by R. Alemany (LIP/CMS)
on behalf of

ATLAS CMS

Outline:

1. Introduction
2. Some experimental remarks
3. Extra Dimensions (ADD, TeV^{-1}, RS, UED, BH)
4. Extra Gauge Bosons
5. How to discriminate between models
6. Conclusion

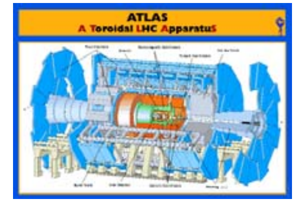
1. Introduction

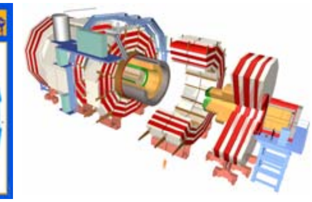
- Theorist argue in different ways, as we heard from S. Pokorski's talk, that there should exist physics Beyond the Standard Model. This is one of the reasons why the LHC and its detectors are being built.

- During this talk I will review the most recent results, from the experimental (simulation) point of view, on:
  - Extra Dimensions
  - Extra Gauge Bosons

- … but one must keep in mind that nature may prove to be more creative than we are, and that something completely unexpected may be discovered at LHC…

2. Some experimental remarks





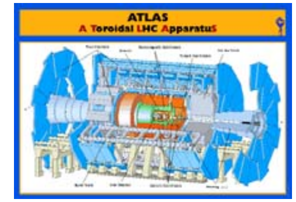
- Theoretical uncertainties:
  - Parton Distribution Functions (PDF)
  - Hard process scale (Q^2)
  - NNLO vs NLO vs LO calculations (K factors)

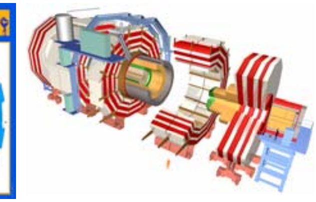
  affect the S and B magnitudes, the cut efficiency, the significance ...

- Detector uncertainties:
  - **Alignment**: key element in the performance of track reconstruction:
    - tracker (~ 10 μm)
    - muon system (~100–500 μm)

    Misalignment spoils the intrinsic resolution of the tracking detectors.

    Misalignment sources are:
    - Detector construction tolerances
    - Detector assembly, Magnetic and Gravitational Field effects (~ cm for μ-chambers)
    - During operation: thermal instabilities, e.g. CMS TRK will be operated at ~ -20°C, humidity effects, ...





- Detector uncertainties:
  - **Energy Calibration**: key element in the performance of e/γ/hadrons energy reconstruction. It is composed of:
    - absolute energy scale: a global component
    - channel-to-channel energy scale: relative component ($\equiv$ intercalibration).

  The energy reconstruction has also a systematic uncertainty component coming from misaligned/miscalibrated tracker.

  - **Drift time** and drift velocities (e.g. μ-chambers: Δt_0*(±2ns), drift velocity scaling (±3%)).

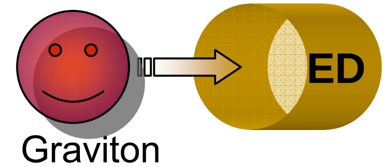
3. Extra Dimensional Models

- The main motivation for the development of theories BSM is the Hierarchy Problem:

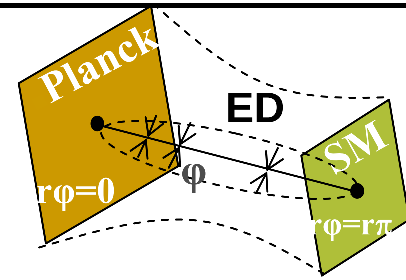
Gravity/EW&Strong ~ $10^{19}/10^{3}$?

- Several possibilities have been suggested to solve this “naturality” problem:
  - Perturvative solutions: Supersymmetry
  - Non- Perturvative solutions: Compositeness and Technicolor
- Alternatively, one can exploit the geometry of space-time via **Extra Dimensional Theories**

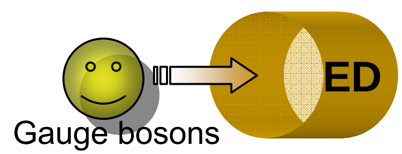
- Large ED (ADD)



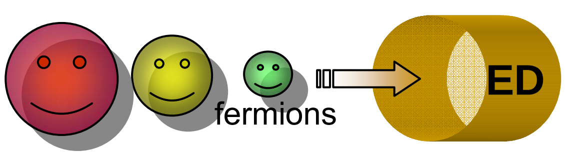
- Randall-Sundrum(Warped ED)



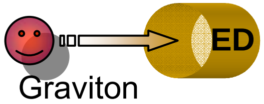
- TeV^{-1} size ED



- Universal ED



ADD Model



- $\mathbf{M_{Pl}}$ is not a fundamental scale, but $\mathbf{M_{EW}}$
- Gravity propagates in a bulk of $4+\delta$ extra dimensions of radius **R** ➔ seen as an infinite tower of KK states in 4-dim.
- Model parameters:
  1. δ**:** number of extra dimensions
  2. $\mathbf{M_{Pl(4+\delta)}}$ (=$\mathbf{M_D}$): fundamental scale (above which new physics enters and modifies the results):

$$M^2_{Pl} \sim \mathbf{M}^{2+\delta}_{\mathbf{Pl(4+\delta)}}\ \mathbf{R}^{\delta}$$

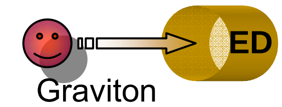
for $M_{Pl} \sim 10^{19}$ GeV and $\mathbf{M_D} \sim M_{EW}$ ➔ $\mathbf{R} \sim 10^{32/\delta}\ 10^{-17}$cm

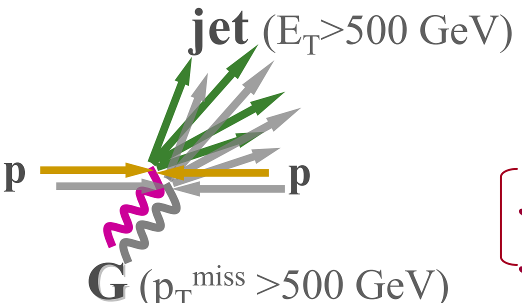
- $m_G \propto n/\mathbf{R}$ ➔ **light $\mathbf{G_n}$** for R < mm
  ➔ $\Delta m_G(KK,KK+1) \in [\sim \text{eV, MeV}]$
- G_n couplings $\propto M_{Pl}^{-1}$ … but m_G<<
  ➔ **high density of KK modes produced** ➔ σ >>

ADD Model Ref: [ADD1,ADD2,ADD3]

ADD expectations in

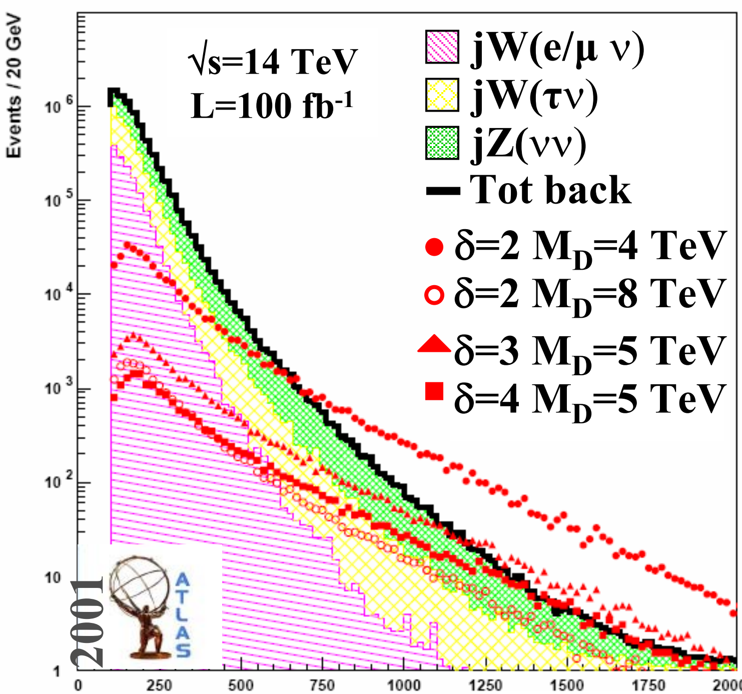
Direct production of G_{KK}





+ veto on e, μ & τ (iso+ID)

jet+Z → jet ν ν
jet+W → jet l ν



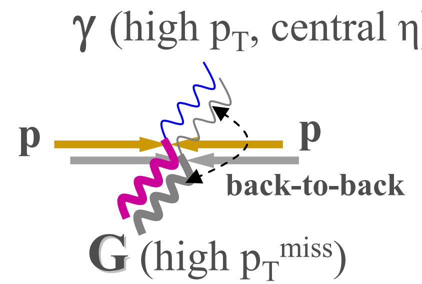
J. Phys., G 27 (2001) 1839-50

$E_T$miss (GeV)

Gen (S+B): ISAJET UVCUT CTEQ3L
Sim/Rec: Fast

For L=100 fb^{-1}
M_D= 7.7:6.2:5.2
δ = 2: 3: 4
(S/√B>5,S>100, E^{jet}_{Tcut}>1TeV)

Zγ → νν γ
W→e(μ,τ)ν,
Wγ → eν γ
γ+jets, QCD,
di-γ, Z^0+jets



$\mathcal{S}$= 2(√(S+B) - √B) > 5 [SIG2] 2006

M_D/δ	2	3	4	5	6
M_D = 1.0 TeV	0.21 fb^{-1}	0.16 fb^{-1}	0.14 fb^{-1}	0.15 fb^{-1}	0.15 fb^{-1}
M_D = 1.5 TeV	0.83 fb^{-1}	0.59 fb^{-1}	0.56 fb^{-1}	0.61 fb^{-1}	0.59 fb^{-1}
M_D = 2.0 TeV	2.8 fb^{-1}	2.1 fb^{-1}	1.9 fb^{-1}	2.1 fb^{-1}	2.3 fb^{-1}
M_D = 2.5 TeV	9.9 fb^{-1}	8.2 fb^{-1}	8.7 fb^{-1}	9.4 fb^{-1}	10.9 fb^{-1}
M_D = 3.0 TeV	47.8 fb^{-1}	46.4 fb^{-1}	64.4 fb^{-1}	100.8 fb^{-1}	261.2 fb^{-1}
M_D = 3.5 TeV	5 σ discovery not possible anymore				

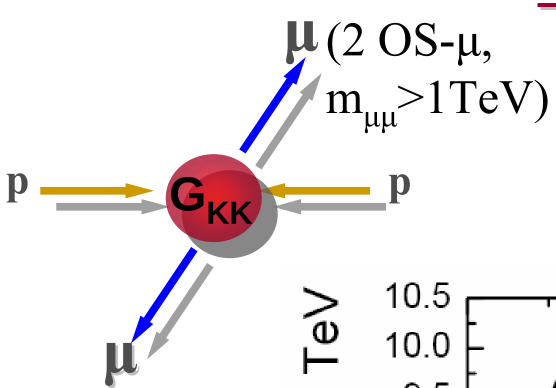
Theoretical systematics included

Gen (S): PYTHIA vs SHERPA, CTEQ6L
Gen (B): PYTHIA vs SHERPA vs CompHEP vs Madgraph(dis)
Sim/Rec: Full

