Dark Matter Collider Searches

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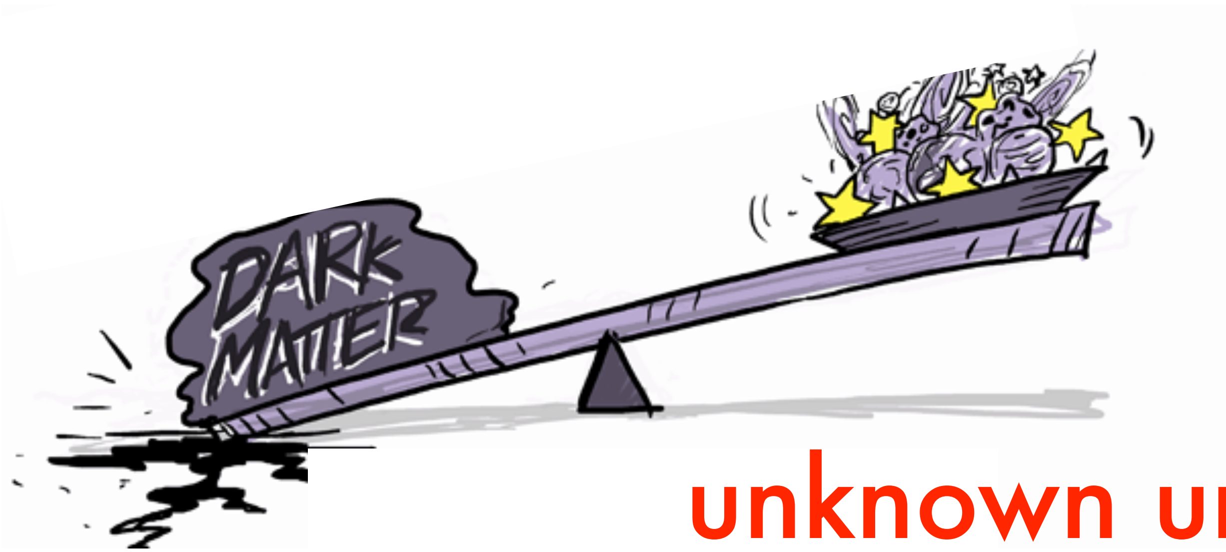
SLAC Summer Institute 2014

What do we know?

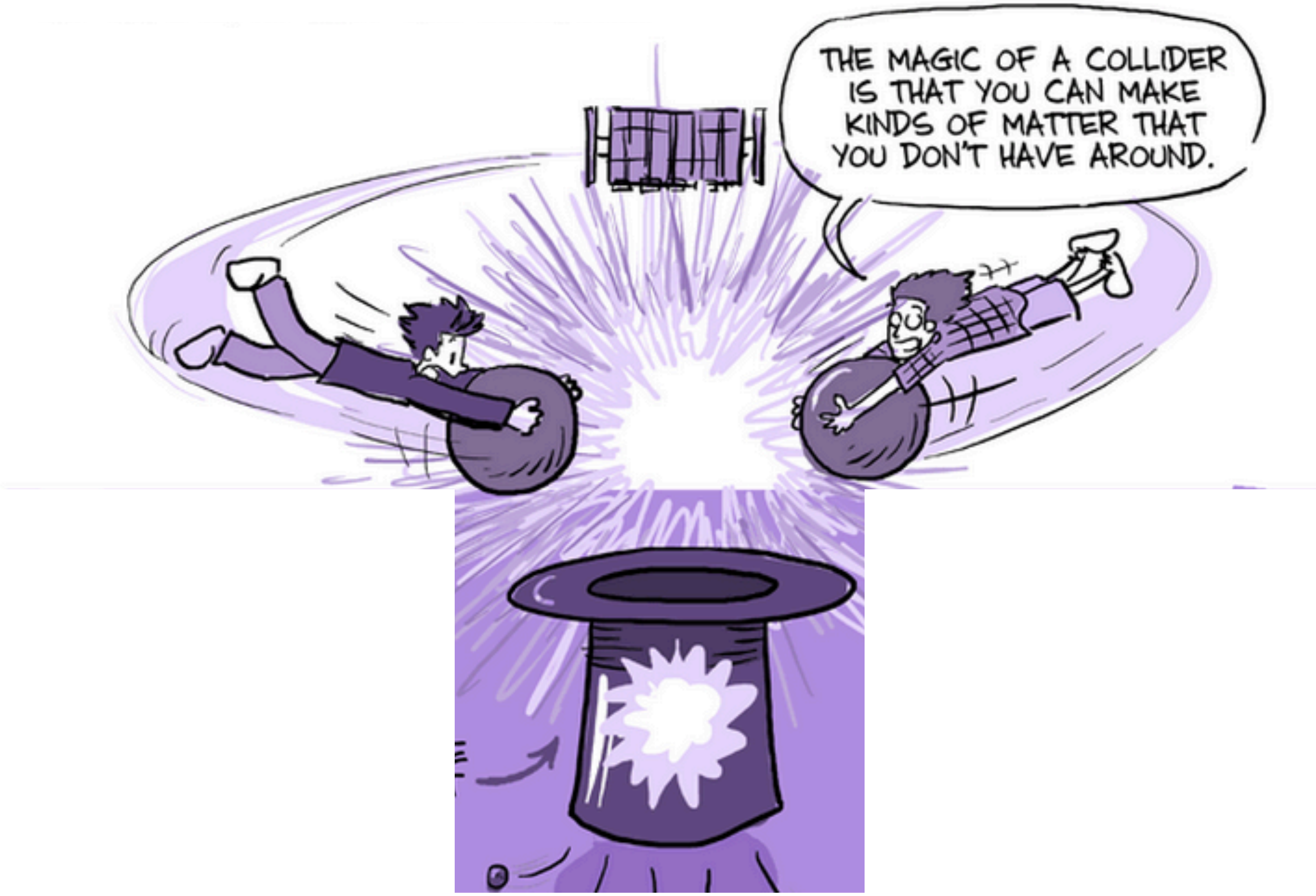


unknown unknown

known unknown

known known

What are colliders good for?



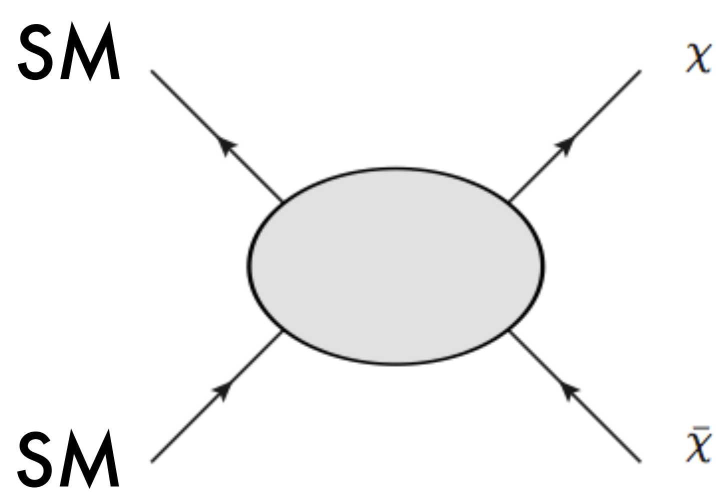
Exploration machine

We can create new forms of matter, *even if we have little or no idea of what we are looking for!*

Interactions

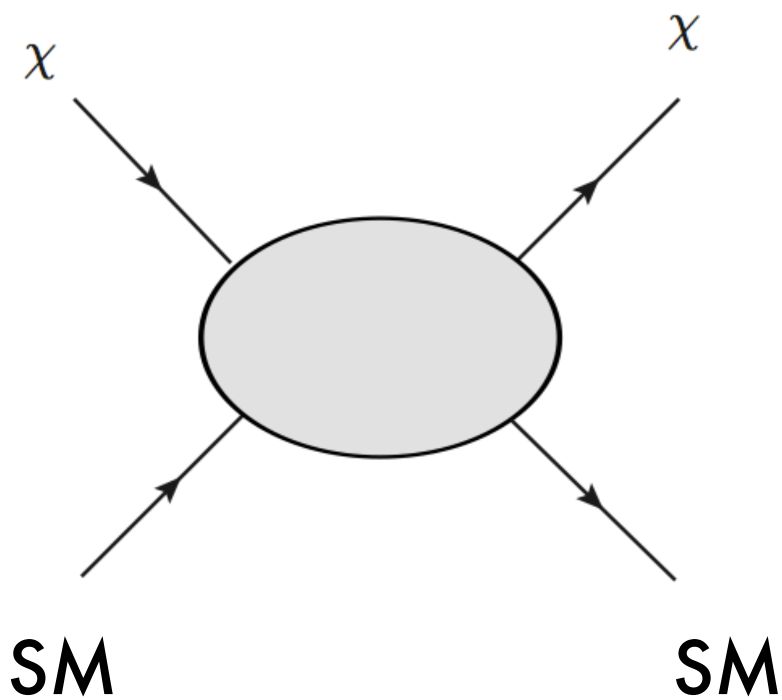
Important caveat:

Requires **some** interaction with SM

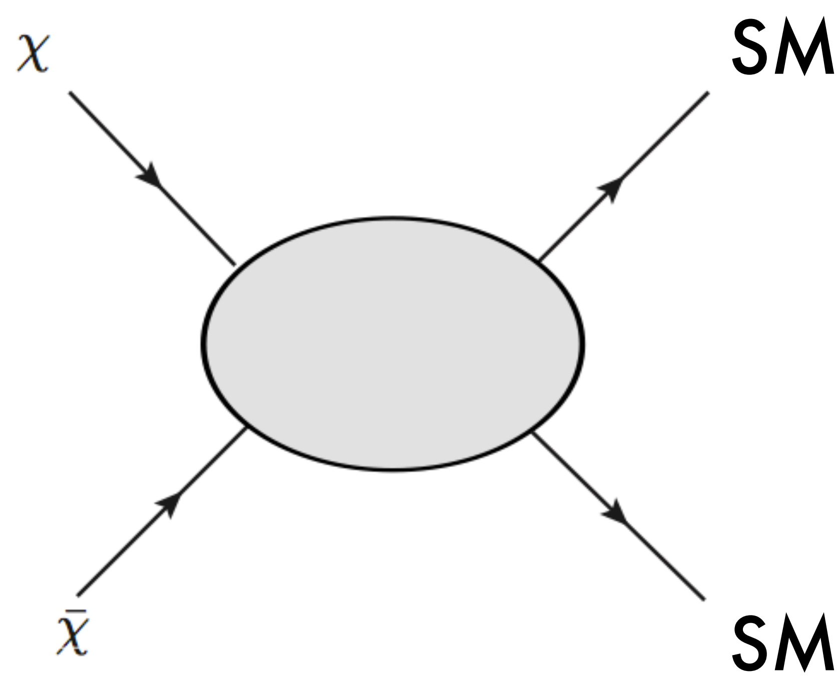


Other experiments

Direct
(Xenon etc)

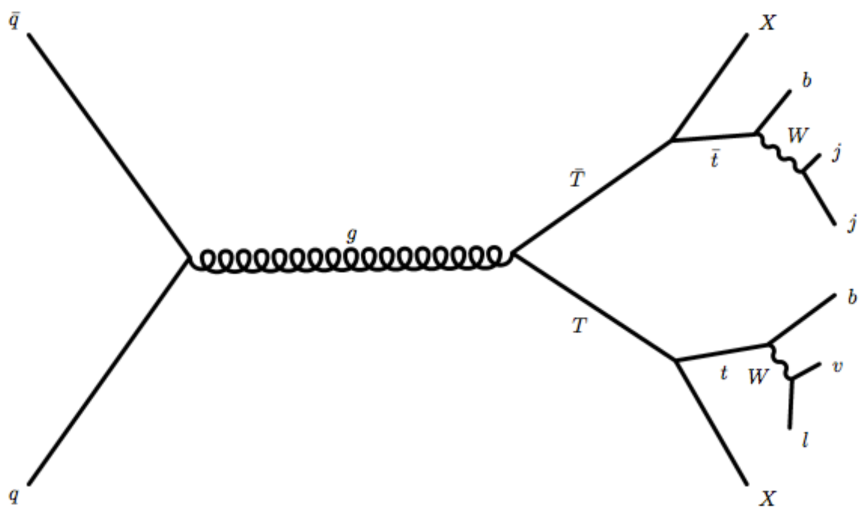


Indirect
(FermiLAT)



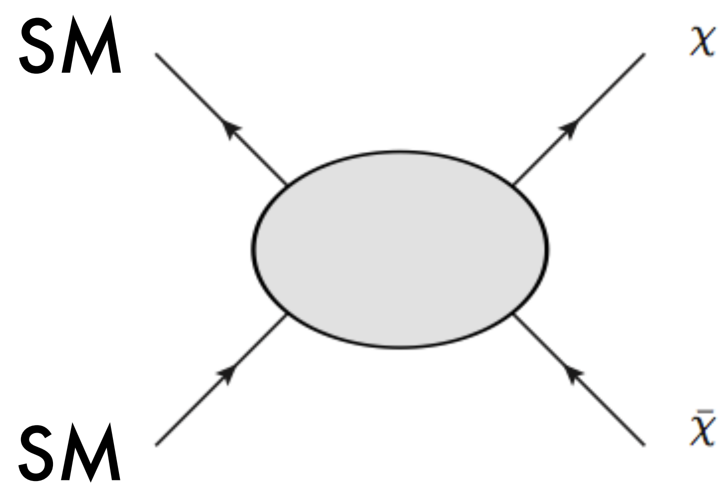
Production

Heavier colored production...



...followed by cascade to WIMPs

Direct weak production...

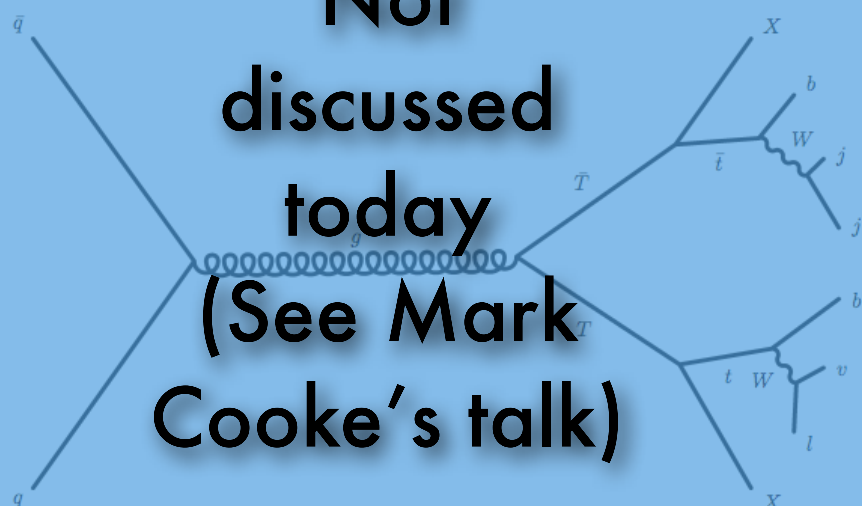


..via intermediate heavy particle

Production

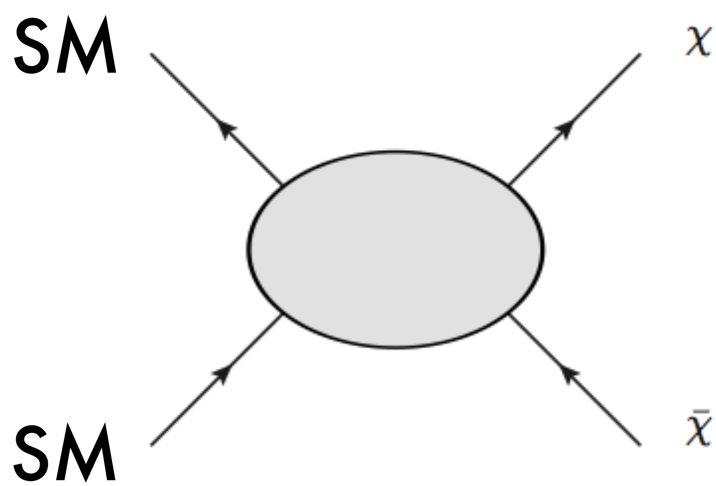
Heavier colored production...

Not discussed today (See Mark Cooke's talk)



...followed by cascade to WIMPs

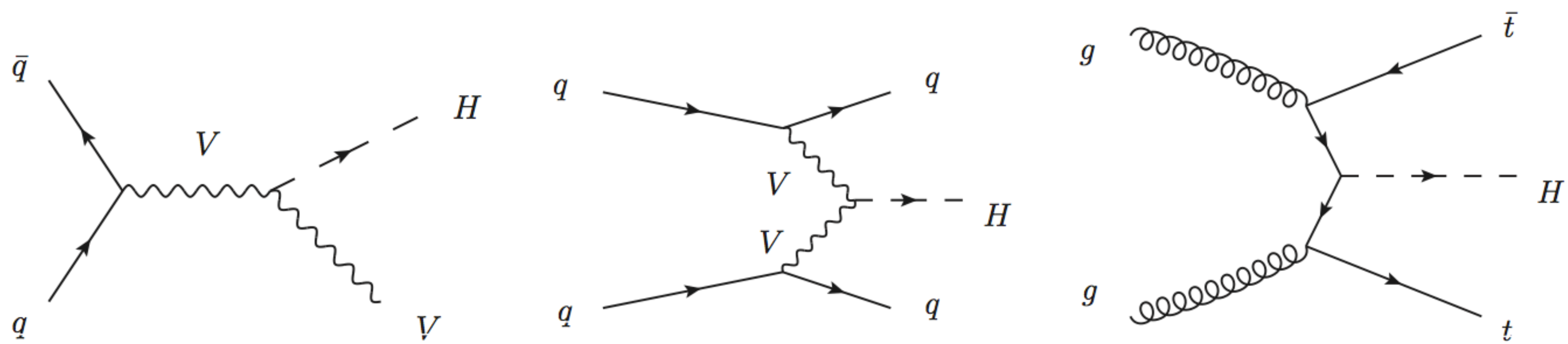
Direct weak production...



..via intermediate heavy particle

Invisible Higgs

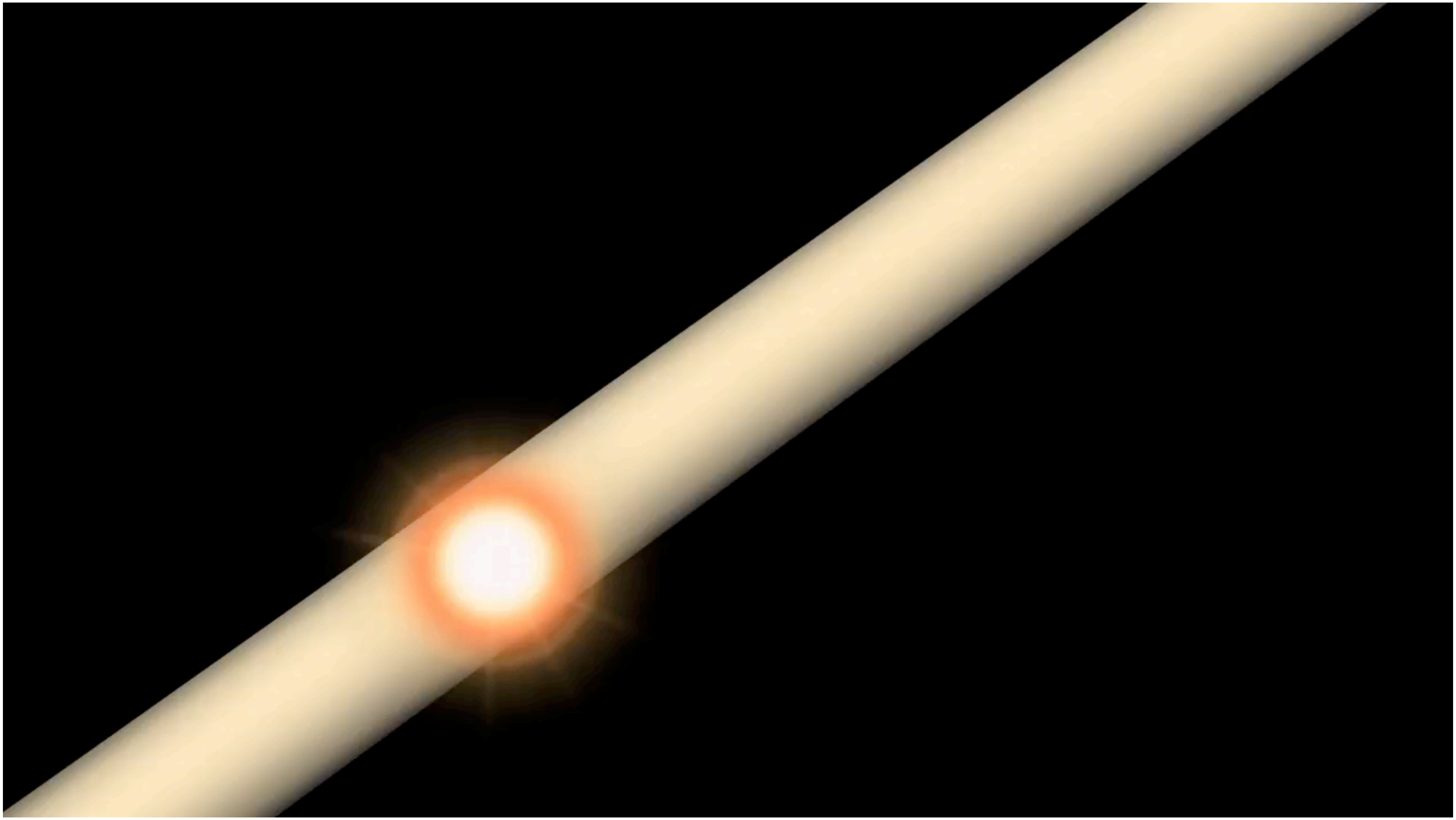
If the Higgs boson decays to DM



Then these signatures can also probe DM at colliders

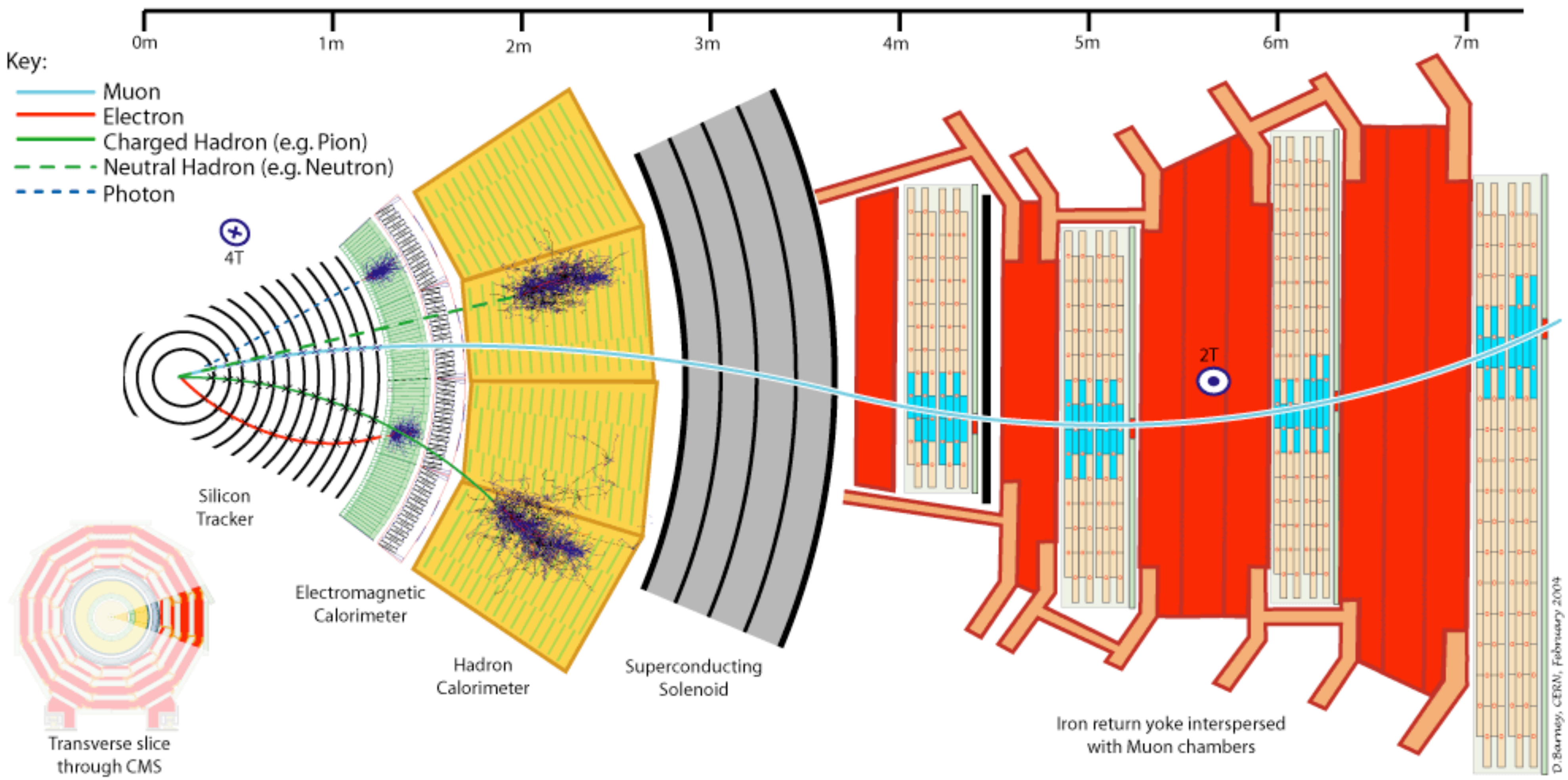
Outline

I. Detector basics
II. Mono-X
III. Invisible Higgs decays
IV. Prospects at future colliders

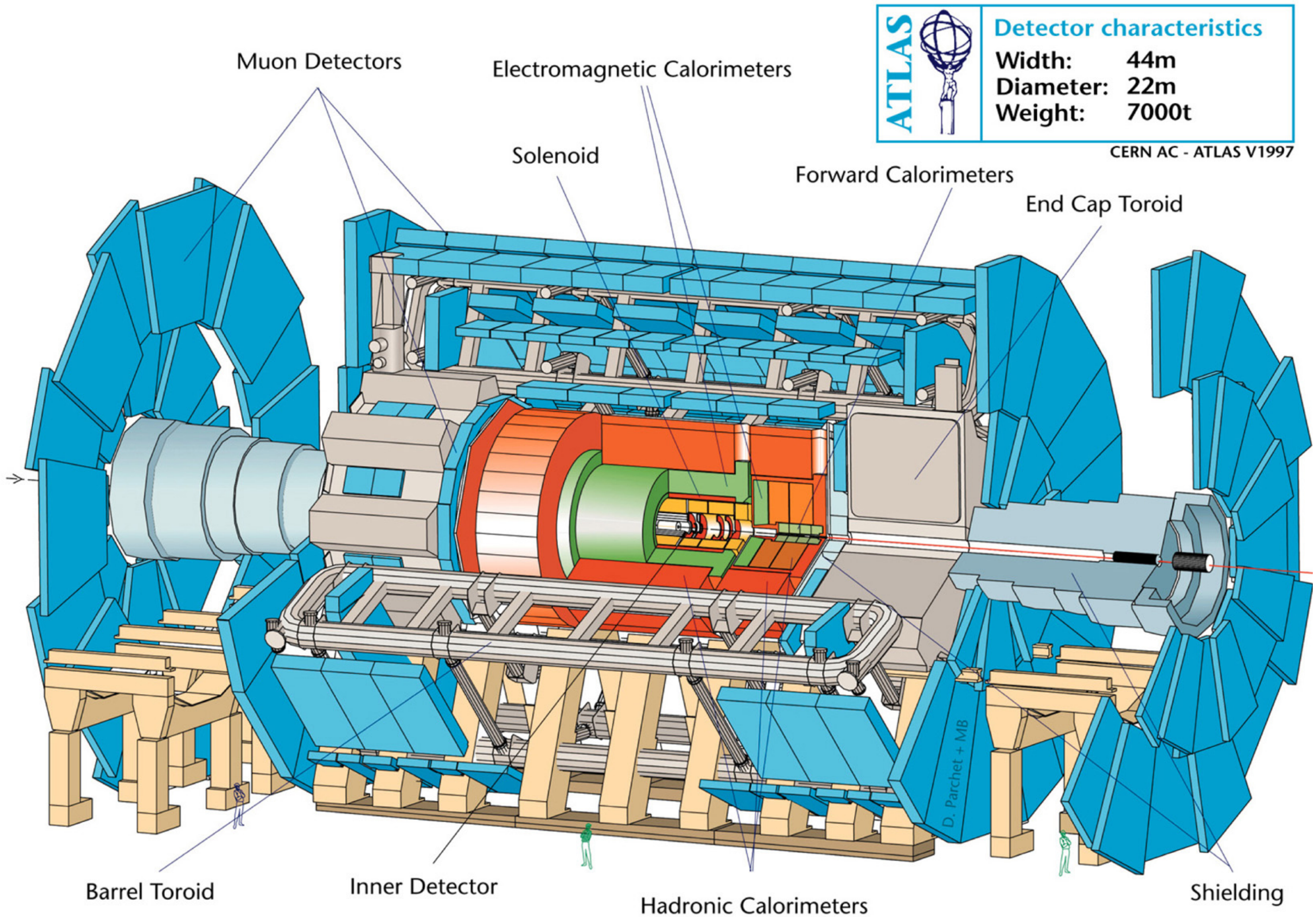


Data

Each event has data from >100M sensors

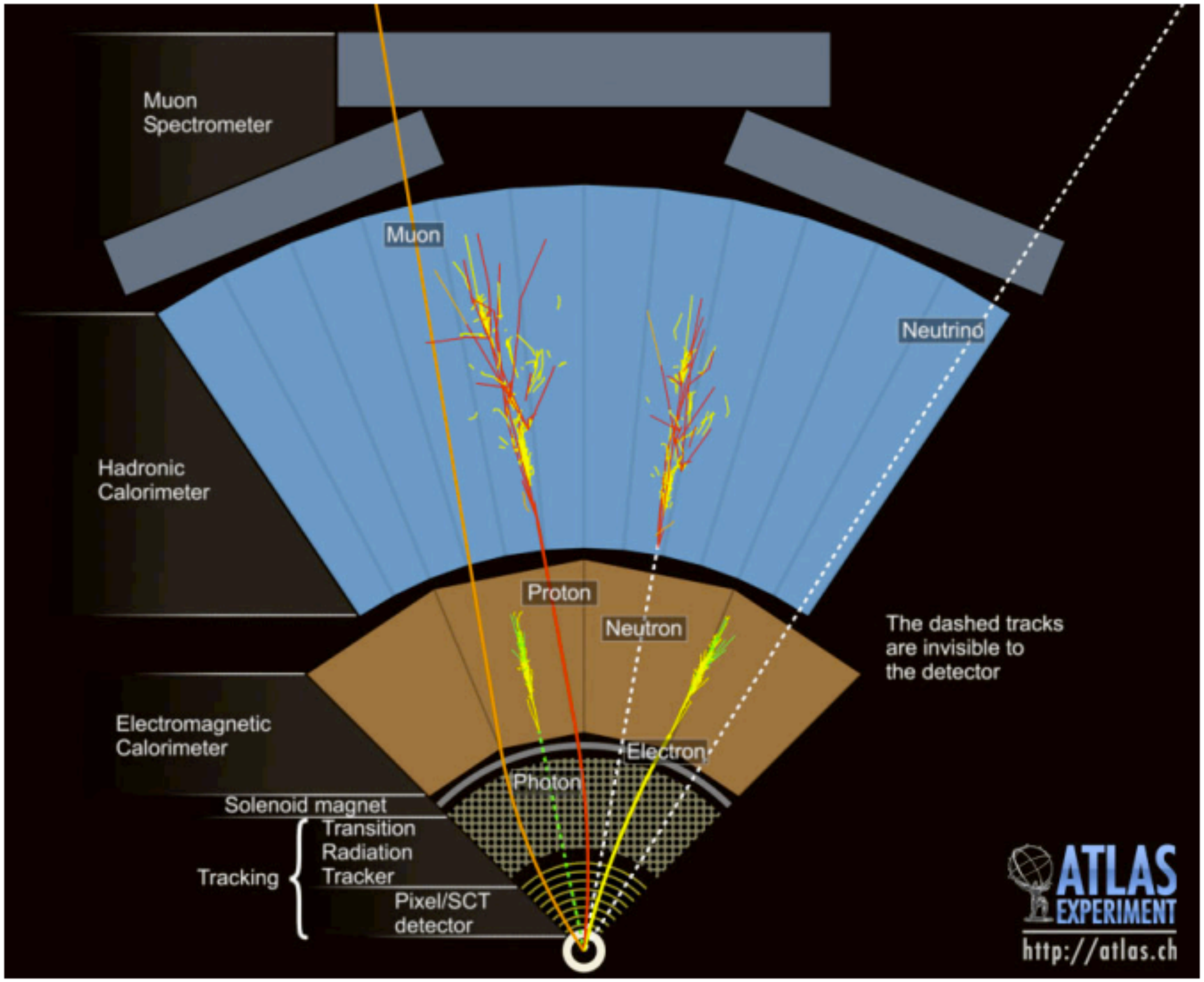


ATLAS



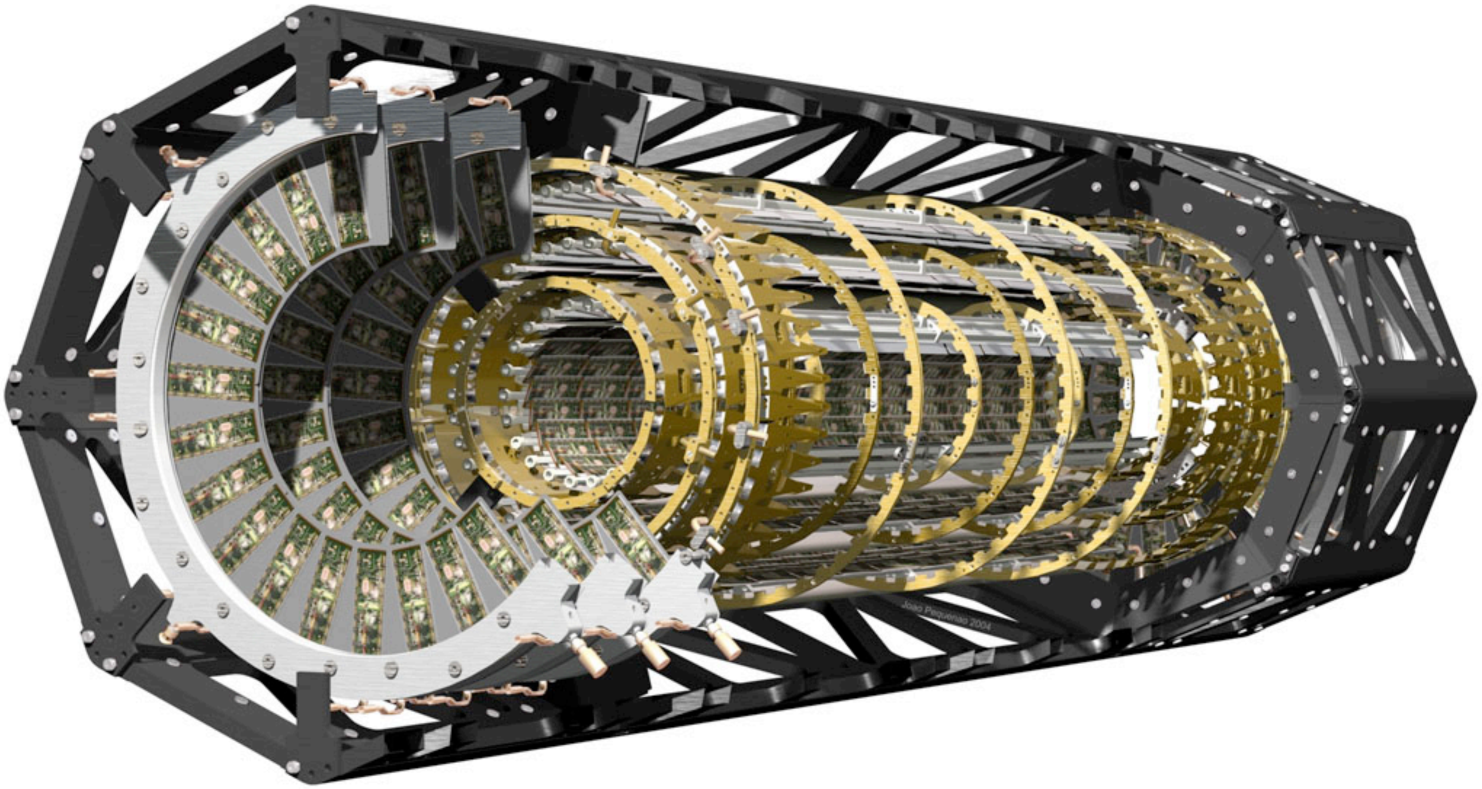
ATLAS
Detector characteristics
Width: 44m
Diameter: 22m
Weight: 7000t
CERN AC - ATLAS V1997
Muon Detectors
Electromagnetic Calorimeters
Solenoid
Forward Calorimeters
End Cap Toroid
Barrel Toroid
Inner Detector
Hadronic Calorimeters
Shielding
D. Parchet + MB

ATLAS



Muon Spectrometer
Muon
Neutrino
Hadronic Calorimeter
Proton
Neutron
The dashed tracks are invisible to the detector
Electromagnetic Calorimeter
Electron
Photon
Solenoid magnet
Tracking
Transition Radiation Tracker
Pixel/SCT detector
ATLAS EXPERIMENT
http://atlas.ch

Pixel tracker



~100 Million Pixels
10 μm precision

ATLAS Collaboration

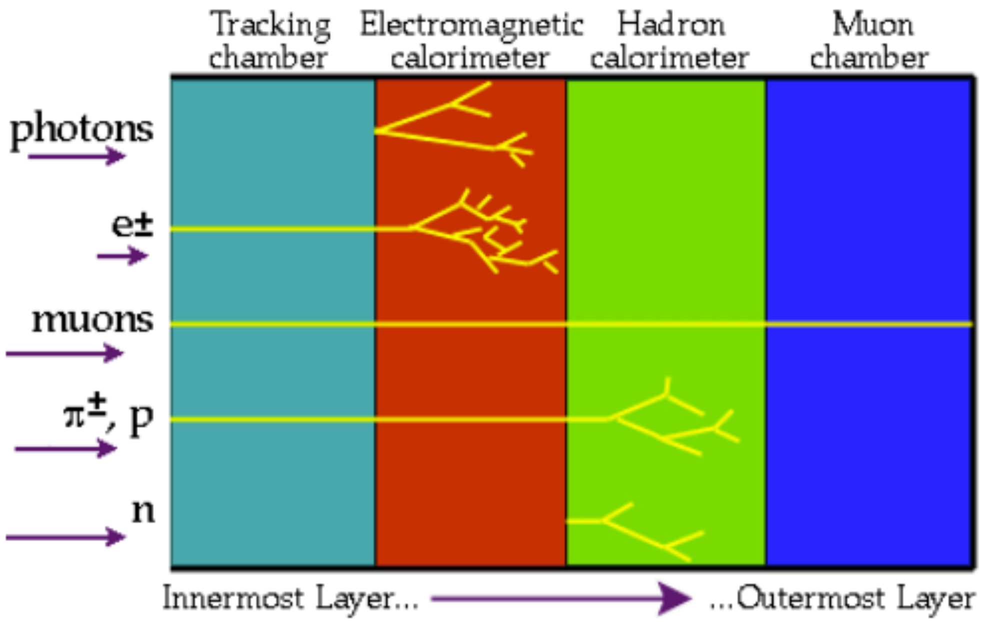
2900 physicists from 37 countries; 172 universities includes 700 students


DRY
24

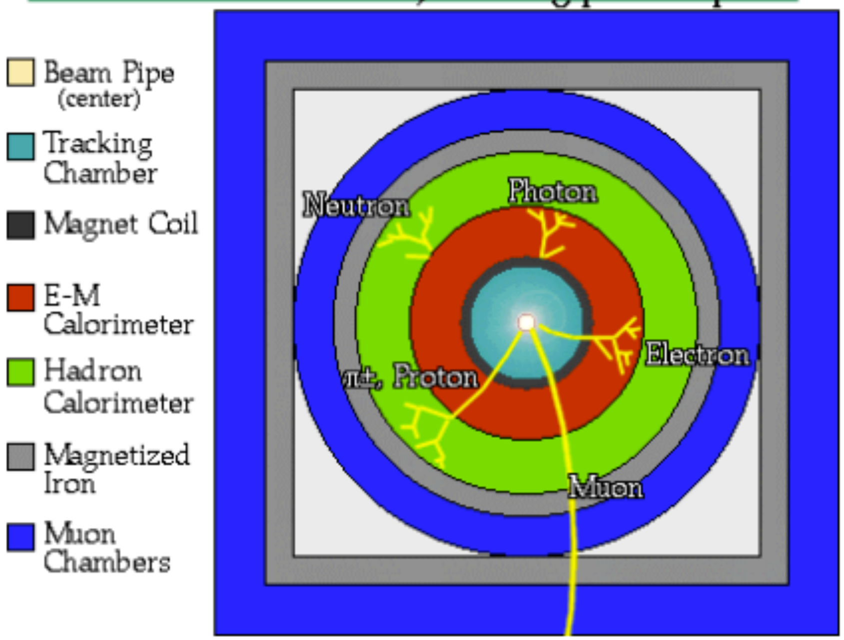
ATLAS author list

The ATLAS Collaboration

Particle ID



A detector cross-section, showing particle paths



Event reconstruction

Tool kit of objects:

