - Discussion of selection techniques (proton tagging vs. rapidity gap) and relevant detector features.
  - Section 3 - QCD processes, i.e. double Pomeron exchange/Durham model.
  - Section 4 - Photon induced and photoproduction processes, i.e. two-photon and photon-Pomeron fusion.
  - Section 5 - Exploratory physics processes: invisible mass, monopoles, anomalous couplings and technipions.

- In this talk I will go into more detail about some (not all) of the topics discussed in the chapter.

- Various changes to content and format from earlier versions:

  - New sections added (e.g. monopoles, ATLAS jet feasibility study).
  - Separation of analysis techniques to individual sections at beginning.
  - Editing/shortening of some sections.
  - Updated format of physics process sections: ordered by topic, and within this divided into a 'Motivation and theory' and 'Experimental results and outlook' sections.
  - Separate, more detailed feasibility studies for exclusive jet and anomalous coupling searches.

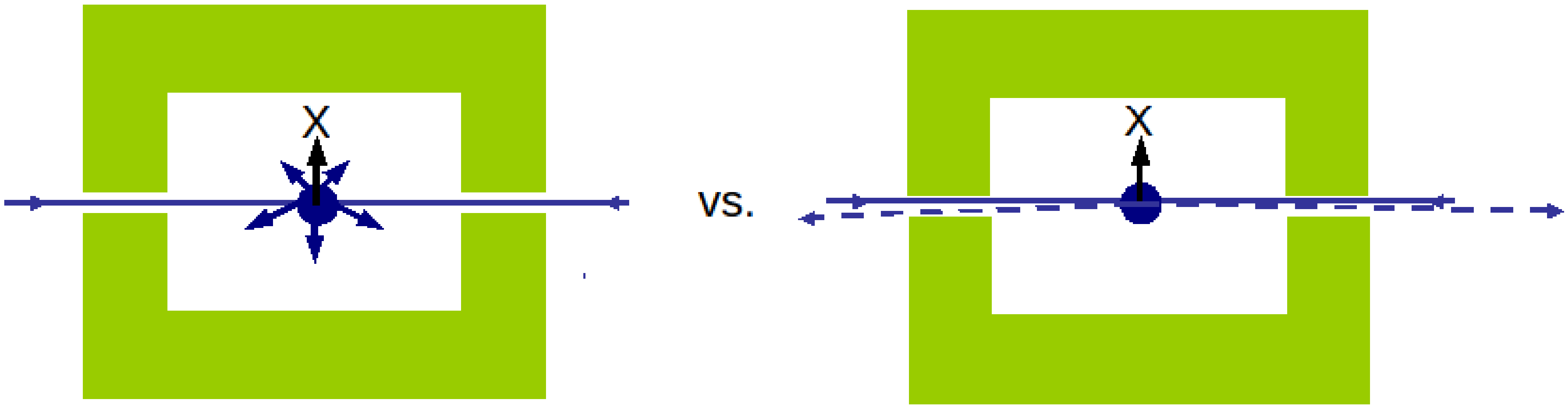
Thank you to referees for many helpful comments

Section 1 - Introduction

CEP is the interaction

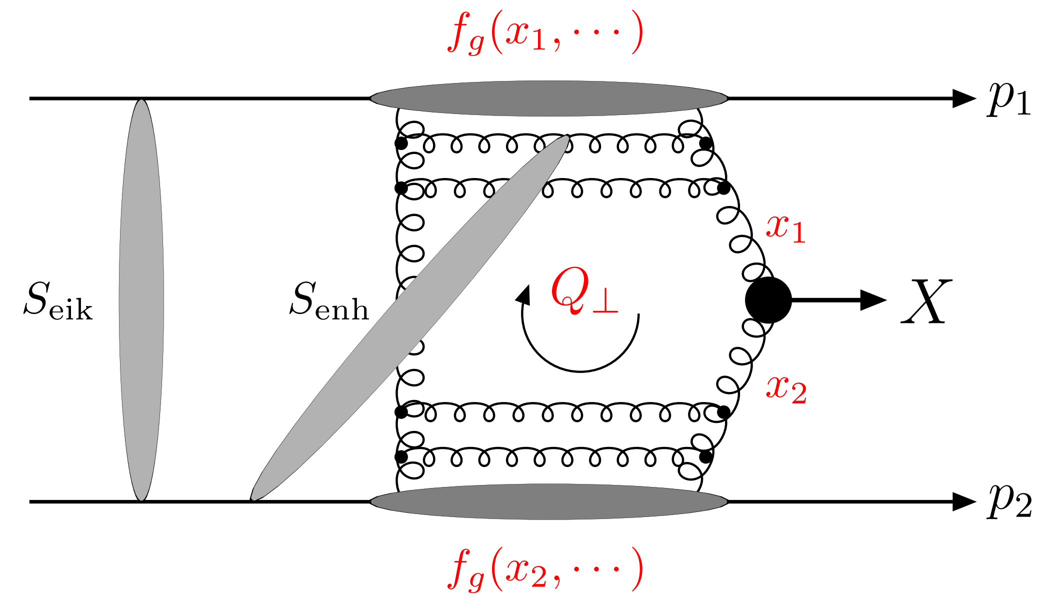
$$pp(\bar{p}) \to p + X + p(\bar{p})$$

- Protons remain intact after collision. Only object of interest X is produced ($X =$ jets, $J/\psi, \pi^+\pi^-, W^+W^-$...) :
    - Clean experimental environment (in absence of pile-up).
    - Can measure outgoing protons - reconstruct X 4-momentum, proton distributions...

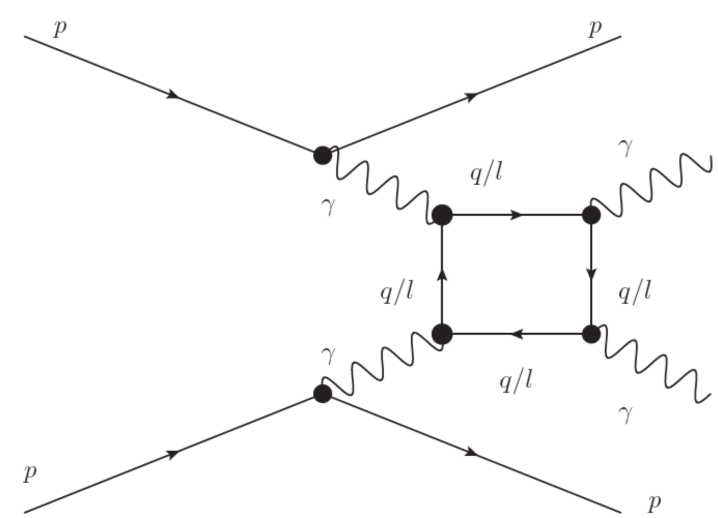


Exclusive final state can be produced via different mechanisms, all discussed in chapter:

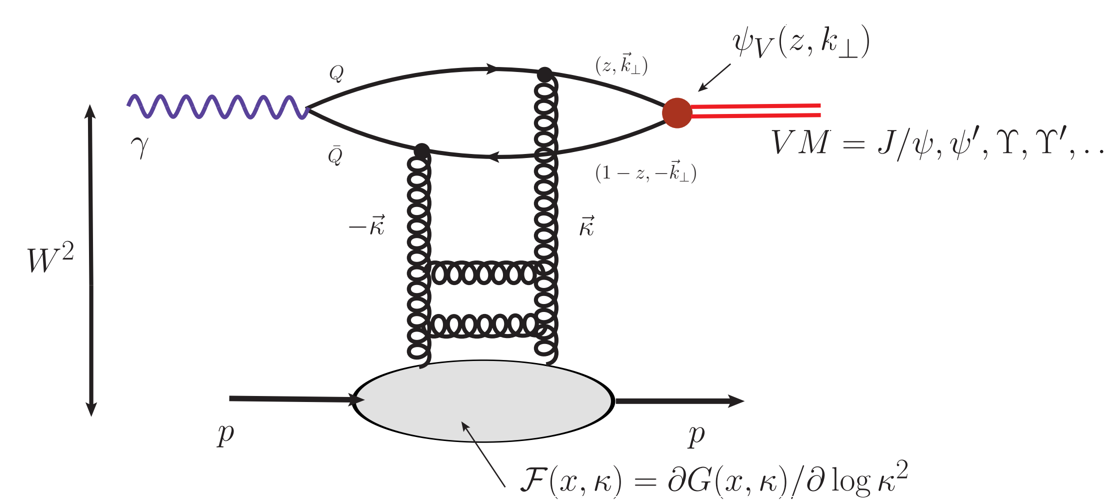
- Gluon-induced (double pomeron exchange)



- Photon-induced



- Photoproduction



Section 1 - Analysis techniques and detectors

Brief discussion of two analysis techniques:

- Proton tagging:
  - Full event kinematics in hadronic collisions.
  - Only way to detect ‘purely’ exclusive events (in absence of pile up).
  - Measured kinematic variables (proton vs. central state) allows further BG rejection.
  - Essential for high-lumi running (exploratory physics).
  - Requires proton taggers (!).
- Rapidity gap:
  - Still possible to select dominantly exclusive events by demanding no additional hadronic activity in large enough rapidity region.
  - Generally prefers larger cross section processes/lower lumi running (i.e. low pile-up), although e.g. vetoing on additional tracks associated with IP possible with pile-up.
  - Has allowed large sample of (dominantly) CEP events to be selected already at the LHC (in particular by LHCb).

In addition: discussion of relevant detector features at LHC.

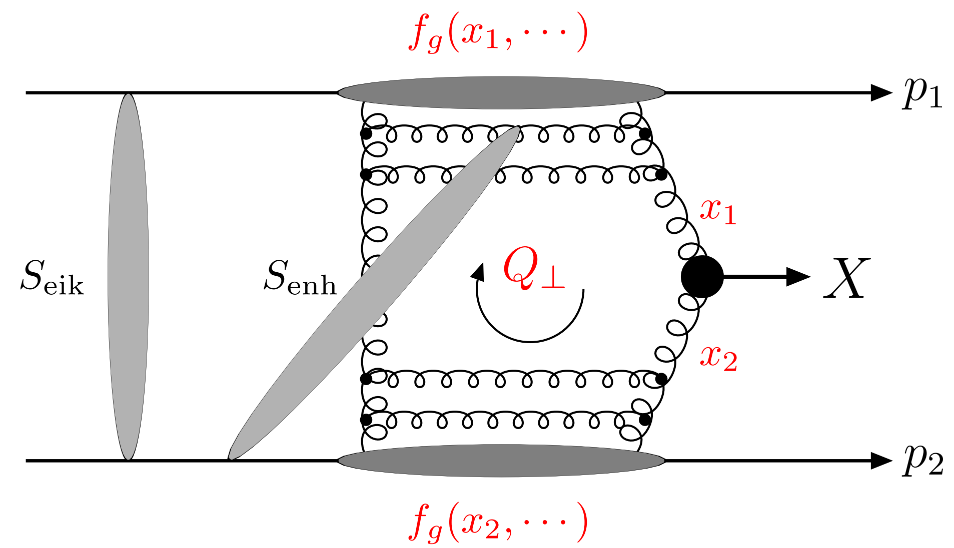
QCD processes

5.3 QCD processes

In this Section, theoretical discussion of CEP processes that proceed via the strong interaction, and motivations for future measurements, are presented.

5.3.1 Introduction

The CEP process may be mediated purely by the strong interaction, in the language of Regge theory proceeding via double Pomeron exchange. In this case, and when the mass of the system, X, produced in the CEP reaction is sufficiently large, a perturbative QCD approach becomes applicable [1, 2, 4, 5],



- 'Double pomeron exchange' in Regge language, but when object mass is high enough can apply pQCD-based approach: 'Durham model'.
- Novel application of pQCD, also requires account of soft physics 'survival factor', S^2.
- Due to CEP kinematics, find that a dynamical selection rule operates, so that produced object has dominantly $J_z^{PC}=0^{++}$ quantum numbers. Leads to various non-trivial results, not seen inclusively.

5.3.2 Forward proton tagging: phenomenological insight and advantages

As well as use in event selection, tagging provides additional information about the quantum numbers of the produced state and the soft survival factor...

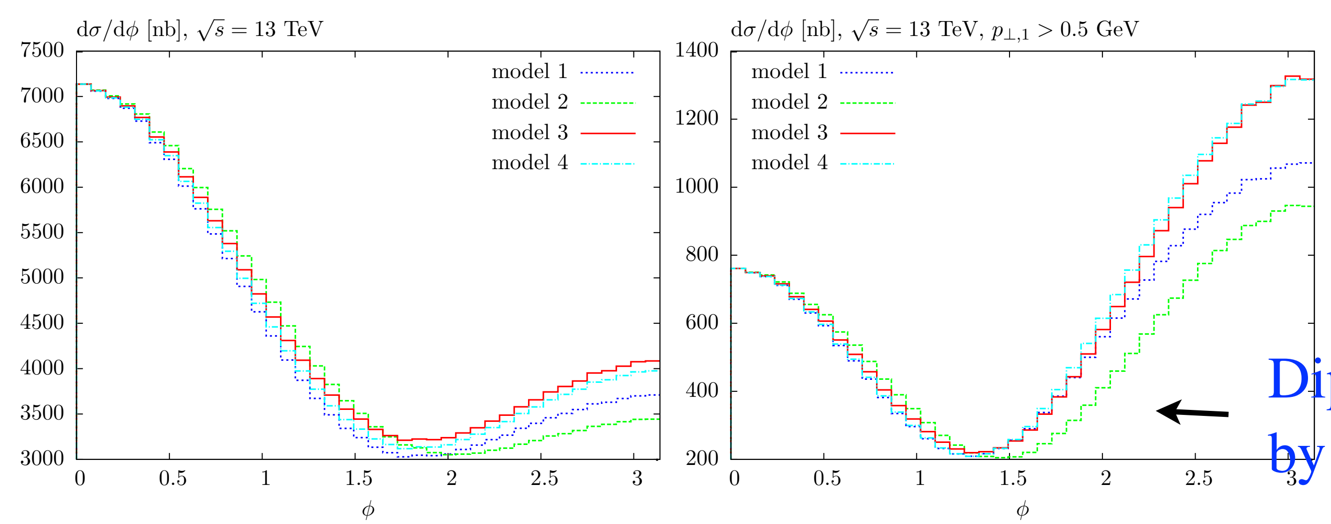
In general, we can write down an expression for the CEP cross section at X rapidity y_X as [127]

$$\frac{d\sigma}{dy_X} = \langle S^2_{\rm enh} \rangle \int d^2\mathbf{p}_{1_\perp} d^2\mathbf{p}_{2_\perp} \frac{|T(\mathbf{p}_{1_\perp},\mathbf{p}_{2_\perp})|^2}{16^2\pi^5} S^2_{\rm eik}(\mathbf{p}_{1_\perp},\mathbf{p}_{2_\perp}) \,, \tag{5.21}$$

Hard amplitude

Soft survival factor

$\longrightarrow$ Distribution of proton $p_\perp$ vectors sensitive to quantum numbers of produced object and survival effects - differential test of survival factor.



