Extended Gauge Symmetries and Extra Dimensions at the Large Hadron Collider

Introduction	Searches at the LHC with CMS and ATLAS
	New gauge bosons and extra dimensions
Signatures & Discoveries	Search for Z' in ee and $\mu\mu$
	Search for W' in e / μ + E_T^{miss}
	Randall-Sundrum gravitons
	Large Extra Dimensions
Measurements	Properties
Conclusions	

See also:
http://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/EXOTICS/
http://cmsdoc.cern.ch/cms/PRS/results/susybsm/susybsm.html

RWTH AACHEN
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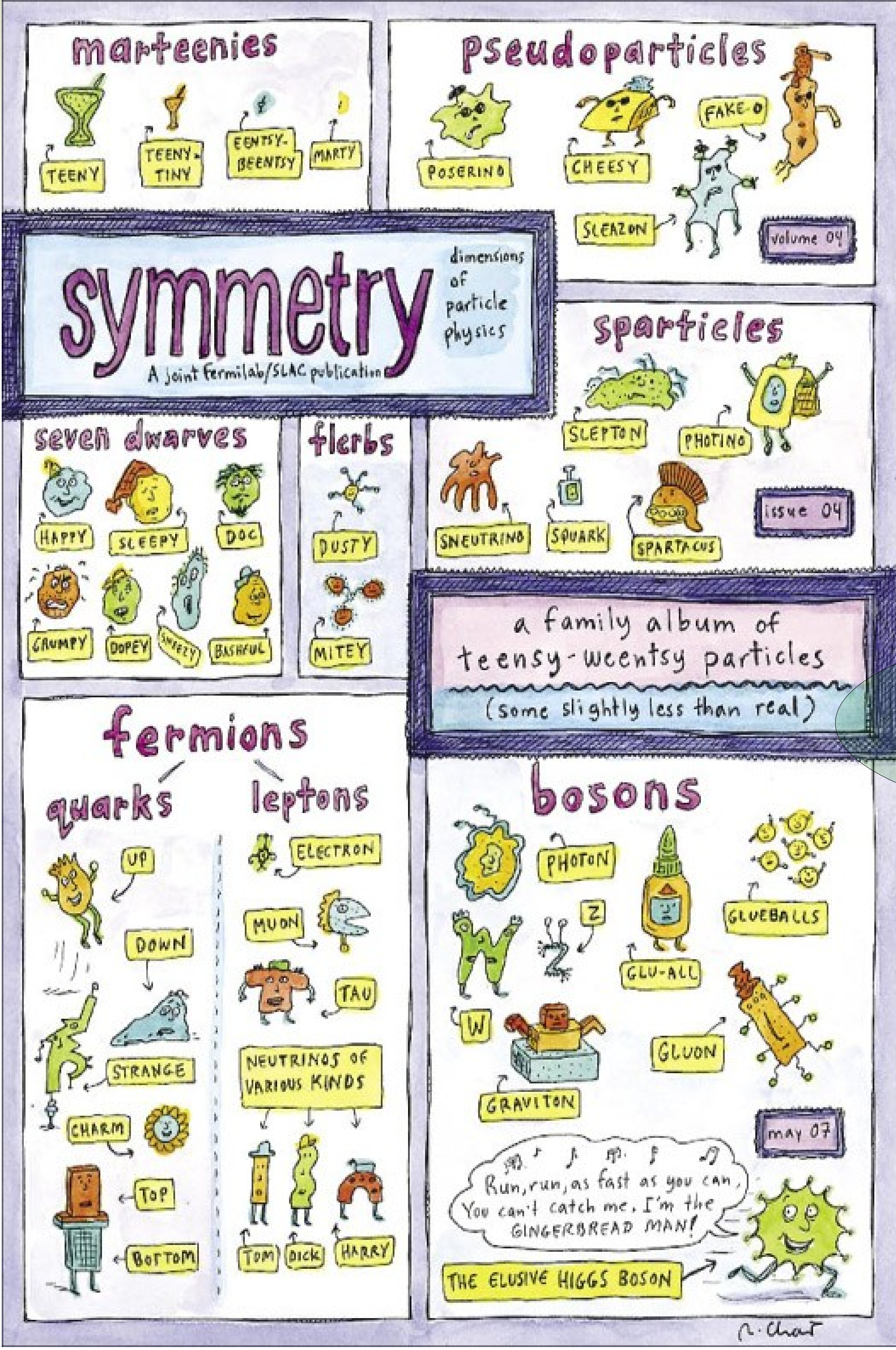
EPS 2007 Manchester

July 19th 2007

bmb+f
Großgeräte der physikalischen Grundlagenforschung



NP Landscape

Supersymmetry

- RPC, RPV, ...
- MSSM, NMSSM, ...
- mSUGRA, GMSB, AMSB, split SUSY, ...

Extra Dimensions

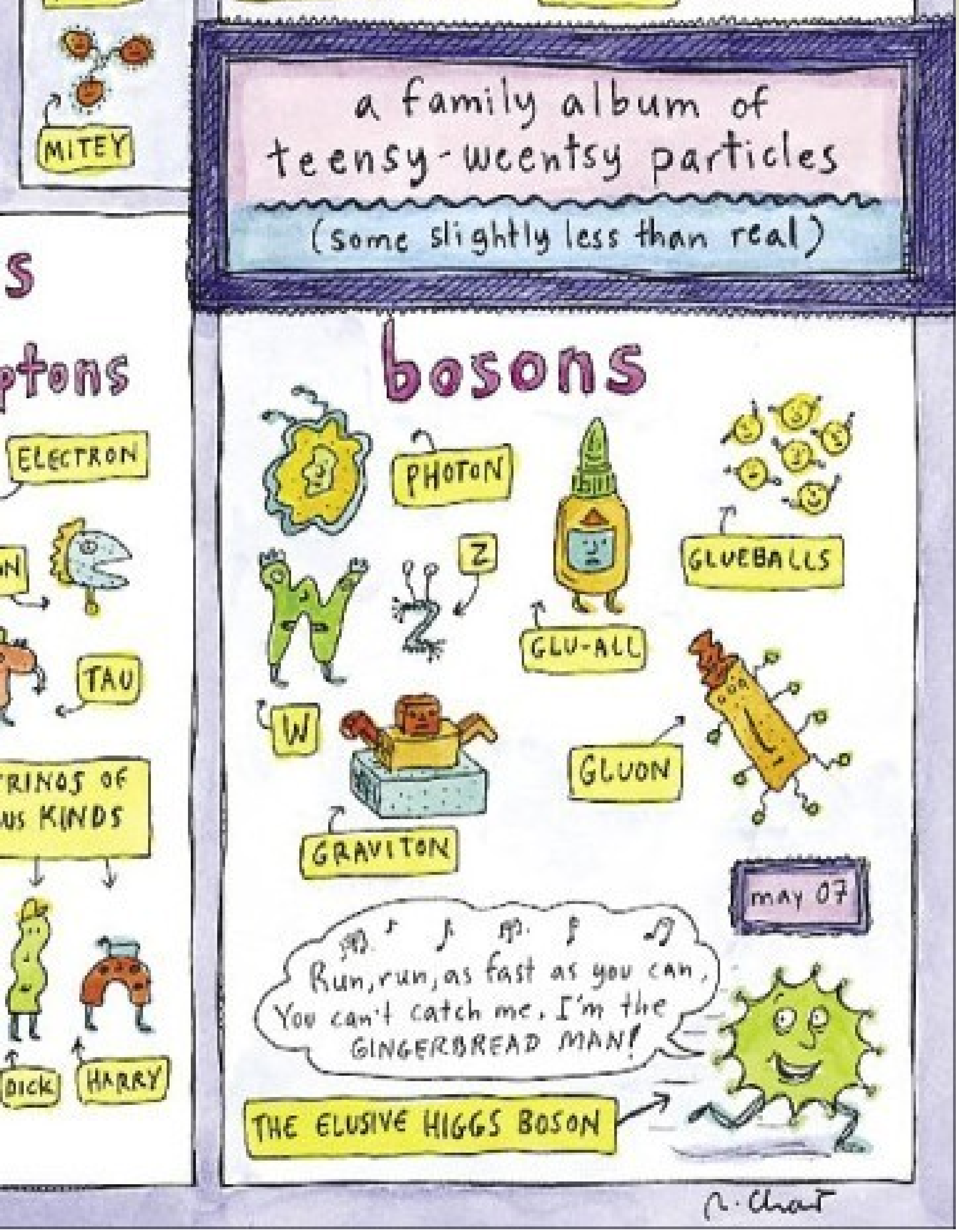
Extra Gauge Bosons (W´, Z´)

Leptoquarks (1st, 2nd, 3rd Generation)

Compositeness (Lepton and Quark Subst.)

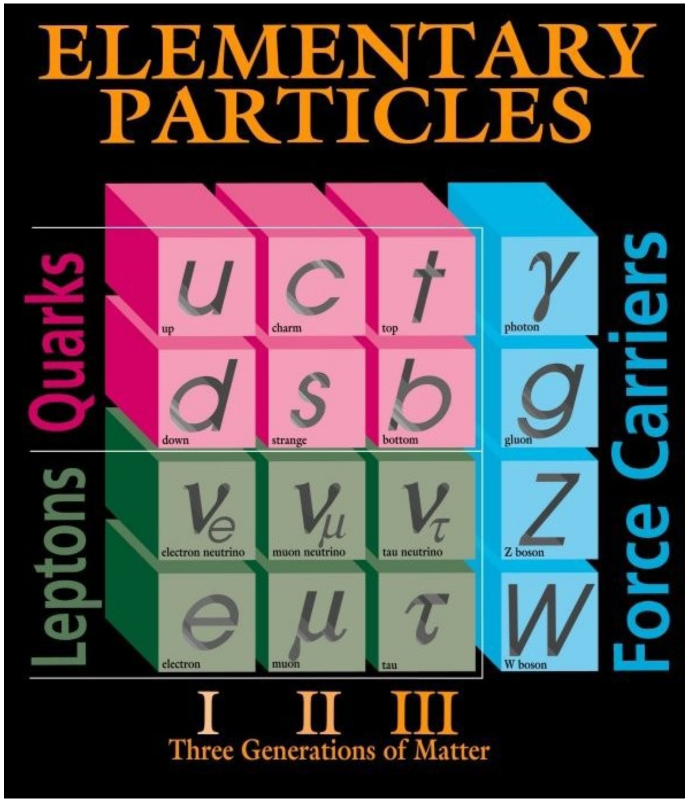
Alternatives (Technicolor, Little Higgs, ...)

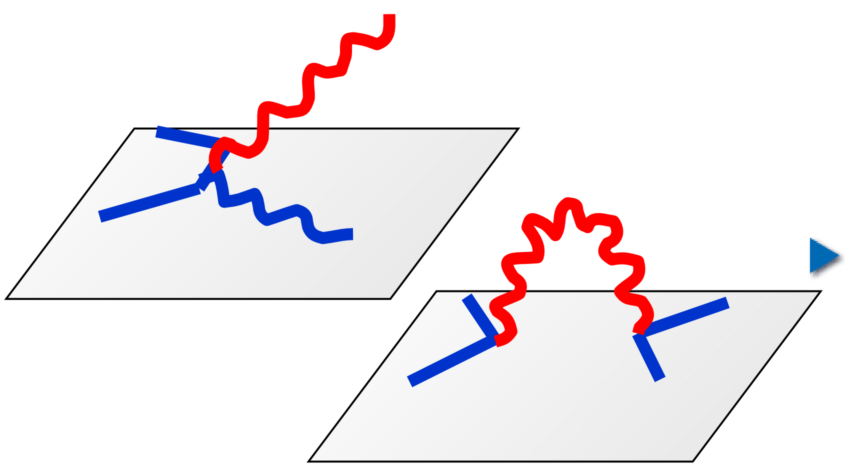
Unknown (Signature Based Searches)


MITEY
a family album of
teensy-weentsy particles
(some slightly less than real)
bosons
ELECTRON
PHOTON
GLUEBALLS
Z
W
GLU-ALL
TAU
W
GLUON
GRAVITON
may 07
Run, run, as fast as you can,
You can't catch me. I'm the
GINGERBREAD MAN!
DICK
HARRY
THE ELUSIVE HIGGS BOSON

NO W' or Z'!?!

"Beyond" Supersymmetry





- Supersymmetric theories are the most popular theories on the market
- Here: two different approaches to searches for new phenomena
- Extend the gauge sector of the Standard Model, introducing new heavy gauge bosons: W', Z'
- Extra dimensions to address the hierarchy problem: why is gravity so weak?
  - Gravity appears weak since gravitons propagate in 4+n dimensions
  - One fundamental scale $M_S \sim O(1\text{ TeV})$
- Many similar collider signatures

Extra Gauge Bosons

- Extended Gauge Symmetries and the associated heavy neutral (Z') and charged (W') gauge bosons are a feature of many extensions of the Standard Model

- Studied in detail in the LHC context are for example
  - Z'_ψ, Z'_χ, Z'_η in E6 and SO(10) GUT groups
  - Left-Right symmetric model (LRM, ALRM)
  - Sequential Standard Model: SM-like W' and Z'

- But also
  - Models with extra dimensions
  - Little/littlest Higgs model
  - Higgs-less: Stückelberg Z'
  - CDDT parameterization (Carena, Daleo, Dobrescu, Tait)

Extra Dimensions – Many Flavors!