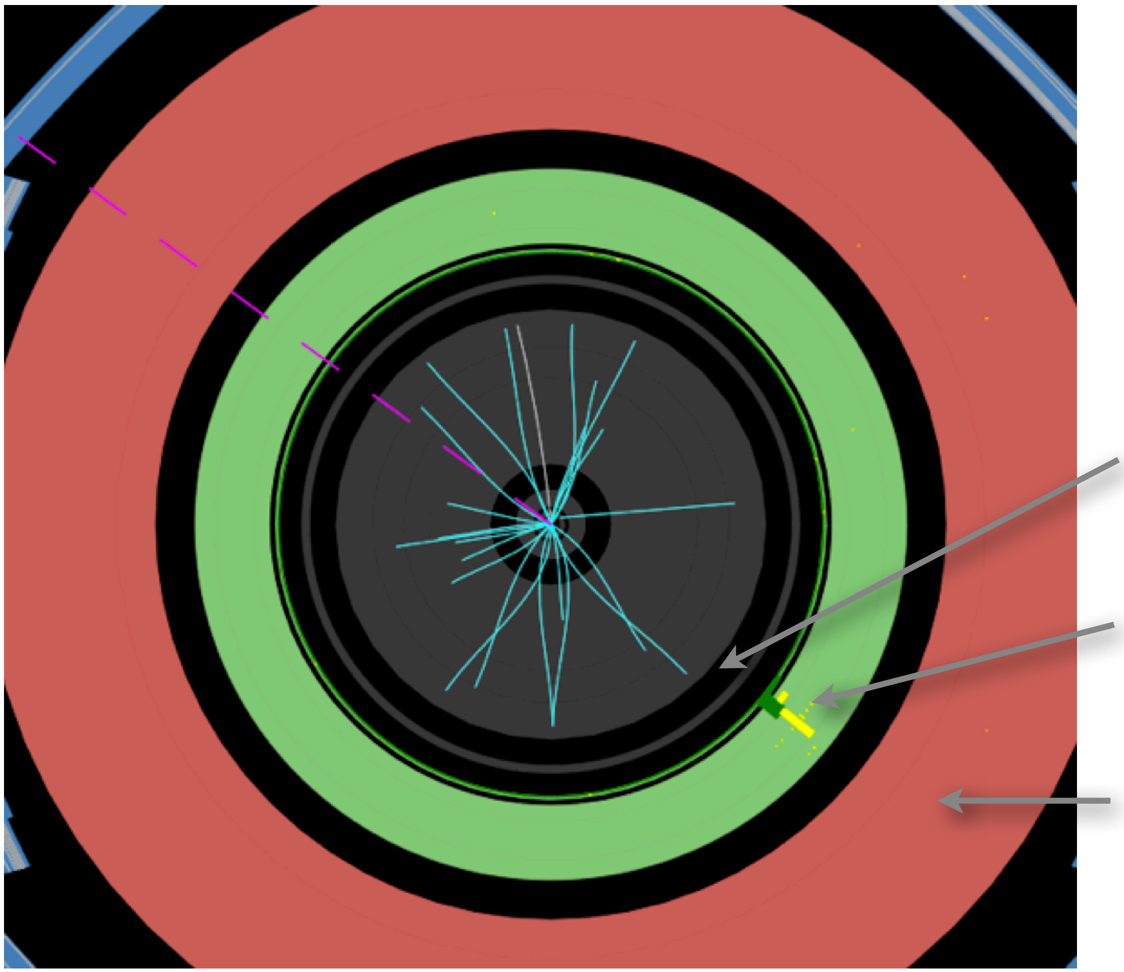
Photons

Charged leptons: e, mu, tau

Jets: with or without b-tag
with or without sub-structure

Invisible: missing transverse energy

Photon

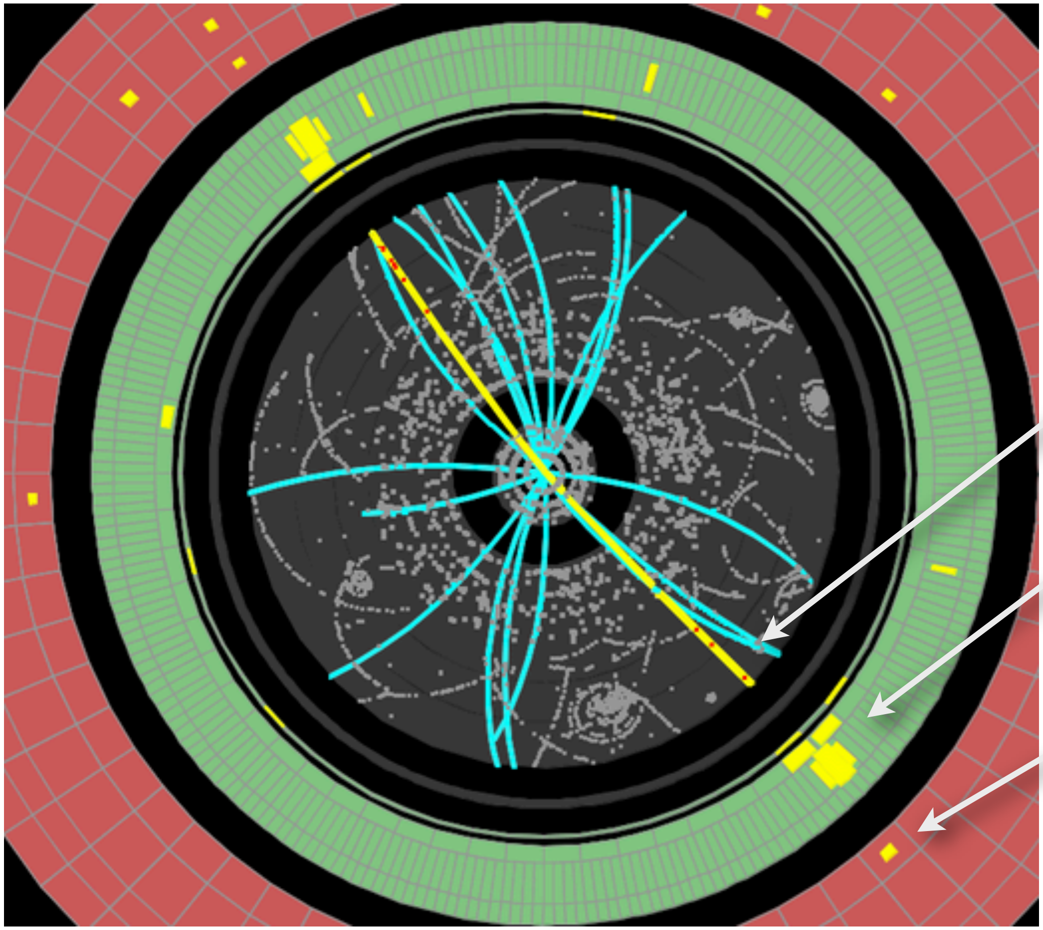


No track

EM splash

No hadronic splash

Electron

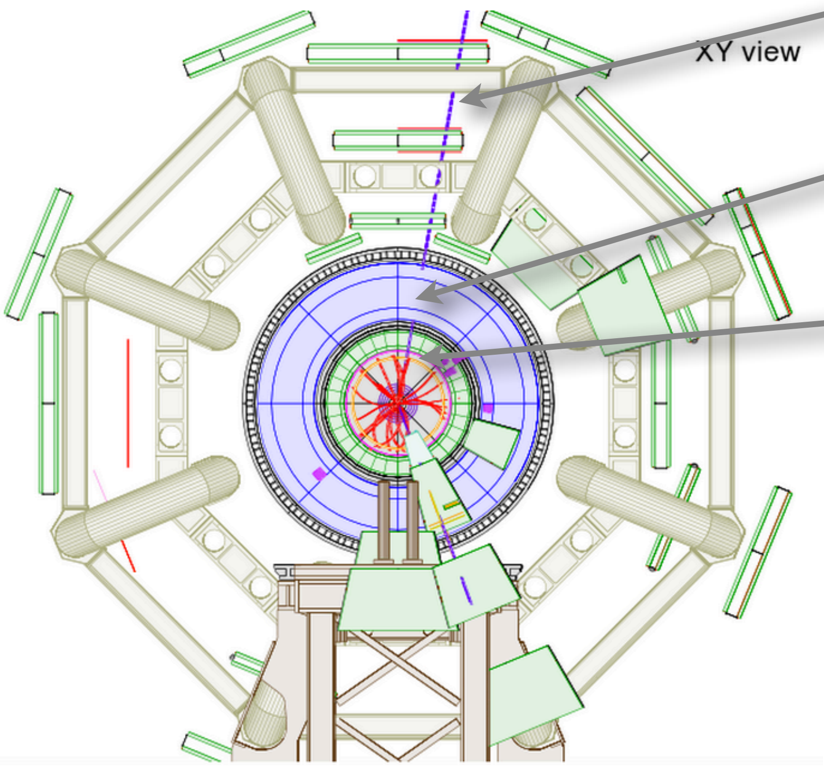


Track

EM splash

No hadronic splash

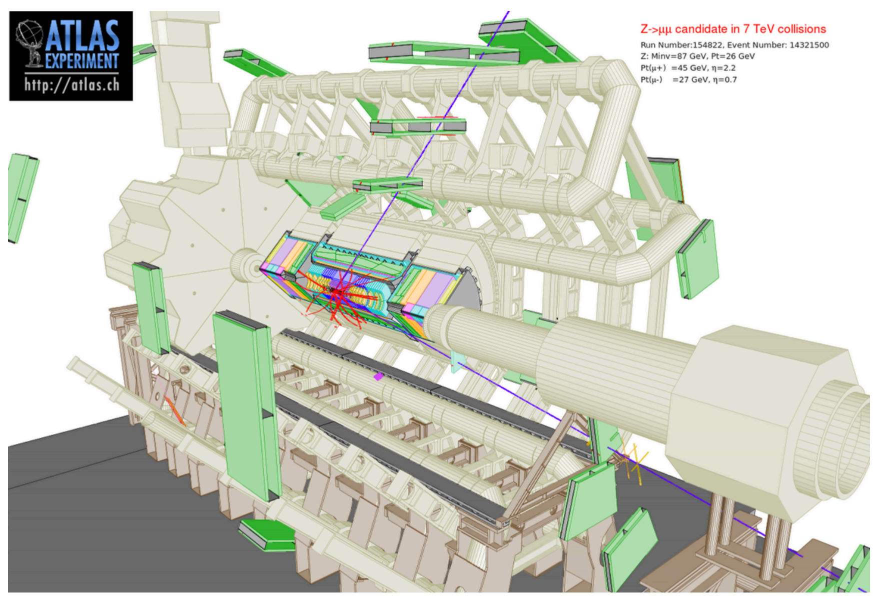
Muon



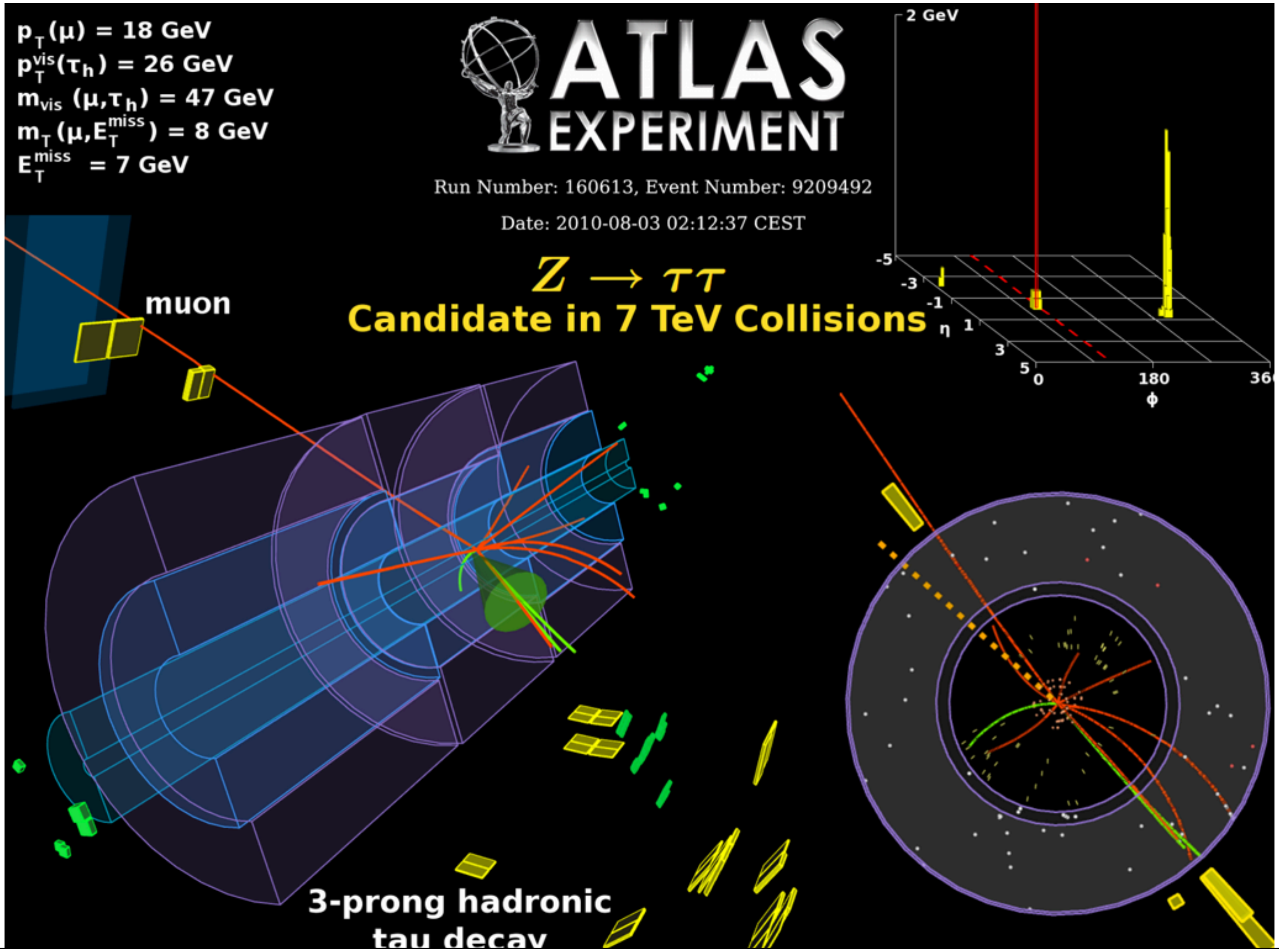
Muon chamber hits

Little calorimeter activity

Track

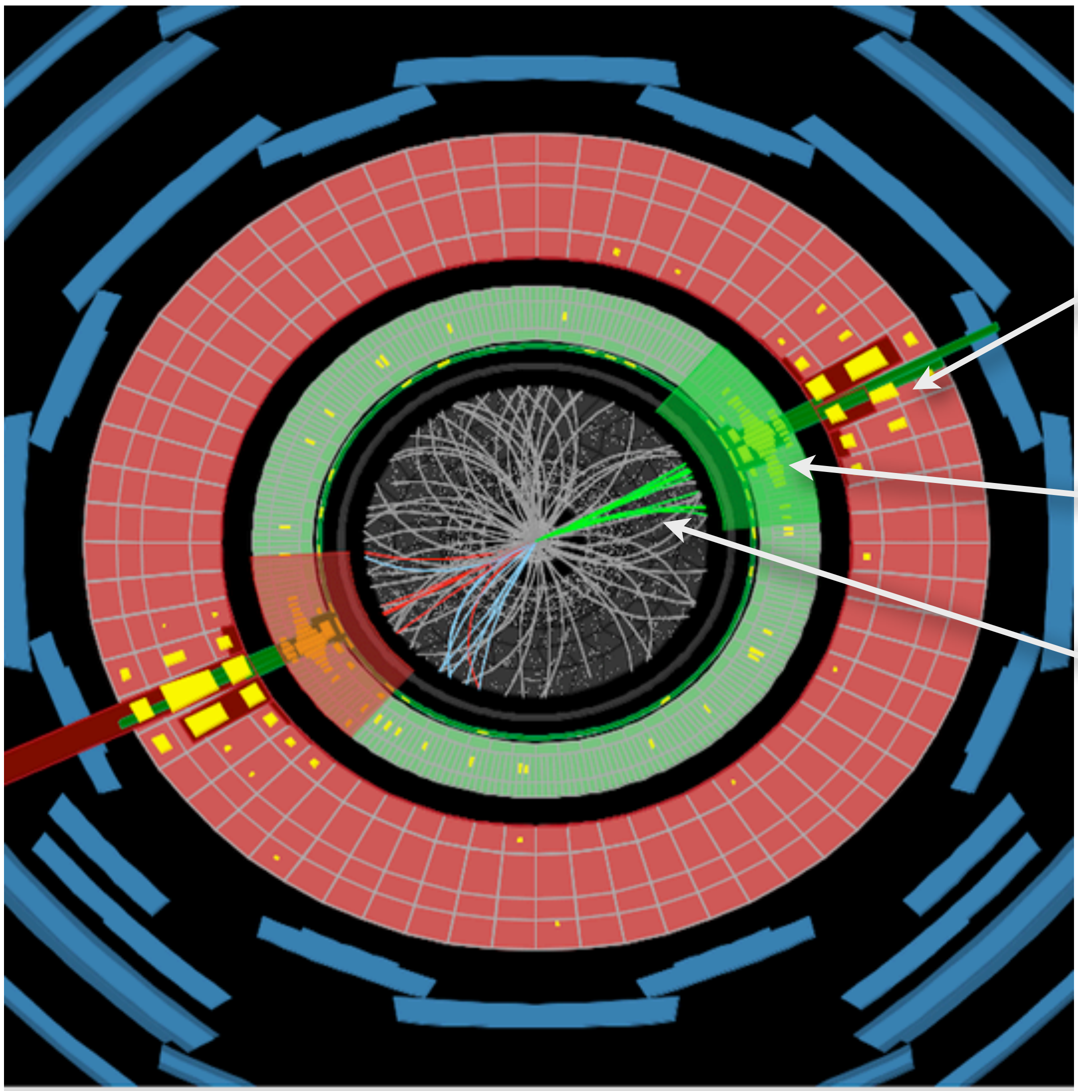


Taus



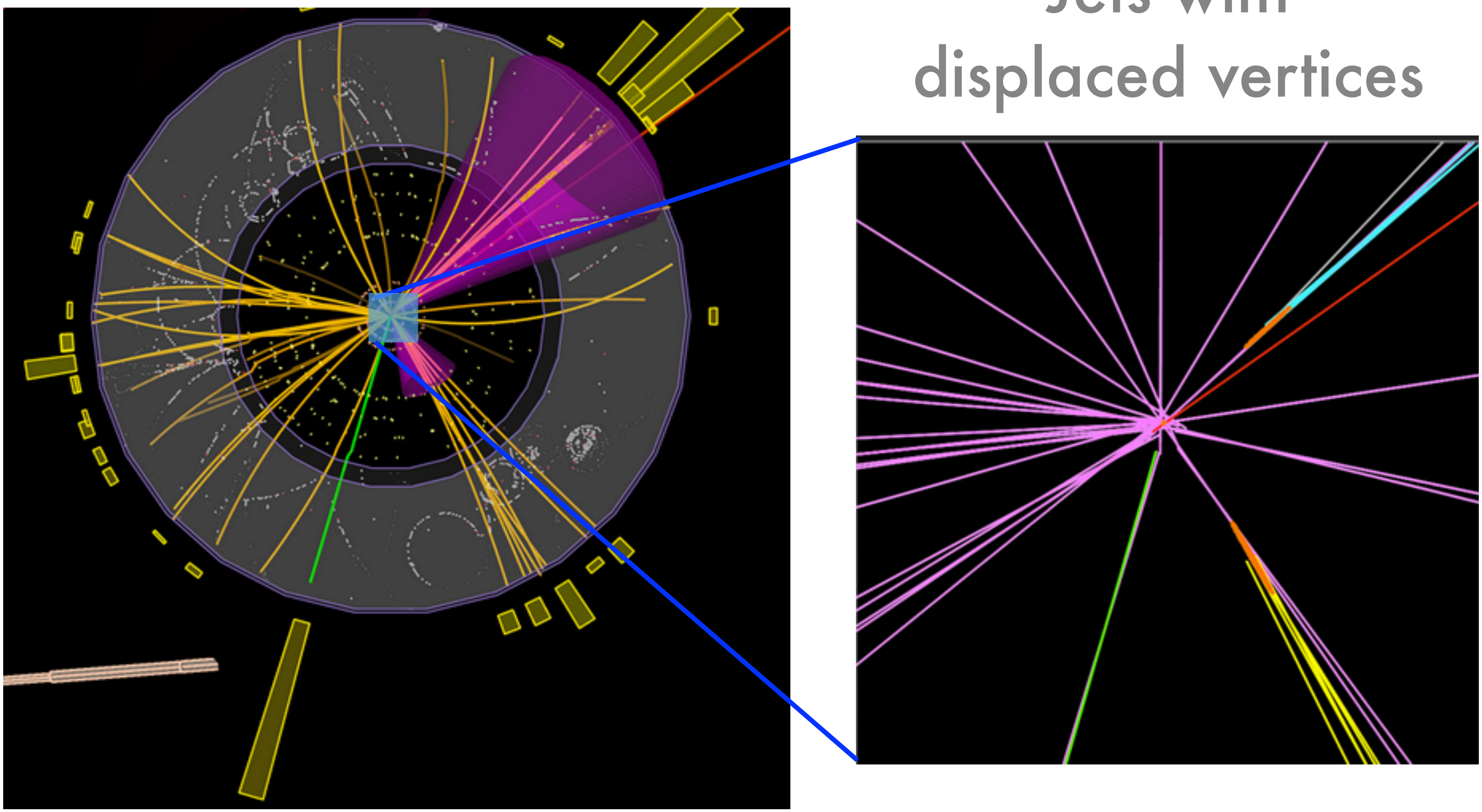
$p_T(\mu)$ = 18 GeV
$p_T^{vis}(\tau_h)$ = 26 GeV
$m_{vis}(\mu,\tau_h)$ = 47 GeV
$m_T(\mu,E_T^{miss})$ = 8 GeV
E_T^{miss} = 7 GeV
ATLAS EXPERIMENT
Run Number: 160613, Event Number: 9209492
Date: 2010-08-03 02:12:37 CEST
$Z \to \tau\tau$
Candidate in 7 TeV Collisions
muon
3-prong hadronic tau decay
2 GeV
η
φ

Jets

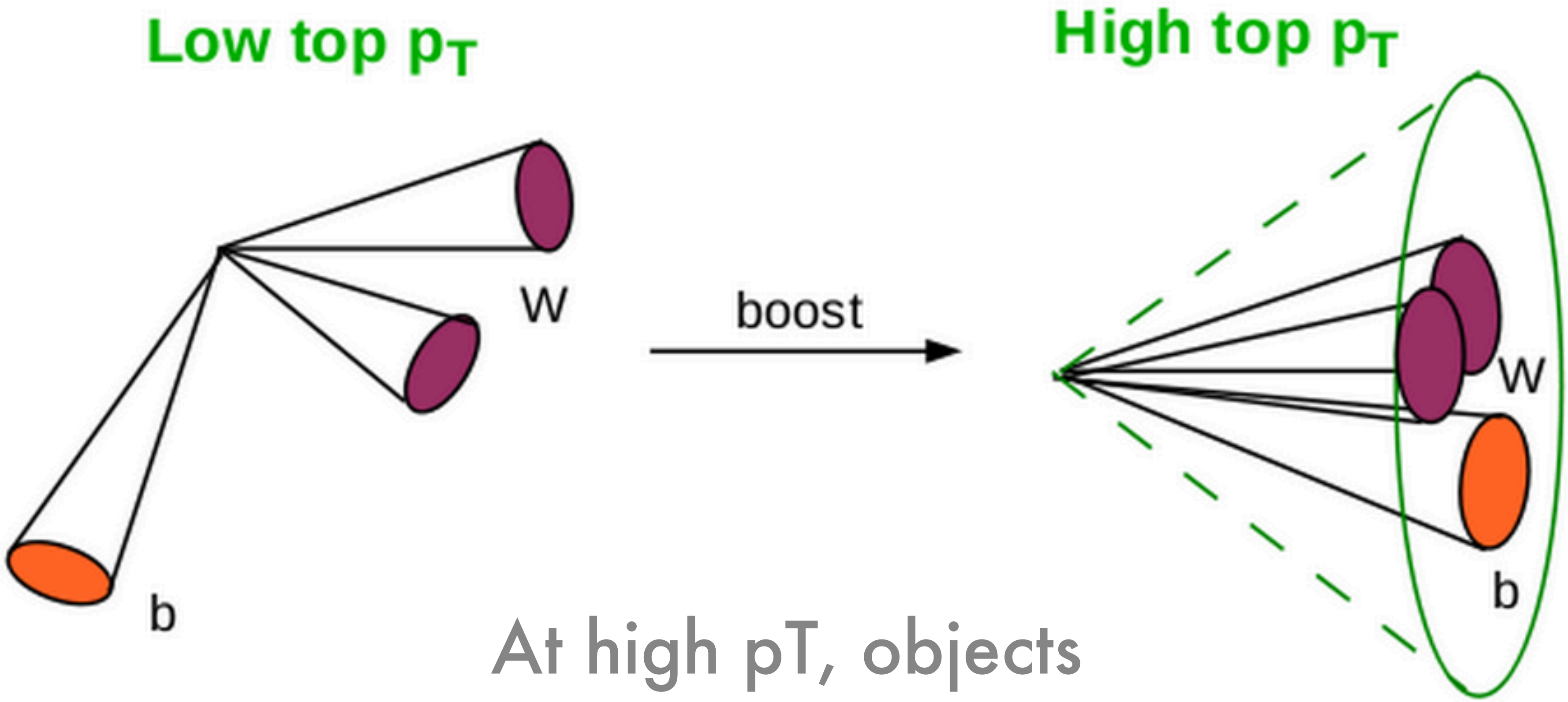


b-jets

Jets with displaced vertices

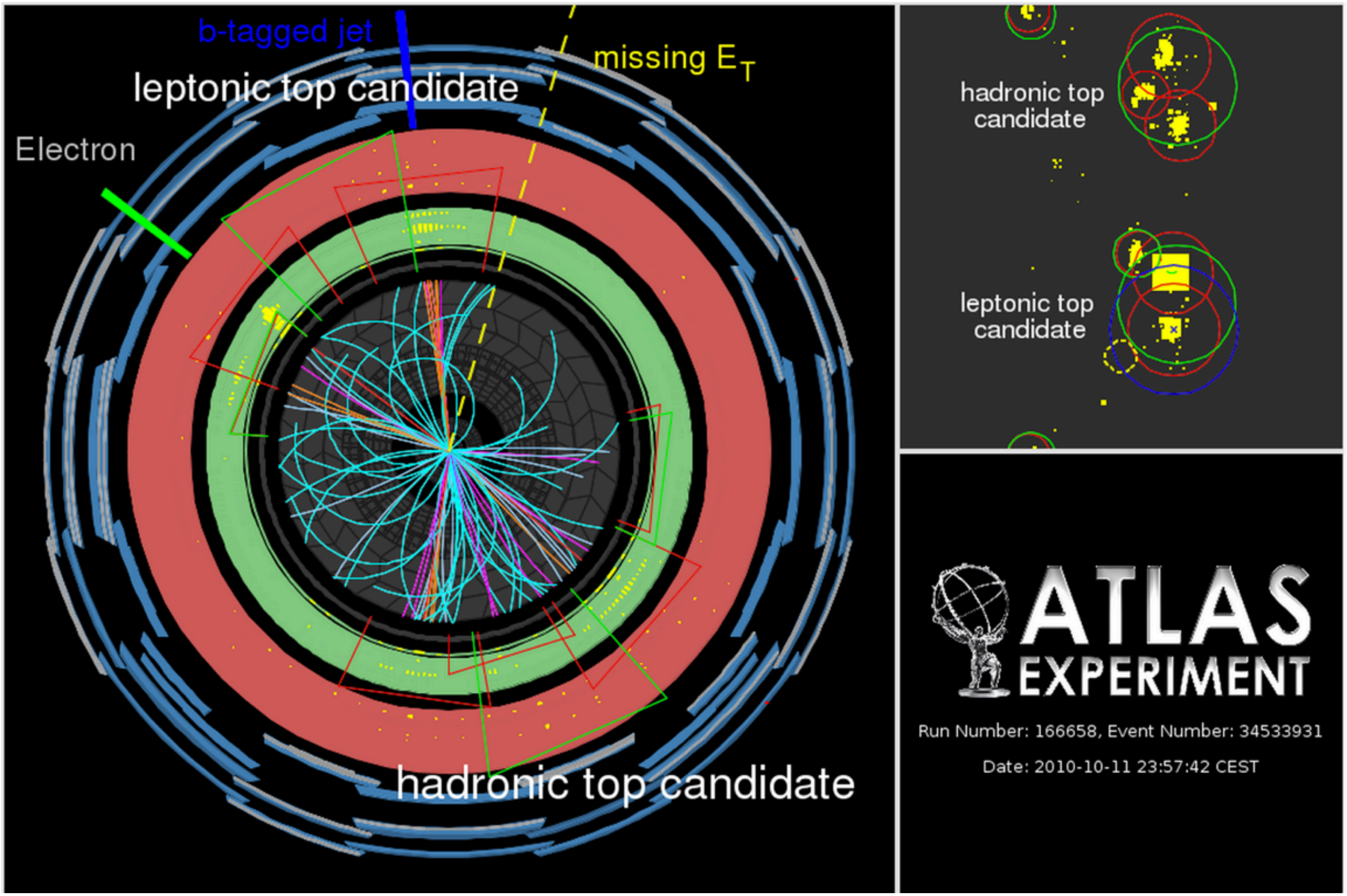


Why jet substructure?

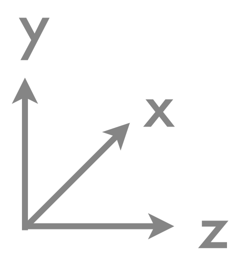


At high pT, objects get boosted and become closer together

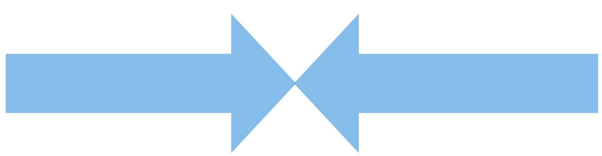
Jet substructure



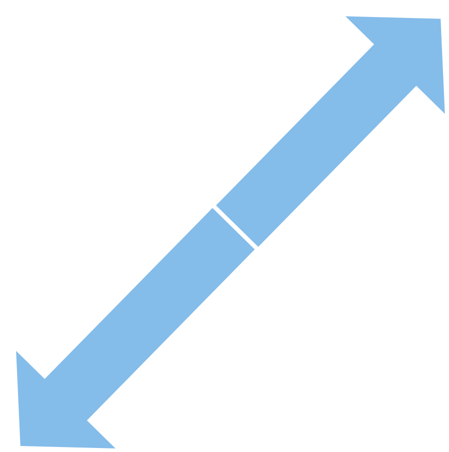
Missing Transverse Mom.



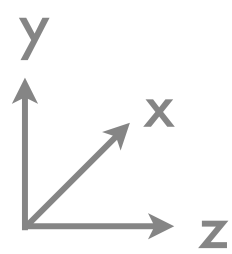
Initial state: pT=0



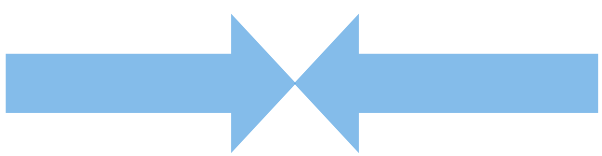
Final state:
visible pT=(0,0)
MET=(0,0)



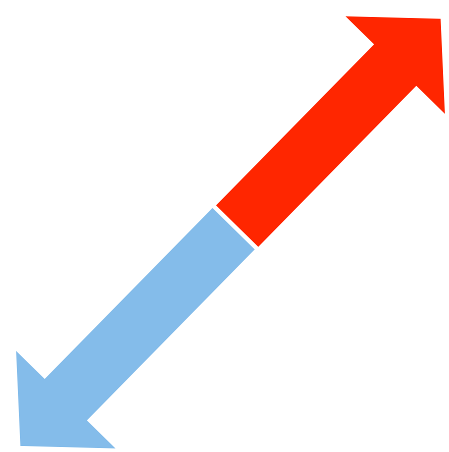
Missing Transverse Mom.



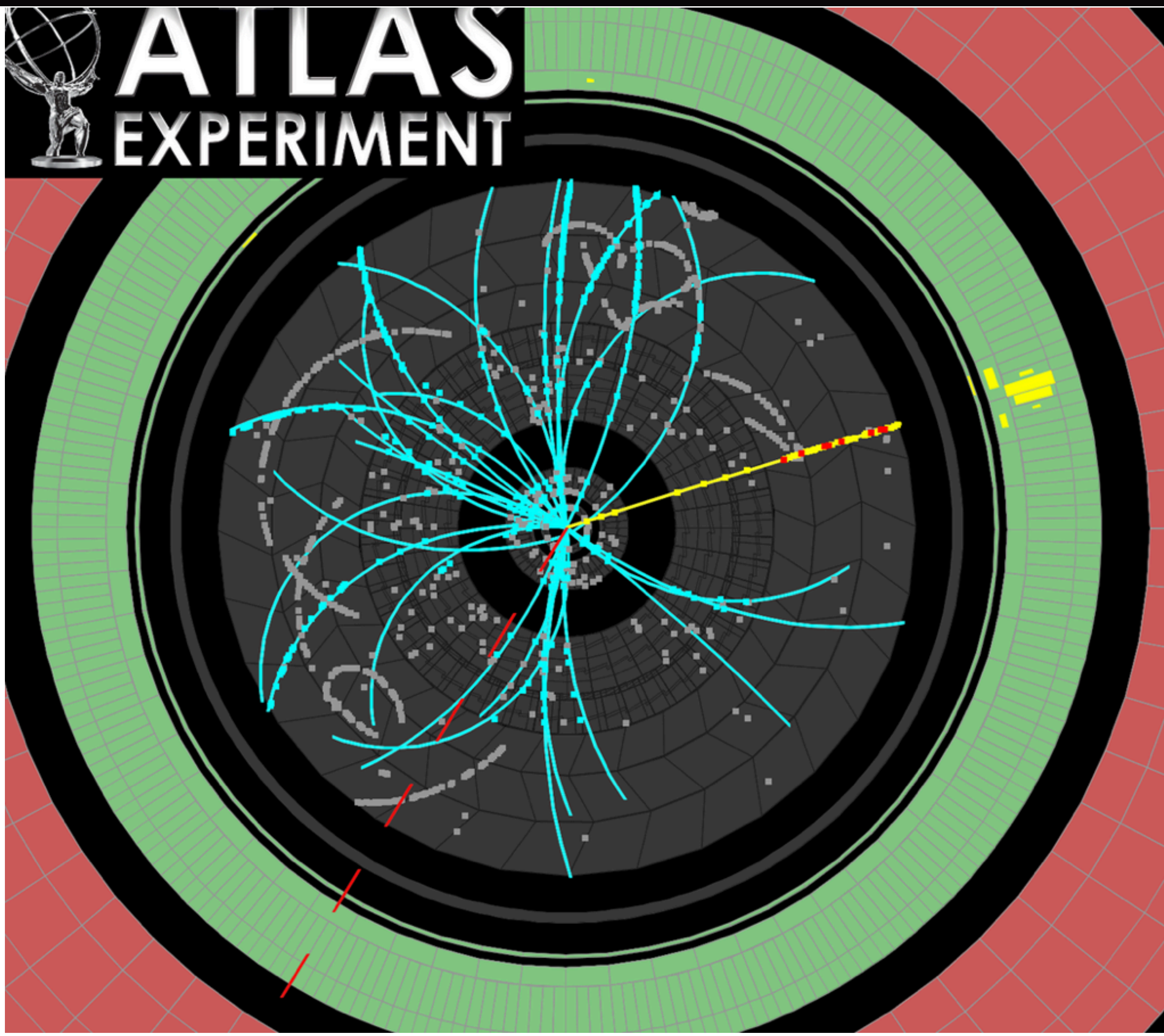
Initial state: pT=0



Final state:
visible pT=(-50,-50)
MET=(50,50)



Missing Transverse Mom.

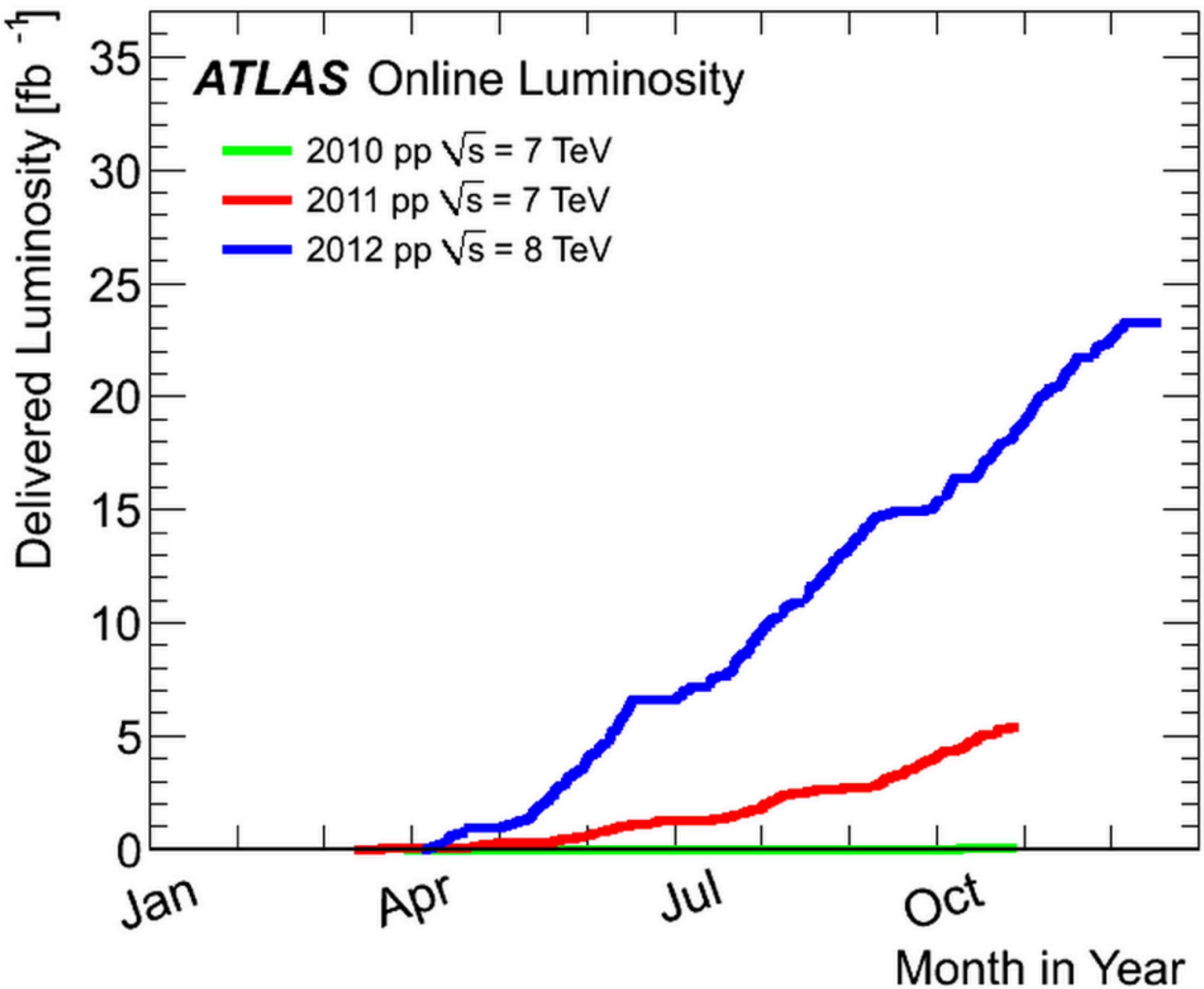


W to e+v

e: visible

v: invisible
 except for MET

LHC dataset



ATLAS Online Luminosity
2010 pp √s = 7 TeV
2011 pp √s = 7 TeV
2012 pp √s = 8 TeV
Delivered Luminosity [fb⁻¹]
Month in Year
Jan
Apr
Jul
Oct
0
5
10
15
20
25
30
35

Outline

I. Detector basics

II. Mono-X

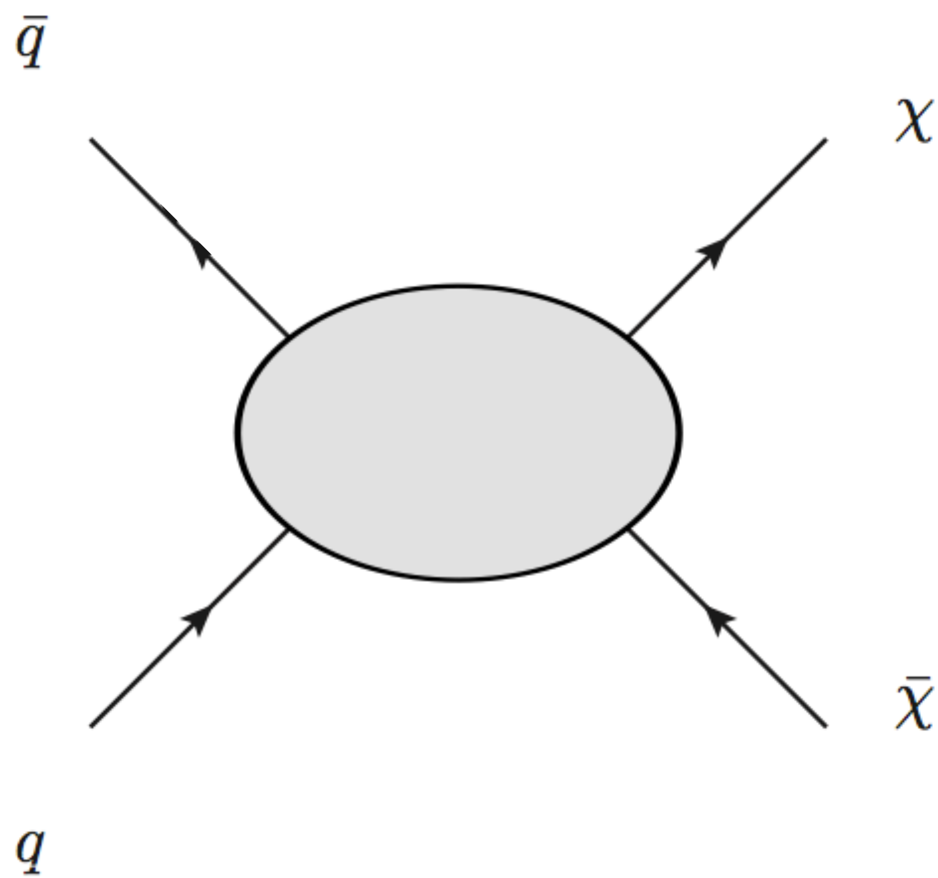
III. Invisible Higgs decays

IV. Prospects at future colliders

mono-X searches

A. Mono-jet
B. Mono-photon
C. Mono-Z
D. Mono-W
E. Mono-H
F. Mono-everything

The basic idea



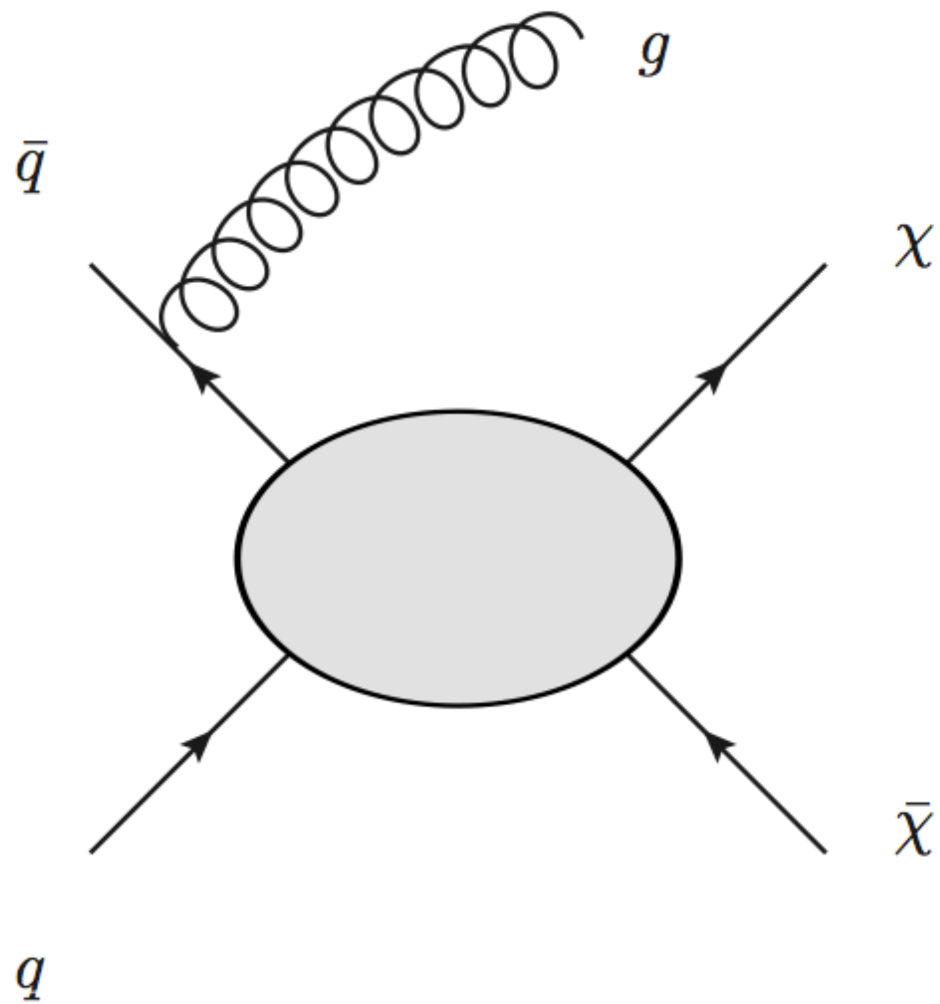
Final state:

Two WIMPs

Detector signature

Nothing

The basic idea



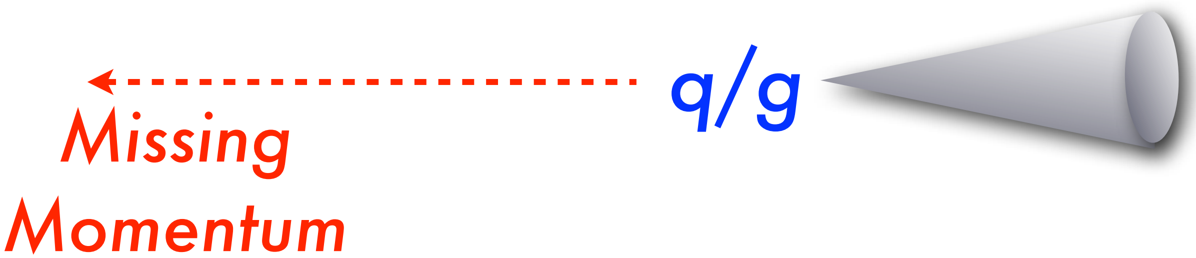
Final state:

Two WIMPs+jet

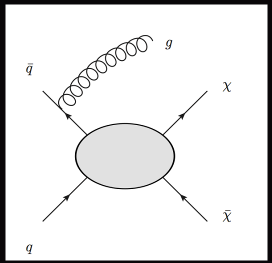
Detector signature

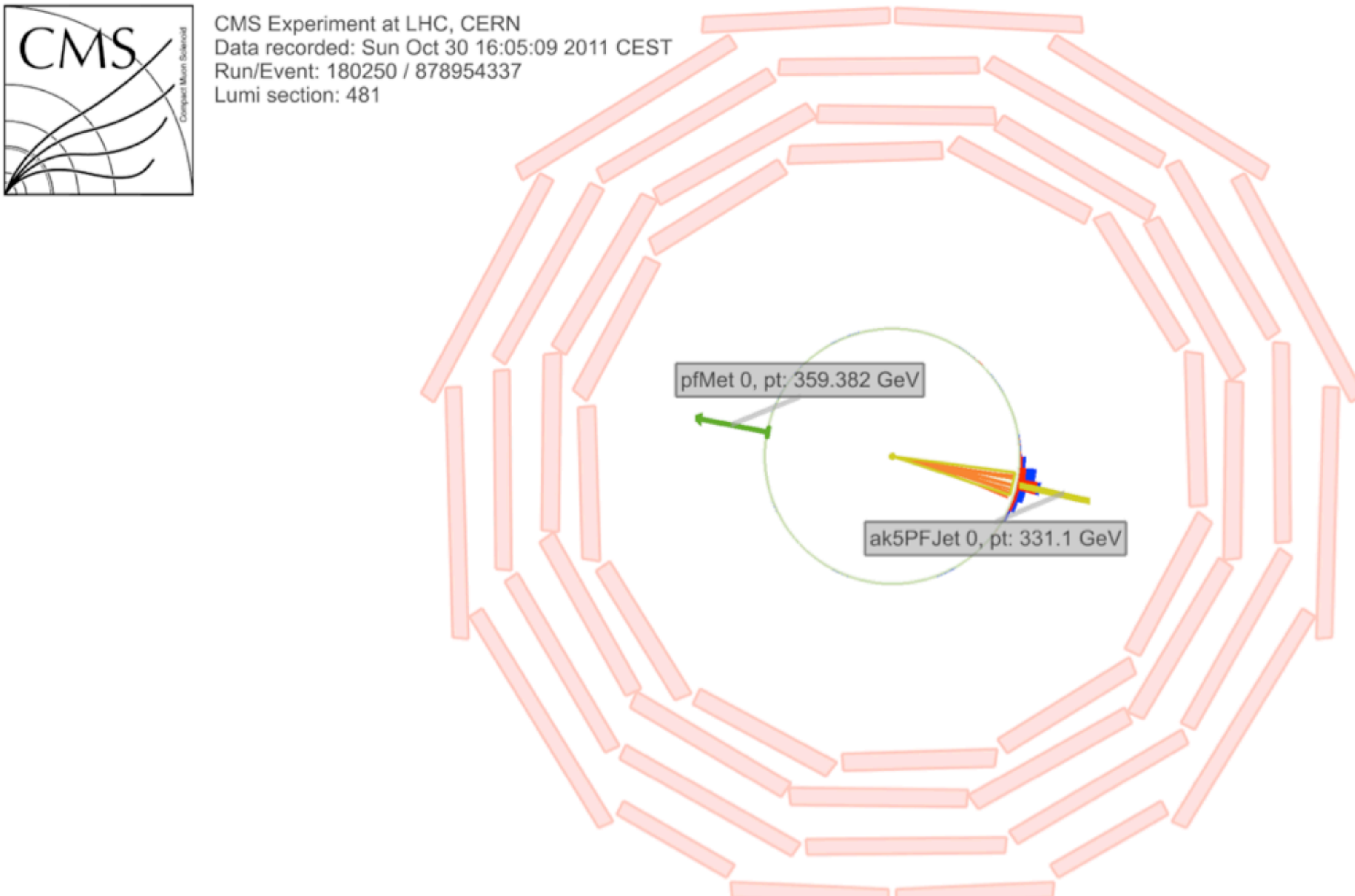
Jet + MET

Mono-jet

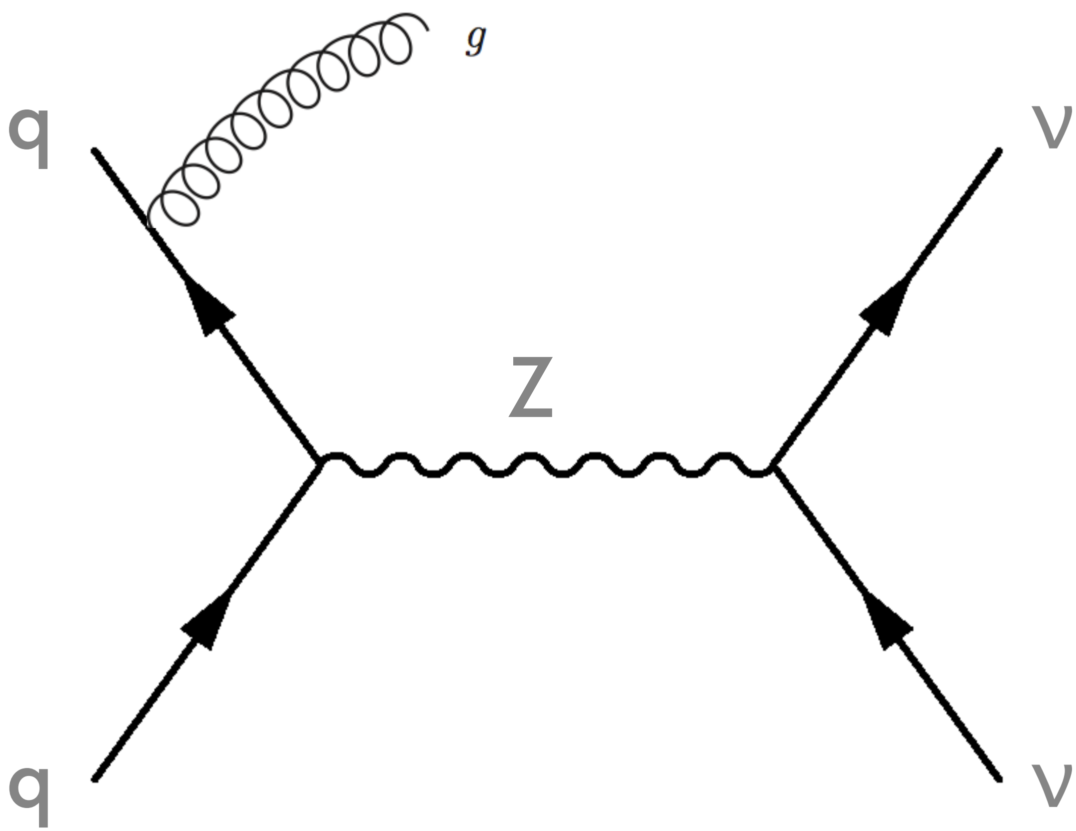


Event display





Backgrounds



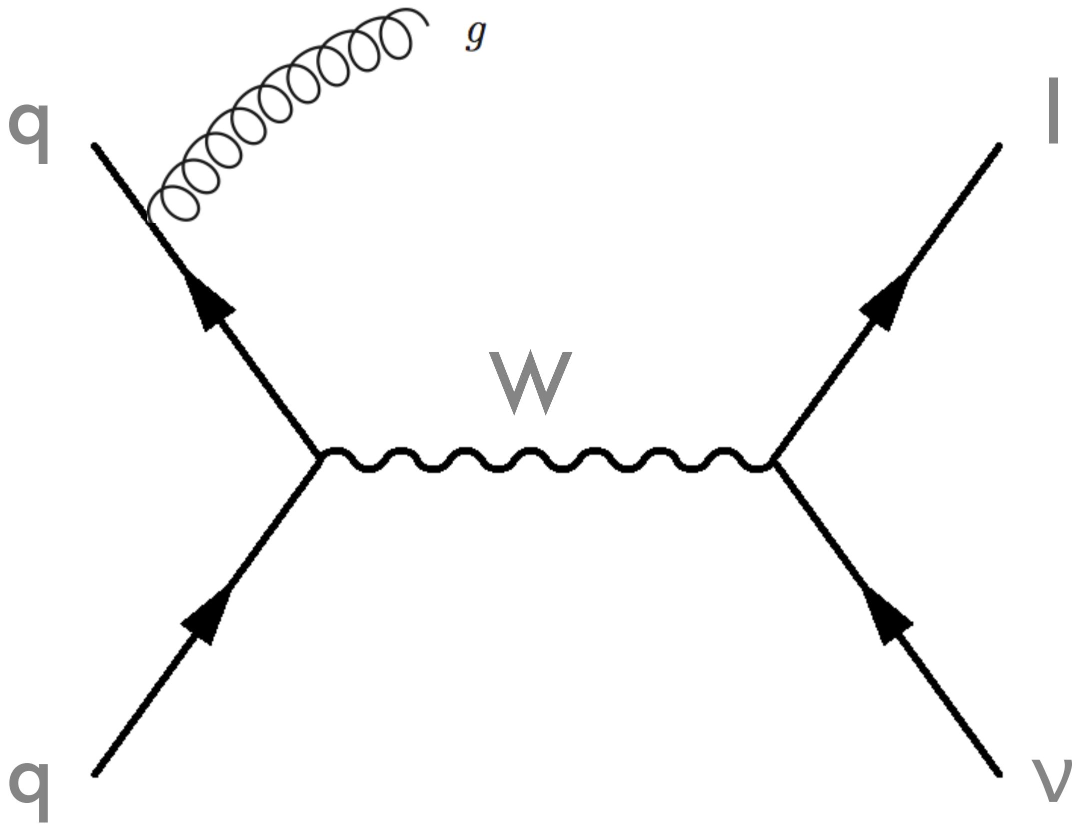
Final state:

jet + MET

Process:

Z to ν ν, with jet

Backgrounds



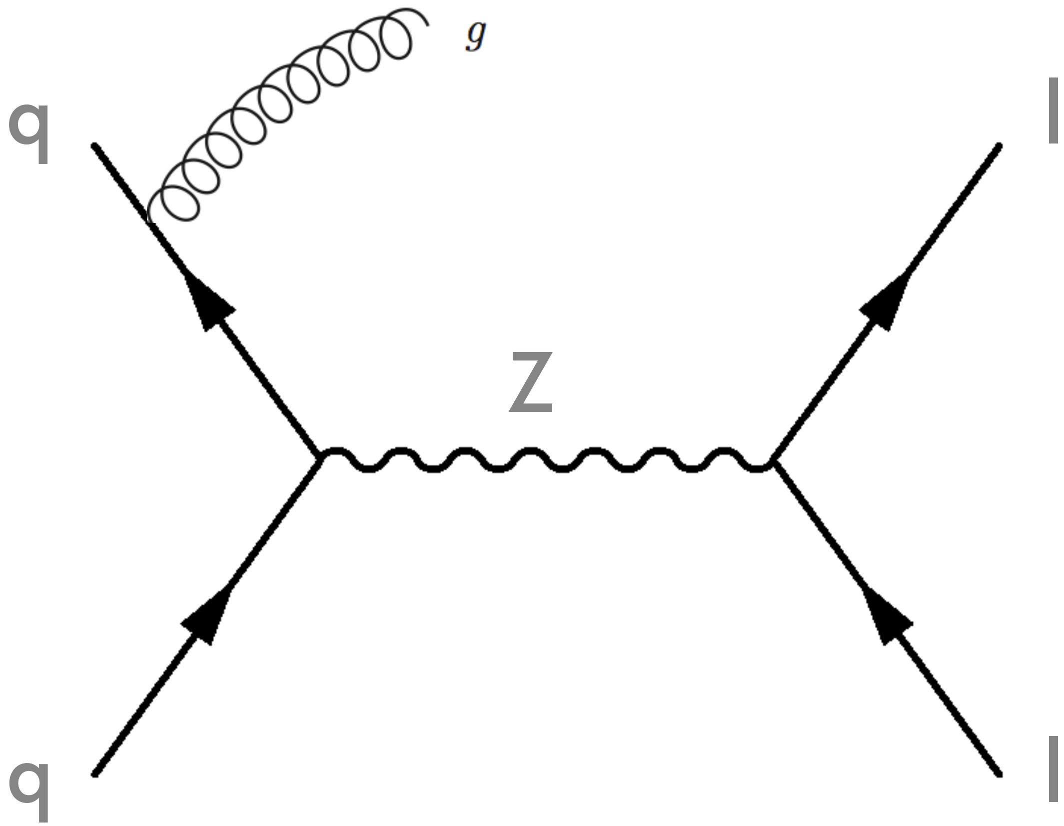
Final state:

jet + MET

Process:

W to l ν, with jet
lost lepton

Backgrounds



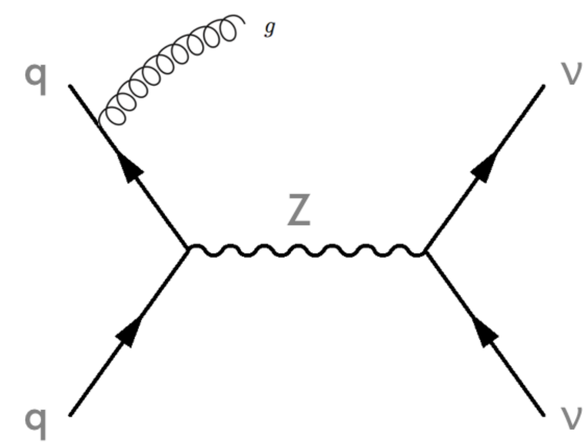
Final state:

jet + MET

Process:

Z to ll, with jet
two lost leptons

Backgrounds



How to estimate?

Idea: theory cross-section σ
efficiency ε from MC

N = L x σ x ε

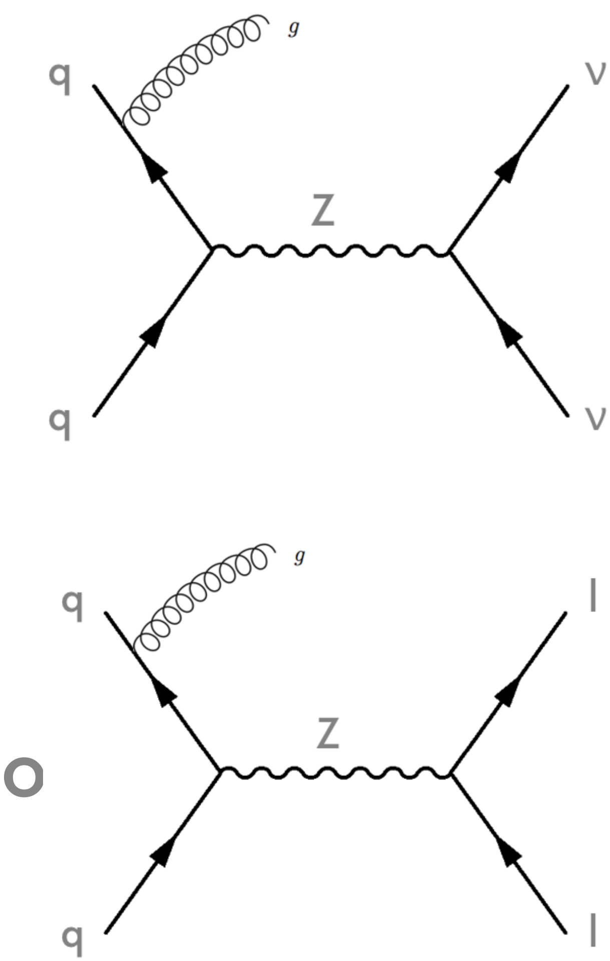
Problem: large theory uncertainties

Backgrounds

How to estimate?

Idea: Z to ν ν from Z to ll

Approach:
(1) measure Z to ll + jet
(2) scale by know branching ratio



Details

N[Z(vv)] = N[Z(ll)] x BF[Z(vv)] / BF[Z (ll)]

Details

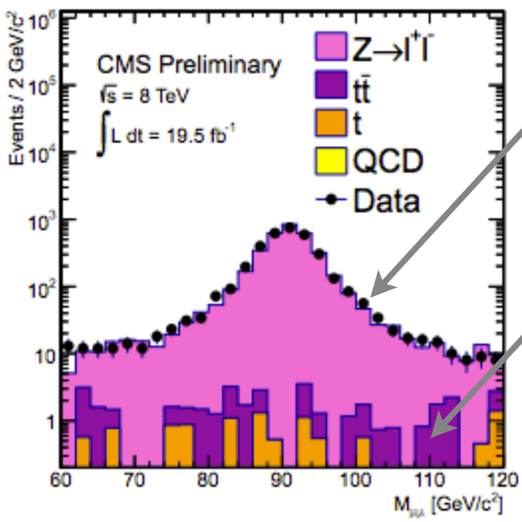
$$N[Z(vv)] = N[Z(ll)] \times BF[Z(vv)] / BF[Z(ll)]$$

$$N[Z(ll)] = N(ll) - N(bg) / \varepsilon$$

Details

N[Z(νν)] = N[Z(ll)] x BF[Z(νν)] / BF[Z (ll)]

N[Z(ll)] = N(ll) - N(bg) / ε



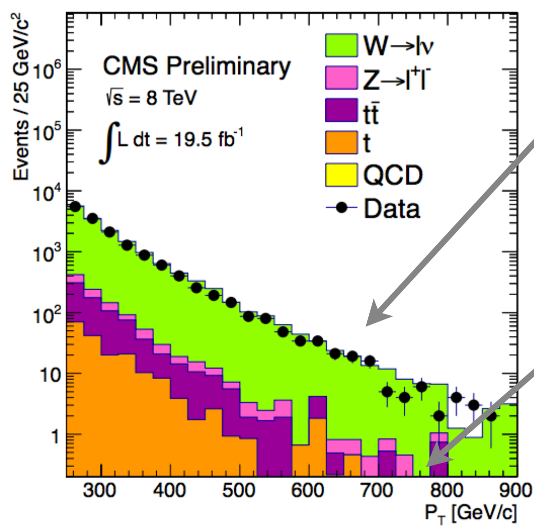
From simulation

CMS PAS EXO-12-048

Details

$$N[W(\text{lost } l)] = N[W(l\nu)] \times (1 - \varepsilon)$$

$$N[W(l\nu)] = [N(l+MET) - N(bg)] / \varepsilon$$



From simulation

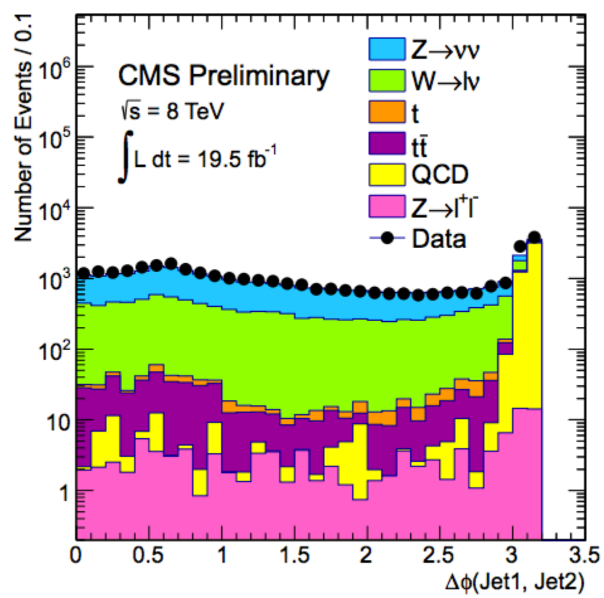
CMS PAS EXO-12-048

Final Selection

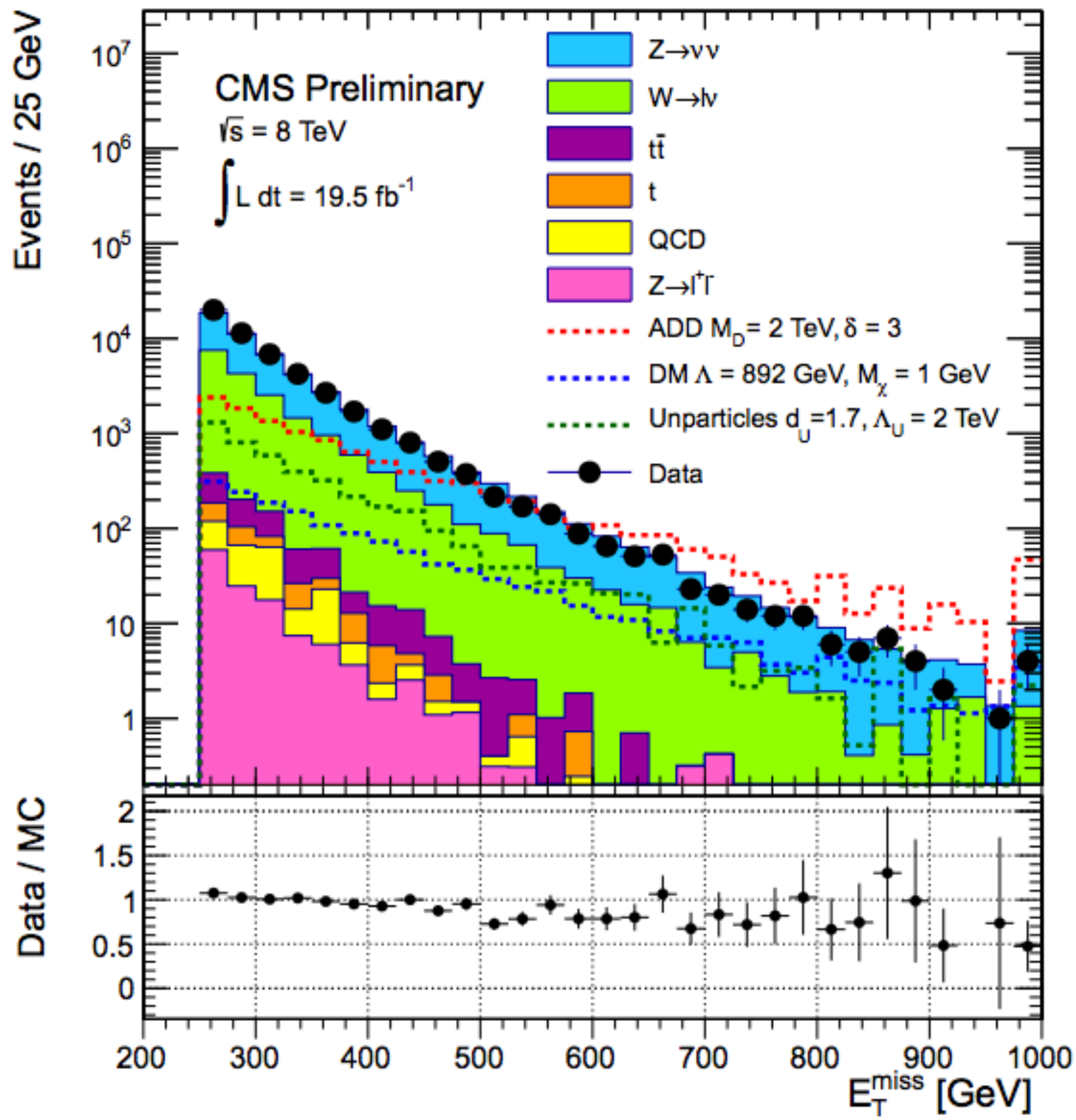
<u>Trigger</u>: MET > 120
or jet pT>80, MET>105

Jet pT > 110
MET> 250,300,350,400,450,500,550

Second jet allowed if dPhi(j1,j2)<2.5
veto if 3+ jets
veto if any leptons with pt>10



Data



CMS Preliminary
√s = 8 TeV
∫L dt = 19.5 fb^-1
Z→νν
W→lν
tt̄
t
QCD
Z→l⁺l⁻
ADD M_D= 2 TeV, δ = 3
DM Λ = 892 GeV, M_χ = 1 GeV
Unparticles d_U=1.7, Λ_U = 2 TeV
Data
Events / 25 GeV
Data / MC
E_T^miss [GeV]

Analysis

Several nested counting experiments

E_T^{miss} (GeV) $\rightarrow$	> 250	> 300	> 350	> 400	> 450	> 500	> 550
$Z(\nu\nu)$+jets	30600 ± 1493	12119 ± 640	5286 ± 323	2569 ± 188	1394 ± 127	671 ± 81	370 ± 58
W+jets	17625 ± 681	6042 ± 236	2457 ± 102	1044 ± 51	516 ± 31	269 ± 20	128 ± 13
$t\bar{t}$	470 ± 235	175 ± 87.5	72 ± 36	32 ± 16	13 ± 6.5	6 ± 3.0	3 ± 1.5
$Z(\ell\ell)$+jets	127 ± 63.5	43 ± 21.5	18 ± 9.0	8 ± 4.0	4 ± 2.0	2 ± 1.0	1 ± 0.5
Single t	156 ± 78.0	52 ± 26.0	20 ± 10.0	7 ± 3.5	2 ± 1.0	1 ± 0.5	0 ± 0
QCD Multijets	177 ± 88.5	76 ± 38.0	23 ± 11.5	3 ± 1.5	2 ± 1.0	1 ± 0.5	0 ± 0
Total SM	49154 ± 1663	18506 ± 690	7875 ± 341	3663 ± 196	1931 ± 131	949 ± 83	501 ± 59
Data	50419	19108	8056	3677	1772	894	508
Exp. upper limit	3580	1500	773	424	229	165	125
Obs. upper limit	4695	2035	882	434	157	135	131

Statistics

If $N_{bg} = X \pm Y$ then $N_{sig} < Z$ @ 95% CL

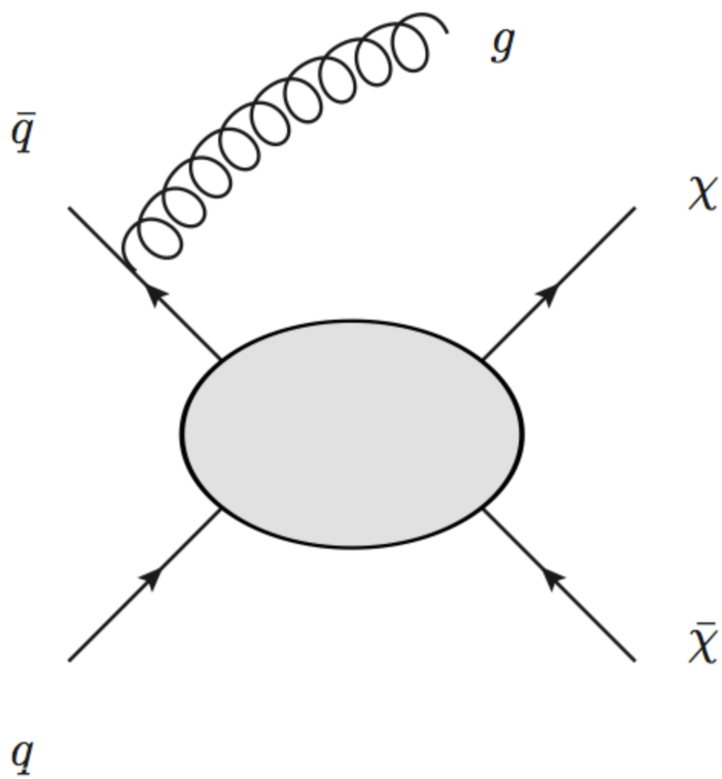
(N_{sig} is model-*independent*)

$N = L \times \sigma_{th} \times \varepsilon_{th}$

$\sigma_{th} = N / L \times \varepsilon_{th}$

(σ_{th} is model-*dependent*)

Where do we get ε_{th}?

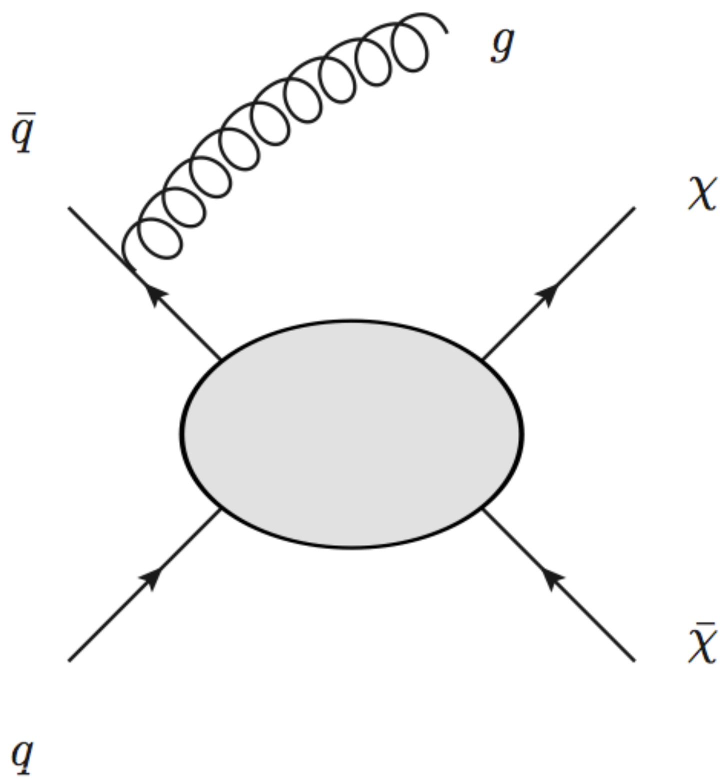


Need a concrete model

Generate simulated events

Measure fraction which survive selection = ε_{th}

Models



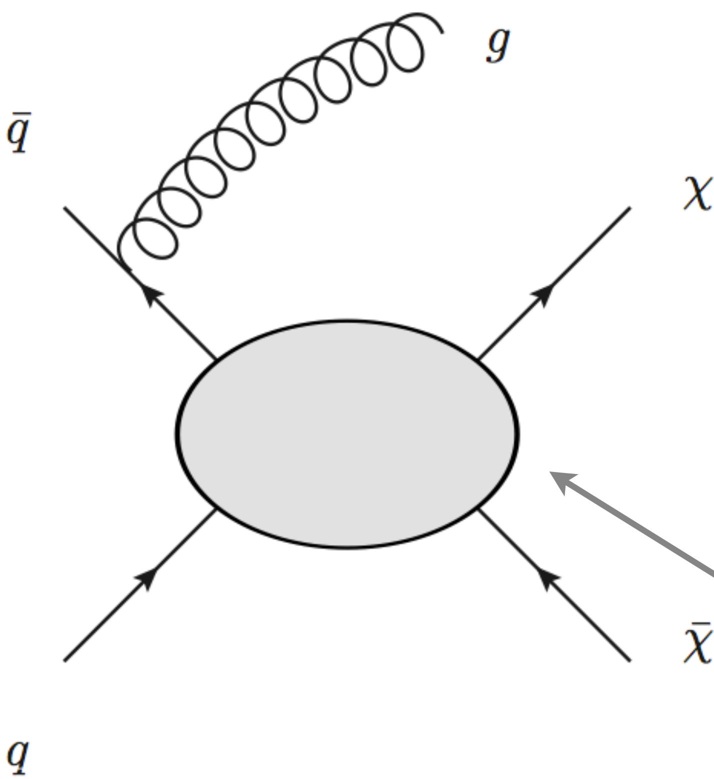
What interaction does DM have with SM particles?

Since our collider uses q/g, we postulate an interaction

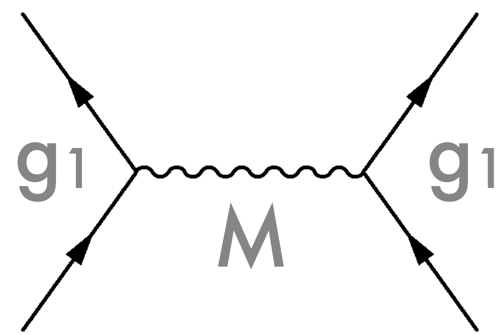
qqXX or ggXX

And try to be agnostic about what goes inside.

Effective Field Theory



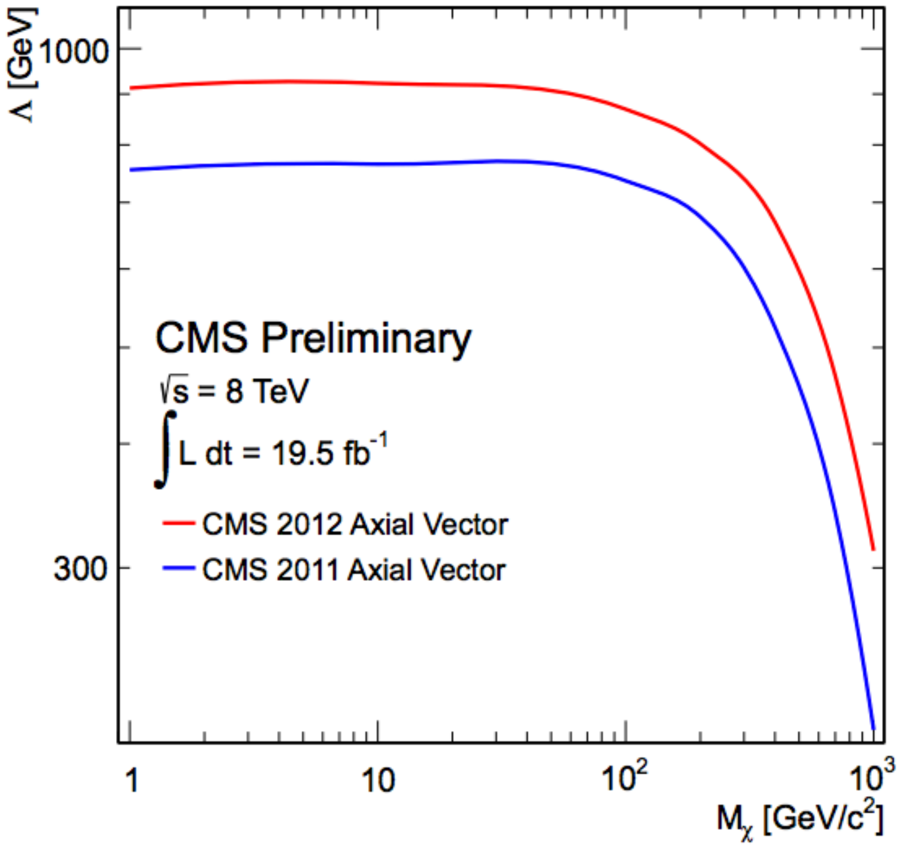
If the interaction is mediated by something heavy, we don't need to know the details.

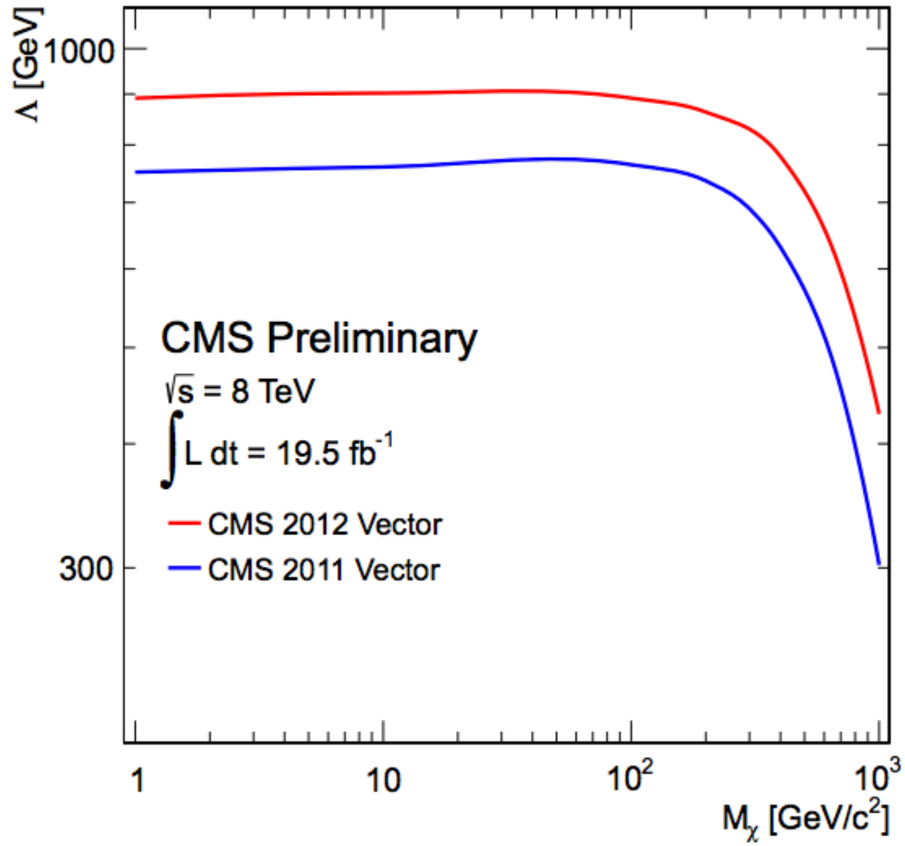


Cut-off mass scale:

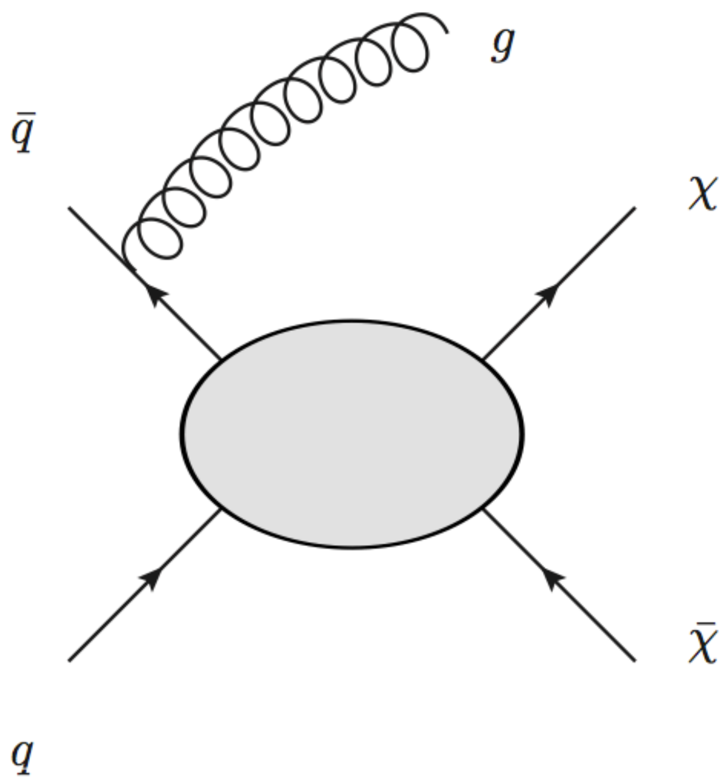
$\Lambda = M/\sqrt{g_1 g_2}$

Limits on Λ

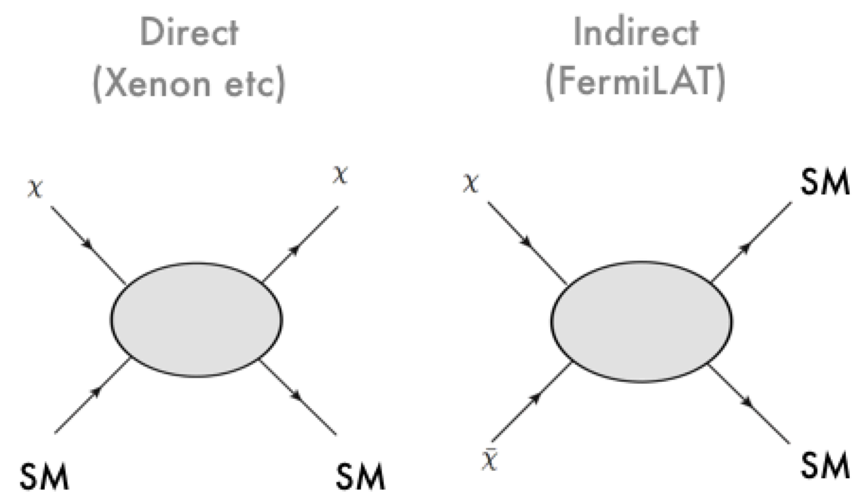




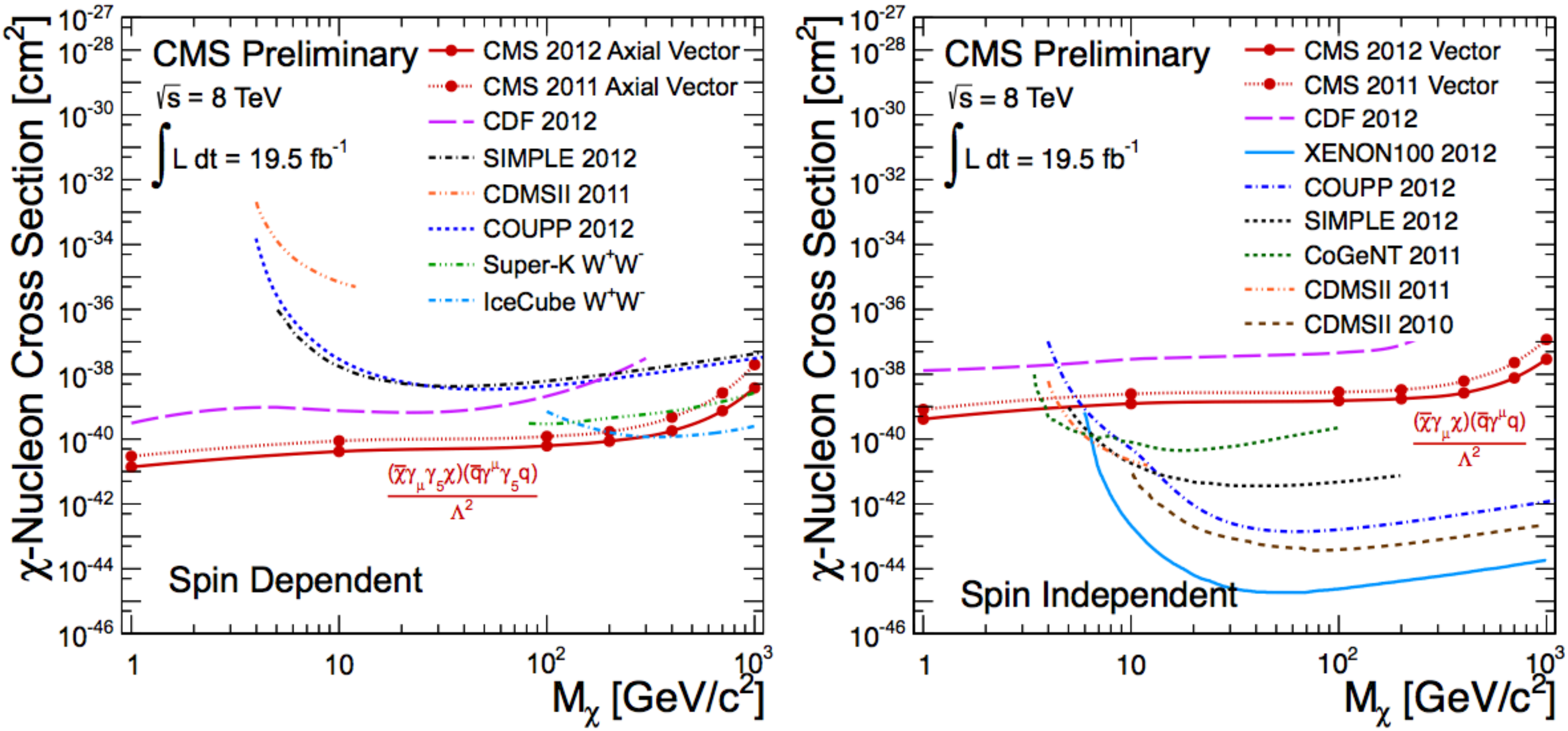
Effective Field Theory



The same model and parameter Λ can be used to predict rates at different experiments



