Exotics Searches at LHC

Cigdem Issever
University of Oxford
ATLAS Experiment, CERN

HASCO Summer School 2014

Acknowledgement

- Hitoshi Murayama,http://arxiv.org/abs/0704.2276v1
- Lykken, http://arxiv.org/pdf/1005.1676.pdf
- CERN 2012/2013/2014 summer school

Discussions with

- Henri Bachacou
- Bryan Lynn
- Christophe Grojean
- Glenn Starkman
- Steven Worm

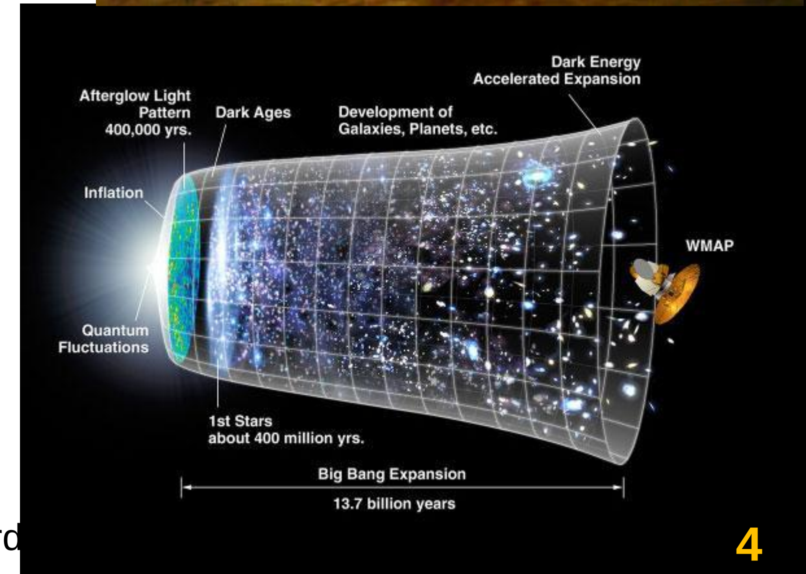
Outline....

- Why search for new physics?
- What are Exotics Searches?
- Examples of Searches

Why search for new physics?

- We are **reSEARCHers**
- We strive for **new understandings**
- Our goal: “create” **KNOWLEDGE**

We are “Wissenschaftler”



Inspiring

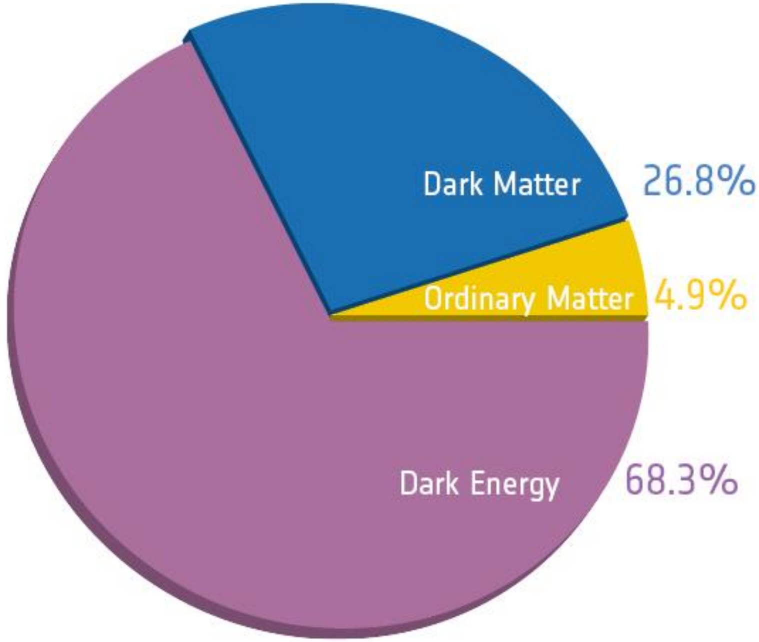
Humbling

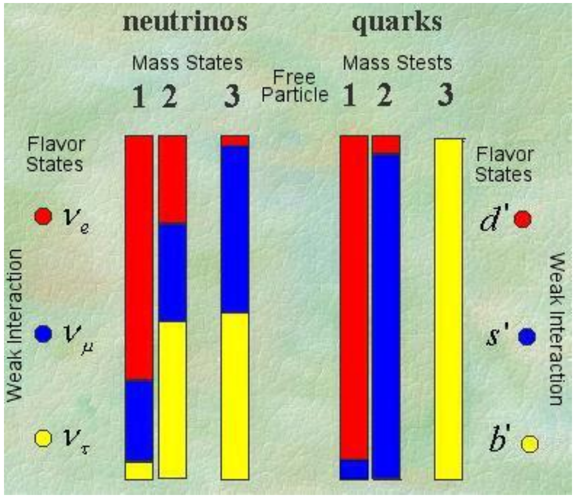
FUN

and a LOT of work…..

Why look beyond *the Standard Model*?

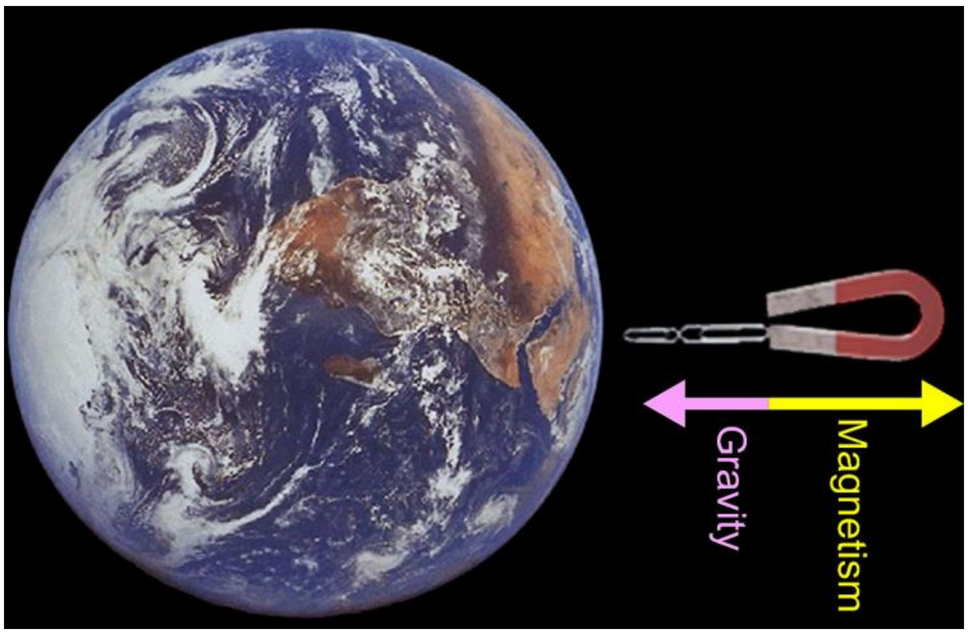
- Experimental Evidence
  - **Non-baryonic dark matter (~27%)**
    - Inferred from gravitational effects
    - Rotational speed of galaxies
    - Orbital velocities of galaxies in clusters
    - Cosmic Microwave Background
    - …..
  - **Dark Energy (~68%)**
    - Accelerated Expansion of the Universe
  - **Neutrinos have mass and mix**
  - **…**





Why look beyond the Standard Model?

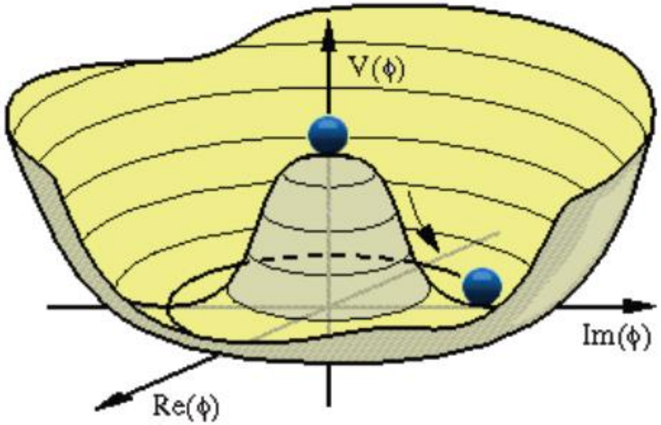
- Aesthetic/Theoretical Reasons
  - Gravity is not included
  - Family structure? Why 3?
  - Hierarchy problem:
    - Why is gravity so weak?



$$
\begin{gathered}
-\frac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \frac{1}{4}g^2_s f^{abc} f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \\
\frac{1}{2}ig^2_s(\bar{q}^\sigma_i \gamma^\mu q^\sigma_j)g^a_\mu + \bar{G}^a\partial^2 G^a + g_s f^{abc}\partial_\mu \bar{G}^a G^b g^c_\mu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - \\
M^2 W^+_\mu W^-_\mu - \frac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \frac{1}{2c^2_w}M^2 Z^0_\mu Z^0_\mu - \frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \frac{1}{2}\partial_\mu H \partial_\mu H - \\
\frac{1}{2}m^2_h H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - M^2 \phi^+ \phi^- - \frac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \frac{1}{2c^2_w}M \phi^0 \phi^0 - \beta_h[\frac{2M^2}{g^2} + \\
\frac{2M}{g}H + \frac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)] + \frac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu \partial_\nu W^-_\mu - \\
W^-_\nu \partial_\nu W^+_\mu)] - igs_w[\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu \partial_\nu W^-_\mu - \\
W^-_\mu \partial_\nu W^+_\mu) + A_\mu(W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)] - \frac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \\
\frac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c^2_w(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + \\
g^2 s^2_w(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w[A_\mu Z^0_\nu(W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-] - \\
\frac{1}{8}g^2\alpha_h[H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2 H^2] - \\
gMW^+_\mu W^-_\mu H - \frac{1}{2}g\frac{M}{c^2_w}Z^0_\mu Z^0_\mu H - \frac{1}{2}ig[W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - \\
W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)] + \frac{1}{2}g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ - \\
\phi^+\partial_\mu H)] + \frac{1}{2}g\frac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) - ig\frac{s^2_w}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + \\
igs_w MA_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) - ig\frac{1-2c^2_w}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + \\
igs_w A_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \frac{1}{4}g^2 W^+_\mu W^-_\mu[H^2 + (\phi^0)^2 + 2\phi^+\phi^-] - \\
\frac{1}{4}g^2\frac{1}{c^2_w}Z^0_\mu Z^0_\mu[H^2 + (\phi^0)^2 + 2(2s^2_w - 1)^2\phi^+\phi^-] - \frac{1}{2}g^2\frac{s^2_w}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + \\
W^-_\mu\phi^+) - \frac{1}{2}ig^2\frac{s^2_w}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \frac{1}{2}g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- + \\
W^-_\mu\phi^+) + \frac{1}{2}ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\frac{s_w}{c_w}(2c^2_w - 1)Z^0_\mu A_\mu\phi^+\phi^- - \\
g^1 s^2_w A_\mu A_\mu\phi^+\phi^- - \bar{e}^\lambda(\gamma\partial + m^\lambda_e)e^\lambda - \bar{\nu}^\lambda\gamma\partial\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + m^\lambda_u)u^\lambda_j - \\
\bar{d}^\lambda_j(\gamma\partial + m^\lambda_d)d^\lambda_j + igs_w A_\mu[-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \frac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \frac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)] + \\
\frac{ig}{4c_w}Z^0_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s^2_w - 1 - \gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(\frac{4}{3}s^2_w - \\
1 - \gamma^5)u^\lambda_j) + (\bar{d}^\lambda_j\gamma^\mu(1 - \frac{8}{3}s^2_w - \gamma^5)d^\lambda_j)] + \frac{ig}{2\sqrt{2}}W^+_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)e^\lambda) + \\
(\bar{u}^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)] + \frac{ig}{2\sqrt{2}}W^-_\mu[(\bar{e}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\lambda\kappa}\gamma^\mu(1 + \\
\gamma^5)u^\lambda_j)] + \frac{ig}{2\sqrt{2}}\frac{m^\lambda_e}{M}[-\phi^+(\bar{\nu}^\lambda(1-\gamma^5)e^\lambda) + \phi^-(\bar{e}^\lambda(1+\gamma^5)\nu^\lambda)] - \\
\frac{g}{2}\frac{m^\lambda_e}{M}[H(\bar{e}^\lambda e^\lambda) + i\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda)] + \frac{ig}{2M\sqrt{2}}\phi^+[-m^\kappa_d(\bar{u}^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + \\
m^\lambda_u(\bar{u}^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j] + \frac{ig}{2M\sqrt{2}}\phi^-[m^\lambda_d(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m^\kappa_u(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1 - \\
\gamma^5)u^\kappa_j] - \frac{g}{2}\frac{m^\lambda_u}{M}H(\bar{u}^\lambda_j u^\lambda_j) - \frac{g}{2}\frac{m^\lambda_d}{M}H(\bar{d}^\lambda_j d^\lambda_j) + \frac{ig}{2}\frac{m^\lambda_u}{M}\phi^0(\bar{u}^\lambda_j\gamma^5 u^\lambda_j) - \\
\frac{ig}{2}\frac{m^\lambda_d}{M}\phi^0(\bar{d}^\lambda_j\gamma^5 d^\lambda_j) + \bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 - \\
\frac{M^2}{c^2_w})X^0 + \bar{Y}\partial^2 Y + igc_w W^+_\mu(\partial_\mu\bar{X}^0 X^- - \partial_\mu\bar{X}^+ X^0) + igs_w W^+_\mu(\partial_\mu\bar{Y}X^- - \\
\partial_\mu\bar{X}^+ Y) + igc_w W^-_\mu(\partial_\mu\bar{X}^- X^0 - \partial_\mu\bar{X}^0 X^+) + igs_w W^-_\mu(\partial_\mu\bar{X}^- Y - \\
\partial_\mu\bar{Y}X^+) + igc_w Z^0_\mu(\partial_\mu\bar{X}^+ X^+ - \partial_\mu\bar{X}^- X^-) + igs_w A_\mu(\partial_\mu\bar{X}^+ X^+ - \\
\partial_\mu\bar{X}^- X^-) - \frac{1}{2}gM[\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c^2_w}\bar{X}^0 X^0 H] + \\
\frac{1-2c^2_w}{2c_w}igM[\bar{X}^+ X^0\phi^+ - \bar{X}^- X^0\phi^-] + \frac{1}{2c_w}igM[\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-] + \\
igMs_w[\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-] + \frac{1}{2}igM[\bar{X}^+ X^+\phi^0 - \bar{X}^- X^-\phi^0]
\end{gathered}
$$

Another Reason: A Higgs boson

- ONLY spin 0 elementary particle
- Couplings are NOT dictated by gauge symmetry
  - Hmm….
- Symmetry breaking
  - Underlying reason?



- Small mass possible if new physics
  - "Fine Tuning Problem"

Higgs is an EXOTIC particle.

Implications of the Higgs Discovery

- Last prediction from an ***experimentally*** well tested model.
  - No real guidance on the model market
  - New insights have to come from experiments
    - **Generic searches!**

Implications of the Higgs Discovery

- Last prediction from an ***experimentally*** well tested model.
  - No real guidance on the model market
  - New insights have to come from experiments
    - **Generic searches!**
- If new boson is the SM Higgs

$$\mathcal{L}_H = (D_\mu H)^\dagger (D^\mu H) - \lambda \left(H^\dagger H\right)^2 + \lambda \boldsymbol{v}^2 H^\dagger H$$

Implications of the Higgs Discovery

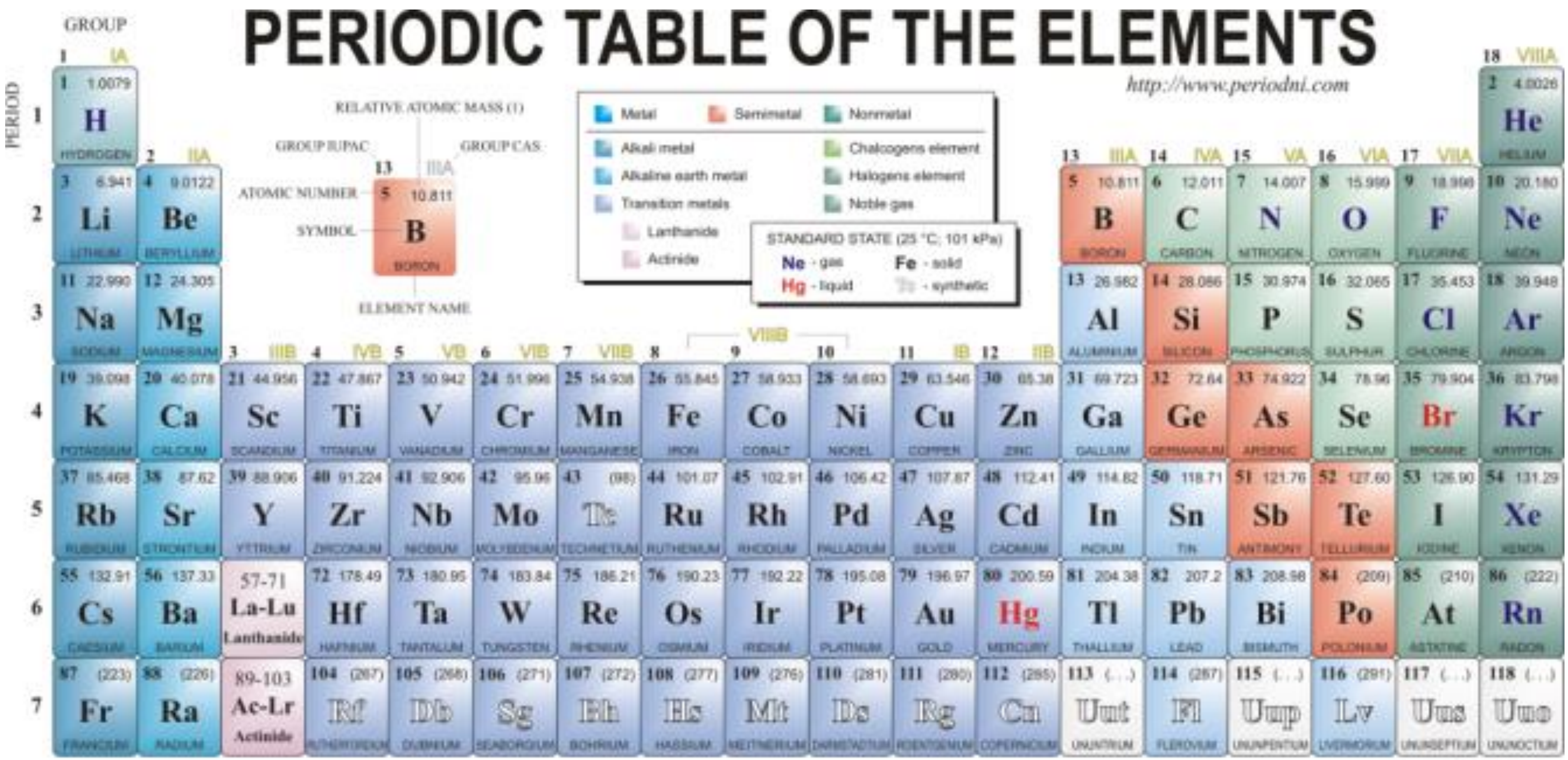
- Last prediction from an ***experimentally*** well tested model.
  - No real guidance on the model market
  - New insights have to come from experiments
    - **Generic searches!**
- If new boson is the SM Higgs

→ Know now ***experimentally*** **scale of Standard Model**.

$$\mathcal{L}_H = (D_\mu H)^\dagger (D^\mu H) - \lambda\left(H^\dagger H\right)^2 + \lambda \boldsymbol{v}^2 H^\dagger H$$

- $\boldsymbol{v = (\sqrt{2}G_F)^{-1/2} \sim 246\ GeV \sim 10^{-16}\ cm}$
- Search beyond this scale → **TeV and above!**

Many Examples for this in History

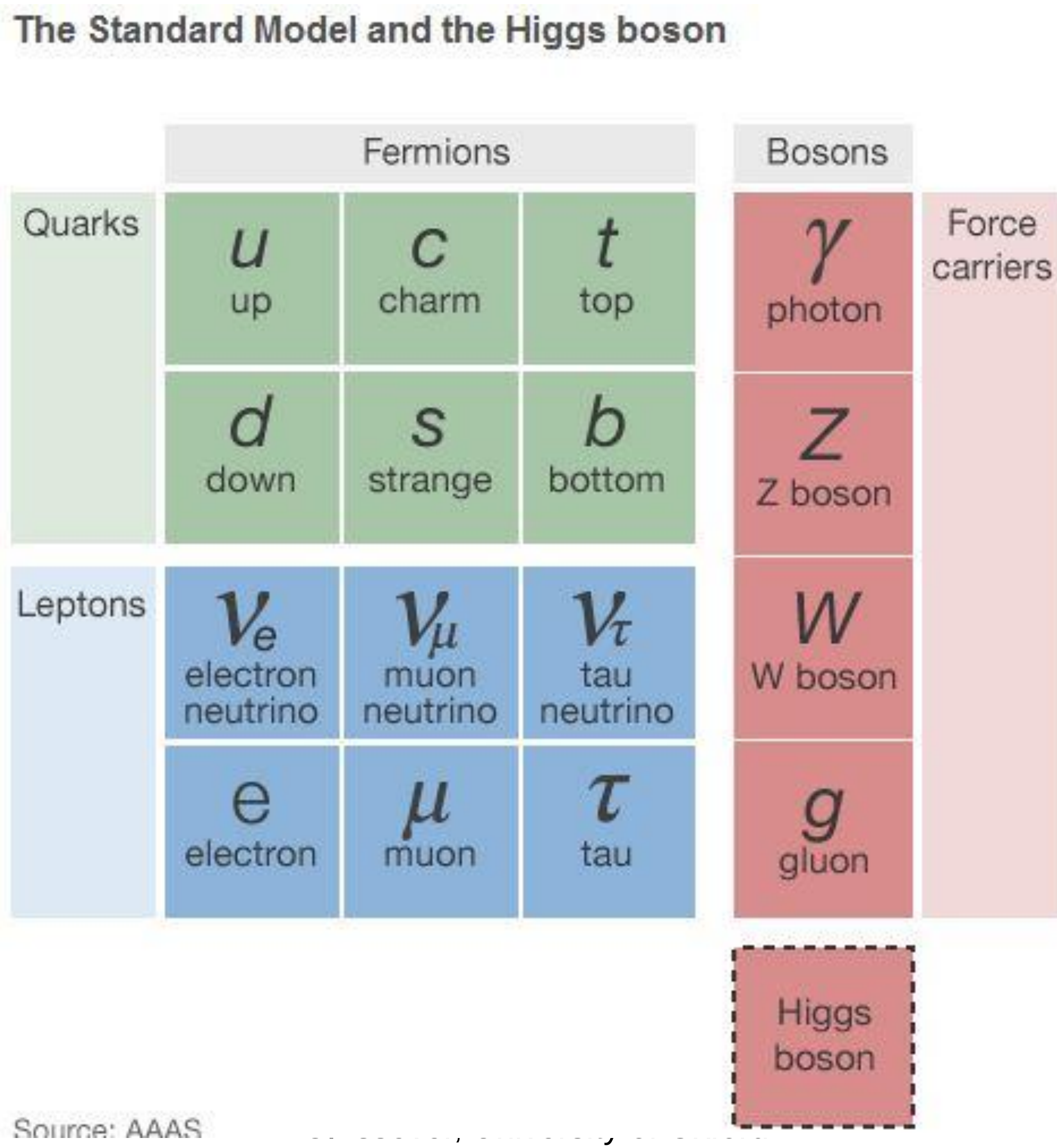


Around **1900** reached atomic scale **10^{-8} cm** $\approx \hbar^2/e^2 m_e$

→ Quantum Mechanics

→ Quantum Electrodynamics

The Periodic Table of Particle Physics

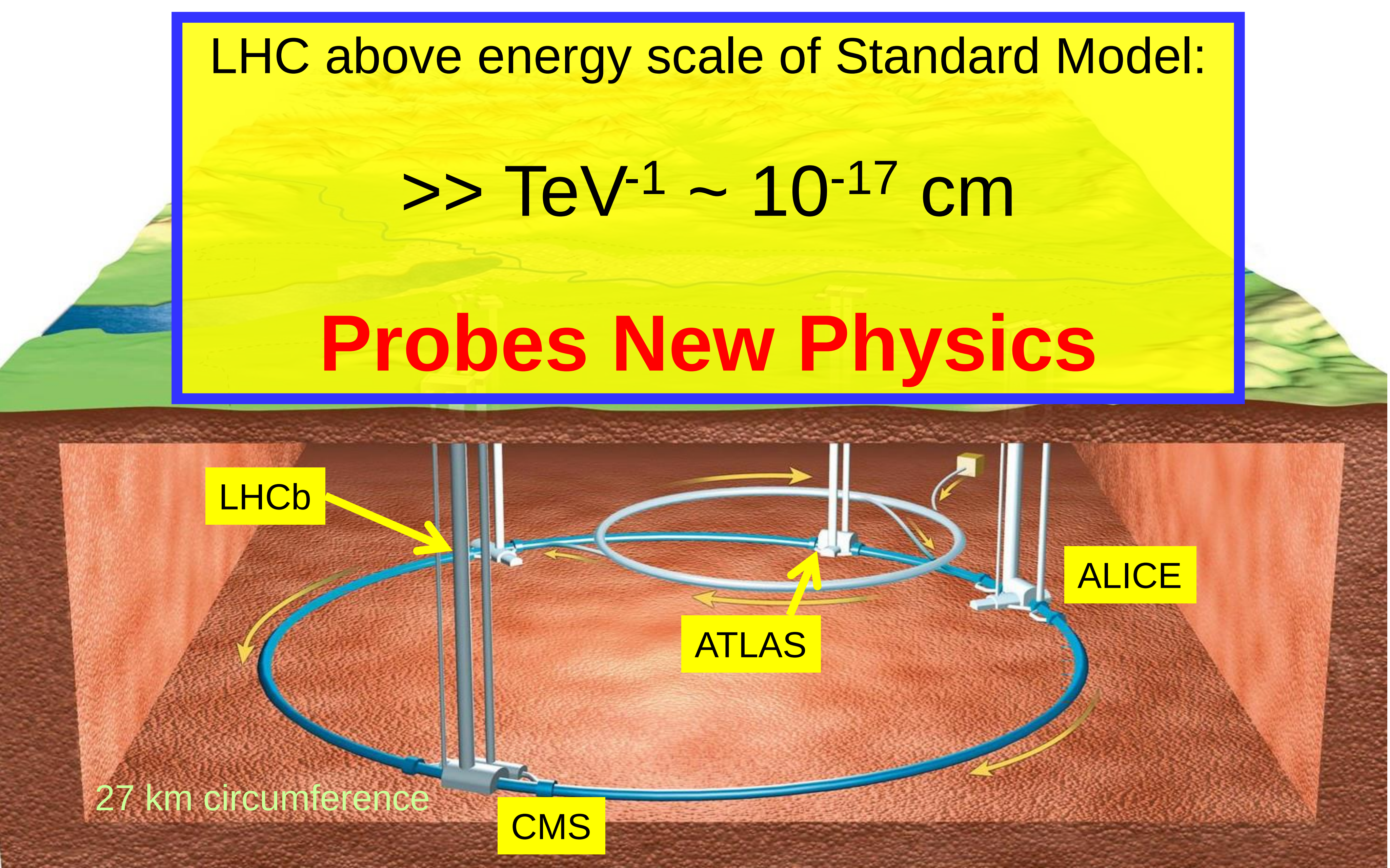


Today …. Very Special Time

LHC above energy scale of Standard Model:

$>> \text{TeV}^{-1} \sim 10^{-17}$ cm

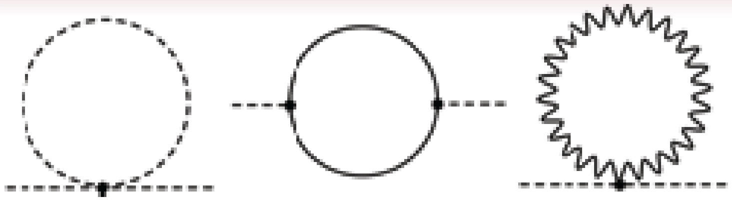
Probes New Physics



What else is there beside SUSY framework?

- SUSY is NOT a model
  - "Symmetry principle characterizing a BSM framework with an infinite number of models"….Lykken
- SUSY mass limits pushed to 1 TeV
  - SUSY becoming more "Exotic" the higher the mass limits get.
- SUSY is only one possible way…..
  - Many more ways to solve problems with Standard Model
  - What if nature has not chosen low scale SUSY?
  - Make sure to cover every feasible corner…

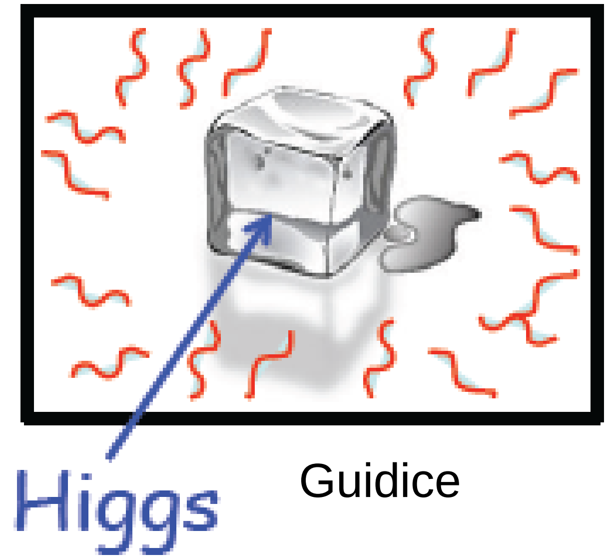
Fine Tuning Problem….



G. Servant $\Rightarrow \delta M_H^2 \propto \Lambda^2$

4 ways to solve it

- Supersymmetry
  - Sparticles cancel particle contributions
- Extra Dimensions
  - Higgs is a vector in 5D
- Higgs is composite
  - Strongly coupled new physics
- There is no fine tuning problem in SM
  - *Not everybody thinks SM has a fine tuning problem*



Guidice

http://arxiv.org/pdf/1306.5647.pdf

Models try to answer questions

- Hierarchy Problem
  - EWK force ~ 10^{32} X Gravity?

  → Extra dimension models
- Fine Tuning Problem

  → SUSY

  → Composite Higgs

  → Extra dimension models
- What is Dark Matter?

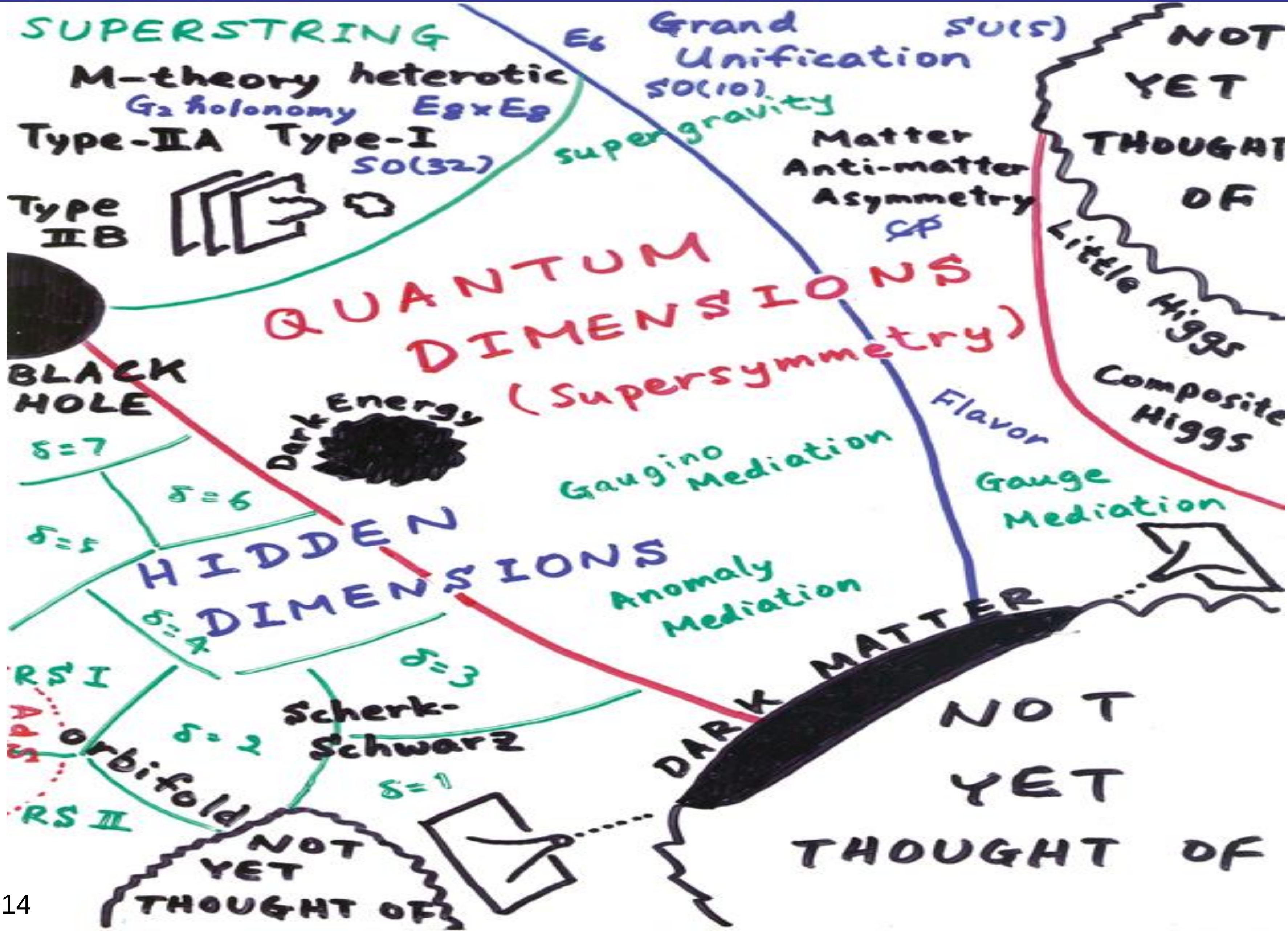
  → SUSY

  → Extra dimensions….
- Family structure in SM?
- Running coupling constants?

  → GUT
- Have elementary particles a sub-structure?
- …..

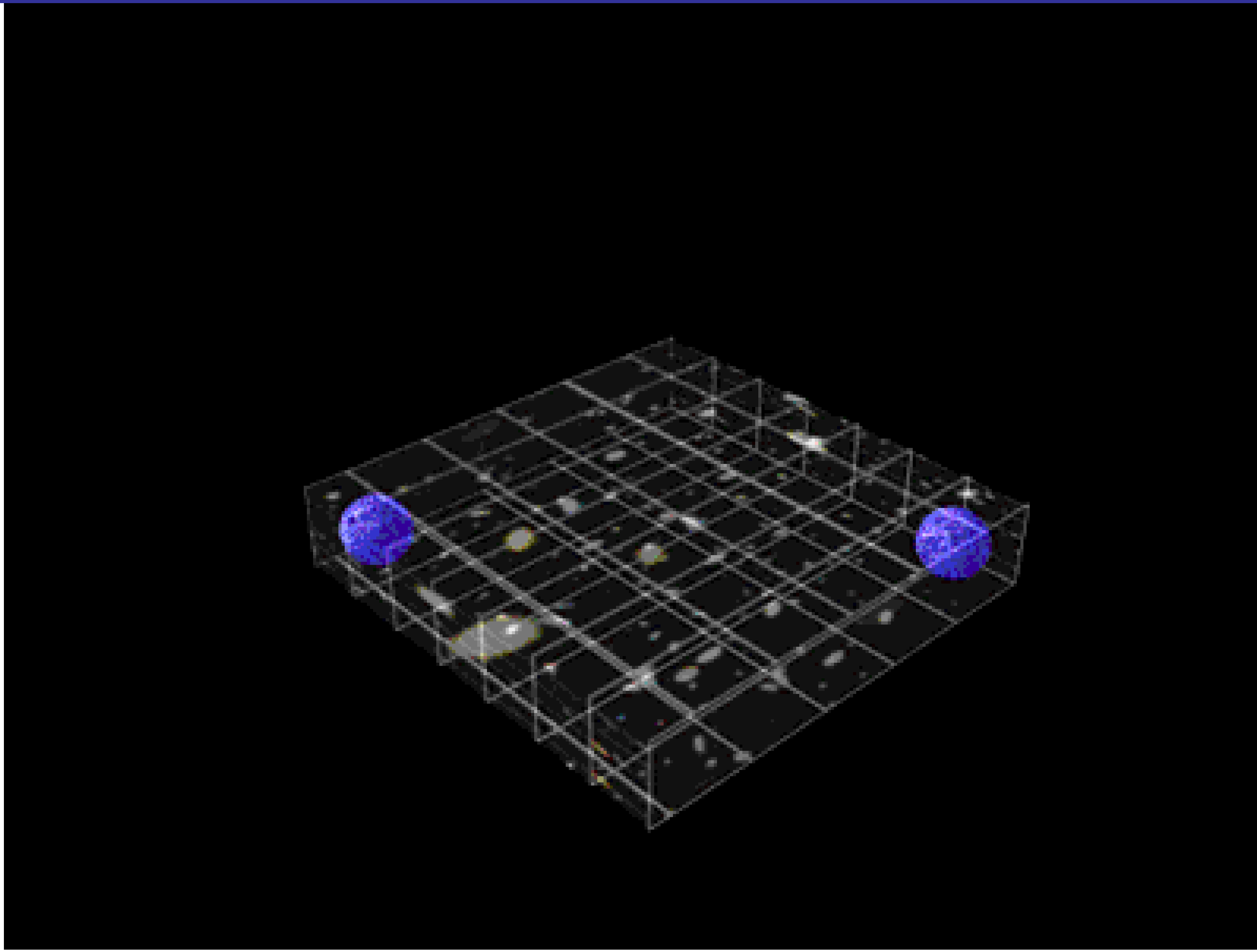
Not all questions may be sensible..

Models



Murayama Hitoshi

Extra Dimensions



Extra Dimensions are not a new idea!

- **1920's Kaluza&Klein unify electromagnetism with gravity**
- **1970 String Theory is born**
  - **QM of oscillating strings**
  - **Bosonic**
- **1971 SUSY enters the stage**
- **1974 Gravitons "pop out" of string theory**

- 1984 Superstring Theory
  - 10, 11 or 26 dimensions needed
  - Compactified
  - SUSY needed for fermions
- 1998 Large Extra Dim.
  - Nima Arkani-Hamed, Savas Dimopoulos, and Gia Dvali
- Warped Extra Dim.(1999)

Geometrisation of Gravitational Field

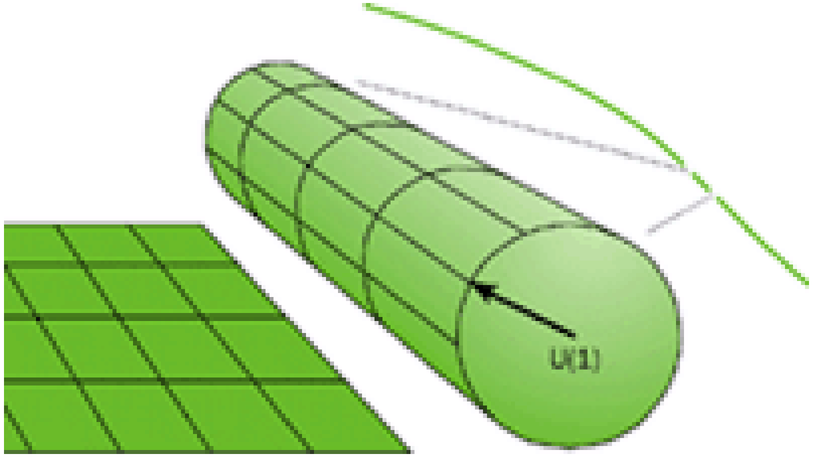
$$G_{\mu\nu} + g_{\mu\nu}\Lambda = 8\pi G T_{\mu\nu}$$

Geometry | Matter

Dynamically correlated

Kaluza-Klein Theory

- Geometrical unification of gravity and electromagnetism

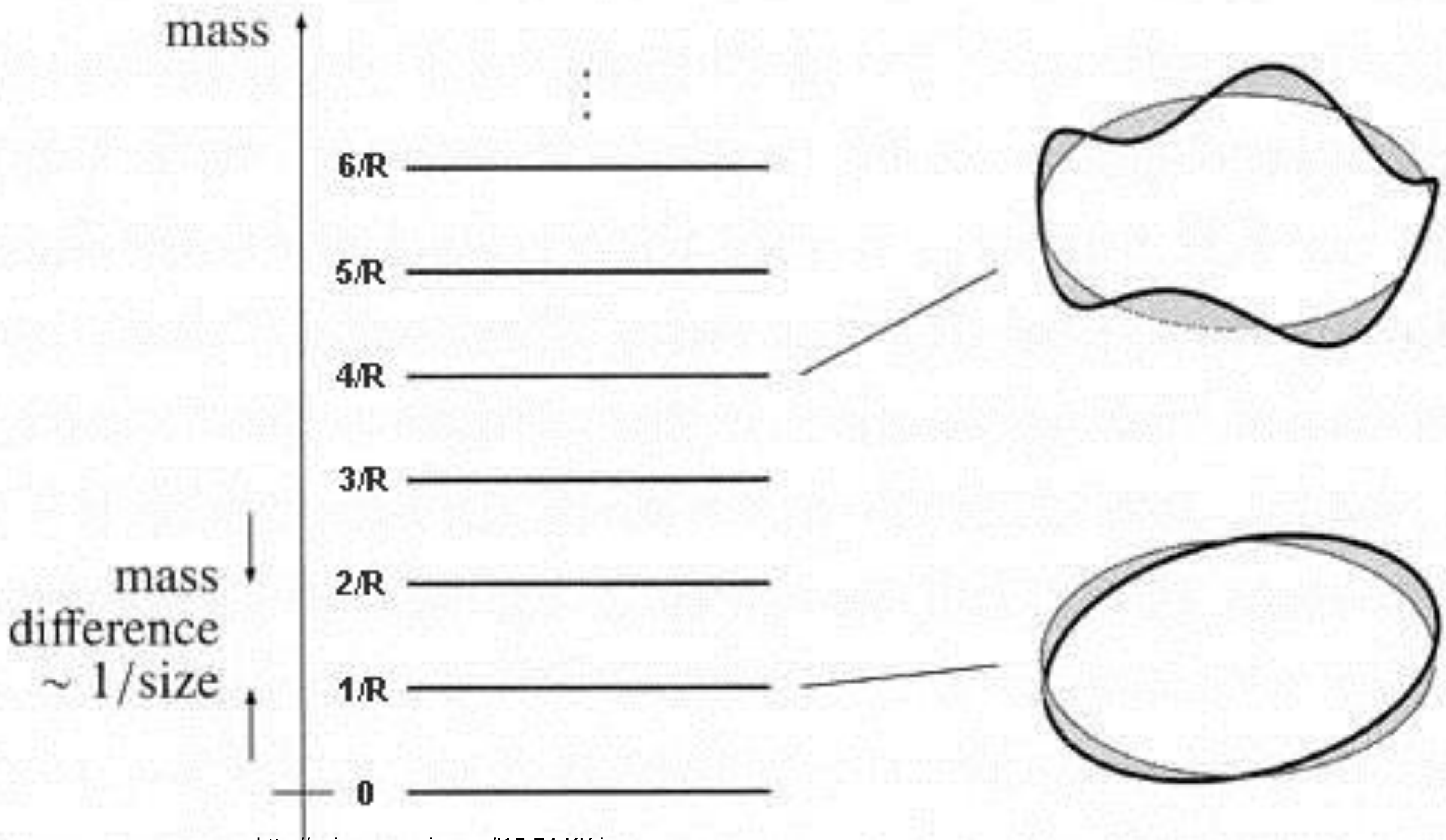


- Formulate GR in 5D

$\rightarrow$ 4D gravity + U(1) gauge theory + scalar field (radion)

- Basis of string theory
- Problems:
  - Classic theory
  - Not chiral, fermions are vector like
  -

KK Particles



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

Where are they?

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

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

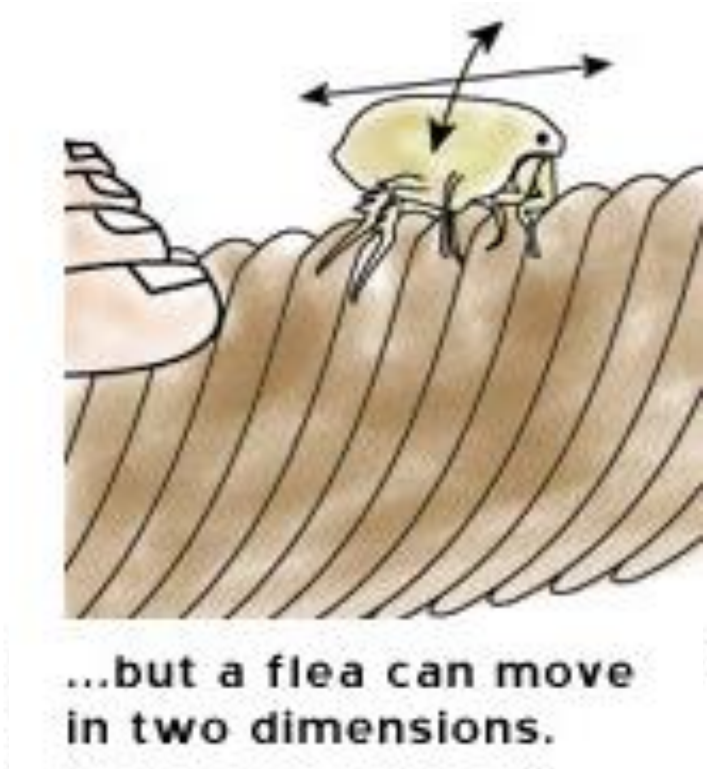
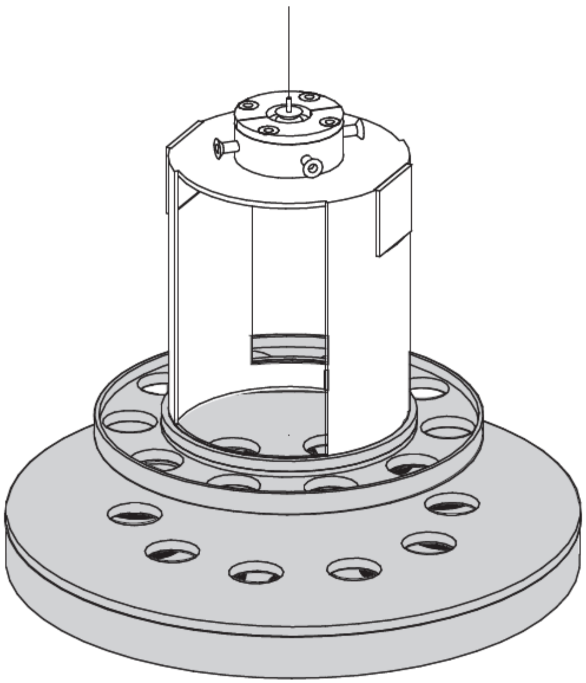


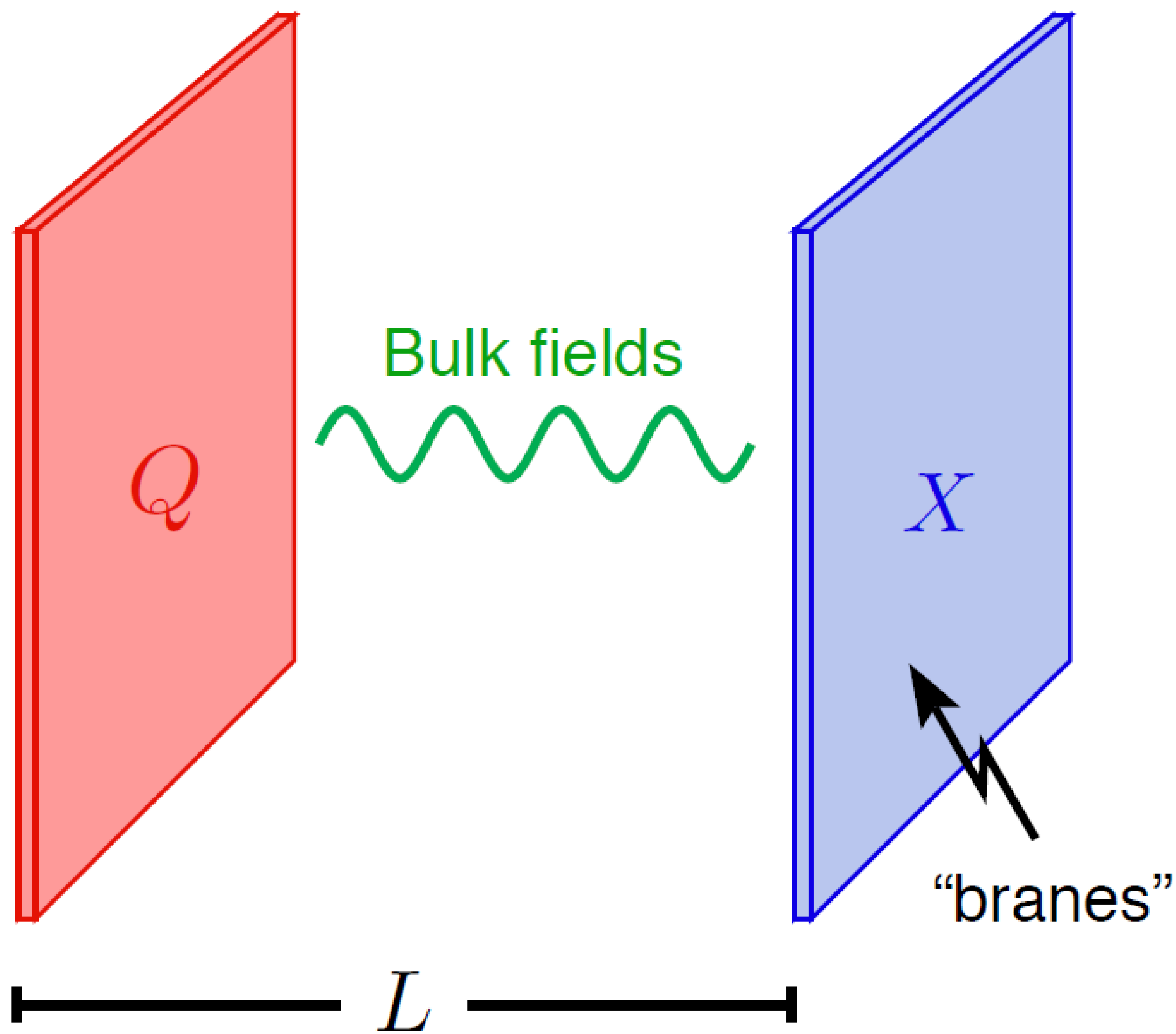
Table Top Experiments



$1/r^2$-law valid for R=44 μm (M_D~4 TeV) at 95%

E.G. Adelberger, Prog.Part.Nucl.Phys. 62 (2009) 102-134

Modern Extra Dimension Models



Gravity in Extra Dimension

At small distances gravity can be very strong,

up to 10^{38} times stronger:

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

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

At large distances gravity seems weak

$$G_D = GL^n$$

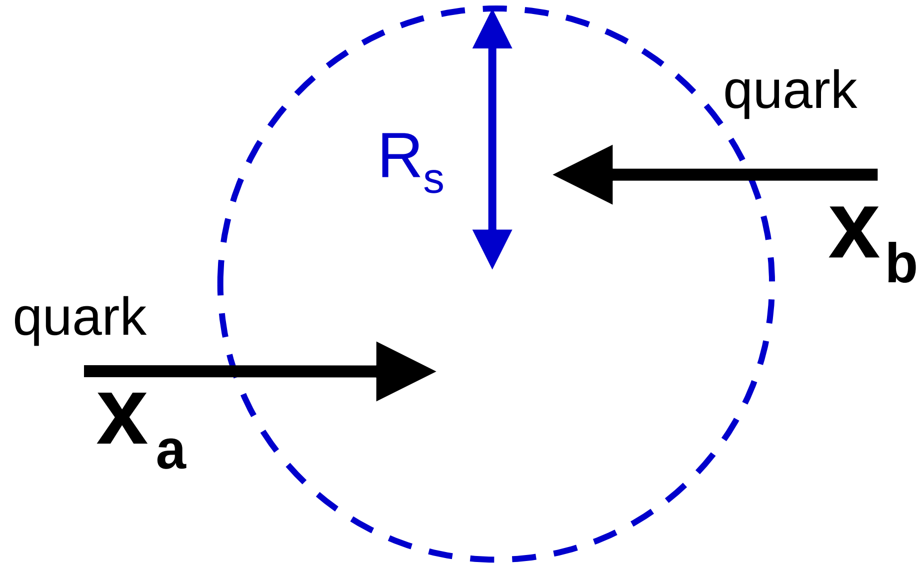
$$F \approx \frac{G_D}{L^n \cdot r^2} \approx \frac{G}{r^2}$$

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

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

Production of Black Holes at the LHC

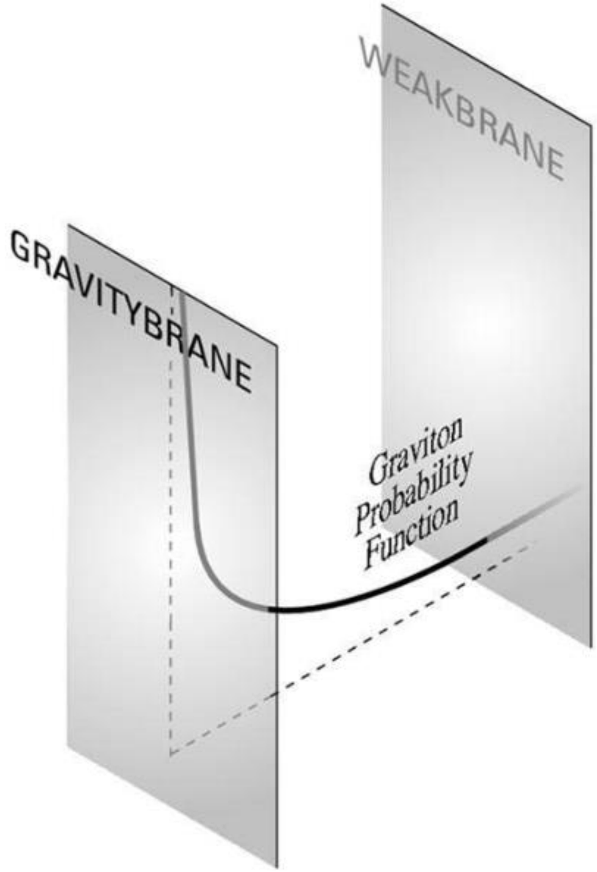
$$R_S = \frac{2\,G*L^n\,M}{c^2}$$



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

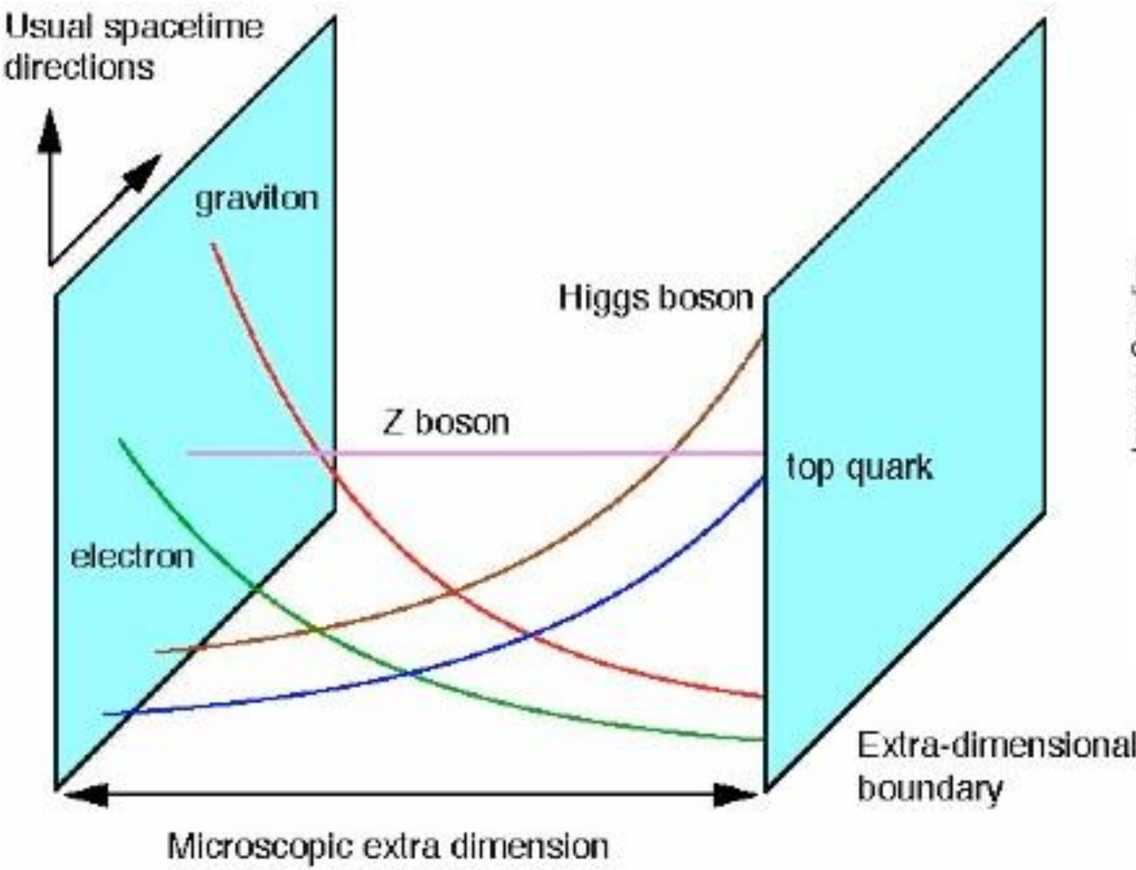
$$R_S^{2quarks} \leq 10^{-18}\,m$$

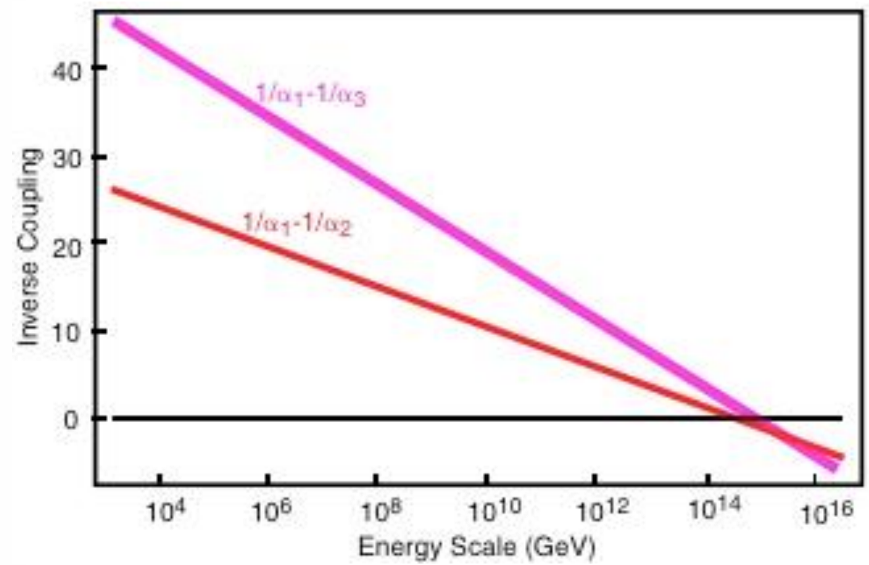
Warped Extra Dimensions



$$ds^2 = \underline{a(y)}^2 dx^\mu dx^\nu \eta_{\mu\nu} + dy^2 \ , \quad \underline{a(y) = e^{-ky}}$$

Other Warped Extra Dimension Models





Supersymmetry

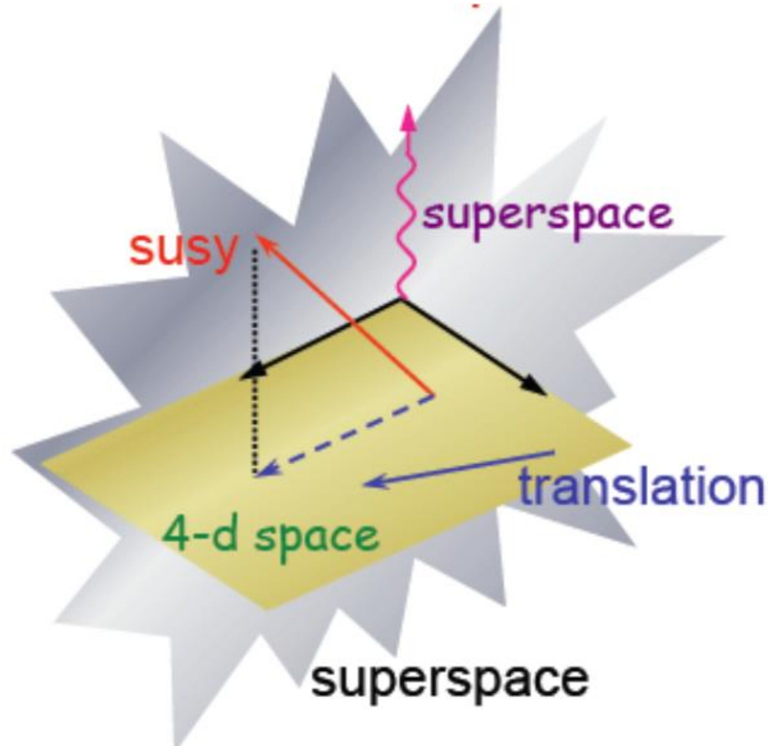
- Geometric interpretation using Superspace

Guidice

4-d space-time

Poincaré

P = (t,x,y,z)

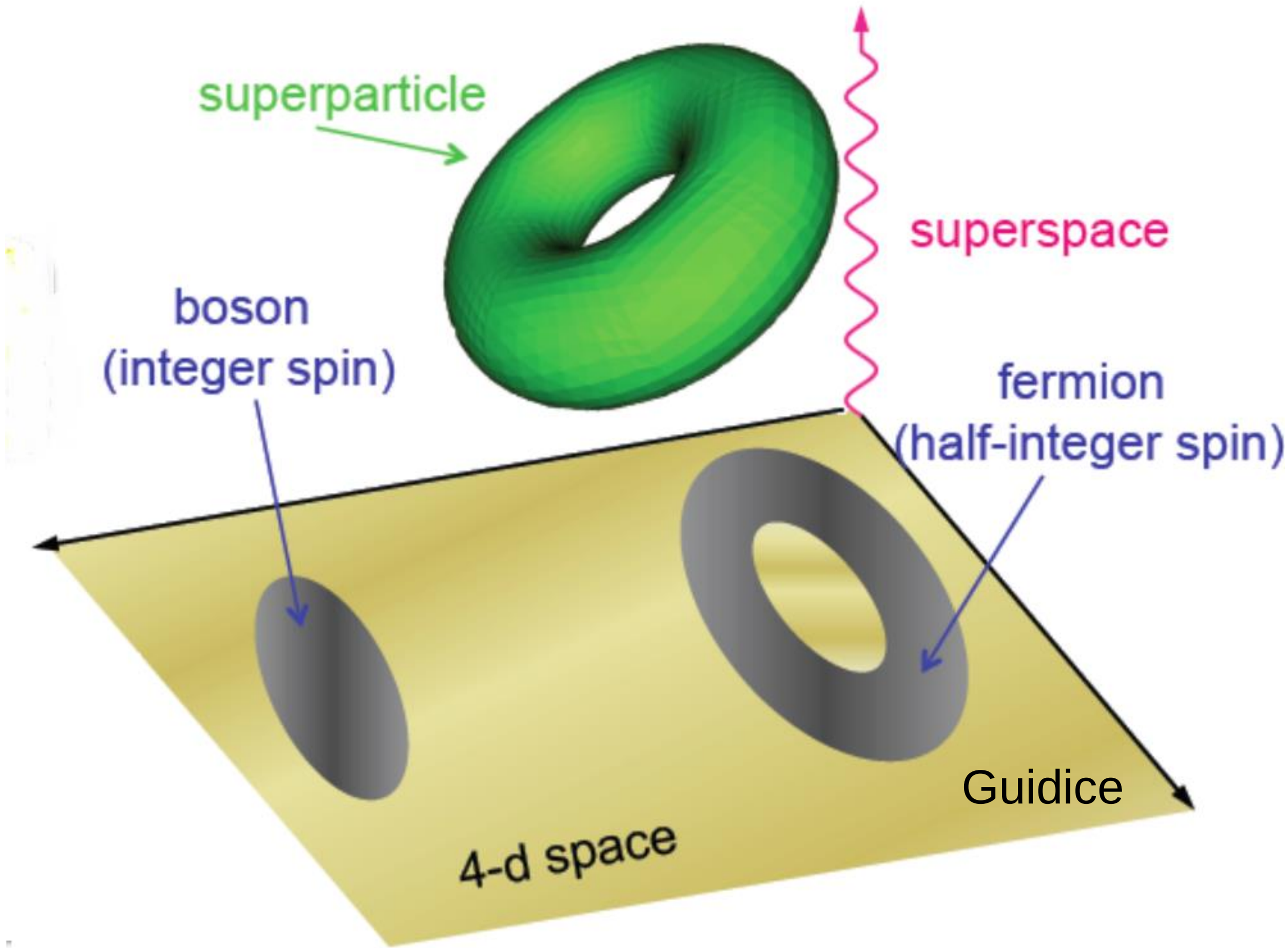


superspace

supersymmetry

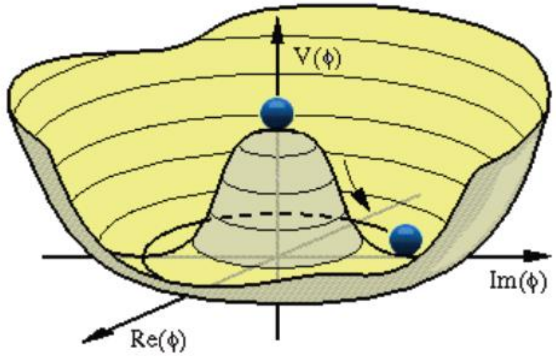
$P = (t,x,y,z,\theta,\bar{\theta})$

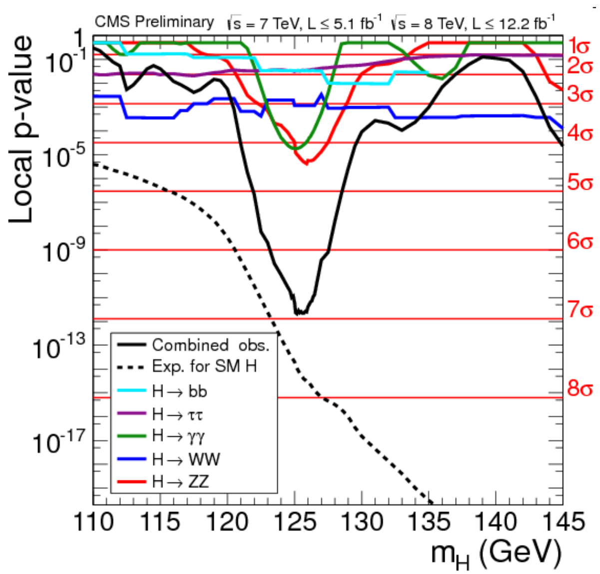
SUSY is Symmetry Group of Superspace

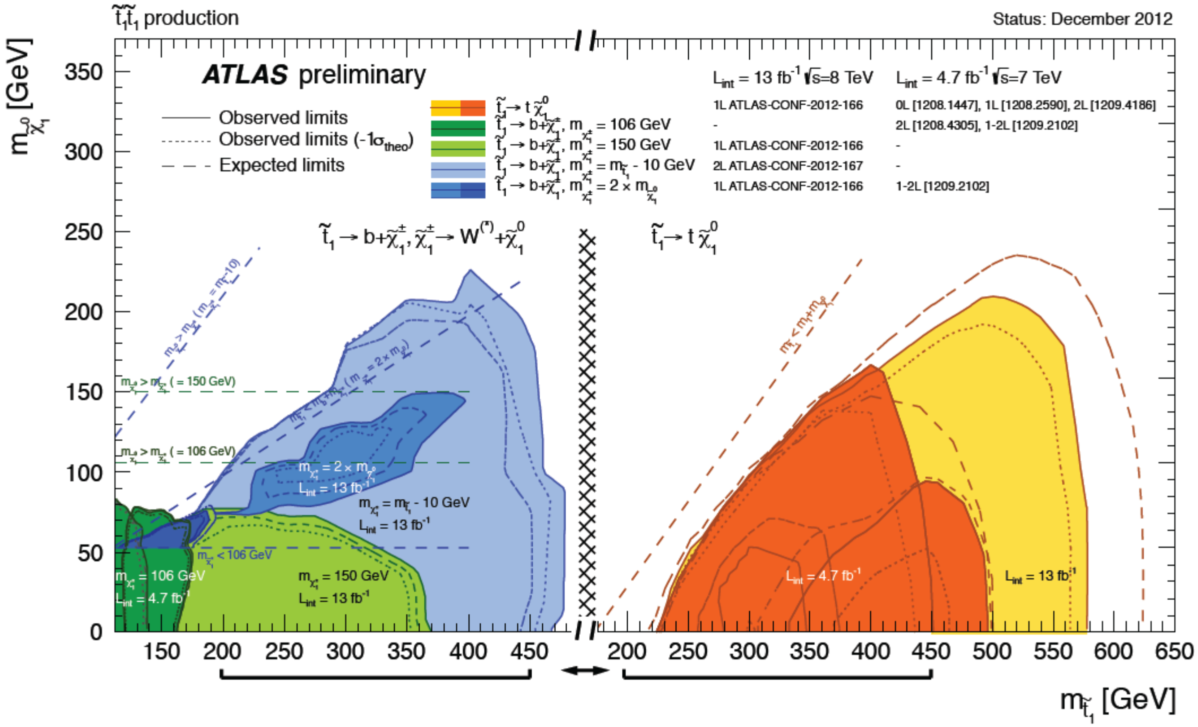


Role of Models in "most" Exotics Searches?

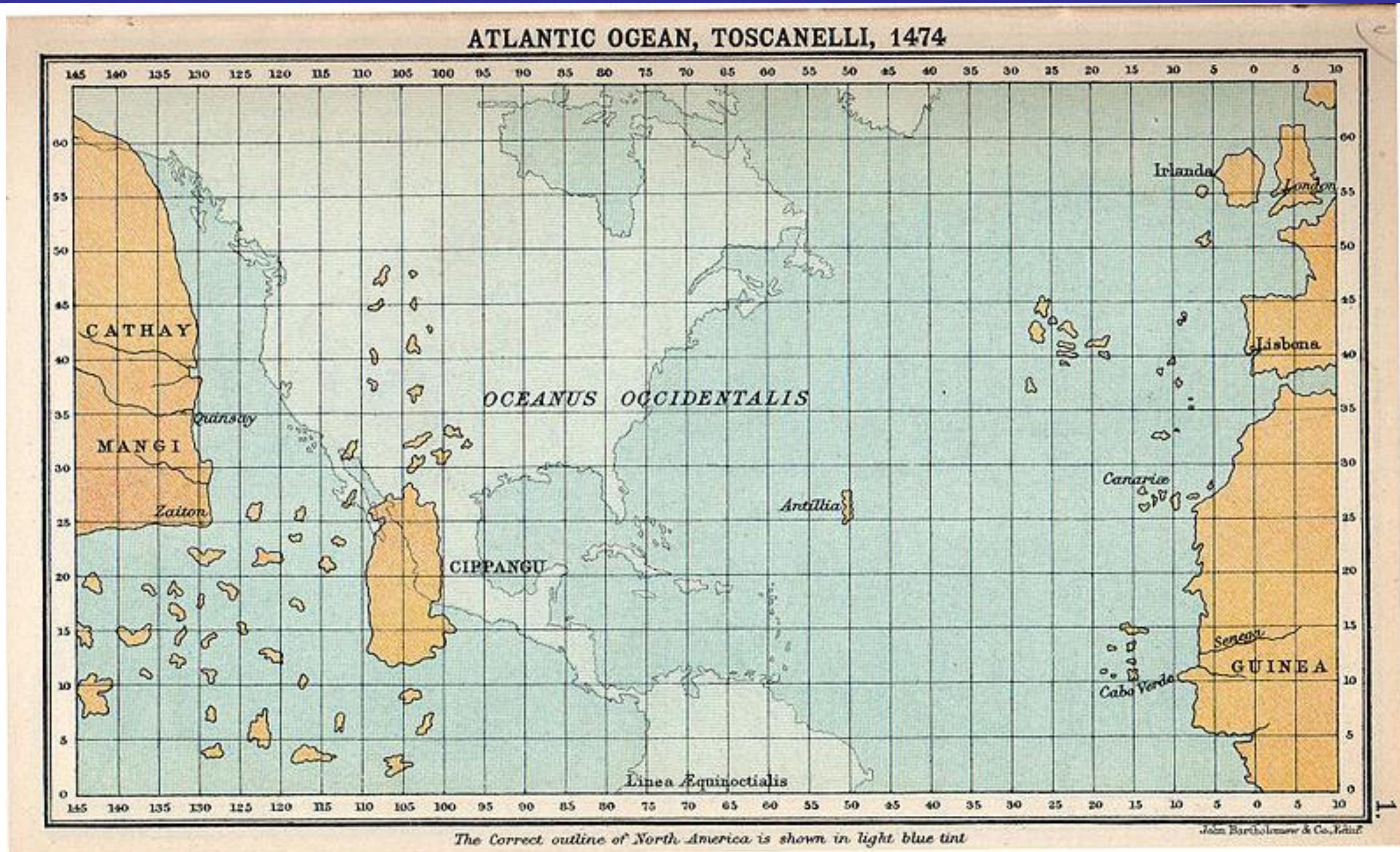
- No specific Model to guide us.
- No unified parameter phase space to map results





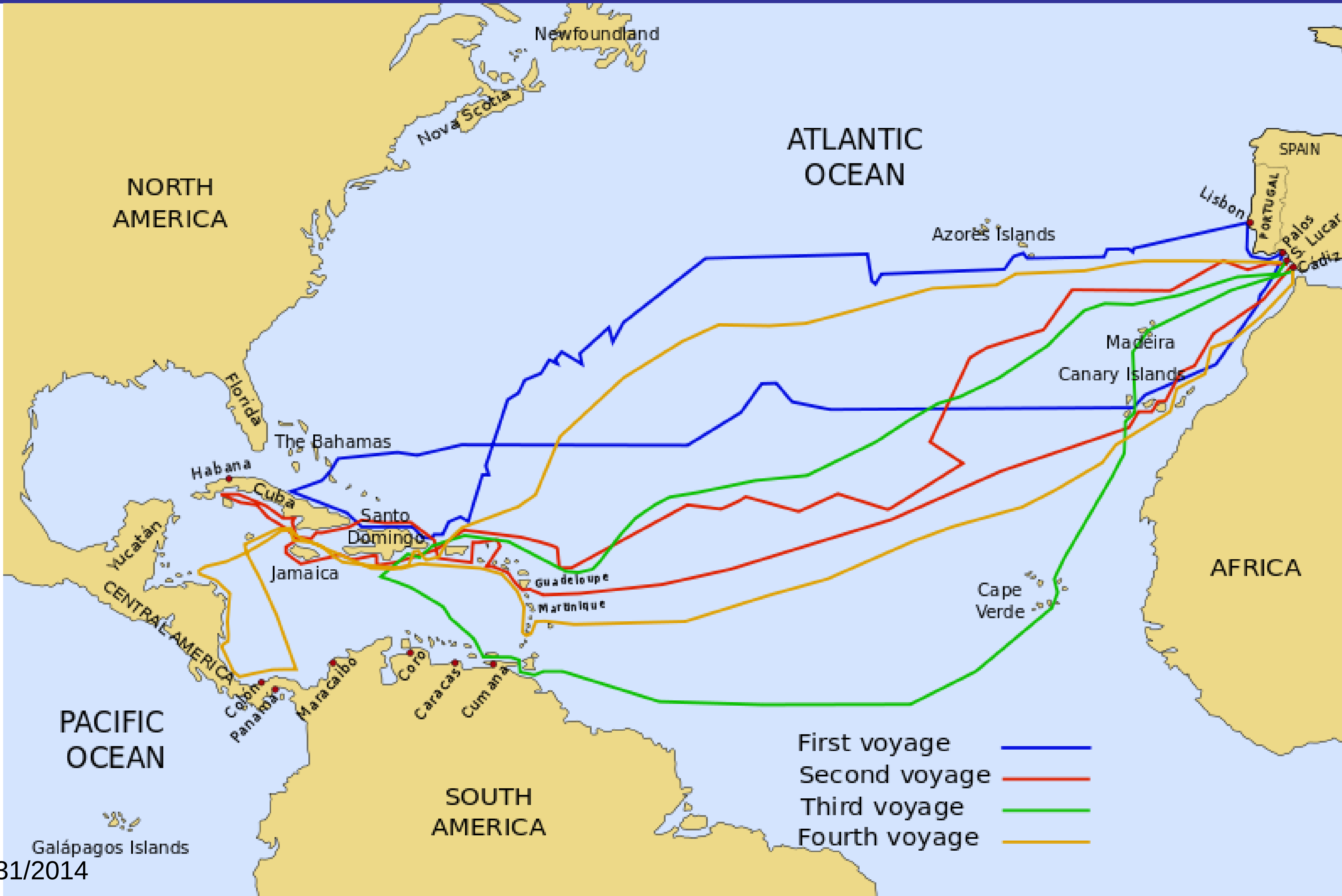


The Role of Models in “most” Exotics Searches



Toscanelli's model of the geography of the Atlantic Ocean, which directly influenced Columbus's plans

The Role of Models in "most" Exotics Searches



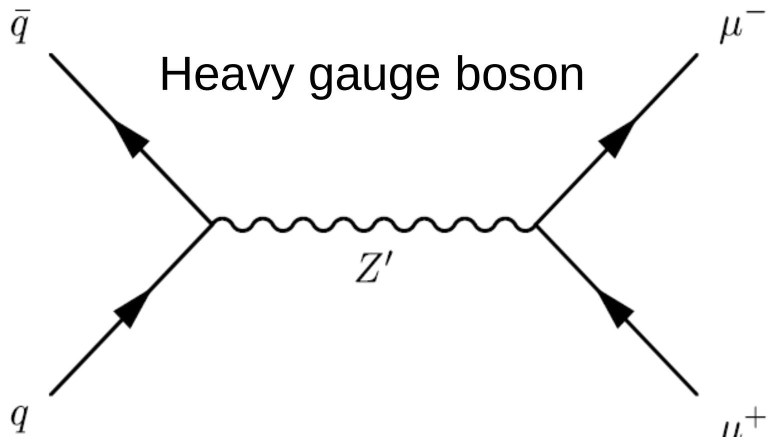
The Role of Models in “most” Exotics Searches

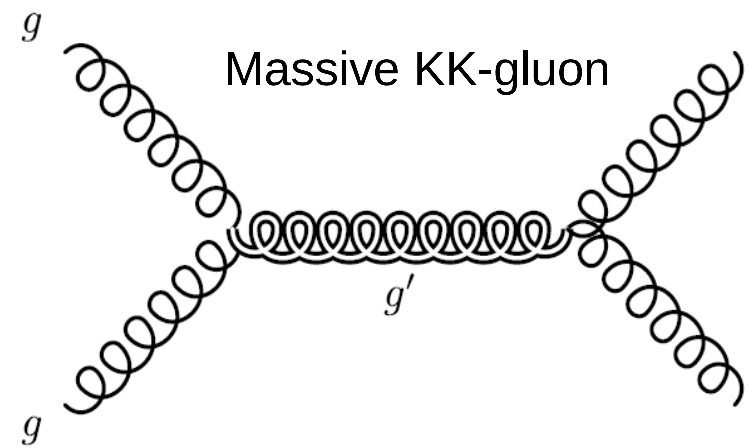
- Models used to quantify our reach.
  - How far did we get?
  - How do we compare to previous searches?

