# High energy photon interactions @ LHC

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- LHC as a high energy γγ and γp collider
- Tagging photoproduction at LHC
- Benchmark processes in γγ and γp
- Summary/Outlook

On behalf of the
**Louvain Photon Group**
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# LHC as a High Energy $\gamma\gamma$ Collider

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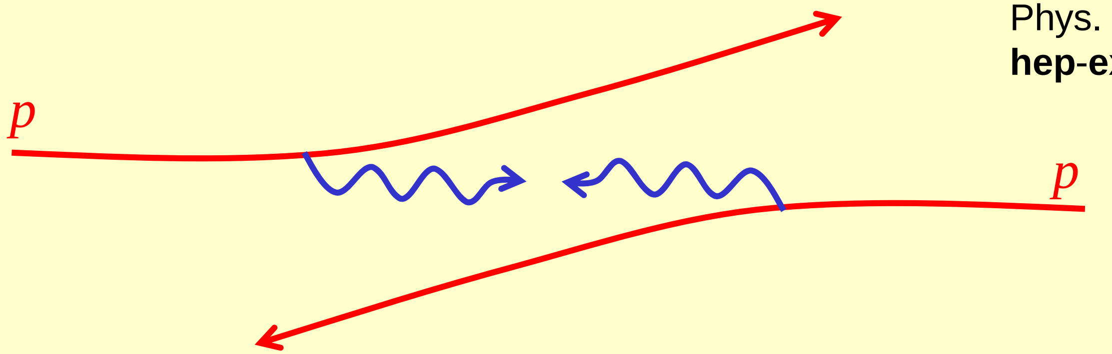
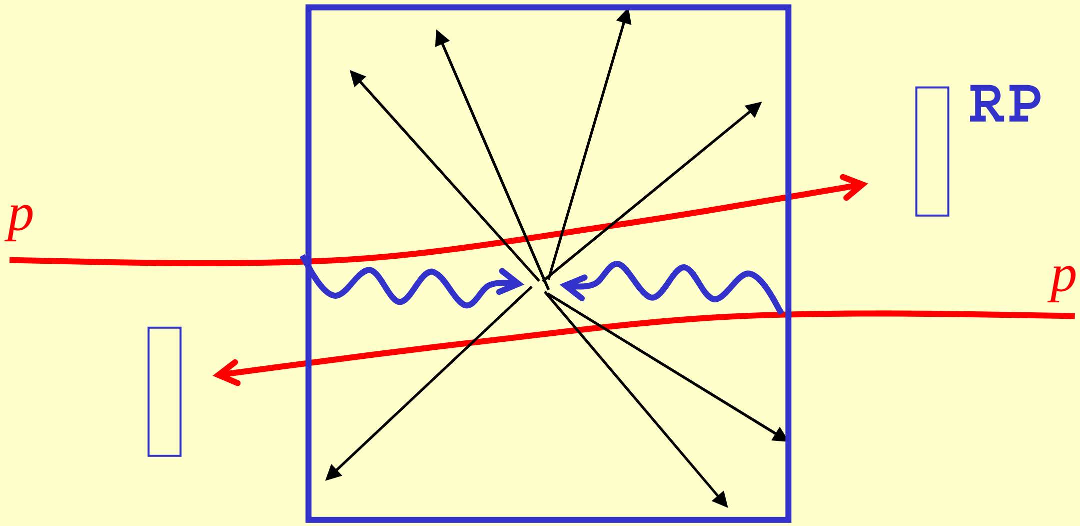


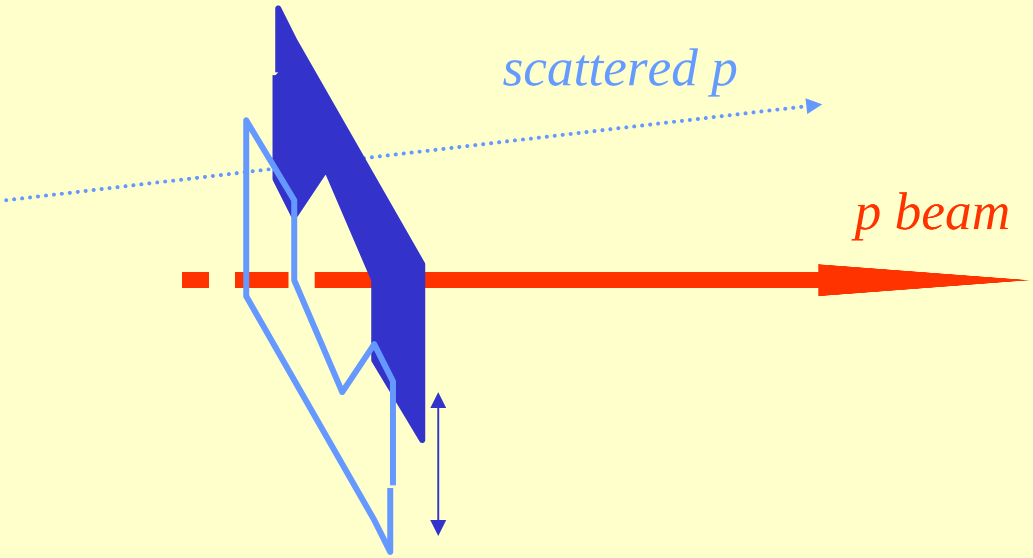

**<u>Highlights</u>:**
- **$\gamma\gamma$ CM energy *W* up to/beyond 1 TeV (and under control)**
- **Large photon flux *F* therefore significant $\gamma\gamma$ luminosity**
- **Complementary (and clean) physics to** *pp* **interactions, eg studies of** *exclusive* **production of heavy particles might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

<u>DISCLAIMER</u>:
This is <u>NOT</u> meant for studying all photon interactions at the LHC but those for which the QCD background is strongly suppressed, as for example in the exclusive production of leptons or gauge bosons.

# How measure these events?

Measure $(\gamma\gamma \rightarrow)$ $X$ in the **CMS or ATLAS** detector <u>and</u> the scattered protons using **very forward** detectors..




..i.e. 'Roman pot' detectors put as far (> 100 m) from the IP and as close to the beam (≥2 mm) as possible

# Kinematics/γγ Luminosity

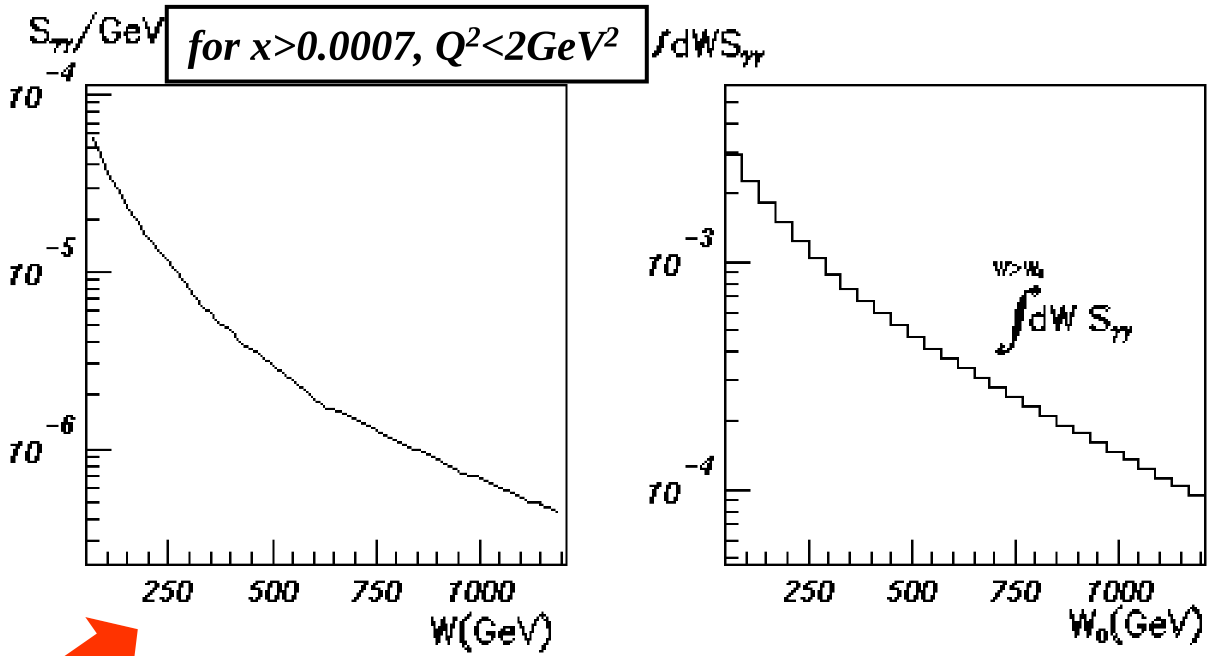
*Virtuality* $Q^2$ of colliding photons vary between kinematical minimum = $M_p^2 x^2/(1-x)$ where $x$ is fraction of proton momentum carried by a photon, and $Q^2_{max} \sim 1/\text{proton radius}^2$

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

Photon flux $\propto 1/Q^2$

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

protons scattered at \`zero-degree' angle




Use EPA à la *Budnev et al.**

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

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

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

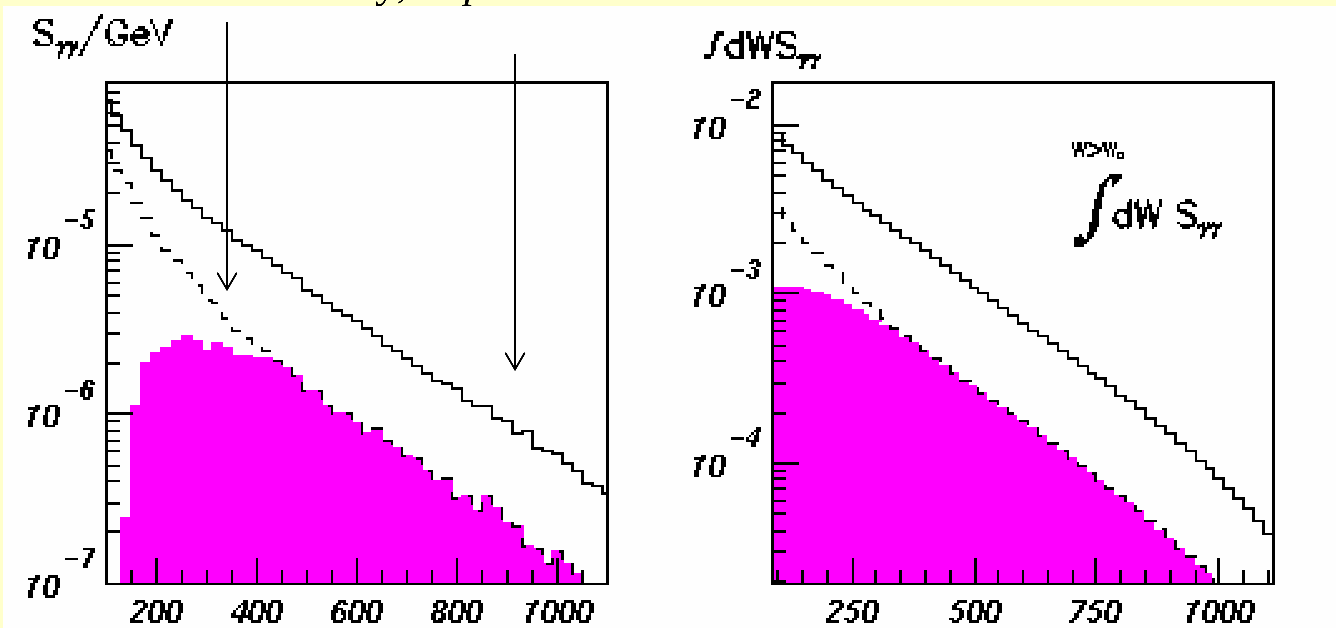
# Tagging two-photon events

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.

