Extra Dimensions and Mini Black Holes at the LHC

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Introduction

- Many theories beyond the Standard Model invoke extra dimensions (EDs) to explain why gravity is so much weaker than the other forces.

- Two popular scenarios of extra dimensions:
  - ADD (N. Arkani-Hamed, S. Dimopoulos, G. Dvali): gravitational force is diluted by propagating through extra dimensions of macroscopic size.
  - RS (L. Randall and R. Sundrum): gravity originates on a hidden 4D brane and is suppressed away from the brane (along the ED) due to the warp factor.

- It is well known that these (and many other) models can be probed by the LHC experiments.

- Focus of this talk:
  - What are the prospects for the forthcoming 2009-10 LHC run?
  - What are the main experimental challenges?

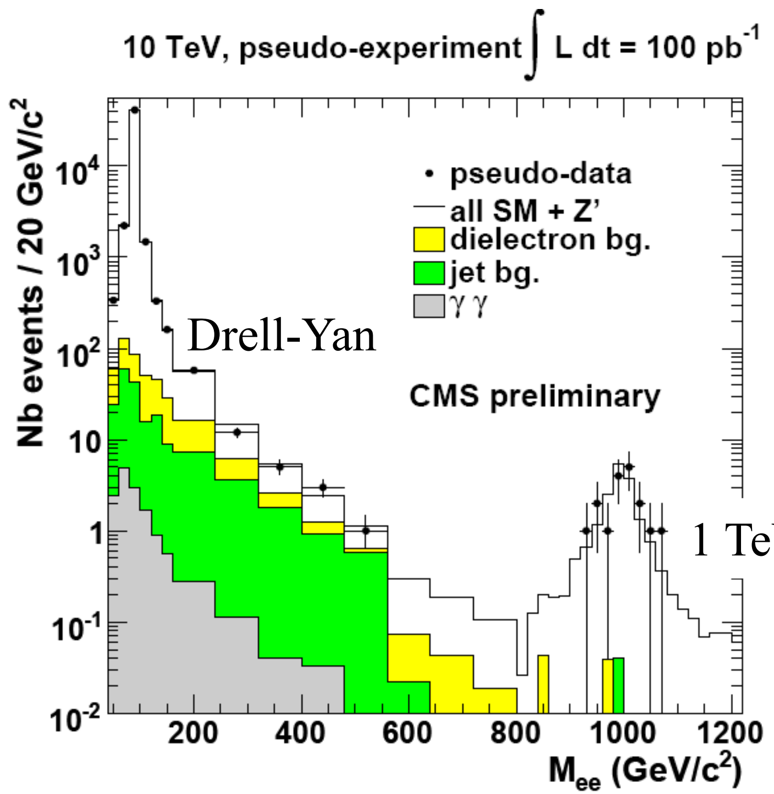
General Comment

The exact scenario for the 2009-10 LHC run is not known yet. The results in this talk (unless explicitly stated otherwise) are for the center-of-mass energy $\sqrt{s}$ of 10 TeV, and assume that an integrated luminosity of 100-200 pb^{-1} is accumulated.

Search for Dilepton Decays of New High-Mass Resonances

- Benchmark signals: Kaluza-Klein gravitons of RSI model (G^*) and various types of additional heavy neutral gauge bosons (Z').
- Dominant (and irreducible) background: Drell-Yan production $pp \rightarrow \gamma^*/Z^0 \rightarrow l^+l^-$.
- Other backgrounds:
  - Two real high-p_T isolated leptons: ttbar, tW, WW
  - At least one jet misidentified as lepton: W+jets, dijets, photon+jets

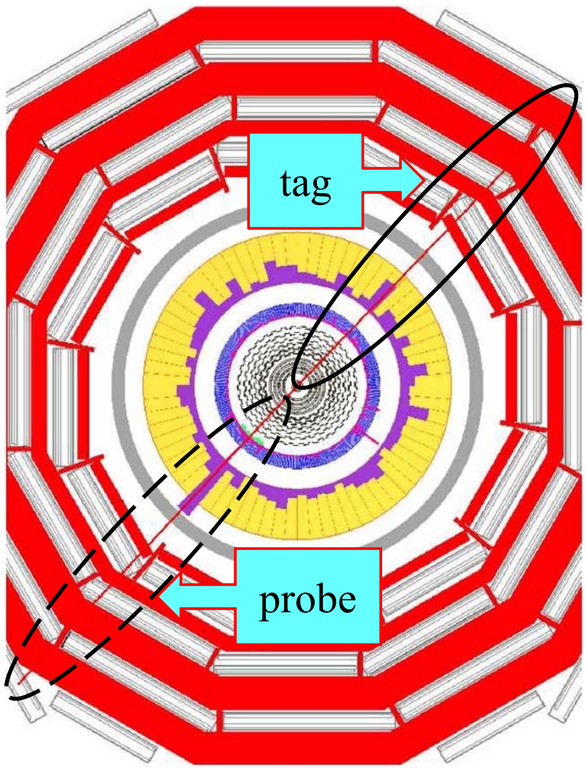
Much smaller than Drell-Yan and reducible



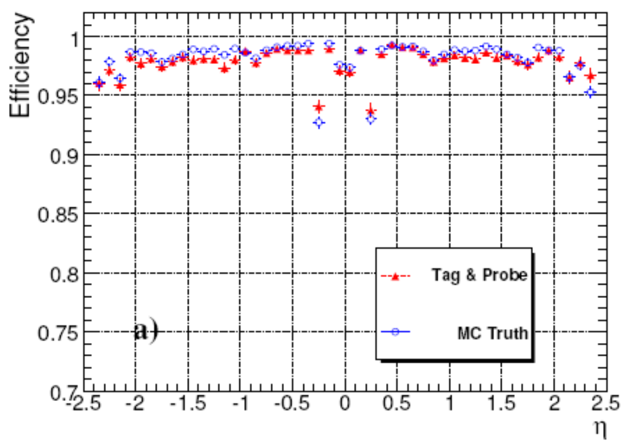
Estimated dielectron invariant-mass spectrum for an integrated luminosity of 100 pb^{-1} (includes 1 TeV Z_{SSM} signal)

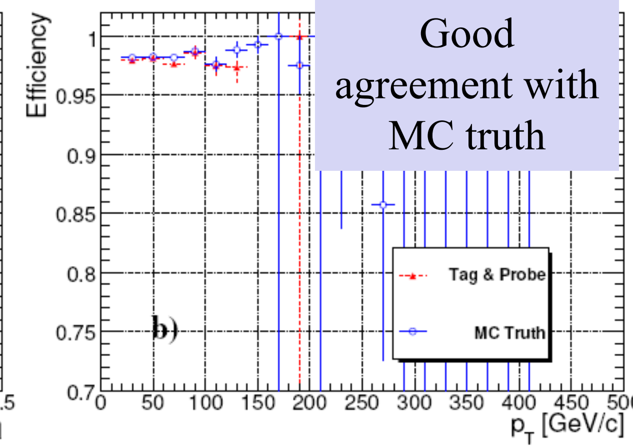
Efficiency Measurements: Tag-and-Probe Method from Tevatron

Example: evaluation of muon reconstruction efficiency in CMS (similar methods used for trigger, electron id and other efficiencies)



- Tag: good-quality, isolated muon
- Require M_{inv} of tag-probe pair to be close to M_Z
- Examine efficiency of interest for the probe