Dip entirely driven by survival factor

Fig. 5.21: Differential cross section $d\sigma/d\phi$, where ϕ is the azimuthal angle between the outgoing proton $p_\perp$ vectors, at the $\sqrt{s} = 13$ TeV LHC, for the four soft models of [130]. Results are also shown for different cuts on the magnitude of the proton $p_\perp$, and for a cut $|y_\pi| < 2$ on the centrally produced pions. For display purposes the predictions are normalized in the first ϕ bin, to the model 1 predictions. Plots from [126] and made using `Dime` MC [132].

5.3.3 Conventional quarkonium production

Motivation and theory

- Conventional χ_{cJ} of much interest: Durham model predicts strong hierarchy in cross section for $J = 0, 1, 2$ spin states.

- Observed already at LHCb. Fair agreement but some hints of a disparity in the χ_{c2}
  - Can theory be trusted for $M_X \sim 3\,\mathrm{GeV}$?
  - What is the role of proton dissociation?

- Future data (other decay modes...) will greatly clarify this.

- In addition can look for χ_b . Higher mass $\longrightarrow$ perturbative approach more reliable.

An observation of the higher mass bottomonium χ_b states, for which the mass scale is safely in the perturbative regime, would provide a more stringent test of the theory. The predicted χ_{b0} cross is ~ 100 pb at $\sqrt{s} = 14$ TeV [21], and a similar hierarchy in spin states to the χ_c case is predicted, but with a negligible χ_{b1} cross section due to the higher mass. It is also worth noting that the spin assignments of the P–wave χ_{bJ} states still need experimental confirmation [43], and so this is an issue which the spin–parity selecting properties of CEP could shed light on.

5.3.3 Conventional quarkonium production

Experimental results and outlook

• LHCb: triggering capability (designed for low mass objects) ideal for CEP. Defocused beams $\longrightarrow$ less pile-up.

• Measurement of $\chi_{cJ} \to J/\psi\gamma \to \mu^+\mu^-\gamma$ made using $37\,\mathrm{pb}^{-1}$ data.

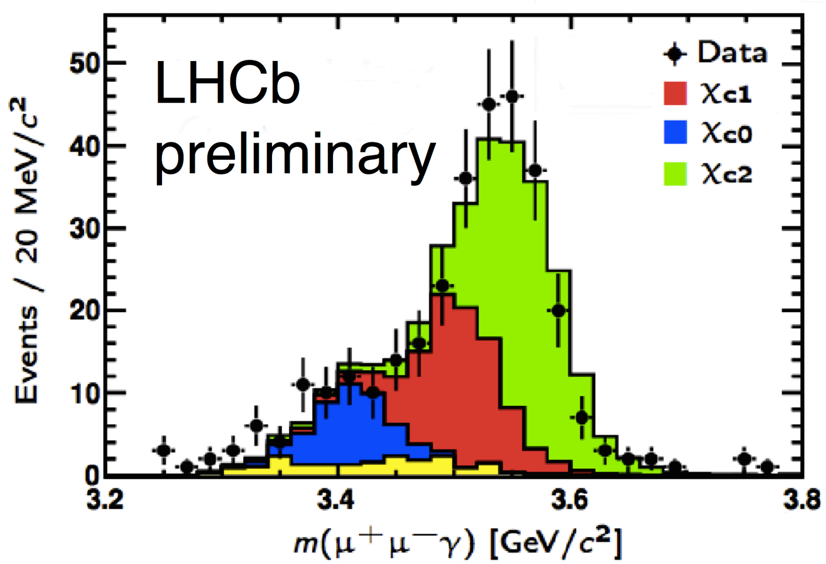


Fig. 5.8: Invariant mass of the di-muon plus photon system in events having no other activity inside LHCb.

• Data in reasonably good agreement with Durham model predictions (some discrepancy for χ_{c2} ?), however sensitivity to proton dissociation unclear.

• About $600\mathrm{pb}^{-1}$ of $7-8\mathrm{TeV}$ data available for further analysis available: higher stats, exclusive component for each state, two-body decays...

• Future: HERSCHEL detector allows diss. BG to be greatly suppressed.

5.3.3 Conventional quarkonium production

Experimental results and outlook

- Proton tagging: with CMS-TOTEM and ALFA the different spin states can be easily seperated in charged particle only final states.

- A preliminary analysis of the July 2012 $\beta^* = 90\mathrm{m}$ run at $\sqrt{s} = 8\mathrm{TeV}$ by CMS-TOTEM shows a few χ_{c0} candidates.

- Future prospects:

to-background ratio. In 5 pb^{-1} of integrated luminosity, more than 1000 χ_{c0} candidates are expected in each of the decay modes ($2(\pi^+\pi^-)$, $3(\pi^+\pi^-)$, $K^+K^-\pi^+\pi^-$). This will allow a good determination of the cross section×branching ratio as well as a detailed study of the azimuthal angular difference $\Delta\phi$ of the outgoing protons for each decay mode separately. According to the predictions of [21], 5 pb^{-1} does

- If Durham predictions underestimate χ_{c2} CEP rate, then would also be visible. If not, a limit could be set.

5.3.9 Jet production

Motivation and theory

• Historically, CDF measurement of exclusive jet production played important role in supporting approach of Durham model.

• Large cross sections: access to wide mass range, providing differential test of theory (Sudakov factor, enhanced rescattering (?)). Realistic observable with tagged protons.

• $q\bar{q}$ jets dynamically suppressed: σ [pb]

M_X(min)	gg	$q\bar{q}$	$b\bar{b}$	ggg	$gq\bar{q}$
75	120	0.073	0.12	6.0	0.14

The different behaviour of the parton–level helicity amplitudes relevant to exclusive jet production leads to some very interesting and non–trivial predictions. For example, if we consider quark jets, the $gg \to q\bar{q}$ amplitudes are given by

$$\mathscr{M}\left((g(\pm)g(\pm) \to q_h\bar{q}_{\bar{h}}\right) = \frac{\delta^{cd}}{N_c}\frac{16\pi\alpha_s}{(1-\beta^2\cos^2\theta)}\frac{m_q}{M_X}(\beta h \pm 1)\delta_{h,\bar{h}}\,, \tag{5.19}$$

$$\mathscr{M}\left((g(\pm)g(\mp) \to q_h\bar{q}_{\bar{h}}\right) = \pm h\frac{\delta^{cd}}{2N_c}8\pi\alpha_s\left(\frac{1\pm h\cos\theta}{1\mp h\cos\theta}\right)^{1/2}\delta_{h,-\bar{h}}\,, \tag{5.20}$$

$\longrightarrow$ expect dominantly gg jets.

• Leads to interesting predictions for the distribution of (ggg, $q\bar{q}g$) exclusive 3-jet events.