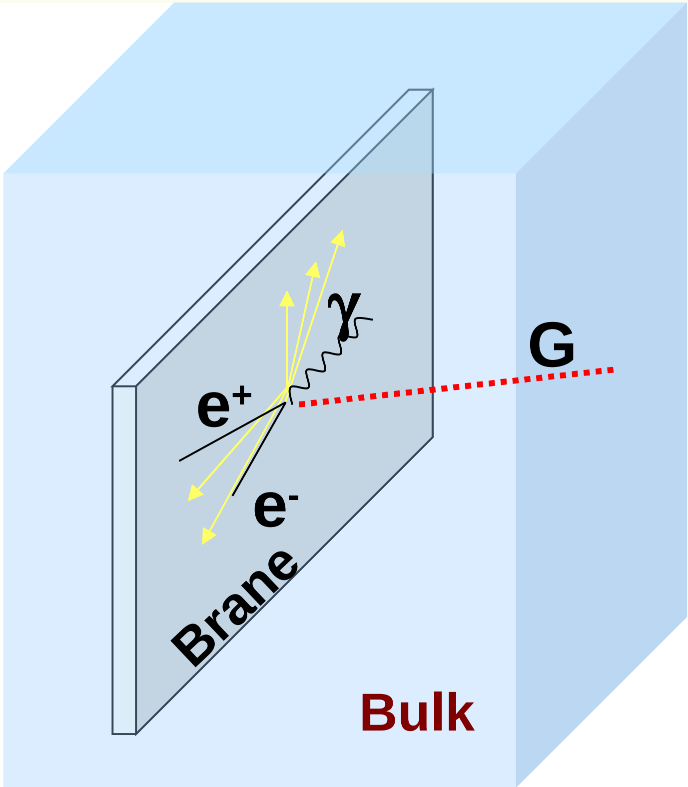
Two classes of models

- **ADD (Arkani-Hamed, Dimopoulos, Dvali)**

  2 or more large (sub mm) EDs

  gravity propagates freely in the bulk

  KK excitations cannot be resolved

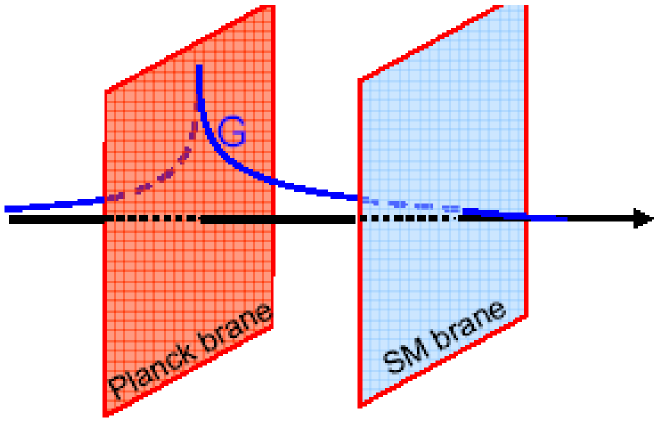


- **RS (Randall, Sundrum)**

  one 5th (infinite) ED with warped geometry

  gravity is localized on a brane other than the SM

  KK excitations have spacings of order TeV



New energy domain:
pp sqrt(s) = 14 TeV
= 7 x Tevatron

New luminosity domain
Design L = 10^{34}cm^{-2}s^{-1}
= 30 x Tevatron

2002

Beam commissioning from May 2008

First collisions at 14 TeV in July

Up to 156 bunches and L ~ 10^{32}cm^{-2}s^{-1} by end 2008 (< 4 interactions / crossing)

Up to 1 fb^{-1} integrated luminosity in 2008

At design luminosity:
- ~100 fb^{-1}/a
- ~20 interactions / crossing

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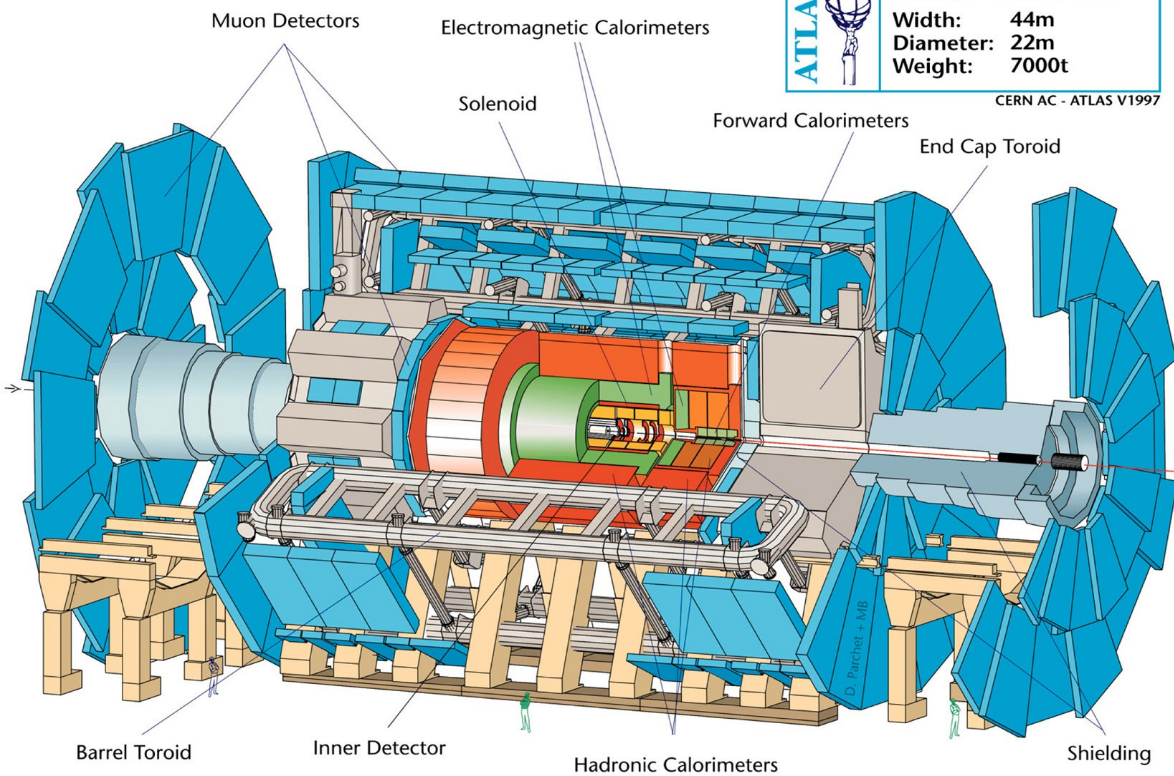
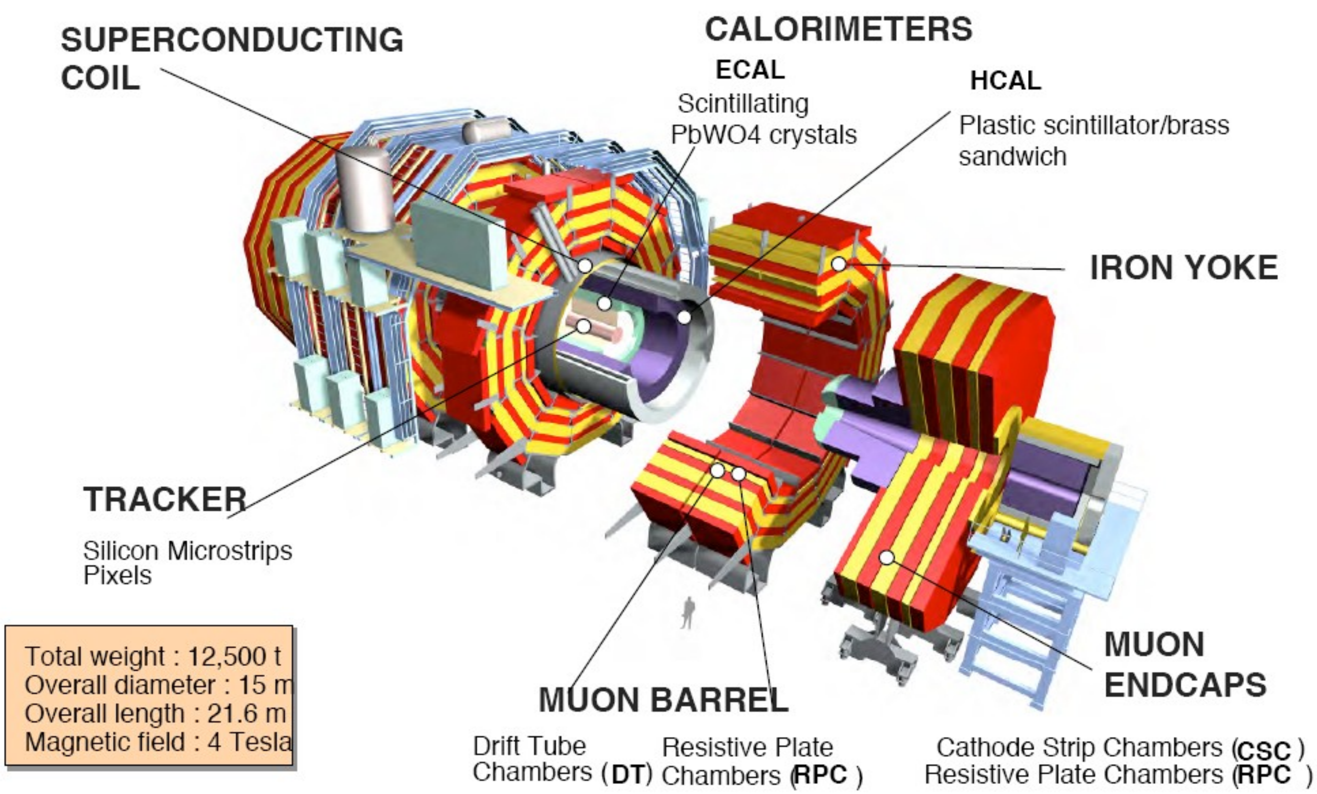
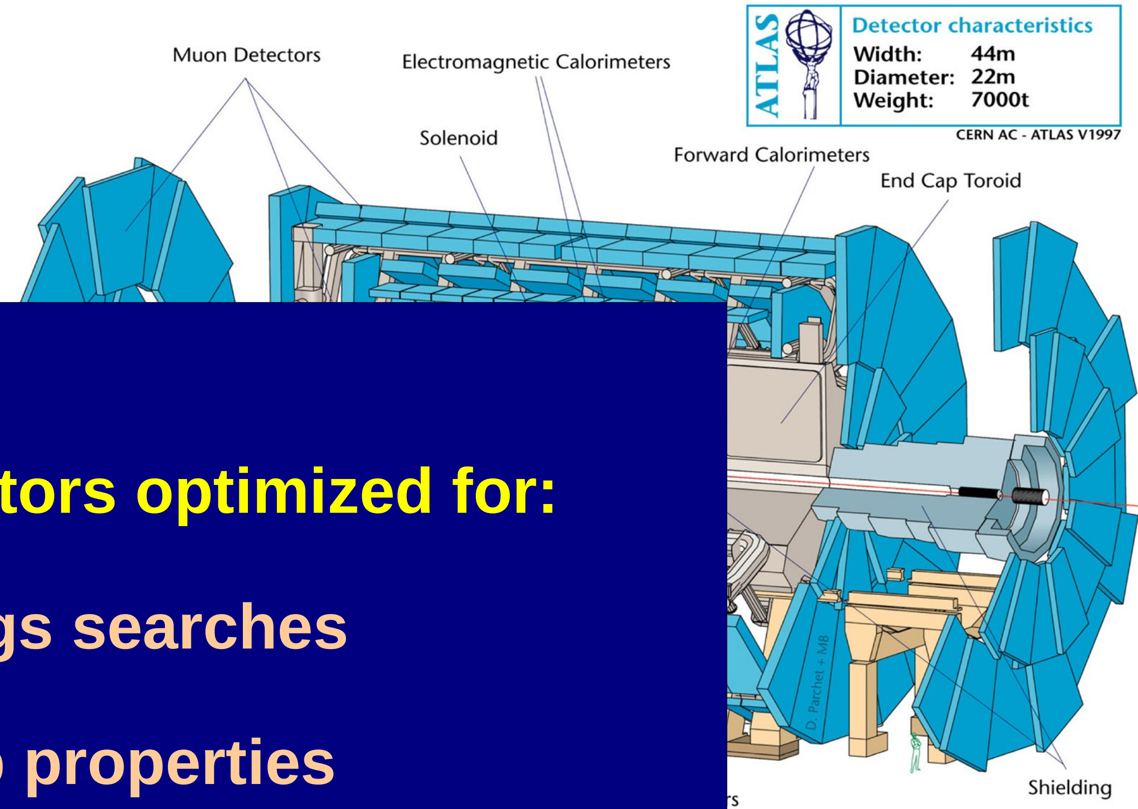
A Toroidal LHC Apparatus





Compact Muon Selenoid

A
Toroidal
LHC
Ap



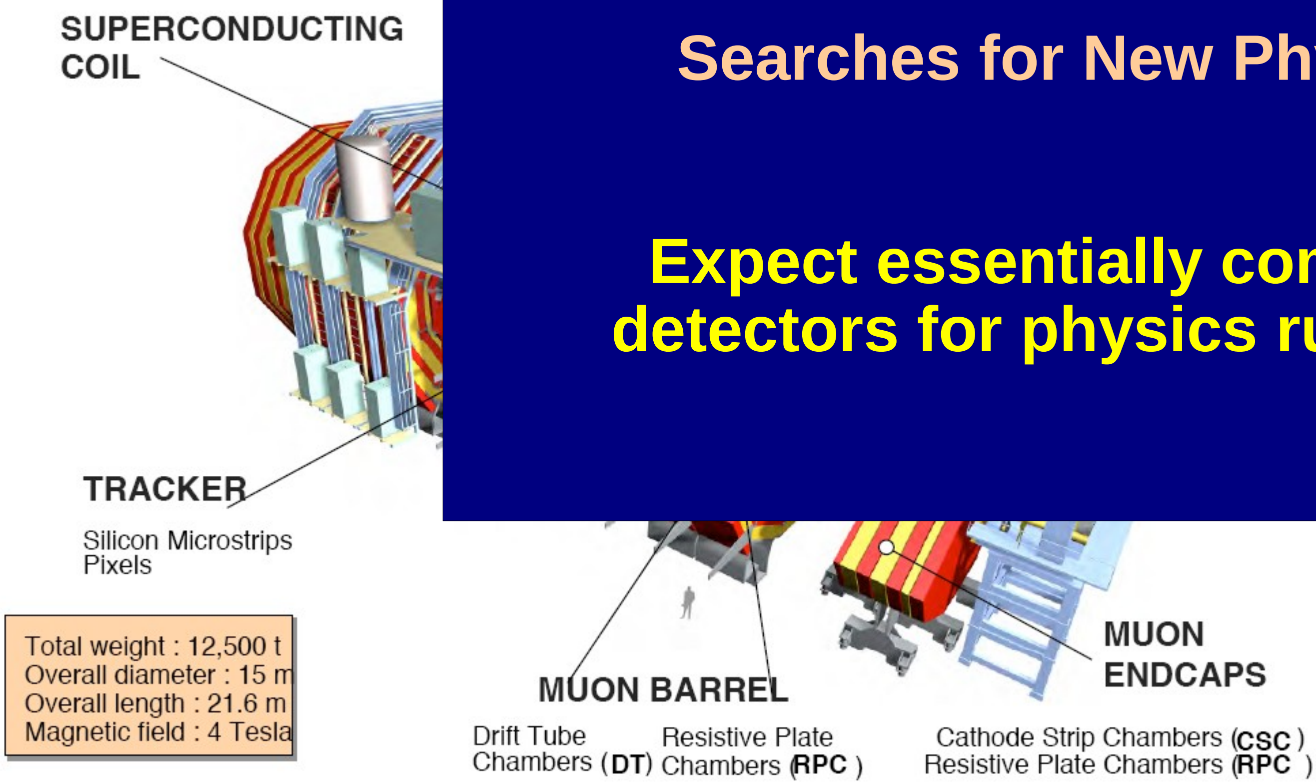
Both detectors optimized for:

Higgs searches

Top properties

Searches for New Physics

Expect essentially complete detectors for physics run 2008



ct
Muon
Selenoid

Main Signatures

Z'	**ee, $\mu\mu$, jj**
W'	**e+E_T^{miss}, μ+E_T^{miss}, jj**
Randall-Sundrum gravitons	**ee, $\mu\mu$, $\gamma\gamma$**
ADD large extra dimensions	**monojets, -γ** **DY spectrum**
Universal extra dimensions	**eeee, $\mu\mu\mu\mu$, ee$\mu\mu$, jj+E_T^{miss}**
Black holes	**high mass,** **high multiplicity,** **high sphericity**