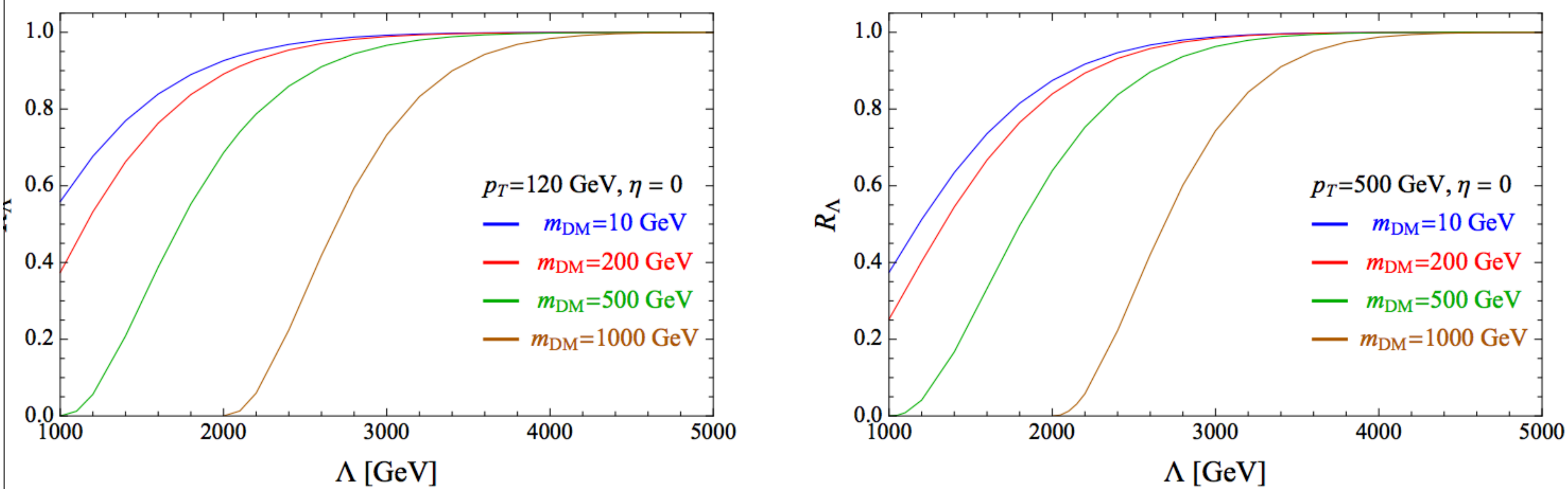
DM limits



CMS Preliminary
√s = 8 TeV
∫L dt = 19.5 fb⁻¹
CMS 2012 Axial Vector
CMS 2011 Axial Vector
CDF 2012
SIMPLE 2012
CDMSII 2011
COUPP 2012
Super-K W⁺W⁻
IceCube W⁺W⁻
Spin Dependent
χ-Nucleon Cross Section [cm²]
Mχ [GeV/c²]
CMS Preliminary
√s = 8 TeV
∫L dt = 19.5 fb⁻¹
CMS 2012 Vector
CMS 2011 Vector
CDF 2012
XENON100 2012
COUPP 2012
SIMPLE 2012
CoGeNT 2011
CDMSII 2011
CDMSII 2010
Spin Independent
χ-Nucleon Cross Section [cm²]
Mχ [GeV/c²]

Problems with EFTs

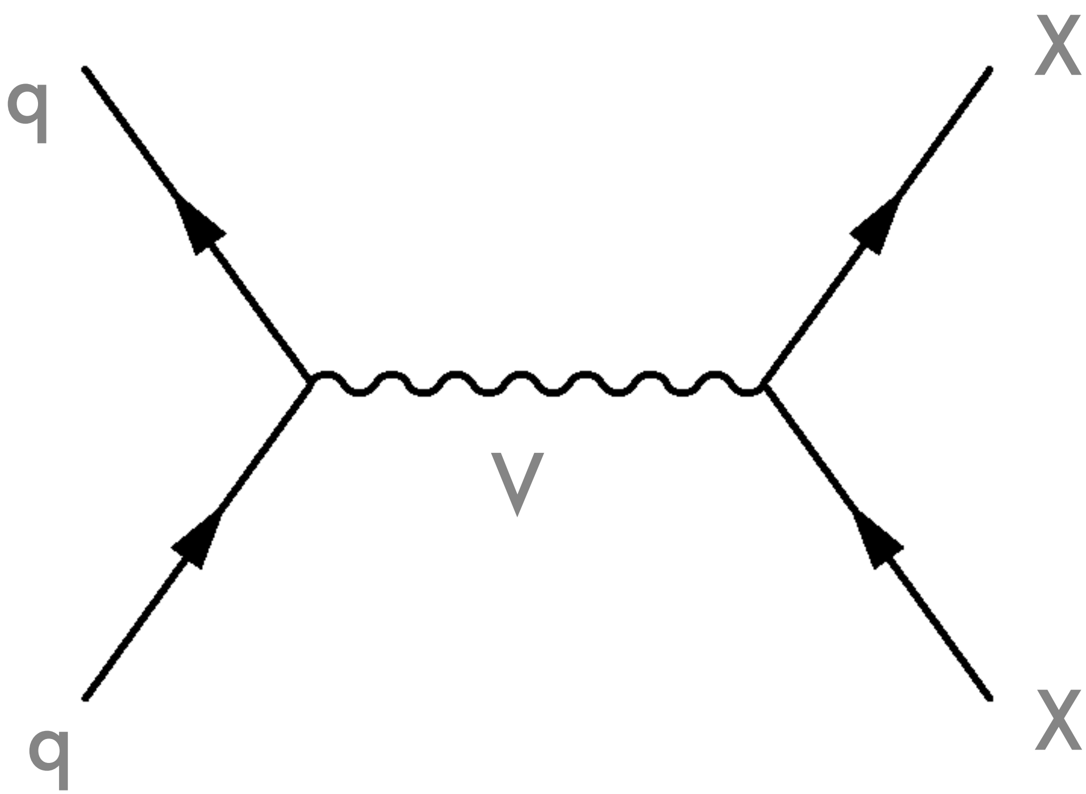
Only valid if momentum transfer Q is less than mass cut-off scale



R = fraction of events where Q< Λ

1307.2253

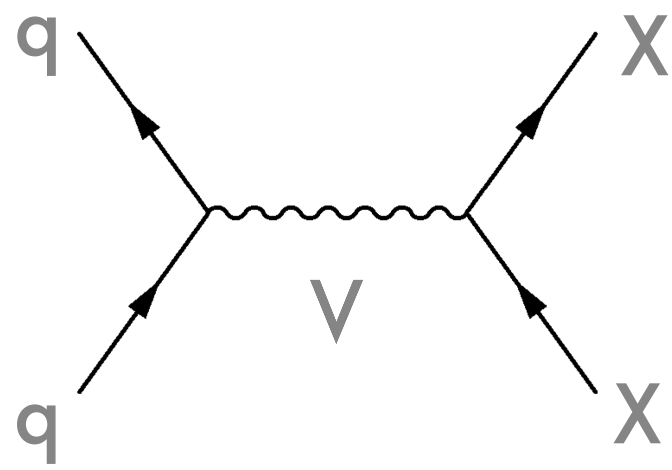
Simplified Models

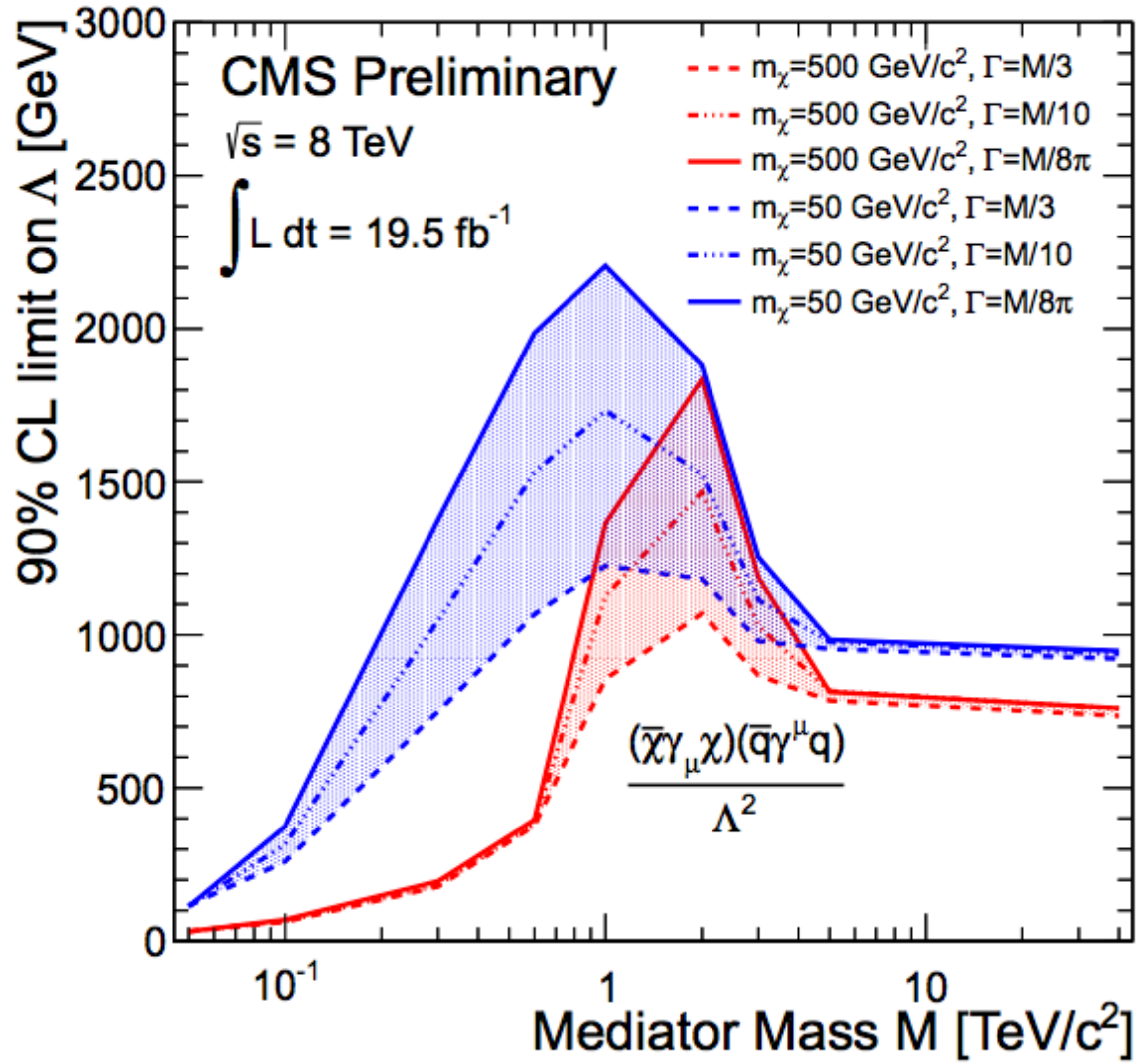


Explicit model:
specify particles
and masses.

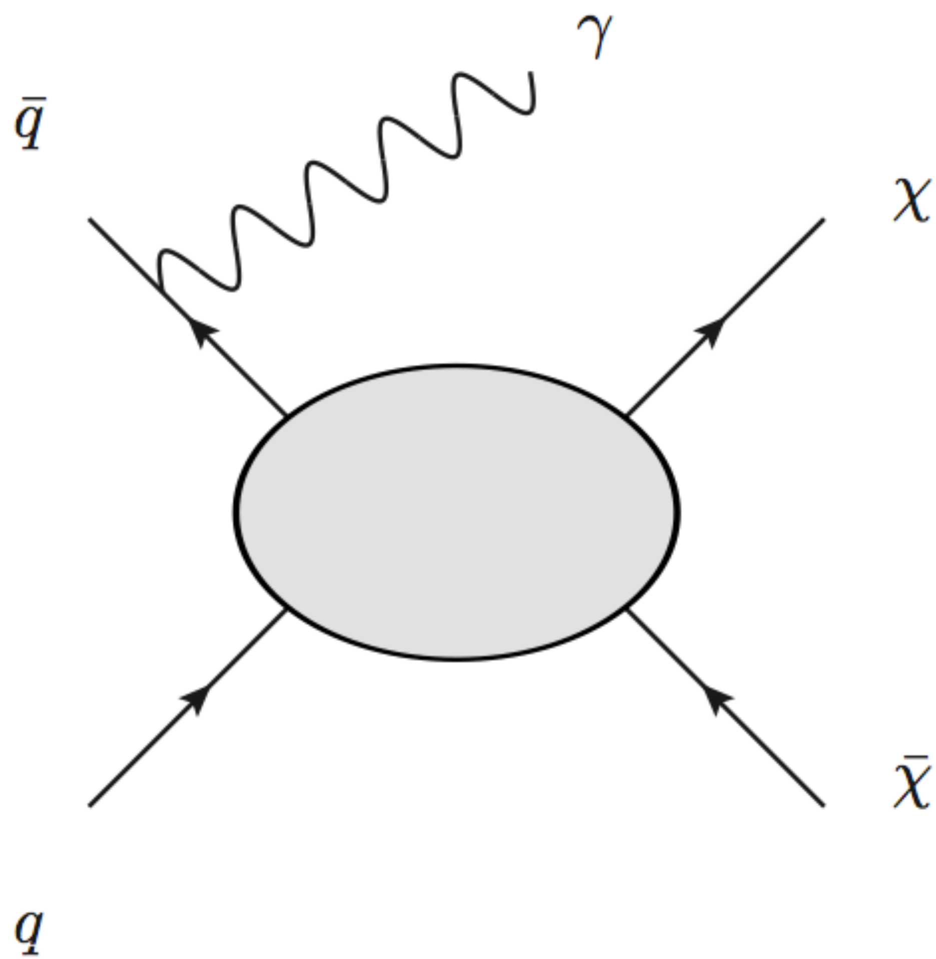
Express results
as limits on σ
so no dependence
on coupling
predictions.

Simplified Models

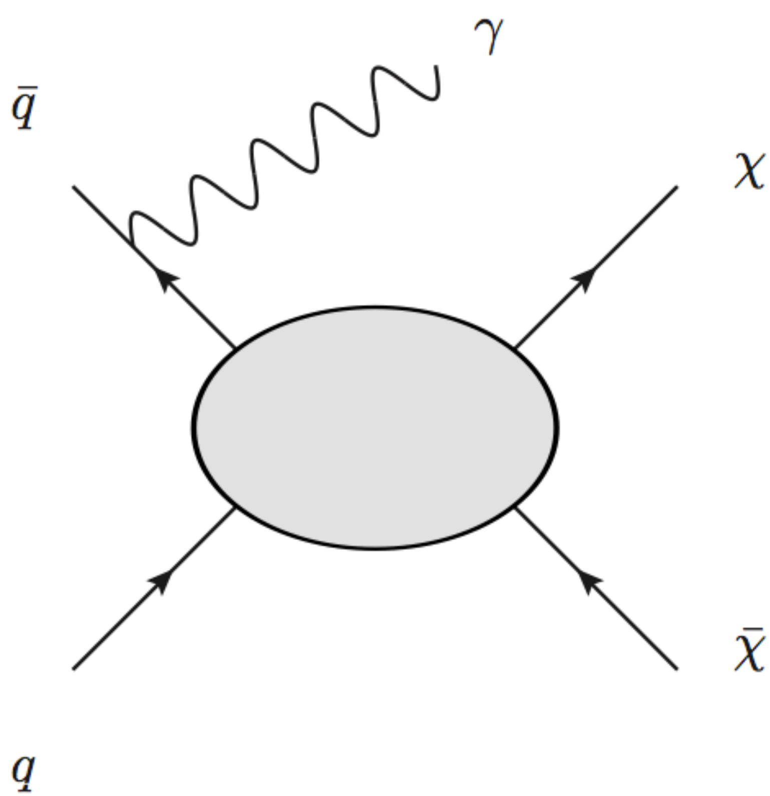




Mono-photon



The basic idea



Final state:

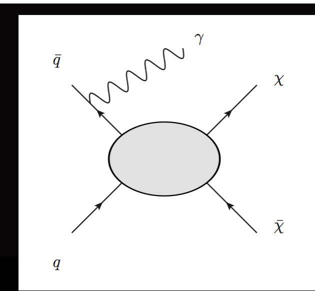
Two WIMPs+photon

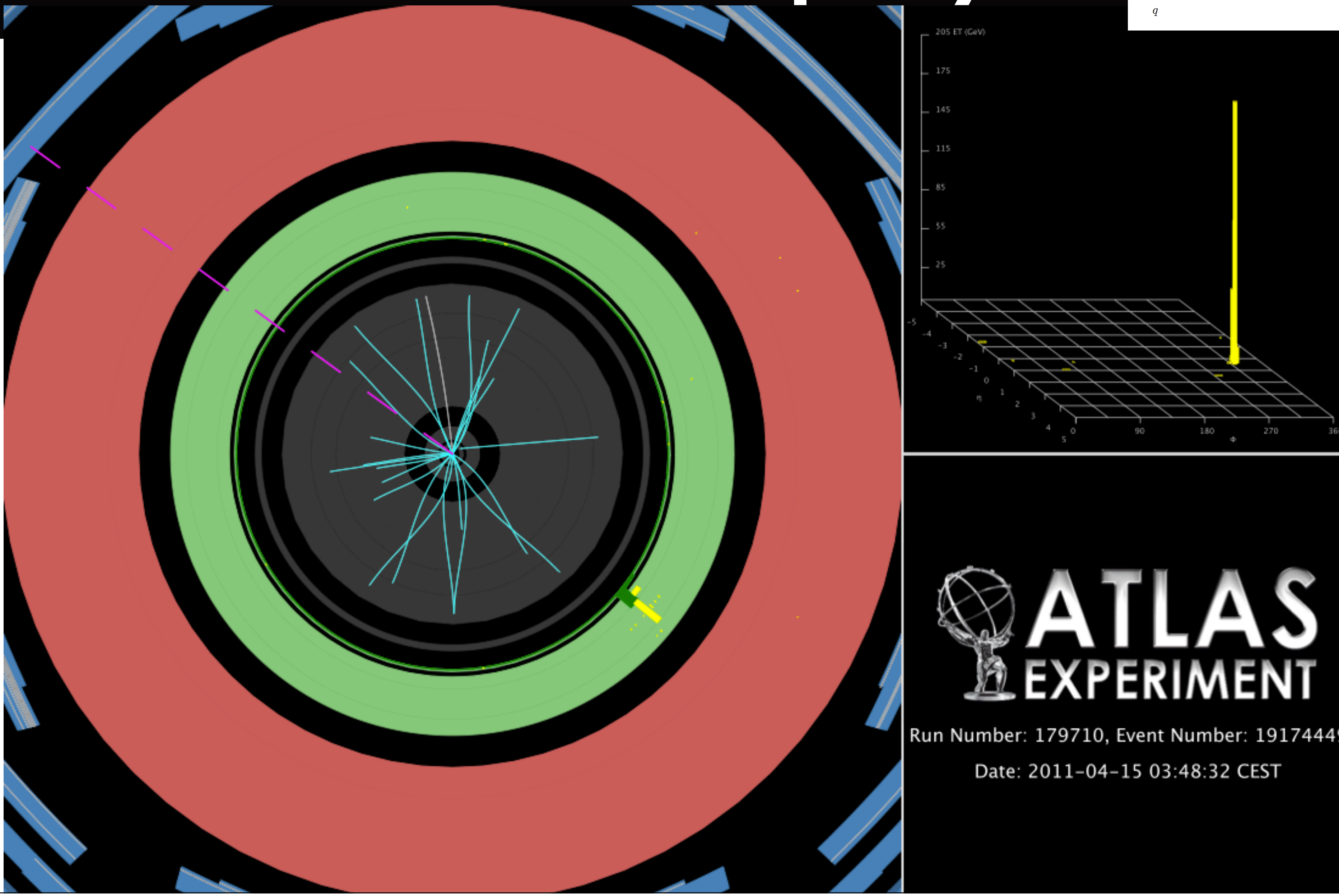
Detector signature

photon + MET

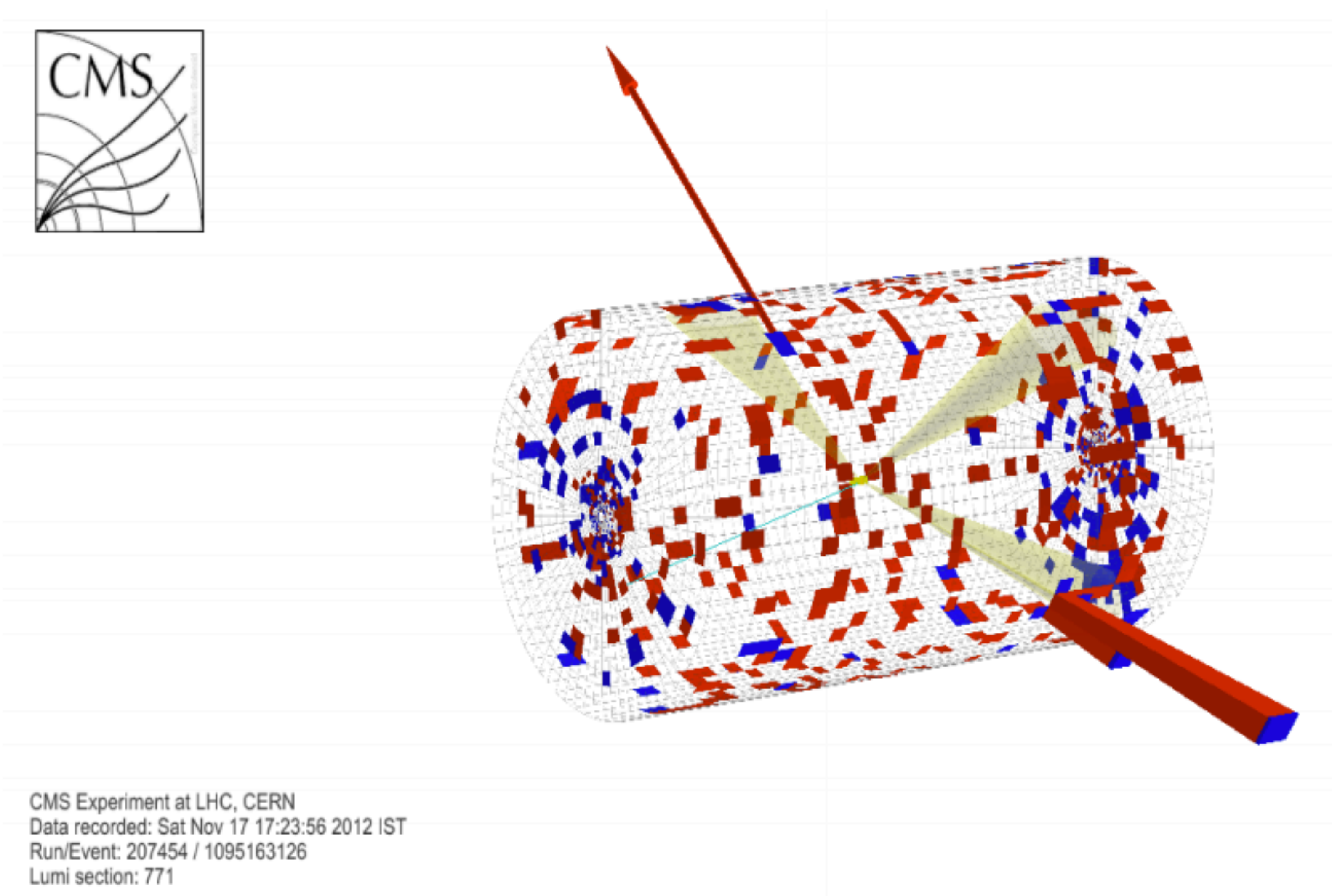
Mono-photon

Event display

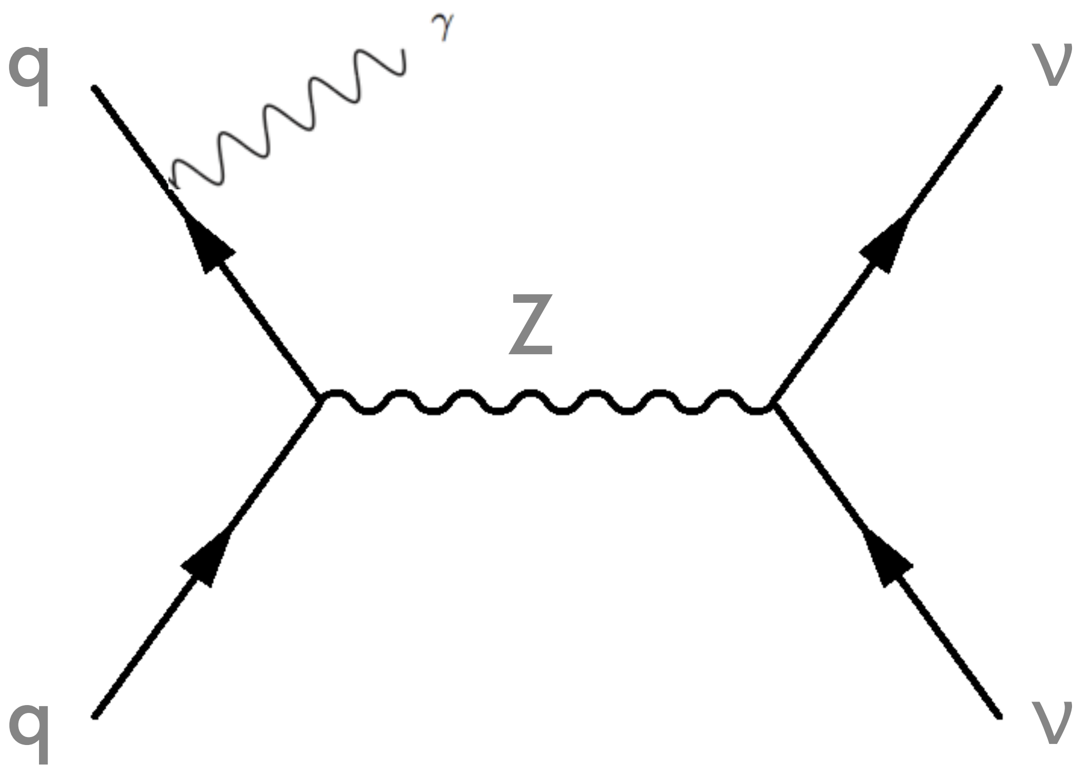




CMS event


CMS
CMS Experiment at LHC, CERN
Data recorded: Sat Nov 17 17:23:56 2012 IST
Run/Event: 207454 / 1095163126
Lumi section: 771

Backgrounds



Final state:

photon + MET

Process:

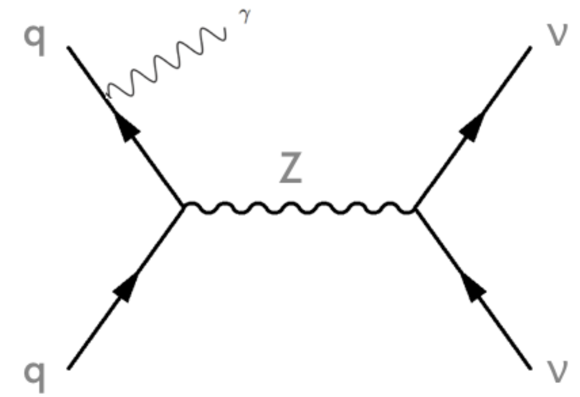
Z to ν ν, with phot.

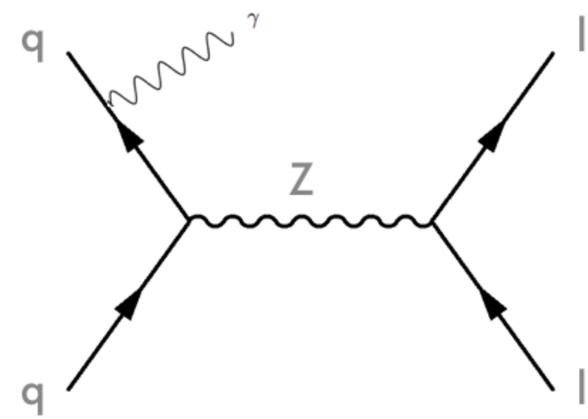
Backgrounds

How to estimate?

Idea: Z to ν ν from Z to ll

Approach:
(1) measure Z to ll + photon
(2) scale by know branching ratios





Backgrounds

How to estimate?

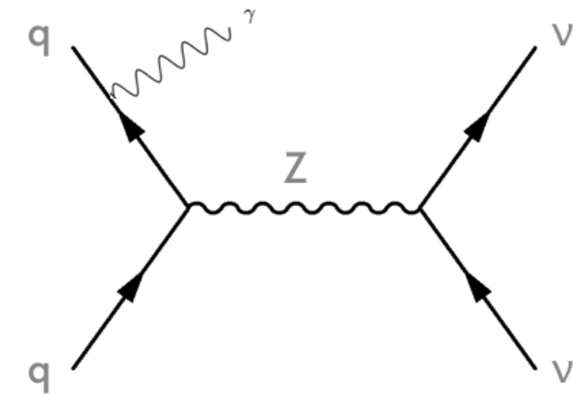
Idea: Z to

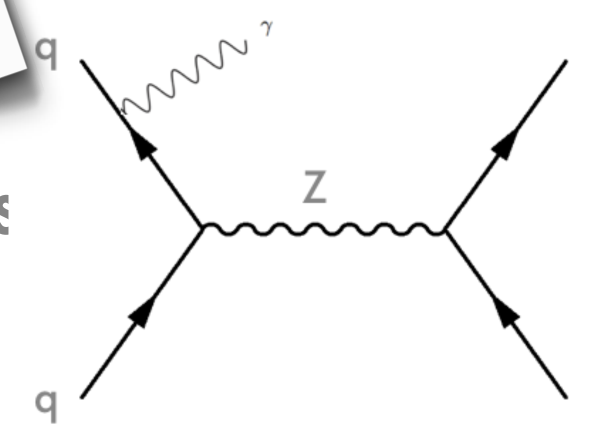
Approach:

(1) measure

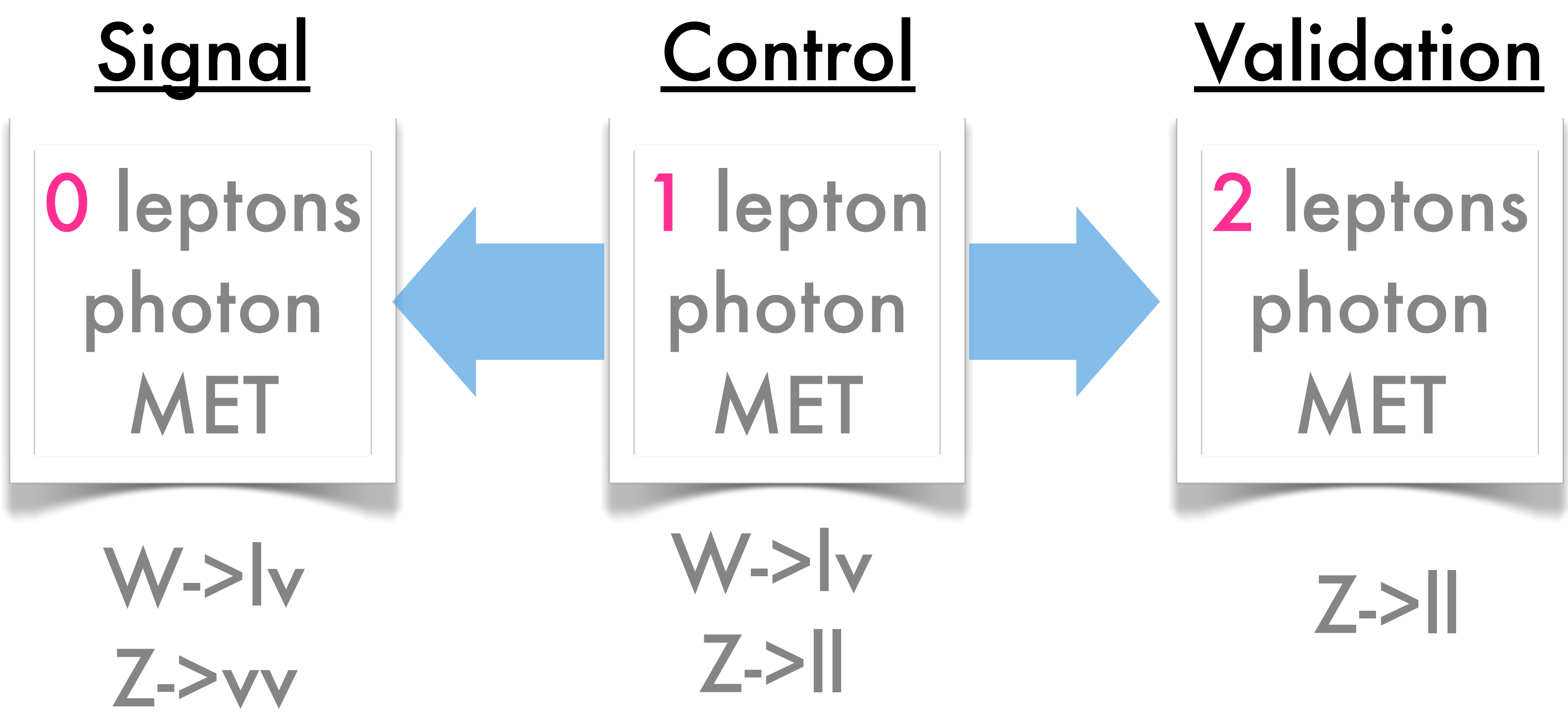
(2) scale by k ching ratios

Not enough events in ll+photon!





Background estimate



Backgrounds

How to estimate?

Idea: l+MET+gamma has more events contributions from Z to ll, W to lv

Approach:

(1) Use MC to predict MET shape

(2) ATLAS: Normalize in l+MET+gamma sample to reduce uncertainties from theory predictions.

Selection

ATLAS

$p_{T\gamma} > 150$
MET > 150
<=1 jet with pt>30
lepton veto
Angular separation

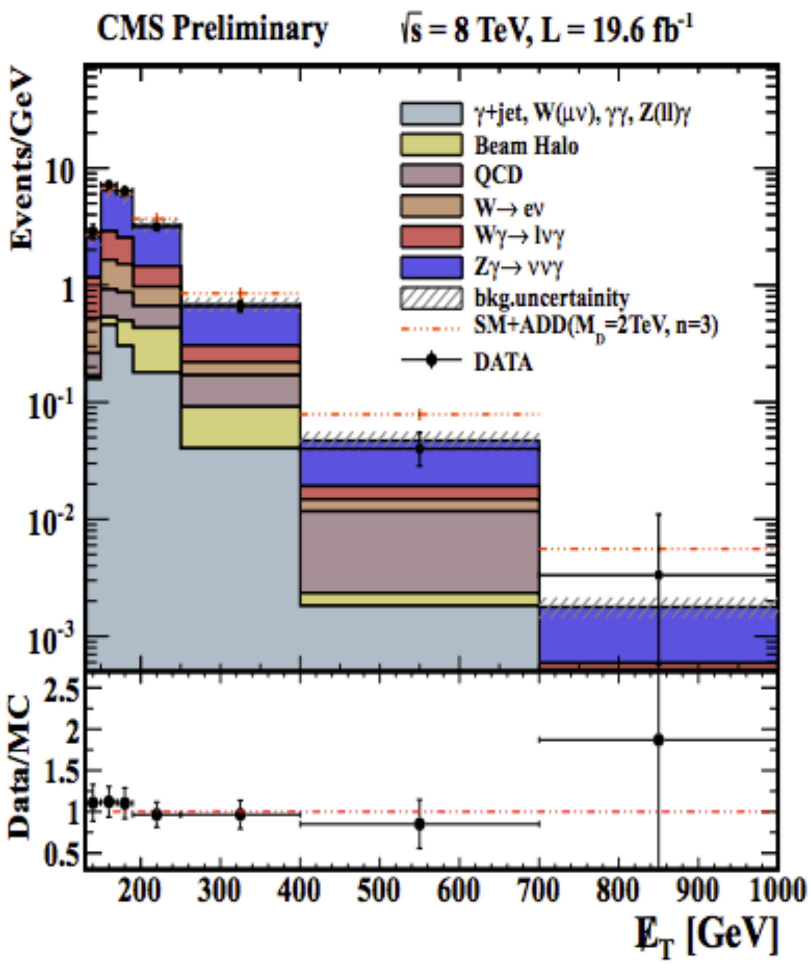
1209.4625

CMS

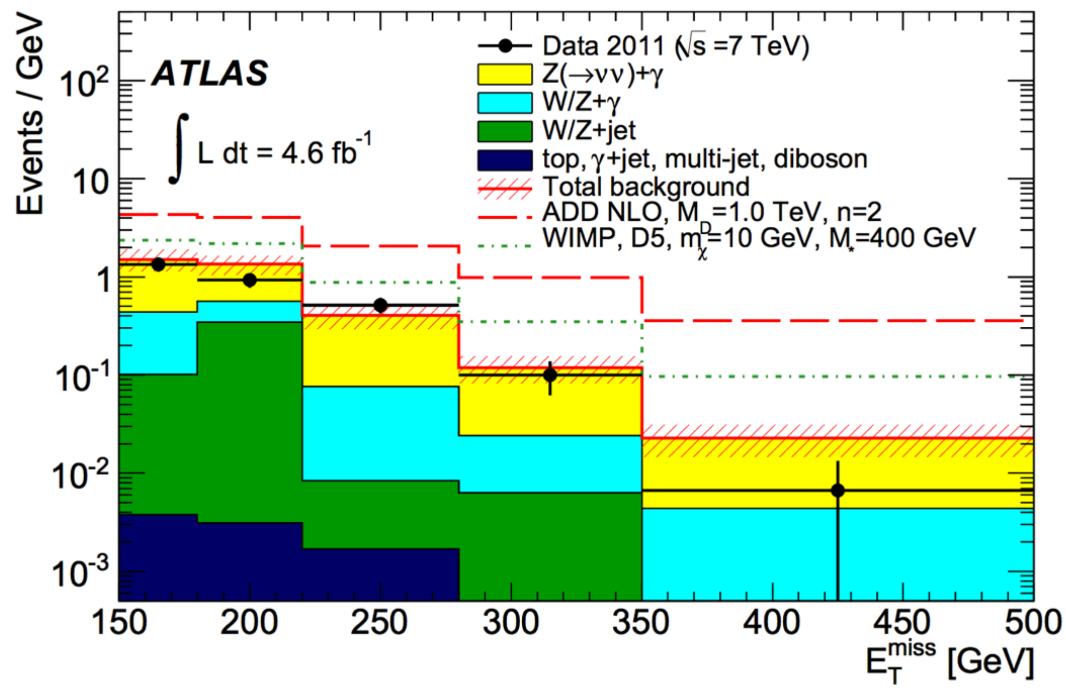
$p_{T\gamma} > 145$
MET > 130
0 jets with pt>40
lepton veto
Angular separation