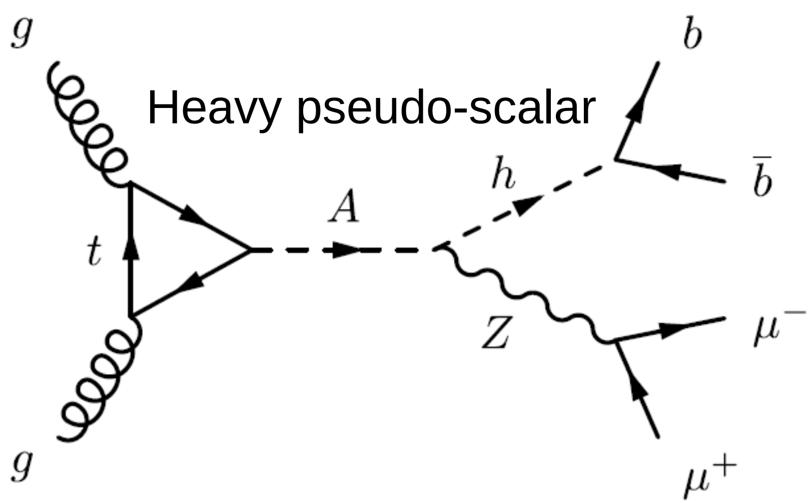
- We use so called Bench Mark Models
  - Used before by other experiments

- Simplified Models or generic resonances

Exotics Search Signatures: s-channel Production

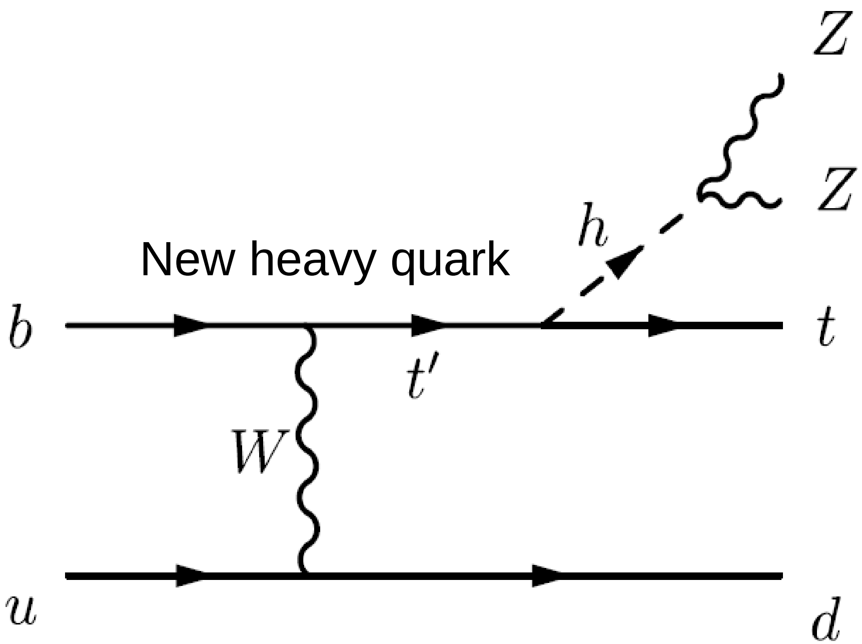


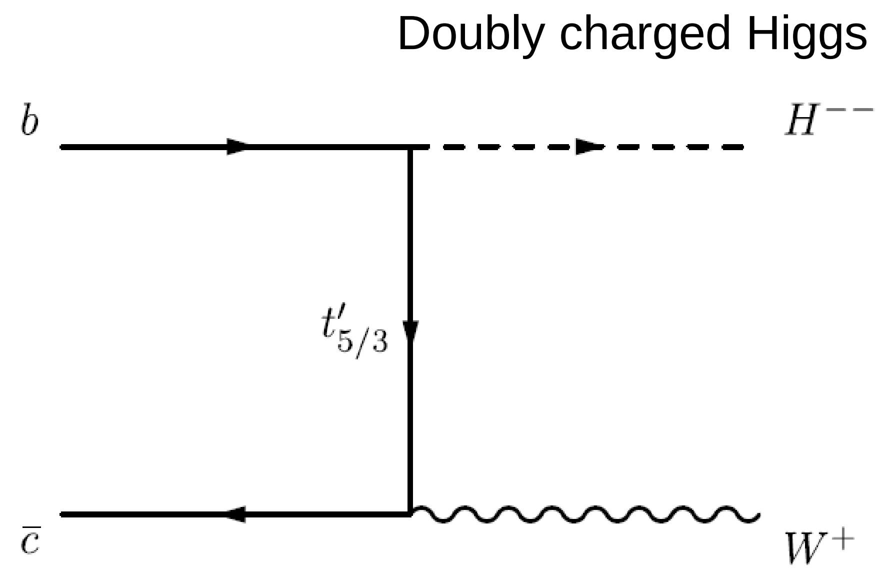


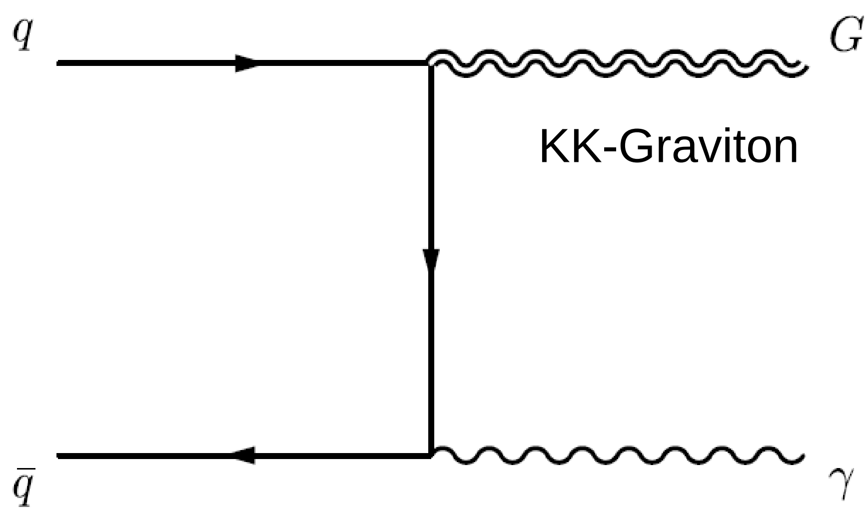


Lykken, http://arxiv.org/pdf/1005.1676.pdf

Exotics Search Signatures: Associate Production





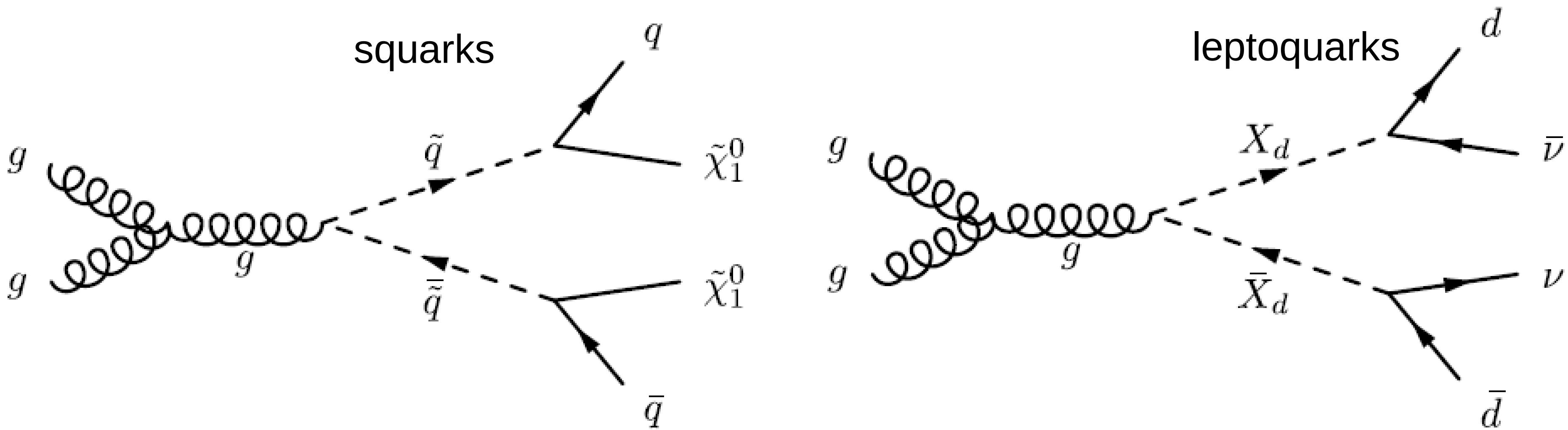


Lykken, http://arxiv.org/pdf/1005.1676.pdf

Exotics Search Signatures: Pair Production

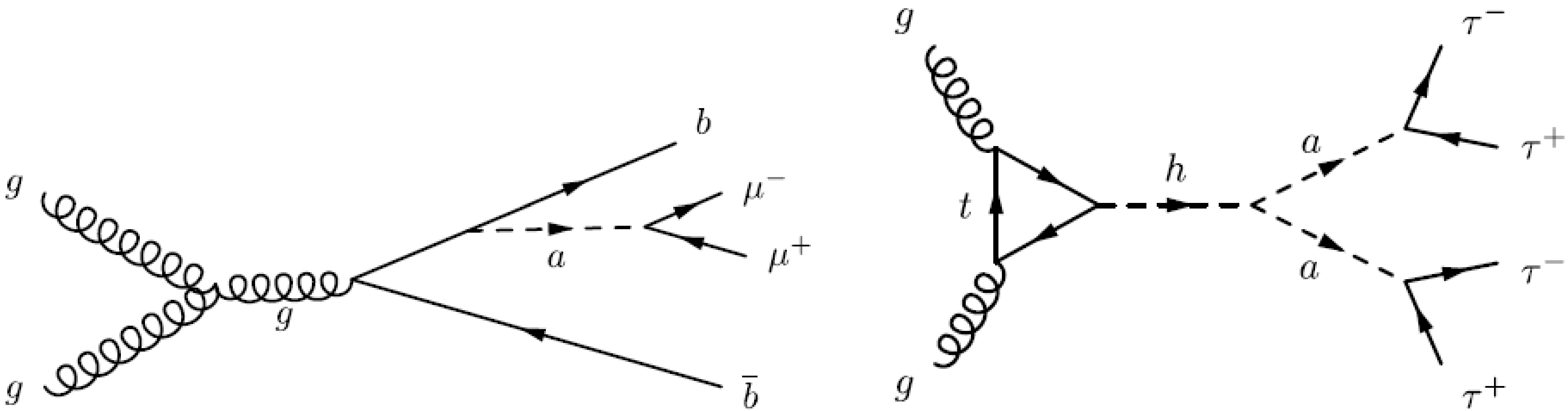
squarks

leptoquarks



Lykken, http://arxiv.org/pdf/1005.1676.pdf

Exotics Search Signatures: BSMstrahlung



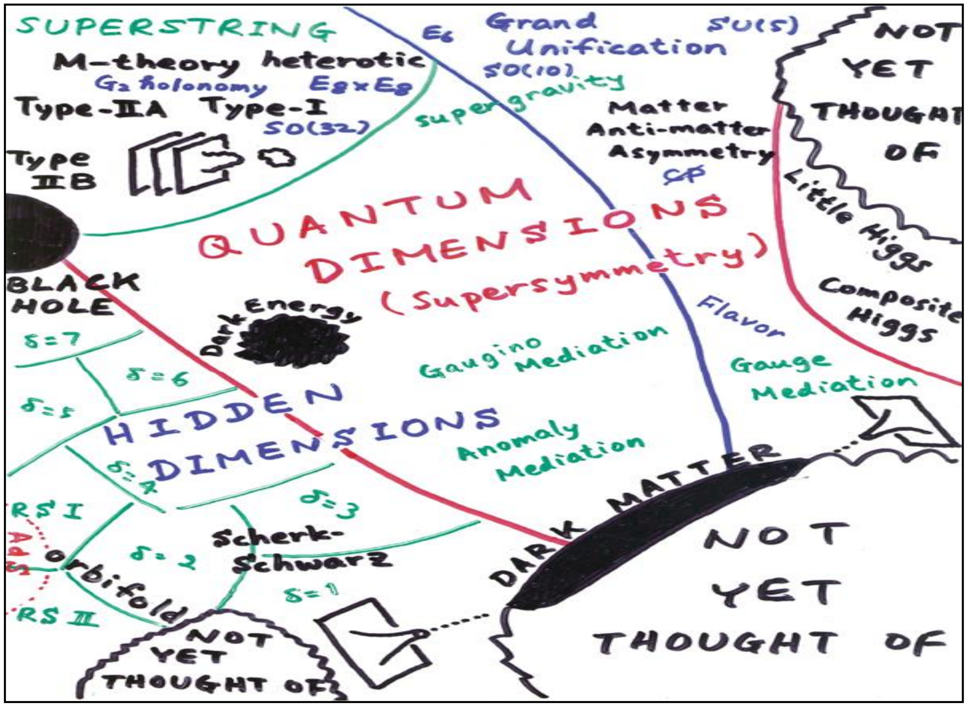
Pseudo-scalar

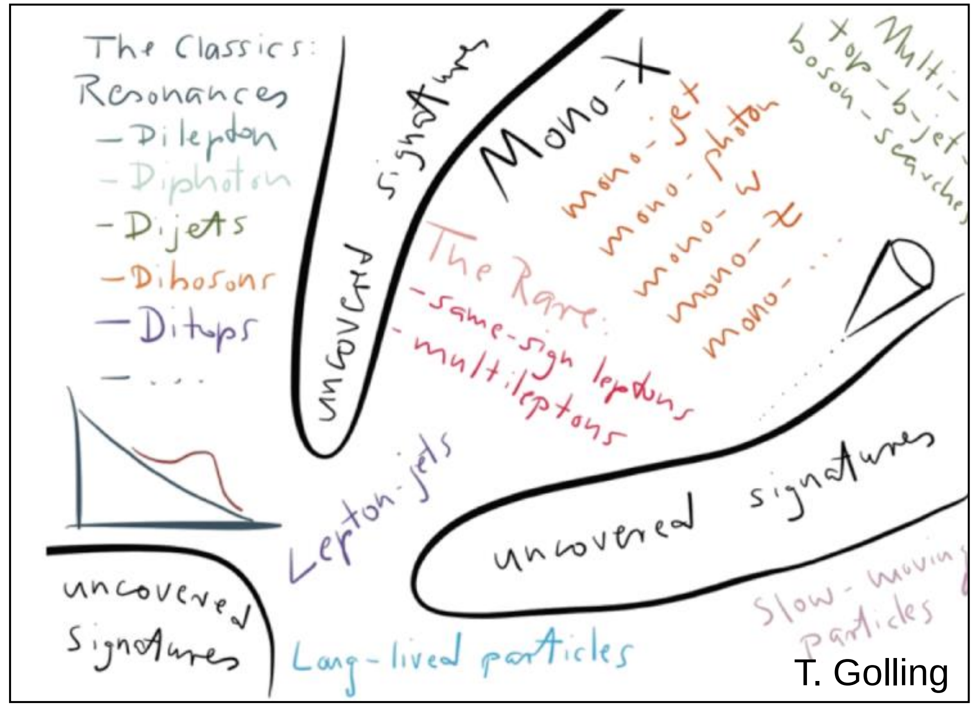
Lykken, http://arxiv.org/pdf/1005.1676.pdf

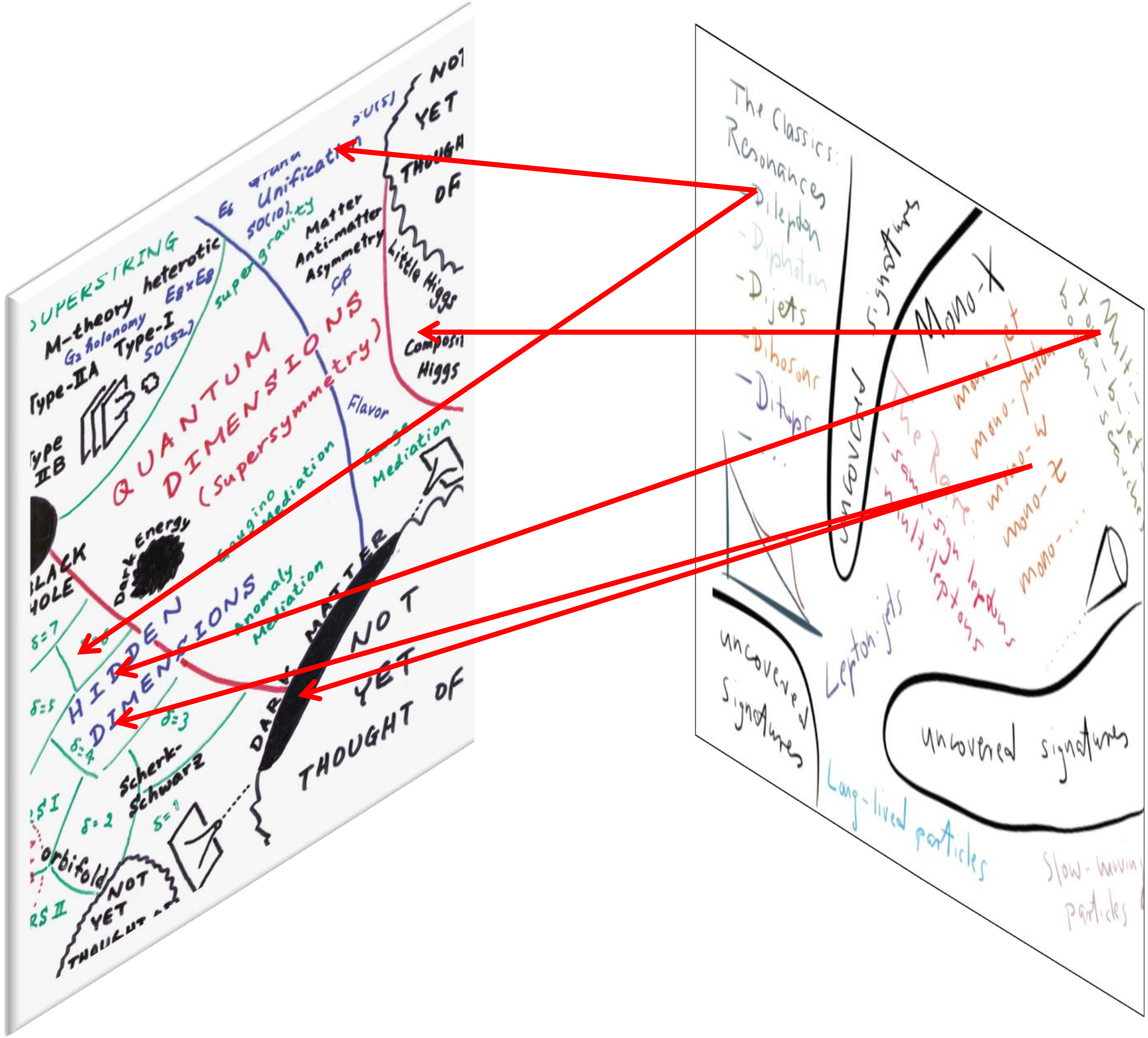
Signature Landscape

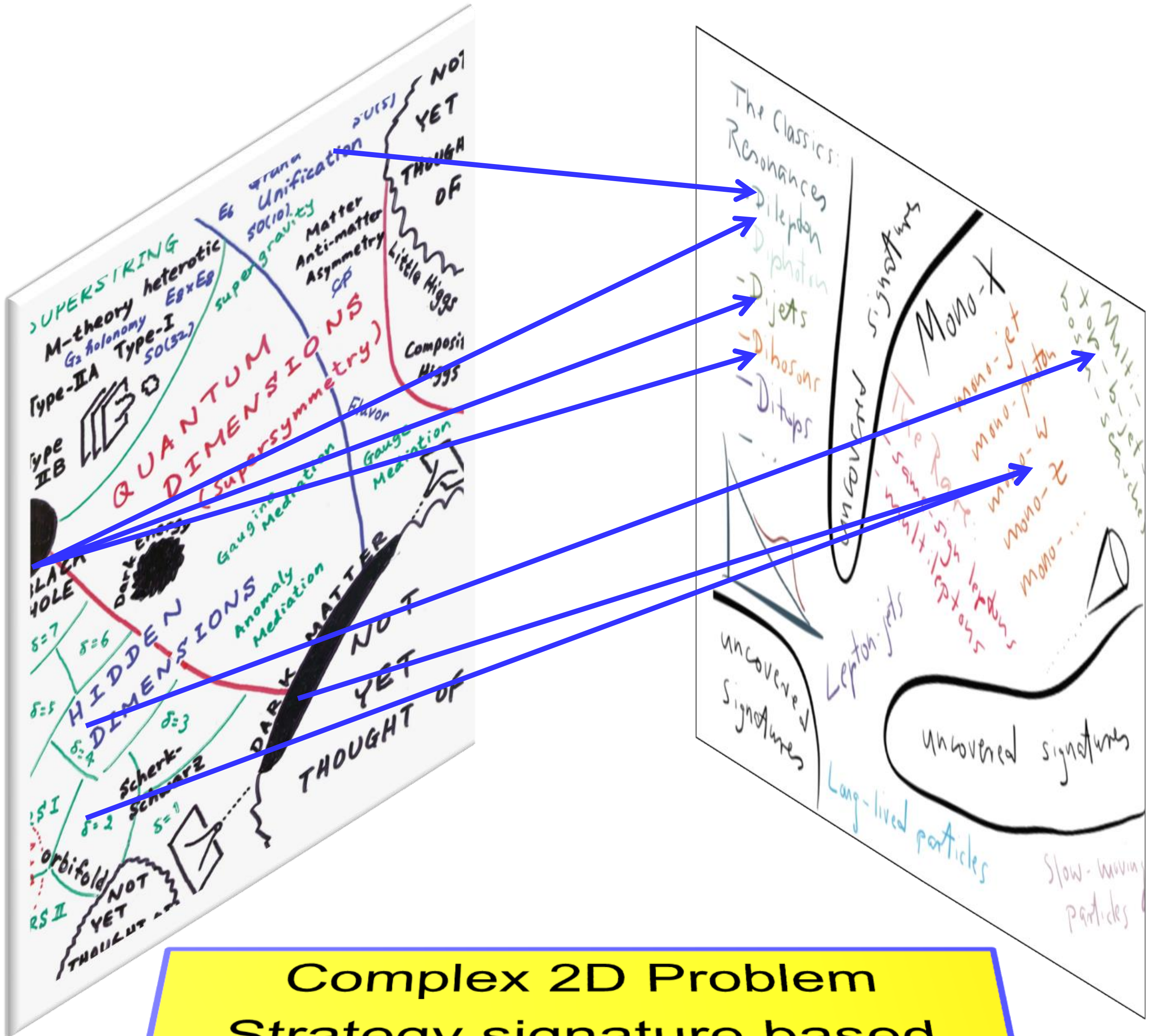
T. Golling

Models and Signatures






SUPERSTRING
M-theory
heterotic
E8×E8
G2 holonomy
Type-I
SO(32)
Type-IIA
Type IIB
supergravity
Grand Unification
E6
SO(10)
SU(5)
Matter Anti-matter Asymmetry
CP
NOT YET THOUGHT OF
Little Higgs
Composite Higgs
QUANTUM DIMENSIONS
(Supersymmetry)
Flavor
Gaugino Mediation
Gauge Mediation
Dark Energy
BLACK HOLE
HIDDEN DIMENSIONS
Anomaly Mediation
DARK MATTER
Scherk-Schwarz
orbifold
The Classics:
Resonances
-Dilepton
-Diphoton
-Dijets
-Dibosons
-Ditops
uncovered signatures
Mono-X
mono-jet
mono-photon
mono-W
mono-Z
mono-...
Multi-b-jet
The Rare: same-sign leptons
multi-leptons
Lepton-jets
Long-lived particles
Slow-moving particles



Complex 2D Problem

Strategy signature based

Cover all possible signatures

Exotics Searches

- Wide range of final states
- Wide range of models

- GENERIC
  - Look for resonances
  - Look for any disagreement from expectations

- Extremes
  - Experimentally
  - Theoretically

Basic Principles of Exotics Searches

- Identify your discriminant!

- Most important: Robust background estimation!

- Biases ?
  - 100% blind analysis → not appropriate at LHC
  - Control regions

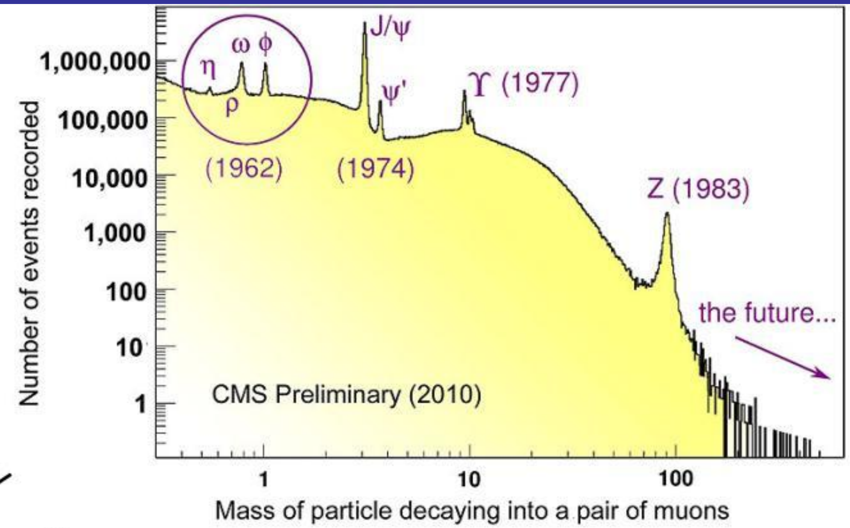
- Trade-off between Signal and Background
  - Do NOT optimize towards a specific model
  - Selection cuts defined by triggers and background reduction.

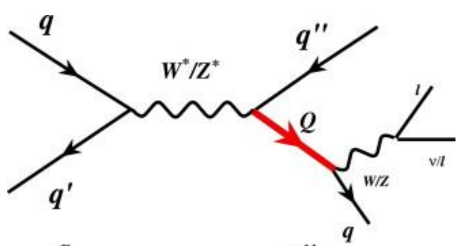
Basic Principles of a Search

- You have a background estimate…what now?
- Check if data agrees with this expectation.
- If it does not agree…
  - Is the significance increasing with more data?
  - Look at time dependences...
  - Cross checks….
  - Discovery if significance is greater than 5 sigma.
- If it does agree….
  - How far did we explore the new physics phase?
  - Use models to quantify the search reach.
  - Useable for others (publish acceptance and efficiencies)

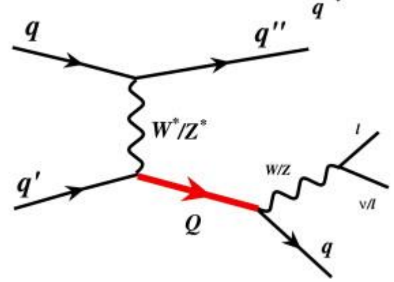
Exotics Searches

- **Heavy resonances**
  - **Dileptons**
  - **Dijets**
  - **Ttbar**
  - **HH**



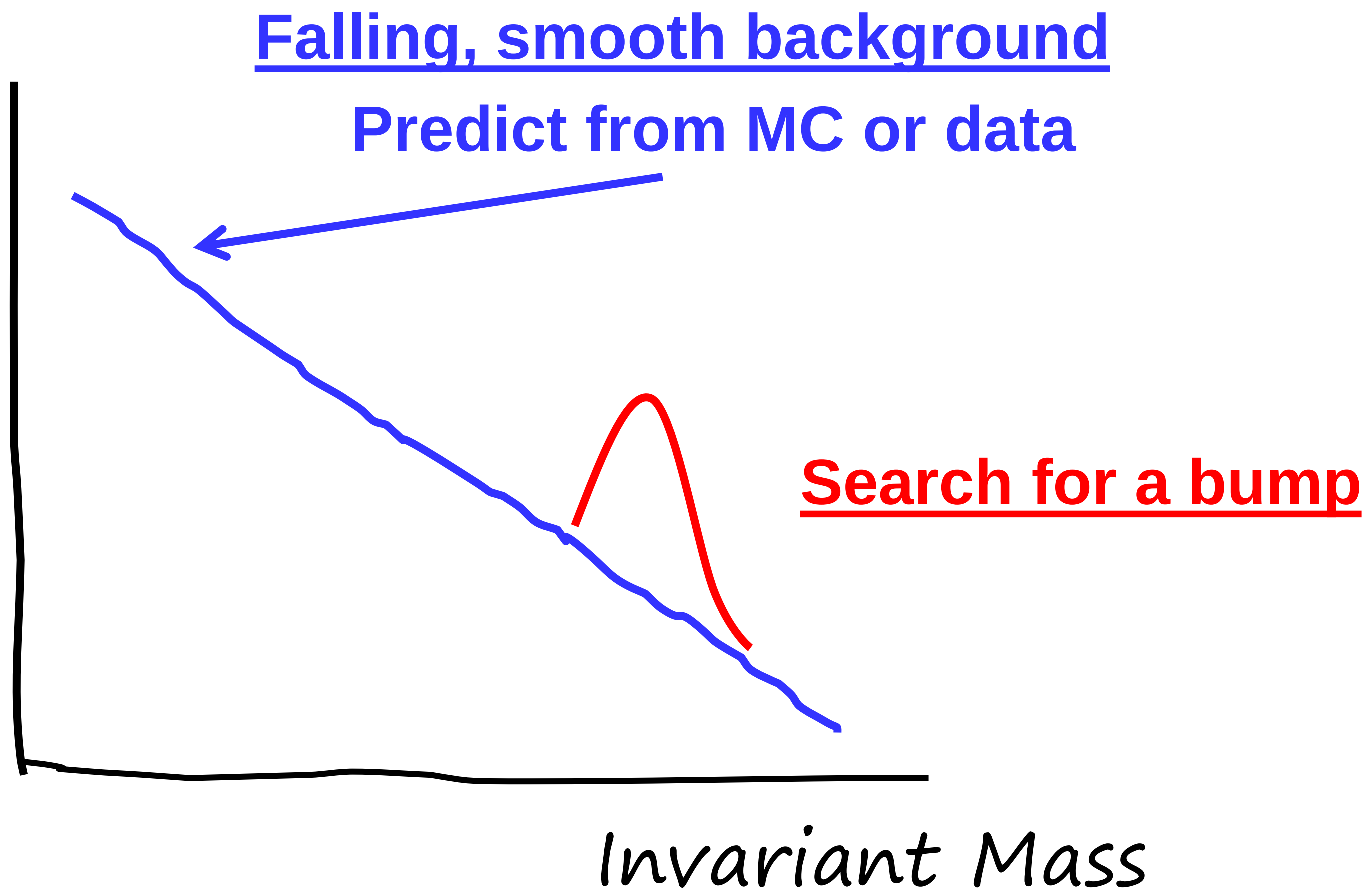


- **Vector-like quarks**



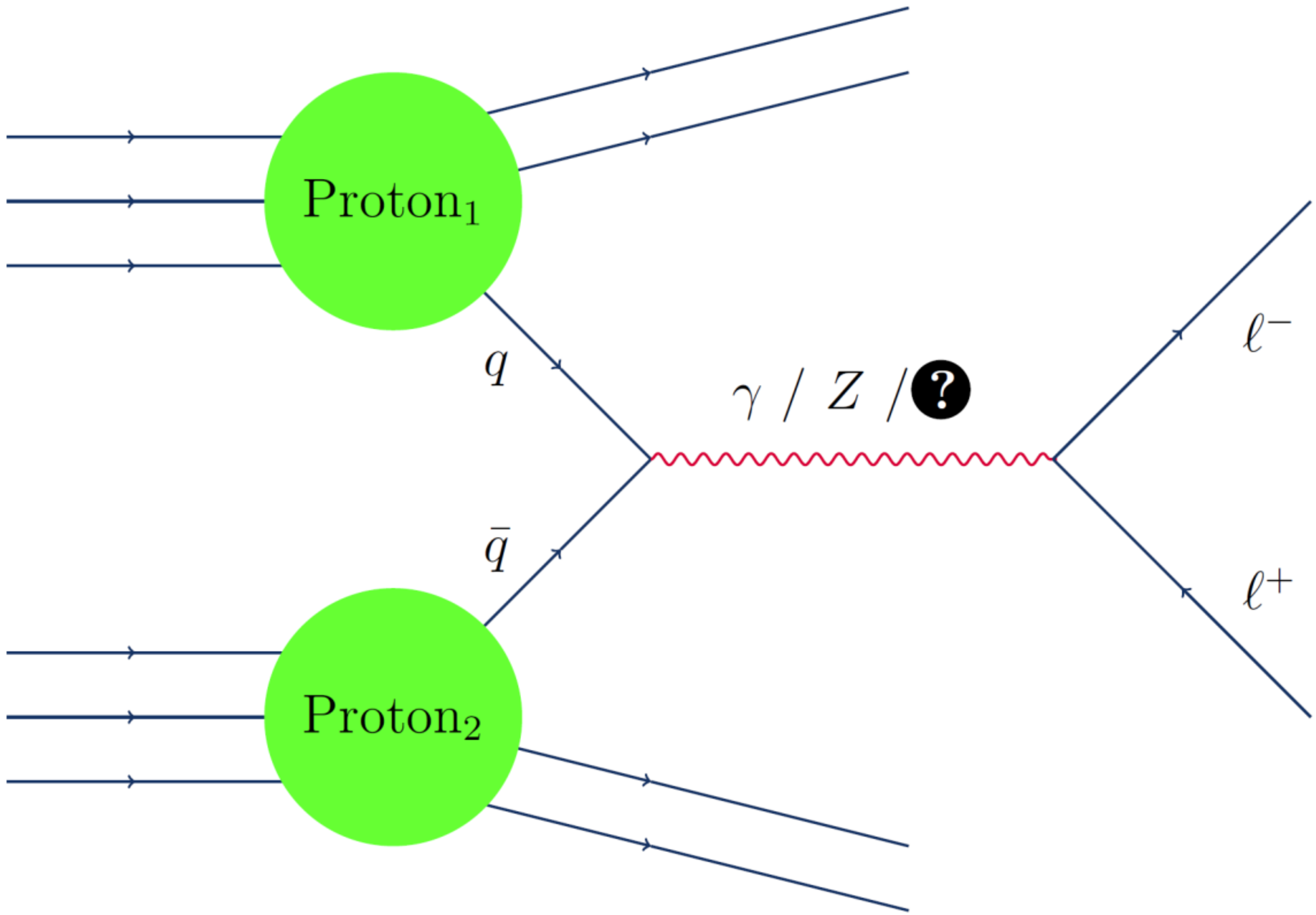
- **Dark matter and extra dimension**

Resonance Searches



Dilepton Resonance Search

Noam Tal Hod
CERN-THESIS-2012-155

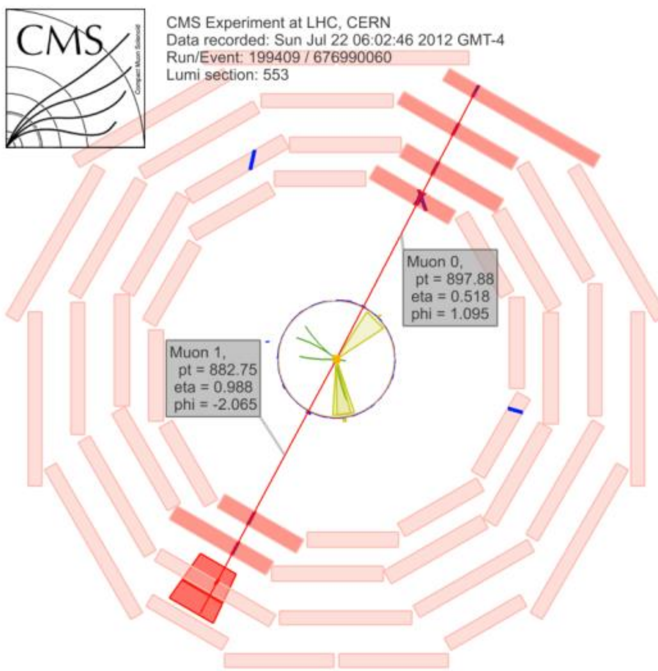


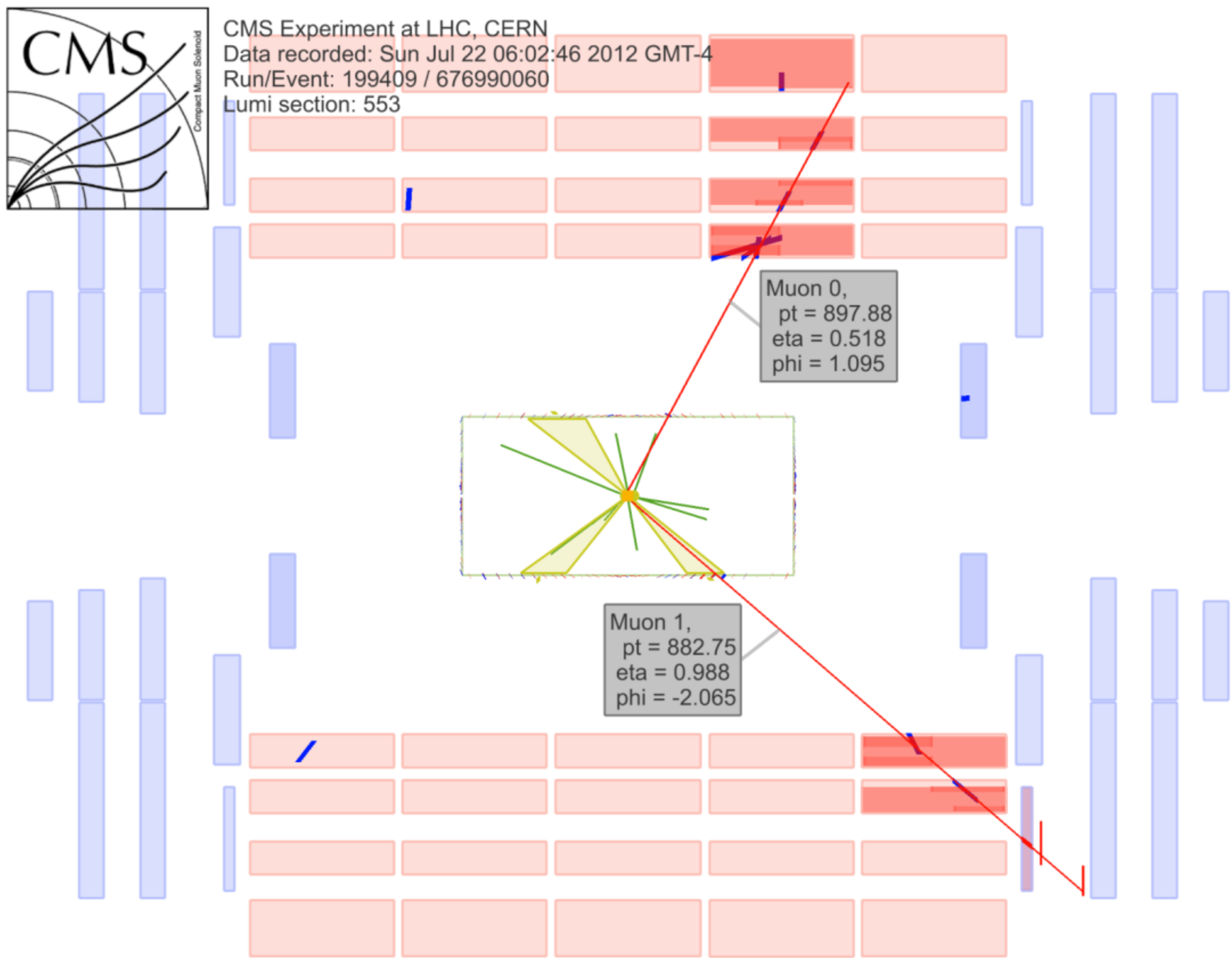
Dilepton Resonance Search

ATLAS-CONF-2013-017
PAS EXO-12-061

- Models:
  - Little Higgs → heavy gauge boson(s) (**Z'**/W')
  - GUT-inspired theories → heavy gauge boson(s) (**Z'**/W')
    - Strong and EWK force merged into one interaction
    - Described by higher symmetry group
      - Popular choices:
        - Left right symmetric models (SO(10))
        - E_6 symmetry models
  - Sequential Standard Model (SSM)
    - Z' carbon copy of Z^0 just heavier
    - Z' decays into any SM lepton-antilepton pair
    - decay into gauge bosons is suppressed by hand
    - not gauge invariant, not very realistic but
    - reference model
  - Randall-Sundrum ED → Kaluza-Klein graviton
  - Technicolor → narrow technihadrons

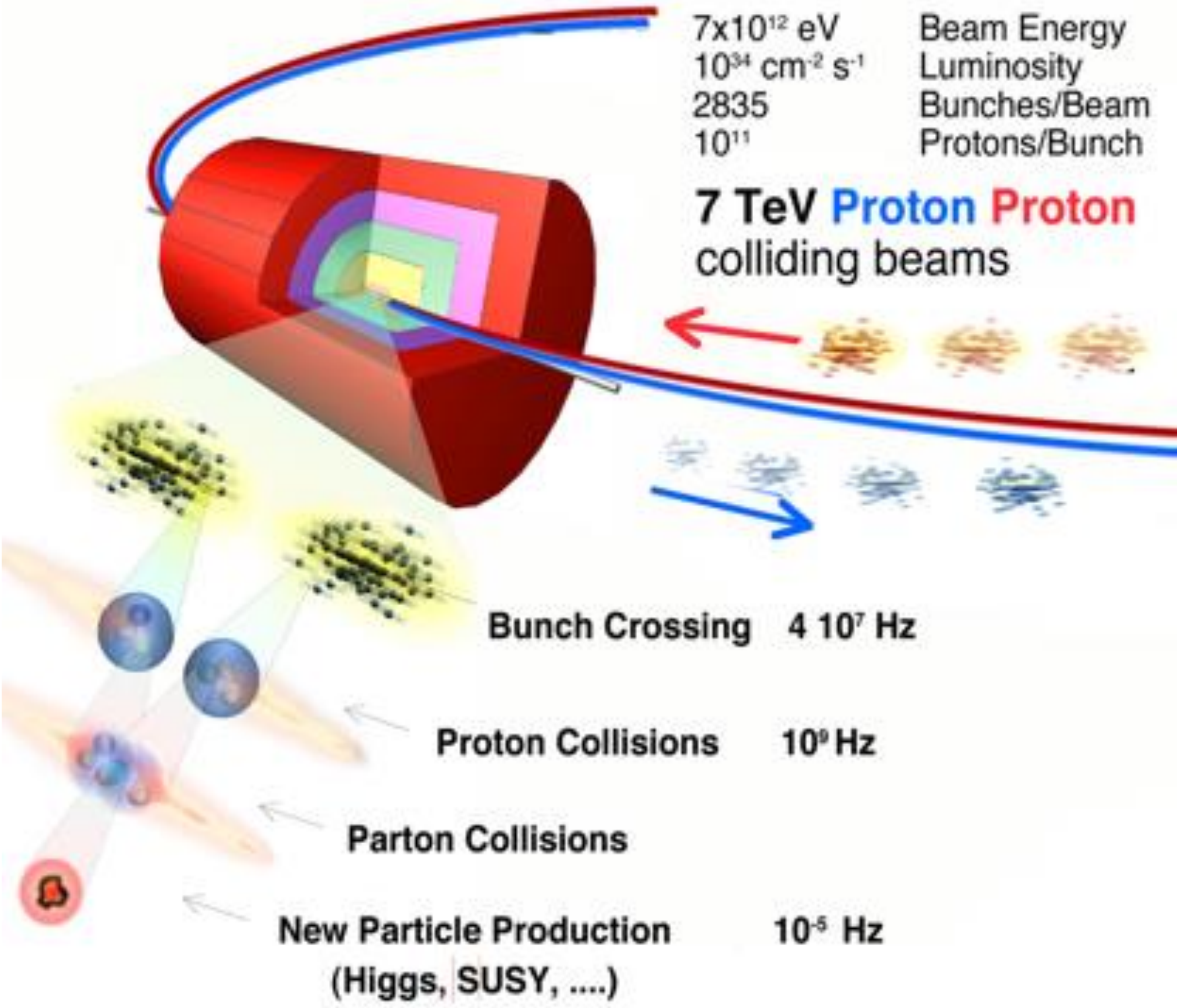
CMS Highest Dimuon Invariant Mass Event; 8 TeV





m_{inv} = 1824 GeV

Proton-Proton Collisions



Luminosity

- Single most important quantity
  - Drives ability to observe new rare processes

$$L = \frac{f * n_{bunch} * N_p^2}{4\pi * \sigma_x * \sigma_y}$$

- revolving frequency f = 11245.5/s
- n_{bunch} = 2808
- N_p = 1.15 x 10^{11} Protons/Bunch
- Area of beams: $4\pi\sigma_x\sigma_y$~40 μm

- Rate of physics processes per unit time ~ L

$$N_{Obs} = \int L dt * \varepsilon * \sigma_{process}$$

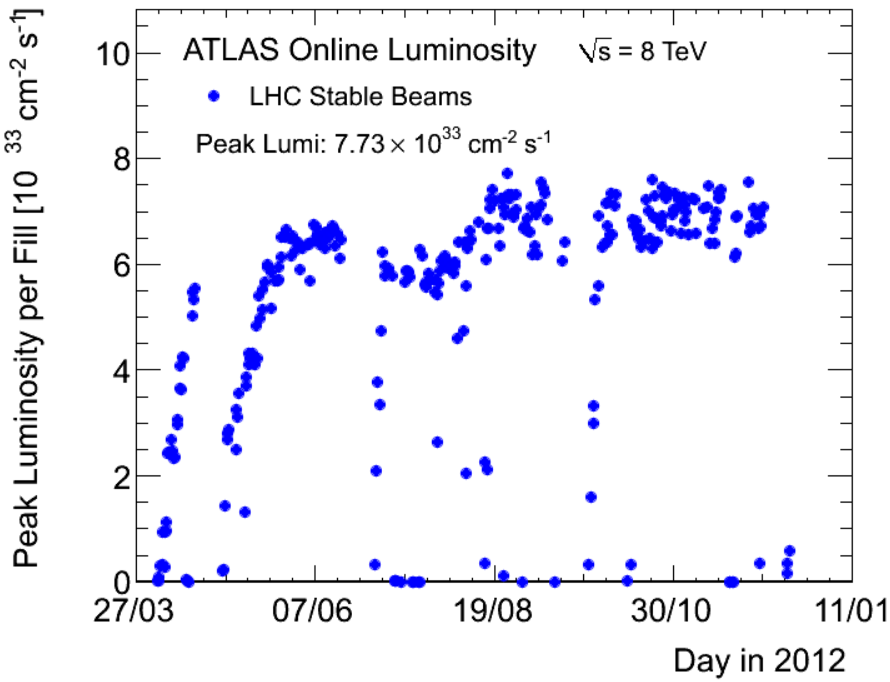
Cross section; given by nature; predicted by theory

Efficiency; optimized by experimentalists

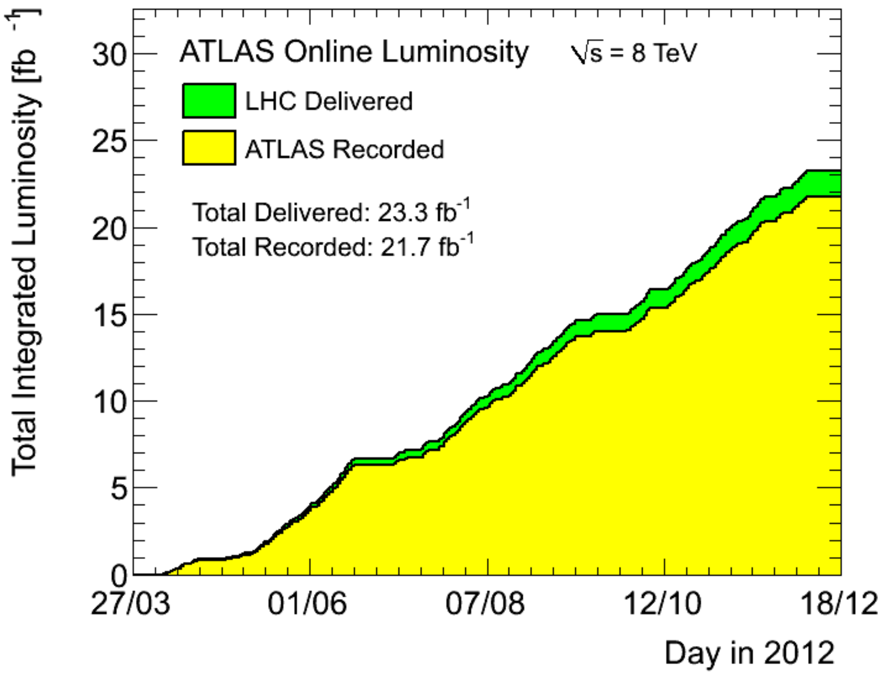
Maximize N_{obs} → max ε and L

Our data sample for 2012

Peak Luminosity in 2012



Integrated Luminosity in 2012



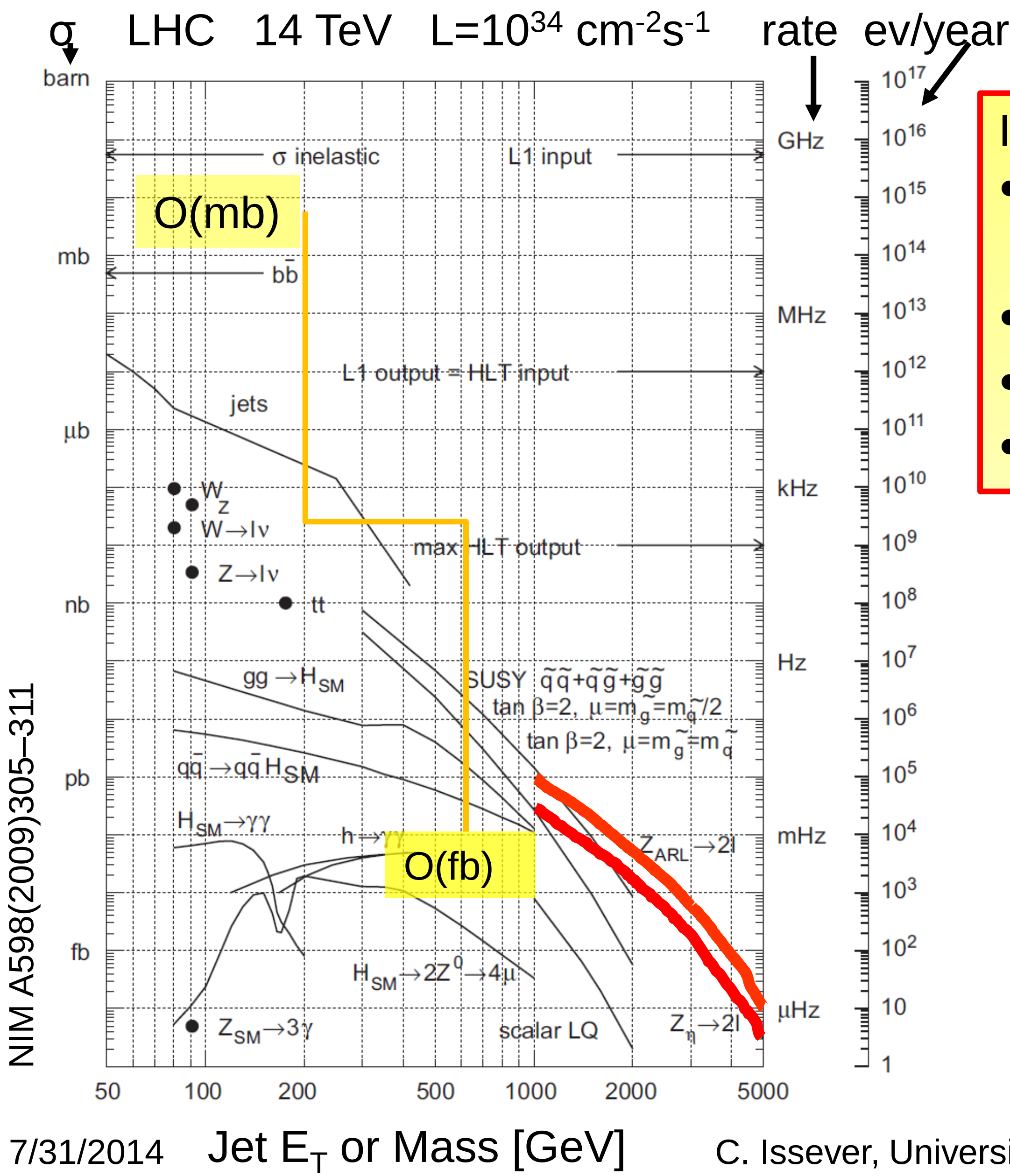
Delivered Integrated L: 23.3 fb^{-1}

Recorded Integrated L: 21.7 fb^{-1}

$1b = 10^{-24}\,cm^2$

$1fb = 10^{-39}\,cm^2$

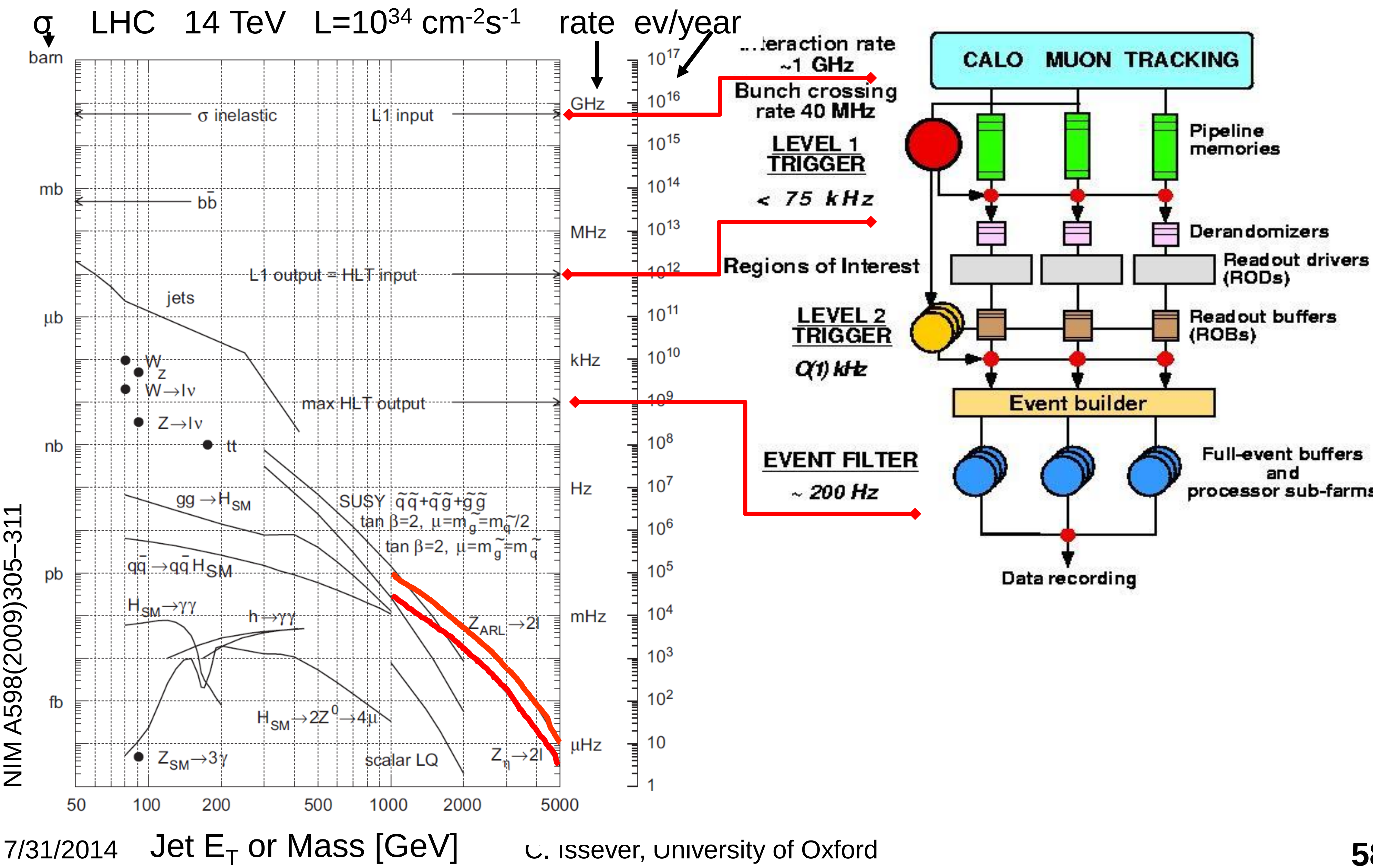
Rates of physics processes @ LHC



Interesting physics swamped by background

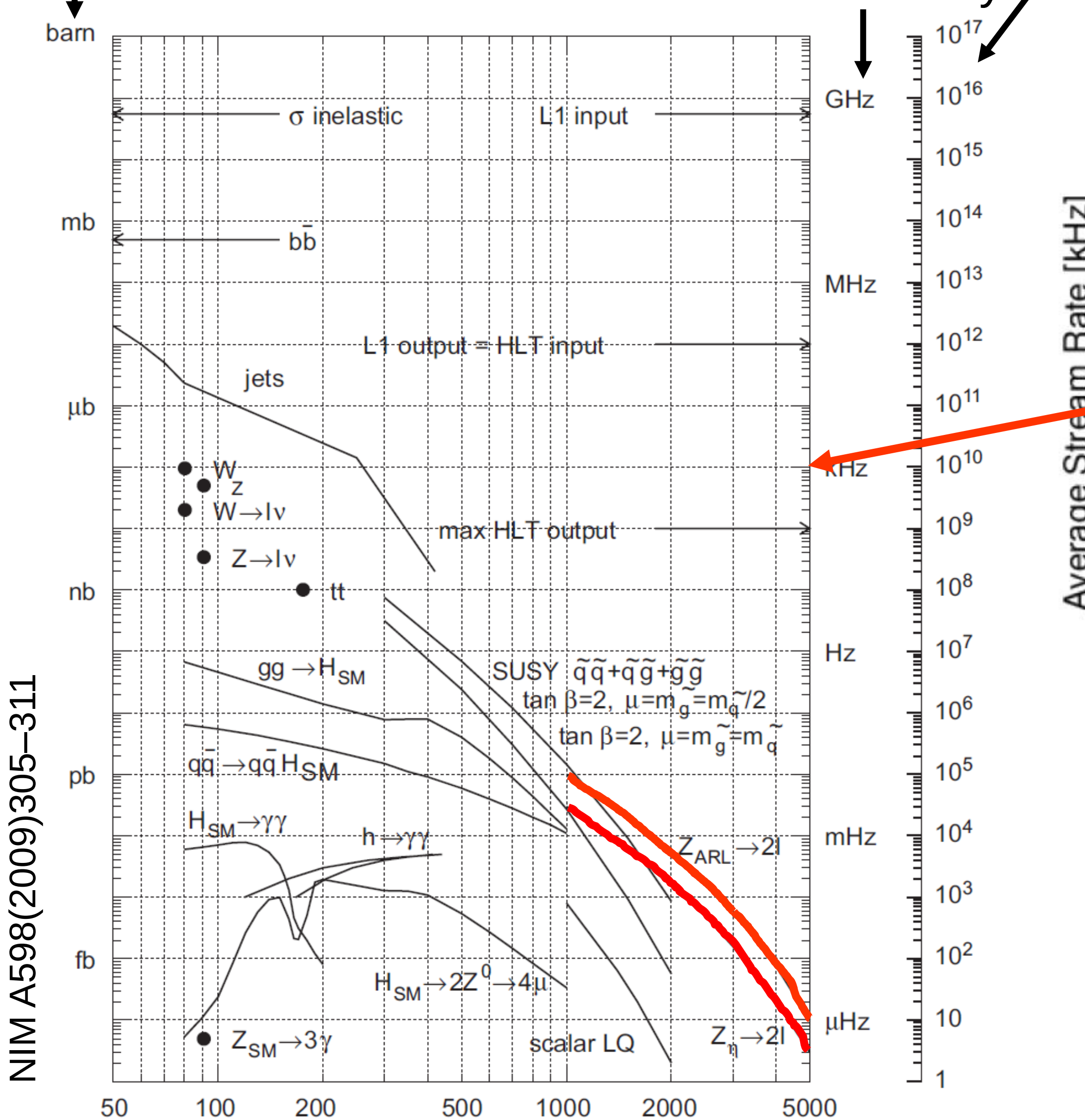
- Cross section for new physics:
  - ~10^{12} times lower !!
- Need to filter → TRIGGER SYSTEMS
- Carefully decide what to record
- You do not have another chance

Compare this to rates of physics processes

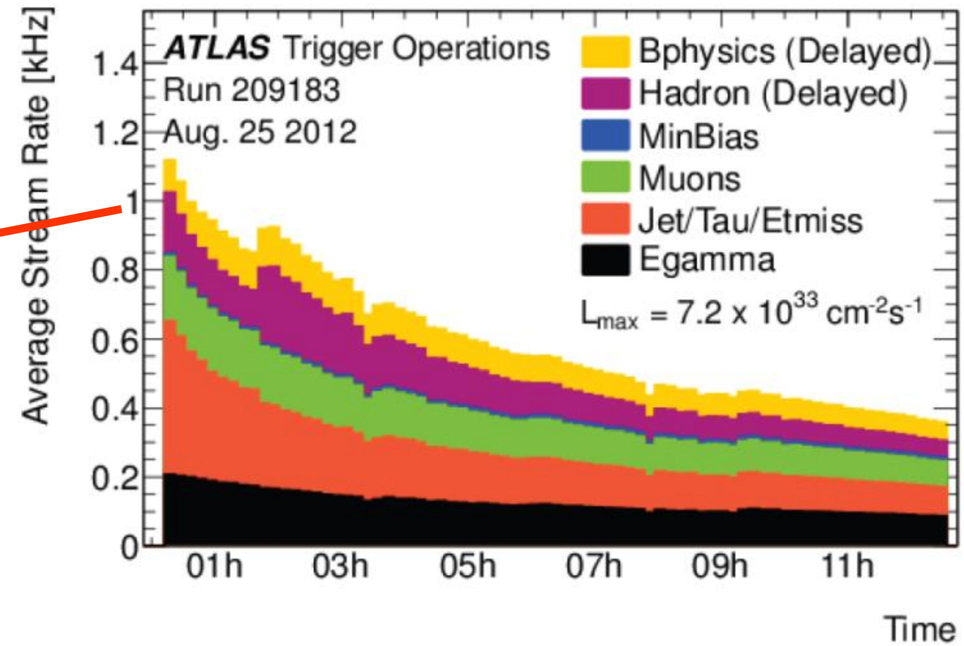


Compare this to rates of physics processes

σ LHC 14 TeV L=10^{34} $cm^{-2}s^{-1}$ rate ev/year



Jet E_T or Mass [GeV]



Dilepton Resonance Search: Trigger Strategy

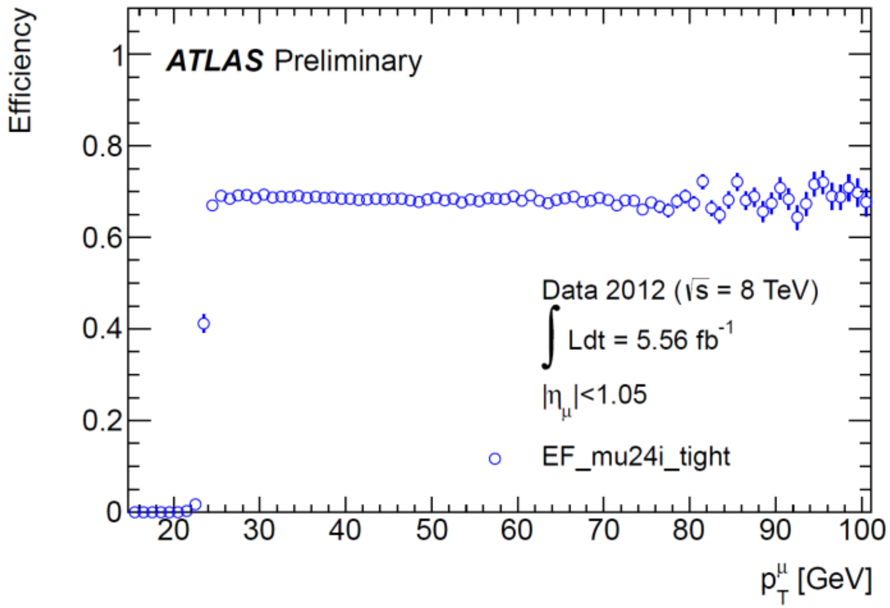
ATLAS

ee channel

- Diphoton trigger
- $E_T > 35$ GeV and $E_T > 25$ GeV

μμ channel

- Single muon triggers
- $E_T > 24$ GeV or $E_T > 36$ GeV



Takuya Nobe, ATL-DAQ-PROC-2012-067

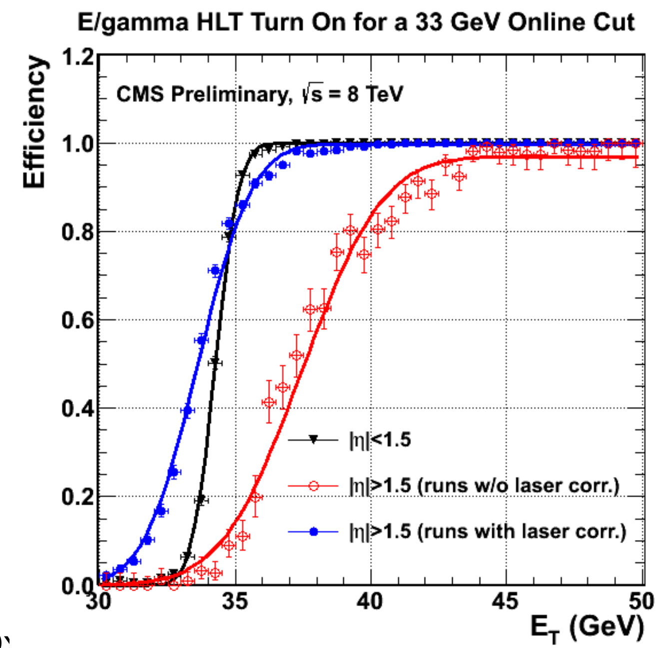
CMS

ee channel

- Dielectron trigger
- Both clusters w $E_T > 33$ GeV

μμ channel

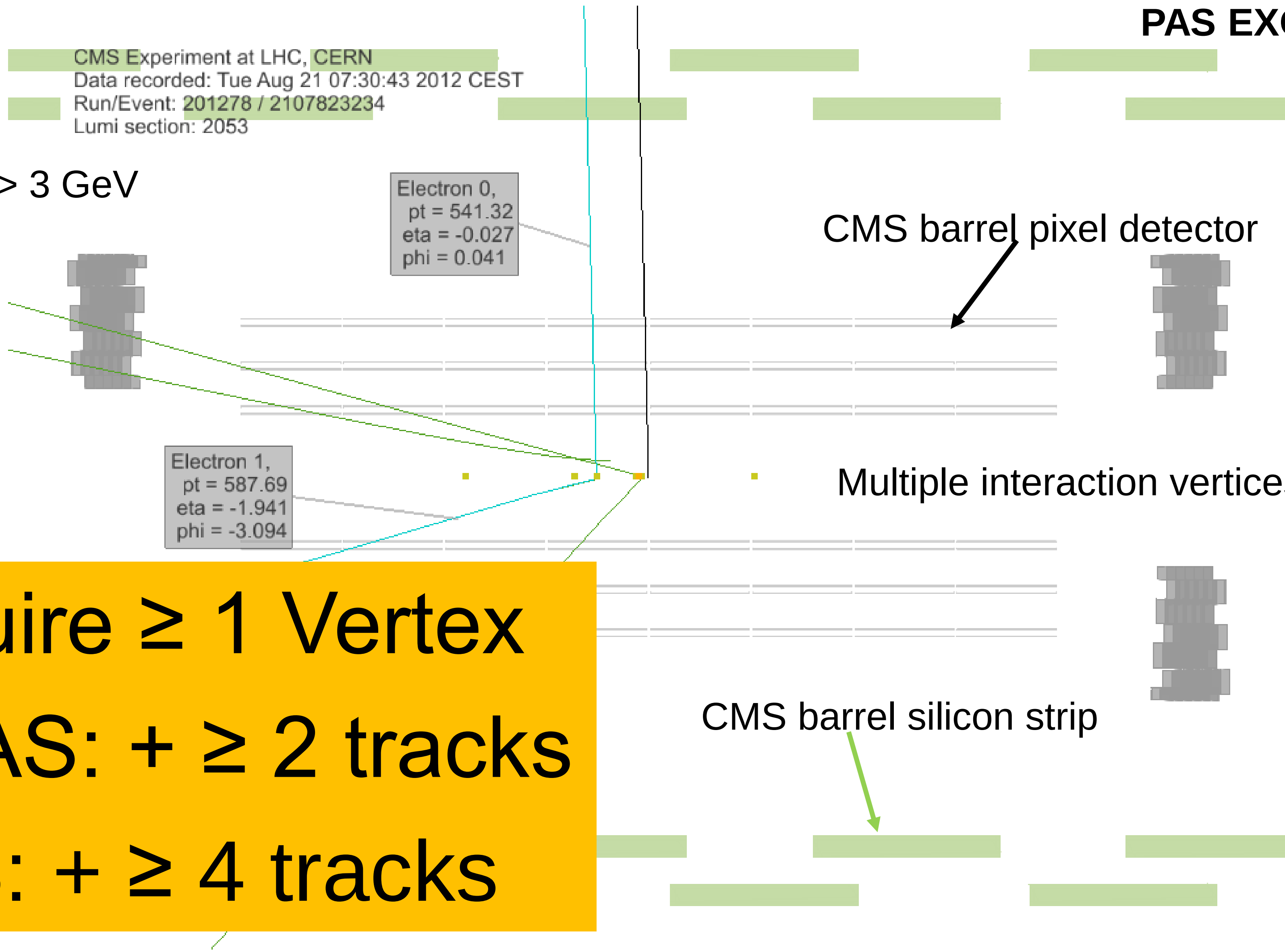
- single muon trigger
- $E_T > 40$ GeV



CMS Di-Electron Event Zoomed into **Inner Detector**

PAS EXO-12-061

Track pT > 3 GeV

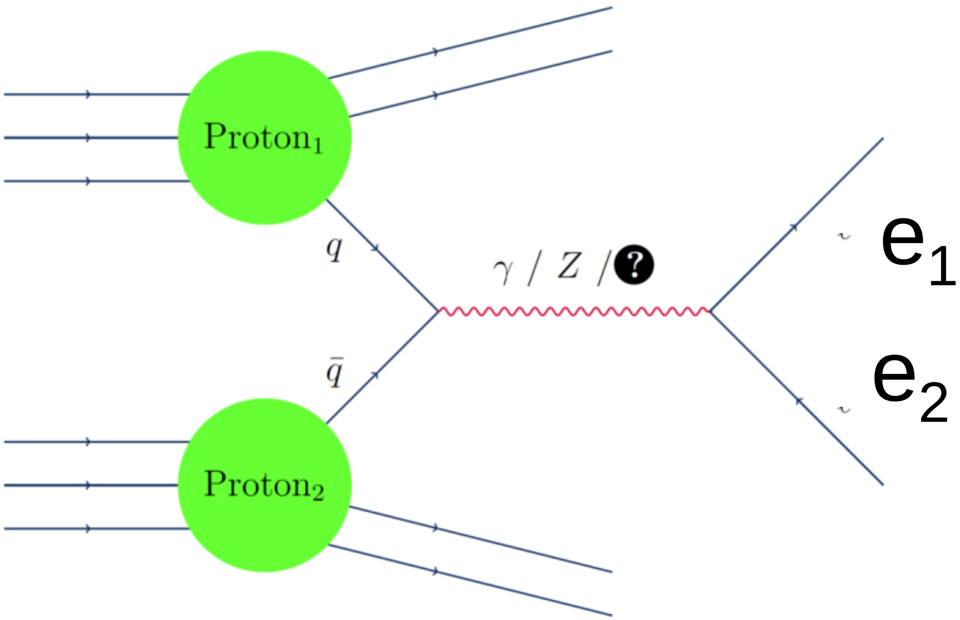


Require ≥ 1 Vertex

ATLAS: + ≥ 2 tracks

CMS: + ≥ 4 tracks

Selection for Di-Electron Channel

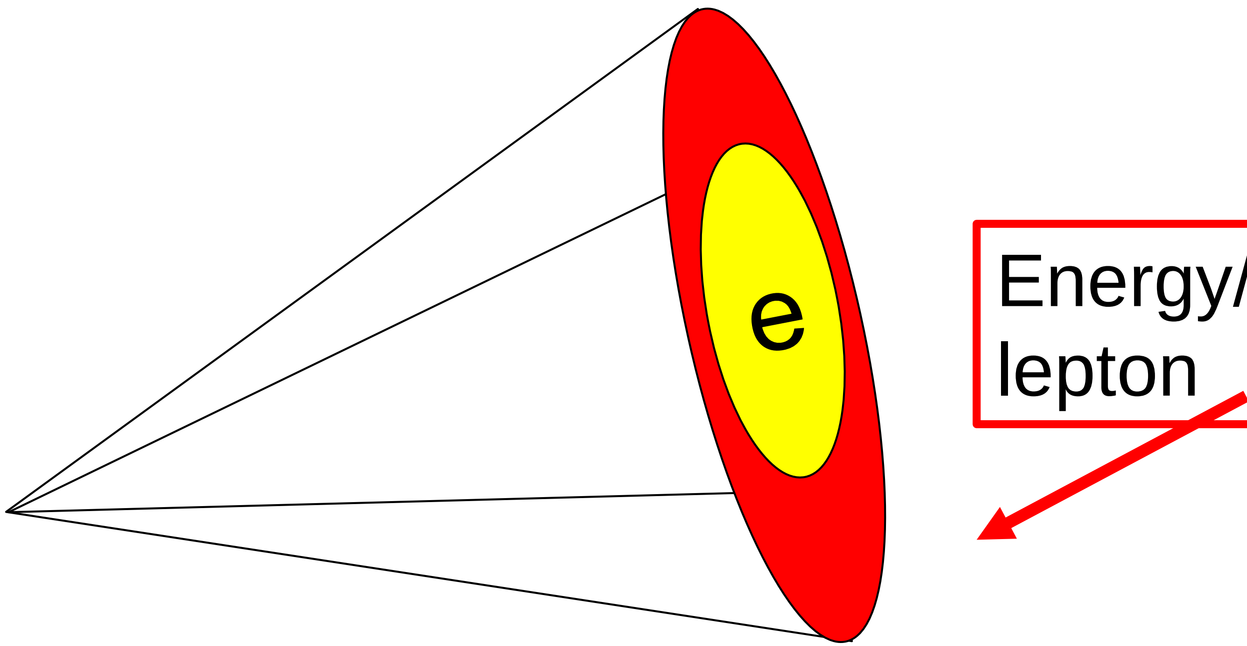


ATLAS	CMS
E_T^1>40GeV	E_T^1>35GeV
E_T^2>30GeV	E_T^2>35GeV

Problem: jets fake electrons

Use isolation to reduce fakes

Electron Isolation $I_{conesize}$



Energy/momentum around lepton

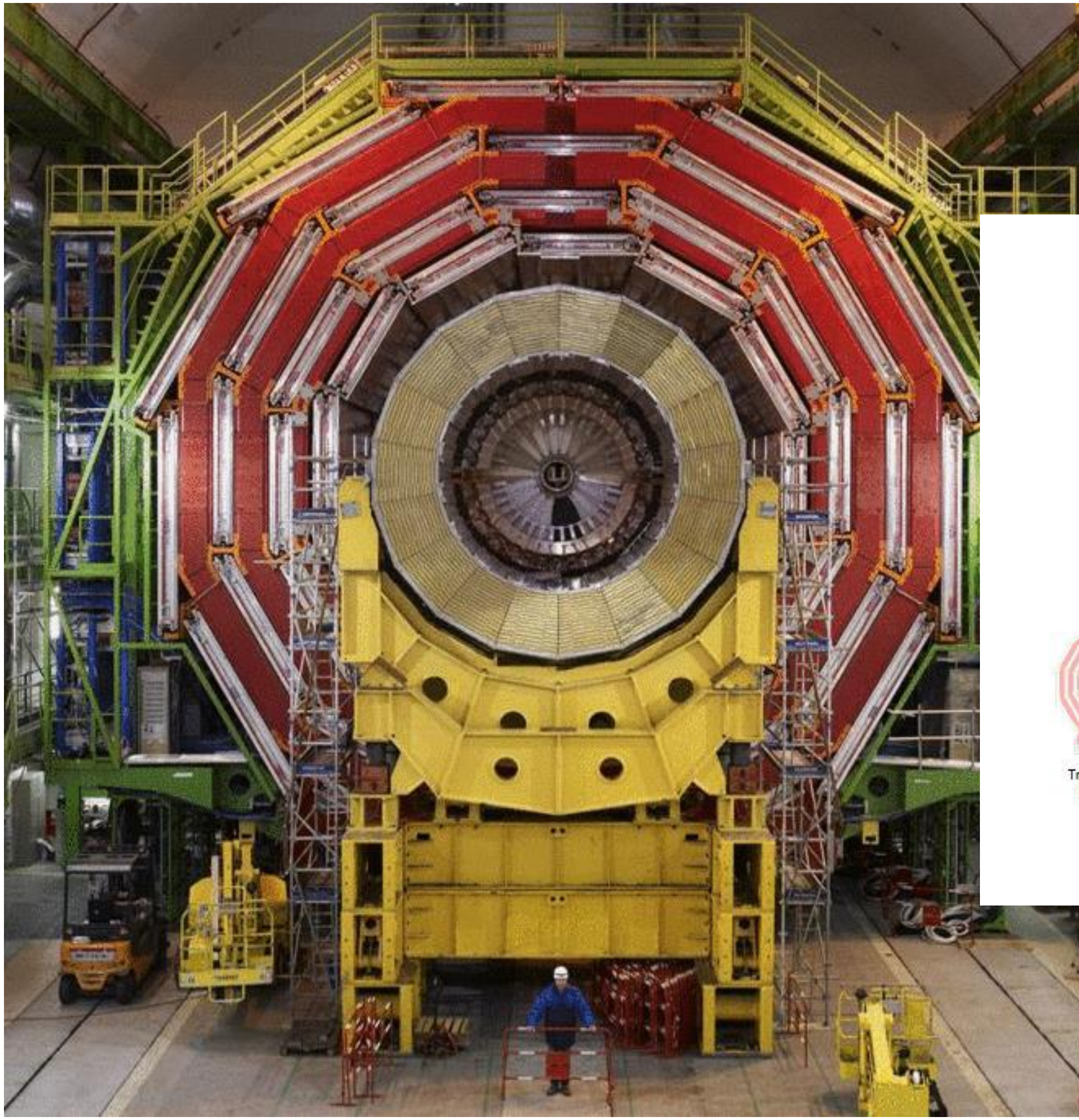
	ATLAS	CMS	
leading	$I^{calo}_{0.2}<0.7\%\cdot E_T + 5$ GeV	$I^{tracker}_{0.3}<5$ GeV	$I^{Calo}_{0.3}<3\%\cdot E_T$
subleading	$I^{calo}_{0.2} <2.2\%\cdot E_T + 6$ GeV		

