Search for TeV-scale bosons in the μ+μ- decay channel in CMS

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- Motivation
- Extensions of the Standard Model and Beyond the SM
  - Extended Gauge Models (Z')
  - RS1-scenario (KK-graviton resonance)
- Cross-sections and expected rates
- Background (DY)
- Forward-backward asymmetry
- Angular distributions
- Conclusions

General Motivations

- the current measurements (D0, CDF) of the Drell-Yan cross-section at high dilepton invariant mass (up to 0.6 TeV) are in good agreement with the Standard Model predictions (NLO)

- study of high mass dileptons at LHC allows one to test the SM at a new energy scale (Drell-Yan production up to 1 ÷ 4 TeV invariant mass region)

- dilepton continuum is very sensitive to any modifications of SM Lagrangian induced by new physics beyond the SM
  - Extended gauge models (Sequential Standard Model, Left-Right Model, E6-, SO(10)- based models)
    - ✓ new gauge bosons, W′ and Z′
    - ✓ horizontal bosons, R
    - ✓ new Higgs bosons, H++, H--
  - Large extra dimension scenarios (ADD, RS, NLED's)
  - Compositeness models

Motivations for dimuon study

- many models beyond the SM predicted new heavy (m ~ a few TeV) boson states
  - Extended gauge models (Z', spin1-state, from SSM, LRM, E6)

    C.-E. Wulz, CMS-NOTE 1993/107

  - Large extra dimension scenarios, Randall-Sundrum RS1 (G_{KK}-graviton, spin-2 state)

    P.Traczyk and G.Wrochna, CMS-NOTE 2002/003,
    M.-C.Lemaire and J.-P.Pansart, CMS-NOTE 2002/020

- di-muon channel is a clear and simple signature of resonances
  - concentrate within certain mass interval
  - good isolation
  - both muons come from the same vertex
  - good effective mass and angular resolution for high-p_T muons
  - low background

Simulation Tools

Signal (Z´) and background (DY) simulation

Pythia 6.217, qqbar → Z´ (no jet veto, other production mechanisms qg → qZ´ will be added in the future) ,

CTEQ5L, K(Z´)= 1, K_{DY} = 1.38

Initial- and final-state radiation are switched on

SSM: Br(μ+μ-) = 0.032

LRM: ⇨ assume *the same* couplings for both left- and right-handed sectors:
$g_L / g_R = 1$ (value as in the SM)
⇨ Br(μ+μ-) = 0.023

χ-, ψ-, and η-models: couplings from J.Rosner, *Phys. Rev.* D35, 2244 (1987)

G_{KK} simulation

Pythia 6.217, qqbar → G_{KK}, gg → G_{KK}, qqbar → gG_{KK}, qg → qG_{KK}, gg → gG_{KK}

Detector Response and Reconstruction

Fast non-GEANT simulation: CMSJET 4.7 (detector response are taken into account by smearing of energy/momentum according to some resolution)

Background

SM Background

- main SM background comes from DY process with large invariant dilepton ($\mu^+\mu^-$) masses
  - an irreducible SM background goes down rapidly when $M_{\mu+\mu-}$ grows
  - at present, no exact NLO and NNLO matrix elements have been used, we have used K = 1.38 (from Tevatron data) for M > 1 TeV
  - σ (Mμ+μ- > 1 TeV) = 9.07 fb (Pythia 6.217)

- Di-bosons: ZZ, WW, ZW (is not taken into account)
  - σ (Mμ+μ- > 1 TeV) = 0.4 fb, less then 4.5 % of Drell-Yan, K=1.4-1.9

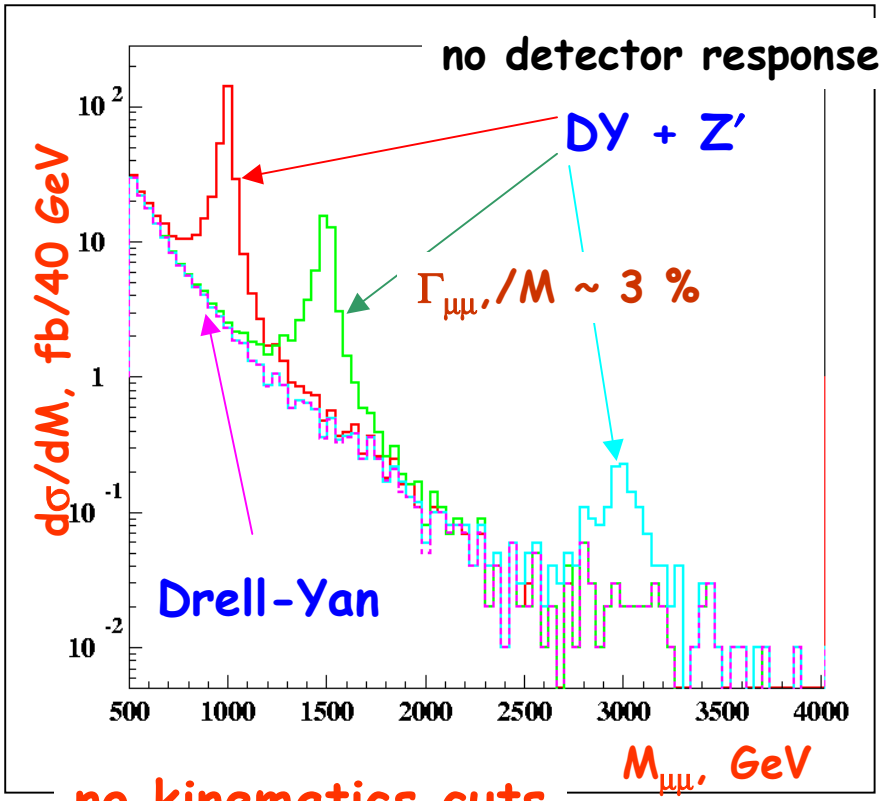
- ttbar-quark (is not taken into account)
  - σ (Mμ+μ- > 1 TeV) = 0.3 fb, ~ 3 % of Drell-Yan, K=1.6

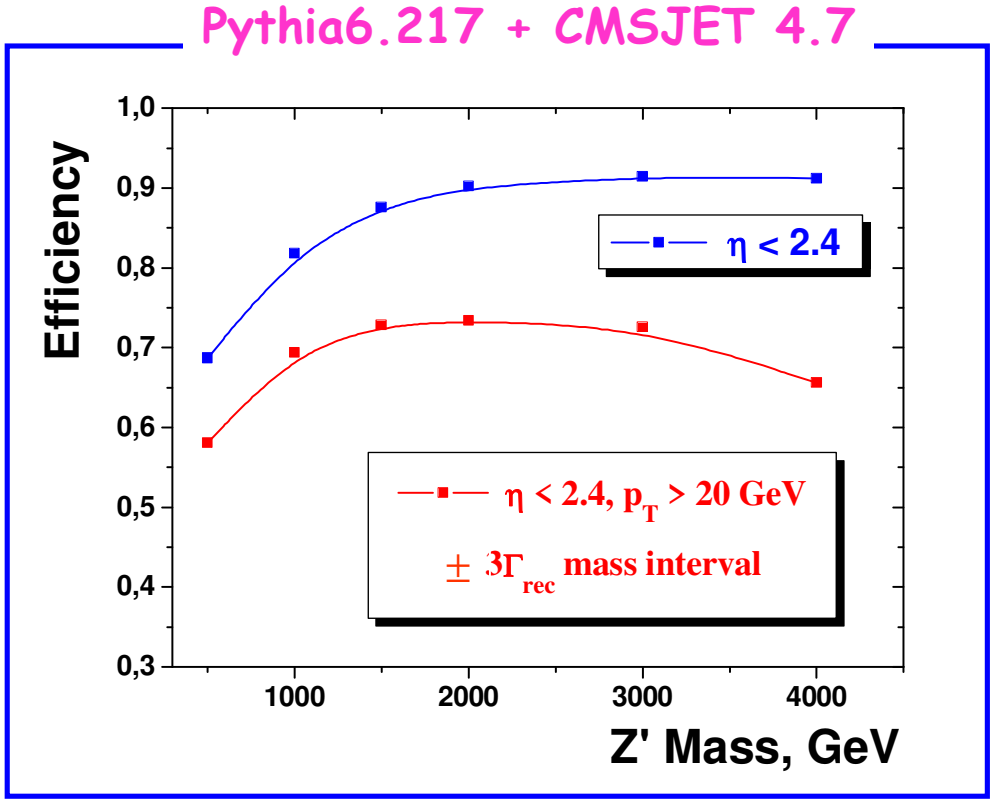
Z′-bosons

Expected Z′ $\rightarrow \mu^+\mu^-$ Rate

we assume no exotic fermions (n_G=0) for SSM, χ-, η-, ψ-models (Br_μ = 0.032)

number of extra fermion generations is n_G=3 (right-handed fermions) for LRM (Br_μ = 0.023)