CMS PAS EXO-12-047

Data

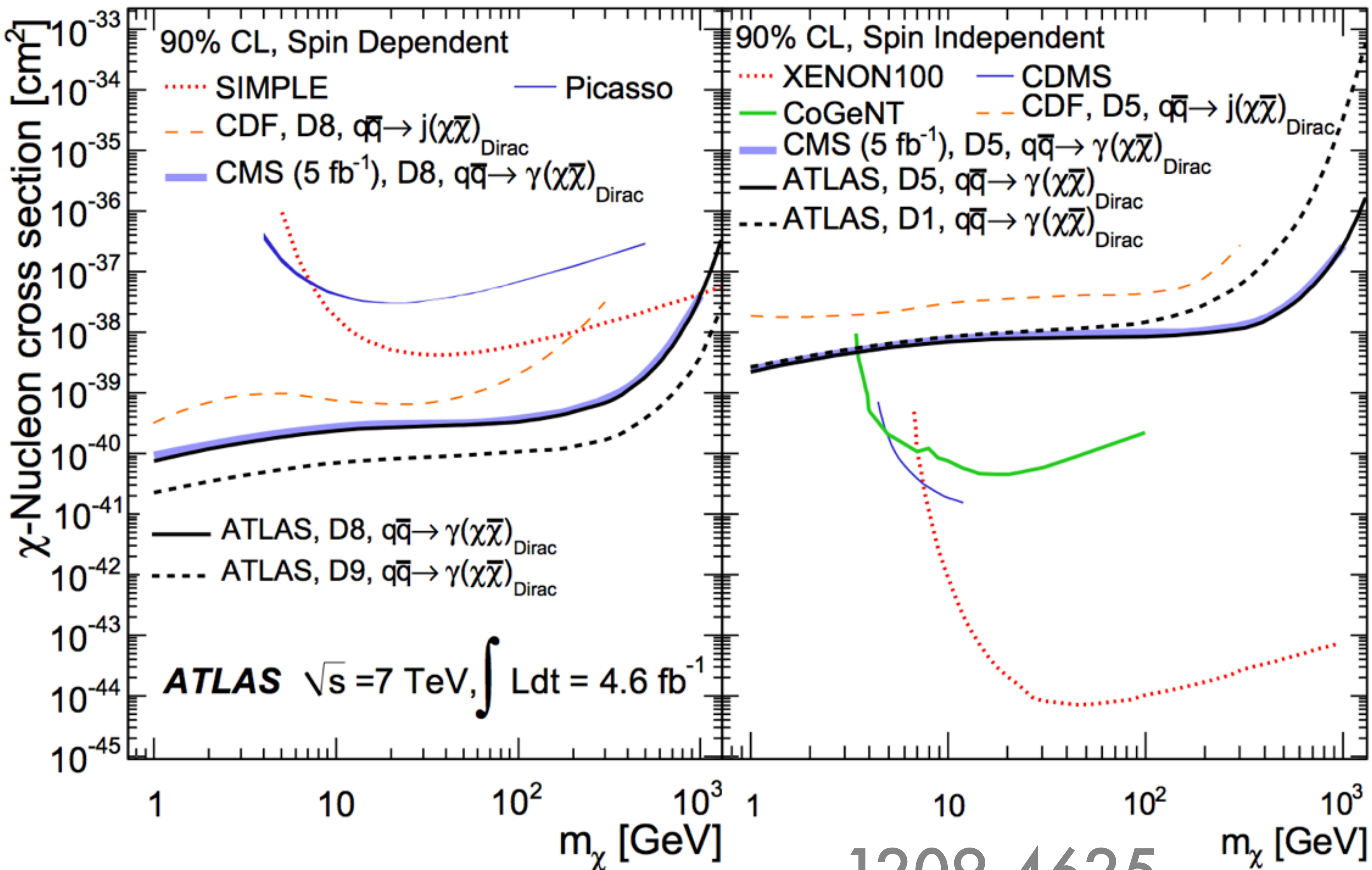


CMS PAS EXO-12-047



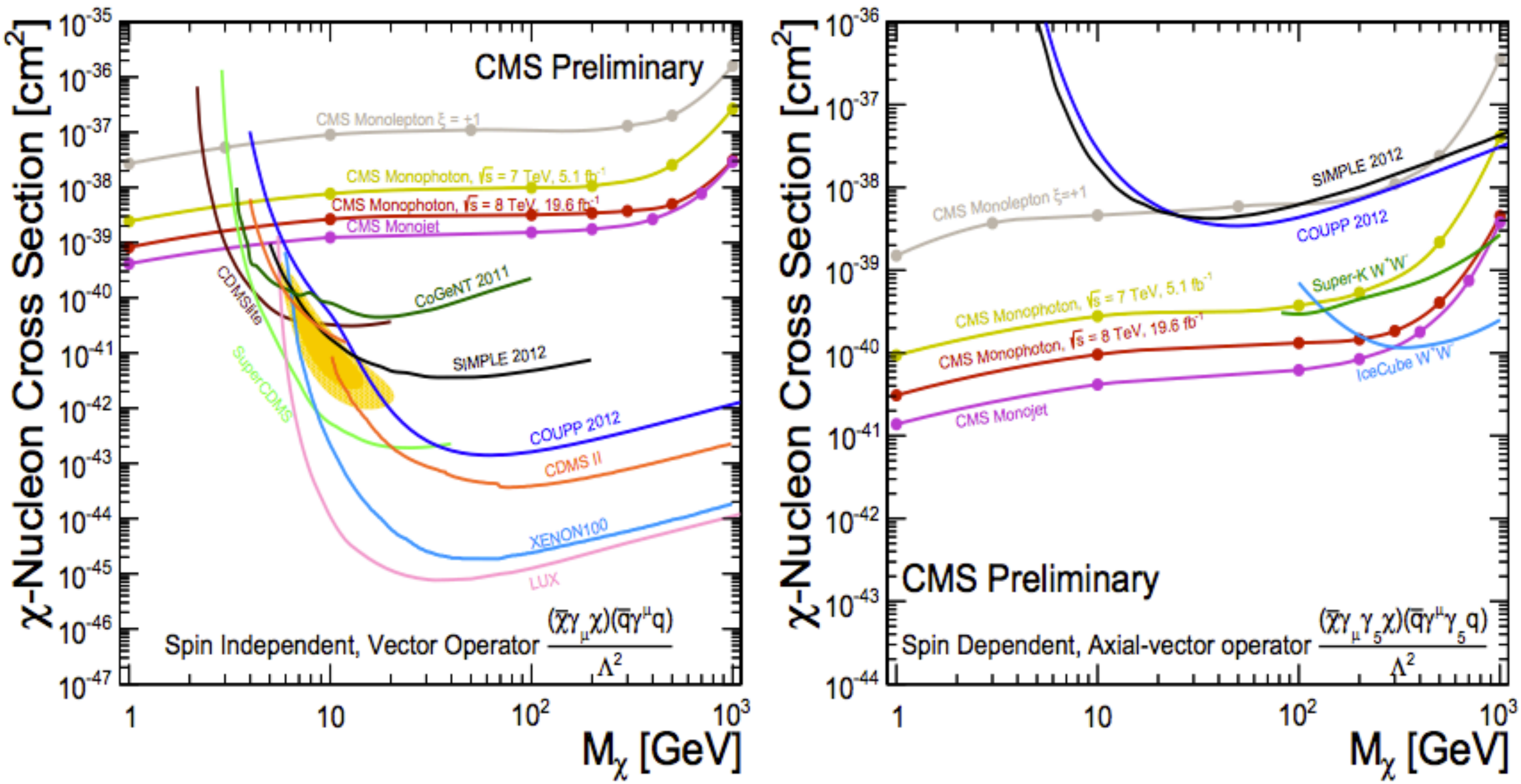
1209.4625

ATLAS Limits



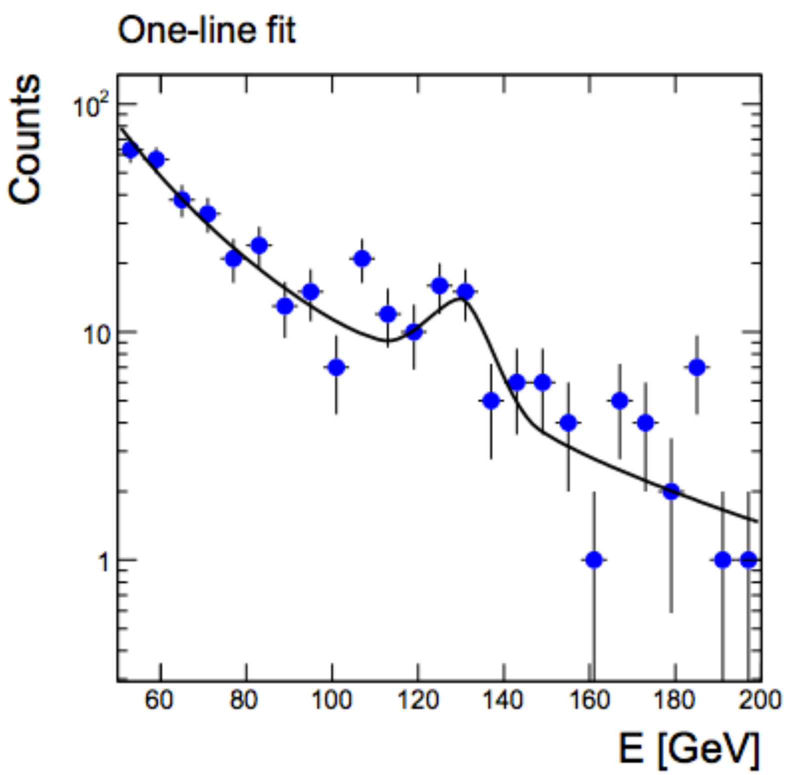
1209.4625

CMS Limits

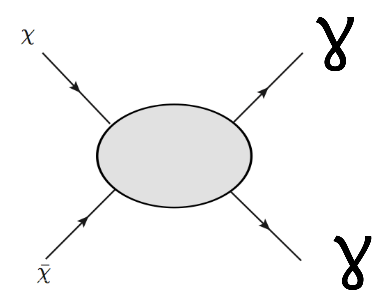


CMS PAS EXO-12-047

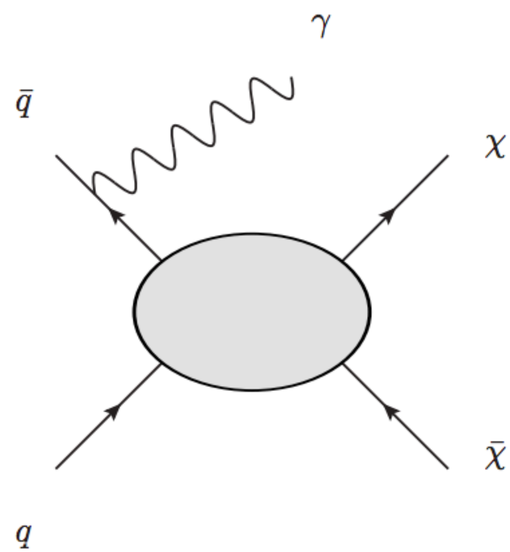
Photons and DM



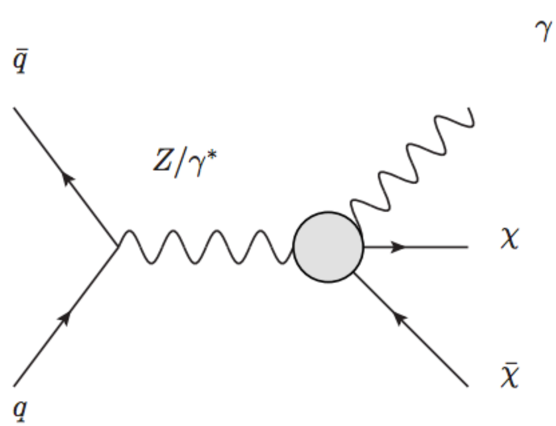
Famous peak
in FermiLAT
spectrum
at E=130 GeV



Can we see that?

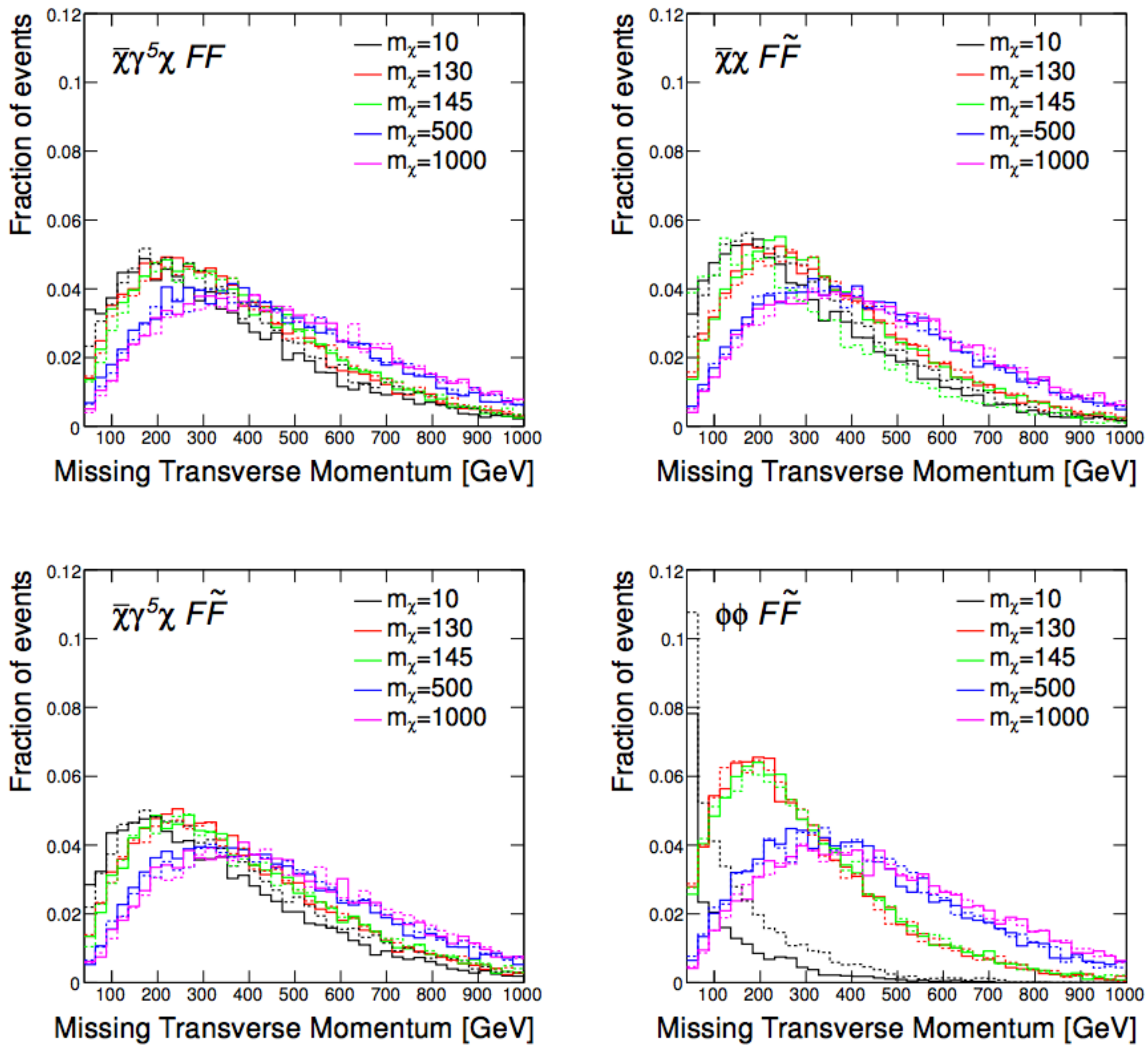


Mostly LHC looks for this



But the same data can tell us about this

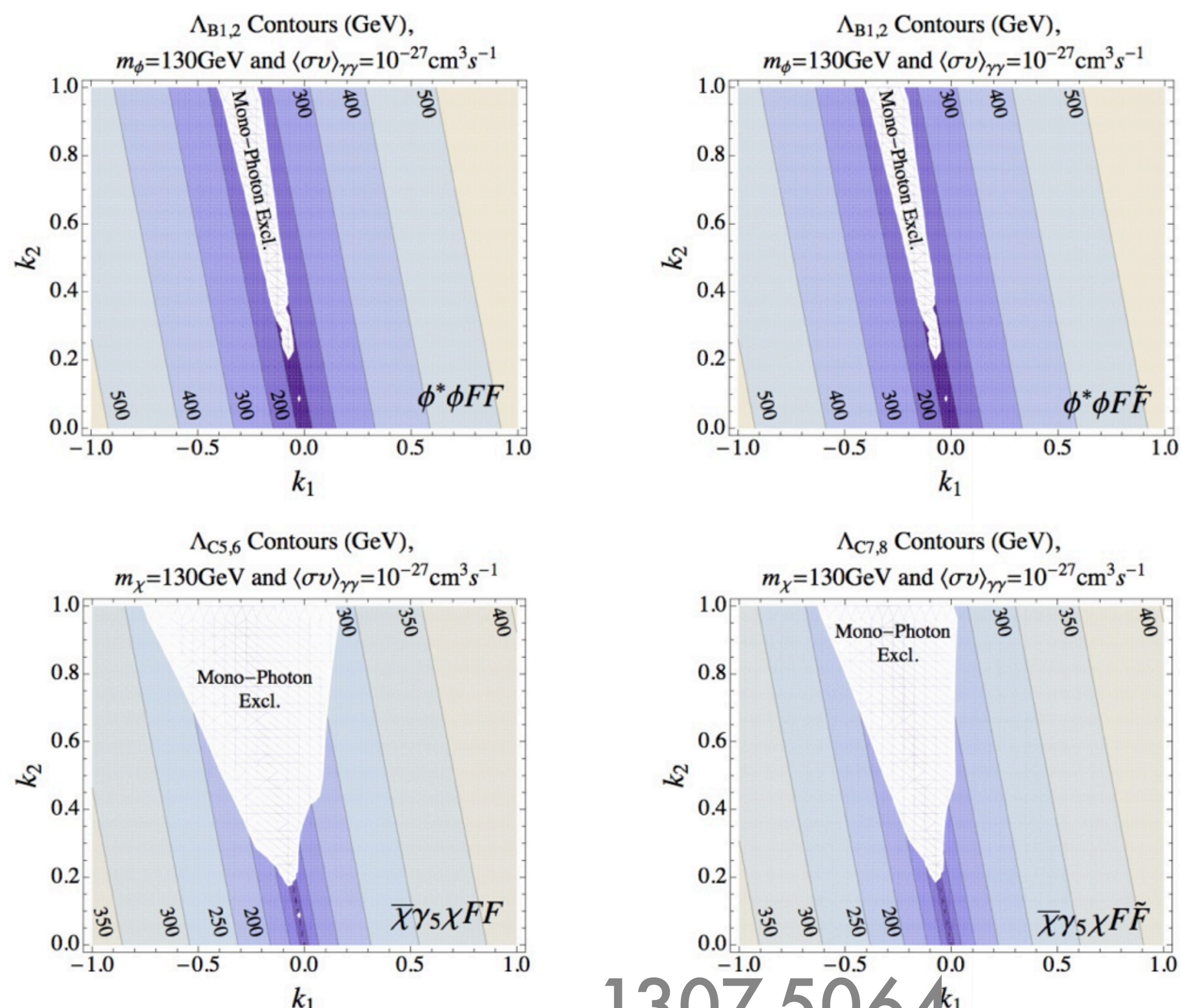
MET



Critical item is spectrum of MET

1307.5064

Results

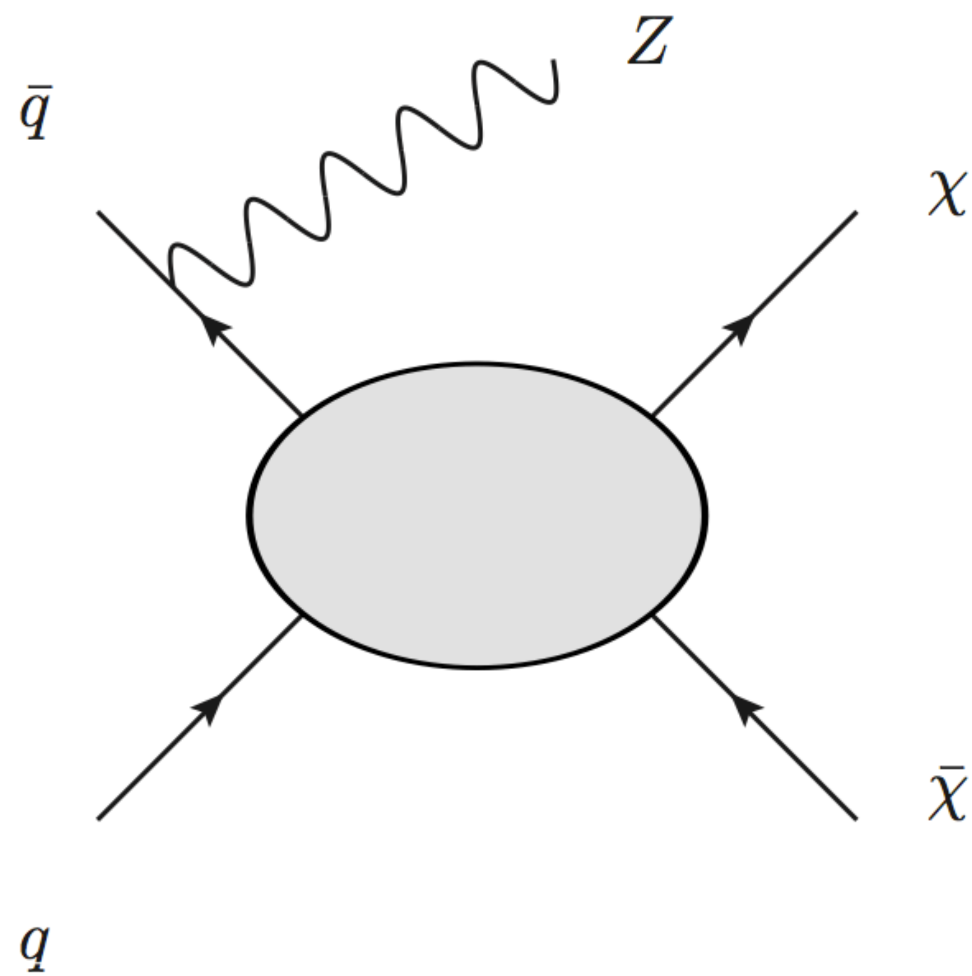


1307.5064

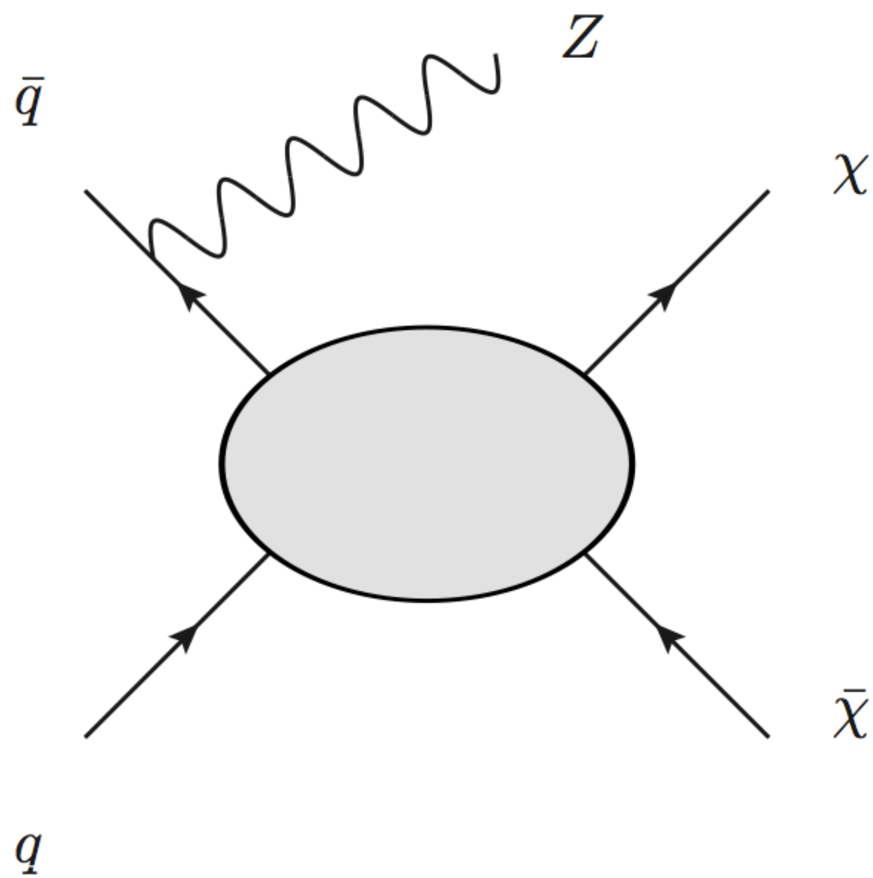
k1 and k2 control relative couplings to EW bosons

$$
\begin{aligned}
g_{WW} &= \frac{2k_2}{s_w^2 \Lambda^{2-3}} \\
g_{ZZ} &= \frac{1}{4 s_w^2 \Lambda^{2-3}} \left(\frac{k_1 s_w^2}{c_w^2} + \frac{k_2 c_w^2}{s_w^2} \right) \\
g_{\gamma\gamma} &= \frac{1}{4 c_w^2} \frac{k_1 + k_2}{\Lambda^{2-3}} \\
g_{Z\gamma} &= \frac{1}{2 s_w c_w \Lambda^{2-3}} \left(\frac{k_2}{s_w^2} - \frac{k_1}{c_w^2} \right),
\end{aligned}
$$

Mono-Z



The basic idea



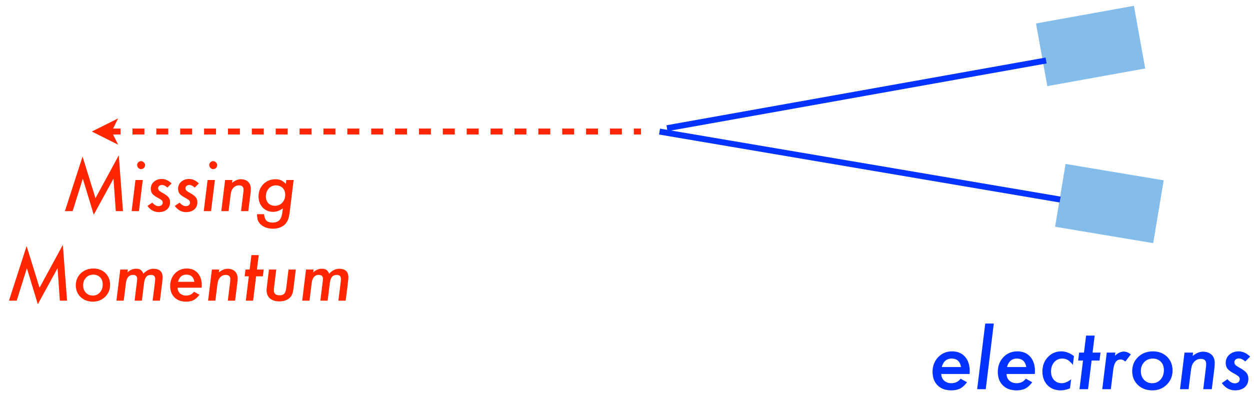
Final state:

Two WIMPs+Z

Detector signature

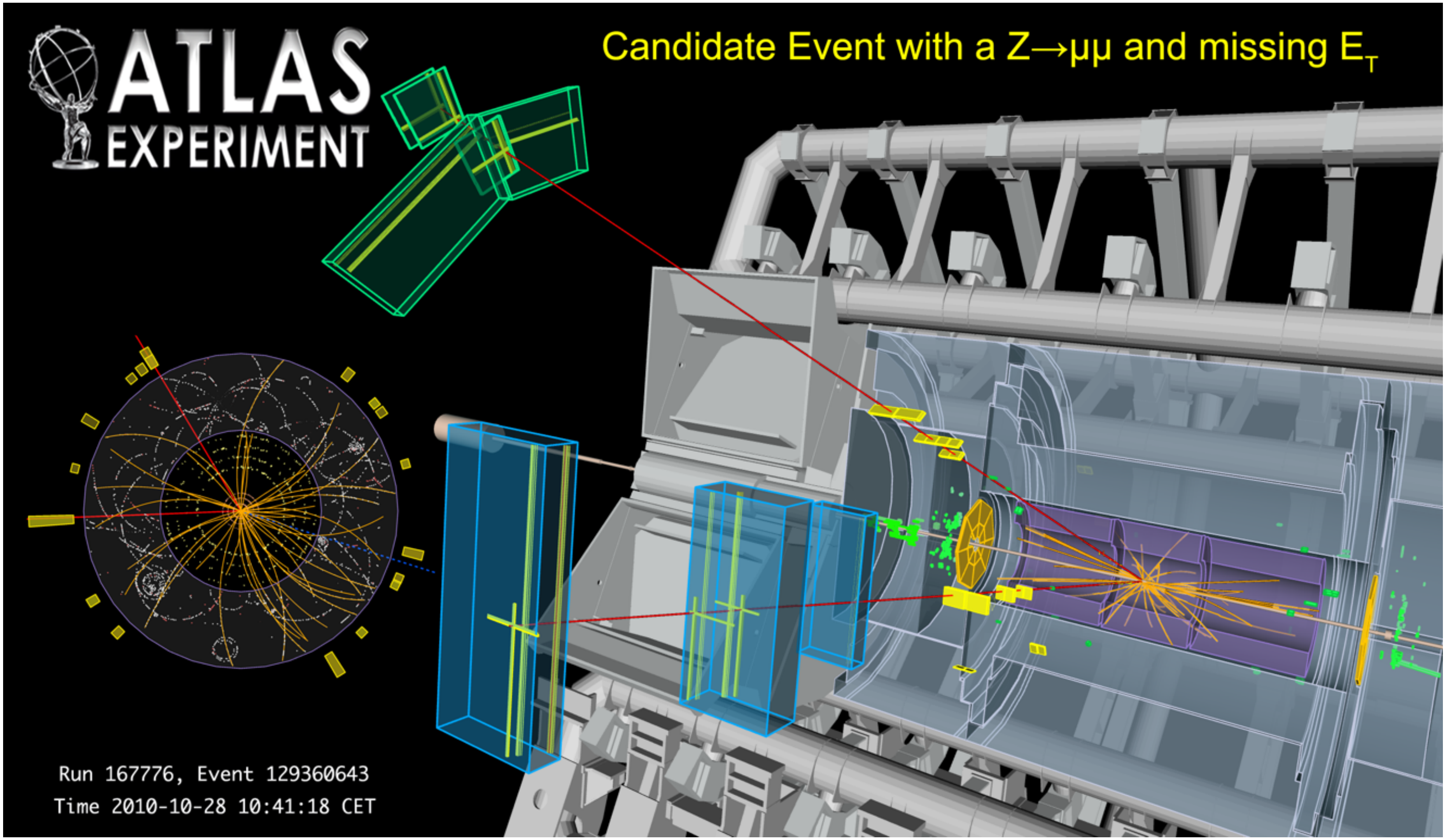
Z(->ll) + MET

Mono-Z leptonic

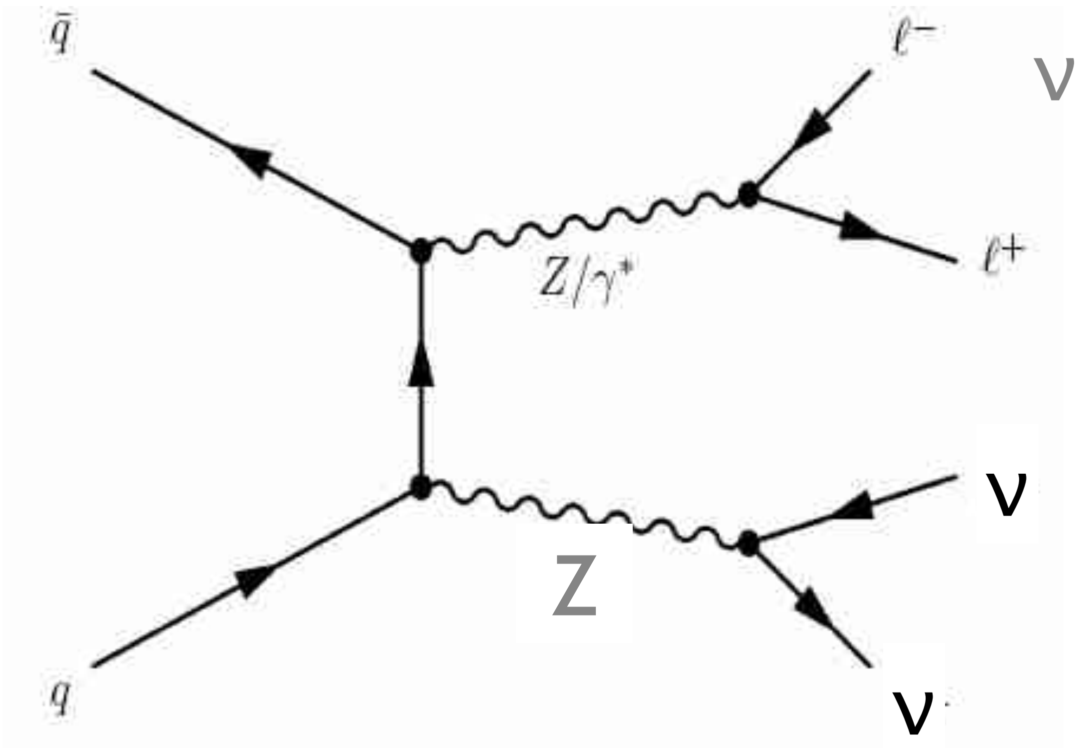


(muons too)

Mono-Z event


ATLAS EXPERIMENT
Candidate Event with a Z→μμ and missing E_T
Run 167776, Event 129360643
Time 2010-10-28 10:41:18 CET

Backgrounds



Final state:

Z + MET

Process:

ZZ to llνν

Others:

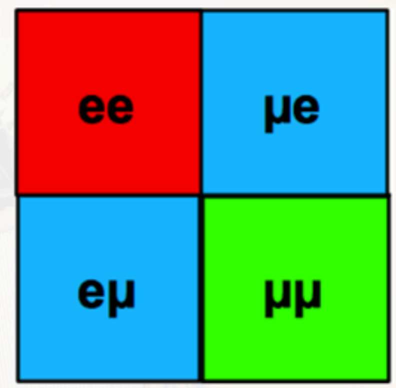
WZ,WW,tt

Wt,Z tt,WZ+jets

e-mu method

WW, tt, and Z→ττ backgrounds

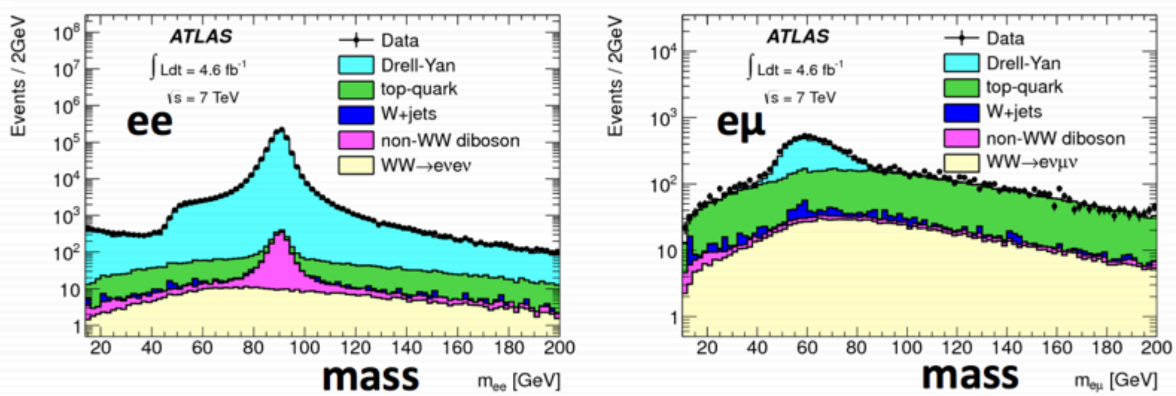
- *Data-driven* background estimate
  - Lower systematic uncertainty
- WW, tt, Wt, and Z→ττ backgrounds contribute to the ee and μμ signal regions **and** eμ region
  - ee:μμ:eμ as 1:1:2
- Correct for different lepton reconstruction efficiencies



from WW cross section paper "Phys. Rev. D 87, 112001 (2013)"

$$N_{ee}^{\text{bkg}} = \frac{1}{2} \times N_{e\mu}^{\text{data,sub}} \times k$$

- k=ratio of avg. elec and muon reconstruction efficiency



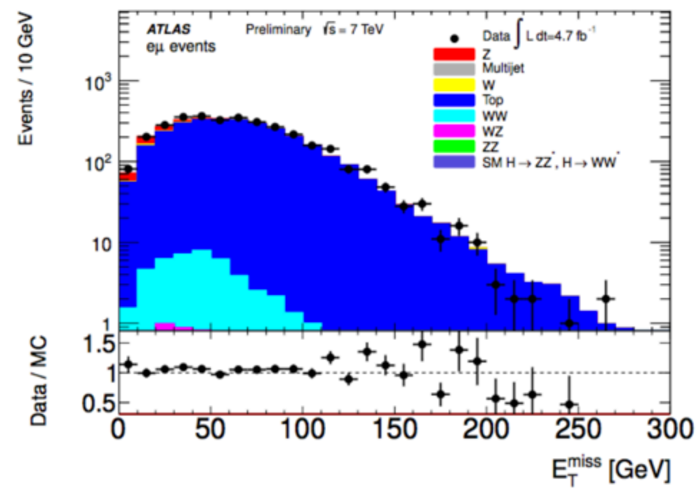
From A. Nelson

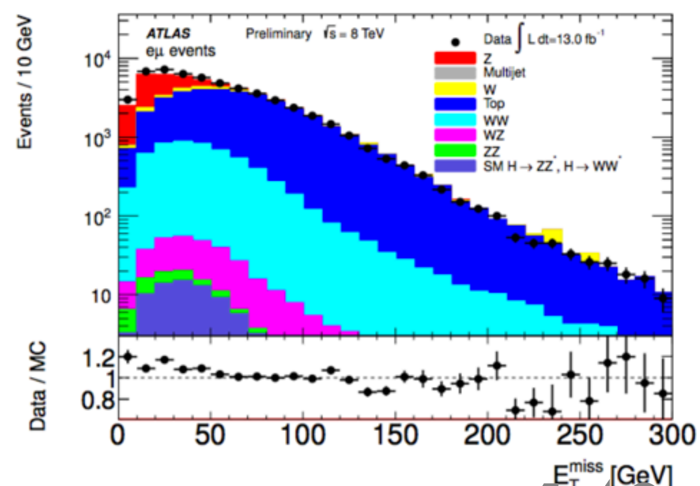
1404.0051

e-mu method

WW, tt, and Z→ττ backgrounds

- Find eμ events satisfying analysis cuts
- Subtract non-WW, tt, Wt, and Z→ττ backgrounds to get $N_{e\mu}$
  - other diboson, W+jets
- Systematic uncertainties
  - Includes:
    - Statistical uncertainty, $N_{e\mu}$
    - Efficiency correction factor, k
    - Systematics on MC subtraction
  - ~75% for mono-Z





From A. Nelson

1404.0051

Selection

two OSSF leptons, pt>20

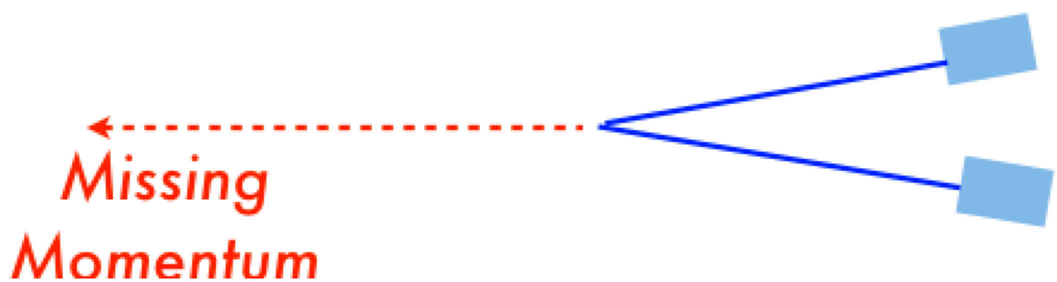
mll in 76-106

dphi(MET, pT_{LL}) > 2.5

$|p_T(\ell\ell) - \not{E}_T|/p_T(\ell\ell) < 0.5$

veto jet, 3rd lepton

MET > 150,250,350,400



1404.0051

Data

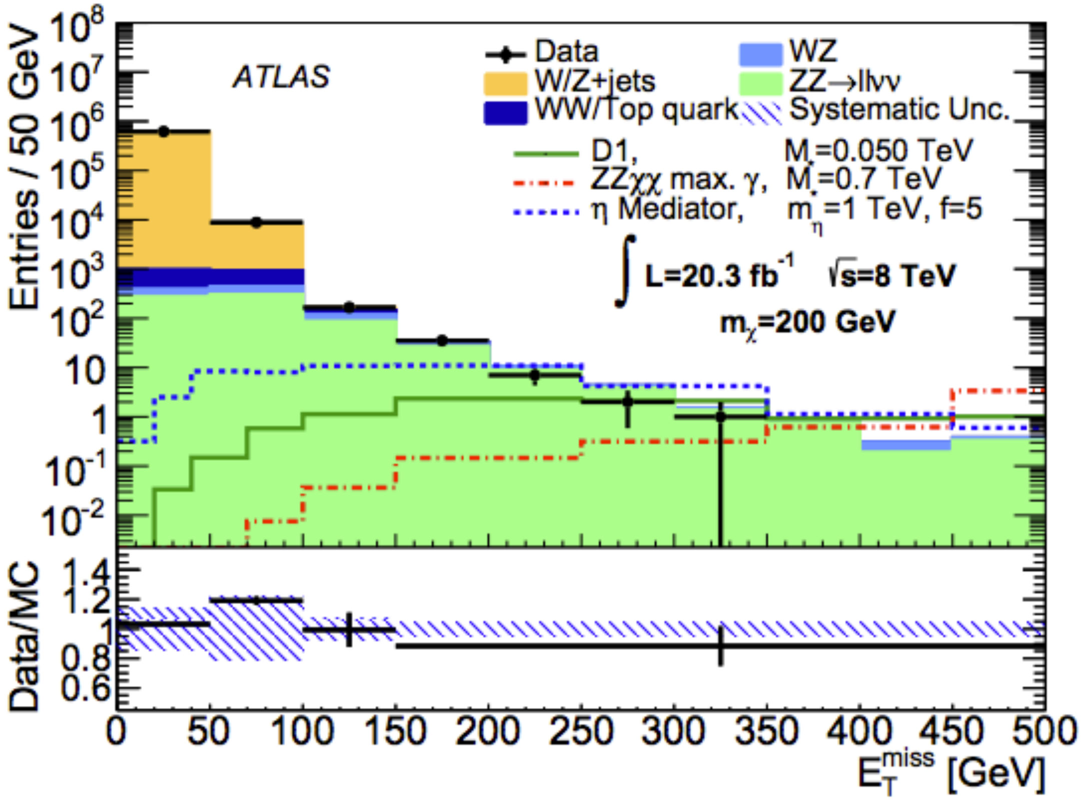
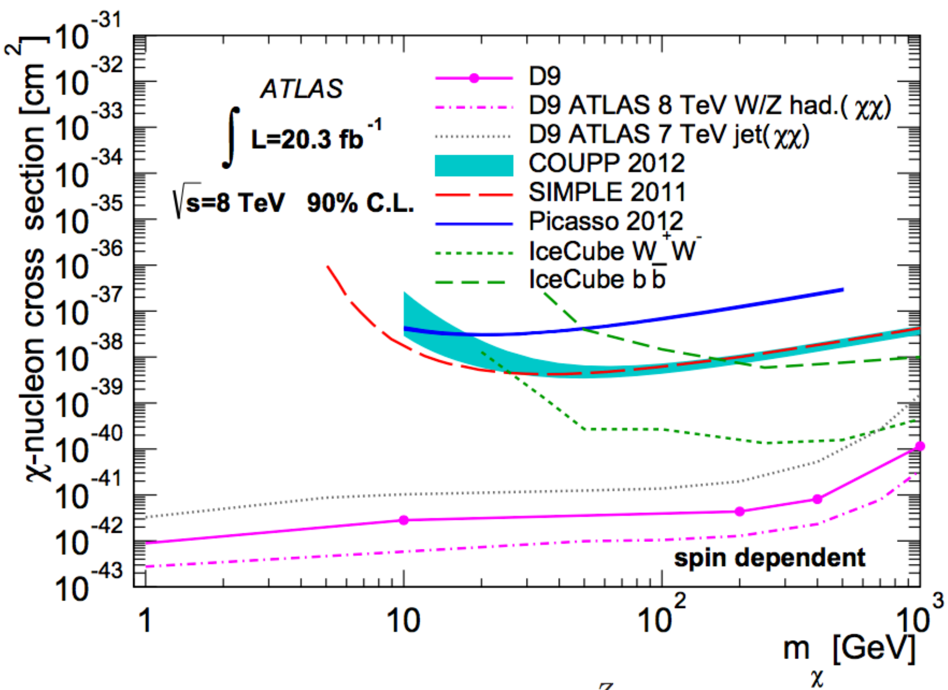
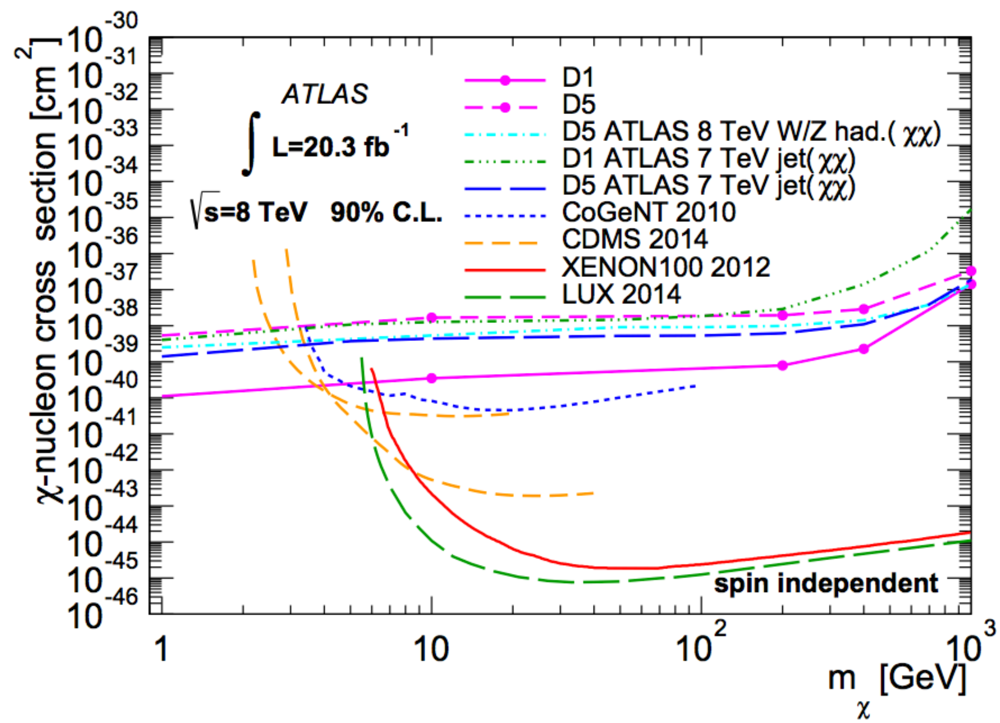


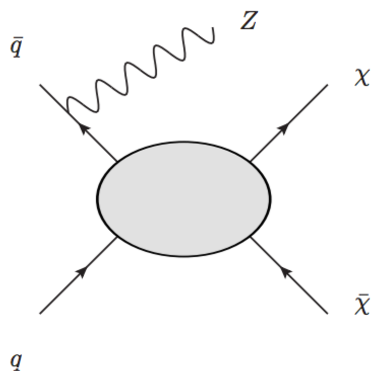
FIG. 11: $\not{E}_T$ distribution of the ATLAS mono-Z with $Z \to \ell\ell$ search [76].

