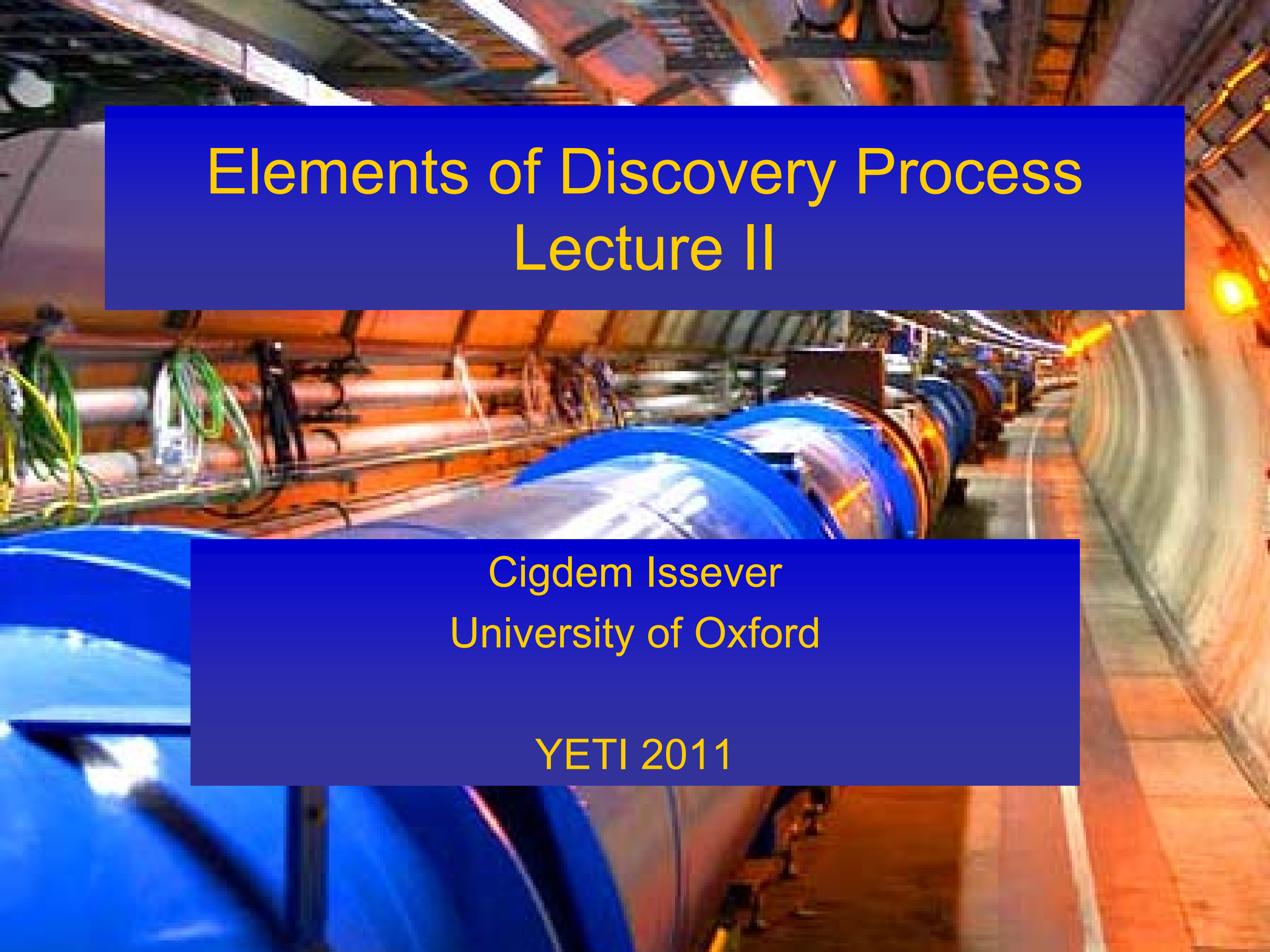


Elements of Discovery Process
Lecture II

Cigdem Issever
University of Oxford

YETI 2011

Example Searches with 2010 data

- Dijet Angular Distribution Searches

- Multi-Object Searches
  - Motivated by low scale gravity models

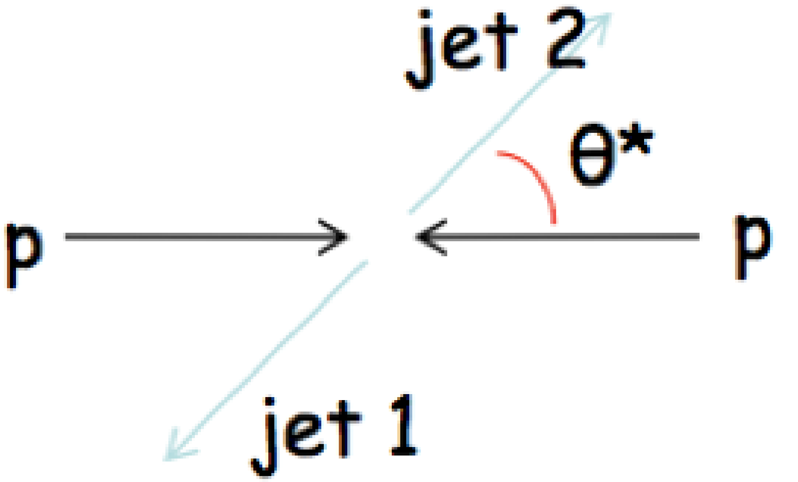
- Gamma gamma + MET Final state
  - UED

Dijet Angular Distribution Search

- Observable

$$\chi = \exp(|y1 - y2|)$$

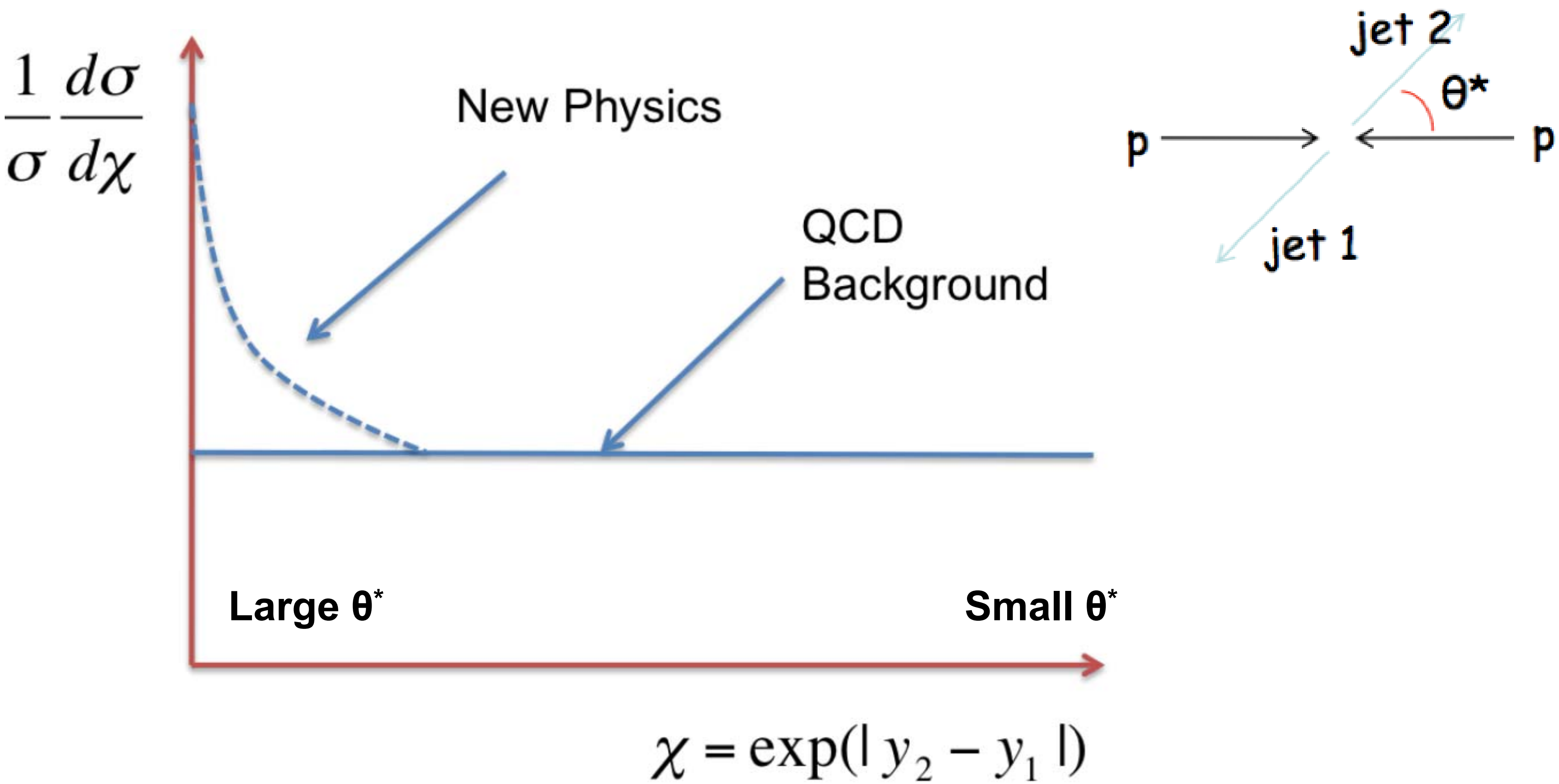
$$\chi = \frac{1+\cos\theta^*}{1-\cos\theta^*}$$



- flat for Rutherford scattering
- relatively flat shape in QCD
- small PDF dependence
- enhancement at low χ for new physics
  - - quark compositeness
  - - ADD large extra dimensions
  - - TeV-1 extra dimensions

(increased scattering at large angles)

Dijet Angular Distribution Search



R. Buckingham

Bench Mark Model: Contact Interaction

- Quark compositeness
  - quarks are composed of more fundamental particles
- Four-fermion contact interaction Lagragian

$$\mathcal{L}_{qqqq}(\Lambda) = \frac{\xi g^2}{2\Lambda_q^2}\bar{\Psi}_q^L \gamma^\mu \Psi_q^L \bar{\Psi}_q^L \gamma_\mu \Psi_q^L$$

- Λ characterize strength of “preon” coupling and physical size of the coupling scale

- *If Λ* >> partonic CM energy
  - Contact interactions suppressed by powers of 1/*Λ*
  - → quarks would appear to be point-like

Dijet Angular Distribution

- AIM: Find BSM physics (s-channel processes)
- Analysis Method
  - X studied in bins of mjj
  - $|y_{j1} - y_{j2}| < \ln 30$
  - $y_{j1} + y_{j2} < 1.5$
  - $pt_{j1} > 60$ GeV
  - $pt_{j2} > 30$ GeV

Advantages: JES and Lumi uncertainties reduce

Combined $y_{j1} + y_{j2}$ and $|y_{j1} - y_{j2}|$ cuts give uniform acceptance in χ