Main Signatures

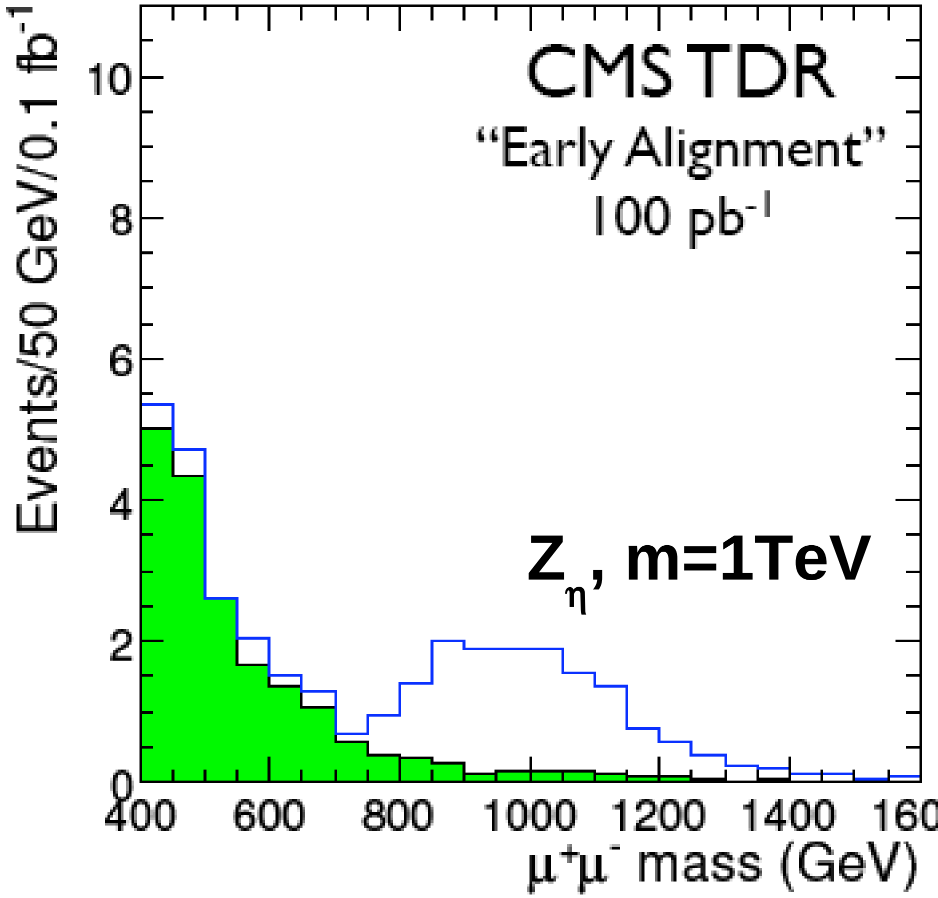
Z'	ee, μμ, jj
W'	$e+E_T^{miss}$, $\mu+E_T^{miss}$, jj
Randall-Sundrum gravitons	ee, μμ, γγ

} Resonant

ADD large extra dimensions	**monojets, -γ** **DY spectrum**
Universal extra dimensions	eeee, μμμμ, eeμμ, $jj+E_T^{miss}$
Black holes	high mass, high multiplicity, high sphericity

Z' – Early Physics

- All results either based on full simulation, or validated fast simulation
- Studied impact of alignment in muon channel – CMS example:
  - "First data", ~ 0.1 fb^{-1}, coarse alignment
  - "Long term", ~ 1 fb^{-1}, full alignment with tracks
- Mass resolution
  - 12% for m = 1 TeV "early"
  - 4% (9%) for 1 (5) TeV "long term"
- Better resolution in ee channel
  - For electron with E_T = 1TeV (CMS): $\Delta E_T / E_T \sim 0.6\%$
- Small impact on discovery reach



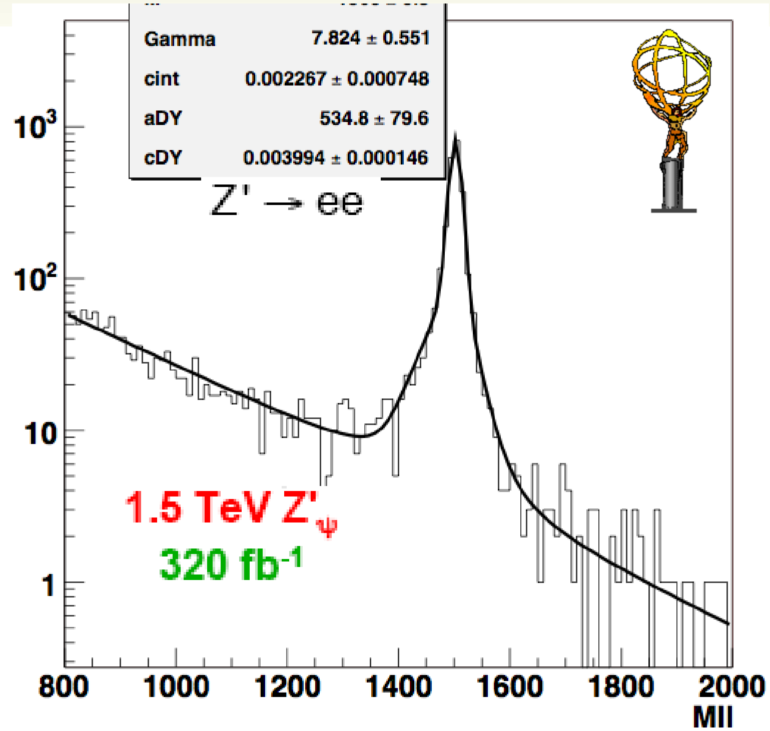
Note: fluctuations "not to scale"!

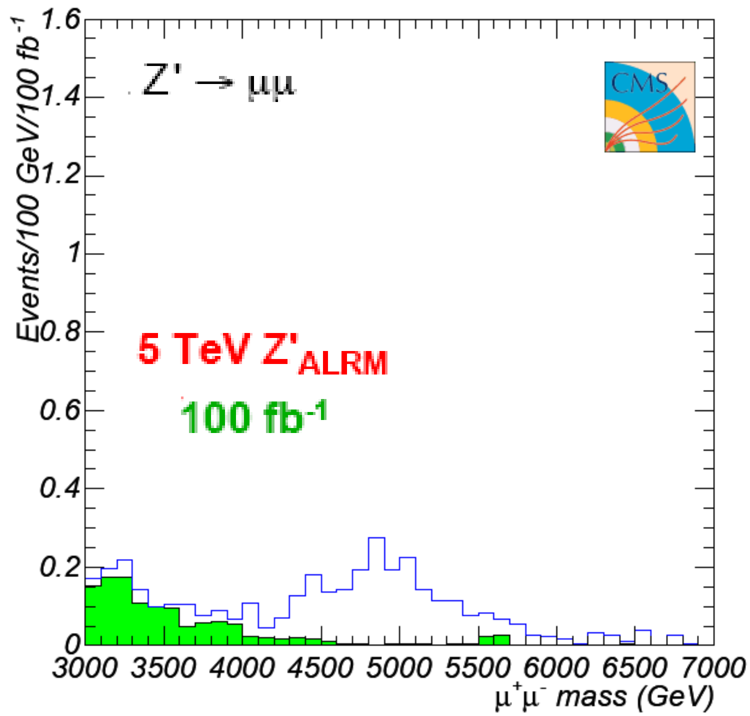
Neutral Gauge Bosons: Z'

- Selection
  - 2 leptons (e, μ) with opposite charge
  - Isolation (but watch muons in calorimeter) – optional
  - Back-to-back in r-phi – optional
- For muons: collect photons in calorimeter to recover energy
- Overall efficiencies (CMS):
  ~ 75 – 85% ($\mu\mu$ @ m = 1 TeV, 5 TeV)
  ~ 80% (ee @ m = 4 TeV)
- Search for BW ⊗ Gaussian excess over SM background shape

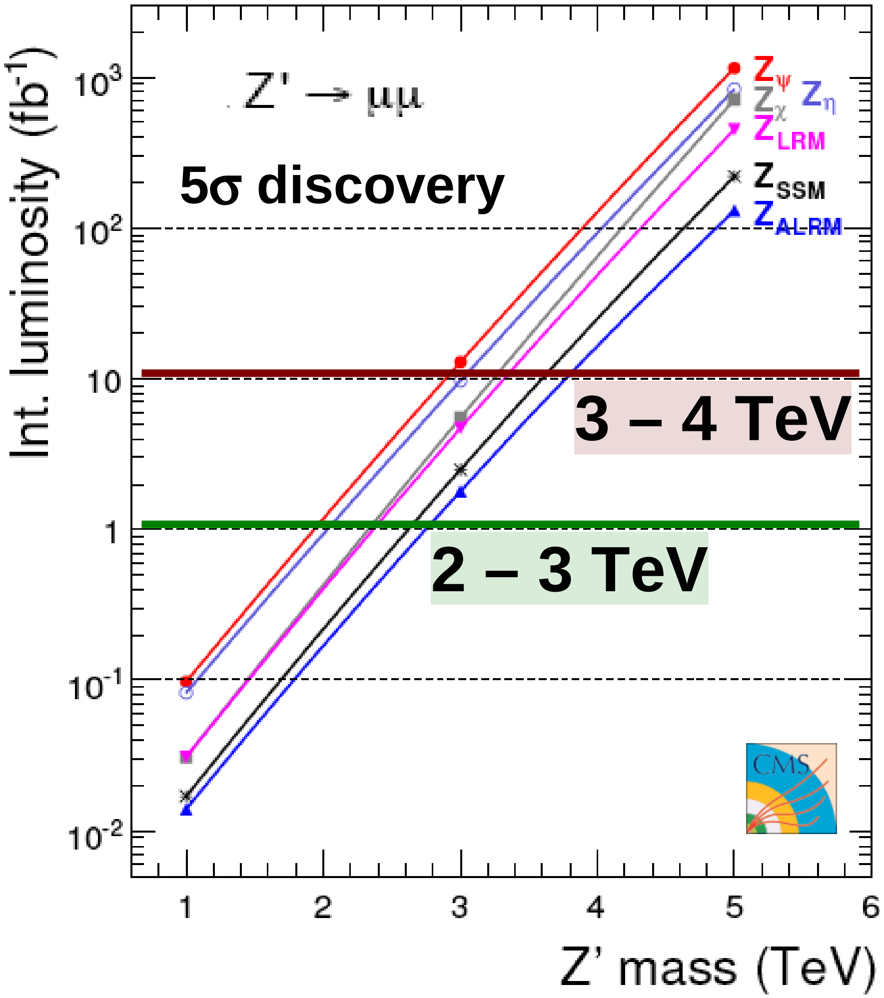
Electrons:	⊕	energy resolution
	⊖	identification
Muons:	⊕	identification
	⊖	p_T resolution

- Note CMS ECAL saturation for Z' above ~ 4 TeV





Z' Discovery Reach

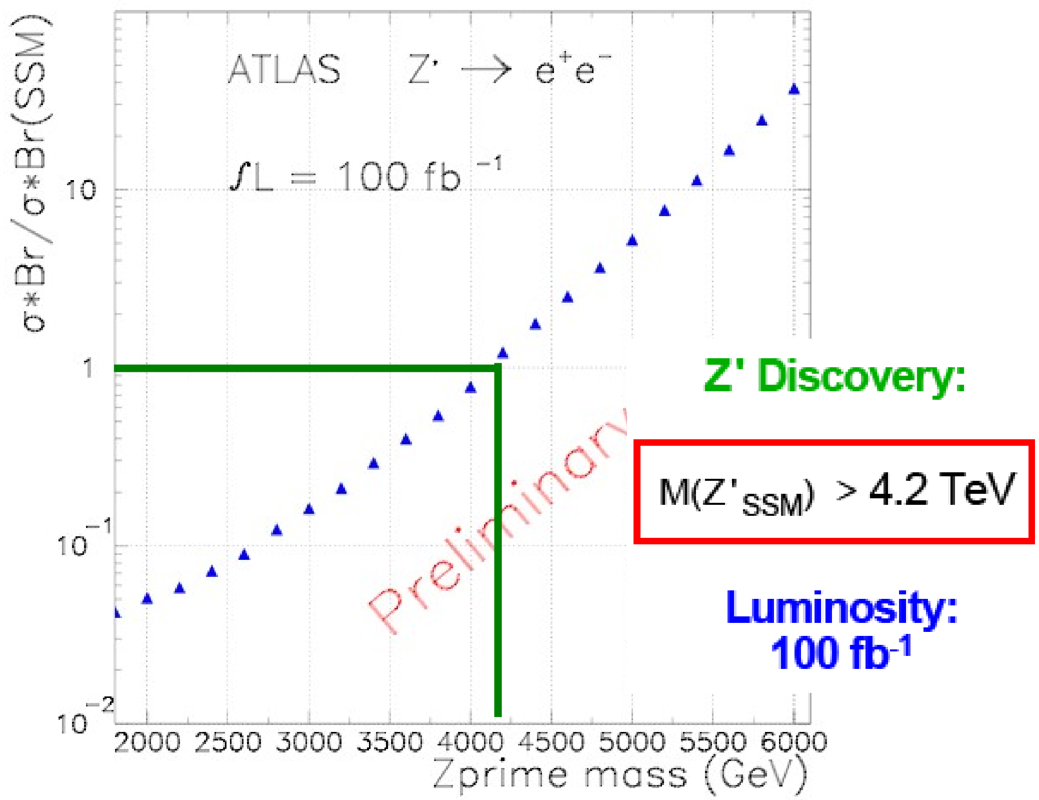


– 95% CL limits about 700 GeV higher at largest masses

– **Tevatron (DØ, CDF; for Z' and W'): m > 1 TeV @ 95% CL**

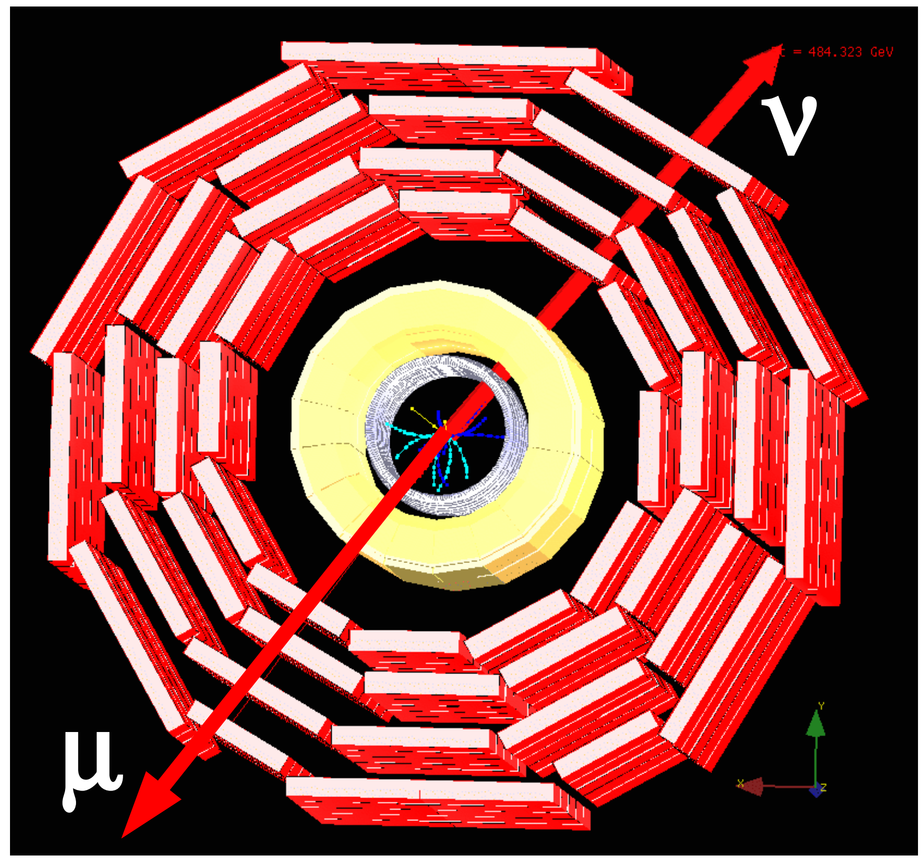
Impact of experimental and theoretical uncertainties studied in detail, example:

PDF uncertainties (CTEQ 6 error PDF's) → cross sections and acceptances for signal and background → 5% (m = 1 TeV) to 25% (m = 5 TeV)



Charged Gauge Bosons: W'

- Sequential Standard Model: W' as heavy copy of SM W boson
  - Couplings like SM W
  - No exotic decays
- Selection
  - Single isolated muon or electron, quality cuts
  - E_T^{miss} calculated from depositions in electromagnetic and hadronic calorimeters, corrected for muons
- Overall efficiency about 90%



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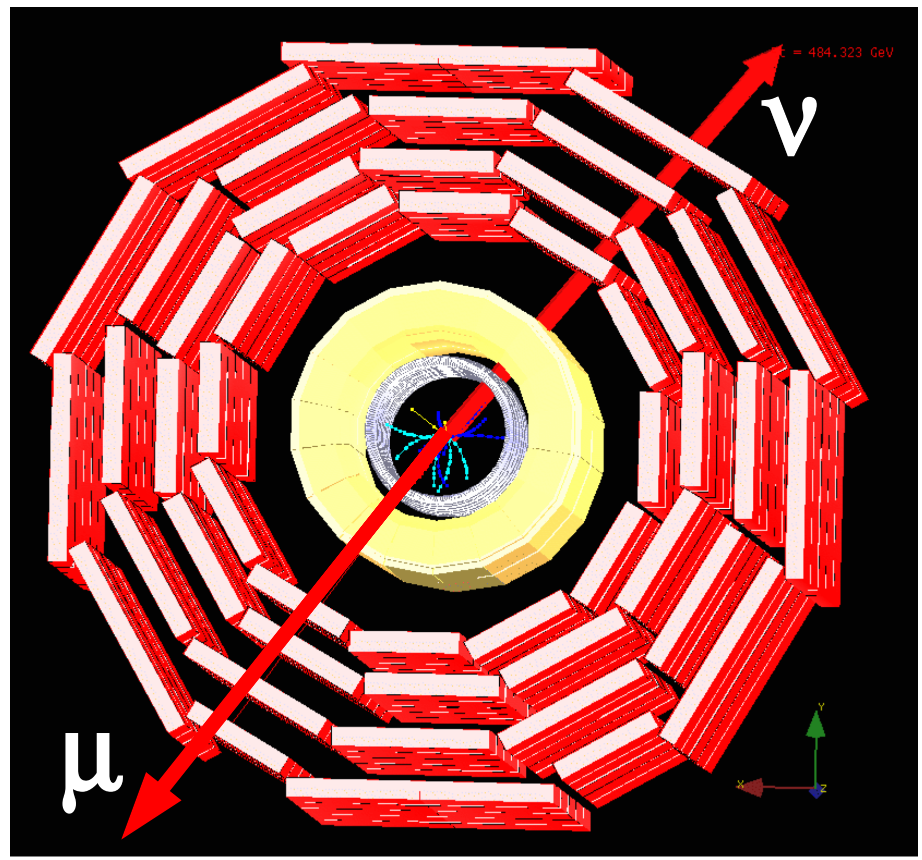

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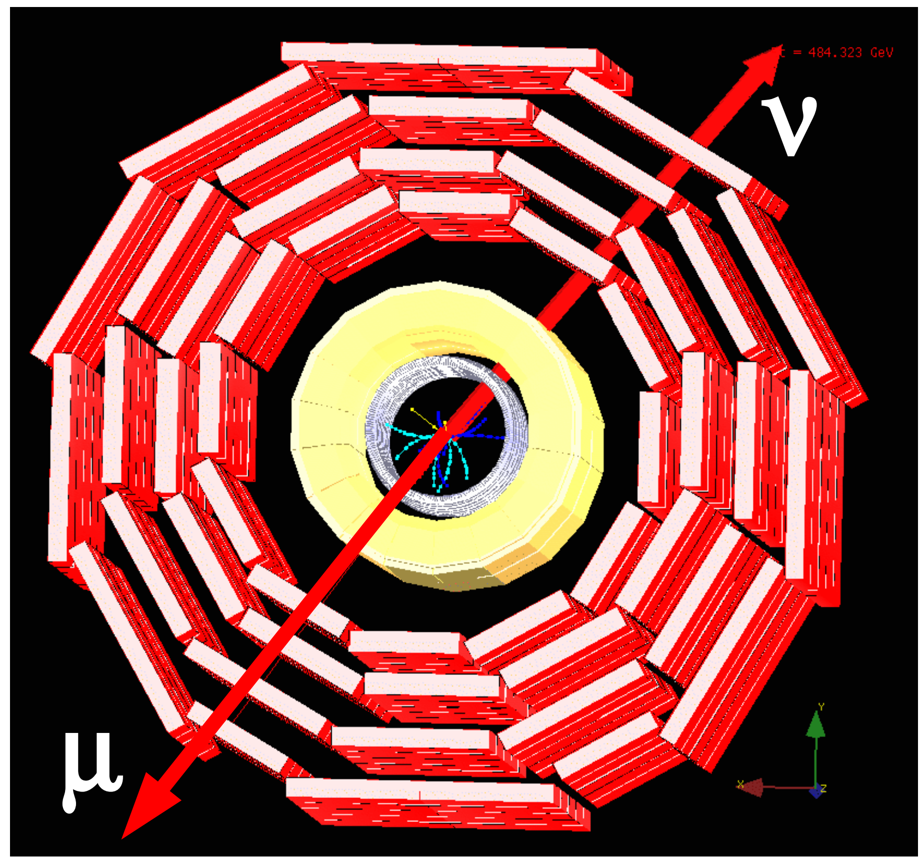
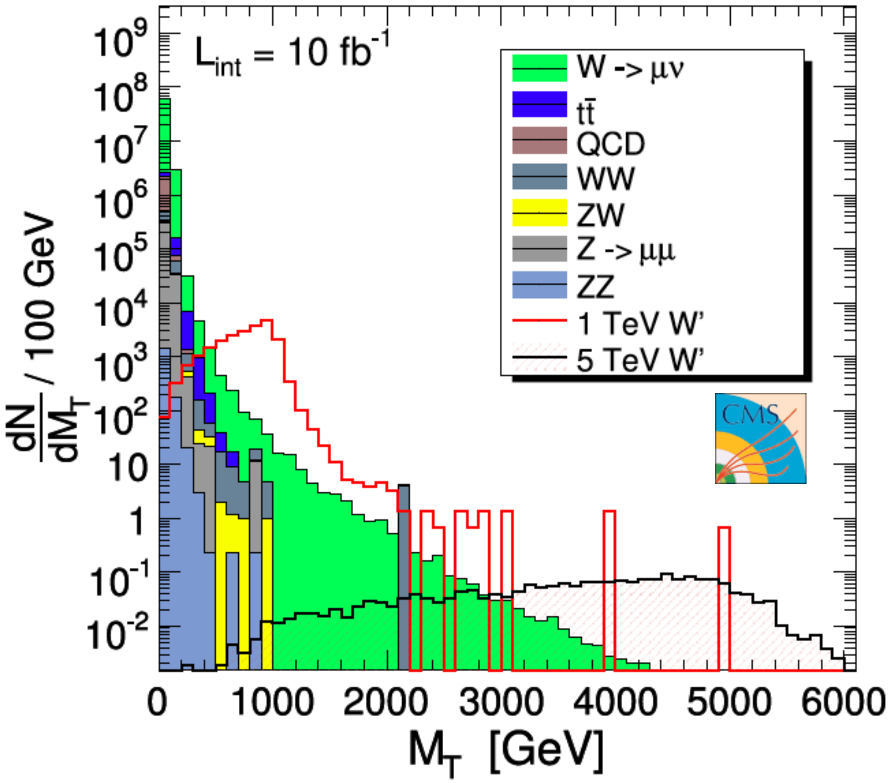
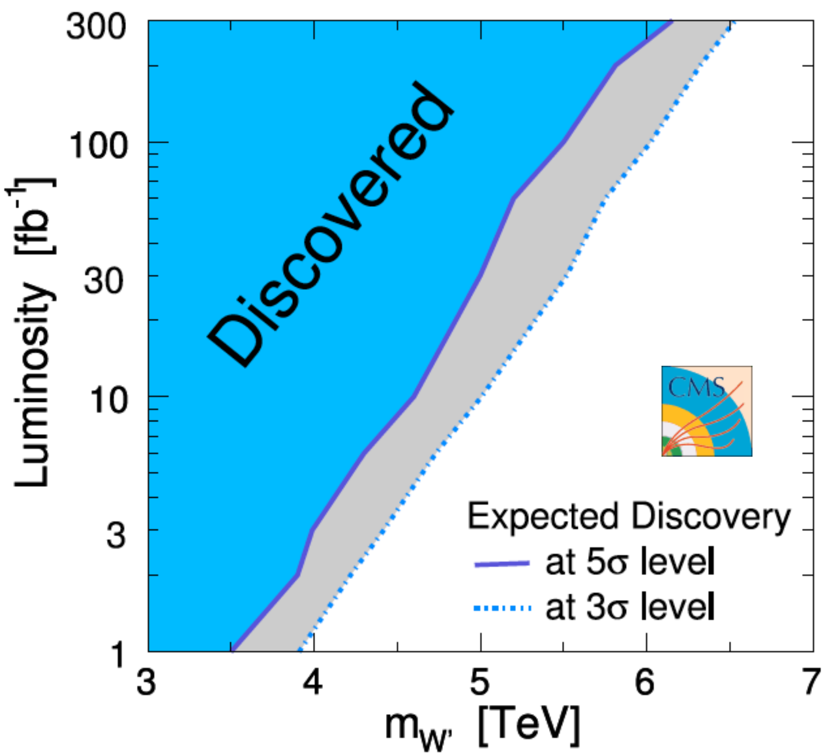
⇒



Charged Gauge Bosons: W'

- Calculate transverse mass and search for excess over SM backgrounds
  - W
  - Top pairs, WW, WZ, ZZ
  - Instrumental background from QCD





W' discovery reach:

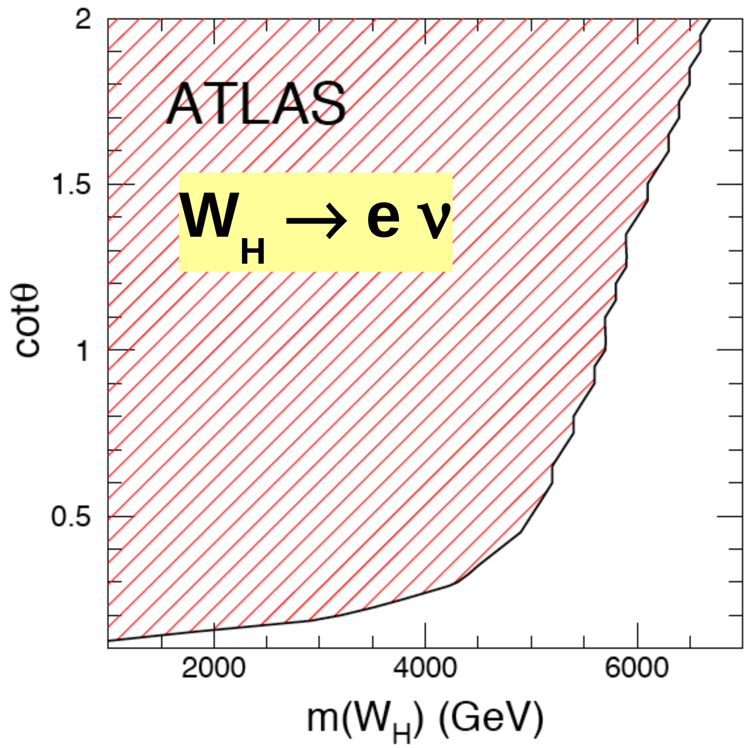
$M(W'_{SSM}) > 4.6$ TeV (for 10 fb^{-1})

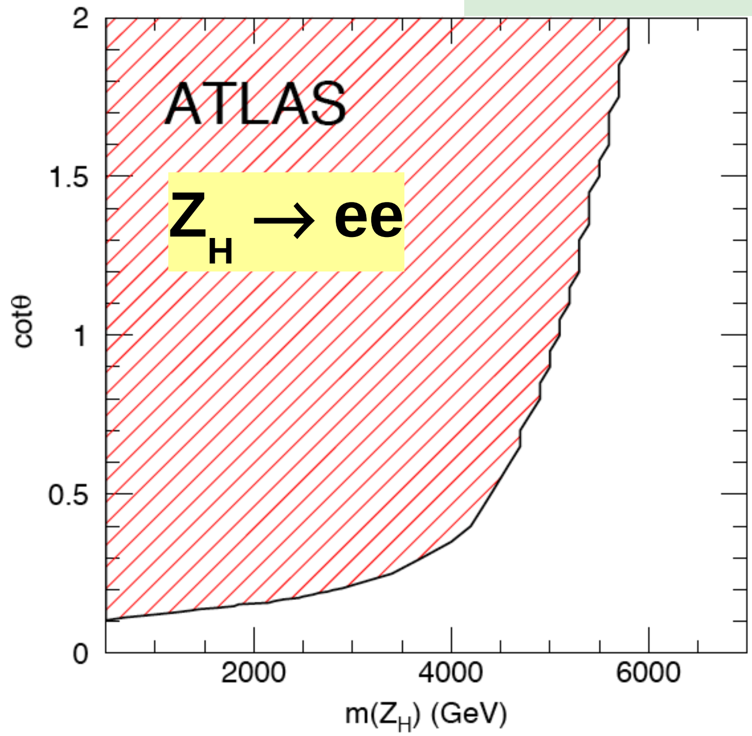
Littlest Higgs Model

- Littlest Higgs Model, Arkani-Hamed et al.: minimal SM extension for solution of hierarchy problem
- Four new gauge bosons: $W_H^{\pm}$, Z_H, A_H
- Masses strongly constrained due to fine-tuning
- Couplings depend on single parameter θ
- Cross section similar to sequential SM

Discovery ($L = 300\ fb^{-1}$, $\cot\theta = 1$)