1404.0051

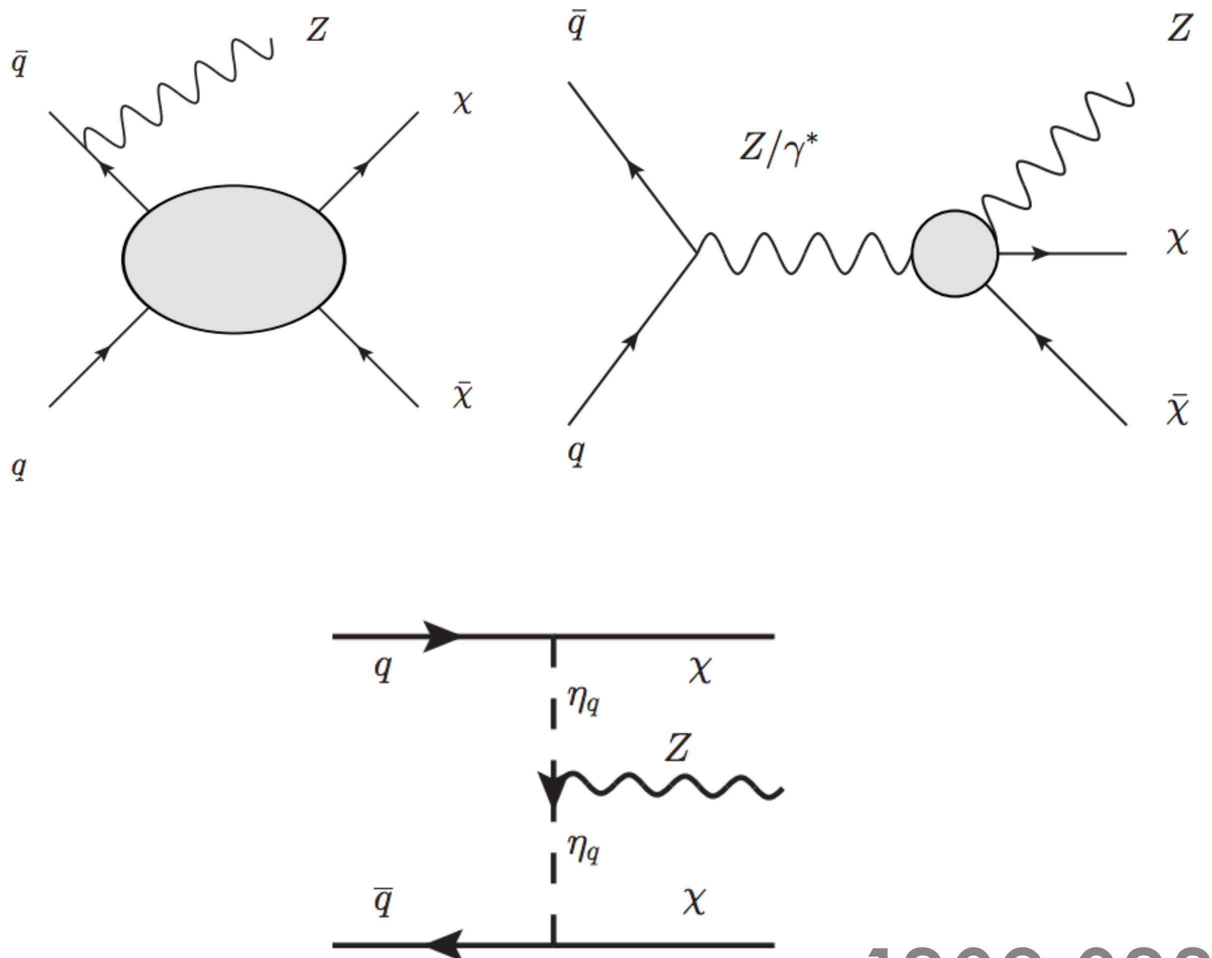
Limits


ATLAS
∫ L=20.3 fb⁻¹
√s=8 TeV 90% C.L.
D9
D9 ATLAS 8 TeV W/Z had.(χχ)
D9 ATLAS 7 TeV jet(χχ)
COUPP 2012
SIMPLE 2011
Picasso 2012
IceCube W+W-
IceCube b b̄
spin dependent
χ-nucleon cross section [cm²]
m_χ [GeV]


ATLAS
∫ L=20.3 fb⁻¹
√s=8 TeV 90% C.L.
D1
D5
D5 ATLAS 8 TeV W/Z had.(χχ)
D1 ATLAS 7 TeV jet(χχ)
D5 ATLAS 7 TeV jet(χχ)
CoGeNT 2010
CDMS 2014
XENON100 2012
LUX 2014
spin independent
χ-nucleon cross section [cm²]
m_χ [GeV]

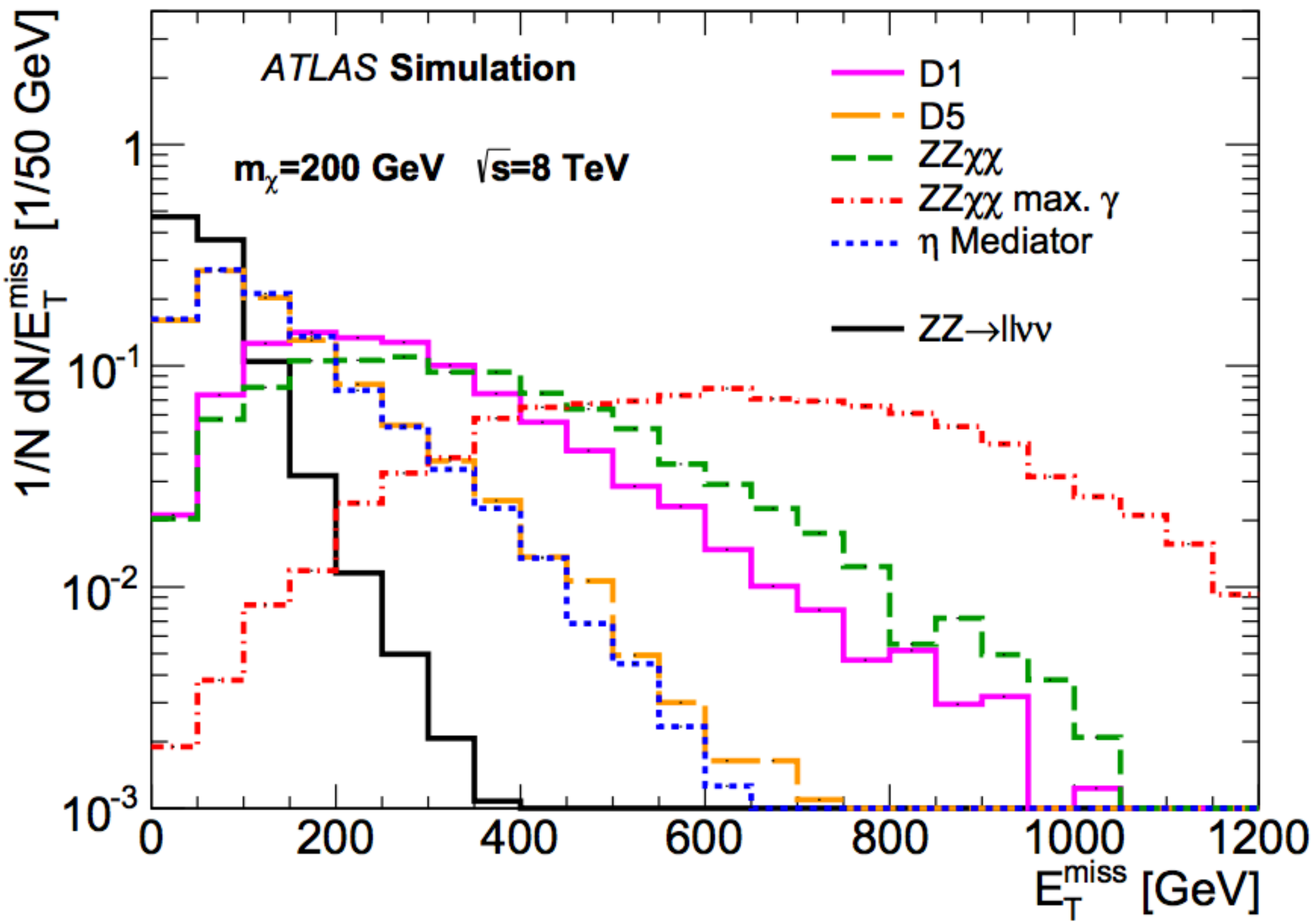

q̄
Z
χ
χ̄
q

Models



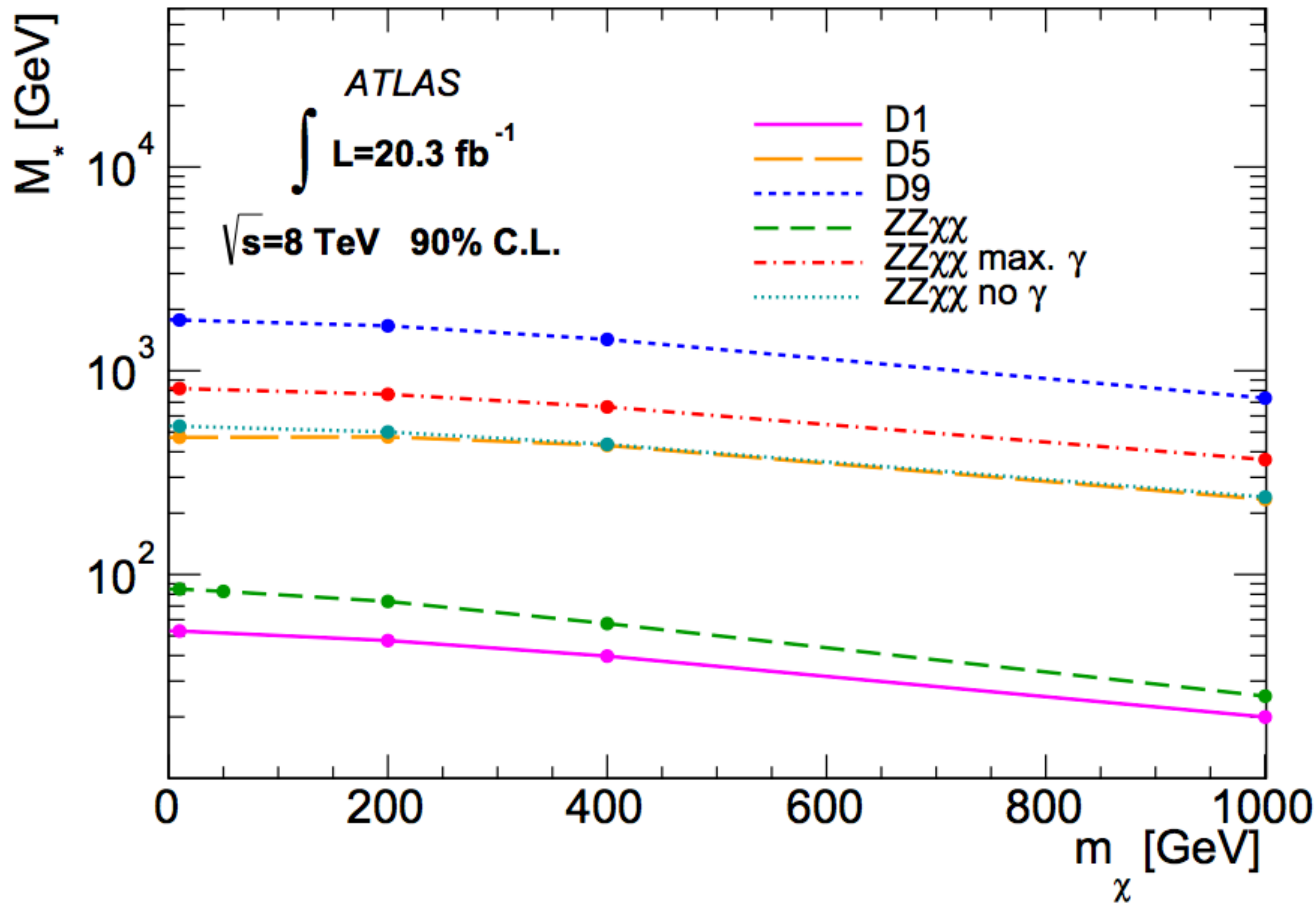
1209.0231

MET shapes

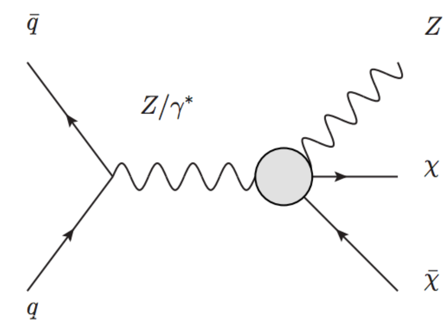


ATLAS Simulation
m_χ=200 GeV $\sqrt{s}$=8 TeV
D1
D5
ZZχχ
ZZχχ max. γ
η Mediator
ZZ→llνν
1/N dN/E_T^{miss} [1/50 GeV]
E_T^{miss} [GeV]
1
10^{-1}
10^{-2}
10^{-3}
0
200
400
600
800
1000
1200

ZZxx limits

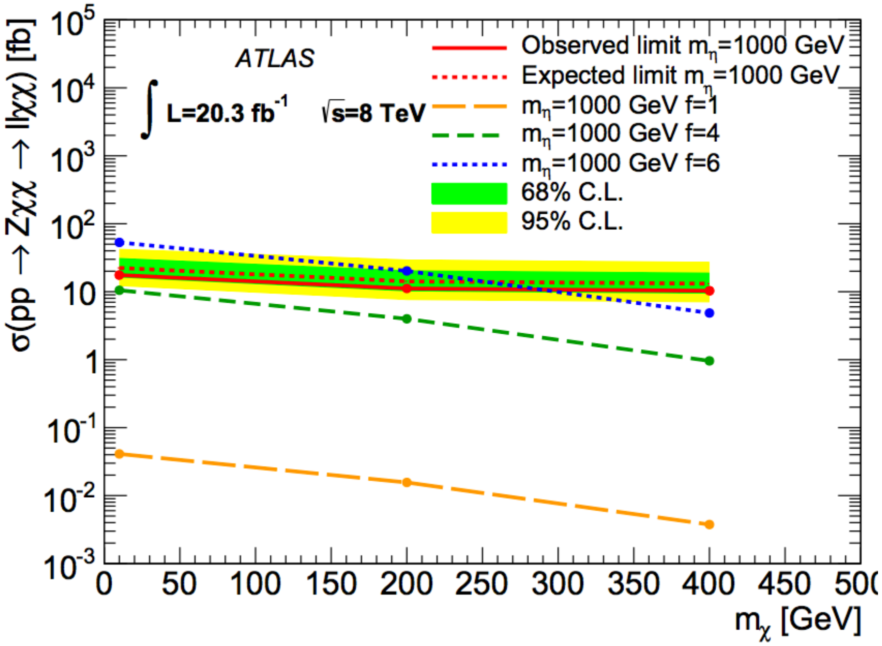


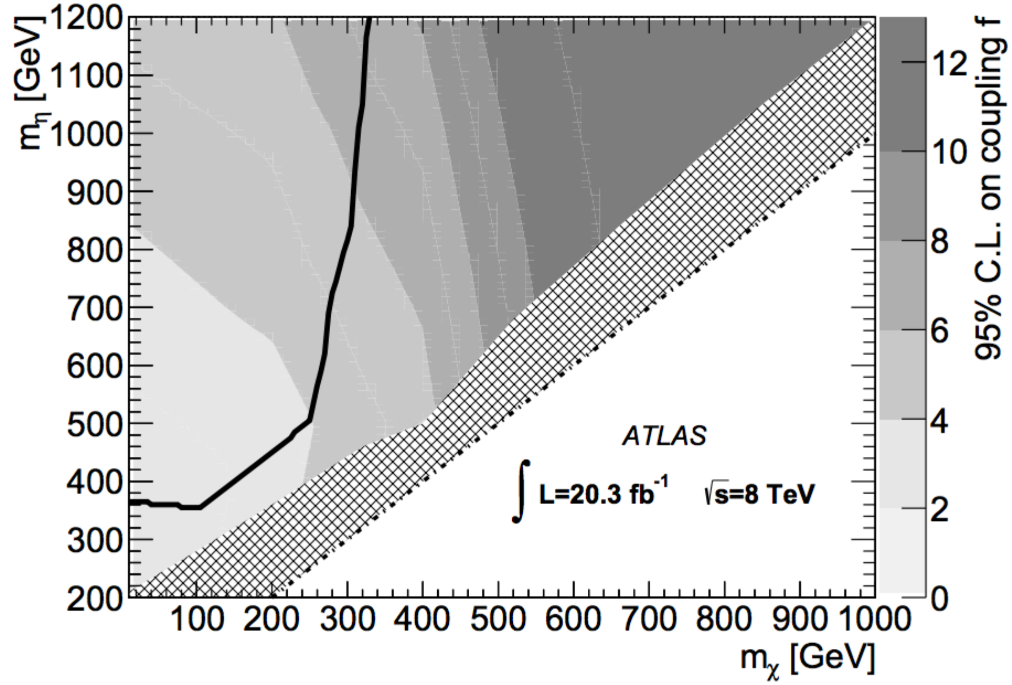
ATLAS
∫ L=20.3 fb⁻¹
√s=8 TeV 90% C.L.
D1
D5
D9
ZZχχ
ZZχχ max. γ
ZZχχ no γ
M* [GeV]
m_χ [GeV]

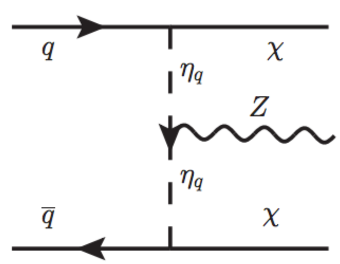


q̄
q
Z/γ*
Z
χ
χ̄

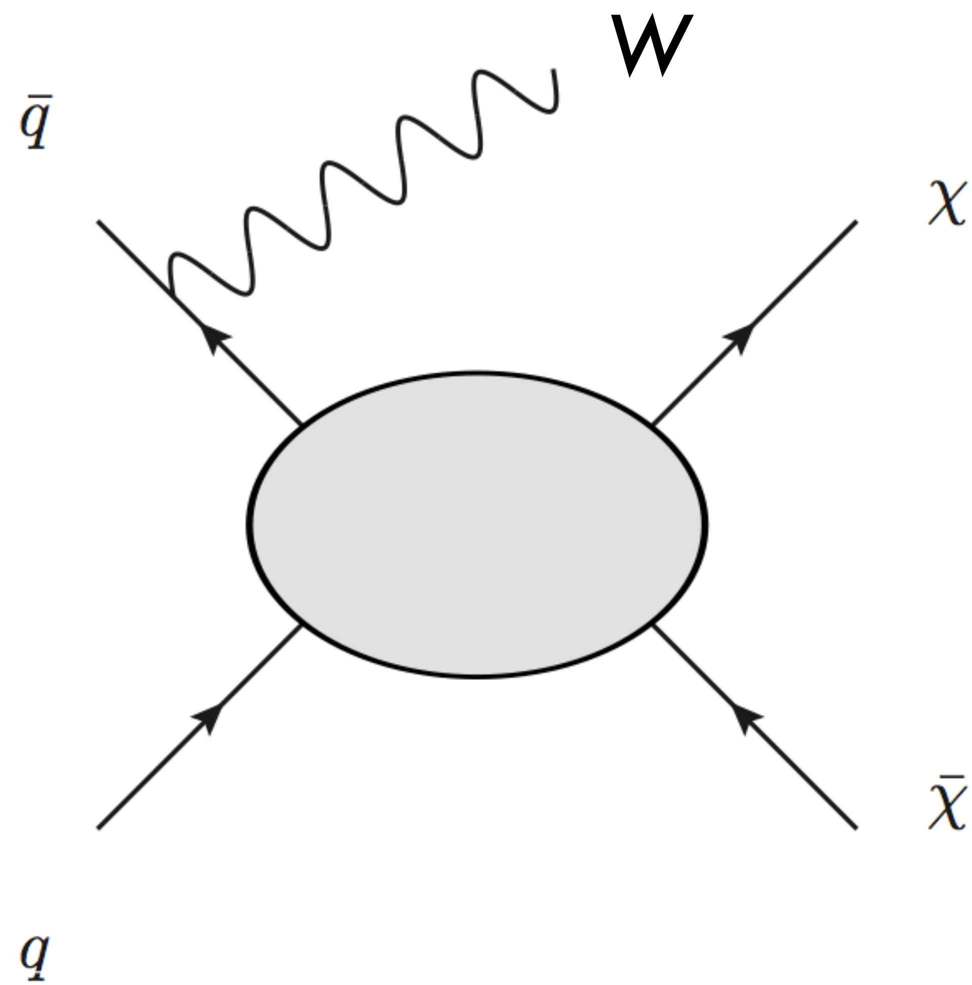
Simplified Model limits



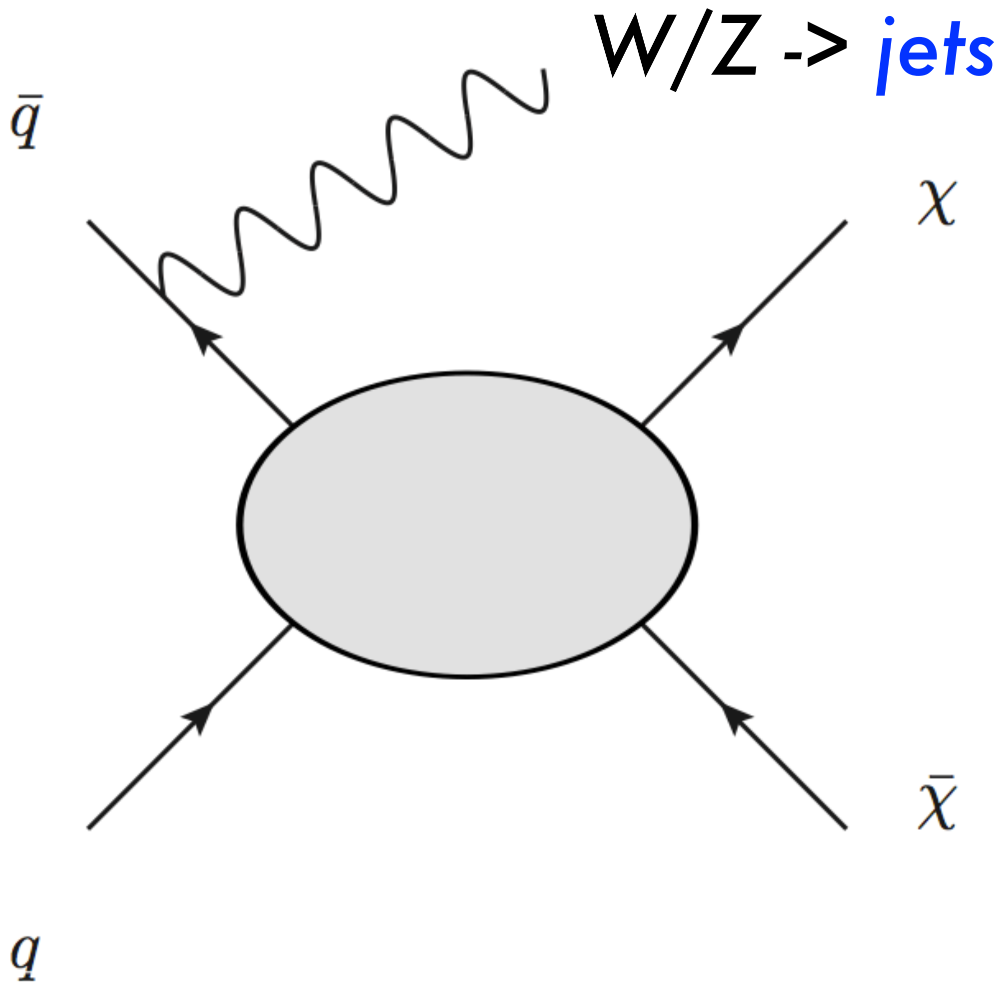




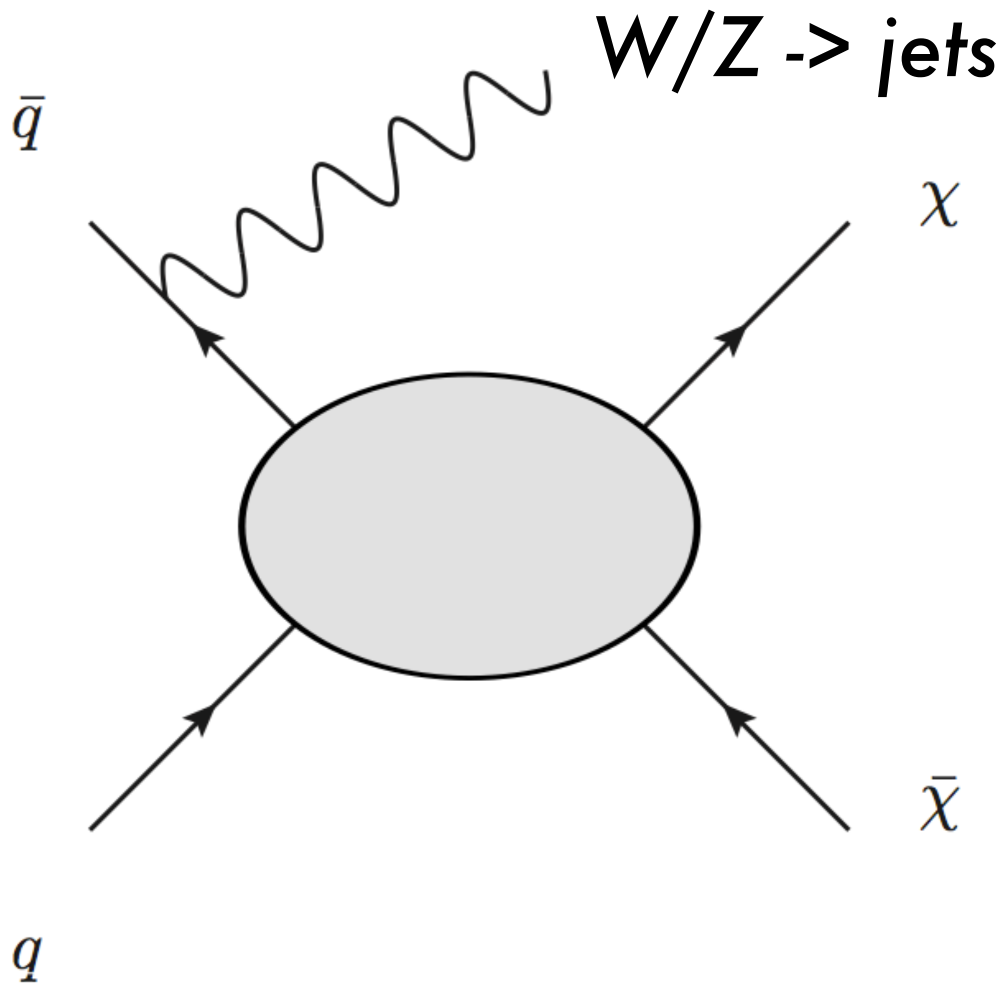
Mono-W



Mono-W



The basic idea



Final state:

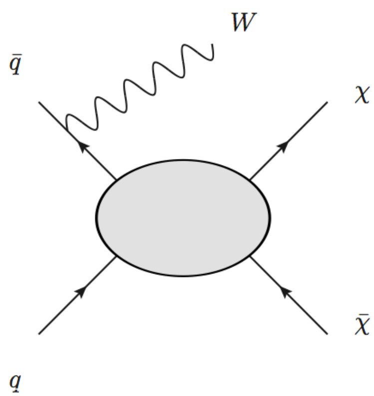
Two WIMPs+two jets

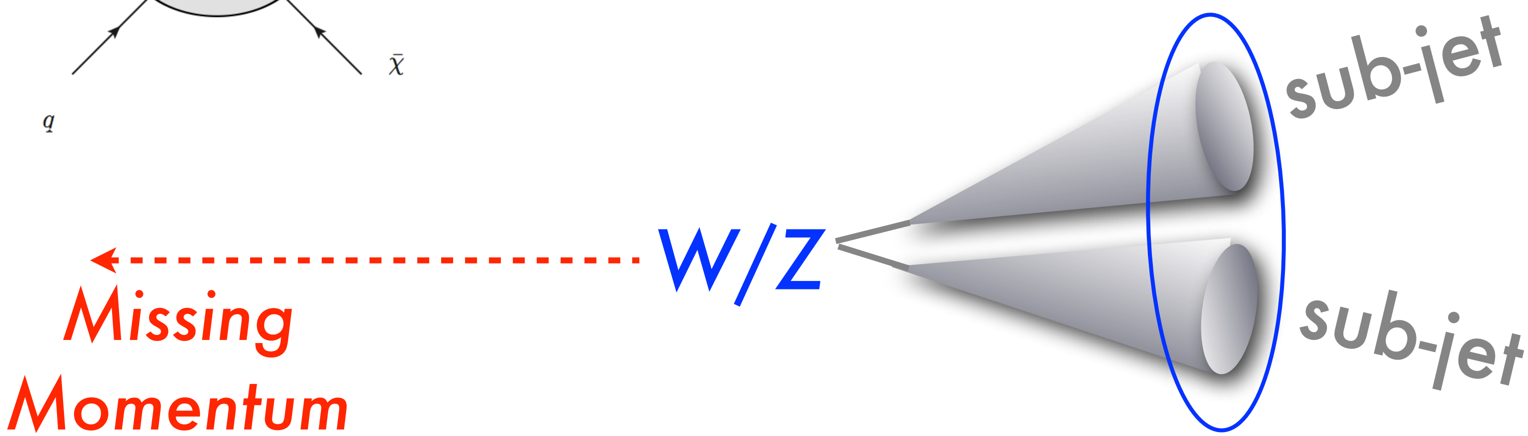
Detector signature

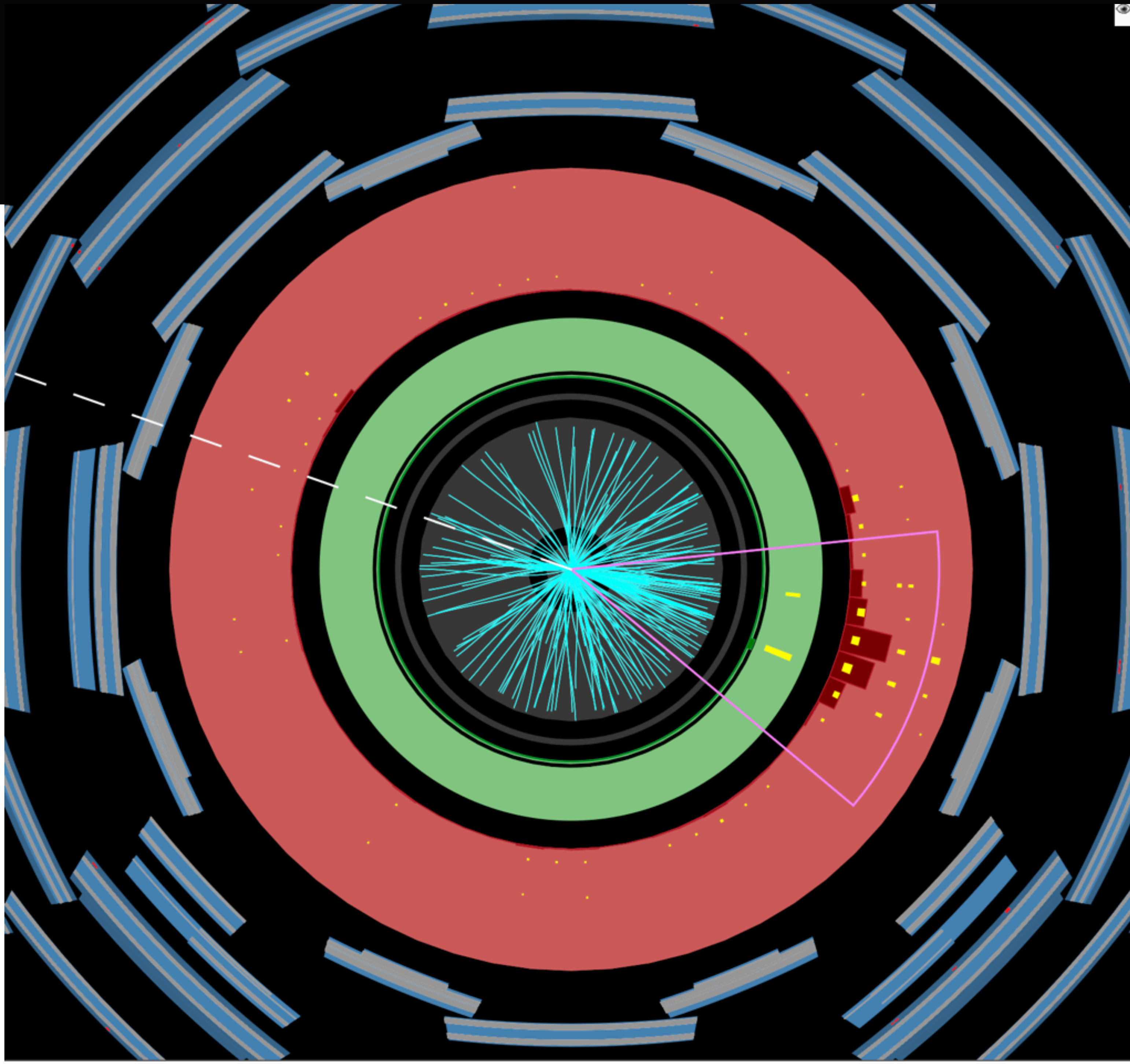
jj + MET

Mono-heavy jet

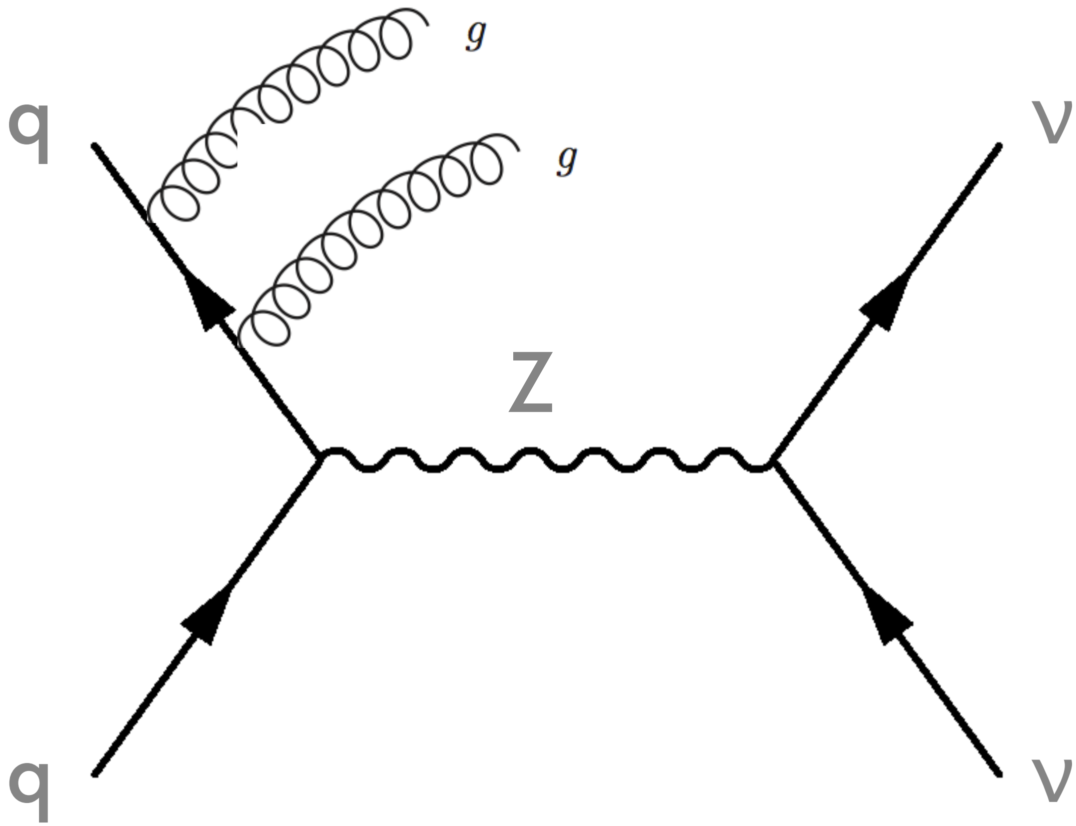
1309.4017 (PRL)







Backgrounds



<u>Final state:</u>

jets + MET

<u>Process:</u>

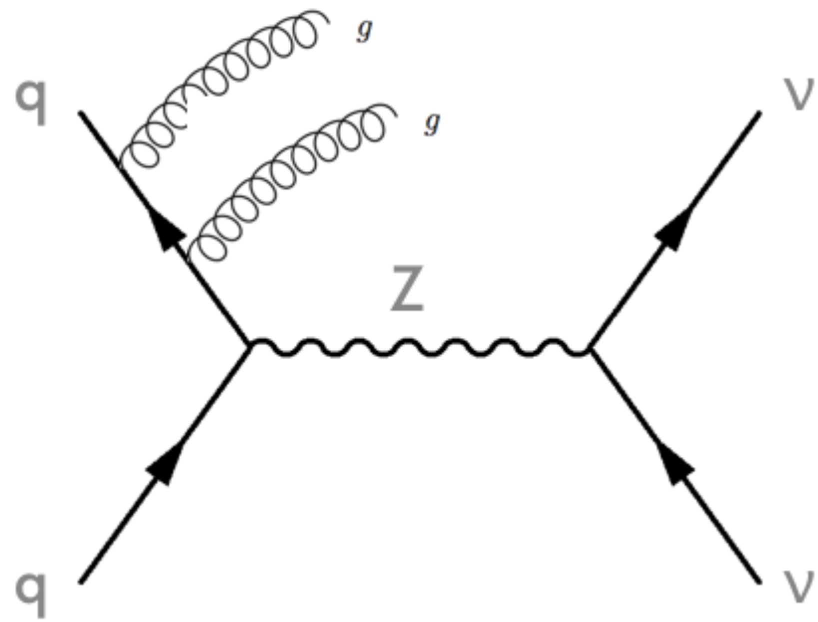
Z to ν ν, with jets

Backgrounds

How to estimate?

Idea: theory cross-section σ
efficiency ε from MC

$N = L \times \sigma \times \varepsilon$



Problem: very large theory uncertainties

Background estimate

Signal

0 leptons
2 jets
MET

W->lv
Z->vv

Control

1 lepton
2 jets
MET

W->lv
Z->ll

Validation

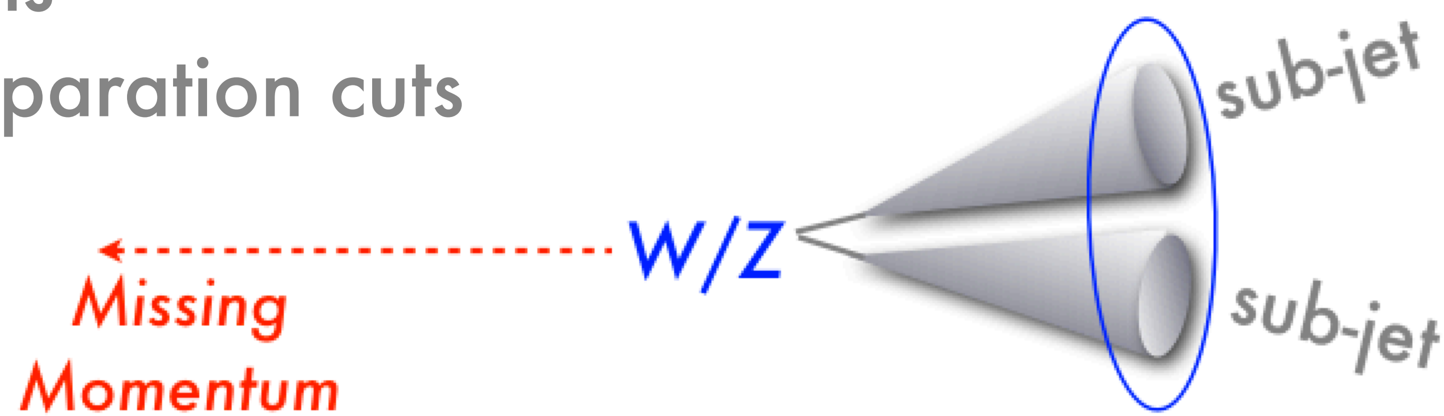
2 leptons
2 jets
MET

Z->ll

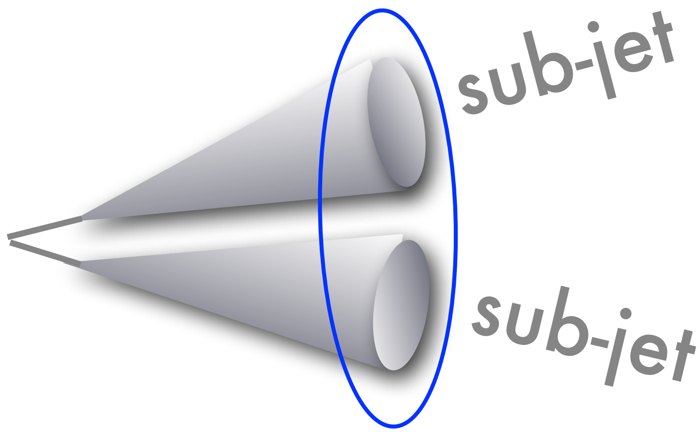
Selection

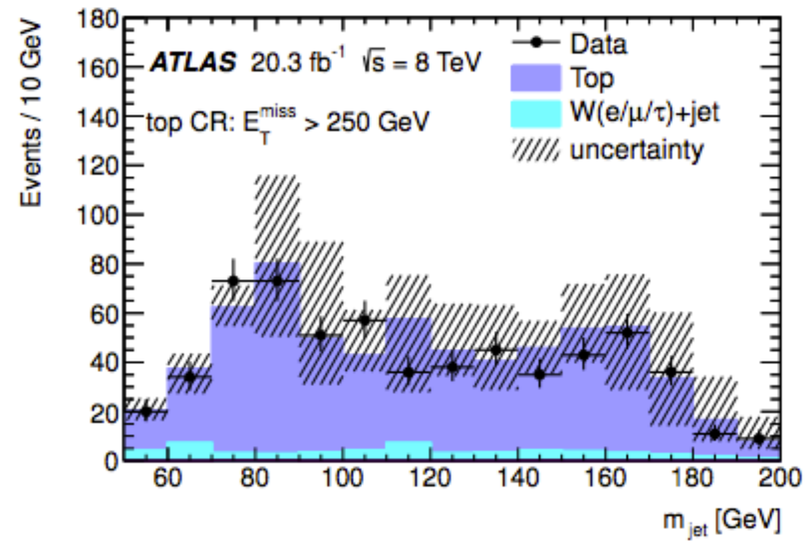
1 fat jet with pT>250
M_{jj} in 50-120
√y>0.4
MET > 350,500
<= 1 narrow jet pt>40
veto leptons
angular separation cuts

$$\sqrt{y} = \min(p_{T1}, p_{T2})\Delta R / m_{jet}$$



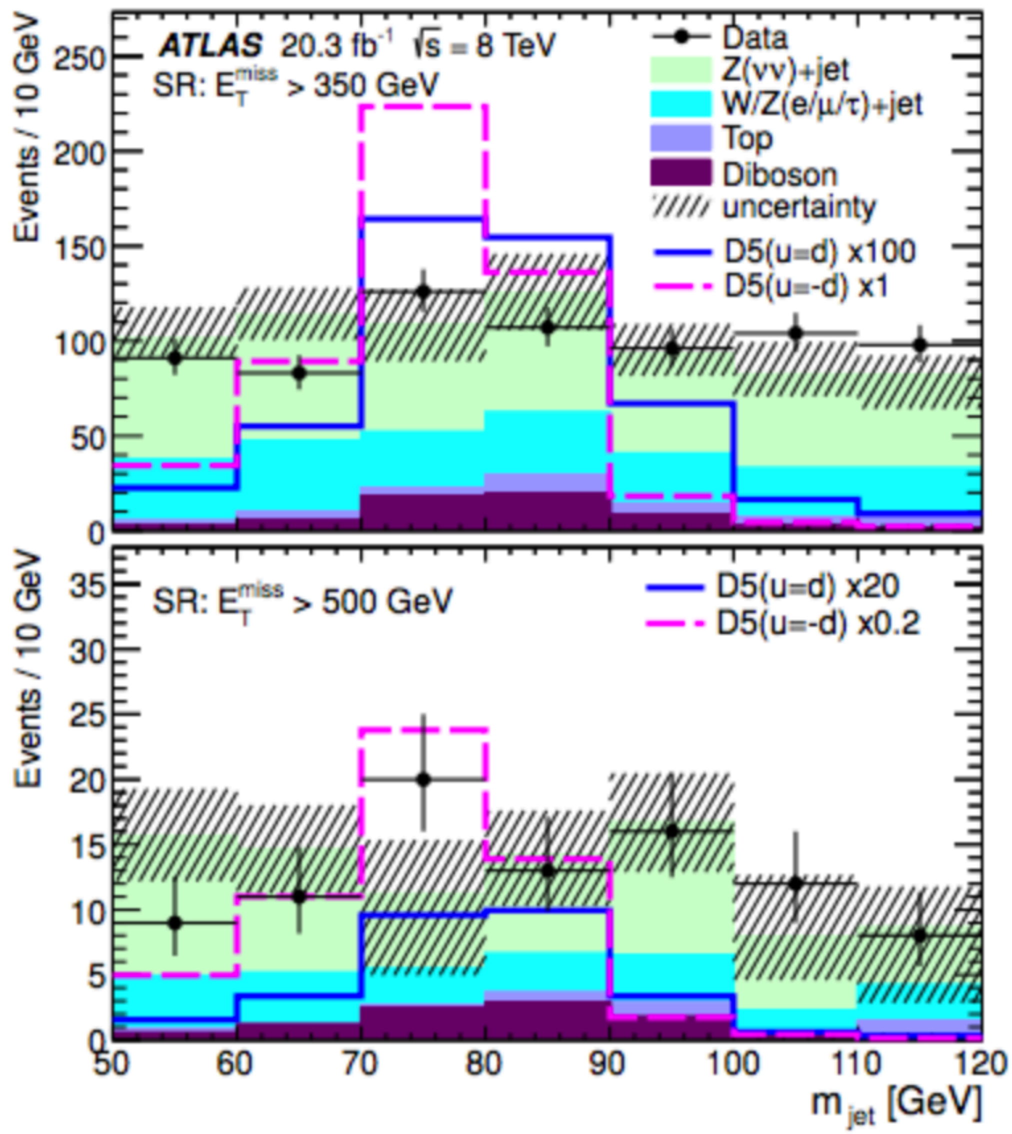
Jet mass





Verify we can see W->jj when we know it is there!