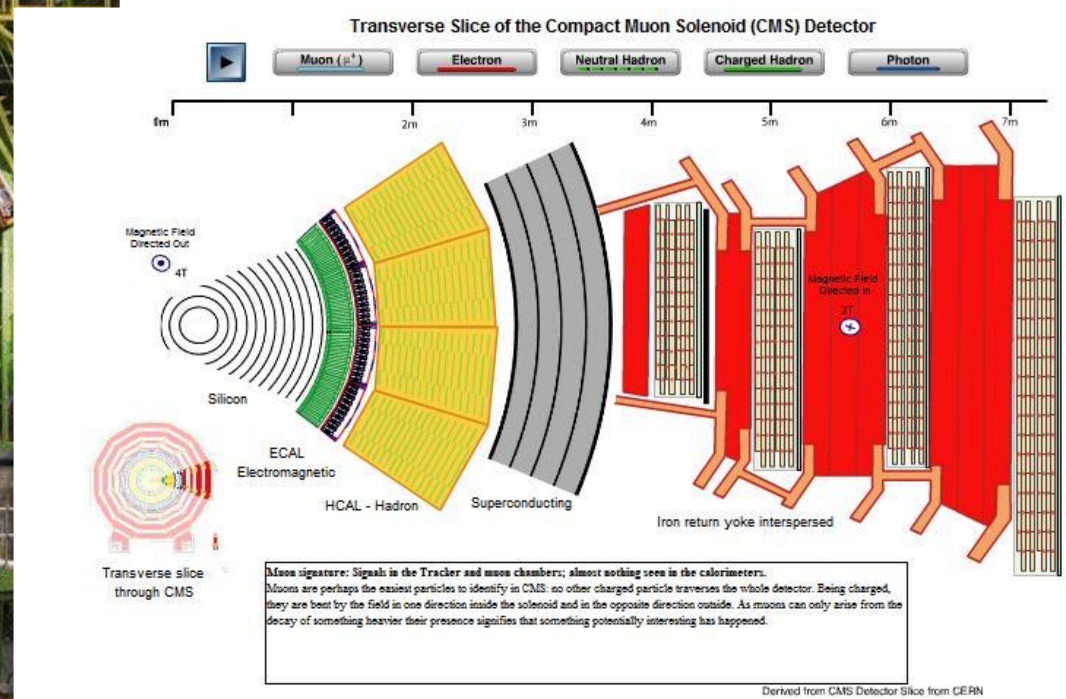
Acceptance x Efficiency after all Selections

ATLAS	CMS
$A \times \varepsilon(m = 2\ \text{TeV}) =$ **73%**	$A \times \varepsilon(m = 2.5\ \text{TeV}) =$ **67%**

Similar

Di-Muon Channel





Dilepton Resonance Search:: μμ selections

ATLAS

- Single muon triggers
- $p_T > 25$ GeV
- $|\eta|<2.4$
- Suppress cosmic rays
  - $|d_0| < 0.2$ mm
  - $|z_0\text{-}z(\text{vertex})|<1$ mm
- Suppress jets faking μ's
  - $\sum p_T(\Delta R<0.3) < 5\% \cdot p_T$
- Require opposite charge

CMS

- Single muon trigger
- $p_T > 45$ GeV
- $|\eta|<2.4$
- Suppress cosmic rays

  $|d_0| < 0.2$ mm

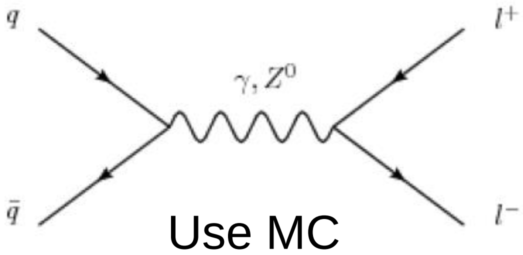
  $|z_0\text{-}z(\text{vertex})|<24$ cm
- Suppress jets faking μ's
  - $\sum p_T(\Delta R<0.3) < 10\% \cdot p_T$
  - $|z_0\text{-}z(\text{vertex})|< 0.2$mm
- Require opposite charge

Very different

$A \times \varepsilon(m = 2\text{ TeV}) = 46\%$ $A \times \varepsilon(m = 2.5\text{ TeV}) = 80\%$

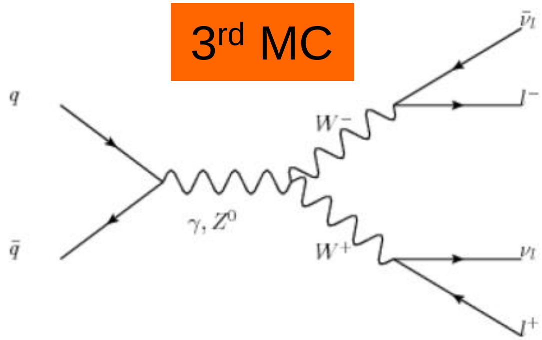
Dilepton Resonance Search: Backgrounds ee

dominant & irreducible



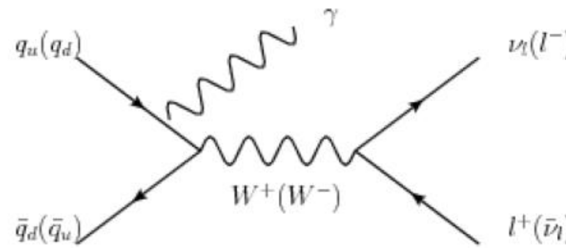
(a) Drell-Yan

3rd MC



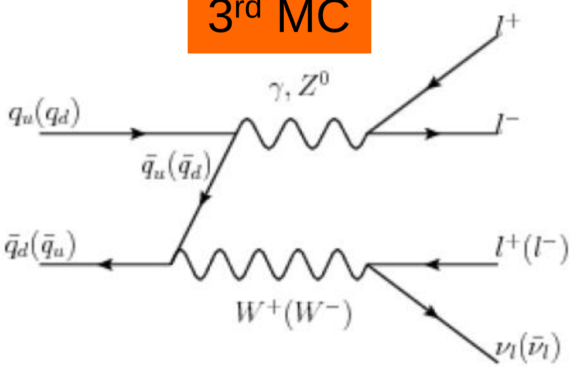
(b) WW

3rd MC



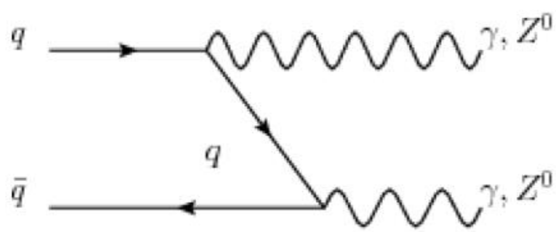
(c) Wγ

3rd MC



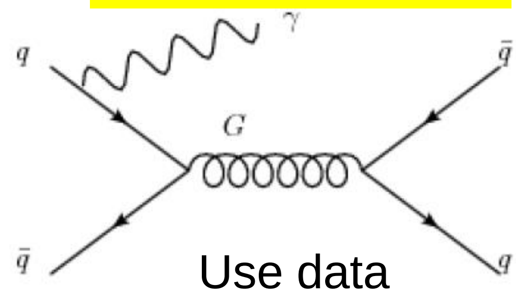
(d) WZ, Wγ

3rd MC



(e) ZZ,Zγ,$\gamma\gamma$

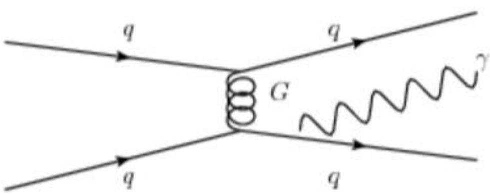
2nd for ee channel



(f) Dijets (without the external photon line),γ+jets

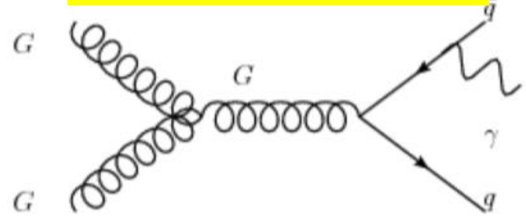
Dilepton Resonance Search: Backgrounds ee

2nd for ee channel data



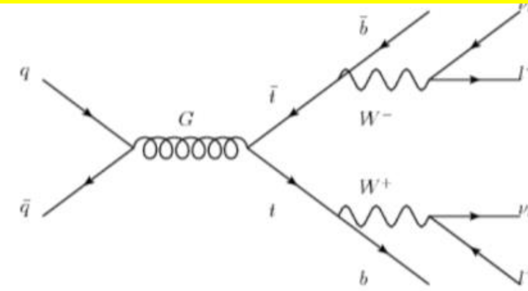
(g) Dijets (without the external photon line), γ+jets

2nd for ee channel data



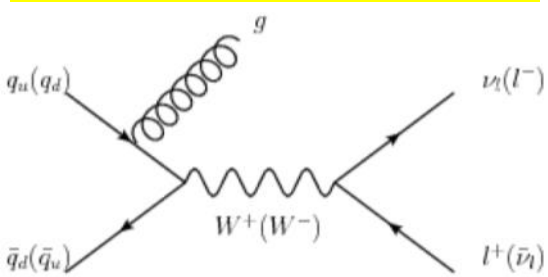
(h) Dijets (without the external photon line), γ+jets

2nd for ee channel semi-leptonic

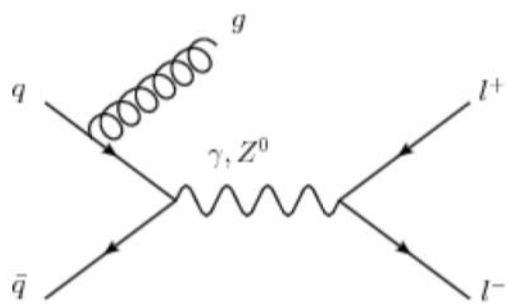


(i) $t\bar{t}$

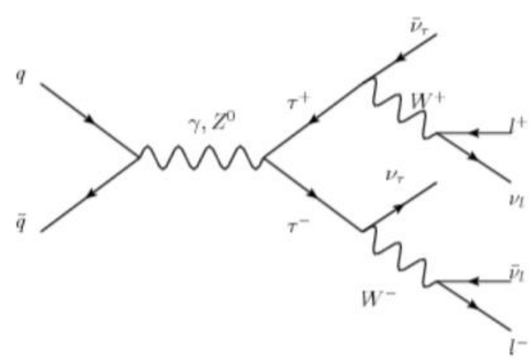
2nd for ee channel data



(j) W+jets



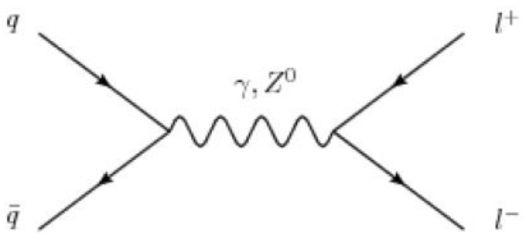
(k) Z+jets



(l) DY to tauons to leptons

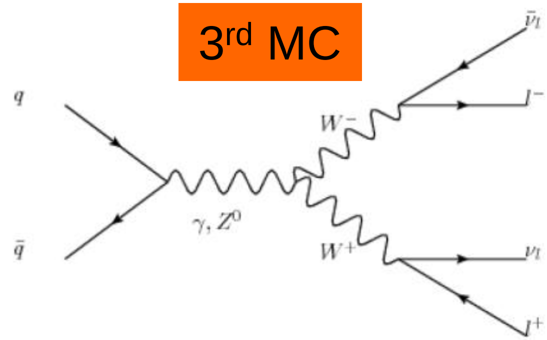
Dilepton Resonance Search: Backgrounds μμ

dominant & irreducible mc



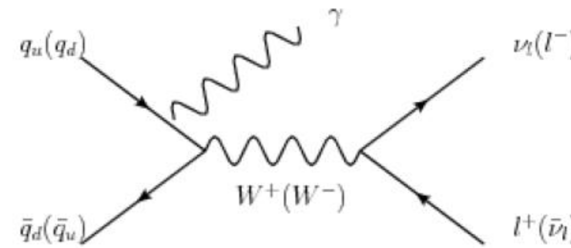
(a) Drell-Yan

3rd MC



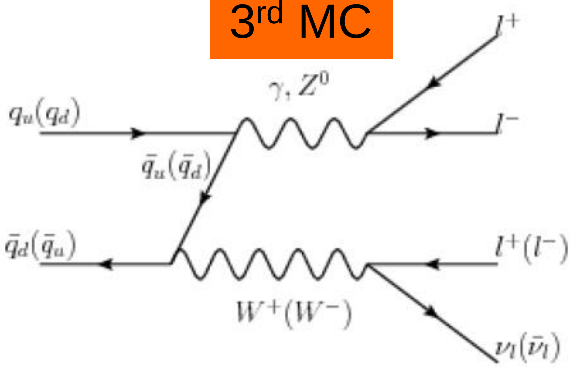
(b) WW

3rd MC



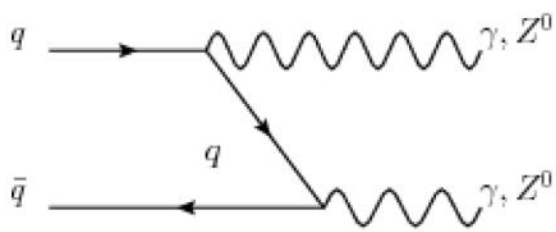
(c) Wγ

3rd MC

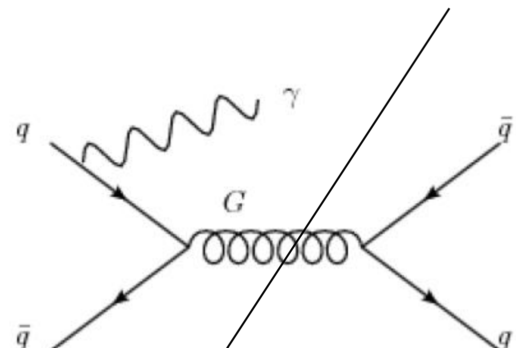


(d) WZ, Wγ

3rd MC



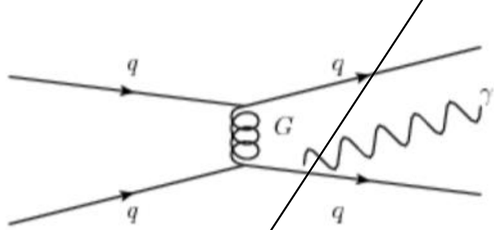
(e) ZZ,Zγ,γγ



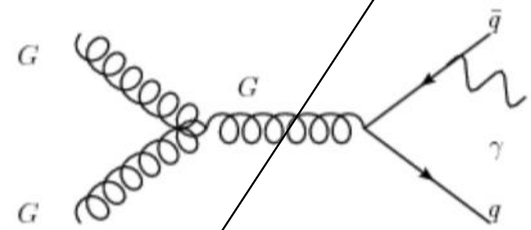
(f) Dijets (without the external photon line),γ+jets

Dilepton Resonance Search: Backgrounds μμ

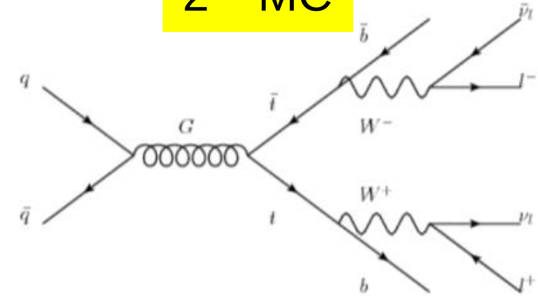
2nd MC



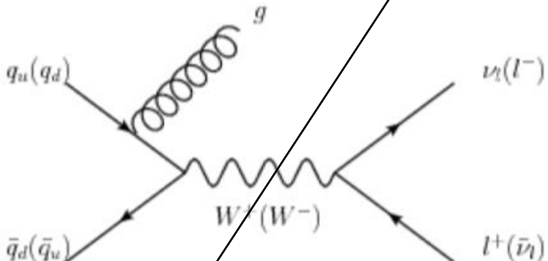
(g) Dijets (without the external photon line), γ+jets



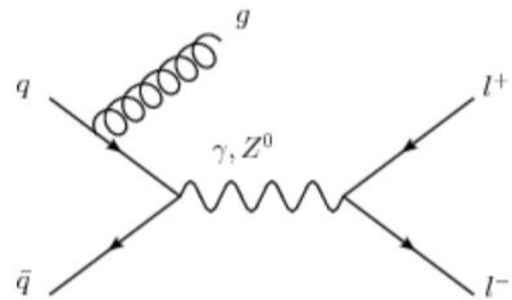
(h) Dijets (without the external photon line), γ+jets



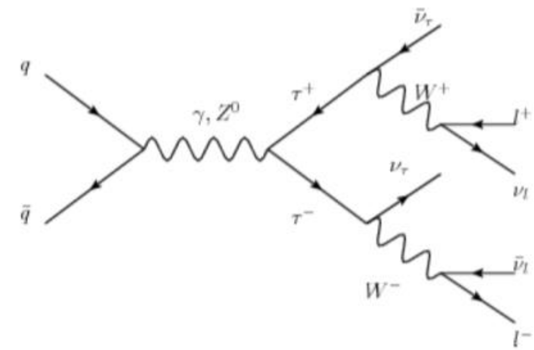
(i) $t\bar{t}$



(j) W+jets



(k) Z+jets



(l) DY to tauons to leptons

Heavy Resonances Search: 8 TeV Dileptons

Backgrounds

- SM Drell-Yan: $\gamma^*/Z \to l^+l^-$
  - shape taken from Monte Carlo
  - normalisation taken from Z peak in data
- t-tbar:
  - where tt goes to e+e-, mu+mu-
  - est. from MC, cross-checked in data
  - also includes $Z \to \tau\tau$, WW, WZ

ee and μμ

- Jet Background:
  - di-jet, W+jet events where the jets are misidentified as electrons/muons

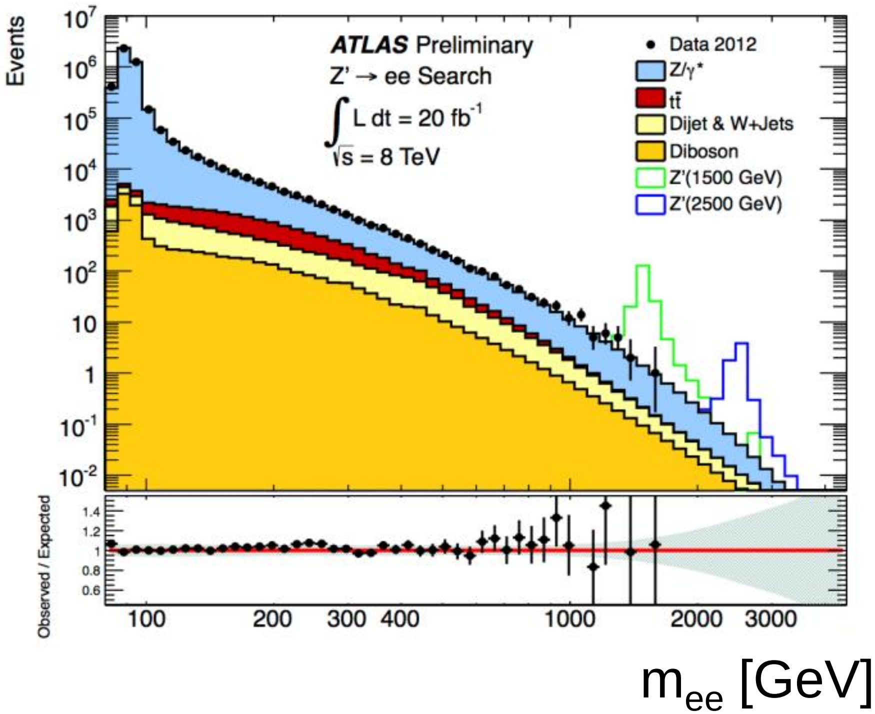
ee

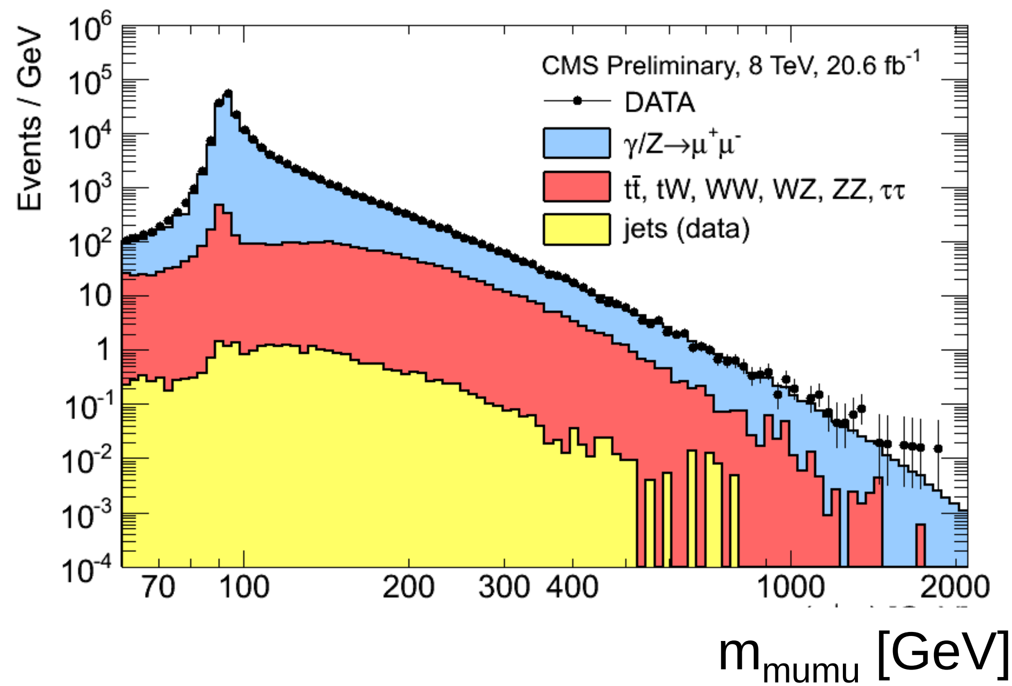
- Cosmic Ray Background:
  - muons from cosmic rays
  - estimated <0.1 event after vertex and angular difference requirements

μμ

Dilepton Search: The Discriminant

ATLAS-CONF-2013-017
PAS EXO-12-061





Invariant mass reach of 1 - 2 TeV

Dilepton Resonance Search: Systematic Uncertainties

Source	Dielectrons		Dimuons	
	Signal	Background	Signal	Background
Normalization	5%	NA	5%	NA
PDF variation	NA	15%	NA	15%
PDF choice	NA	17%	NA	17%
Scale	NA	-	NA	-
α_s	NA	4%	NA	4%
Electroweak corrections	NA	3%	NA	3%
Photon-induced corrections	NA	4%	NA	4%
Efficiency	-	-	6%	6%
Resolution	-	-	-	3% (7%)
W + jet and multi-jet background	NA	9%	NA	-
Diboson and ttbar extrapolation	NA	5%	NA	4%
Total	5%	26%	8%	25% (26%)

Heavy Resonances Search: 8 TeV Dileptons

m_{ee} [GeV]	110 - 200	200 - 400	400 - 800	800 - 1200	1200 - 3000	3000 - 4500
Z/γ^*	119000 ± 8000	13700 ± 900	1290 ± 80	68 ± 4	9.8 ± 1.1	0.008 ± 0.005
$t\bar{t}$	7000 ± 800	2400 ± 400	160 ± 60	2.5 ± 0.6	0.11 ± 0.04	< 0.001
Diboson	1830 ± 210	660 ± 160	93 ± 33	4.8 ± 0.8	0.79 ± 0.26	0.005 ± 0.004
Dijet, W + jet	3900 ± 800	1260 ± 310	230 ± 110	8.6 ± 2.4	0.9 ± 0.6	0.004 ± 0.006
Total	131000 ± 8000	18000 ± 1100	1780 ± 150	84 ± 5	11.6 ± 1.3	0.017 ± 0.009
Data	133131	18570	1827	98	10	0

ATLAS-CONF-2013-017

$m_{\mu\mu}$[GeV]	110 - 200	200 - 400	400 - 800	800 - 1200	1200 - 3000	3000 - 4500
Z/γ^*	111000 ± 8000	11000 ± 1000	1000 ± 100	49 ± 5	7.3 ± 1.3	0.033 ± 0.029
$t\bar{t}$	5900 ± 900	1900 ± 400	140 ± 60	2.7 ± 0.7	0.16 ± 0.08	< 0.001
Diboson	1520 ± 190	520 ± 140	62 ± 26	2.8 ± 1.0	0.38 ± 0.28	0.002 ± 0.003
Total	118000 ± 8000	13300 ± 1100	1160 ± 120	55 ± 5	7.8 ± 1.3	0.035 ± 0.029
Data	118701	13349	1109	48	8	0

What do you do now?

- Observed numbers consistent with background???
- Many ways to do it → Statistics Lectures/Tutorial
- One way e.g.:
  - $P(n \geq n_{obs}) = 1 - f(n; s = 0; b) = 1 - \sum_{n=0}^{n_{obs}-1} \frac{b^n}{n!} e^{-b}$
  - Probability, assuming s = 0, to observe as many events or more for a given expected background amount, b.
- For 800 – 1200 GeV bin in μμ
  - b = 55, n_{obs}=48 →P=84%

Heavy Resonances Search: 8 TeV Dileptons

ATLAS-CONF-2013-017

m_{ee} [GeV]	110 - 200	200 - 400	400 - 800	800 - 1200	1200 - 3000	3000 - 4500
Z/γ^*	119000 ± 8000	13700 ± 900	1290 ± 80	68 ± 4	9.8 ± 1.1	0.008 ± 0.005
$t\bar{t}$	7000 ± 800	2400 ± 400	160 ± 60	2.5 ± 0.6	0.11 ± 0.04	< 0.001
Diboson	1830 ± 210	660 ± 160	93 ± 33	4.8 ± 0.8	0.79 ± 0.26	0.005 ± 0.004
Dijet, W + jet	3900 ± 800	1260 ± 310	230 ± 110	8.6 ± 2.4	0.9 ± 0.6	0.004 ± 0.006
Total	131000 ± 8000	18000 ± 1100	1780 ± 150	84 ± 5	11.6 ± 1.3	0.017 ± 0.009
Data	133131	18570	1827	98	10	0

Analysis: P(ee) = 18%

Analysis: P(μμ) = 98%

$m_{\mu\mu}$[GeV]	110 - 200	200 - 400	400 - 800	800 - 1200	1200 - 3000	3000 - 4500
Z/γ^*	111000 ± 8000	11000 ± 1000	1000 ± 100	49 ± 5	7.3 ± 1.3	0.033 ± 0.029
$t\bar{t}$	5900 ± 900	1900 ± 400	140 ± 60	2.7 ± 0.7	0.16 ± 0.08	< 0.001
Diboson	1520 ± 190	520 ± 140	62 ± 26	2.8 ± 1.0	0.38 ± 0.28	0.002 ± 0.003
Total	118000 ± 8000	13300 ± 1100	1160 ± 120	55 ± 5	7.8 ± 1.3	0.035 ± 0.029
Data	118701	13349	1109	48	8	0

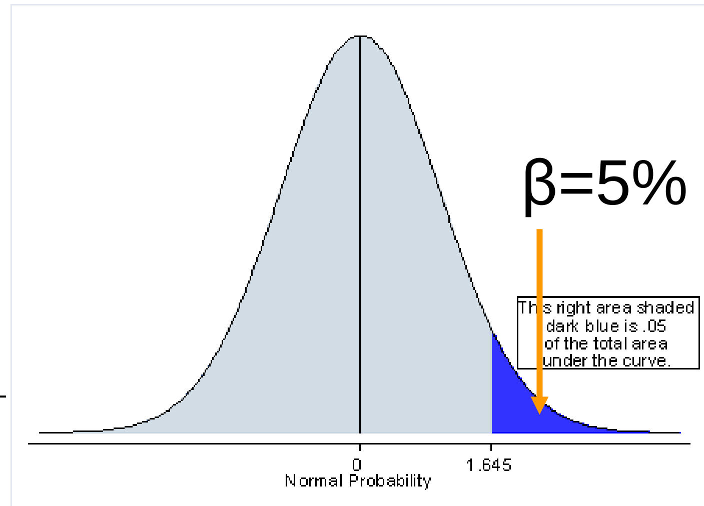
No deviation from expectation found.

We did not find any deviation…..

- Quantify the sensitivity and reach of our analysis
- Again, many ways to do it….
  - “Religious” wars are being fought about this…..

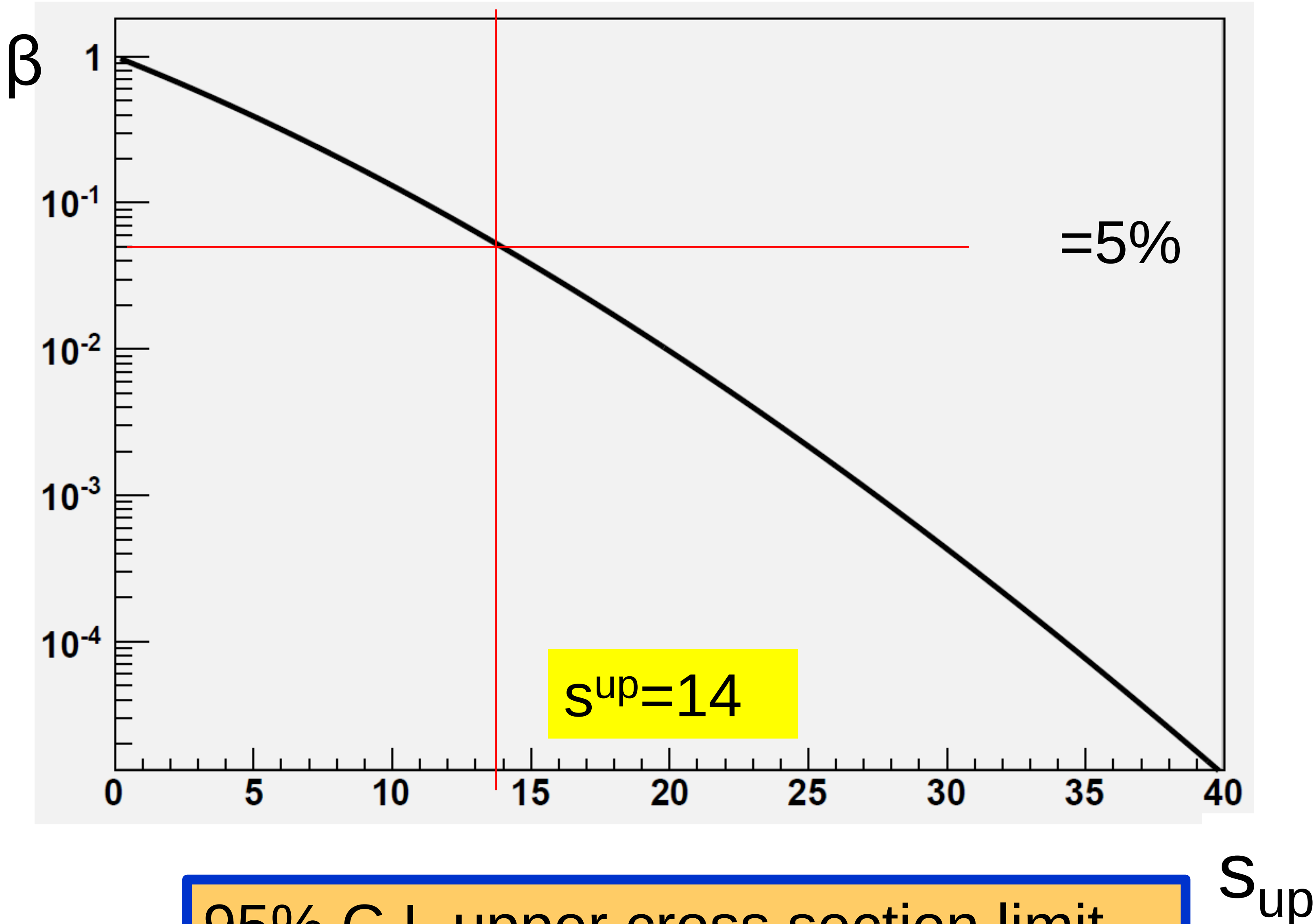
Back of the envelope demonstration…..to get the idea

- $n_{obs} = s + b$
- We want an upper limit (bound on s) given we expect b background events and have observed n_{obs} events.
- Use Bayesian method with uniform prior density
- $\beta = e^{-s^{up}} \sum_{n-0}^{n_{obs}} (s^{up})^n / n!$ solve this numerical
- We ignore error on b….
- We ignore systematic errors



- $\beta = e^{-s^{up}} \sum_{n-0}^{n_{obs}} (s^{up})^n / n!$ solve this numerical

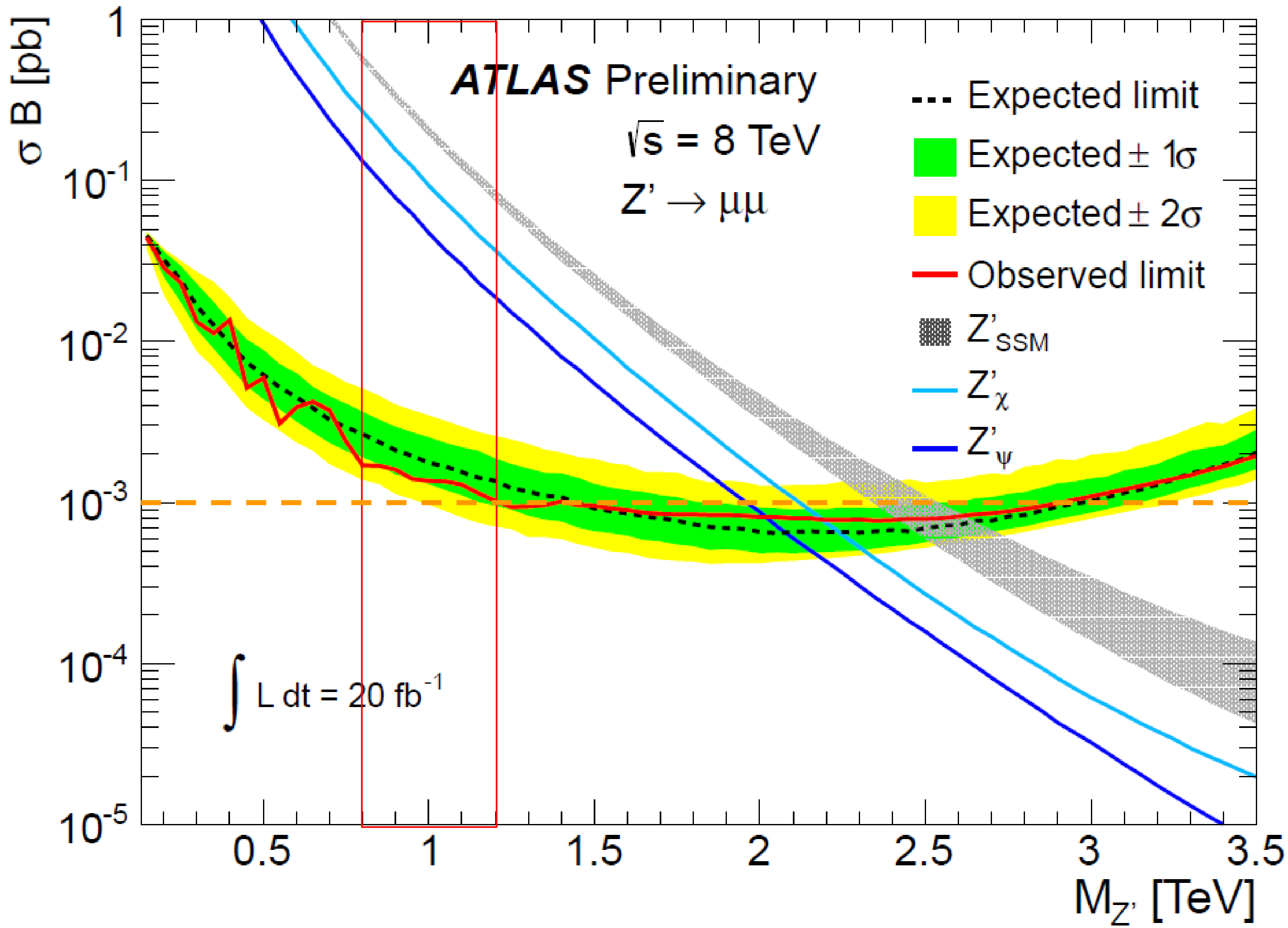
- Back to our example
  - 800 GeV < $m_{\mu\mu}$ < 1200 GeV
  - We have observed n_{obs} = 48 events
  - We expect b=55 background events
  - Our Acceptance x Efficiency ~ 50%
  - We have analysed L = 20 fb-1 of data



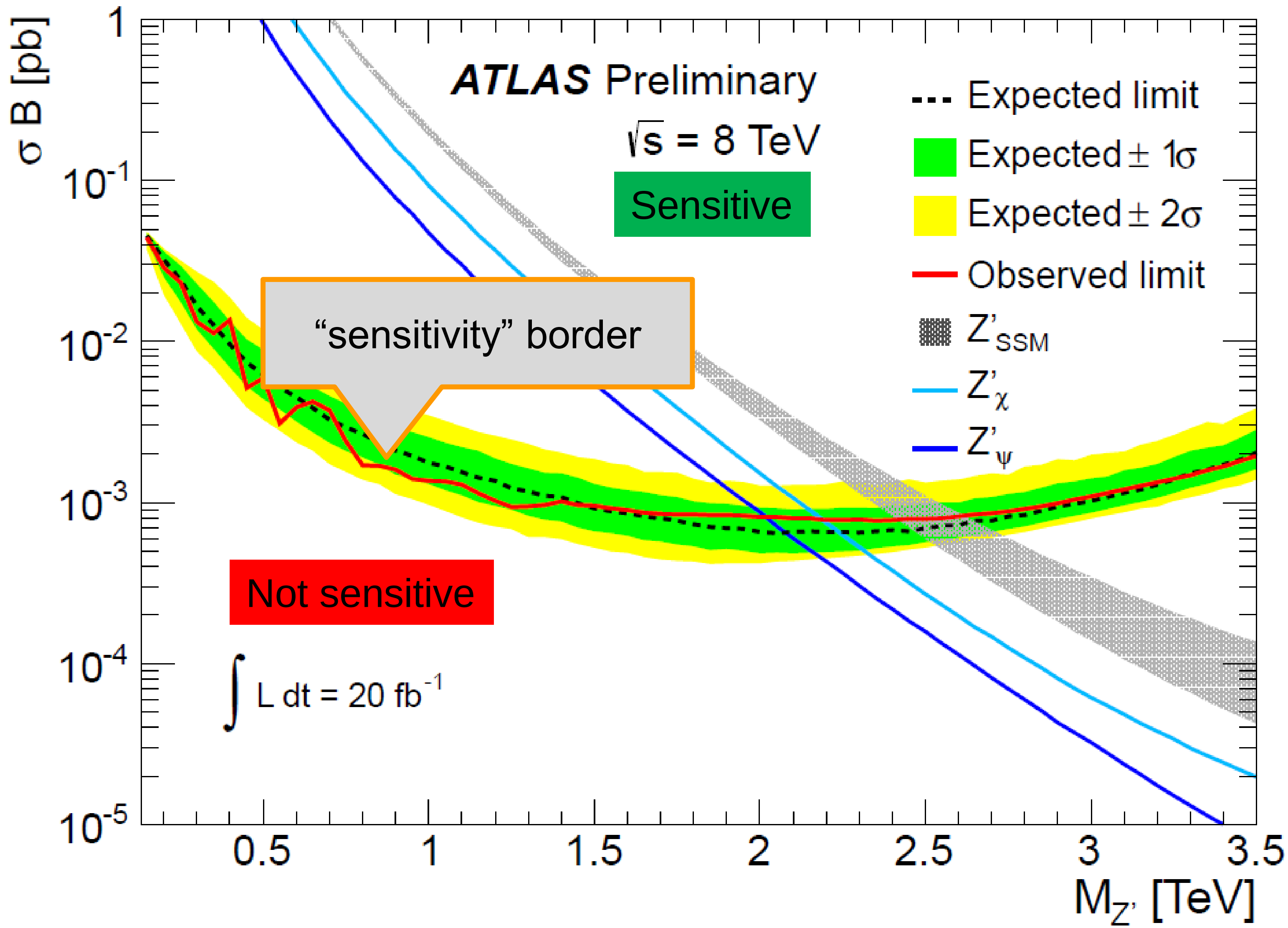
95% C.I. upper cross section limit

14/20fb-1 = 0.7fb ~ 1fb = $\mathbf{10^{-3}}$ **pb**

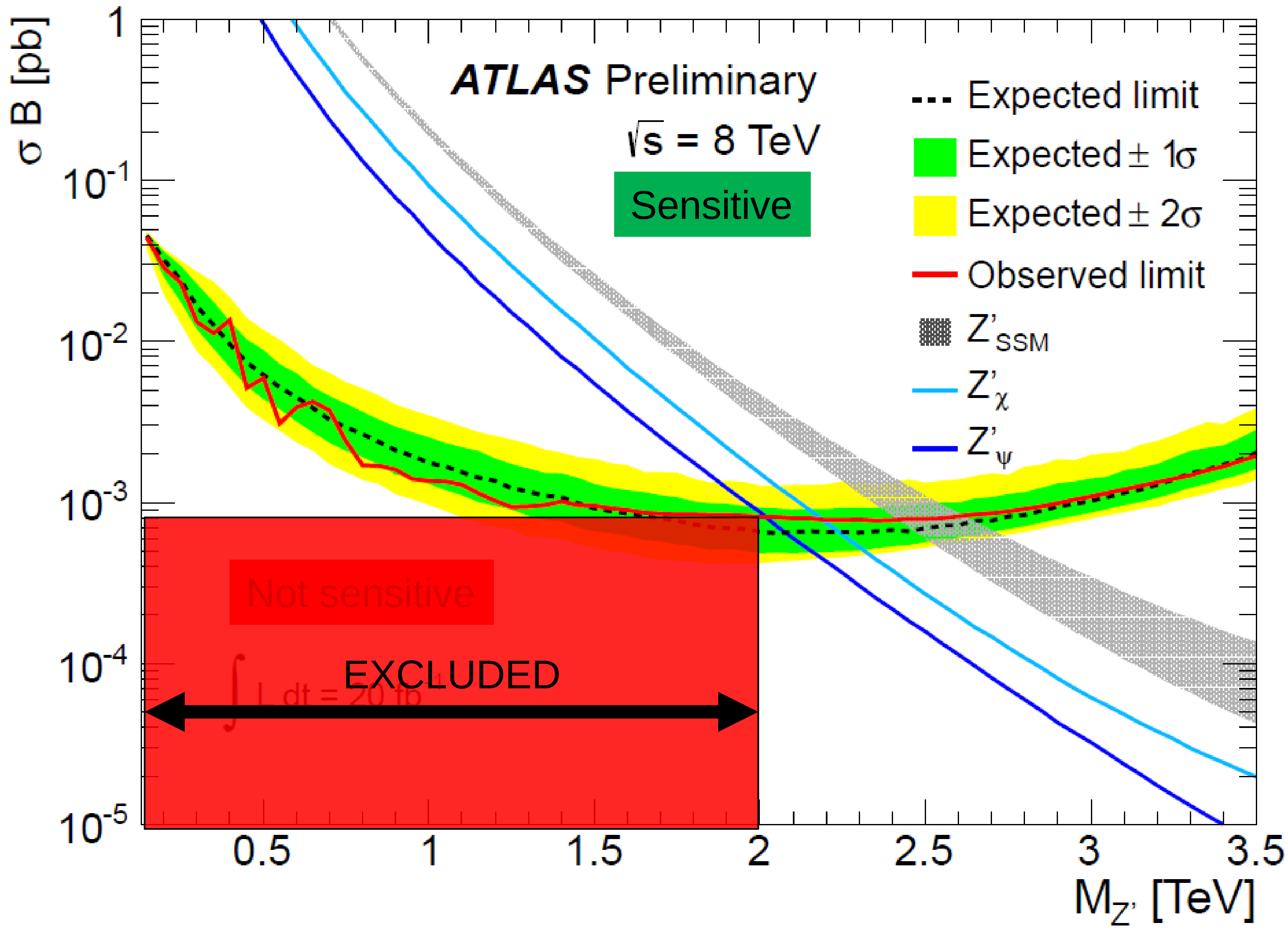
Let us compare with the published limit…



Let us compare with the published limit…

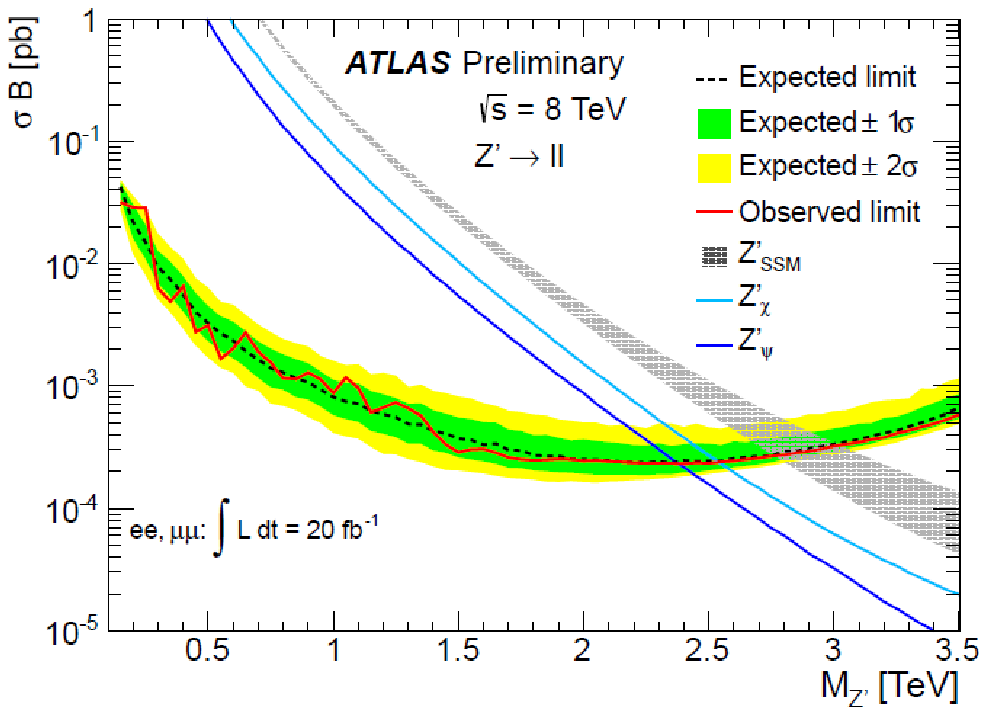


Let us compare with the published limit…

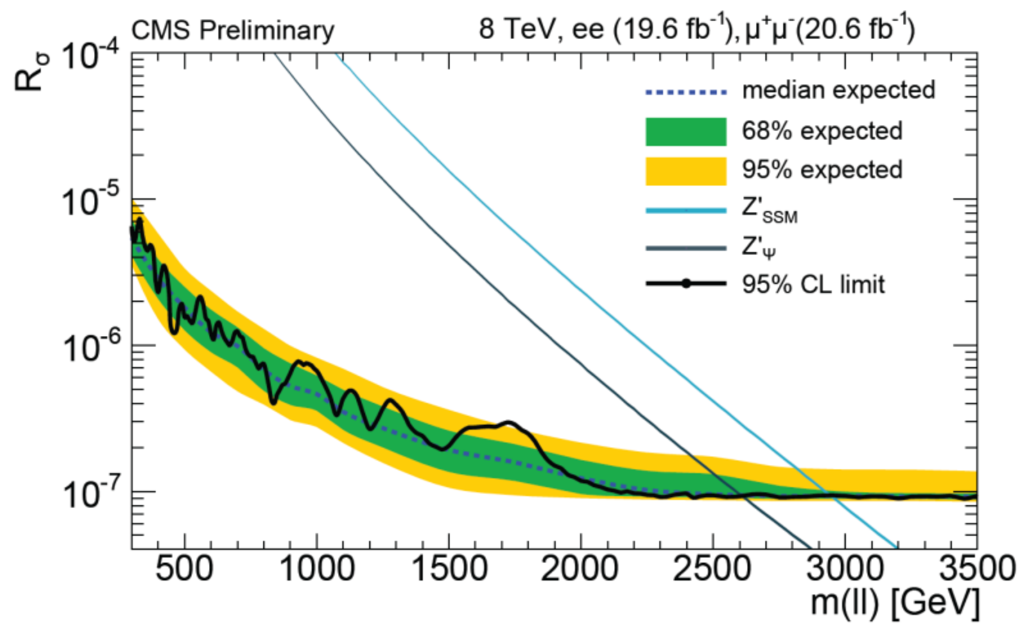


Limits for both channels combined

ATLAS



CMS

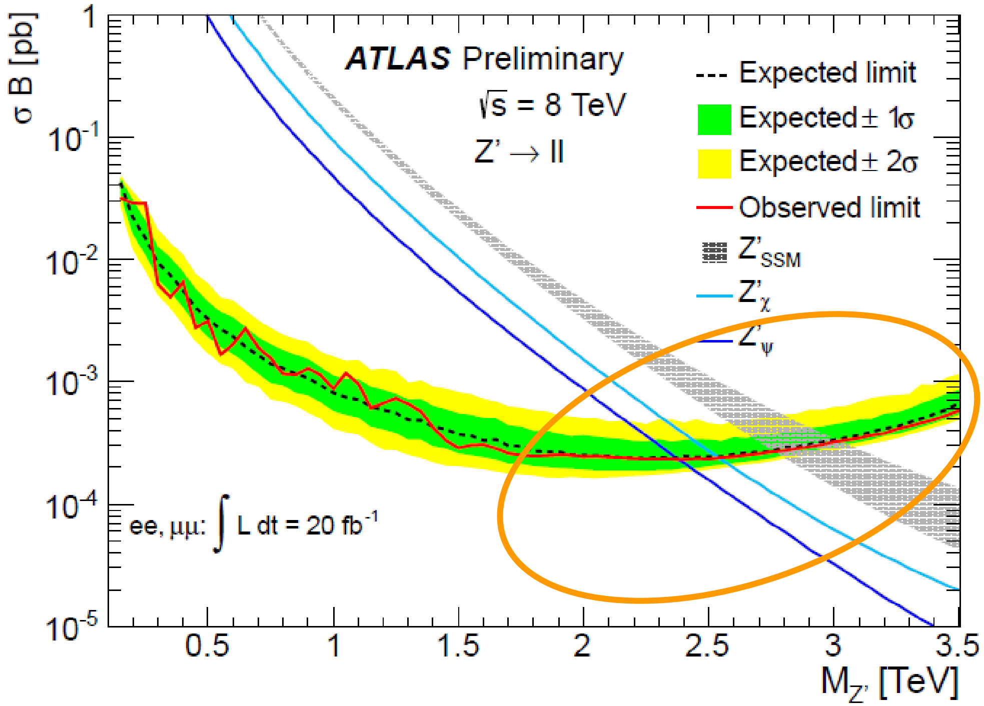


Z'_{SSM} > 2.86 TeV@ 95% C.L.

Z'_{SSM} > 2.96 TeV@ 95% C.L.

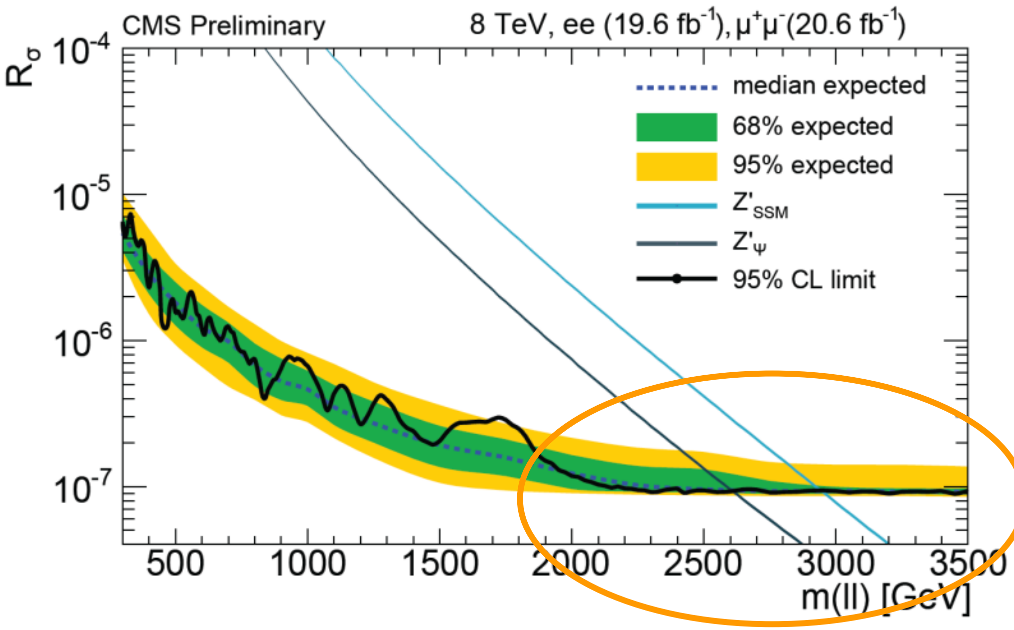
Let us discuss a bit the difference btw ATLAS/CMS

ATLAS



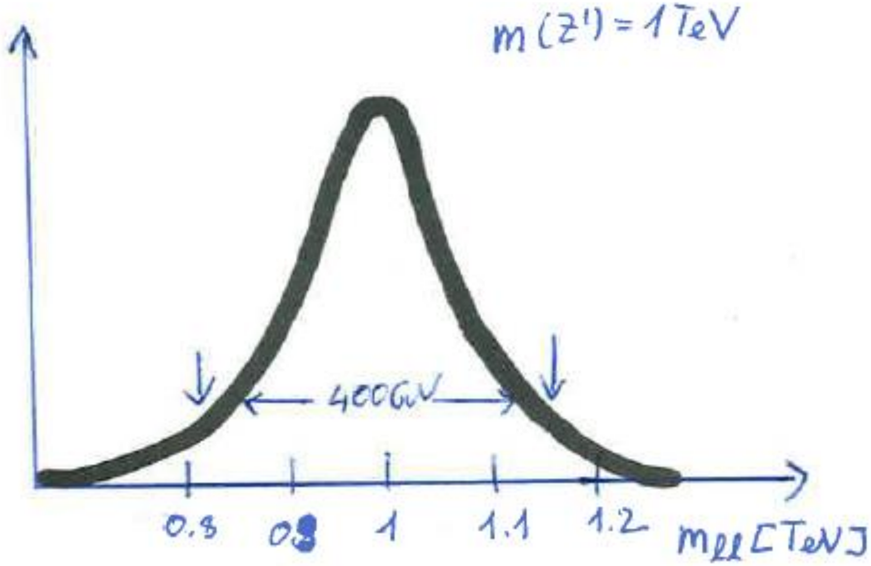
$Z'_{SSM} > 2.86$ TeV@ 95% C.L.

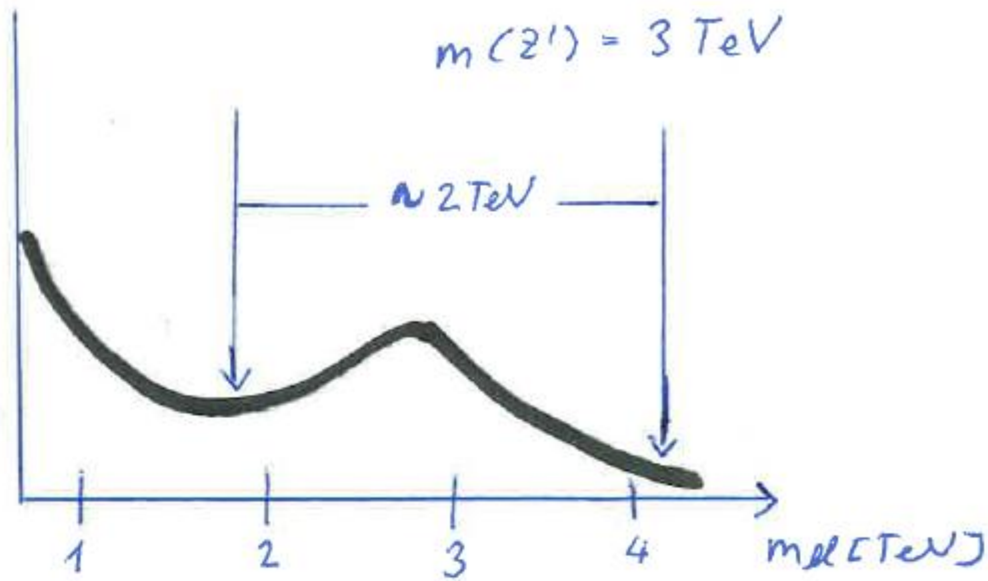
CMS

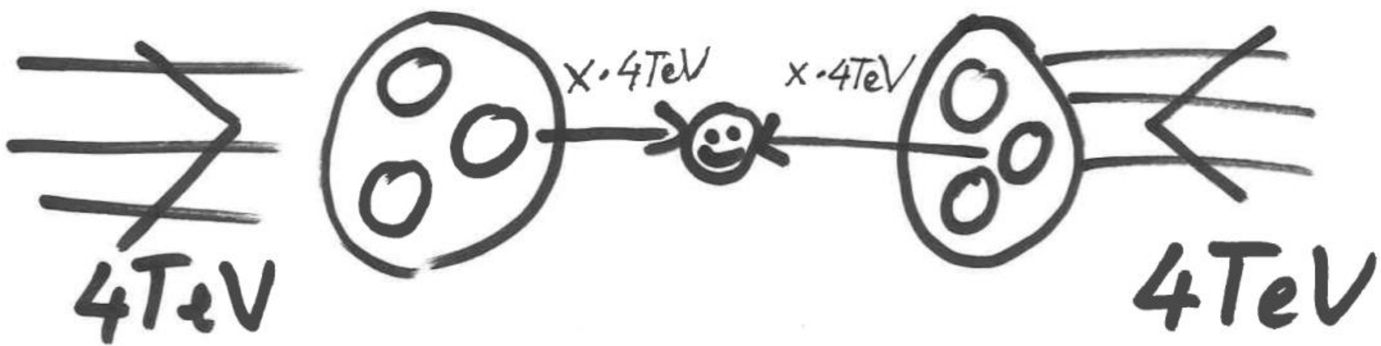


$Z'_{SSM} > 2.96$ TeV@ 95% C.L.

