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Anomalously Interacting Z′ Bosons

keywords: Z-prime, Z-star
W-prime, W-star

M.V. Chizhov
(Sofia University and JINR)

in collaboration with

V.A. Bednyakov, J.A. Budagov
(JINR)
G. Dvali
(CERN , Max Planck Institute, New York University)

Excited particles (compositeness)

$$\mathcal{L}_{\psi^*} = \frac{g}{\Lambda} \bar{\psi}^* \sigma^{\mu\nu} \psi \cdot \left(\partial_\mu Z_\nu - \partial_\nu Z_\mu \right)$$

Searches for excited fermions ψ^* have been performed at LEP, HERA and the Tevatron, and are also planned for the CMS and ATLAS experiments at the LHC.

*ψ^* why not **Z^* ?***

$$\mathcal{L}_{Z^*} = \frac{g}{\Lambda} \bar{\psi} \sigma^{\mu\nu} \psi \cdot \left(\partial_\mu Z^*_\nu - \partial_\nu Z^*_\mu \right)$$

M. C., V. A. Bednyakov, and J. A. Budagov, Proposal for chiral bosons search at LHC via their unique new signature, *Phys. Atom. Nucl.* **71** (2008) 2096; arXiv:0801.4235

Z^* has different interactions than Z' !

$$\mathcal{L}_{Z'} = \bar{\psi} \gamma^\mu \left(g_V + g_A \gamma^5 \right) \psi \cdot Z'_\mu$$

Standard Model extension

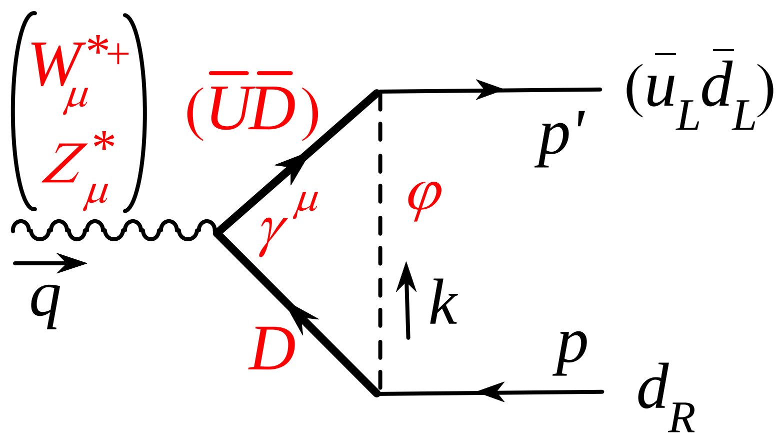
Additional Z′ or W′ gauge bosons occur usually in abelian U(1)′ or adjoint SU(2)′ extensions of the Standard Model.
The goal of this talk is to provide a motivation for introduction of new spin-1 bosons with the internal quantum numbers identical to the Standard Model Higgs doublet, transforming under fundamental representation of SU(2), from the Hierarchy Problem point of view.

$$\begin{pmatrix} H^{+} \\ H^{0} \end{pmatrix} \leftrightarrow \begin{pmatrix} W_{\mu}^{*+} \\ Z_{\mu}^{*} \end{pmatrix}$$

Standard Model symmetry $SU(2)_L \times U(1)_Y$

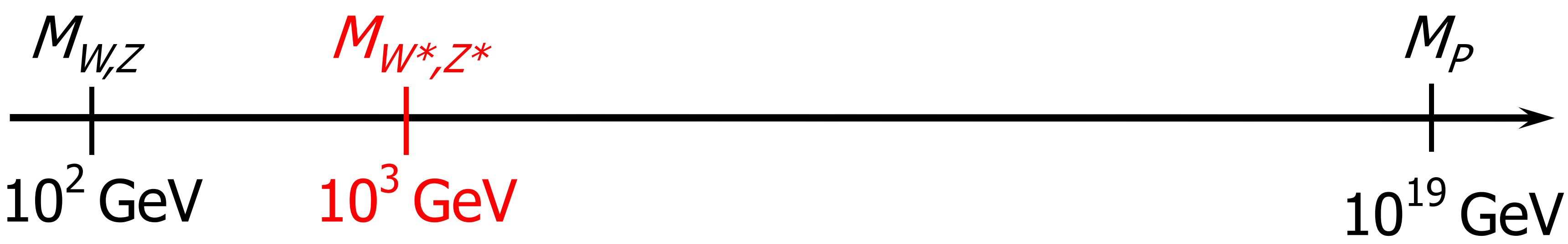
$$\frac{g}{M}\left(\bar{u}_L\,\bar{d}_L\right)\sigma^{\mu\nu}d_R\left[\partial_\mu\begin{pmatrix}W_\nu^{*+}\\ Z_\nu^{*}\end{pmatrix}-\partial_\nu\begin{pmatrix}W_\mu^{*+}\\ Z_\mu^{*}\end{pmatrix}\right]$$

M.C. and G. Dvali, Origin and Phenomenology of Weak-Doublet Spin-1 Bosons, arXiv:0809.0924



Motivation for SM extension

The main theoretical motivation for beyond the Standard Model physics around TeV energies is provided by the Hierarchy Problem.



We show, that there are at least three different classes of theories which explain the lightness of the Higgs doublets and predict appearance of new spin-1 doublets not far from the weak scale.

1. SU(3) extension of SM

$SU(3) \supset SU(2)\times U(1)$ **$8=3+2+\bar{2}+1$**

$$\begin{pmatrix} \boxed{\begin{matrix} W^3 & W^+ \\ W^- & -W^3 \end{matrix}} & \boxed{\begin{matrix} W^{*+} \\ Z^* \end{matrix}} \\ \boxed{\begin{matrix} W^{*-} & \bar{Z}^* \end{matrix}} & \boxed{B} \end{pmatrix}$$

New vector bosons are transformed under fundamental representation of $\mathbf{SU(2)_L}$ (coset gauge bosons)

They belong to fragments **2** (**$\bar{2}$**) and become massive during the spontaneous symmetry breaking SU(3) →SU(2)×U(1) by the two independent Higgs triplets **$3_H=1_H+2_H$** и **$3'_H=1'_H+2'_H$**. The lightness of the Higgs doublets is guaranteed, because they are related to the vectors by symmetry.

Z.G. Berezhiani & G.Dvali, Bull. Lebedev Phys. Inst. 5(1989)55; Kratk. Soobshch. Fiz. 5(1989)42;
G. Dvali, G.F. Giudice and A. Pomarol, Nucl. Phys. B478 (1996) 31;
G.R. Dvali, Phys. Lett. B 324 (1994) 59.

2. Extra dimensions

Let us consider a doublet of the gauge fields in N-dimension Minkowski space. Then its the fifth and the subsequent components can play a role of the Higgs fields (so-called Gauge-Higgs unification)

$$\begin{pmatrix} W_M^{*+} \\ Z_M^{*} \end{pmatrix} = \begin{pmatrix} W_\mu^{*+}, H^+, \ \dots \\ Z_\mu^{*} \ \ , H^0, \ \dots \end{pmatrix}$$

N.S. Manton, Nucl. Phys. B 158 (1979) 141;
D.B. Fairlie, J. Phys. G 5 (1979) L55; Phys. Lett. B 82 (1979) 97.

The lightness of the Higgs doublets is guaranteed by the gauge symmetry. This symmetry is spontaneously broken by compactification. In this way the mass of the Higgs doublet is controlled by the compactification scale, as opposed to the high-dimensional cutoff of the theory.

3. Technicolor

techni-π, techni-ρ, techni-ω …

What else?