J. Weng et al. CMS NOTE 2006/129

ADD expectations in CMS

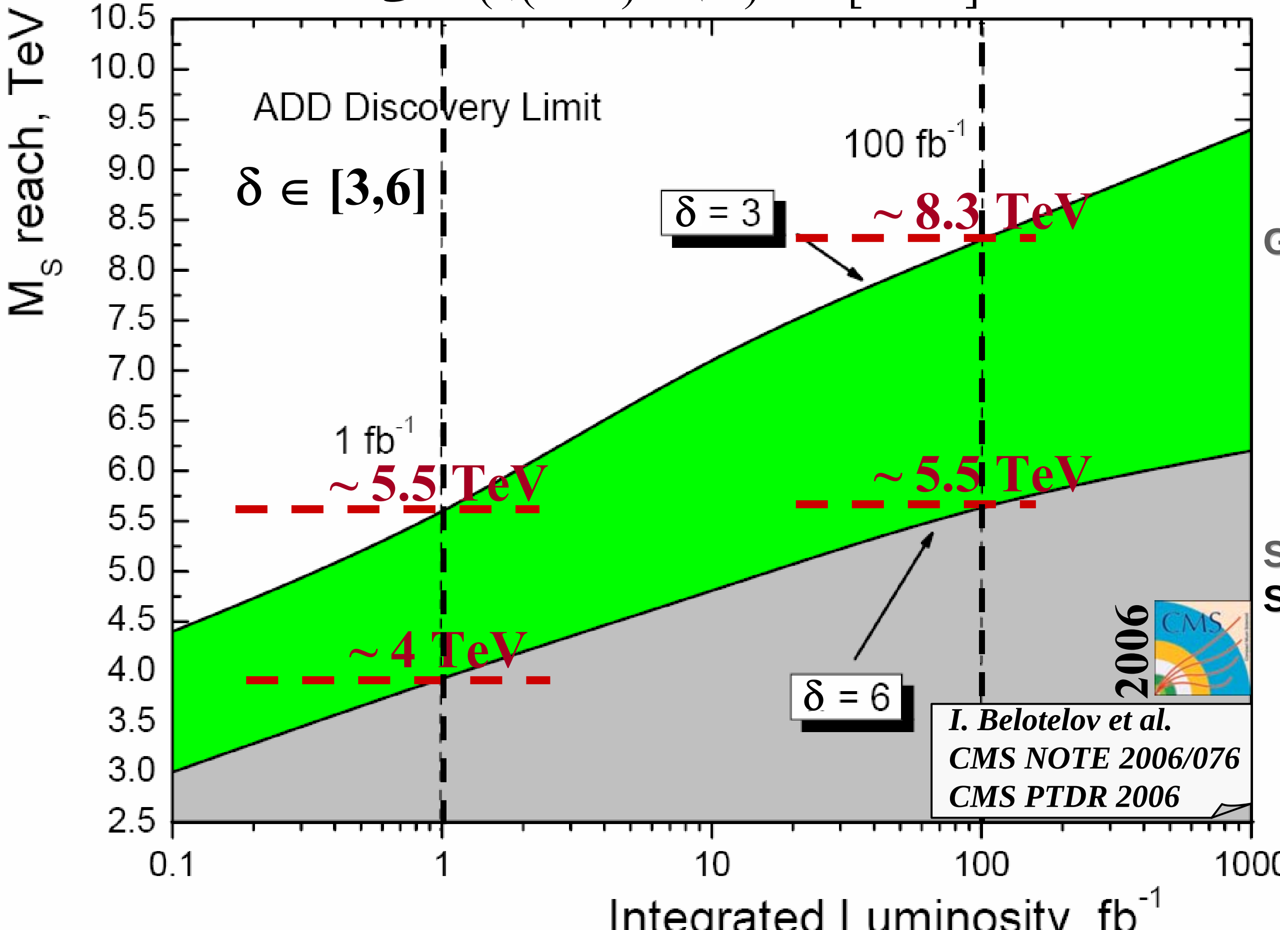
Virtual production of G_{KK}



$\sigma = \sigma_{SM} + \sigma_{INT}\eta + \sigma_{KK}$
$\eta = f(M_D, \delta, \sqrt{s})$

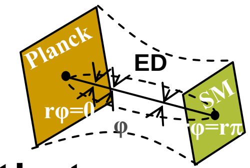
$Z/\gamma \rightarrow \mu\mu$
ZZ,WZ,W
W,tt

$S = 2(\sqrt{(S+B)} - \sqrt{B}) > 5$ [SIG2]



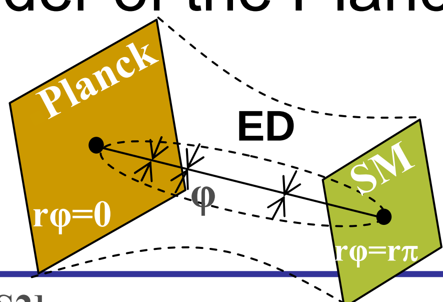
Gen (S):
@LO+
K=1.38
STAGEN+
PYTHIA
ISR&FSR
CTEQ6L
Sim/Rec: Full
Syst Uncert:
theoretical +
μ & TRK
misalignment
TRG system

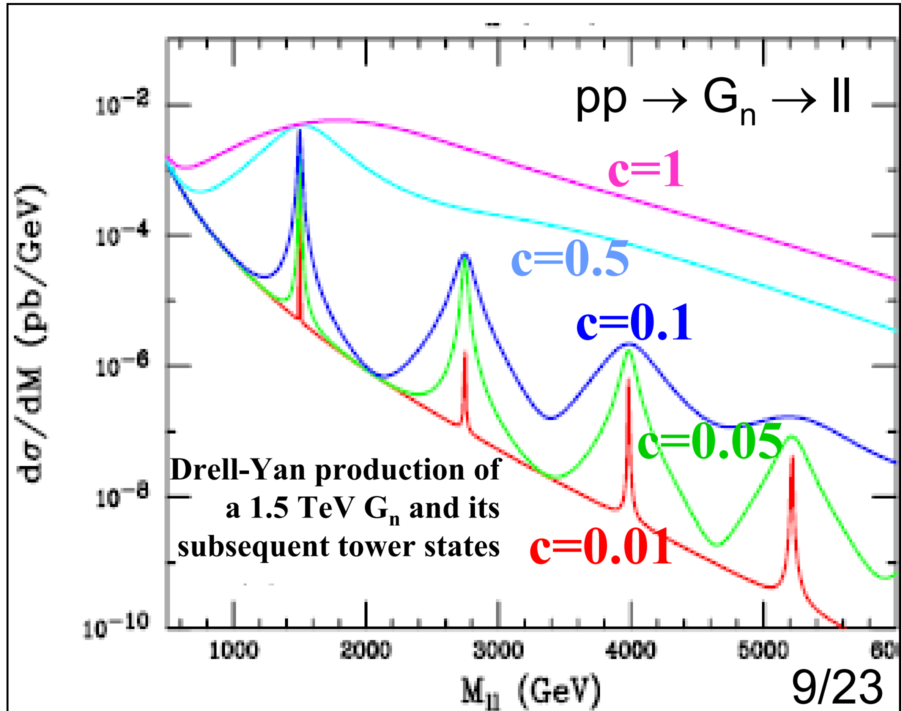
RS(1) model



- Gravity propagates in a 5-dim bulk of finite extent with two rigid boundaries of (3+1) dim that extend infinitely
- SM fields are constraint on one of the 3-brane (y = **R**π)
- $m(G_n) = \mathbf{k} x_n e^{-\mathbf{k}R\pi} = x_n(k/\bar{M}_{Pl})\Lambda_\pi \sim$ **TeV**
- G_n **couplings** $\propto \Lambda_\pi^{-1}$ (n≥1)
- Model parameters:

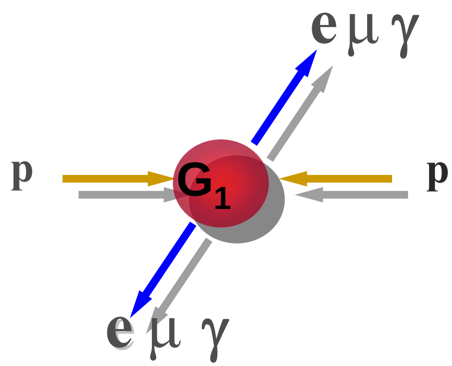
  1. Λ_π: the scale of physical processes in the TeV bran
  2. **$c=k/\bar{M}_{Pl}$**, k is a scale of the order of the Planck scale





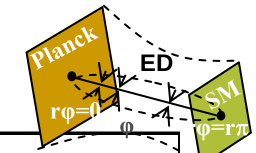
Ref: [RS1,RS2]

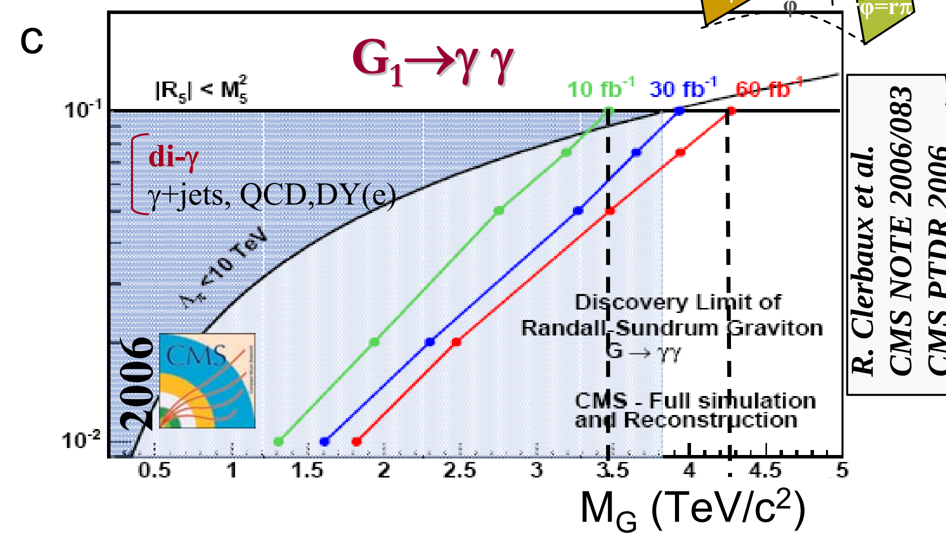
RS(1) expectations in CMS

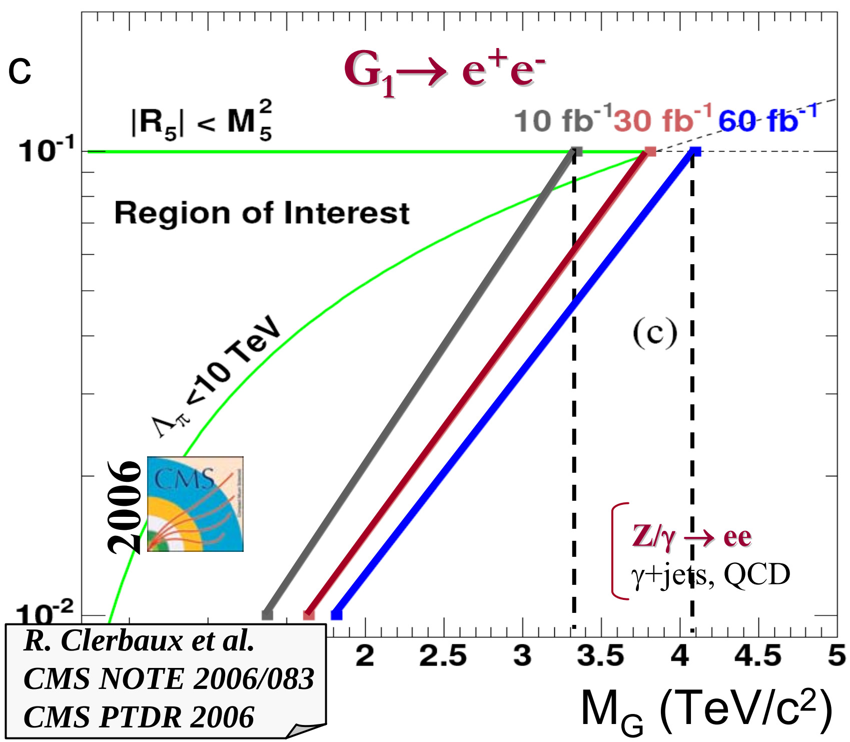


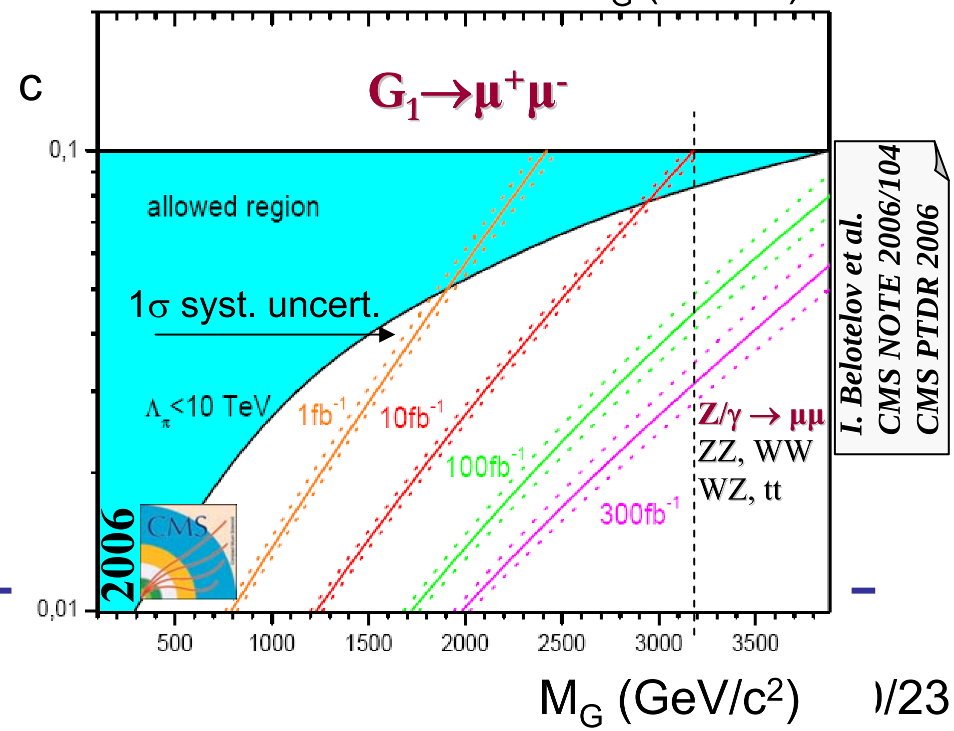
Full simulation and reconstruction

$\mathcal{S}=\sqrt{(2[(S+B)\log(1+S/B)-S])}$ [SIG1]