Signal Shapes and Parton Luminosities



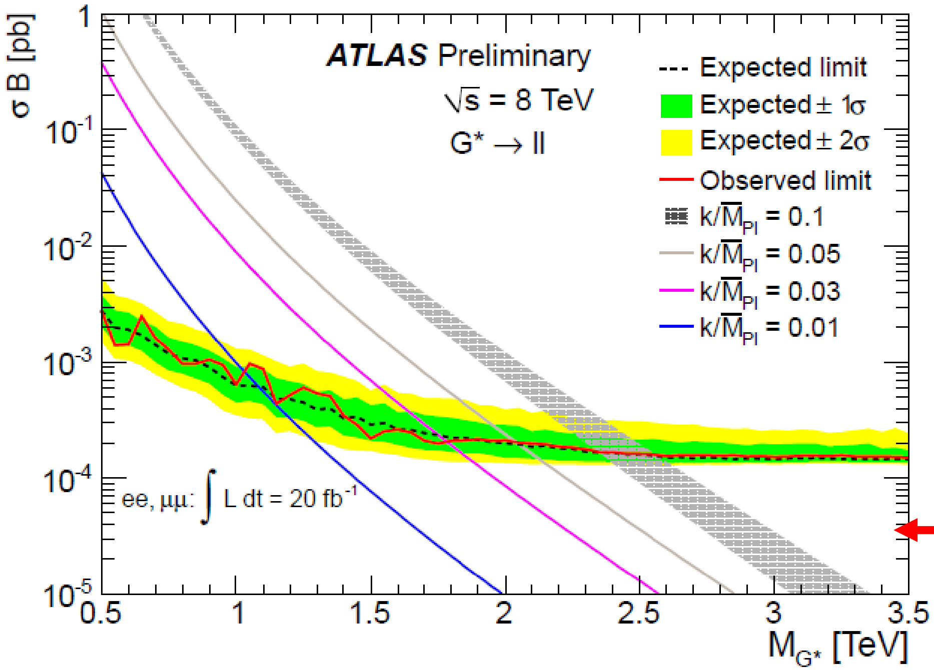




ATLAS CMS Differences in the Limit Setting

ATLAS

- Uses signal templates for limits
- Loss of sensitivity at high masses
  - Parton luminosities
- Upper cross section limits model specific



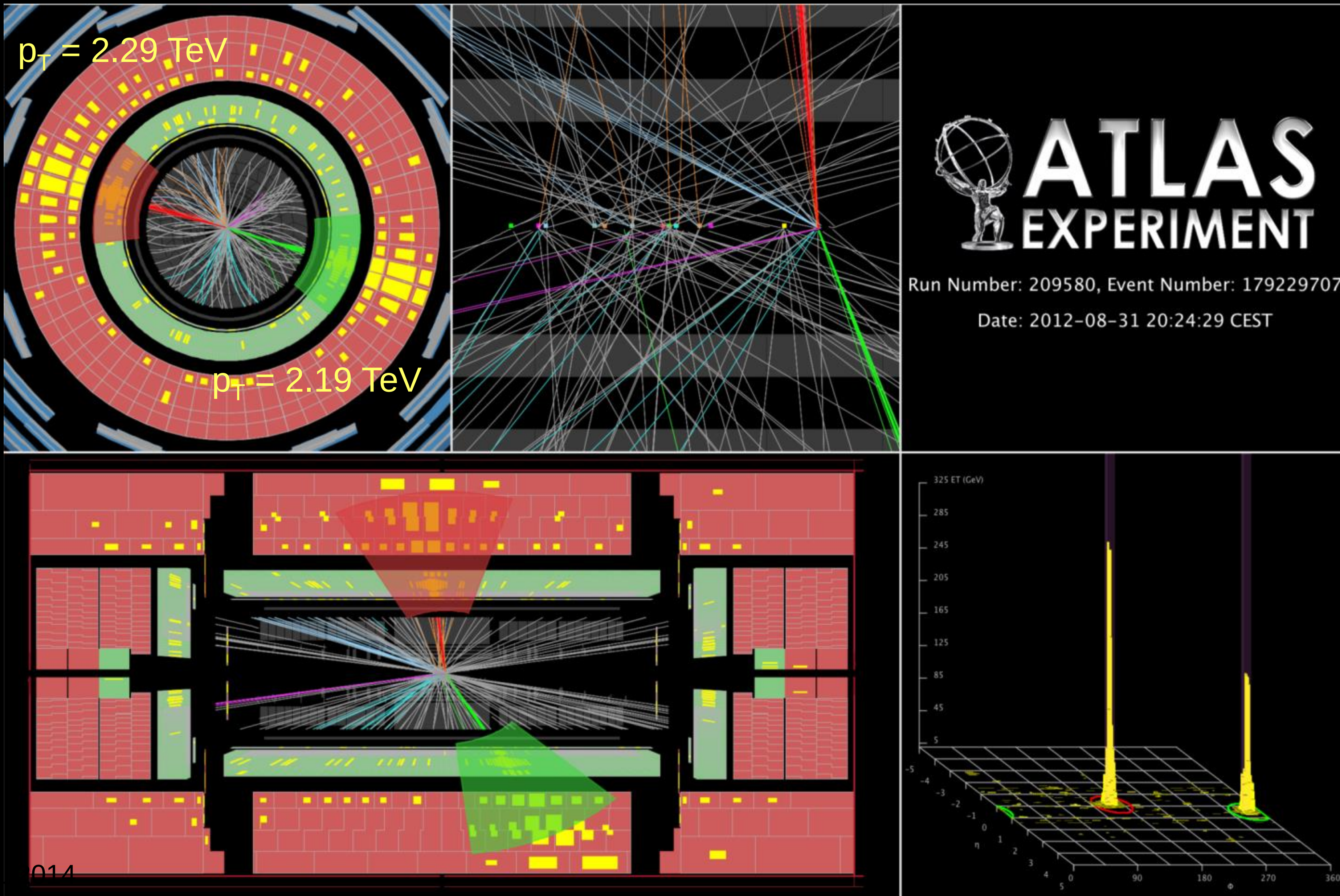
CMS

- Uses narrow resonance
  - For cross section upper limit
  - Cross section upper limits less model dependent
  - Give outside world description of what was done
- Take signal shapes within +-40% of the mass peak into account to compute theory curves
- Not sensitive to parton luminosities
- generic resonance search

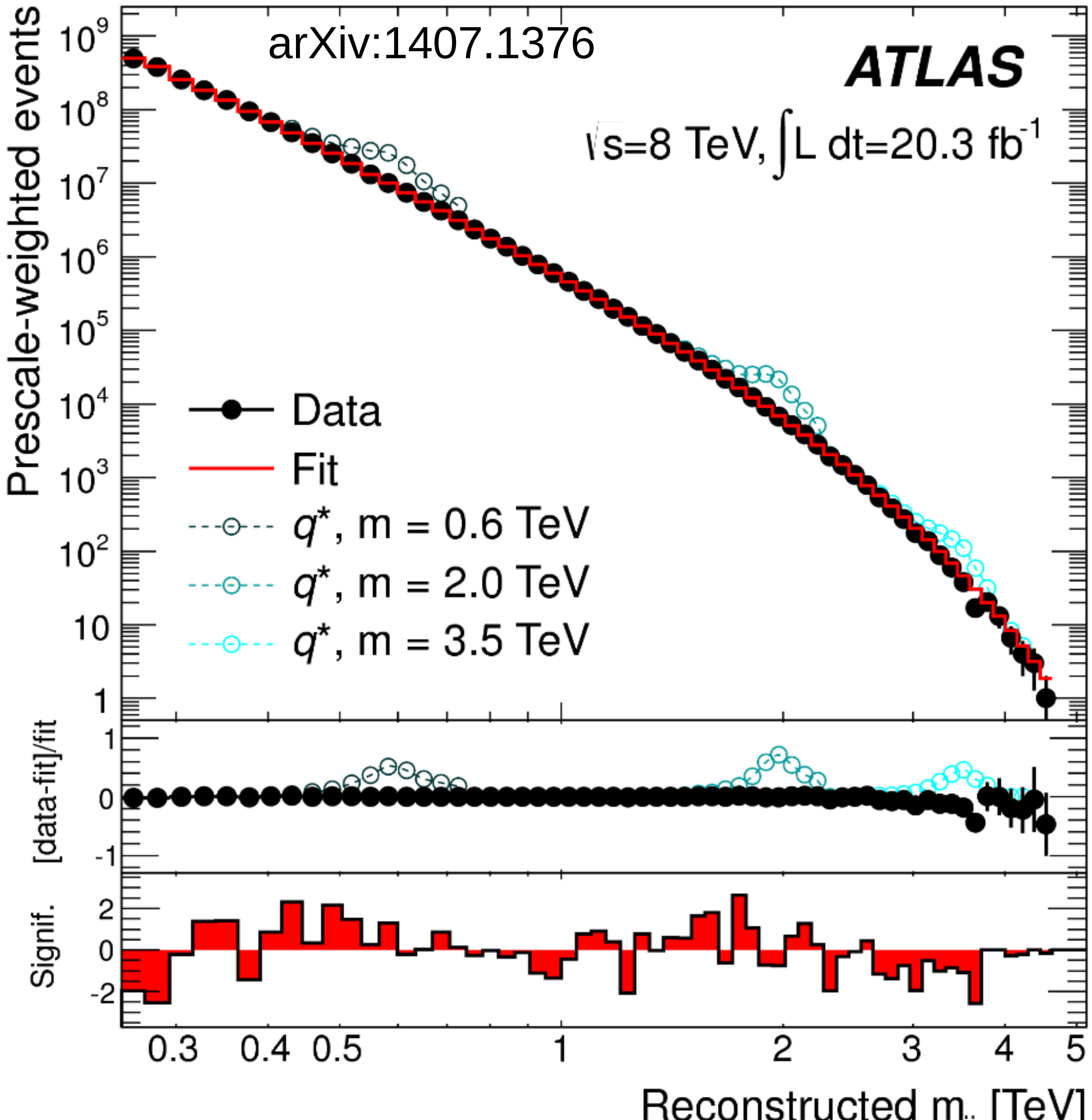
KK Graviton narrow resonance

Obs limit does not go up

Dijet Event Display with m_{inv} = 4.69 TeV

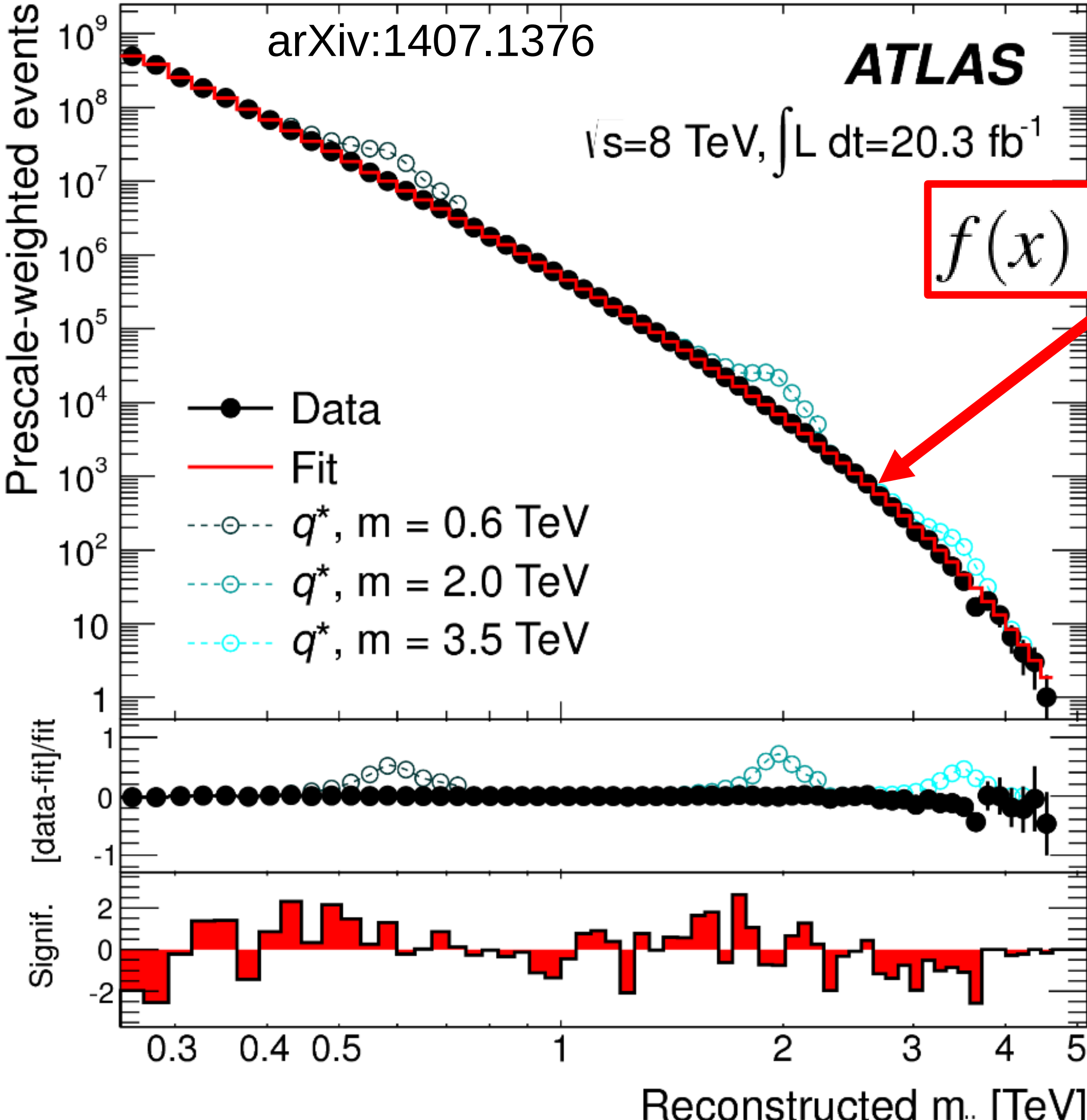


Heavy Resonance Search: 8 TeV Dijets



Probing
quark structure
~ 5 TeV

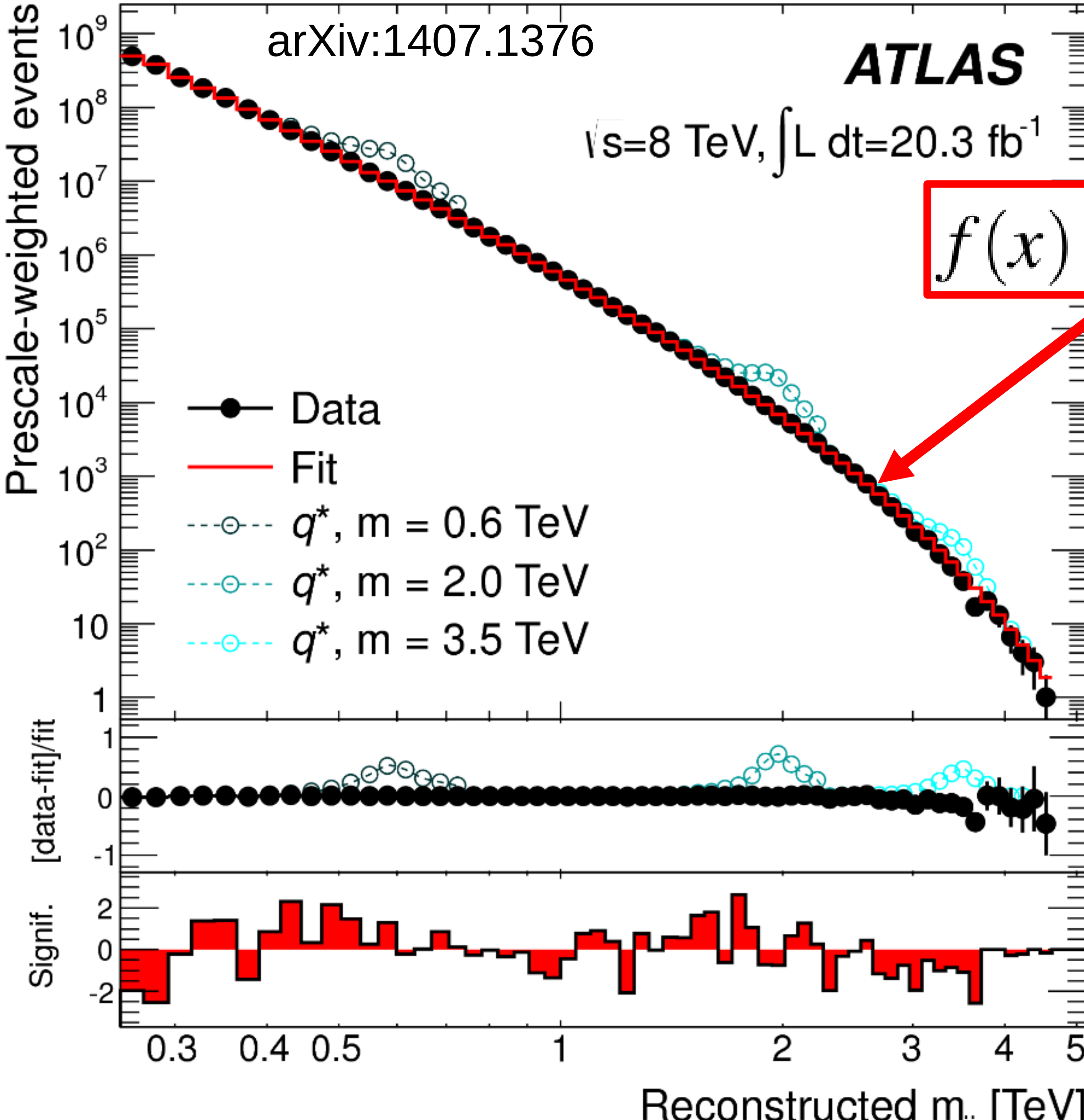
Heavy Resonance Search: 8 TeV Dijets



$$f(x) = p_1(1-x)^{p_2} x^{p_3 + p_4 \ln x}$$

$$x \equiv m_{jj}/\sqrt{s}$$

Heavy Resonance Search: 8 TeV Dijets



$$f(x) = p_1(1-x)^{p_2} x^{p_3 + p_4 \ln x}$$

$$x \equiv m_{jj}/\sqrt{s}$$

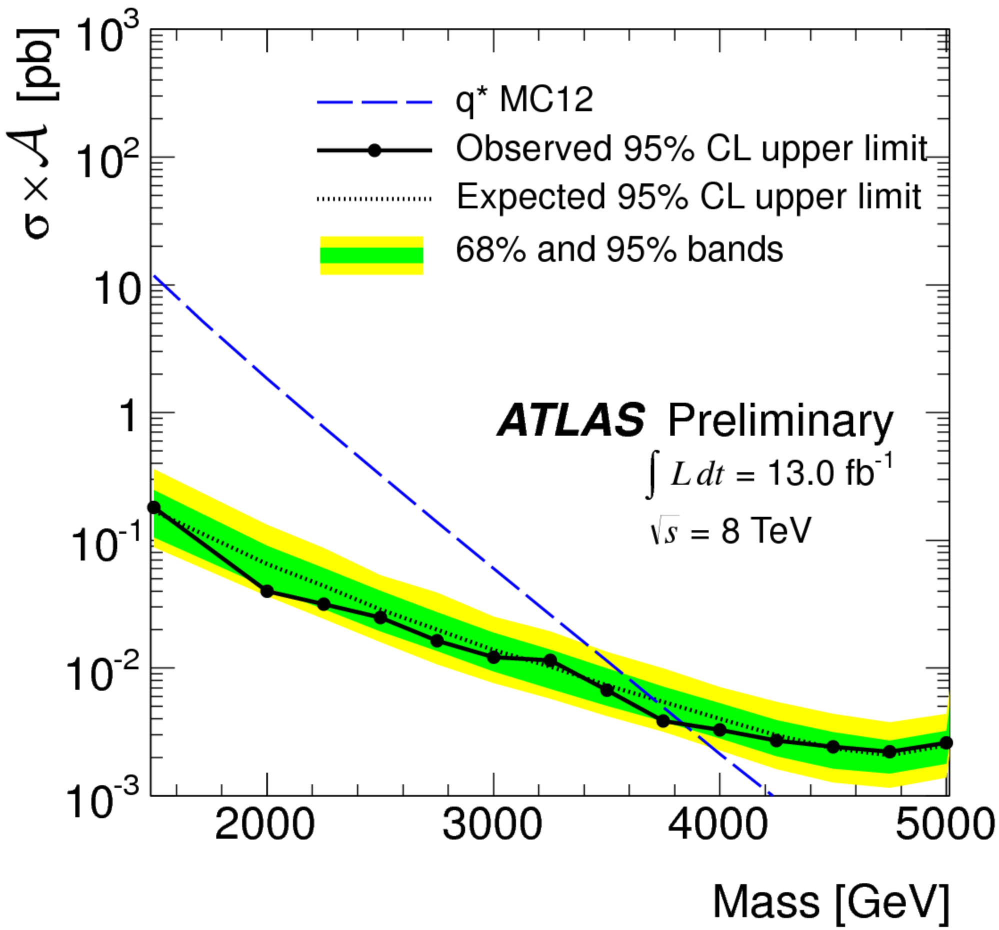
Global χ^2/NDF=79/56

P-value = 0.27

Fit describes data

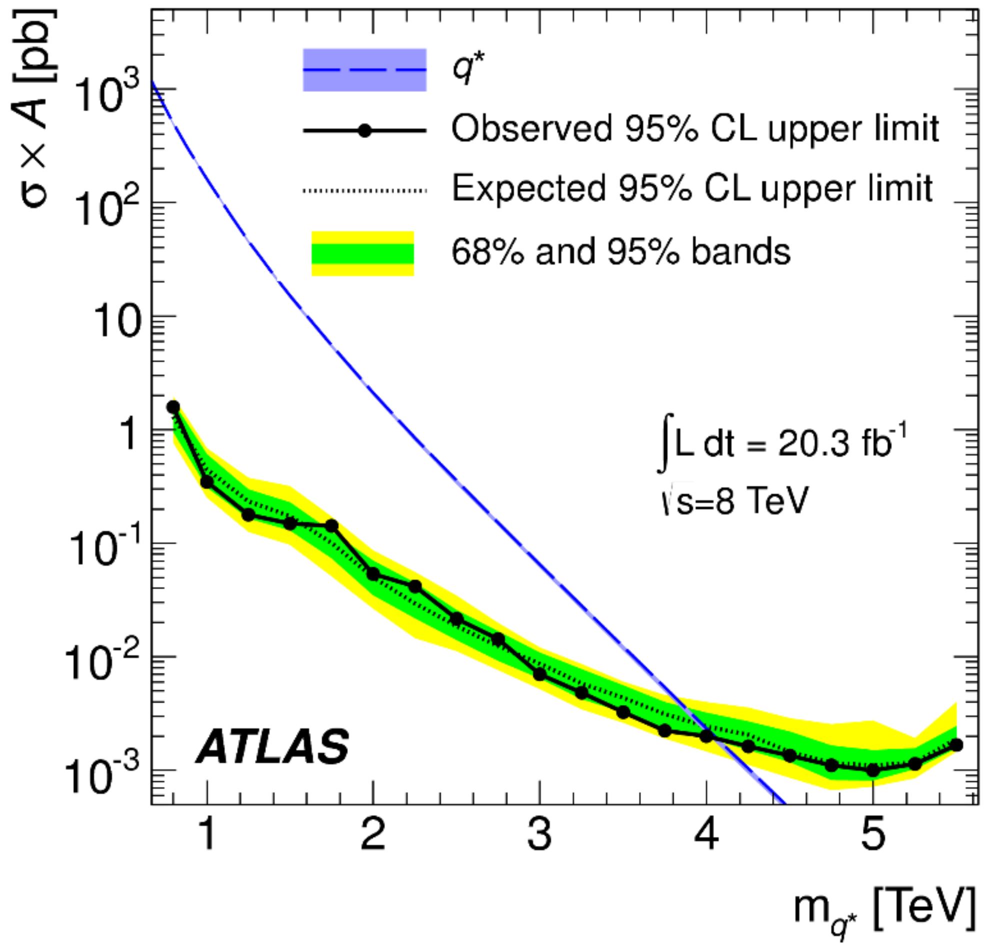
Heavy Resonance Search: 8 TeV Dijets

Previous Results: 13 fb^{-1}



m > 3.84 TeV at 95% CL

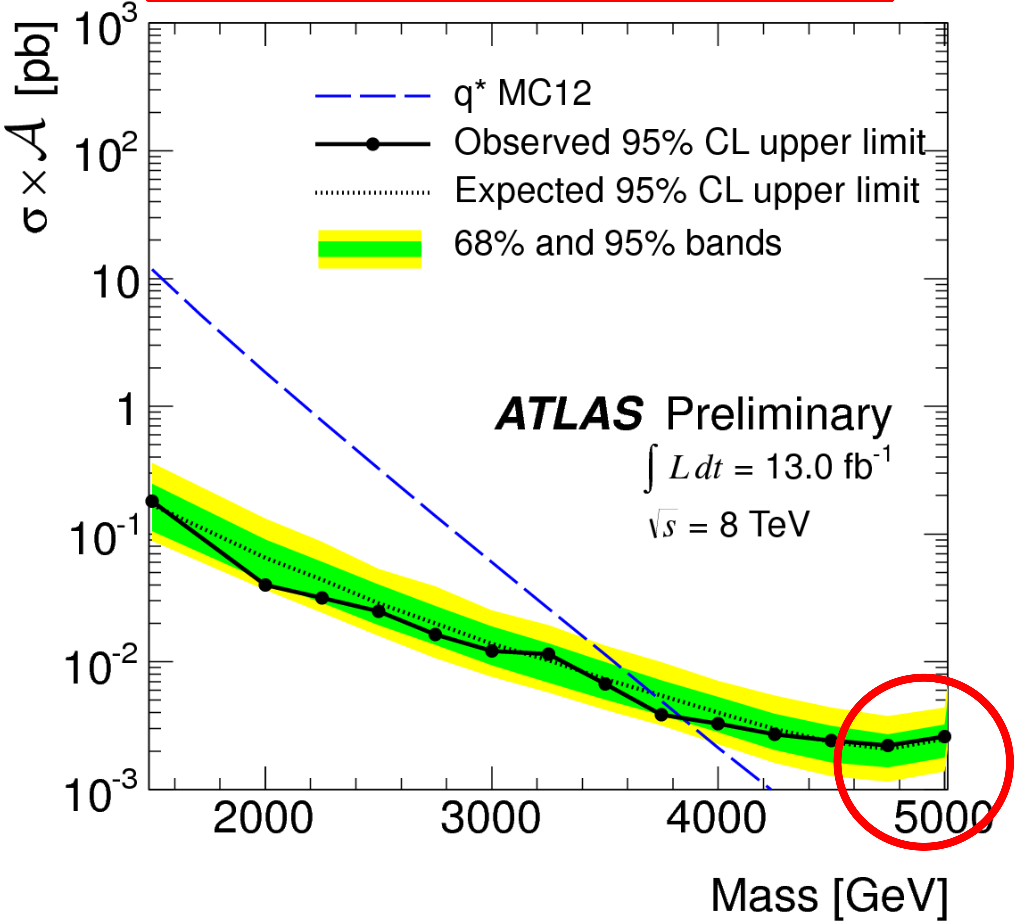
New Results: 20 fb^{-1}



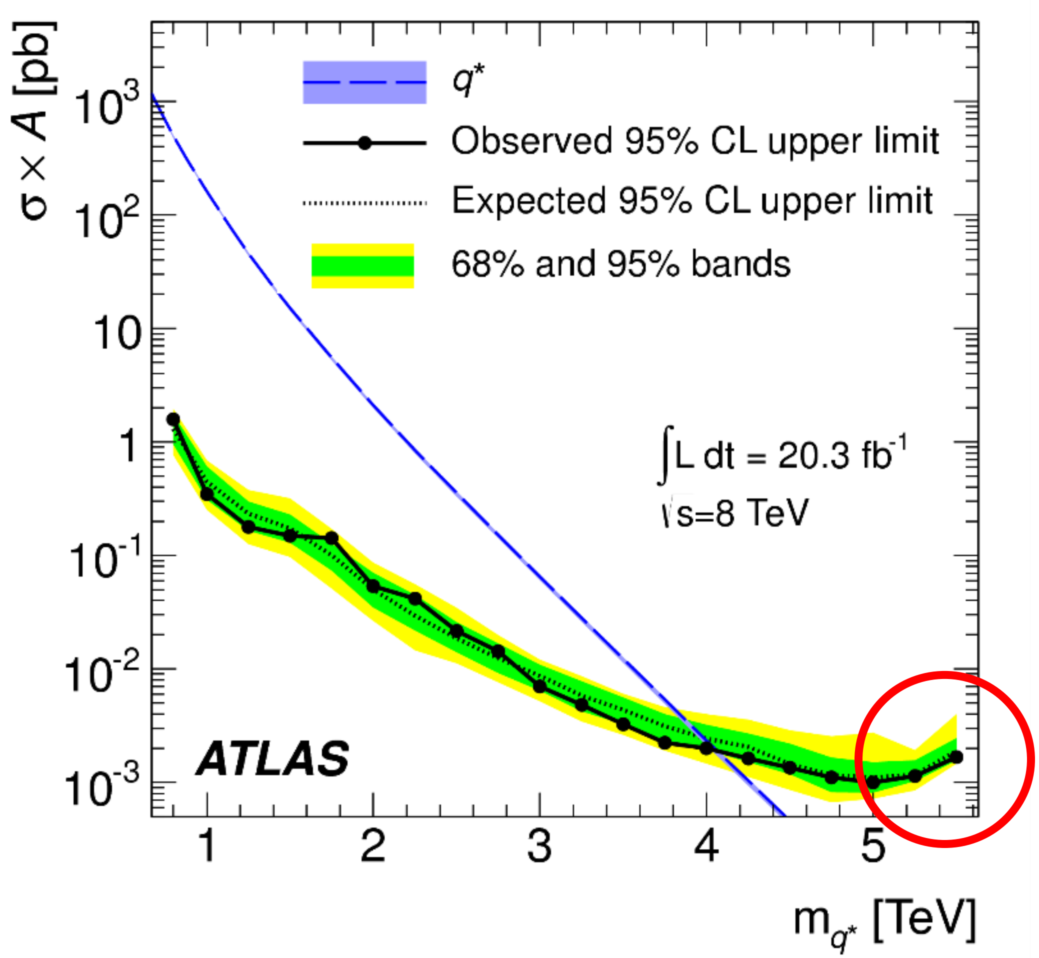
m > 4.09 TeV at 95% CL

Heavy Resonance Search: 8 TeV Dijets

Previous Results: 13 fb^{-1}

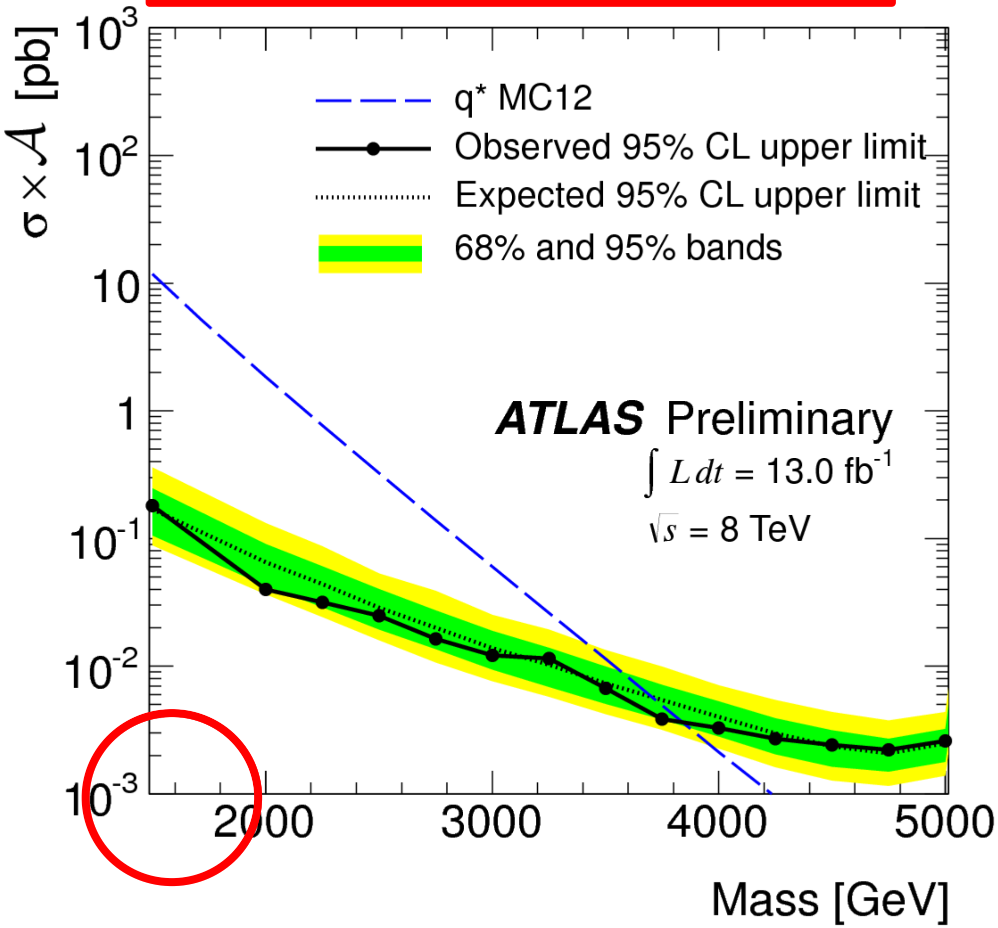


New Results: 20 fb^{-1}

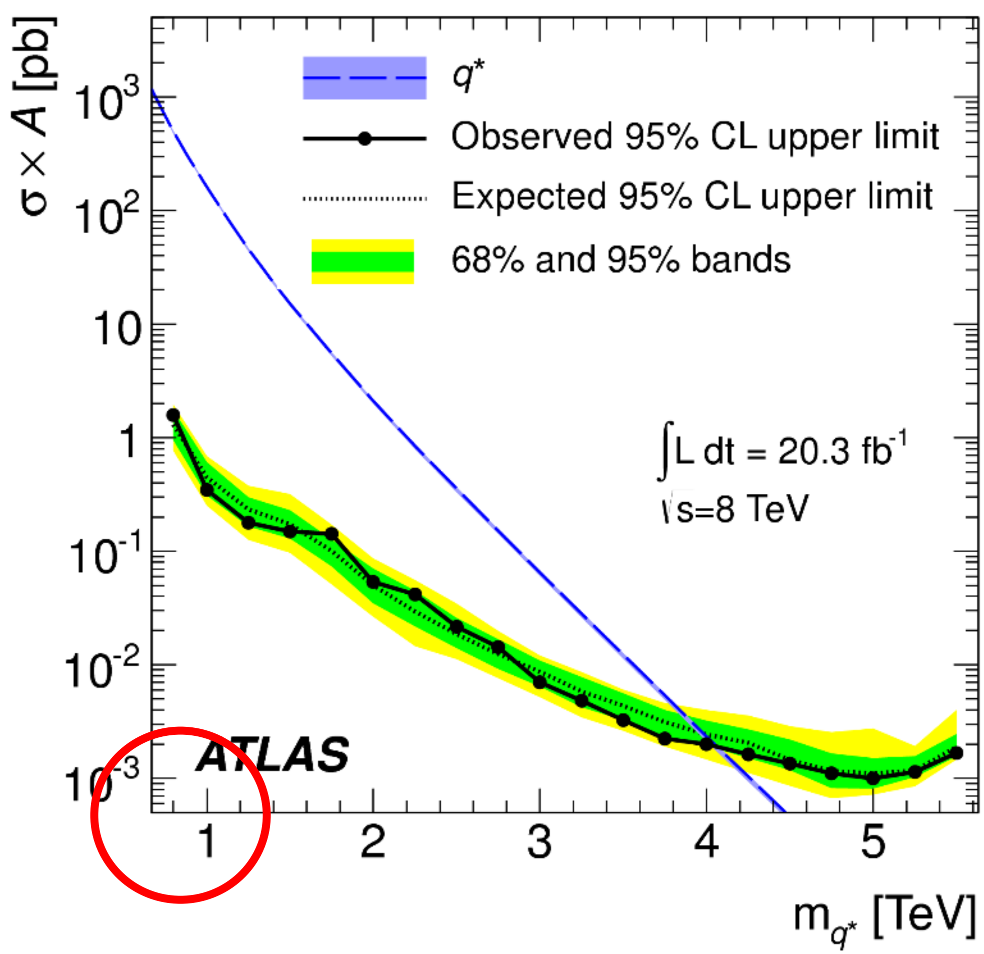


Heavy Resonance Search: 8 TeV Dijets

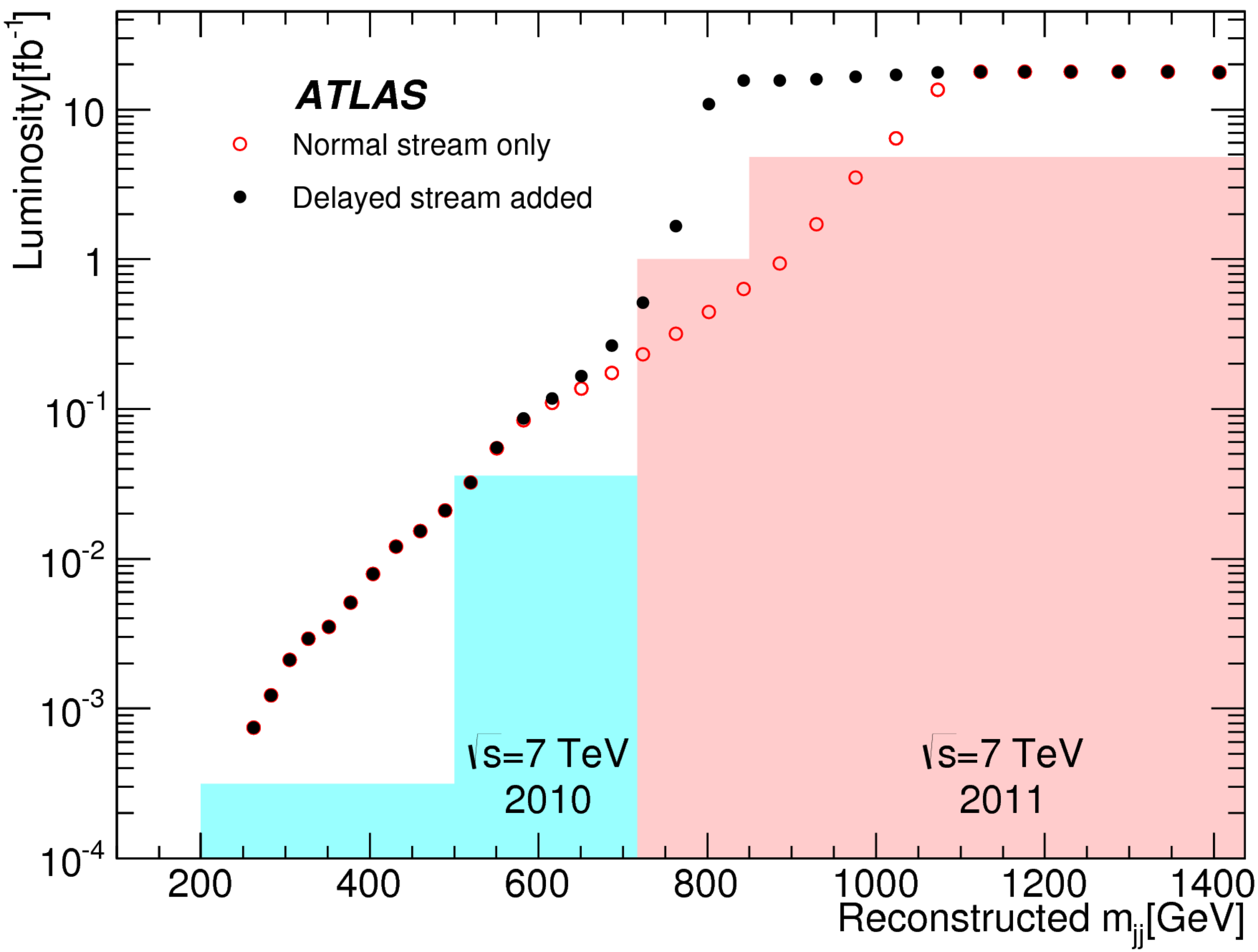
Previous Results: 13 fb^{-1}



New Results: 20 fb^{-1}



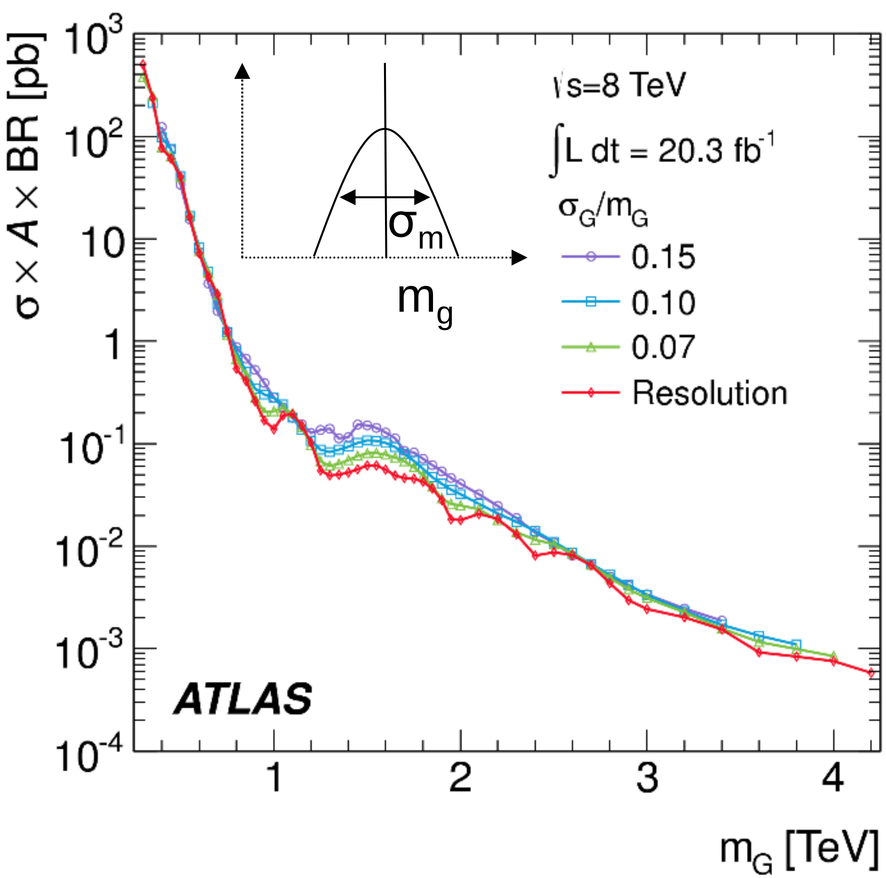
Extending Reach to low invariant masses

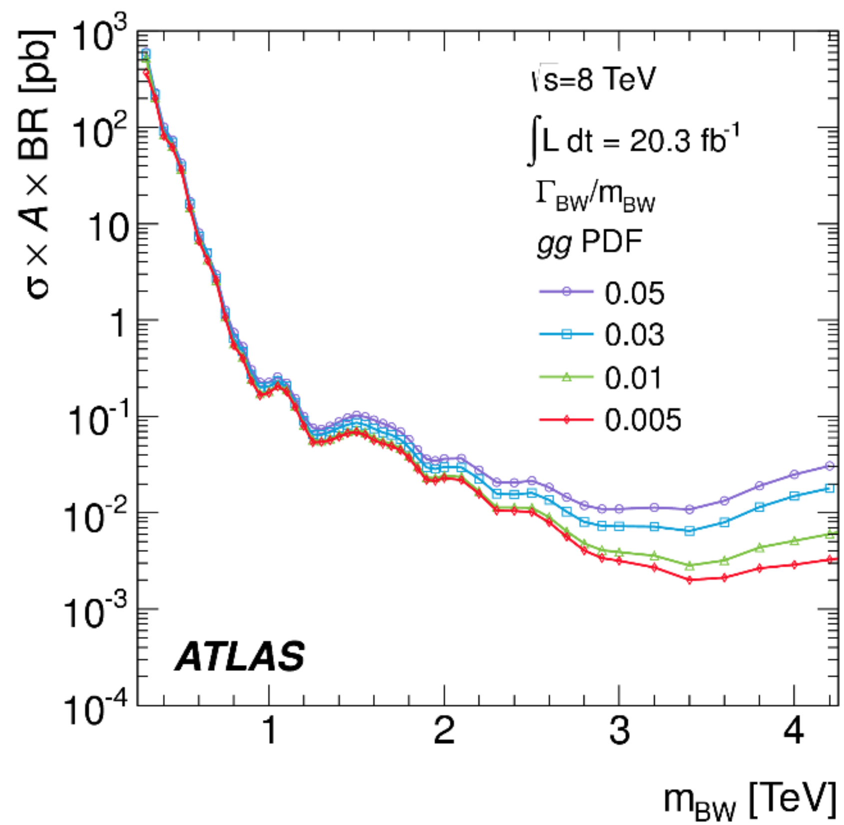


Heavy Resonance Search: 8 TeV Dijets

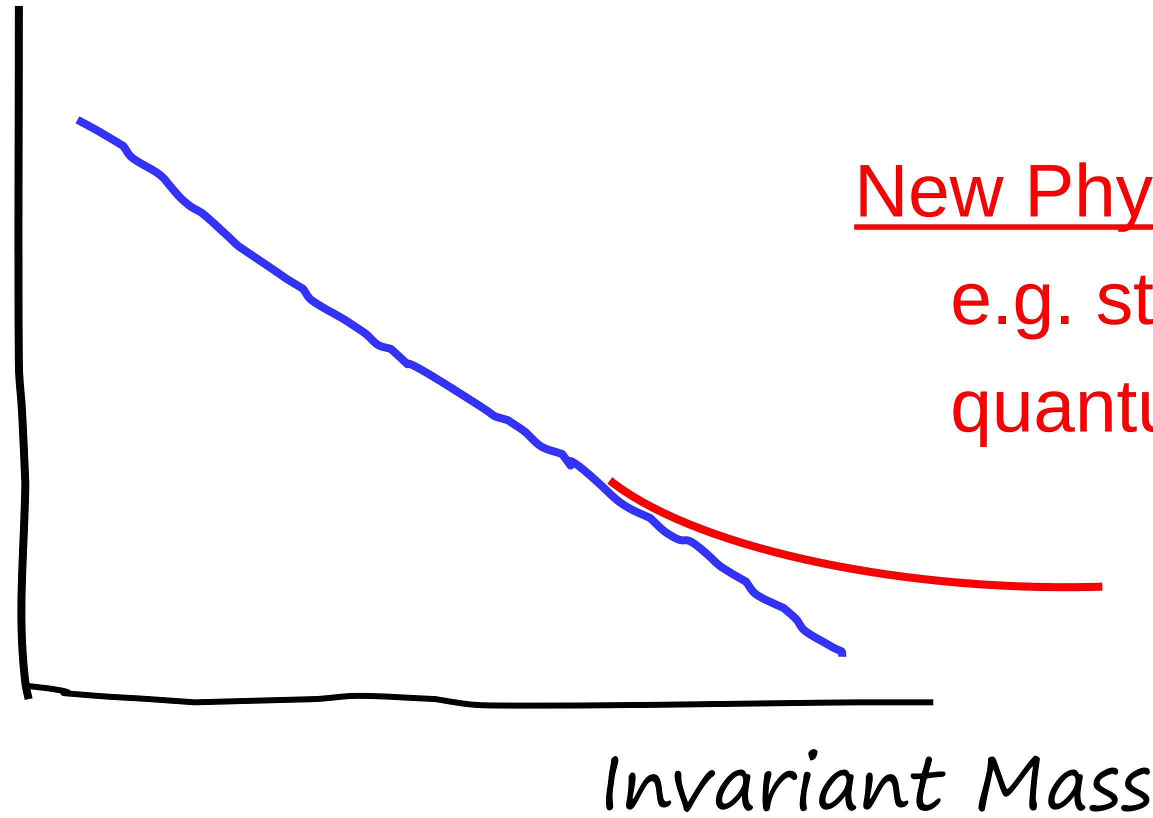
Gaussian resonance limits: mean mass, $m_{G,}$ and 3 σ_G

Breit Wigner x PDF





Search for Excess in Tail

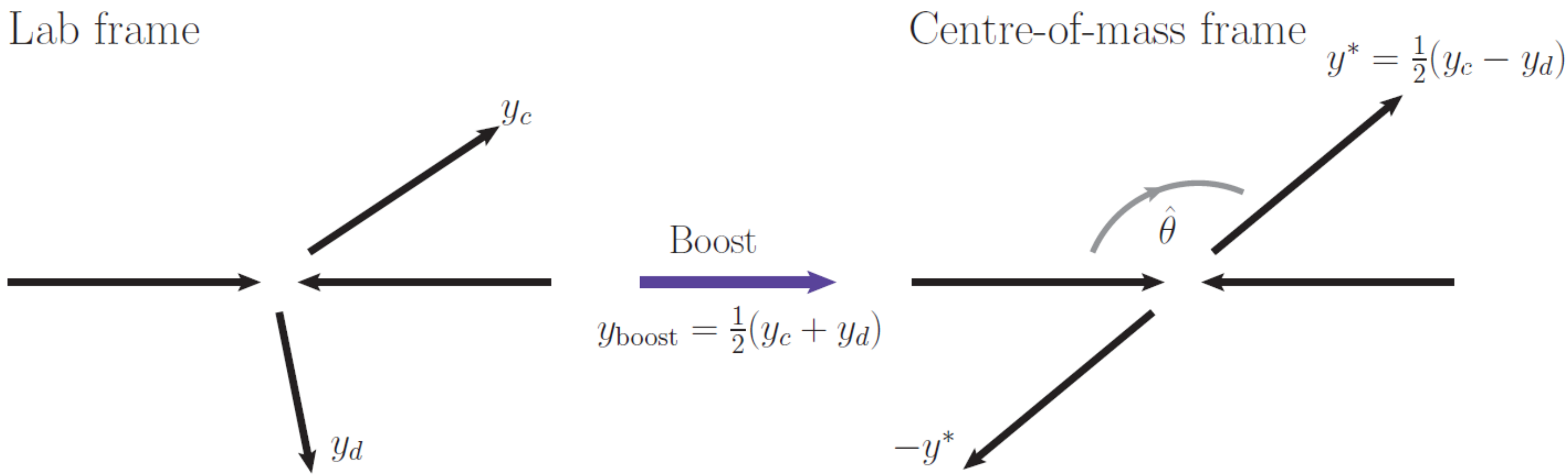


New Physics

e.g. strong gravity

quantum black holes

Search for Threshold Effects: Dijet Angular



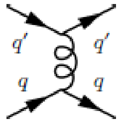
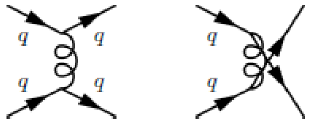
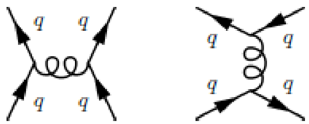
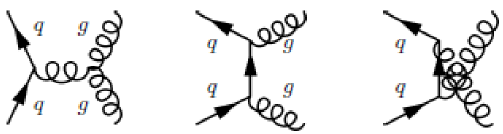
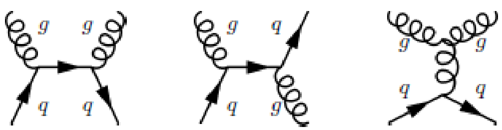
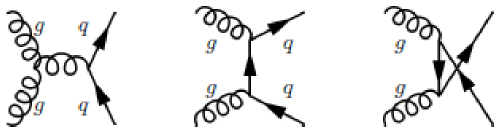
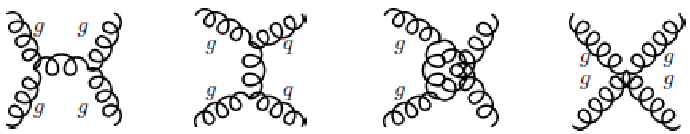
$\mathrm{d}\hat{\sigma}/\mathrm{d}(\cos\hat{\theta}) \propto \sin^{-4}(\hat{\theta}/2)$ t-channel Spin-1 exchange

$$\chi = \frac{1+|\cos\hat{\theta}|}{1-|\cos\hat{\theta}|} \sim \frac{1}{1-|\cos\hat{\theta}|} \propto \frac{\hat{s}}{\hat{t}}$$

$$\frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}\chi} \propto \frac{\alpha_s^2}{\hat{s}} \quad (\hat{s}\ \text{fixed}) \quad \hat{s} = m_{jj}$$

Constant in χ for fixed m_{jj}

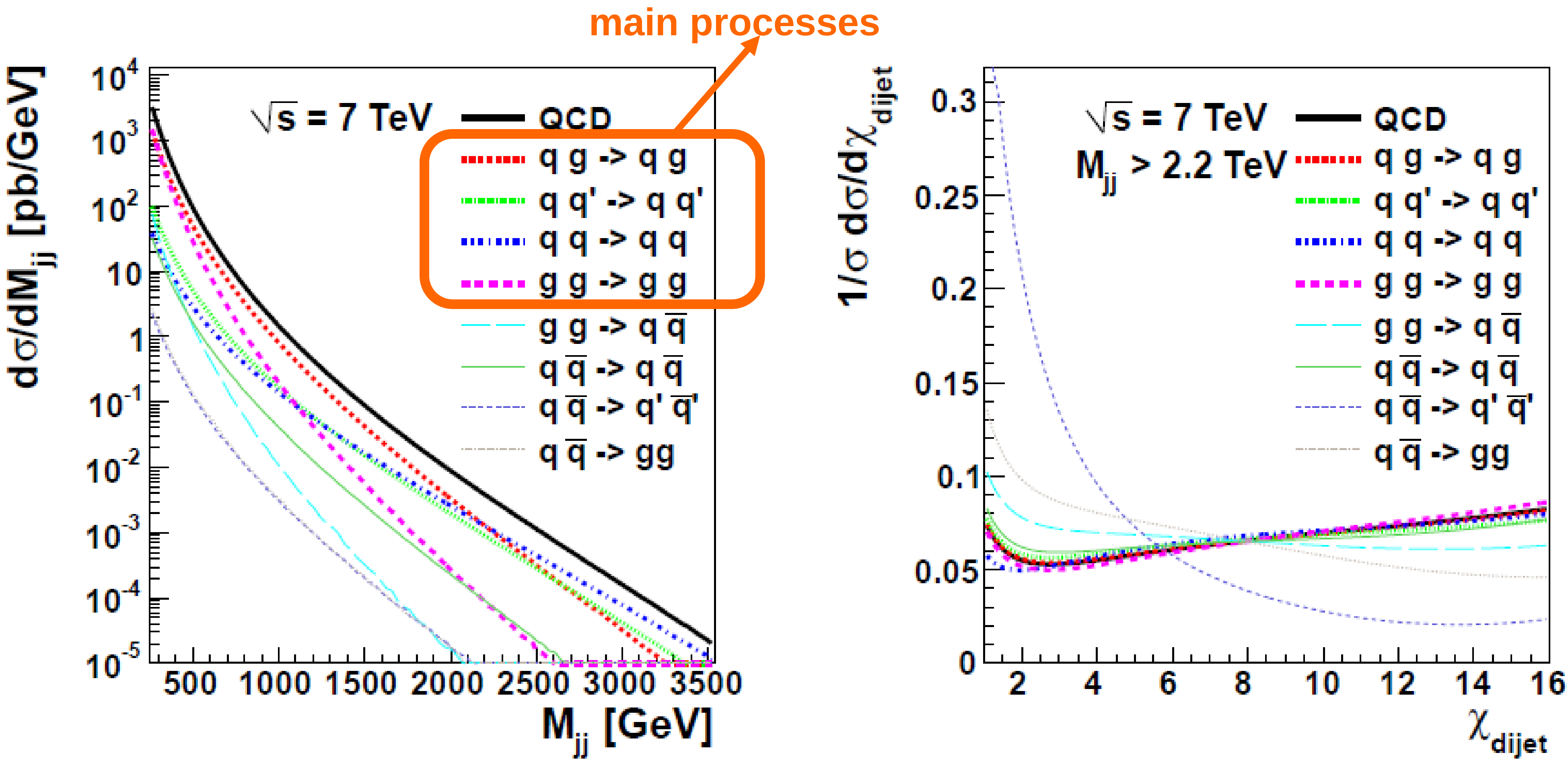
Search for Threshold Effects: Dijet Angular

Process	Cross section	Diagrams
$qq' \to qq' = q\bar{q}' \to q\bar{q}'$	$\frac{64}{9}\alpha_s^2\left(\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}\right)$	
$qq \to qq$	$\frac{64}{9}\alpha_s^2\left(\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}+\frac{\hat{s}^2+\hat{t}^2}{\hat{u}^2}-\frac{2}{3}\frac{\hat{s}}{\hat{u}\hat{t}}\right)$	
$q\bar{q} \to q'\bar{q}'$	$\frac{64}{9}\alpha_s^2\left(\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}\right)$	
$q\bar{q} \to q\bar{q}$	$\frac{64}{9}\alpha_s^2\left(\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}+\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}-\frac{2}{3}\frac{\hat{u}^2}{\hat{s}\hat{t}}\right)$	
$q\bar{q} \to gg$	$\frac{128}{3}\alpha_s^2\left(\frac{4}{9}\frac{\hat{t}^2+\hat{u}^2}{\hat{t}\hat{u}}-\frac{\hat{u}^2+\hat{t}^2}{\hat{s}^2}\right)$	
$qg \to qg$	$16\alpha_s^2\left(\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}-\frac{4}{9}\frac{\hat{s}^2+\hat{u}^2}{\hat{s}\hat{u}}\right)$	
$gg \to q\bar{q}$	$\frac{8}{3}\alpha_s^2\left(\frac{1}{3}\frac{\hat{t}^2+\hat{u}^2}{\hat{t}\hat{u}}-\frac{3}{4}\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}\right)$	
$gg \to gg$	$72\alpha_s^2\left(3+\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}+\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}+\frac{\hat{s}^2+\hat{t}^2}{\hat{u}^2}\right)$	

QCD is a bit more complicated…..

Andreas Dominik Hinzmann

Search for Threshold Effects: Dijet Angular



low M_{jj} gg and qg dominate

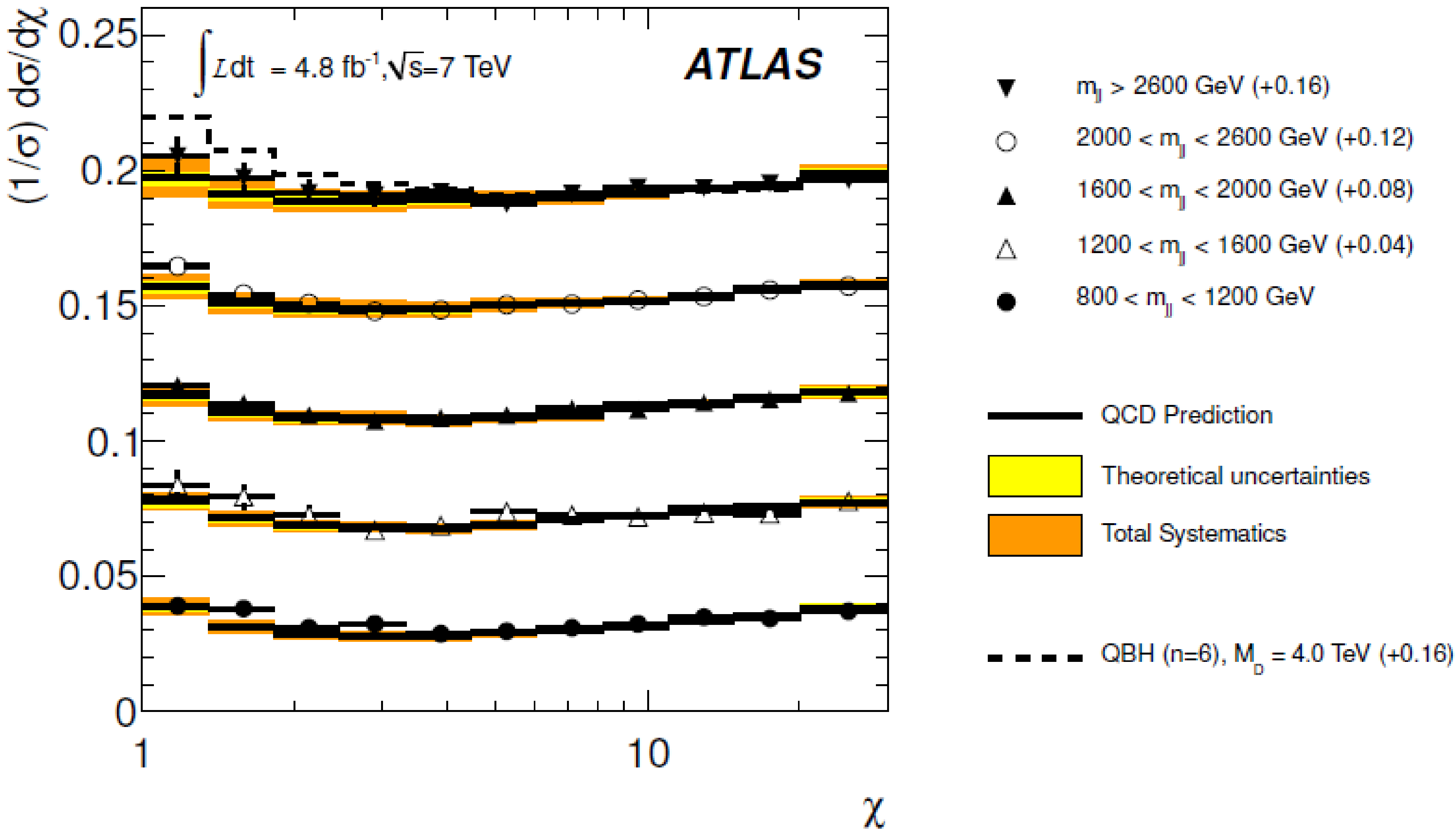
high M_{jj} qq dominate

QCD ~ flat in χ

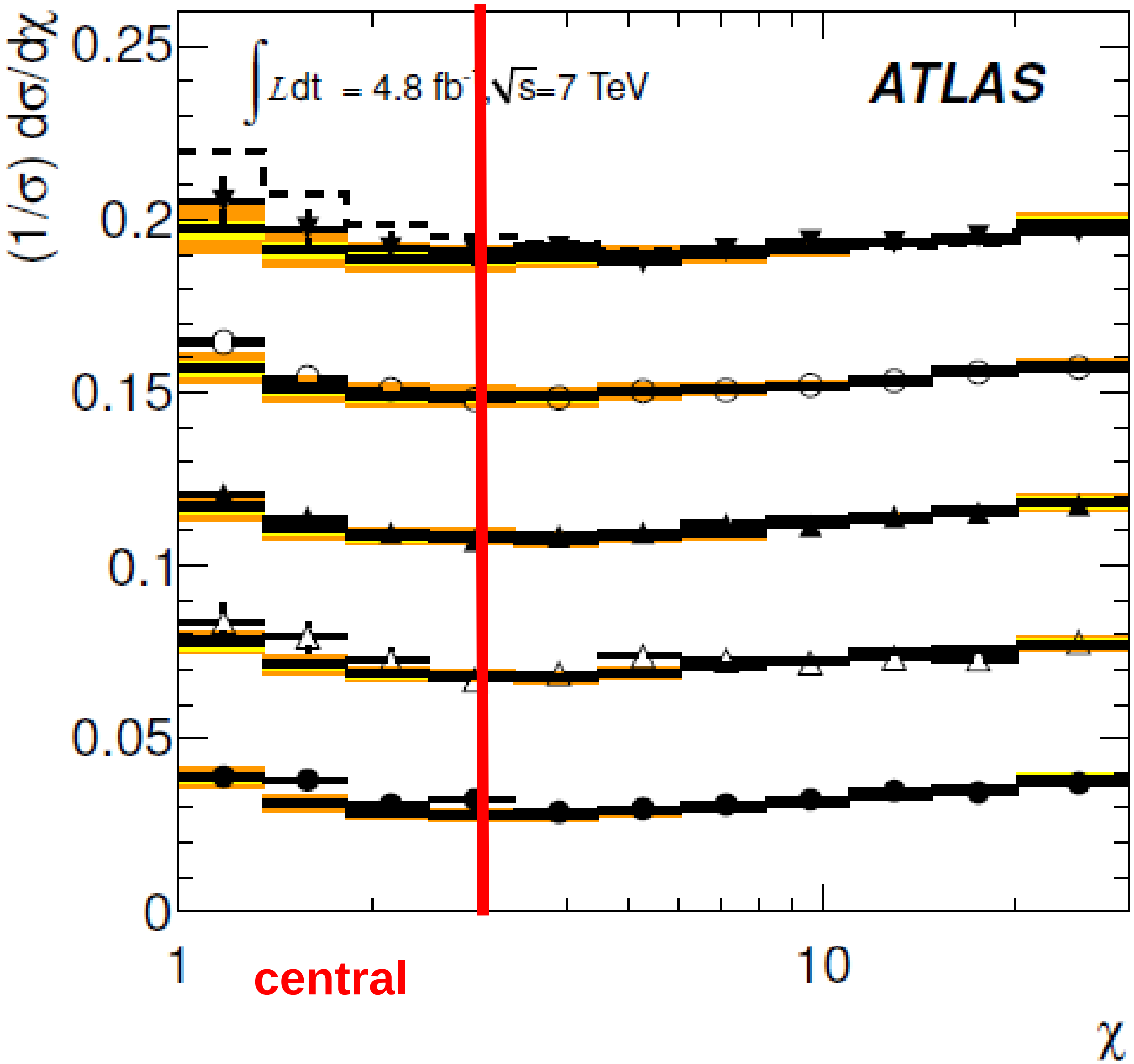
Andreas Dominik Hinzmann

Search for Threshold Effects: Dijet Angular

arXiv:1210.1718



Finer binning in m_{jj} using $F_\chi(m_{jj})$

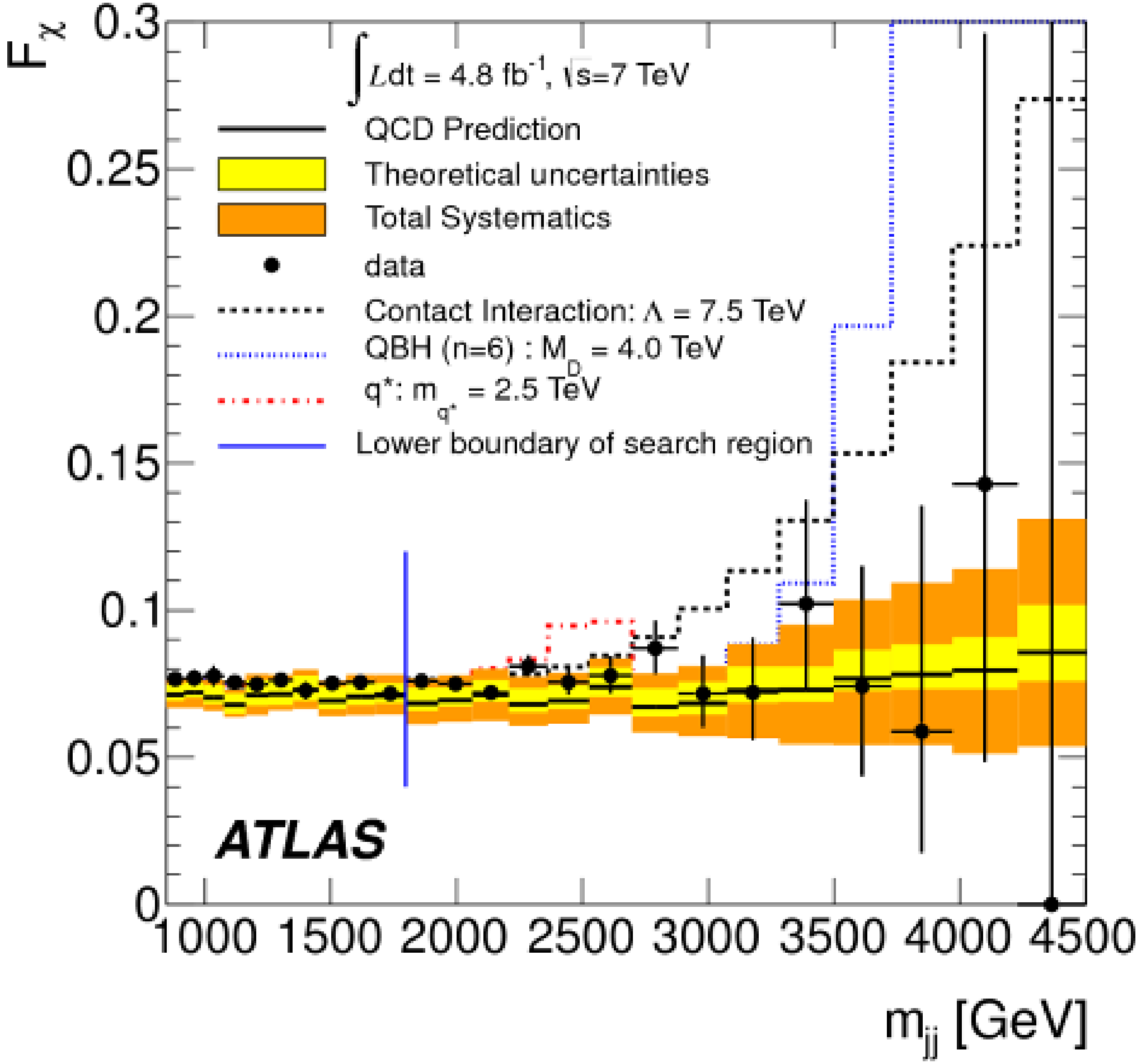


Finer binning in m_{jj} using $F_\chi(m_{jj})$

$$F_\chi(m_{jj}) \equiv \frac{dN_{central}/dm_{jj}}{dN_{total}/dm_{jj}}$$

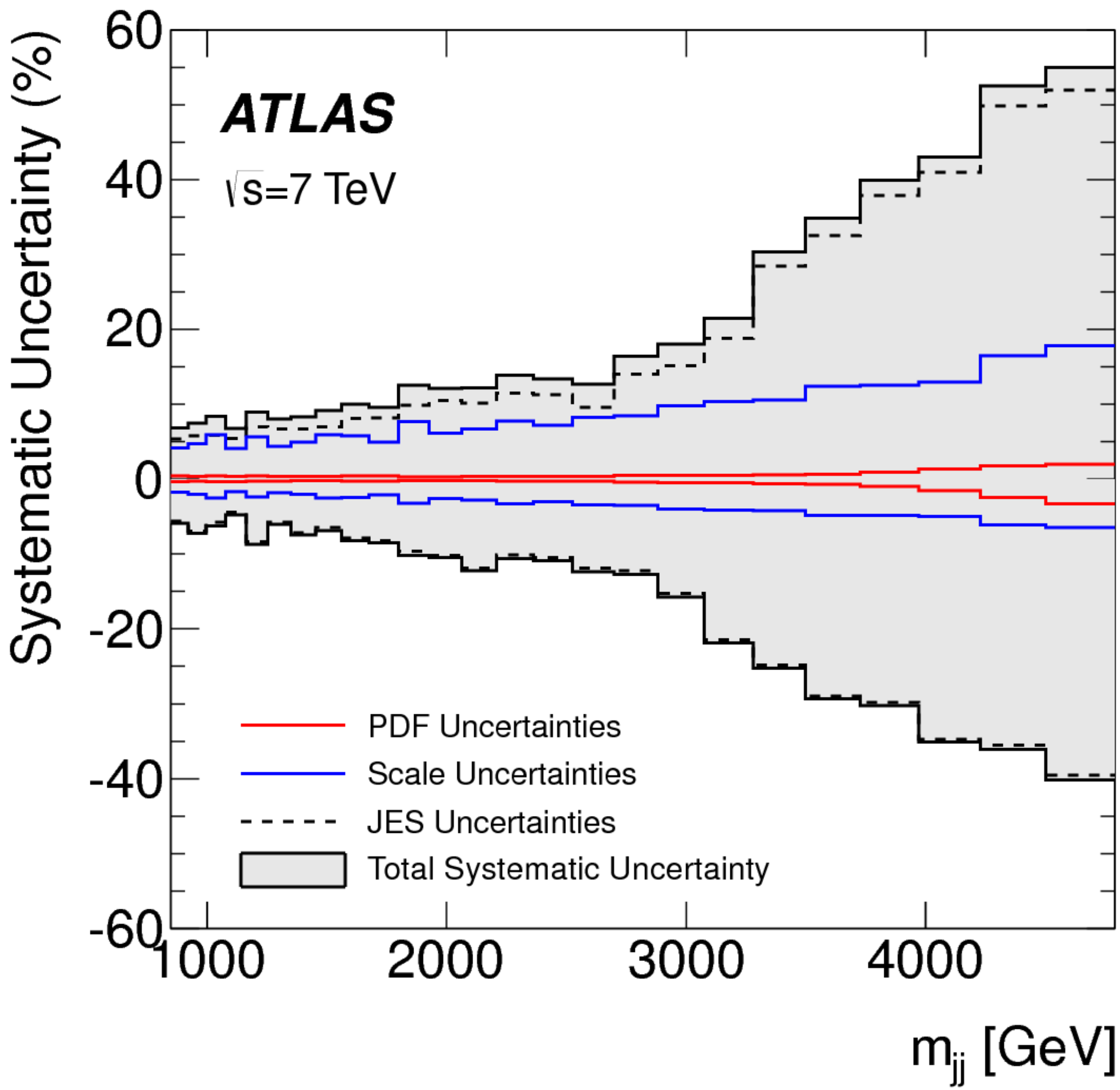
Search for Threshold Effects: Dijet Angular

arXiv:1210.171º



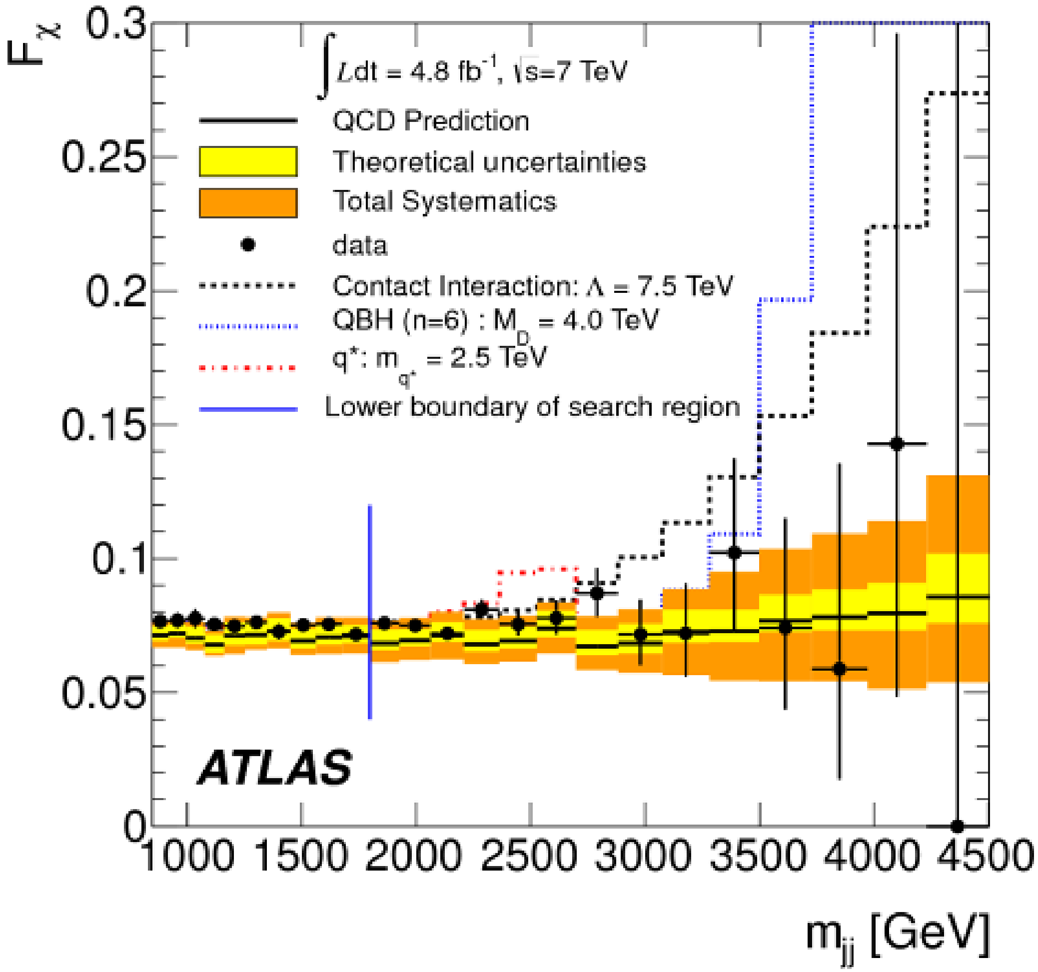
Search for Threshold Effects: Dijet Angular

arXiv:1210.1718



Search for Threshold Effects: Dijet Angular

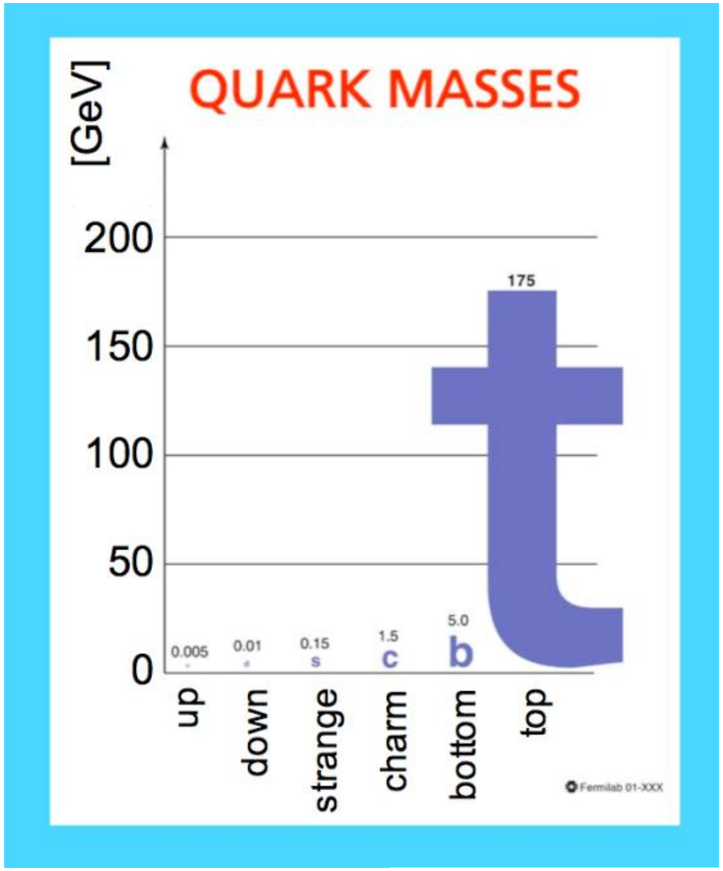
arXiv:1210.1718

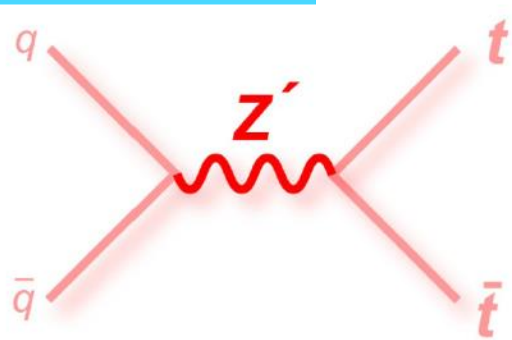


Models and Limits:

- Quark contact interaction (quark compositeness)
  - **Λ>7.6 TeV (7.7 TeV)**
- Quantum Black holes
  - M_D>4.1 TeV (4.2 TeV) n=6

New Physics Searches with high-pt top quarks

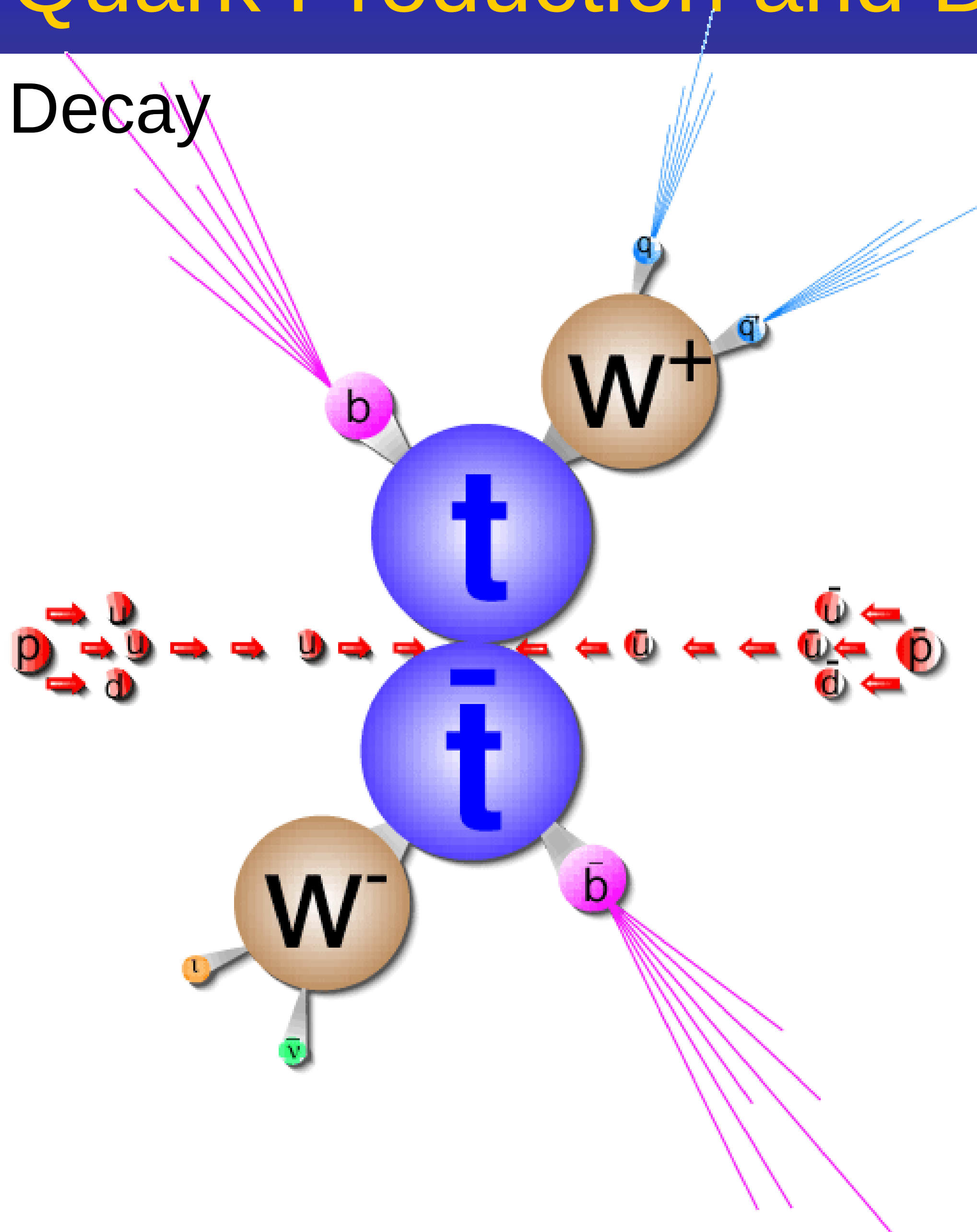




- Huge mass of top
  - Bizarre → New Physics?
- Coupled to EWK symmetry breaking
- LHC is a top factory
- Heavy new particles
  - Couple strongly to top
  - Produce boosted tops