Results Phys. Lett. B694 (2011) 327-345

- $3.1\ pb^{-1}$ in Aug. 2010

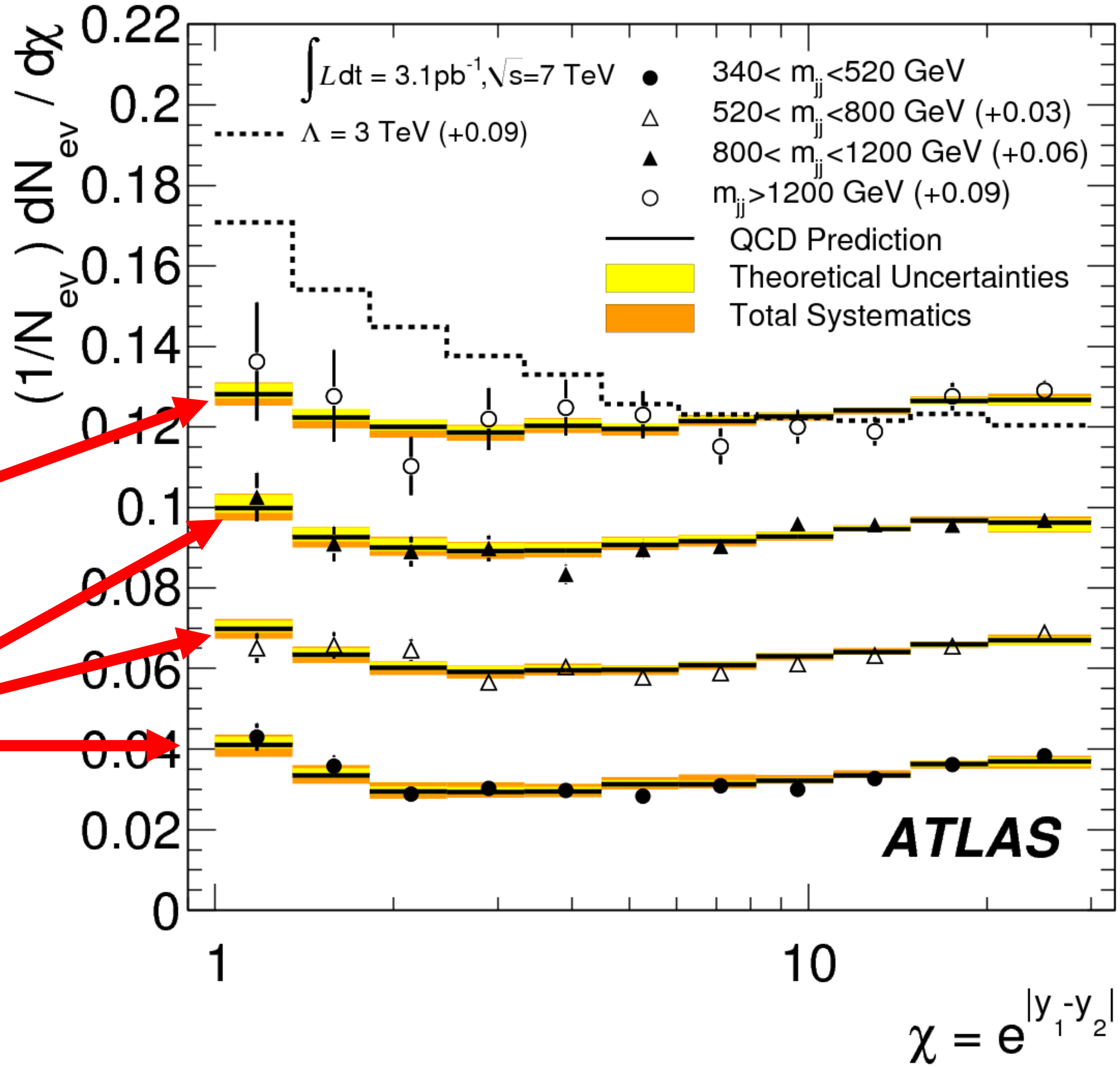
- Dominant uncertainties
  - NLO QCD renormalization and factorization scales
  - PDF uncertainties.
  - Jet Energy Scale

- resulting bin-wise uncertainties are for χ
  - 3% for the combined NLO QCD scales
  - 1% for the PDF error
  - 9% Jet Energy Scale

Results

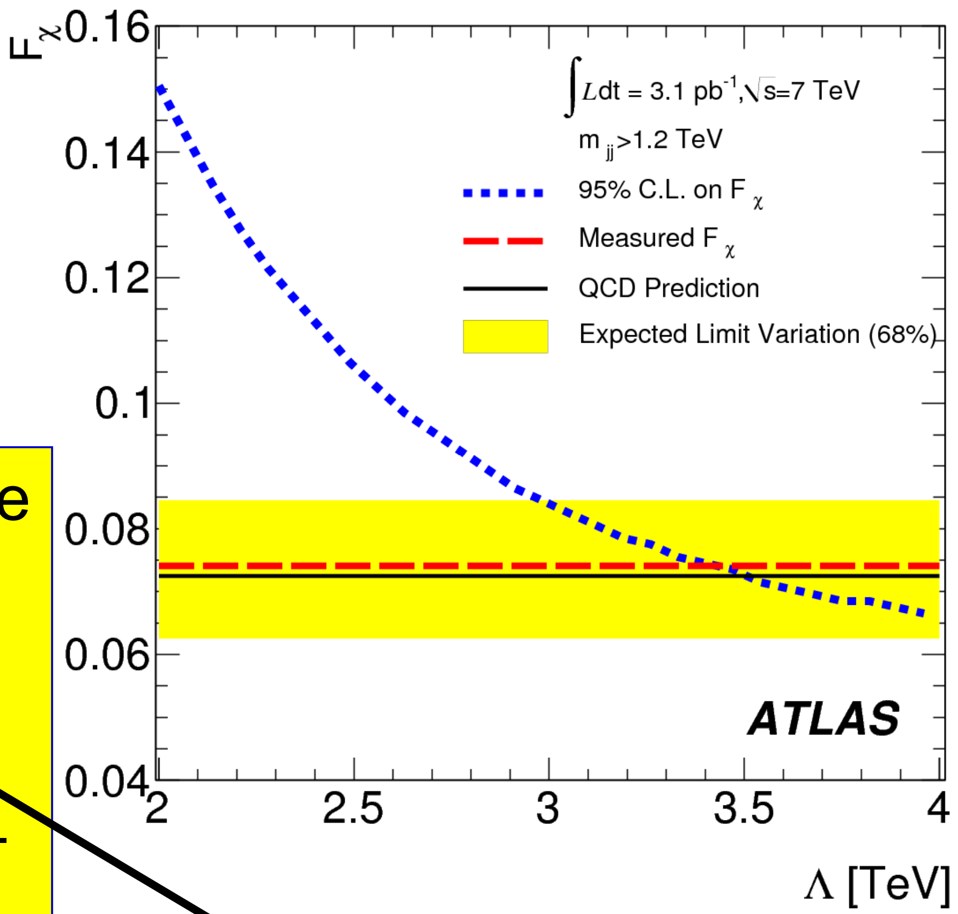
Signal Region

Control Region



Determination of Exclusion Limits

$$F_\chi = \frac{\#\chi < 3.32}{\#\text{all}}$$



Expected limit: Λ< 3.5 TeV at the 95% CL

Observed limit: **Λ< 3.4 TeV** at the 95% CL.

Previous Tevatron limit: Λ=2.8 – 3.1 TeV

CMS: expected Λ< 2.4 TeV

observed Λ< 4 TeV

$\sim 6 \cdot 10^{-5}$ fm

Extra Dimensions

No theory of first principles

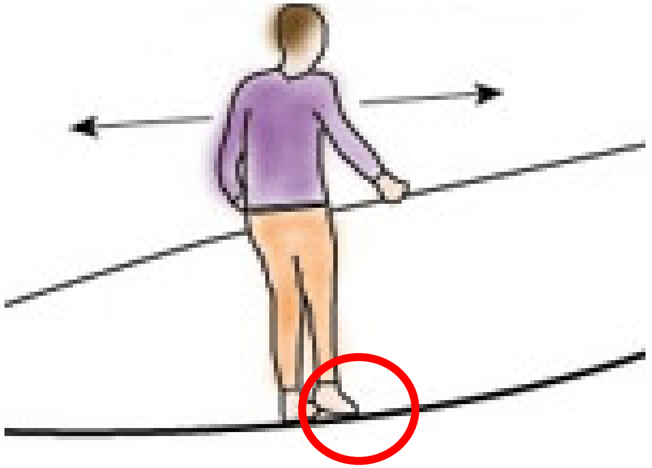
Provide simplified framework with testable results

Can help us to gain insights about the underlying theory

Extra Dimension (ED) Models

- ED may explain complexity of particle physics
- Where are they?

http://www.particleadventure.org/frameless/extra_dim.html



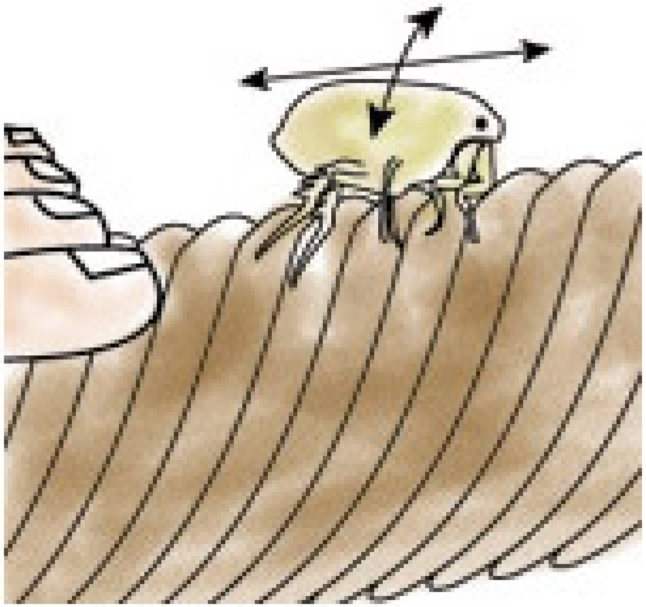
An acrobat can only move in one dimension along a rope..

Gravity is escaping into the extra dimensions.

Extra Dimension (ED) Models

- ED may explain complexity of particle physics
- Where are they?

http://www.particleadventure.org/frameless/extra_dim.html



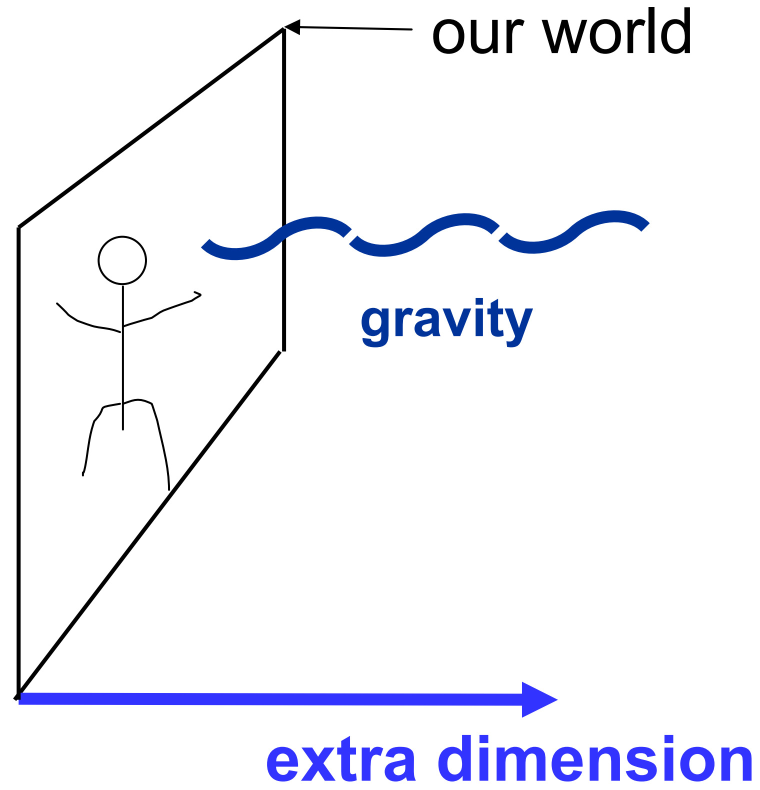
...but a flea can move
in two dimensions.

Gravity is escaping into the extra dimensions.

Extra Dimension (ED) Models

- ED may explain complexity of particle physics
- Where are they?

http://www.particleadventure.org/frameless/extra_dim.html



Gravity is escaping into the extra dimensions.