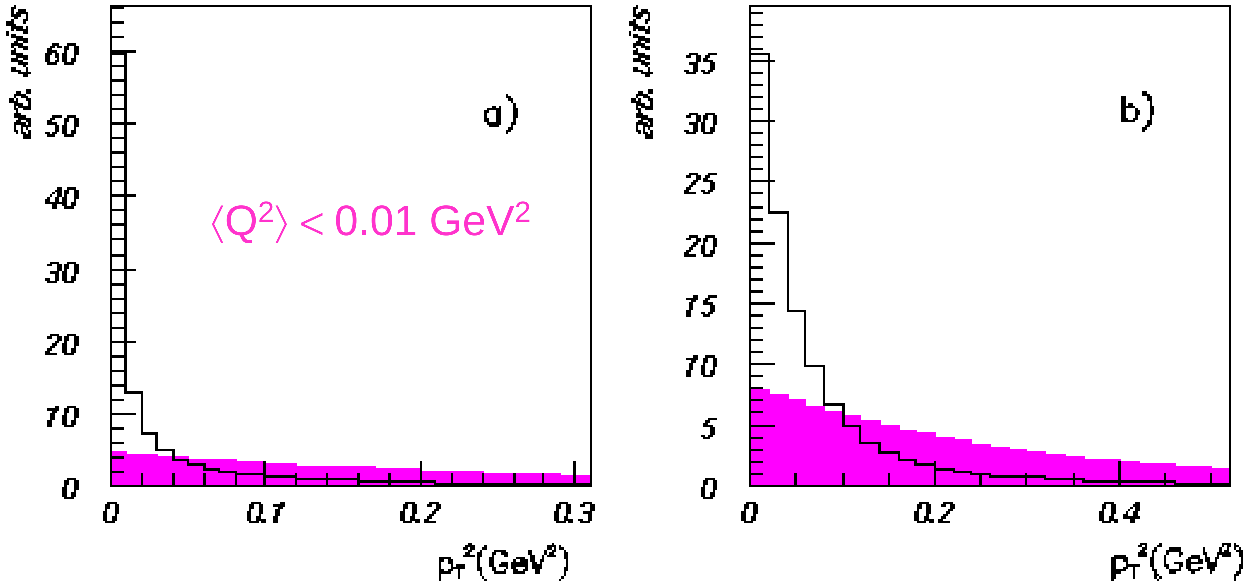



Color: double-tags, hence *elastic* scattering only

**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 $p_T^2 < 2\ GeV^2$

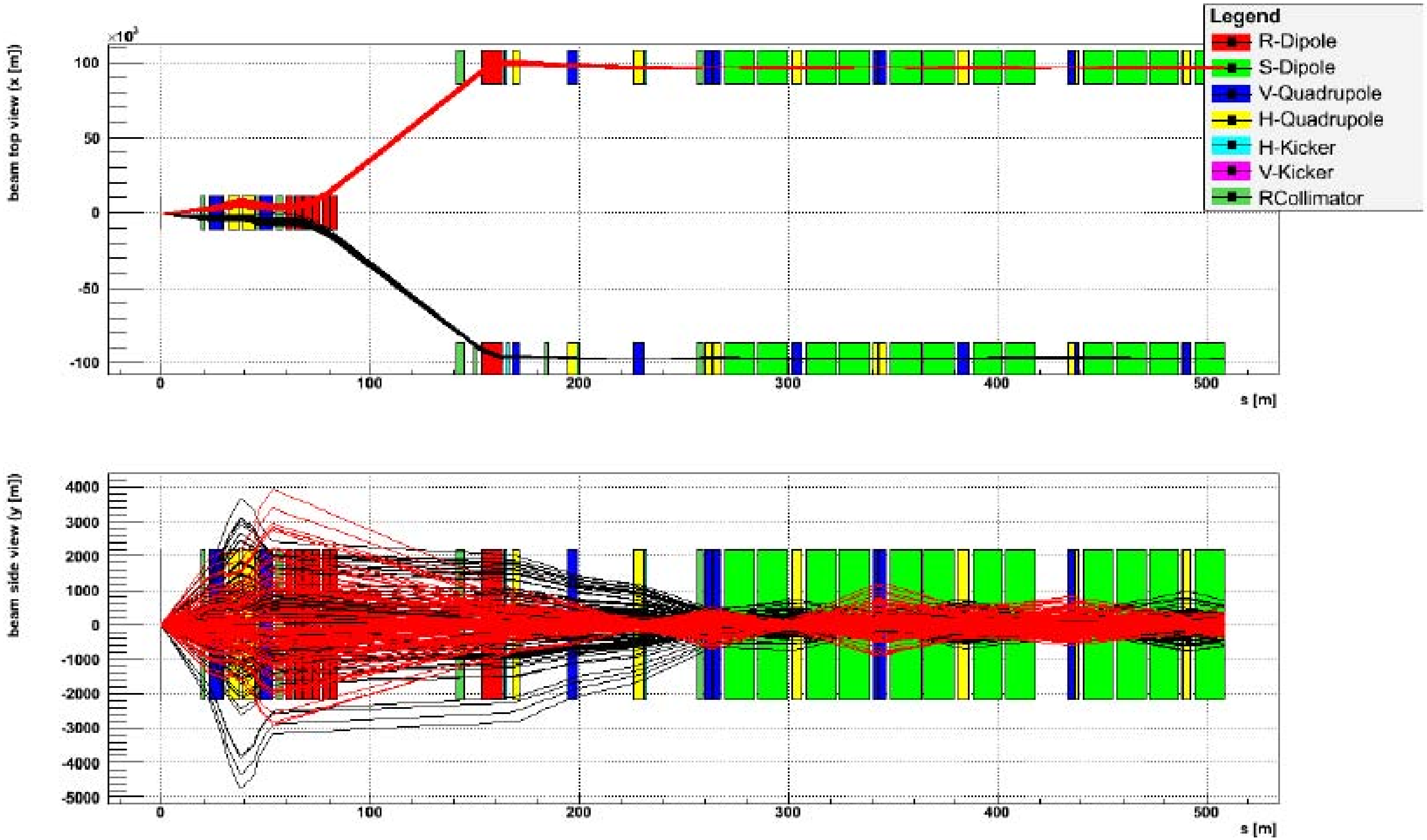



$p_T$ gives powerful separation handle provided that size of $\gamma\gamma$ and pomeron-pomeron cross-sections are not too different