Data



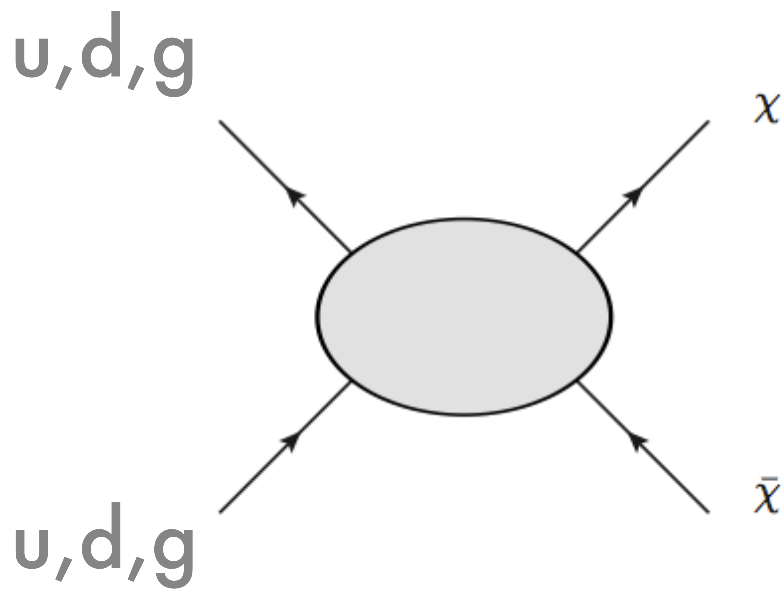
ATLAS 20.3 fb⁻¹ √s = 8 TeV
SR: E_T^{miss} > 350 GeV
Data
Z(νν)+jet
W/Z(e/μ/τ)+jet
Top
Diboson
uncertainty
D5(u=d) x100
D5(u=-d) x1
Events / 10 GeV
SR: E_T^{miss} > 500 GeV
D5(u=d) x20
D5(u=-d) x0.2
Events / 10 GeV
m_{jet} [GeV]

Data

Process	$E_T^{miss} > 350$ GeV	$E_T^{miss} > 500$ GeV
$Z \to \nu\bar{\nu}$	402^{+39}_{-34}	54^{+8}_{-10}
$W \to \ell^{\pm}\nu$, $Z \to \ell^{\pm}\ell^{\mp}$	210^{+20}_{-18}	22^{+4}_{-5}
WW, WZ, ZZ	57^{+11}_{-8}	$9.1^{+1.3}_{-1.1}$
$t\bar{t}$, single t	39^{+10}_{-4}	$3.7^{+1.7}_{-1.3}$
Total	707^{+48}_{-38}	89^{+9}_{-12}
Data	705	89

Collider power

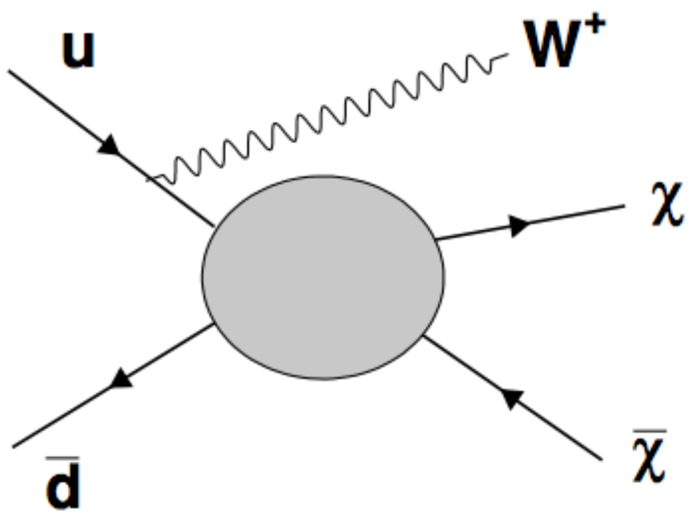
Unique possibility



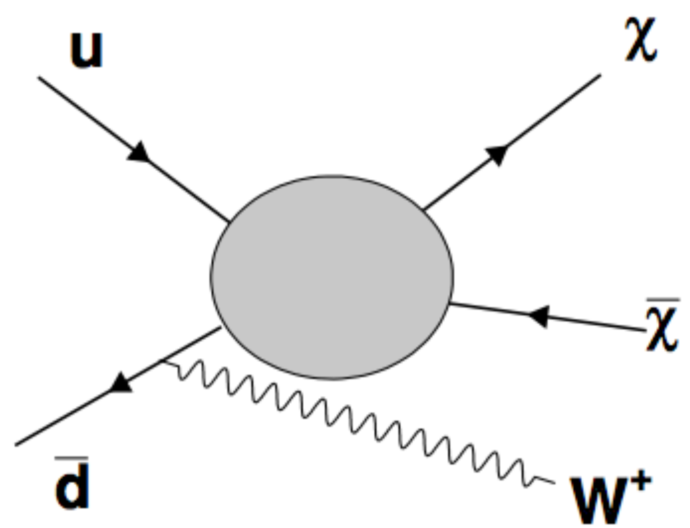
to probe **up-type, down-type** and **gluon** couplings

Interference

ddXX

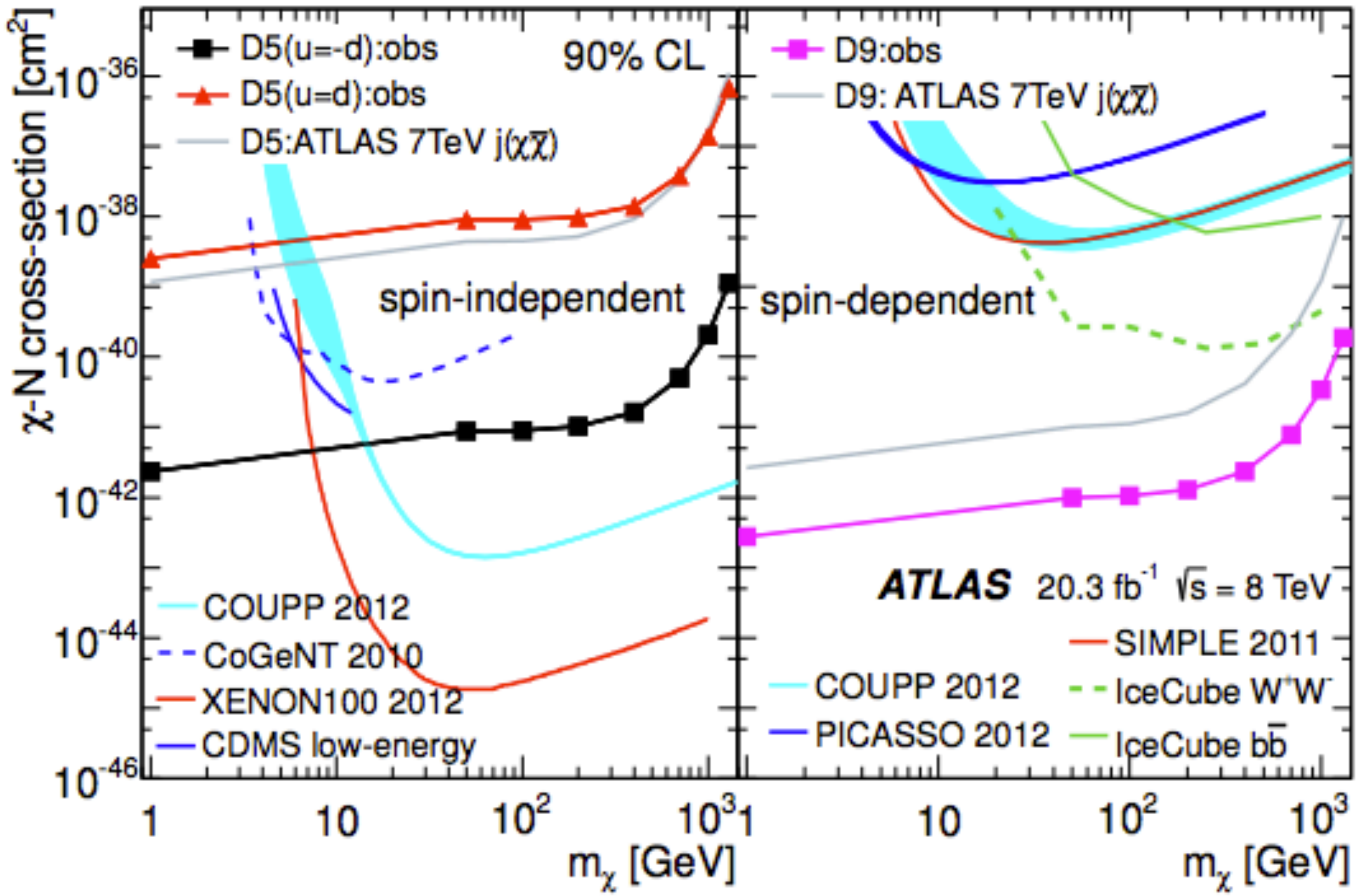


uuXX



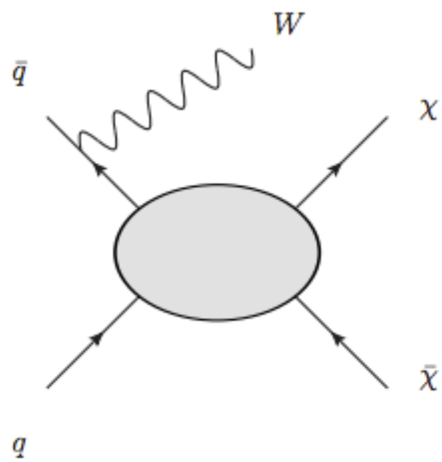
If sign of u and d couplings are opposite, large constructive interference, giving signal rates larger than mono-jet!

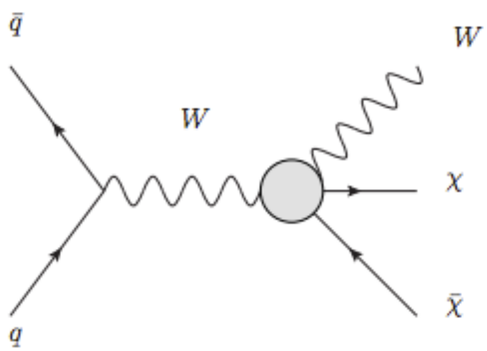
DM limits

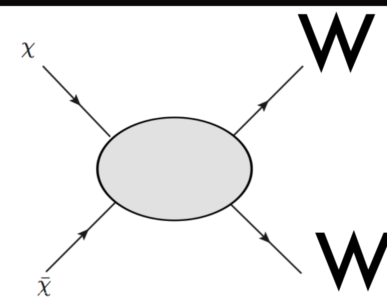


χ-N cross-section [cm²]
10^{-36}
10^{-38}
10^{-40}
10^{-42}
10^{-44}
10^{-46}
D5(u=-d):obs
D5(u=d):obs
D5:ATLAS 7TeV j(χχ̄)
90% CL
spin-independent
COUPP 2012
CoGeNT 2010
XENON100 2012
CDMS low-energy
1
10
10^2
10^3
m_χ [GeV]
D9:obs
D9: ATLAS 7TeV j(χχ̄)
spin-dependent
ATLAS 20.3 fb^{-1} $\sqrt{s}$ = 8 TeV
SIMPLE 2011
COUPP 2012
IceCube W^+W^-
PICASSO 2012
IceCube $b\bar{b}$

Reinterpret







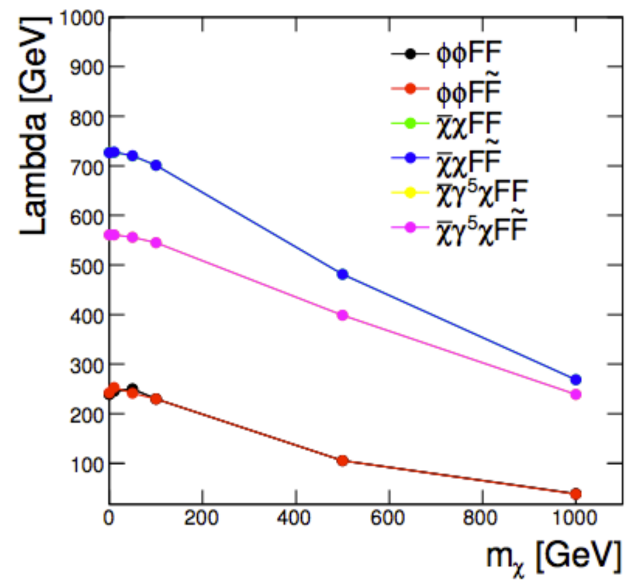
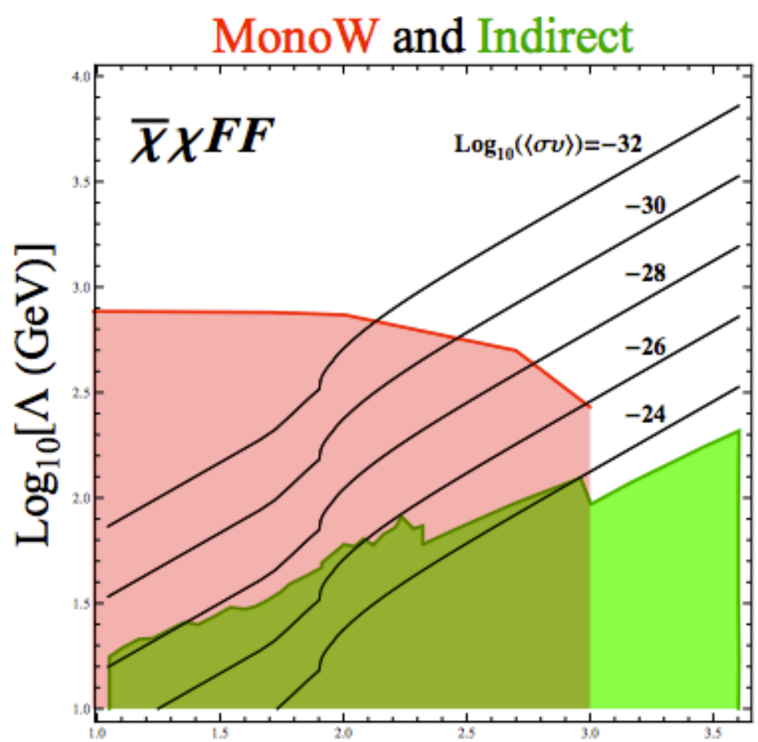
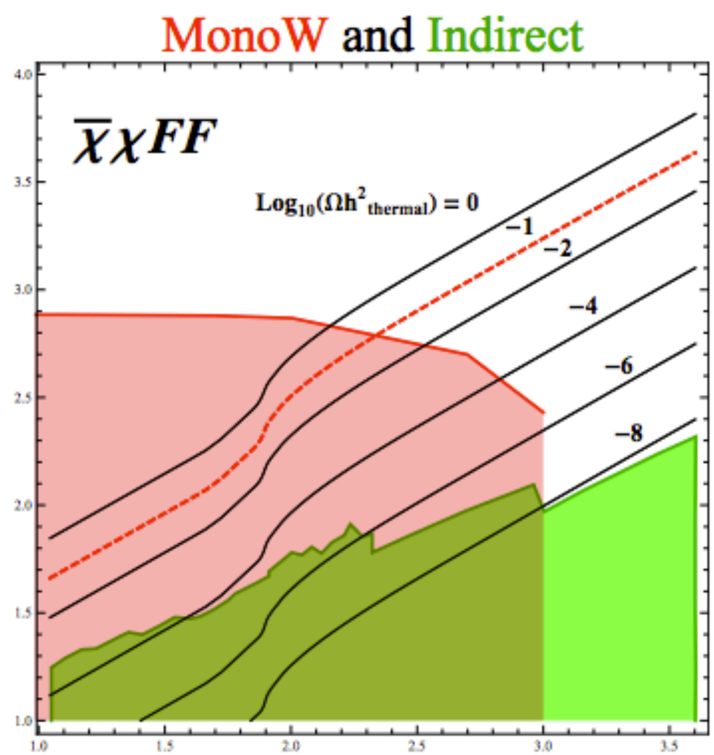


FIG. 4: Limits on Λ as a function of m_χ.

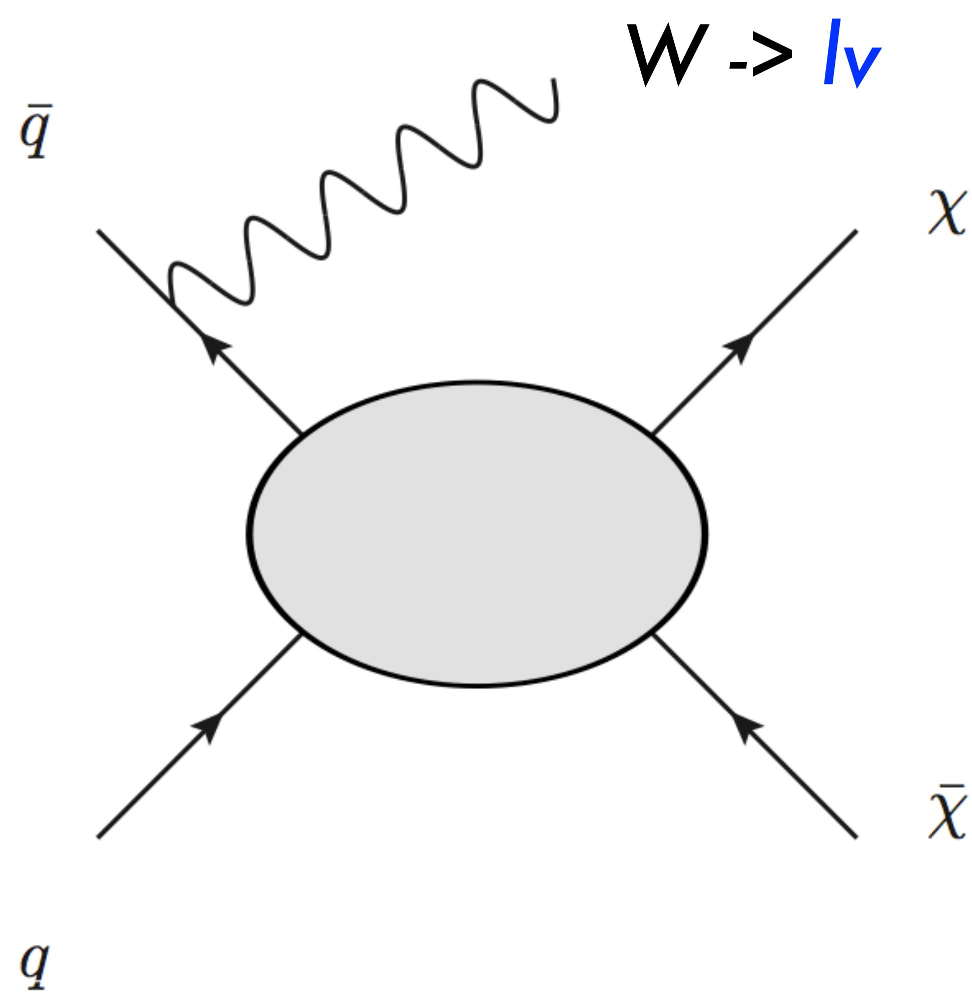
1403.6734

Collider->Indirect

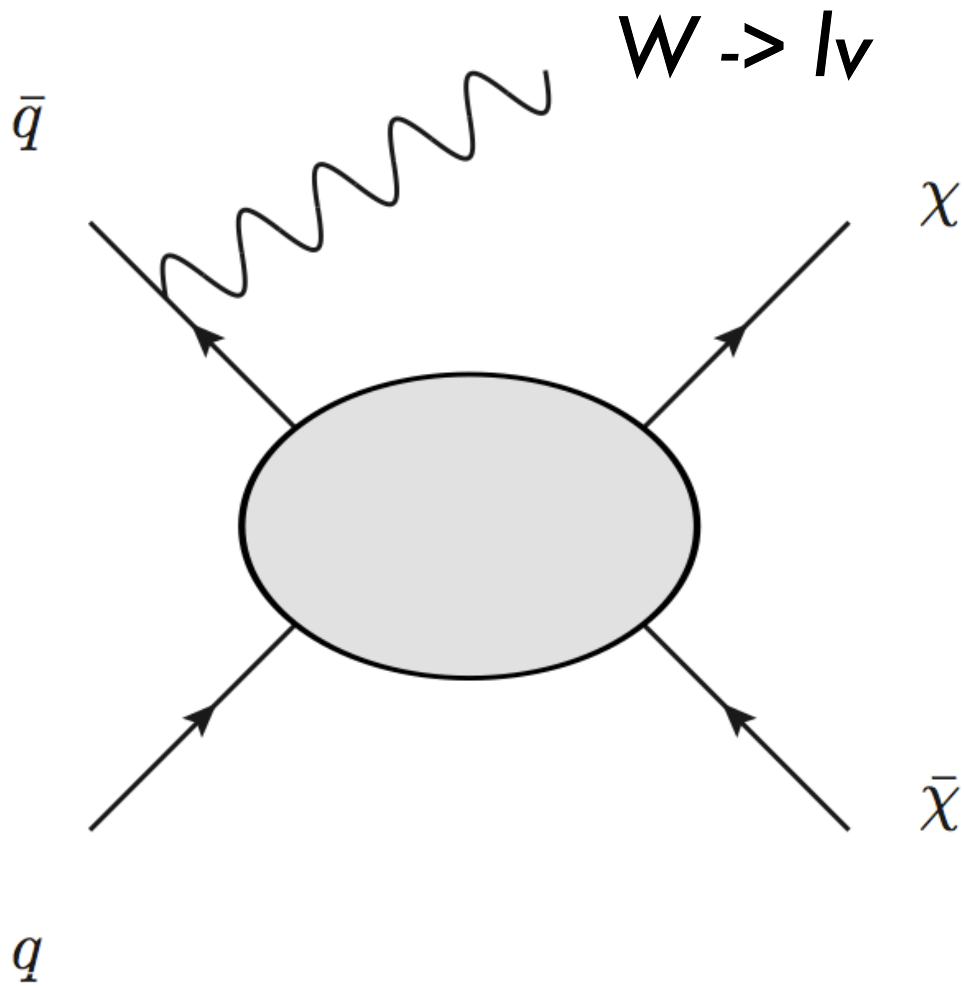




Mono-W



The basic idea



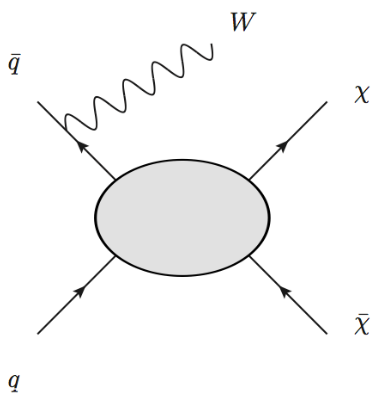
Final state:

Two WIMPs+lepton

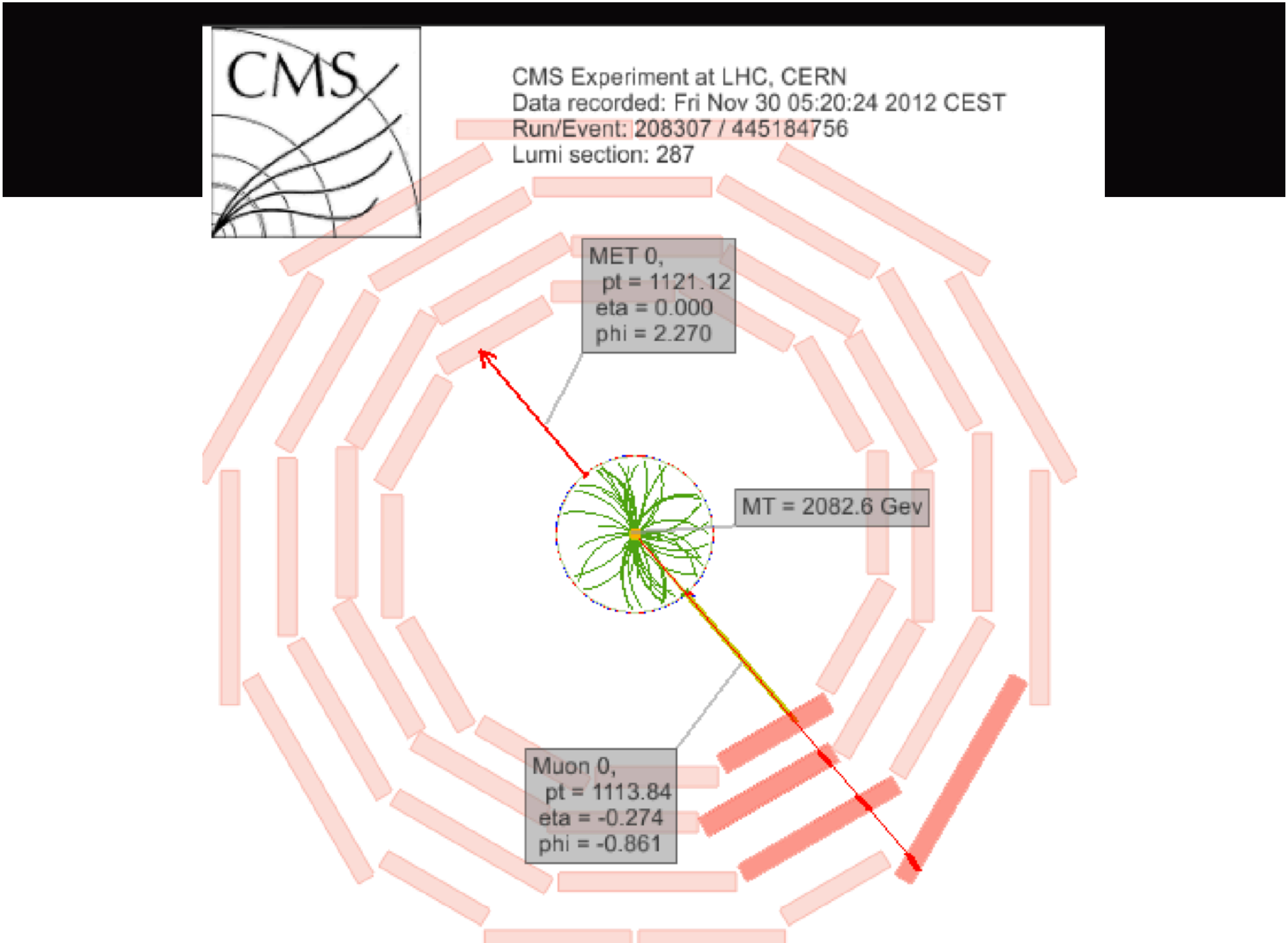
Detector signature

lepton + MET

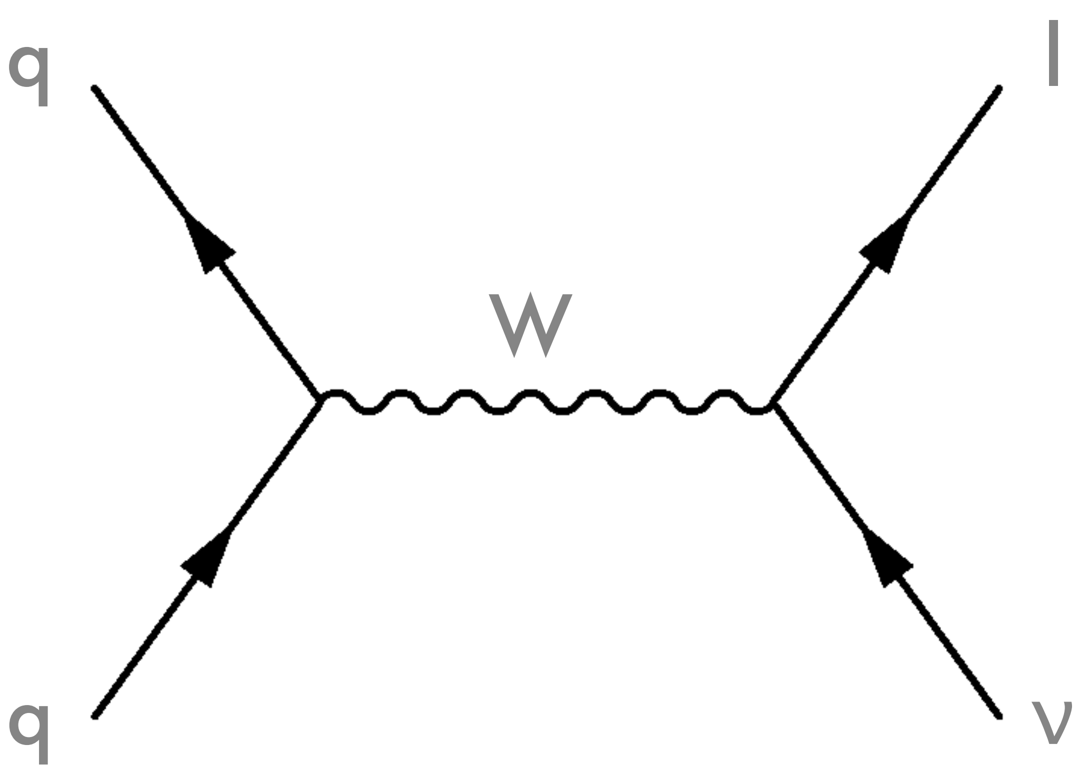
Mono-lepton



(muons too)


CMS
CMS Experiment at LHC, CERN
Data recorded: Fri Nov 30 05:20:24 2012 CEST
Run/Event: 208307 / 445184756
Lumi section: 287
MET 0,
pt = 1121.12
eta = 0.000
phi = 2.270
MT = 2082.6 Gev
Muon 0,
pt = 1113.84
eta = -0.274
phi = -0.861

Backgrounds



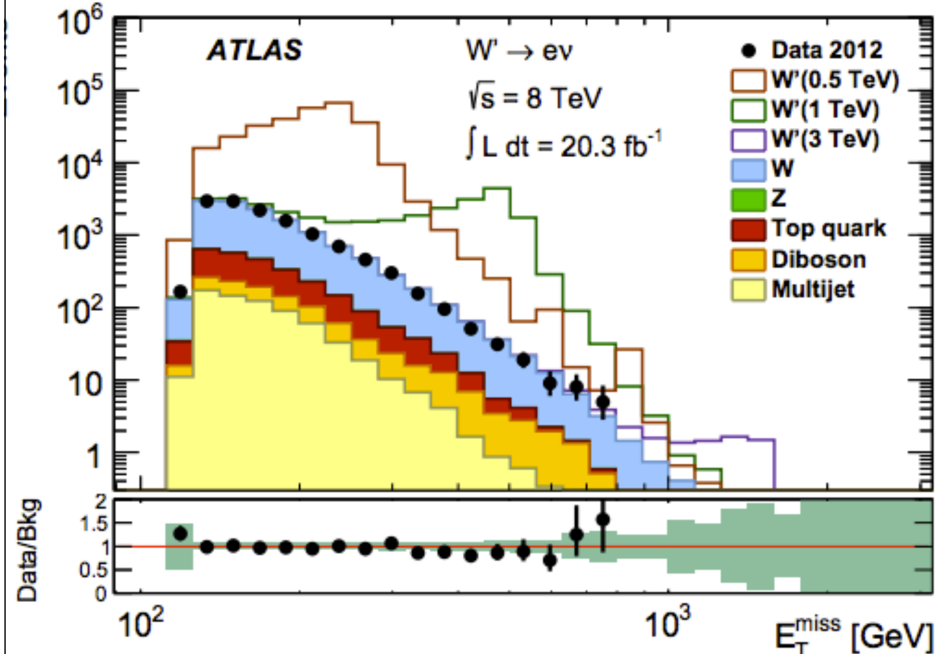
Final state:

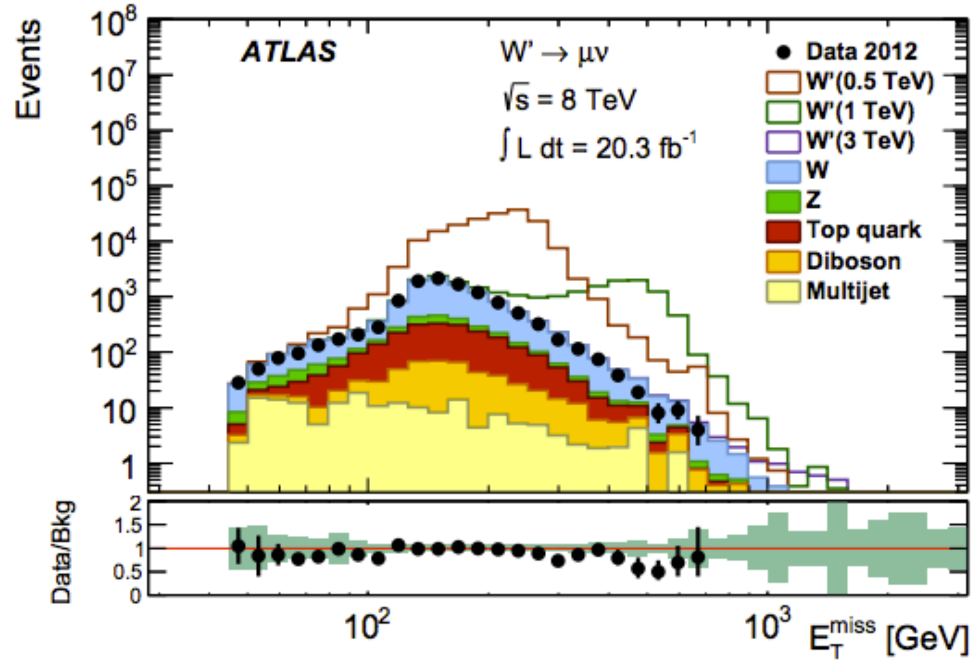
lepton + MET

Process:

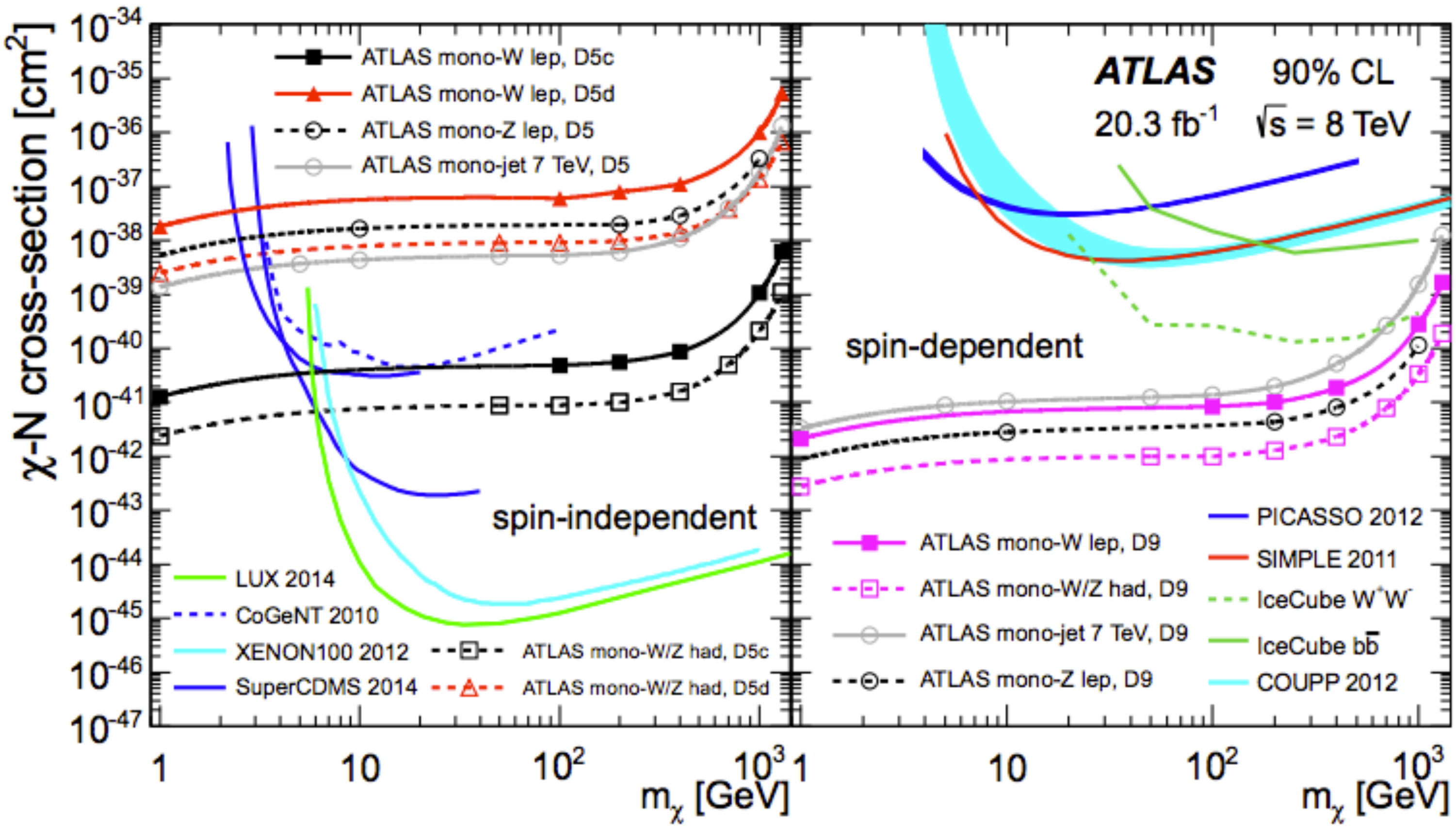
W to l ν

Data


ATLAS
W' → eν
√s = 8 TeV
∫L dt = 20.3 fb⁻¹
Data 2012
W'(0.5 TeV)
W'(1 TeV)
W'(3 TeV)
W
Z
Top quark
Diboson
Multijet
Data/Bkg
E_T^miss [GeV]

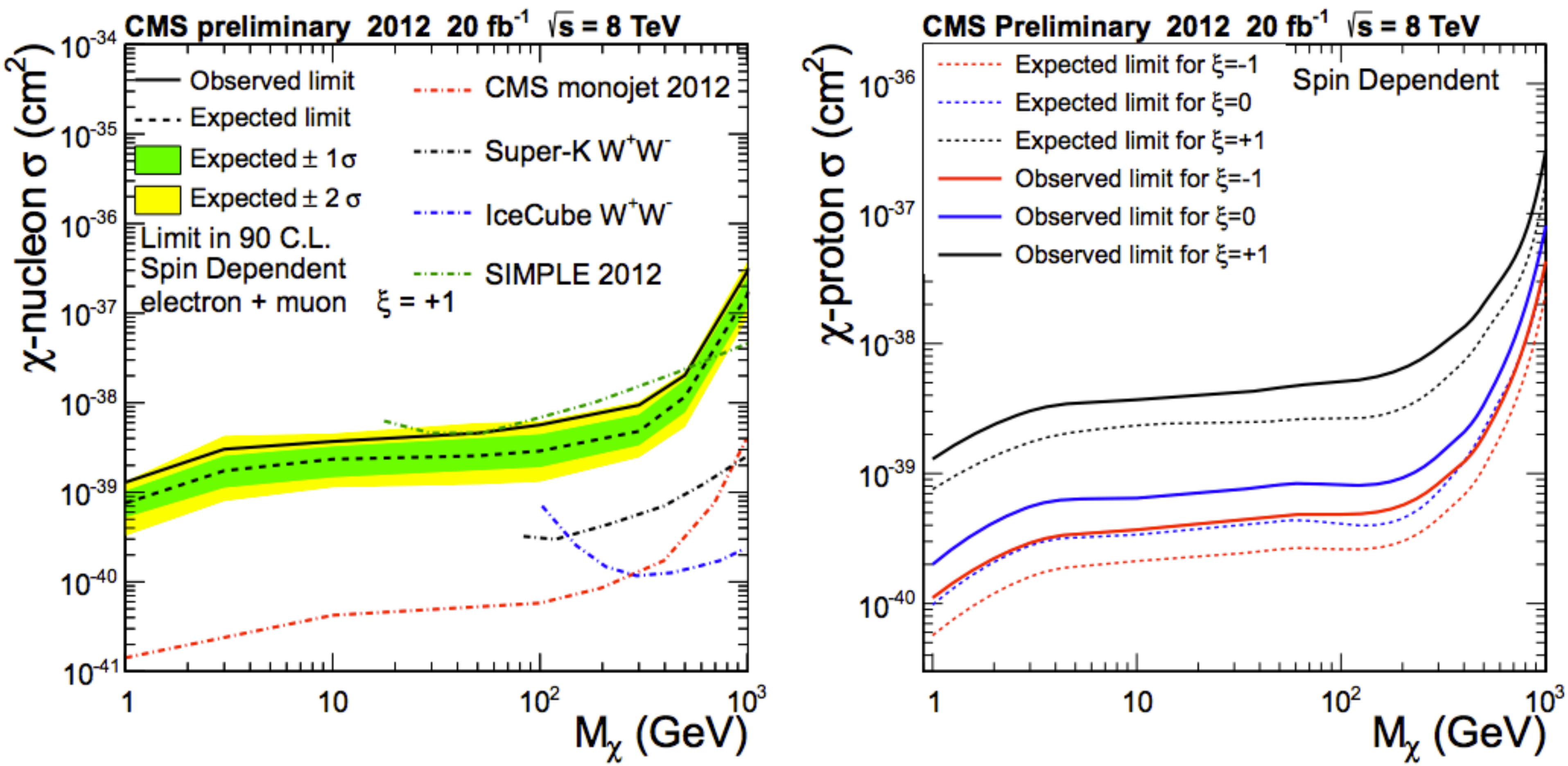

ATLAS
W' → μν
√s = 8 TeV
∫L dt = 20.3 fb⁻¹
Events
Data 2012
W'(0.5 TeV)
W'(1 TeV)
W'(3 TeV)
W
Z
Top quark
Diboson
Multijet
Data/Bkg
E_T^miss [GeV]

ATLAS Limits



1407.7494

CMS Limits



CMS PAS EXO-13-004

Mono-Higgs

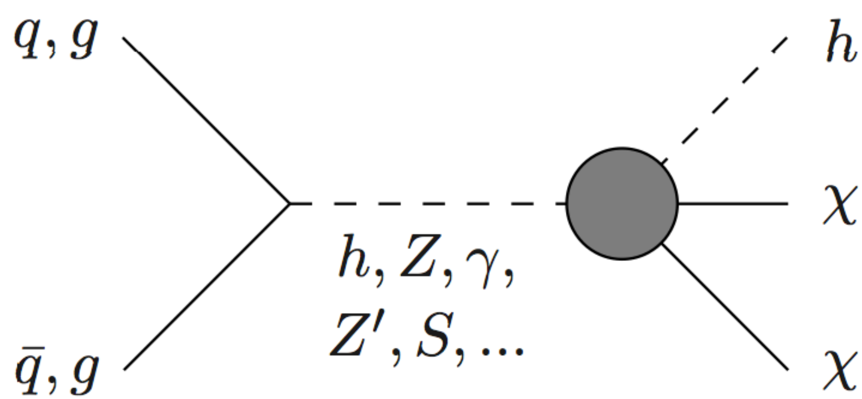


FIG. 1: Schematic diagram for mono-Higgs production in pp collisions mediated by electroweak bosons (h, Z, γ) or new mediator particles such as a Z' or scalar singlet S. The gray circle denotes an effective interaction between DM, the Higgs boson, and other states.