Gravity in Extra Dimension

At small distances gravity can be very strong,

up to 10^{38} times stronger:

$$F \approx \frac{G_D}{r^{n+2}}$$

$$G_D = GL^n$$

At large distances gravity seems weak

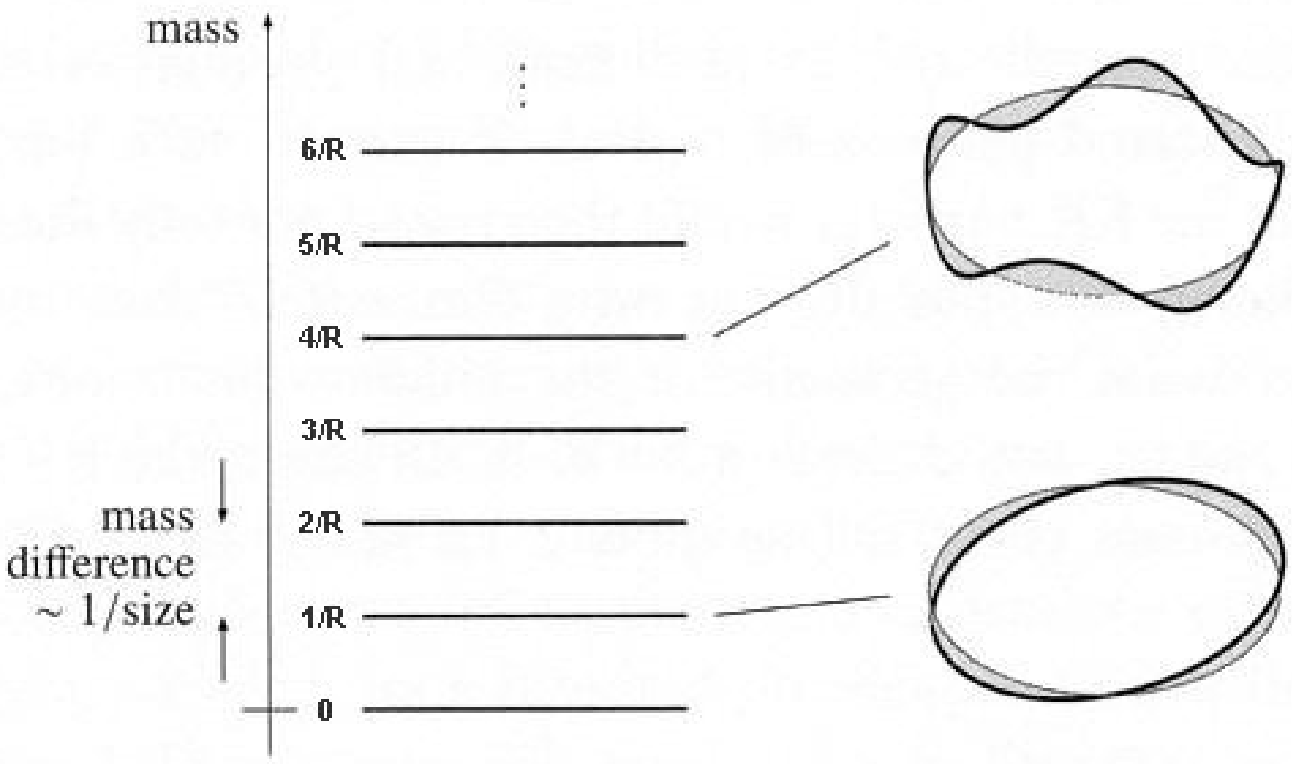
$$F \approx \frac{G_D}{L^n \cdot r^2} \approx \frac{G}{r^2}$$

$$M_D^{n+2} = \frac{(2\pi)^n}{8\pi G_D}$$

G is “diluted” strength of gravity in our 3-dim. space.

G_D is the (4+n)-dimensional Newton gravity constant.

KK particles



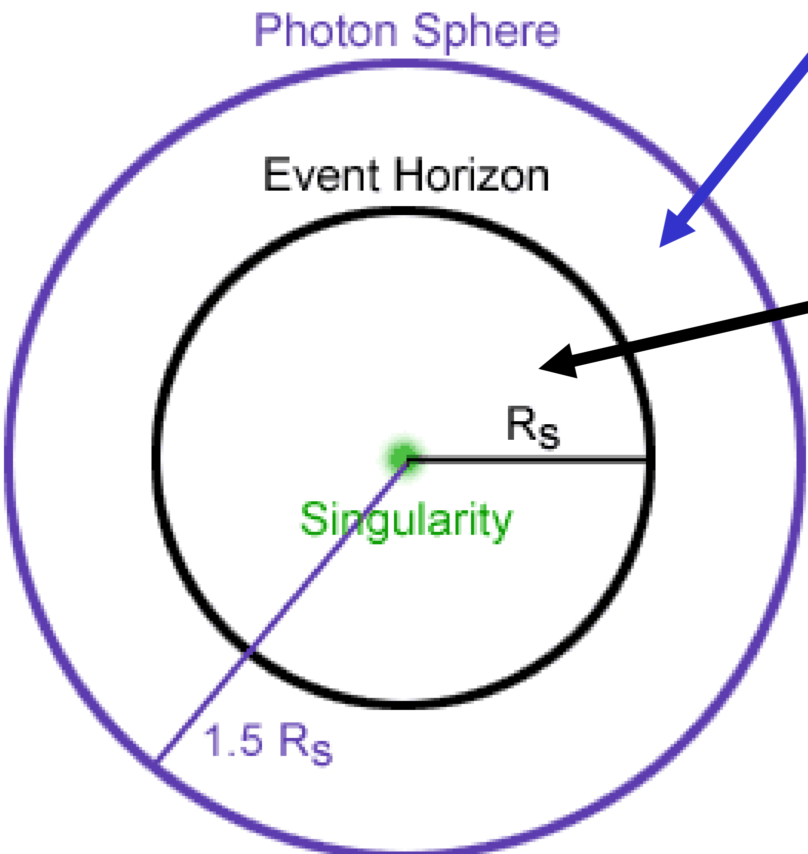
http://universe-review.ca/I15-74-KK.jpg

Schwarzschild Black Holes

- **non-rotating**
- **uncharged**

can't orbit black hole

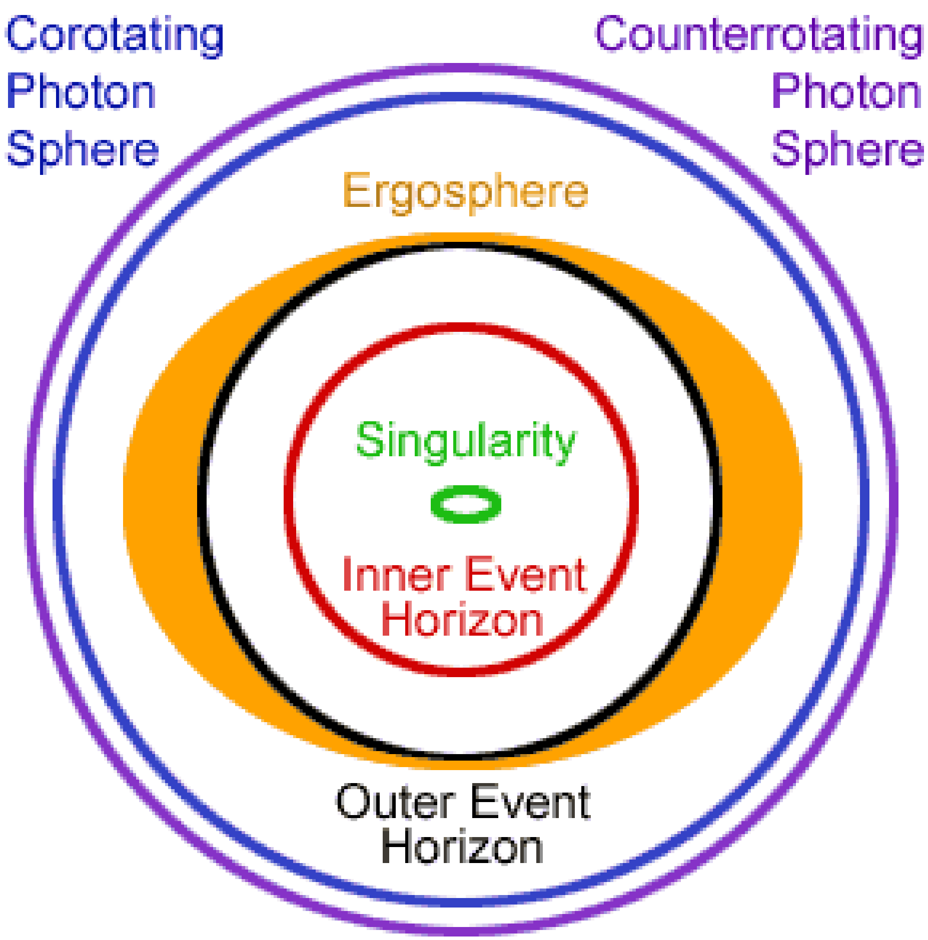
nothing can escape



http://www.gothosenterprises.com/black_holes/rotating_black_holes.html

Rotating Black Holes – Kerr Solution

- **rotating massive body**
- **frame dragging**
- **ergosphere:**
  - particles have to co-rotate
- **Penrose effect**
  - BH emits energetic particles→energy loss

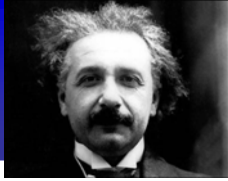


http://www.gothosenterprises.com/black_holes/rotating_black_holes.html

The "No-Hair Theorem"

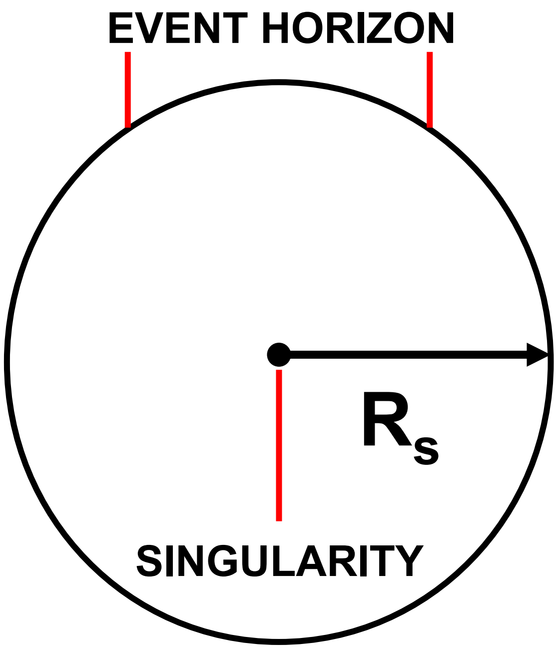
- Black holes are characterized by their
  - Energy,
  - Angular momentum,
  - Electric charge.
- Do **NOT** conserve B, L or flavour

Production of Black Holes



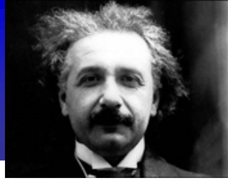
Bring mass closer than its
Schwarzschild Radius, R_S,

$$R_S = \frac{2GM}{c^2}$$



and a black hole will form!

Production of Black Holes



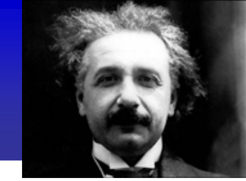
Bring mass closer than its **Schwarzschild Radius, R_S,**

$$R_S = \frac{2GM}{c^2}$$

$R_S^{Earth} = 8.8\text{mm}$

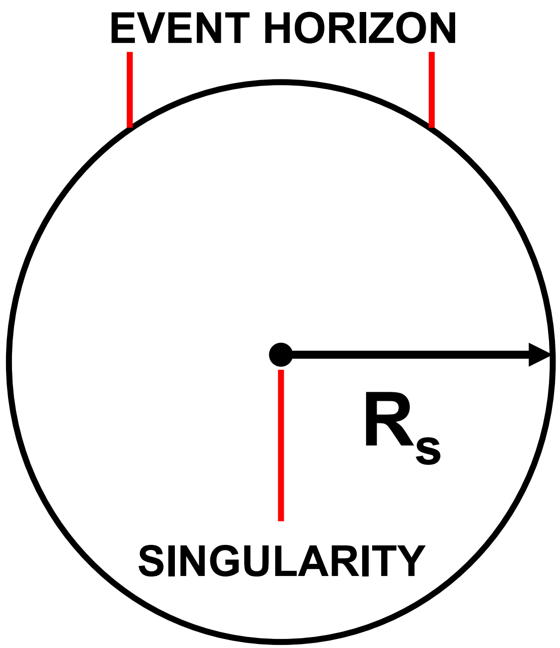
and a black hole will form!

Production of Black Holes



Bring mass closer than its **Schwarzschild Radius, R_S,**

$$R_S = \frac{2GM}{c^2}$$

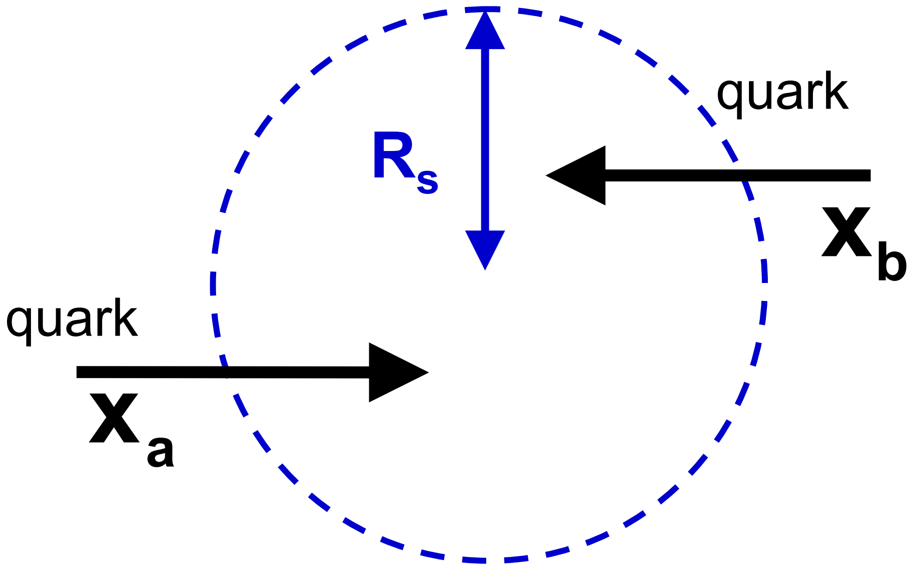


$R_S^{Earth} = 8.8mm$

and a black hole will form!

