High Energy Photon Interactions @ LHC

Krzysztof Piotrzkowski

Center for Particle Physics and Phenomenology (CP3), Université Catholique de Louvain

UCL

- LHC as a high energy γγ (and γp) collider
- Benchmark processes in γγ (and γp)
- Summary/Outlook

Results for photon physics at the LHC has been obtained within

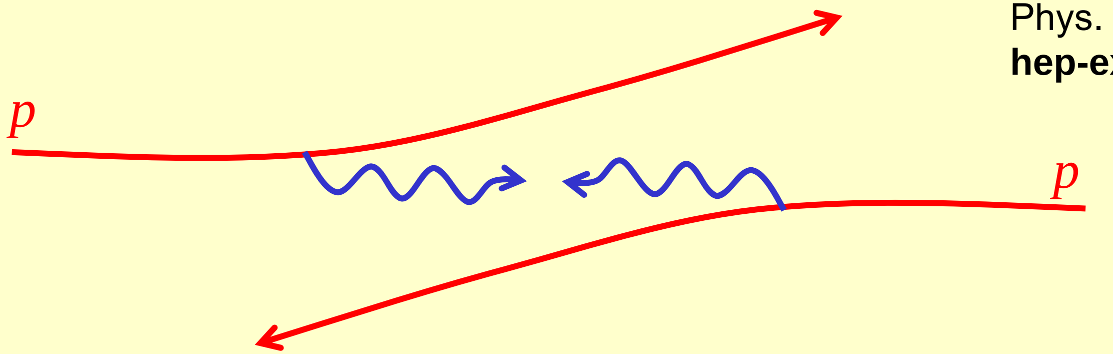
Louvain Photon Group of CP3

J.de Favereau, V. Lemaître, Y. Liu, S. Ovyn, T. Pierzchała, KP, X. Rouby, N.Schul, M. Vander Donckt

Presented at PHOTON2007 in Paris and SUSY07 in Karlsruhe

LHC as a High Energy γγ Collider

Phys. Rev. **D63** (2001) 071502(R)
hep-ex/0201027



Observation:
Provided <u>efficient</u> measurement of very forward-scattered protons one can study high-energy γγ collisions at the LHC

<u>Highlights</u>:
- **γγ CM energy *W* up to/beyond 1 TeV (and under control)**
- **Large photon flux *F* therefore significant γγ luminosity**
- **Complementary (and clean) physics to *pp* interactions, eg studies of exclusive production of heavy particles might be possible ➡ opens new field high energy γγ (and γp) physics**

DISCLAIMER:

This is NOT meant for studying all photon interactions at the LHC but those for which the QCD background can be strongly suppressed, as for example in the exclusive production of pairs of charged particles.

This IS meant for studying production of *selected* final states in photon interactions at the LHC.

Note: At Tevatron available energy too small for EW physics (but enough for lepton pairs – CDF recently published measurement of exclusive two-photon production of *ee* pairs)

Initial inspiration:

DESY 93–173
UCD–93–39
December 1993

$\gamma\gamma$ PRODUCTION OF NON–STRONGLY INTERACTING $\mathcal{SUSY}$ PARTICLES AT HADRON COLLIDERS

J. Ohnemus[1], T.F. Walsh[2], and P.M. Zerwas[3]

Kinematics/γγ Luminosity

Virtuality Q^2 of colliding photons vary between kinematical min = $M_p^2 x^2/(1-x)$ where x is fraction of proton momentum carried by a photon, and Q^2_{max} ~ $1/\text{proton radius}^2$

Photon flux $\propto 1/Q^2$

$Q^2 - Q^2_{min} \approx s\theta^2/4$

protons scattered at `zero-degree' angle

$$W^2 = s\, x_1\, x_2$$

Use EPA à la *Budnev et al.**

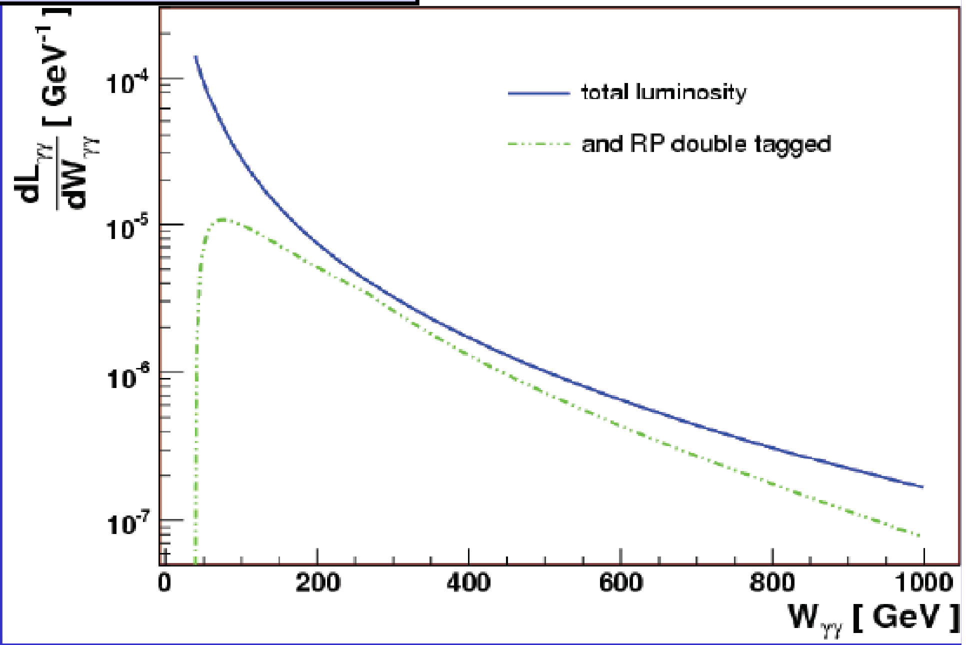
** error found in the elastic (Q^2 integrated) γ flux for protons!*

luminosity peaked at low $W_{\gamma\gamma}$

sizable charged pair production

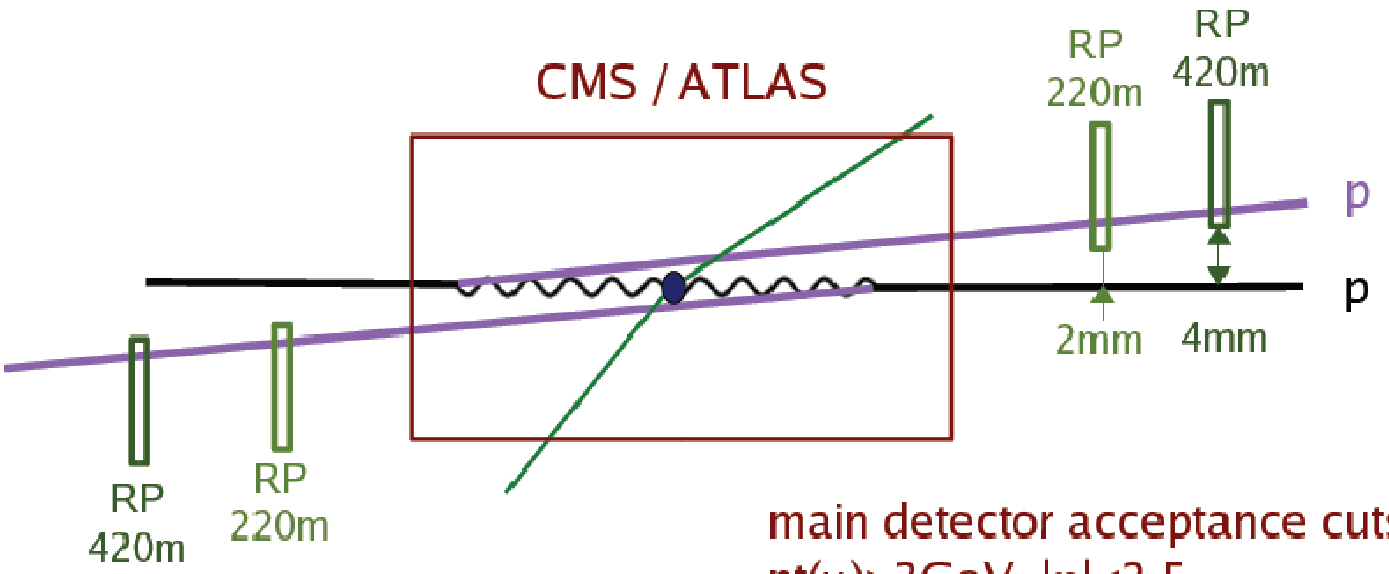
$$\sigma_{pp} = \int \sigma(W_{\gamma\gamma}) \frac{dL_{\gamma\gamma}}{dW_{\gamma\gamma}} dW_{\gamma\gamma}$$

for $x>0.0007$, $Q^2<2GeV^2$



$\int dWS_{\gamma\gamma}$ = 'γγ : pp luminosity'

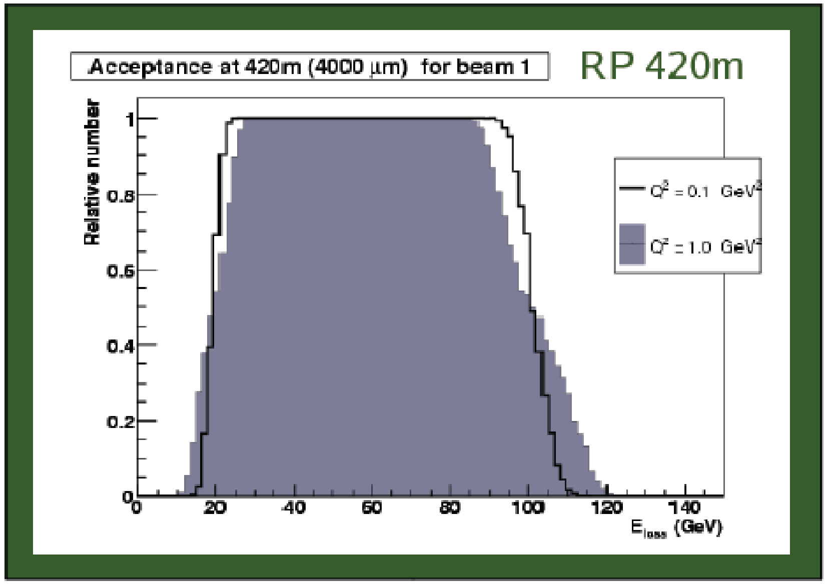
Note: it's few times larger if one of protons is allowed to break up



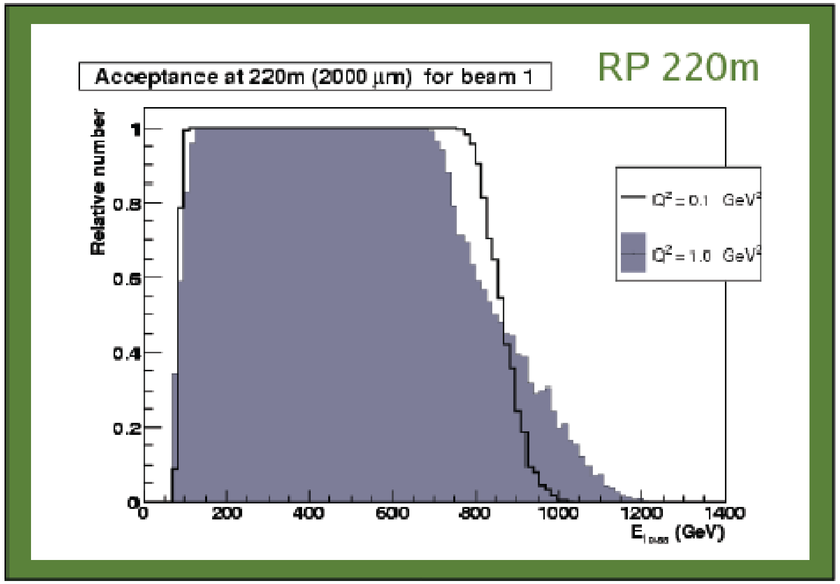
main detector acceptance cuts
pt(μ)>3GeV, |η|<2.5

RP acceptance :