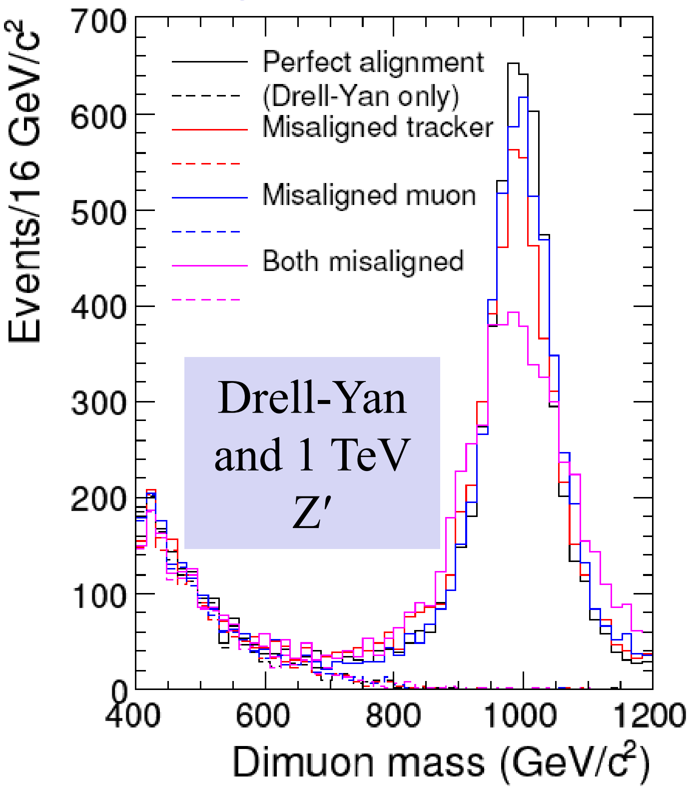


Good agreement with MC truth

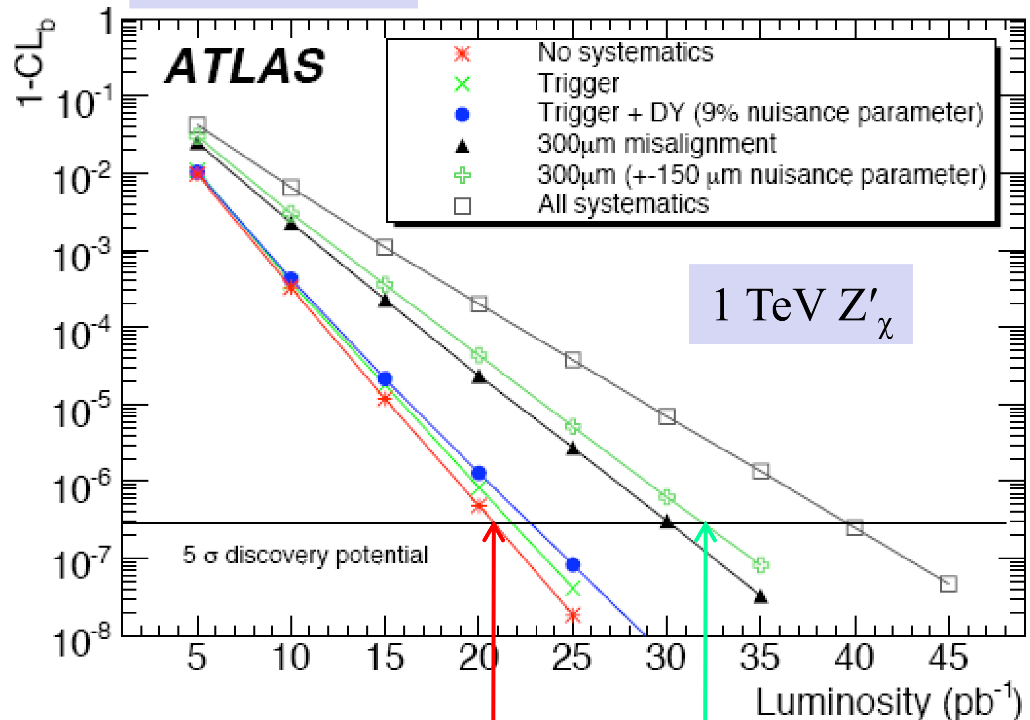
- $60 < M_{\mu\mu} < 120$ GeV; p_T reach is up to ~150 GeV
- Upper cut on $M_{\mu\mu}$ removed: p_T reach extends to ~200 GeV (larger background)

Misalignment and High-p_T Muons

- Both tracker and muon misalignment affect dimuon mass resolution at high $M_{\mu\mu}$. At startup, the effect can be big.
- For expected values of misalignments, shape of Drell-Yan mass spectrum is largely unaffected. Trigger and offline reconstruction efficiencies remain unchanged as well.



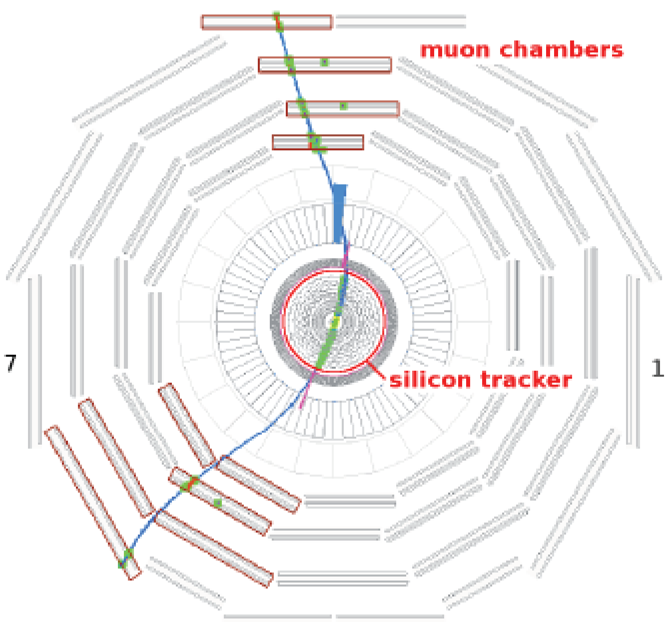
√s=14 TeV

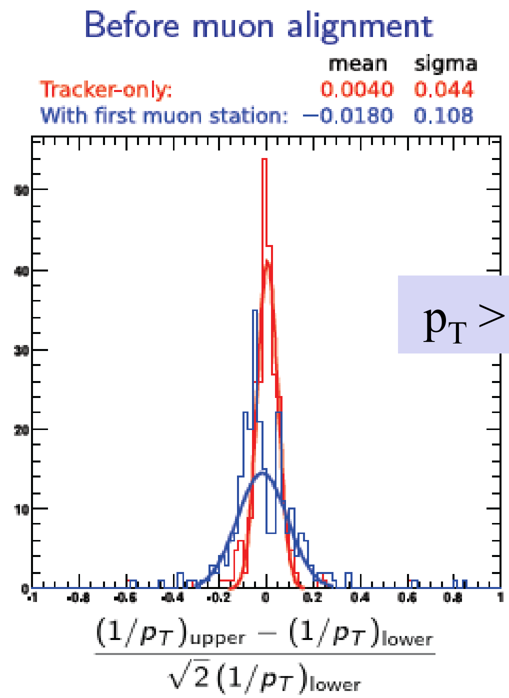


Alignment: ideal non-ideal

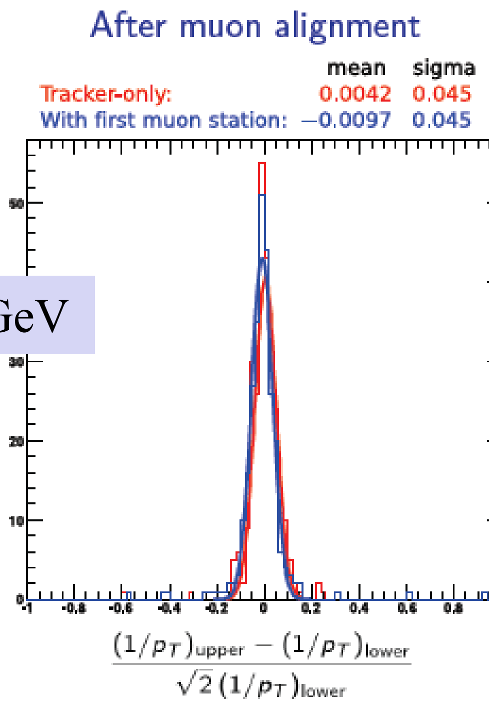
Real High-p_T Muons at LHC

- Month-long "Cosmic Run at Four Tesla" in CMS (Oct-Nov 2008): wealth of data to study alignment, resolution, efficiency, reconstruction of high-p_T muons, etc.
- One example: Select cosmic muons with a topology similar to that expected in *pp* collisions, and reconstruct their trajectories as two independent tracks, in top and bottom halves of the detector. Estimate resolution by comparing $1/p_T$ of upper half with $1/p_T$ of lower half.