Production of Black Holes at the LHC

$$R_S = \frac{2\,G^*L^n\,M}{c^2}$$



$$M = \sqrt{s x_a x_b} = \sqrt{\hat{s}}$$

$$R_S^{2quarks} \leq 10^{-18}\,m$$

BH production @ LHC

Semi Classical Production Cross Section

$$\sigma_{ab\rightarrow BH}(\hat{s}) \approx \pi R_h^2$$

valid for $M >> M_D$

$$\sigma_{pp\rightarrow BH+X}(s) =$$

$$\sum_{a,b}\int_{\frac{M^2}{s}}^{1} dx_a \int_{\frac{M^2}{x_a s}}^{1} dx_b f_a(x_a) f_b(x_b) \sigma_{ab\rightarrow BH}(\hat{s})$$

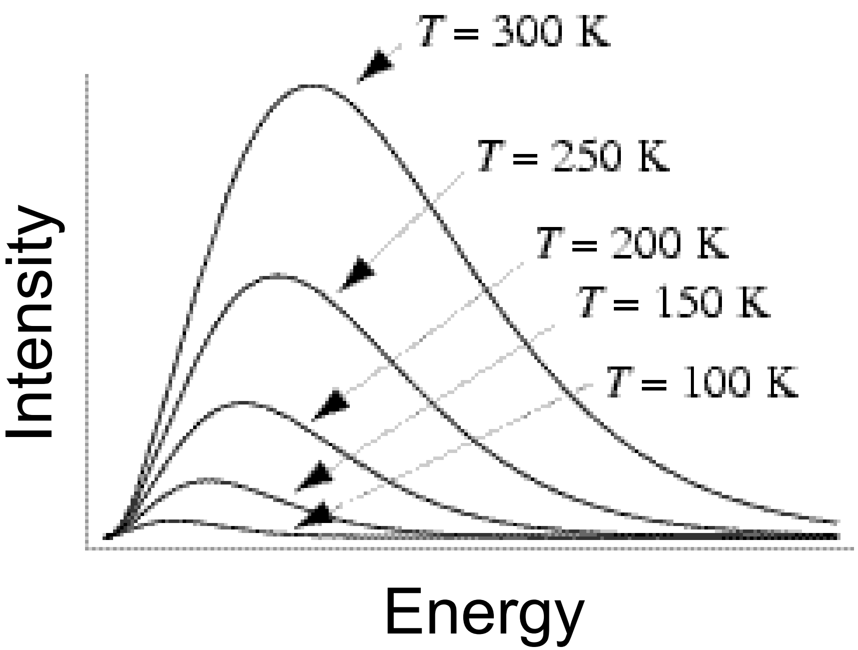
parton distribution functions

Black Holes decay!

- Astronomical BH -- **COLD**
  Low Evaporation Rate
- Micro BH -- **HOT**
  High Evaporation Rate

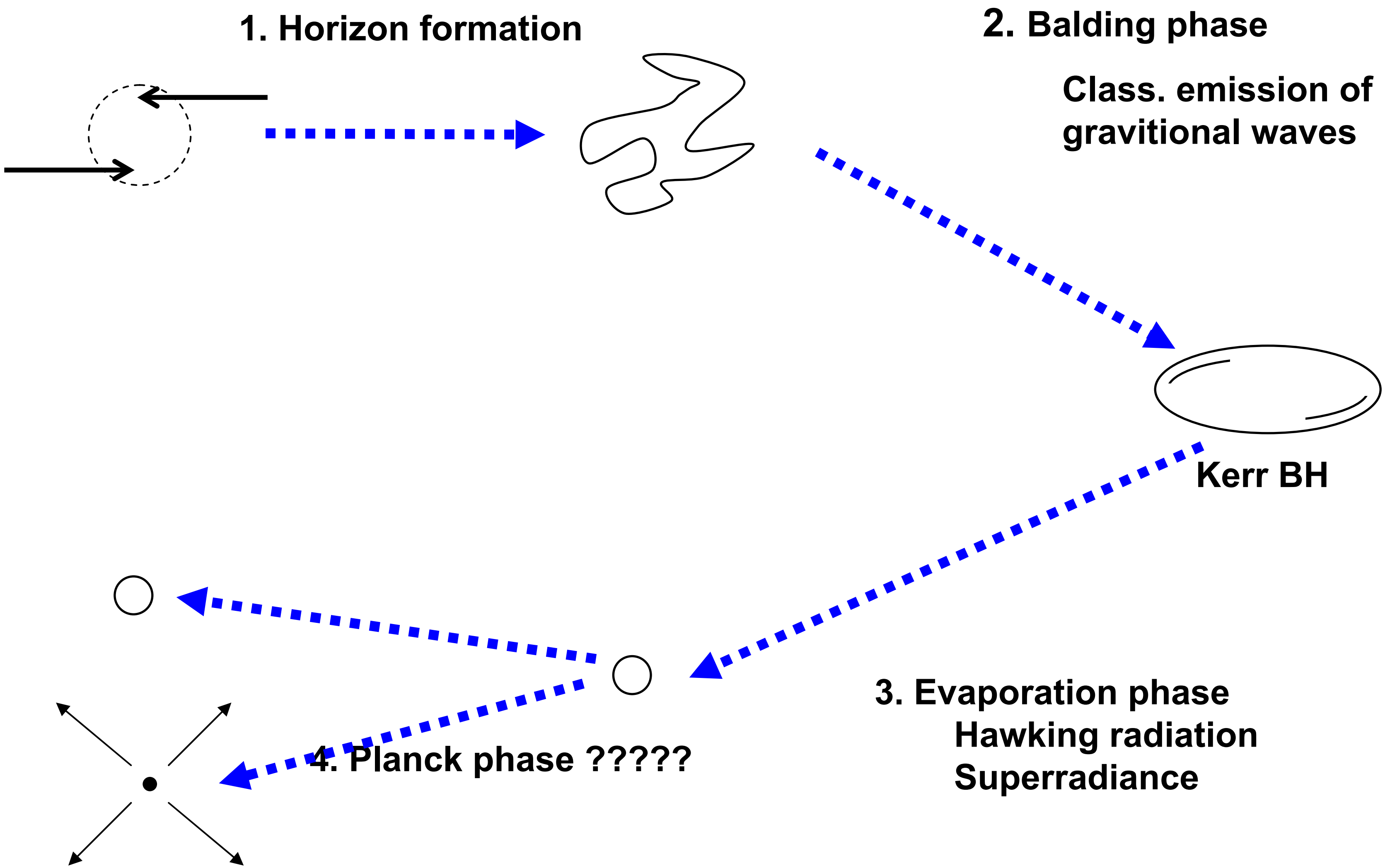
$$T_H \approx 10^{-6} \frac{M_\odot}{M} [K]$$

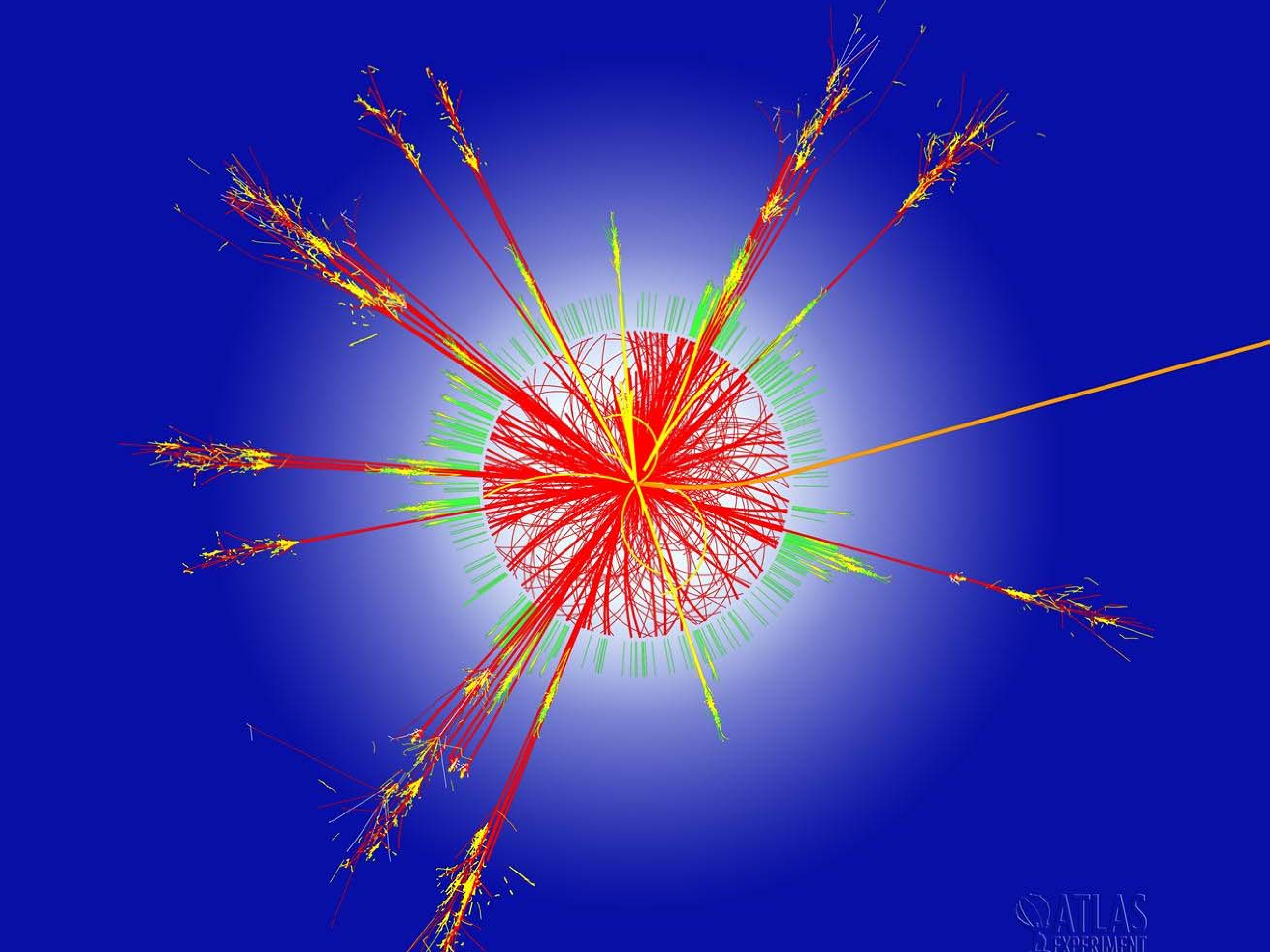
emit particles ≈ **black body** thermal spectrum.



- BH lifetime @ LHC
  ~ 10^{-27}–10^{-25} s
- Decays with equal probability to all particles.

Time Evolution of Black Holes

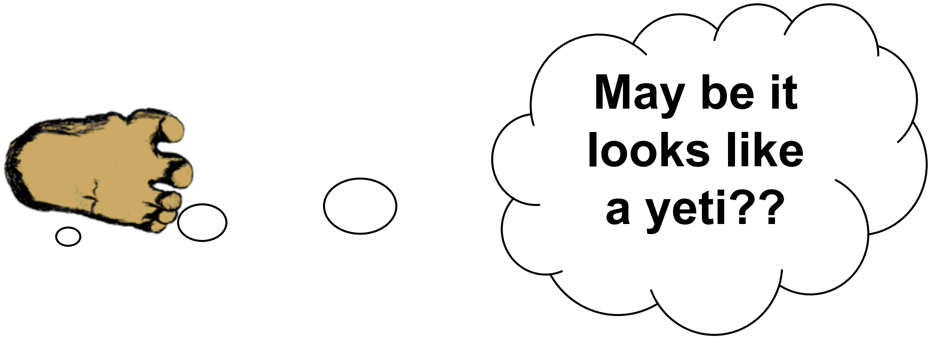



ATLAS
EXPERIMENT

Footprints of Microscopic Black Holes

- **hadron : lepton ≈ 5 : 1**
- **Theoretical uncertainties large**
- **high multiplicities**

  10 – 40 particles/event
- **decay product’s energies up to TeV**



Search for an enhancement of multi--body final states at high masses

- Search motivated by low-scale gravity and/or weakly-couple string theory.