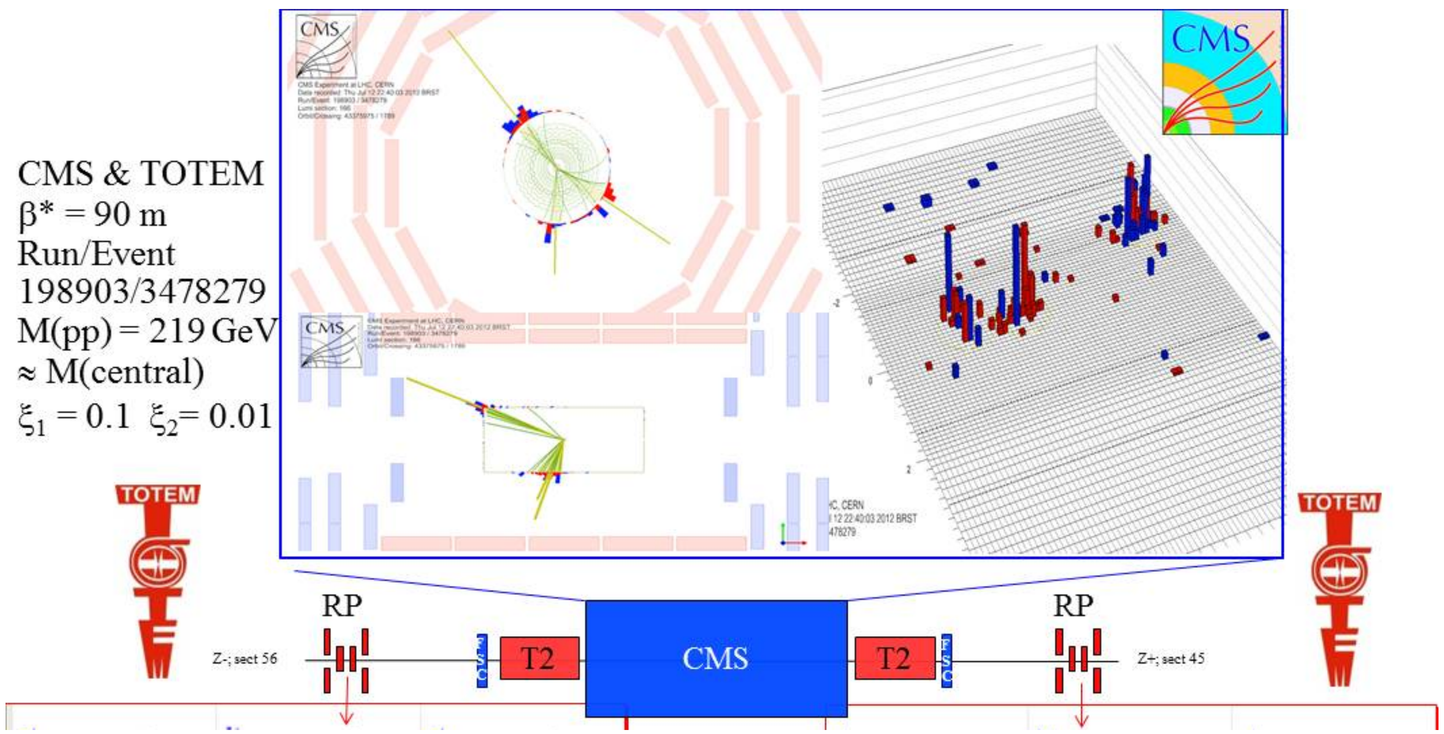
5.3.9 Jet production

Experimental results and outlook

• In high β^* runs CMS-TOTEM and ATLAS-ALFA can study central diffractive jet events with at any M_X. Complementary to CT-PPS/AFP acceptance in standard LHC running, which is sensitive to $M_X \gtrsim 300\mathrm{GeV}$.

• With $100\,\mathrm{pb}^{-1}$ of high β^* CMS-TOTEM running:

- Expect about 10000 CEP events with $M_X > 60\,\mathrm{GeV}$. Expect BG much lower.
- Obtained sample will enable studies of azimuthal angle $\Delta\phi$ between proton vectors, proton $p_\perp$ distributions, and system M_X distribution - comprehensive test of theory (inc. gap survival probability)