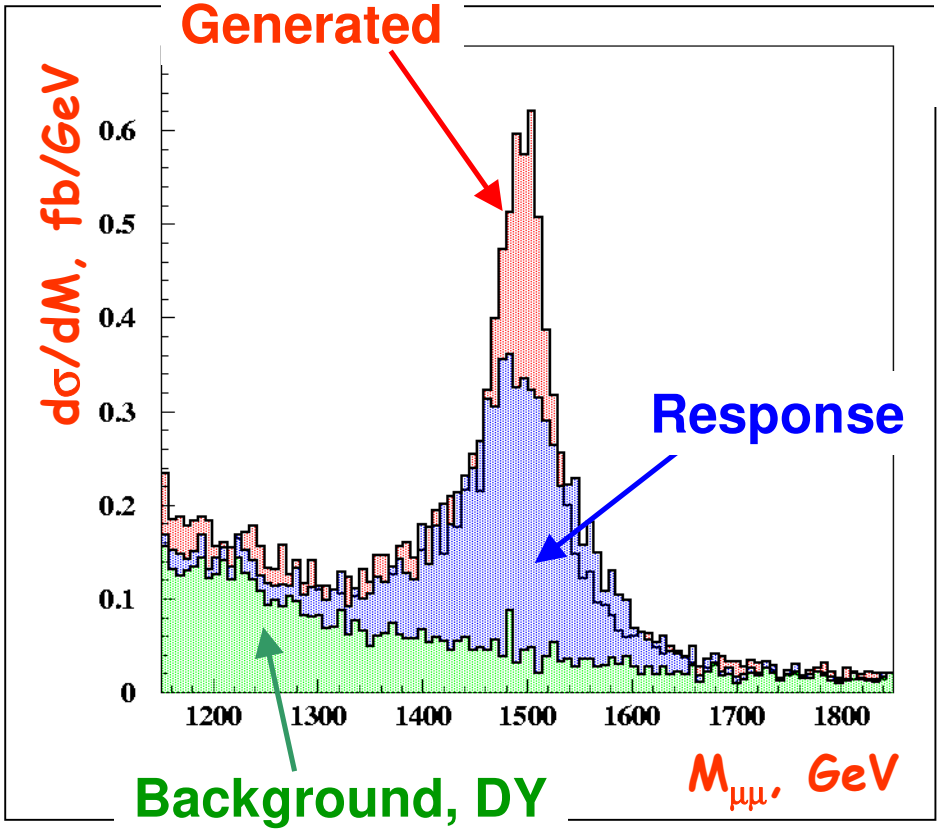
Discovery Limit for Z′

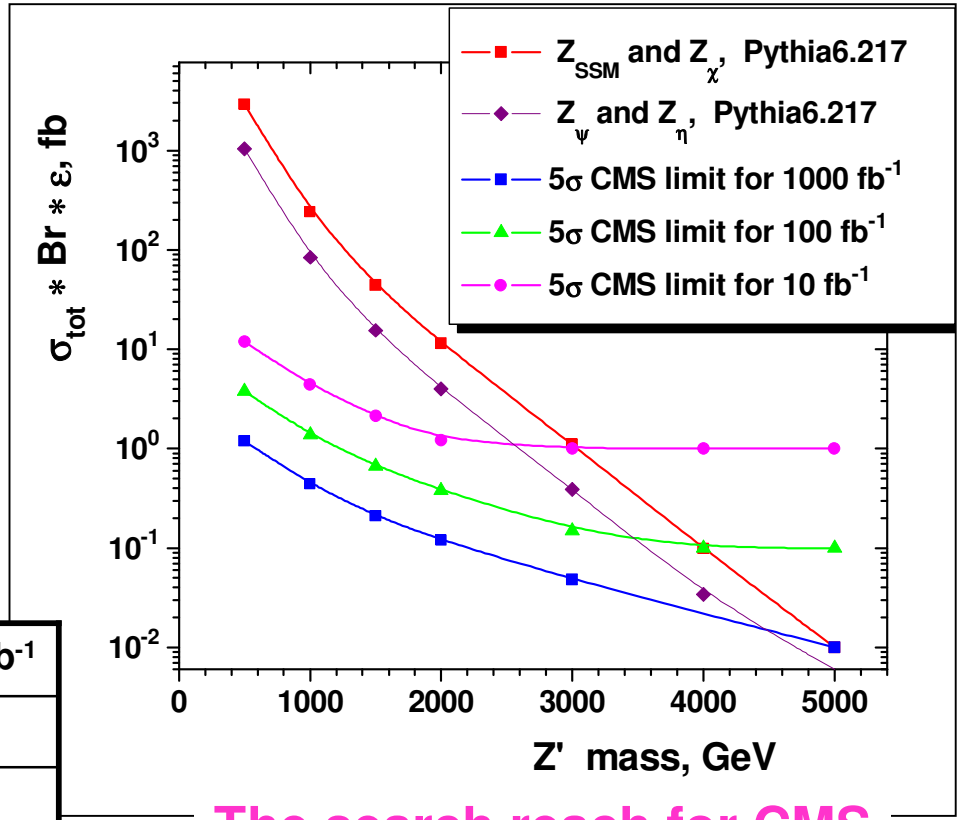
Pythia 6.217 + CMSJET 4.7

$N_{min} = \max(5\sqrt{N_B},\ 10)$

N_B is the number of Drell-Yan background inside $\pm 3\Gamma_{rec}$ mass window after cuts

$|\eta| \le 2.4,\ p_T \ge 20$ GeV





	10 fb^{-1}	100 fb^{-1}	1000 fb^{-1}
SSM, χ-model	3.01	3.96	5.0
ψ- and η-models	2.54	3.46	4.48
LR-model	2.96	4.08	5.35

The search reach for CMS (in TeV)

Z′ Forward-Backward Asymmetry

$$A_{FB}(y) = \frac{F(y) - B(y)}{F(y) + B(y)}$$

qqbar → Z′→ μ+μ-

F(y) is number of μ with cos(θ*) > 0,
B(y) is number of μ with cos(θ*) < 0,
θ* is the angle in the di-muon C.M. (Z′ rest frame) between the μ- and one (fixed) of the proton beams,
y is Z′ rapidity

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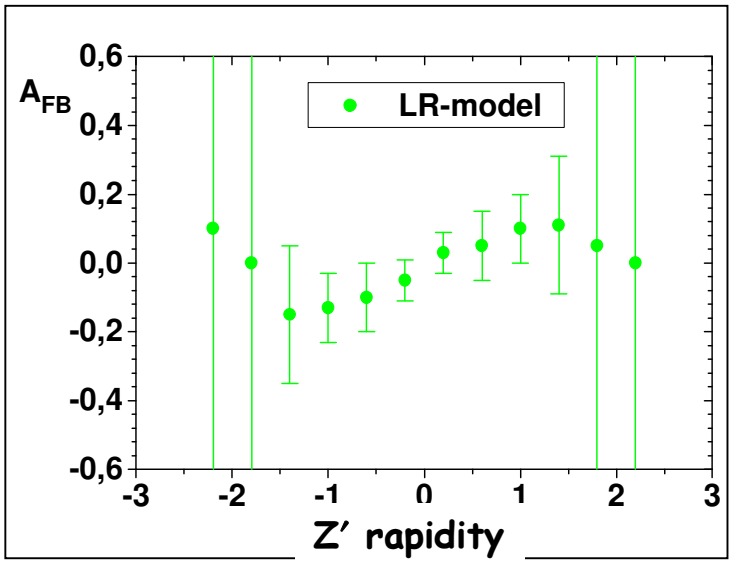
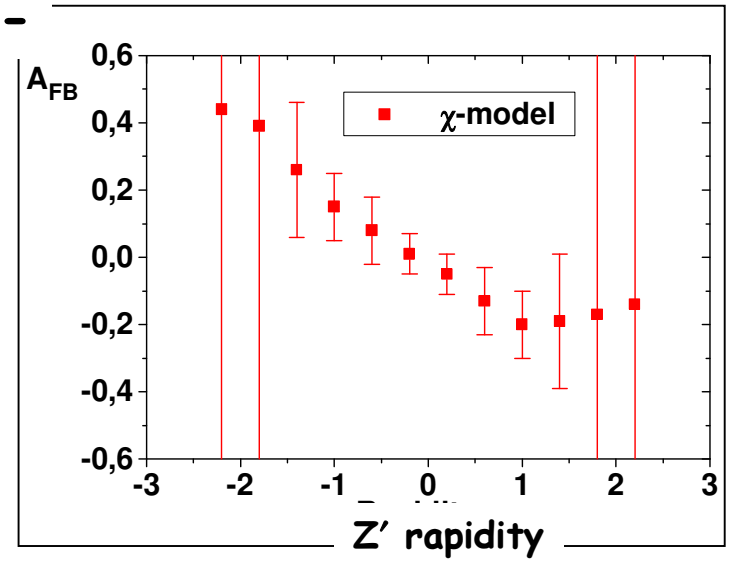
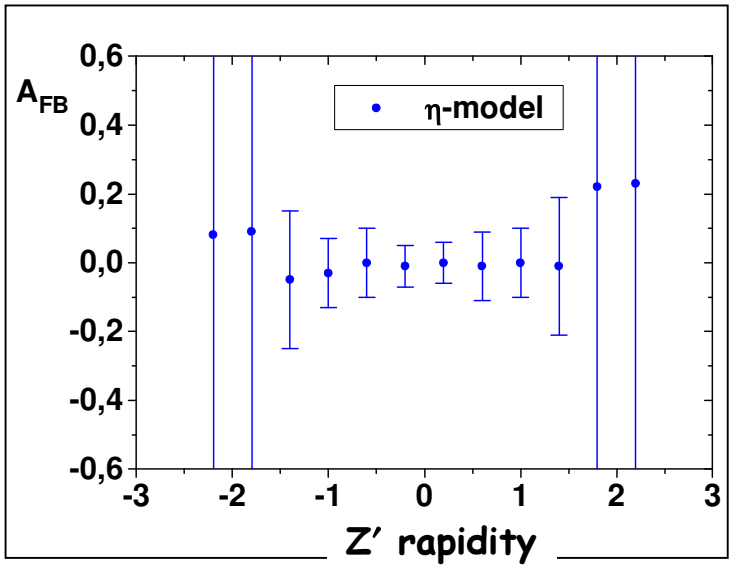
$M_{Z'}$ = 2.0 TeV

100 fb^{-1}





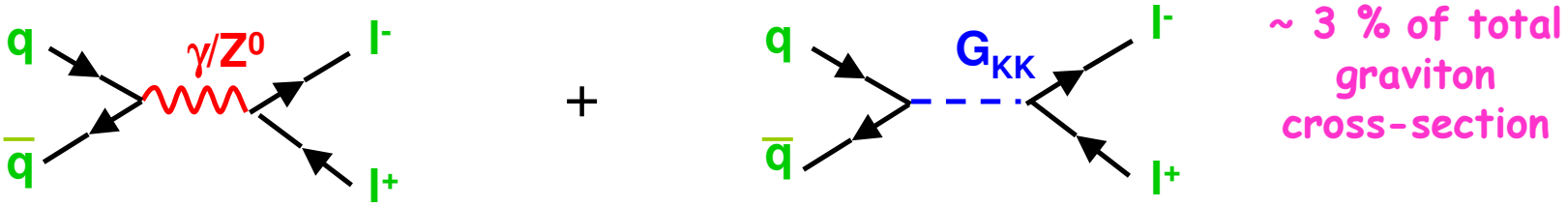


rapidity-dependence of forward-backward asymmetry in Z′→μ⁺μ⁻ decays for various models has a very distinctive behaviour