20GeV < tagged photon E < 120GeV



120GeV < tagged photon E < 900GeV

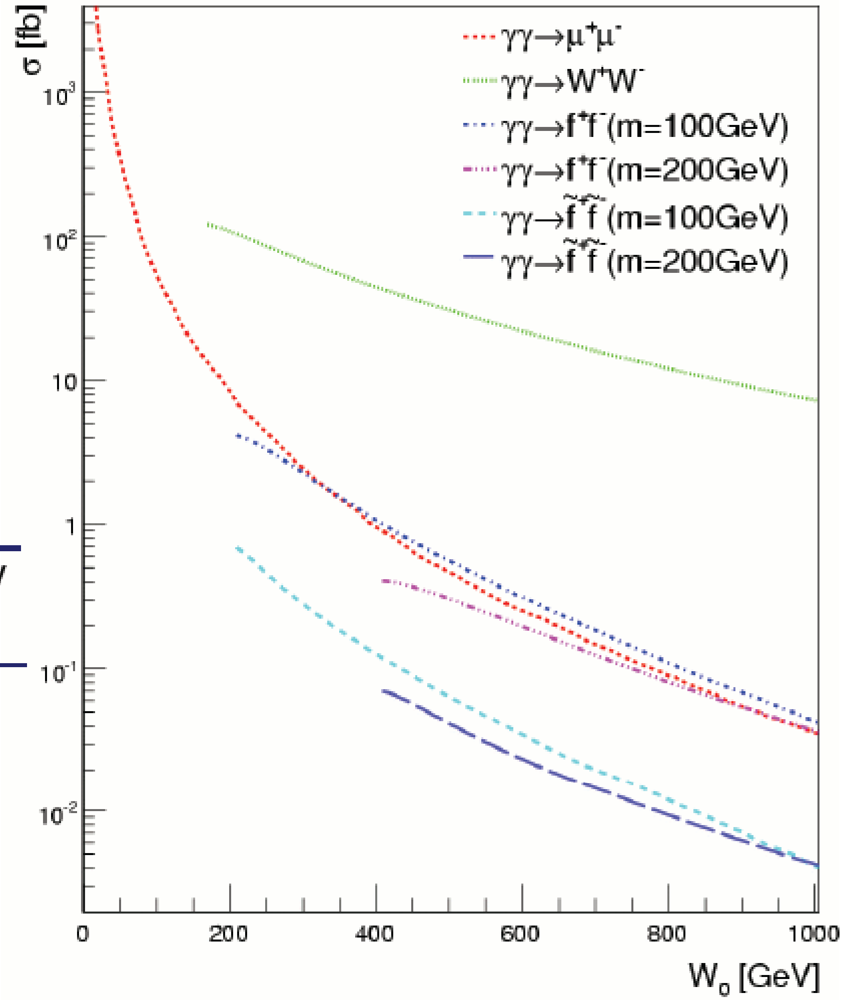


Hector : J. de Favereau, X. Rouby and K. Piotrzkowski

Benchmark $\gamma\gamma$ processes:

- $\gamma\gamma \to \mu\mu$ first $\gamma\gamma$ process to be seen
- $\gamma\gamma \to W^+W^-$ very interesting SM process 103fb
- New physics !

Processes	[fb]	Generator
$\gamma\gamma \to \mu\mu$	72 500	LPAIR pt > 2 GeV $\lvert\eta\rvert$ < 3.1
W^+W^-	103	
f^+f^- (m=100GeV)	4.1	MadGraph
f^+f^- (m=200GeV)	0.41	/
$\tilde{f}^+\tilde{f}^-$ (m=100GeV)	0.69	MadEvent
$\tilde{f}^+\tilde{f}^-$ (m=200GeV)	0.07	



Cross sections for $\gamma\gamma$ processes as a function of the minimal $\gamma\gamma$ cms energy W_0

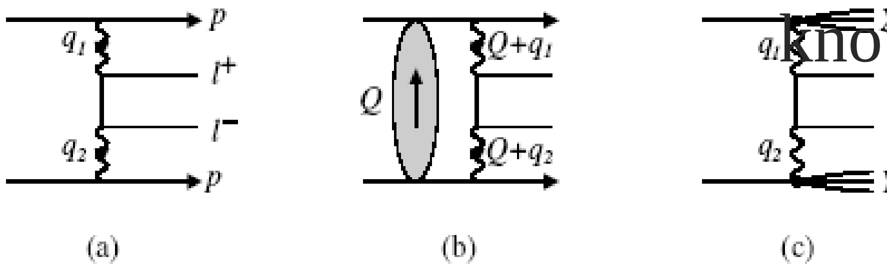
moreover :
lepton final states
clear signature – background suppression

Exclusive lepton pairs

Done at HERA, done at Tevatron!

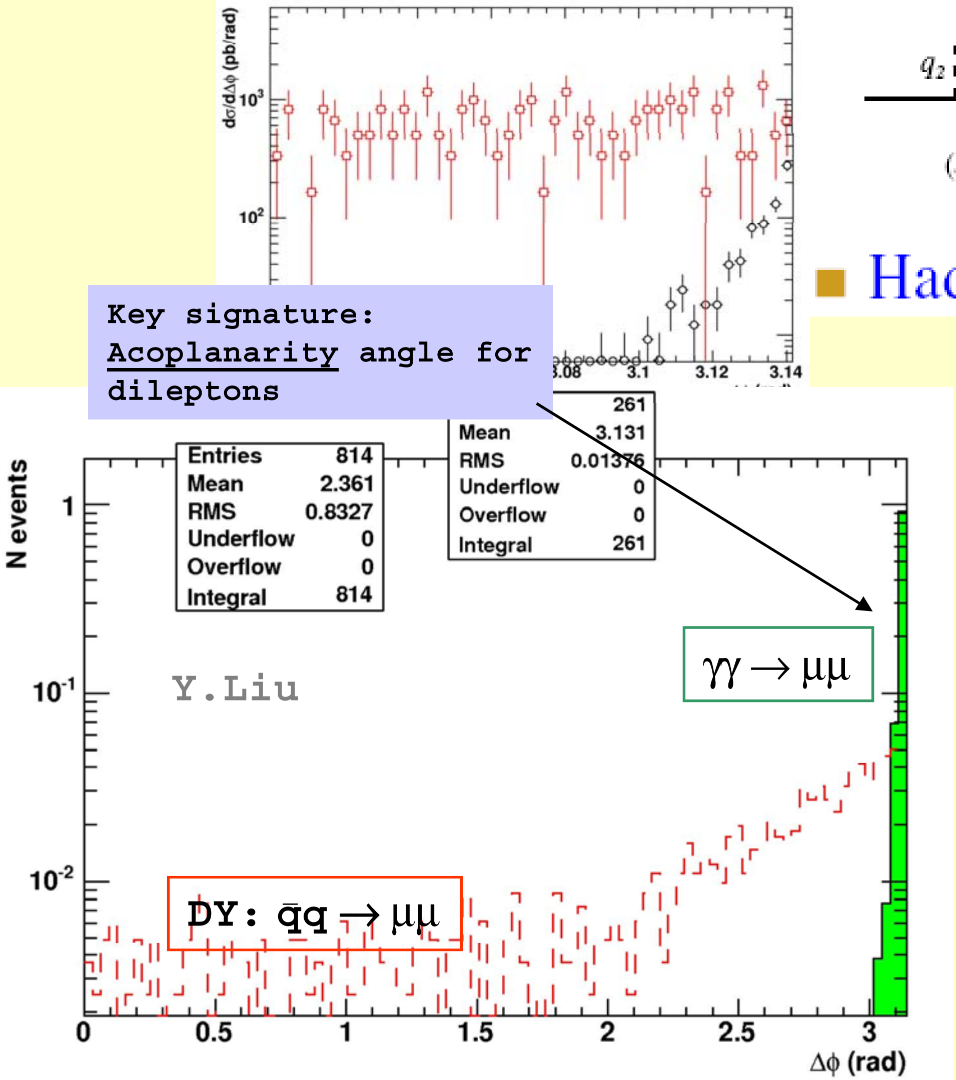
QED process (a) production σ precisely known

event generator LPAIR based on ME by Vermaseren



- Hadronic corrections [(b) (c)] small.

Key signature: <u>Acoplanarity</u> angle for dileptons



Calibration process both for luminosity and energy scales, has striking signatures and can be well triggered and reconstructed by central detectors <u>alone</u>

Observed CMS cross-section for di-muons is about 3 pb

T.Pierzchala

$\gamma\gamma \rightarrow$ WW probing anomalous couplings $\gamma\gamma$WW

$$L_6^0 = \frac{-e^2}{8}\frac{a_0^W}{\Lambda^2} F_{\mu\nu} F^{\mu\nu} W^{+\alpha} W^-_\alpha$$

$$L_6^C = \frac{-e^2}{16}\frac{a_C^W}{\Lambda^2} F_{\mu\alpha} F^{\mu\beta} (W^{+\alpha} W^-_\beta + W^{-\alpha} W^+_\beta)$$

Commonly used Lagrangian
for anomalous quartic vector boson couplings
which conserves C, P as well as local U(1)em

investigating $\gamma\gamma \rightarrow W^+W^- \rightarrow \mu^+\mu^-\bar{\nu}_\mu\nu_\mu$ effective cross sections (σ_{acc}) are:

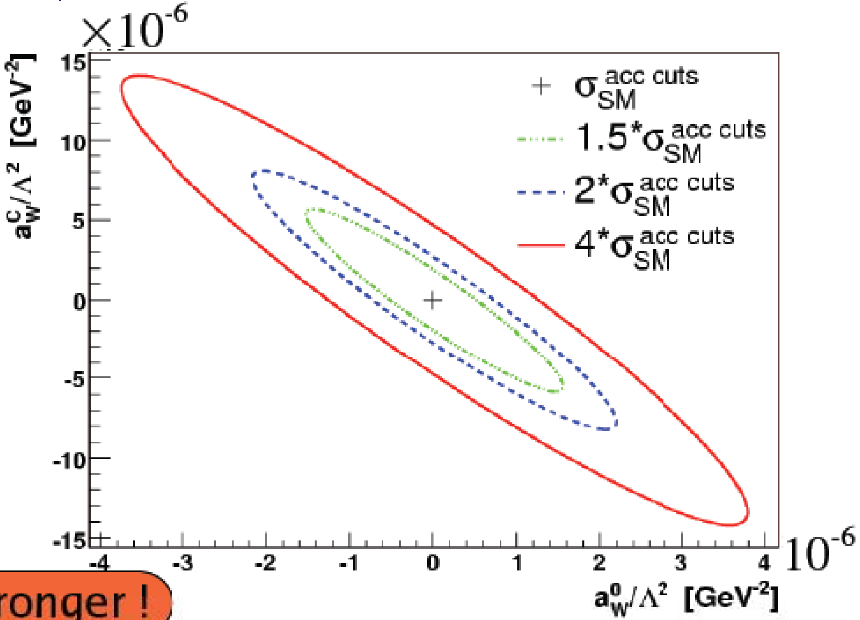
SM here background	pt(μ)>3 GeV	pt(μ)>10 GeV
σ_{acc}	0.76 fb	0.72 fb
σ_{acc} (with RP)	0.66 fb	0.62 fb

no other background than SM $\gamma\gamma \rightarrow$WW
for 30 fb^{-1} expected 22.8 (18.6) events

while current OPAL limits are:

-0.020 GeV < a_0^W < 0.020 GeV

-0.052 GeV < a_C^W < 0.037 GeV



we expect limits to be ~ 10 000 times stronger !