π^0 $I^G(J^{PC}) = 1^-(0^{-+})$

Mass $m = 134.9766 \pm 0.0006$ MeV (S = 1.1)
$m_{\pi^\pm} - m_{\pi^0} = 4.5936 \pm 0.0005$ MeV
Mean life $\tau = (8.4 \pm 0.6) \times 10^{-17}$ s (S = 3.0)
$c\tau = 25.1$ nm

$$\bar{q}\gamma^\mu q \cdot V_\mu \quad s=1, \; \ell=0$$

$\rho(770)$ [j] $I^G(J^{PC}) = 1^+(1^{--})$

Mass $m = 775.49 \pm 0.34$ MeV
Full width $\Gamma = 149.1 \pm 0.8$ MeV
$\Gamma_{ee} = 7.04 \pm 0.06$ keV

$\omega(782)$ $I^G(J^{PC}) = 0^-(1^{--})$

Mass $m = 782.65 \pm 0.12$ MeV (S = 1.9)
Full width $\Gamma = 8.49 \pm 0.08$ MeV
$\Gamma_{ee} = 0.60 \pm 0.02$ keV

techni-*a*, techni-*f*

$$\bar{q}\gamma^\mu\gamma^5 q \cdot A_\mu \quad s=1, \; \ell=1$$

$a_1(1260)$ [m] $I^G(J^{PC}) = 1^-(1^{++})$

Mass $m = 1230 \pm 40$ MeV [n]
Full width $\Gamma = 250$ to 600 MeV

$f_1(1285)$ $I^G(J^{PC}) = 0^+(1^{++})$

Mass $m = 1281.8 \pm 0.6$ MeV (S = 1.6)
Full width $\Gamma = 24.3 \pm 1.1$ MeV (S = 1.4)

$h_1(1170)$ $I^G(J^{PC}) = 0^-(1^{+-})$

Mass $m = 1170 \pm 20$ MeV
Full width $\Gamma = 360 \pm 40$ MeV

$b_1(1235)$ $I^G(J^{PC}) = 1^+(1^{+-})$

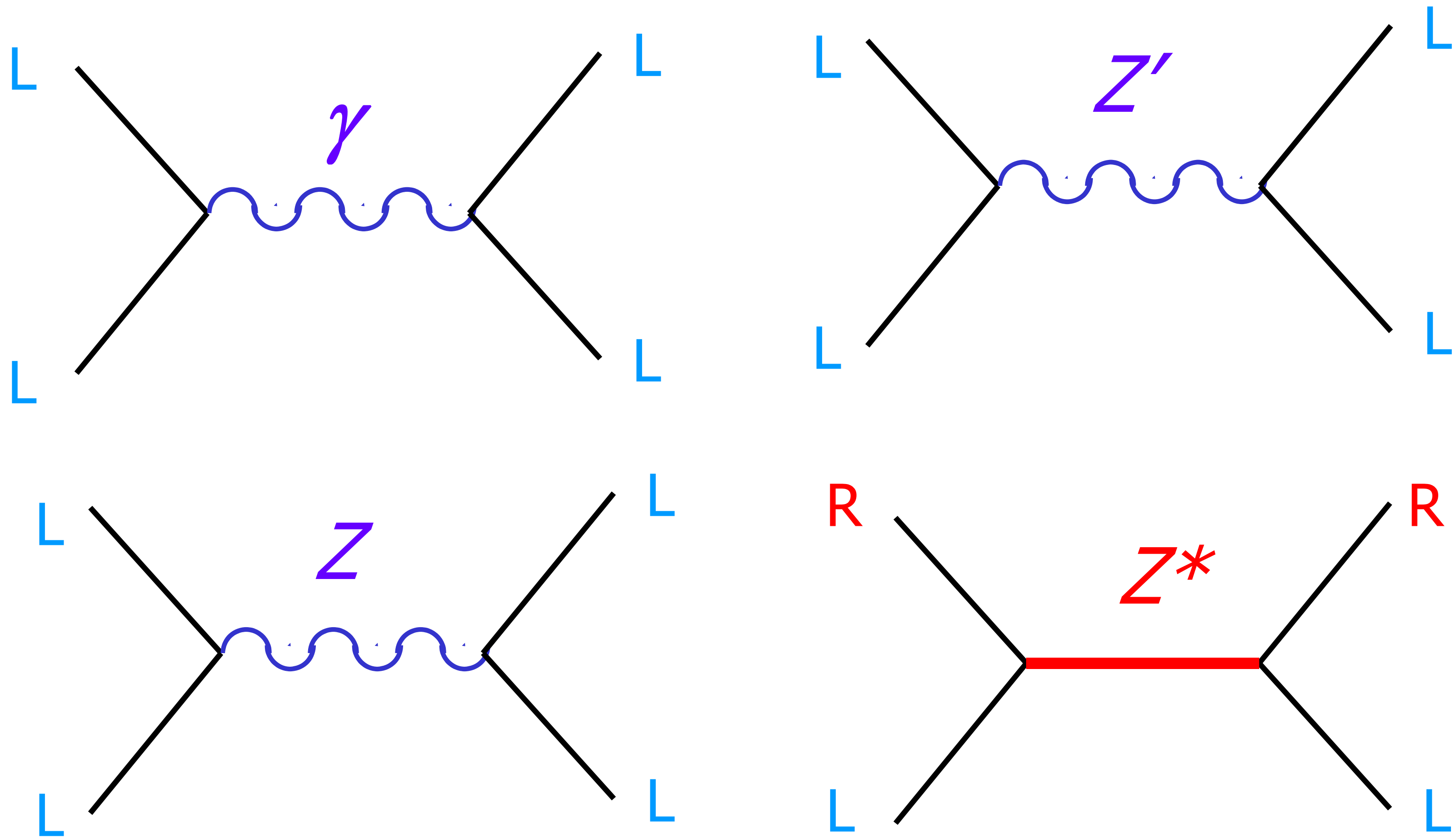
Mass $m = 1229.5 \pm 3.2$ MeV (S = 1.6)
Full width $\Gamma = 142 \pm 9$ MeV (S = 1.2)

techni-*b*, techni-*h*

$$\bar{q}\sigma^{\mu\nu}\gamma^5 q \cdot \left(\partial_\mu A^*_\nu - \partial_\nu A^*_\mu\right) \quad s=0, \; \ell=1$$

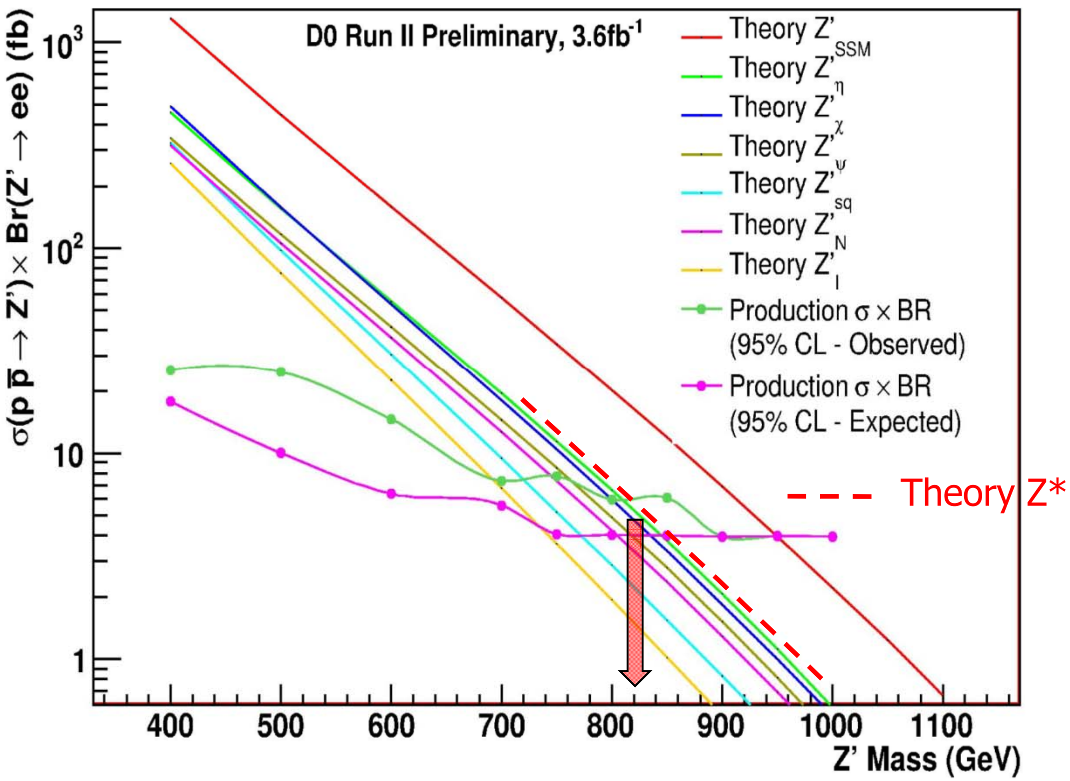
? ? ?