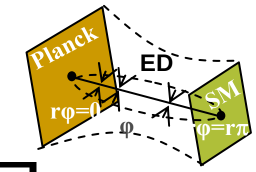


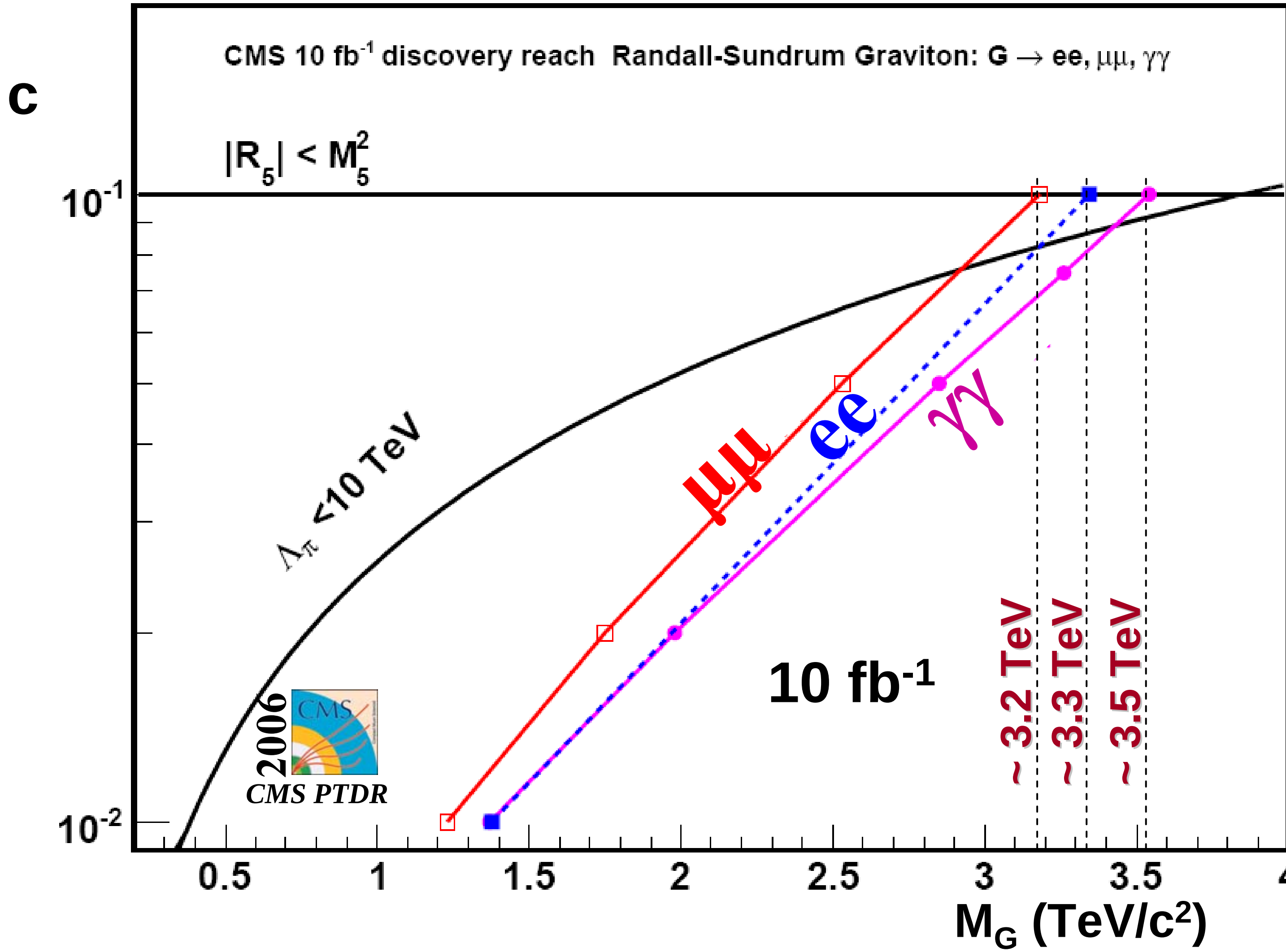






RS(1) expectations in CMS





TeV^{-1}-size ED models

bosons ED

Ref: [TEV1]

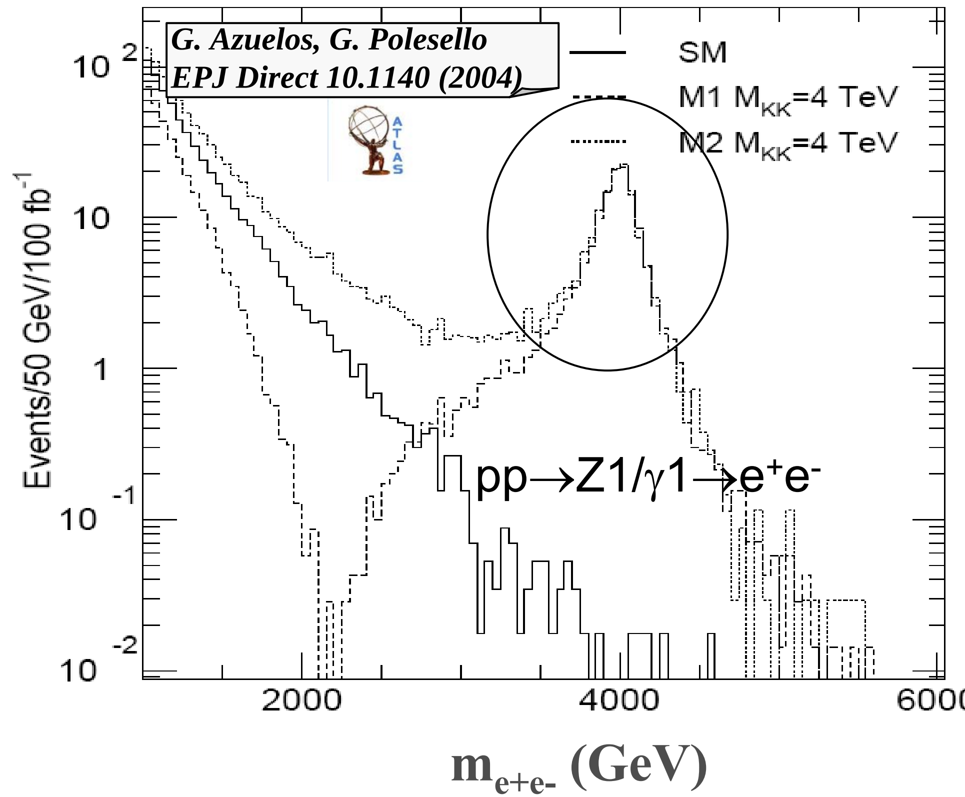
The results shown in the following assume:

- Higgs in the bulk ➔ the VEV of H_0 ➔ SSB ➔ $m(gauge_n)=[m_0^2+nn/R^2]^{1/2}$
- $\delta=1$
- Fermions localized at specific points in the TeV^{-1} dim but not on a rigid brane (suppress of a number of dangerous processes).

Two models:

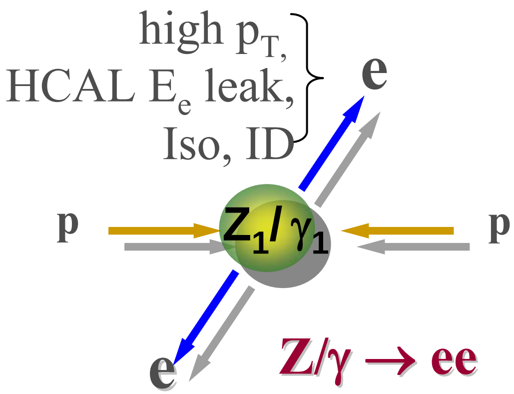
M1: All SM fermions localized at the same orbifold point ➔ KK gauge states coupling to SM fermions is $\sqrt{2}g$ ➔ destructive interf. between SM gauge bosons and KK excitations.

M2: quark and leptons localized at opposite fixed orbifold points ➔ constructive interference.

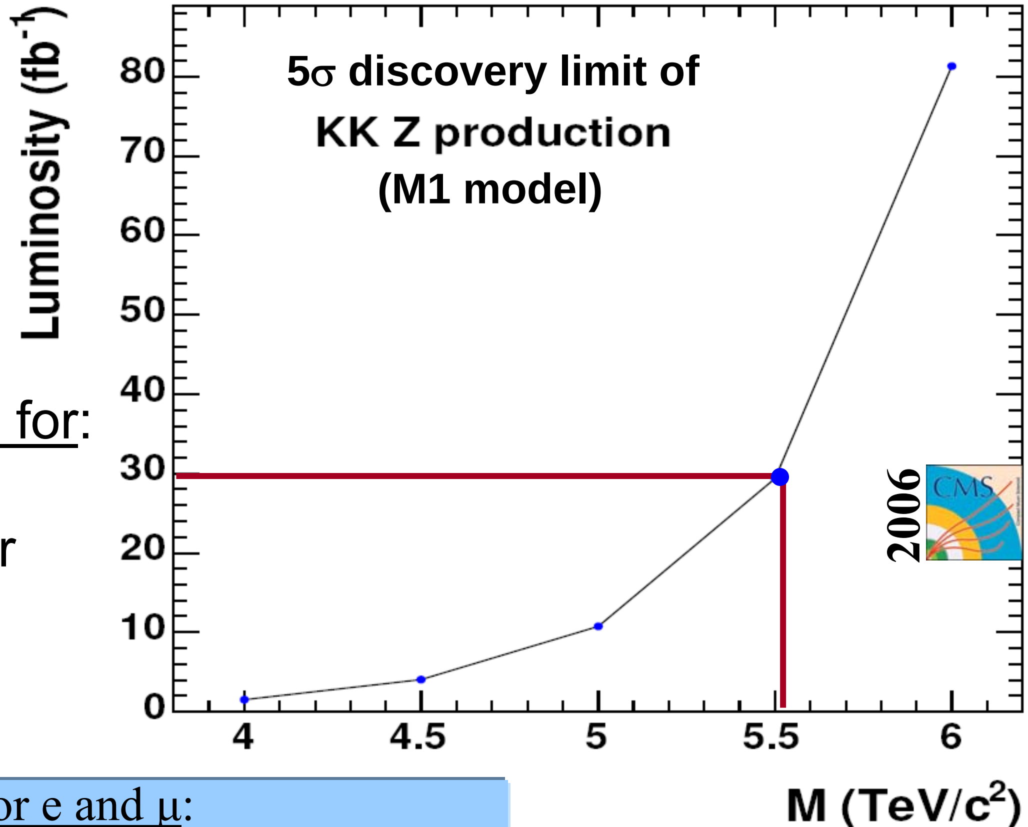


TeV^{-1} expectations in

Invariant mass analyses



$\mathcal{S}=\sqrt{(2[(S+B)\log(1+S/B)-S])} > 5$ [SIG1]