$\gamma\gamma \rightarrow ZZ$

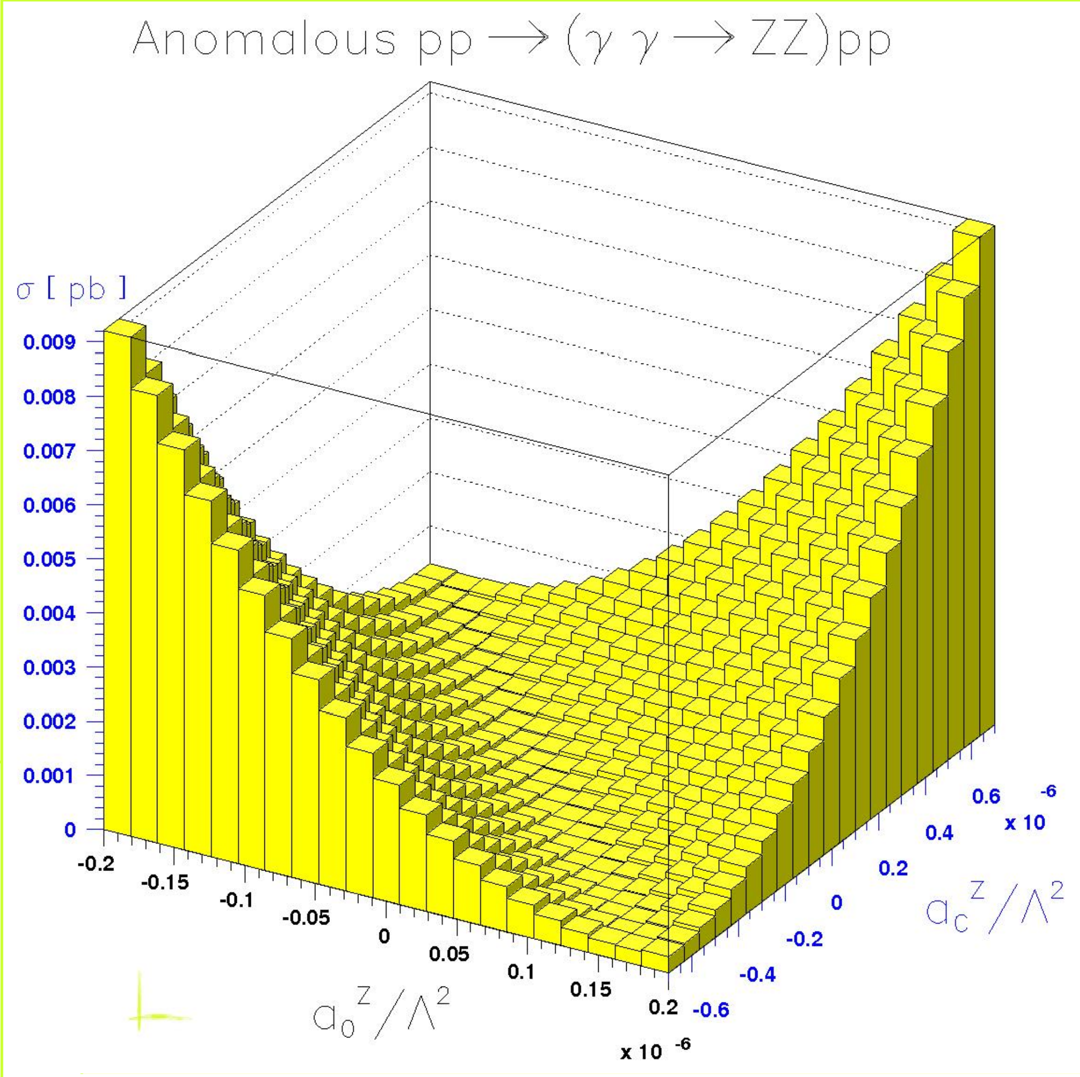
Two-photon production of W and Z boson pairs at LHC is ideal to study quartic gauge couplings a_0^W, a_c^W, a_0^Z, a_c^Z (LEP limits are poor due to limited phase space)

- In SM $\gamma\gamma \rightarrow ZZ$ quantum effect (suppressed by 10^{-3}) for $\int L_{pp}\, dt = 30\, fb^{-1} \Rightarrow$ about 5 SM Z pairs will be produced
- our limits estimations

assuming no background

$$-0.2\cdot 10^{-6}\ \mathrm{GeV}^{-2} < a_0^Z/\Lambda^2 < 0.2\cdot 10^{-6}\ \mathrm{GeV}^{-2}$$

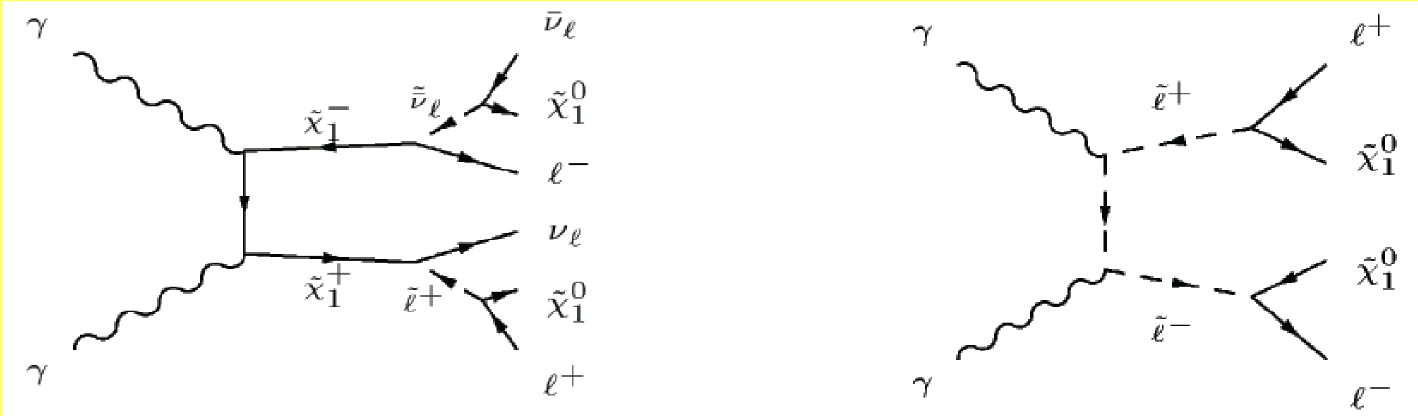
$$-0.7\cdot 10^{-6}\ \mathrm{GeV}^{-2} < a_c^Z/\Lambda^2 < 0.7\cdot 10^{-6}\ \mathrm{GeV}^{-2}$$



- Should be possible to detect these events (esp. fully leptonic decays) even at highest *pp* luminosities

Exclusive two-photon production of charged SUSY pairs –
Production x-sections defined only by mass, charge and spin!

- Very clean signature: Two (and only two) opposite charged leptons and missing energy



Three post-WMAP mSugra benchmark points checked:

- LM1: light LSP, light sleptons & charginos, Tan(β)=10
- LM2: medium LSP, heavy sleptons&charginos, Tan(β)=30
- LM6: heavy LSP, medium right sleptons, Tan(β)=10

m [GeV]	LM1	LM2	LM6
$\tilde{\chi}_1^0$	97	141	162
$\tilde{l}_R^+$	118	229	175
$\tilde{l}_L^+$	184	301	283
$\tilde{\tau}_1^+$	109	155	168
$\tilde{\tau}_2^+$	188	313	285
$\tilde{\chi}_1^+$	180	265	303
H^+	386	448	592

First acceptance studies: Modified CalcHep for $\gamma\gamma \to$ SUSY pair generation, and Pythia for decays

Lepton (e/μ) acceptance cuts: $p_T > 3$ (10) GeV, $|\eta| < 2.5$; irreducible background due to $\gamma\gamma \to$ WW

Benchmark		LM1	LM2	LM6
σ [fb]	$\tilde{l}^+_R \tilde{l}^-_R$	0.805	0.087	0.220
	$\tilde{l}^+_R \tilde{l}^-_R$	0.185	0.032	0.040
	$\tilde{\tau}^+_i \tilde{\tau}^-_i$	0.611	0.180	0.148
	$\tilde{\chi}^+_1 \tilde{\chi}^-_1$	0.605	0.144	0.087
	$H^+ H^-$	0.006	0.003	0.001
	$W^+ W^-$		103	
σ acc	$\tilde{l}^+_R \tilde{l}^-_R$	0.633(0.479)	0.075(0.074)	0.177(0.087)
	$\tilde{l}^+_R \tilde{l}^-_R$	0.144(0.135)	0.014(0.012)	0.036(0.035)
	$\tilde{\tau}^+_i \tilde{\tau}^-_i$	0.023(0.006)	0.008(0.001)	0.003(0.001)
	$\tilde{\chi}^+_1 \tilde{\chi}^-_1$	0.103(0.029)	0.006(0.001)	0.033(0.028)
	$W^+ W^-$		4.057(3.512)	

Large signal acceptance, and not very sensitive to minimal accepted lepton p_T

Irreducible WW background issue

• Use lepton flavor sharing in final state:
For example, in SUSY case sharing between ee–eμ/μe–μμ is 45–10–45%, and for WW decays 25–50–25%

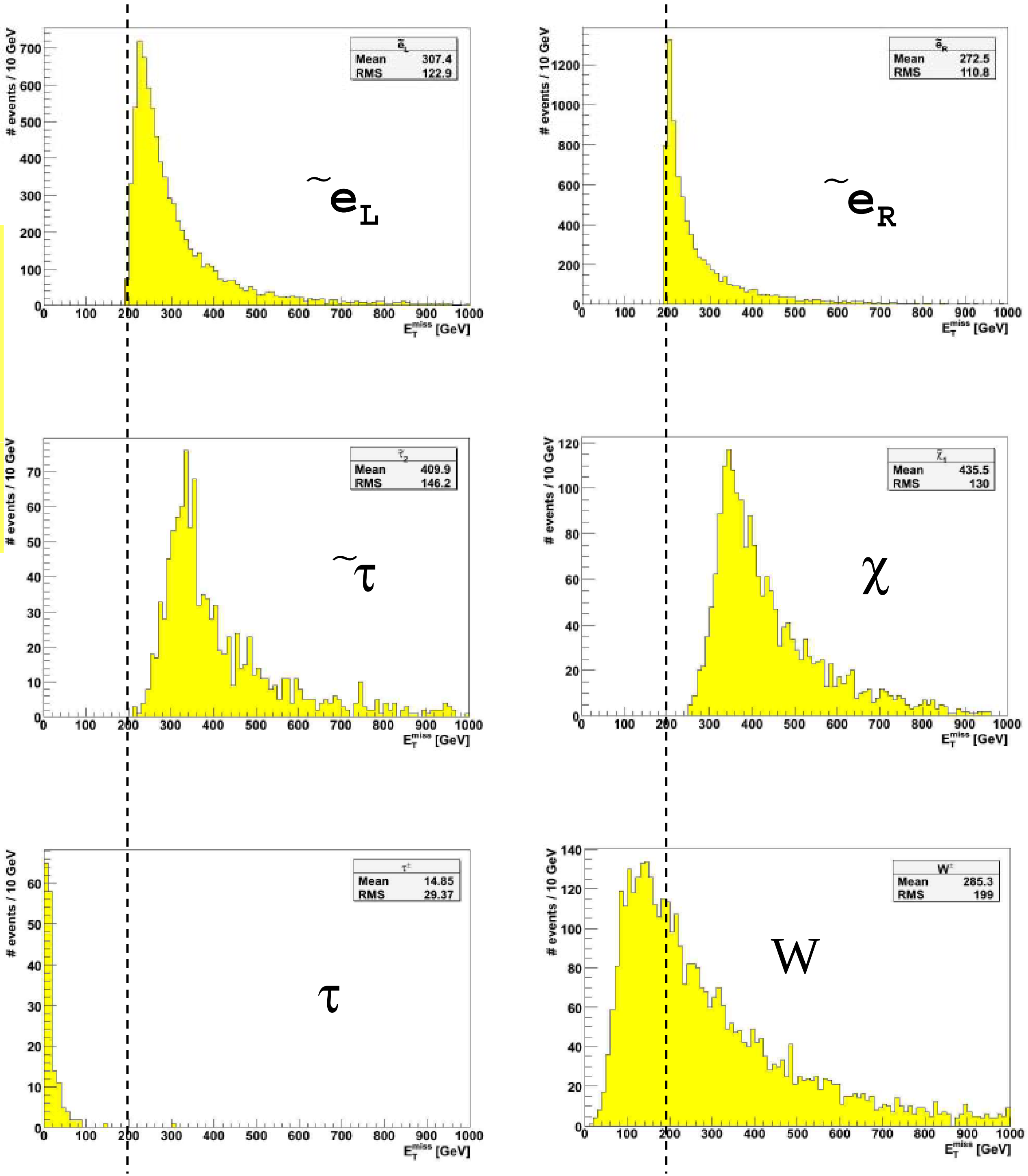
• (To increase statistics: Consider inclusion of tau-jets in analysis)