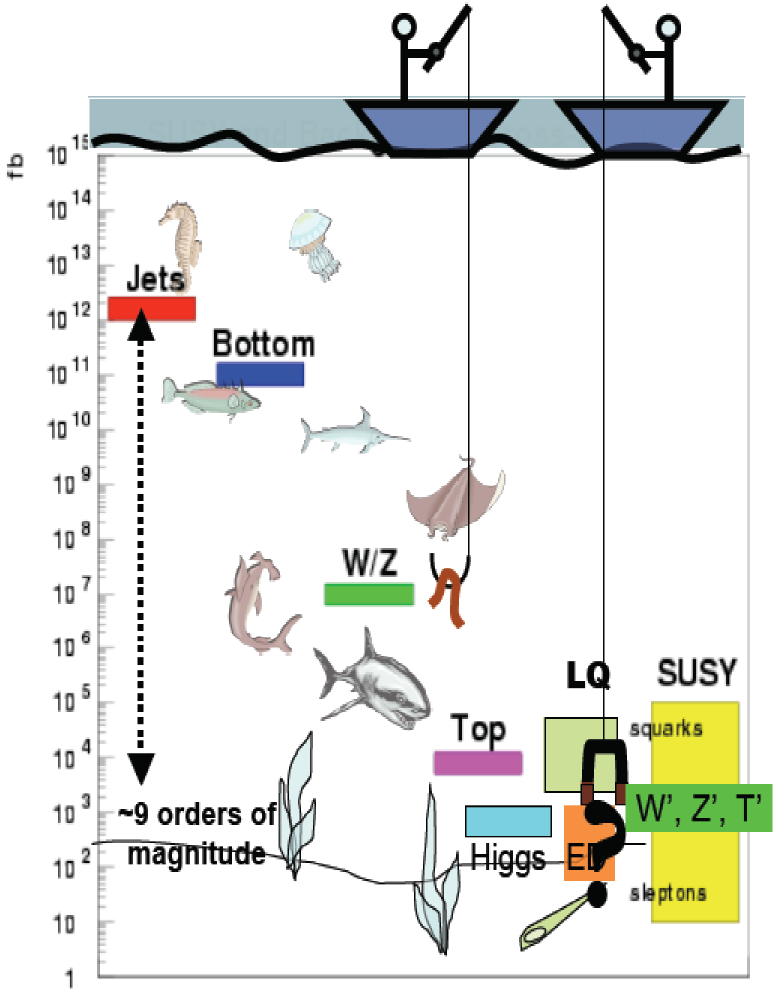
Electroweak interactions



Tevatron constraints on Z'

and Z*





From Aurelio Juste talk

Tevatron vs LHC competition

Tevatron: $\sigma(p\bar{p} \to Z'_{\mathrm{SSM}} \to ee) > \sigma(p\bar{p} \to Z^* \to ee)$

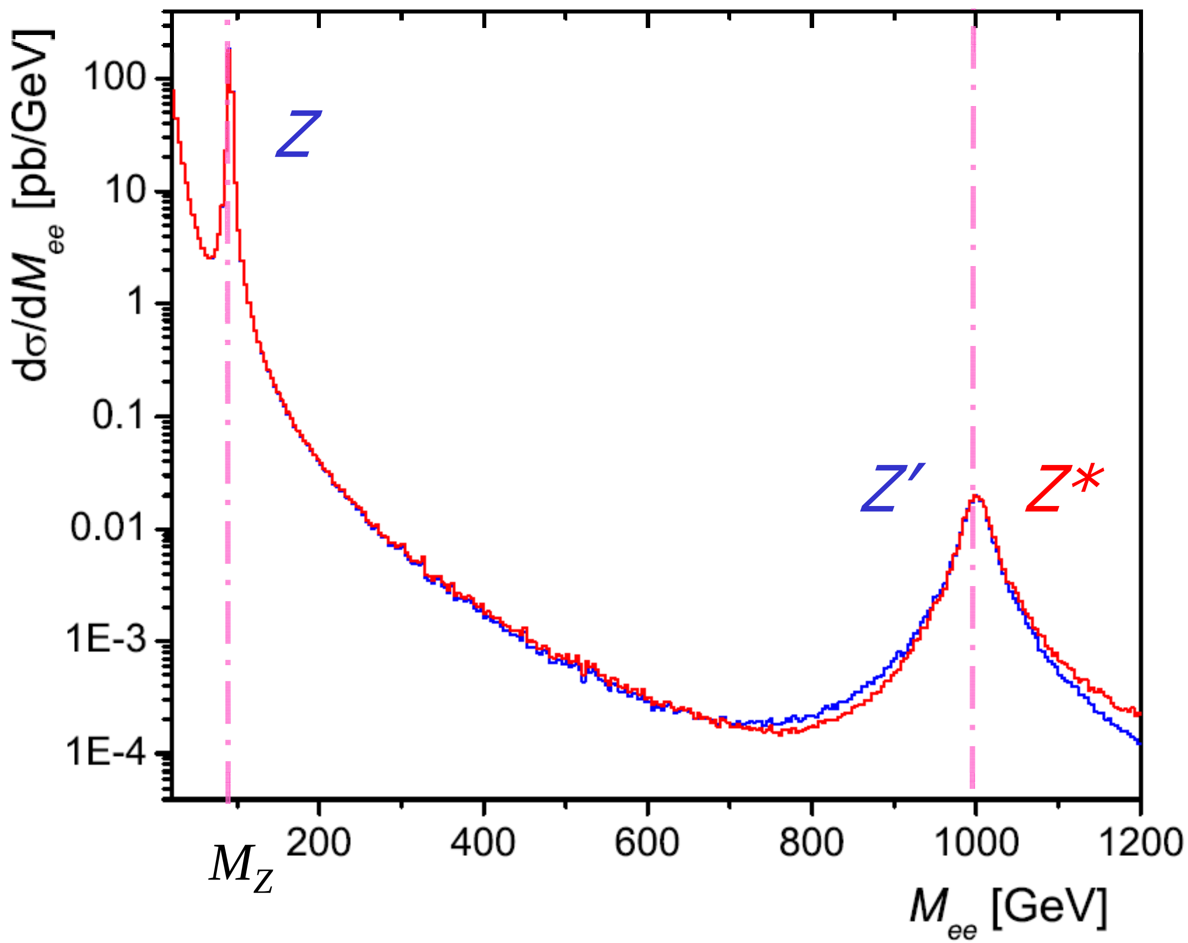
Exclusion limit: $M_{Z'_{\mathrm{SSM}}} > M_{Z^*}$

LHC: $\sigma(p\bar{p} \to Z'_{\mathrm{SSM}} \to ee) < \sigma(p\bar{p} \to Z^* \to ee)$

Exclusion limit: $M_{Z'_{\mathrm{SSM}}} < M_{Z^*}$

Invariant dilepton mass distributions

Several models predict new high mass neutral resonances that could decay into dilepton pairs(Z′, G, TC, KK, …)