$M(W_H) > 5.7$ TeV
$M(Z_H) > 5.1$ TeV

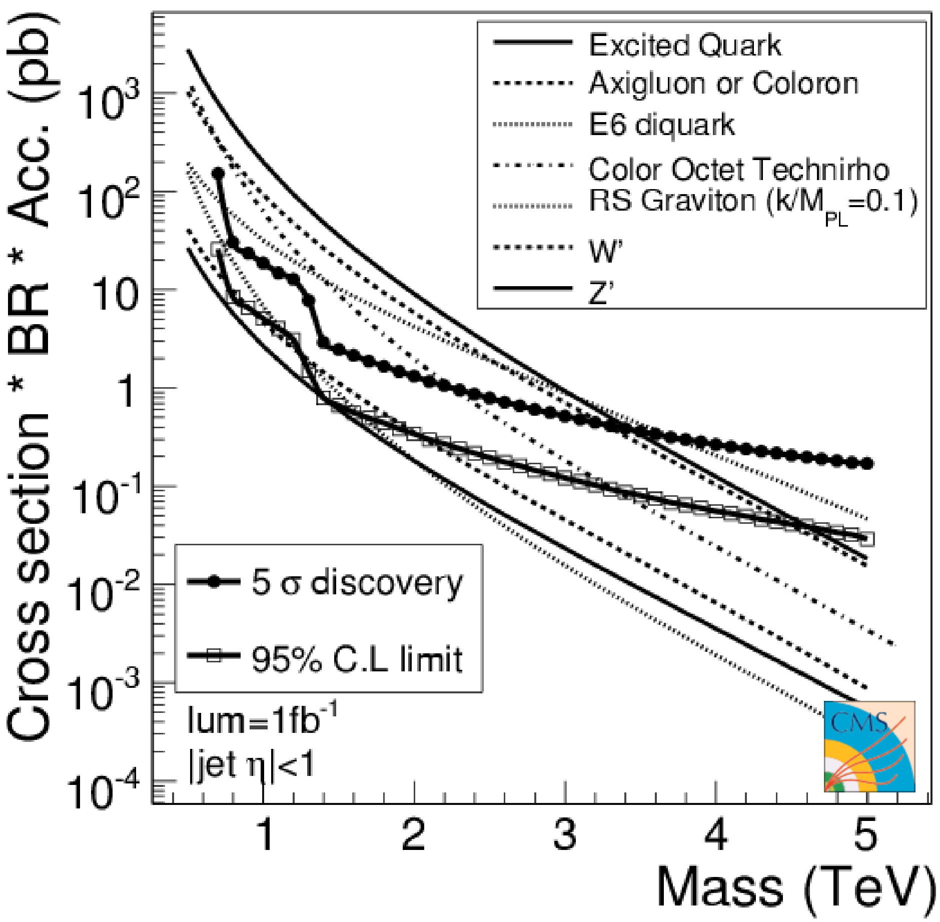




Dijets and Other Channels

Dijets:

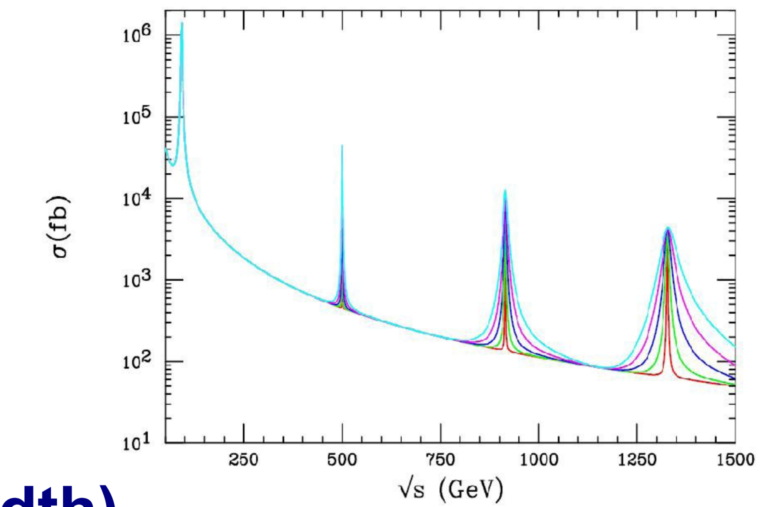
Complementary channel to search for W', Z', RS gravitons (and more)



Different systematics than lepton channels

- Other Z' decay channels considered: ττ, ttbar, WW, WZ, RH neutrinos, ...

Randall-Sundrum Gravitons



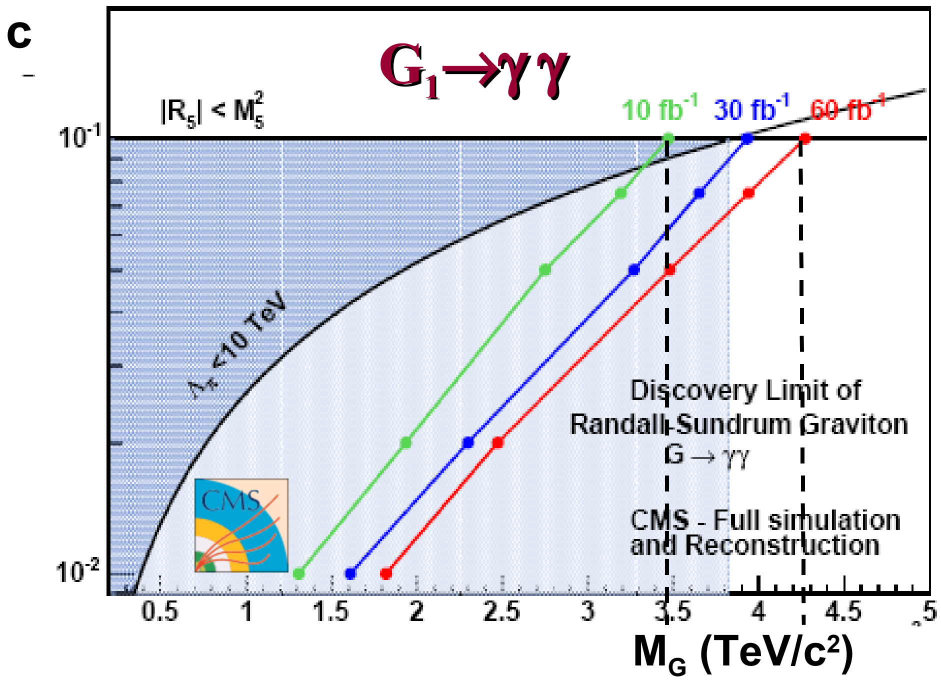
RS model:

One 5th (infinite) ED with warped geometry

Signature: **narrow, high mass resonances**

Model parameters:

Mass and coupling ($c=\kappa/M_{Pl} \rightarrow$ width)

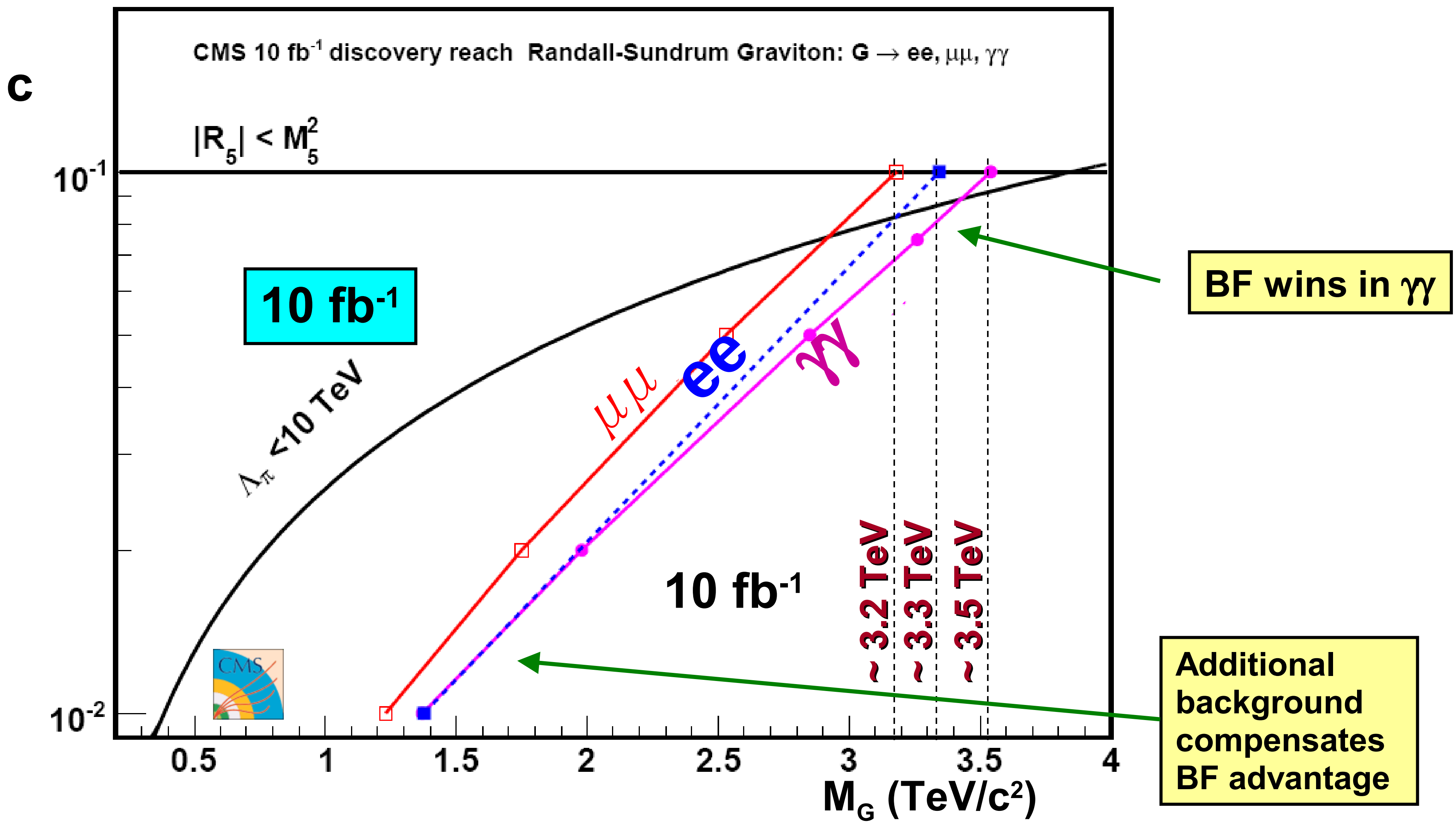


Spin 2 ⇒ BF($\gamma\gamma$) ~ 2 x BF(ll)

Backgrounds: prompt $\gamma\gamma$, γ + jets,
QCD, DY ee

Potential to discriminate RS G and Z'

Randall-Sundrum Gravitons

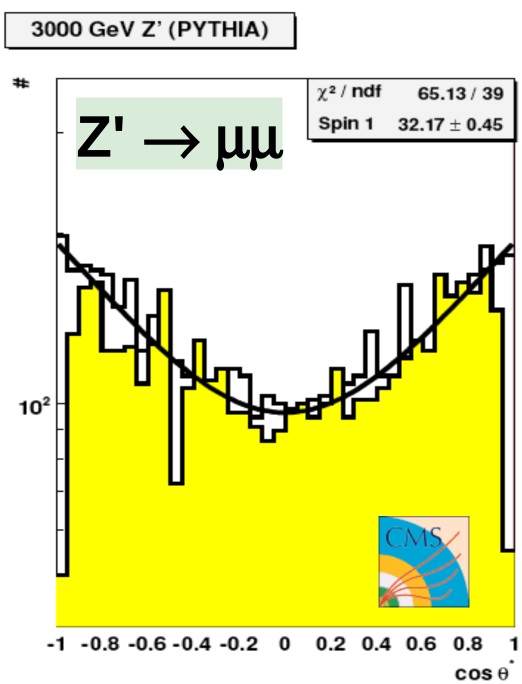


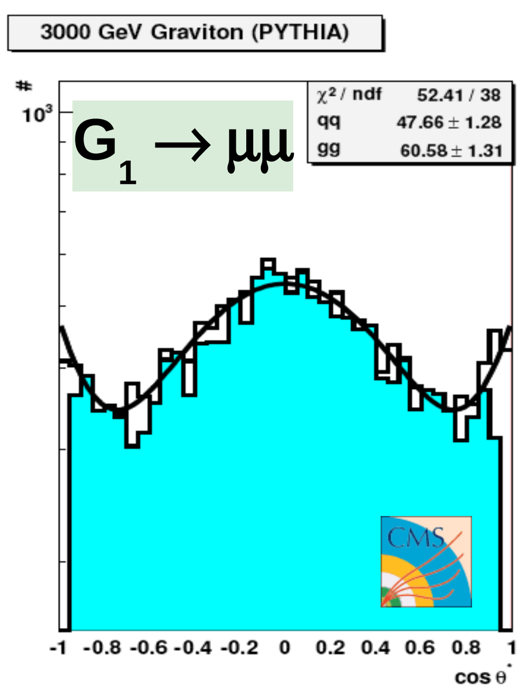
Properties, or: which Resonance?

- Measurements:
  - Mass – "easy"
  - Couplings (decays)
  - Width – marginal (depending on model), e channel only?
  - Cross section – challenging to reach precision; ratios?
  - Spin – need lots of data

Need all!

- Example: separate spin 2 (RS graviton) and spin 1 (Z')
  - Measure decay angular distribution cos(θ*)





Discrimination:

M_{Z'/G^*} = 1.2 - 3 TeV

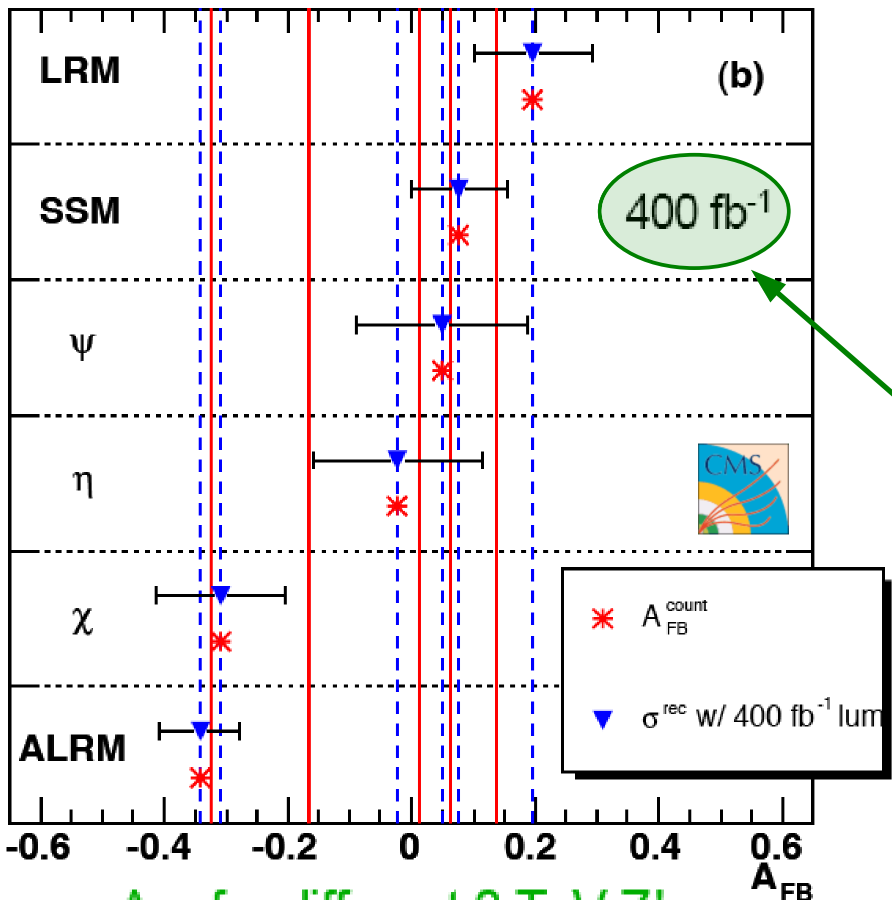
(c = 0.01-0.1, 300 fb^{-1}, 2σ)

RS graviton has also large BF to γγ

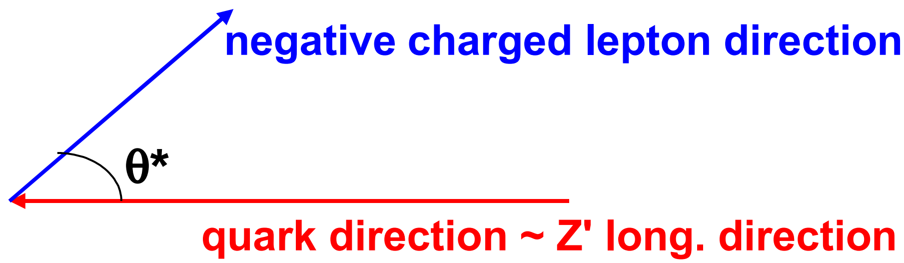
Which Z'?