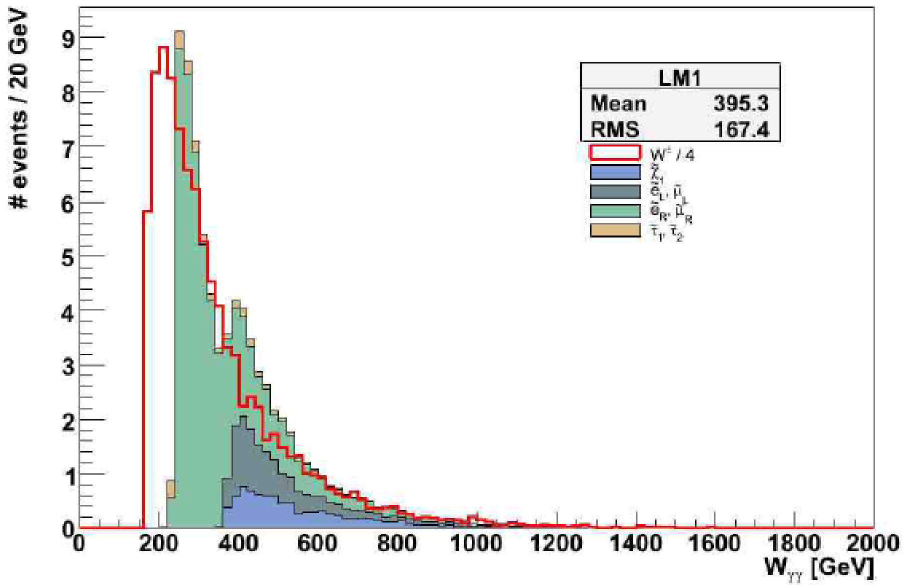
• In SUSY case much more missing energy due to LSPs → first, missing E_T can be tried…

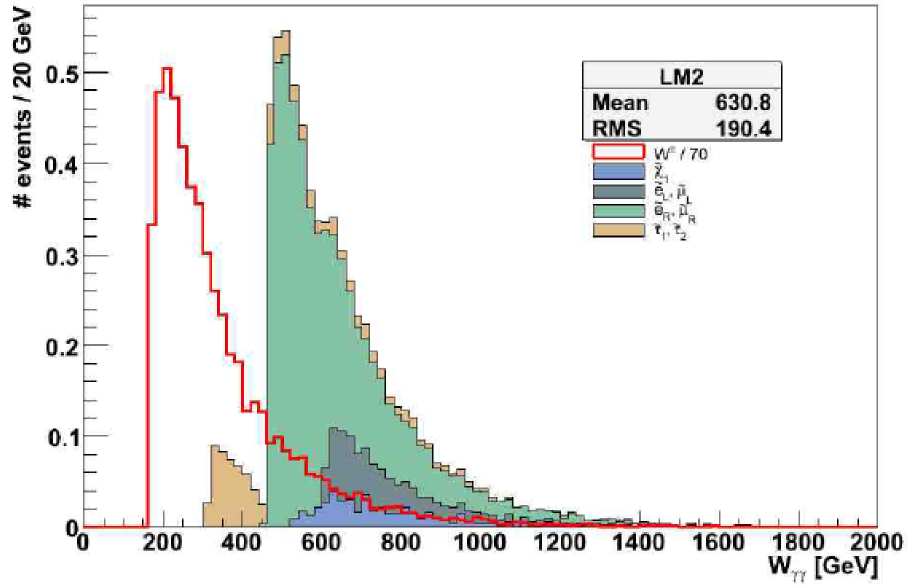
• Finally, assuming installed VFDs, event kinematics can be fully reconstructed by measuring forward protons (~75% acceptance possible); however, thanks to significant cross-sections interesting measurements should be possible already at low luminosity using central detectors <u>only</u>…

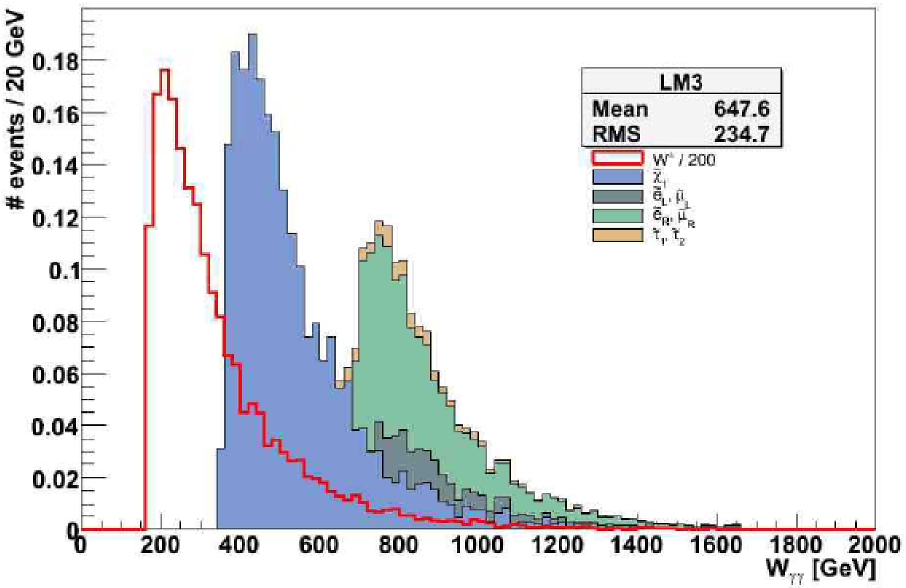
LM1 point: WW suppression by factor ~2 using missing E_T; two-photon $\tau^+\tau^-$ pairs excluded

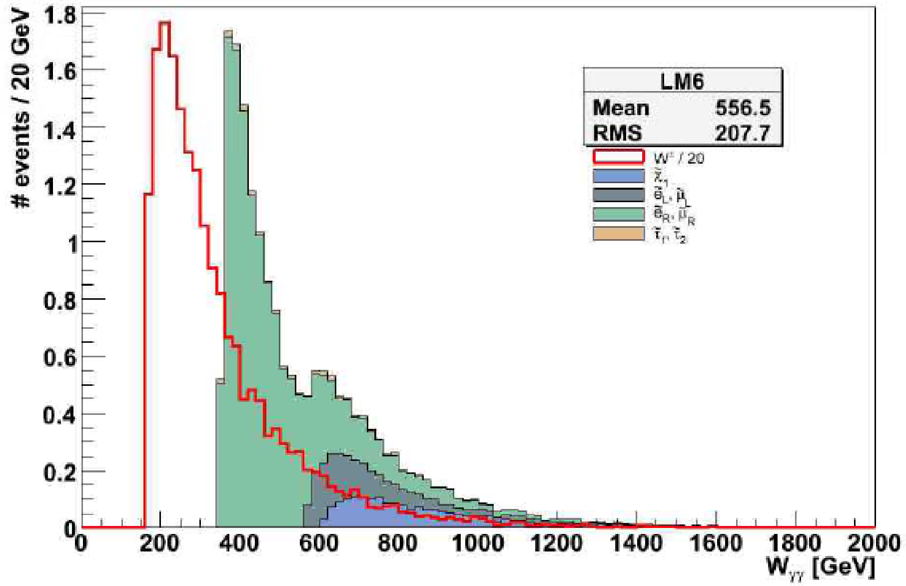
Could be further tightened using reconstructed $W_{\gamma\gamma}$ …




LM1
Mean 395.3
RMS 167.4
W± / 4
events / 20 GeV
W_γγ [GeV]


LM2
Mean 630.8
RMS 190.4
W± / 70
events / 20 GeV
W_γγ [GeV]


LM3
Mean 647.6
RMS 234.7
W± / 200
events / 20 GeV
W_γγ [GeV]


LM6
Mean 556.5
RMS 207.7
W± / 20
events / 20 GeV
W_γγ [GeV]

Preliminary observations

Exclusive two-photon production of SUSY pairs is sizeable at LHC for sparticle masses below ~200 GeV

• Large signal acceptance and low irreducible WW background

• Very forward proton detectors crucial for exclusive event selection at high luminosity (triple coincidence condition)/ background control and suppression/data interpretation

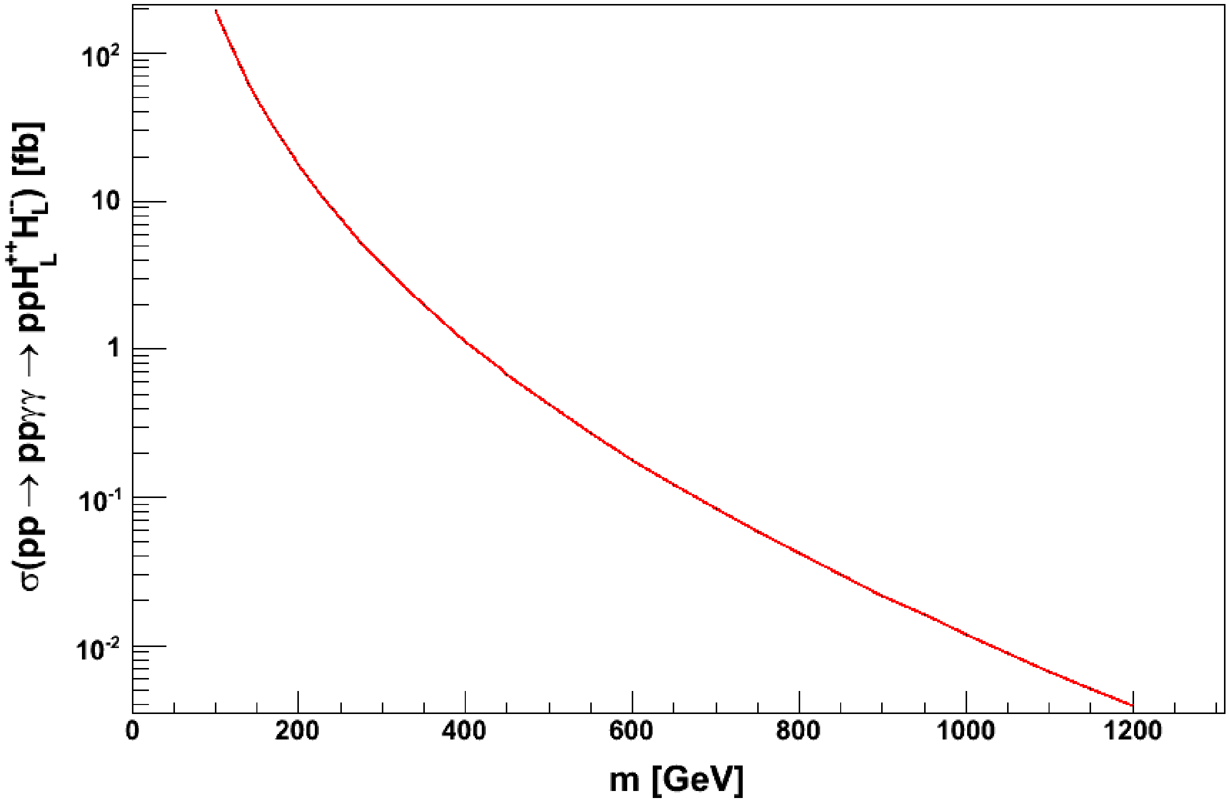
• This is a very interesting, novel laboratory for searches for any new phenomena in high-energy $\gamma\gamma$ collisions…

As for example, due to recently proposed sweet-spot SUSY, with light (~116 GeV) long-lived staus…