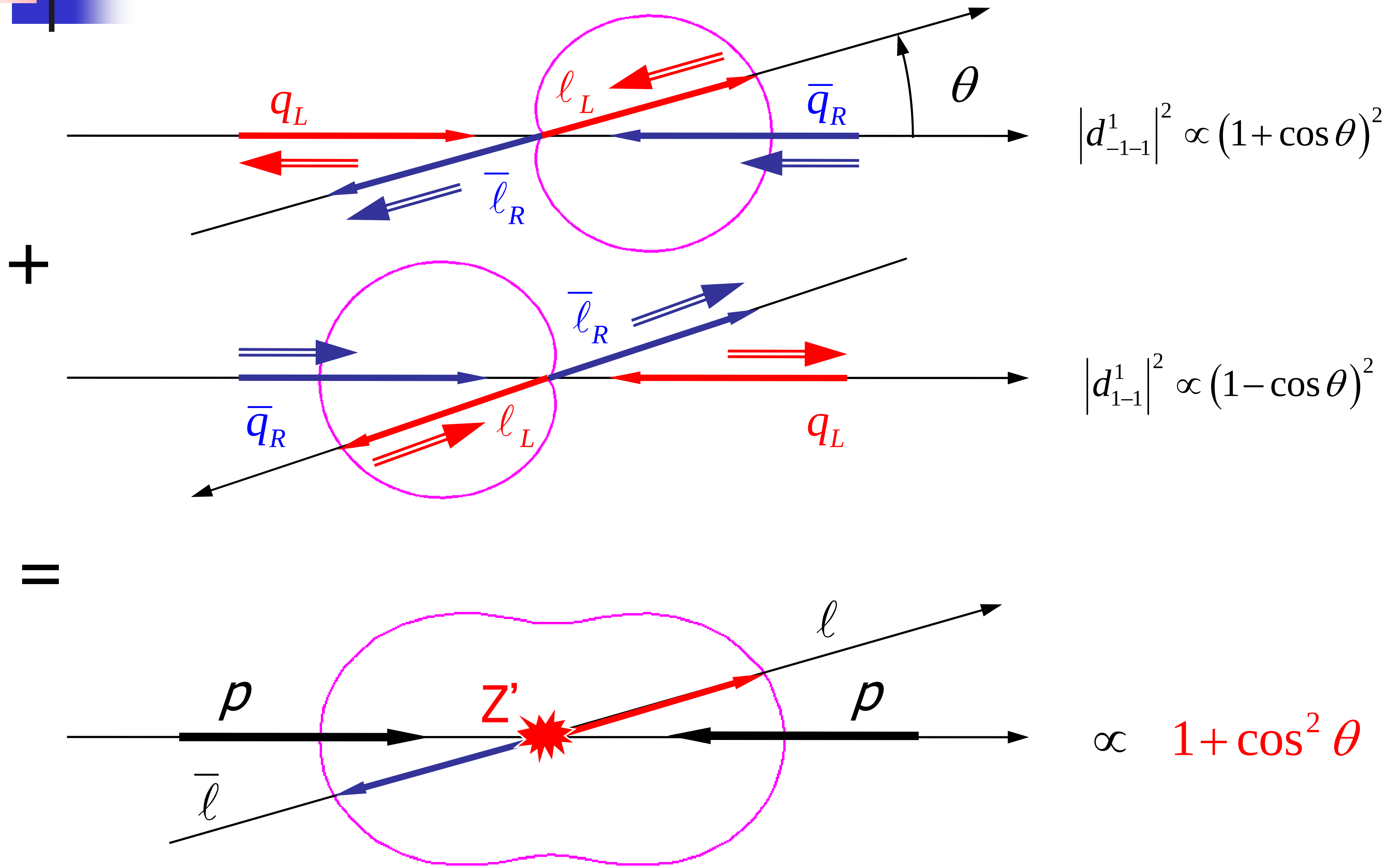
Two-body scattering process $A(\lambda_a) + B(\lambda_b) \to C(\lambda_c) + D(\lambda_d)$

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta\,\mathrm{d}\phi} = \frac{1}{64\pi^2 s}\left(\frac{p_f}{p_i}\right)\left|M_{\lambda_a\lambda_b;\lambda_c\lambda_d}(s,\theta,\phi)\right|^2, \quad \text{where} \begin{cases} p_f = \Delta^{1/2}\left(s, m_c^2, m_d^2\right)/2\sqrt{s}, \\ p_i = \Delta^{1/2}\left(s, m_a^2, m_b^2\right)/2\sqrt{s}, \\ \Delta\left(s, m_1^2, m_2^2\right) \equiv \left(s - m_1^2 - m_2^2\right)^2 - 4m_1^2 m_2^2 \end{cases}$$

$$M_{\lambda_a\lambda_b;\lambda_c\lambda_d}(s,\theta,\phi) = \sum_{J=\max\left\{\begin{smallmatrix}\lambda_i=\lambda_a-\lambda_b \\ \lambda_f=\lambda_c-\lambda_d\end{smallmatrix}\right\}}^{\infty} (2J+1)\, d^J_{\lambda_i\lambda_f}(\theta)\, \mathrm{e}^{\mathrm{i}(\lambda_i-\lambda_f)\phi} M^J_{\lambda_a\lambda_b;\lambda_c\lambda_d}(s)$$

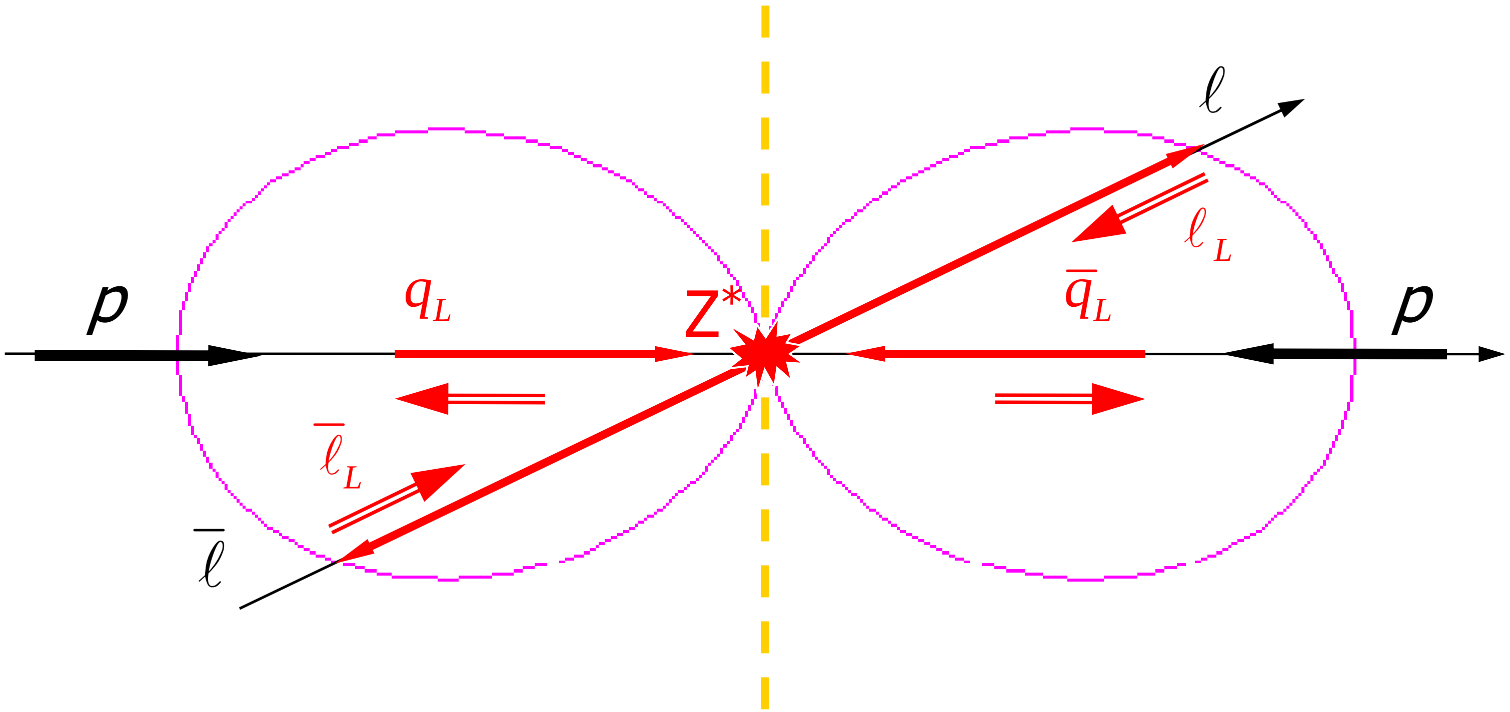
reduced matrix element

Angular distribution of Z'