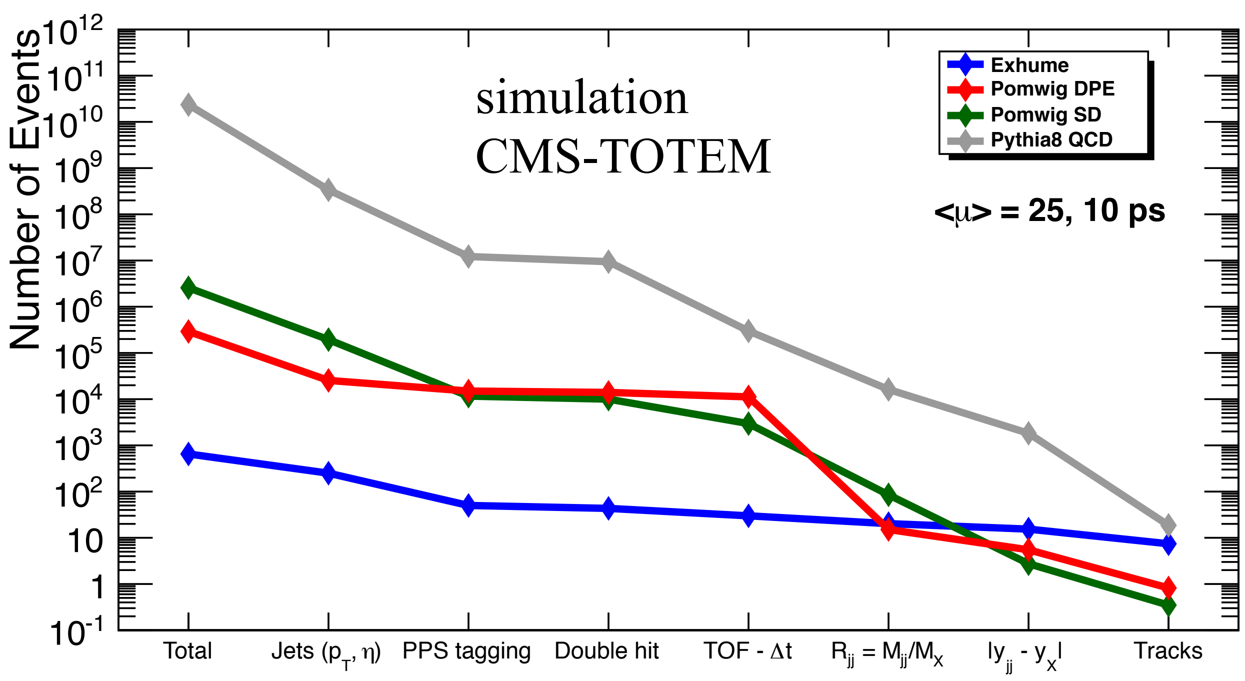


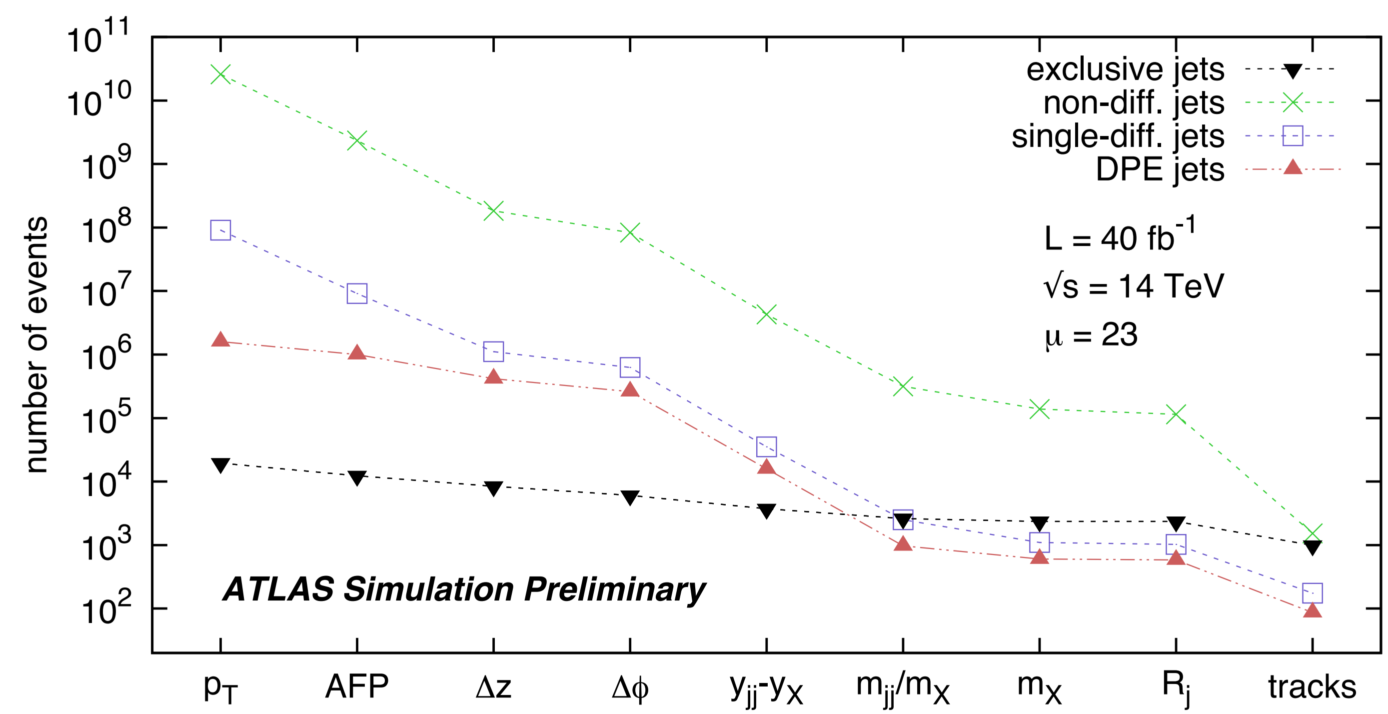
5.3.9 Jet production

5.3.10 Jet production: ATLAS feasibility study 5.3.11 Jet production: CT–PPS feasibility study

- Summaries presented of detailed ATLAS and CT-PPS feasibility studies for exclusive jet measurements with tagged protons during high-lumi LHC running.

- Dominant BG from non-diff. events overlayed with pile-up protons. With suitable cuts, and using timing detectors, realistic S/B looks to be feasible:

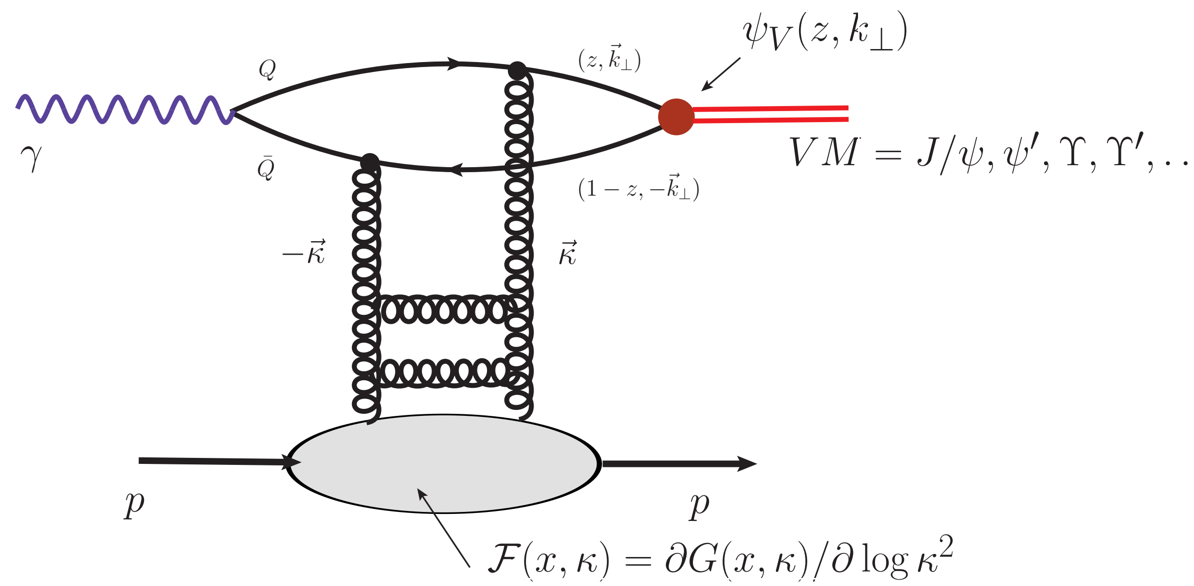




- More challenging as μ increases.

5.4.4 Diffractive photoproduction $\gamma p \to V p$

Motivation and theory



- Fusion of C-odd photon and C-even pomeron $\longrightarrow$ produce C-odd object.
- C-odd vector mesons of special interest, in particular heavy quarkonia, where pQCD can be applied:

  - pQCD model sensitive to low-x (unintegrated) gluon PDF in uncertain region. Saturation effects?
  - Different approaches possible: $k_\perp$-factorization, dipole model...
  - Potential tool for (C-odd) odderon production (different $p_\perp$distributions).

Motivation and theory

Two largely equivalent approaches to modelling the exclusive photoproduction of a vector meson of mass M_V at a γp center-of-mass energy W, applicable at small values of $x = M_V^2/W^2$, are the color-dipole approach and k_T-factorization.

Need to go beyond standard collinear factorization

- Consider 'colour dipole' model:

$$\sigma(x,r) = \frac{4\pi}{3}\alpha_S \int \frac{d^2\kappa}{\kappa^4} \frac{\partial xg(x,\kappa^2)}{\partial \log(\kappa^2)} \left[1 - \exp(i\kappa r)\right], \quad (5.4)$$

Sensitive to low-x gluon

and '$k_\perp$-factorization' approach:

$$\Im m\, \mathscr{M}_{\lambda_\gamma,\lambda_V}(W,\Delta^2=0) = W^2 \frac{c_\Upsilon \sqrt{4\pi\alpha_{em}}}{4\pi^2} \int \frac{d^2\kappa}{\kappa^4} \alpha_S(q^2) \mathscr{F}(x_1,x_2,\kappa) \times \int \frac{dz d^2k}{z(1-z)} \psi_V(z,k) I_{\lambda_\gamma,\lambda_V}(z,k,\kappa), \quad (5.8)$$

Here, the unintegrated gluon distribution $\mathscr{F}(x_1,x_2,\kappa_1)$ is appears off-diagonal ("skewed") in longitudinal

5.4.4 Diffractive photoproduction $\gamma p \to V p$

Experimental results and outlook

- LHCb: J/ψ and $\psi(2S)$ production measured in $\mu^+\mu^-$ channel at $\sqrt{s} = 7\,\mathrm{TeV}$.