- As model independent as possible <u>in the context of low scale gravity.</u>
  - Due to lack of reliable prediction in strong-gravity regime (general UV-complete quantum gravity).

- Large deviation from SM in a signal that is anticipated to have a high acceptance.

ATLAS-CONF-2010-088

Search Aims

- Search for deviations from SM
  - high multiplicity
  - high invariant mass final-state topologies.
- Perform search for a new interaction threshold
- In the absence of a signal,
  - derive an upper limit on such possible final states.

Observables

- N= number of objects (electrons, photons, muons, jets) passing object selections in the final state.
- Σp_T= scalar sum of the transverse momentum of the objects selected.

$$\sum \mathbf{p_T} = \sum_{\mathbf{i=objects}} |\mathbf{p_{Ti}}|$$

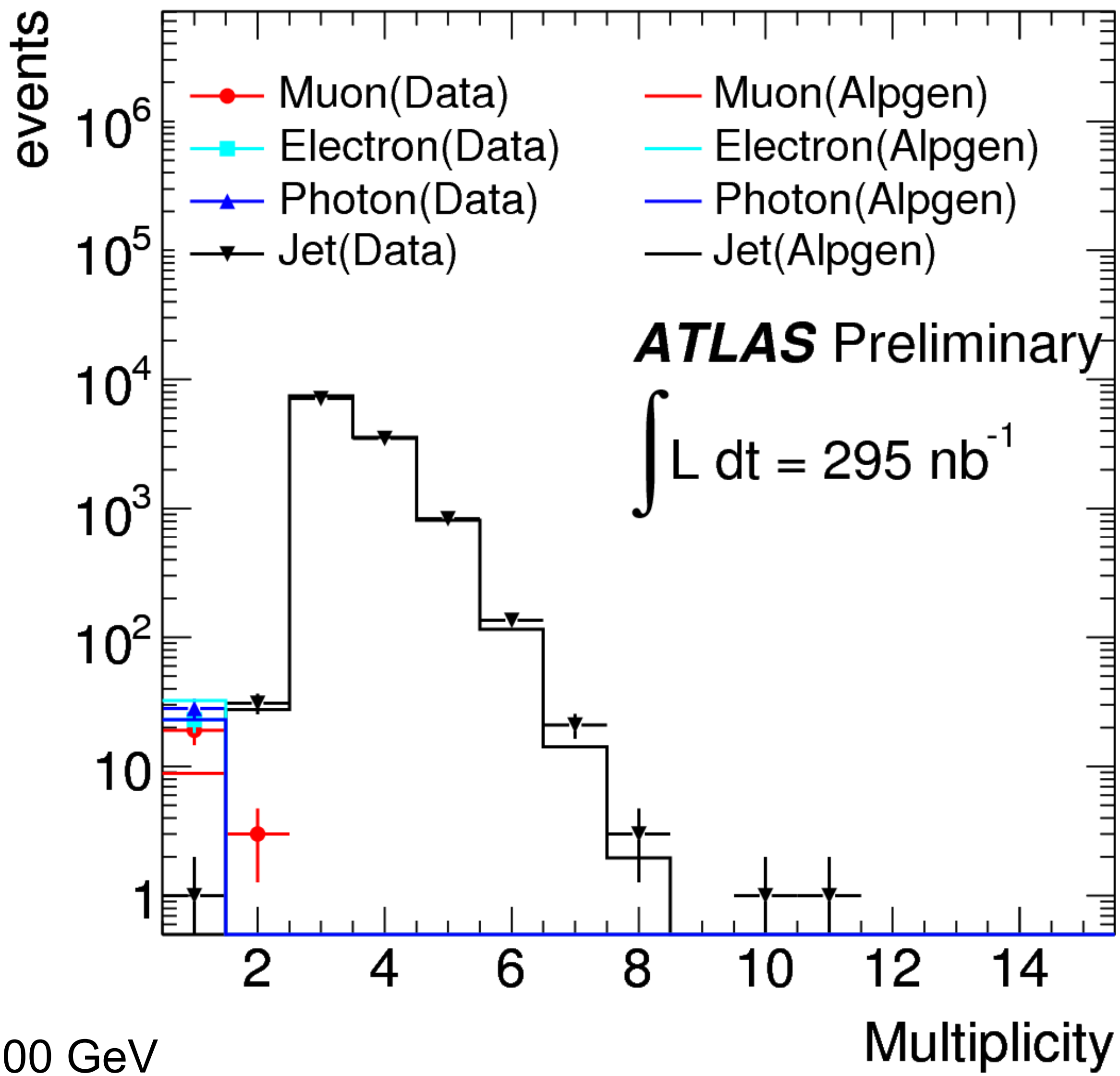
- invariant (effective) mass of the final state
  - electrons, photons, muons, plus MET.

$$\mathbf{m_{inv}} = \sqrt{\mathbf{p}^2} \textbf{ and } \mathbf{p} = \sum_{\mathbf{i=object}} \mathbf{p_i} + (\mathbf{E_T^{miss}}, \mathbf{E_x^{miss}}, \mathbf{E_y^{miss}}, \mathbf{0})$$

Event Selection

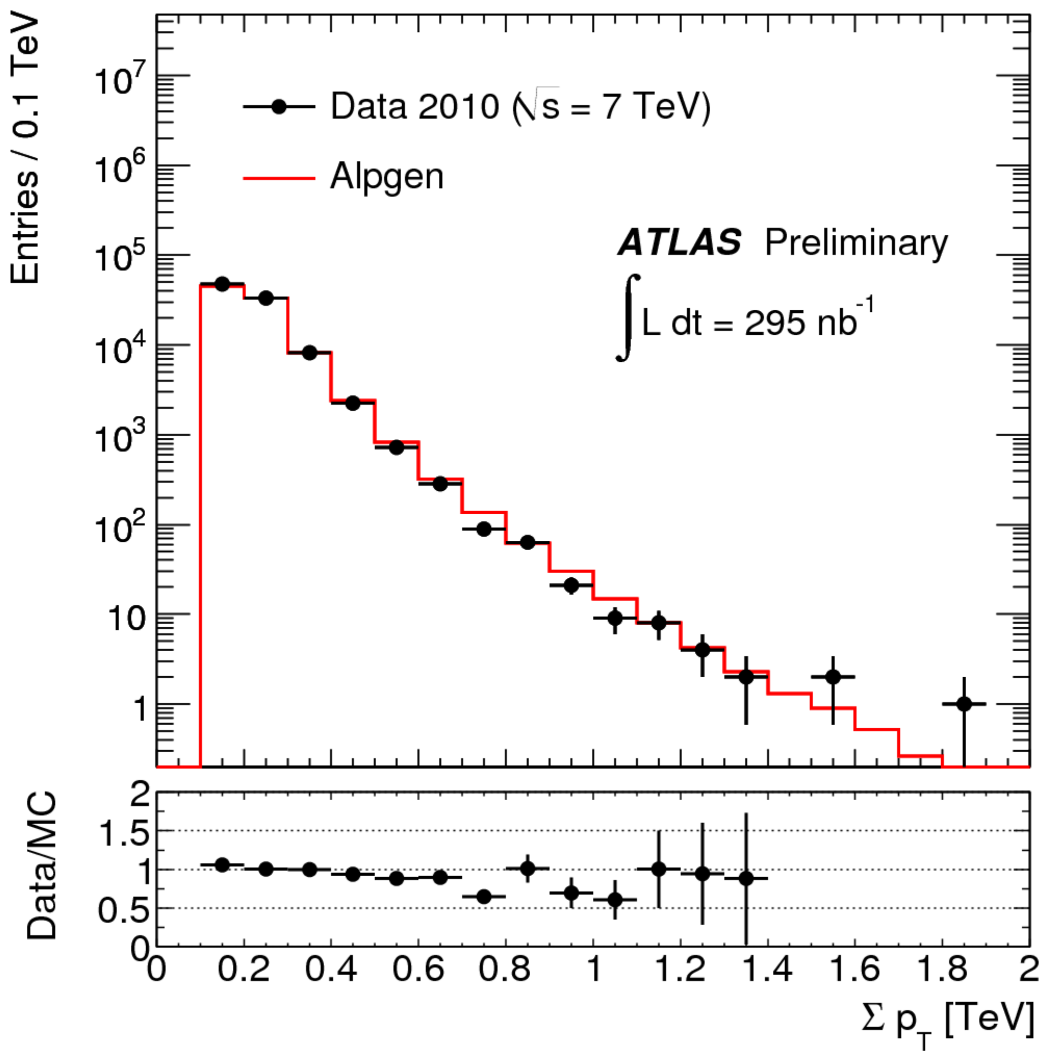
- Single jet and muon trigger
- Vertex Quality cuts
  - >5 tracks from at least one primary vertex
  - $|z_{beam}-z_{rec}| < 15$ cm
- Require good jets
- Object Selection
  - Electrons with pT > 20 GeV
  - Muons with pT > 20 GeV
  - Photons with pT > 20 GeV
  - Jets (antikt,0.4) with pT > 40 GeV
- At least 3 objects pass our selections

Multiplicity Distribution



$\sum p_T > 300$ GeV

Scalar Sum P_T



$N_{objects} > 3$

Definition of Signal and Control Region

- Experimental lower limits on
  - M_D = 940 GeV for n= 6
  - M_D= 800 GeV for n> 6.
- Search for a sharp interaction threshold from M_D.
- Final states produced by such interactions are expected to have large Σp_T for their m_{inv} values.

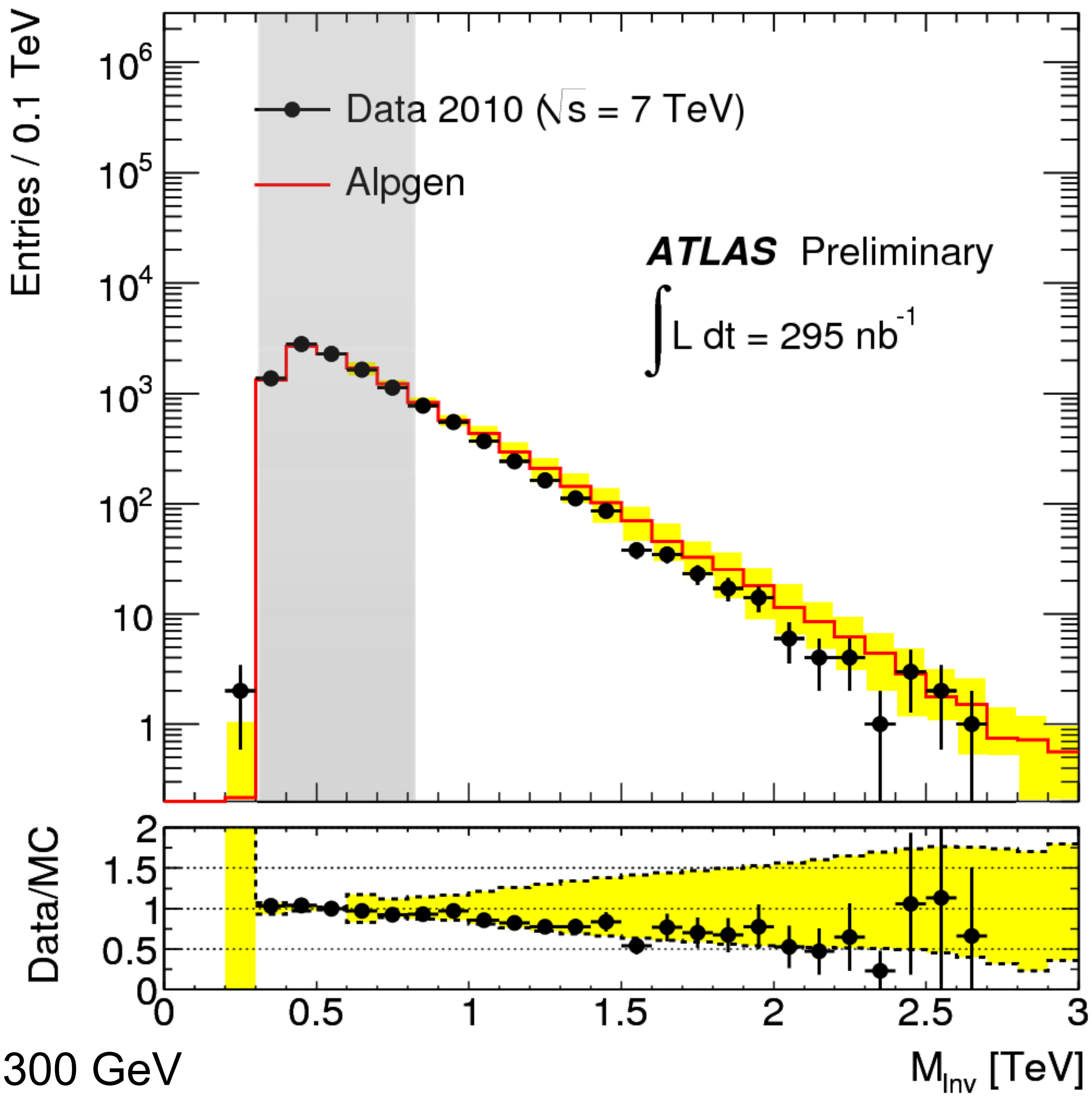
Definition of the Control and Signal Region

- The MC samples are normalised to the data in a control region, where we do not expect a signal.