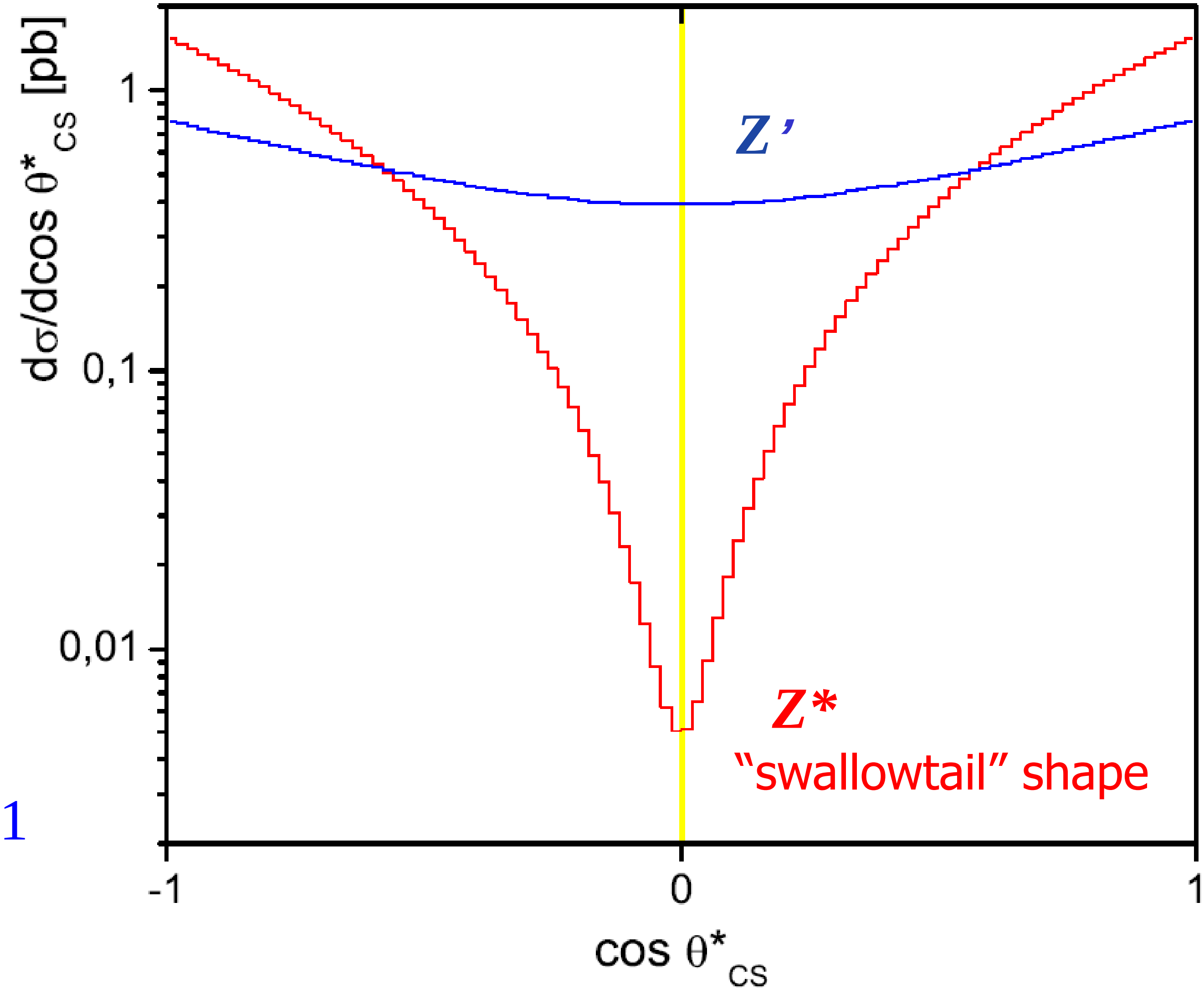
Angular distribution of Z*

In contrast to the Z' and W' bosons the excited bosons have anomalous couplings to matter.
This leads to a distinctive signature of their production at the hadron colliders.



$$\left|d^1_{00}\right|^2 \propto \cos^2\theta$$

Lepton angular distributions in Collins-Soper frame.



$A + B\cos^2 \vartheta_{CS}$

$Z' : A = B \approx 1$

$Z^* : A \approx 0,\ B \approx 1$

Spin-1 and graviton angular distributions

1102 CMS Collaboration

Table 3.10. Angular distributions for the decay products of spin-1 and spin-2 resonances, considering only even terms in $\cos\theta^*$.

Channel	d-functions	Normalised density for $\cos\theta^*$
$q\bar{q} \to G^* \to f\bar{f}$	$\lvert d^2_{1,1}\rvert^2 + \lvert d^2_{1,-1}\rvert^2$	$P_q = \frac{5}{8}(1 - 3\cos^2\theta^* + 4\cos^4\theta^*)$
$gg \to G^* \to f\bar{f}$	$\lvert d^2_{2,1}\rvert^2 + \lvert d^2_{2,-1}\rvert^2$	$P_g = \frac{5}{8}(1 - \cos^4\theta^*)$
$q\bar{q} \to \gamma^*/Z^0/Z' \to f\bar{f}$	$\lvert d^1_{1,1}\rvert^2 + \lvert d^1_{1,-1}\rvert^2$	$P_1 = \frac{3}{8}(1 + \cos^2\theta^*)$

$$P_1^* = \frac{3}{2}\cos^2\theta*$$

3.3.6. Discriminating between different spin hypotheses

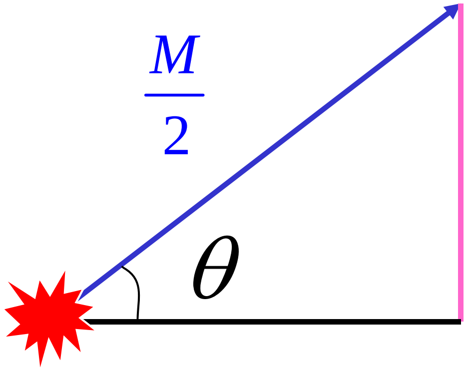
The fractions of generated events arising from these processes are denoted by ϵ_q, ϵ_g, and ϵ_1, respectively, with $\epsilon_q + \epsilon_g + \epsilon_1 = 1$. Then the form of the probability density $P(\cos\theta^*)$ is

$$P(\cos\theta^*) = \epsilon_q P_q + \epsilon_g P_g + \epsilon_1 P_1. \; + \varepsilon_1^* P_1^* \quad (3.24)$$

is not complete!