Or, due to multi-charged particles production…

Doubly charged Higgs bosons

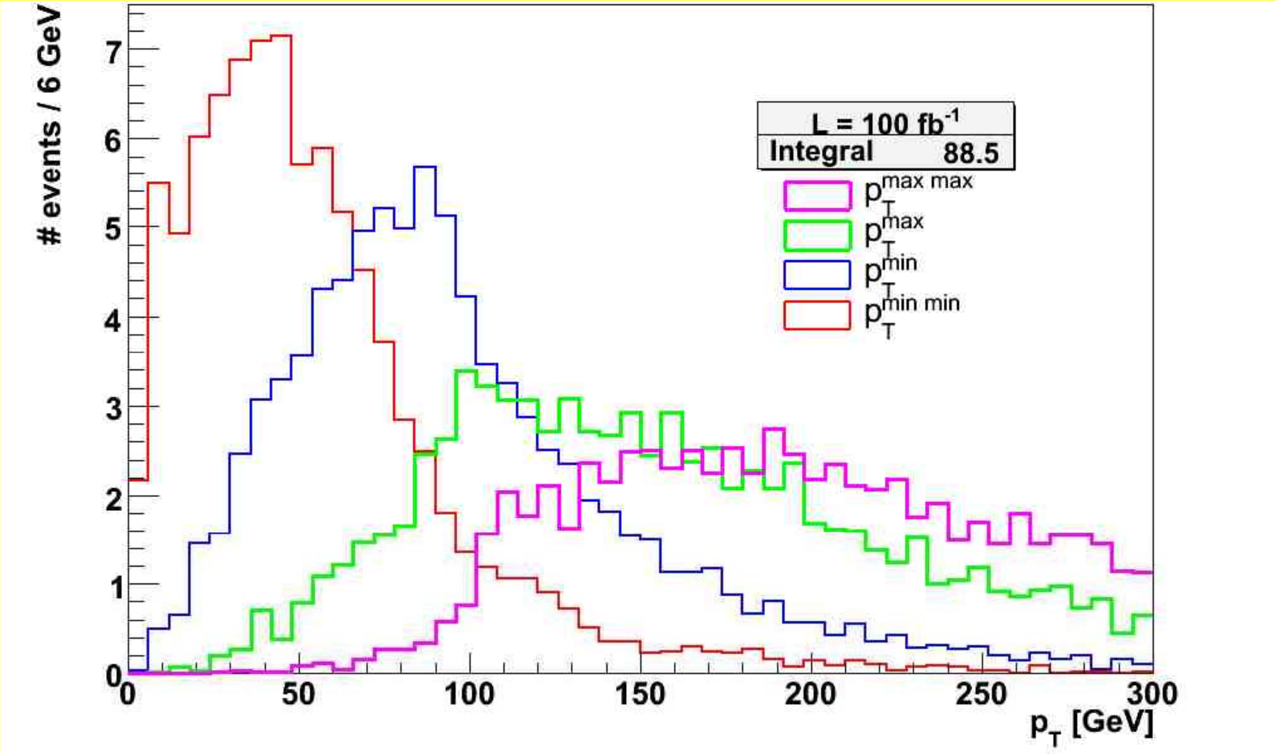
L-R symmetric model implemented in CalcHep for $\gamma\gamma$ event generation, then passed to Pythia for $H^{++/--}$ decays (tau decays suppressed)



Signal amplified by factor 16, with unique signature…

Doubly charged Higgs bosons, cont'd

Example: 200 GeV Higgs case – use 4 lepton 'golden' events:
$e^+e^+\mu^-\mu^-$ **or** $e^-e^-\mu^+\mu^+$ with acceptance cuts,
$p_T > 3$ GeV, $|\eta| < 2.5$:



Note: 'Irreducible' background $\gamma\gamma \to \tau^+\tau^+\tau^-\tau^- \to e^+e^+\mu^-\mu^-$ or $e^-e^-\mu^+\mu^+$ negligible!

Summary/Outlook

• High-energy (at electroweak scale and beyond) photon-photon interactions have significant cross-sections at the LHC!

• Tagging high energy photon (and diffractive) interactions at LHC, and at high luminosity, can be done by supplementing central detectors with very forward proton detectors.

• Using double tagging, two-photon exclusive production, for example di-leptons (+ missing E_T) can be studied at nominal LHC luminosity.

• This offers novel, exciting and complementary SUSY/BSM seraches

• Note: Triggering (at Level 1) of photon interaction is almost 'given', since both ATLAS and CMS are designed to trigger well on high p_T leptons!

We cannot miss it!

Tagging two-photon interactions in HI collisions

Effective luminosity of $\gamma\gamma$ collisions is high, especially for *ArAr* case at LHC (comparable to *pp*), and two-photon production is enhanced ($\sim Z^4$), due to coherence, with respect to pomeron-pomeron case

$\Rightarrow$ LHC optics in Heavy Ion mode similar to the *pp* one, hence assume same tagging range $0.1>x>0.01$

This has two consequences:

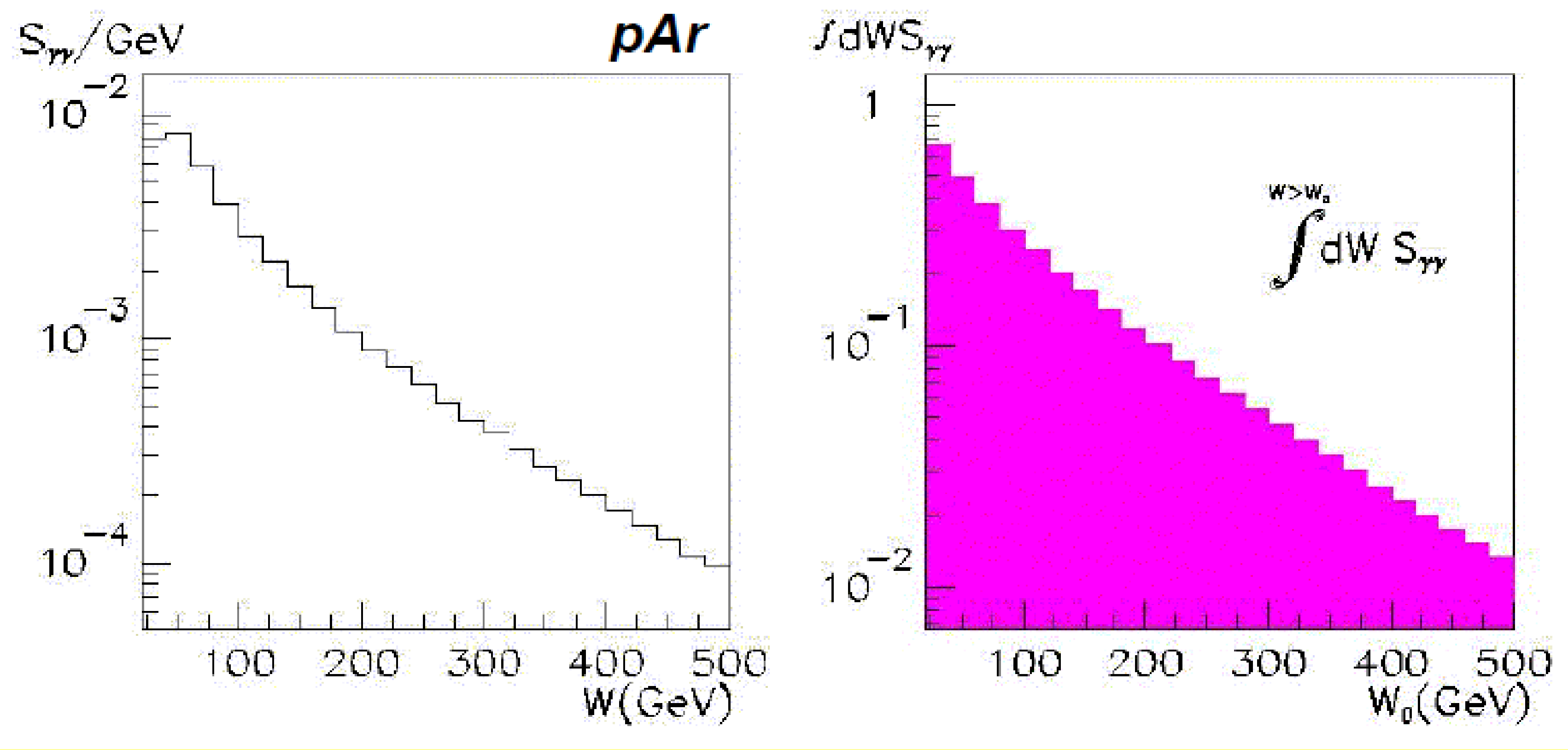
- Tagged W values are very large and corresponding luminosity is small (coherence loss), e.g. for 140 TeV beams W range is approximately 4-25 (0.5-25) TeV for double (single) tagging

- Intrinsic HI beam divergence results in large p_T smearing, much bigger than typical values for two-photon events

FP420 **will allow for tagging also forward light ions as *Ar* or *Ca***
-> place to make medium-energy $\gamma\gamma$, and diffractive physics!

Tagging $\gamma\gamma$ interactions in HI collisions II

More exciting is possibility of measuring very forward protons in *pA* collisions - in such a case full signature of $\gamma\gamma$ events is recovered (for single tags)

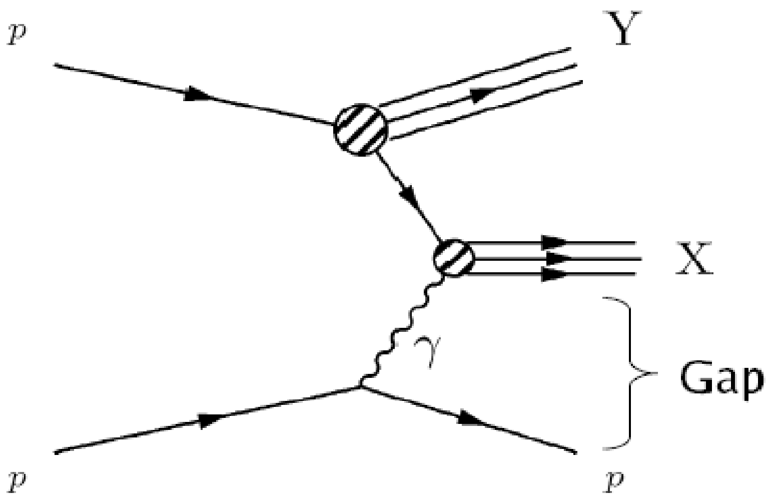


At W = 100 GeV $S_{\gamma\gamma}$ is almost 100 bigger than for *pp* case, i.e. one needs ‘only’ 300 pb^{-1} *pAr* sample to achieve similar $\gamma\gamma$ statistics

LHC : a new HERA collider !

Photoproduction is traditionally studied at e-p colliders

pp (γq/g → XY) p



- γp events can also be tagged at the LHC

  ➡ e.g. Using Large Rapidity Gaps (LRG)

- Higher luminosity than $\gamma\gamma$ events

- Probe electroweak sector up to/beyond 2 TeV !

Using EPA

$$\sigma_{pp} = \int \sigma_{\gamma q/g}(\hat{W}_{\gamma q/g}) f_{\gamma}(x_1) f_{q/g}(x_2, Q^2) dx_1 dx_2$$

where $\hat{W}^2_{\gamma q/g} = 4 E_p x_1 x_2$

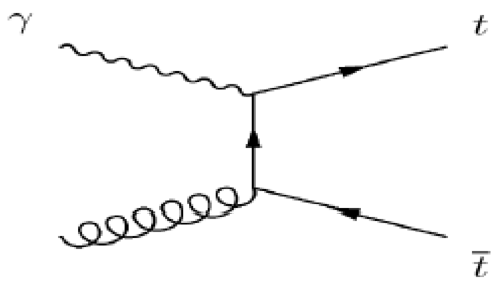
BUT pp events are more dangerous backgrounds than in $\gamma\gamma$ interactions!