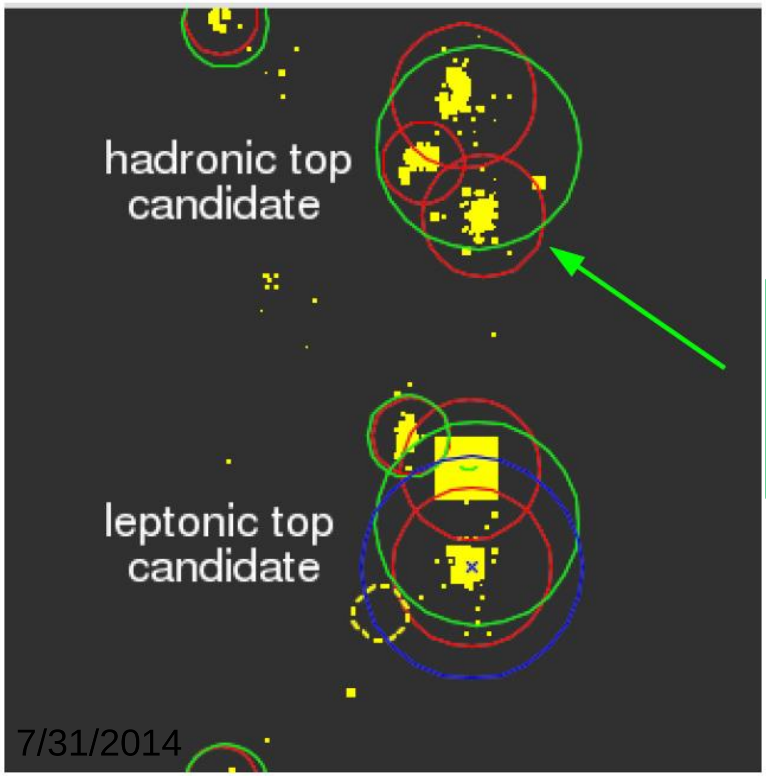
Top Quark Production and Decay

Semi-Leptonic Decay

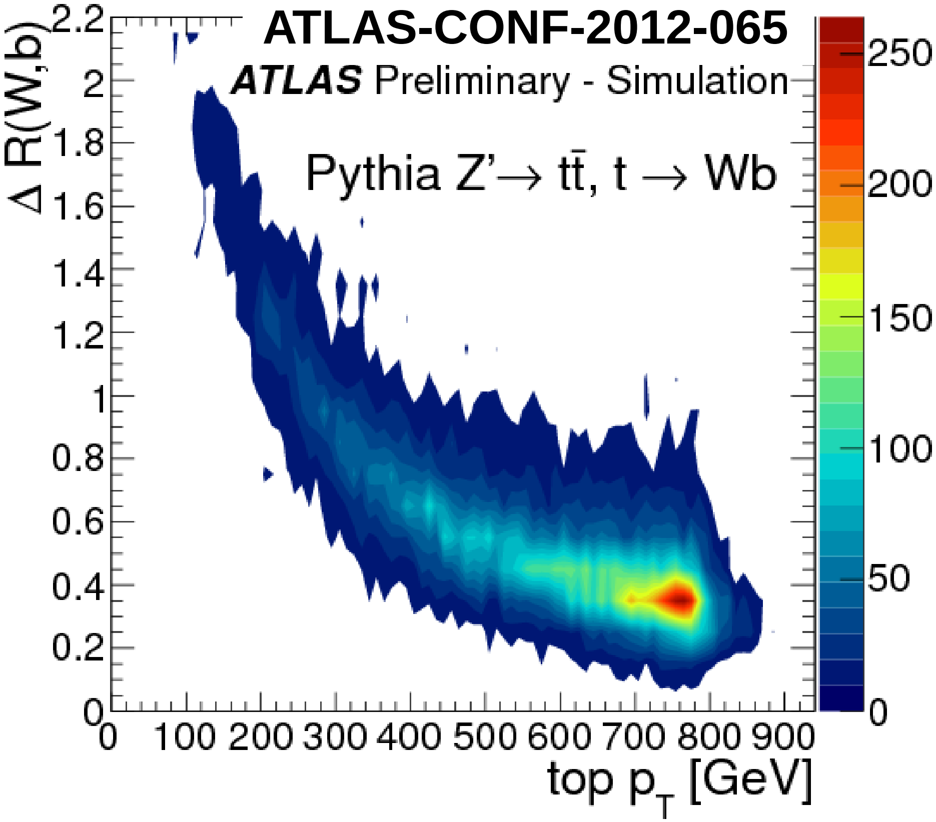


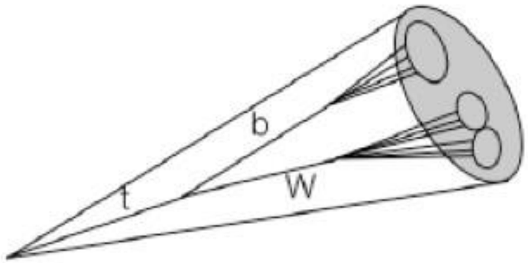
Boosted Regime

- Rule of thumb: $dR \sim \frac{2m}{p_T}$
- top with p_T > 350 GeV decay products within R~1

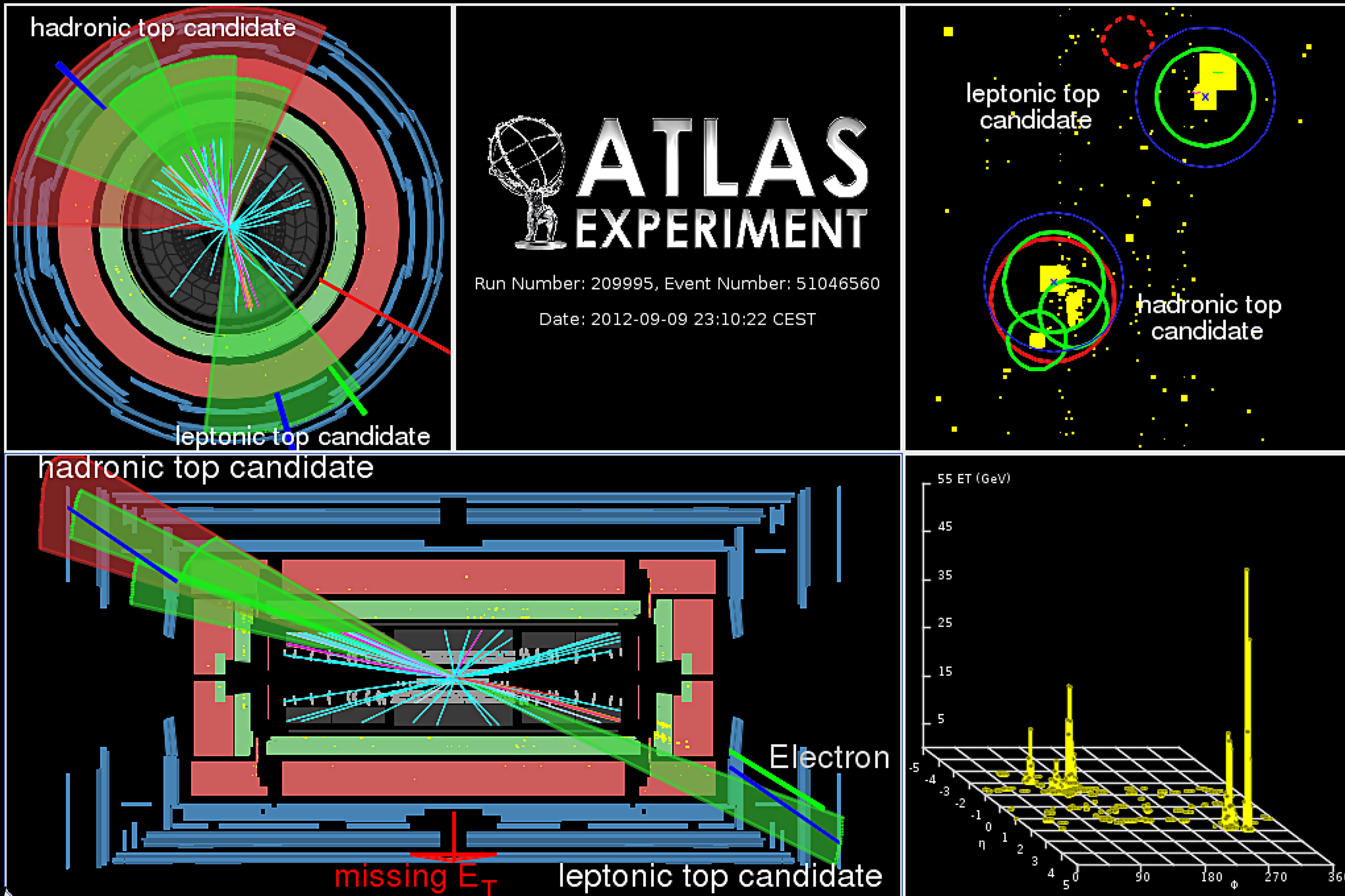


R = 1
m_j=197 GeV
E_T=356 GeV

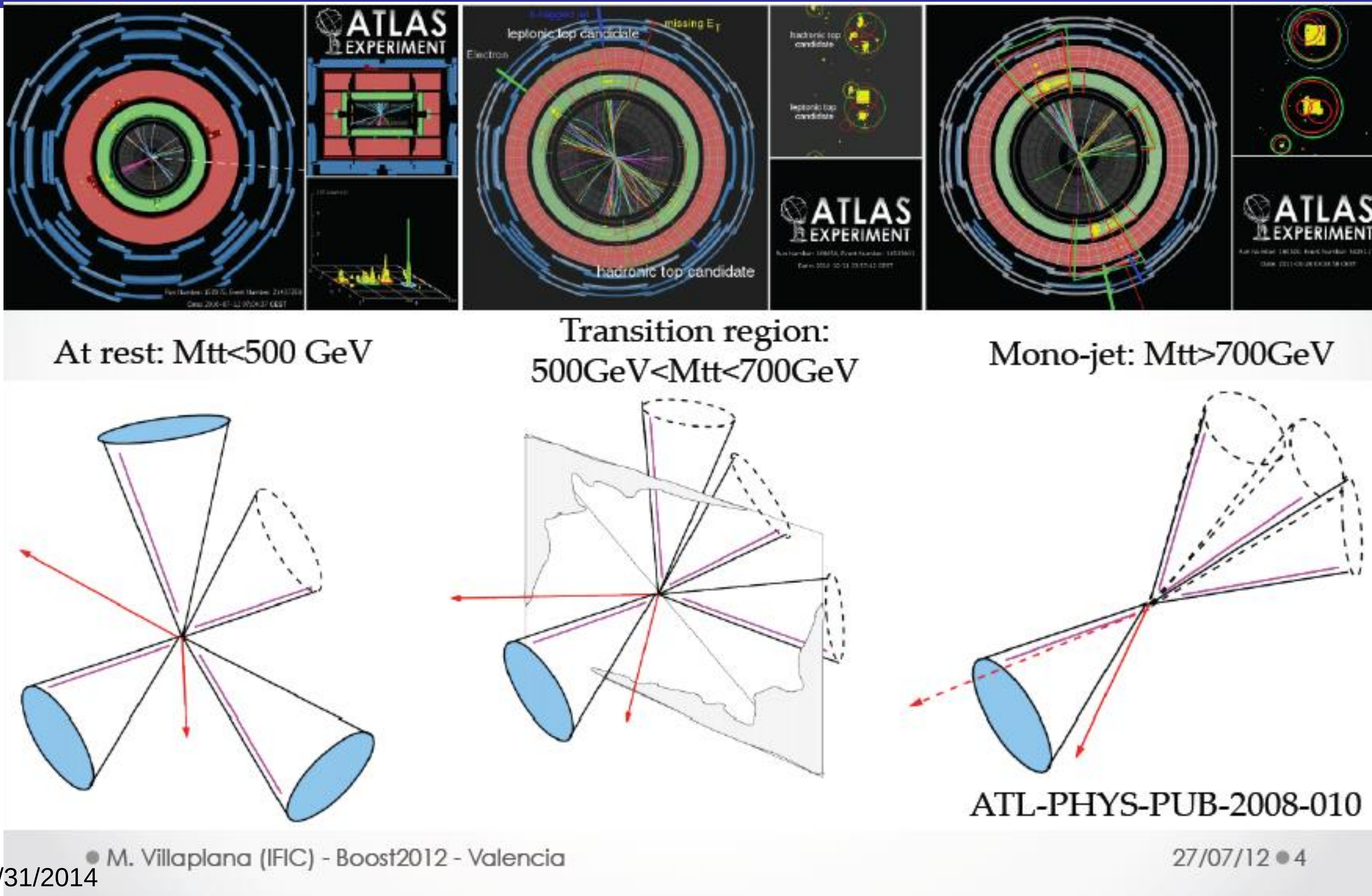




Boosted Top Event Candidate with m_{ttbar}=2.5 TeV

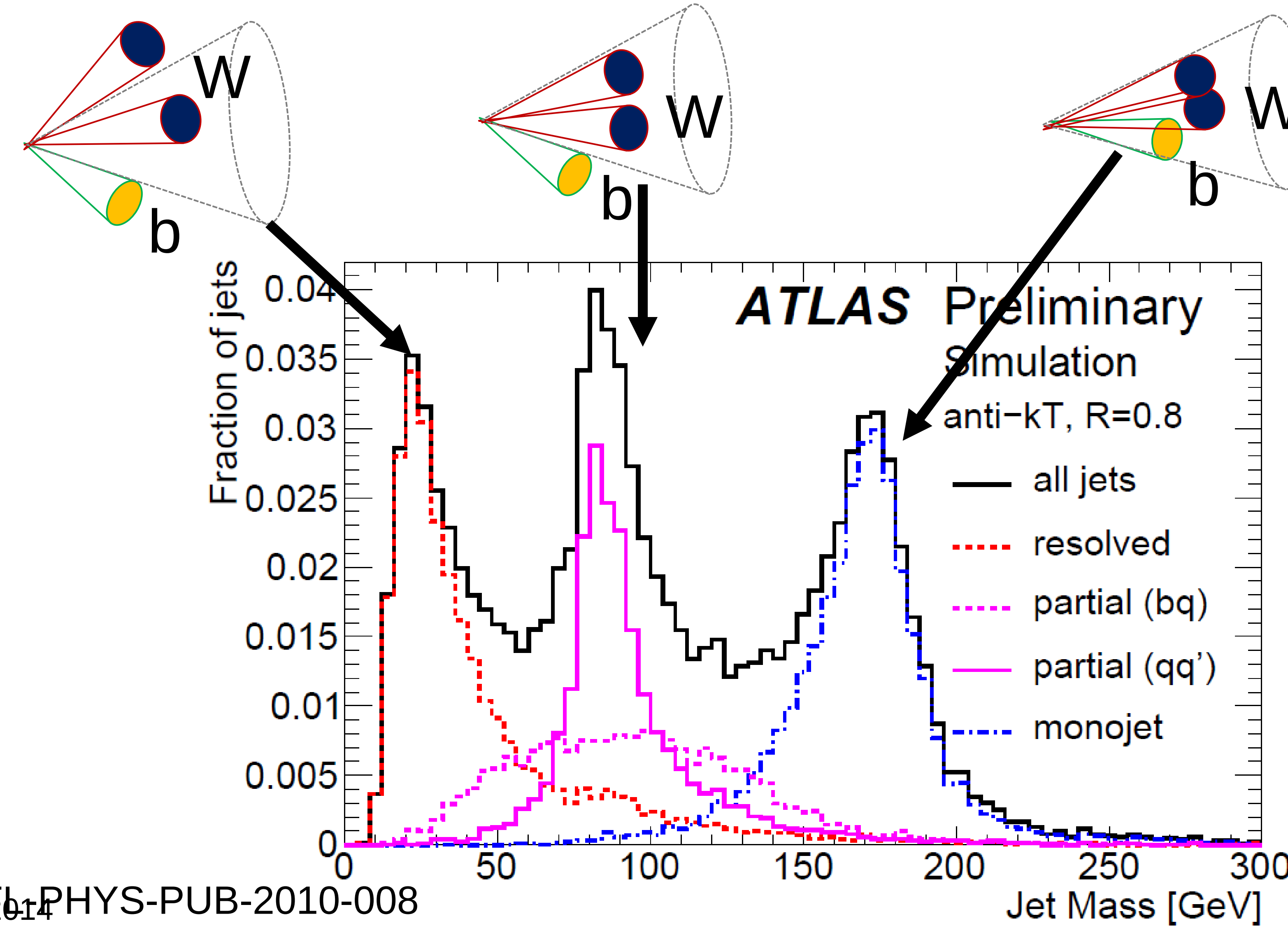


Top Reconstruction @ LHC: 3 Regimes



Jet Substructure: jet mass

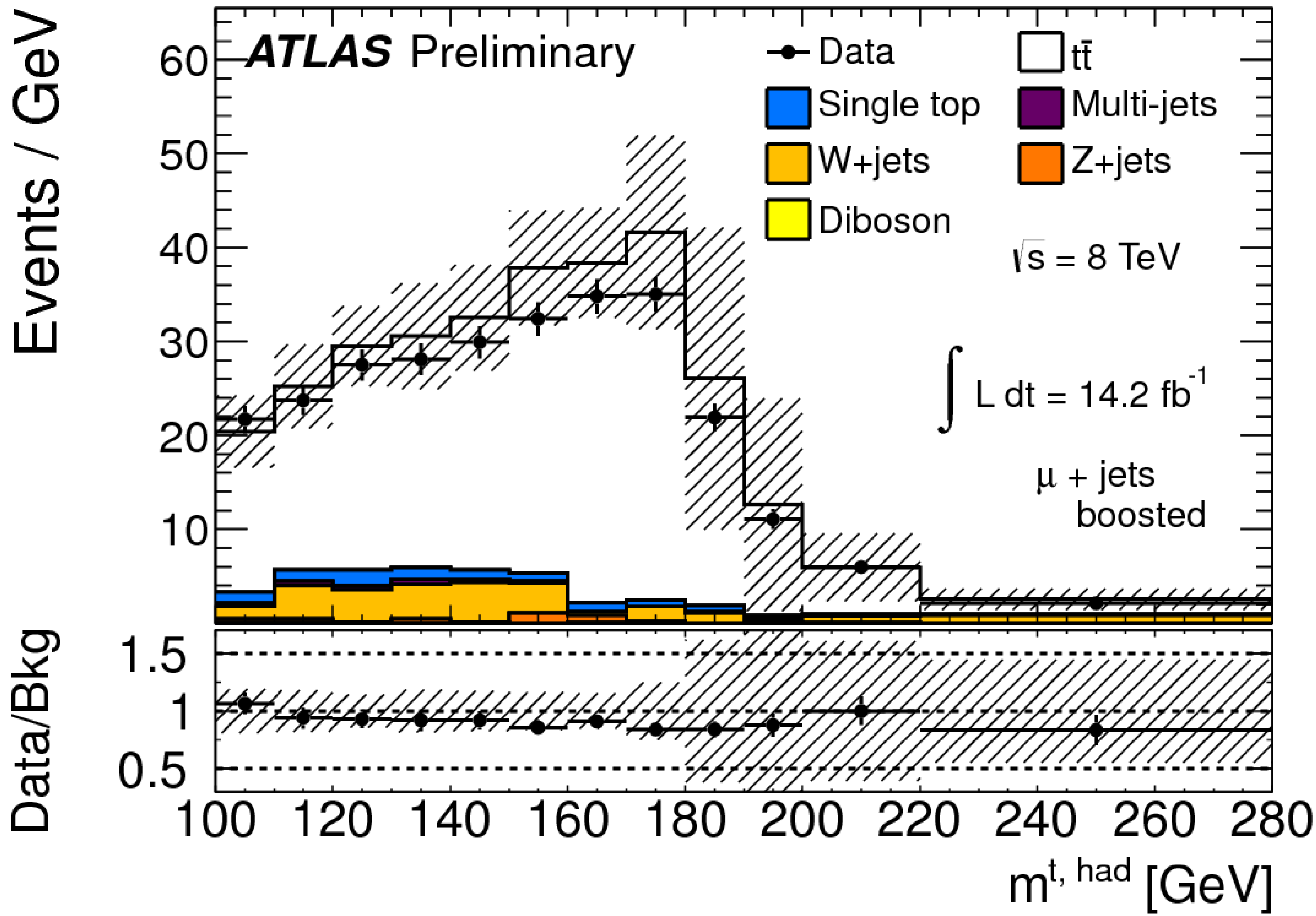
- Use jet substructure to “tag” boosted tops



ATL-PHYS-PUB-2010-008

Jet Mass

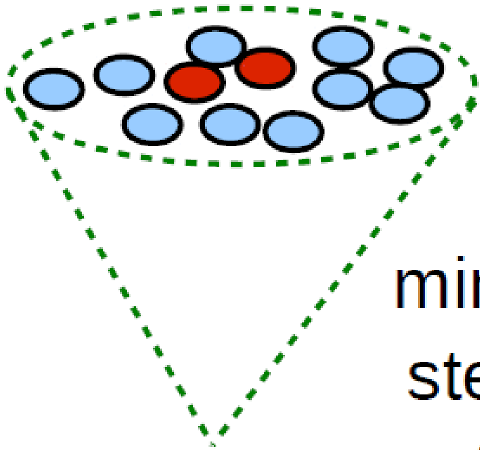
ATLAS-CONF-2013-052



Jet Substructure: Splitting Scale

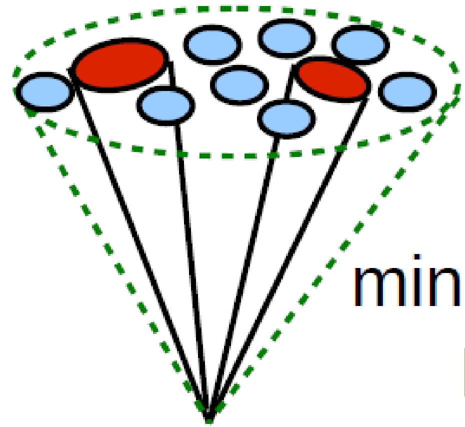
E. Thompson, Jet Substructure and Boosted top-tagging at ATLAS

QCD



min p_T x dR = steeply falling spectrum

Boosted W boson

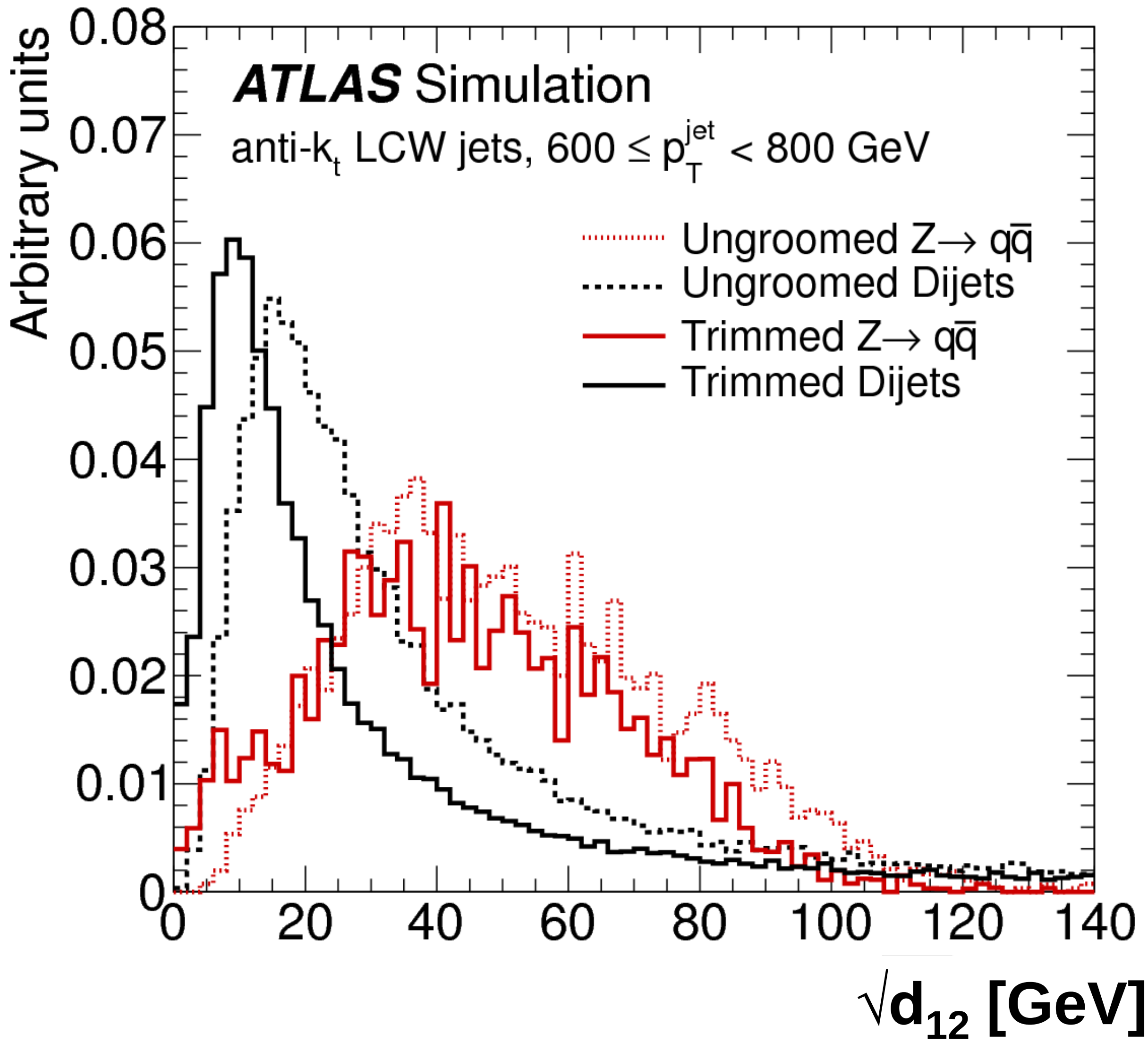


min p_T x dR = M_{jet} / 2

$$d_{ij} = \min({p^2}_{Ti}, {p^2}_{Tj}) \times {\Delta R^2}_{ij}/R^2$$

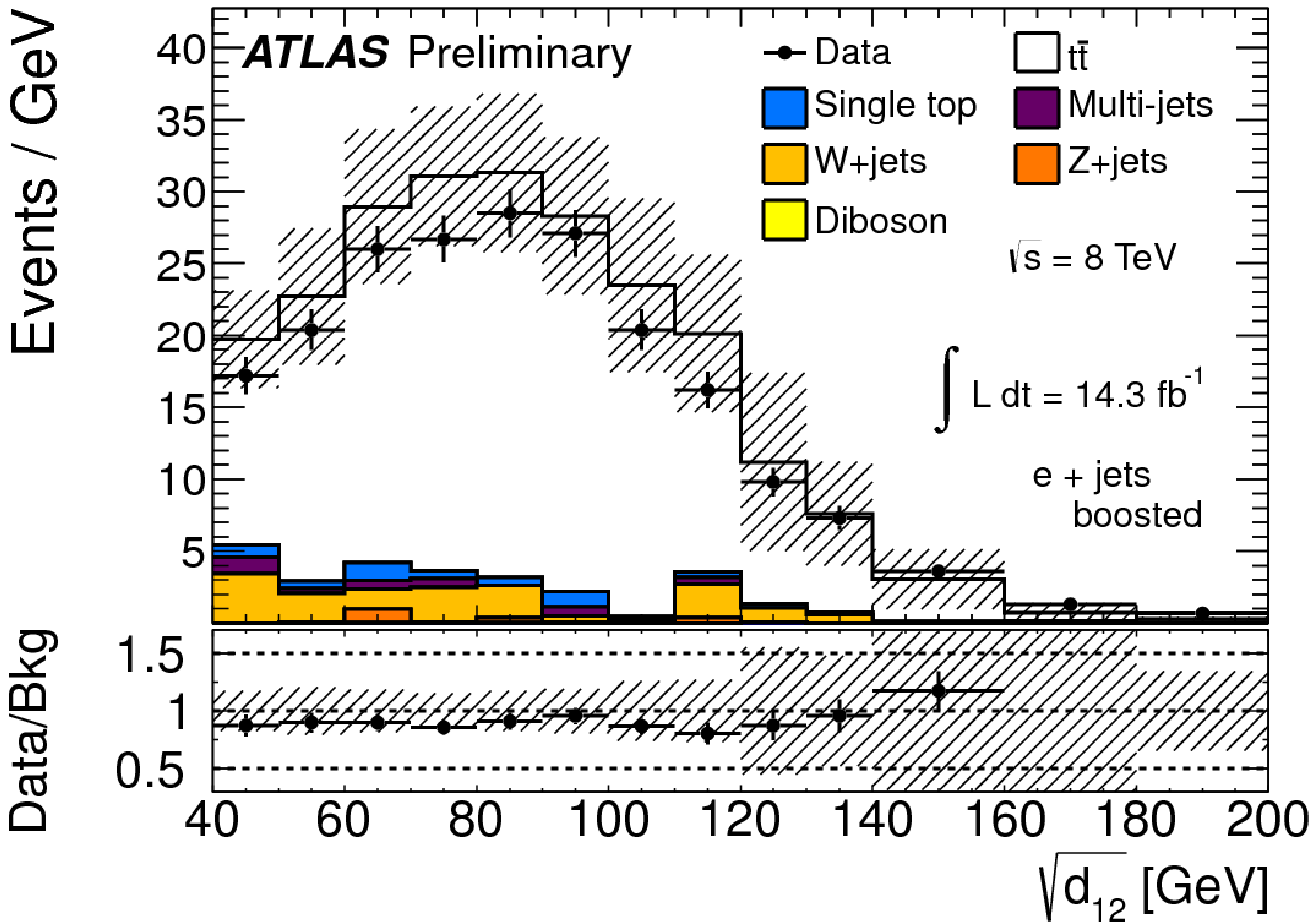
Jet Substructure: Splitting Scales

CERN-PH-EP-2013-069, arXiv:1306.4945



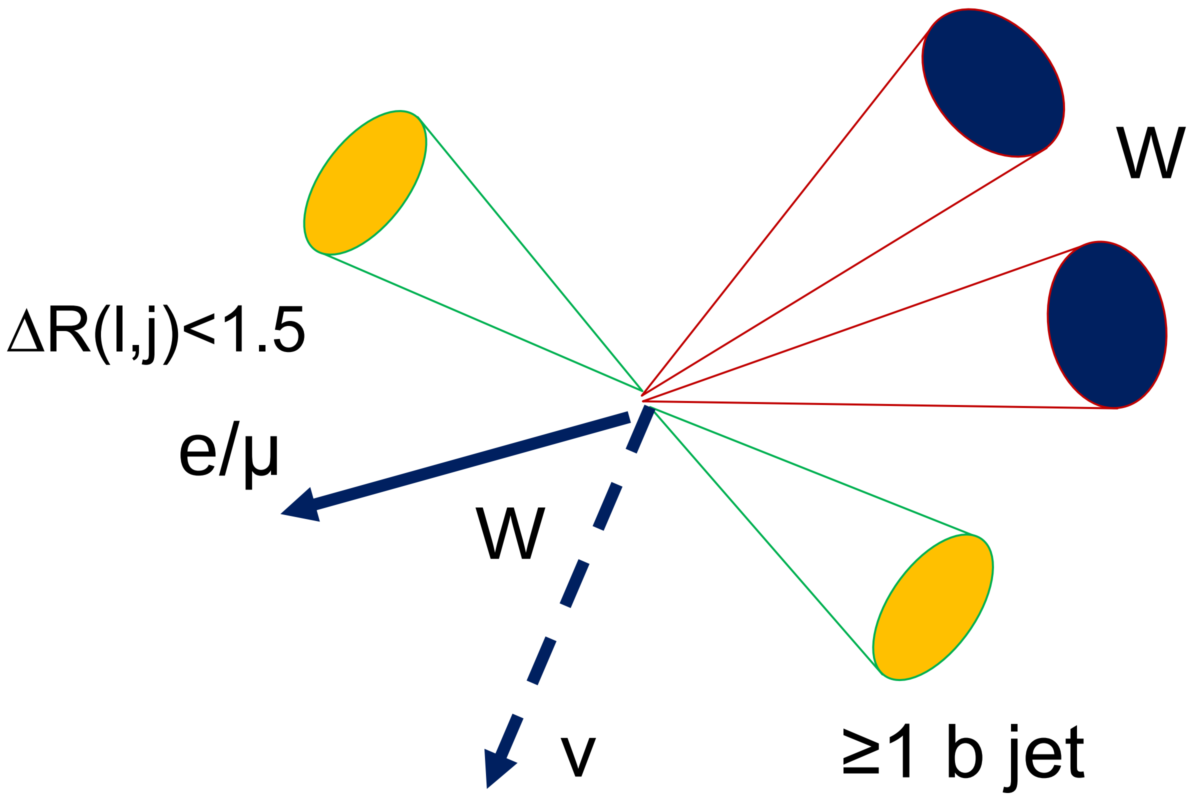
Jet Substructure: Splitting Scale

ATLAS-CONF-2013-052



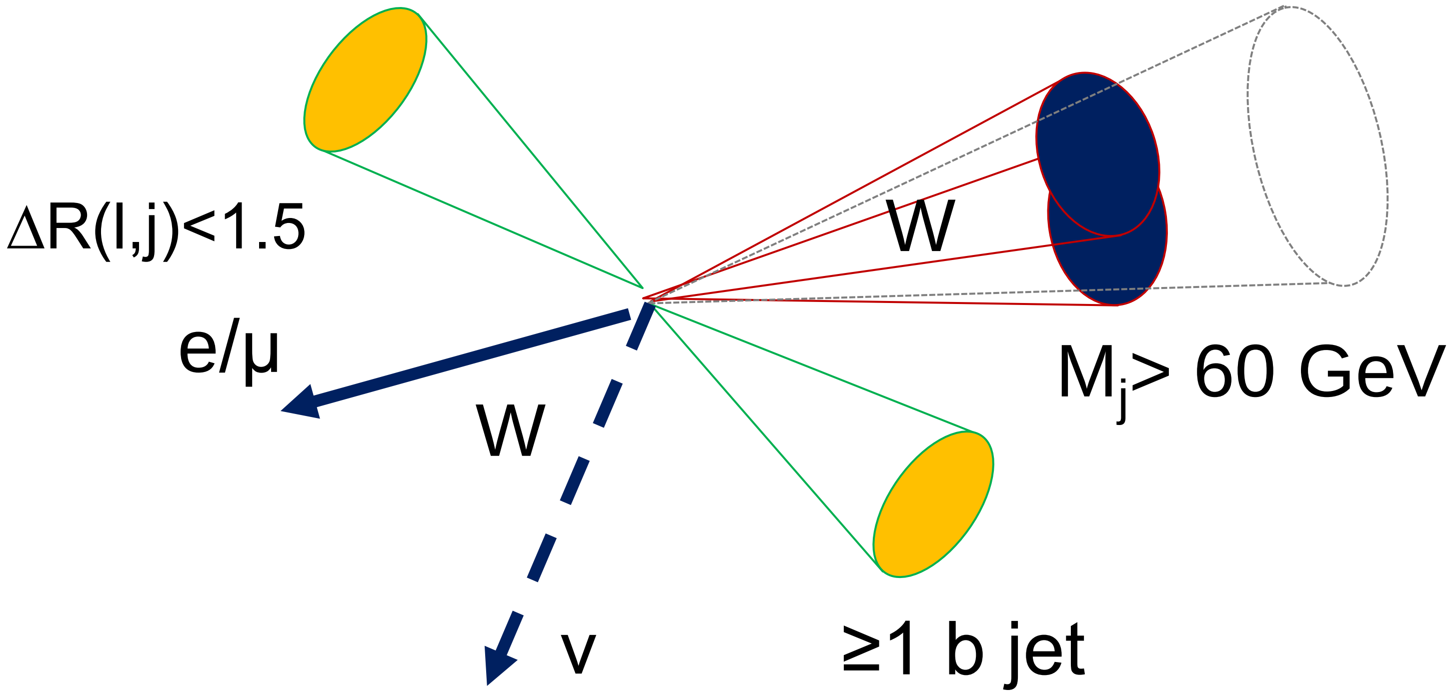
Resolved Selection

$\geq$ 4 small jets, j, with p_T> 25 GeV, $|\eta|$<2.5



Merged Selection

3 small jets, j, with p_T> 25 GeV, |η|<2.5



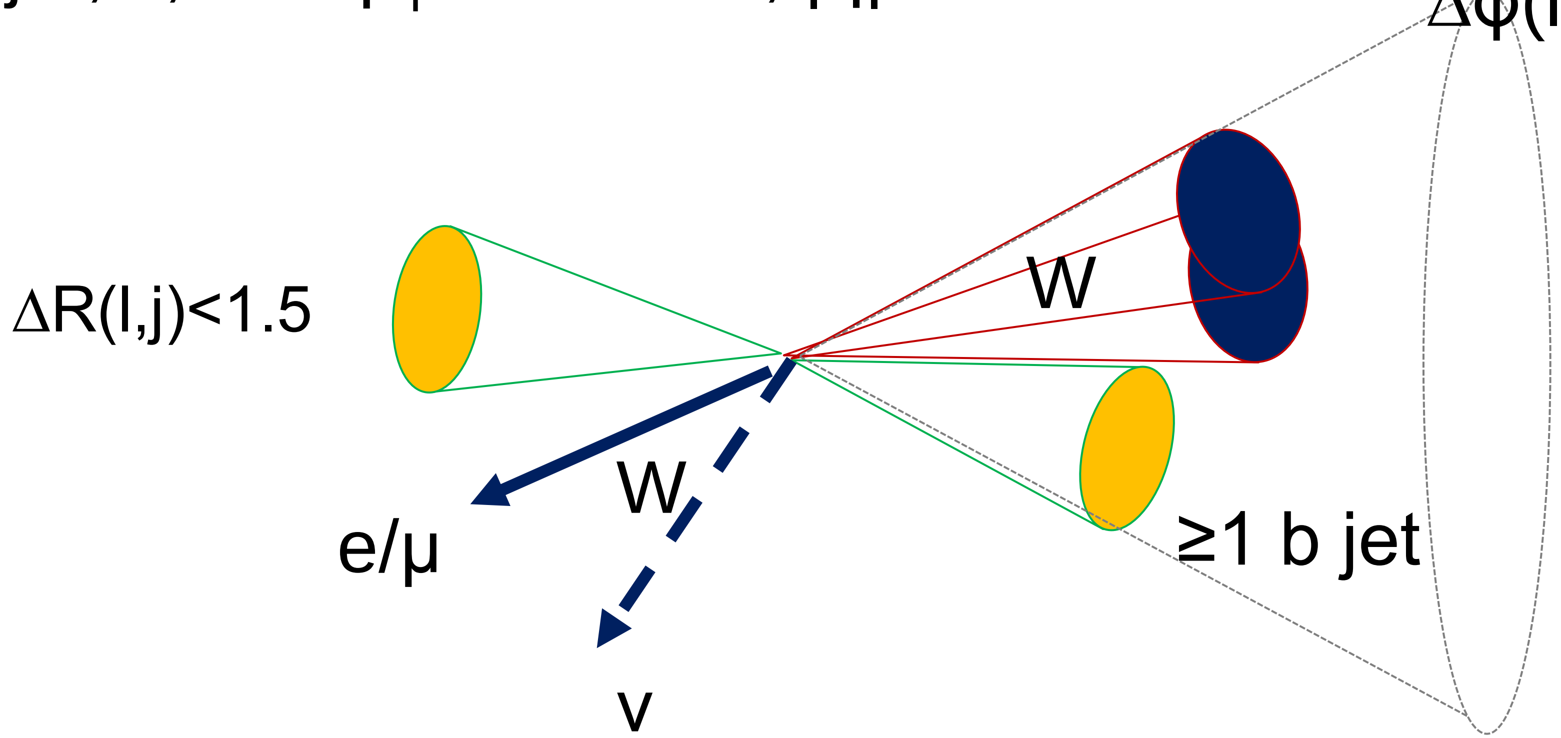
Boosted Selection

≥1 small jet, j, with p_T> 25 GeV, |η|<2.5

≥1 fat-jet, J, with p_T>300 GeV, |η|<2.0

ΔR(l,J)>1.5

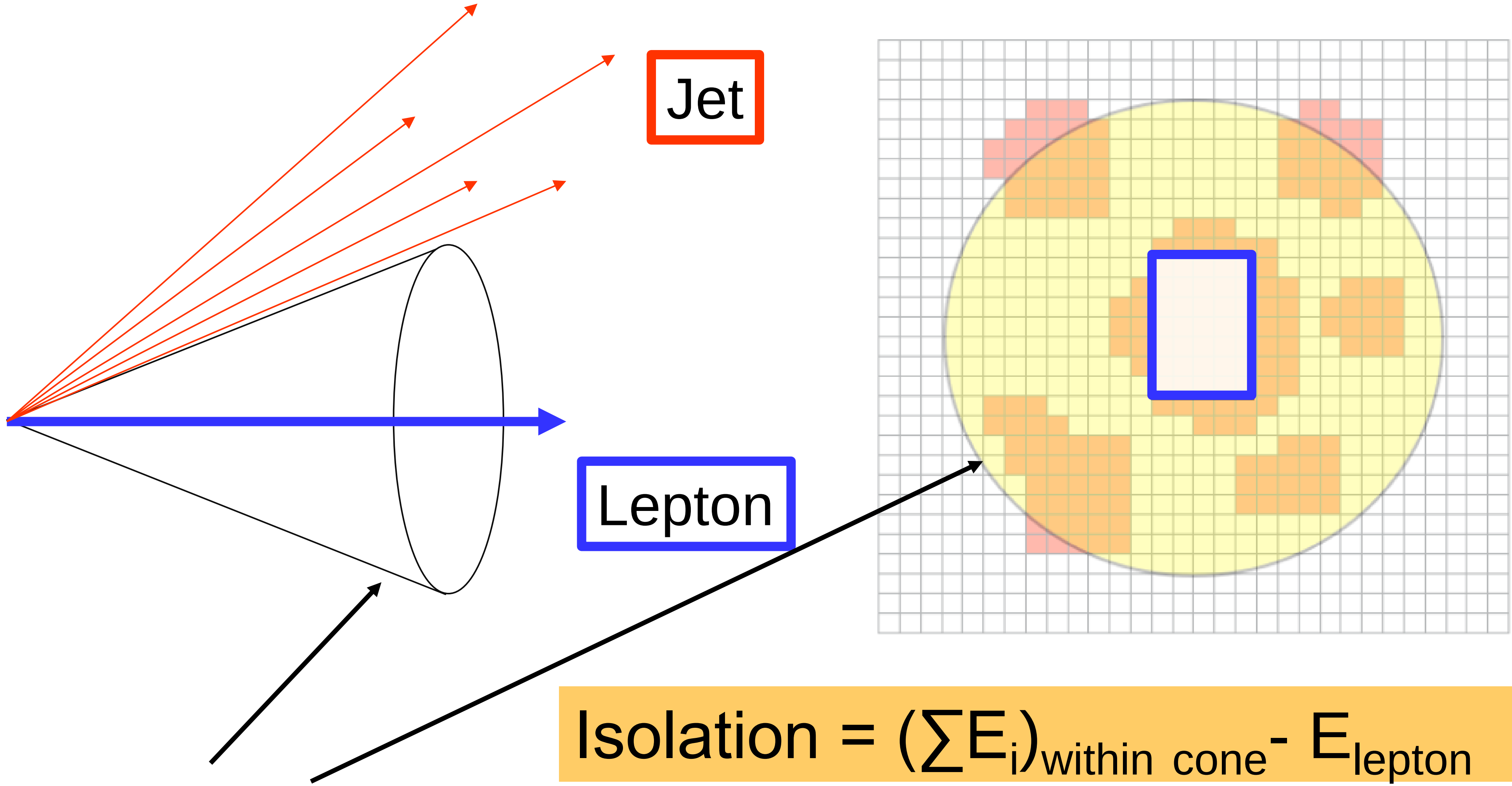
Δφ(l.J)>2.3



M_J> 100 GeV

$\sqrt{d_{12}} > 40$ GeV

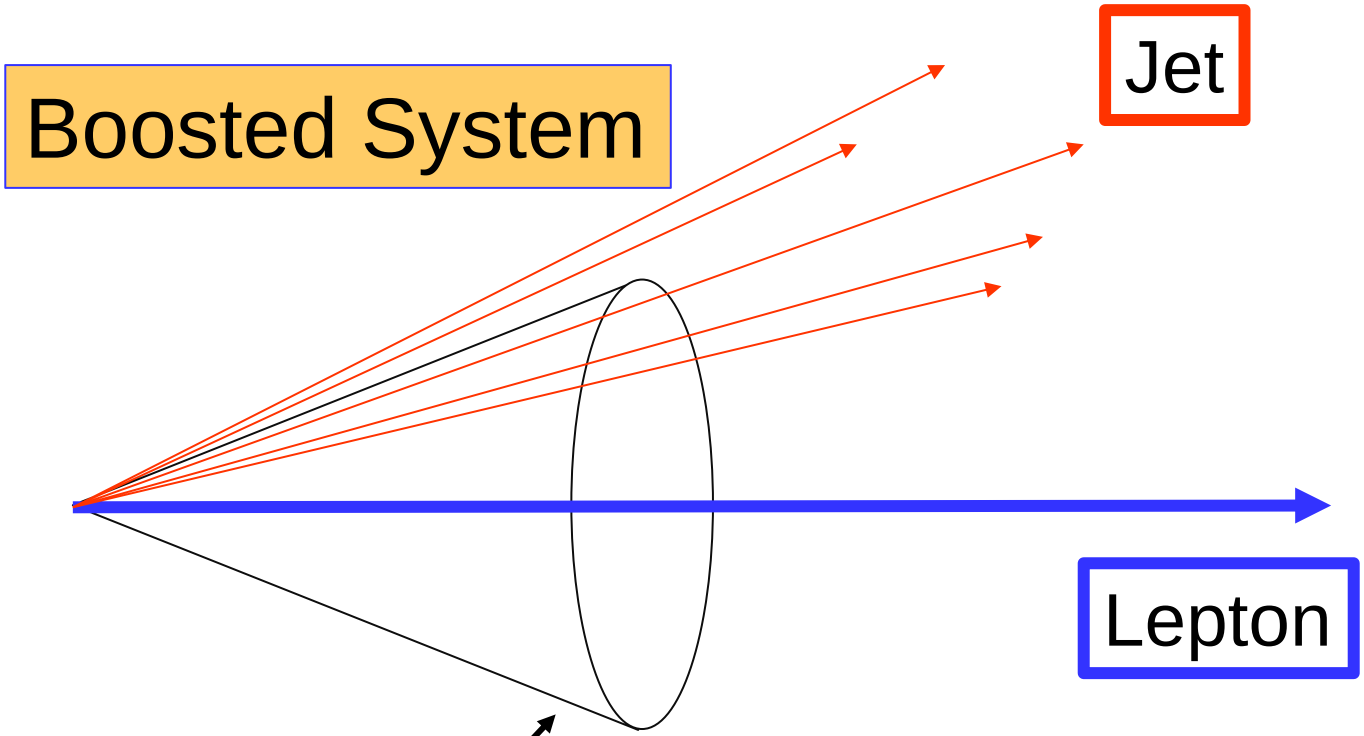
Fixed Cone Size Lepton Isolation



$$\text{Isolation} = (\sum E_i)_{\text{within cone}} - E_{\text{lepton}}$$

"Fixed" Isolation Cone

Fixed Cone Size Isolation



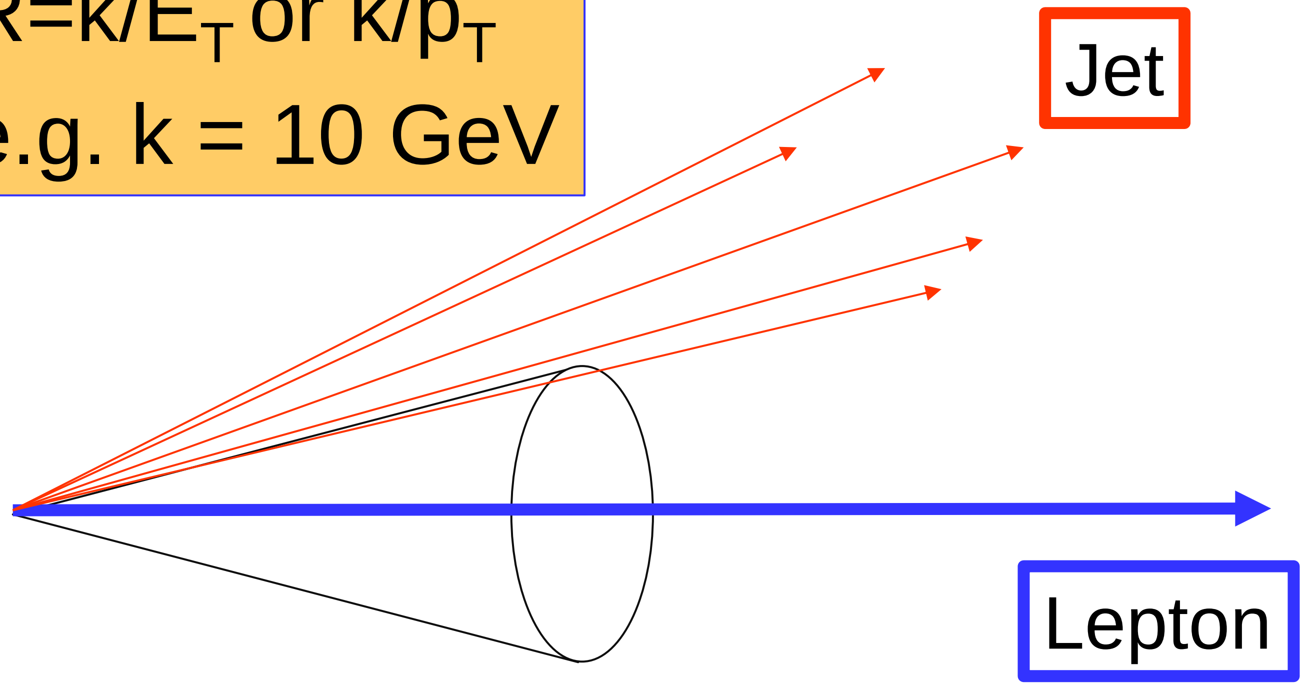
Inefficiency increases with boost !!!

“Fixed” Isolation Cone

"Mini"-Isolation

$R=k/E_T$ or k/p_T

e.g. k = 10 GeV

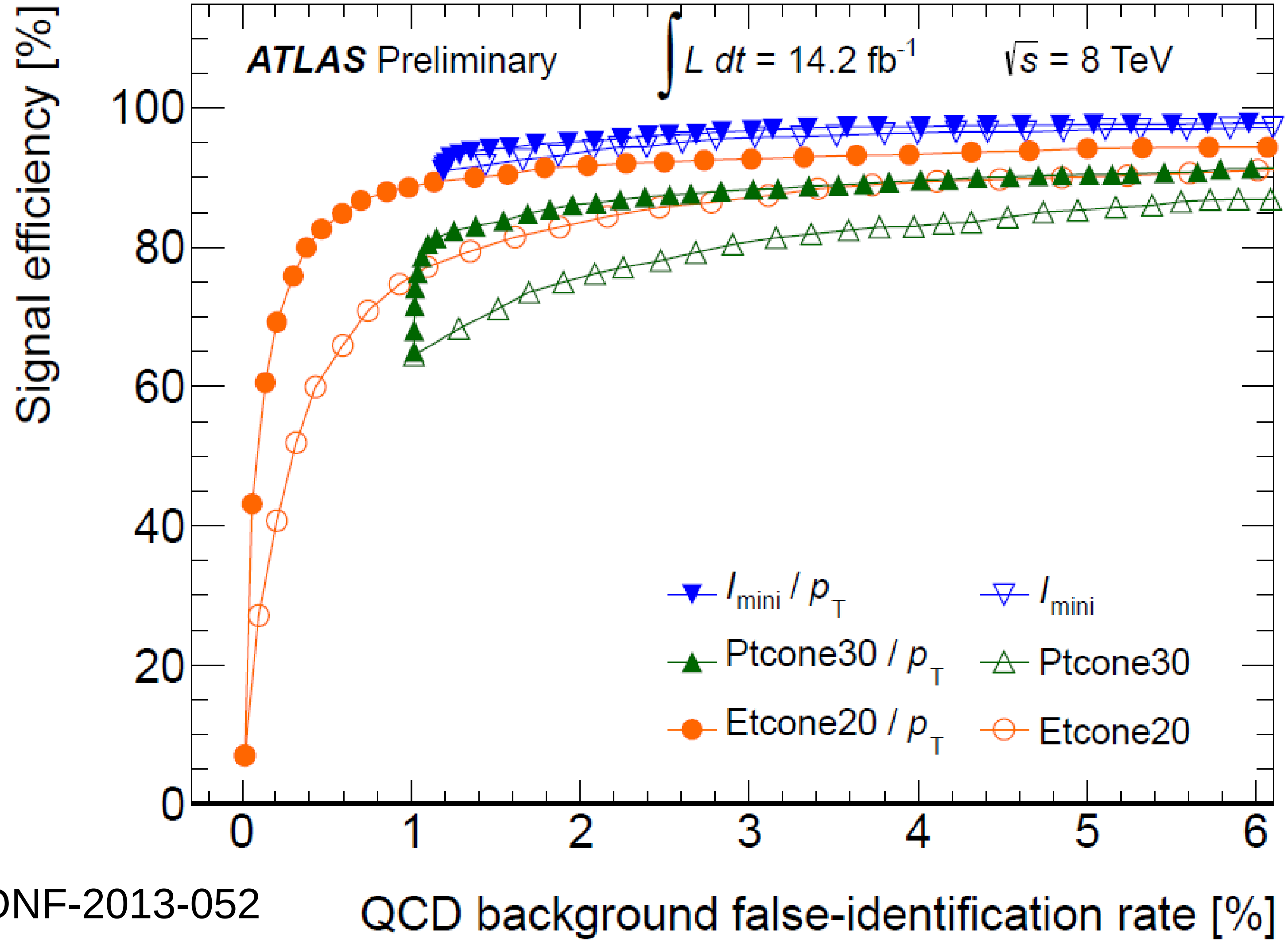


$I_{mini}<0.05*E_T$ (for electrons)

$I_{mini}<0.05*p_T$ (for muons)

"Variable" Isolation Cone

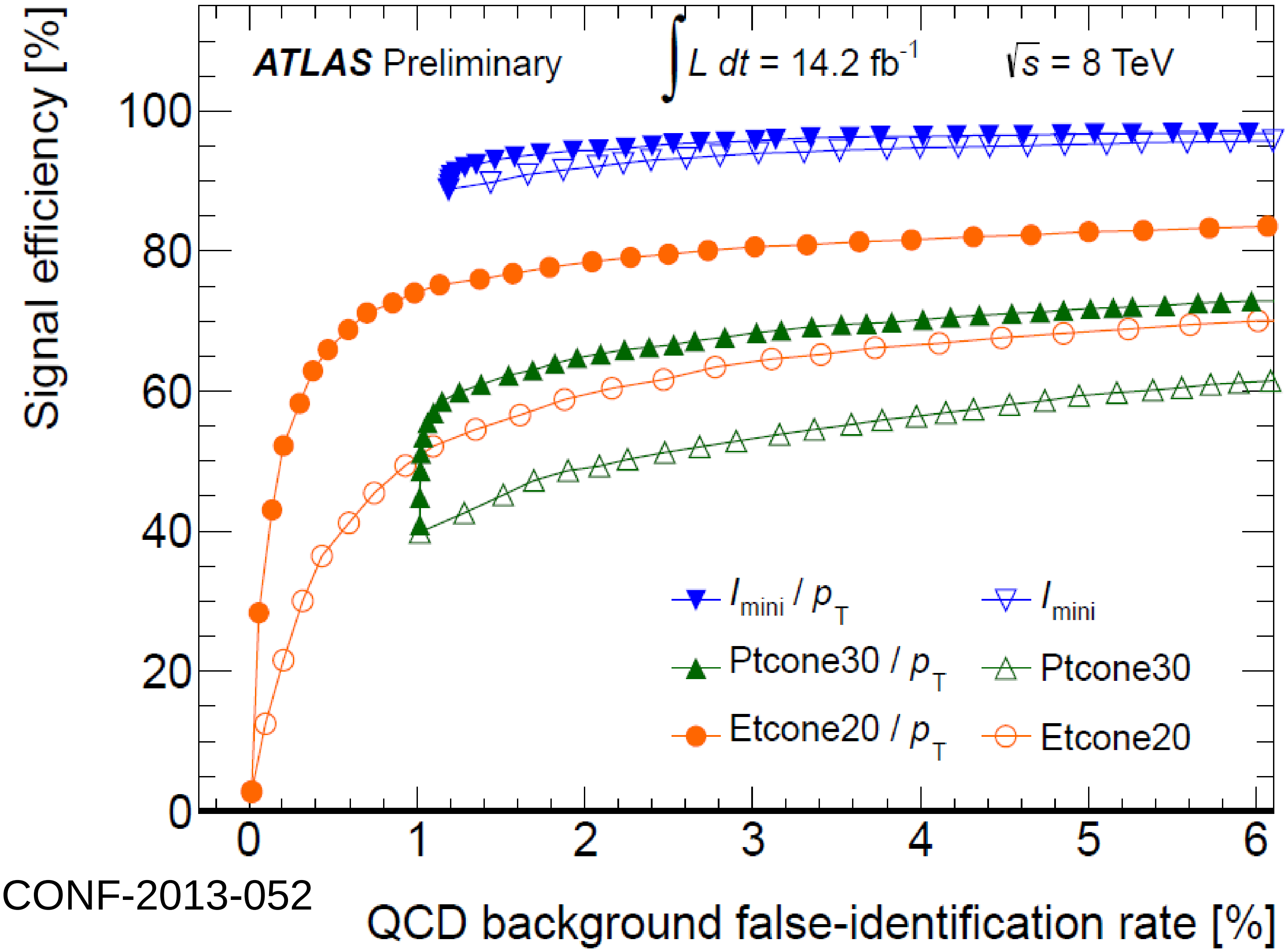
Efficiency Comparisons



ATLAS-CONF-2013-052

(b) 1.0 TeV Z'

Efficiency Comparisons

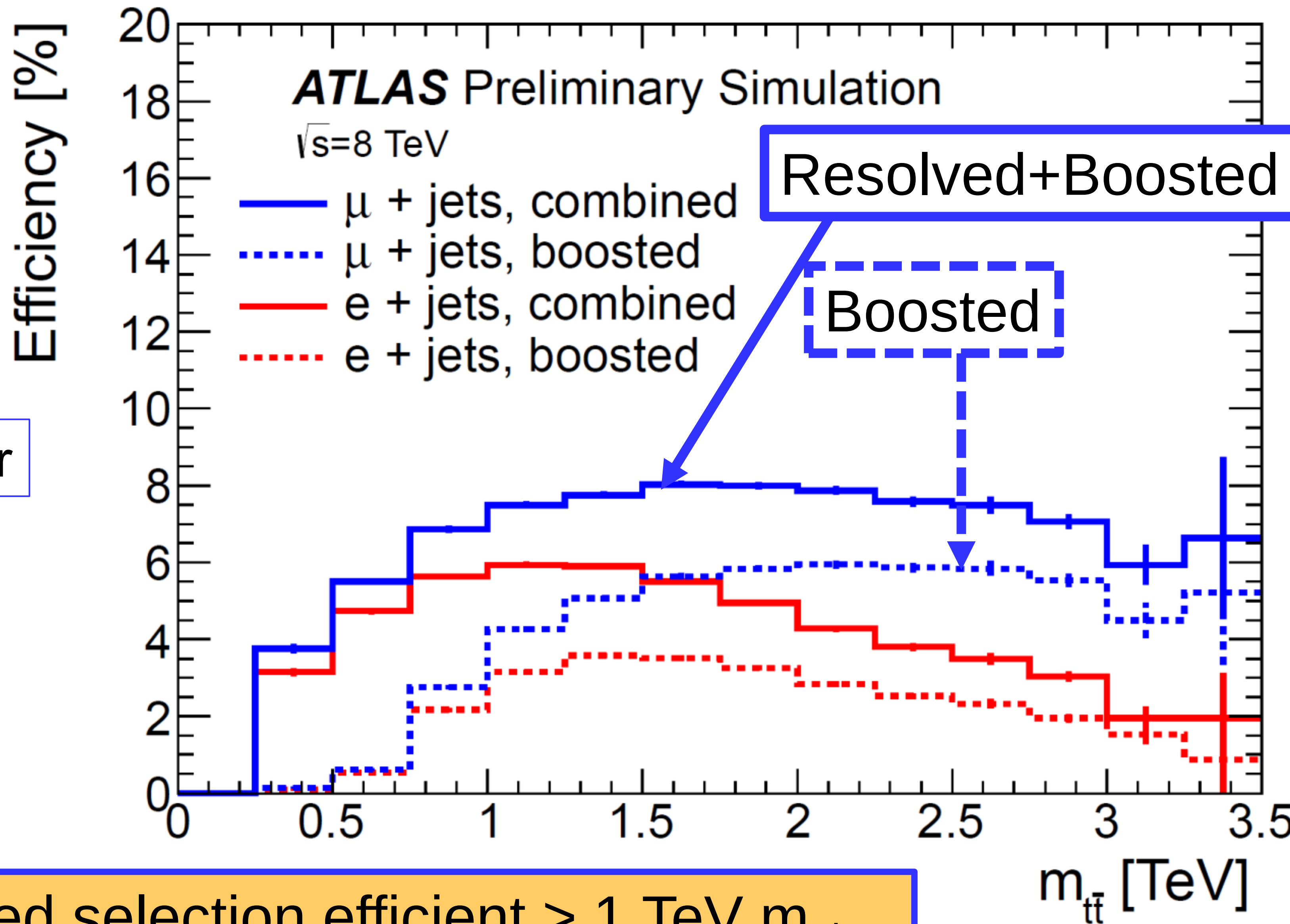


ATLAS-CONF-2013-052

(d) 2.0 TeV Z'

Geometrical Acceptance + Selection Efficiencies

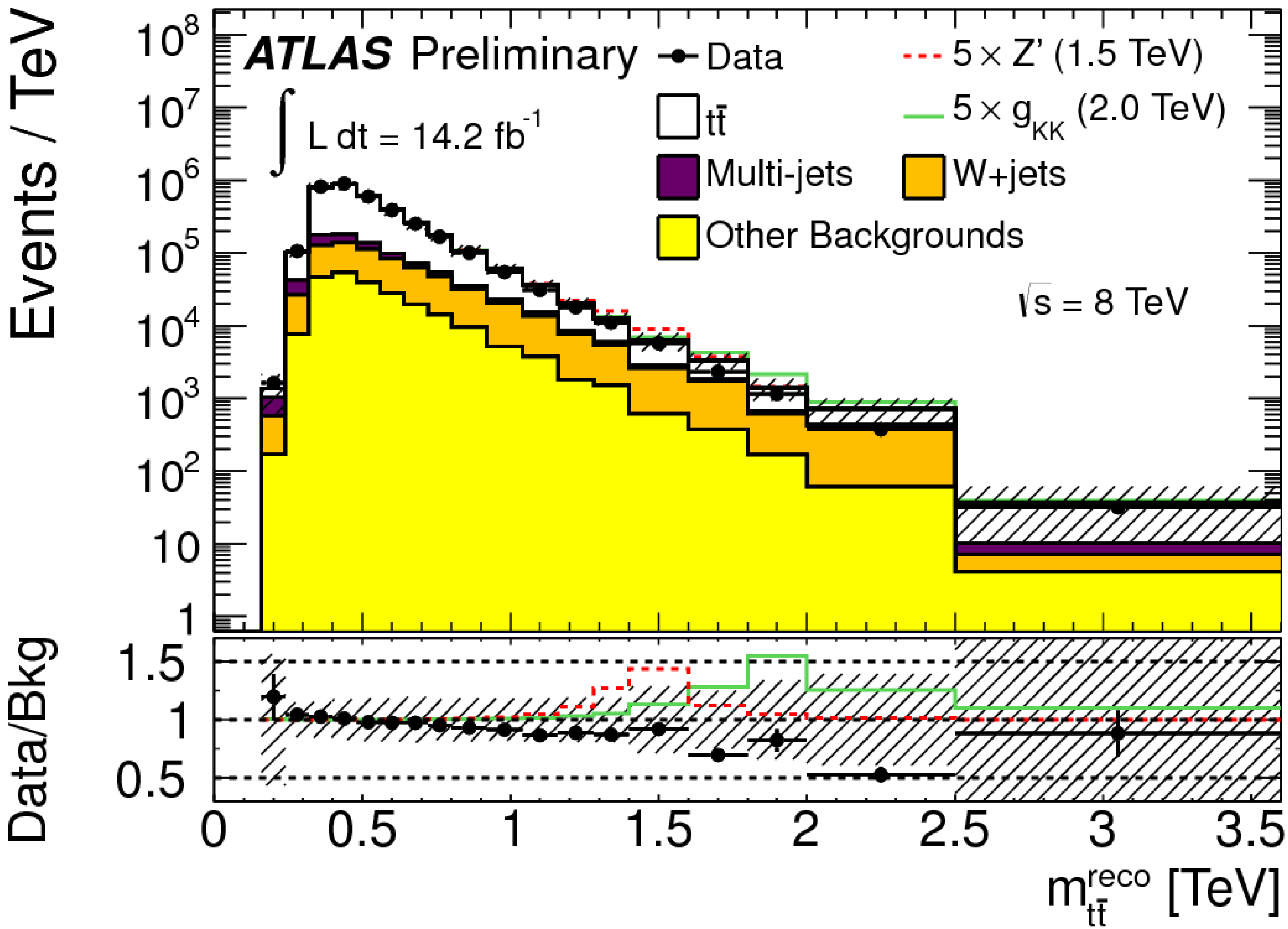
Z'→ttbar



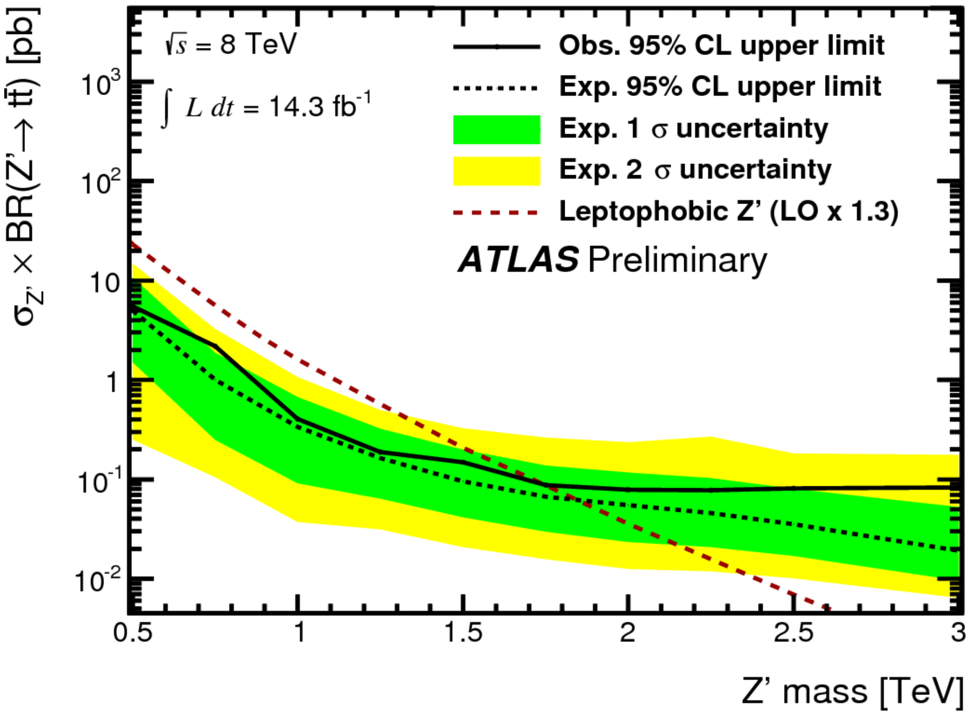
Boosted selection efficient > 1 TeV m_{ttbar}