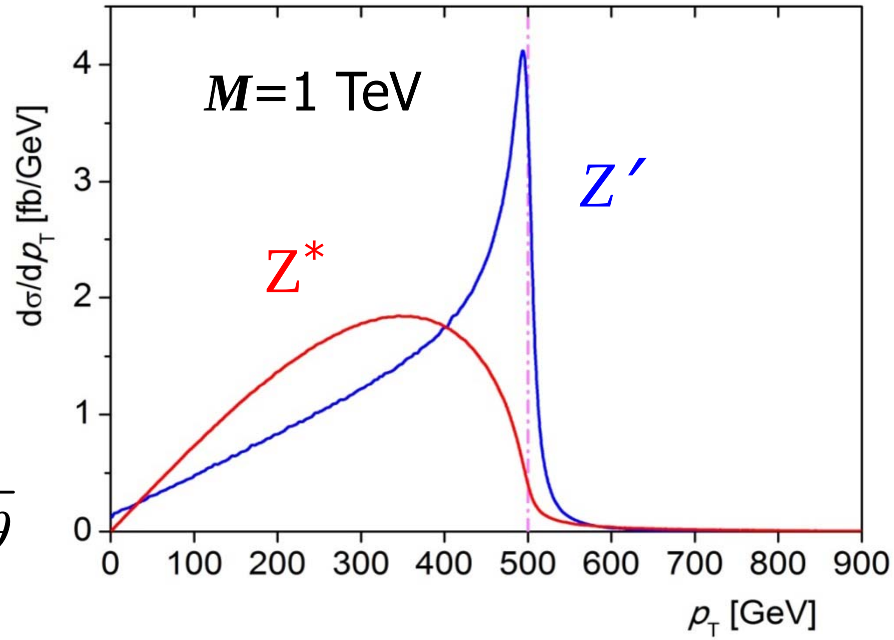
Unexpected consequence of new angular distribution

Jacobian factor for $\cos\theta \rightarrow p_T$



$$p_T = \frac{M}{2}\sin\theta$$

$$\frac{d\cos\theta}{dp_T} = -\frac{2\sin\theta}{M\cos\theta}$$



$$\frac{d\sigma}{dp_T} = \left|\frac{d\cos\theta}{dp_T}\right| \cdot \frac{d\sigma}{d\cos\theta} = \frac{2\sin\theta}{M\cos\theta} \cdot \frac{d\sigma}{d\cos\theta}$$

"The divergence at $\theta = \pi/2$ which is the upper endpoint $p_T \approx M/2$ of the p_T distribution stems from the Jacobian factor and is known as a *Jacobian peak*; it is characteristic of **all** two-body decays …"

Vernon D. Barger, Roger J.N. Phillips
"Collider Physics"

wrong!

CalcHEP calculations for $L = 200\ \mathrm{pb}^{-1}$ @ 7 TeV

In the case that such bosons will be observed as resonance peaks above the Z boson tail in the invariant dilepton mass distribution, we suggest to investigate in addition three more experimentally accessible distributions already on the early stage of the LHC data-taking.

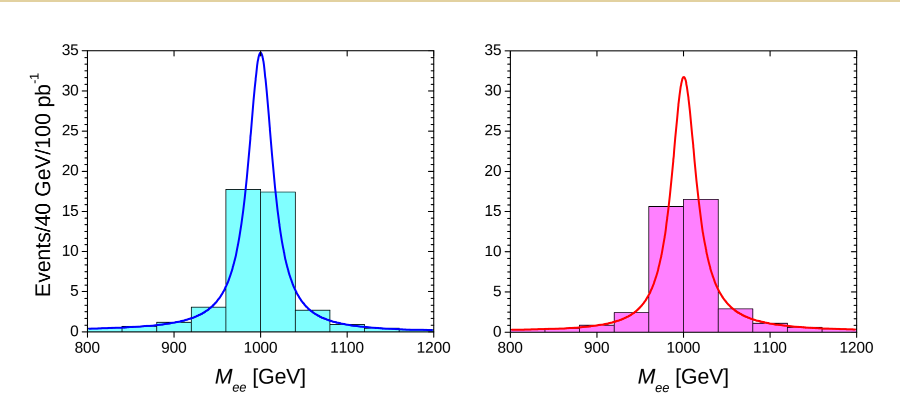
These are the differential distributions as a function of a transverse momentum of the lepton, the Collins–Soper angle and the difference of the pseudorapidities of the lepton and the antilepton.

All these distributions are related to the spin properties of the new boson and should play crucial role in the analysis of their interactions.

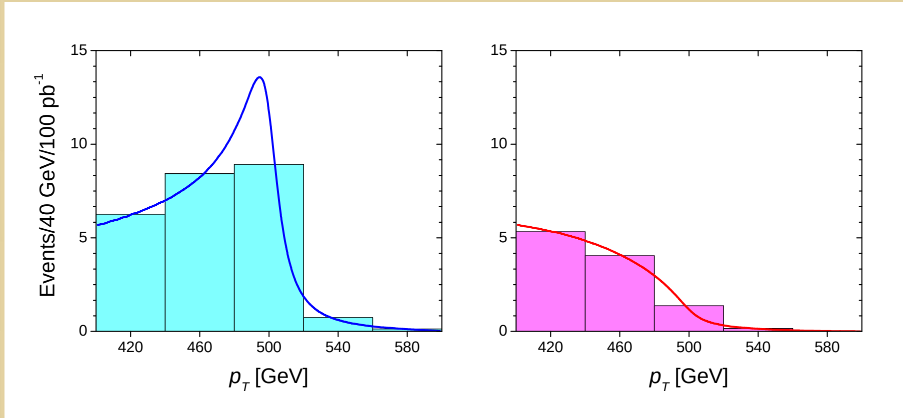
Comparison between Z′ and Z* for $M_{Z'} = M_{Z^*} = 1\ \mathrm{TeV},\ L = 200\ \mathrm{pb}^{-1}$ @ 7 TeV