G_{KK}-resonance

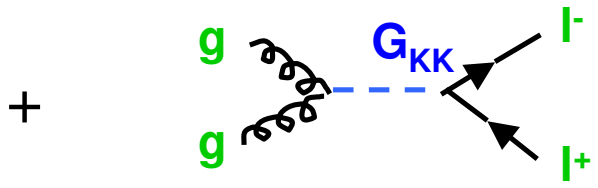
G_{KK} graviton production (RS1)

- virtual production
  - the SM exchange by γ or Z boson interferes with the exchange by graviton ($qq \rightarrow G_{KK} \rightarrow \mu^+\mu^-$)



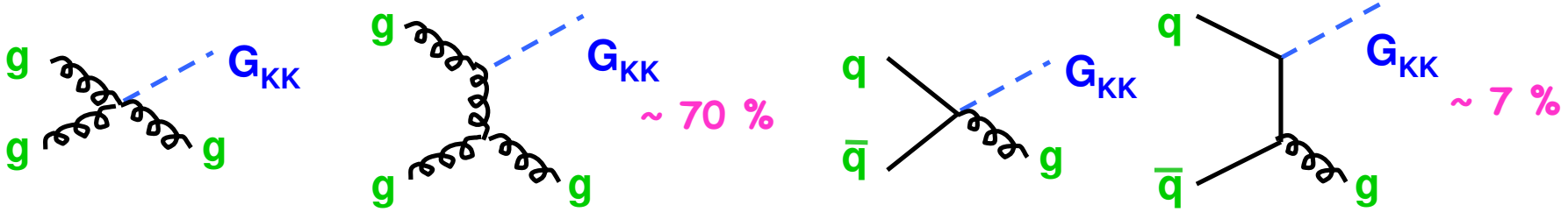
~ 3 % of total graviton cross-section

  - there is also gluon-gluon initiated graviton exchange process which has no the SM analogue ($gg \rightarrow G_{KK} \rightarrow \mu^+\mu^-$)



~ 10 - 11 %

- real graviton production, i.e. graviton emission ($qq \rightarrow gG_{KK}$, $qg \rightarrow qG_{KK}$, $gg \rightarrow gG_{KK}$ with $\mu^+\mu^-$ + jet in the final state)



~ 70 %

~ 7 %

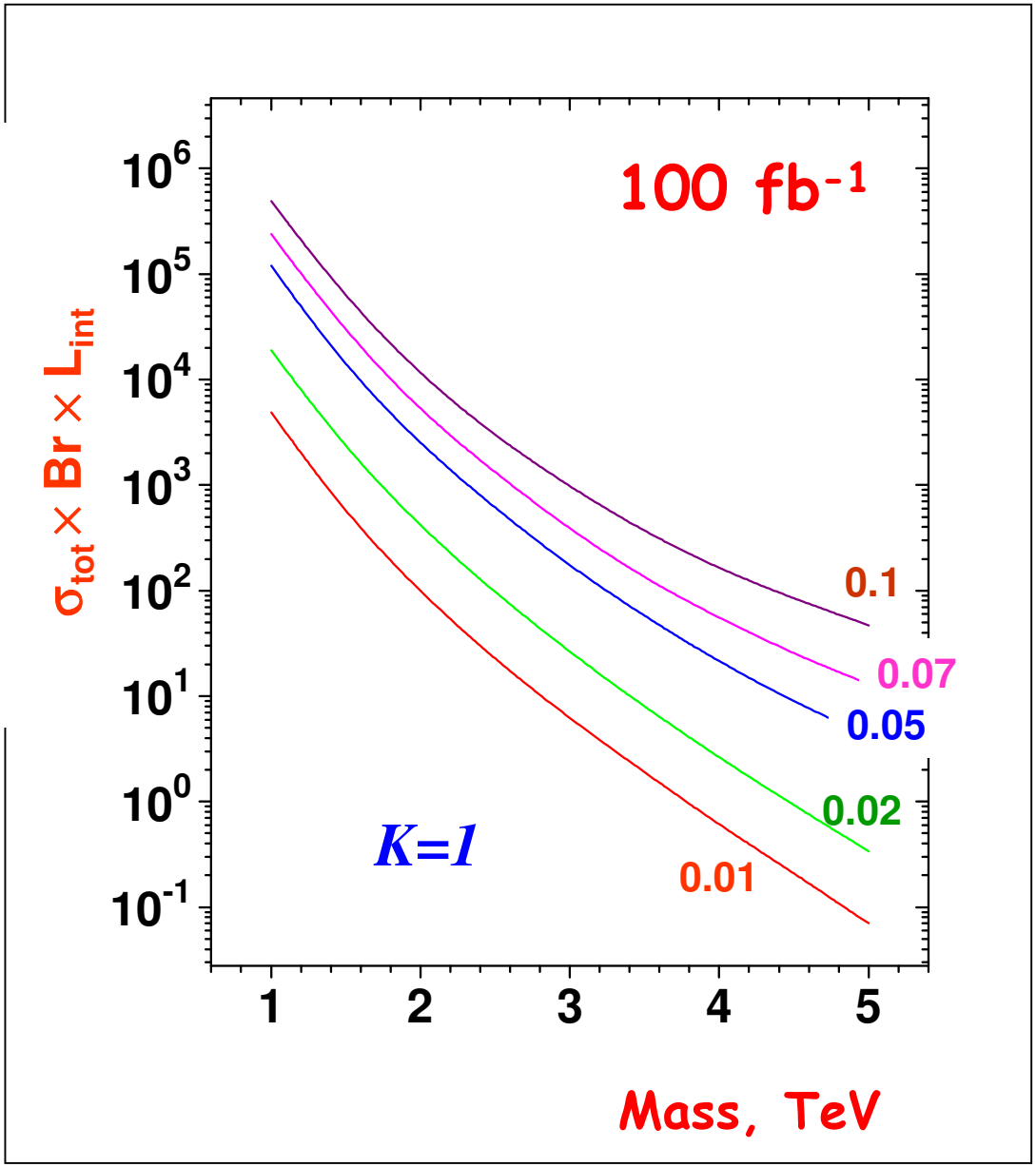
Expected $G_{KK} \rightarrow \mu^+\mu^-$ Rates

5 diagrams were computed (virtual and real graviton production)

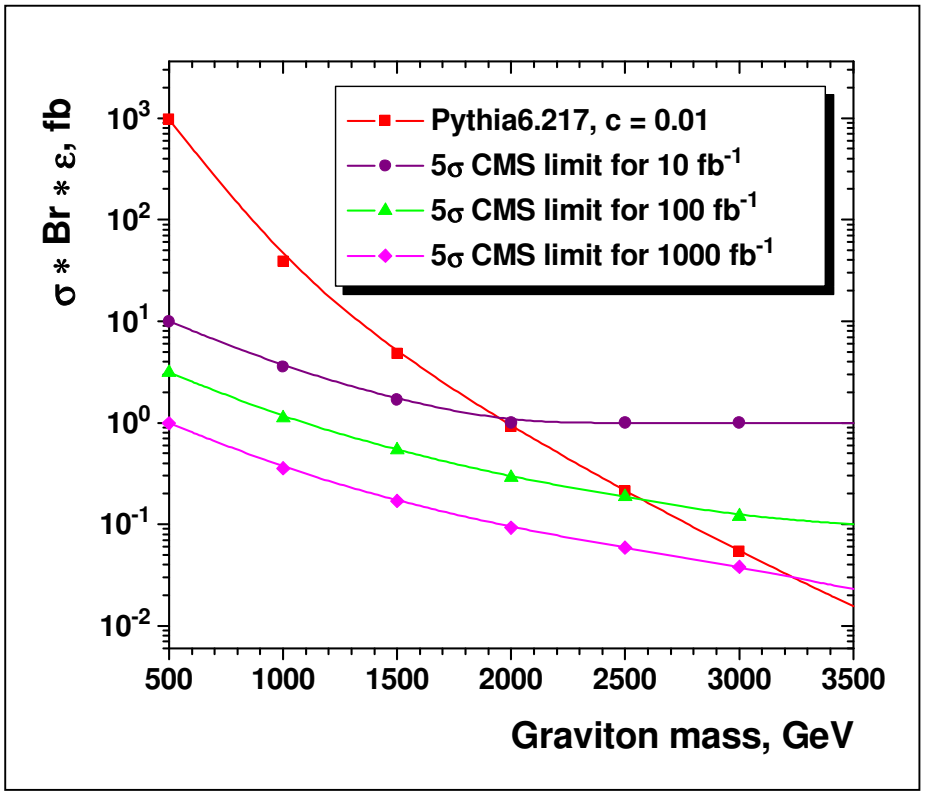
Br ($G_{KK} \rightarrow \mu+\mu-$) = 0.0205

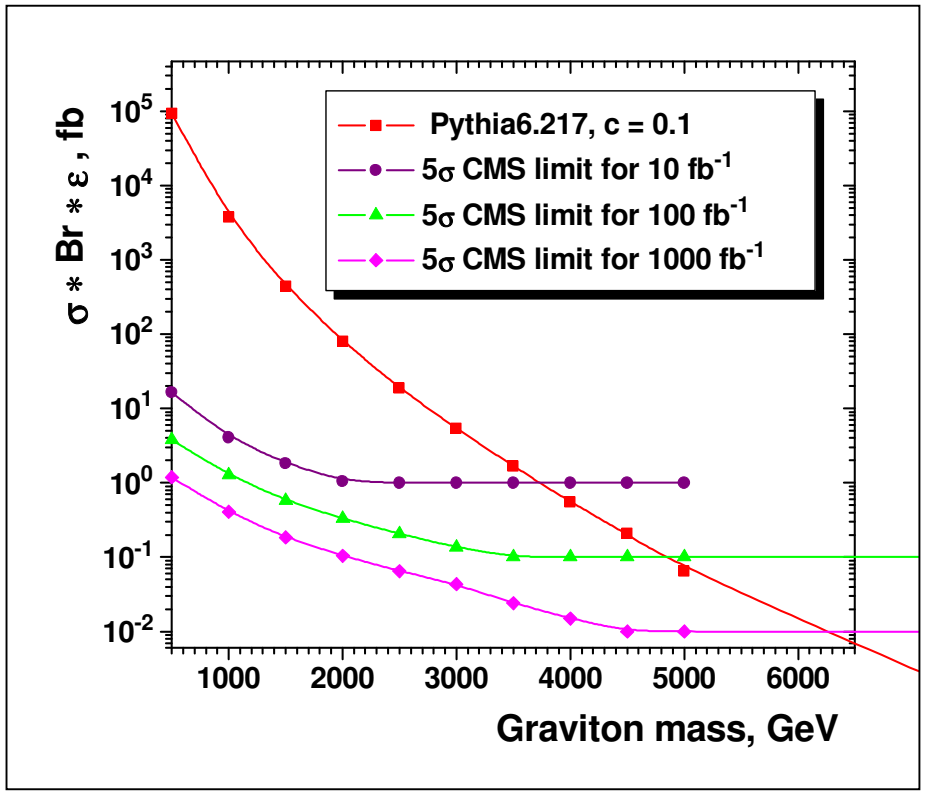
$G_{KK} \rightarrow \mu+\mu-$ rates were computed for the different coupling constants
$c = k/M_{Pl}$ = 0.01, 0.02, 0.05, 0.07, 0.1

k is the AdS_5 curvature



Discovery Limit for G_{KK}





The search reach for CMS (in TeV)