Gen (S+B):
Ext+PYTHIA
PHOTOS
CTEQ6.1M
Sim/Rec:
Full
Pile-up @low
Lumi (10^{33})
Syst Uncert:
Theoretical

2006

R. Clerbaux et al.
CMS NOTE 2006/083
CMS PTDR 2006

CMS events corrected for:

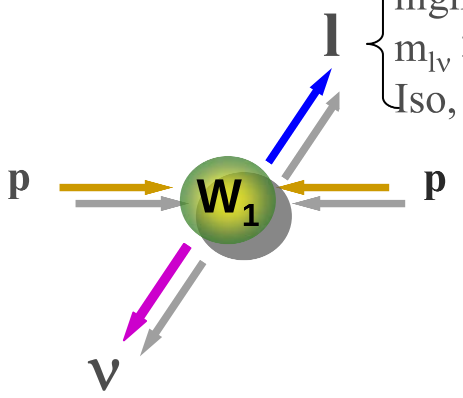
- ECAL **electronics saturation** (MGPA) for E_T>1.7 TeV (3 TeV Endcaps)

ATLAS expectations for e and μ:
($\mathcal{S}=(S-B)/\sqrt{B} > 5$ & $S > 10$ (e,μ))
Fast simu/reco
R^{-1} = 5.8 TeV @100 fb^{-1}

G. Azuelos, G. Polesello
EPJ Direct 10.1140 (2004)

TeV^{-1} expectations in

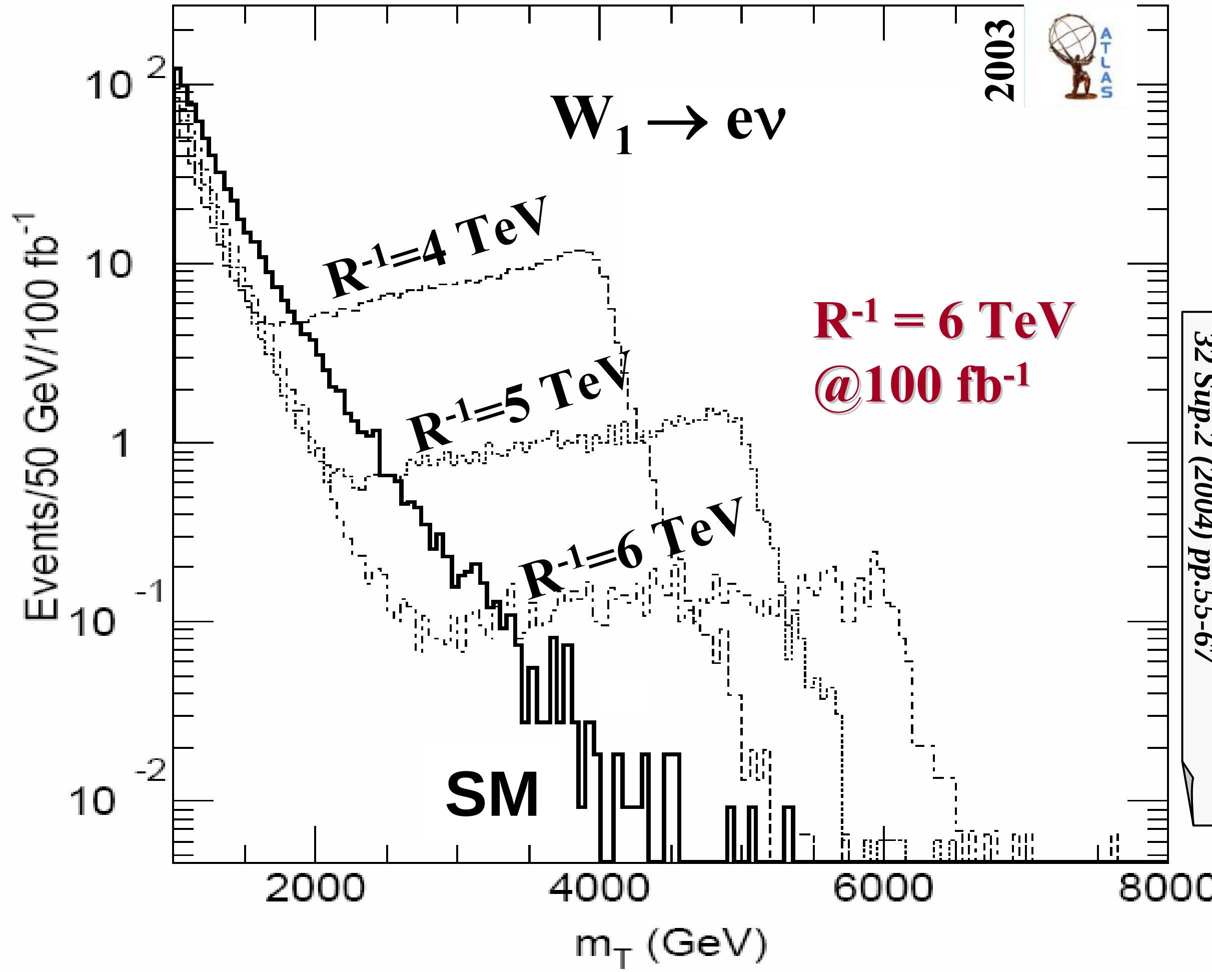
bosons → ED



l:
- high p_T > 200 GeV
- $m_{l\nu}$ > 1 TeV
- Iso, ID. jet veto

- **W→lν**
- tt, WW, WZ, ZZ

$\mathcal{S}$=(S-B)/√B > 5 & S > 10 (e,μ)

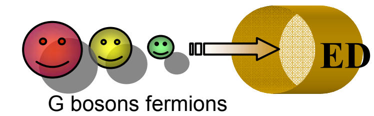


G. Polesello, M. Prata EPJ Direct C 32 Sup.2 (2004) pp.55-67

ATLAS: $g_1 \to$ tt, bb
Fast simu/reco
tt ➔ R^{-1} = 3.3 TeV
bb ➔ R^{-1} = 2.7 TeV
for 300 fb^{-1}

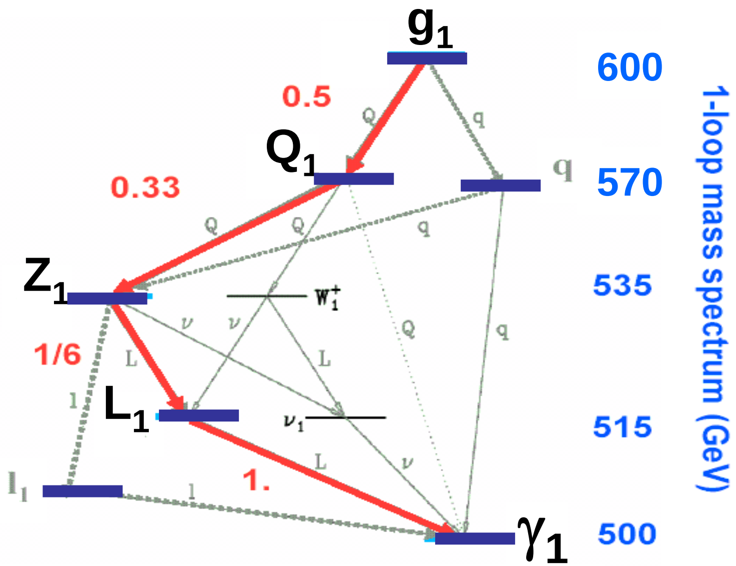
L. March, E. Ros, B. Salvachua, ATL-PHYS-PUB-2006-002

UED Scenarios



Standard (M)UED

- All particles propagate in ED
- KK parity conservation ➔ the lightest massive KK particle (**LKP**) **is stable** (dark matter candidate).
- ∃ mass degeneration except if radiative corrections included:

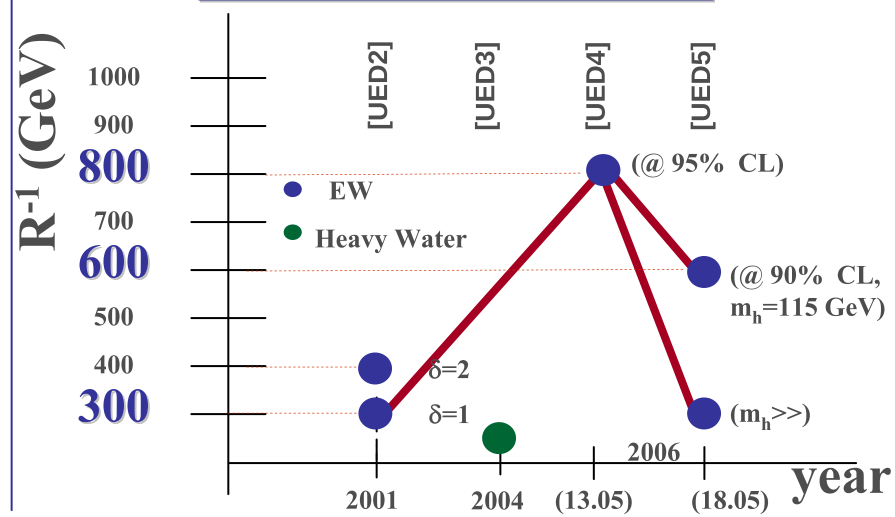


- Model parameters: **δ (= 1), R, Λ**

Fat brane

- SM brane is endowed with a finite thickness in the ED.
- **Gravity-matter interactions** break KK number conservation:
  - 1[st] level KK states **decay to G+SM**.
  - If radiative corrections ➔ mass degeneracy is broken and γ and leptons are produced.

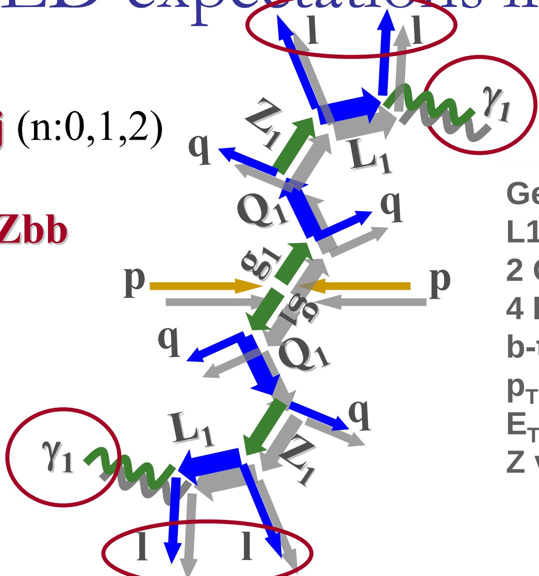
Lower bounds on UED



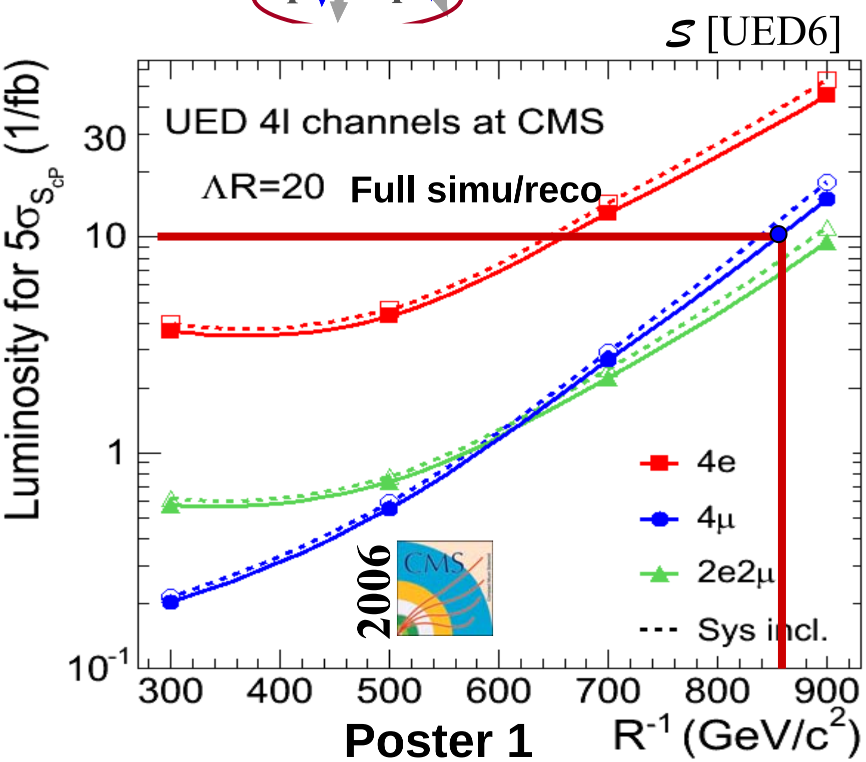
Ref: [UED1]