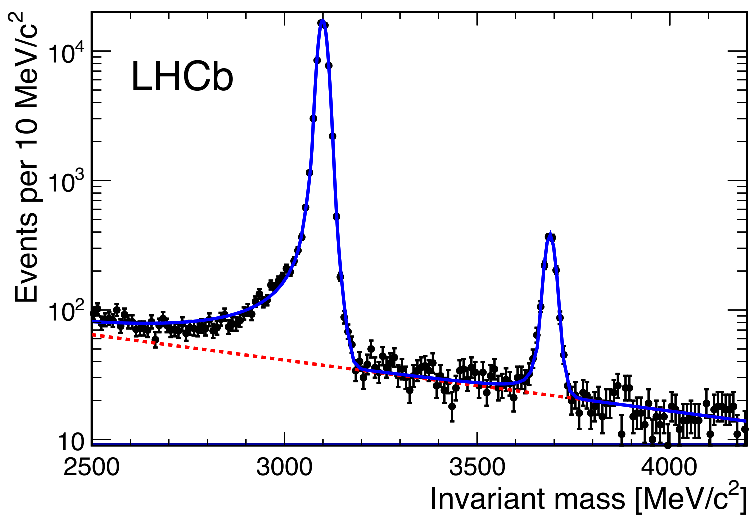


Fig. 5.3: Invariant mass of selected di-muon candidates in 930 pb^{-1} of data.

- After corrections (in particular for proton dissociation):

Next run: HERSCHEL

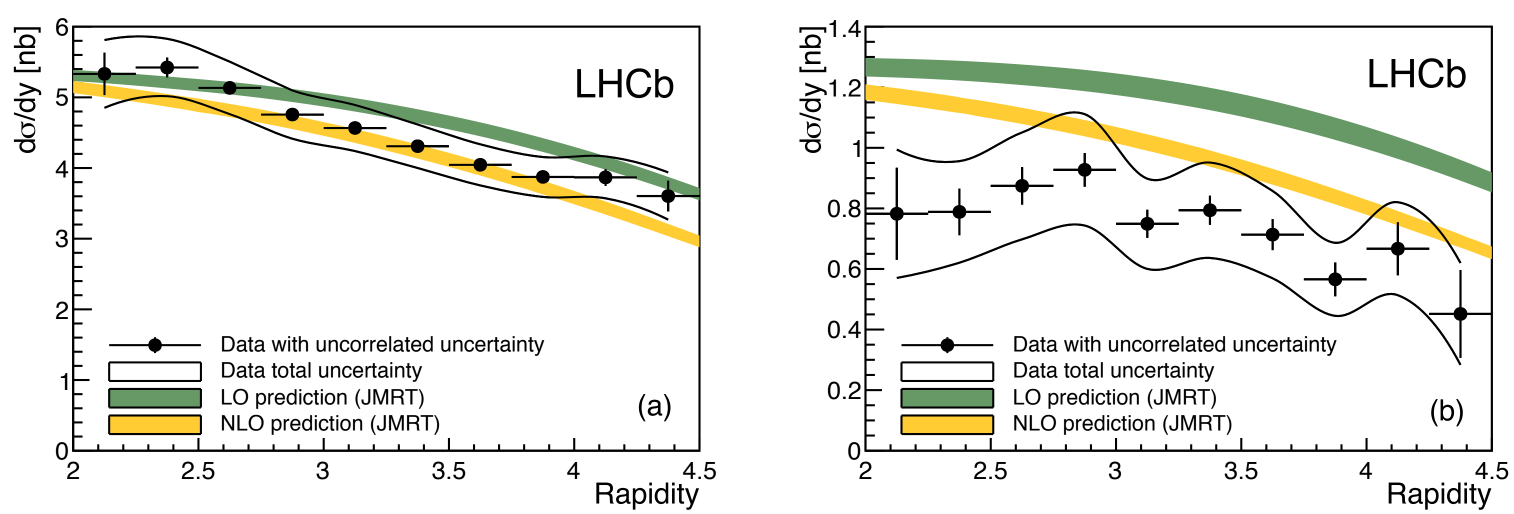


Fig. 5.5: Differential cross-section for (a) J/ψ and (b) $\psi(2S)$ compared to LO and NLO predictions.

- ALICE: measurement in ultraperipheral p-Pb collisions. Consistent with LHCb.

5.4.4 Diffractive photoproduction $\gamma p \to V p$

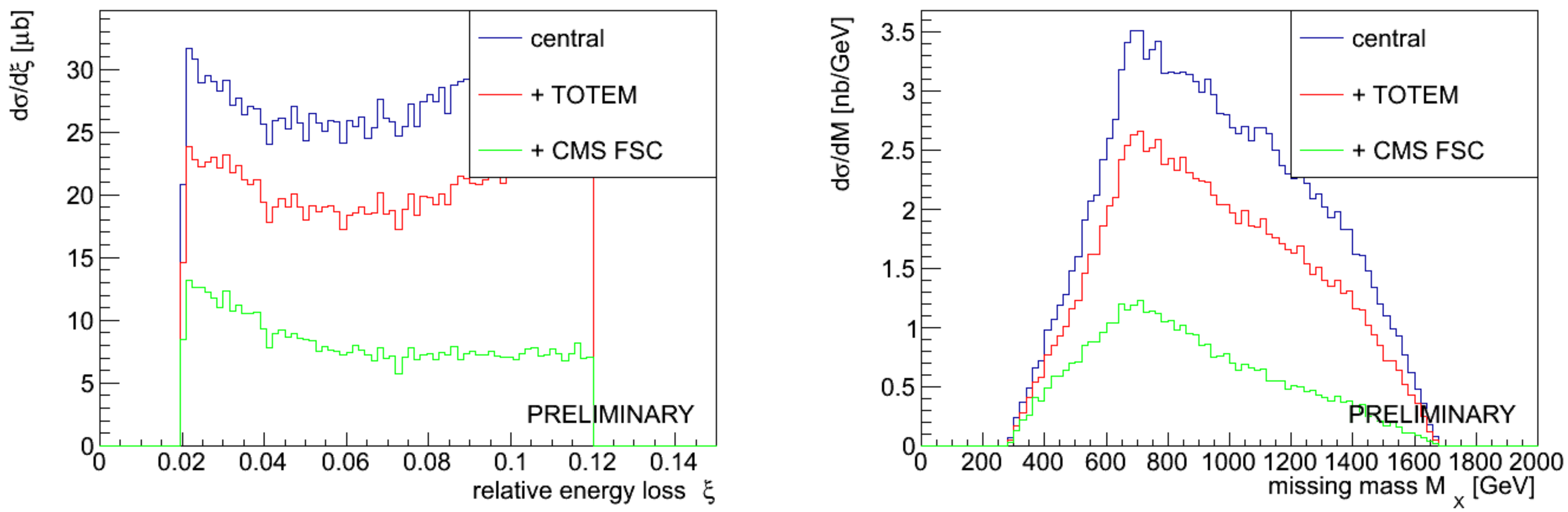
Experimental results and outlook

- In addition can look at photoproduction with tagged protons.
  - Extrapolating from LHCb need $\sim 1\,\mathrm{pb}^{-1}$ lumi. to perform measurement.
  - Expect $\sim 1000\ J/\psi$ candidates in $\mu^+\mu^-$ decay mode with $5\,\mathrm{pb}^{-1}$.
  - Proton tagging: no dissociation, even at higher $p_\perp \to$ sensitivity to Odderon, through measurement of proton $p_\perp$ distribution.