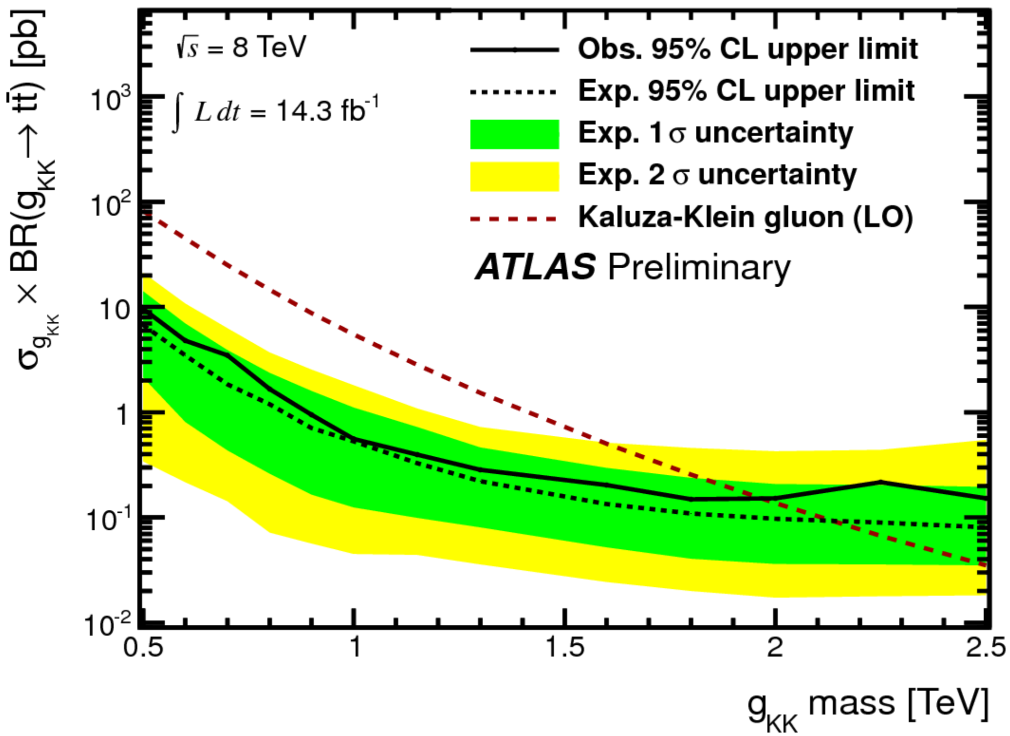
Discriminant distribution m_{ttbar}

- $m_{t\bar{t}}$ resolved + boosted in *e*+jets and *μ*+jets



Heavy Resonances Search: Ttbar





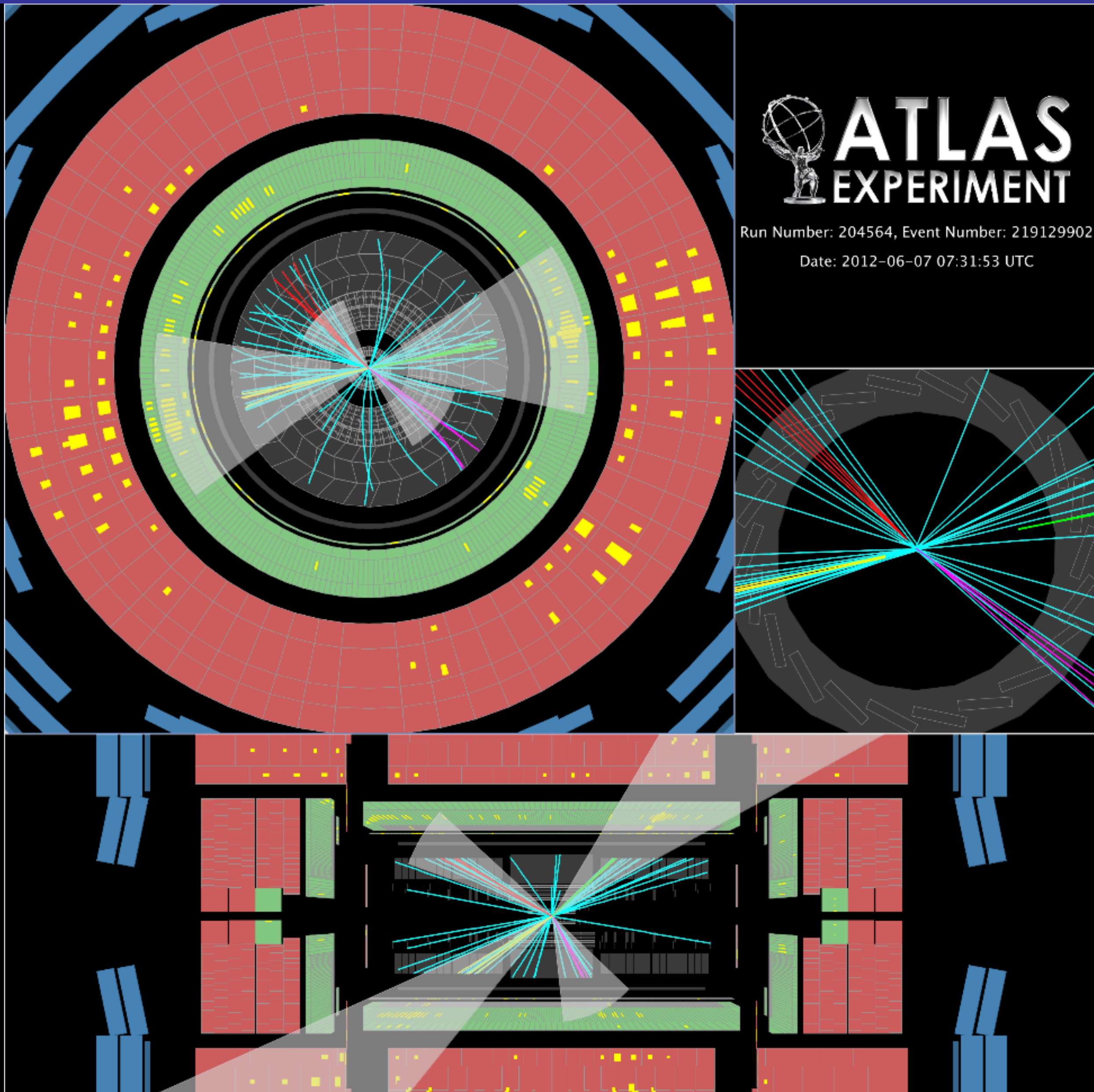
m(Z') > 1.8 TeV @95% Cl

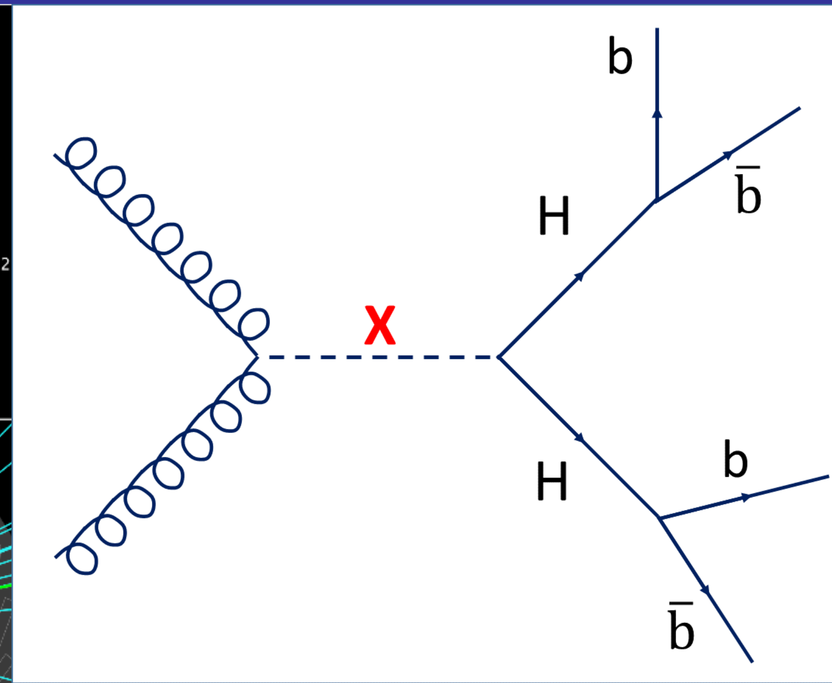
Γ/m(Z') = 1.2%

m(g_{KK}) > 2.0 TeV @95% Cl

Γ/m(g_{KK}) = 15%

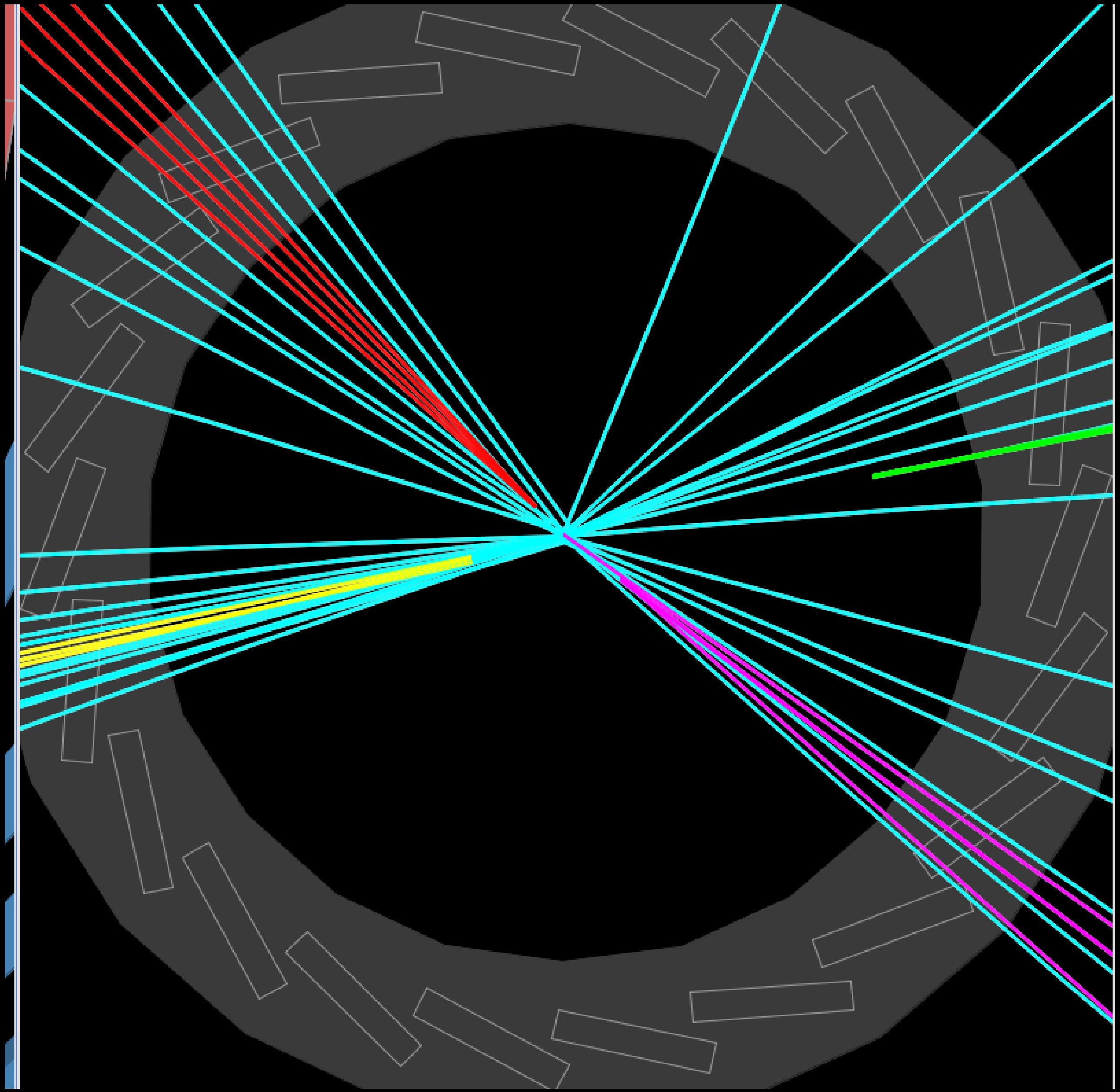
Resonance Searches with Higgs Pairs



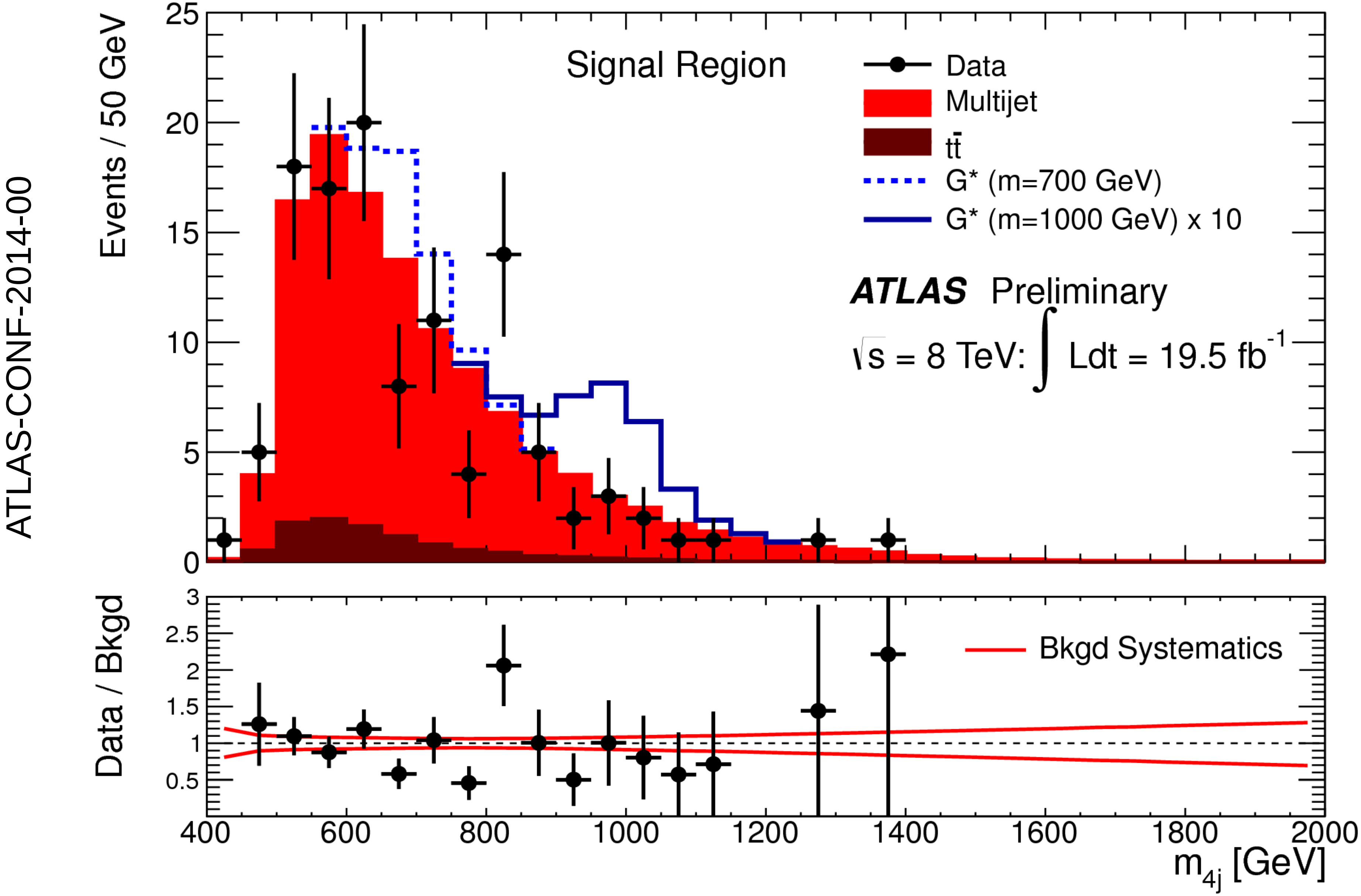


ATLAS-CONF-2014-00

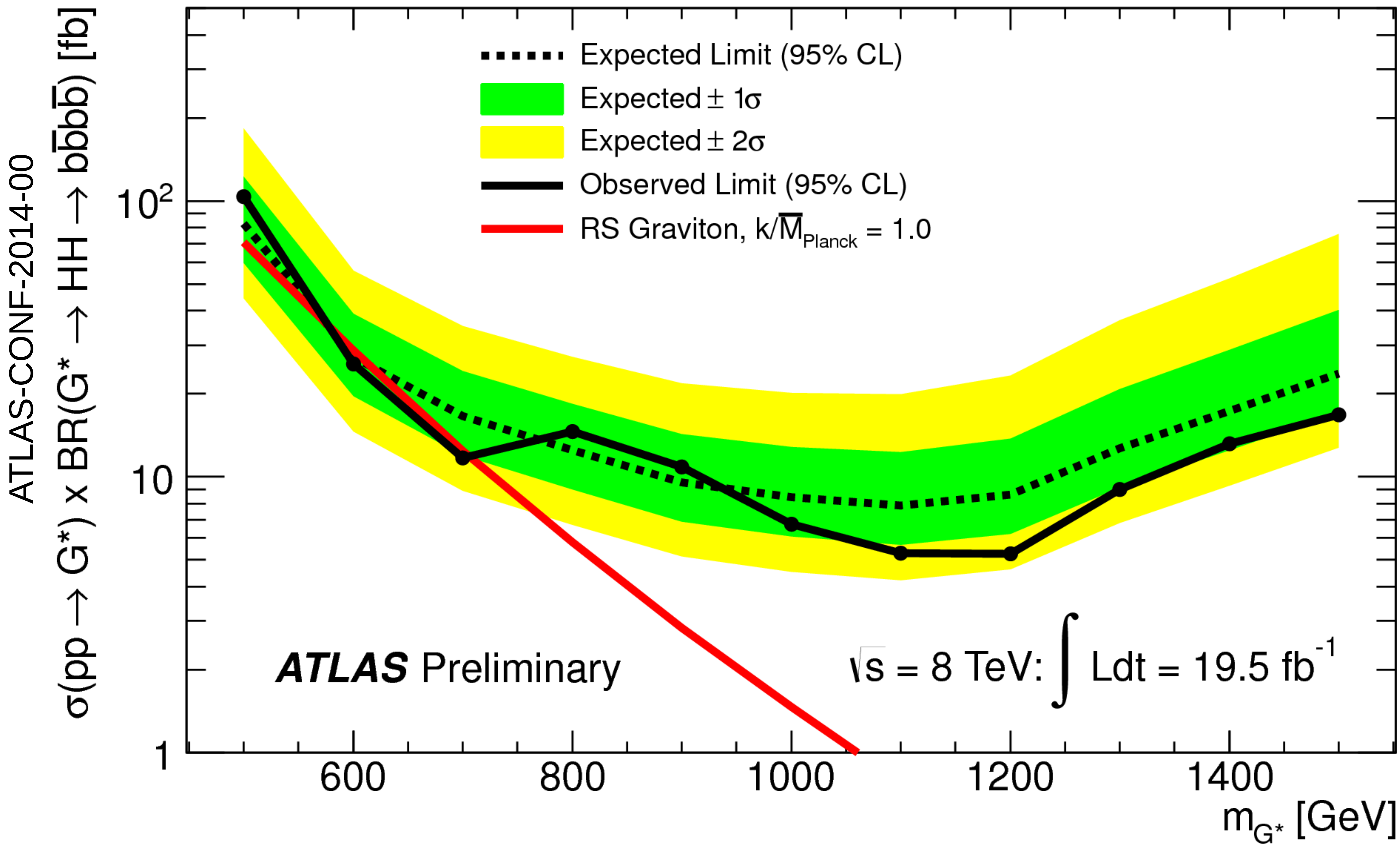
Resonance Searches with Higgs Pairs



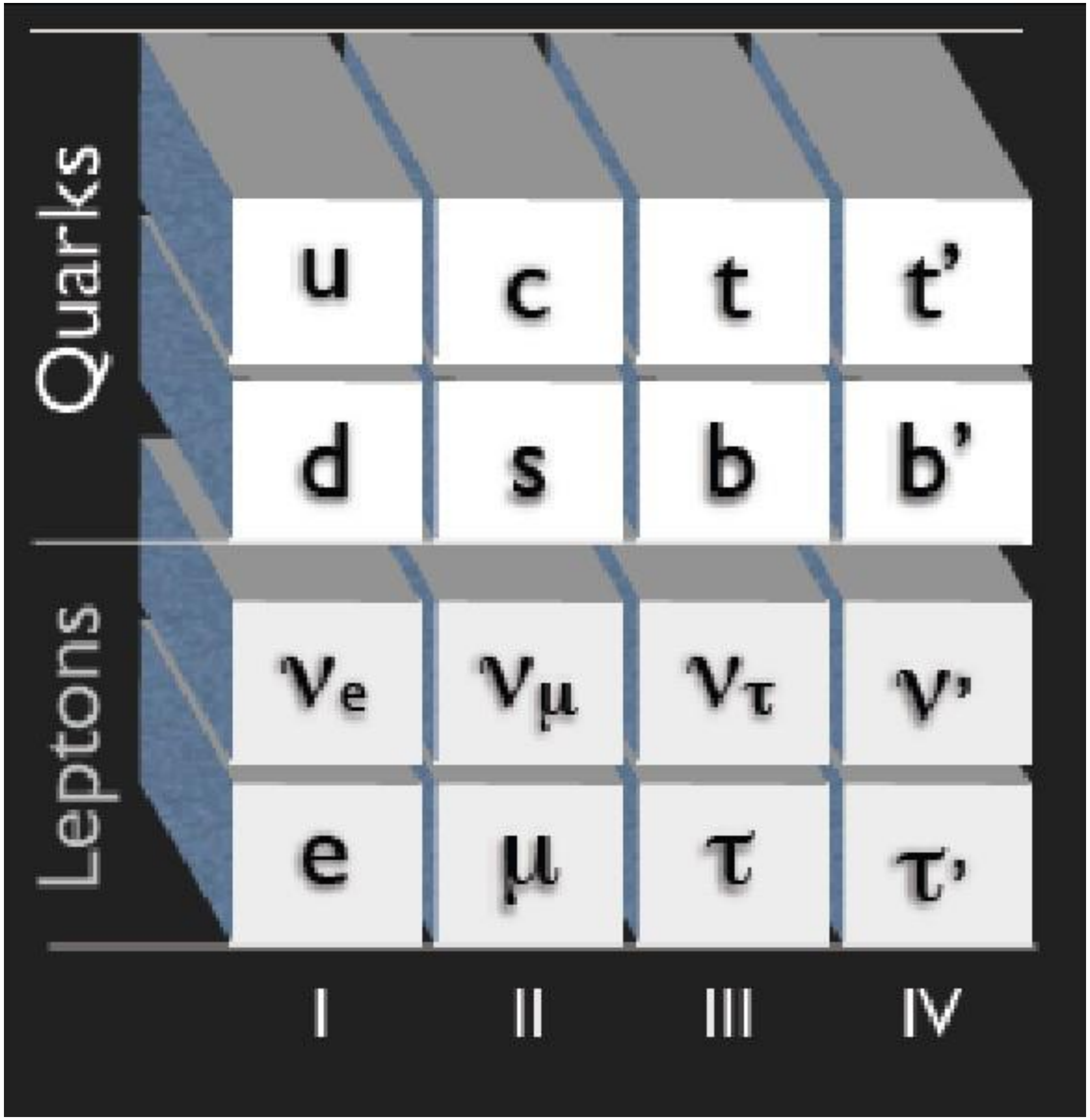
2H → 4 b resonance search



$2H \rightarrow 4$ b resonance search

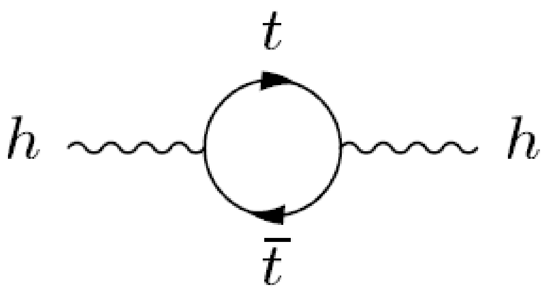


Heavy Quarks



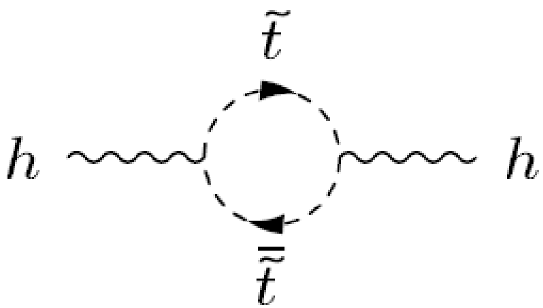
Fine Tuning Problem and SUSY

- Same problem with Higgs



$$\Delta\mu^2_{\mathrm{top}} = -6\frac{h_t^2}{4\pi^2}\frac{1}{r_H^2}$$ ~ (100 GeV)^2

125 GeV = (huge number)-(huge number) even more fine tuned!

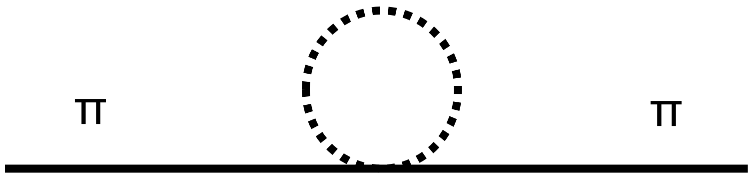


Add new particles (spin symmetry): SUSY

$$\Delta\mu^2_{\mathrm{stop}} + \Delta\mu^2_{\mathrm{top}} = -6\frac{h_t^2}{4\pi^2}(m^2_{\tilde{t}} - m^2_t)\log\frac{1}{r_H^2 m^2_{\tilde{t}}}.$$

Composite Higgs

- But there is another way….look at QCD

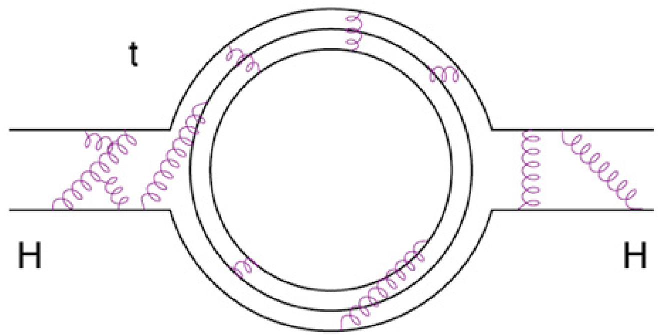


Pion mass is not divergent.

Why?

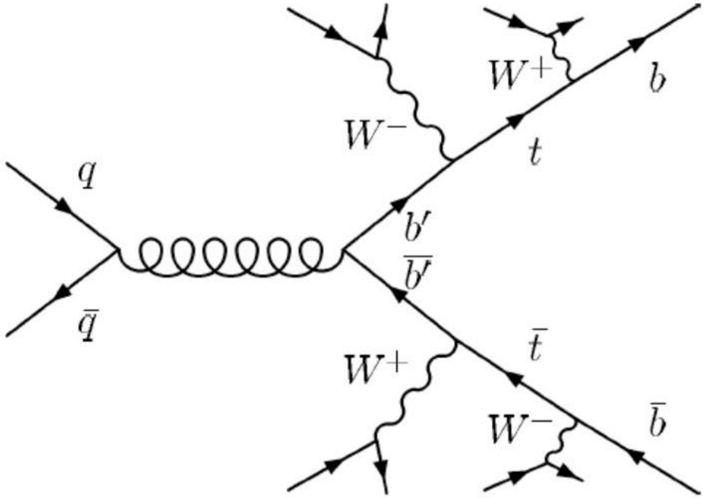
It is a composite particle!

- **Assume Higgs is a composite particle**
  - Changes couplings
  - Introduces new partners to top quarks
  - Vector-like quarks…
    - (both chiralities same under SU(2)xU(1)
  - Solves fine-tuning problem….

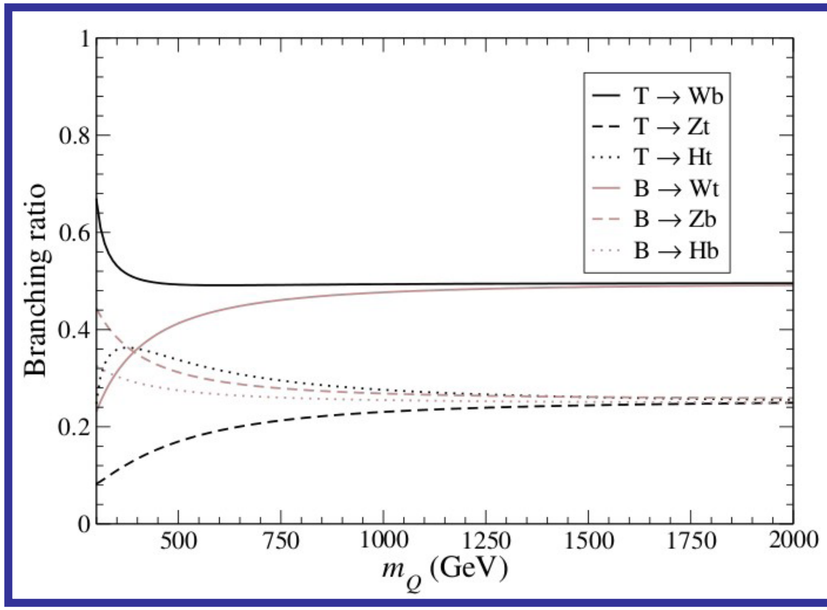


4th Generation and Heavy Quarks

- 4th generation would significantly enhance Higgs production cross section
  - (almost) excluded by observed Higgs cross-section
  - t't' → WbWb (100%): just like t-tbar but heavier
  - b'b' →WtWt (100%): just like ttbar but messier

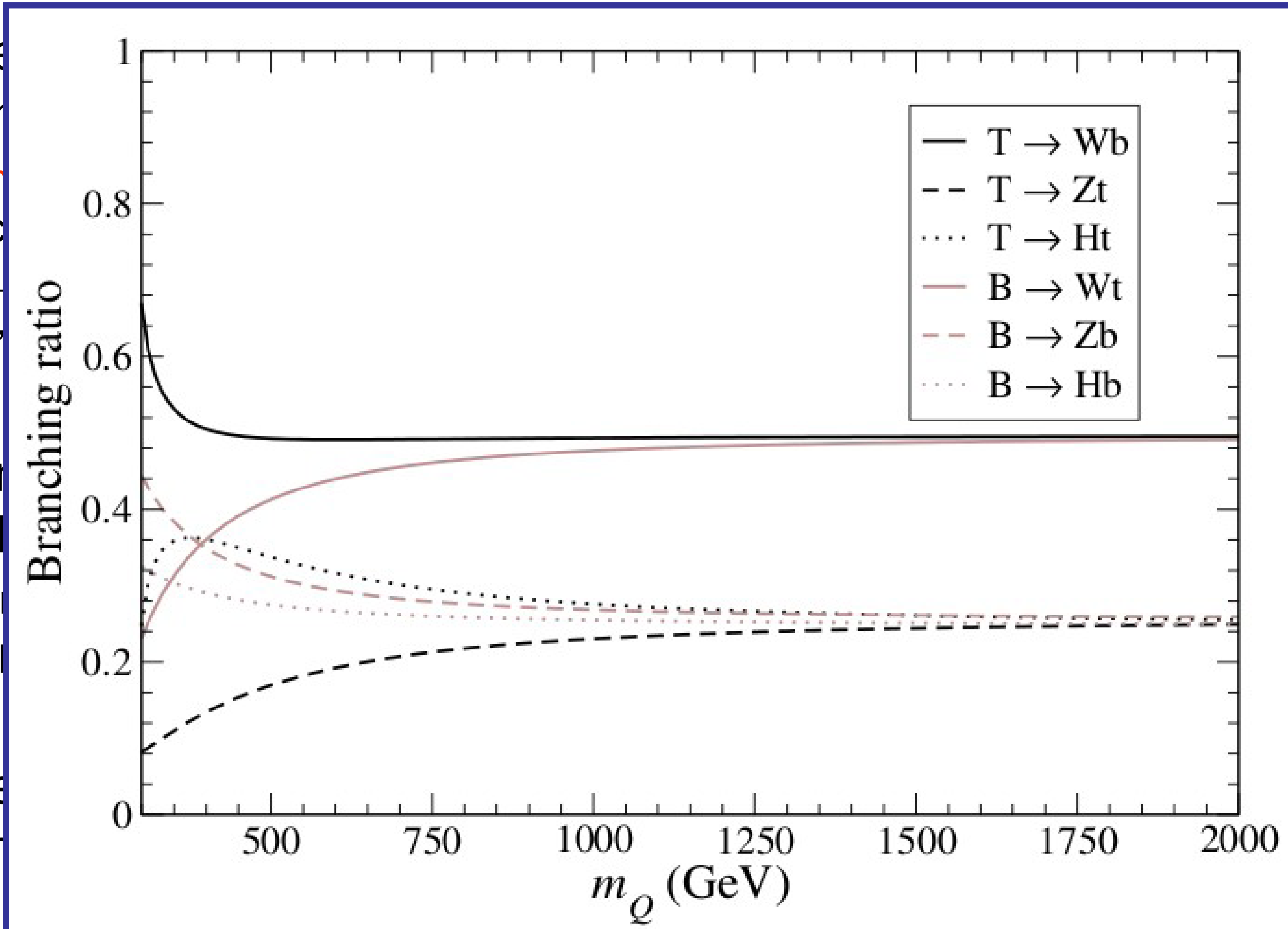


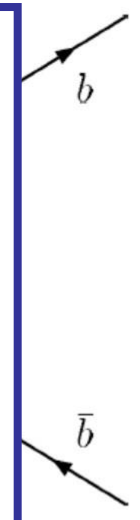
- Beyond 4th generation: **Vector-Like Quarks** in Composite Higgs theories
  - More diverse phenomenology
  - T': Decays to Wb, Zt, Ht
  - B': Decays to Wt, Zb, Hb
- Loose constraints on CKM4 → decays to light quarks possible!

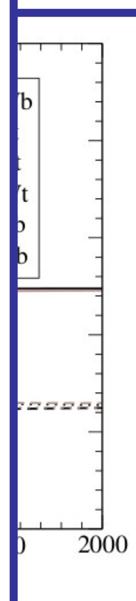


4th Generation and Heavy Quarks

- 4th ge
  enhar
  - (alr
    sec
  - t't' -
  - b'b'



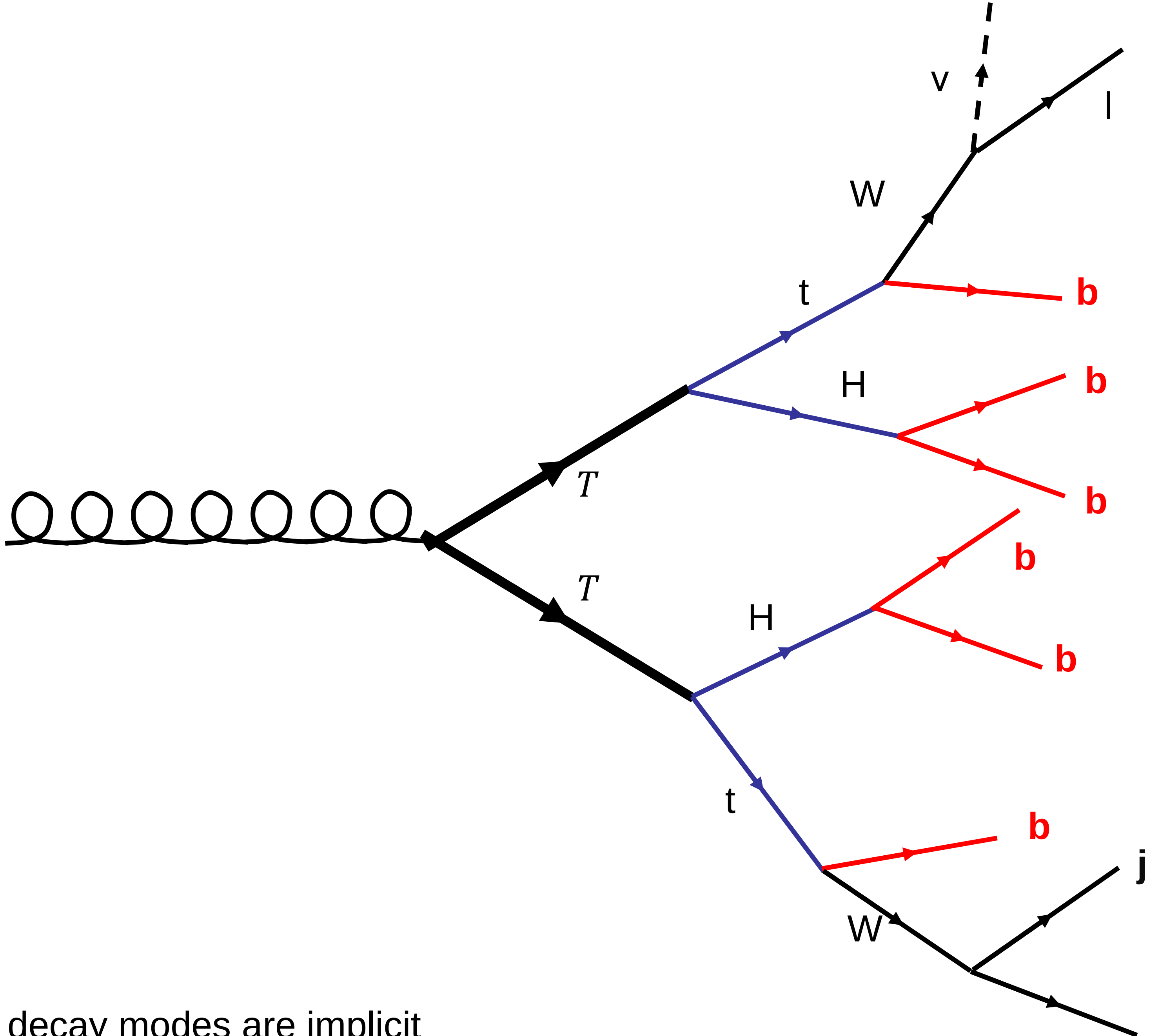




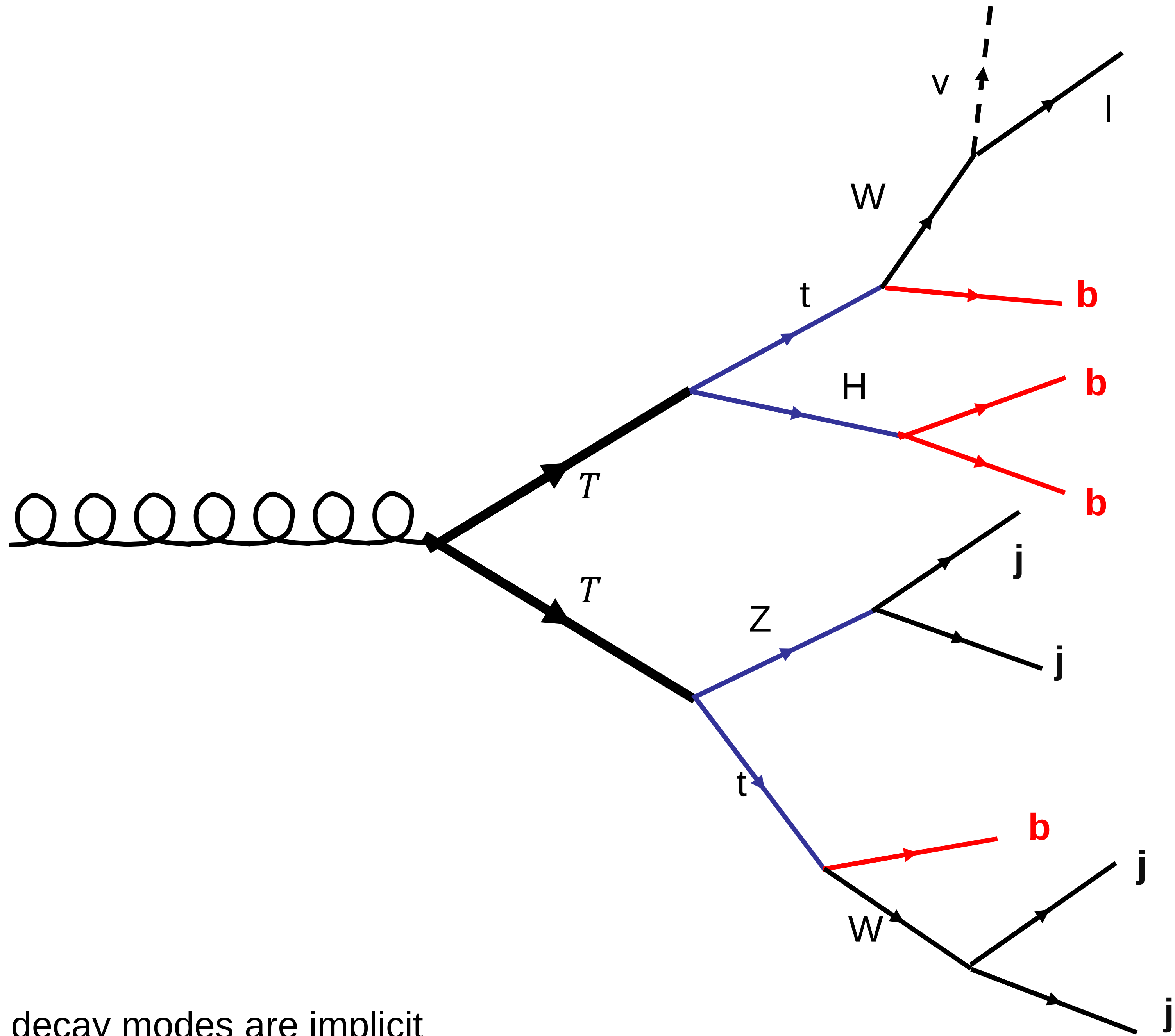
- Beyor
  Quarl
  - Mo
  - T': I
  - B':
- Loose
  to ligh

$t' \rightarrow \mathbf{H}\ t$

ATLAS-CONF-2013-018

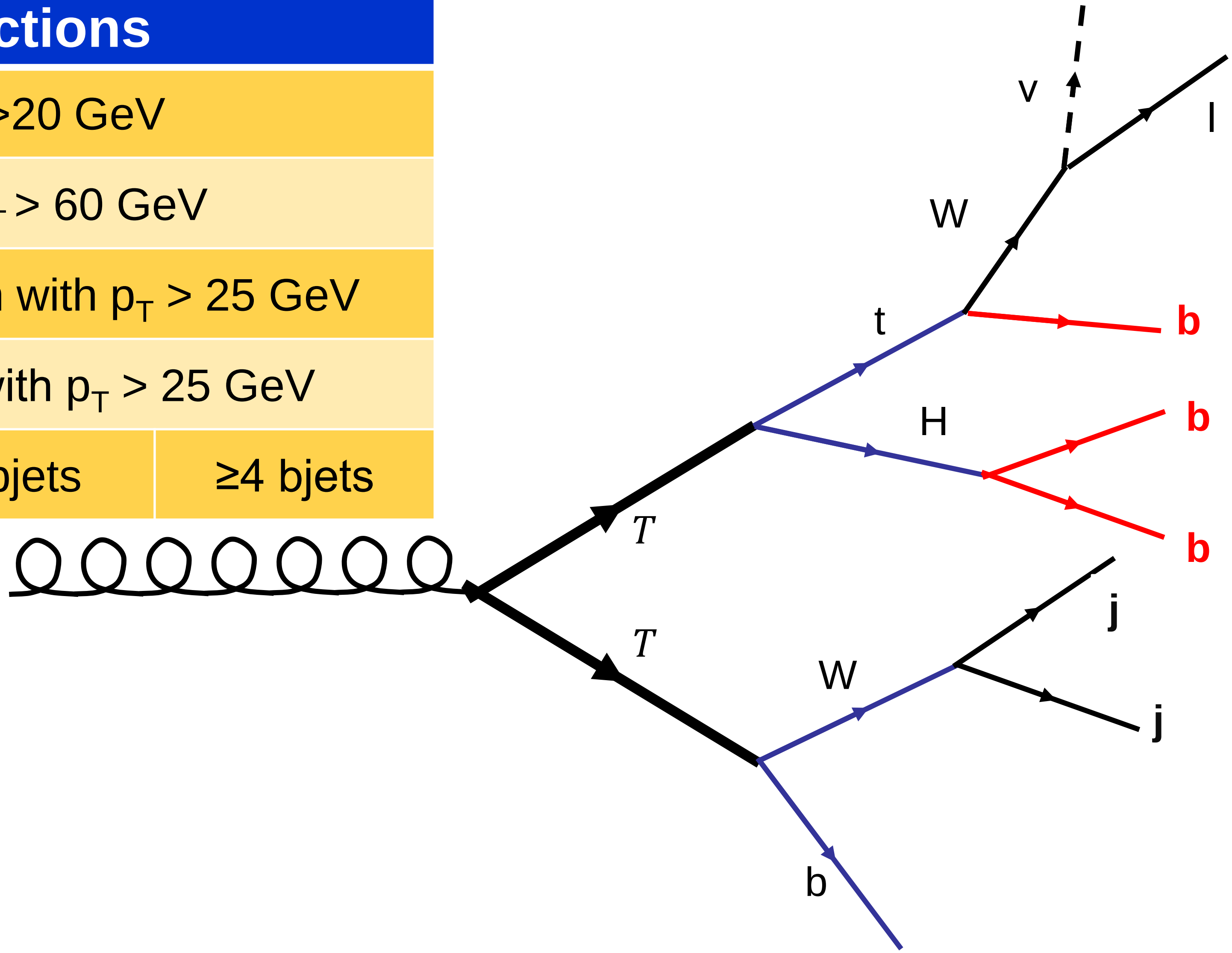


Complex-conjugate decay modes are implicit



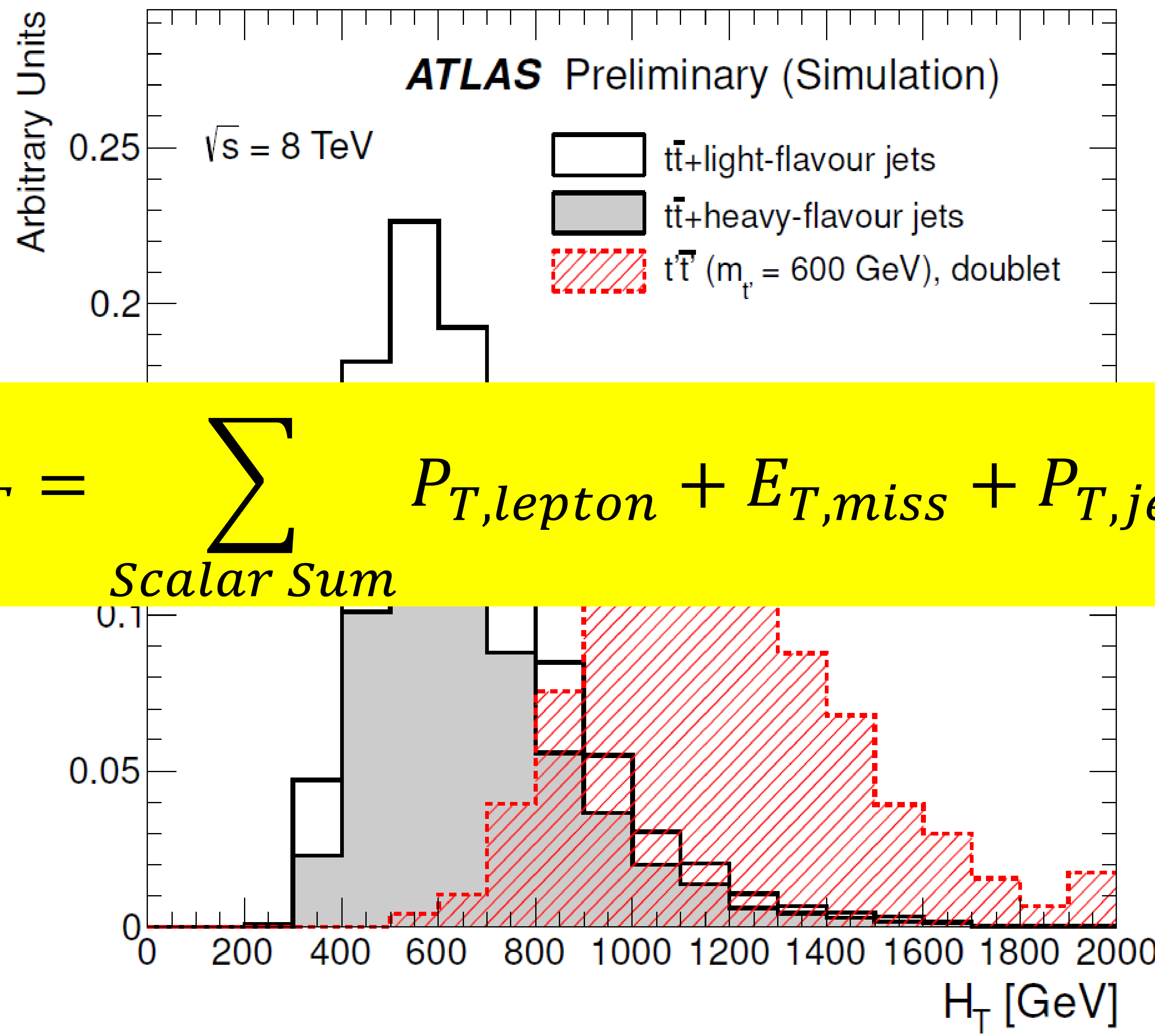
Complex-conjugate decay modes are implicit

Selections		
$E_T^{miss} > 20$ GeV		
$E_t^{miss} + m_T > 60$ GeV		
1 Isolated lepton with $p_T > 25$ GeV		
≥ 6 akt4 jets with $p_T > 25$ GeV		
2 bjets	3 bjets	≥4 bjets



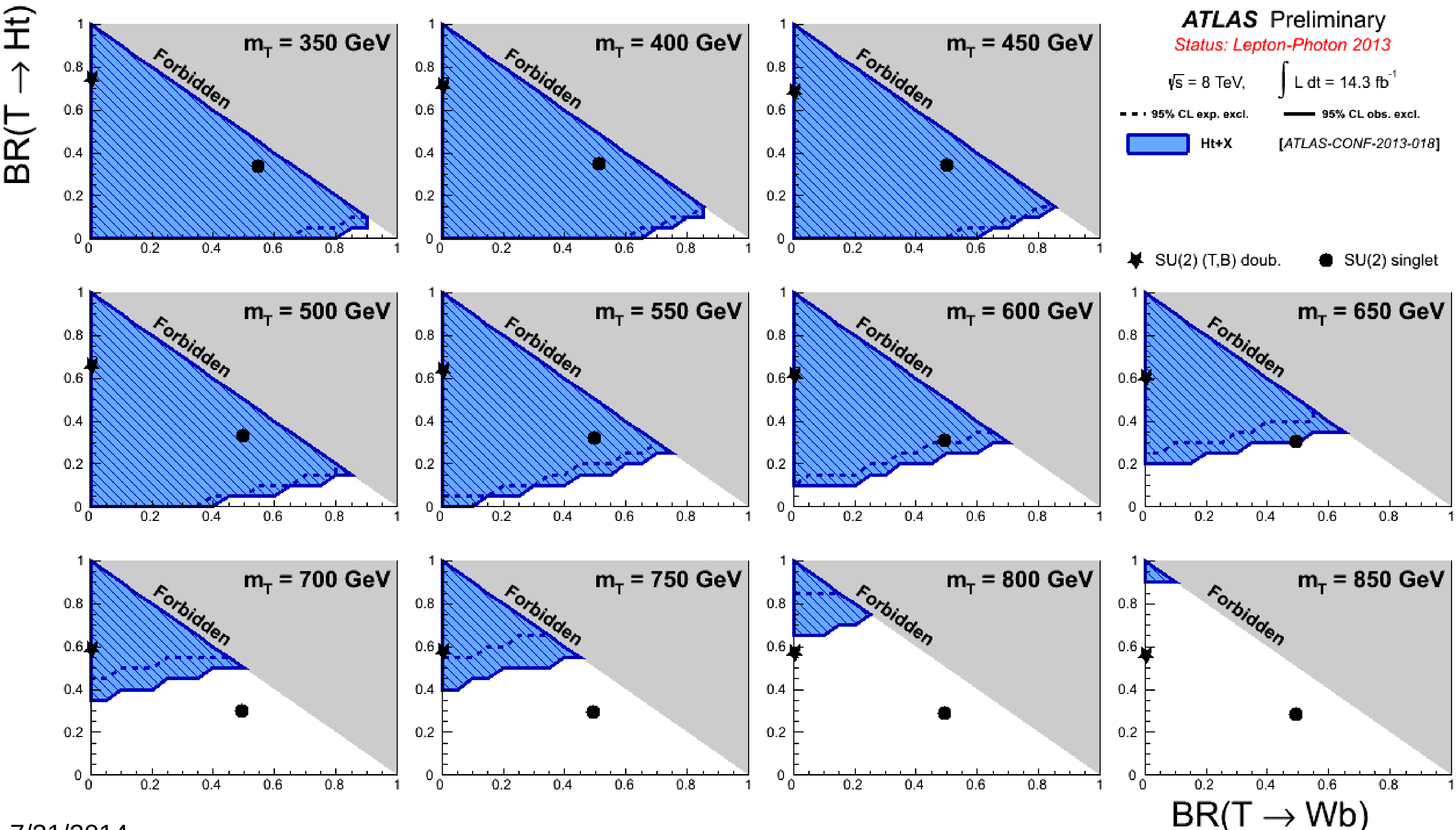
Complex-conjugate decay modes are implicit

Discriminant Variable H_T

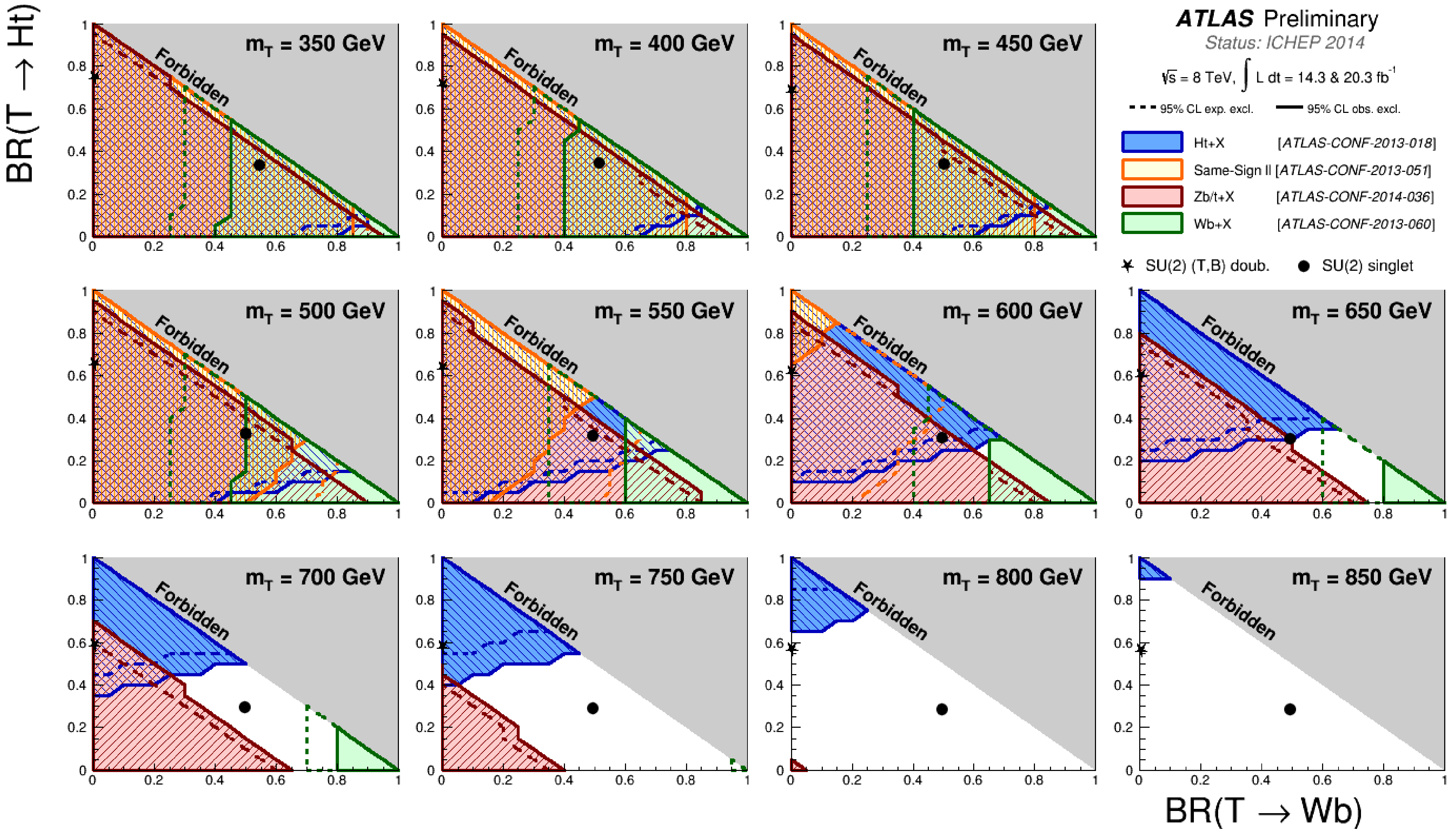


$$H_T = \sum_{Scalar\ Sum} P_{T,lepton} + E_{T,miss} + P_{T,jets}$$

Exlusion Limits for Vector Like T Quark



Exlusion Limits for Vector Like T Quark



Inclusive Same-Sign Dilepton Search

1210.4538

- Model independent approach
  - Limit presented in terms of fiducial cross-section limit

$$\sigma_{95}^{\text{fid}} = \frac{N_{95}}{\varepsilon_{\text{fid}} \times \int \mathcal{L}dt}$$

95% CL upper limit on yield (given N_{obs} and N_{bkg})

Reconstruction and Selection efficiency
Within acceptance

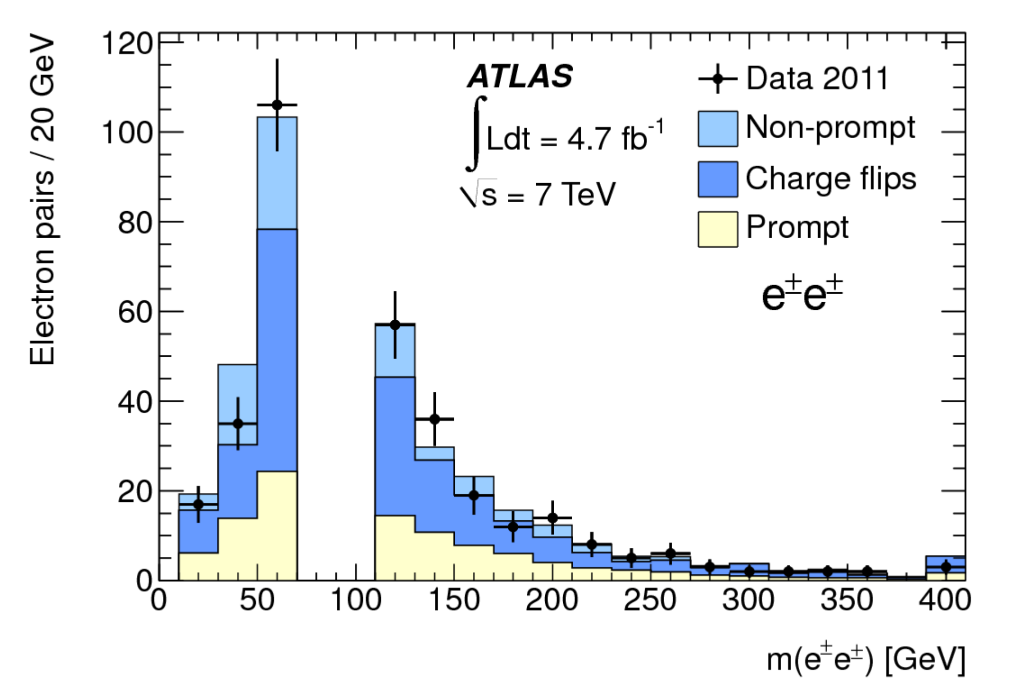
  - σ^{fid} is (almost) model-independent
  - Can turn σ^{fid} into σ^{total} with generator-level information only
  - Caveat: not exactly model-independent → must be conservative

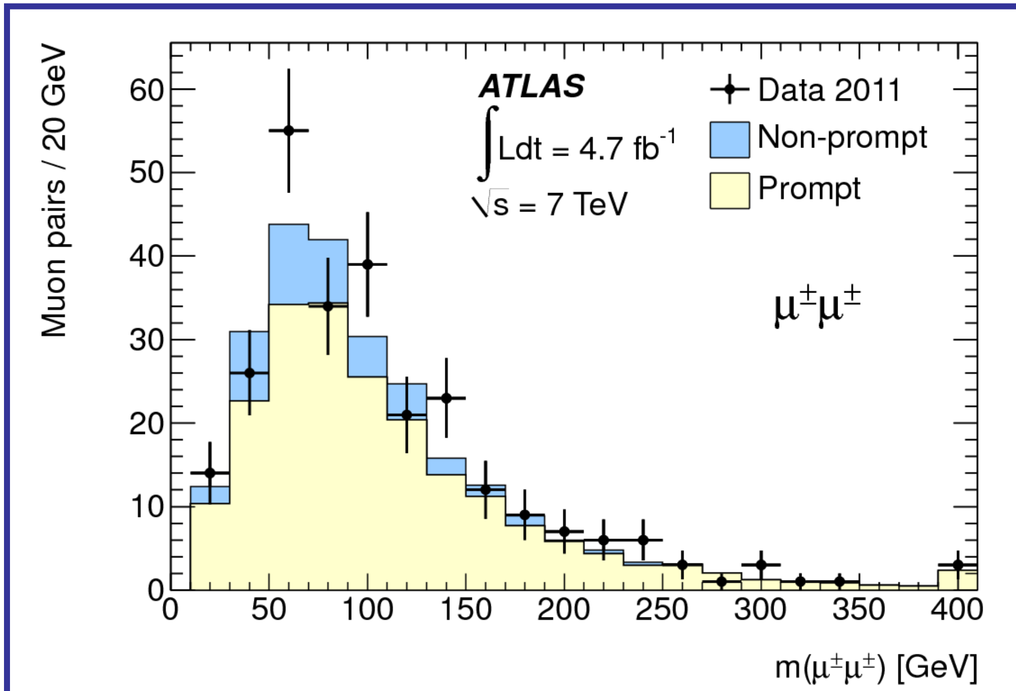
Particle-level definition of acceptance

	Electron requirement	Muon requirement
Leading lepton p_T	$p_T > 25$ GeV	$p_T > 20$ GeV
Sub-leading lepton p_T	$p_T > 20$ GeV	$p_T > 20$ GeV
Lepton η	$\|\eta\| < 1.37$ or $1.52 < \|\eta\| < 2.47$	$\|\eta\| < 2.5$
Isolation	$p_T^{\text{cone}0.3}/p_T < 0.1$	$p_T^{\text{cone}0.4}/p_T < 0.06$ and $p_T^{\text{cone}0.4} < 4$ GeV $+ 0.02 \times p_T$

Inclusive Same-Sign Dilepton Search

1210.4538





Inclusive Same-Sign Dilepton Search

1210.4538

- 95% upper limits
  - 1.7 fb and 64 fb

Fiducial cross section upper limits

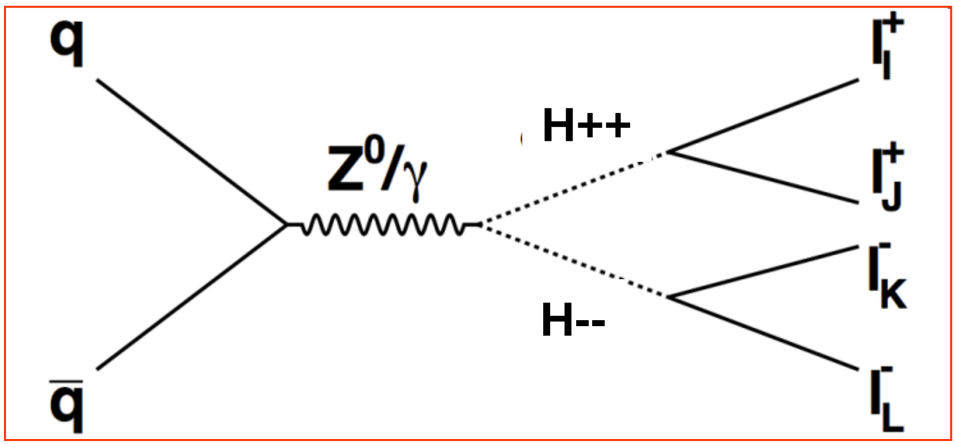
Mass	ee		eμ		μμ	
	exp	obs	exp	obs	exp	obs

Mass range	expected $e^\pm e^\pm$	observed $e^\pm e^\pm$	expected $e^\pm \mu^\pm$	observed $e^\pm \mu^\pm$	expected $\mu^\pm \mu^\pm$	observed $\mu^\pm \mu^\pm$
	95% C.L. upper limit [fb]					
$m > 15$ GeV	46^{+15}_{-12}	42	56^{+23}_{-15}	64	$24.0^{+8.9}_{-6.0}$	29.8
$m > 100$ GeV	$24.1^{+8.9}_{-6.2}$	23.4	$23.0^{+9.1}_{-6.7}$	31.2	$12.2^{+4.5}_{-3.0}$	15.0
$m > 200$ GeV	$8.8^{+3.4}_{-2.1}$	7.5	$8.4^{+3.4}_{-1.7}$	9.8	$4.3^{+1.8}_{-1.1}$	6.7
$m > 300$ GeV	$4.5^{+1.8}_{-1.3}$	3.9	$4.1^{+1.8}_{-0.9}$	4.6	$2.4^{+0.9}_{-0.7}$	2.6
$m > 400$ GeV	$2.9^{+1.1}_{-0.8}$	2.4	$3.0^{+1.0}_{-0.8}$	3.1	$1.7^{+0.6}_{-0.5}$	1.7
	e^+e^+		$e^+\mu^+$		$\mu^+\mu^+$	
$m > 15$ GeV	$29.1^{+10.2}_{-8.6}$	22.8	$34.9^{+12.2}_{-8.6}$	34.1	$15.0^{+6.1}_{-3.3}$	15.2
$m > 100$ GeV	$16.1^{+5.9}_{-4.3}$	12.0	$15.4^{+5.9}_{-4.1}$	18.0	$8.4^{+3.2}_{-2.4}$	7.9
$m > 200$ GeV	$7.0^{+2.9}_{-2.2}$	6.1	$6.6^{+3.5}_{-1.8}$	8.8	$3.5^{+1.6}_{-0.7}$	4.3
$m > 300$ GeV	$3.7^{+1.4}_{-1.0}$	2.9	$3.2^{+1.2}_{-0.9}$	3.2	$2.0^{+0.8}_{-0.5}$	2.1
$m > 400$ GeV	$2.3^{+1.1}_{-0.6}$	1.7	$2.4^{+0.9}_{-0.6}$	2.5	$1.5^{+0.6}_{-0.3}$	1.8
	e^-e^-		$e^-\mu^-$		$\mu^-\mu^-$	
$m > 15$ GeV	$23.2^{+8.6}_{-5.8}$	25.7	$26.2^{+10.6}_{-7.6}$	34.4	$12.1^{+4.5}_{-3.5}$	18.5
$m > 100$ GeV	$12.0^{+5.3}_{-2.8}$	18.7	$11.5^{+4.2}_{-3.5}$	16.9	$6.0^{+2.3}_{-1.9}$	10.1
$m > 200$ GeV	$4.9^{+1.9}_{-1.2}$	4.0	$4.6^{+2.1}_{-1.2}$	4.5	$2.7^{+1.1}_{-0.7}$	4.4
$m > 300$ GeV	$2.9^{+1.0}_{-0.6}$	2.7	$2.7^{+1.1}_{-0.6}$	3.5	$1.5^{+0.8}_{-0.3}$	1.7
$m > 400$ GeV	$1.8^{+0.8}_{-0.4}$	2.3	$2.3^{+0.8}_{-0.5}$	2.5	$1.2^{+0.4}_{-0.0}$	1.2

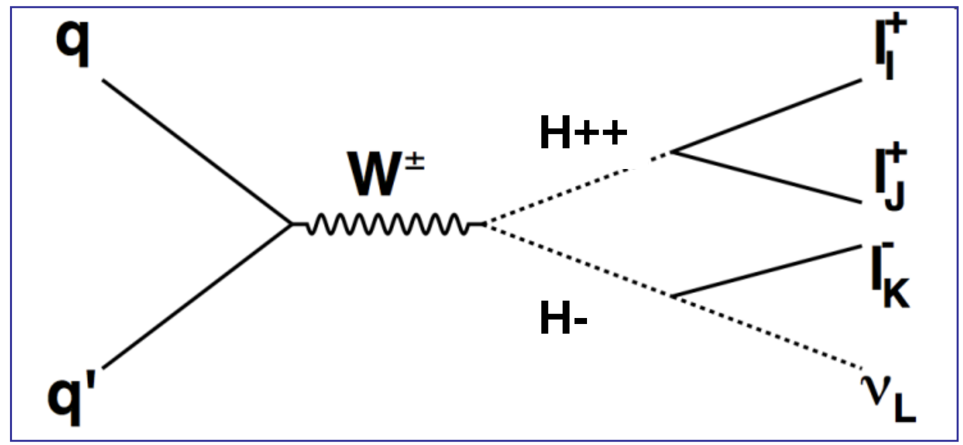
	e^-e^-	
$m > 15$ GeV	$23.2^{+8.6}_{-5.8}$	25.7
$m > 100$ GeV	$12.0^{+5.3}_{-2.8}$	18.7
$m > 200$ GeV	$4.9^{+1.9}_{-1.2}$	4.0
$m > 300$ GeV	$2.9^{+1.0}_{-0.6}$	2.7
$m > 400$ GeV	$1.8^{+0.8}_{-0.4}$	2.3

Inclusive Same-Sign Dilepton Search: $H^{++/--}$ Limits

- Models explaining non-zero neutrino masses predict $H^{++/--}$
  - e.g. minimal type II seesaw model
    - additional scalar field
    - triplet (under $SU(2)_L$ with Y=2): $H^{++/--}$,$H^{+/-}$, H^0



pair production



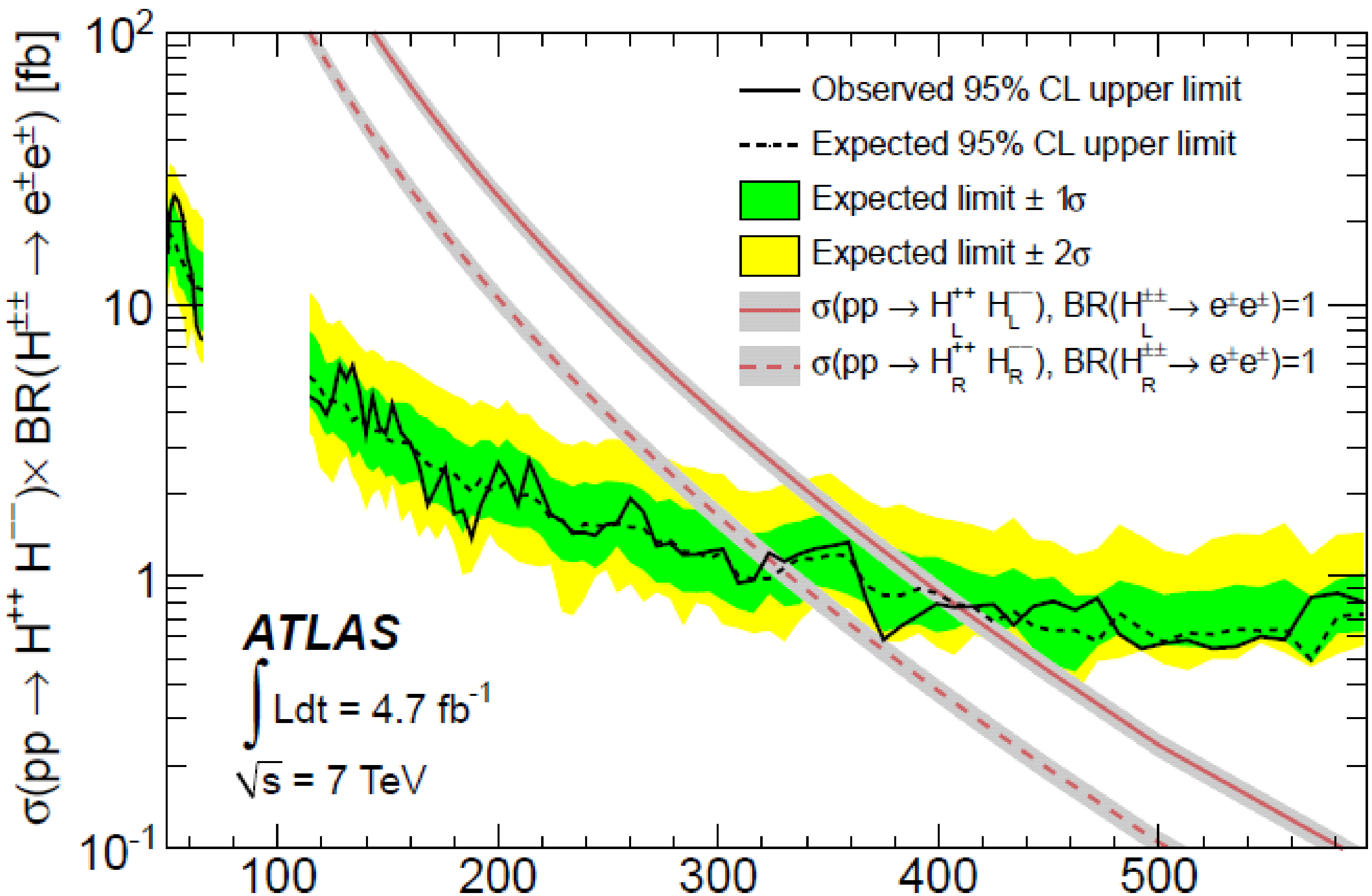
associate production

Signature: same-sign leptons

Doubly Charged Higgs Limits

arXiv:1210.5070

- Used e.g. limits on doubly charged Higgs



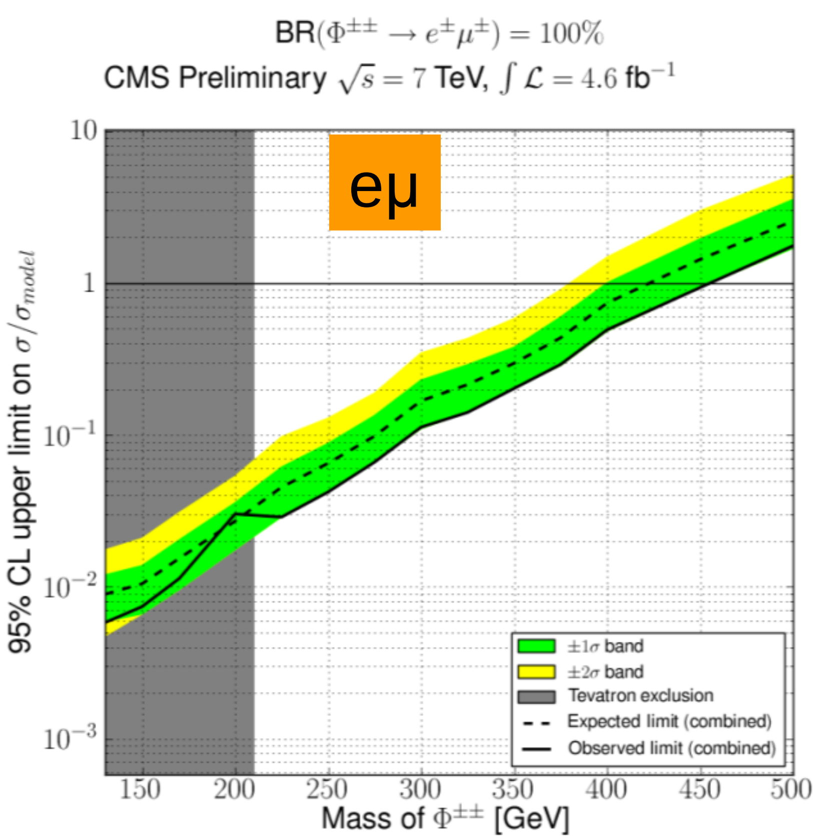
Pair production: $M(H^{++/--}) > 409$ GeV

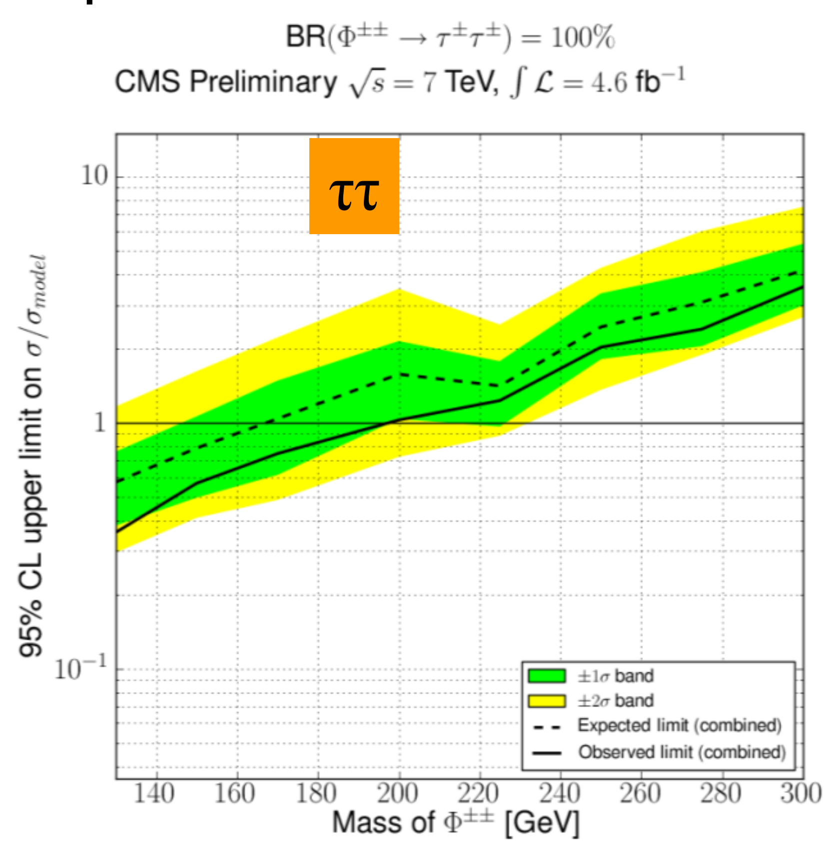
Doubly Charged Higgs Limits

- Example of more optimized search

arXiv:1207.2666

- Includes also τ-channel and associate production.