γp cross sections

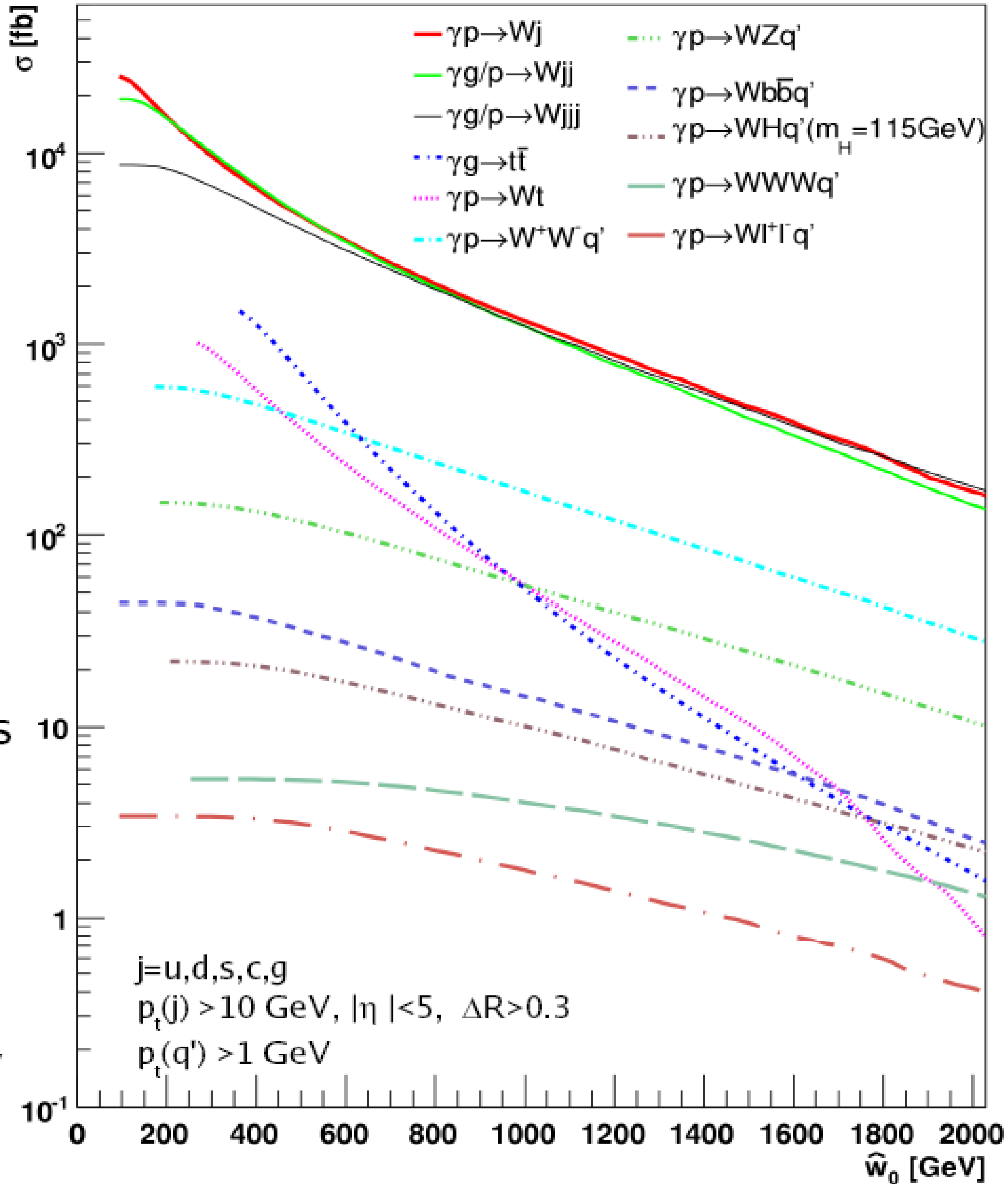
Obtained using MadGraph/MadEvent

- Large variety of processes
- Significant cross sections up to 2 TeV

  e.g.



1.5 pb



- Alternative way to pp interactions to study

  1. Higgs search
  2. Top physics (e.g. $|V_{tb}|$)
  3. New phenomena up to 2 TeV

- Very good S/B expected

Both 220 and 420 m detectors are essential for tagging photon interactions (both photon-photon and photon-proton) at the LHC:

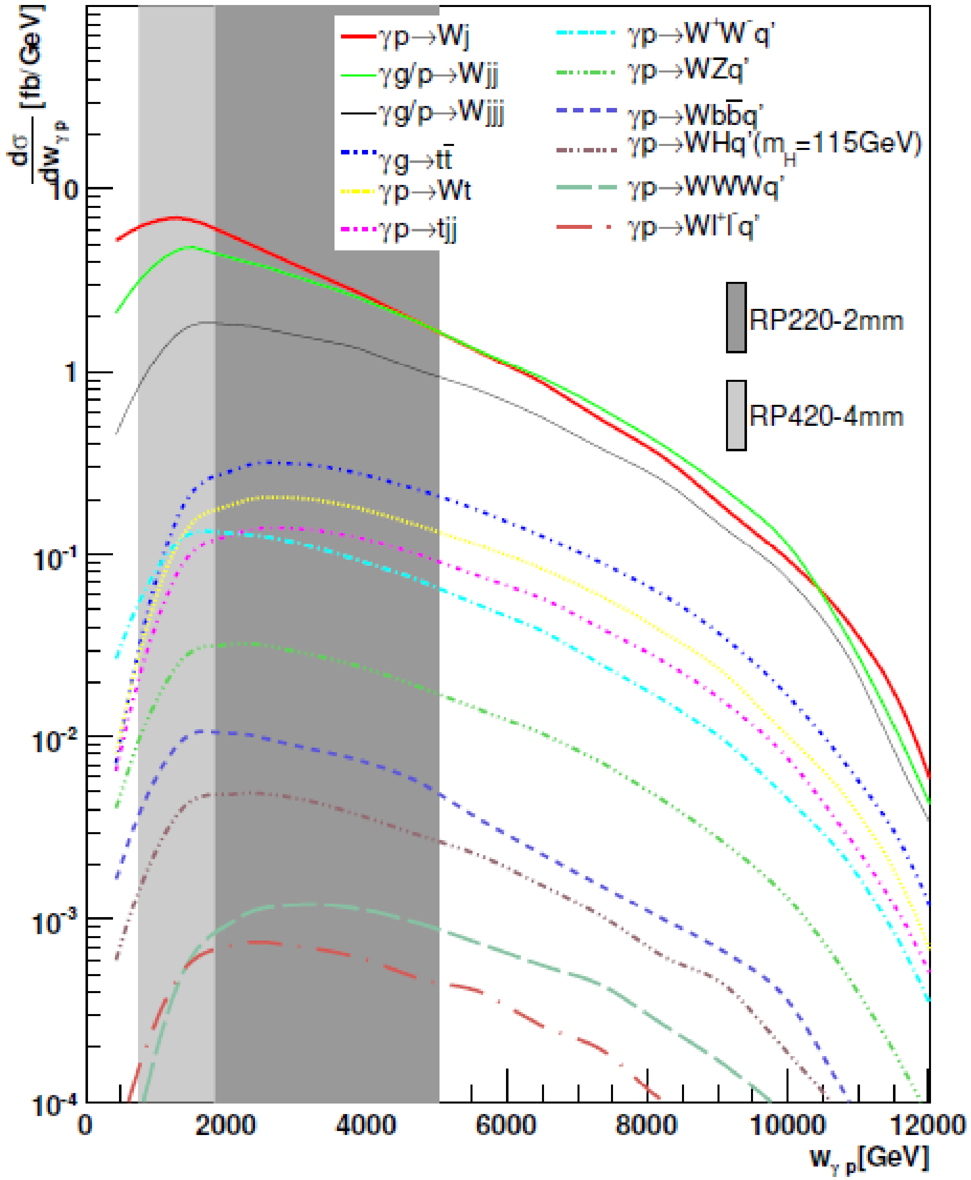
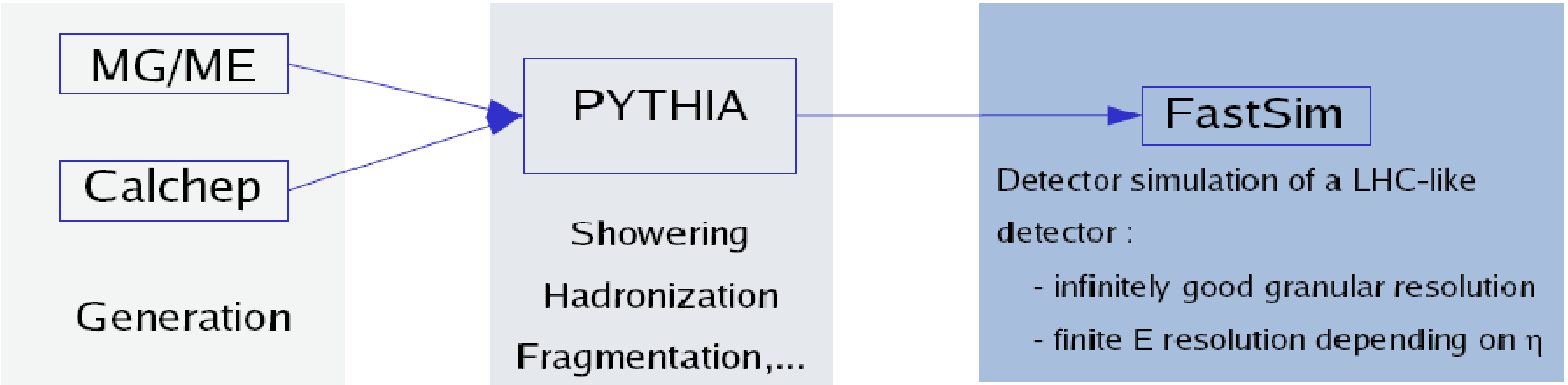


Fig. 6. pp differential cross-sections for $pp(\gamma q/g \to N)pX$ processes as a function of the cms energy in photon-proton collisions, $W_{\gamma p}$. The acceptance of roman pots (220m at 2mm from the beam axis and 420m at 4 mm from the beam axis) is also sketched.

Simulation procedure

Jets in the final state require careful simulation of acceptance cuts!

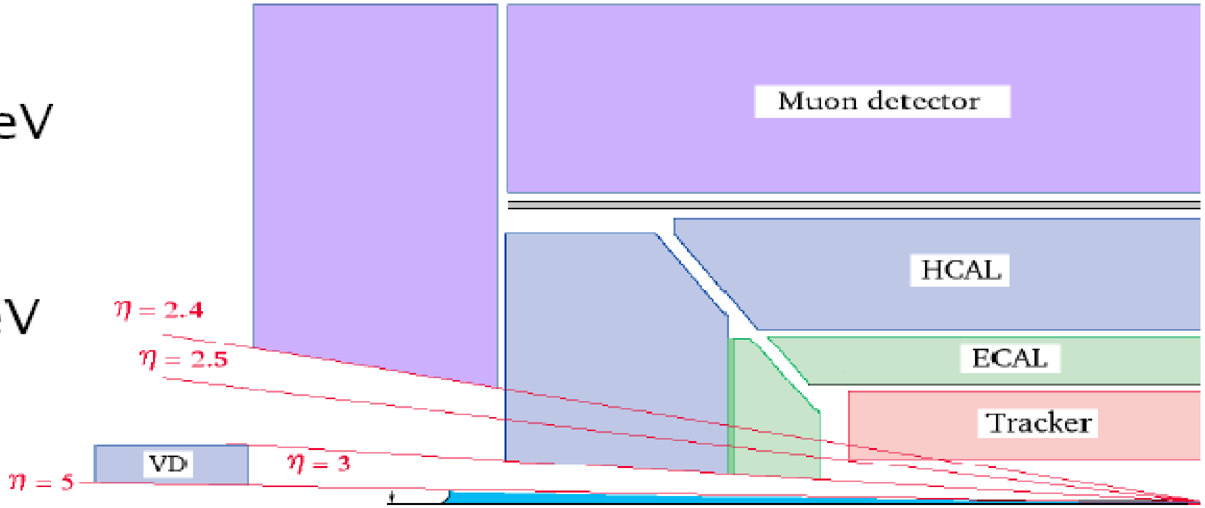


Objects reconstruction

Leptons : $|\eta| < 2.5$, $p_T > 10$ GeV

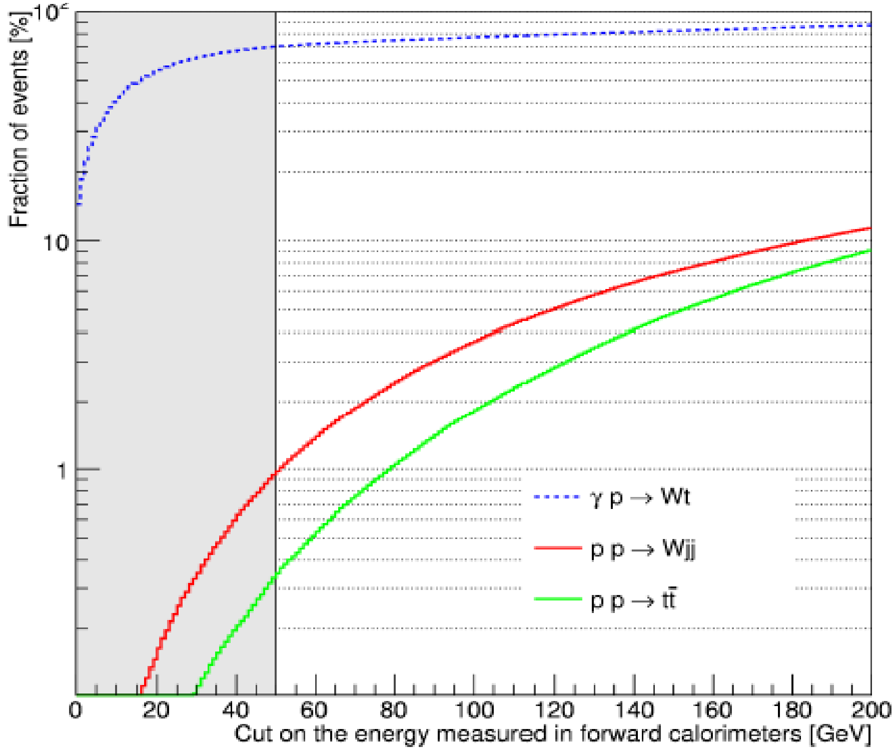
Jets : reconstructed in a cone
$R = 0.7$ for $|\eta| < 3$, $p_T > 20$ GeV
b-tagging : for $|\eta| < 2.5$