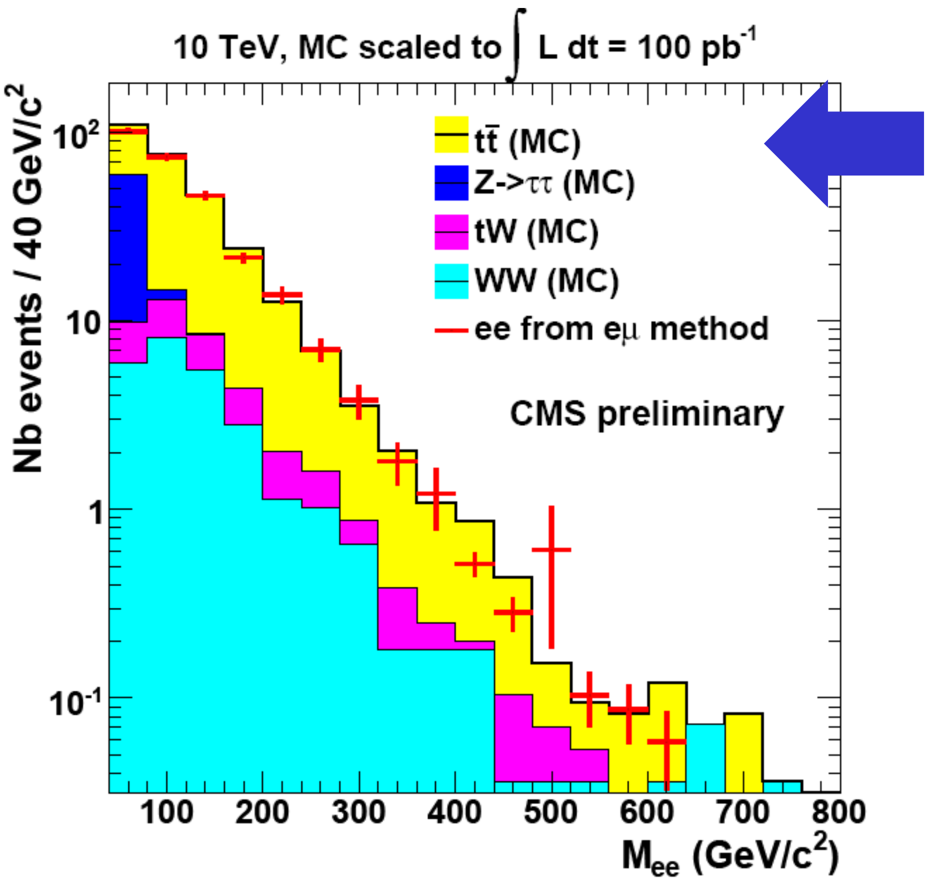


$p_T > 200$ GeV



Non-Drell-Yan Backgrounds: Data-Driven Methods

Every physics analysis at the LHC is devising methods to estimate various backgrounds from data – particularly important at LHC startup, before validity of MC is demonstrated.



- ttbar, tW, diboson backgrounds to e^+e^- and $\mu^+\mu^-$: from eμ events
  - Need to correct for differences in efficiencies and for contamination of non-genuine eμ events.
- ttbar background: from b-tagged events
- Leptons in jets: from rate of leptons in events with identified jets
- Leptons in jets: from events rejected by isolation cuts

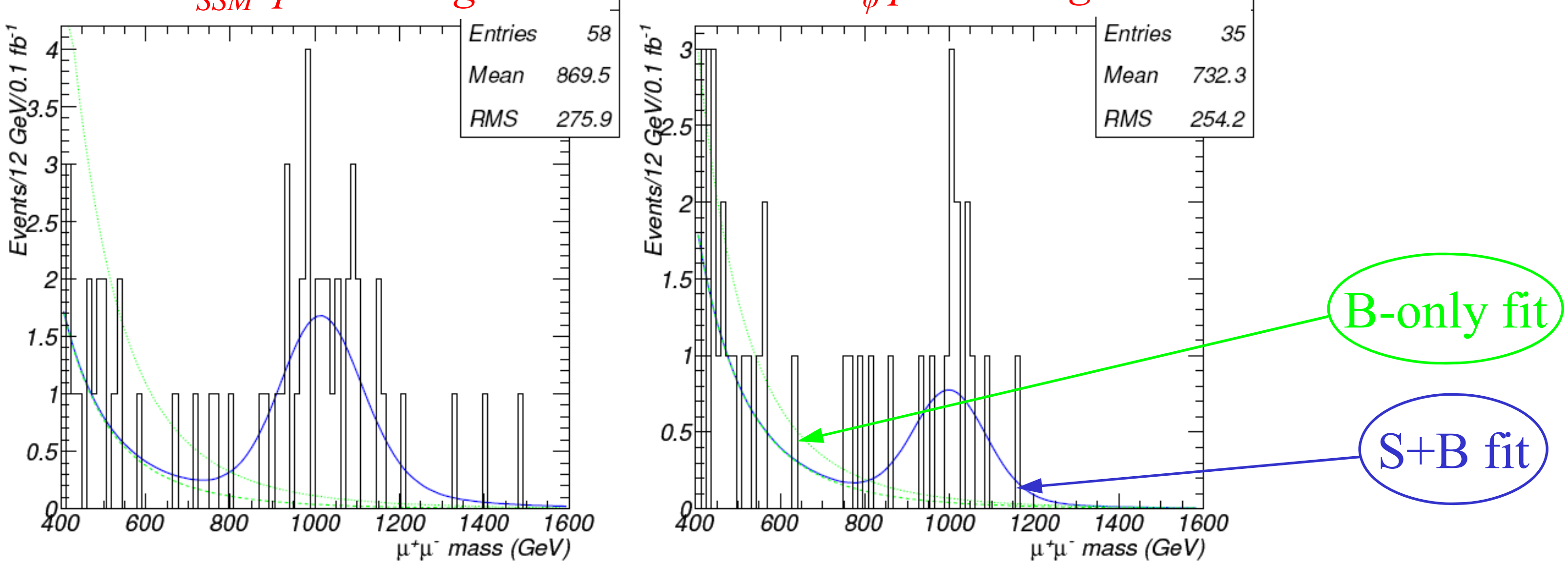
Control sample: same-sign dileptons

Minimizing Systematic Uncertainties

- Peak-search algorithm explores difference in shape between possible signal from new resonances ("bumps") and continuum background.
- No constraints on the absolute background level: fit assumes only background shape is known.