- Predictions are extrapolated to the signal region.

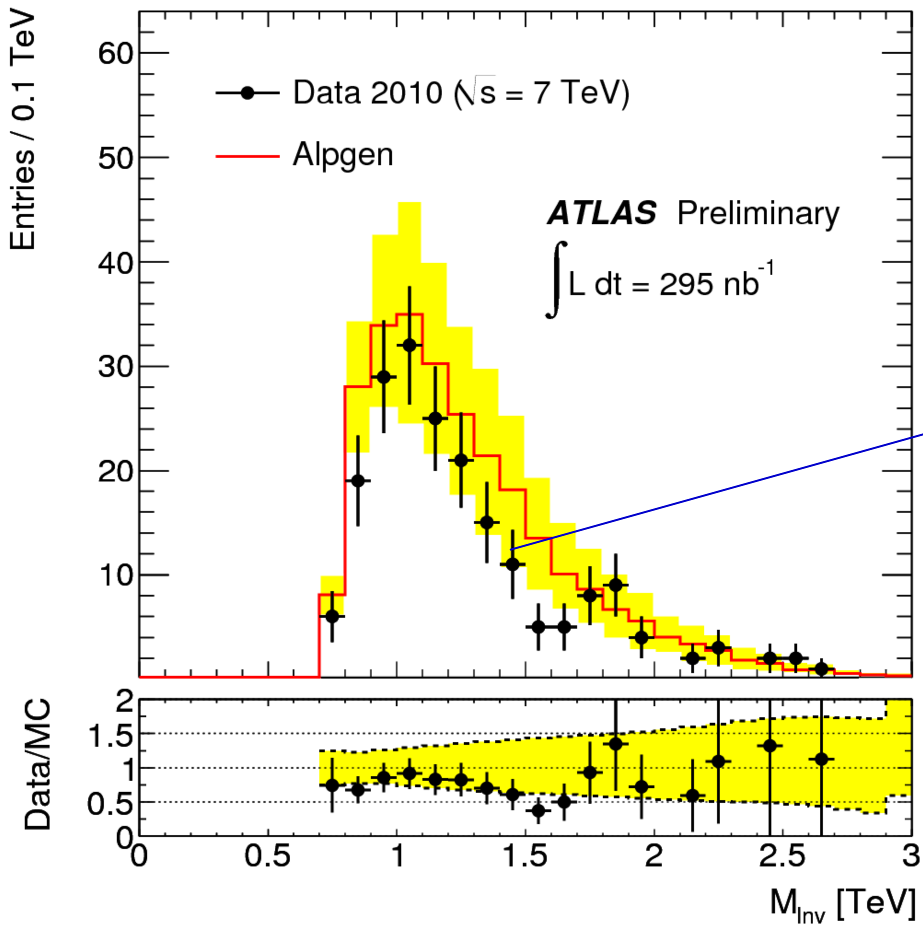
- Control region kinematically close to the signal.
- Control region:
  - $\Sigma p_T > 300$ GeV and $300 < m_{inv} < 800$ GeV
- Signal region:
  - $\Sigma p_T > 700$ GeV and $m_{inv} > 800$ GeV.

Mass Distribution



$\sum p_T$ > 300 GeV

Signal Region



total background prediction is 254 ±18 (stat) ±84 (syst)

Total uncertainty, systematic dominated

ΣpT> 700 GeV and $m$inv> 800 GeV

Summary of the Systematics

Systematic Uncertainties		
Background (QCD)	± 66.5	26%
PDF (choice)		$\pm 12\%$
PDF (error set)		$+6.8\%$
PDF (error set)		-5.2%
Control region		$\pm 10\%$
Un-simulated backgrounds		$\pm 0.6\%$
Including e, γ, μ		$\pm 0.2\%$
Missing transverse energy		$\pm 0.02\%$
JES		$\pm 11.0\%$
JES (MET)		$\pm 0.5\%$
JER		$\pm 0.6\%$
Systematic uncertainty	$+84$	$+33\%$

Multi-Object Results

- No deviation from the SM expectation is observed.
- (295 +-32) nb-1of data yields **193 data** events.
- Consistent with QCD expectation of **254 ±18 ±84**.
- Upper limit on the **cross-section ×acceptance** of **0.34 nb@ 95% C.L.** for final states with at lease 3 objects, Σ*p*T> 700 GeVand *m*inv> 800 GeV.

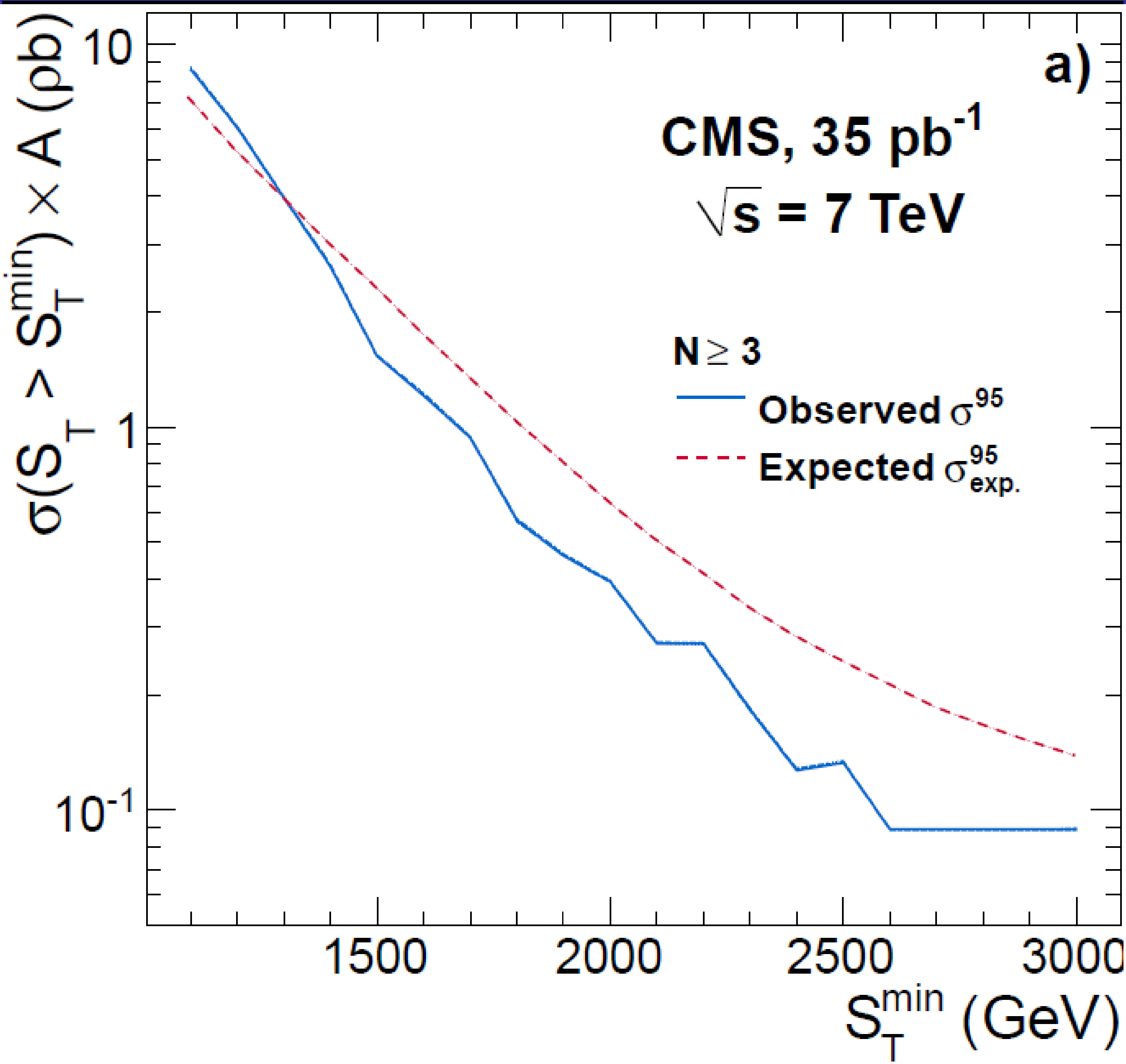
Can we exclude Black Holes? -- NO

- For benchmark, we consider multi-body final states generated by BlackMax and Charybdis, for which we obtain an acceptance of 58%.
  - Predictions are semi-classical
  - **Not valid in the regime close to $M_{D!}$**

- For this acceptance, upper limit on the production cross-section would be 0.6 nb.

- New physics cross section < 0.6 nb @ 95 C.L.
  - Conservative since acceptance is rising for higher M_{min}

CMS performed similar analysis with 35pb-1



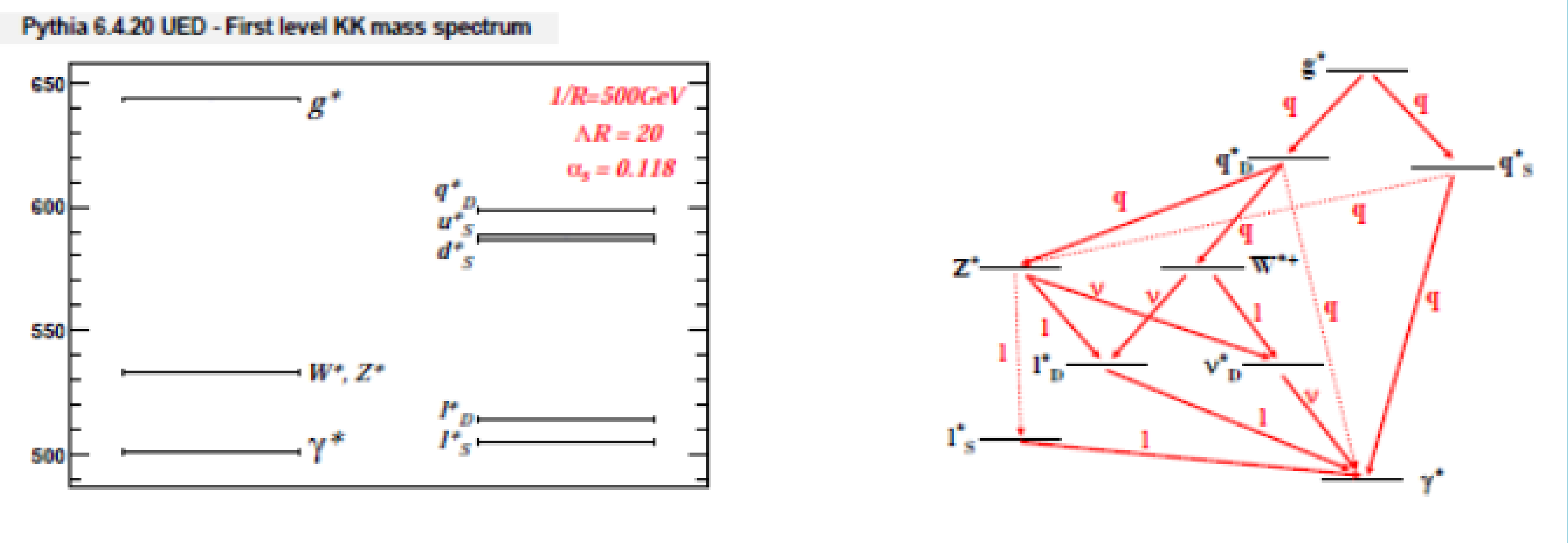
Diphoton + MET Search

Introduction/theory

Consider model with a single Universal Extra Dimension

"Universal" == ALL SM particles propagate into the extra dim
n=1,2,3,… Kaluza Klein (KK) excitations for each SM particle (n=0)
R : compactification scale, with 1/R ~1TeV

→ strong production of pairs of KK quarks and/or gluons, which cascade decay down to LKP (γ^*)