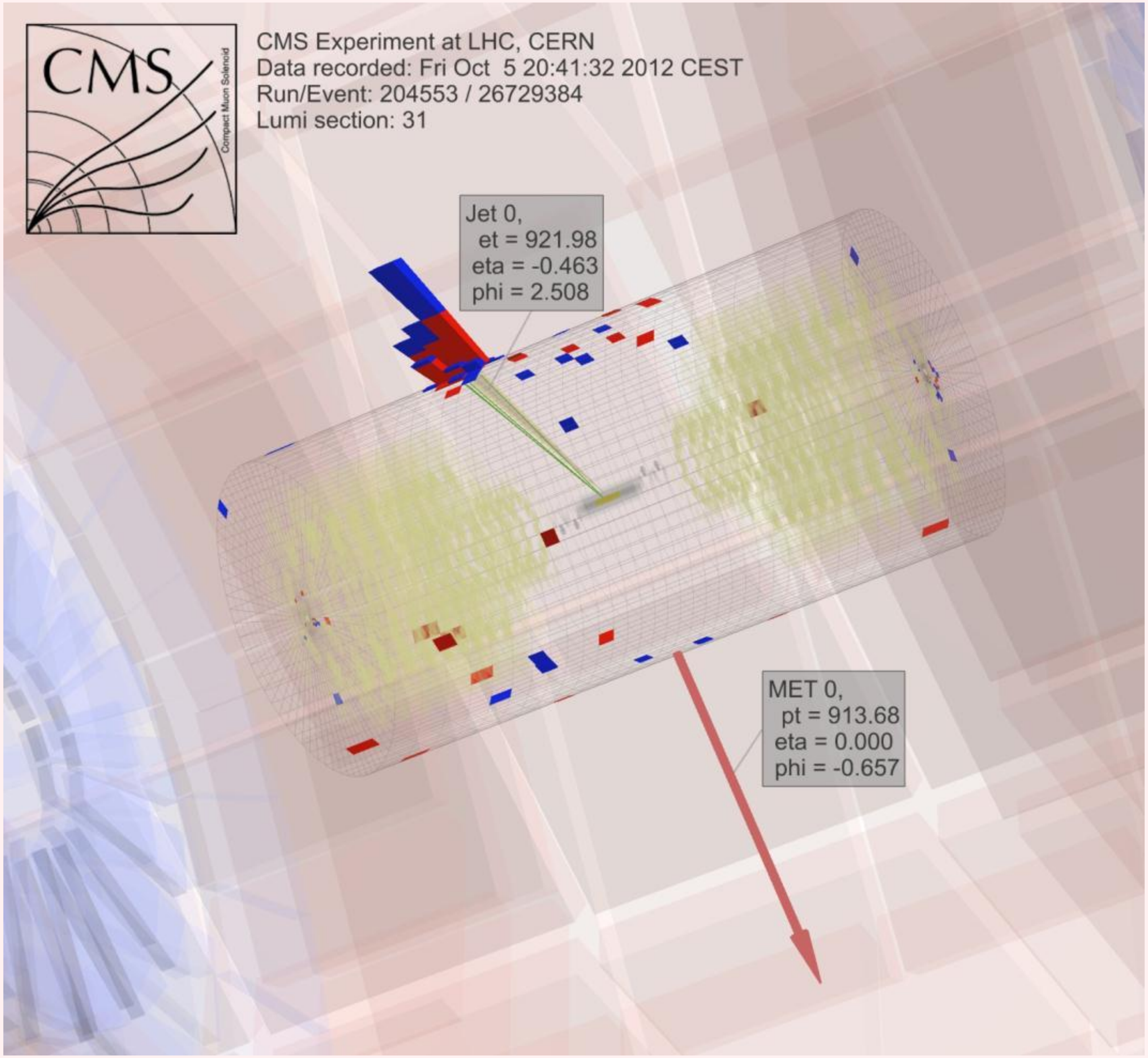




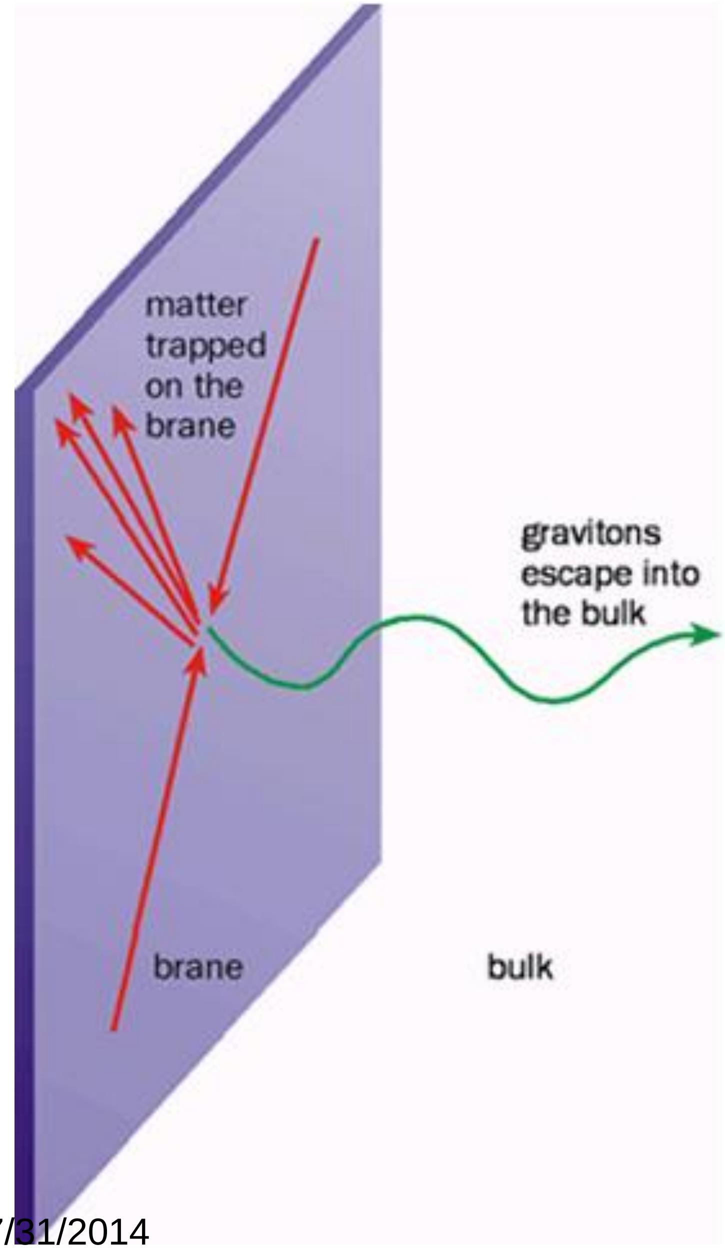
Combined eμ: M($H^{++/--}$) > 455 GeV

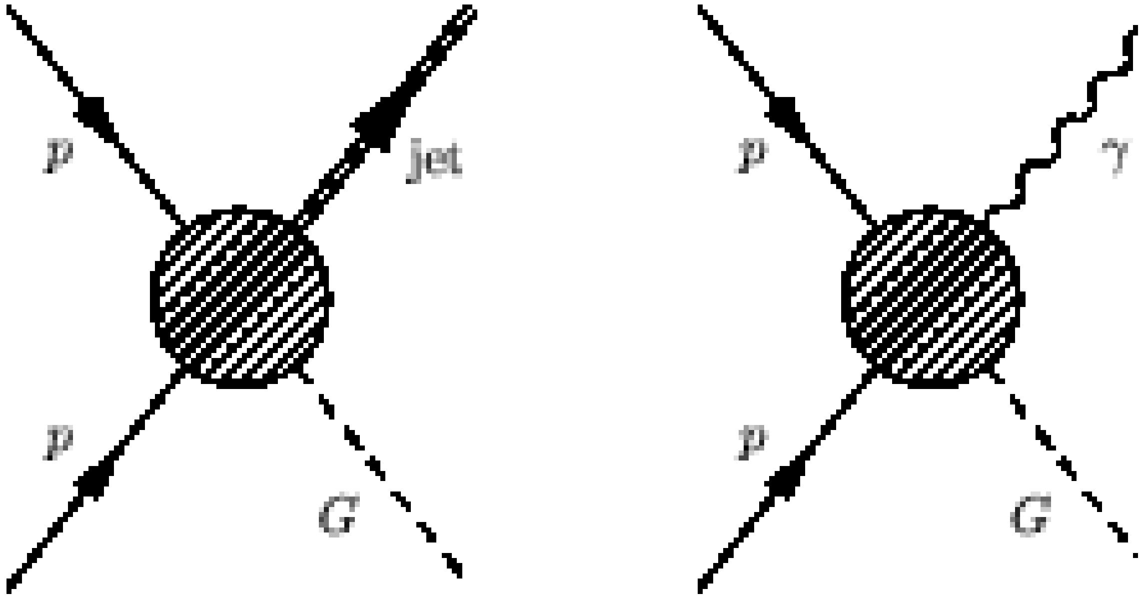
Combined ττ: M($H^{++/--}$) > 198 GeV

Mono Jet Event Display



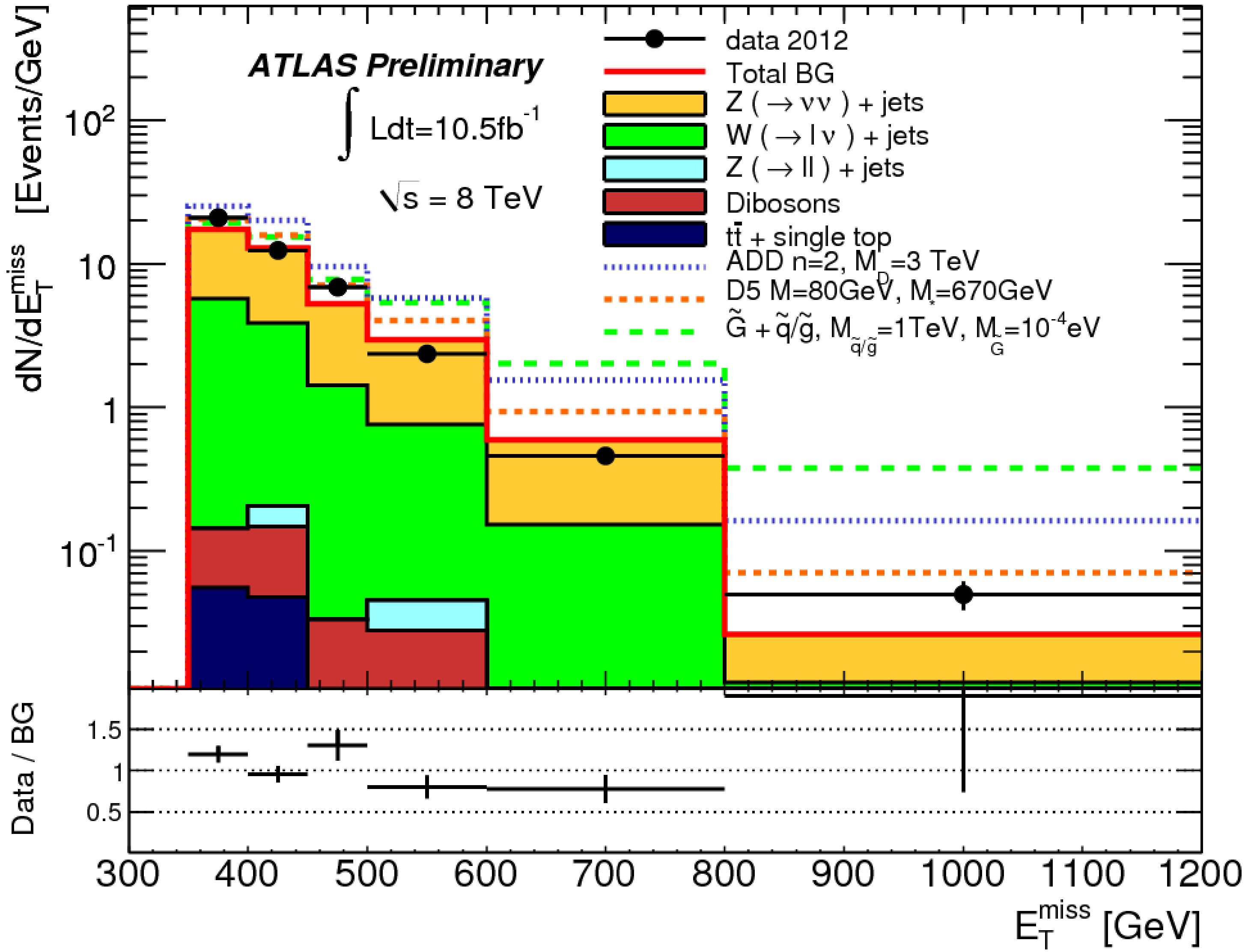
Graviton Production in Extra Dimensions



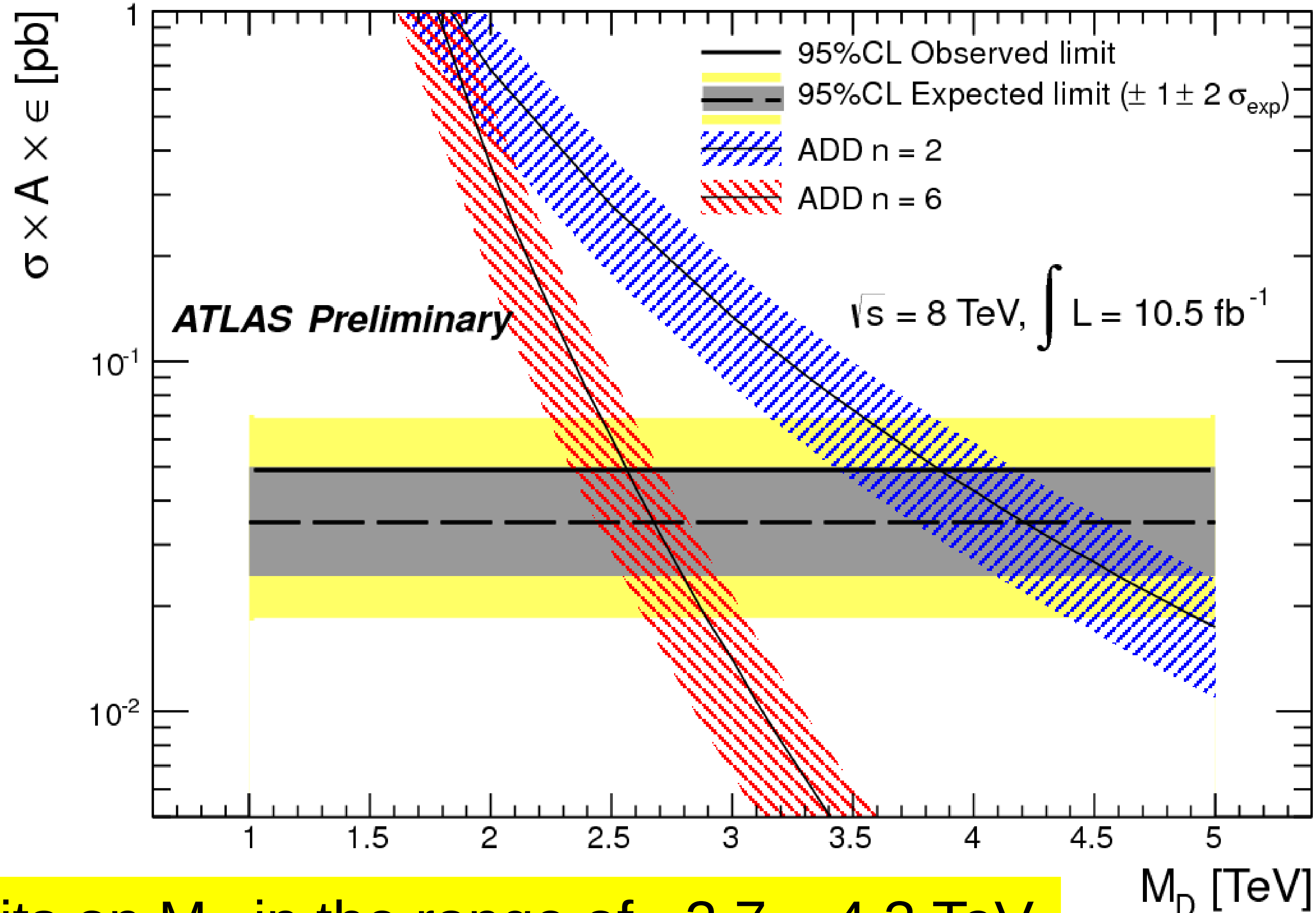


ME_T Distribution of Mono Jet Analysis

ATLAS-CONF-2012-147



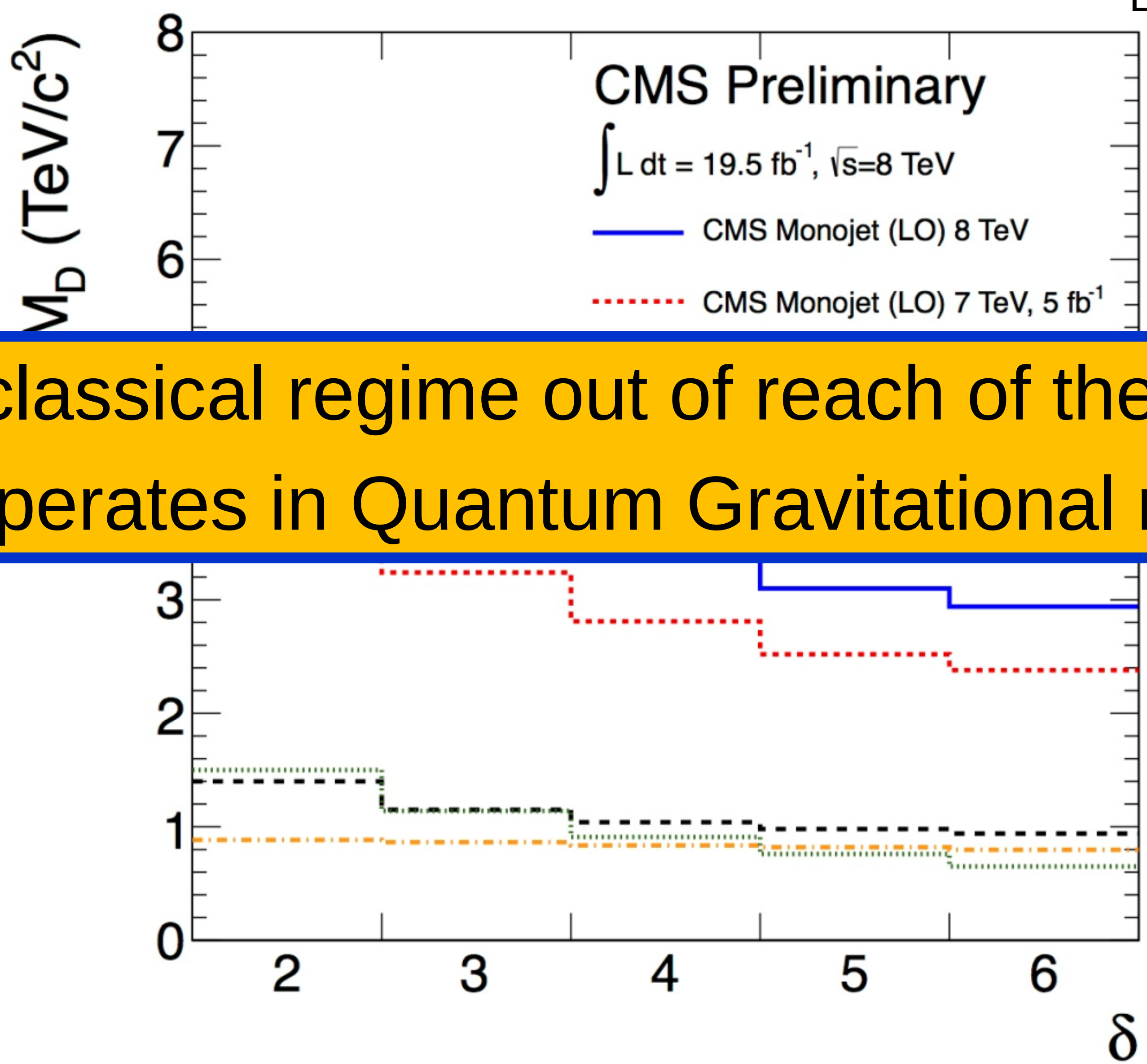
Exclusion Limits



Limits on M_D in the range of ~2.7 – 4.3 TeV

Exclusion Limits on M_D from CMS

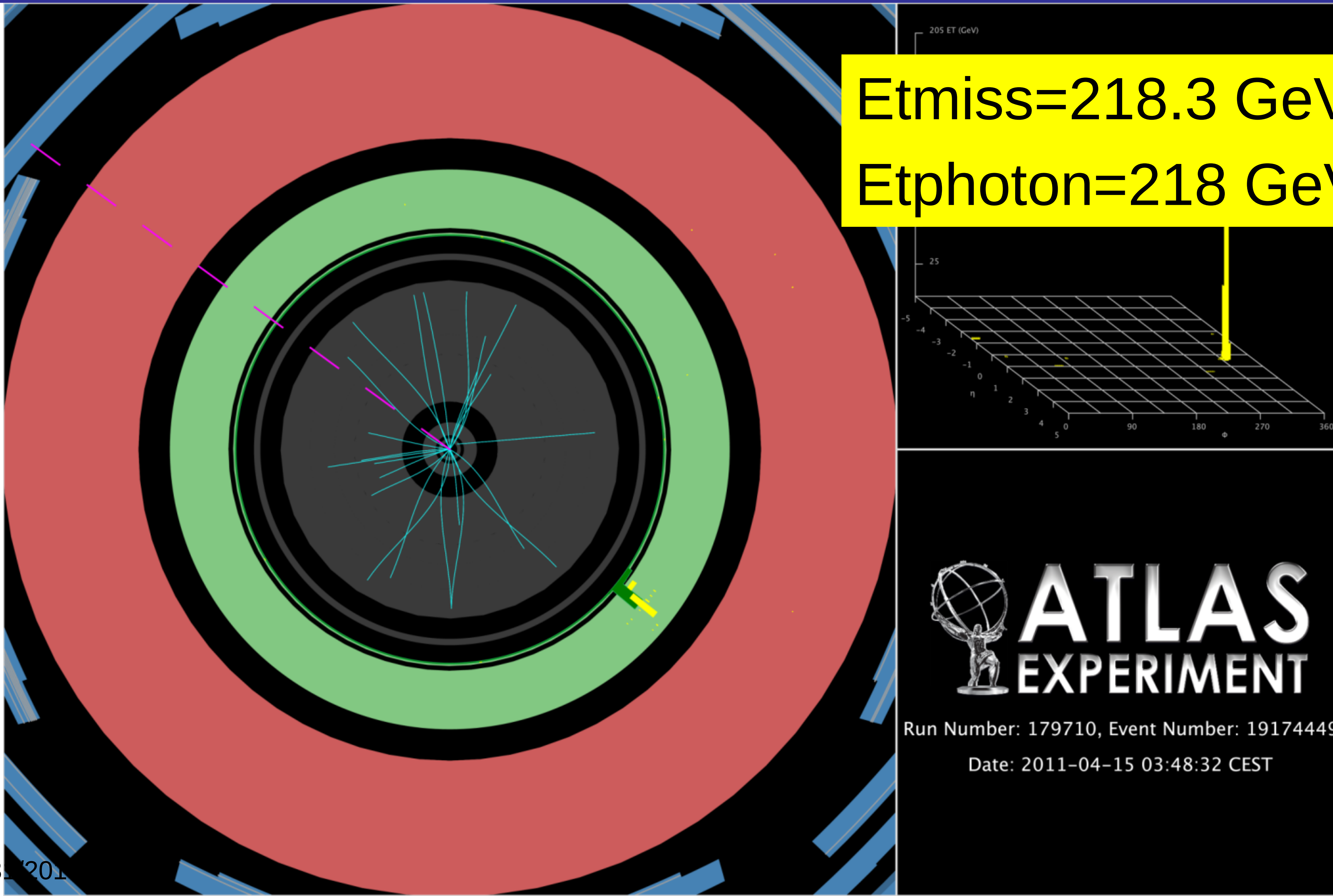
EXO-12-048 PAS



Semi-classical regime out of reach of the LHC

LHC operates in Quantum Gravitational regime

Mono Photon Searches for Extra Dimensions

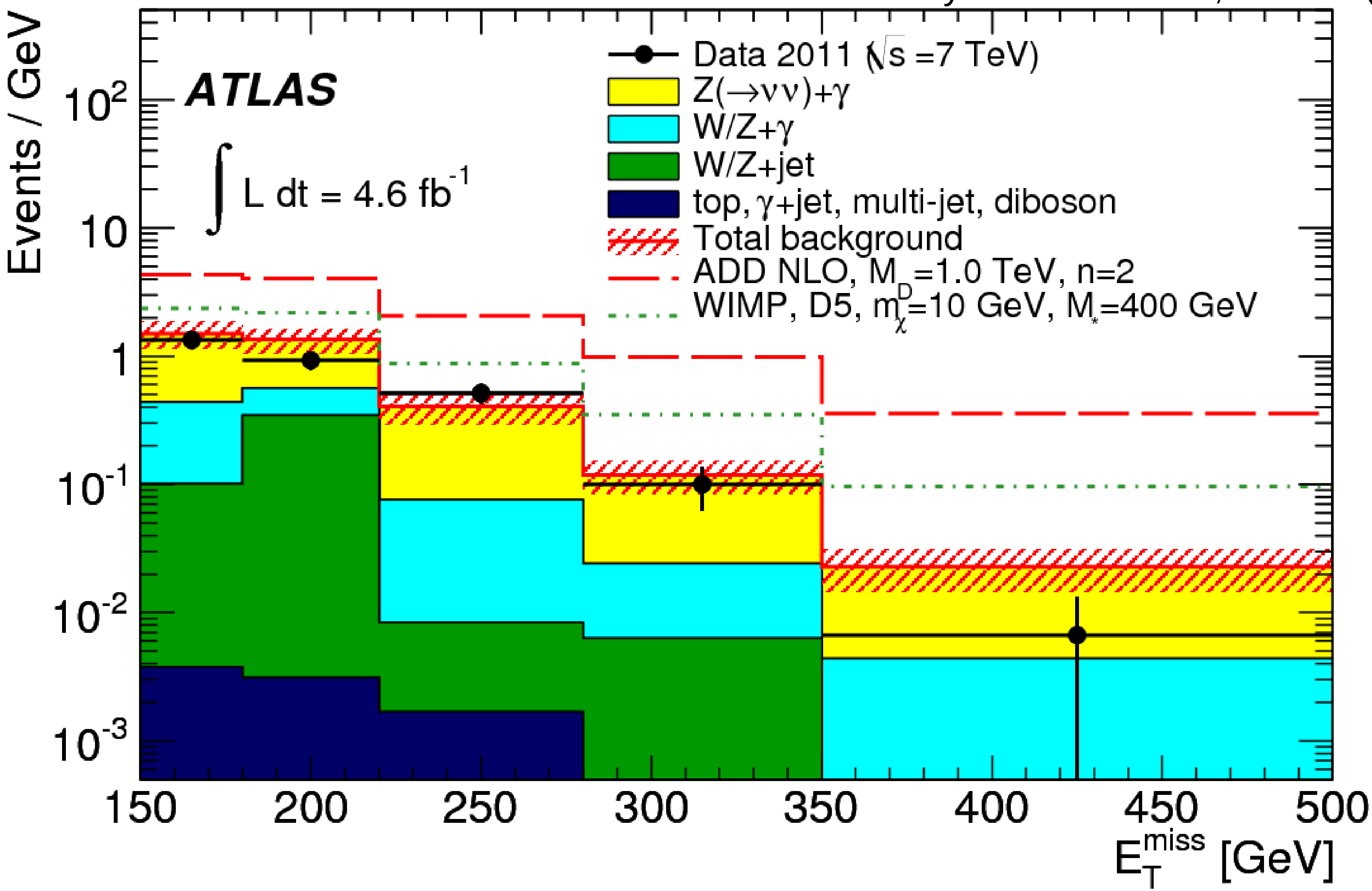


Etmiss=218.3 GeV

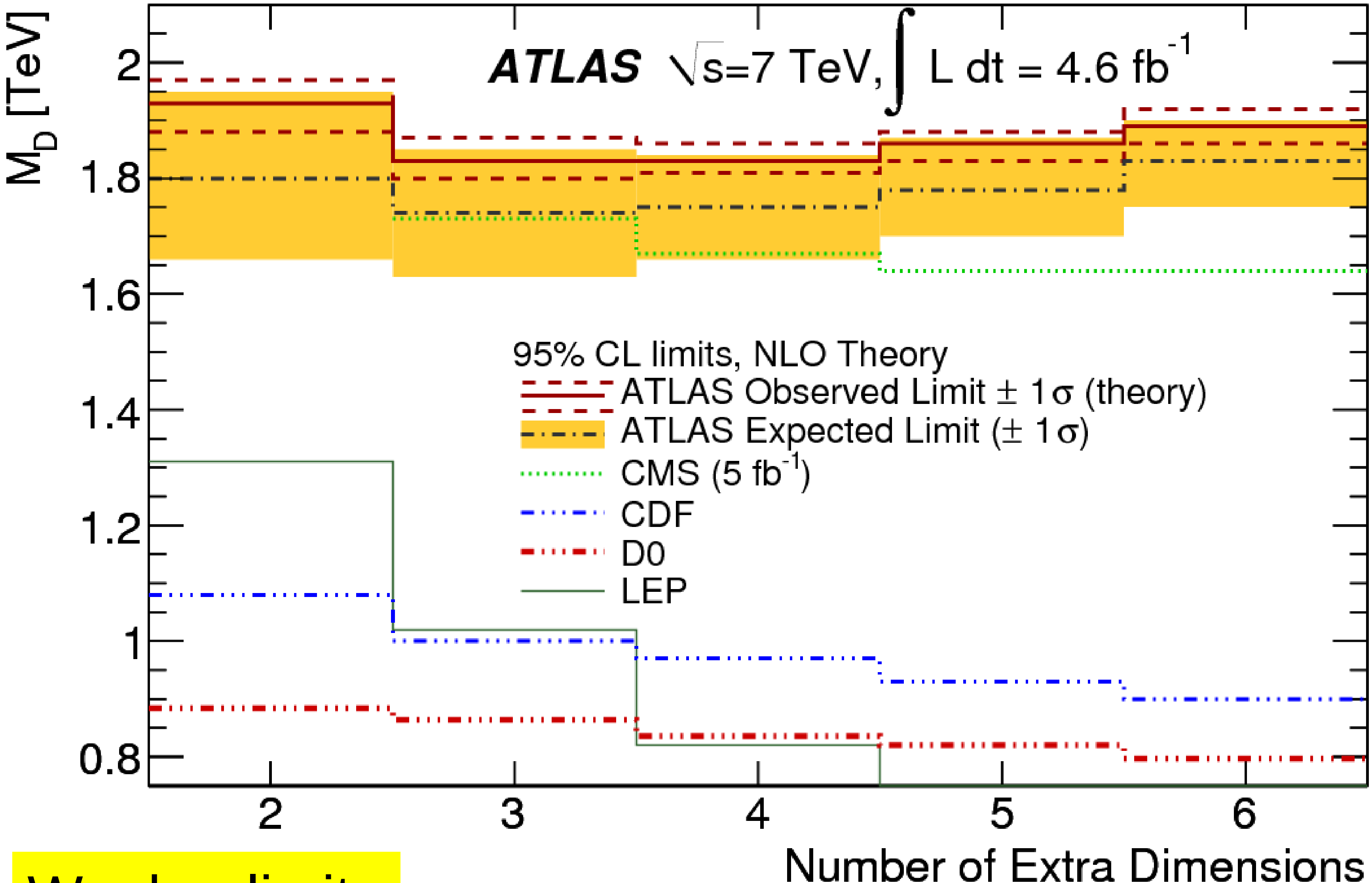
Etphoton=218 GeV

The Discriminant

Phys. Rev. Lett 110, 011802 (2013)



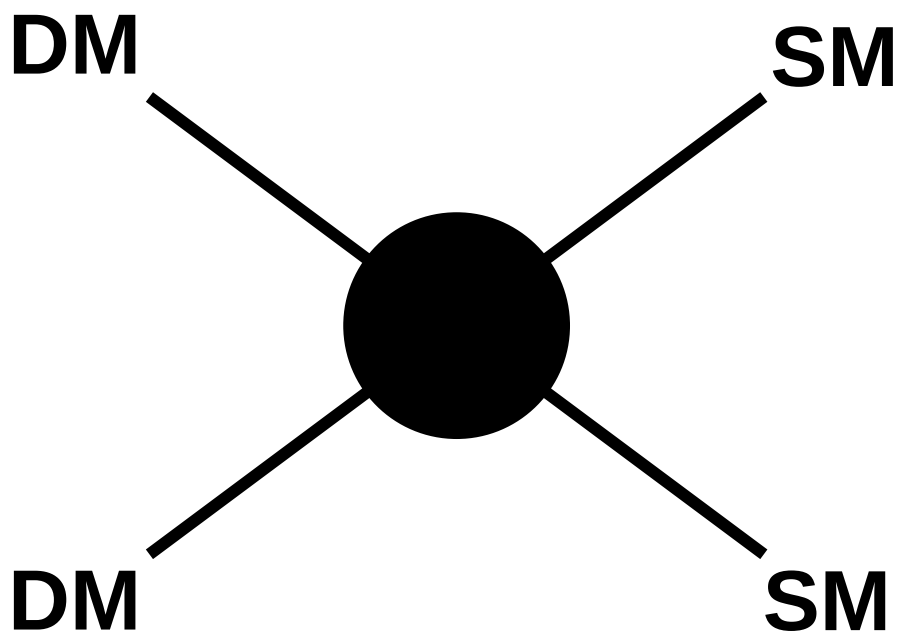
Limits on M_D in Mono Photon Search



Weaker limits

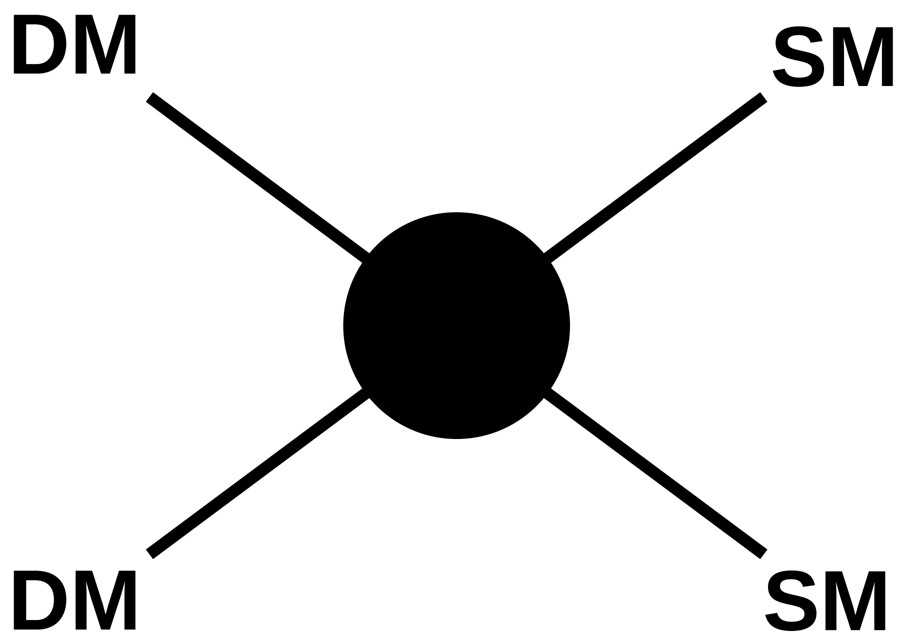
Dark Matter Detection

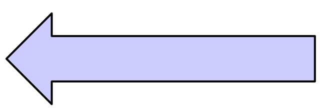
M. Fedderke



Dark Matter Detection

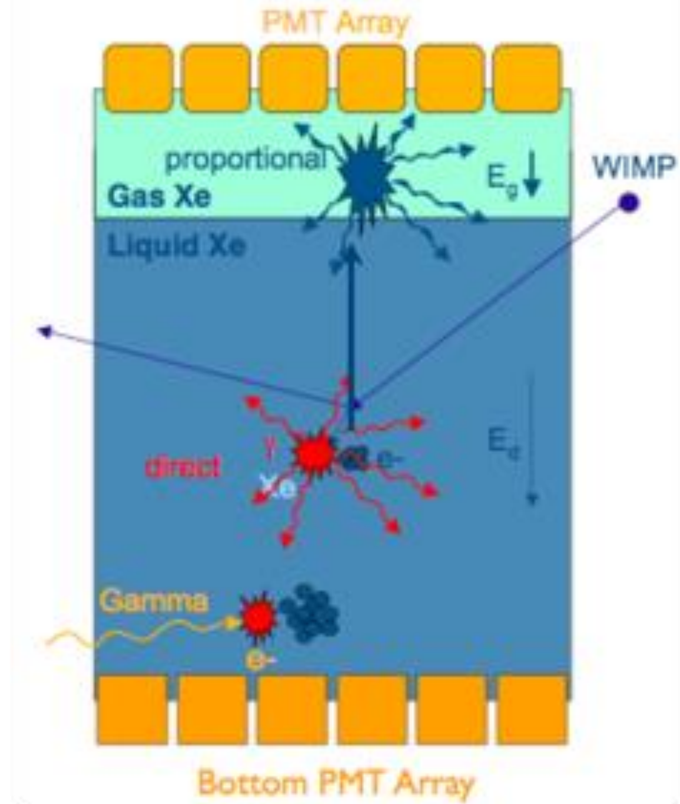
M. Fedderke

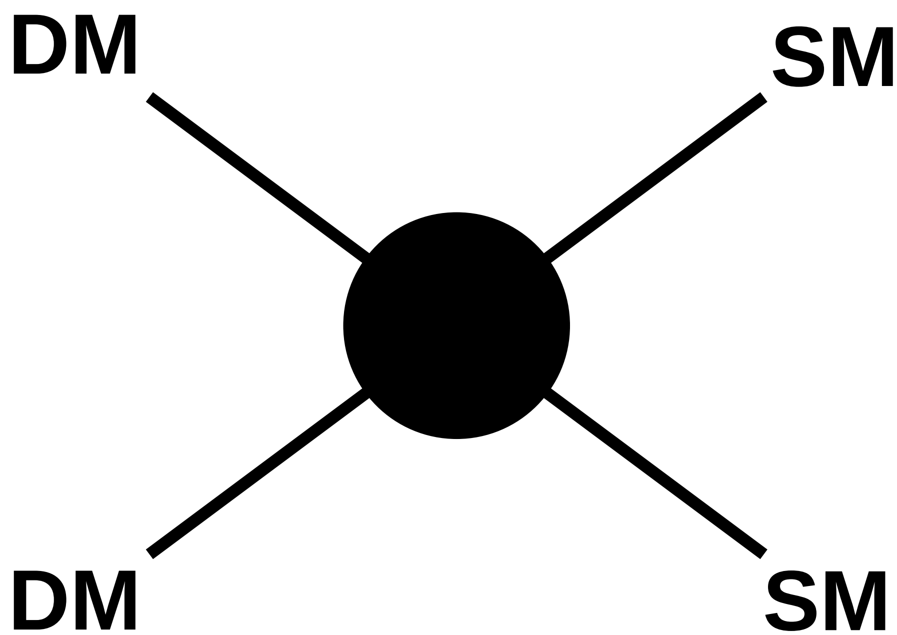




Collider Production

M. Fedderke



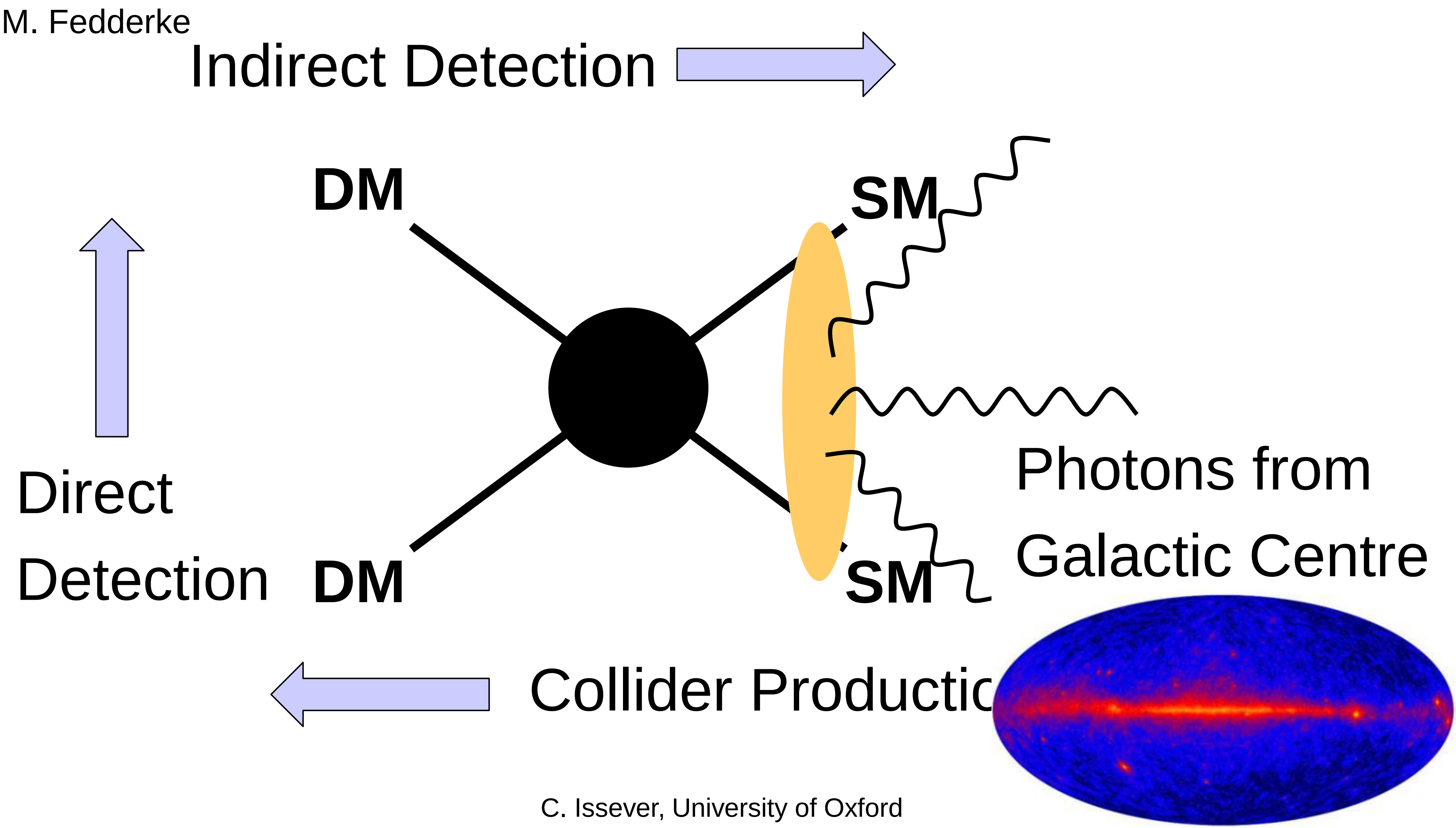


Direct

Detection

Collider Production

Dark Matter Detection

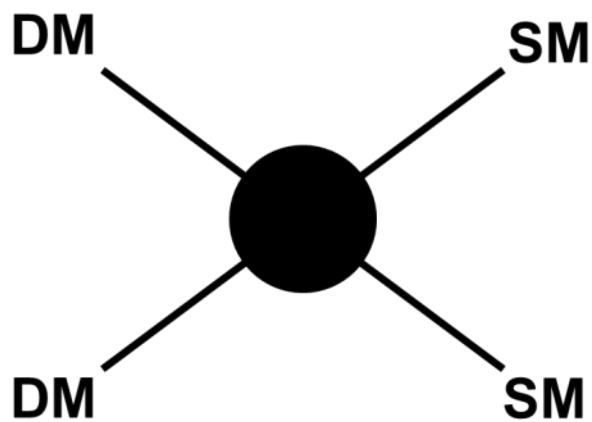


DM Interpretations of Mono-Object Analyses

Idea: Effective Theory

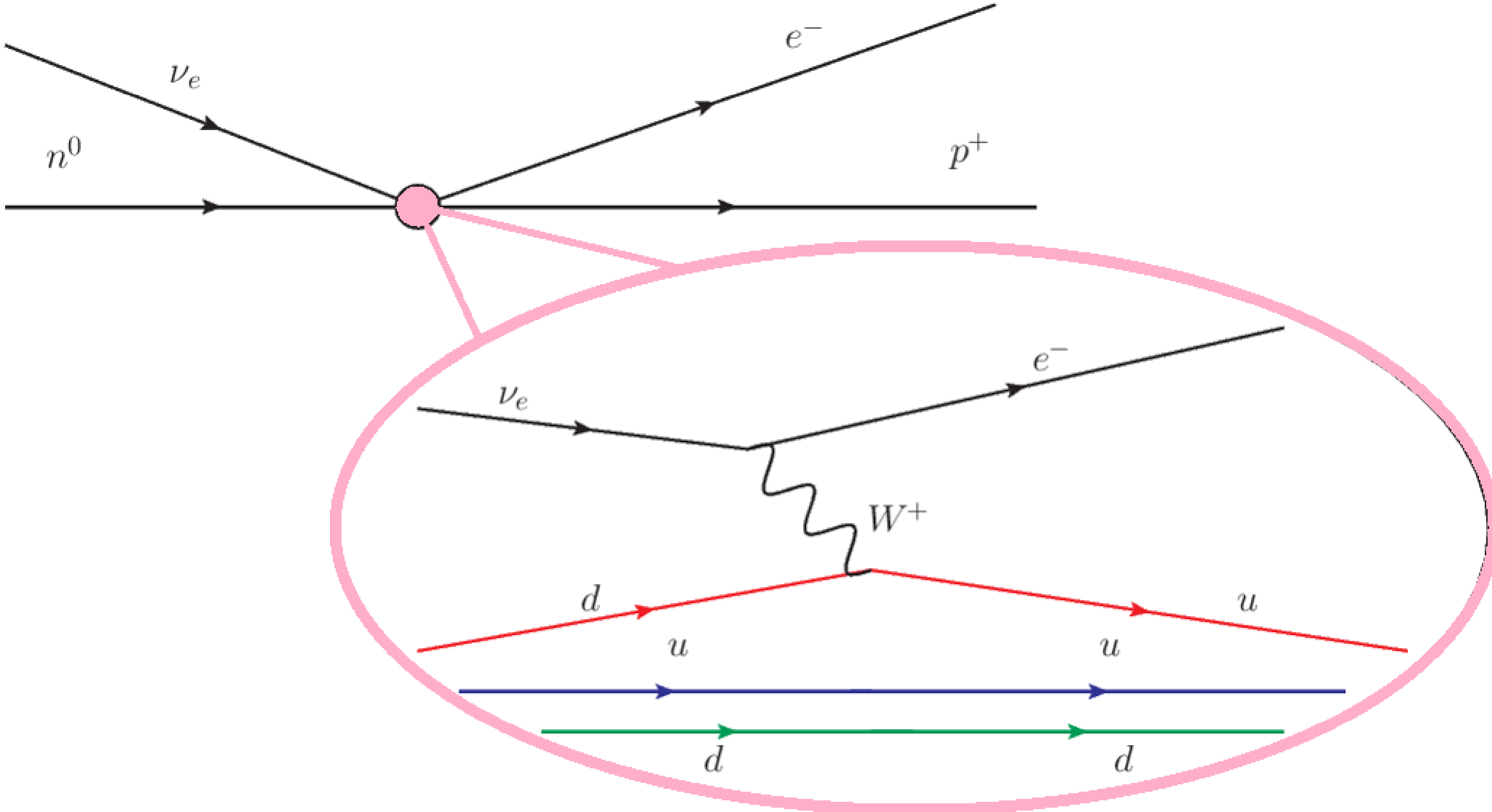
Johanna Gramling

- Heavy particle mediating interaction btw DM and SM



- too heavy to be on-shell → can be integrated out
- interaction treated as contact interaction!

Like Fermi's Theory of Beta Decay



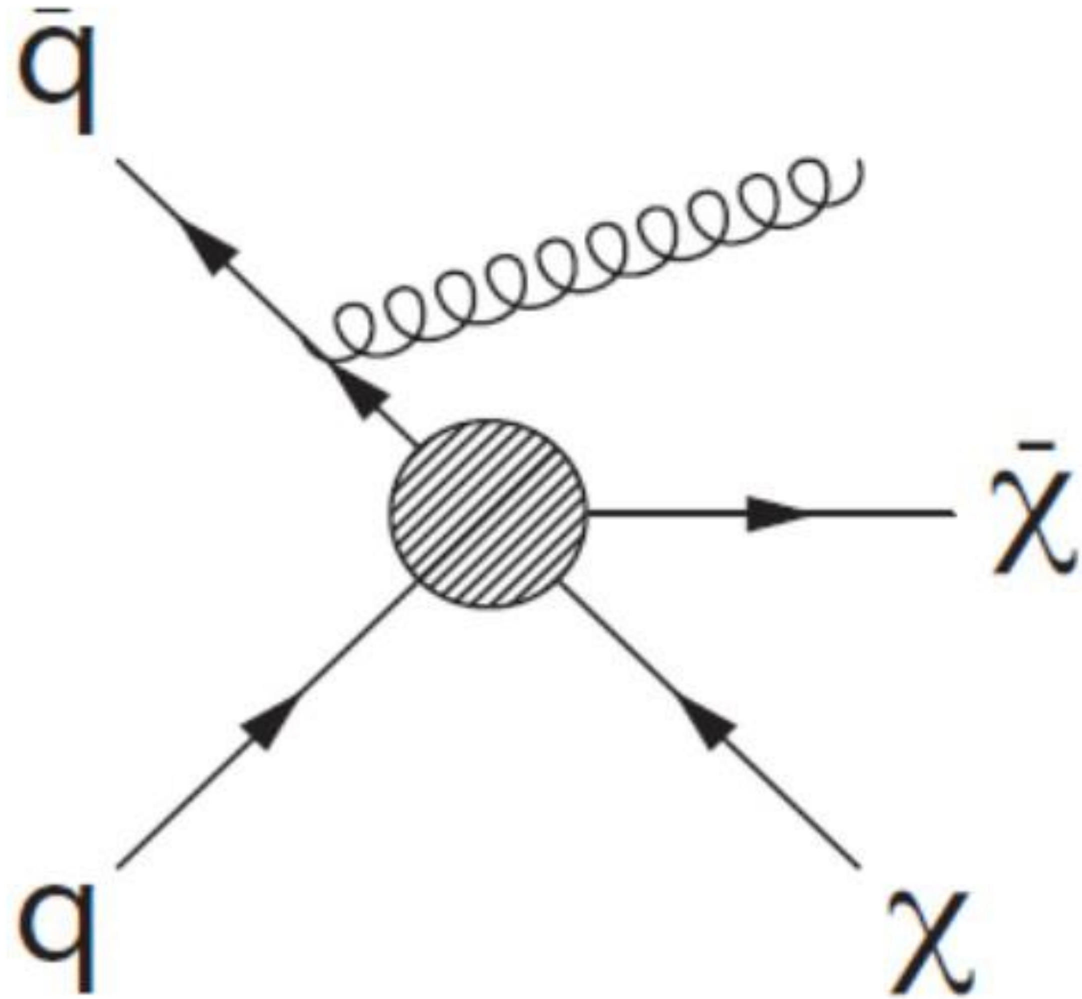
Advantage of Effective Theory

arXiv:1008.1783

- Model depends only on a few parameters
  - dark matter mass, $\mathbf{m_\chi}$
  - cut-off scale **Λ or $\mathbf{M_*}$**
  - much easier than e.g. a full SUSY model
- Allows easy comparison to direct or indirect DM detection experiments
- DM
  - Fermion: Dirac or Majorana
  - Scalar: Complex or Real

$$\Lambda = \frac{m_M}{\sqrt{g_q g_\chi}}$$

Dark Matter Production at a Collider



Dark Matter (DM) Production at LHC $pp \to \chi\chi + X$

Effective interactions coupling DM to SM quarks or gluons

1210.4491v2

Name	Initial state	Type	Operator
D1	qq	scalar	$\frac{m_q}{M_\star^3}\bar{\chi}\chi\bar{q}q$
D5	qq	vector	$\frac{1}{M_\star^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$
D8	qq	axial-vector	$\frac{1}{M_\star^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$
D9	qq	tensor	$\frac{1}{M_\star^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$
D11	gg	scalar	$\frac{1}{4M_\star^3}\bar{\chi}\chi\alpha_s(G_{\mu\nu}^a)^2$

characteristic set

Conditions of EFT

1. $g_q, g_\chi < 4\pi \rightarrow \frac{m_M}{4\pi} < \Lambda$ (to stay in perturbative regime)
2. $m_M > m_\chi$ (M can not be produced, but χ can)
   - $\Lambda > \frac{m_M}{4\pi} > \frac{m_\chi}{4\pi}$

Johanna Gramling

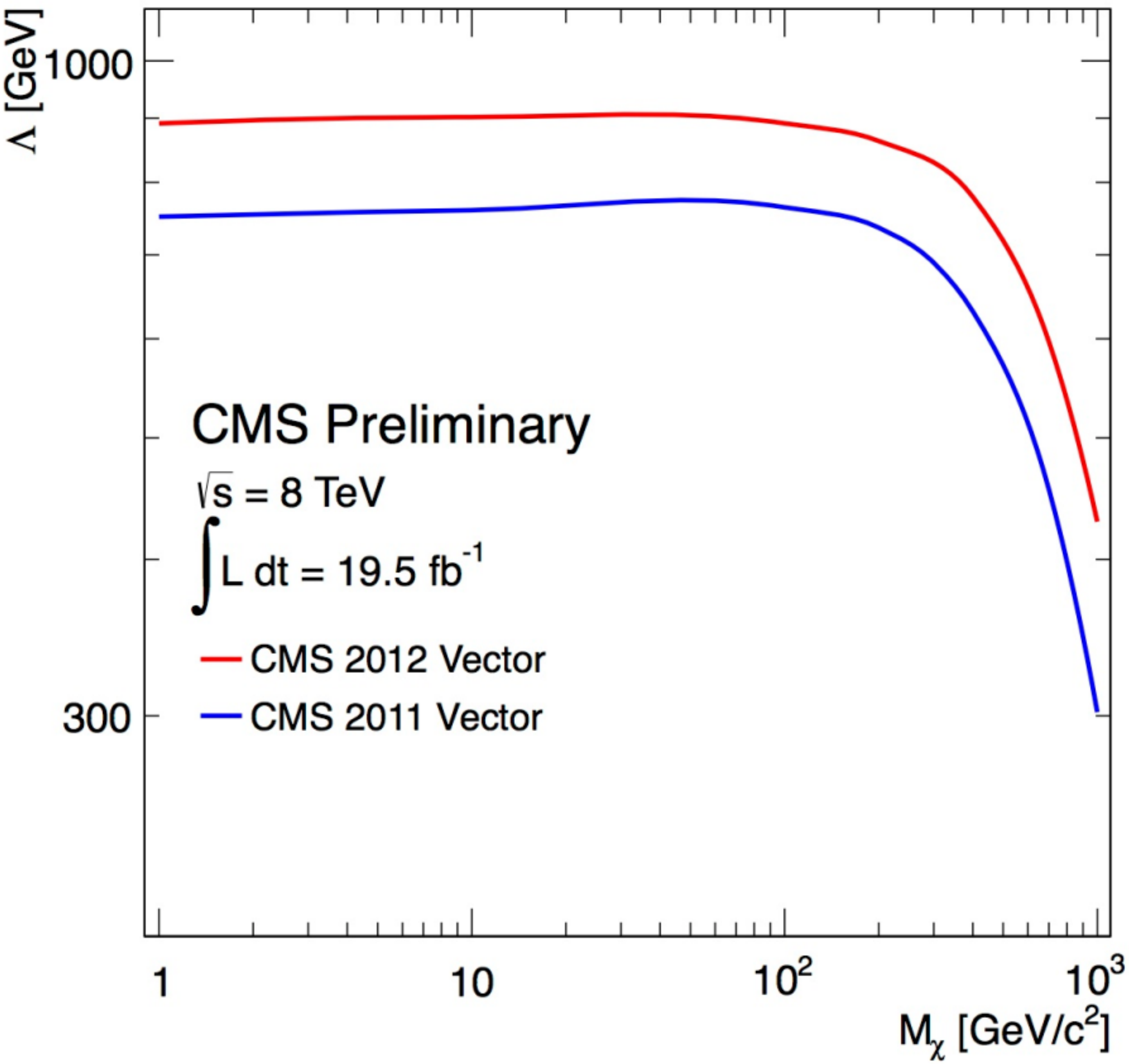
3. $m_M > Q_{TR}$
   - $\Lambda > \frac{m_M}{4\pi} > \frac{Q_{TR}}{4\pi}$
4. $Q_{TR} > 2m_\chi$ (DM pair-produced on-shell)

Combining 3 & 4 gives stronger constraint than 2!

- $\Lambda > \frac{Q_{TR}}{4\pi} > \frac{2m_\chi}{4\pi}$

Spin Independent Limits on Λ

EXO-12-048 PAS



Let say $\sqrt{g_q g_\chi}=1$

- $\Lambda > Q_{TR} > 2m_\chi$
- @LHC
  - $Q_{TR} \sim O(1\text{TeV})$
- Limits on Λ
  - < 1 TeV
  - Validity of EFT approach questionable

Johanna Gramling

Intensive Discussion about how to interpret Mono-X analyses

- G. Busonia, A. De Simonea, E. Morgantec, A. Riotto
  - "On the Validity of the Effective Field Theory for Dark Matter Searches at the LHC", arXiv:1307.2253v1
  - Derive stronger bounds than currently used by LHC experiments

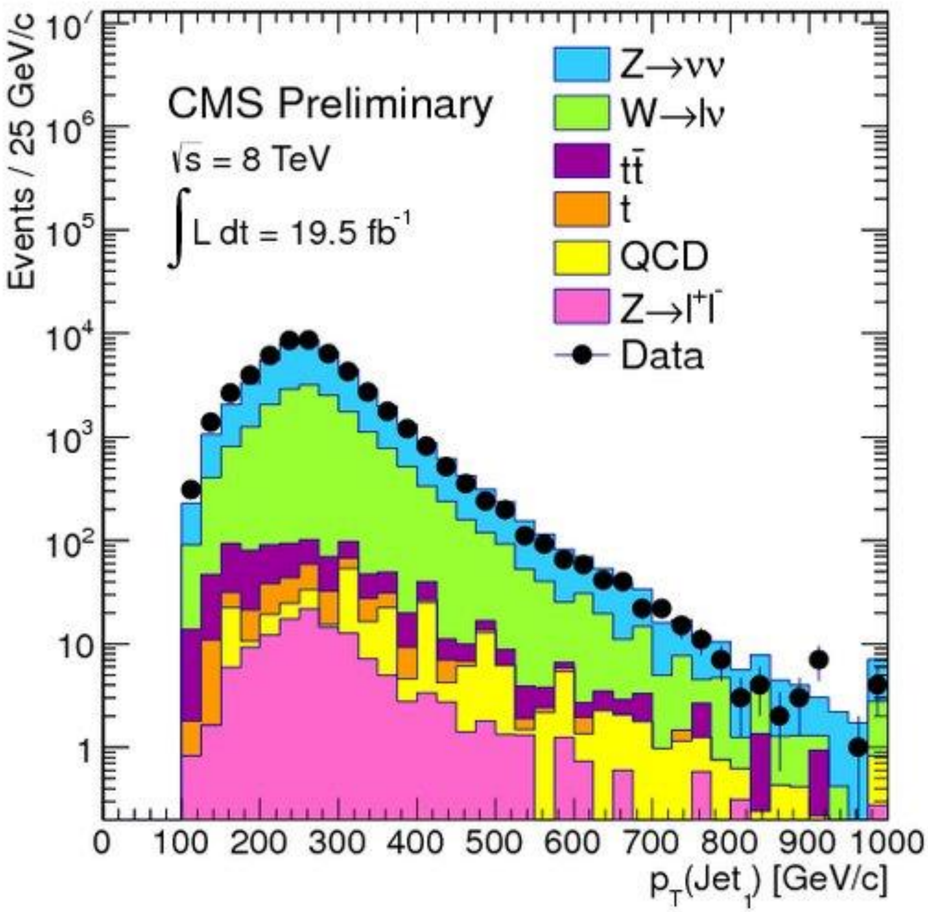
- New models:
  - A. DiFranzo, K. I. Nagao, A. Rajaraman, T.M.P. Tait,
    - "Simplified Models for Dark Matter Interacting with Quarks", arXiv:1308.2679v1
  - S. Chang, R. Edezhath, J. Hutchinson, and M. Luty,
    - "Effective WIMPs", arXiv:1307.8120v1
  - Yang Bai and Joshua Berger,
    - "Fermion Portal Dark Matter", arXiv:1308.0612v2

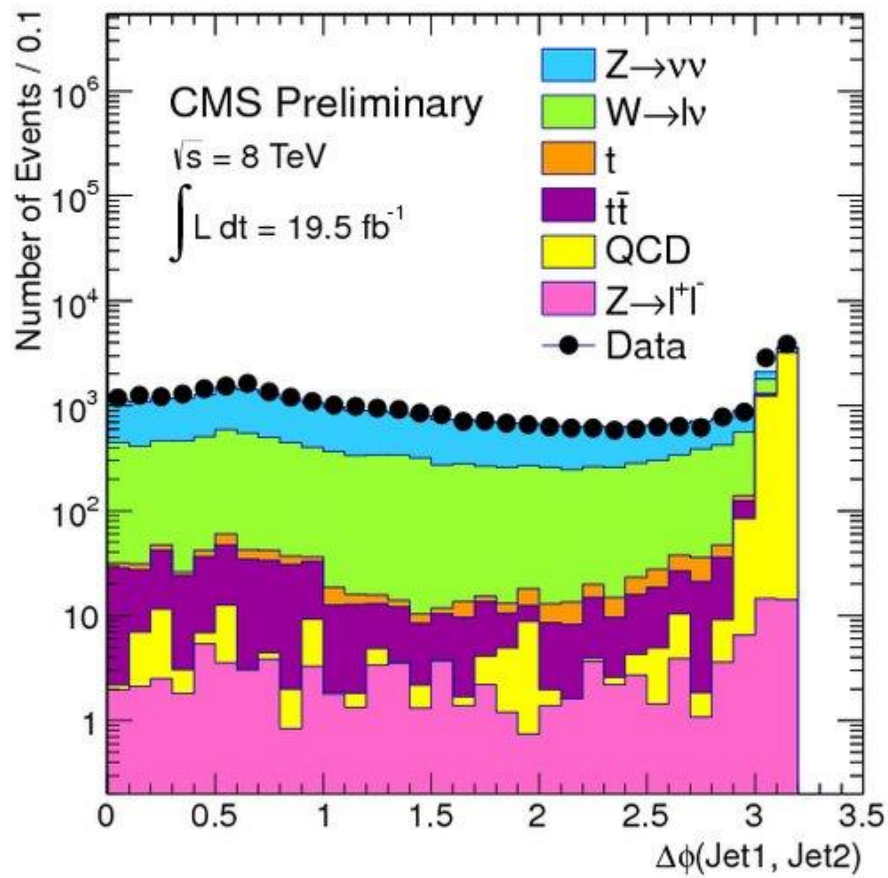
Coming back to CMS Mono-Jet Search

EXO-12-048 PAS

Selections
≥1 good vertex
> 20% E_{jet} from charged hadrons
<70% E_{jet} from neutral hadrons or photons
p_T(jet1) > 110 GeV && $\|\eta_{jet1}\| < 2.4$
no more than 2 jets with p_T>30GeV in $\|\eta\| < 4.5$ & except $\Delta\varphi$(j1,j2) <2.5
no isolated leptons

Selection Variable Distributions

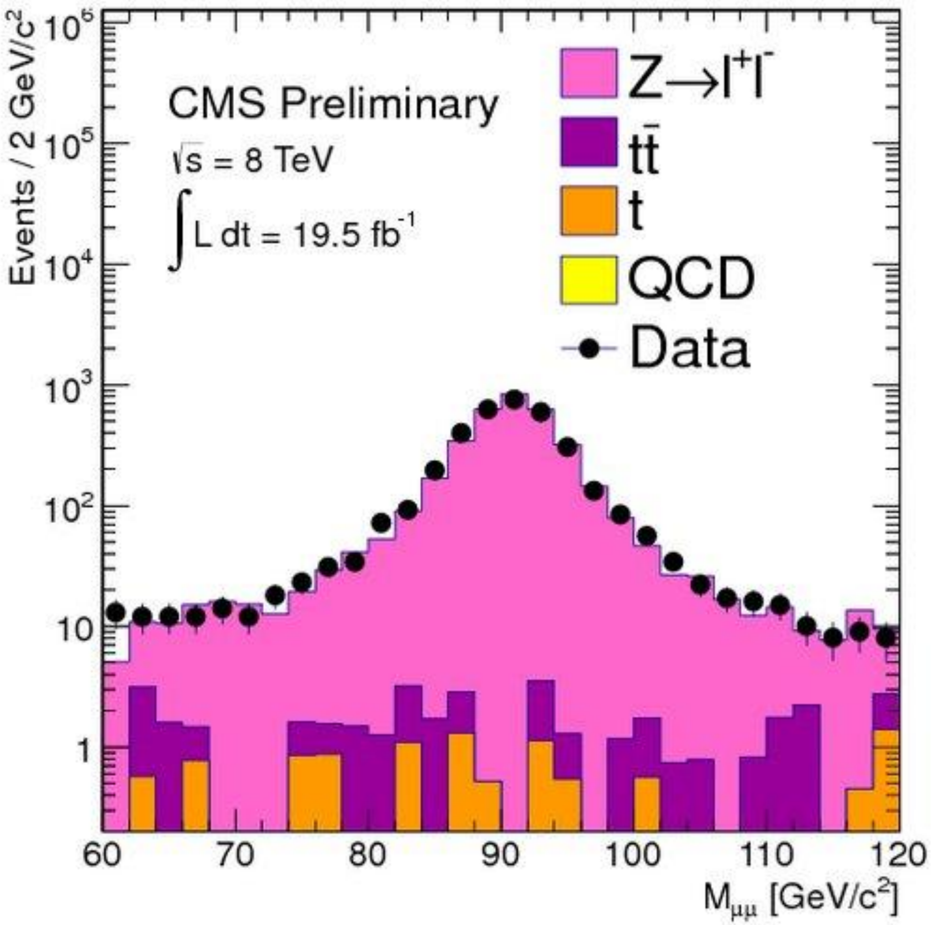


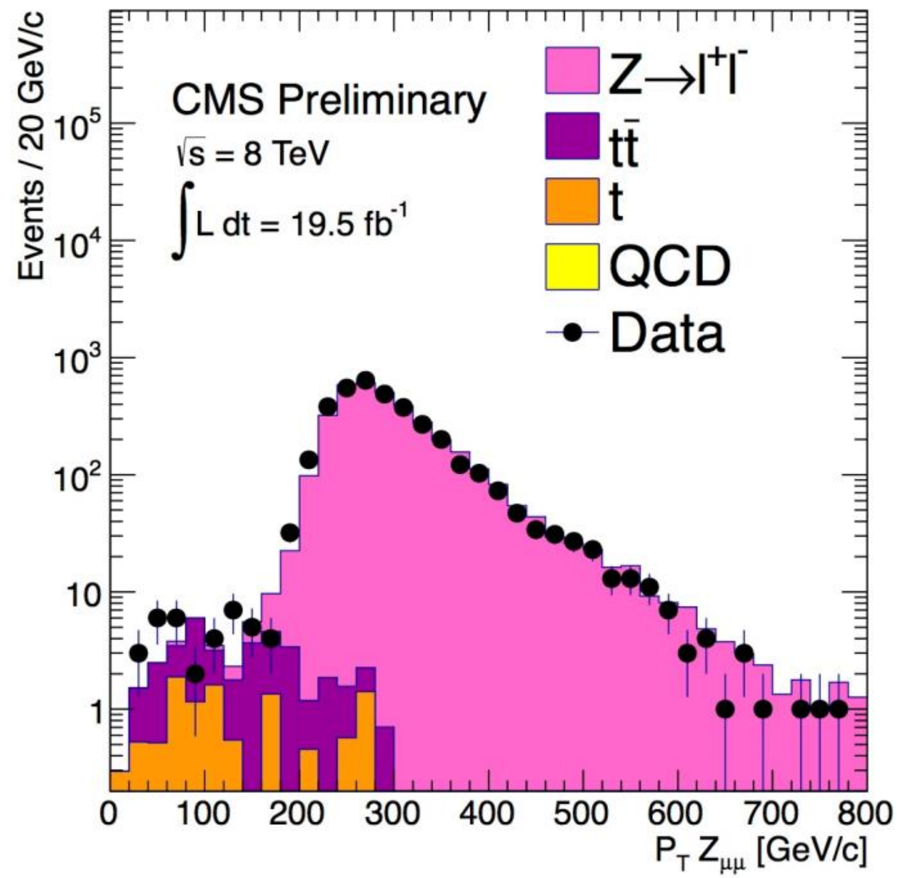


Background: Z(νν)+jet

- Use data to estimate background
- Select Z(μμ)+jet applying all selections BUT lepton veto
- 2 μ with p_T > 20 GeV && $|\eta|<2.1$
- ≥ 1 isolated μ
- 60 GeV < $m_{\mu\mu}$ < 120 GeV

Distribution of Z(μμ) + jet Sample



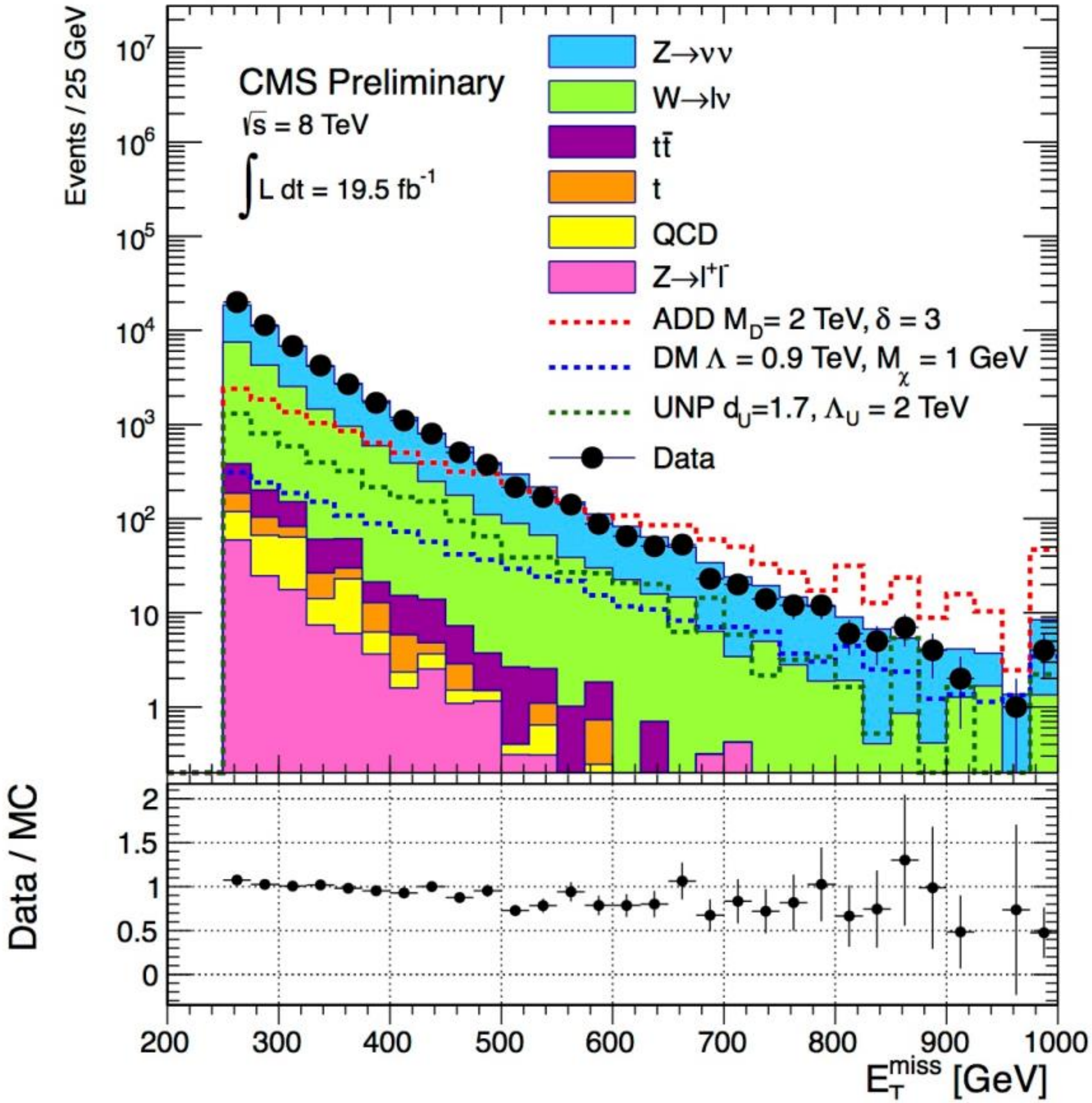


Background: Z(νν)+jet

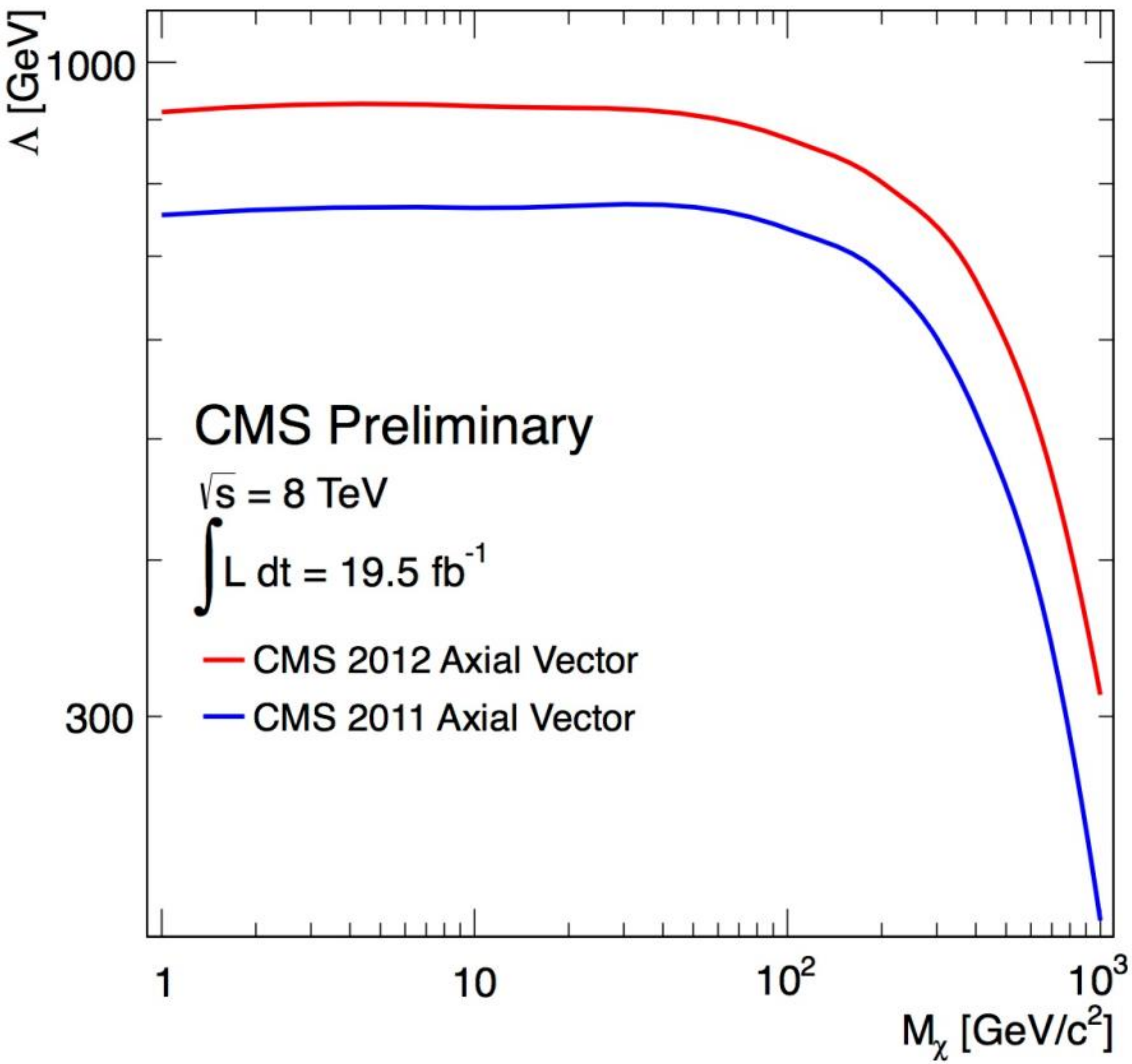
- Use data to estimate background
- Select Z(μμ)+jet applying all selections BUT lepton veto
- 2 μ with p_T > 20 GeV && |η|<2.1
- ≥ 1 isolated μ
- 60 GeV < $m_{\mu\mu}$ < 120 GeV

$$N(\mathrm{Z}(\nu\nu)) = \frac{N^{\mathrm{obs}} - N^{\mathrm{bgd}}}{A \times \epsilon} \cdot R\left(\frac{\mathrm{Z}(\nu\nu)}{\mathrm{Z}(\mu\mu)}\right)$$

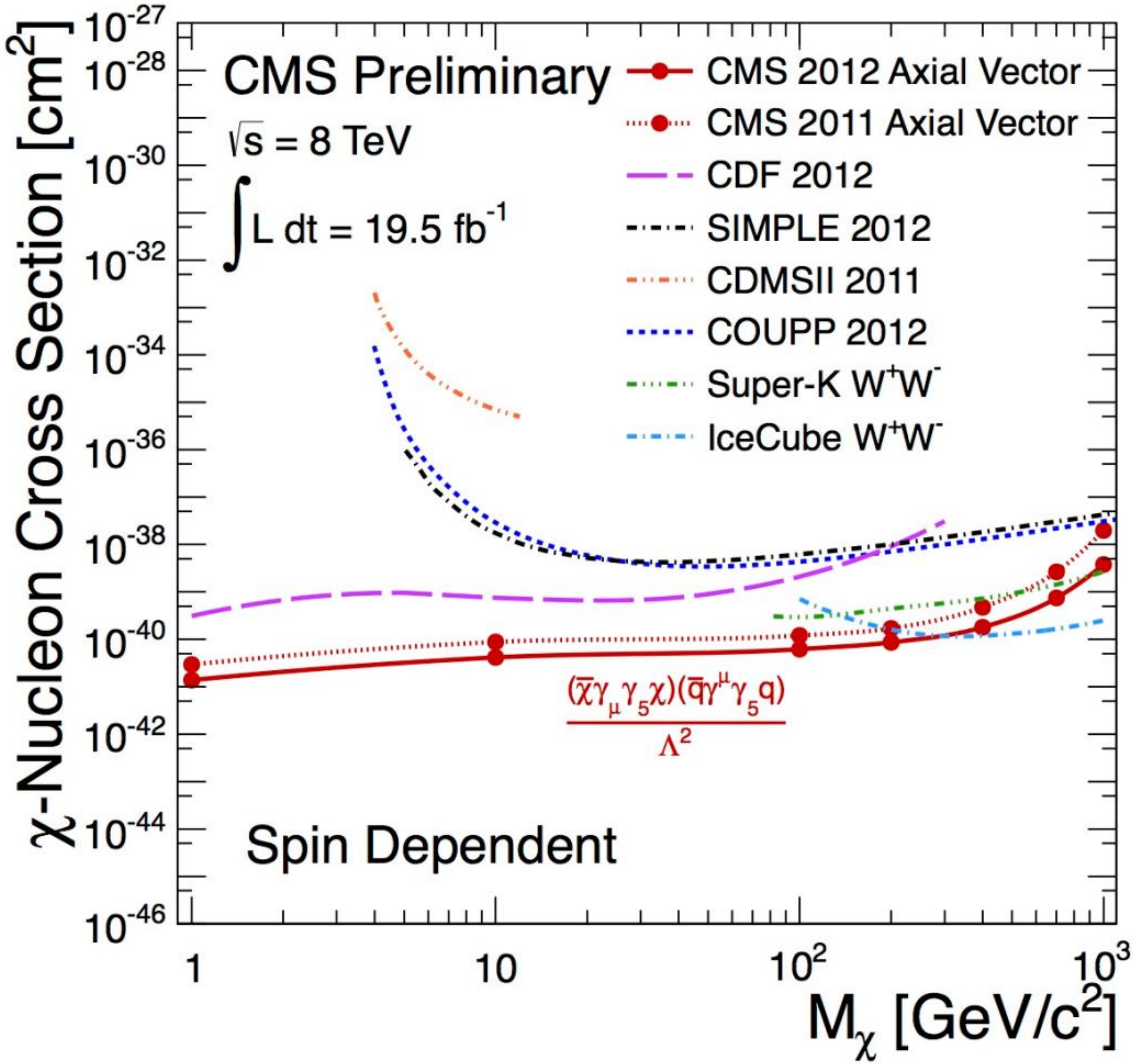
Missing E_T Distribution after all Selections