	10 fb^{-1}	100 fb^{-1}	1000 fb^{-1}
c = 0.01	1.95	2.58	3.22
c = 0.1	3.74	4.84	6.25

CMS is able to test RS1 scenario up to 1.95 TeV and 3.74 TeV mass limit for c = 0.01 and c = 0.1, respectively, even at 10 fb^{-1}

Angular Distributions

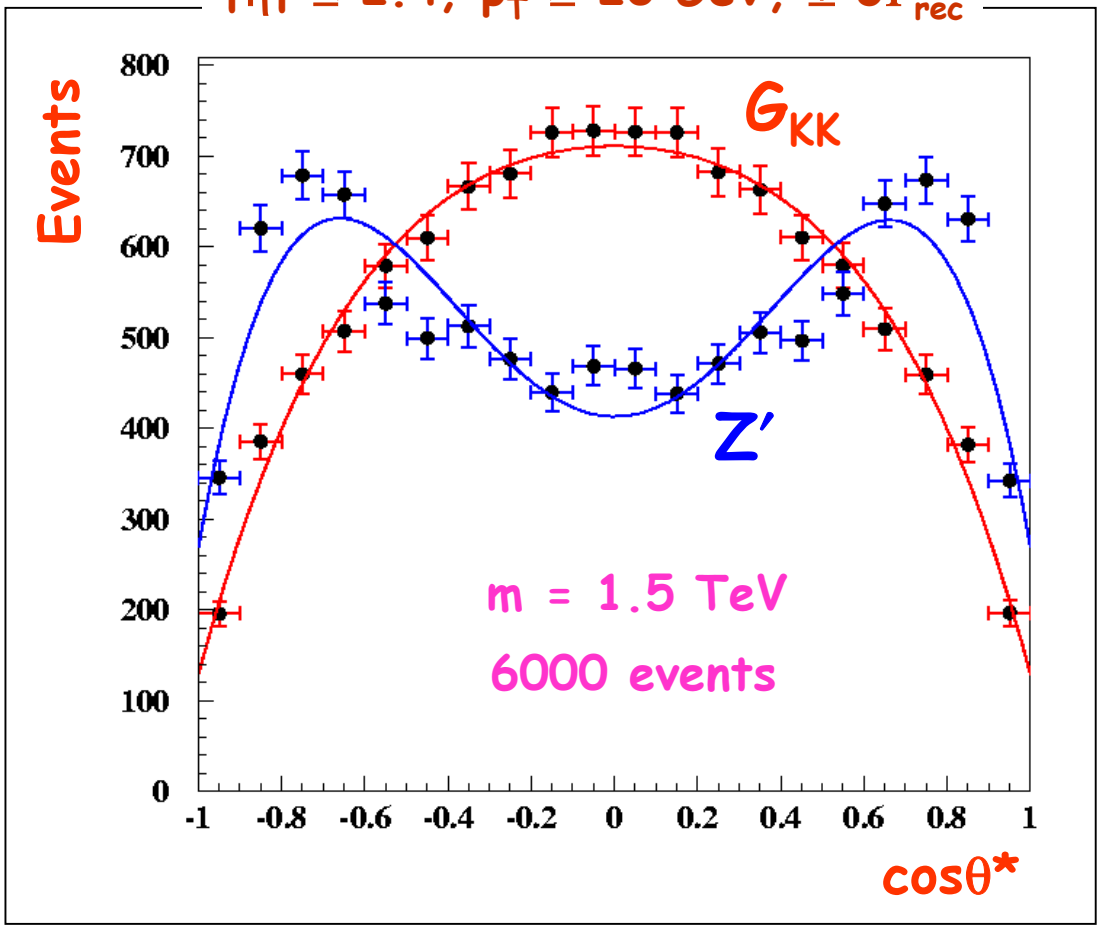
θ^* is the angle of μ's in the Z′ (G_{KK}) rest frame

Theoretical expectations:

Processes	angular distributions
$qq \to Z' \to \mu\mu$	$1 + \cos^2\theta^*$
$qq \to g_{KK} \to \mu\mu$	$1 - 3\cos^2\theta^* + 4\cos^4\theta^*$
$gg \to g_{KK} \to \mu\mu$	$1 - \cos^4\theta^*$

$qq \to Z' \to \mu\mu$ (K=1), 100 fb^{-1}

$qq, gg \to G_{KK} \to \mu\mu$
(K=1, c=0.1), 10 fb^{-1}



Conclusions

- CMS detector performance allows to perform precise measurements of di-muon pairs up to invariant masses of about 4 TeV or even higher
- study of a Drell-Yan muon pair production enables to check-up the SM within this mass region

Any deviations from SM predictions (excess or deficit) will indicate the new phenomena beyond SM

- extra gauge boson Z′ can be observed in the dimuon channel with $S/\sqrt{B} \geq 5$ for masses up to 2.5 ÷ 3.0 for 10 fb^{-1} TeV 3.5 ÷ 4.1 TeV for 100 fb^{-1} integrated luminosity
- on the assumption c=0.01 g_{KK} can be observed in the dimuon channel with $S/\sqrt{B} \geq 5$ for masses up to 1.9 for 10 fb^{-1} and 2.6 TeV for 100 fb^{-1}
- forward-backward asymmetry of muons (from Z′) can be used for more detailed study of the Z′ origin model
- spin-2 states (graviton) can be distinguished from spin-1 states (Z′) by analyzing angular distribution of muons

Supplement

Z′-bosons

Expected Z′ $\rightarrow \mu^+\mu^-$ Rate

we assume no exotic fermions (n_G=0) for SSM, χ-, η-, ψ-models (Br_μ = 0.032)

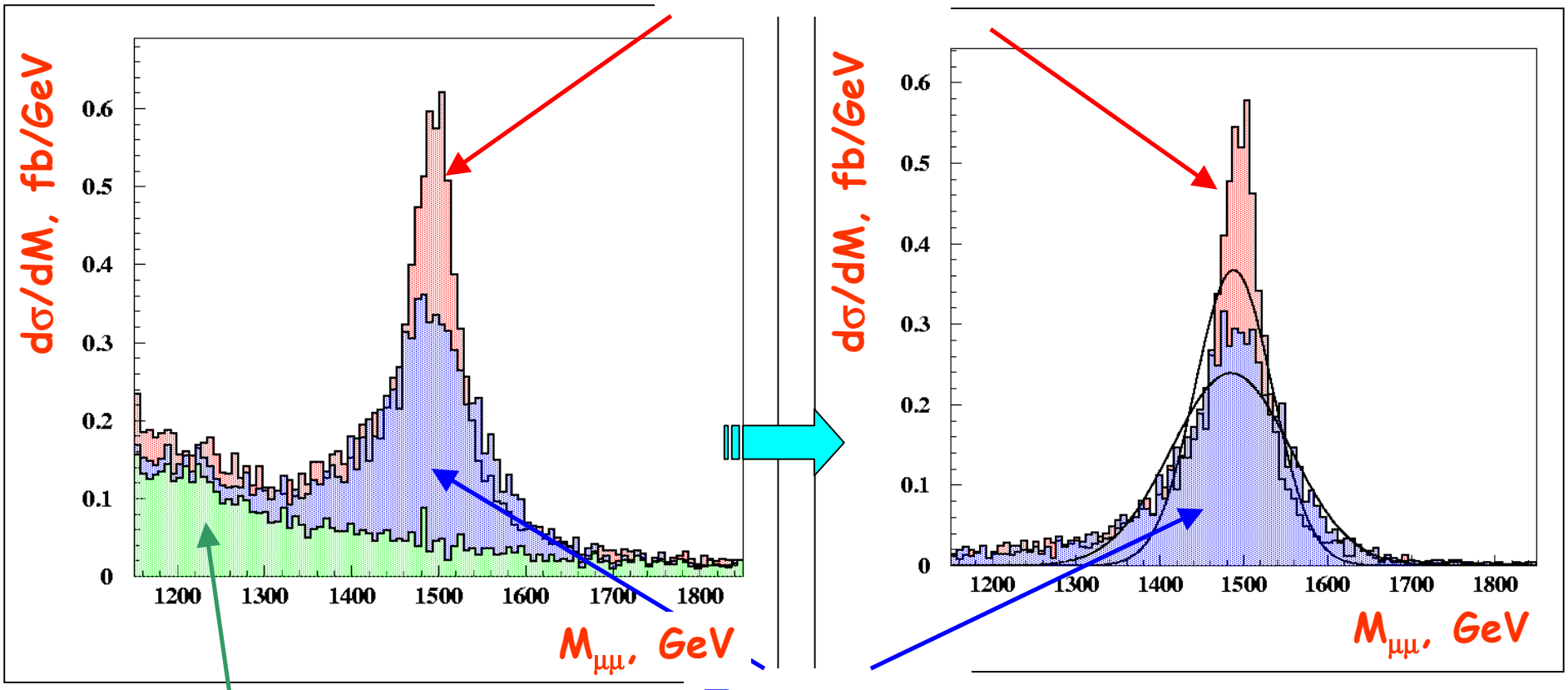
number of extra fermion generations is n_G=3 (right-handed fermions) for LRM (Br_μ = 0.023)