- tagging efficiency : 40%,
- mistagging of 1% for j=u,d,s,g
- mistagging of 10% for j=c.



Observability of photo-induced processes is determined using acceptance cuts with these thresholds

Detection and tagging



Very low luminosity phase ($<10^{33}$ cm^{-2} s^{-1})

- Small event pile-up

➡ Large rapidity gap (LRG) signature can be used

- For example, forward energy flows (into $3<|\eta|<5$) in one of the two hemispheres less than 50 GeV

Advantage : independent on very forward detectors features (Roman Pots)

Drawback : - low integrated luminosity expected

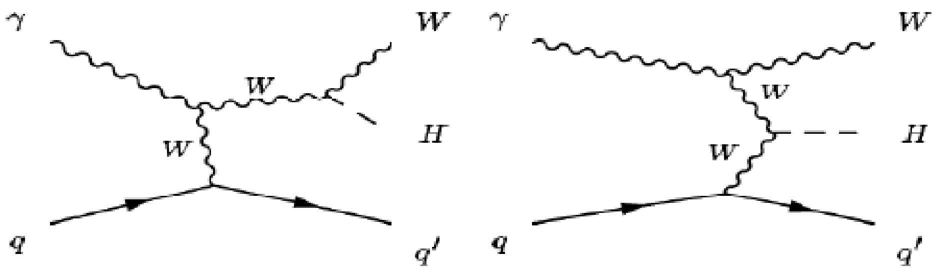
- kinematics is less constrain

- Expected integrated luminosity of 1 fb^{-1}

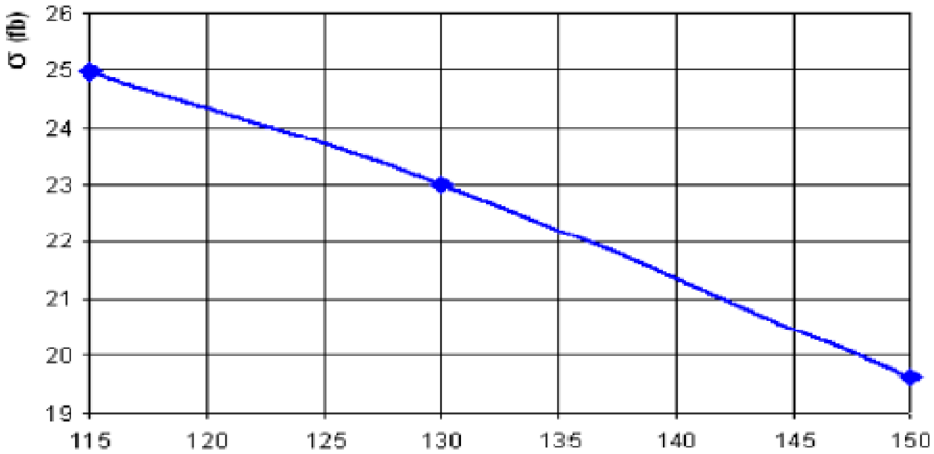
Low luminosity phase (~ 10^{33} cm^{-2} s^{-1})

- Use of very forward detector is mandatory !
- Exclusivity cuts can be applied (e.g. vetoing soft tracks from event vertex)
- Expected integrated luminosity of 10-30 fb^{-1}

Associated WH production



Obtained using MadGraph/MadEvent



- Associated production of WH has significant cross section at LHC !
- tt less overwhelming than in pp case!

Five topologies where studied

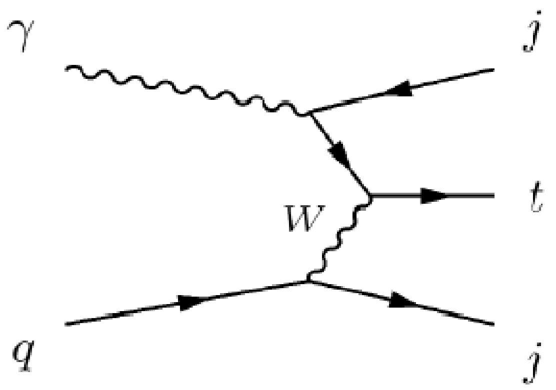
- WH → lνbb, l=e,μ,τ,
- WH → $W\tau^+\tau^-$ → jjl^+l^-, l=e,μ,
- WH → $W\tau^+\tau^-$ → $jjl^+\tau_h$, l=e,μ,
- WH → WW^+W^- → lll, l=e,μ,τ,
- WH → WW^+W^- → $jjl^\pm l^\pm$, l=e,μ,τ.

	M_H=115 GeV			M_H=170 GeV	
Topology	lνbb	jjl^+l^-	$jjl^+\tau_h$	lll	$jjl^\pm l^\pm$
σ WHq' [fb]	5.42	0.14	0.52	0.55	1.17
σ_{acc}	0.11	0.01	0.04	0.07	0.23
Irreducible backgrounds (tt, Wt, Wzq', WWW, Wllq' Wbbq')					
σ_{acc} bkg	3.21	28.6	8.26	1.44	0.30

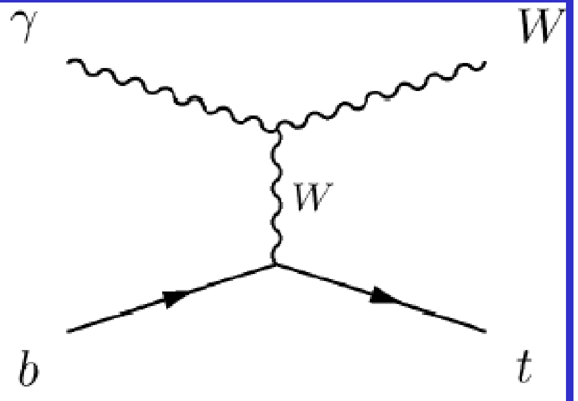
Results after application of acceptance cuts

- Very small statistics ➡ not a discovery channel
- Interesting sensitivity for 2 topologies : lνbb and $jjl^\pm l^\pm$
- For analysis, more specified cuts can be applied.

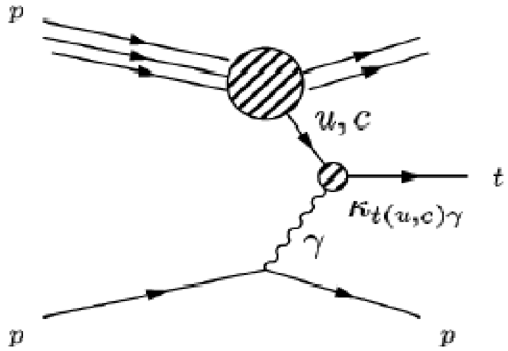
The LHC is a Top factory!



t-channel



Wt-channel



Anomalous top

pp vs γp cross sections

	pp	γp
Wt-channel	~ 60 pb	~ 1pb
t-channel	~ 245 pb	~ 6.2 fb
Wjjj	~ 35 nb	8.7 pb
tt	~ 720 pb	1.5 pb

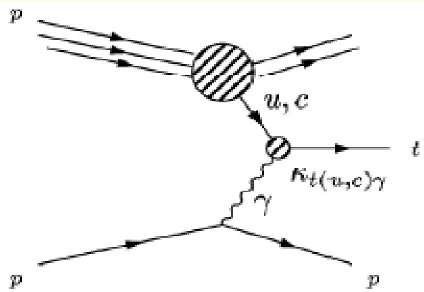
Physics highlights

- Wt and t-channel related to V_{tb}
- Sensitivity to new physics : FCNC
- Possibility to study top properties (mass, charge,...)

- Wt-channel : more favorable background condition than pp case $\frac{\sigma_{Wt}}{\sigma_{tt}} \simeq 0.7$
- What kind of uncertainty is reachable on $|V_{tb}|$?

Anomalous top production

J. de Favereau

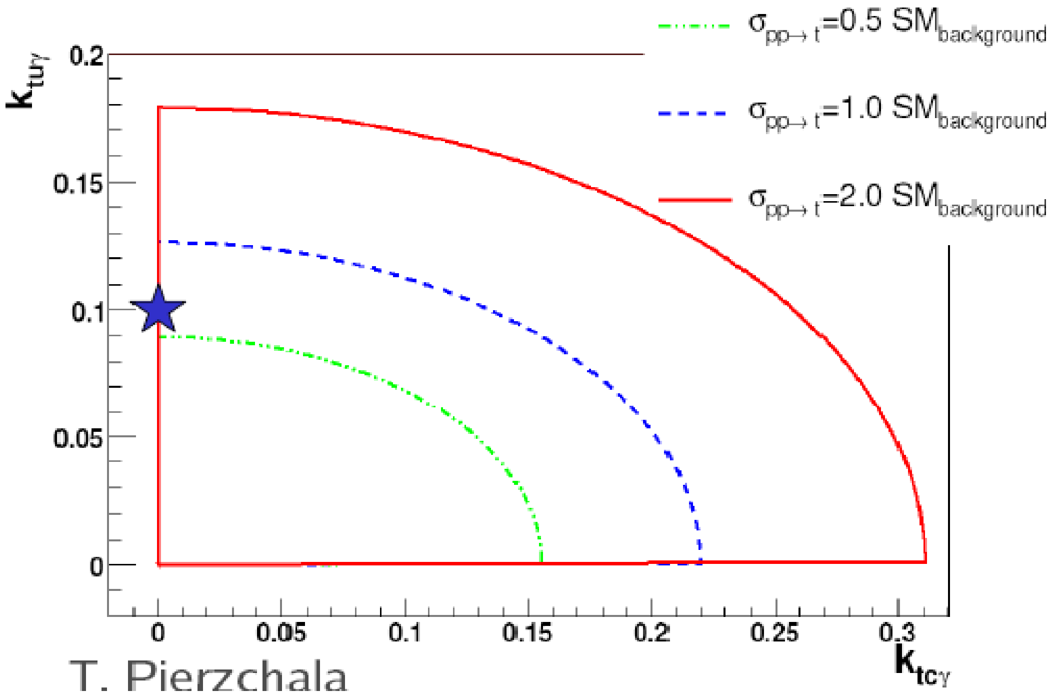


Effective Lagrangian for anomalous coupling :

$$L = ie_t t \frac{-\sigma_{\mu\nu} q^\nu}{\Lambda} k_{tu\gamma} u A^\mu + ie_t t \frac{-\sigma_{\mu\nu} q^\nu}{\Lambda} k_{tc\gamma} c A^\mu + h.c.$$

- Current limit obtained by Zeus : $k_{tu\gamma} \approx 0.18$
- At HERA only u-quark relevant, at LHC also c-quark contribute

$$\sigma_{pp \to t} = \alpha_u k^2_{tu\gamma} + \alpha_c k^2_{tc\gamma}$$



T. Pierzchala

Results after acceptance cuts
($k_{tu\gamma}$ = 0.1, $k_{tc\gamma}$ = 0)

Topology	IE^T_{mis} b
σ t [fb]	3680
σ_{acc}	123.8
Irreducible backgrounds (Wj, Wc)	
σ_{acc} bkg	198.1

Limit on $k_{tu\gamma}$ could be significantly improved even at very low luminosity !