UED expectations in

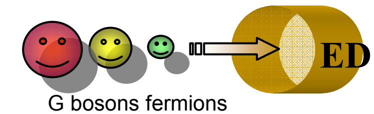
tt+nj (n:0,1,2)
4b
ZZ, Zbb



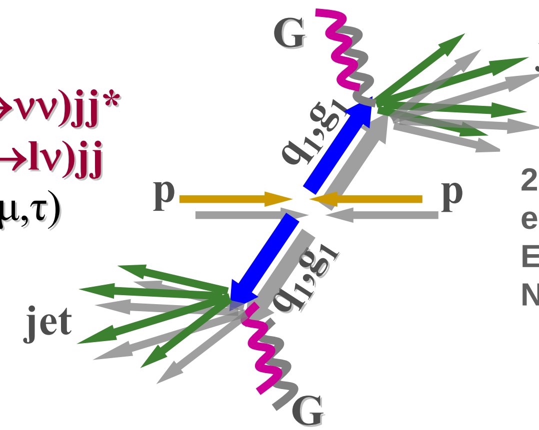
Geo accep
L1,HLT
2 OSSF
4 ISO
b-tag veto
$p_T^l<$
E_T^{miss}
Z veto



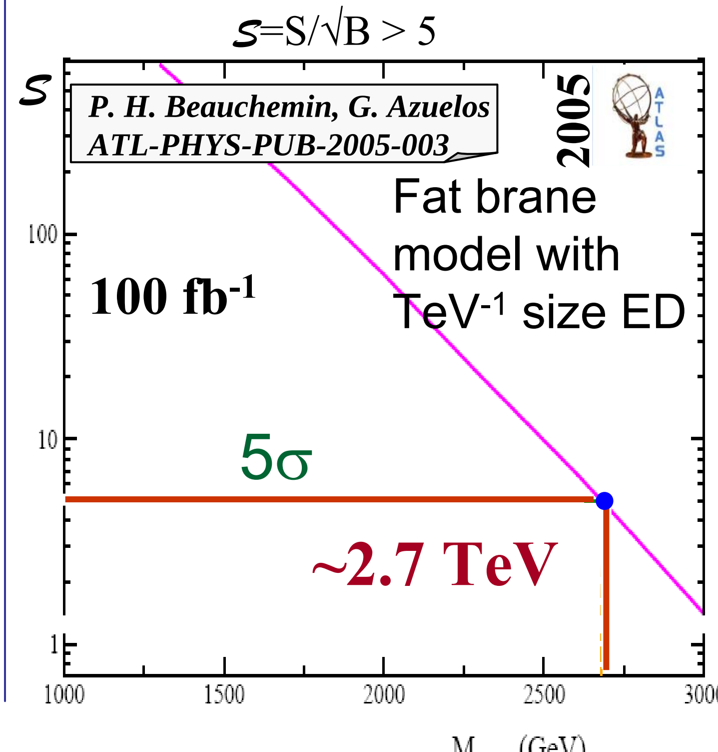
Poster 1



Z(→νν)jj*
W(→lν)jj
(l:e,μ,τ)



2 back-to-back energetic jets + E_T^{miss} > 775 GeV
No ISO leptons



Gen(S+B):
CTEQ5L
B:Estimate of PYTHIA using Z/W+j(+nj from ISR&FSR)
Sim/Reco:
- Fast
- Cascade decays suppr.
- n ≥ 2 kinem. suppr.
- Proton top flavour content ignored

4. Extra Gauge Bosons (Z', W')

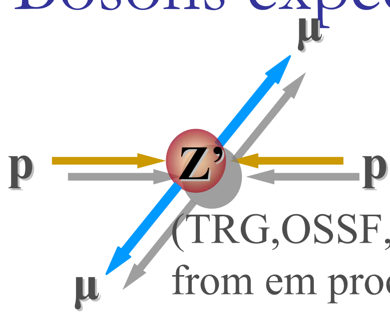
- Predicted by:
  - Super-string inspired and GUT theories;
  - Left-Right Symmetric Models based on the gauge group $SU(3)_C x SU(2)_L x SU(2)_R x U(1)_{B-L}$ predicting substructures of the known "elementary particles";
  - Little Higgs Models.

- ∃ stringent limits from precision EW experiments and direct searches

- TEVATRON ~ 1 TeV

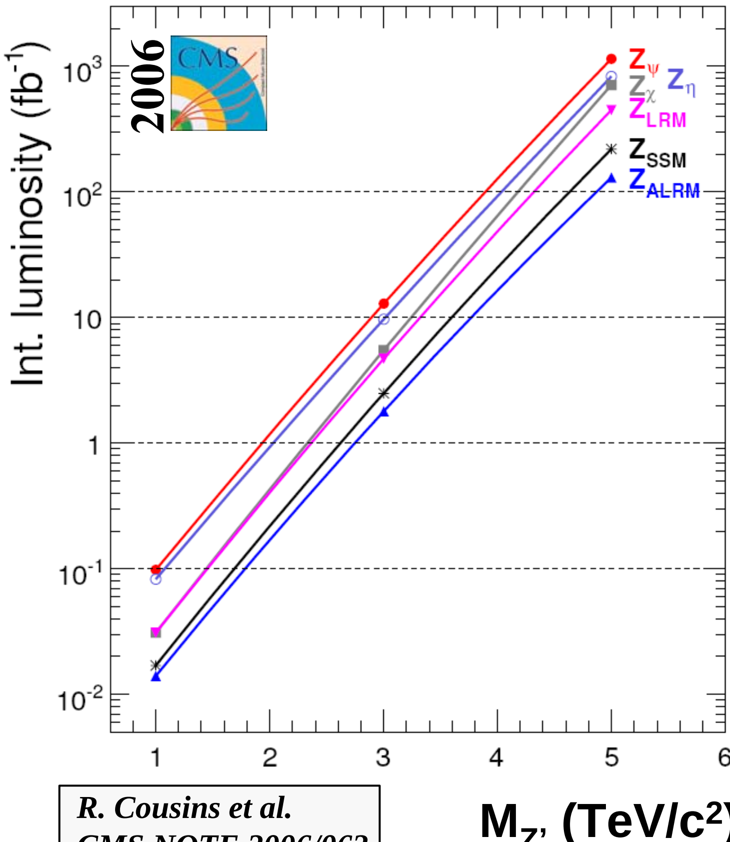
Extra Gauge Bosons expectations in CMS

$Z/\gamma \rightarrow \mu\mu$



(TRG,OSSF, E_μ recov. from em processes)

$\mathcal{S}_{\mathcal{L}}=\sqrt{(2 \ln(\mathcal{L}_{S+B}/\mathcal{L}_B)} > 5$



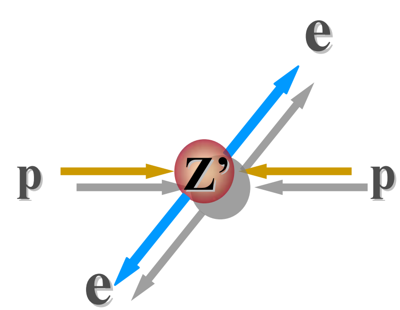
Gen (S+B):
- PYTHIA
- CTEQ6L
- K=1.35

Sim/Rec:
- Full
- pile-up (ine+dif) for low (5 evt) & high (25 evt) lumi.

Systemat. uncert.:
- Theoretical
- Muon+TRK missalignment

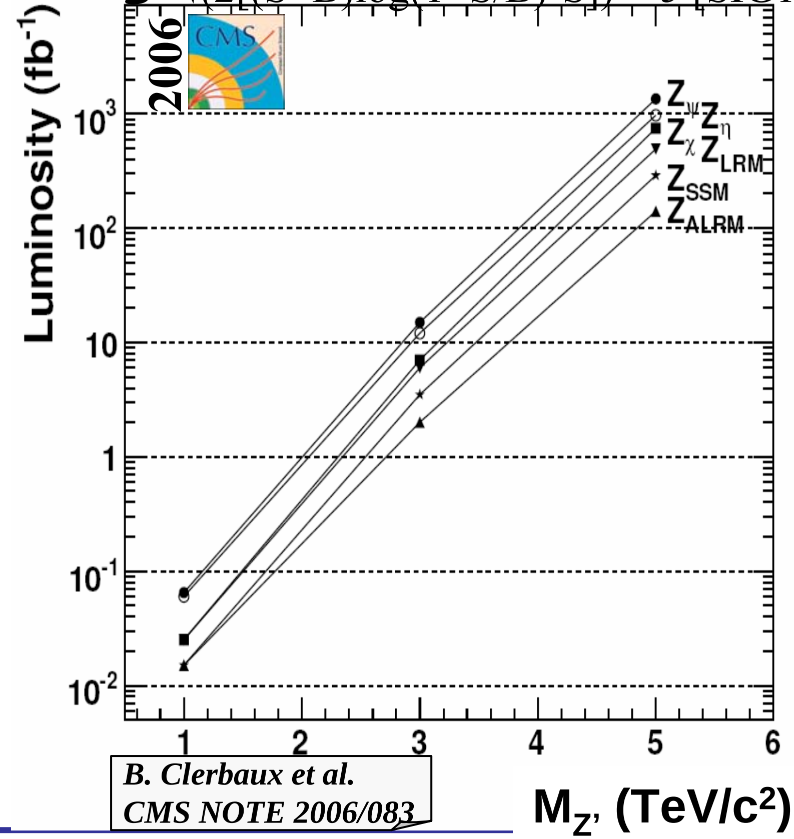
R. Cousins et al.
CMS NOTE 2006/062
CMS PTDR 2006