If embed UED model in a larger space with N large dim (of size^{-1} ~ eV) where only gravitons propagate, then gravity mediated decays become possible

$\gamma^* \rightarrow \gamma$ + Graviton → High pT diphoton + MET

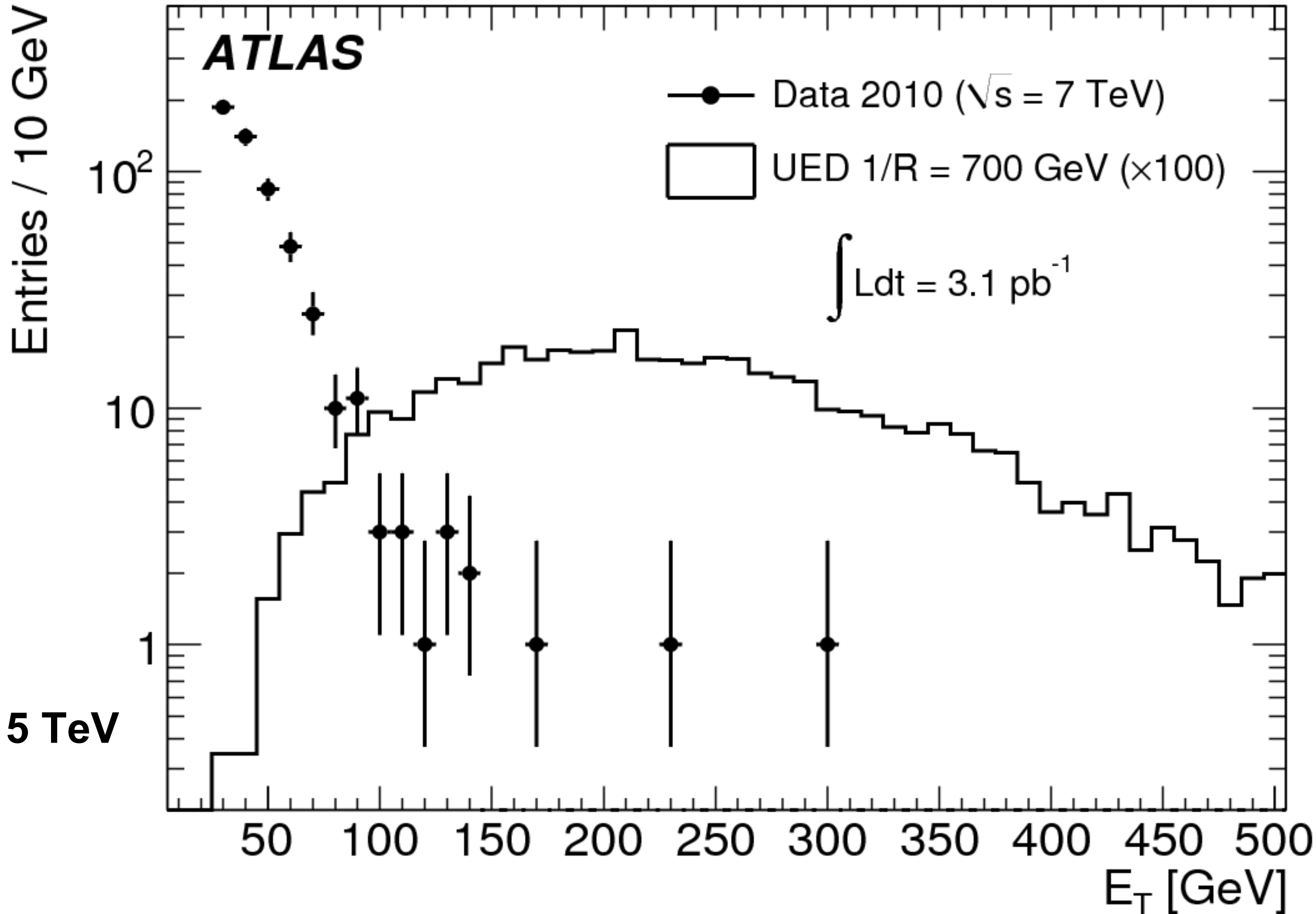
D0 Tevatron excludes 1/R < 477 GeV @ 95% CL [arXiv:1008.2133]

UED Signal

- **2 hard, central photons**
- Cascade Decay → Jets
  - High-P_T Jets: e.g. for 1/R = 700 GeV
    - mean ~ 100 GeV
    - Tails up to 400 GeV
  - **Presence or absence of jets is NOT used**
- **Large MET (Key distribution for this analysis)**

UED Signal

hep-ex > arXiv:1012.4272



N = 6

MD = 5 TeV

Et of the leading photon

Analysis Strategy

- Use data to predict background
- Define signal region such that expected background < 1
  - This is done BEFORE one looks into data
- Aimed for high efficiency to have good sensitivity
- Compare number of observed events to SM background expectation in signal region
  - MET > 75 GeV

Event Selection

- 2 “loose” photons with $E_T > 25$ GeV
- $|\eta| < 1.37$ OR $1.52 < |\eta| < 1.81$
- Isolation cut on both photons (Etcone20 < 35 GeV)

- For BKG: one photon fails loose requirement
- MET cut to define signal region
  - MET > 75 GeV

Systematics

- Analysis is not systematics dominated

Source of uncertainty	Uncertainty
Integrated luminosity	11%
Photon reconstruction and identification	4%
Effect of pileup	2%
$E_{\mathrm{T}}^{\mathrm{miss}}$ reconstruction and scale	1%
Signal MC statistics	1%
Total	12%

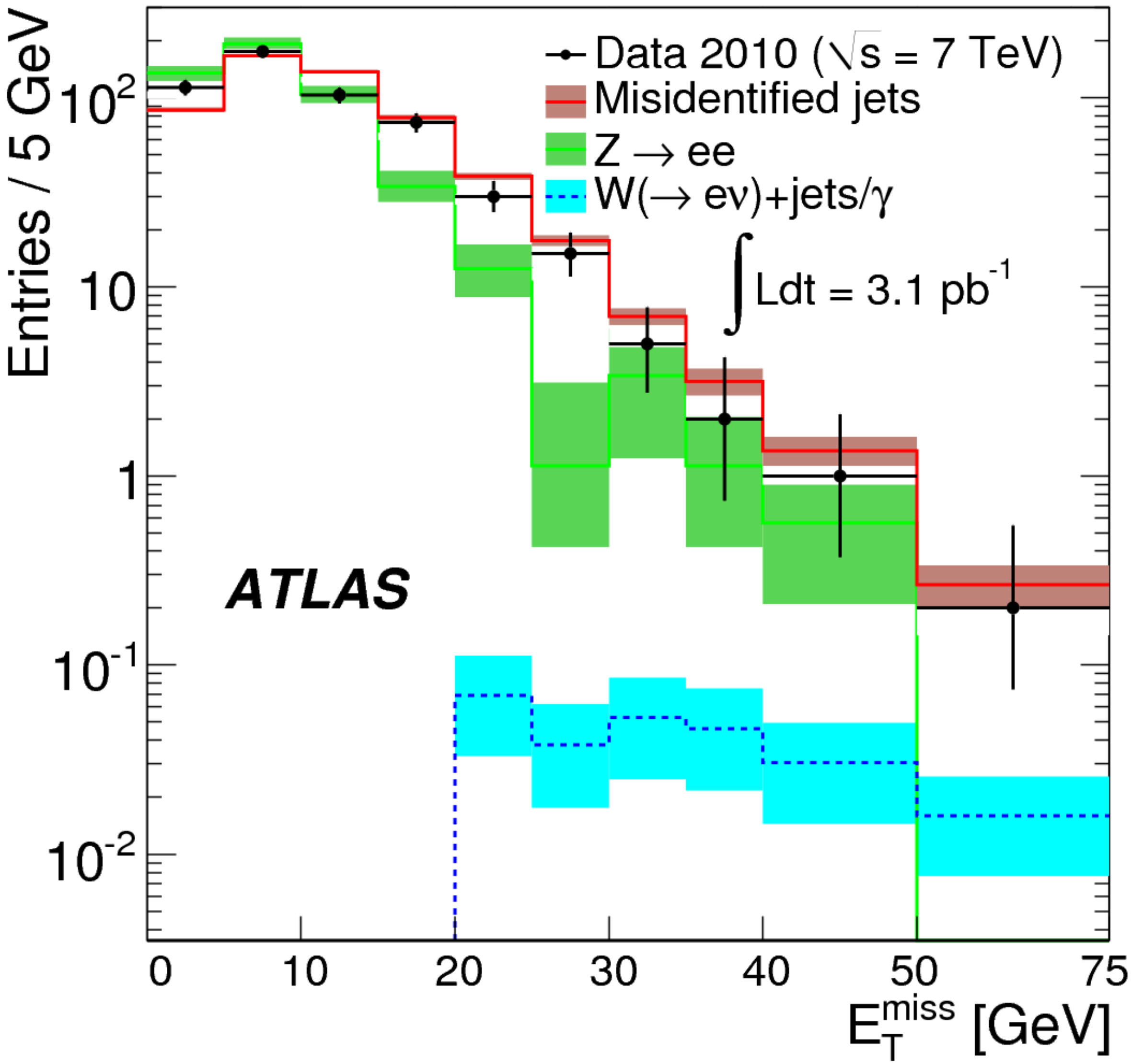
Background Sources

- QCD Background
  - Dominant background
  - SM γγ, γ+jet, multijet events with jets faking photons
  - **Modeled with data**
- W→(enu) + jets/γ
  - Small background
  - e misidentified as γ,
  - 2nd γ either real photon from W + γ or W+jets, jets faking γ
  - **Modeled with data**
- W/Z+ γ γ
  - Irreducible background
  - Negligle for current data set

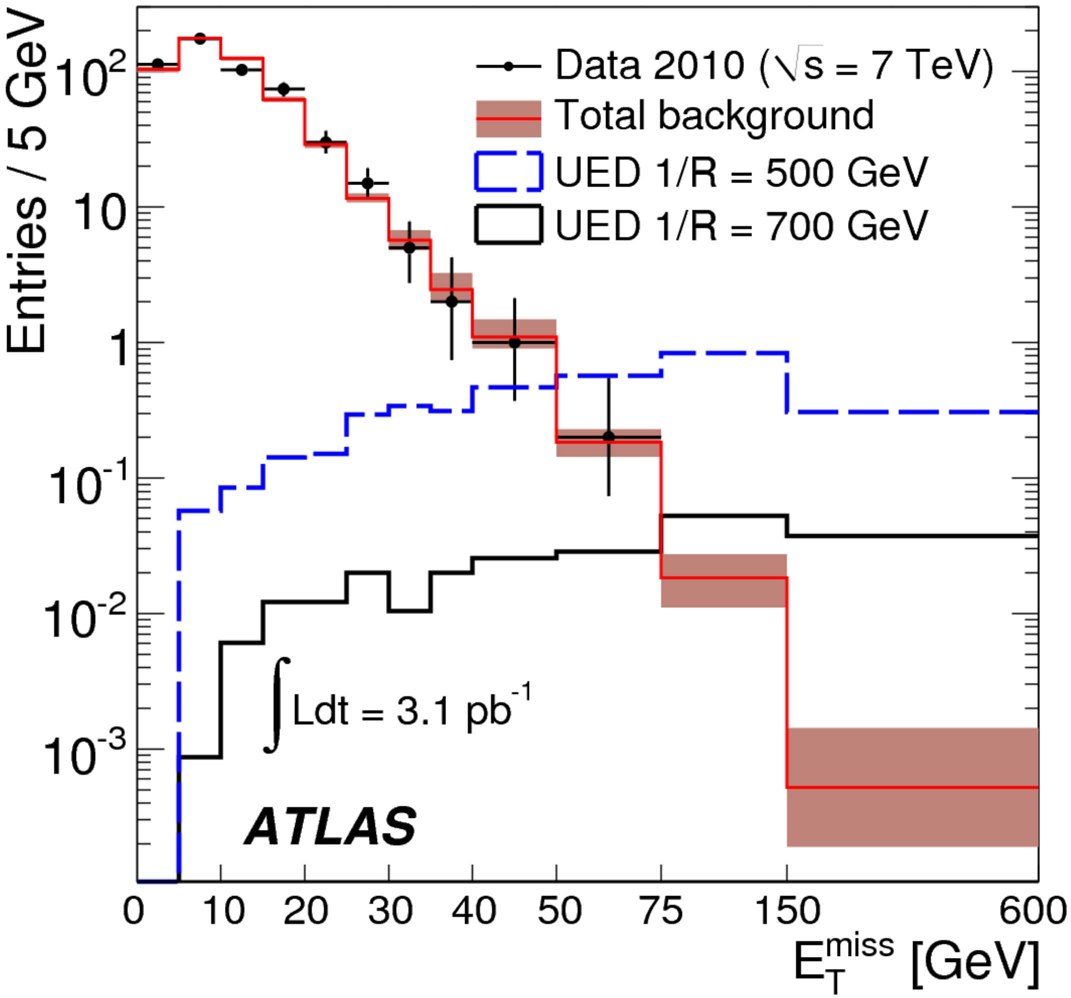
Modelling the QCD background

- Use Z -> ee to model MET response to SM γγ
  - MET response dominated by CAL response to 2 EM objects
  - Confirmed with MC that this works reasonably well
- Model MET response to jets faking γ
  - Sample where at least one photon *fails* photon ID cuts
- Model QCD background by weighted mean of
  - Z→ee and misidentified jets sample
  - Fix overall normalization to MET<20 GeV region
  - Determine relative contributions by fit to this region
  - Fit returns (35 +- 22) % for Z→ ee contribution