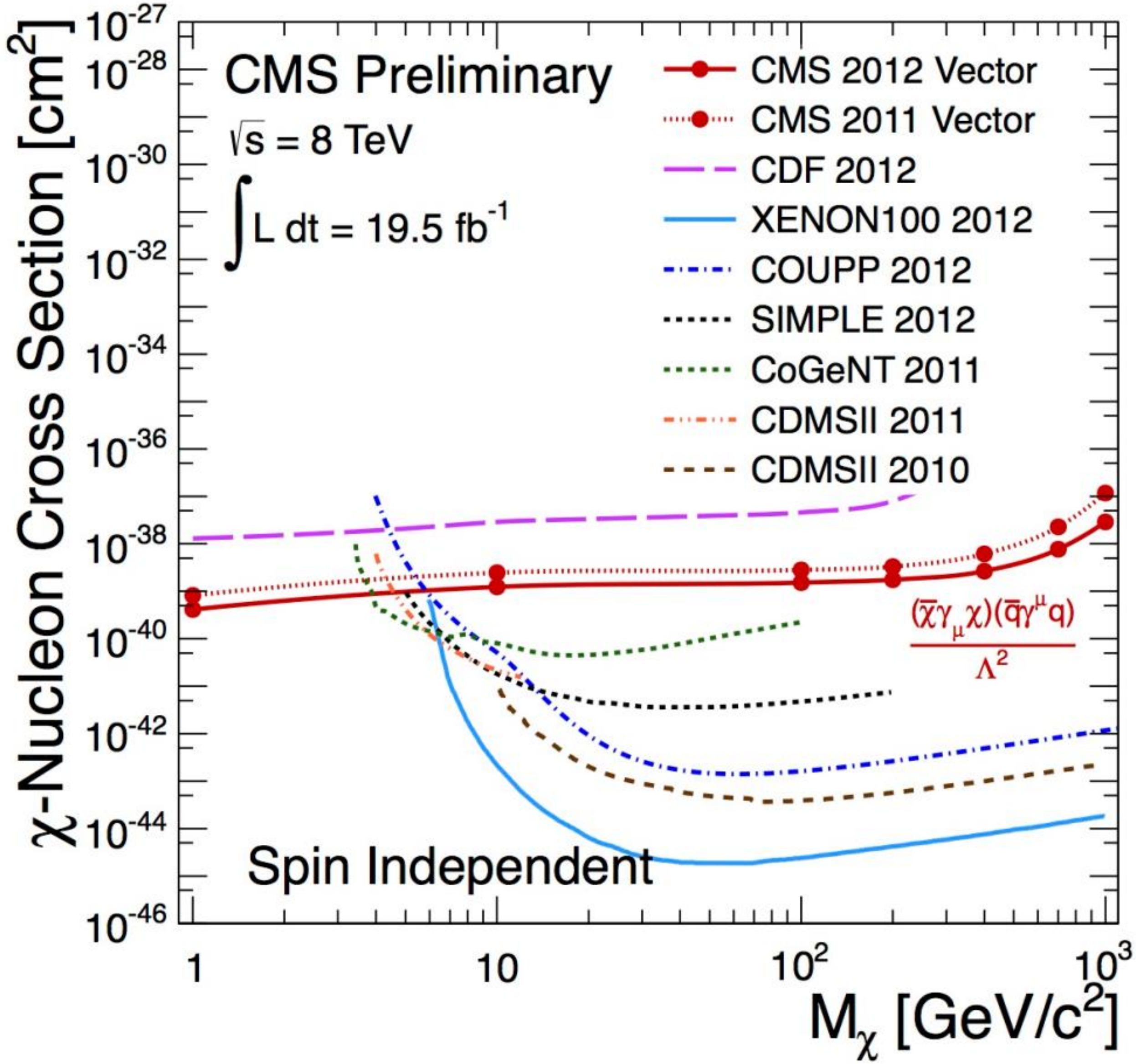
Spin Dependent Limits on Λ



Darkmatter-Nucleon Cross Section Limit



DM-Nucleon cross section upper limits



ATLAS Exotics Searches* - 95% CL Exclusion

Status: ICHEP 2014

ATLAS Preliminary

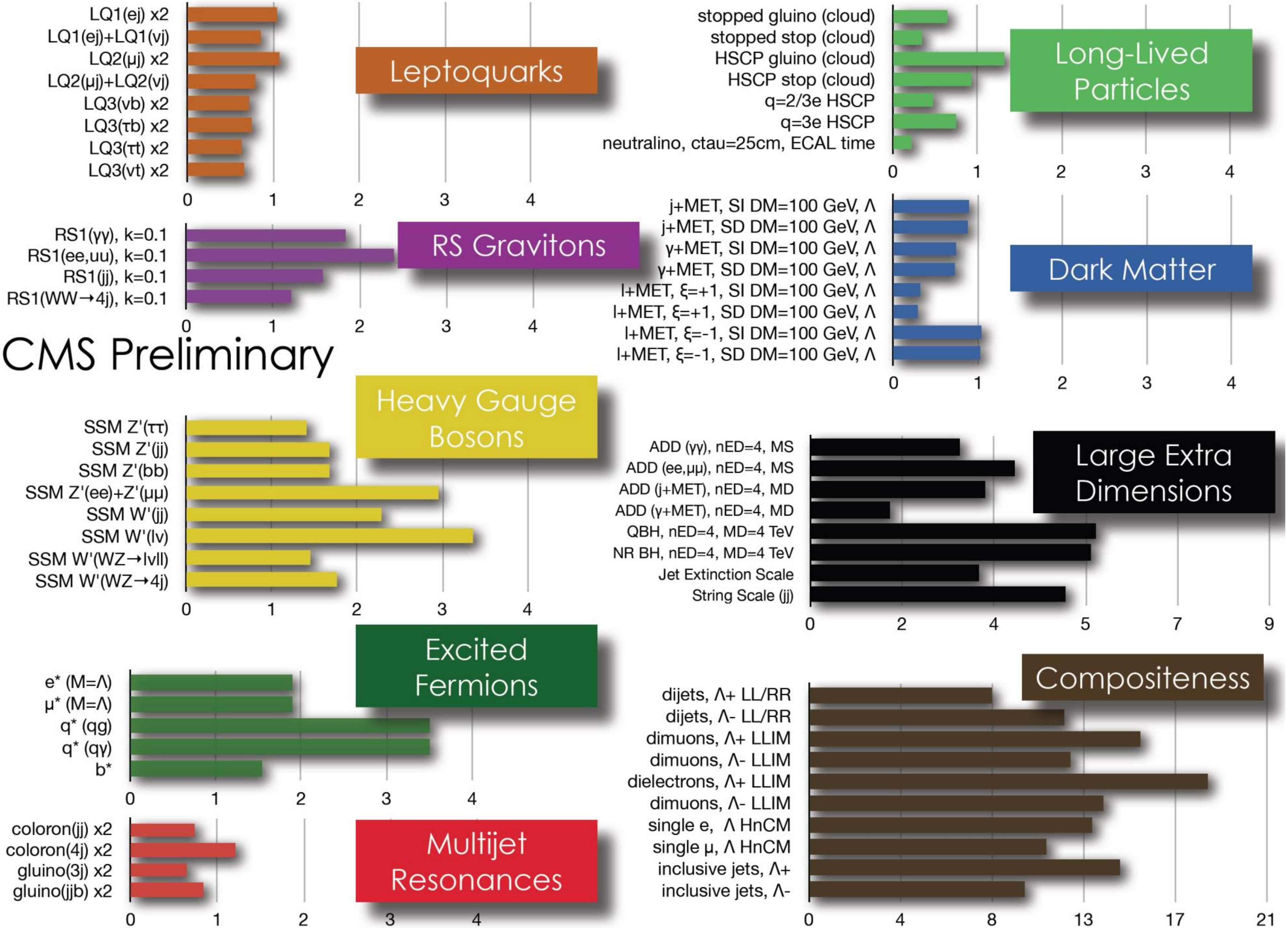
$\int \mathcal{L}\, dt = (1.0 - 20.3)\ \text{fb}^{-1}$ $\sqrt{s} = 7, 8$ TeV

	Model	ℓ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt[\text{fb}^{-1}]$	Mass limit		Reference
Extra dimensions	ADD $G_{KK} + g/q$	–	1-2 j	Yes	4.7	M_D 4.37 TeV	$n = 2$	1210.4491
	ADD non-resonant $\ell\ell$	2 e, μ	–	–	20.3	M_S 5.2 TeV	$n = 3$ HLZ	ATLAS-CONF-2014-030
	ADD QBH $\to \ell q$	1 e, μ	1 j	–	20.3	M_{th} 5.2 TeV	$n = 6$	1311.2006
	ADD QBH	–	2 j	–	20.3	M_{th} 5.82 TeV	$n = 6$	to be submitted to PRD
	ADD BH high N_{trk}	2 μ (SS)	–	–	20.3	M_{th} 5.7 TeV	$n = 6$, $M_D = 1.5$ TeV, non-rot BH	1308.4075
	ADD BH high $\sum p_T$	≥ 1 e, μ	≥ 2 j	–	20.3	M_{th} 6.2 TeV	$n = 6$, $M_D = 1.5$ TeV, non-rot BH	1405.4254
	RS1 $G_{KK} \to \ell\ell$	2 e, μ	–	–	20.3	G_{KK} mass 2.68 TeV	$k/\overline{M}_{Pl} = 0.1$	1405.4123
	RS1 $G_{KK} \to WW \to \ell\nu\ell\nu$	2 e, μ	–	Yes	4.7	G_{KK} mass 1.23 TeV	$k/\overline{M}_{Pl} = 0.1$	1208.2880
	Bulk RS $G_{KK} \to ZZ \to \ell\ell qq$	2 e, μ	2 j / 1 J	–	20.3	G_{KK} mass 730 GeV	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2014-039
	Bulk RS $G_{KK} \to HH \to b\bar{b}b\bar{b}$	–	4 b	–	19.5	G_{KK} mass 590-710 GeV	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2014-005
	Bulk RS $g_{KK} \to t\bar{t}$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	14.3	g_{KK} mass 2.0 TeV	BR = 0.925	ATLAS-CONF-2013-052
	S^1/Z_2 ED	2 e, μ	–	–	5.0	$M_{KK} \approx R^{-1}$ 4.71 TeV		1209.2535
	UED	2 γ	–	Yes	4.8	Compact. scale R^{-1} 1.41 TeV		ATLAS-CONF-2012-072
Gauge bosons	SSM $Z' \to \ell\ell$	2 e, μ	–	–	20.3	Z' mass 2.9 TeV		1405.4123
	SSM $Z' \to \tau\tau$	2 τ	–	–	19.5	Z' mass 1.9 TeV		ATLAS-CONF-2013-066
	SSM $W' \to \ell\nu$	1 e, μ	–	Yes	20.3	W' mass 3.28 TeV		ATLAS-CONF-2014-017
	EGM $W' \to WZ \to \ell\nu\, \ell'\ell'$	3 e, μ	–	Yes	20.3	W' mass 1.52 TeV		1406.4456
	EGM $W' \to WZ \to qq\ell\ell$	2 e, μ	2 j / 1 J	–	20.3	W' mass 1.59 TeV		ATLAS-CONF-2014-039
	LRSM $W'_R \to t\bar{b}$	1 e, μ	2 b, 0-1 j	Yes	14.3	W' mass 1.84 TeV		ATLAS-CONF-2013-050
	LRSM $W'_R \to t\bar{b}$	0 e, μ	≥ 1 b, 1 J	–	20.3	W' mass 1.77 TeV		to be submitted to EPJC
CI	CI $qqqq$	–	2 j	–	4.8	Λ 7.6 TeV	$\eta = +1$	1210.1718
	CI $qq\ell\ell$	2 e, μ	–	–	20.3	Λ 21.6 TeV	$\eta_{LL} = -1$	ATLAS-CONF-2014-030
	CI $uutt$	2 e, μ (SS)	≥ 1 b, ≥ 1 j	Yes	14.3	Λ 3.3 TeV	$\lvert C \rvert = 1$	ATLAS-CONF-2013-051
DM	EFT D5 operator (Dirac)	0 e, μ	1-2 j	Yes	10.5	M_* 731 GeV	at 90% CL for $m(\chi) < 80$ GeV	ATLAS-CONF-2012-147
	EFT D9 operator (Dirac)	0 e, μ	1 J, ≤ 1 j	Yes	20.3	M_* 2.4 TeV	at 90% CL for $m(\chi) < 100$ GeV	1309.4017
LQ	Scalar LQ 1st gen	2 e	≥ 2 j	–	1.0	LQ mass 660 GeV	$\beta = 1$	1112.4828
	Scalar LQ 2nd gen	2 μ	≥ 2 j	–	1.0	LQ mass 685 GeV	$\beta = 1$	1203.3172
	Scalar LQ 3rd gen	1 e, μ, 1 τ	1 b, 1 j	–	4.7	LQ mass 534 GeV	$\beta = 1$	1303.0526
Heavy quarks	Vector-like quark $TT \to Ht + X$	1 e, μ	≥ 2 b, ≥ 4 j	Yes	14.3	T mass 790 GeV	T in (T,B) doublet	ATLAS-CONF-2013-018
	Vector-like quark $TT \to Wb + X$	1 e, μ	≥ 1 b, ≥ 3 j	Yes	14.3	T mass 670 GeV	isospin singlet	ATLAS-CONF-2013-060
	Vector-like quark $TT \to Zt + X$	2/$\geq$3 e, μ	$\geq$2/$\geq$1 b	–	20.3	T mass 735 GeV	T in (T,B) doublet	ATLAS-CONF-2014-036
	Vector-like quark $BB \to Zb + X$	2/$\geq$3 e, μ	$\geq$2/$\geq$1 b	–	20.3	B mass 755 GeV	B in (B,Y) doublet	ATLAS-CONF-2014-036
	Vector-like quark $BB \to Wt + X$	2 e, μ (SS)	≥ 1 b, ≥ 1 j	Yes	14.3	B mass 720 GeV	B in (T,B) doublet	ATLAS-CONF-2013-051
Excited fermions	Excited quark $q^* \to q\gamma$	1 γ	1 j	–	20.3	q^* mass 3.5 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1309.3230
	Excited quark $q^* \to qg$	–	2 j	–	20.3	q^* mass 4.09 TeV	only u^* and d^*, $\Lambda = m(q^*)$	to be submitted to PRD
	Excited quark $b^* \to Wt$	1 or 2 e, μ	1 b, 2 j or 1 j	Yes	4.7	b^* mass 870 GeV	left-handed coupling	1301.1583
	Excited lepton $\ell^* \to \ell\gamma$	2 e, μ, 1 γ	–	–	13.0	ℓ^* mass 2.2 TeV	$\Lambda = 2.2$ TeV	1308.1364
Other	LSTC $a_T \to W\gamma$	1 e, μ, 1 γ	–	Yes	20.3	a_T mass 960 GeV		to be submitted to PLB
	LRSM Majorana ν	2 e, μ	2 j	–	2.1	N^0 mass 1.5 TeV	$m(W_R) = 2$ TeV, no mixing	1203.5420
	Type III Seesaw	2 e, μ	–	–	5.8	$N^\pm$ mass 245 GeV	$\lvert V_e \rvert$=0.055, $\lvert V_\mu \rvert$=0.063, $\lvert V_\tau \rvert$=0	ATLAS-CONF-2013-019
	Higgs triplet $H^{\pm\pm} \to \ell\ell$	2 e, μ (SS)	–	–	4.7	$H^{\pm\pm}$ mass 409 GeV	DY production, BR($H^{\pm\pm} \to \ell\ell$)=1	1210.5070
	Multi-charged particles	–	–	–	4.4	multi-charged particle mass 490 GeV	DY production, $\lvert q \rvert = 4e$	1301.5272
	Magnetic monopoles	–	–	–	2.0	monopole mass 862 GeV	DY production, $\lvert g \rvert = 1 g_D$	1207.6411

$\sqrt{s} = 7$ TeV | $\sqrt{s} = 8$ TeV

10^{-1} 1 10 **Mass scale [TeV]**

*Only a selection of the available mass limits on new states or phenomena is shown.


Leptoquarks
LQ1(ej) x2
LQ1(ej)+LQ1(νj)
LQ2(μj) x2
LQ2(μj)+LQ2(νj)
LQ3(νb) x2
LQ3(τb) x2
LQ3(τt) x2
LQ3(νt) x2
Long-Lived Particles
stopped gluino (cloud)
stopped stop (cloud)
HSCP gluino (cloud)
HSCP stop (cloud)
q=2/3e HSCP
q=3e HSCP
neutralino, ctau=25cm, ECAL time
RS Gravitons
RS1(γγ), k=0.1
RS1(ee,uu), k=0.1
RS1(jj), k=0.1
RS1(WW→4j), k=0.1
Dark Matter
j+MET, SI DM=100 GeV, Λ
j+MET, SD DM=100 GeV, Λ
γ+MET, SI DM=100 GeV, Λ
γ+MET, SD DM=100 GeV, Λ
l+MET, ξ=+1, SI DM=100 GeV, Λ
l+MET, ξ=+1, SD DM=100 GeV, Λ
l+MET, ξ=-1, SI DM=100 GeV, Λ
l+MET, ξ=-1, SD DM=100 GeV, Λ
CMS Preliminary
Heavy Gauge Bosons
SSM Z'(ττ)
SSM Z'(jj)
SSM Z'(bb)
SSM Z'(ee)+Z'(μμ)
SSM W'(jj)
SSM W'(lν)
SSM W'(WZ→lνll)
SSM W'(WZ→4j)
Large Extra Dimensions
ADD (γγ), nED=4, MS
ADD (ee,μμ), nED=4, MS
ADD (j+MET), nED=4, MD
ADD (γ+MET), nED=4, MD
QBH, nED=4, MD=4 TeV
NR BH, nED=4, MD=4 TeV
Jet Extinction Scale
String Scale (jj)
Excited Fermions
e* (M=Λ)
μ* (M=Λ)
q* (qg)
q* (qγ)
b*
Compositeness
dijets, Λ+ LL/RR
dijets, Λ- LL/RR
dimuons, Λ+ LLIM
dimuons, Λ- LLIM
dielectrons, Λ+ LLIM
dimuons, Λ- LLIM
single e, Λ HnCM
single μ, Λ HnCM
inclusive jets, Λ+
inclusive jets, Λ-
Multijet Resonances
coloron(jj) x2
coloron(4j) x2
gluino(3j) x2
gluino(jjb) x2

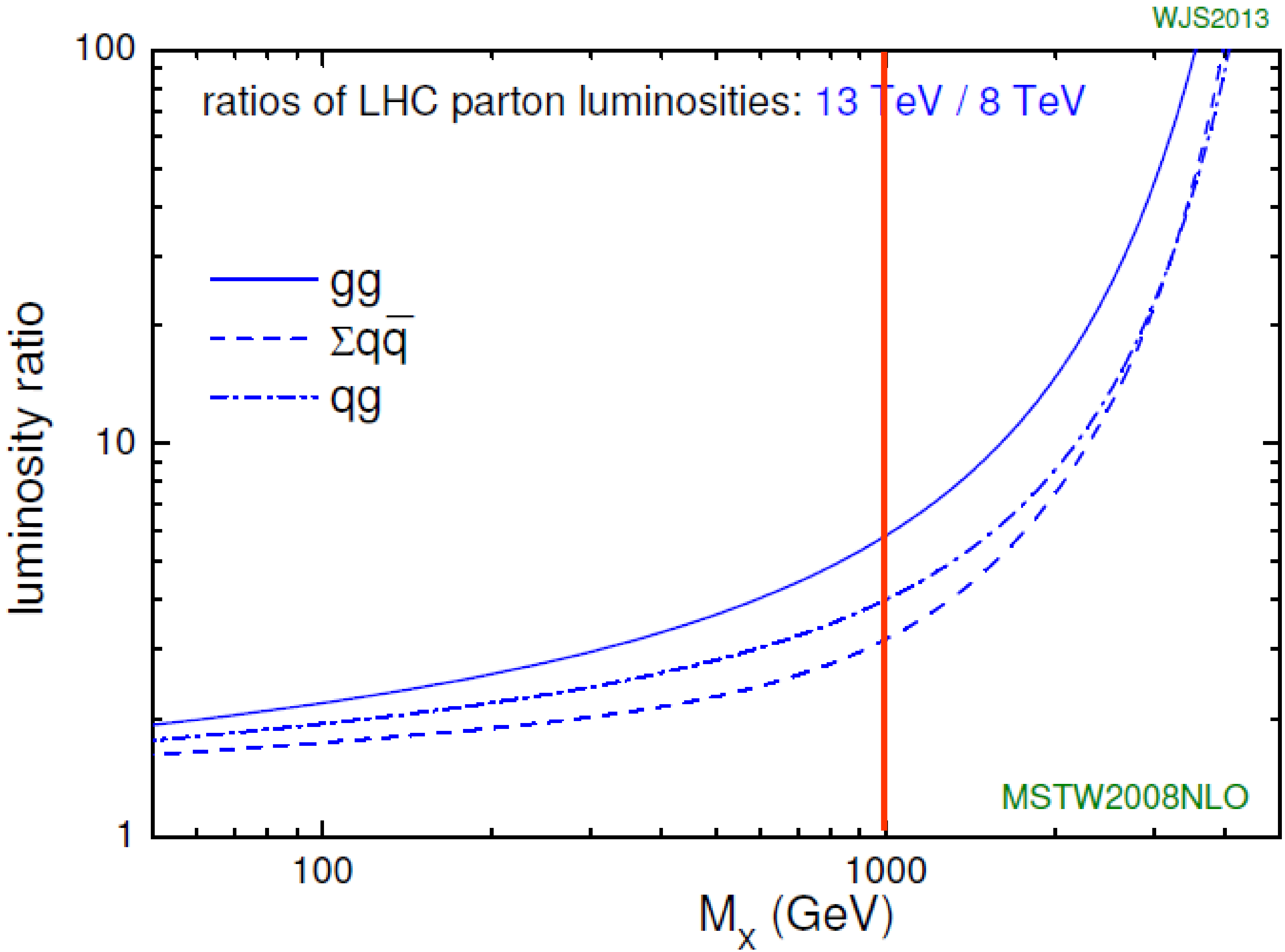
Conclusions

The Standard Model

C. Grojean, A. Weiler

There is new physics out there!

Expectation for Run2



Conclusions: Physics Priorities for HL-LHC

- If no new physics @ Run2
  - Precision measurements
    - Higgs
    - W,Z
    - Top

  ↔ EWK Symmetry Breaking

- If new physics found @ Run2
  - Study its properties
  - Understand what we have found

Literature for Further Reading

- Technicolor and related models
  - http://dx.doi.org/10.1016/0370-1573(81)90173-3
  - http://dx.doi.org/10.1103/RevModPhys.55.449
  - http://inspirehep.net/record/205523?ln=en
  - http://dx.doi.org/10.1016/0146-6410(83)90005-4
- Extra Dimensions
  - http://arxiv.org/pdf/hep-ph/0302189.pdf
  - http://arxiv.org/pdf/gr-qc/0312059.pdf
- Exotics new particles
  - http://dx.doi.org/10.1016/0370-1573(89)90071-9
  - http://dx.doi.org/10.1142/S0217751X88000035
- GUT: http://dx.doi.org/10.1016/0370-1573(81)90059-4

Backup Slides

Standard Model Lagrangian

$$\mathcal{L}_{SM} = -\frac{1}{4g'^2} B_{\mu\nu} B^{\mu\nu} - \frac{1}{2g^2} \mathrm{Tr}(W_{\mu\nu} W^{\mu\nu}) - \frac{1}{2g_s^2} \mathrm{Tr}(G_{\mu\nu} G^{\mu\nu})$$

$$+ \bar{Q}_i i \not{D} Q_i + \bar{L}_i i \not{D} L_i + \bar{u}_i i \not{D} u_i + \bar{d}_i i \not{D} d_i + \bar{e}_i i \not{D} e_i$$

Above: Describes gauge fields and interactions

$\not{D}$ determined by **gauge quantum numbers**

strange

	$SU(3)$	$SU(2)$	$U(1)$	chirality
Q	3	2	$+1/6$	left
U	3	1	$+2/3$	right
D	3	1	$-1/3$	right
L	1	2	$-1/2$	left
E	1	1	-1	right

Gravity is not included!!

Standard Model Lagrangian

$$\mathcal{L}_{SM} = -\frac{1}{4g'^2}B_{\mu\nu}B^{\mu\nu} - \frac{1}{2g^2}\mathrm{Tr}(W_{\mu\nu}W^{\mu\nu}) - \frac{1}{2g_s^2}\mathrm{Tr}(G_{\mu\nu}G^{\mu\nu})$$
$$+\bar{Q}_i i\not{D} Q_i + \bar{L}_i i\not{D} L_i + \bar{u}_i i\not{D} u_i + \bar{d}_i i\not{D} d_i + \bar{e}_i i\not{D} e_i$$
$$+(Y_u^{ij}\bar{Q}_i u_j \tilde{H} + Y_d^{ij}\bar{Q}_i d_j H + Y_l^{ij}\bar{L}_i e_j H + \mathrm{h.c.})$$

- Responsible for mass and mixing of quark masses
- Responsible for charged lepton masses
- Generation index: i, j = 1,2,3
- Why 3 families?
- No neutrino masses or mixing included

Standard Model Lagrangian

$$\mathcal{L}_{SM} = -\frac{1}{4g'^2}B_{\mu\nu}B^{\mu\nu} - \frac{1}{2g^2}\mathrm{Tr}(W_{\mu\nu}W^{\mu\nu}) - \frac{1}{2g_s^2}\mathrm{Tr}(G_{\mu\nu}G^{\mu\nu})$$
$$+\bar{Q}_i i\not{D}Q_i + \bar{L}_i i\not{D}L_i + \bar{u}_i i\not{D}u_i + \bar{d}_i i\not{D}d_i + \bar{e}_i i\not{D}e_i$$
$$+(Y_u^{ij}\bar{Q}_i u_j \tilde{H} + Y_d^{ij}\bar{Q}_i d_j H + Y_l^{ij}\bar{L}_i e_j H + \mathrm{h.c.})$$
$$+(D_\mu H)^\dagger(D^\mu H) - \lambda(H^\dagger H)^2 - m^2 H^\dagger H + \frac{\theta}{32\pi^2}\epsilon^{\mu\nu\rho\sigma}\mathrm{Tr}(G_{\mu\nu}G_{\rho\sigma}).$$

θ term in QCD

Periodic: 0 - 2π

Violates T and CP

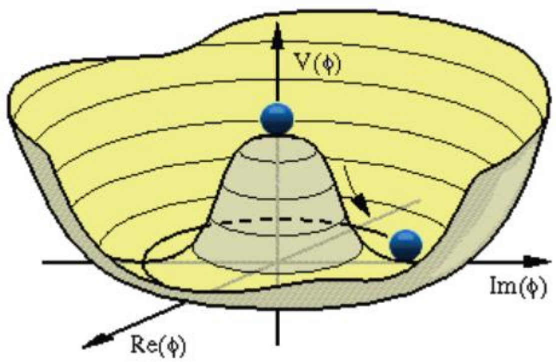
Strong CP Problem in SM

- Why is $\theta < 1.2 \times 10^{-10}$???
- Natural value ~ 1

Standard Model Lagrangian

$$\mathcal{L}_{SM} = -\frac{1}{4g'^2}B_{\mu\nu}B^{\mu\nu} - \frac{1}{2g^2}\mathrm{Tr}(W_{\mu\nu}W^{\mu\nu}) - \frac{1}{2g_s^2}\mathrm{Tr}(G_{\mu\nu}G^{\mu\nu})$$
$$+\bar{Q}_i i\not{D}Q_i + \bar{L}_i i\not{D}L_i + \bar{u}_i i\not{D}u_i + \bar{d}_i i\not{D}d_i + \bar{e}_i i\not{D}e_i$$
$$+(Y_u^{ij}\bar{Q}_i u_j\tilde{H} + Y_d^{ij}\bar{Q}_i d_j H + Y_l^{ij}\bar{L}_i e_j H + \mathrm{h.c.})$$
$$+(D_\mu H)^\dagger(D^\mu H) - \lambda(H^\dagger H)^2 - m^2 H^\dagger H + \frac{\theta}{32\pi^2}\epsilon^{\mu\nu\rho\sigma}\mathrm{Tr}(G_{\mu\nu}G_{\rho\sigma}).$$

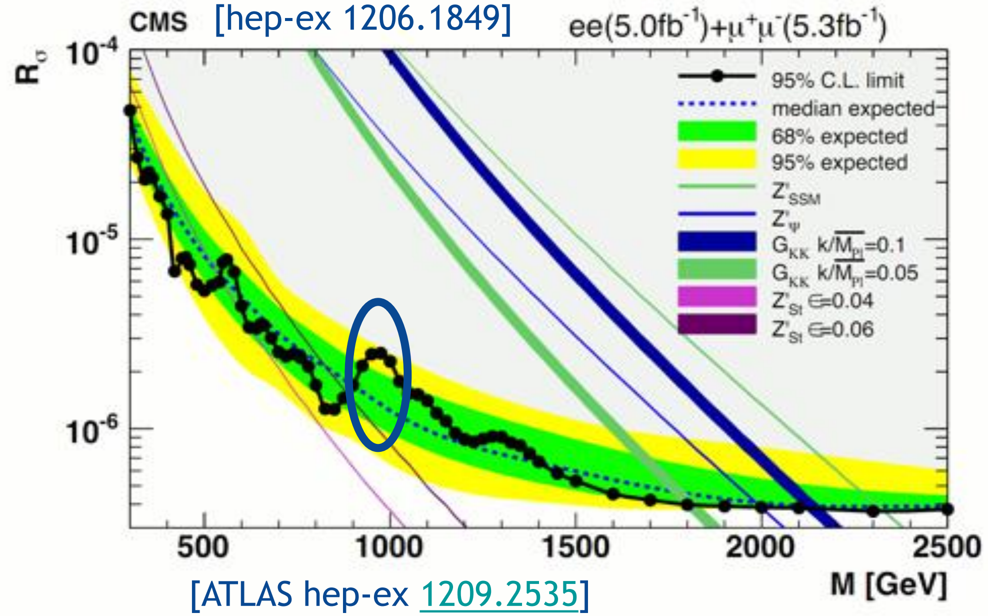
Higgs field

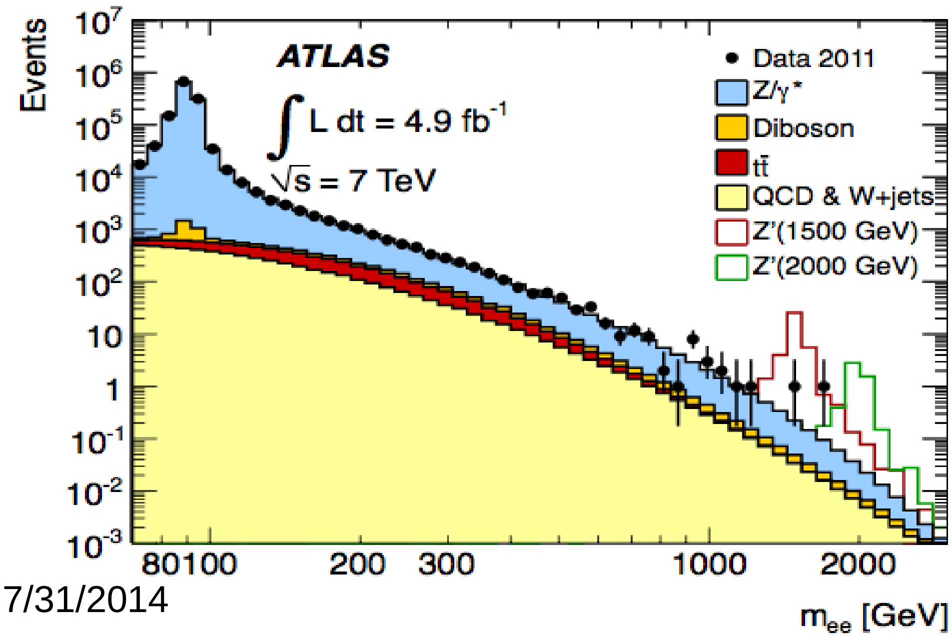


Z' in 2011 Data?

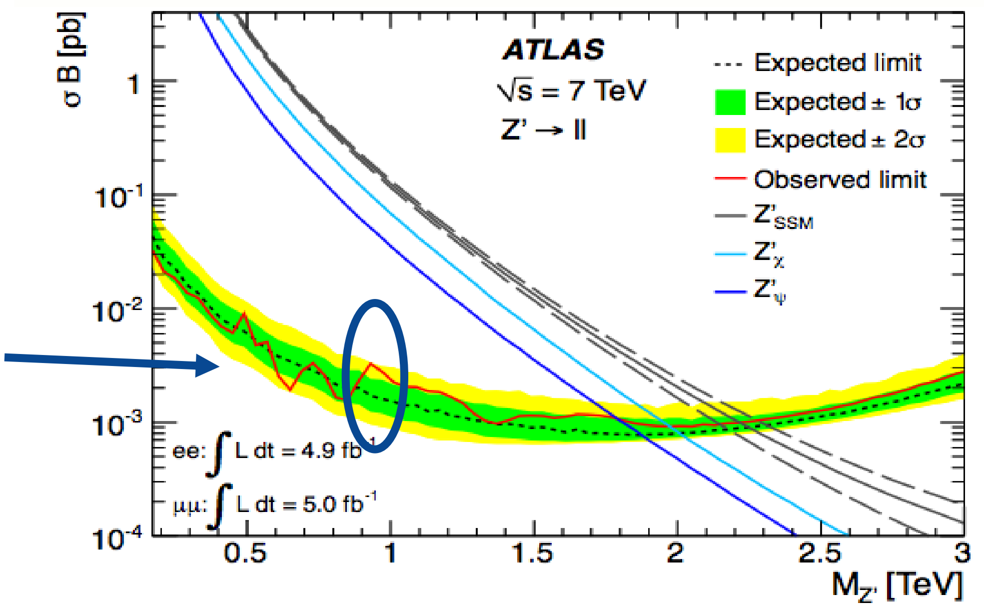
- Interesting features in dilepton spectra
  - around 2σ each for CMS & ATLAS in e+μ
  - similar in scale to 2011 Higgs excess

[hep-ex 1206.1849]





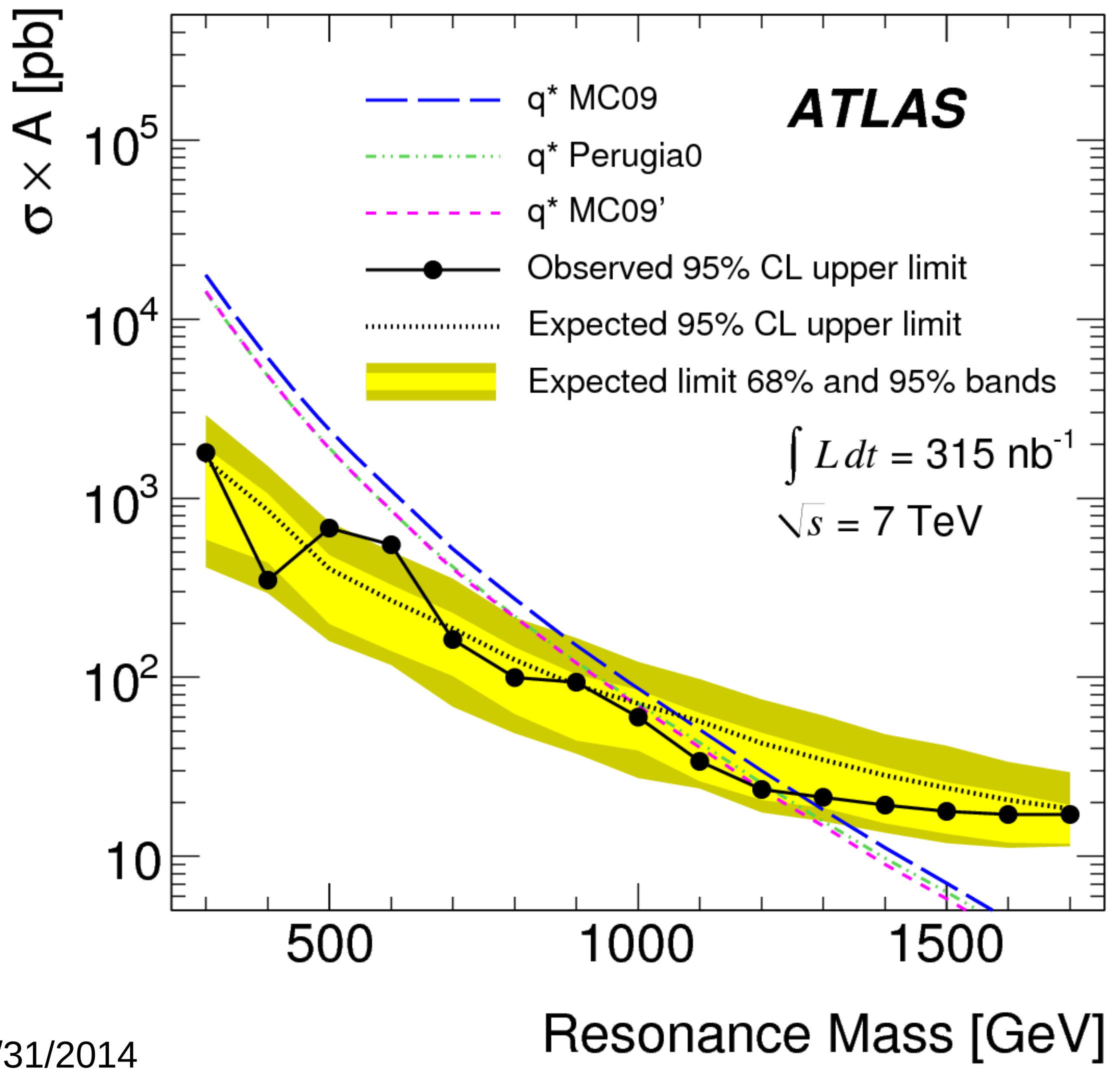
[ATLAS hep-ex 1209.2535]



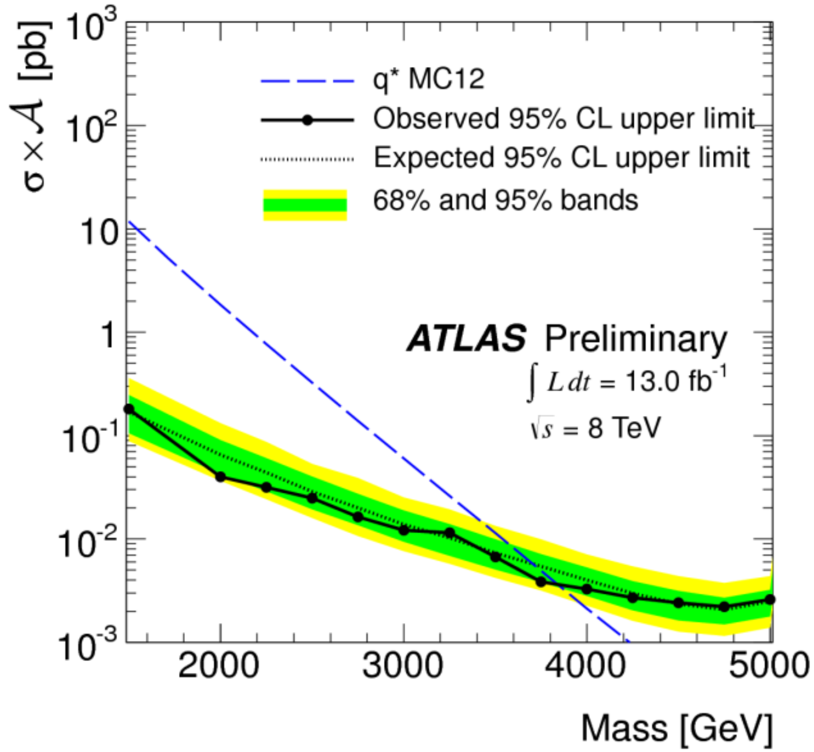
Mono Jet Signal Region Definitions

Signal regions	SR1	SR2	SR3	SR4
Common requirements	Data quality + trigger + vertex + jet quality + $\lvert\eta^{\mathrm{jet1}}\rvert < 2.0$ + $\lvert\Delta\phi(\mathrm{p}_{\mathrm{T}}^{\mathrm{miss}}, \mathrm{p}_{\mathrm{T}}^{\mathrm{jet2}})\rvert > 0.5$ + $N_{\mathrm{jets}} \leq 2$ + lepton veto			
$E_{\mathrm{T}}^{\mathrm{miss}}$, $p_{\mathrm{T}}^{\mathrm{jet1}}$ >	120 GeV	220 GeV	350 GeV	500 GeV

"Although the results of this analysis are interpreted in terms of the ADD model and WIMP pair production, the event selection criteria have not been tuned to maximize the sensitivity to any particular BSM scenario. To maintain sensitivity to a wide range of BSM models, four sets of overlapping kinematic selection criteria, designated as SR1 to SR4, are defined (table 2)."



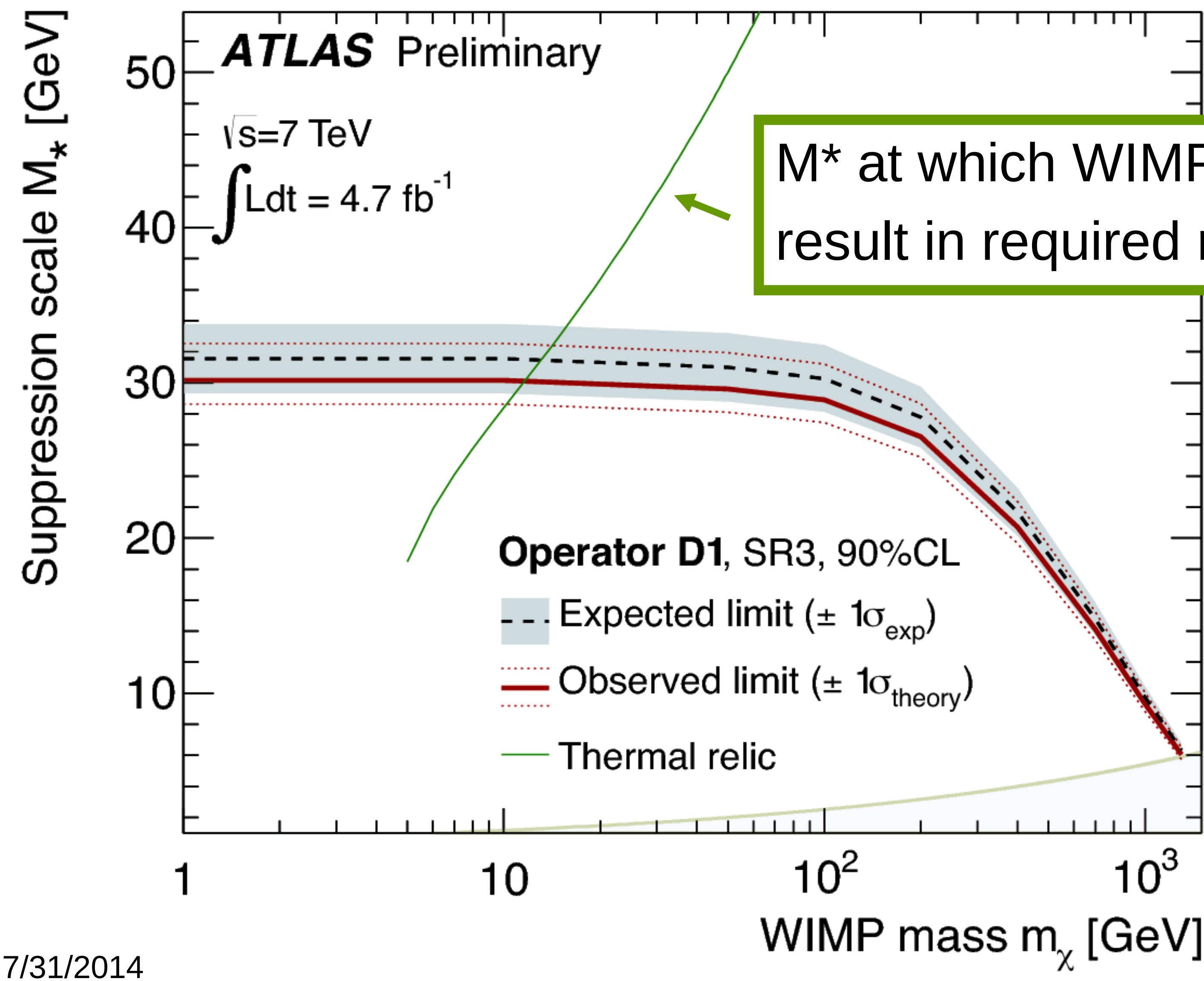
ATLAS
q* MC09
q* Perugia0
q* MC09'
Observed 95% CL upper limit
Expected 95% CL upper limit
Expected limit 68% and 95% bands
$\int L\,dt$ = 315 nb^{-1}
$\sqrt{s}$ = 7 TeV
$\sigma \times A$ [pb]
Resonance Mass [GeV]



q* MC12
Observed 95% CL upper limit
Expected 95% CL upper limit
68% and 95% bands
ATLAS Preliminary
$\int L\,dt$ = 13.0 fb^{-1}
$\sqrt{s}$ = 8 TeV
$\sigma \times \mathcal{A}$ [pb]
Mass [GeV]

Limits on Dark Matter – Mono Jet

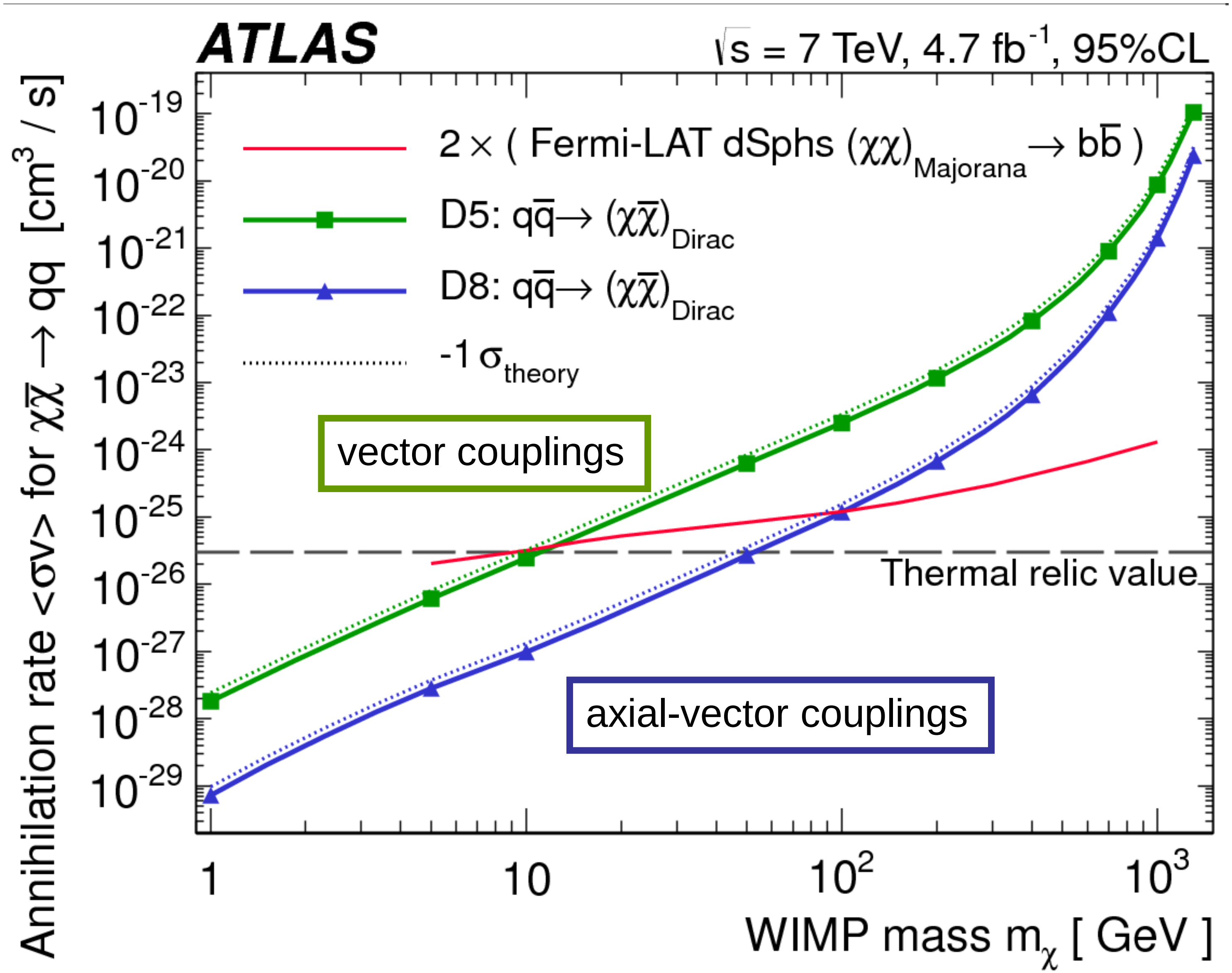
90% CL lower limits on M*



M* at which WIMPs of a given mass result in required relic abundance

convert

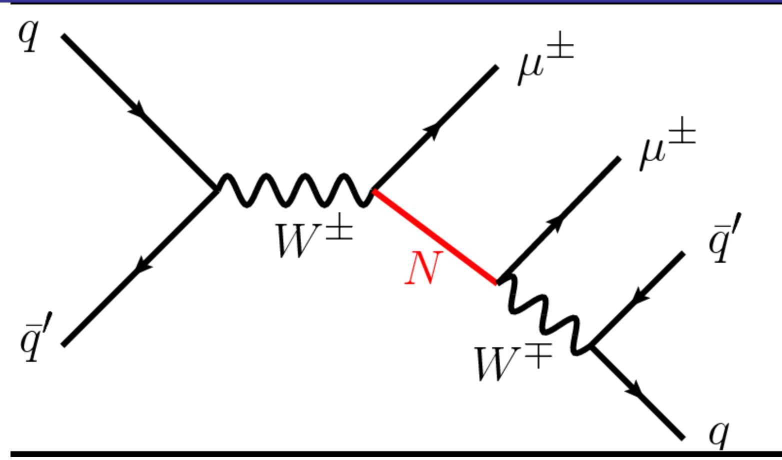
Limits on the annihilation rate of WIMPs

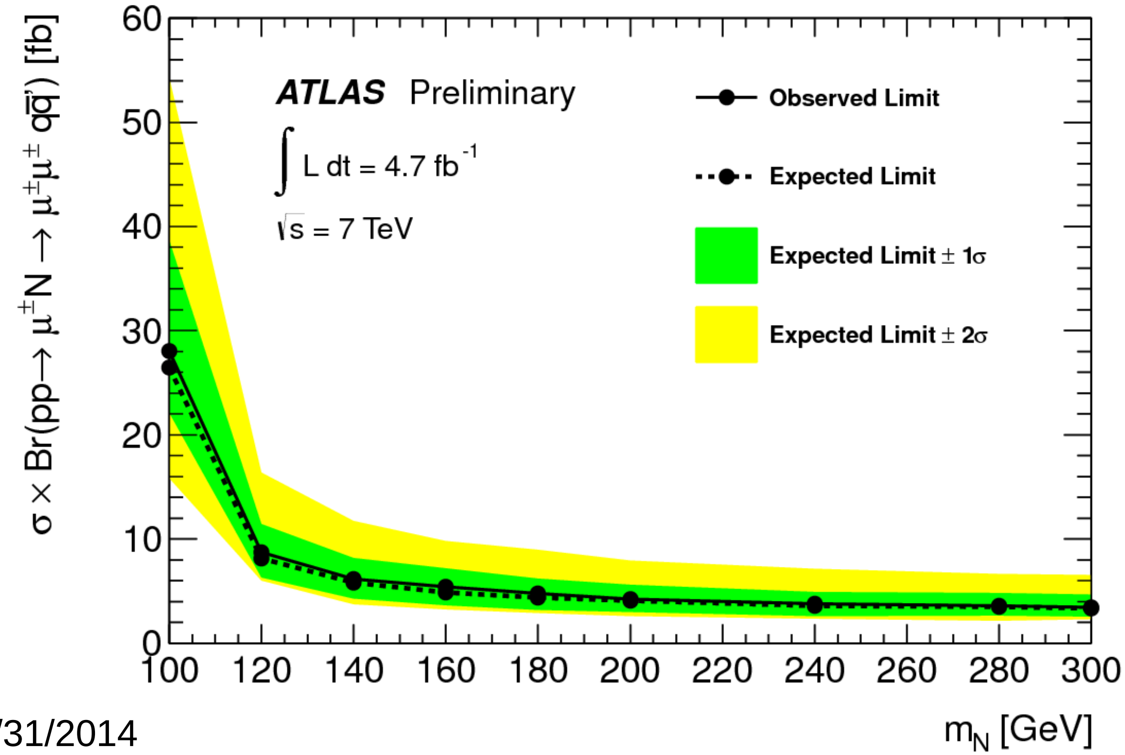


Majorana Neutrino Search in same-sign leptons

ATLAS-CONF-2012-139

- Two same-sign muons
- ≥2 jets and low ME_T



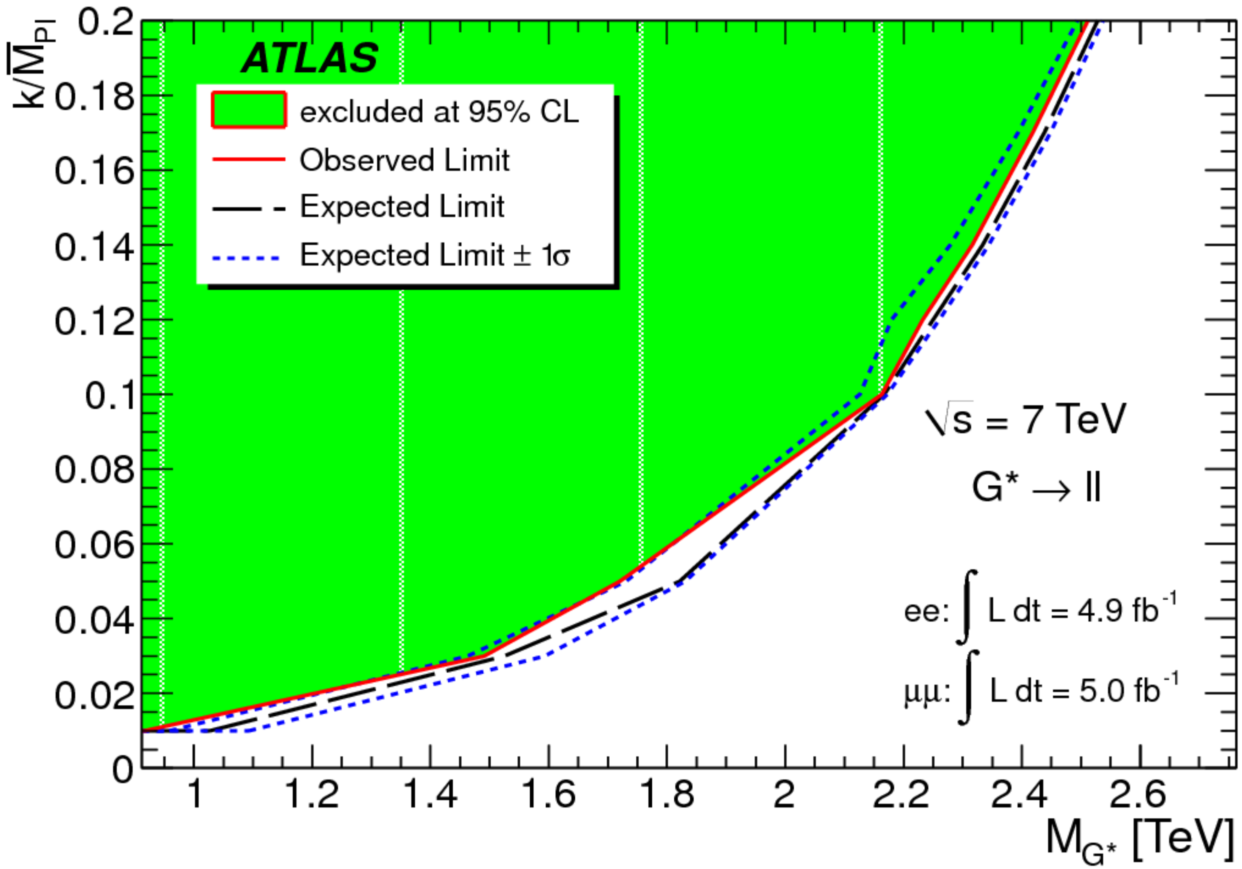


observed limits range from 28 to 3.4 fb for heavy neutrino masses between 100 and 300 GeV

Search for Heavy Resonance: dilepton channel

- Limits as a function of RS graviton mass and coupling

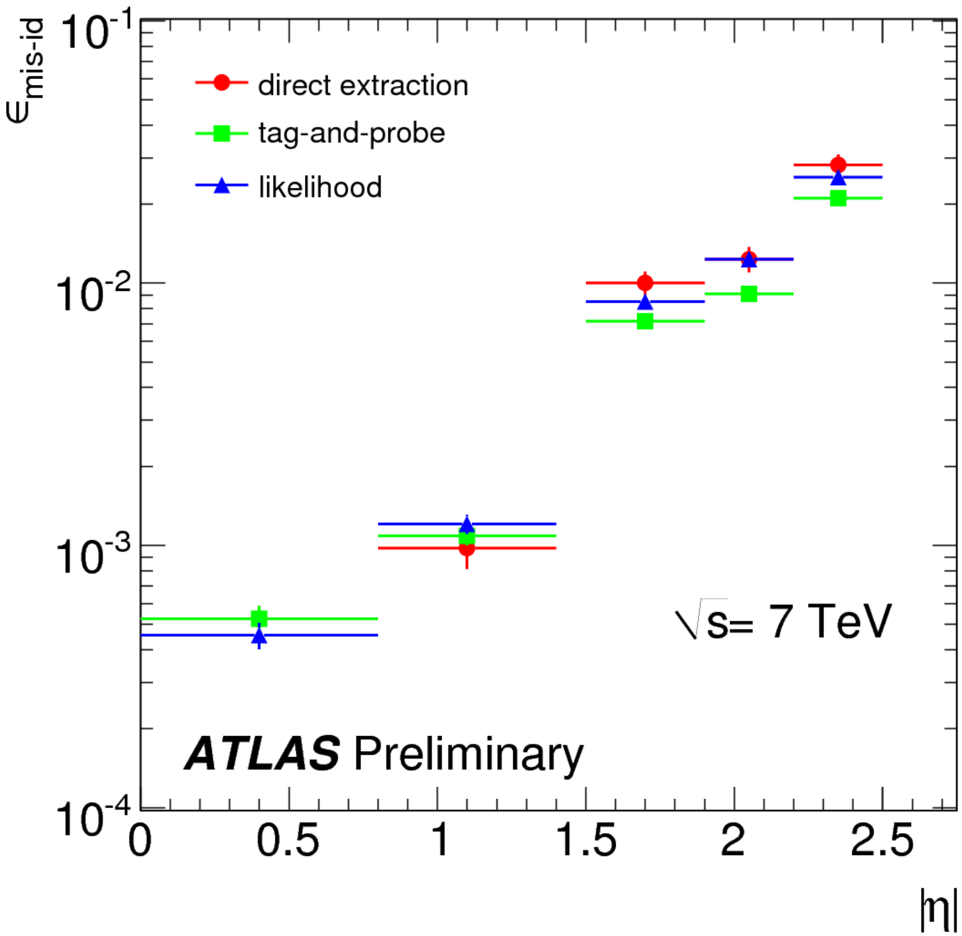
  m(RS graviton, k/MPl = 0.1) > 2.16 TeV at 95% CL

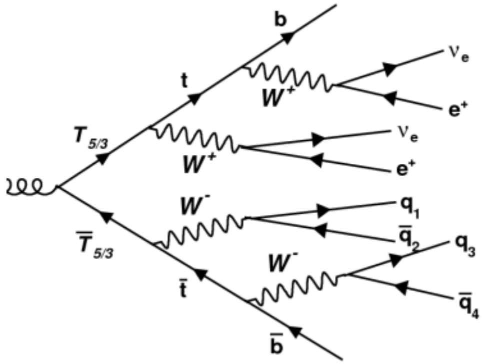


Exotic Same-Sign Dilepton Signatures: b', $T^{5/3}$

Charge mis-id rate

ATLAS-CONF-2012-130





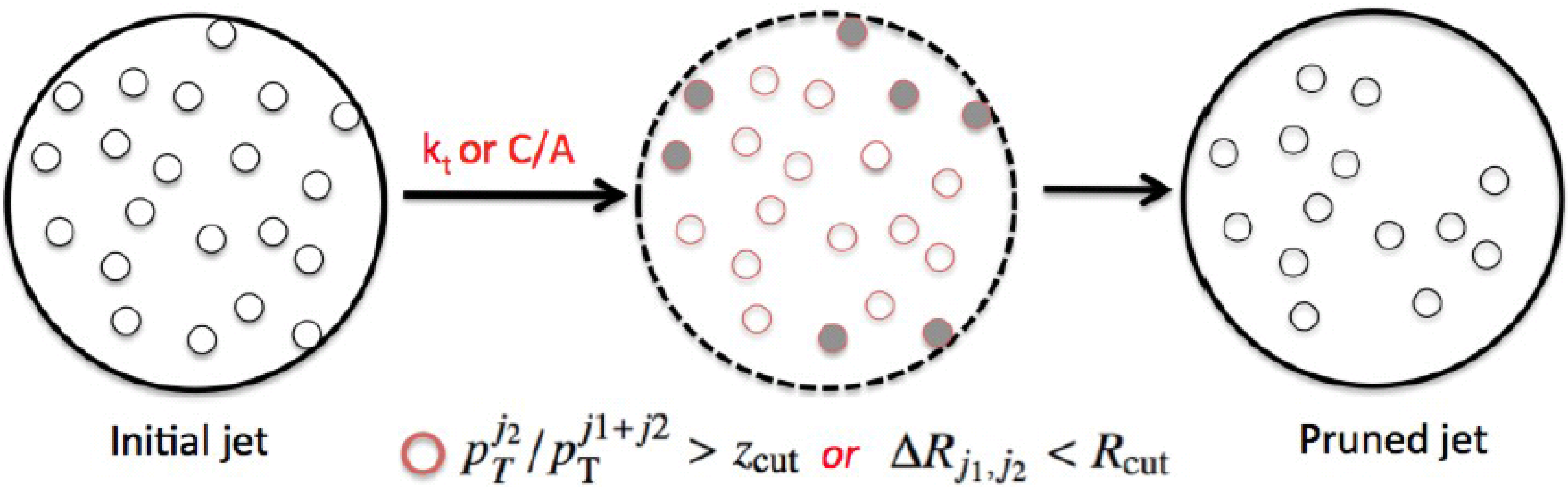
- 2 isolated same-sign leptons (*e* or μ)
- ME_T > 40 GeV
- ≥2 jets (≥1 b-tagged jet)
- large overall transverse momentum
  - H_T > 550 GeV

4 events observed

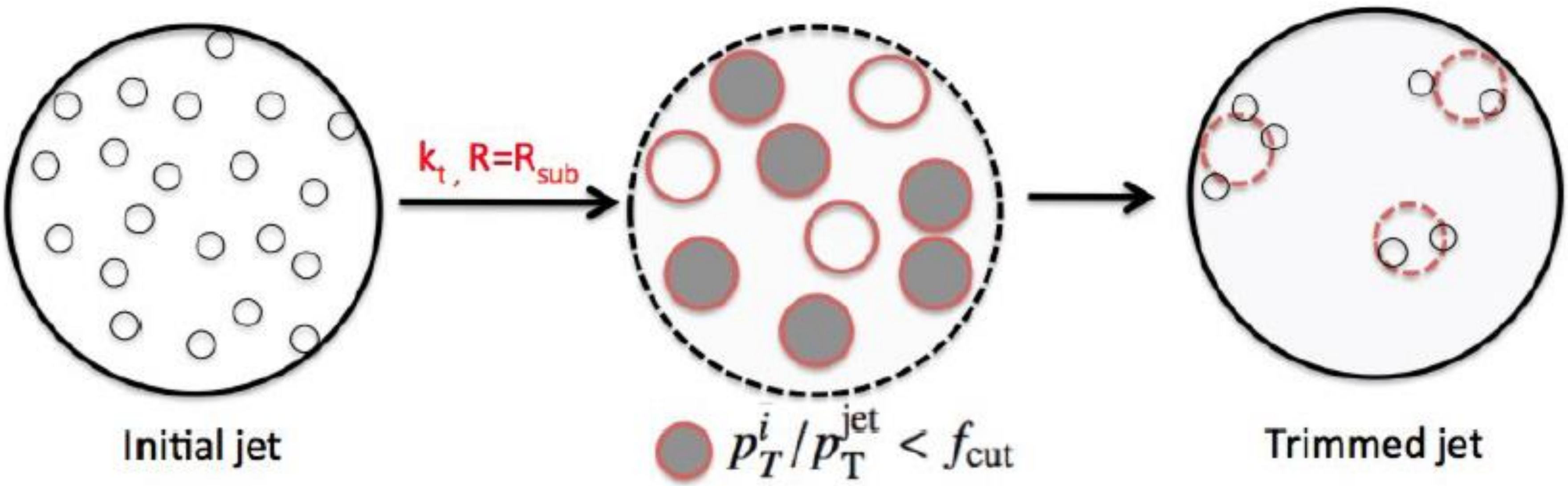
expected background of 5.6±1.7

Jet Grooming

- "Pruning":
- Start with a fat jet (R ~ 1 or more)
- Run k_t or C/A algorithm on clusters within the fat jet
- At each step, if merging of two clusters fails, remove cluster with smallest pT

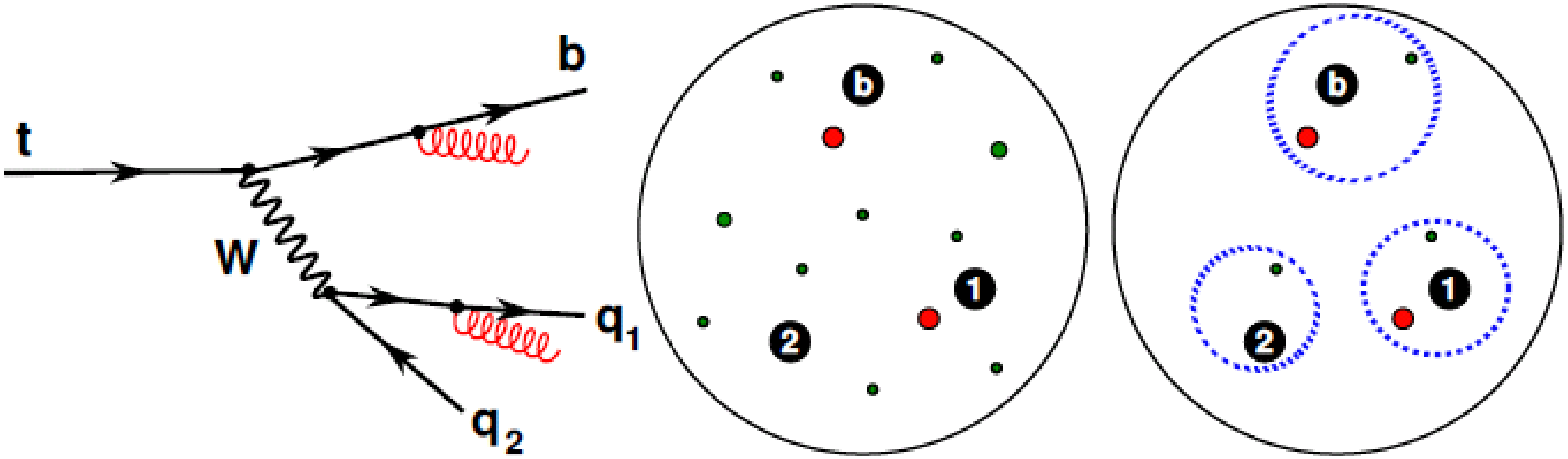


- "Trimming":
- Start with a fat jet (R ~ 1 or more)
- Run k_t algorithm on clusters within the fat jet
- Keep only jets with pT > pT(fat jet) . f_{cut}



H. Bachacou, IRFU Gif, 20-21/09/2012 30

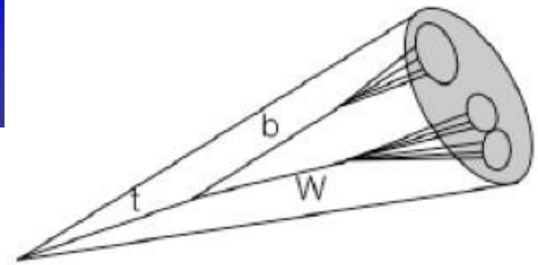
HEPTopTagger (Filtering)



1. Decompose until $m_{j_i} < 30\,\text{GeV}$ with mass drop requirement $m_{j_i} < \mu\, m_{\text{large jet}}$
2. Investigate 3 subjets and their constituents
3. Re-cluster using C/A with parameter $R = \min(0.3, \min_{ij} \Delta R(j_i, j_j)/2)$
4. Use only 5 hardest subjets of last step
5. Built exactly 3 subjets from the selected constituents

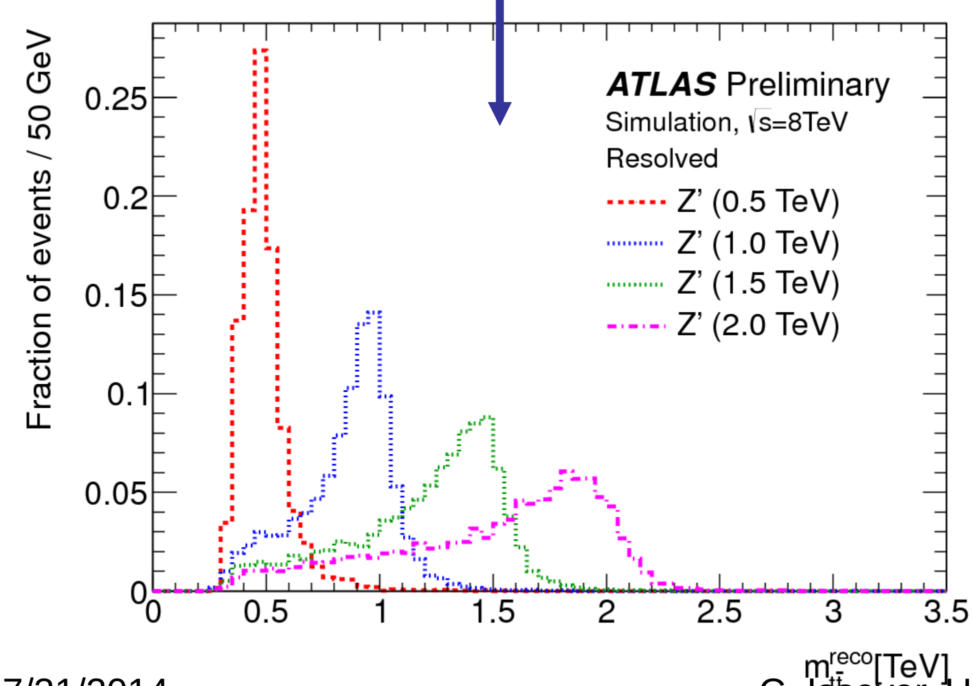
S. Fleischmann

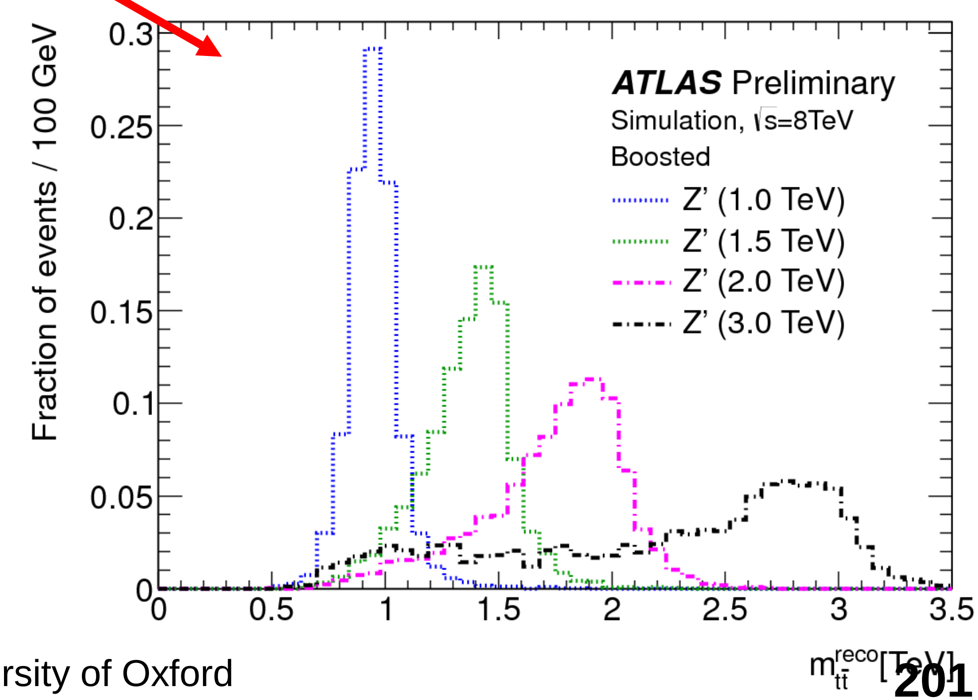
Heavy Resonances Search: Ttbar



ATLAS-CONF-2013-052

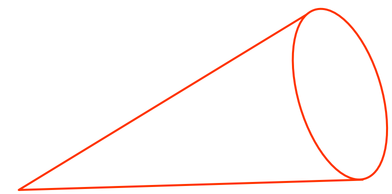
- Lepton+jets channel
- Models: e.g. bulk-RS (esp. KK gluons) and Leptophobic Z’
  - Large Branching Ratio to top-antitop
- Taking full advantage of boosted techniques
- Combining **resolved** and **boosted** reconstructions



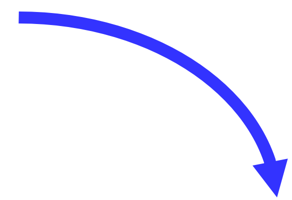


Heavy Resonances Search: Object Selection

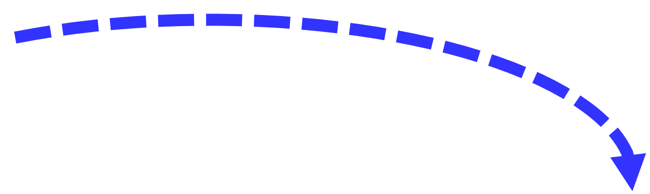
- Jets
  - Small jets: pT > 25 GeV && |η|<2.5
  - Large jets: pT > 300 GeV && |η| < 2.0
  - Require that at least one of the small jets is b-tagged



- Electrons
  - pT > 25 GeV && |η|<1.37, 1.52<|η|<2.47
  - Mini Isolation: $I_{mini} < 0.05\ E_T$
  - z-impact parameter within 2mm of PV

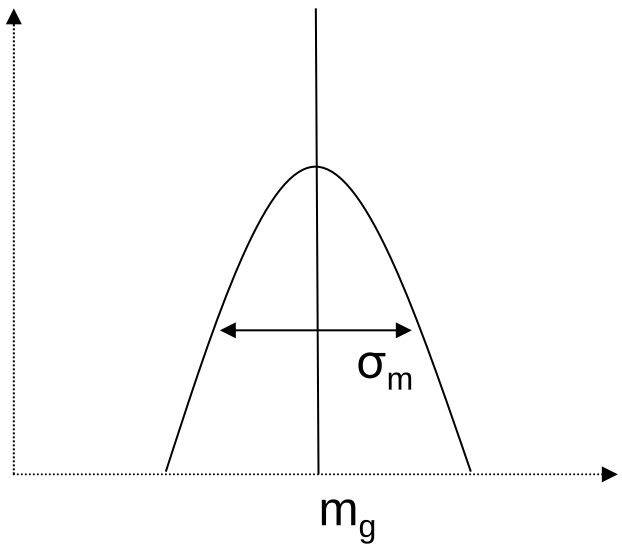


- Muons
  - pT > 25 GeV && |η|<2.5
  - $I_{mini} < 0.05$ pT
  - z-impact parameter within 2mm of PV



Selections Continued

- Optimized for high-pt tops && reduce ttbar bkg
- High-pt single electron or muon trigger
- >1 primary vertex with ≥ 5 tracks of p_T > 0.4 GeV
- Electron channel
  - ME_T > 30 GeV && $m_T = \sqrt{2p_T ME_T(1 - cos\Delta\varphi)}$>30 GeV
- Muon channel
  - ME_T > 20 GeV && $ME_T + m_T$ > 60 GeV



σ_m
m_g

Strong CP Problem of QCD

- QCD allows for CP violation
  - Has an effective strong CP violating term, Θ
  - $0 < \Theta < 2\pi$ possible ranges of values
  - CP violating interactions originating from QCD → neutron electric dipole moment non zero
  - But neutron dipole moment measurements → $\Theta \sim 0$
  - Not natural. Why?
- One solution: Peccei–Quinn mechanism
  - Introduce new symmetry
  - Θ becomes particle → Axion
- Axions are predicted to change to and from photons in the presence of strong magnetic

Particle Accelerators

hep-ph/0201029, hep-ex/0605101, hep-ph/9909294, hep-ex/0710.3338,
hep-ex/0707.2524, Phys. Lett. B568 (2003) 35-47, ZEUS-prel-07-028

- **DESY:**
  - **H1: $M_s^- > 0.78$ TeV and $M_S^+ > 0.82$ TeV**
  - **ZEUS: $M_s^- > 0.9$ TeV and $M_s^+ > 0.88$ TeV**
- **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

- **Places the most stringent lower limits on M_D in ADD**
- **Supernova cooling due to KK Graviton 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 > 27 (2.4) 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**