Mass, GeV	Number of muon pairs at 100 fb^{-1}				
	Z'_{SSM}	Z'_{LR}	Z'_{χ}	Z'_{ψ}	Z'_{η}
500	5.9×10^5	4.2×10^5	5.3×10^5	1.88×10^5	
1000	4×10^4	3.1×10^4	3.6×10^4	1.26×10^4	
1200	1.8×10^4	1.4×10^4	1.6×10^4	5700	
1500	6800	4970	6000	2100	
2000	1730	1200	1522	535	
2500	670	360	470	166	
3000	190	124	170	60	
4000	30	20	26	9	
5000	8	4	5		

no kinematics cuts

Signal/Background Events for Z′

Pythia 6.217 + CMSJET 4.7, $|\eta| \leq 2.4$, $p_T \geq 20$ GeV



Z′ Forward-Backward Asymmetry

$$A_{FB}(y) = \frac{F(y) - B(y)}{F(y) + B(y)}$$

$pp \rightarrow Z' \rightarrow \mu^+\mu^-$

F(y) is number of μ with cos(θ*) > 0,
B(y) is number of μ with cos(θ*) < 0,
θ* is the angle in the di-muon C.M. (Z′ rest frame) between the μ- and one (fixed) of the proton beams,
y is Z′ rapidity

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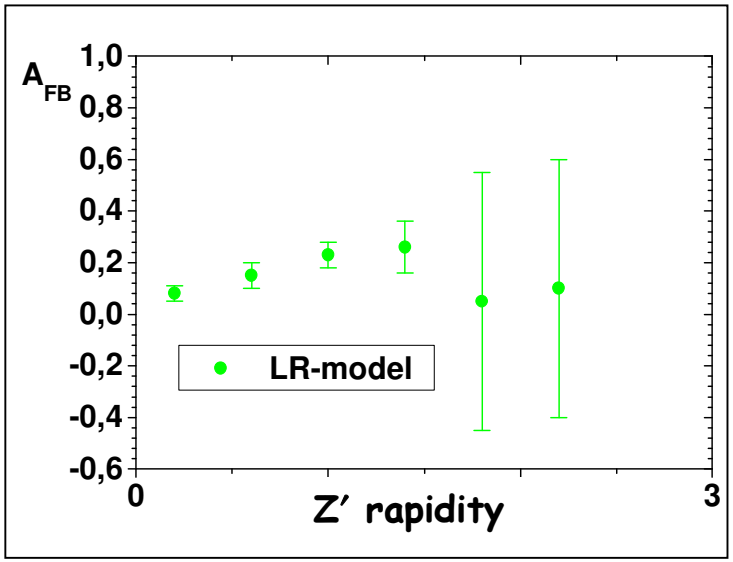
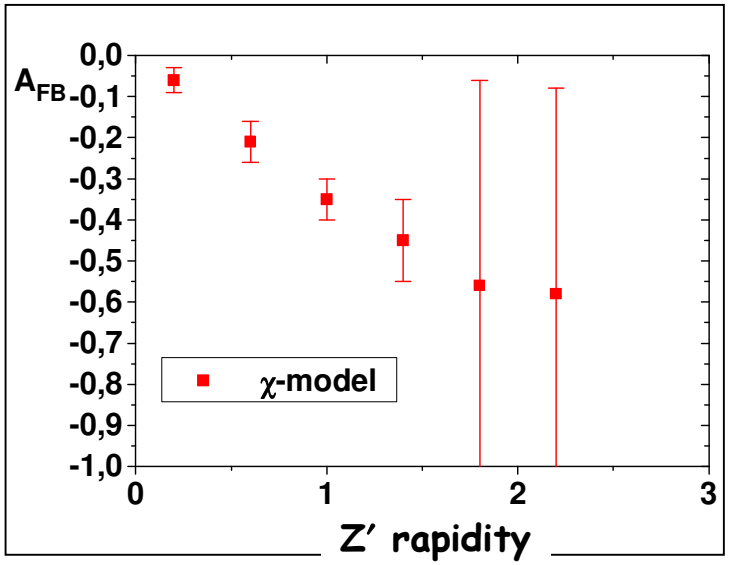
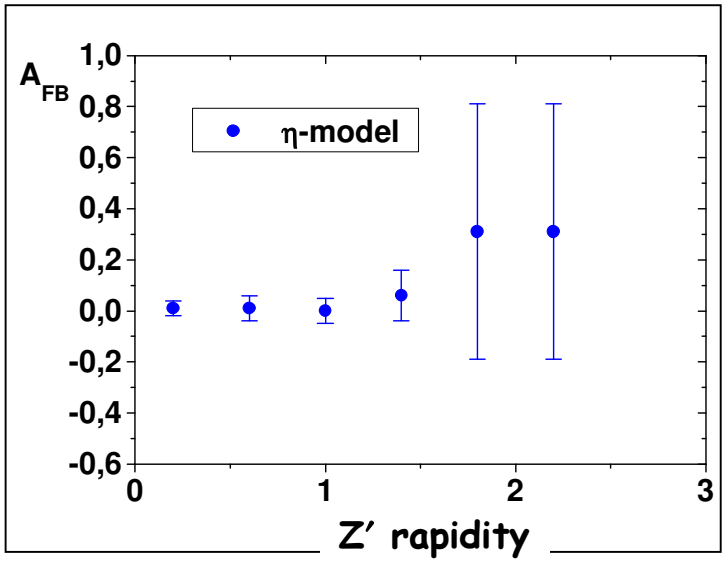
$M_{Z'}$ = 2.0 TeV

100 fb^{-1}







rapidity-dependence of forward-backward asymmetry in $Z' \rightarrow \mu^+\mu^-$ decays for various models has a very distinctive behaviour

Z′ Forward-Backward Asymmetry

$|\eta| \leq 2.4,\ p_T \geq 20\ GeV,\ \pm 5\Gamma_{rec}$

χ-model	0.5 TeV	1.0 TeV	1.5 TeV	3.0 TeV
$\|y\| < 2.8$	$(-3.4 \pm 0.8) \times 10^{-4}$	$(-6.2 \pm 0.4) \times 10^{-3}$	$(-1.7 \pm 0.2) \times 10^{-2}$	$(-5.9 \pm 5.9) \times 10^{-2}$
$0.5 < y < 1.5$	-0.185 ± 0.004	-0.269 ± 0.004	-0.332 ± 0.014	-0.538 ± 0.143
$-1.5 < y < -0.5$	0.197 ± 0.004	0.269 ± 0.004	0.317 ± 0.004	0.415 ± 0.101
$1.5 < y < 2.8$	-0.368 ± 0.006	-0.389 ± 0.012	-0.397 ± 0.053	-1.0 ± 1.0
$-2.8 < y < -1.5$	0.355 ± 0.006	0.413 ± 0.012	0.457 ± 0.051	1.0 ± 0.7

strong mass-dependence of forward-backward asymmetry in $Z' \rightarrow \mu^+\mu^-$!!!

G_{KK}-resonance

Large Extra Dimensions: RS1

L.Randall and R. Sundrum, Phys. Rev. Lett. 83,3370 (1999), Phys. Rev. Lett. 83,4690 (1999)

- Our world is one of the branes embedded into the 5 dimensional anti-de Sitter space (non-factorizable geometry) with curvature k

$$ds^2 = e^{-2krc\phi}\,\eta_{\mu\nu}dx^\mu dx^\nu + r^2_c d\phi^2$$

- Configuration assumes 2 branes on the distance z_C each from other: one with the positive tension σ at z = 0, and the other with the negative tension $-\sigma$ what is located at z_C

- SM matter lives on the 4-brane with induced Minkowski metric and the negative brane tension (RS1 scenario). The 4-al gravity in our World is induced by zero graviton mode

- A fundamental scale parameter of the theory (not Planck scale)

$$\Lambda_\pi = \overline{M}_{Pl} e^{-kr_c\pi},\ c^* = 2x_1 \frac{k}{\overline{M}_{Pl}}$$

- Kaluza-Klein excitations of the graviton states (G_{KK}) should be observable at collider energies as spin-2 individual resonances with masses $m_n = ke^{-krc\pi}\,x_n$, where are x_n roots of the Bessel functions $J_1(x_n) = 0$. First excitation is

$$m_1 = k\,x_1\,e^{-krc\pi} = 3.83(k/\overline{M}_{Pl})\Lambda_\pi \sim \text{a few TeV}, \text{ where } 0.01 < k/\overline{M}_{Pl} < 1$$