5.5 Exploratory physics

The study of BSM signatures in the CEP channel, which usually have very low cross sections and signal to background ratios, can be very competitive with and complementary compared to standard LHC searches.

• Range of topics to consider (magnetic monopole searches, missing mass, technipions), with detailed study of anomalous coupling searches presented.



(a) (b)

Fig. 5.42: Distributions of (a) relative momentum loss and (b) missing mass for events with the signature of invisible particle production (empty central detectors and two forward protons with $0.02 < \xi < 0.12$). The effect of an additional veto from the TOTEM tracker and CMS FSCs is presented.

6 Prospects for high luminosity measurements

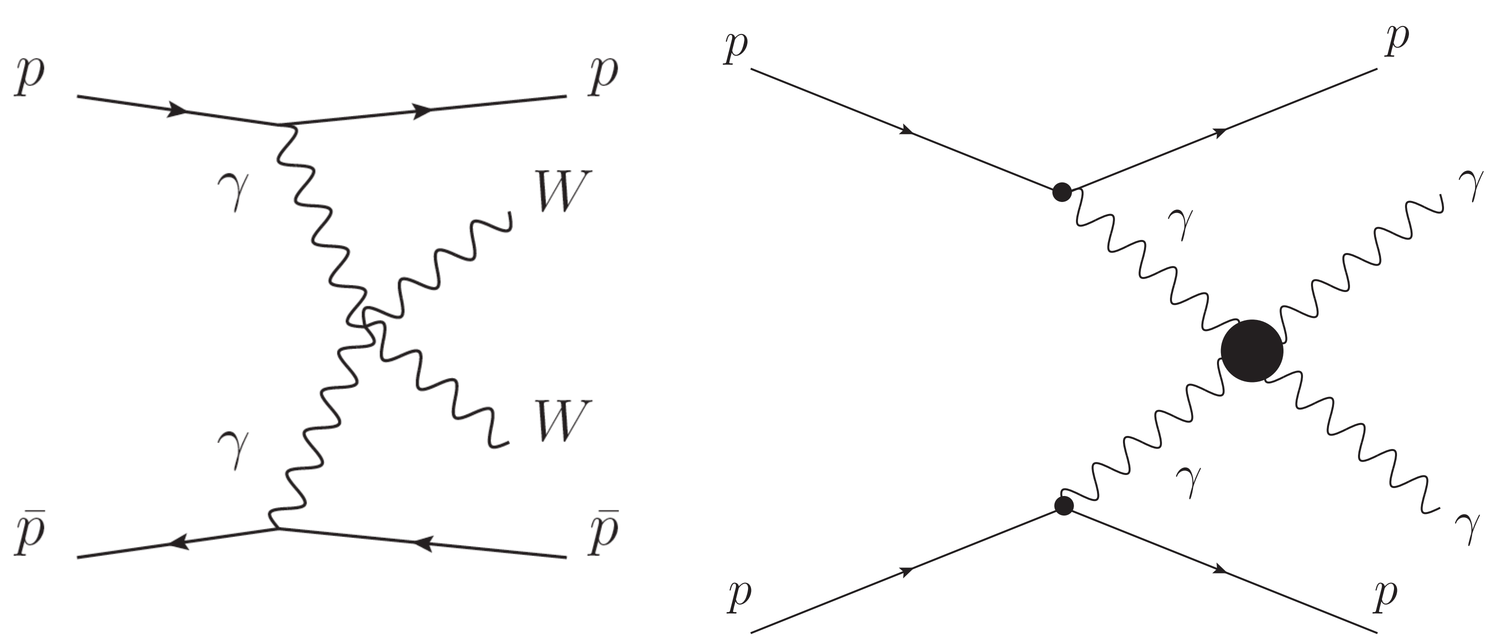
6.1 Standard Model exclusive $\gamma\gamma$, WW and ZZ production

- SM W^+W^-production: pure QED process. Direct probe of EW symmetry breaking.

- Reject pile-up by counting number of tracks fitted to primary vertex.

- Detailed study finds:

> After simple cuts to select exclusive W pairs decaying into leptons, such as a cut on the proton momentum loss of the proton ($0.0015 < \xi < 0.15$) — we assume the protons to be tagged in AFP or CT-PPS at 210 and 420 m — on the transverse momentum of the leading and second leading leptons at 25 and 10 GeV respectively, on $E_T^{miss} > 20$ GeV, $\Delta\phi > 2.7$ between leading leptons, and $160 < W < 500$ GeV, the diffractive mass reconstructed using the forward detectors, the background is found to be less than 1.7 event for 30 fb^{-1} for a SM signal of 51 events [178].



6.3 Quartic *WW* and *ZZ* anomalous couplings

- Predicted in BSM (e.g. extra dimension) models.
- Study based on parameterization of G. Belanger and F. Boudjema, Phys. Lett. B **288** (1992) 201.
- Find much increased reach (or discovery potential) beyond existing limits.

Proton tagging the only known way to provide such stringent limits.