M.C., Disentangling between Z′ and Z* with first LHC data, arXiv:0807.5087

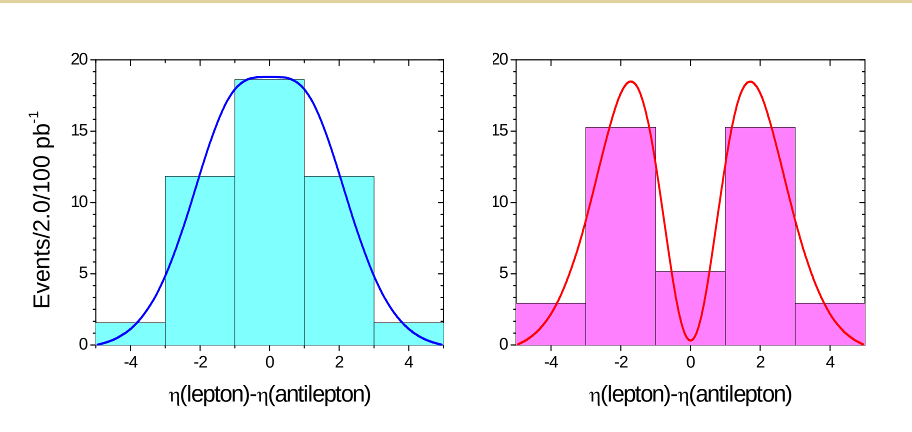
invariant mass



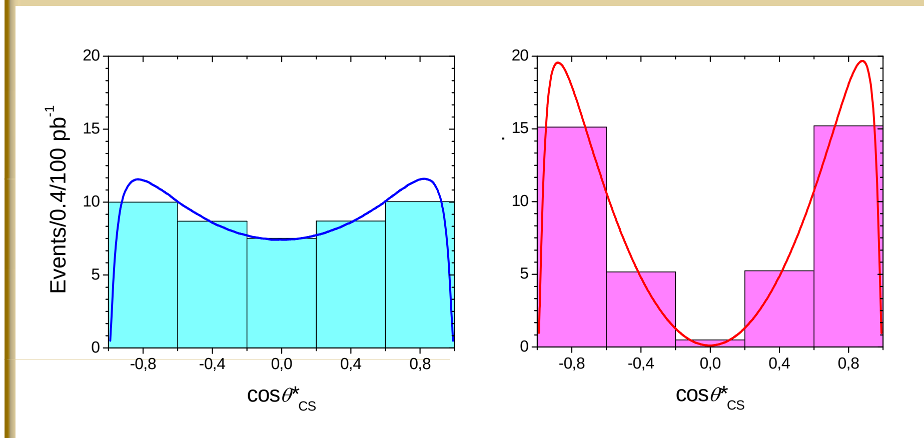
transverse momentum



pseudorapidity difference



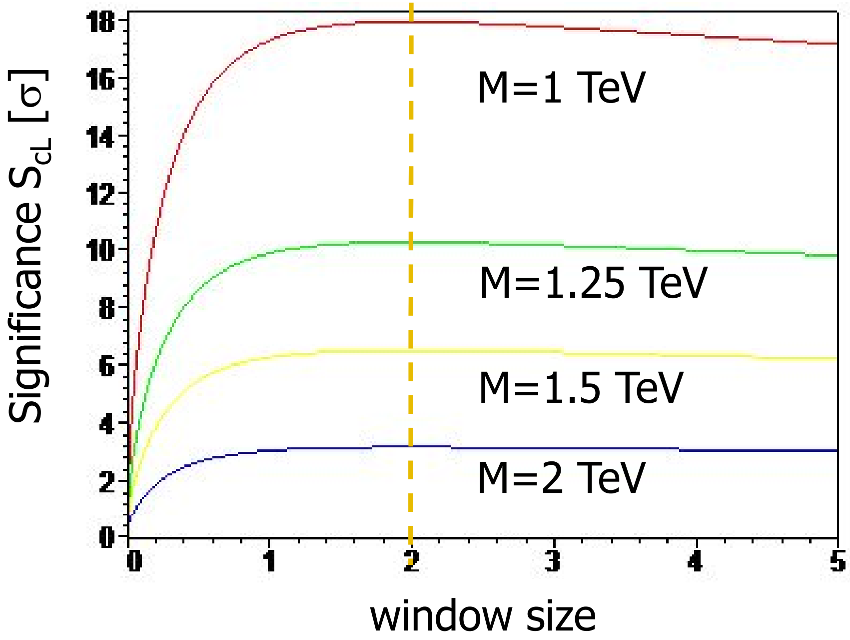
angular distribution

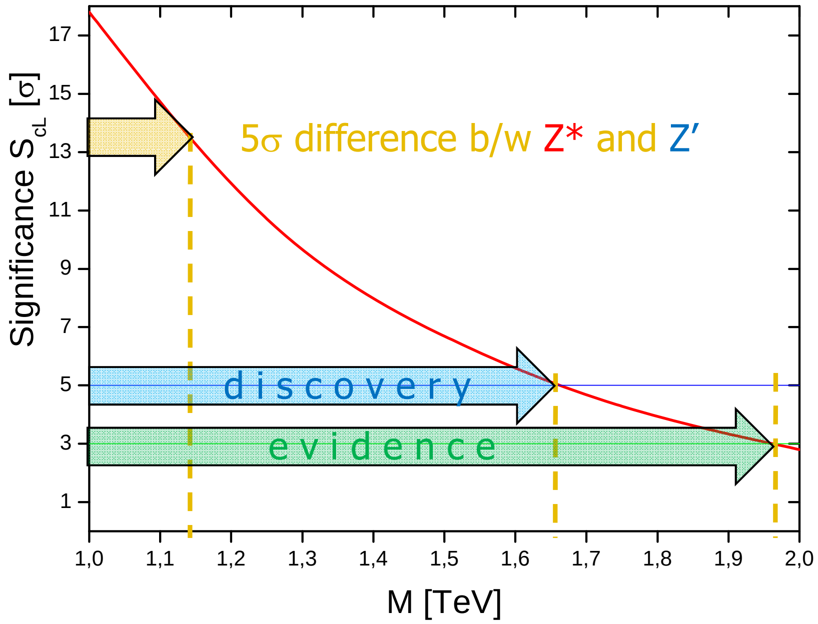


Discovery potential for $L = 200\ \text{pb}^{-1}$ @ 7 TeV

"Number Counting" approach $$S_{cL} = \sqrt{2\left[(s+b)\ln\left(1+\frac{s}{b}\right)-s\right]}$$

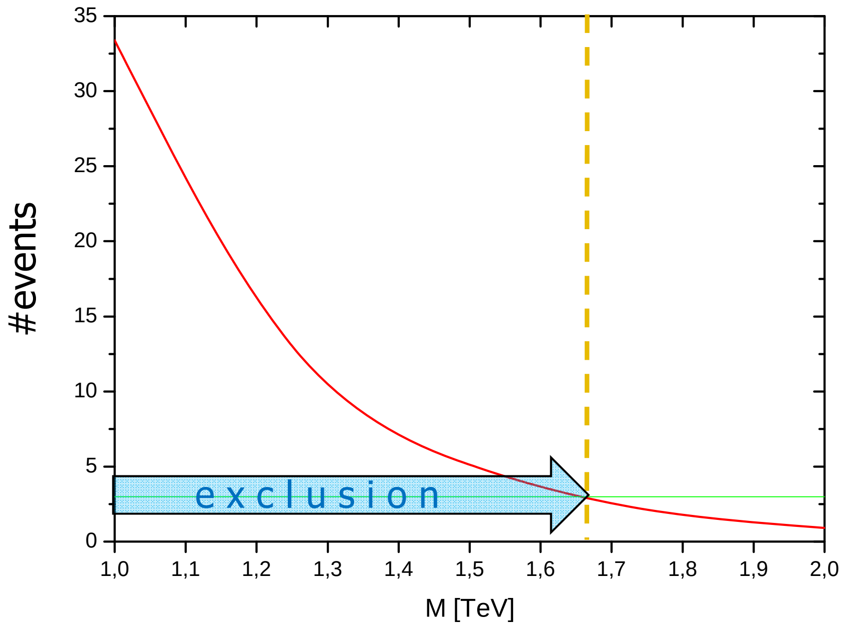
(without accepting of detector resolution and efficiencies)





Estimation of exclusion limit for $L = 200\ \text{pb}^{-1}$ @ 7 TeV

If looking for an excess in the invariant dilepton mass distribution with window $(1\pm0.07)M$ above 1 TeV we have not find any events (which is in agreement with the SM), then it is still allowed for 3 signal events to fluctuate down to 0 with probability of 5%.



Other early searches for 'exotics'

In ATLAS 'Exotics' refers to anything BSM besides SUSY and Higgs (SM, SUSY)

Other resonances...

- lepton – jet resonances
  - Leptoquarks
  - R-parity violating SUSY
  - E6-inspired exotic quarks → W or Z + jet
  - Heavy leptons → W or Z + lepton
- lepton – MET resonances
  - W' gauge bosons
  - W_H Little Higgs
- photon-jet or photon-lepton resonances
  - excited quarks
  - excited leptons