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

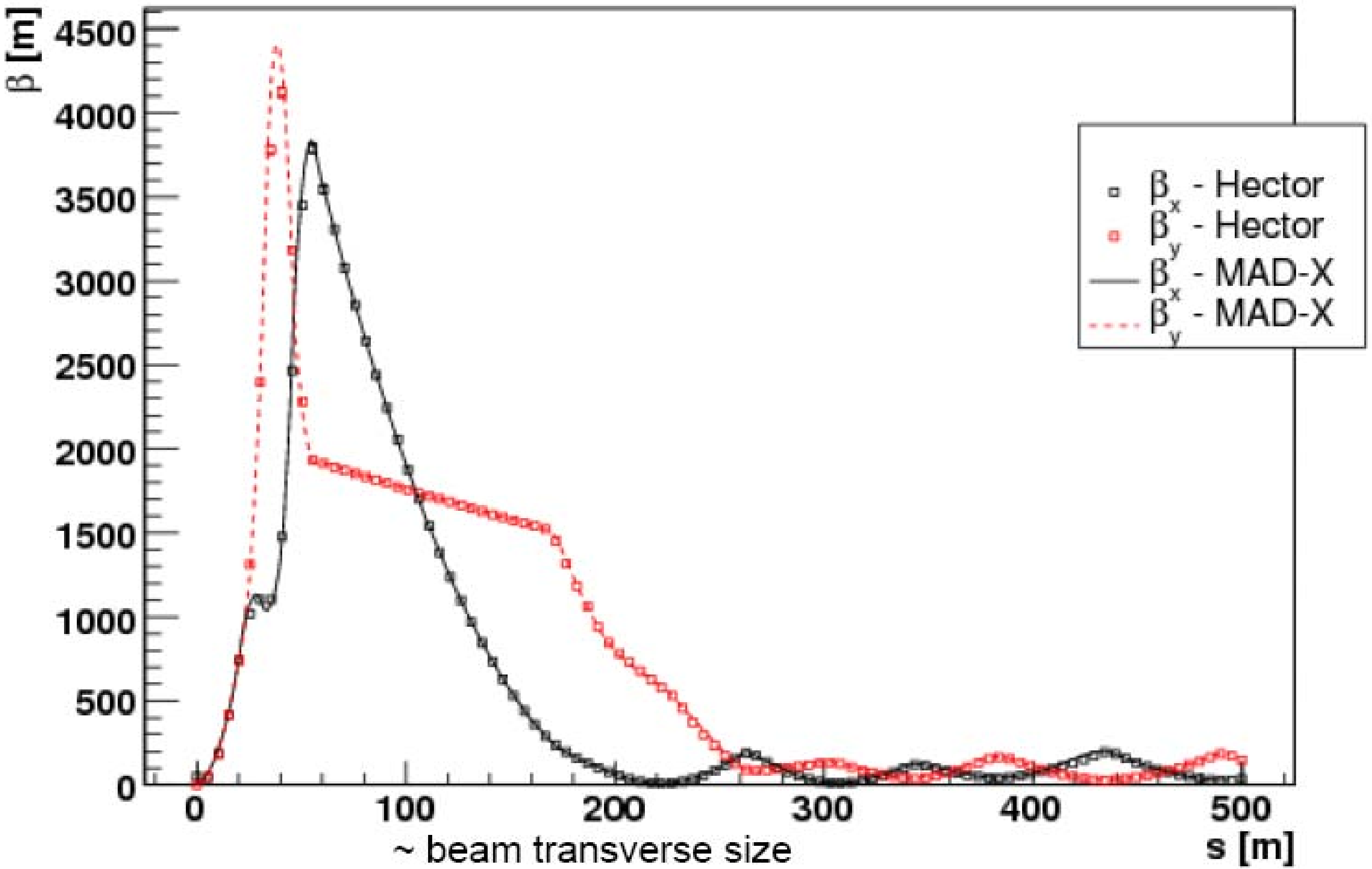
J.de Favereau & X.Rouby

# The LHC beams (on the right of CMS) :



# Validation (I)

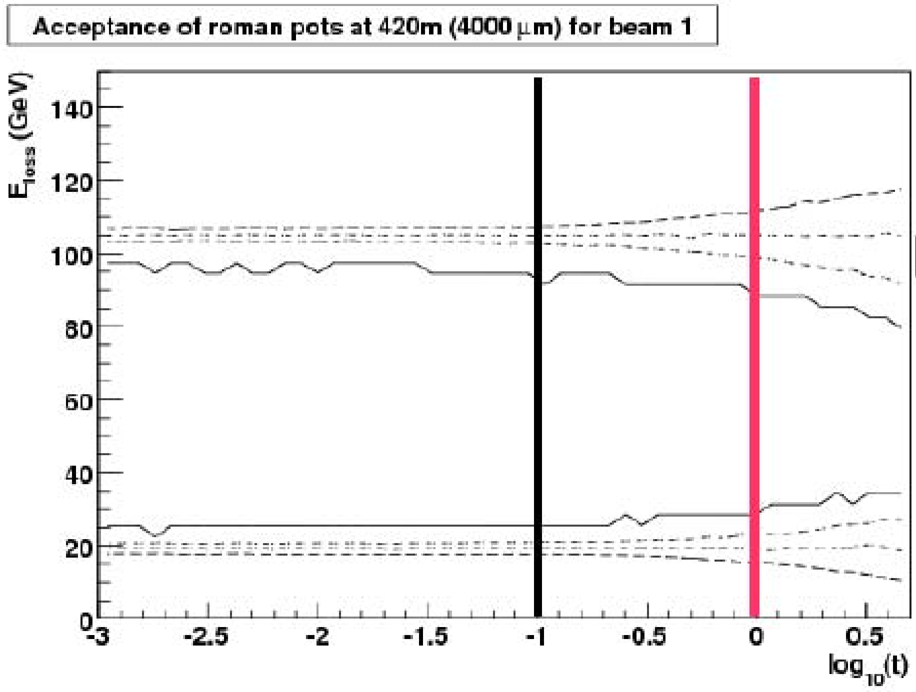
β functions - beam 1, forward

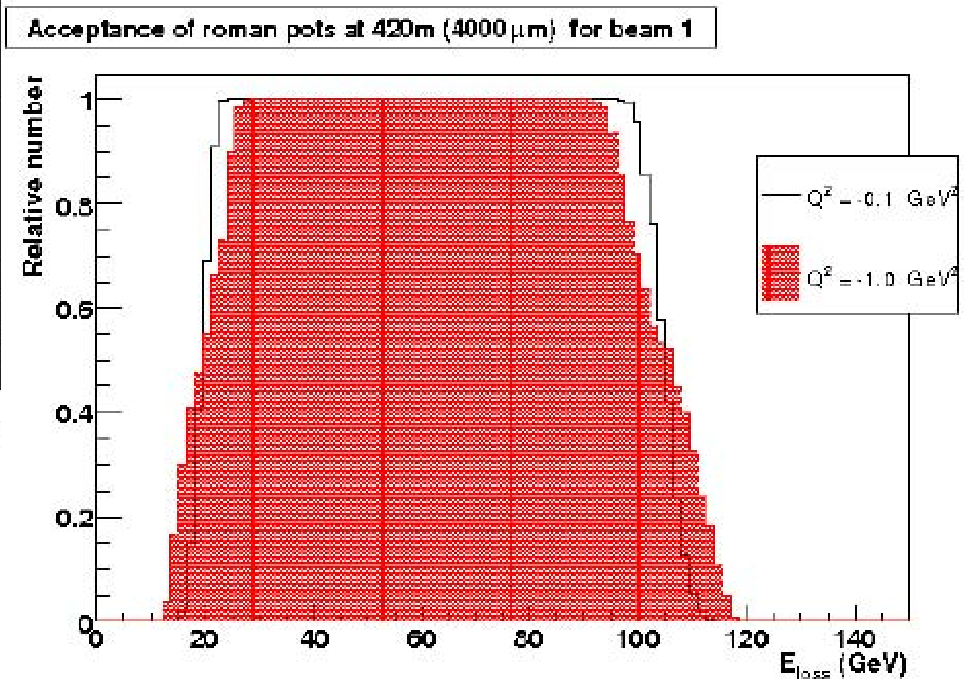



~ beam transverse size

# Direct physics output (II)

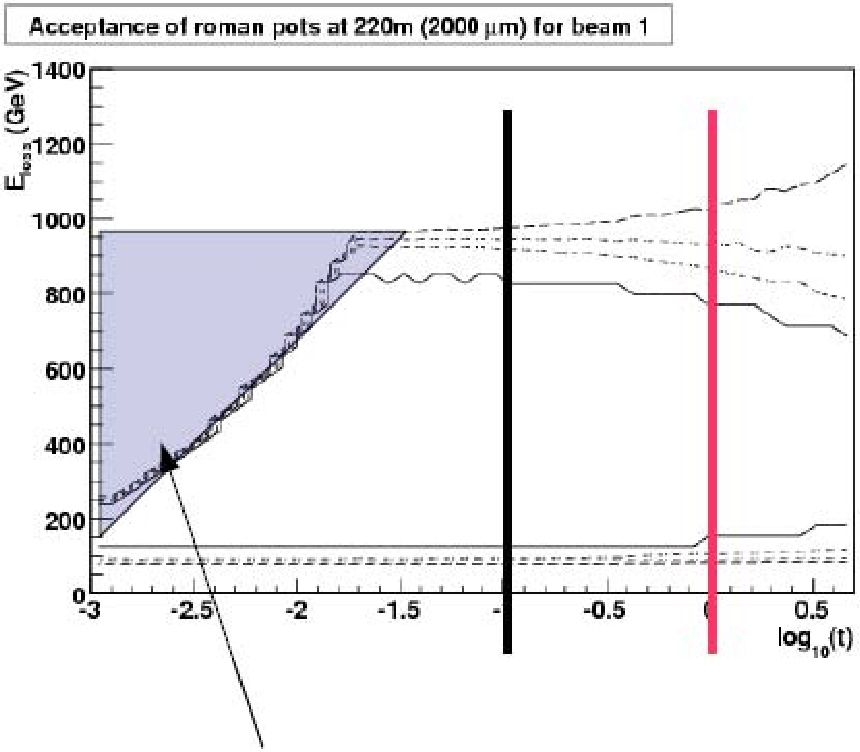
## RP acceptances (420m) beam 1



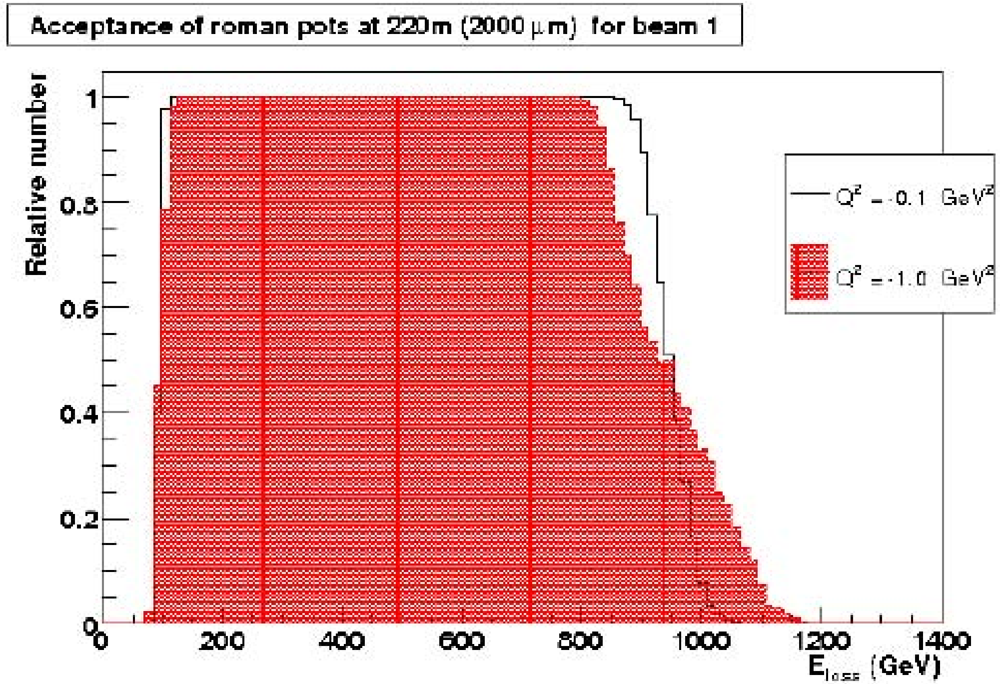
# Hector Direct physics output (II)

## RP acceptances (220m) :




Forbidden by kinematics

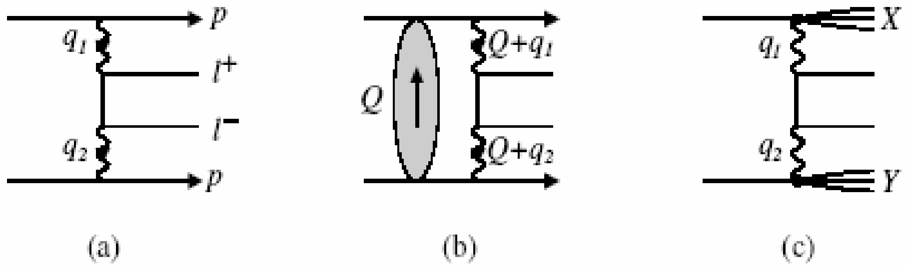
Which protons are detected ?



# Exclusive lepton pairs

- QED process (a) production $\sigma$ precisely known

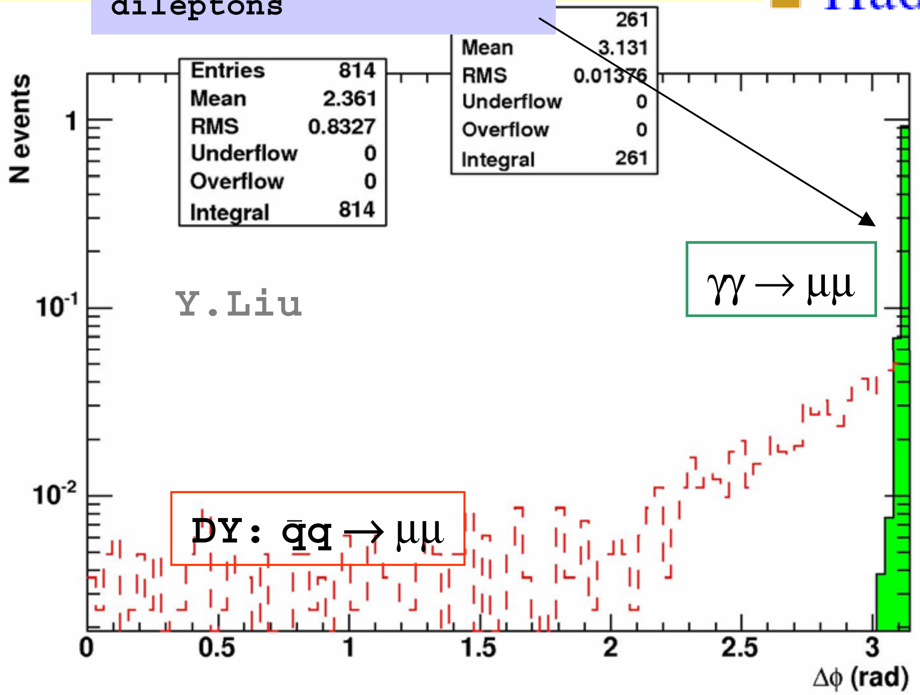
event generator LPAIR based on ME by Vermaseren




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

Done at HERA, being done at Tevatron!