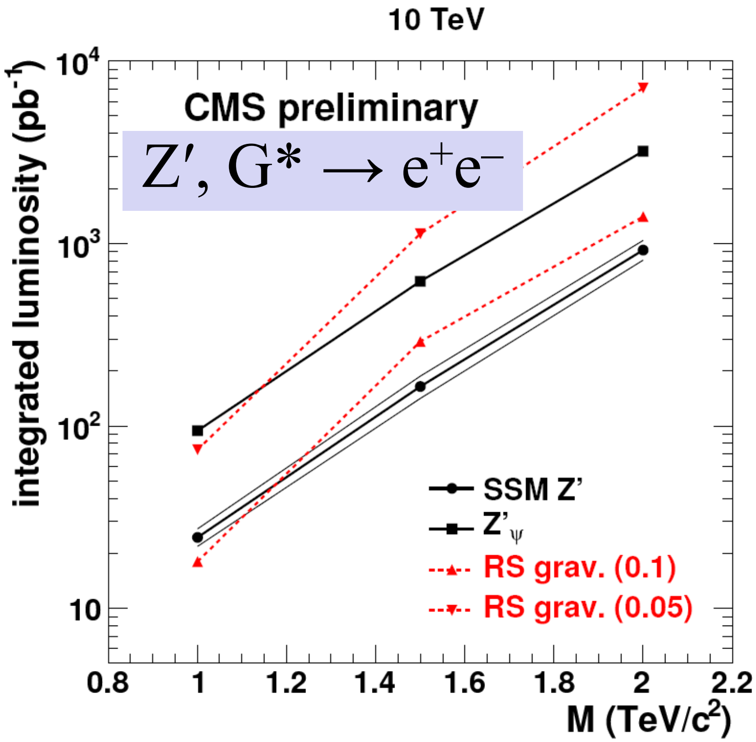
Examples: simulated S+B mass spectra and fits for two typical MC experiments, for $\int L dt = 100\ pb^{-1}$ ($\sqrt{s} = 14$ TeV).

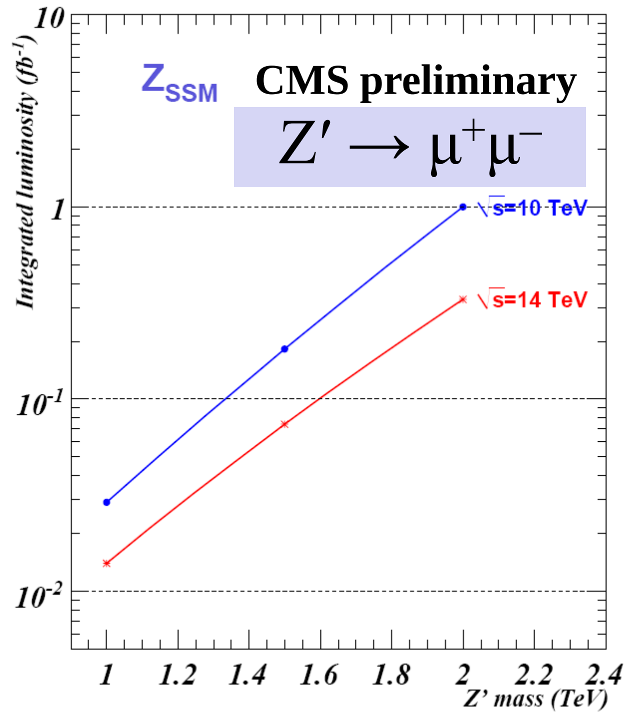
1 TeV Z_{SSM} plus background | *1 TeV Z_{ψ} plus background*



For setting an upper limit, normalize high-mass dileptons to Z^0 peak.

Discovery Potential for RSI G* and Z′





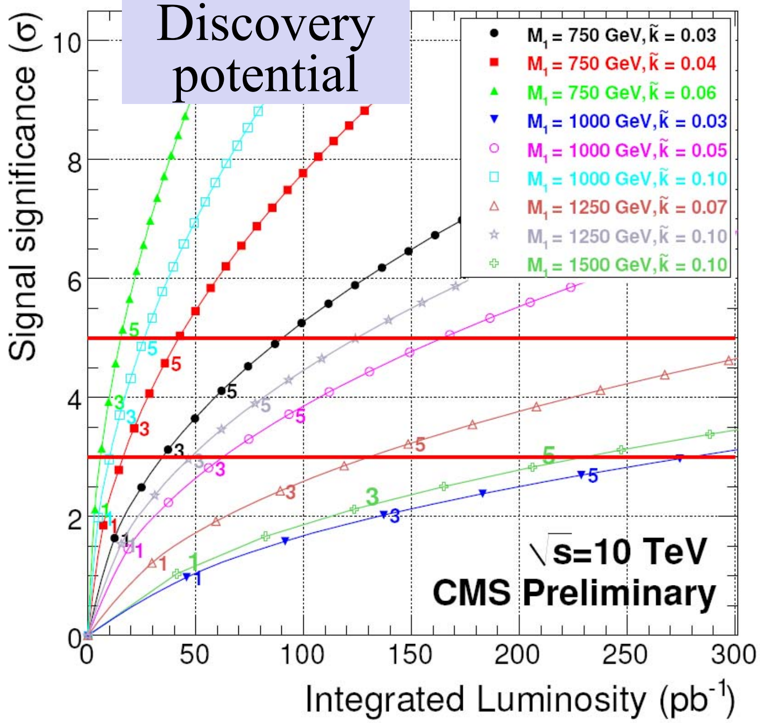
(Use likelihood-ratio estimator S_L and usual convention $S > 5$)

- If LHC operates at $\sqrt{s}$ = 10 TeV, an integrated luminosity of 100 pb^{-1} should be sufficient to probe the RSI G* mass region of up to 1.3-1.5 TeV in each leptonic decay channel (and in each experiment).
  - Work on combining results from ee and μμ channels is in progress.
- Similar mass reach in G* → γγ decay channel (next slide); G^* and Z' will also be searched for in dijet and ττ channels.

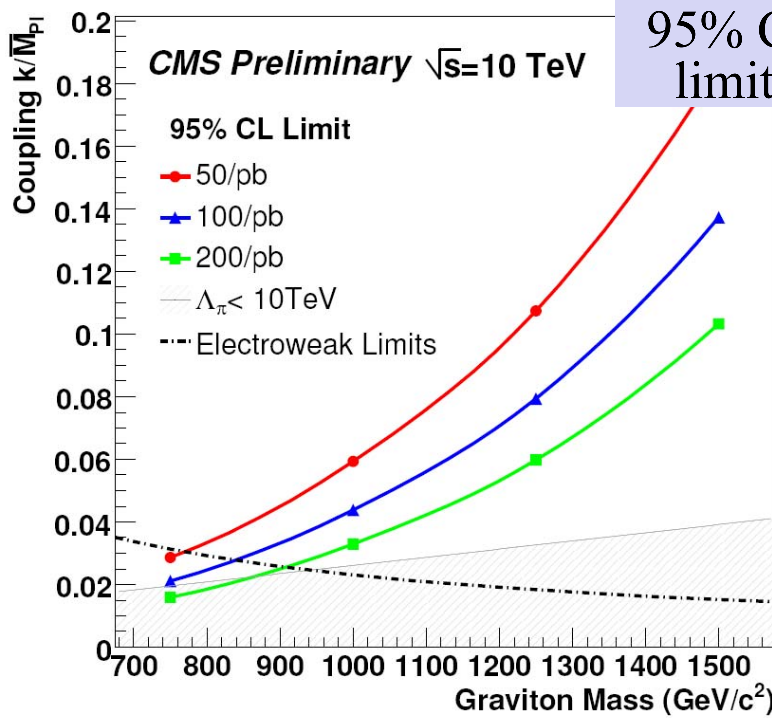
Search for RS Gravitons in γγ

Use results of the search for large extra dimensions in γγ channel (next two slides) to probe the sensitivity to G*→γγ.