$Z/\gamma \rightarrow ee$



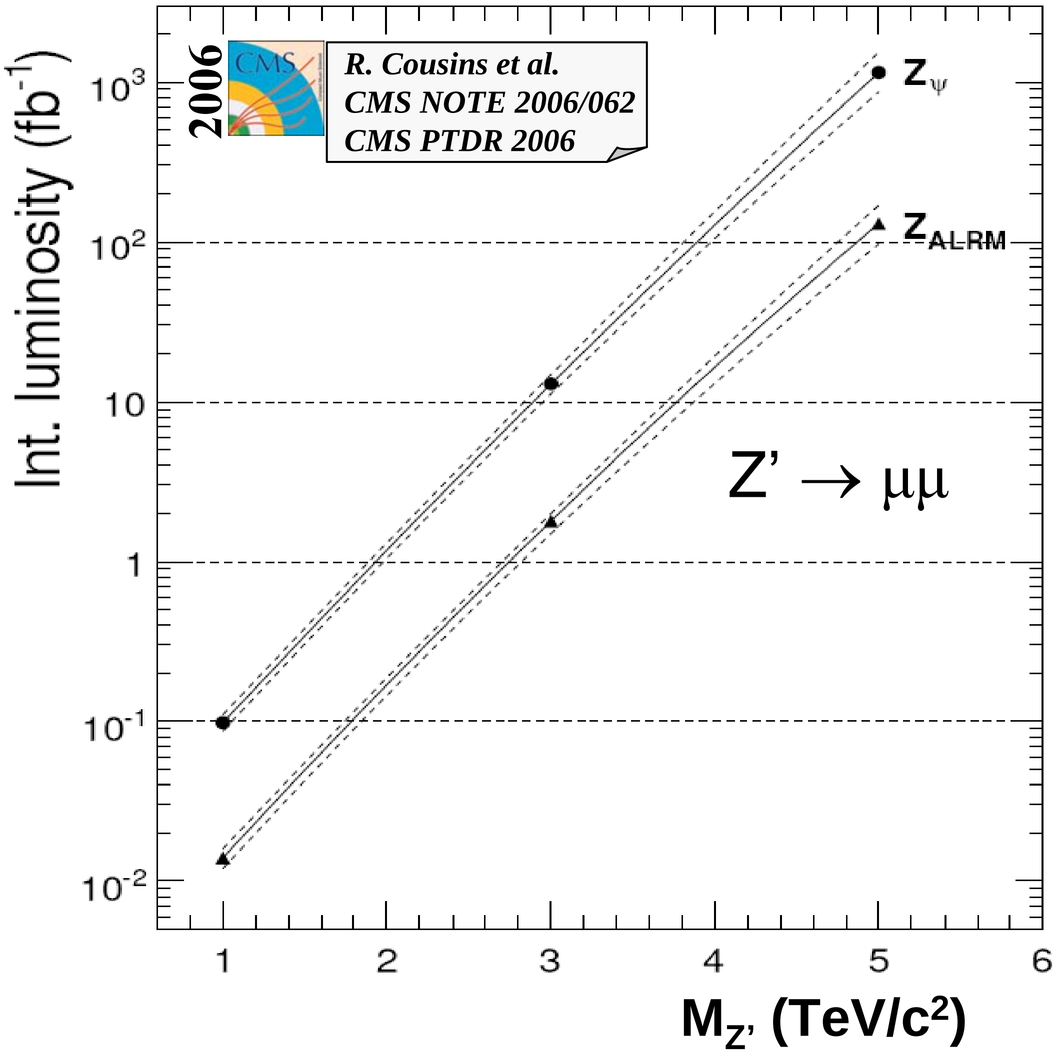
Same analysis as Z_1/γ_1 @CMS

$\mathcal{S}=\sqrt{(2[(S+B)\log(1+S/B)-S])} > 5$ [SIG1]



B. Clerbaux et al.
CMS NOTE 2006/083

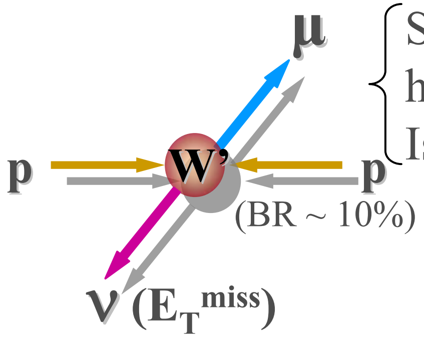
Extra Gauge Bosons expectations in CMS



Effects of 1σ theoretical uncertainties on the integrated luminosity need to reach a 5σ significance for two Z' models:

- Asymmetric Left-Right Model (ALRM)
- GUT theory (Ψ)

Extra Gauge Bosons expectations in CMS

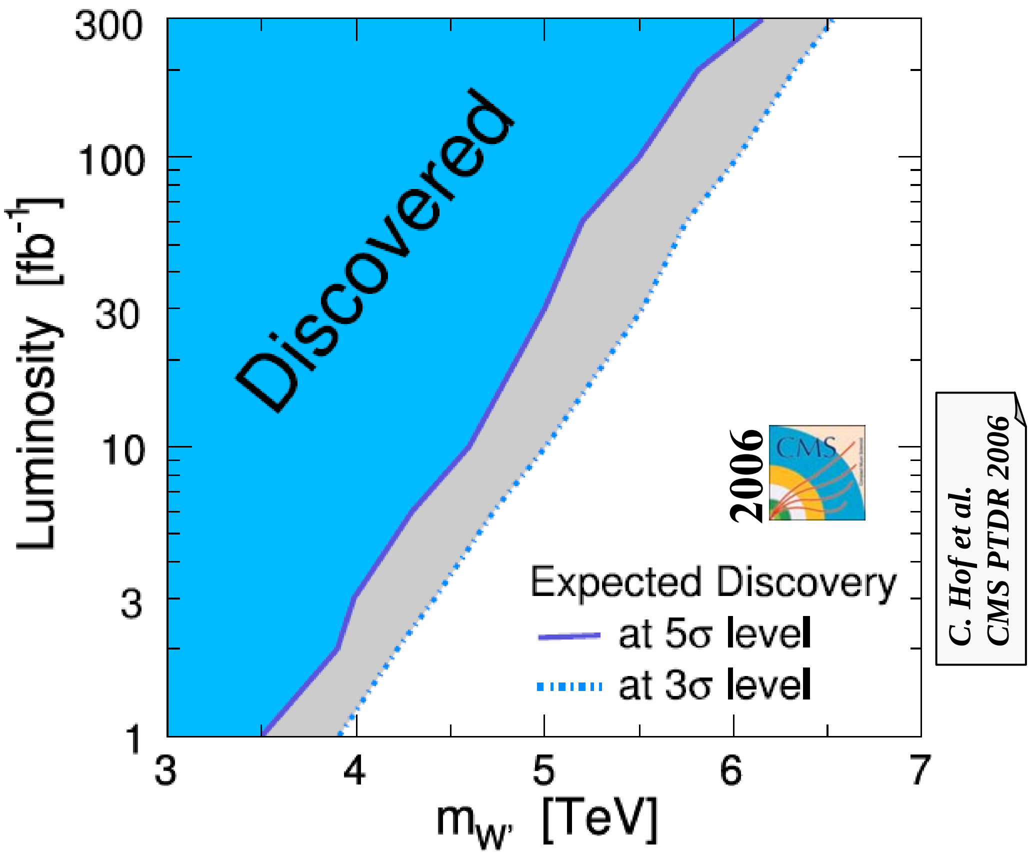


Single μ trg
high pT
Iso-μ ID

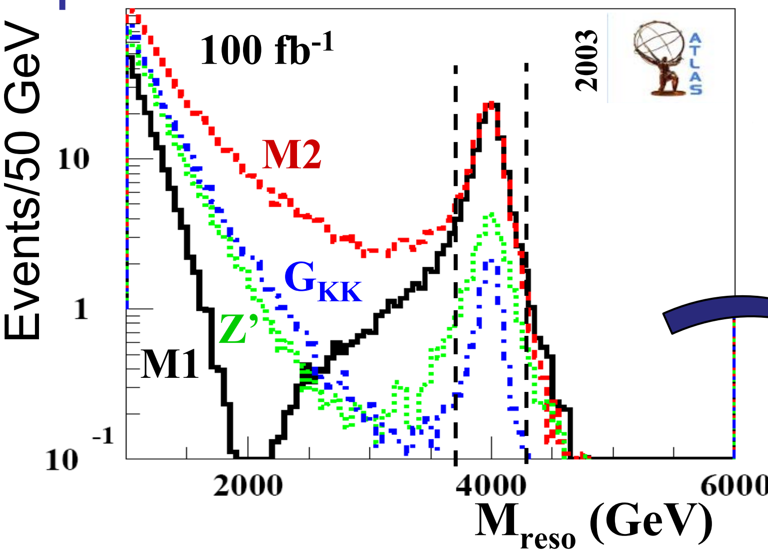
W→ μν
Z→ μμ,
WW incl., ZW incl.
tt\bar incl

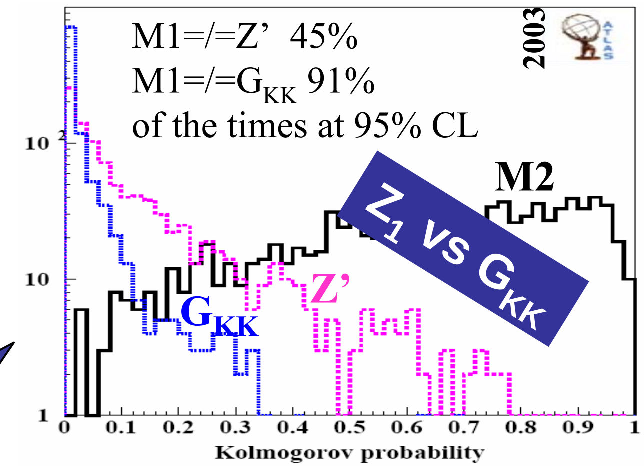
CMS looks for charged spin-1 boson, W' from the Reference Model by Altarelli.