Key signature: Acoplanarity angle for dileptons




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

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

**Invariant mass distribution driven by $p_T$ acceptance.**

**Still significant around upsilon mass!**

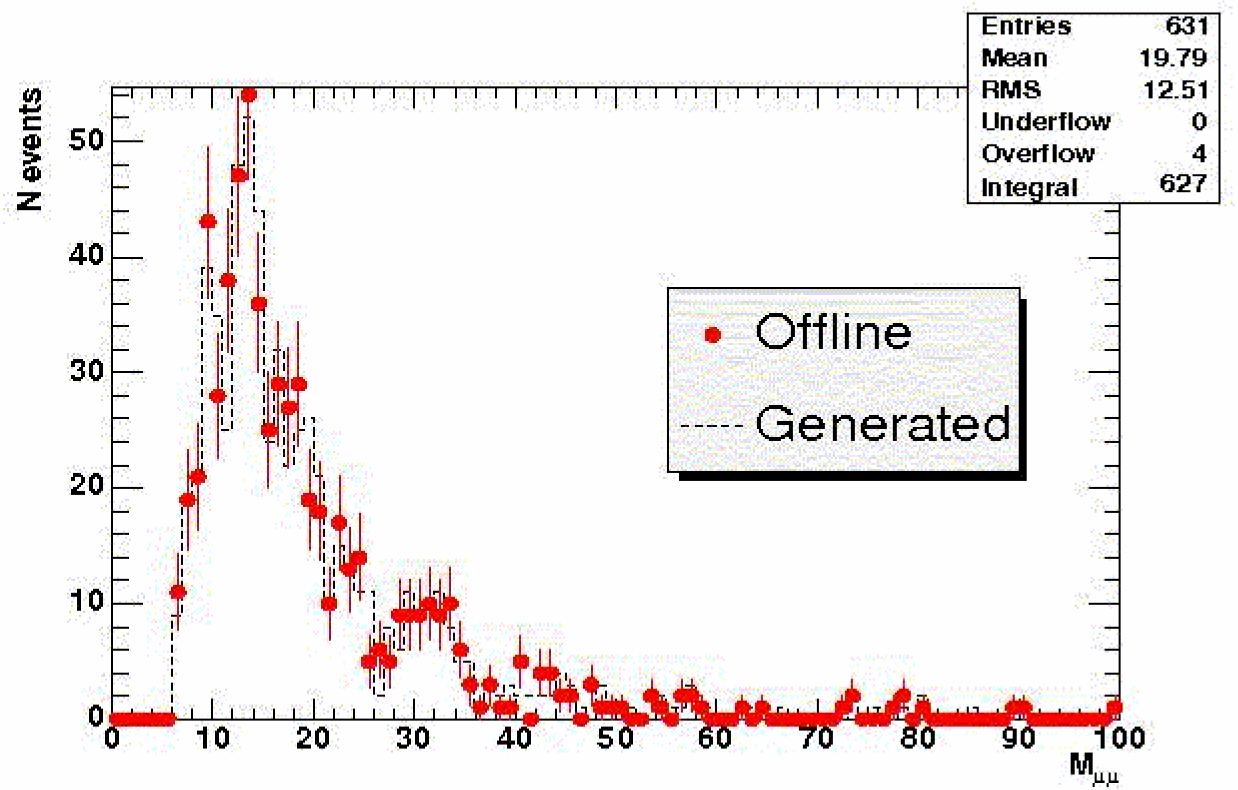



Figure 11: The reconstructed and generated di-muon mass.

# Infer $E_\gamma$ at initial state.

- When both leptons are observed, the energy of the $\gamma\gamma$ at initial state can be infered -assumption : their transverse momenta are small

(1) $$M_{l+l-} = 4E_{\gamma 1}E_{\gamma 2};$$

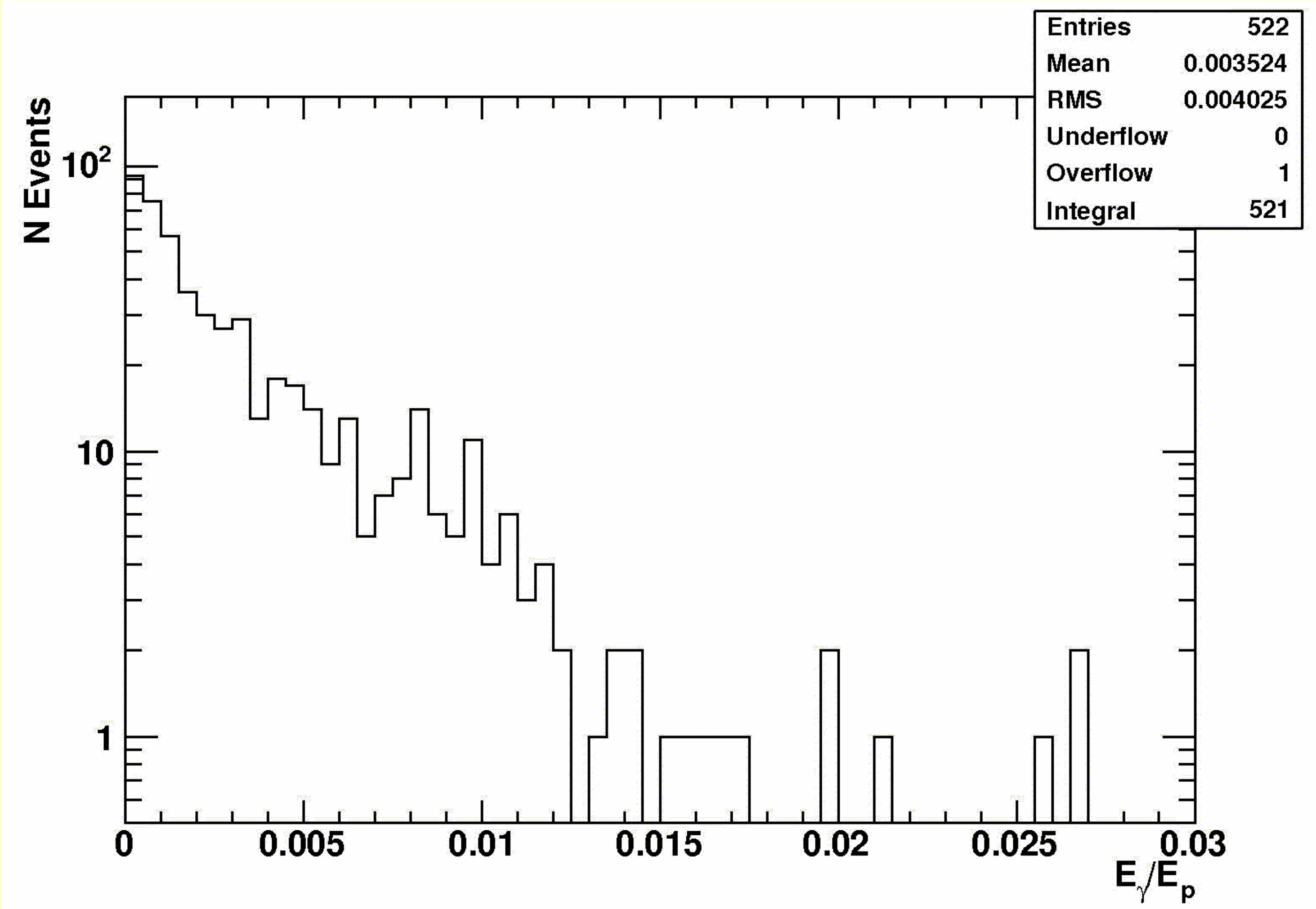
(2) $$Y_{l+l-} = \frac{1}{2}\log\frac{E_{\gamma 1}}{E_{\gamma 2}} \quad (\text{take } P_{z\gamma 2} < 0)$$

where, $M_{l+l-}, Y_{l+l-}$ are the invariant mass, rapidity of the $l^+l^-$ two body system respectively.

- This can be used to calibrate forward detectors.

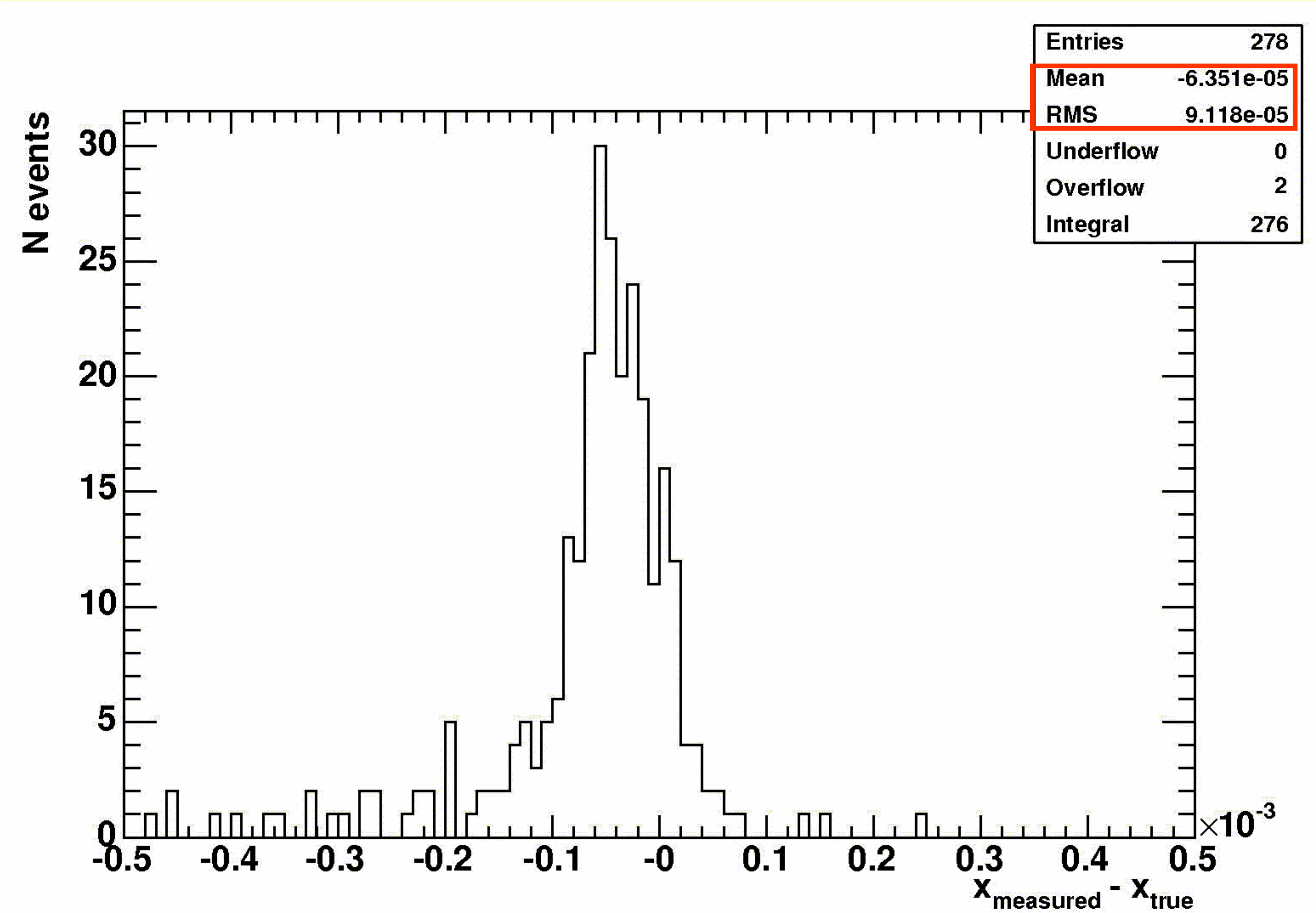
CMS week,March 18,2005 – p.12/1

Distribution of the proton energy loss for the reconstructed (and triggered) dimuon pairs:




**Perfectly suited for FP420 momentum calibration**

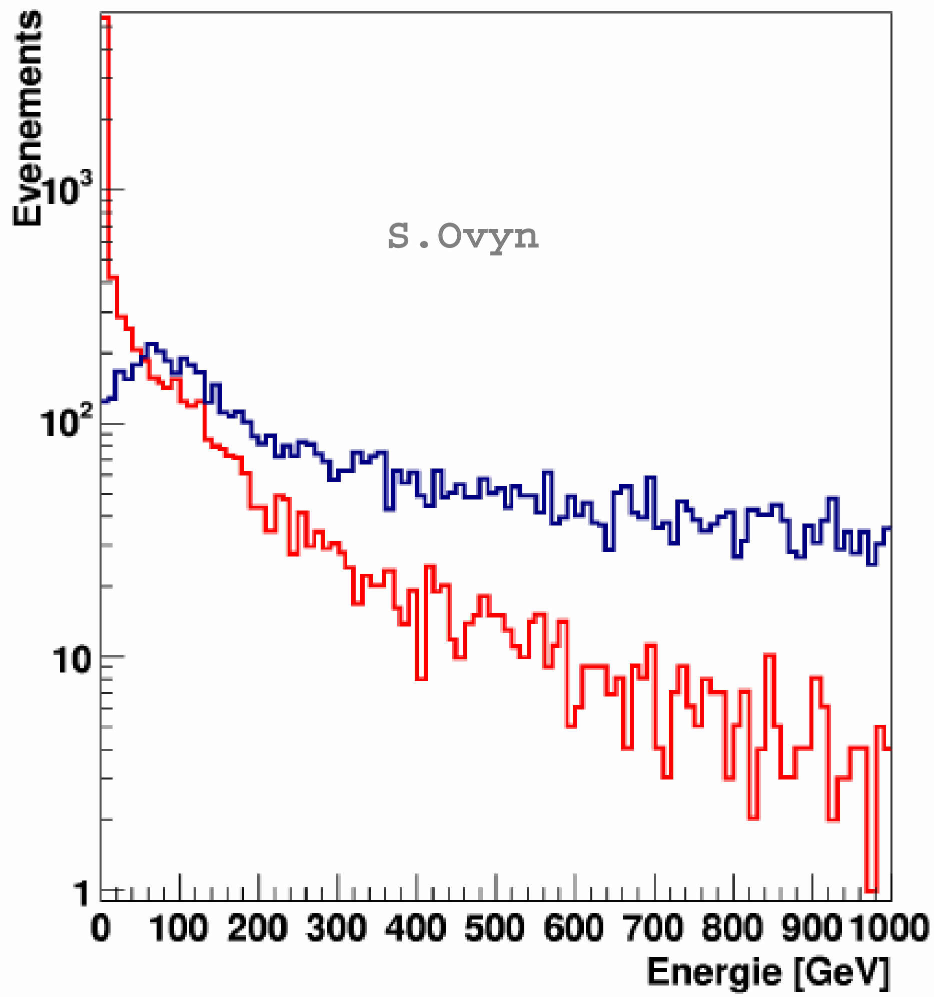
## Resolution of the proton energy loss for the reconstructed dimuon pairs:



## Selecting photon-proton events at (very) low luminosity

At luminosity up to $10^{33}$ (small event pileup) rapidity gap signature can be used:

For example, forward energy flows (into $5>|\eta|>3$) for two hemispheres (red-photon and blue-proton) is compared for associated WH photo-production




Finally, exclusivity cuts can be applied, by vetoing soft tracks from event vertex…

# $\gamma p$ interactions @ LHC – super HERA @ CERN

Photon-proton interactions can also be tagged at the LHC; and have significantly higher energy reach and luminosity yield than $\gamma\gamma$ events

Example assumptions:

- $0.01 < x_1 < 0.1$, photon tagging range
- $0.005 < x_2 < 0.3$, Bjorken-$x$ range for partons

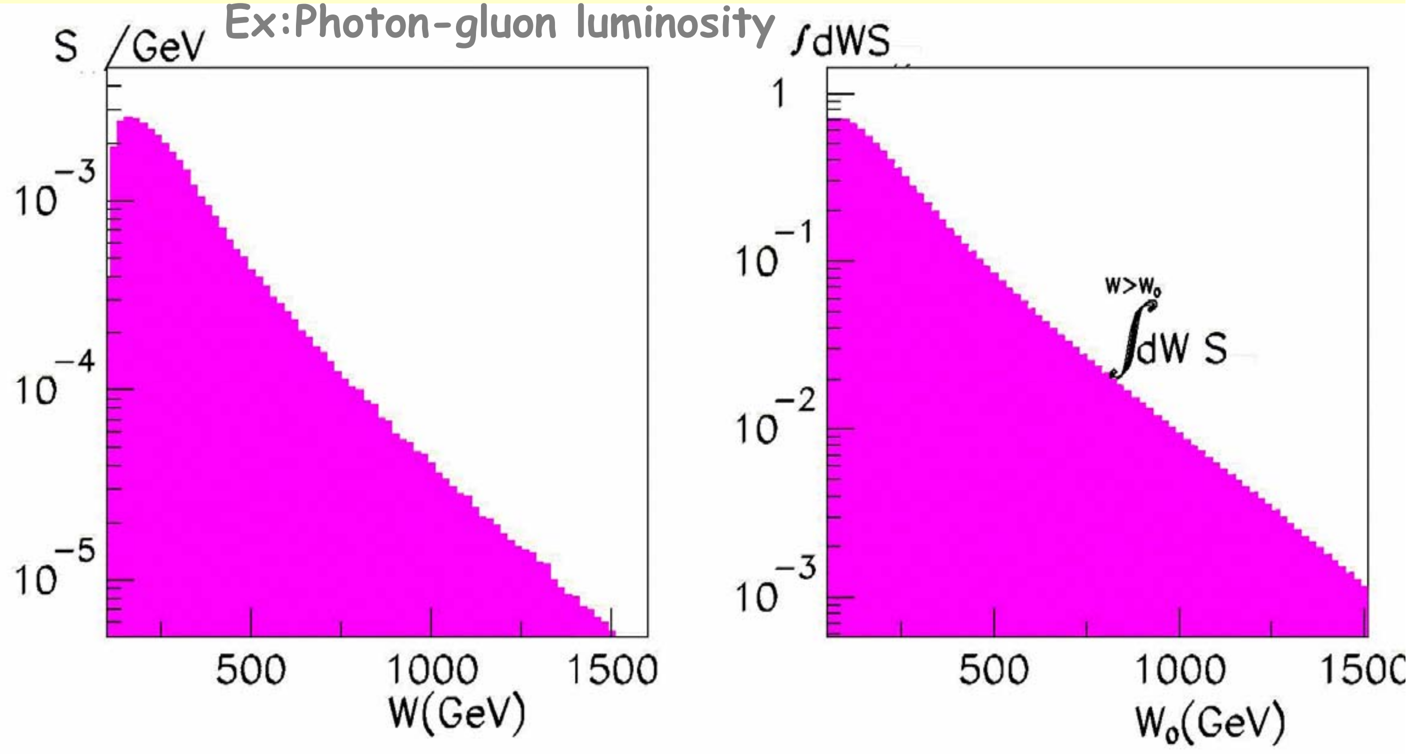
+ use MRST2001 (at $Q^2=10^4$ GeV$^2$) for proton pdf