Discovery potential



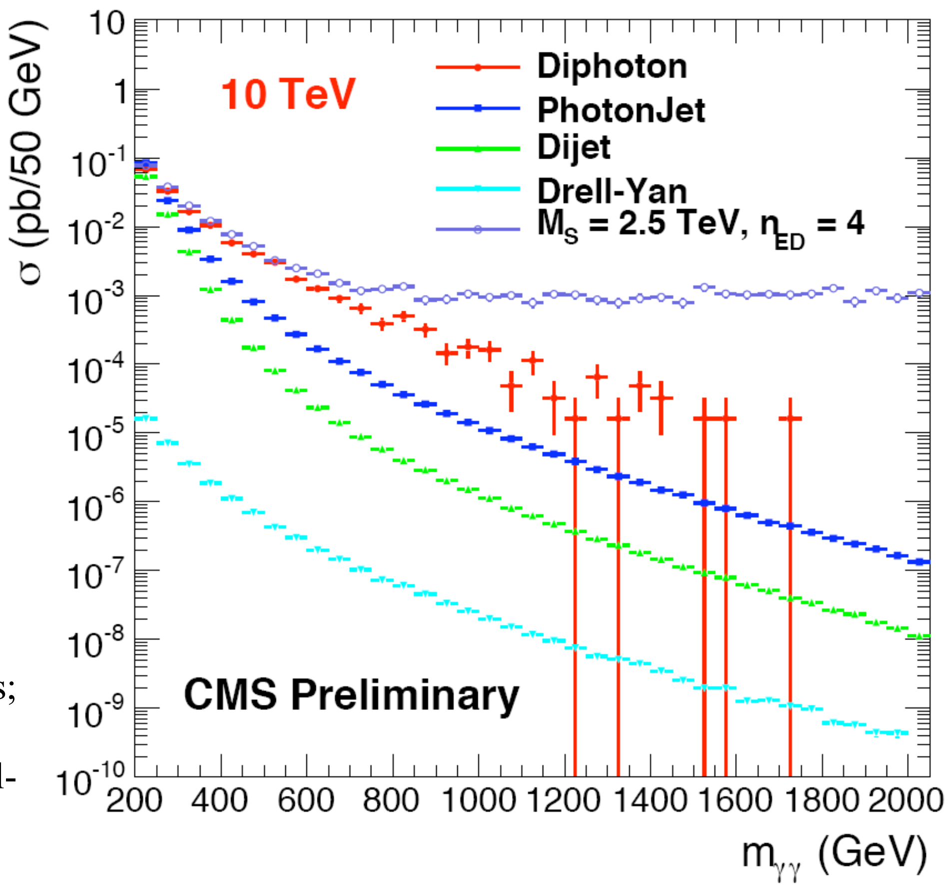
95% CL limits



With an integrated luminosity of 100 pb^{-1}: 5σ significance for G* (c=0.1) with the mass of up to 1.2 TeV; 95% CL upper limit for up to 1.4 TeV.

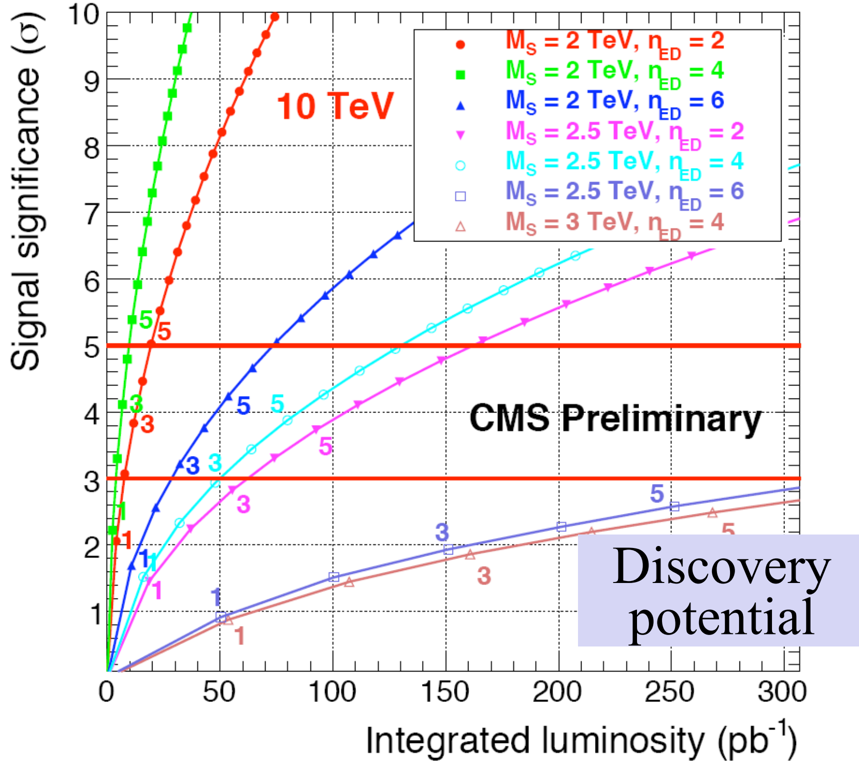
Search for Large Extra Dimensions in $\gamma\gamma$

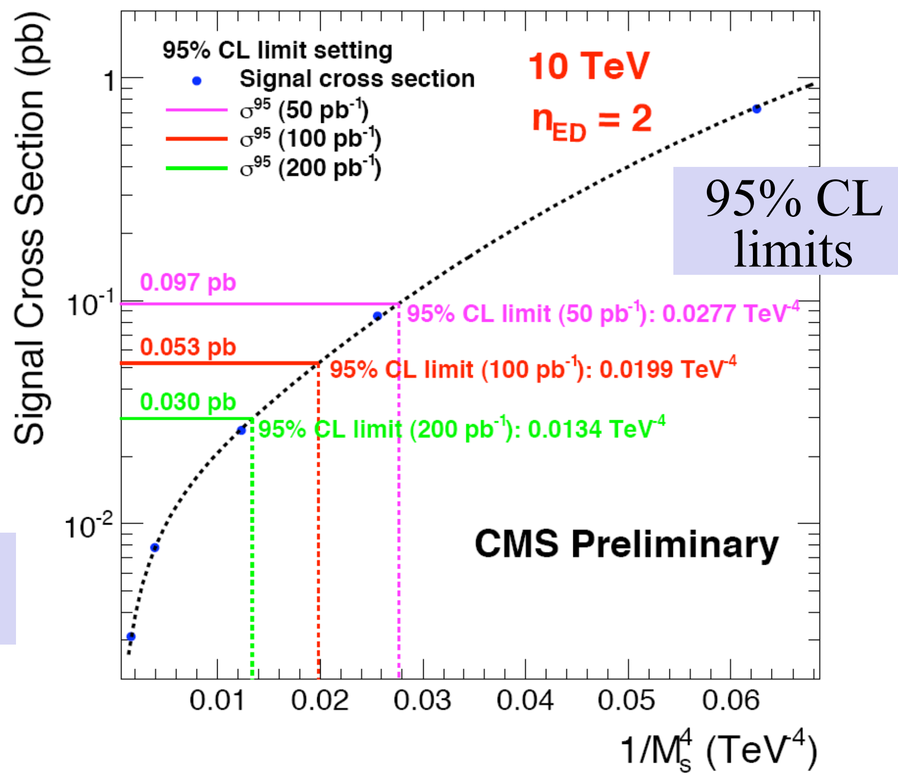
- Virtual graviton decays; small energy spacing between the adjacent Kaluza-Klein modes.
- Signature: non-resonant enhancement of the $M_{\gamma\gamma}$ spectrum at high masses.
- Dominant (and irreducible) background: prompt diphotons; obtained by normalizing MC-based shape to data at low $M_{\gamma\gamma}$.
- Other backgrounds:
  - Jets faking photons in γ-jet and dijet events; measured in samples of identified jets.
  - Electrons reconstructed as photons in Drell-Yan events; measured from $Z \rightarrow ee$.
- Efficiency estimated by using the tag-and-probe method on $Z \rightarrow ee$ to get ε_e, and scaling it by the MC ratio of $\varepsilon_\gamma/\varepsilon_e$.