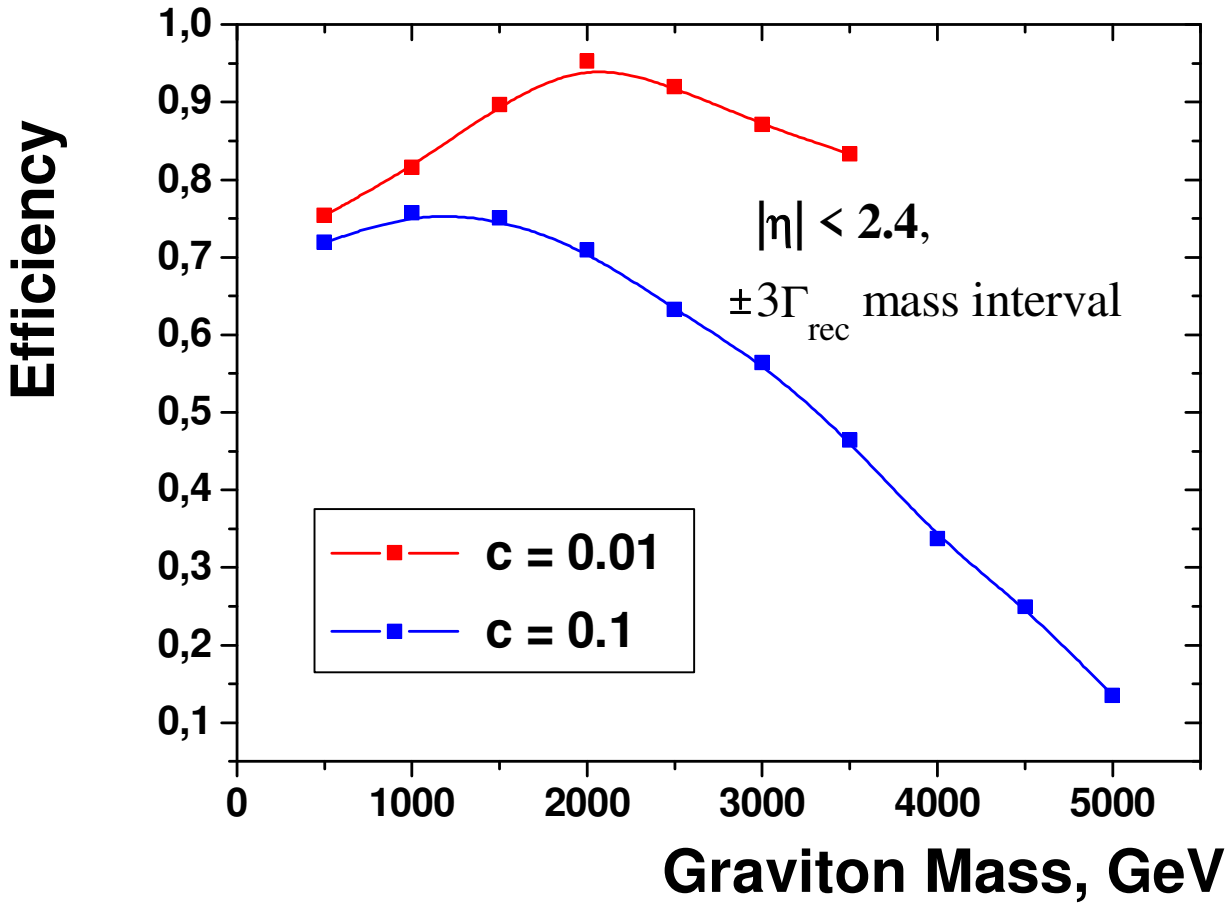
G_{KK} graviton production (RS1)

- virtual graviton: the SM exchange by γ or Z boson interferes with the exchange by graviton ($qq \rightarrow G_{KK}$)
- there is also gluon-gluon initiated graviton exchange process which has no the SM analogue ($gg \rightarrow G_{KK}$)
- for real graviton production, i.e. graviton emission ($qq \rightarrow gG_{KK}$, $qg \rightarrow qG_{KK}$, $gg \rightarrow gG_{KK}$)

M (TeV) / σ, fb	1 c=0.1 (0.01)	1.5, c=0.1 (0.01)	3.0 c=0.1 (0.01)
ffbar → G*	129 (1.34)	23 (0.24)	0.633 (0.006)
gg → G*	567 (5.33)	62 (0.53)	0.94 (0.004)
qqbar → gG*	345 (3.29)	65 (0.64)	1.84 (0.017)
qg → qG*	599 (5.78)	72 (0.64)	1.05 (0.007)
gg → gG*	3350 (31.5)	368 (3.32)	4.98 (0.028)
total	4990 (47.2)	590 (5.38)	9.45 (0.062)

G_{KK} selection efficiency

Pythia 6.217 + CMSJET 4.7, $|\eta| \leq 2.4$, $p_T \geq 20$ GeV, $\pm 3\Gamma_{rec}$