$$S(W) = f_\gamma(x_1) \otimes f_p(x_2)$$

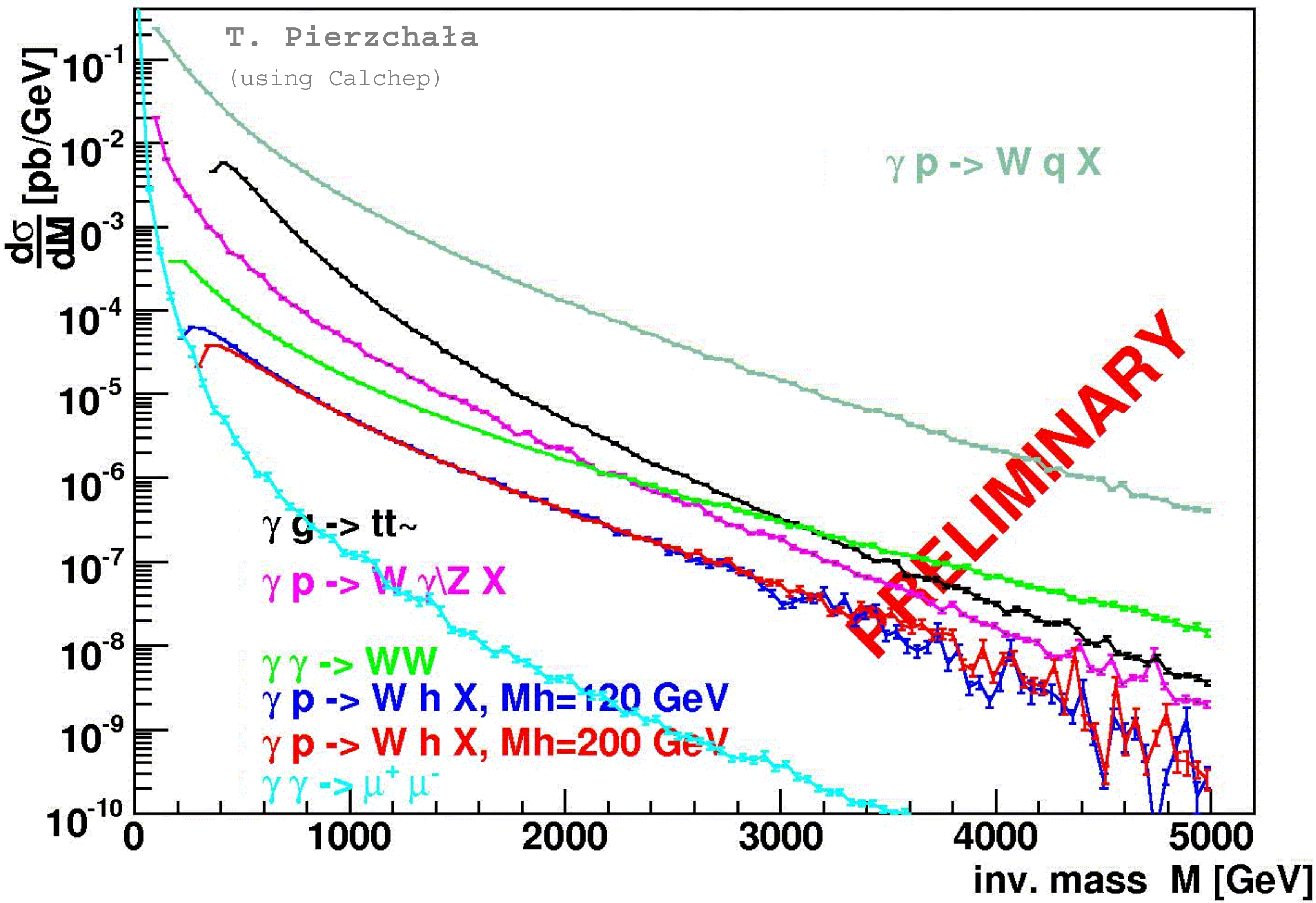
$$W^2 = 4E_p x_1 x_2$$

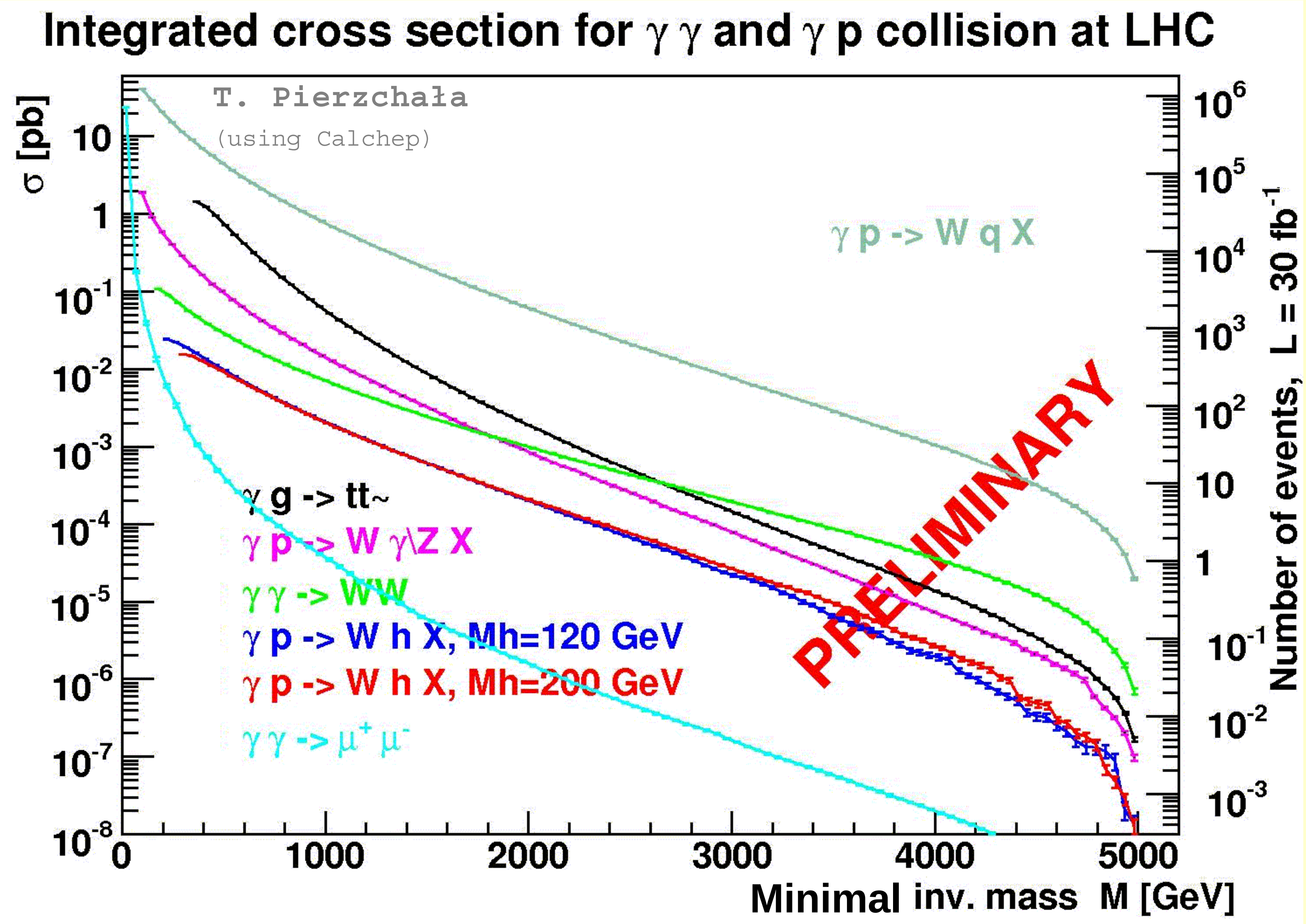
$$d\sigma_{pp}/dW = S\,\sigma_{\gamma g/q}$$

$$\sigma_{pp} = \int dW\, S\,\sigma_{\gamma g/q}$$



# Differential cross section for γ γ and γ p collision at LHC




Integrated cross section for γ γ and γ p collision at LHC
T. Pierzchała
(using Calchep)
σ [pb]
10
1
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7
10^-8
γ p -> W q X
γ g -> tt~
γ p -> W γ\Z X
γ γ -> WW
γ p -> W h X, Mh=120 GeV
γ p -> W h X, Mh=200 GeV
γ γ -> μ+ μ-
PRELIMINARY
0
1000
2000
3000
4000
5000
Minimal inv. mass M [GeV]
10^6
10^5
10^4
10^3
10^2
10
1
10^-1
10^-2
10^-3
Number of events, L = 30 fb^-1

**Q1: Can one select photon-induced events among very many *pp* interactions?**

Inclusive- (*pp*) vs. photo-production: Examples

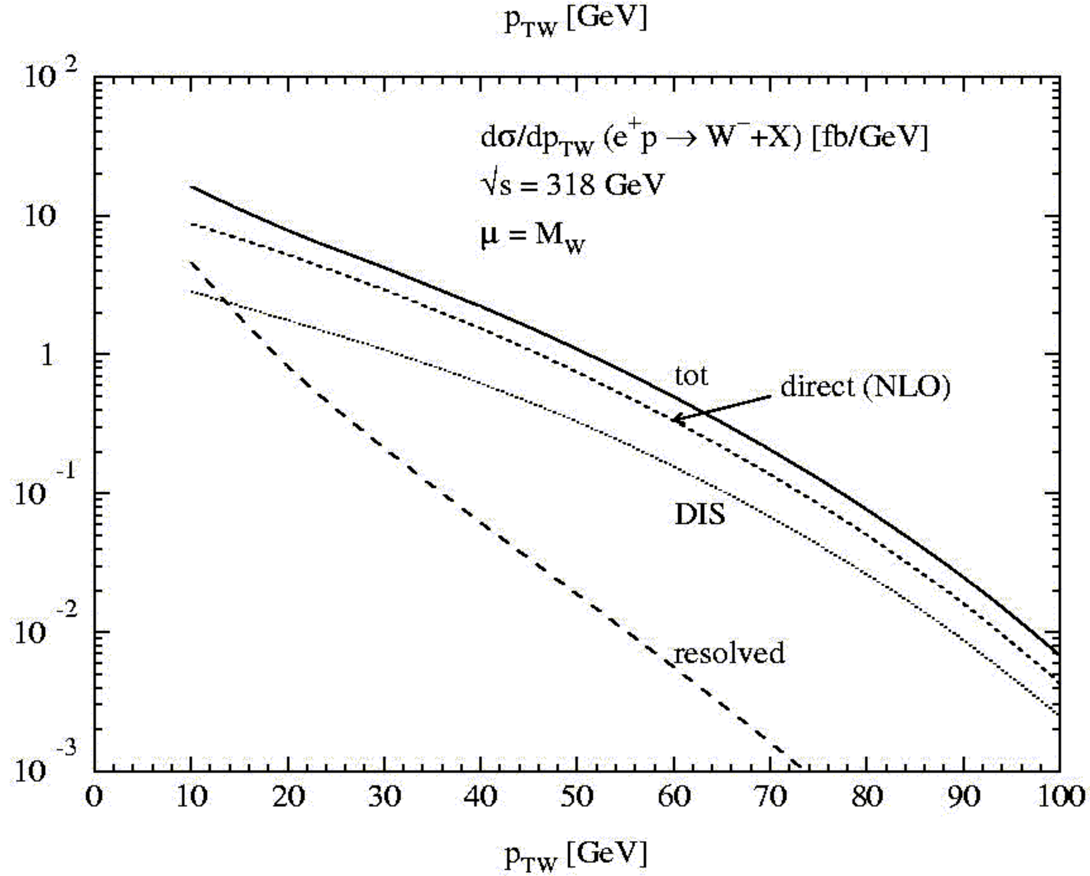
| *Process*/$\sigma$[pb] | *pp* | $\gamma\gamma$ or $\gamma p$ |
|---|---|---|
| WW | ~ 70 | 0.2 |
| $t\bar{t}$ | ~ 600 | 1.5 |
| WH | ~ 1.2 | 0.03 |

← *pp* needs large suppression, more difficult at high luminosities

**Q2: What about diffractive irreducible backgrounds?**

**A: For above, only important for top photo-production (similar size)**

# Single W photoproduction: Studied at HERA

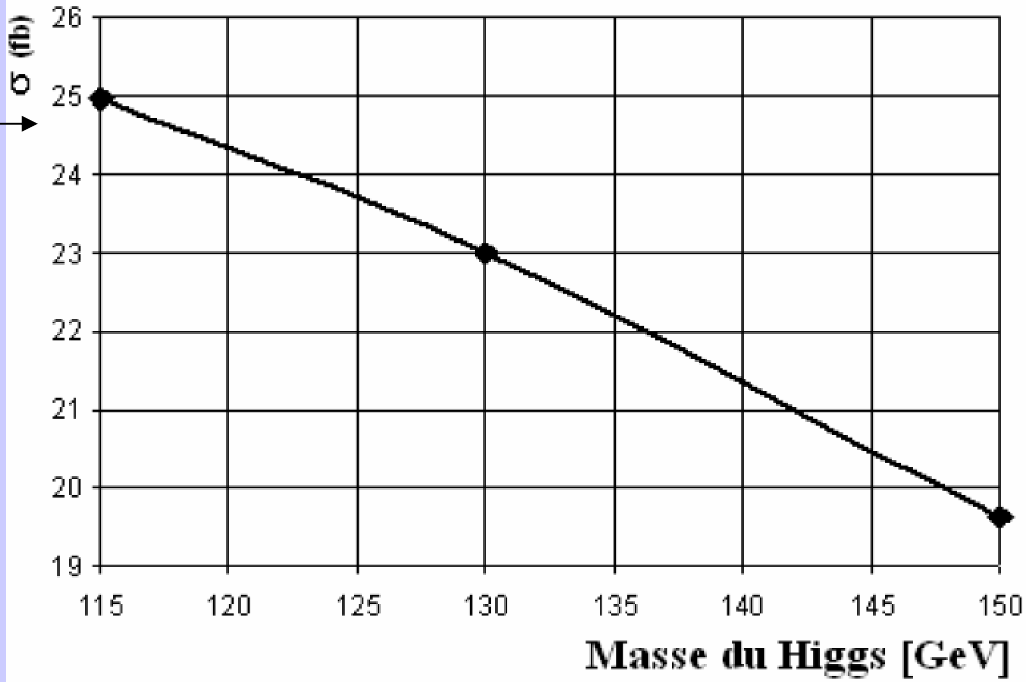



*Diener et al.*

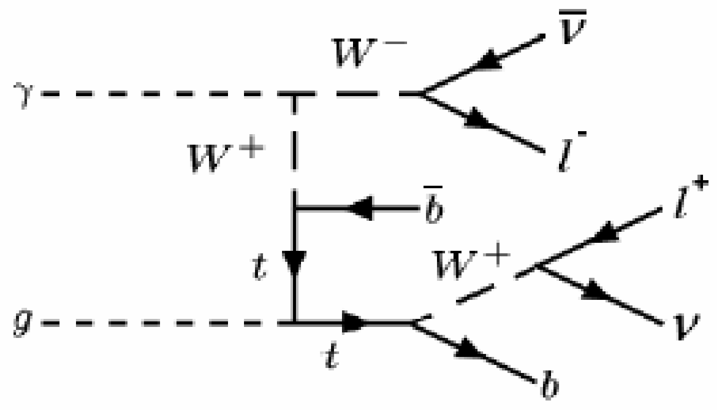
Figure 8: *Transverse momentum distributions of W bosons at HERA. The full curves show the total $p_{TW}$ distributions, while the broken lines exhibit the individual LO DIS, NLO direct and LO resolved contributions. The upper plot is for $W^+$ production and the lower for $W$ bosons.*

# Higgs and top photoproduction

Associated photoproduction of WH has significant cross-section at LHC and much better signal-to-background ratio; low mass region should be accesible.