Count events with two high-E_T isolated photons, each with $|\eta_\gamma| < 1.5$, in the mass region of $M_{\gamma\gamma} > 700$ GeV.

Search for Large Extra Dimensions in γγ





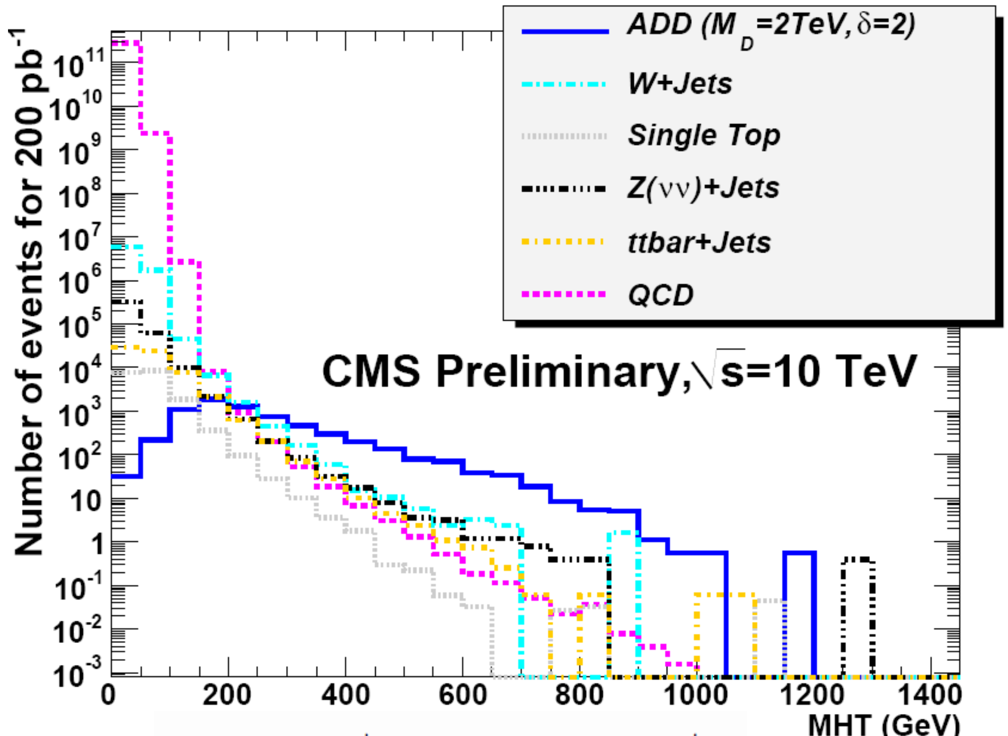
n_{ED}	95% CL Limit on M_S		
	50 pb^{-1}	100 pb^{-1}	200 pb^{-1}
2	2.5 TeV	2.7 TeV	2.9 TeV
3	3.0 TeV	3.3 TeV	3.5 TeV
4	2.6 TeV	2.8 TeV	3.0 TeV
5	2.3 TeV	2.5 TeV	2.7 TeV
6	2.1 TeV	2.3 TeV	2.5 TeV
7	2.0 TeV	2.2 TeV	2.4 TeV

Up to a factor of two higher sensitivity compared to the Tevatron

Large EDs will also be searched for in dilepton channels

Search for Large Extra Dimensions in Monojets

- Complementary to the above search: production of real graviton recoiling against a quark or gluon.
- Signature: large missing E_T back-to-back with high-p_T jet.
- Dominant backgrounds: $Z \to \nu\nu$ + jets and $W \to l\nu$ + jets with the lepton lost; estimated by selecting $W \to \mu\nu$ + jets, and reweighting by the ratios of cross sections and efficiencies.
- Select events containing no isolated leptons, and only one or two high-p_T jets.

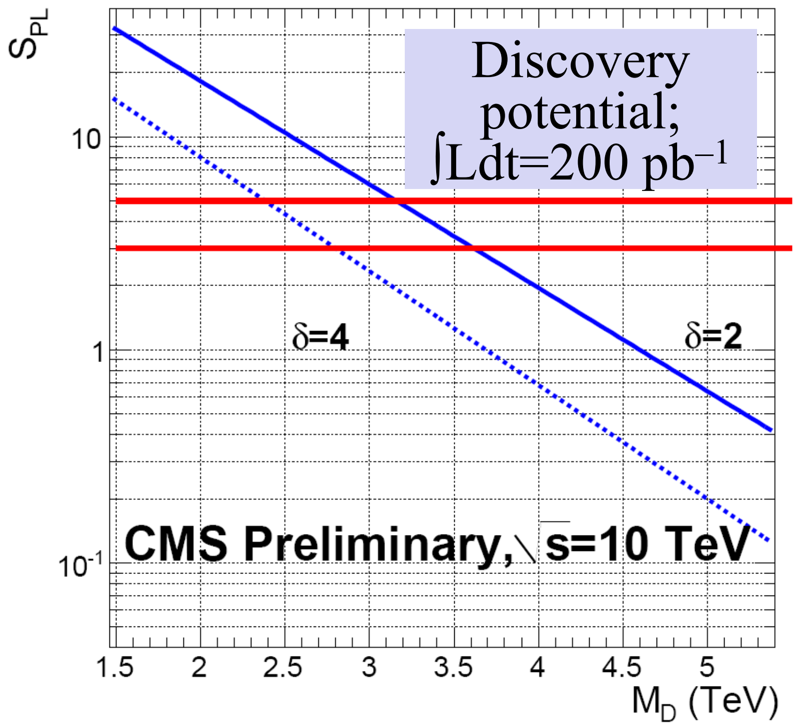


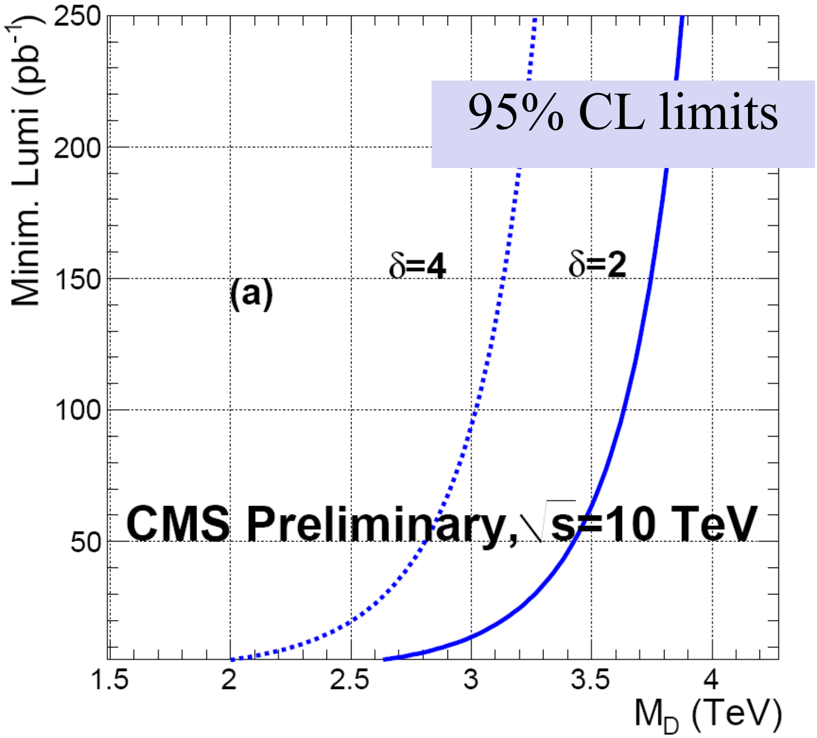
$$MHT = \left| \sum_{p_T(\mathrm{jet}) > p_T^0} \vec{p}_T(j) \right|$$

$(p_T^0 = 30\text{ GeV})$

Count events with $MHT > 250$ GeV and $|\eta_{jet}| < 1.7$.