Probe underlying model by measuring forward-backward asymmetry

$$\frac{d\sigma}{d\cos\theta^\star} \propto \frac{3}{8}(1+\cos^2\theta^\star) + A_{FB}\cos\theta^\star \qquad A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$



A_{FB} for different 3 TeV Z'



Need:

– large amounts of data

– high |η| coverage (~2), or even more data...

Large Extra Dimensions

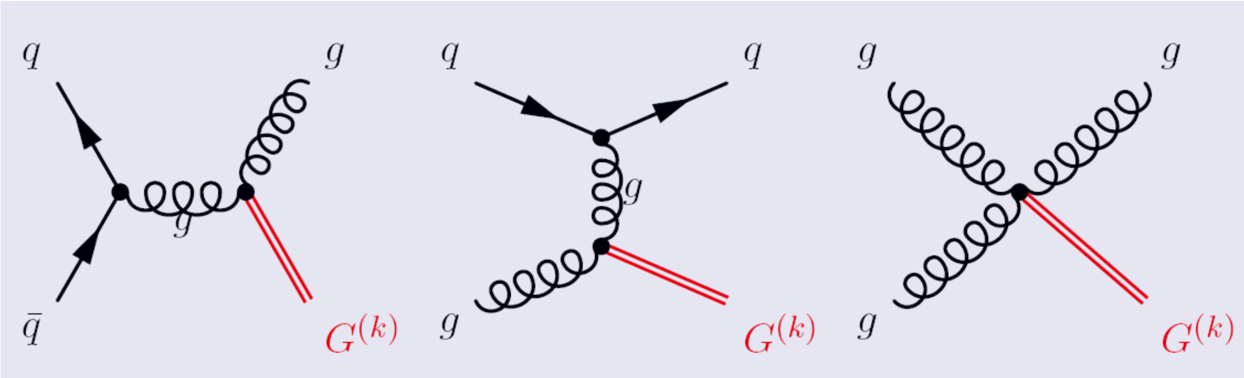
Main search streams:

Real graviton emission

Apparent energy-momentum non-conservation in 3D-space

$\Rightarrow$ "Monojets", V+E_T^{miss}

Direct sensitivity to the fundamental Planck scale M_D

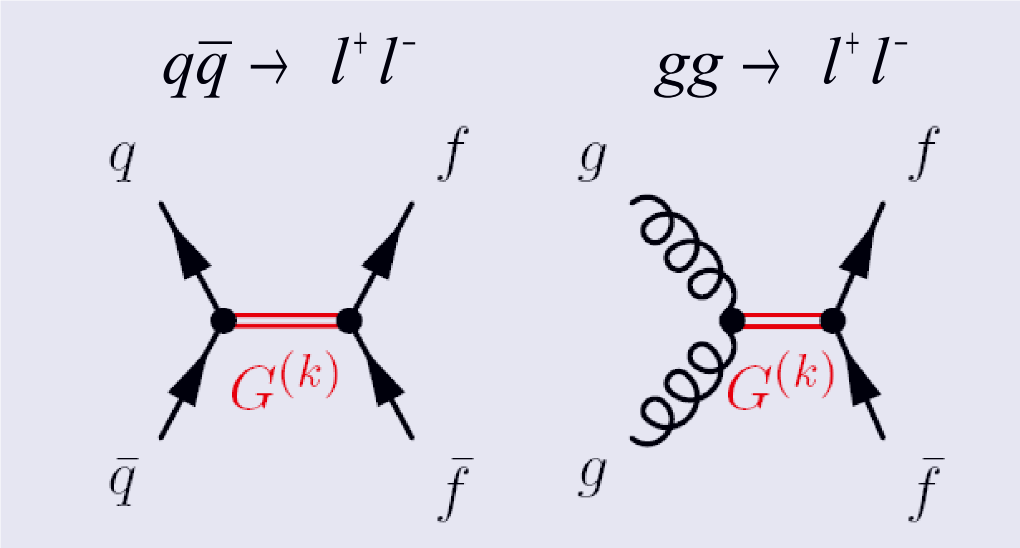


Virtual graviton exchange

$\Rightarrow$ Modified SM cross sections

Sensitivity to the theory cutoff M_S

(M_S expected to be ~ M_D)



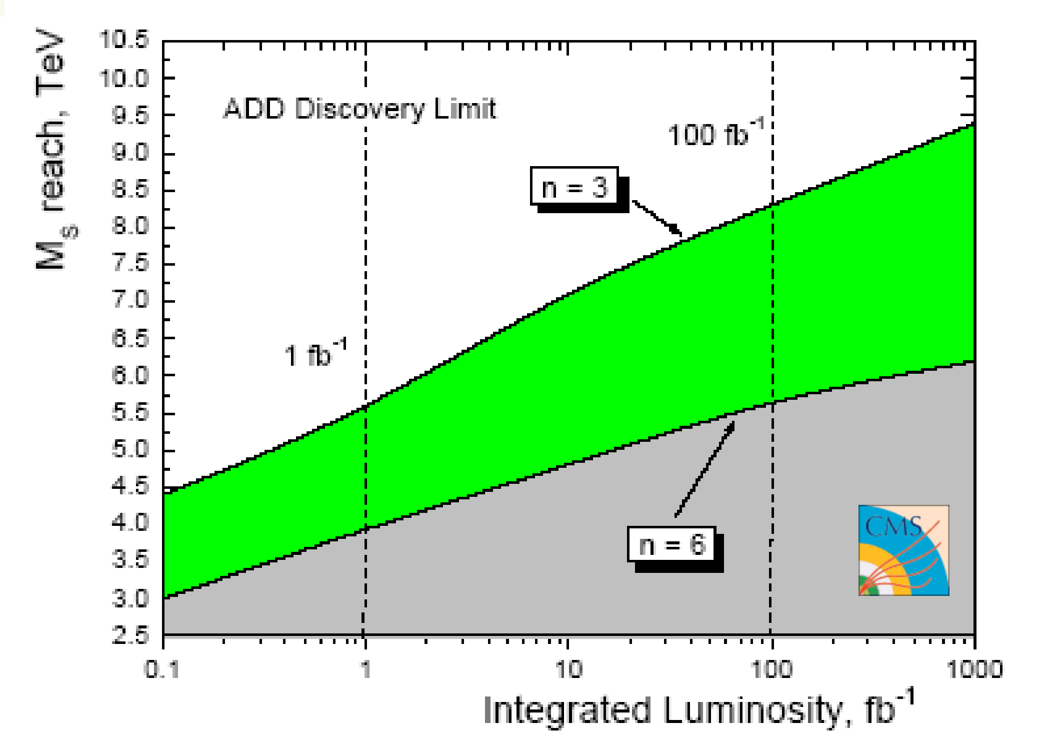
Large Extra Dimensions (ee, μμ, γγ)

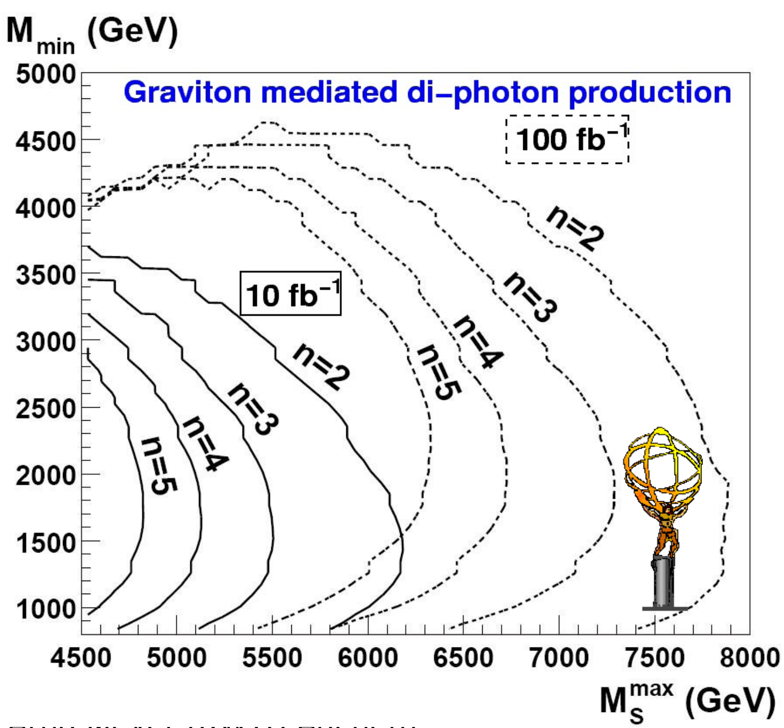
Virtual graviton production

$$pp \to G_{KK} \to \mu\mu$$

Two opposite sign muons in the final state with M(μμ) > 1 TeV

Irreducible background from Drell-Yan, also ZZ, WW, WZ, ttbar (suppressed after selection cuts)





Virtual graviton production

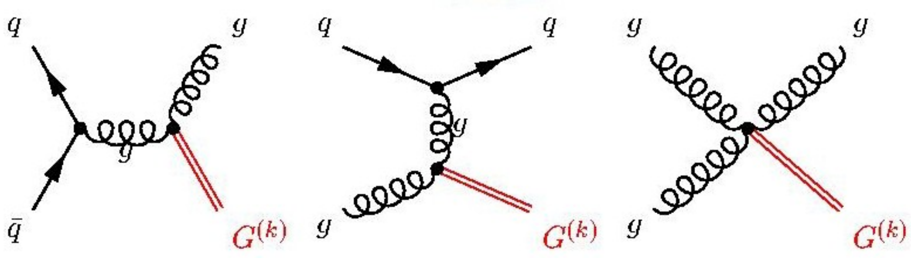
$$pp \to G_{KK} \to \gamma\gamma$$

Discovery with 100 fb^{-1} for

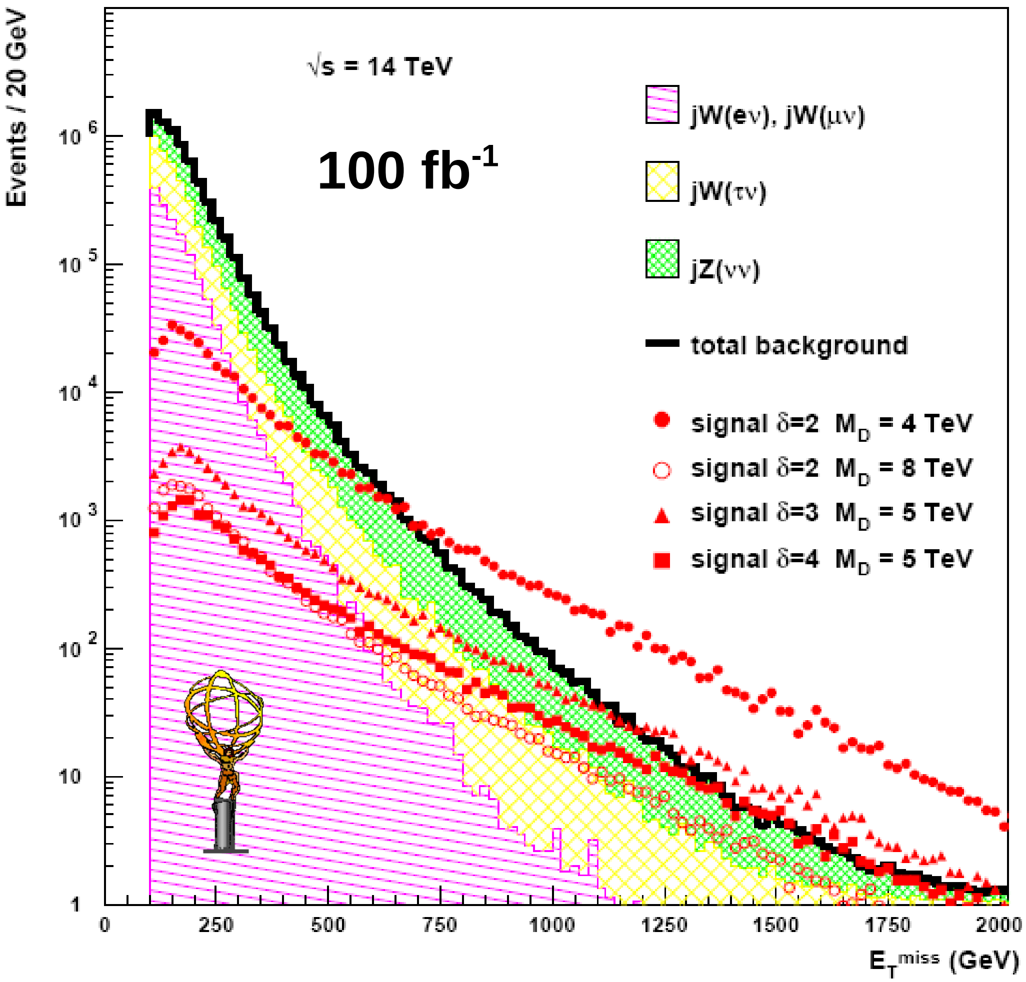
M_S = 6.3 ... 7.9 TeV (n = 5 ... 2)

(Tevatron (DØ): m > 1.43 TeV @ 95% CL, n=4)

Large Extra Dimensions (Monojets)



- Real graviton production
- Jet + missing E_T signature
- Experimentally "challenging"
- Can probe extra dimensions up to M_D = 6 – 9 TeV with 100 fb^{-1}