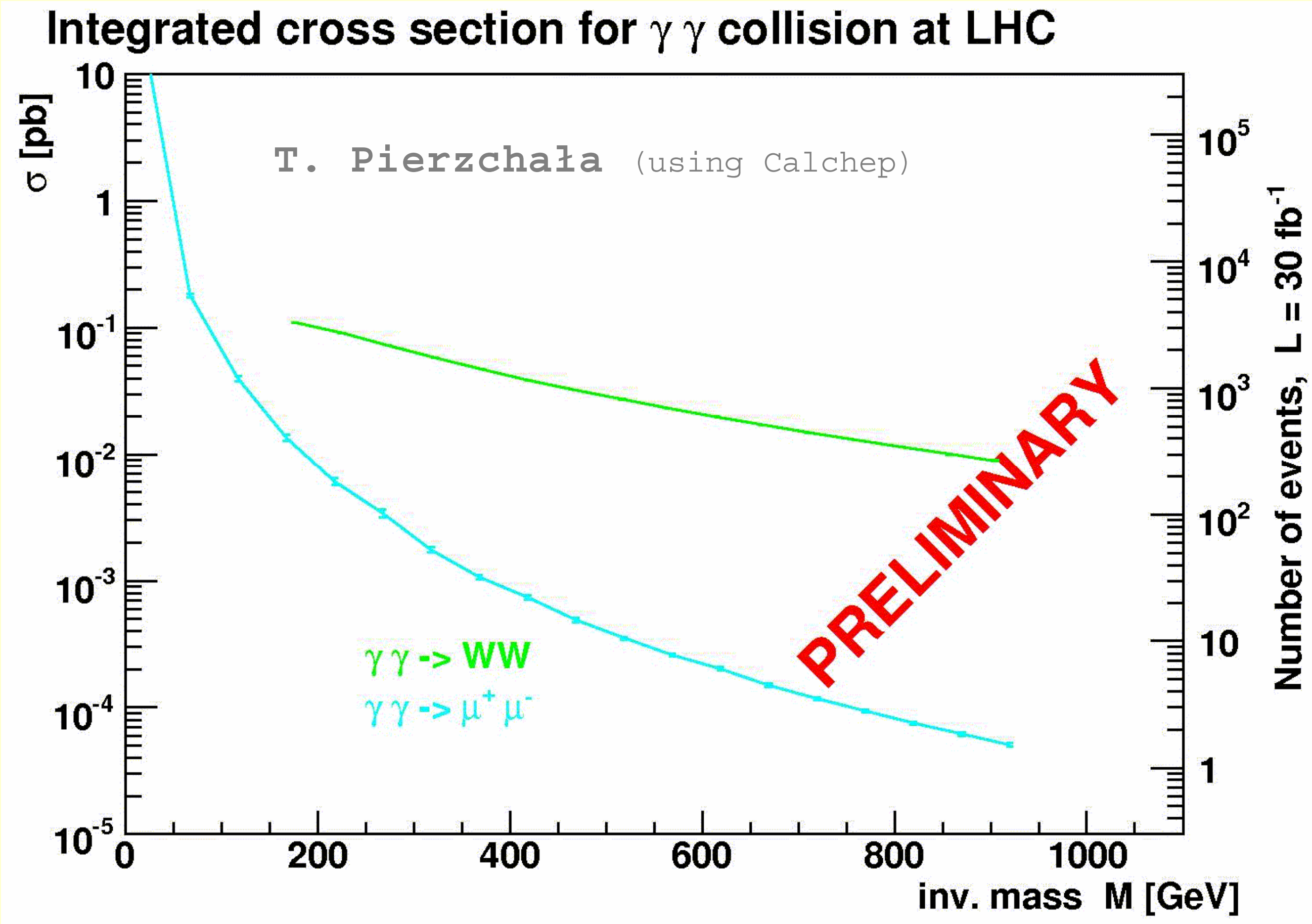

Important backgrounds to WH deserve their own studies, as photo-production of top pairs, WZ, or single top (as at HERA):




Single top production ($\gamma q \to t$) could be used to study anomalous $\gamma qt$ coupling; level of Wq background (~ 100 fb/GeV) indicates possibility of significant improvement wrt HERA

# Exclusive two-photon pair production

**Large cross-section for WW pairs extending to very high invariant masses - possibility of searches for physics BSM**




**Muon pairs produced with invariant masses beyond 100 GeV, hence pairs of massive charged particles could be searched for**

# Anomalous quartic gauge couplings

- imposing C,P conservation, local $U(1)_{em}$, global $SU(2)_c \Rightarrow \ \rho = 1$

$$\mathcal{L}_6^0 = -\frac{e^2}{8}\frac{a_0^{\mathrm{W}}}{\Lambda^2} F_{\mu\nu}F^{\mu\nu}W^{+\alpha}W^-_\alpha - \frac{e^2}{16\cos^2\theta_W}\frac{a_0^{\mathrm{Z}}}{\Lambda^2} F_{\mu\nu}F^{\mu\nu}Z^\alpha Z_\alpha,$$

$$\mathcal{L}_6^{\mathrm{c}} = -\frac{e^2}{16}\frac{a_{\mathrm{c}}^{\mathrm{W}}}{\Lambda^2} F_{\mu\alpha}F^{\mu\beta}(W^{+\alpha}W^-_\beta + W^{-\alpha}W^+_\beta) - \frac{e^2}{16\cos^2\theta_W}\frac{a_{\mathrm{c}}^{\mathrm{Z}}}{\Lambda^2} F_{\mu\alpha}F^{\mu\beta}Z^\alpha Z_\beta.$$

- current limits form OPAL (hep-ex/0402021)

$$-0.007\ \mathrm{GeV}^{-2} < \ a_0^{\mathrm{Z}}/\Lambda^2 \ < 0.023\ \mathrm{GeV}^{-2},$$

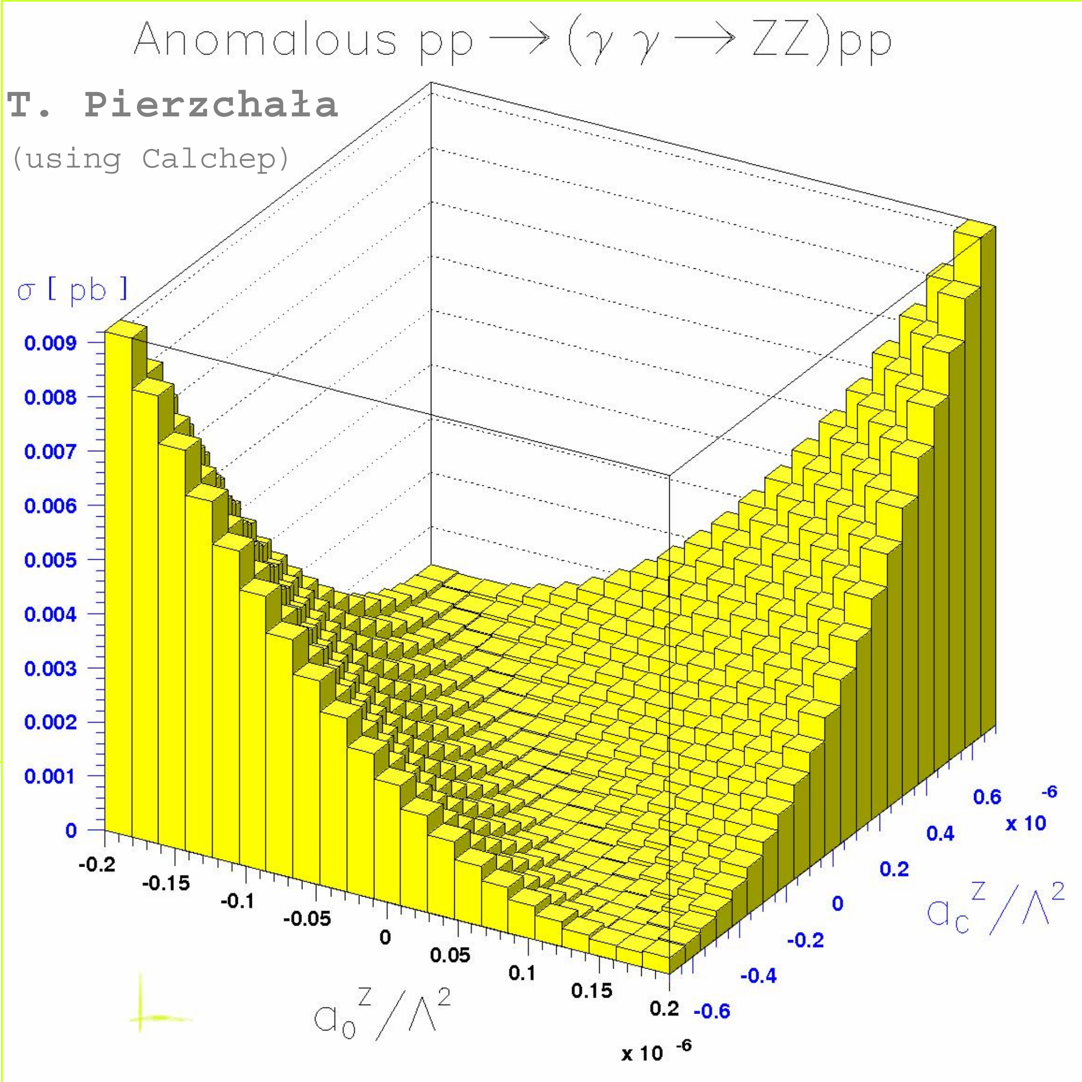
$$-0.029\ \mathrm{GeV}^{-2} < \ a_{\mathrm{c}}^{\mathrm{Z}}/\Lambda^2 \ < 0.029\ \mathrm{GeV}^{-2},$$

$$-0.020\ \mathrm{GeV}^{-2} < \ a_0^{\mathrm{W}}/\Lambda^2 \ < 0.020\ \mathrm{GeV}^{-2},$$

$$-0.052\ \mathrm{GeV}^{-2} < \ a_{\mathrm{c}}^{\mathrm{W}}/\Lambda^2 \ < 0.037\ \mathrm{GeV}^{-2},$$

# $\gamma\gamma \to ZZ$

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

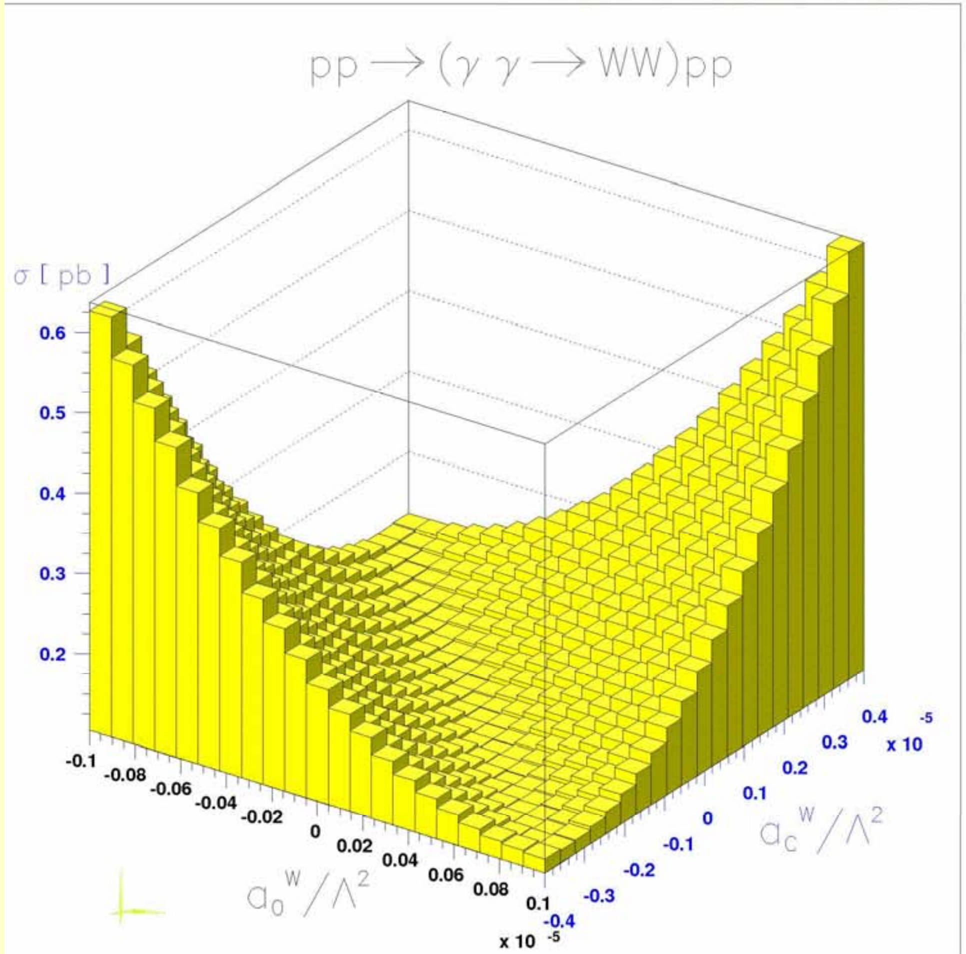
assuming no background

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

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

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

# $\gamma\gamma \to$ WW




- SM $\gamma\gamma \to WW$ for $\int L_{pp}\, dt$=30 $fb^{-1} \Rightarrow$ about 3000 W pairs will be produced (leptonic + semileptonic)
- we expect at least 10 000 $\times$ stronger limits:

$$-0.1{\cdot}10^{-5}\ \mathrm{GeV}^{-2} < a_0^{\mathrm{W}}/\Lambda^2 < 0.1{\cdot}10^{-5}\ \mathrm{GeV}^{-2}$$

$$-0.4{\cdot}10^{-5}\ \mathrm{GeV}^{-2} < a_c^{\mathrm{W}}/\Lambda^2 < 0.4{\cdot}10^{-5}\ \mathrm{GeV}^{-2}$$