Search for Large Extra Dimensions in Monojets





Sensitivity similar to that in the diphoton channel

Real graviton emission will also be searched for in the γ+jet channel

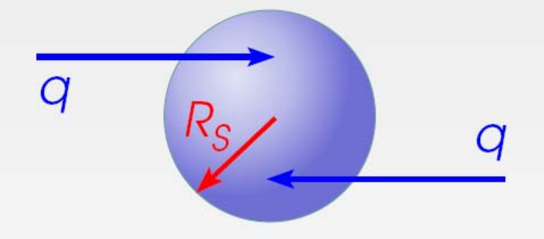
Mini Black Holes at LHC

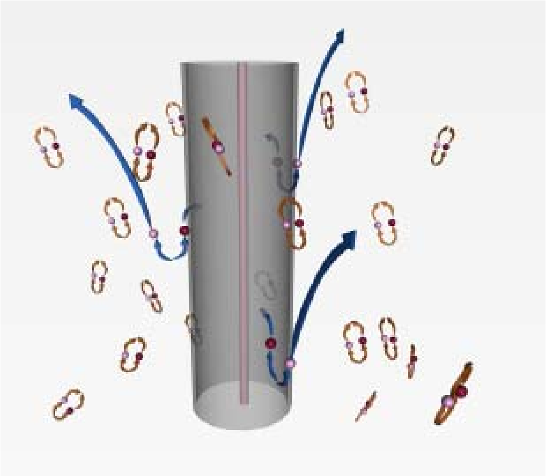
- If the impact parameter of two partons is smaller than the Schwarzchild radius $R_S = 2Gm/c^2$, a black hole is produced.
- In the presence of compact EDs,
  - At distances $r < R_{ED}$, gravity is much stronger than in the 3D scenario
  - Therefore, R_S is significantly increased

→ Black holes can be produced easier

- If produced, light black holes should undergo Hawking evaporation: particle pairs produced by vacuum fluctuations may be split, one particle falling into the black hole, the other projected outward.

→ Very distinct signature



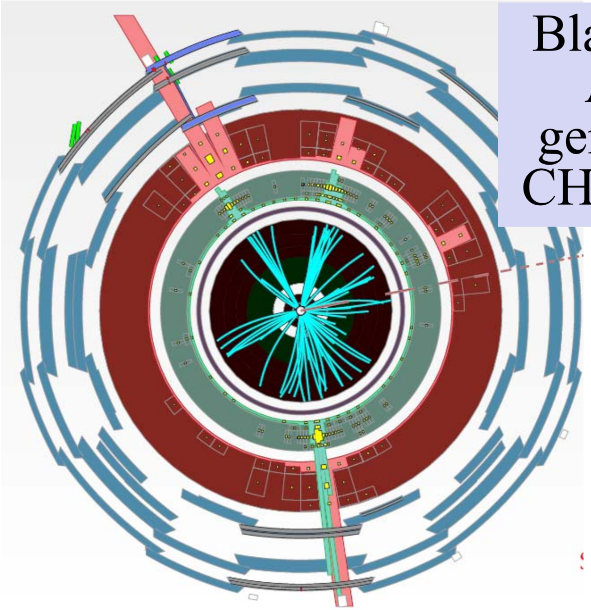


Graphics from V. Lendermann

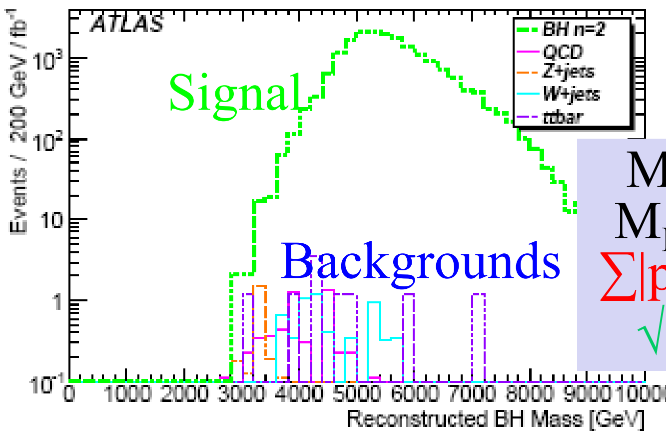
Search for Mini Black Holes

- Signature (also for string balls): large number of high-p_T final-state particles and jets; large missing E_T.
- Largest backgrounds: ttbar, dijets, W+jets.
- Select events containing at least one high-p_T lepton and with large $\sum|p_T|$ of all reconstructed objects; reconstruct M_{BH}.

Many assumptions involved, but if the predicted signature is correct, it should be detectable.



Black hole in ATLAS, generated by CHARYBDIS



$M_D = 1$ TeV
$M_{BH} > 5$ TeV
$\sum|p_T|>2.5$ TeV
$\sqrt{s}=14$ TeV

Summary

- We presented some recent studies by ATLAS and CMS dedicated to searches for extra dimensions, new gauge bosons, and mini black holes in the forthcoming 2009-10 LHC run.
- Current focus of the analyses is on the data-driven methods of estimating backgrounds and efficiencies, and on the techniques to minimize systematic uncertainties.
- The scenario in which an integrated luminosity of ~100 pb^{-1} is accumulated at $\sqrt{s}$=10 TeV offers good chances to go beyond the existing limits.

Further Reading

- ATLAS:
  - Expected Performance of the ATLAS Experiment, arXiv:0901.0512 (1828 pages).
  - ATL-PHYS-PUB-2009-011: Search for highly-excited string states with ATLAS.

- CMS:
  - SBM-07-002: Search for New High-Mass Resonances Decaying to Muon Pairs in the CMS Experiment.
  - EXO-09-004: Search for Large Extra Dimensions in the Diphoton Final State.
  - EXO-09-006: Search for High-Mass Resonances Decaying into an Electron Pair in CMS at 10 TeV with 100 pb^{-1}.
  - EXO-09-009: Search for Randall-Sundrum Gravitons in the Diphoton Final State.
  - EXO-09-013: Search for Monojet from ADD Extra Dimensions at $\sqrt{s}$=10 TeV.

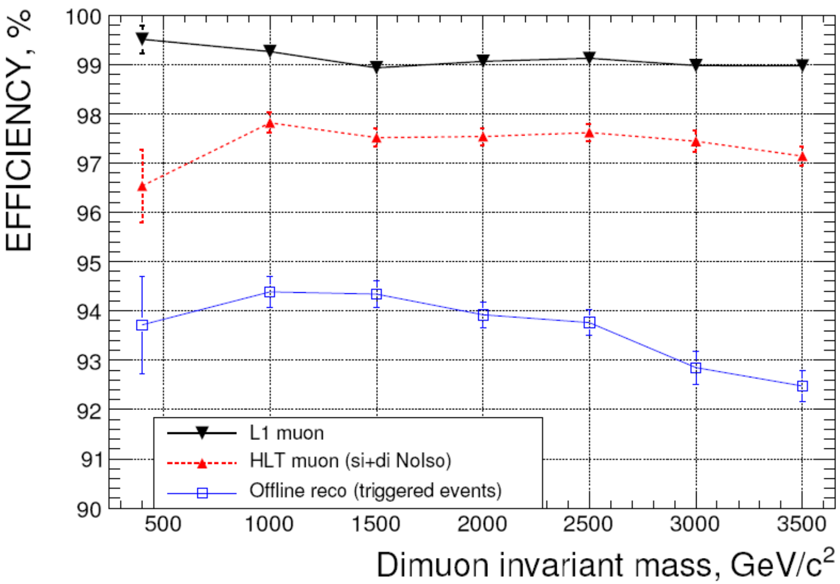
Available at https://twiki.cern.ch/twiki/bin/view/CMS/PhysicsResults