Components of the QCD Background modelling



Expected QCD Background



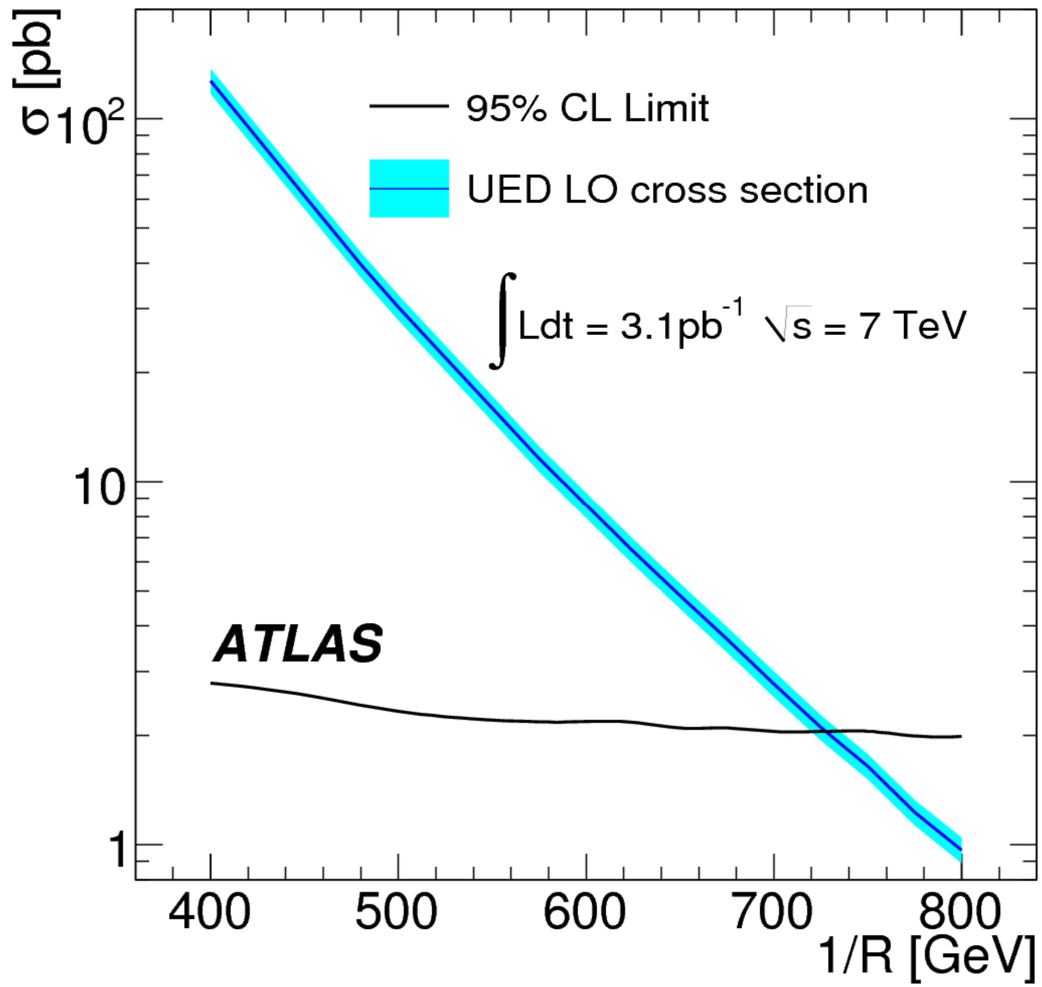
Signal region

- Expected BKG

$0.32 \pm 0.16^{+0.37}_{-0.1}$

Results

- Excellent agreement between data and expected backgrounc
- Observe 0 events in signal region
- 1/R < 728 GeV 95% (
  excluded
  - Tevatron: 1/R<477 Ge



Concluding Remarks

- Searches are NOT measurements
- Needs are different
  - Need to be fast
  - Not miss the signal
  - New machine….can not do blind analyses
  - BUT need to avaid positive or negative biasing
- Need to understand your background and systematic
- Unfolding usually not desirable in searches
  - Introduces biases
- Model independent search strategies and presentation of results

Searches in 2011

- LHC will run most likely at 8 TeV
  - Good news for searches
  - Push further into new energy regimes
  - Higher cross sections for massive new particles
- Aims for 1 – 2 fb-1 of integrated luminosity
  - Should see SUSY if it is there
  - Explore semi-classical black holes
  - Signatures we will be looking at will become more complex
  - Trileptons
  - Boosted top, W, b signatures
  - Hidden Valley
  - Lepton jets….
- It will be very exciting.

Elements of Discovery Process

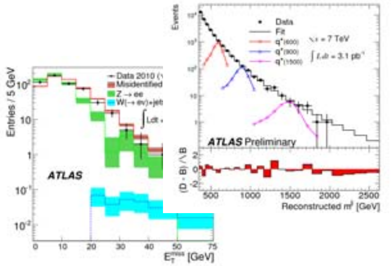
Theoretical Insight

Interplay of theory and experiment is essential

Accelerator Advances

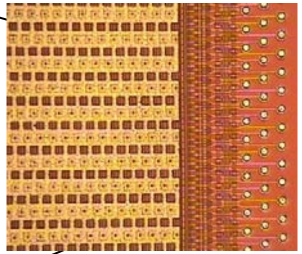
At the LHC we can create and study new interactions

New Physics: Our Understanding of the World



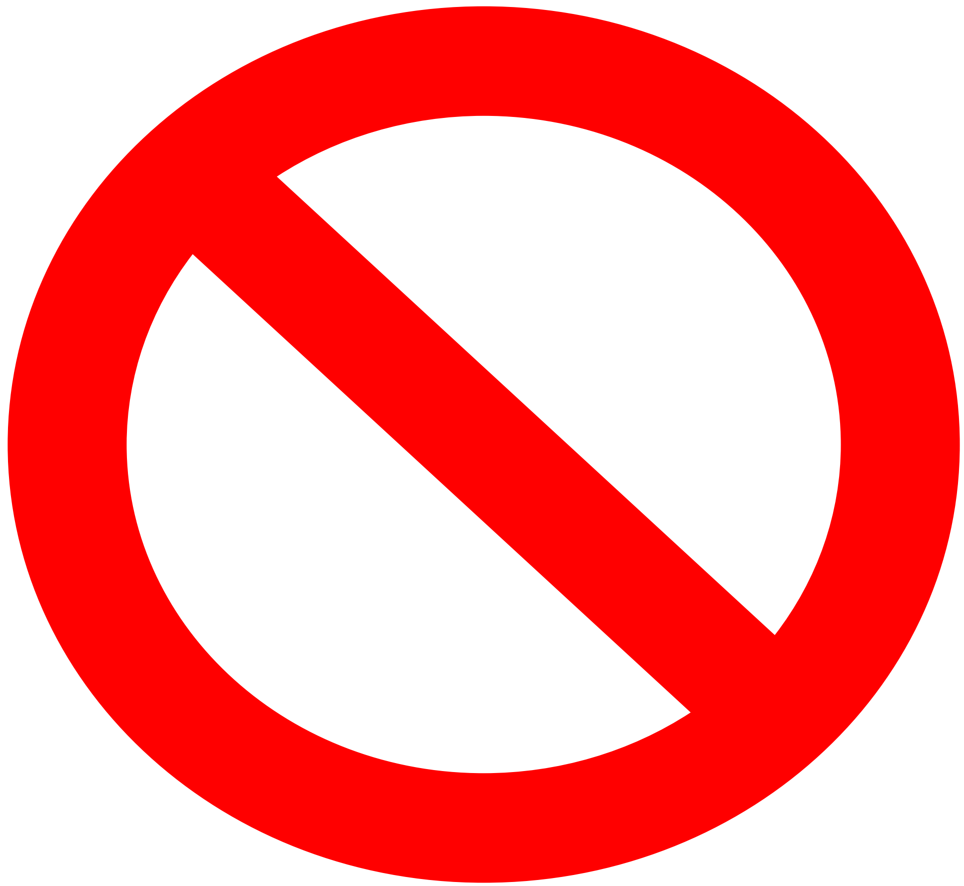
New Detectors, Computing Tools

With new developments come new capabilities



Data Analysis:

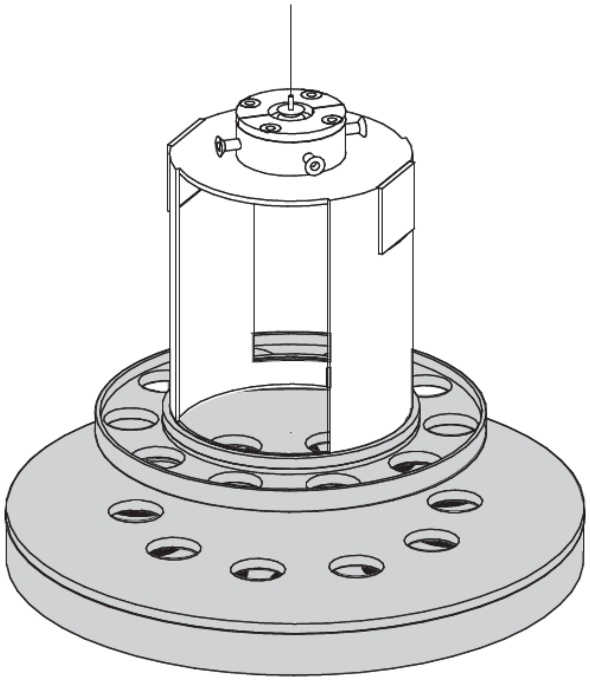
Not missing the signal is key



Experimental Limits

- **Table top**
- **Particle accelerators**
- **Astrophysical observations**
- **Cosmic-ray measurements**
- **Cosmological considerations**

Table Top Experiments



$1/r^2$-law valid for R=44 μm at 95%

Ann.Rev.Nucl.Part.Sci.53:77-121,2003, hep-ph/0307284

Particle Accelerators

hep-ph/0201029, hep-ex/0605101, hep-ph/9909294, hep-ex/0710.3338, hep-ex/0707.2524

- **LEP:**
  - M_D =1.5 TeV for n = 2 ⇔ R = 0.2 μm
  - M_D = 0.75 TeV for n = 5 ⇔ R = 400 fm
- **CDF:**
  - M_D = 1.33 TeV, n = 2 ⇔R = 0.27 μm
  - M_D = 0.88 TeV for n = 6 ⇔ R = 31fm
- **D0 (ll, gg):**
  - M_D = 1.23 TeV lower limit

Astrophysical and Cosmological Constraints

hep-ph/0304029, hep-ph/0309173, hep-ph/0307228

- **Most stringent lower limits on M_D in ADD**
- **Supernova cooling due to KK G emission**
  - **SN 1987A did not emit more KK G than compatible with neutrino signal durations observed by Kamiokande and IMB places the limits: $M_D > 22$ (2) TeV for n = 2 (3).**
- Energetic Gamma Ray Experiment Telescope (EGRET)
  - **Cosmic γ-ray-bkg:**
    - **$M_D > 70$ (5) TeV for n = 2 (3)**
  - **Neutron star halo of 100 MeV γ-rays:**
    - **$M_D >$ 97, 8, 1.5 TeV for n = 2, 3, 4**
  - **All neutron stars in the galactic bulge:**
    - **$M_D >$ 1130, 57, 7, 1.8 TeV for n = 2, 3, 4, 5**
- **Neutron star heating:**
  - **$M_D >$1760, 77, 9, 2 TeV for n = 2, 3, 4, 5**
- **Ultra high-energy cosmic-ray neutrinos:**
  - **lower bound M_D = 1 to 1.4 TeV , n = 4 to 7**