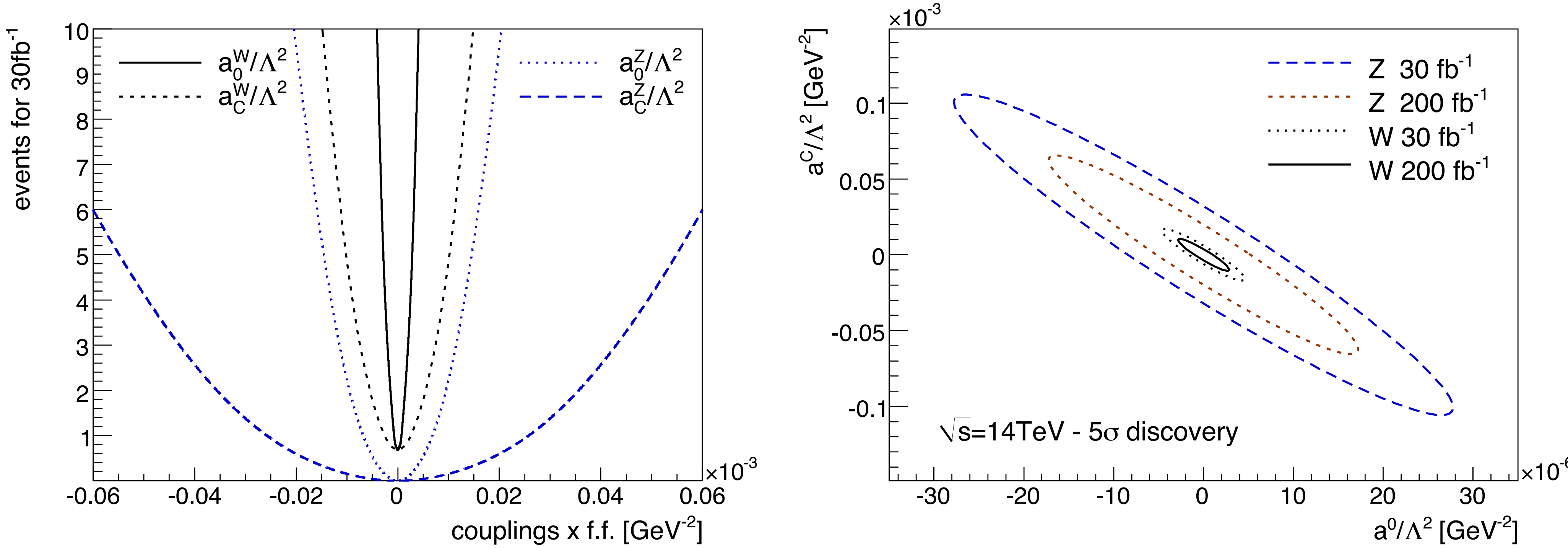


Fig. 5.33: (left) Number of events for signal due to different values of anomalous couplings after all cuts (see text) for a luminosity of 30 fb^{-1} and (right) 5σ discovery contours for all the *WW* and *ZZ* quartic couplings at $\sqrt{s} = 14$ TeV for a luminosity of 30 fb^{-1} and 200 fb^{-1}.

6.4 Quartic photon anomalous couplings

- Anomalous 4-photon interactions common in BSM models, e.g. loops of heavy charged particles, dilatons expected in strongly-coupled theories and KK gravitons can all induce anomalous couplings:

$$\mathscr{L}_{4\gamma} = \zeta_1^{\gamma} F_{\mu\nu}F^{\mu\nu}F_{\rho\sigma}F^{\rho\sigma} + \zeta_2^{\gamma} F_{\mu\nu}F^{\nu\rho}F_{\rho\lambda}F^{\lambda\mu}$$

- Again find much increased sensitivity to these couplings.

Luminosity	300 fb^{-1}	300 fb^{-1}	300 fb^{-1}	3000 fb^{-1}
pile-up (μ)	50	50	50	200
coupling (GeV^{-4})	≥ 1 conv. γ 5 σ	≥ 1 conv. γ 95% CL	all γ 95% CL	all γ 95% CL
ζ_1 f.f.	$1. \cdot 10^{-13}$	$9. \cdot 10^{-14}$	$5. \cdot 10^{-14}$	$2.5 \cdot 10^{-14}$
ζ_1 no f.f.	$3.5 \cdot 10^{-14}$	$2.5 \cdot 10^{-14}$	$1.5 \cdot 10^{-14}$	$7. \cdot 10^{-15}$
ζ_2 f.f.	$2.5 \cdot 10^{-13}$	$1.5 \cdot 10^{-13}$	$1. \cdot 10^{-13}$	$4.5 \cdot 10^{-14}$
ζ_2 no f.f.	$7.5 \cdot 10^{-14}$	$5.5 \cdot 10^{-14}$	$3. \cdot 10^{-14}$	$1.5 \cdot 10^{-14}$

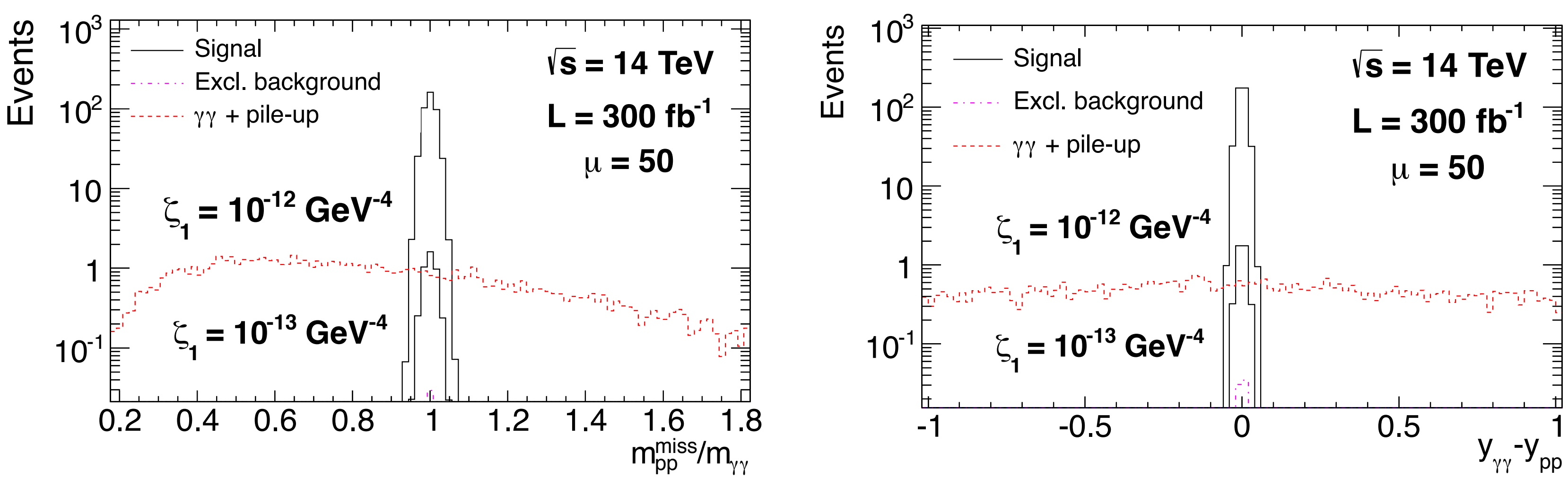


Fig. 5.35: Diphoton to missing proton mass ratio (left) and rapidity difference (right) distributions for signal considering two different coupling values (10^{-12} and 10^{-13}GeV^{-4}, see Eq. 5.28) and for backgrounds after requirements on photon p_T, diphoton invariant mass, p_T ratio between the two photons and on the angle between the two photons. At least one converted photon is required. The integrated luminosity is 300 fb^{-1} and the average pile-up is $\mu = 50$.

Processes not mentioned...

- QCD:
  - ‘Exotic’ quarkonia: $X(3872)$, $Y(3940)$...
  - Photon pairs
  - Light meson pairs: $\pi\pi$, KK, $\eta(')\eta(')$, $\phi\phi$...
  - Low mass resonances and glueballs
  - Quarkonia pairs: $J/\psi J/\psi$, $J/\psi\psi(2S)$, $\psi(2S)\psi(2S)$...
- Two-photon collisions : l^+l^-(luminosity monitor)
- Exploratory physics:
  - Invisible objets/missing momenta
  - Magnetic monopoles
  - New strong dynamics/technipions

Conclusion

- The CEP chapter contains a rich physics menu.

- Motivations and possibilities for gluon and photon induced measurements discussed.

- LHCb: wide range of measurements already made, with more to come.

- CMS-TOTEM/ALFA: wide range of very interesting measurements, with tagged protons, using $\sim 1 - 100\,\mathrm{pb}^{-1}$ of integrated lumi. of high β^* running.

- High lumi. running: SM vector boson production and (BSM) anomalous coupling measurements/exclusion. The latter possible with much higher precision than currently possible otherwise.

- Many processes not discussed here but in chapter. ‘Final’ version in draft report: see there for more details.