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

N.Schul

# Charginos / sleptons

Dans l'extension supersymétrique minimale du modèle standard, existence de particules chargées scalaires (sleptons) et fermioniques (charginos) massives

- Masses limites: m( $\tilde{\chi}_1^{\pm}$ ) > 101 GeV

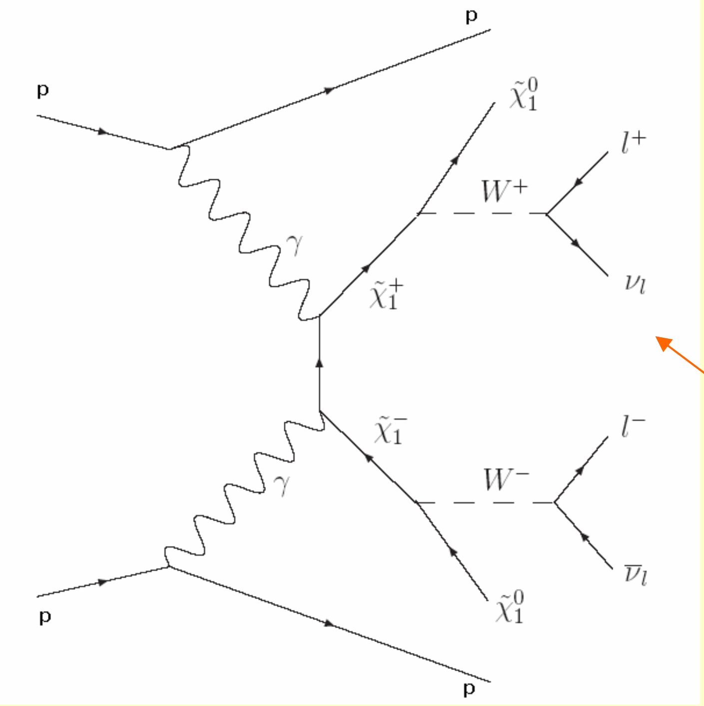
[Ref: OPAL Coll., *Search for chargino production at LEP,* hep-ex/0401026]

m( $\tilde{e}_R$ ) > 96 GeV

m( $\tilde{\mu}_R$ ) > 87 GeV

m( $\tilde{\tau}_R$ ) > 83 GeV

[Ref: ALEPH Coll., *Search for scalar leptons in e+ e- collisions,* Phys. Lett. B5269]




Exemple

- Production d'une paire de charginos par interaction $\gamma\gamma$:

topologie simple de l'état final:

2 protons vers l'avant + 2 leptons + énergie manquante

# SUSY: chargino case

Simple production mechanisms and decay modes:

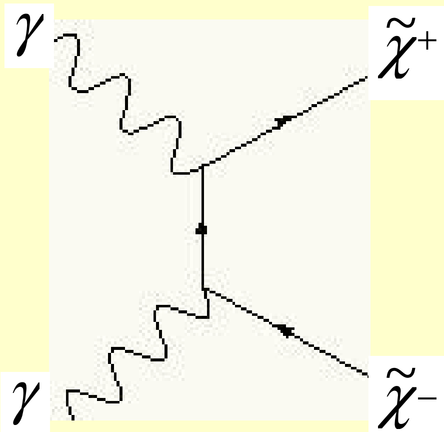
$$\tilde{\chi}^{\pm} \rightarrow \tilde{\chi}^{0} + \ell^{\pm} + \nu_{\ell}$$

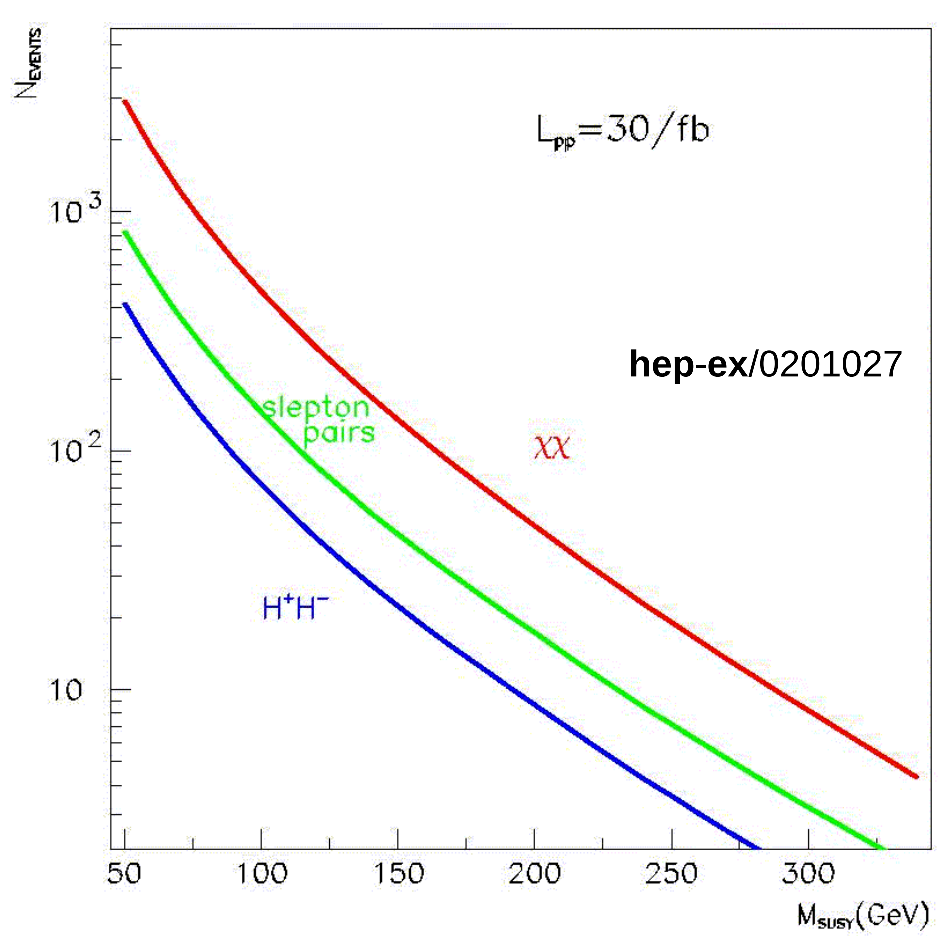
Charged Leptons

and

Missing energy

WW is background



# 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:

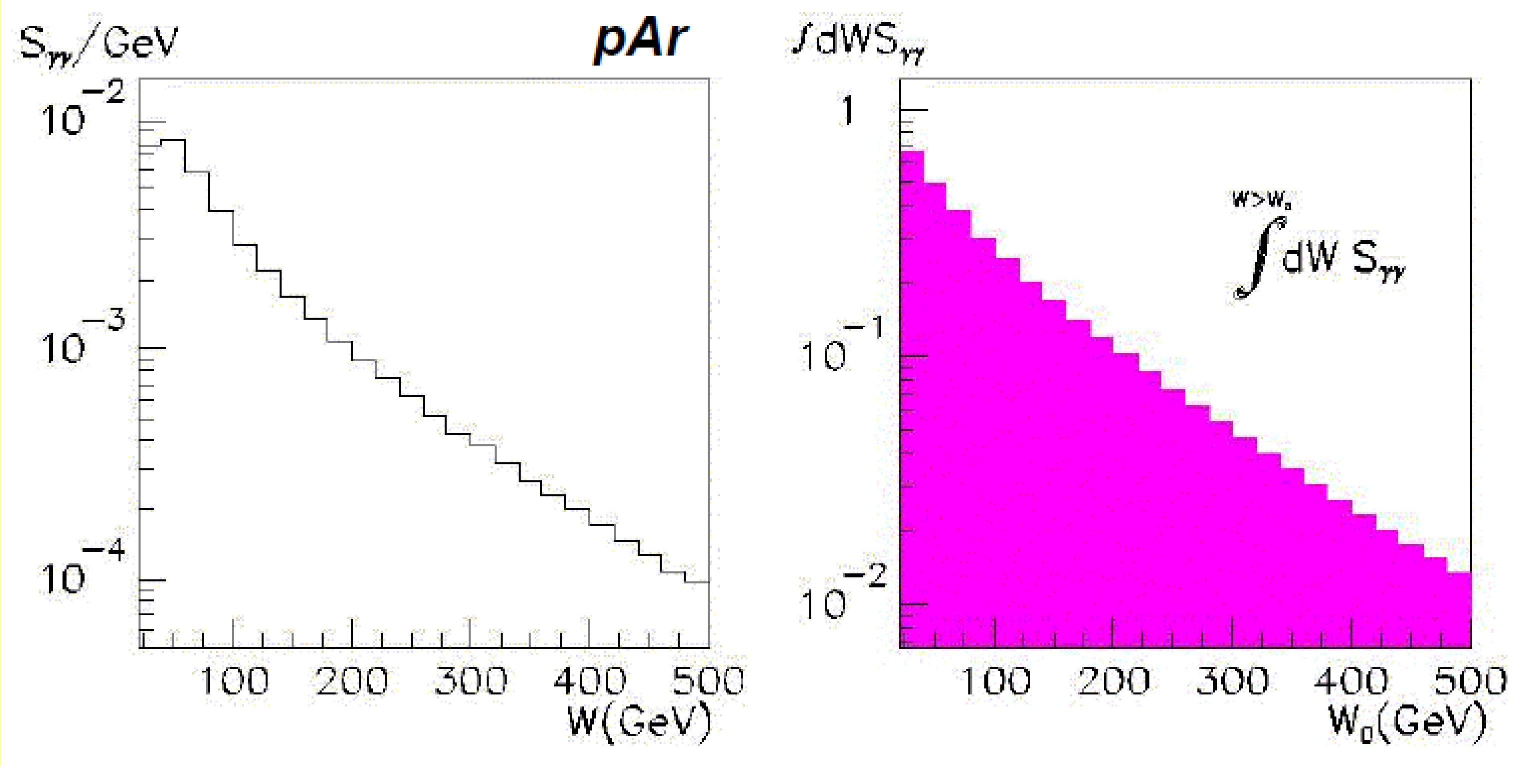
• Tagged *W* values are very large and corresponding luminosity is small (coherence loss), e.g. for 140 TeV beams *W* range is approximately 4-25 (0.5-25) TeV for double (single) tagging

• 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***

# 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

# Summary/Outlook

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

- Tagging high energy photon (and diffractive) interactions at LHC can be done by supplementing central detectors with very forward spectrometers.

- This offers new, exciting and complementary physics studies in parallel to 'nominal' ones

- We should make sure that from Day 1 of LHC running triggers and selection algorithms for exclusive events in *pp* are in place…

- We must make the best of the LHC!