SN-ATLAS-2001-005

Universal Extra Dimensions

SM particles can propagate in small (TeV^{-1} size) ED; compactification radius R
KK particles produced in pairs
KK-parity; decay cascades down to lightest KK-particle = KK photon

$$g_1 \to q_1 + \bar{q}$$
$$q_1 \to Z_1 + q$$
$$Z_1 \to l_1 + \ell^\pm$$
$$l_1 \to \ell^\mp + \mathrm{LKP}(\gamma_1)$$

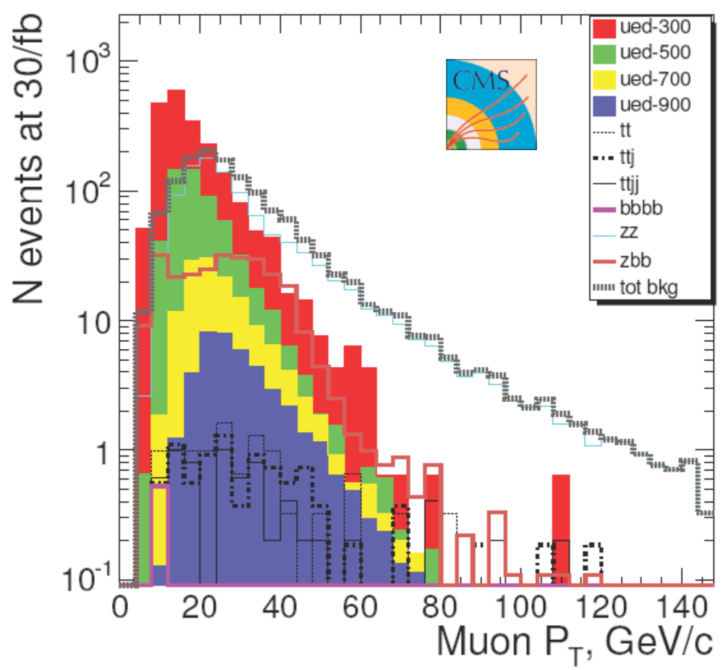
Signal: 4 leptons + jets + E_T^{miss}

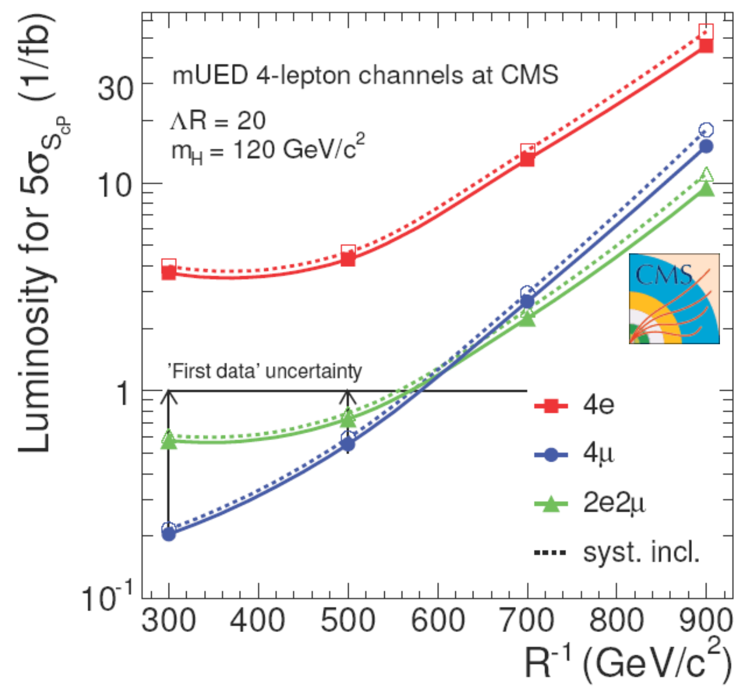
(Atlas: dijets + E_T^{miss})

2 pairs OSSF isolated leptons

Missing E_T

Z veto

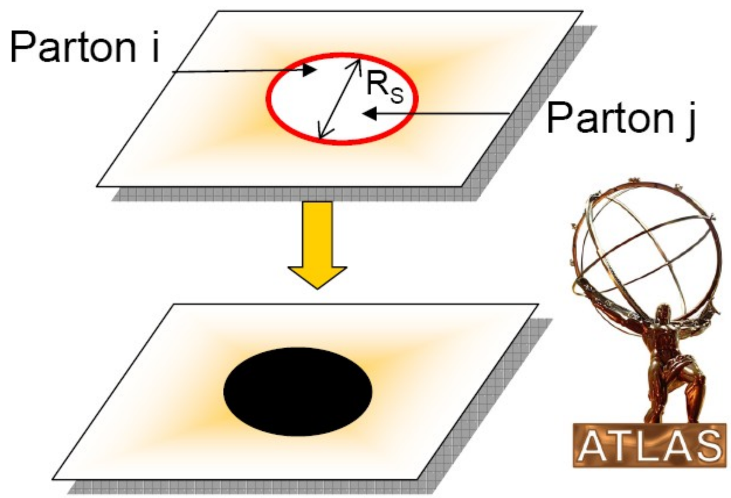


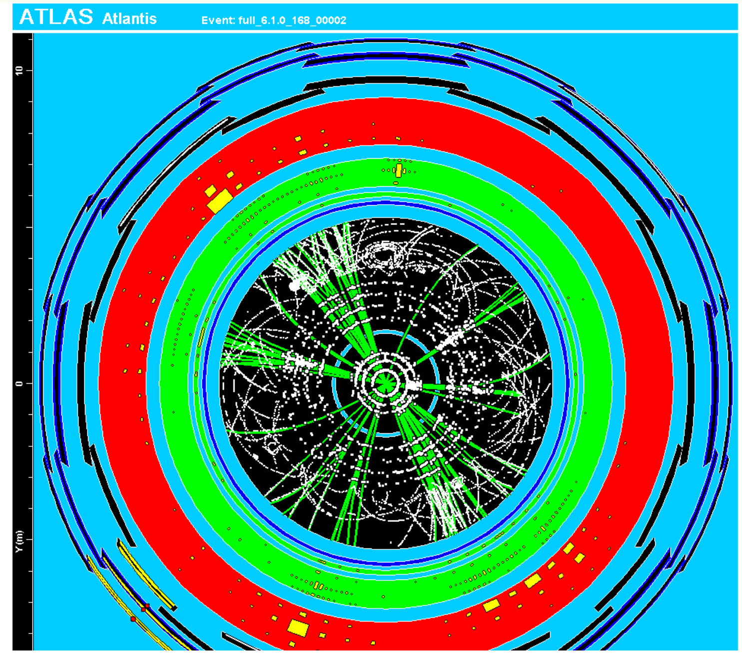


μ trigger thresholds lower than for e

Micro Black Holes

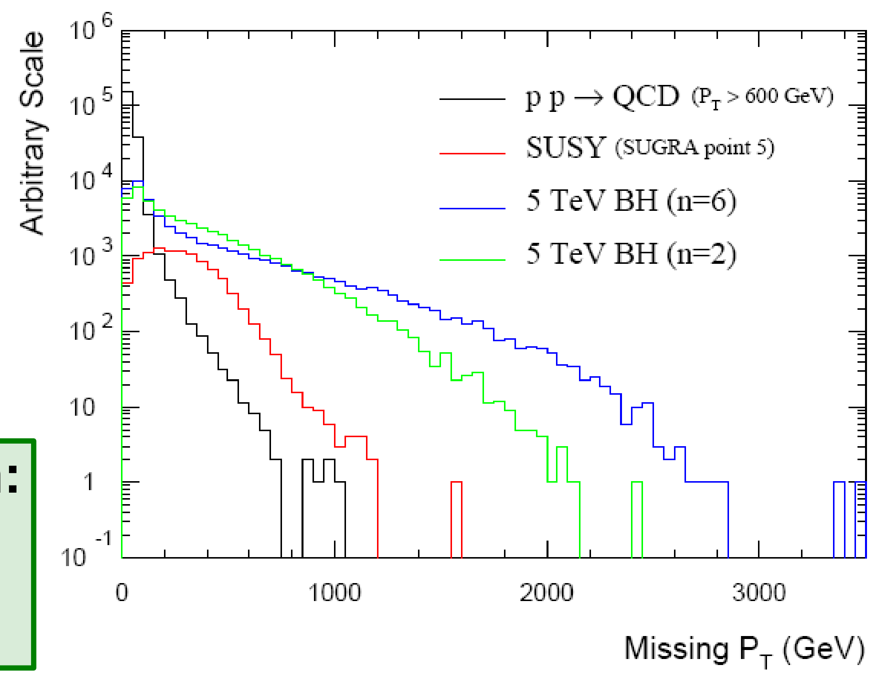
M_{pl} ~ 1 TeV:
Partons with impact parameter less than Schwarzschild radius can form black holes





Lifetime ~ 10^{-27} s

Decay through Hawking radiation into democratic spectrum of SM particles



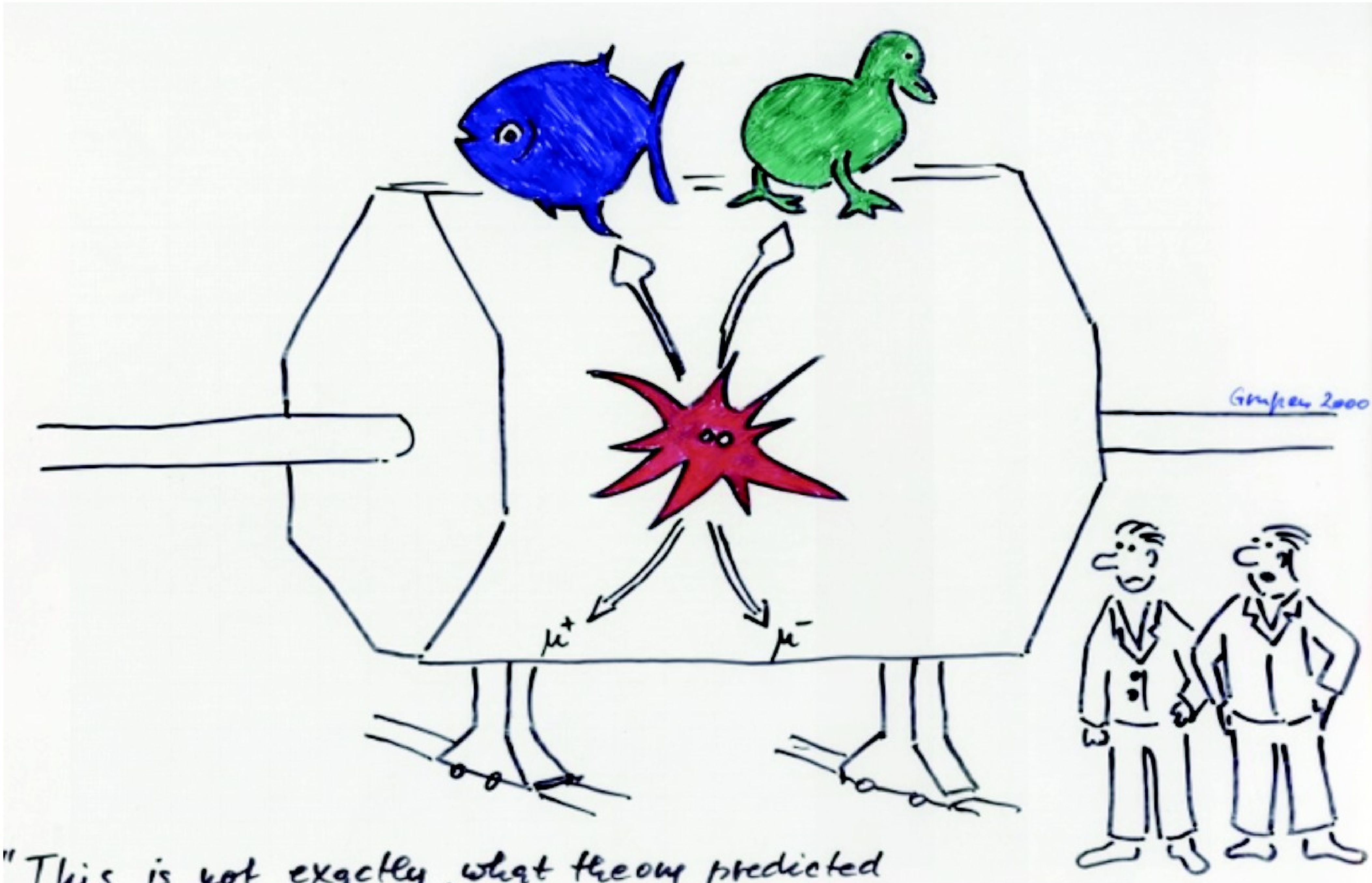
- **High particle multiplicity**
- **Large mass ($M_{BH} > M_{Pl}$)**
- **Hadrons : leptons ~ 5 : 1**
- **Spherical events**
- **Large missing E_T**

Discovery reach:
$M_{pl} < 5$ TeV
with 1 fb^{-1}

ATL-PHYS-2004-033

Conclusions

- Detailed studies of the LHC discovery potential for resonant and non-resonant dilepton (and diphoton) production
  - Some systematics will only be known after start-up
- Discovery reach for extra gauge bosons W' and Z'
  - First 100 pb^{-1} beyond Tevatron
  - With 10 fb^{-1} ~ 3 TeV
  - With 100 – 300 fb^{-1} ~ 5 TeV
- Models can be discriminated using angular distributions
- RS gravitons: can cover theoretically preferred region with < 100 fb^{-1}
- Complementary channels to look for signs of large extra dimensions
- Have to look in all channels to be prepared for the unexpected


Grupen 2000
μ^+
μ^-
"This is not exactly, what theory predicted

Backup

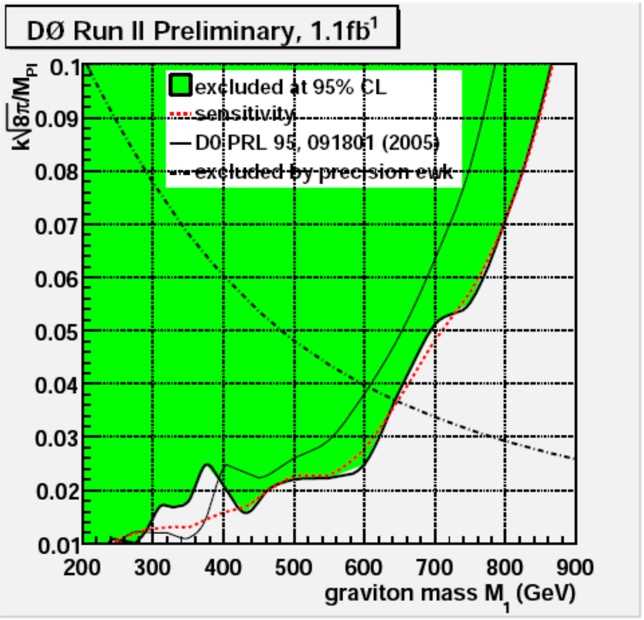
Previous Limits

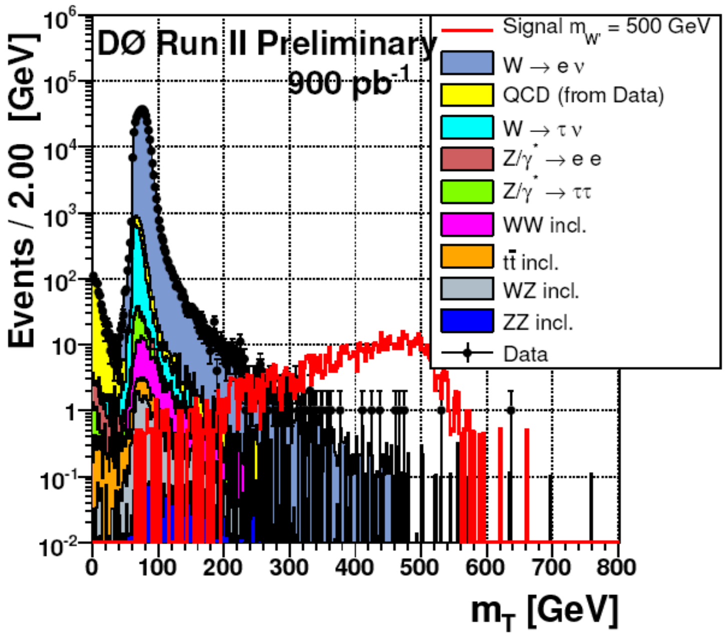
Resonances (W', Z', ~RS-Graviton):