Survival probability/rescattering

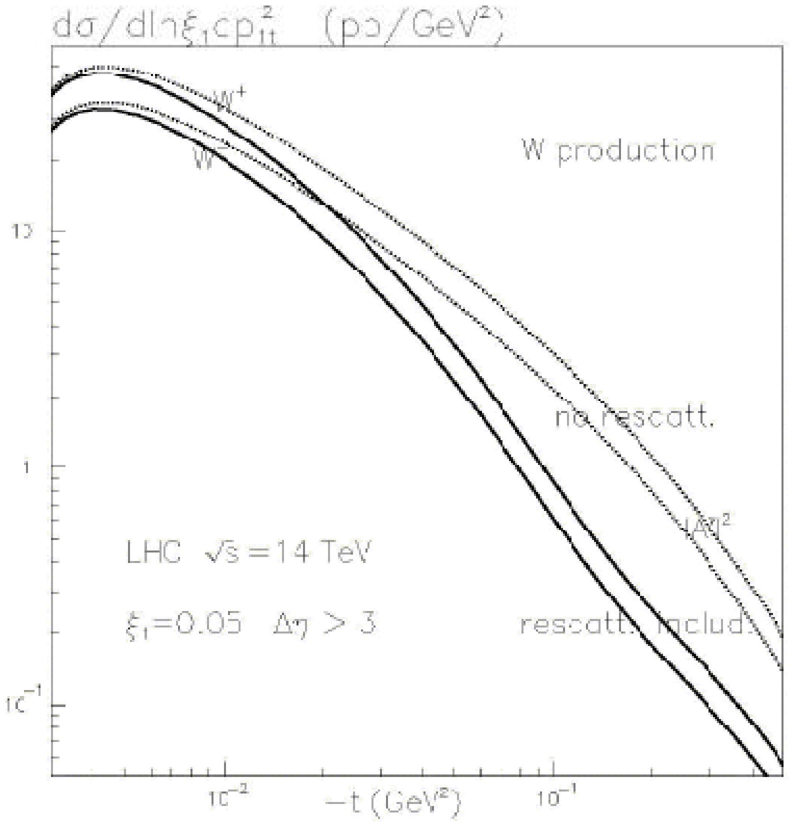


Fig. 9. The differential cross section for $pp \to p + W^{\pm} + X$ at the LHC. The dotted and continuous curves correspond, respectively, to the predictions without and with the rescattering effects of Figs. 8b,c. In each case W^+ production corresponds to the upper one of the pair of curves. The rapidity gap between the quark recoil jet and the W boson is taken to satisfy $\Delta\eta > 3$

V. Khoze et al. EPJC (2002)

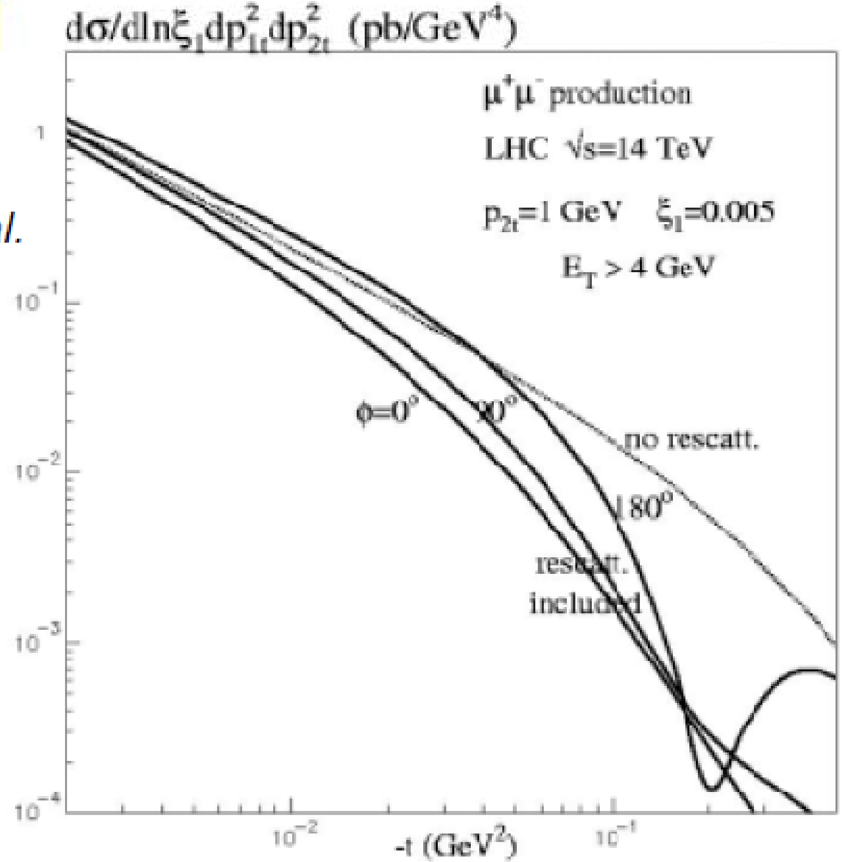


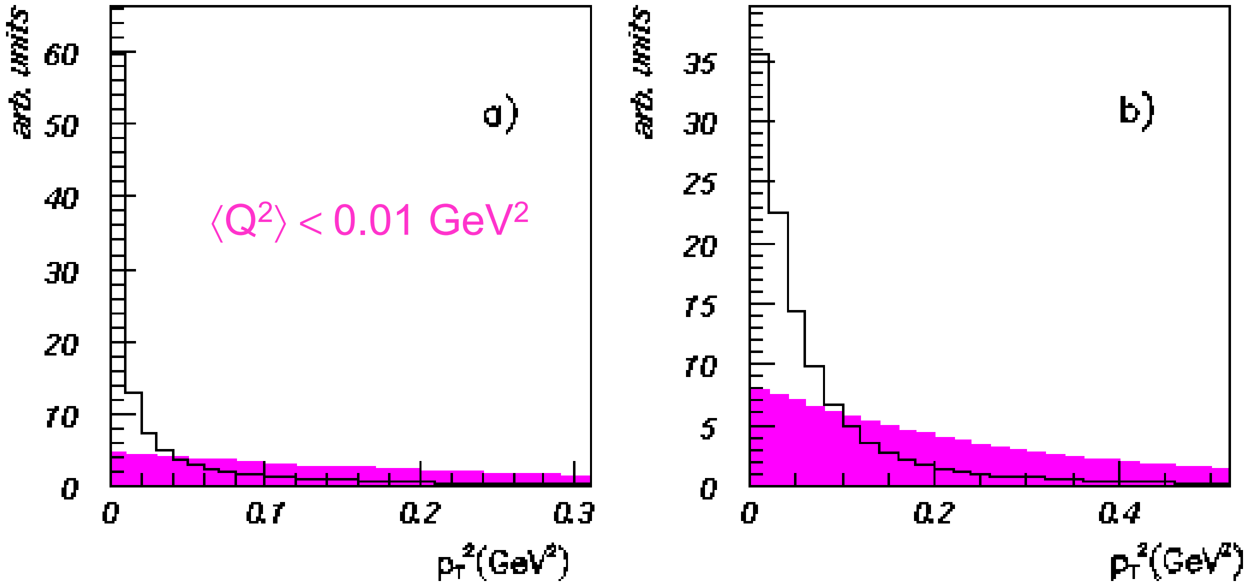
Fig. 10. The cross section for $pp \to p + (\mu^+\mu^-) + p$ at the LHC energy, with (continuous curves) and without (dotted curve) rescattering effects included. The rescattering effects are shown for three values of the azimuthal angle ϕ between the transverse momenta, $\vec{p}_{1t}$ and $\vec{p}_{2t}$, of the outgoing protons

Use photoproduction to scan/verify rescattering models ($p_T^2 \sim Q^2 \sim -t$ controls impact parameter involved): proton detection essential!

Problem: <u>Same</u> signature (one or two very forward protons) has also *central diffraction* (i.e. *pomeron-pomeron* scattering) in strong interactions

Both processes weakly interfere, and transverse momentum of the scattered protons are in average much softer in two-photon case

a) `true' distributions; b) distributions smeared due to beam intrinsic p_T; all plots normalized for $p_T^2 < 2\ GeV^2$



p_T gives powerful separation handle provided that size of $\gamma\gamma$ and pomeron-pomeron cross-sections are not too different

Assuming ultimate p_T resolution ≈ 100 MeV; i.e. neglecting detector effects

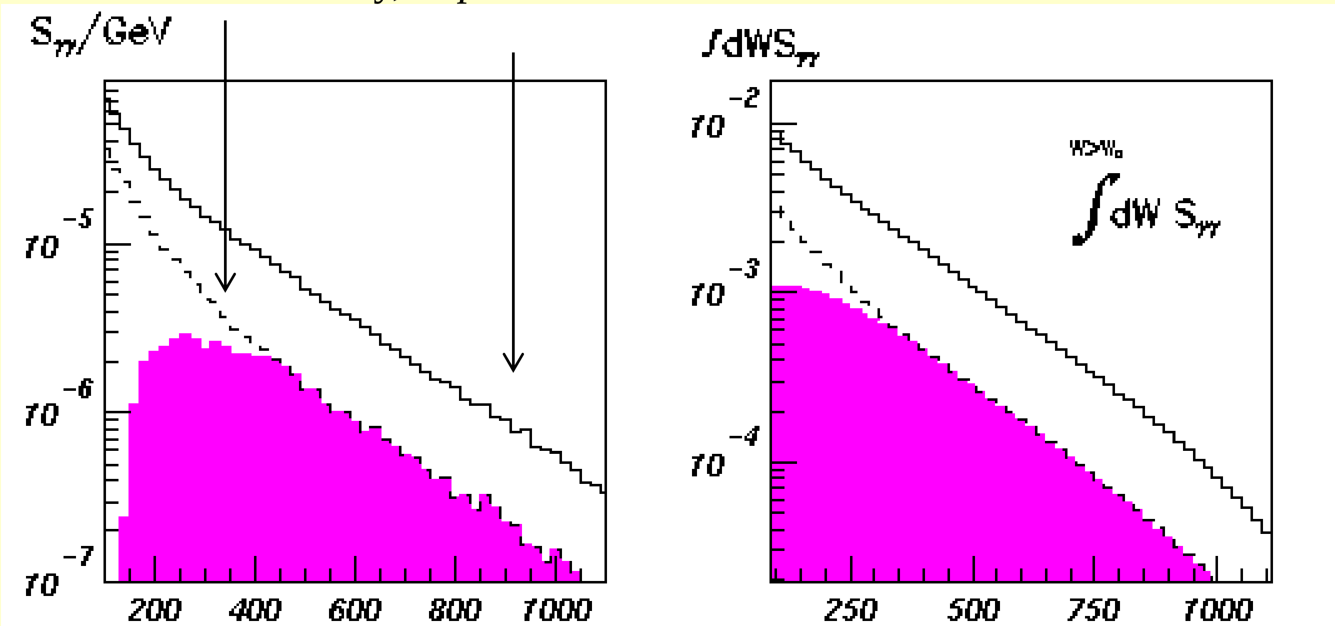
Tagging two-photon events

Assume detector stations at ~220 m where approximately $x > 0.01$ range accessible

Note: If only one forward *p* detected – single tag, but then non-elastic, *p* dissociative photon emission is possible

Assume $0.1>x>0.01$, and $Q^2<2$ GeV^2 and for dissociative mass $M_N < 20$ GeV

Single tags:
elastic only, or *p-diss.* incl.



Color: double-tags, hence *elastic* scattering only