L ~ 10^{33} $cm^{-2}s^{-1}$, with pile-up of 3.5

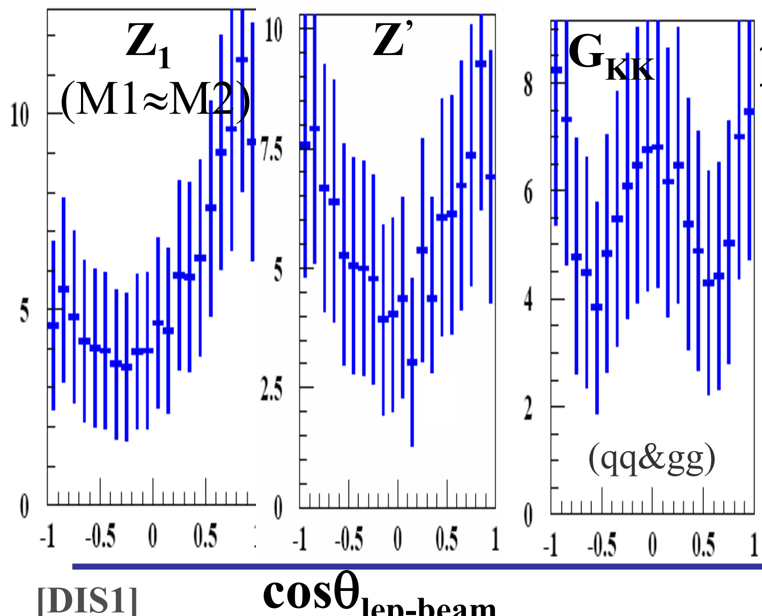


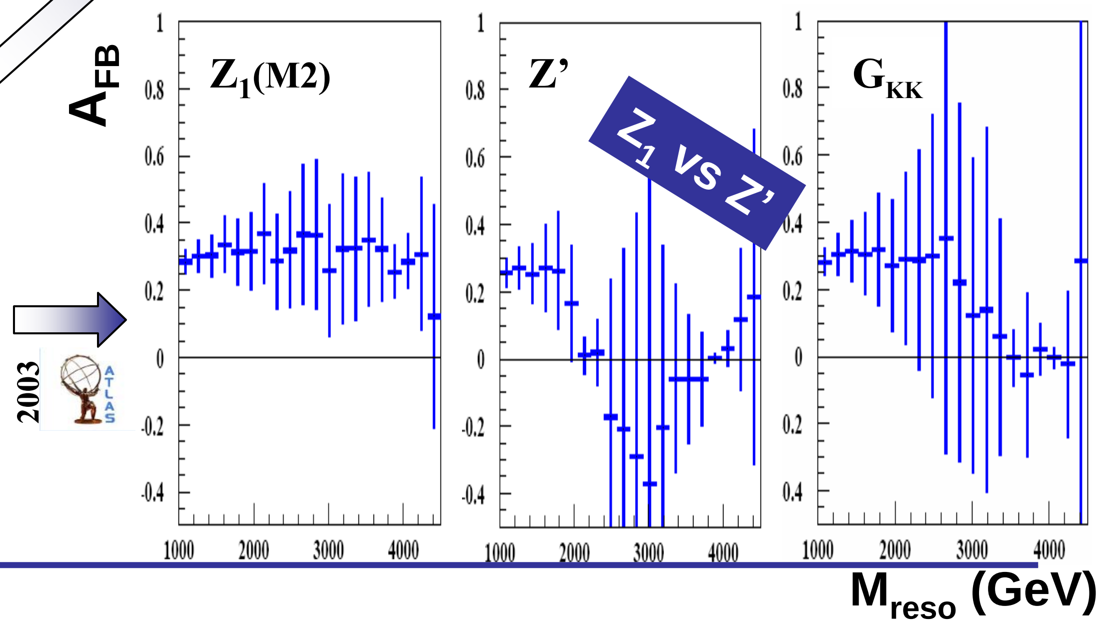
5. How to discriminate models





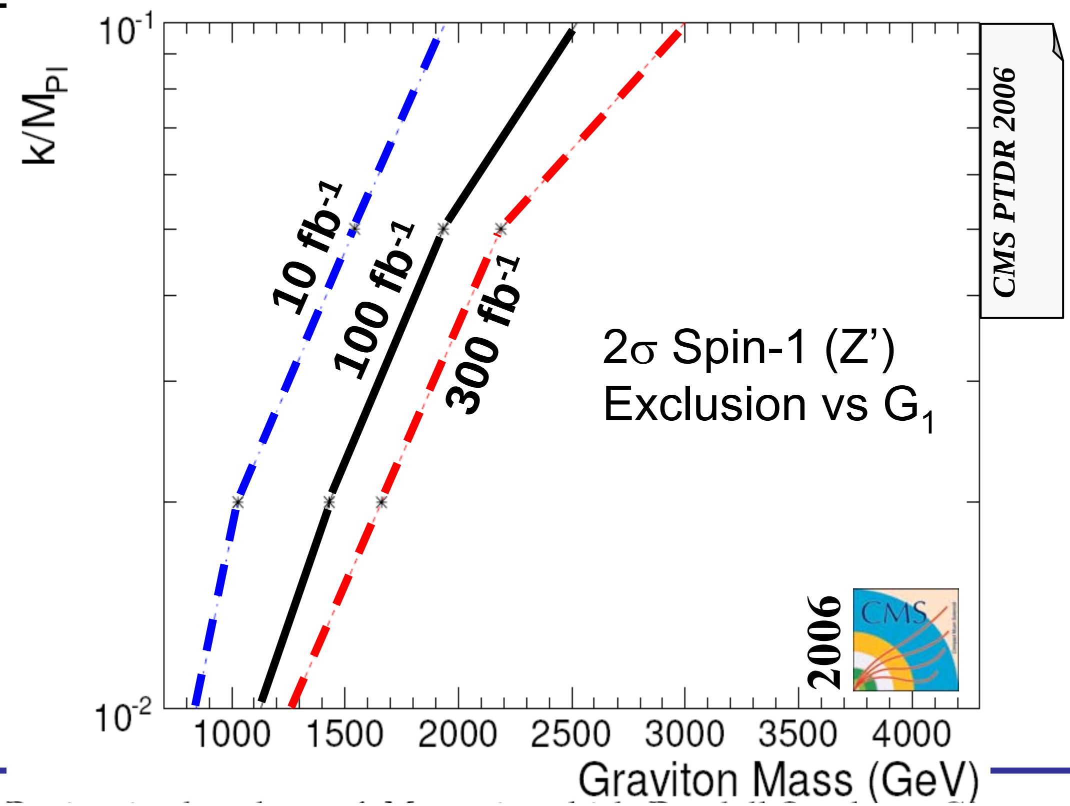
For higher resonance masses (e.g. 5 TeV) need more luminosity to keep discrimination power





How to discriminate models

- **Method**: unbinned likelihood ratio statistics incorporating the angles of the decay products [DIS3].
- The statististical technique has been applied to fully simu/reco events.
- Two spin hypothesis are treated symmetrically.
- $\sigma(G_1) = \sigma(Z')$



[DIS2,DIS3]

Conclusions

- We have revised the most recent results on different Extra Dimensions scenarios and Extra Gauge Bosons:

Model	Mass reach	Int. Lum.(fb^{-1})	Syst. Includ
ADD Direct G_{KK}	**M_D~2.5 TeV $\forall\delta$**	10	Theo
ADD Virtual G_{KK}	**M_D~5 - 4 TeV $\delta\in$[3-6]**	1	Theo+Exp
RS	**M_{G1}~3.5 TeV**, **c**=0.1 (~all the allowed region)	10	Theo(+Exp di-μ)
TeV^{-1} (Z_1/γ_1)	**M_{Z1} ~ 5 TeV**	10	Theo
TeV^{-1} (W_1)	**M_{W1} ~ 6 TeV**	100	
mUED	**R^{-1} ~ 900 GeV** (ΛR=20)	10	Theo+Exp
Fat brane	**R^{-1} = 2.7 TeV**	100	
GUT,SSM,(A)LR Z'	**$M_{Z'}$ ~ 3 - 4 TeV**, f(model)	10	Theo+Exp
Altarelli	**$M_{W'}$ ~ 3 - 4 TeV**	10	Theo+Exp

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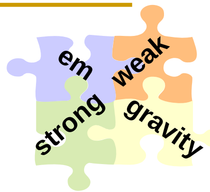
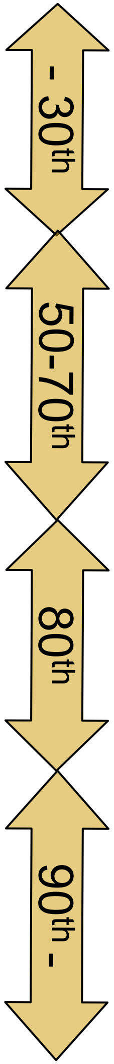
Talk shortenings

- ADD: Arkani-Hamed, Dimopoulos and Dvali model
- RS: Randall and Sundrum model
- UED: Universal Extra Dimensions
- BH: Black Holes
- Iso: Isolation algorithm
- ID: Lepton Identification
- S: Number of signal events that survive the selection cuts
- B: Number of background events that survive the selection cuts
- Ext.: external generator interfaced to PYTHIA
- IP: Interaction Point
- SSB: Spontaneous Symmetry Breaking
- VEV: Vacuum Expectation Value.
- g: SM coupling
- MET: Missing Transverse Energy
- TRK: Tracker detector
- TRG: Trigger
- EW: Electroweak

Back up slides

Overview



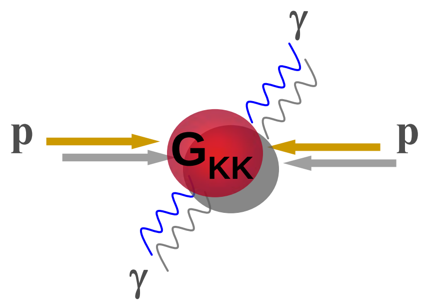


- The first ED ideas appeared when gravity and the electromagnetism were the only known interactions (1 ED theories):

  G. Nordström (**1912**), T. **Kaluza** (**1919**) & O. **Klein** and H. Mandel (**1926**)
- The discovery of new interactions complicated more the overall picture: using a single extra dimension, as a mean of reaching a unified description, was not able to accommodate the strong and weak forces. Therefore physics research focused on *gauge theories.*
- The development of new theories: *string theories* and *supergravity*, changed the interpretation of ED theories in the sense they were given a "physical" meaning.
- In recent years, *ED quantum field theories* have received a great deal of attention:
  - The scale at which the ED effects can be relevant could be around a few TeV, even hundreds of GeV, clearly a challenge for the next accelerators (e.g. LHC).
  - It is a new point of view to study many long-standing problems in physics: hierarchy, neutrino physics, new candidates for dark matter…

ADD expectations in

Virtual production of G_{KK}



The main results of our study could be summarized as follows

- Gravity with extra dimensions could be probed with the ATLAS detector up to a scale $M_S^{max} \simeq 4.9 - 6.3(6.3 - 7.9)$ TeV for low(high) luminosity in the process of di-photon production and up to $M_S^{max} \simeq 5.1 - 6.6(6.6 - 7.9)$ TeV in the process of di-lepton production, depending on the number of extra dimensions.

- For each value of n considered, there is an optimal lower cutoff on the invariant mass, where the reach in gravity scale M_S is maximal.

- Definite correlations exist between the deviation from the SM predictions for different observables in different channels. This could allow to distinguish the scenario considered here from other SM extensions as well as from variant scenarios with different number n of extra dimensions.

- It is important "to go beyond the leading term" for the summed graviton propagator to be able to disentangle the dependence of observables on n and M_S.

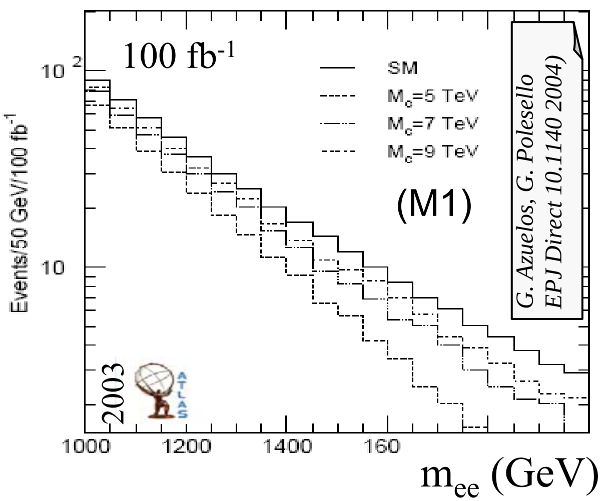
TeV^{-1} expectations in

Off-peak region analyses

- If R^{-1} beyond the LHC reach via direct mass peak reconstruction ➔ study the off-peak region ➔ How?

- look at the σ_{TOT}/event_rate w.r.t. DY background for a m_{ll} range as a f(R^{-1}).

- Very sensitive to the degree of systematic uncertainties.



- ATLAS 5σ reach for R^{-1}:
  - ~ 8 TeV @100 fb^{-1} (15% SM deviation)
  - ~10.5 TeV @300 fb^{-1} (~ 10% deviation)

bosons ➔ ED

Event kinematics analyses

- Results using event kinematic variables (only e+e-):
  - Fraction of the proton momentum carried by parton i
  - Scattering angle in the partonic c.m.e

- An optimal measurement of R^{-1} can be obtained by a likelihood fit to the reconstructed kinematical variables:
  - For one lepton flavour:
    R^{-1} = 9.5, 11 & 12 TeV
    @100, 200 & 300 fb^{-1} respectively.
  - Assuming similar sensitivity for e & μ:
    $R^{-1} \cong$ 13.5 TeV @ 300 fb^{-1}

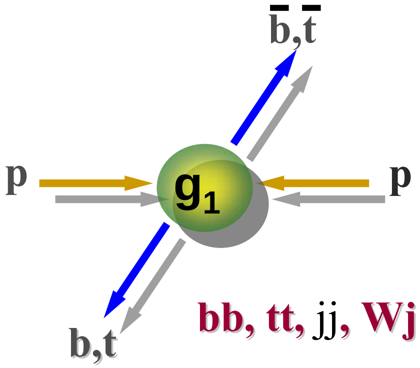
- Studied systematics :
  - how p_T^e scales with energy for > TeV?
    ➔"rule" experimental limit reduces by 2% for each % of uncertainty in the energy calibration of 2 TeV electrons.
  - QCD higher order corrections (main effect ➔ modification of the p_T^{ll} distribution due to ISR).
  - EW corrections.
  - PDFs.