Back-up Slides

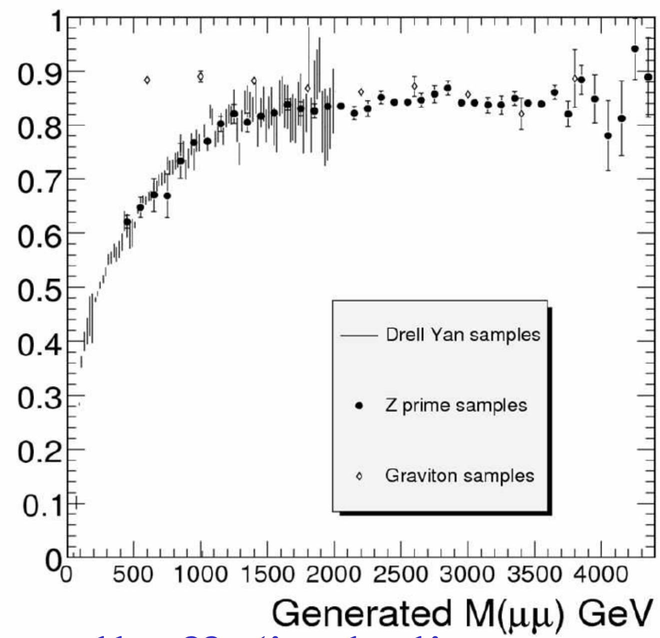
Z′ and G*: Selection Criteria and Efficiencies

- Event is selected as a dimuon candidate if:
  - It passes logical OR of single-muon and dimuon non-isolated trigger paths.
  - It contains at least one pair of oppositely-charged muons reconstructed offline.
  - p_T of each muon in a pair is larger than 20 GeV.
  - Both muons are isolated in the tracker.

$\sqrt{s}$=14 TeV



Algorithmic trigger and reco eff.

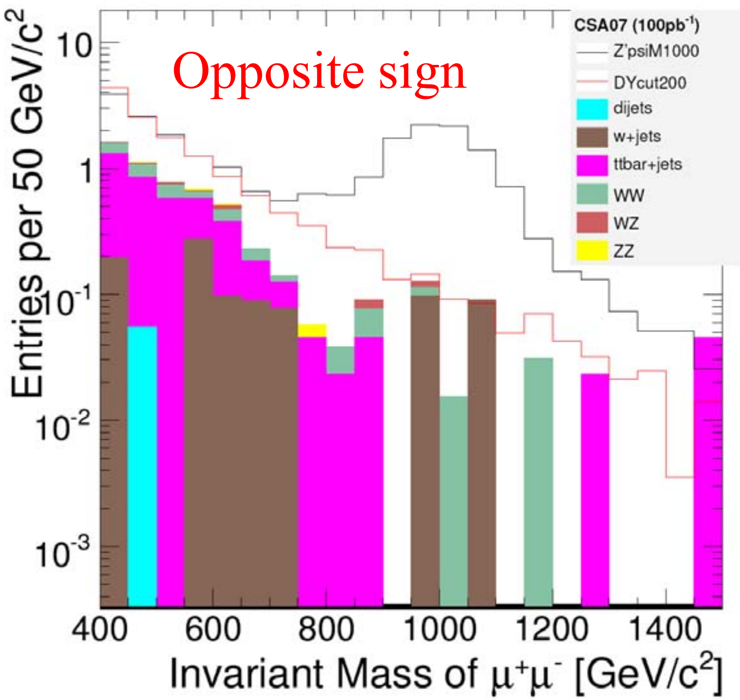


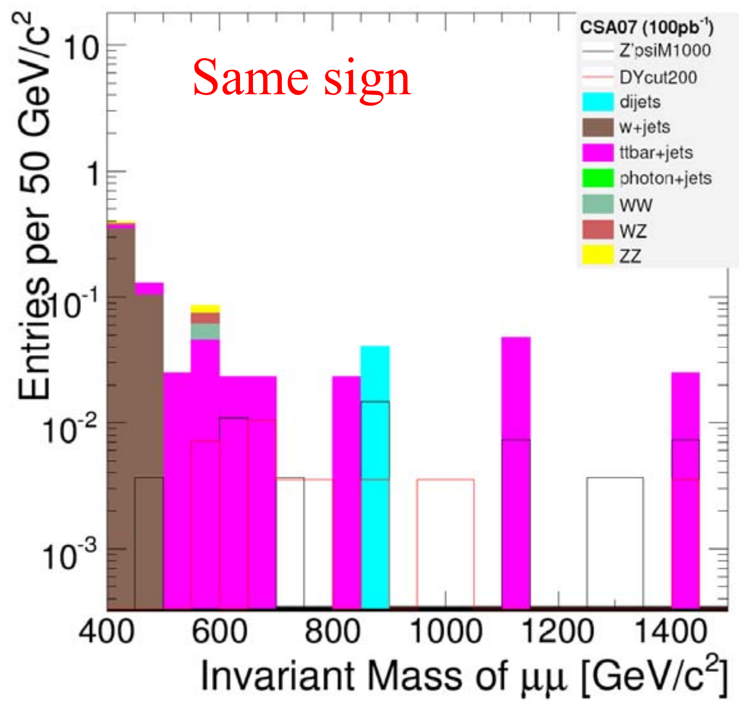
Overall eff. (including acceptance)

Dimuon Mass Spectra w/ Isolation Cut

Apply isolation cut (and p_T > 20 GeV cut):

$\sqrt{s}$=14 TeV





- Dijet contribution is very small.
- Largest non-Drell-Yan background is
  - > 400 GeV, t-tbar (about ¼ of Drell-Yan).
  - > 1 TeV, W+jets.

Search for Resonances: Fitting Procedure

- Generate ensembles of MC experiments:
  - Number of events in each experiment fluctuates according to Poisson distribution with a mean of $\sigma \cdot Br \cdot (\int L dt) \cdot \varepsilon$.
  - Add Drell-Yan contribution from lower masses.
- In each experiment, fit $M_{\mu\mu}$ values using an unbinned maximum likelihood:

$$p(M_{\mu\mu}) = \frac{N_s}{N_{tot}} \cdot p_s(M_{\mu\mu}; m_0, \Gamma) + \left(1 - \frac{N_s}{N_{tot}}\right) \cdot p_b(M_{\mu\mu})$$

  - p_s (signal pdf) is a convolution of a Breit-Wigner with a Gaussian smearing.
  - p_b (background pdf) is an exponential, $exp(-k \cdot M_{\mu\mu}^{0.3})$, with the slope parameter k determined from fits to Drell-Yan events.

Up to three free parameters: signal fraction (N_s / N_{tot}), signal mean (m_0), and signal FWHM (Γ).

No constraints on the absolute background level: fit assumes only background shape is known.

Significance

- Use likelihood-ratio estimator S_L to calculate significance of an observed "signal":

$$S_L = \sqrt{2\ln(L_{S+B}/L_B)},$$ where

  - L_{S+B} is the maximum likelihood from the signal-plus-background fit (p),
  - L_B is the maximum likelihood from the background-only fit (p_b).

Dedicated MC study (described in CMS Note 2005/002) showed that S_L behaves as desired in the tail above several sigma in the small-statistics low-background regime.

- Usual convention: $S > 5$ is necessary to establish a discovery (probability of $2.9 \cdot 10^{-7}$ that the pure background would mimic a signal).