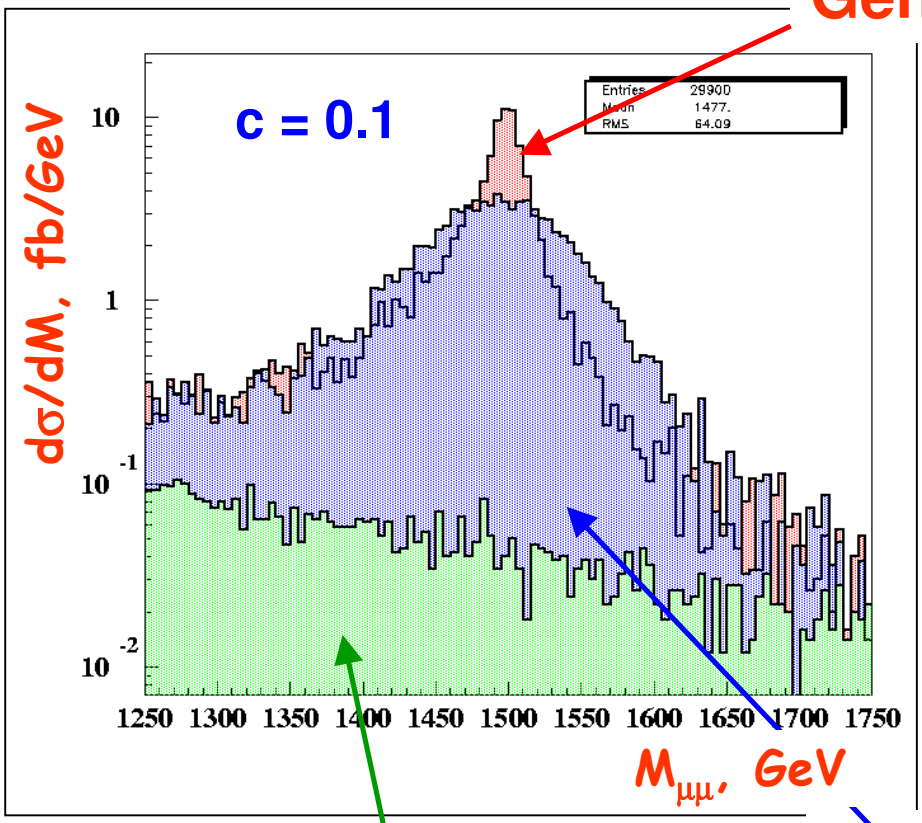


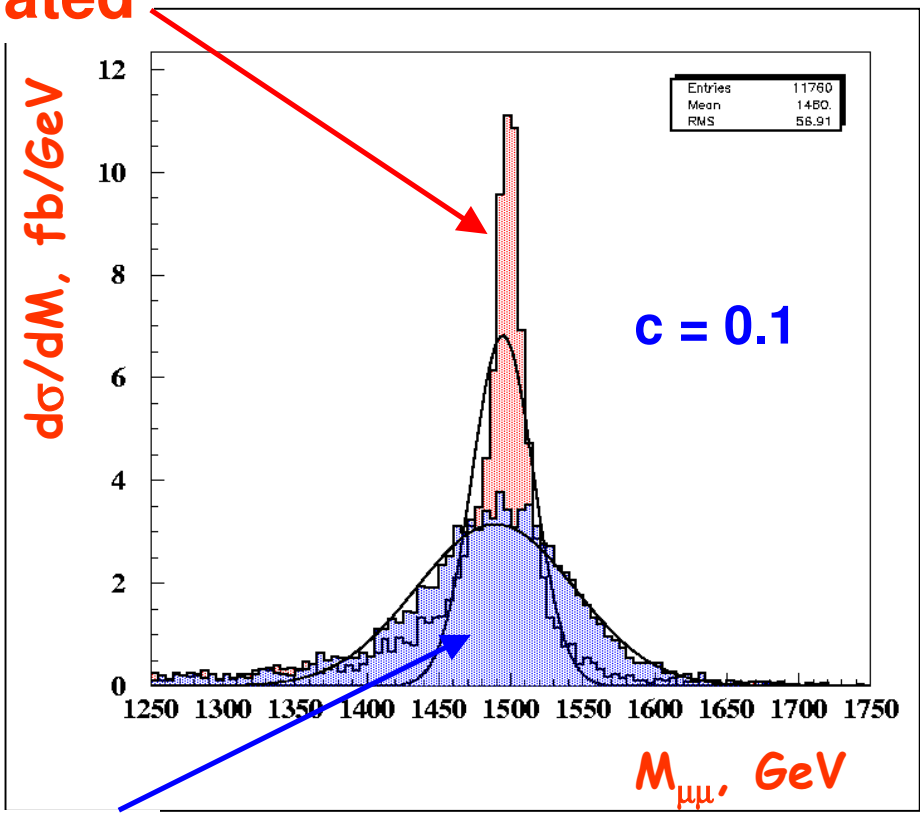
$\Gamma_G \sim m_G c^2$

Signal/Background Events for G_{KK}

Pythia 6.217 + CMSJET 4.7, $|\eta| \leq 2.4$, $p_T \geq 20$ GeV

Generated



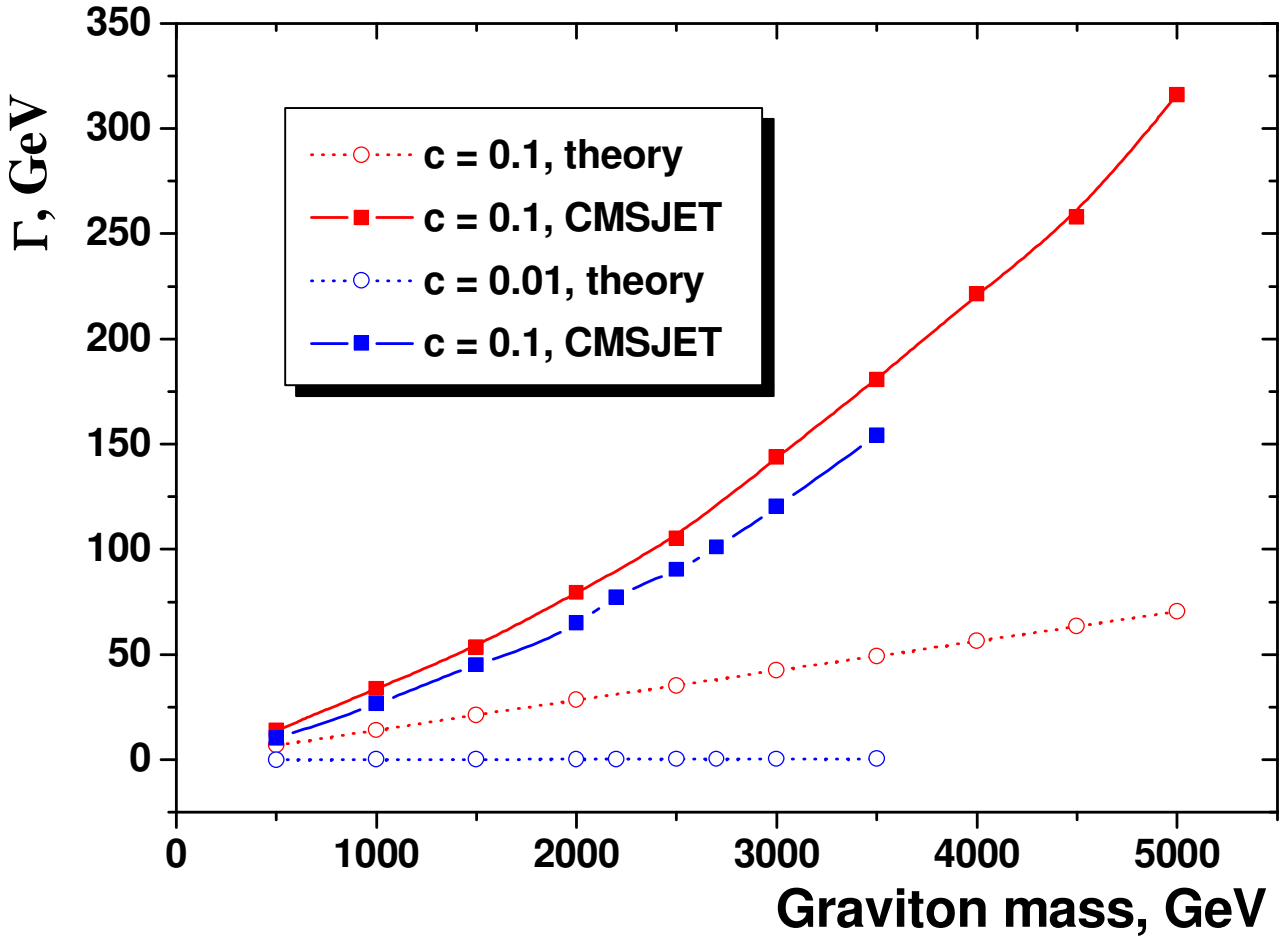


Response

Background, DY

Detector response for G_{KK}

Pythia 6.25 + CMSJET 4.7, $|\eta| \leq 2.4$, $p_T \geq 20$ GeV



Angular Distributions

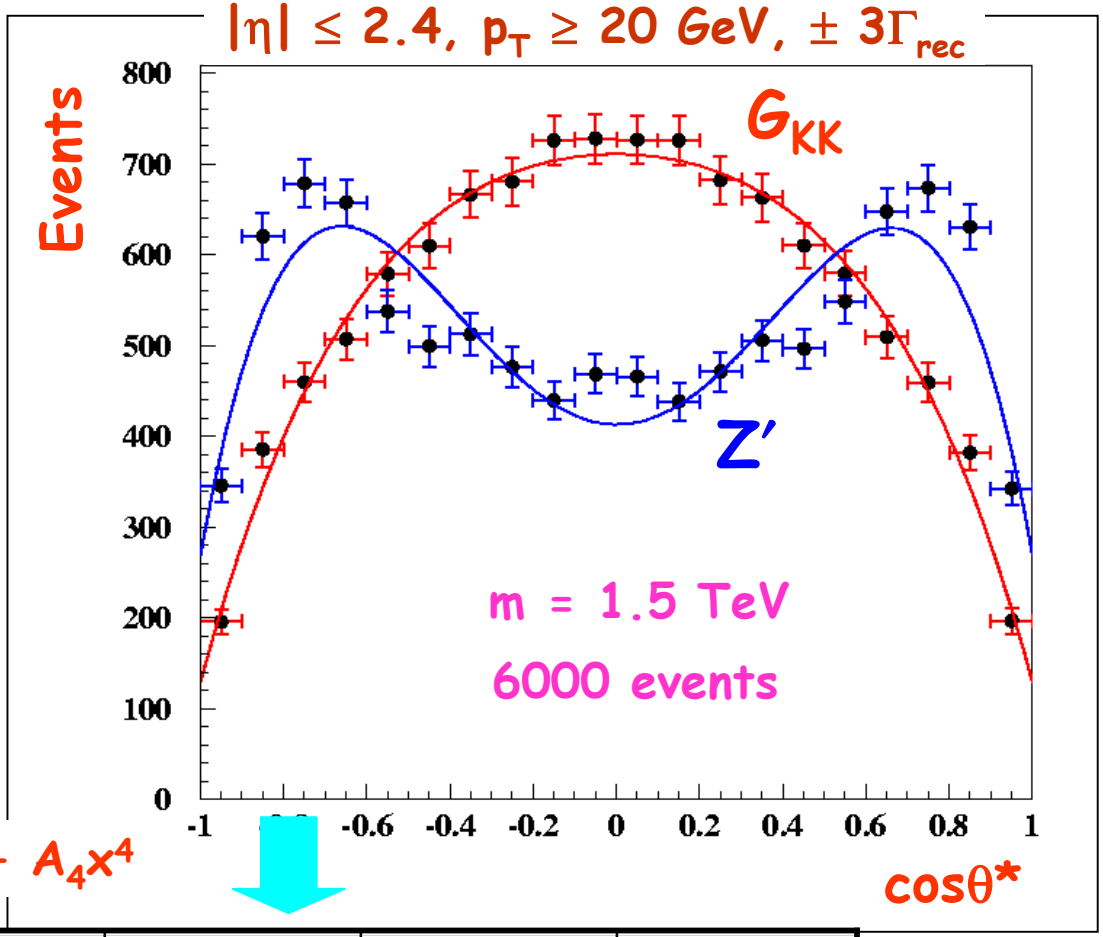
θ^* is the angle of μ's in the Z′ (G_{KK}) rest frame

Theoretical expectations:

Processes	angular distributions
$qq \to Z' \to \mu\mu$	$1 + \cos^2\theta^*$
$qq \to g_{KK} \to \mu\mu$	$1 - 3\cos^2\theta^* + 4\cos^4\theta^*$
$gg \to g_{KK} \to \mu\mu$	$1 - \cos^4\theta^*$

$qq \to Z' \to \mu\mu$ (K=1), 100 fb^{-1}

$qq, gg \to G_{KK} \to \mu\mu$
(K=1, c=0.1), 10 fb^{-1}



$F(x) = A_0 + A_1x + A_2x^2 + A_3x^3 + A_4x^4$

State	A_0	A_1	A_2	A_3	A_4
$qq \to Z' \to \mu\mu$	412 ± 9	-2.45 ± 22	995 ± 62	2.57 ± 32	-1140± 67
$qq, gg \to g_{KK} \to \mu\mu$	710 ± 11	-0.35 ± 22	-318 ± 61	0.36 ± 30	-264 ± 62

Angular Distributions

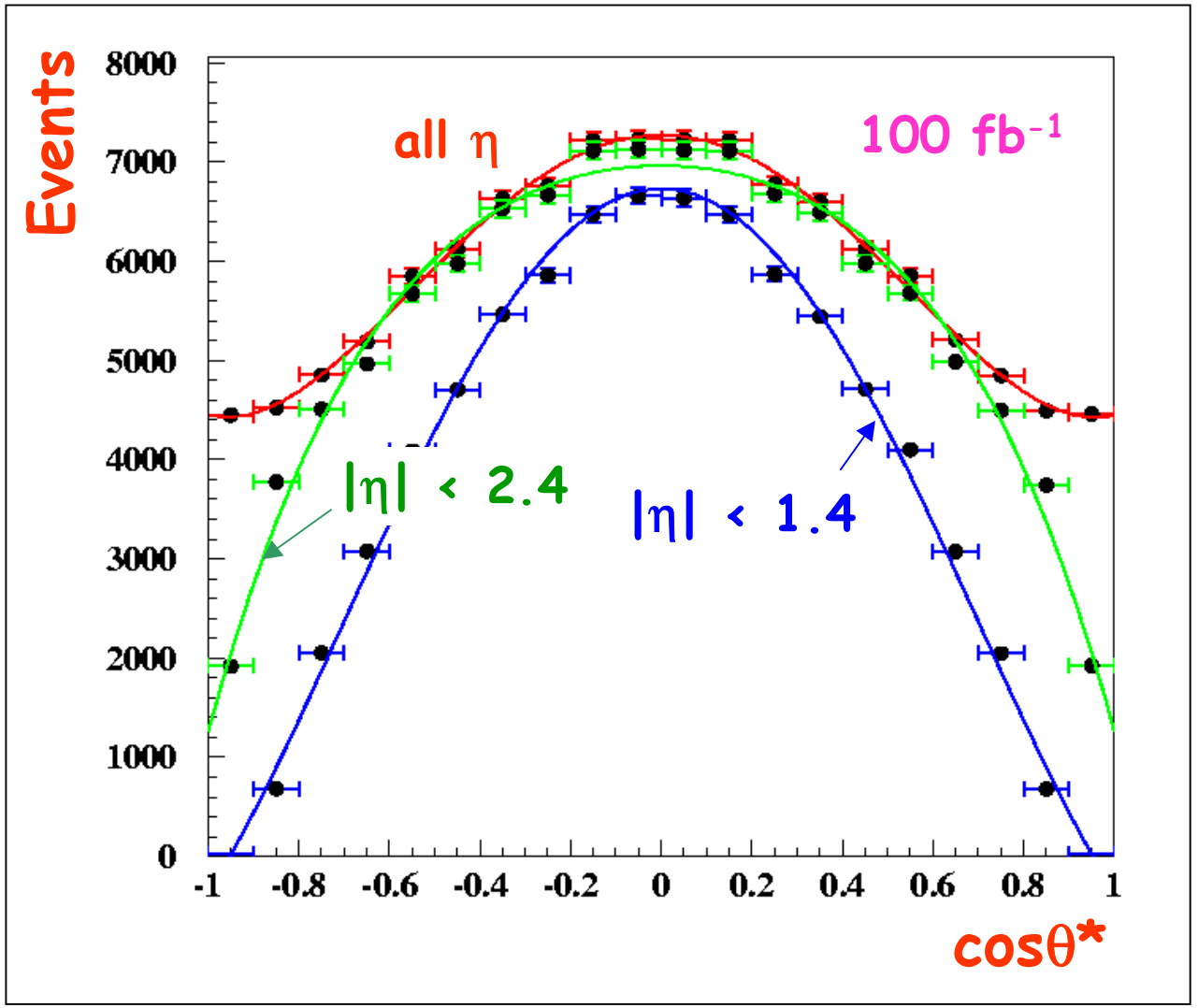
θ^* is the angle of μ's in the G_{KK} rest frame