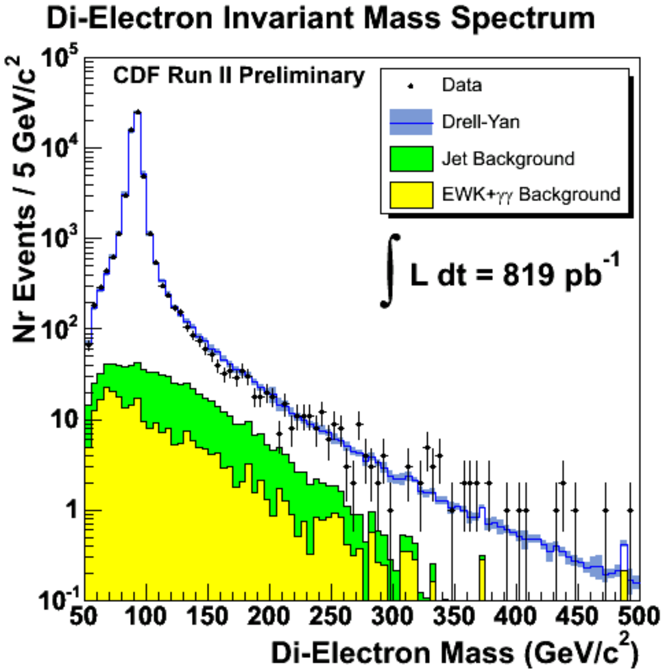
M > 1 TeV **DØ and CDF Run II**

Large Extra Dimensions:

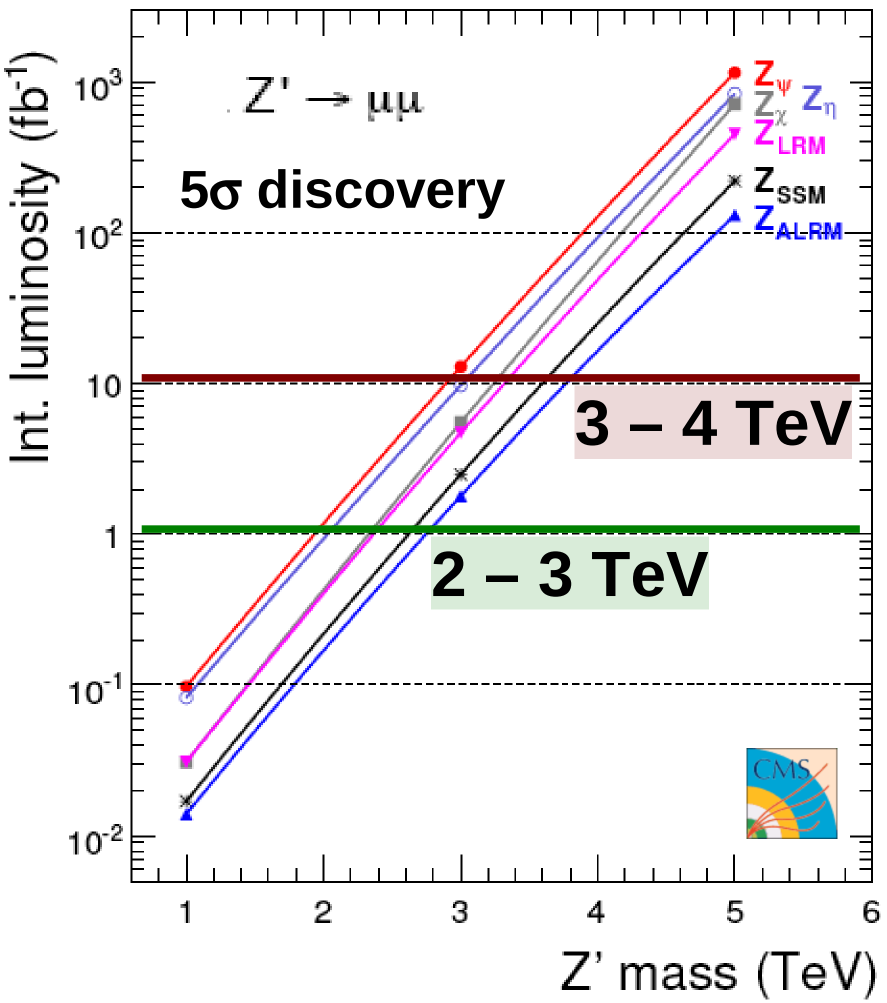
M_S > 1.43 TeV **DØ Run I+II** (GRW formalism)







Z' Discovery Reach



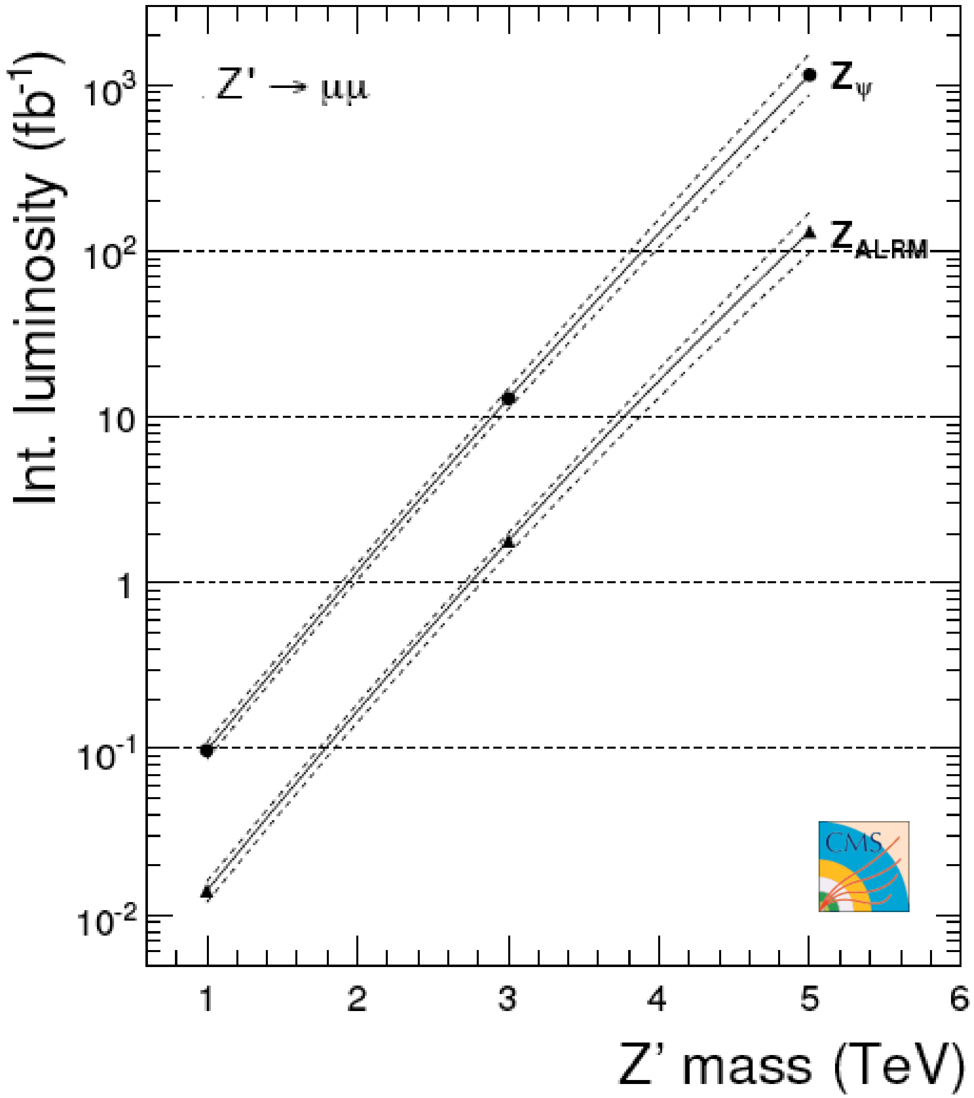
Model	Γ/M %	$Z' \to \mu^+\mu^-$ BR in %	$\sigma^{LO} \cdot$ Br, full interference, fb (PYTHIA)		
			1 TeV/c^2	3 TeV/c^2	5 TeV/c^2
Z_{SSM}	3.1	3.0	610	2.8	0.050
Z_ψ	0.6	4.0	340	1.7	0.032
Z_η	0.7	3.4	370	1.8	0.035
Z_χ	1.3	5.7	500	2.2	0.038
Z_{LRM}	2.2	2.3	500	2.3	0.040
Z_{ALRM}	1.6	8.6	740	3.7	0.077

Constant NNLO k-factor 1.35 applied

95% CL limits about 700 GeV higher at largest masses

Systematic Uncertainties (typical)

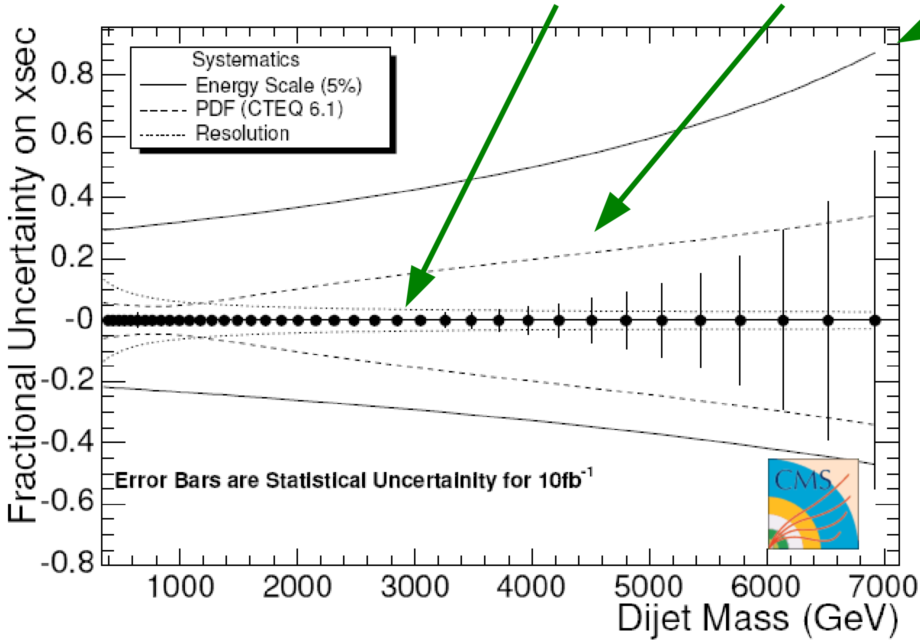
- Experimental
  - Luminosity: 5%
  - Shape and normalization of signal and background
  - Alignment
- Theoretical
  - PDF uncertainties from CTEQ 6.1 error PDF's → cross sections and acceptances for signal and background → 5% (m = 1 TeV) to 25% (m = 5 TeV)
  - Renormalization / factorization scale (up to 25% for m = 5 TeV)
  - Higher order corrections

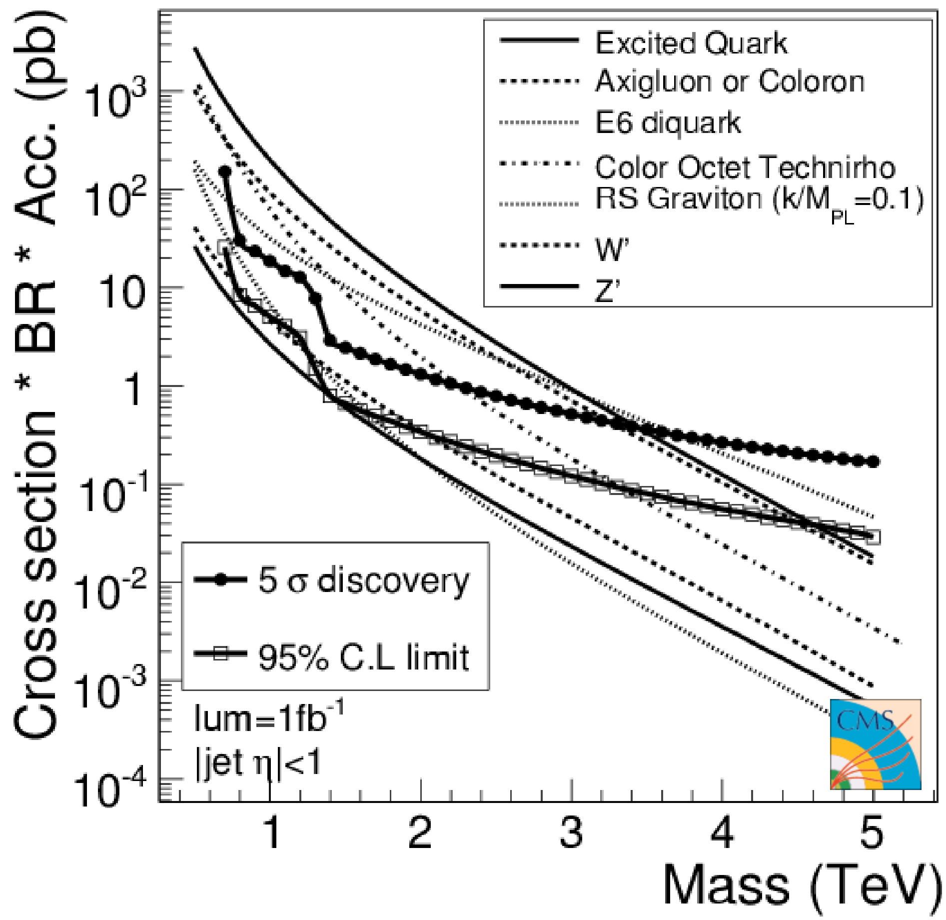


Dijets

Complementary channel to search for W', Z', RS gravitons (and more)

Resolution PDF's Jet energy scale (5% here, 10% initially, 1% ultimately)





- Other Z' decay channels considered: taus, ttbar, WW, WZ, RH neutrinos, ...