2003

G. Azuelos, G. Polesello
EPJ Direct 10.1140 (2004)

TeV^{-1} expectations in ATLAS

bosons → ED



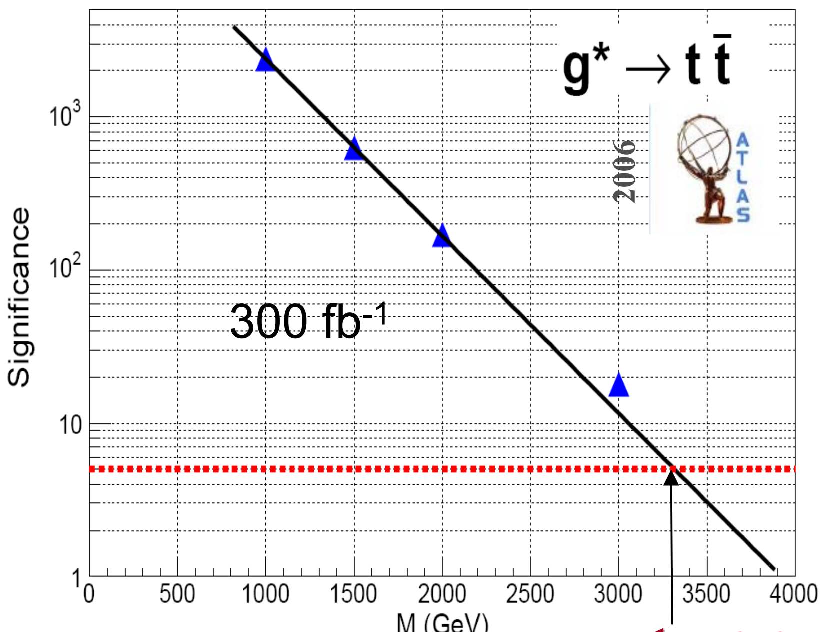
b: 2 b-tagged jets with p_T^b cut $=f(m(g_1))$

t: one t lepton decay (p_T^{lep}>25 GeV), E_T^{miss}>25 GeV, 2 b-tagged jets with $\Delta R(b_{1(2)}$-lep)<2(>2), p_T^b cut $=f(m(g_1))$

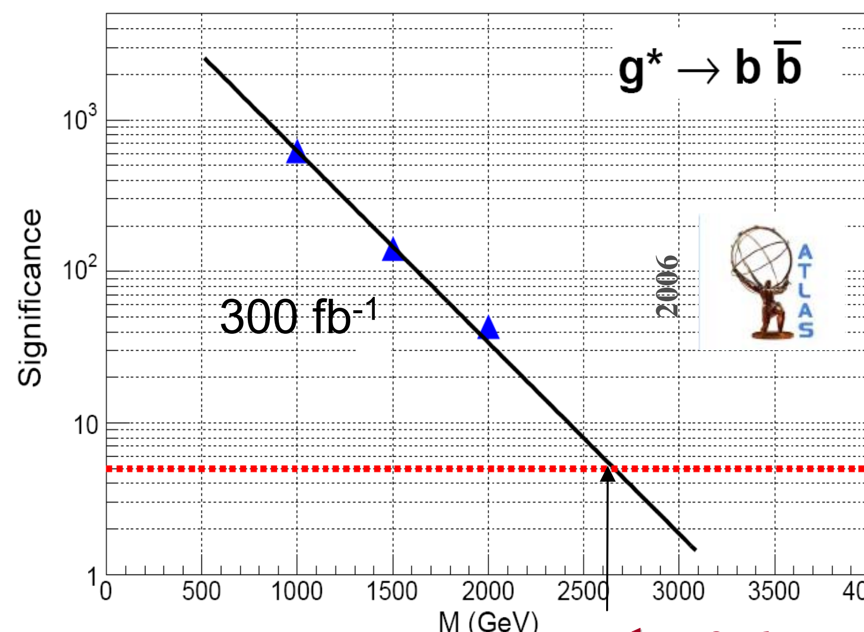
Gen(S): PYTHIA, CTEQ5L

Sim(S): Fast

L. March, E. Ros, B. Salvachua, ATL-PHYS-PUB-2006-002



R^{-1} = 3.3 TeV



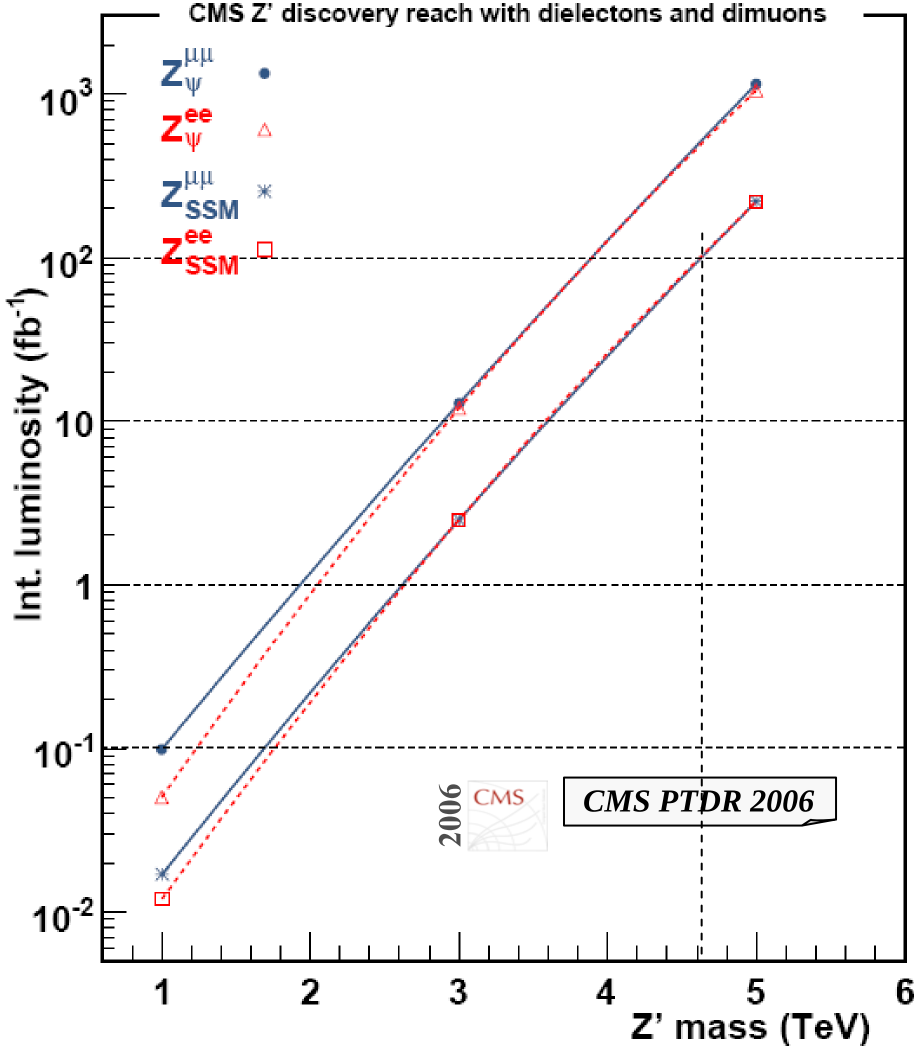
R^{-1} = 2.65 TeV

(Note: heavy quarks appearing in the light quark sample as a result of gluon splitting are excluded in this analysis; the enhancement of the signal due to the contribution of Z_1/γ_1 production (lower than g_1) is not taken into account in this analysis)

Extra Gauge Bosons (Z', W')

- Predicted by:
  - Super-string inspired and GUT theories;
  - Left-Right Symmetric Models based on the gauge group $SU(3)_C xSU(2)_L xSU(2)_R xU(1)_{B-L}$ predicting substructures of the known "elementary particles"; and
  - Little Higgs Models.
- ∃ stringent limits from precision electro-weak (EW) experiments and direct searches.
- The existence of a Z' affects EW data:
  - Because Z-Z' mixing pushes the Z mass below the SM expectations.
  - SM expectations are themselves modified by mixing since = f(weak angle), and this angle is confused or distorted by the effects of mixing on other observables.
  - Both the mixing and heavy particle exchange lead as well to other changes in the predictions for the various observables, implying new terms in the effective interactions relevant to each process and leading to different apparent vales of the weak angle determined in different processes.
- Thus the limits from precision experiments vary significantly from model to model because of the different chiral couplings to the ordinary fermions.
- Typically:
  - $m_{Z'}$ >~ 400 GeV and Z-Z' mixing angle < few 10^{-3} for models in which the Z' couples significantly to charged leptons.
  - $m_{Z'}$ >~ 300-600 GeV for models with suppressed couplings to charged leptons can tolerate much larger mixings (several %) but with the dominant constraint from the shift in the light Z mass.
- At LHC should be possible to discover a heavy Z' with mass up to 5 TeV through its leptonic decay.
- If a Z' exists it should be possible to deeply study its couplings via:
  - F-B asymmetries
  - rapidity distributions
  - rare decays ($Z' \rightarrow Wl\nu$)
  - associated productions with a Z, W or γ

Extra Gauge Bosons expectations in CMS



Combined expectation from:
Z' $\rightarrow e^+e^-$
Z' $\rightarrow \mu^+\mu^-$
for Sequential SM (SSM)
and one GUT theory (Ψ).

Mini (quantum) Black Holes (Exploring energies above the fundamental theory scale: the transplanckian region ($\sqrt{s} >> M_{Pl(4+\delta)}$))

- One of the consequences of large ED is the possibility to produce BH @LHC.
- A BH produced in the 4+δ dimensions has a Schwarzschild radius given by: $R_{s(4+\delta)} = f(\mathbf{M_{Pl(4+\delta)}}, \mathbf{M_{BH}}, \boldsymbol{\delta})$
- If the IP of a p-p collision is smaller than $R_{s(4+\delta)}$, BH can be produced at LHC with

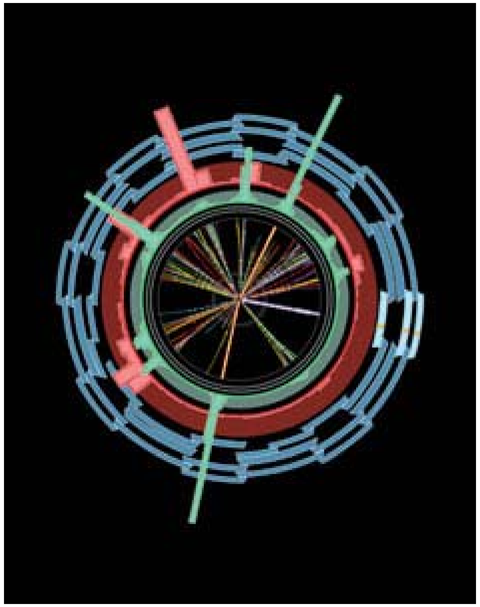
  $$\sigma(M_{BH}) = \pi R^2_{s(4+\delta)}$$

  at parton level and in the semi-classical approach.

- E.g. for $M_{Pl(4+\delta)} \sim 2$ TeV, $\sigma \sim$ pb.
- Once produced, it is expected that they decay thermally via Hawking radiation, with a typical life time of 10^{-27} s.
- BH events are expected to evaporate democratically by emission of all particle types, therefore BH can be a source of new particles.
- Characteristic signatures:
  - events are spherical
  - jet/lepton decay ratio ➔5:1
  - high multiplicity

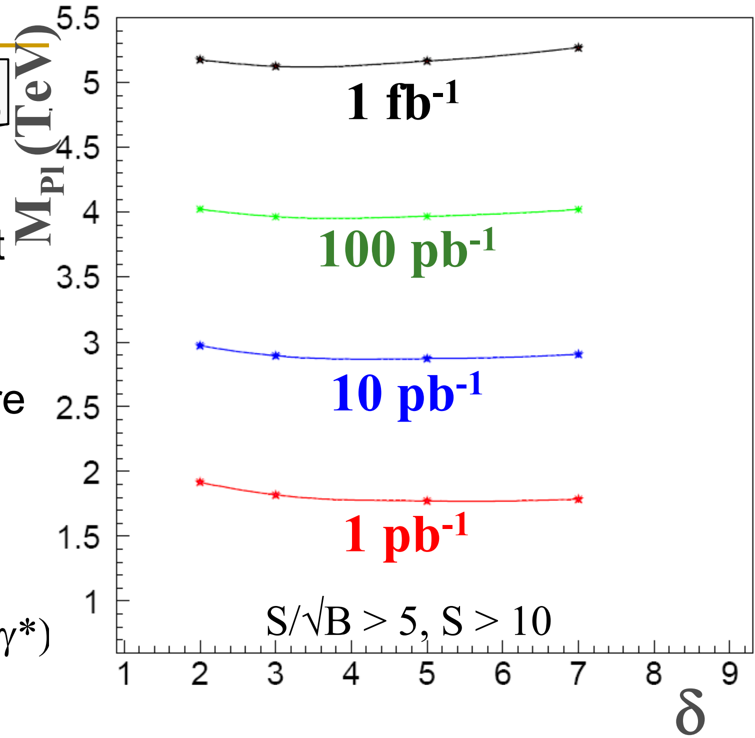
BH expectations in ATLAS

J. Tanaka et al.
Eur. Phys. J. C41 19-33 (2005)



Cuts: ISR-cut, p_T thresholds, multip.(with E>300 GeV)>3, at least one: e.OR.γ, R_2(Fox-Wolfram moments)<0.8 ➔ lower values of R_2 means more spherical events; E_T^{miss}<100 GeV

- qq, qq\bar, qg, gg
- tt\bar
- WW, WZ, ZZ, γγ, γV (V: W,Z,γ*)
- qV (V:W,Z,γ(*))



$\delta=3, M_{BH}^{min}=1$TeV