$qq, gg \rightarrow G_{KK} \rightarrow \mu\mu$
(K=1, c=0.1)

m = 1.5 TeV

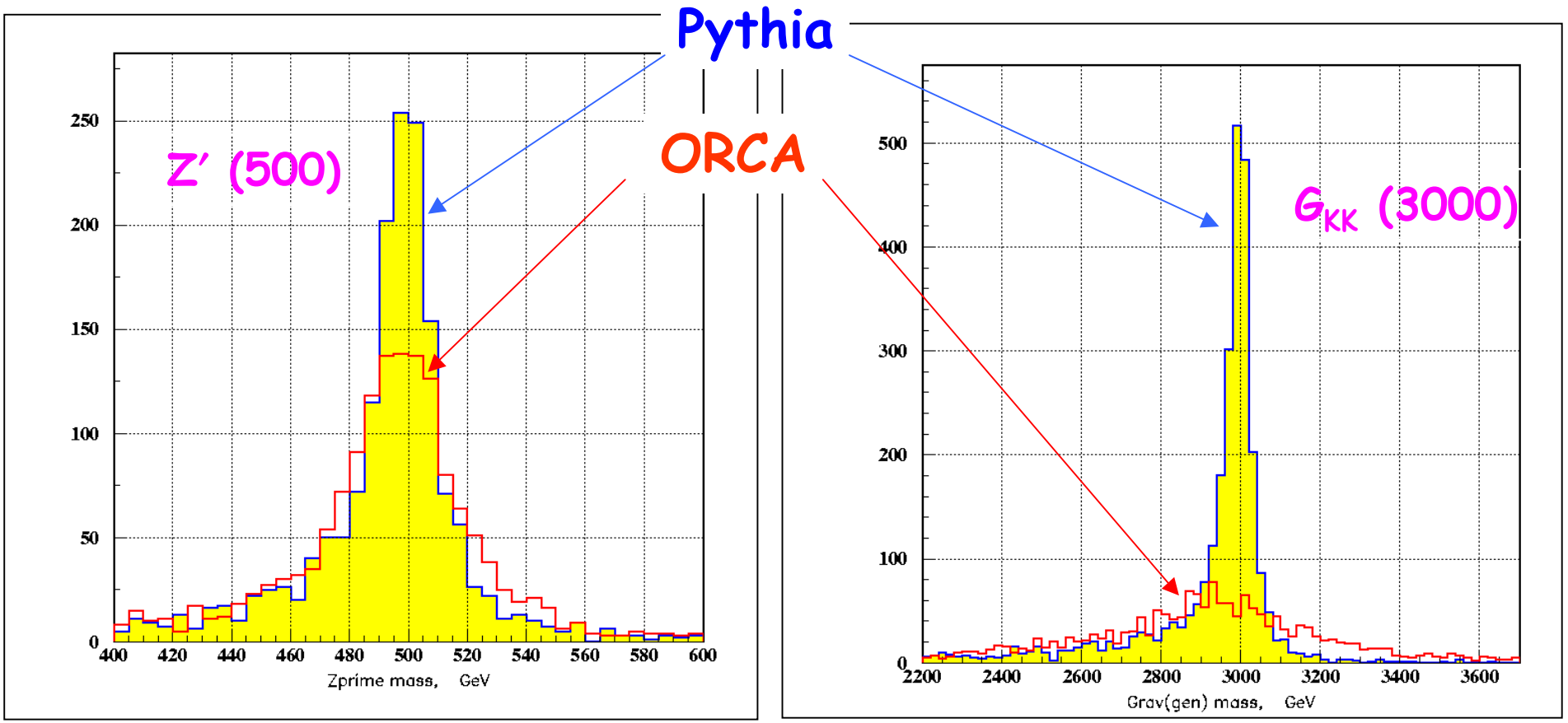
$N \approx 5.8 \cdot 10^4$

p_T > 20 is equivalent to p_T > 100 GeV



Mass reconstruction in ORCA 6.3.0

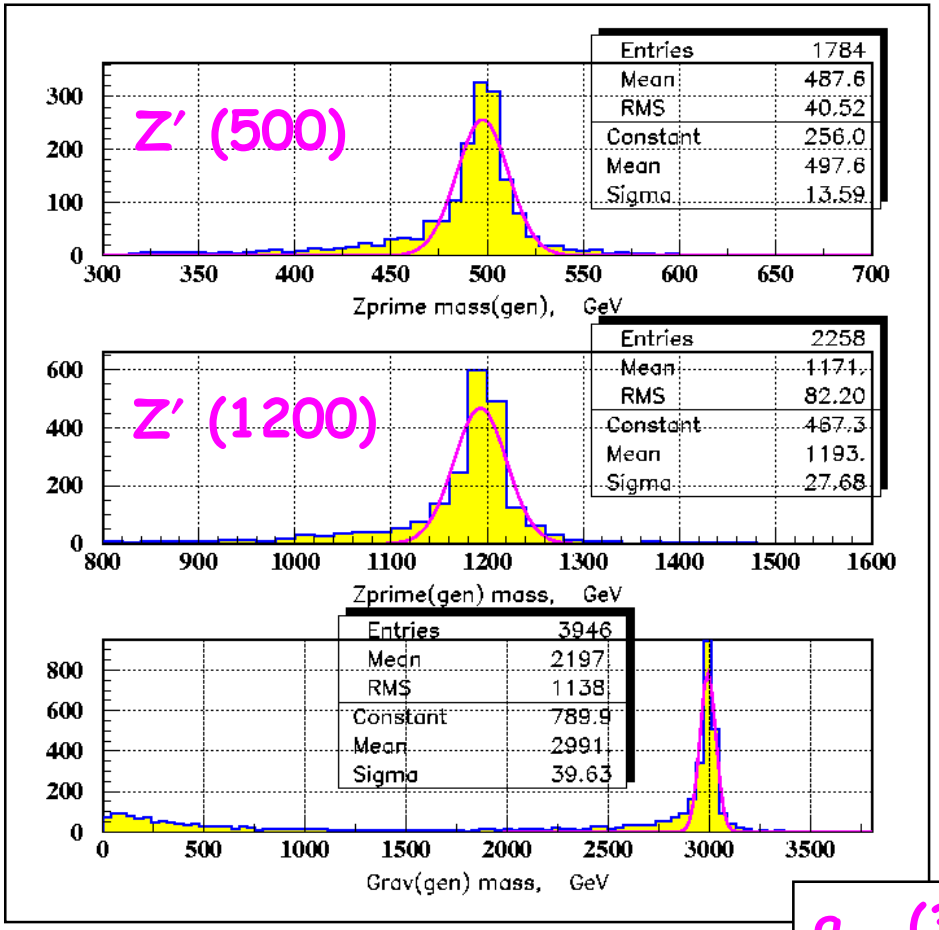
Full ORCA (L3, muon system + tracker) reconstruction



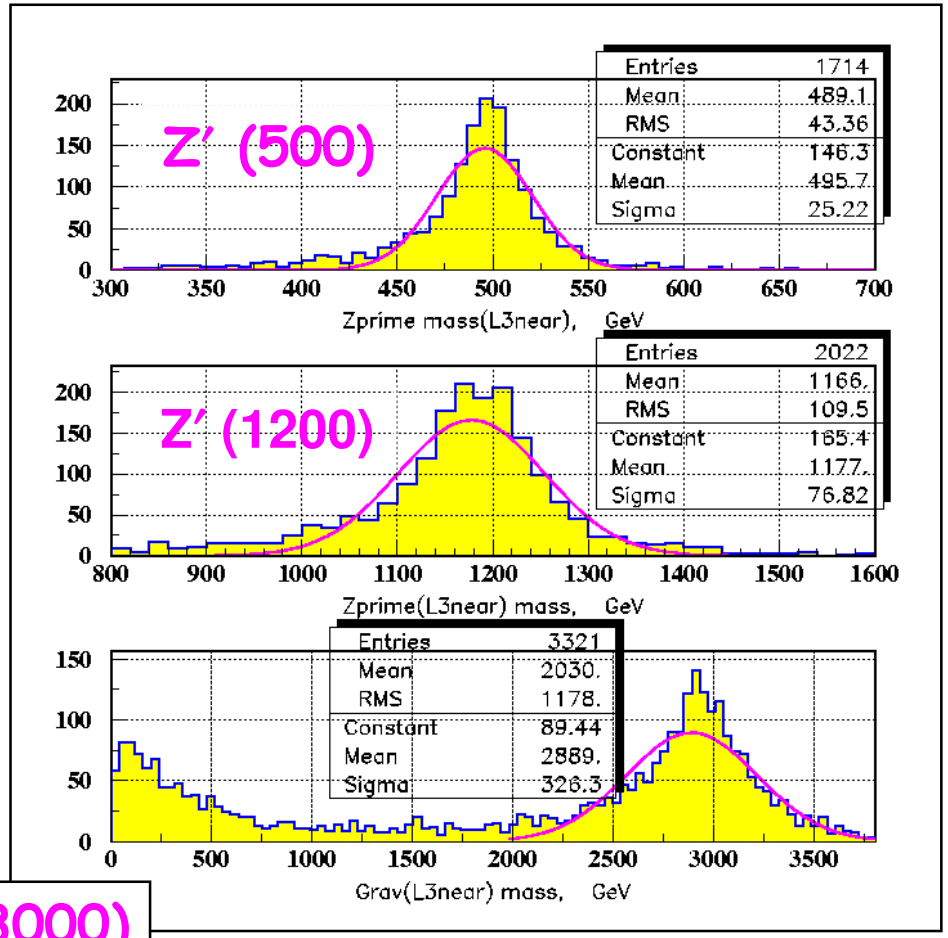
ORCA reconstruction of high-p_T muons still to be tuned !!!

Mass reconstruction in ORCA 6.3.0

Invariant mass of muon pairs from Pythia



Full ORCA reconstruction of invariant mass



g_{KK} (3000)