\+ excited bosons

... and spectacular signatures such as many high pt leptons and jets

- microscopic black holes from extra-dimensional models

Searches for excesses in tails will take longer

- e.g. Drell-Yan tail
  - Extra dimensions
  - Compositeness

ATL-PHYS-INT-2010-022

ATLAS NOTE

ATL-COM-PHYS-2009-609

November 13, 2009

Search for spin-1 excited bosons with ATLAS

M. V. Chizhov[1,2], V. A. Bednyakov[2], J. A. Budagov[2],
O. L. Fedin[3], V. P. Maleev[3], E. V. Sedykh[3]

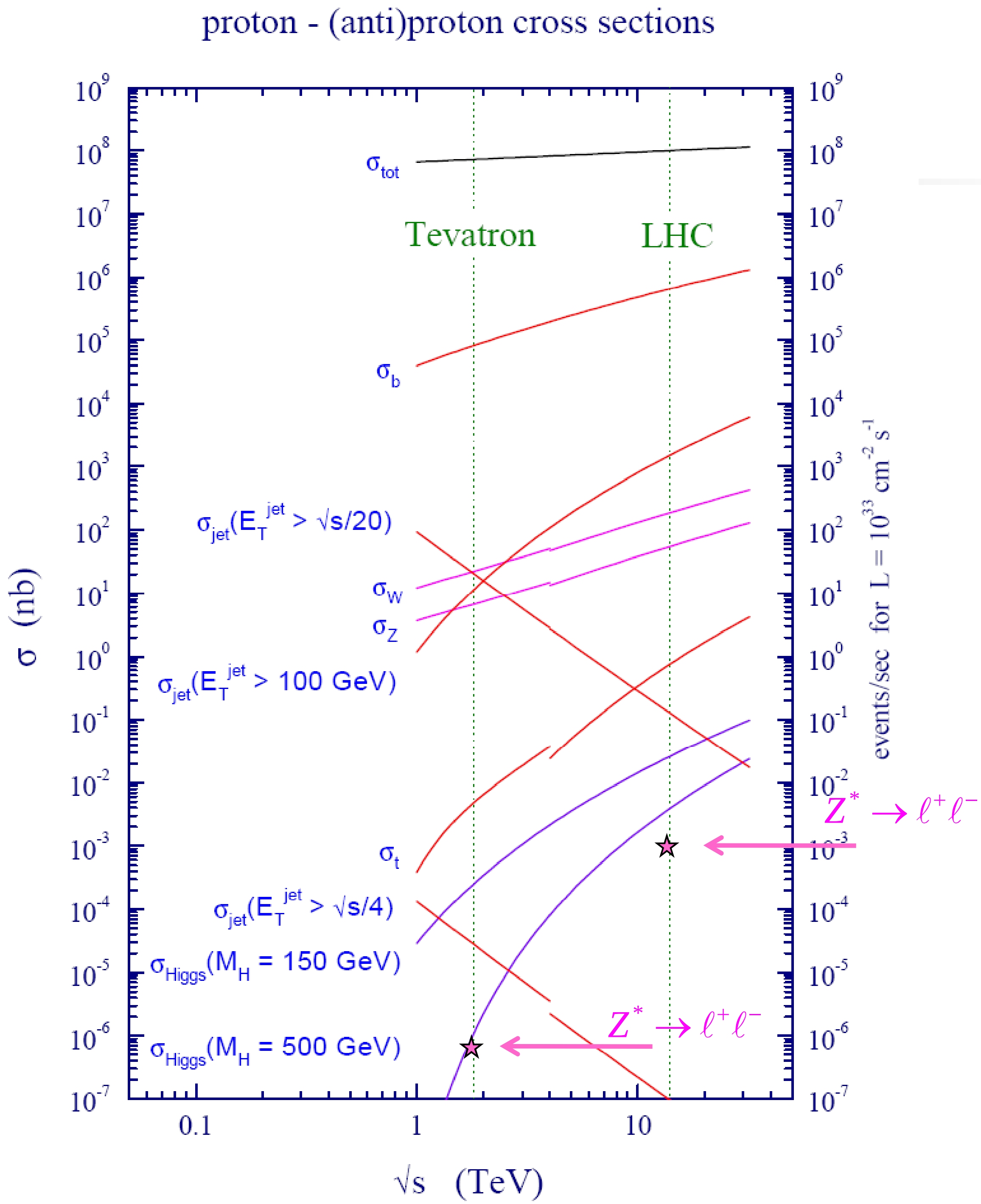
[1] Centre for Space Research and Technologies,
Faculty of Physics, University of Sofia, 1164 Sofia, Bulgaria
[2] Dzhelepov Laboratory of Nuclear Problems,
Joint Institute for Nuclear Research, 141980, Dubna, Russia
[3] Petersburg Nuclear Physics Institute,
Gatchina, Leningrad district 188300, Russia

Abstract

New excited neutral bosons, Z^*, can be produced at the hadron collider in the quark-antiquark channel and detected through their subsequent decays into lepton pairs. It makes them very interesting objects for early searches with the first few tens of pb^{-1} of the LHC data at $\sqrt{s} = 10$ TeV. Moreover, in contrast with the other heavy neutral resonances, they have unique signatures in transverse momentum, pseudorapidity and angular distributions, which help to discriminate them easily from others. In this note we present the event generation for the inclusive process $pp \to Z^* \to e^+e^-$ and preliminary results of ATLAS sensitivity to this process on the basis of full detector simulations.

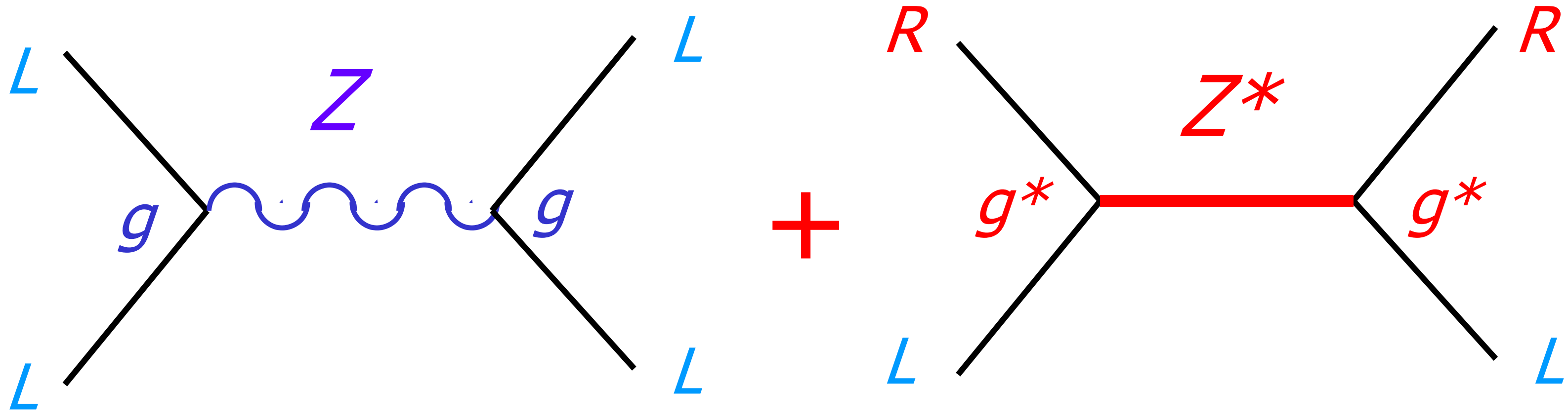
Conclusions

- There are intense searches for excited fermions, but not for bosons at electroweak scale.
- In contrast to the gauge bosons the excited bosons have anomalous couplings to matter. This leads to a distinctive signature of their production at the hadron colliders.
- The clearest channel for their discovery with early LHC data should be the dilepton one.
- With 200 pb^{-1} @ 7 TeV it is possible to discover the excited bosons with mass up to 1.65 TeV, if they are exist.
- However, disentangling between Z′ and Z* is possible only for the masses up to 1.15 TeV.
- In the case of absence of the signal, the excited bosons with masses up to 1.65 TeV will be excluded at the 95% C.L.
- Discovery of new type distributions will point out an existence of a compositeness, a new symmetry and, even, extra dimensions.



proton - (anti)proton cross sections
σ (nb)
events/sec for L = 10^33 cm^-2 s^-1
√s (TeV)
0.1
1
10
σ_tot
Tevatron
LHC
σ_b
σ_jet(E_T^jet > √s/20)
σ_W
σ_Z
σ_jet(E_T^jet > 100 GeV)
σ_t
σ_jet(E_T^jet > √s/4)
σ_Higgs(M_H = 150 GeV)
σ_Higgs(M_H = 500 GeV)
Z* → ℓ+ℓ−
Z* → ℓ+ℓ−

Electroweak physics



$G_F \sim (g/M_W)^2$ $\quad$ $G_T \sim (g^*/M_T)^2$

if $g^* \sim g$ *and* $G_T \sim 10^{-2} G_F$: $\quad M_T \sim 10\, M_W$

(centiweak interaction)

$$\mathcal{L}_{\left(Z^{*}W^{*}\right)} = \frac{g_u}{\Lambda}\left(\bar{u}_L\ \bar{d}_L\right)\sigma^{\mu\nu}u_R \cdot \left[\partial_\mu\begin{pmatrix} Z_\nu^{*} \\ W_\nu^{*-} \end{pmatrix} - \partial_\nu\begin{pmatrix} Z_\mu^{*} \\ W_\mu^{*-} \end{pmatrix}\right]$$

$$+\frac{g_d}{\Lambda}\left(\bar{u}_L\ \bar{d}_L\right)\sigma^{\mu\nu}d_R \cdot \left[\partial_\mu\begin{pmatrix} -W_\nu^{*+} \\ \bar{Z}_\nu^{*} \end{pmatrix} - \partial_\nu\begin{pmatrix} -W_\mu^{*+} \\ \bar{Z}_\mu^{*} \end{pmatrix}\right] + \text{h.c.}$$