Models: EFT

$$\lambda|H|^2|\chi|^2$$ Scalar wimp

$$\frac{1}{\Lambda}|H|^2\bar{\chi}\chi\,, \quad \frac{1}{\Lambda}|H|^2\bar{\chi}i\gamma_5\chi$$ Fermion wimp

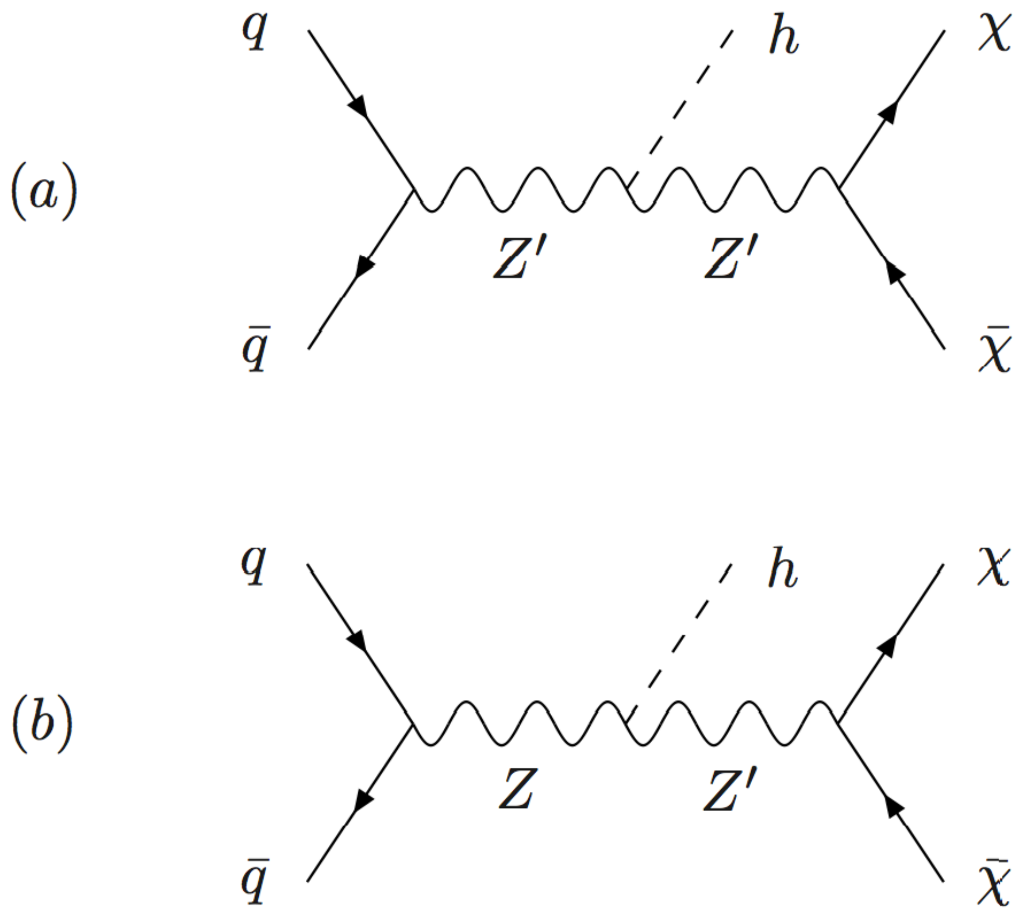
Other EFTs

Allow ZhXX-like vertices

$$\frac{1}{\Lambda^2}\chi^\dagger i\overleftrightarrow{\partial^\mu}\chi H^\dagger iD_\mu H$$ Scalar wimp

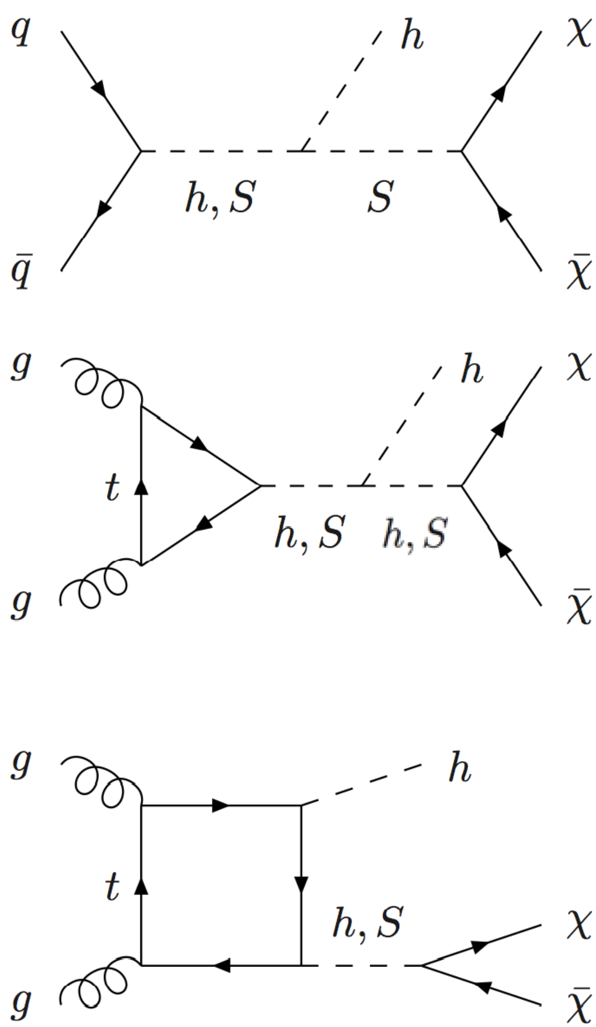
$$\frac{1}{\Lambda^4}\bar{\chi}\gamma^\mu\chi B_{\mu\nu}H^\dagger D^\nu H\,.$$ Fermion wimp

Simplified models: vector



with and without Z-Z′ mixing

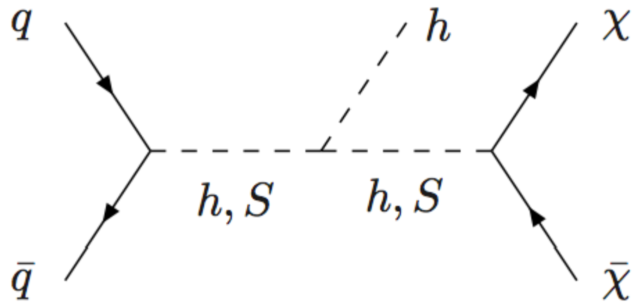
Simplified models: scalar



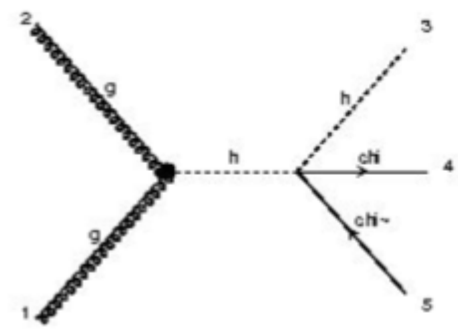
Box implemented as effective vertex in madgraph

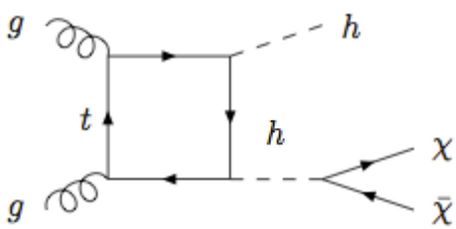
Vertices

di-Higgs

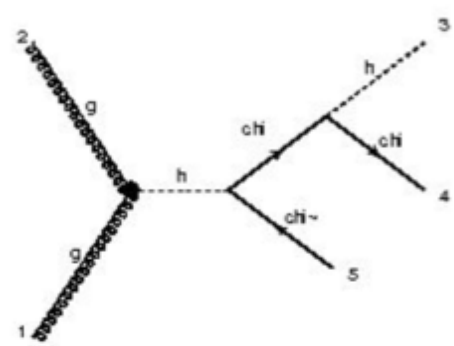


4-point vertex





Off-shell s-channel Higgs



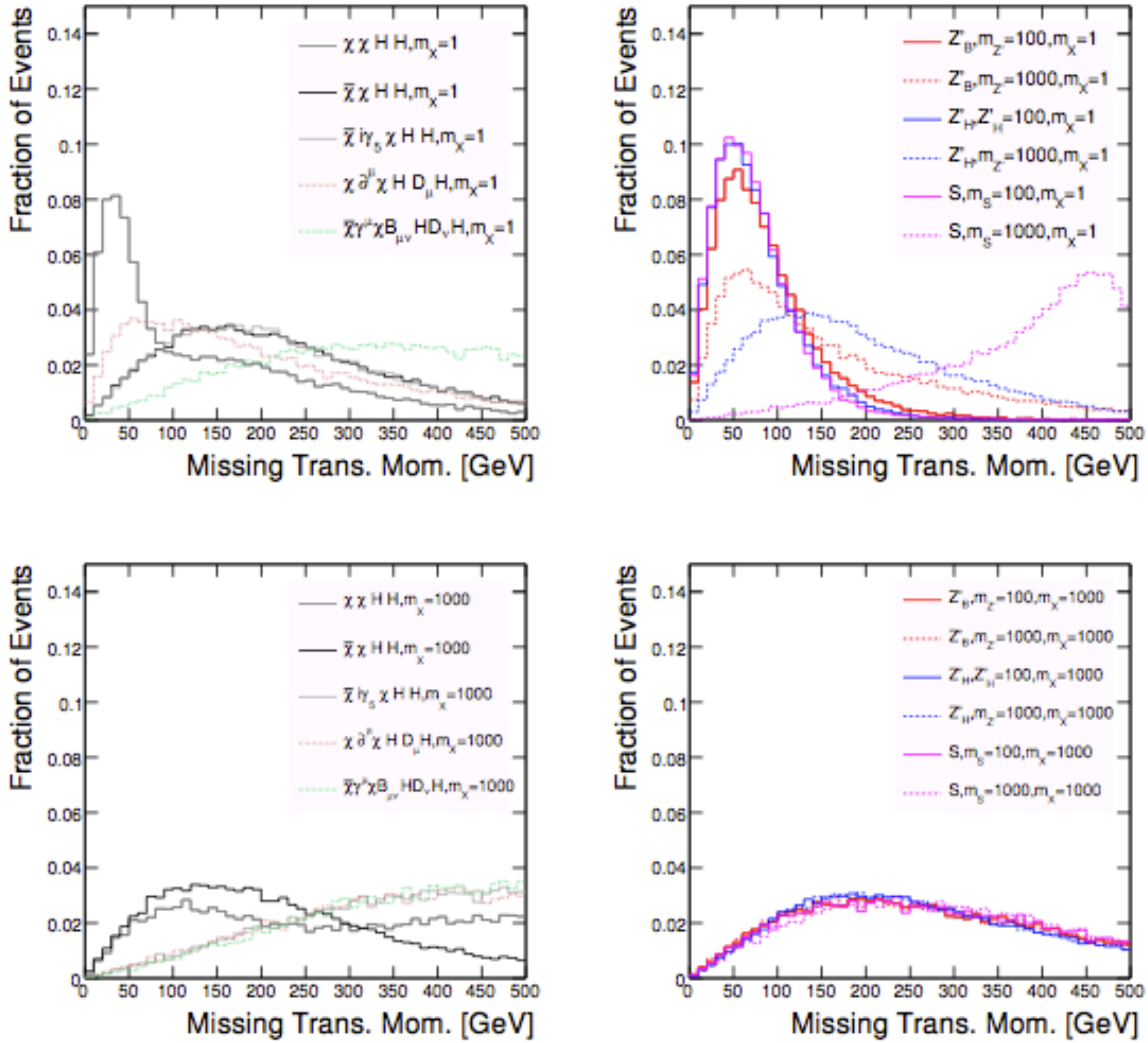
(1) h->XX limited by invisible Higgs for mx<mh/2

(2)For large coupling, h->XX grows, suppresses SM H decays!

MET

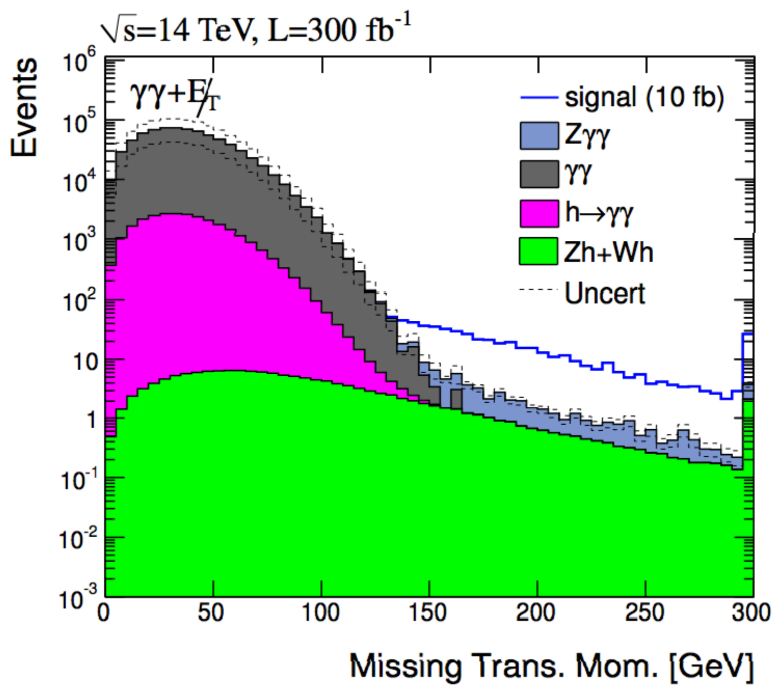
mx=1 GeV

mx=1 TeV



EFTs Simp. models

Gamma-gamma



Selection

- two photons
- $m_{\gamma\gamma}$ in [110-130]
- MET > 100, 250 (8,14 TeV)

Backgrounds

- $h \to \gamma\gamma$ + fake MET
- $\gamma\gamma$ + fake MET
- $Z\gamma\gamma$, $Z \to \nu\nu$
- Zh, $Z \to \nu\nu$ + Wh, $W \to l\nu$

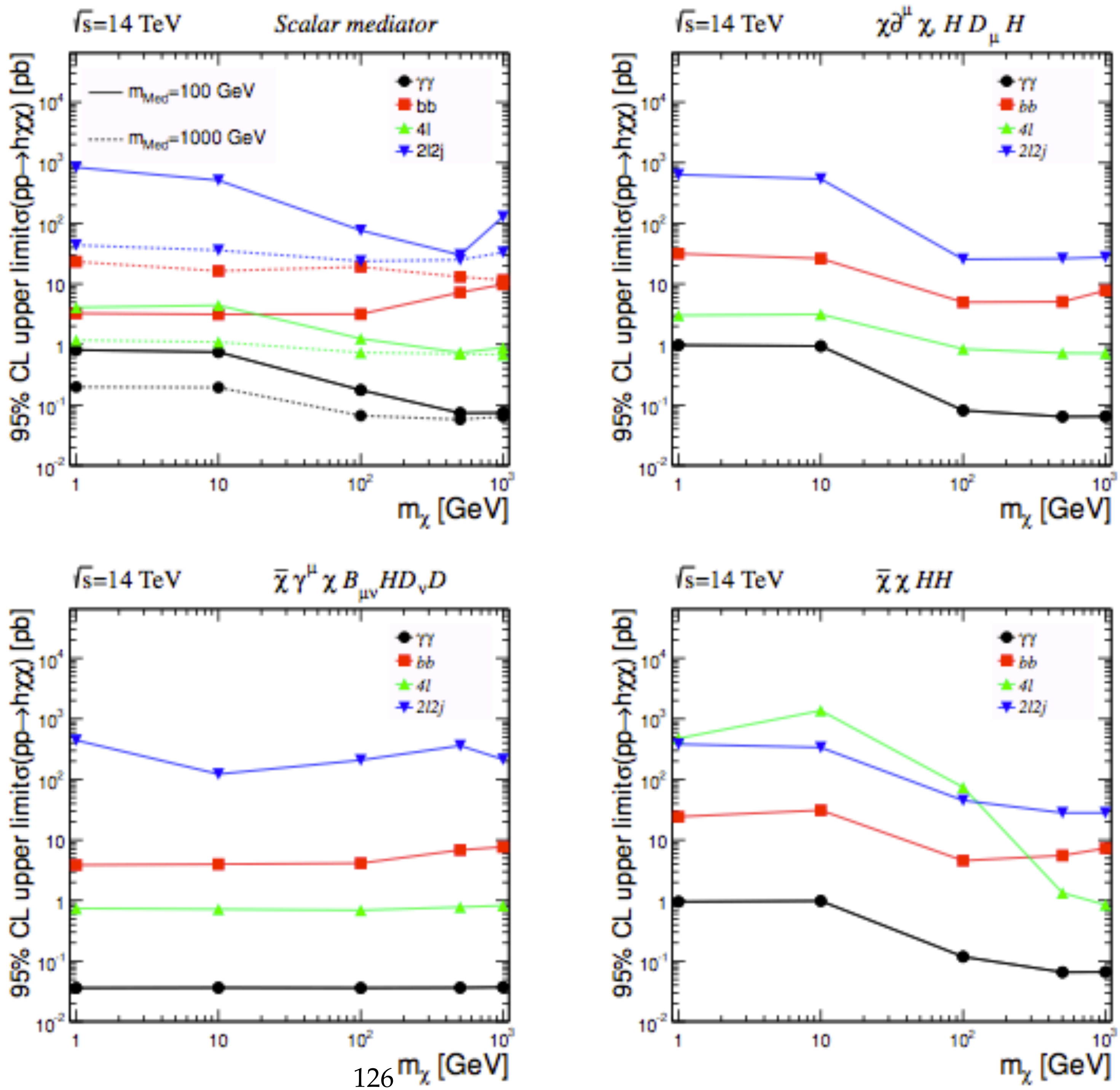
[redacted]

Assuming

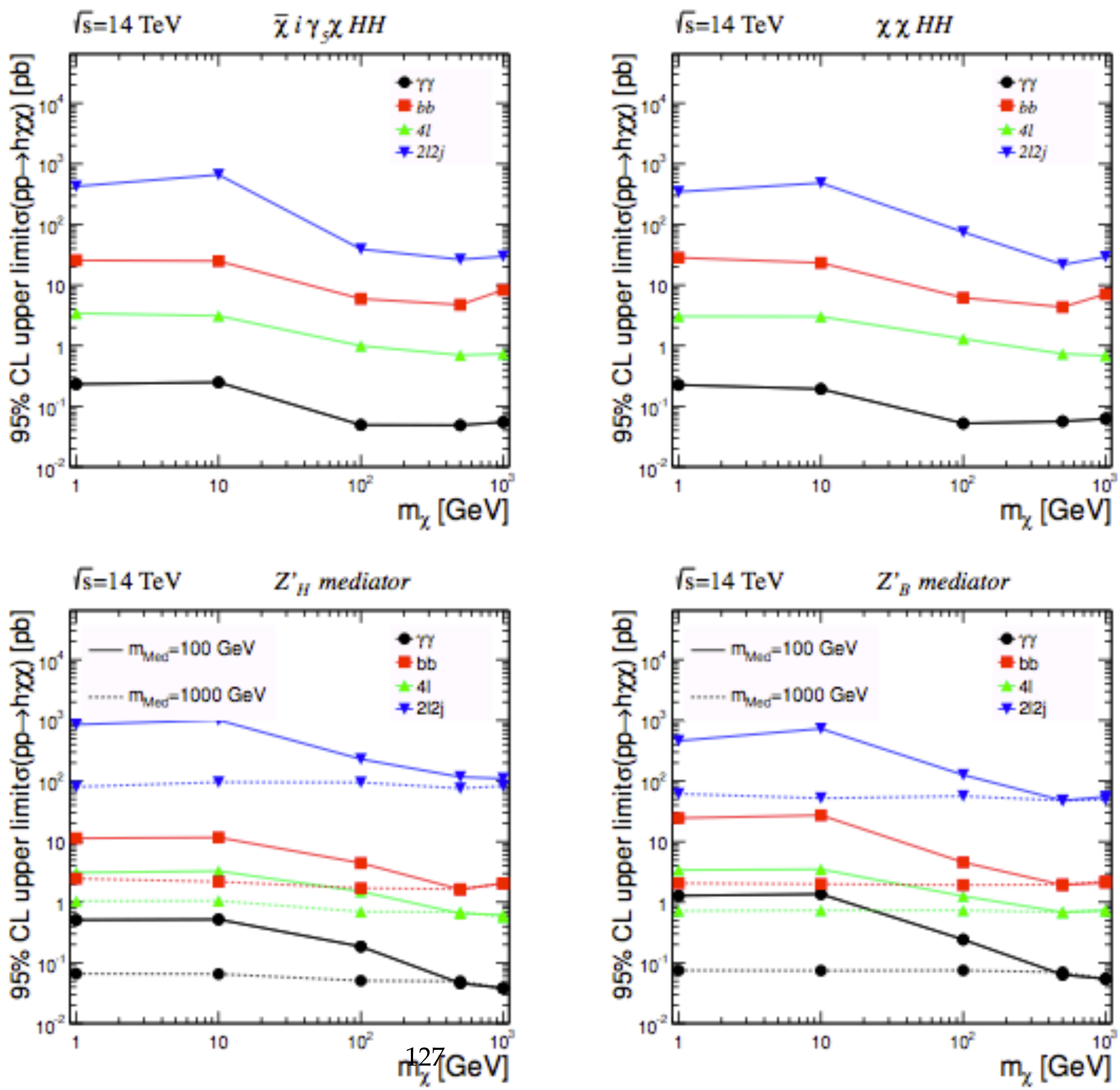
h→SM

rates are

unchanged



Assuming $h \rightarrow SM$ rates are unchanged



Parameter limits

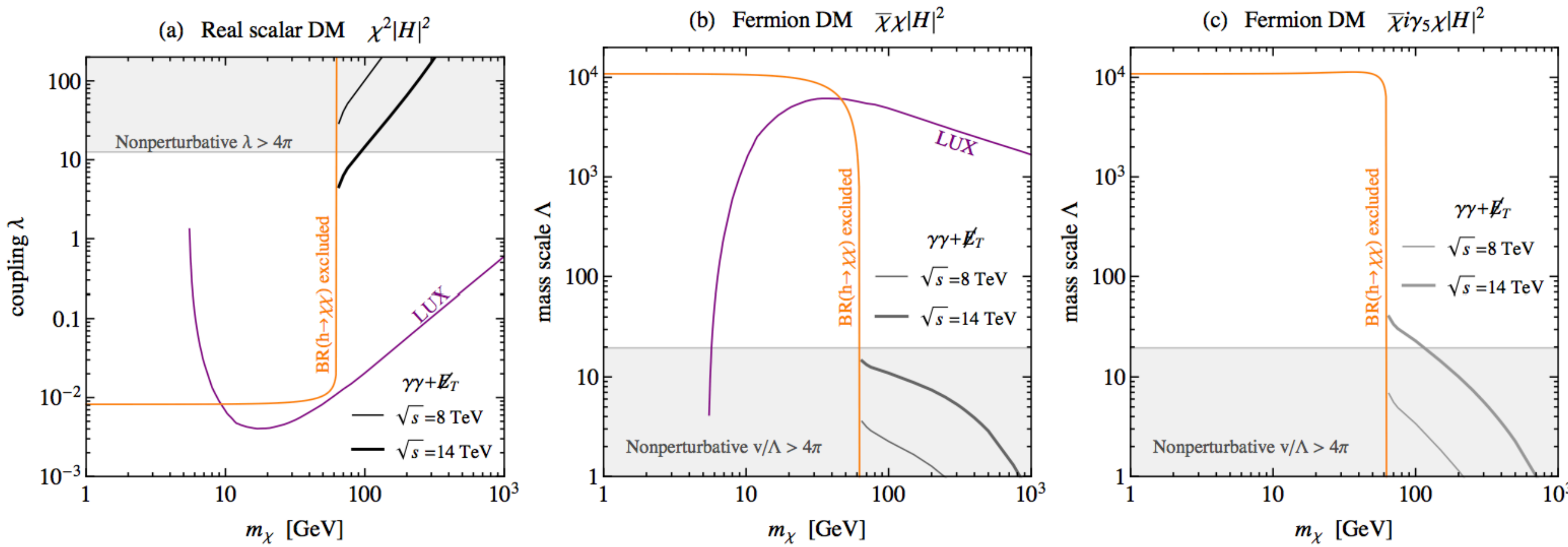


FIG. 20: Projected LHC mono-Higgs sensitivities at $\sqrt{s} = 8$ TeV (20 fb^{-1}) and 14 TeV (300 fb^{-1}), with $\gamma\gamma + \not{E}_T$ final states, on Higgs portal effective operators. All constraint contours exclude larger coupling λ or smaller mass scale Λ. Shaded region is excluded based on perturbativity arguments; orange contours denote limits from invisible h decays; purple contours are exclusion limits from LUX.

<u>Note:</u>

for $m_x < m_h/2$, no valid limits.

Large Lambda boosts h→XX, suppresses h→visible

Parameter limits

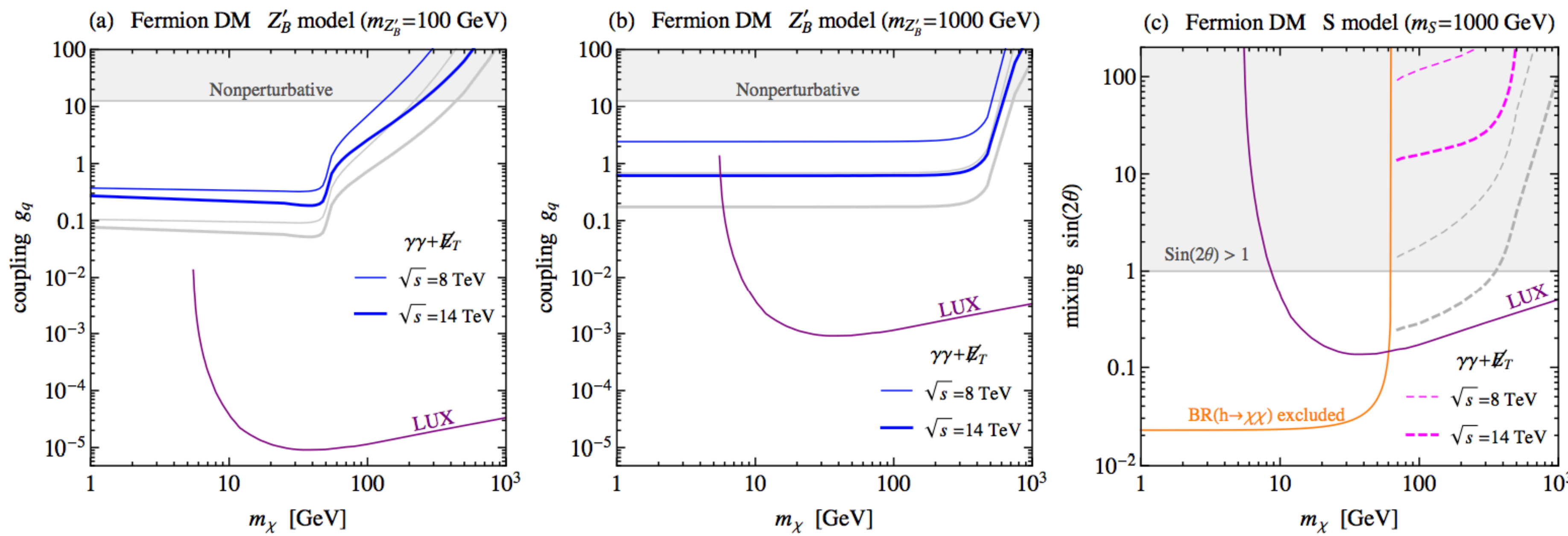
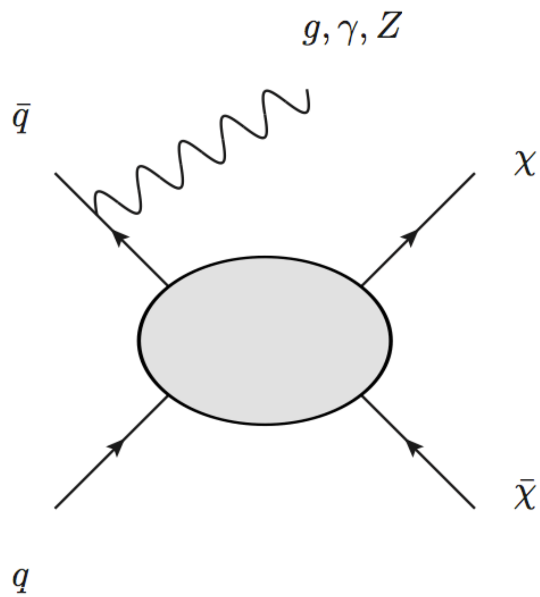


FIG. 22: Projected LHC mono-Higgs sensitivities at $\sqrt{s} = 8$ TeV (20 fb^{-1}) and 14 TeV (300 fb^{-1}), with $\gamma\gamma + \not{E}_T$ final states, on simplified models. All constraint contours exclude larger couplings or mixing angles. Shaded region is excluded based on perturbativity arguments or requiring $\sin\theta \leq 1$; orange contour denotes limit from invisible h decays; purple contours are exclusion limits from LUX.

Combination

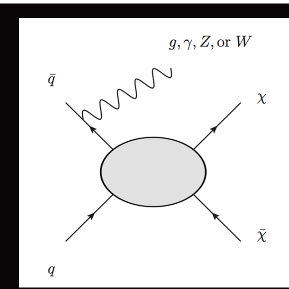


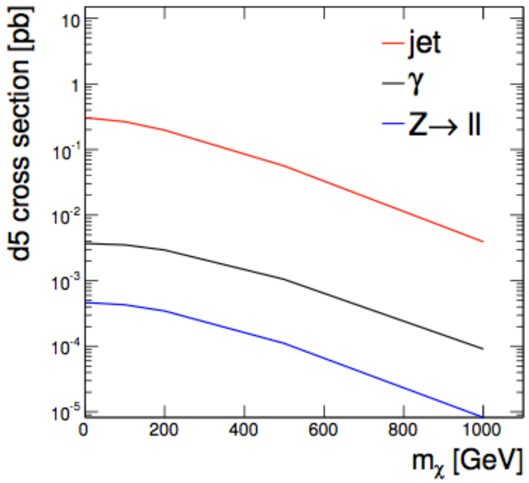
Channel	Bg.	Obs	Limit (N)	Eff	Limit (σ) (fb)
ATLAS jet+$\not{E}_T$	750 ± 60	785	126.5	3.0%	897
CMS jet+$\not{E}_T$	1224 ± 101	1142	125.9	3.2%	837
ATLAS $\gamma + \not{E}_T$	137 ± 20	116	27.6	18%	32.6
CMS $\gamma + \not{E}_T$	71.9 ± 9.1	73	21.4	11%	41.4
ATLAS $Z + \not{E}_T$	92.4 ± 5.3	84	14.3	8.7%	35.0

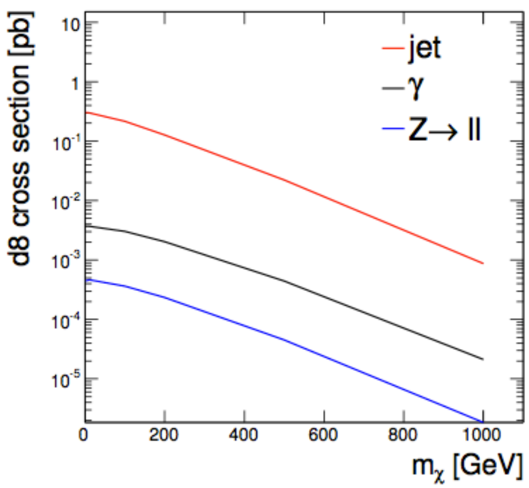
TABLE I: 90% CL limits on N_{events}, efficiencies for $m_\chi = 10$ GeV, and limits on $\sigma(pp \to \chi\chi + X)$ using the D5 operator.

1302.3619

Combination







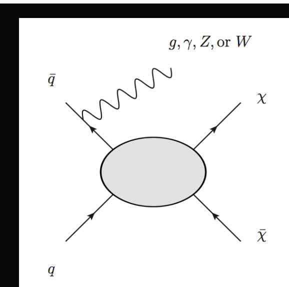
D5, WIMP mass of 10 GeV

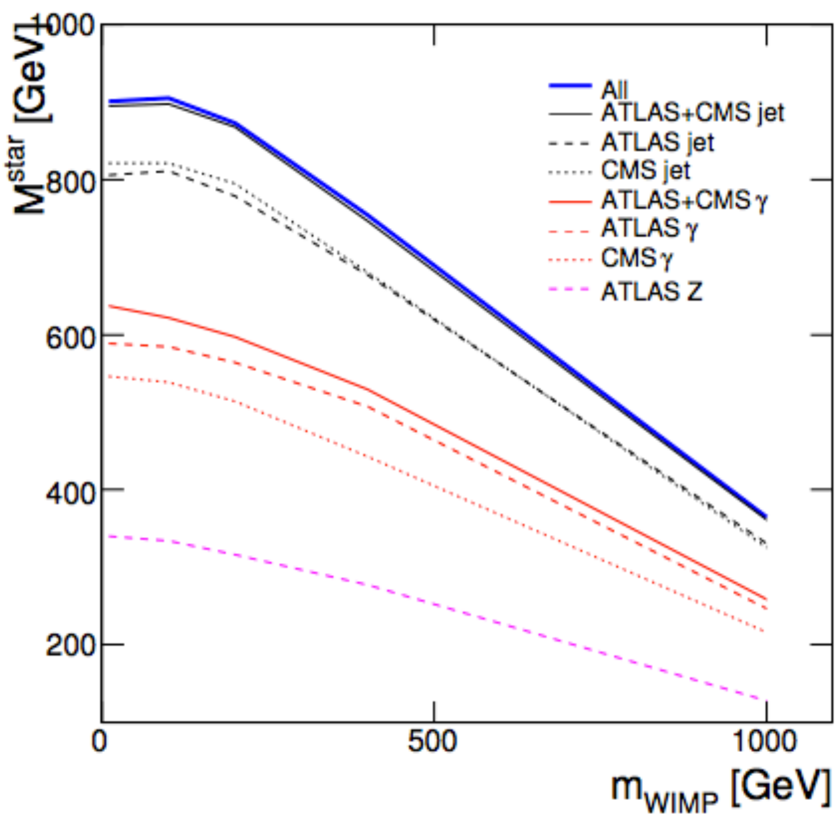
Channel	Limit σ (fb)	Prediction ($M_\star = 1$ TeV)	Limit $M_\star$ (TeV)		
ATLAS jet+$\not{E}_T$	897	370	0.800	0.894	0.900
CMS jet+$\not{E}_T$	837	370	0.821		
ATLAS $\gamma + \not{E}_T$	32.6	3.7	0.589	0.637	
CMS $\gamma + \not{E}_T$	41.4	3.7	0.546		
ATLAS $Z + \not{E}_T$	35.0	0.5	0.340		

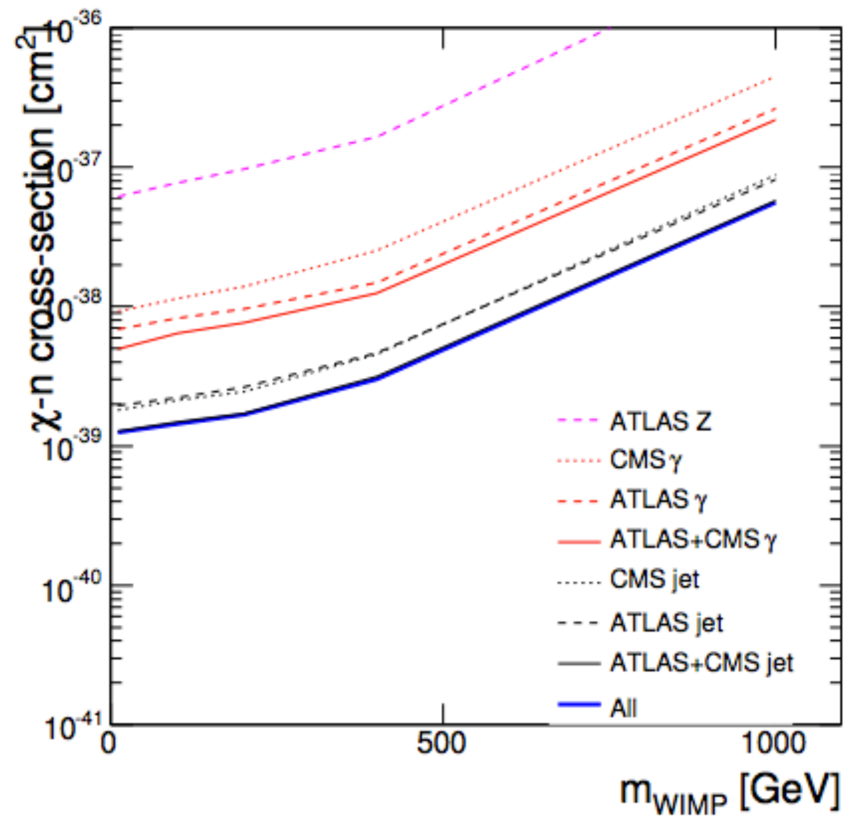
TABLE II: 90% CL limits on $\sigma(pp \to \chi\chi + X)$ for $m_\chi = 10$ GeV, theory prediction for $M_\star = 1$ TeV, and limits on $M_\star$ using the D5 operator.

1302.3619

Combined: D5

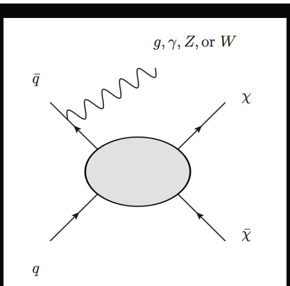


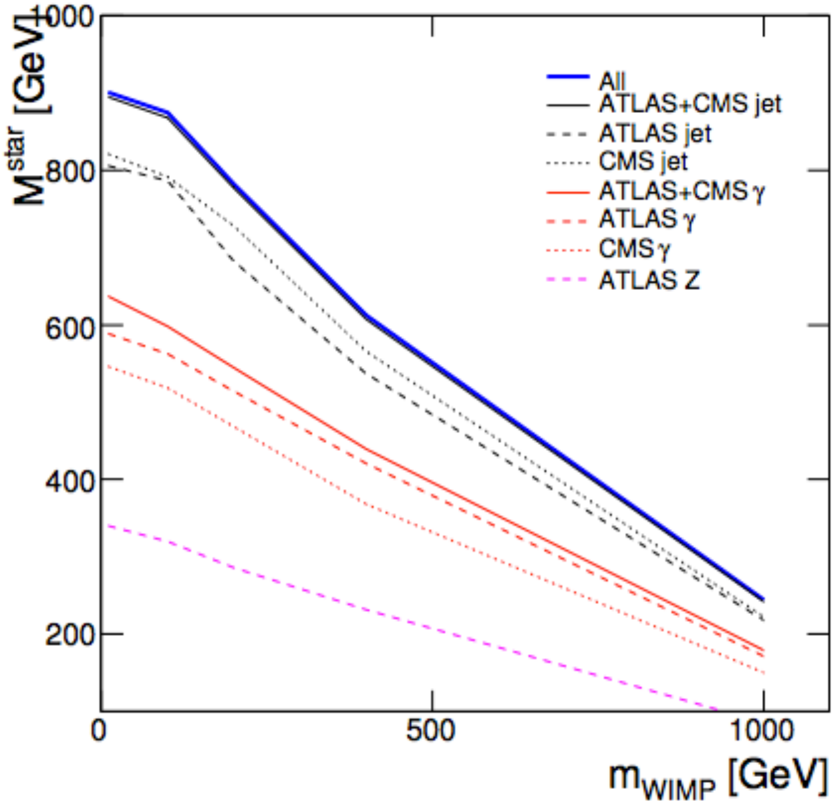


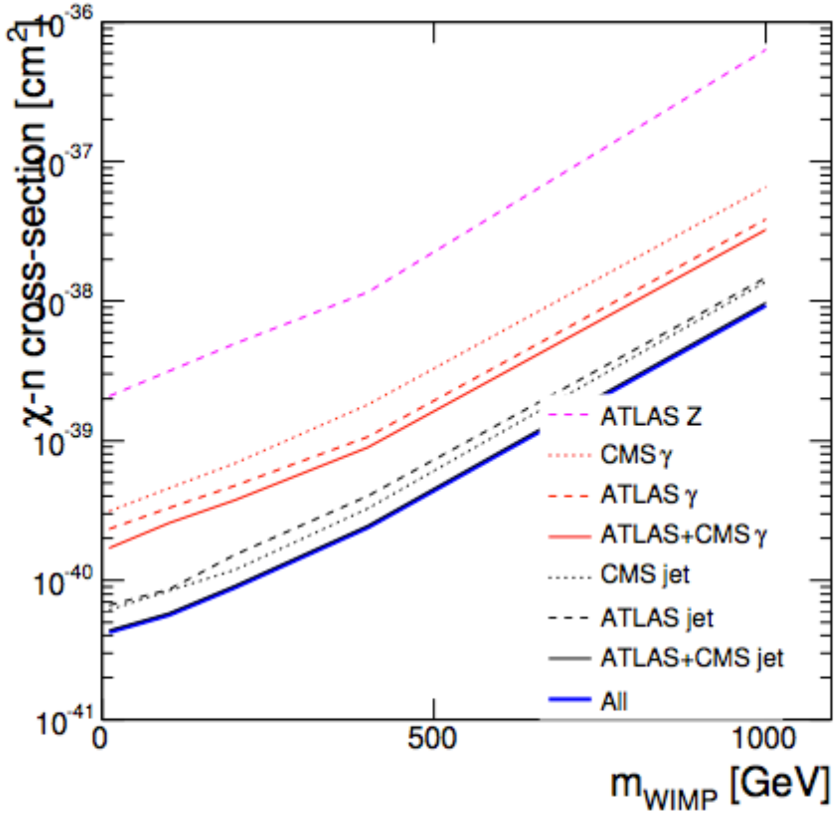


1302.3619

Combined: D8







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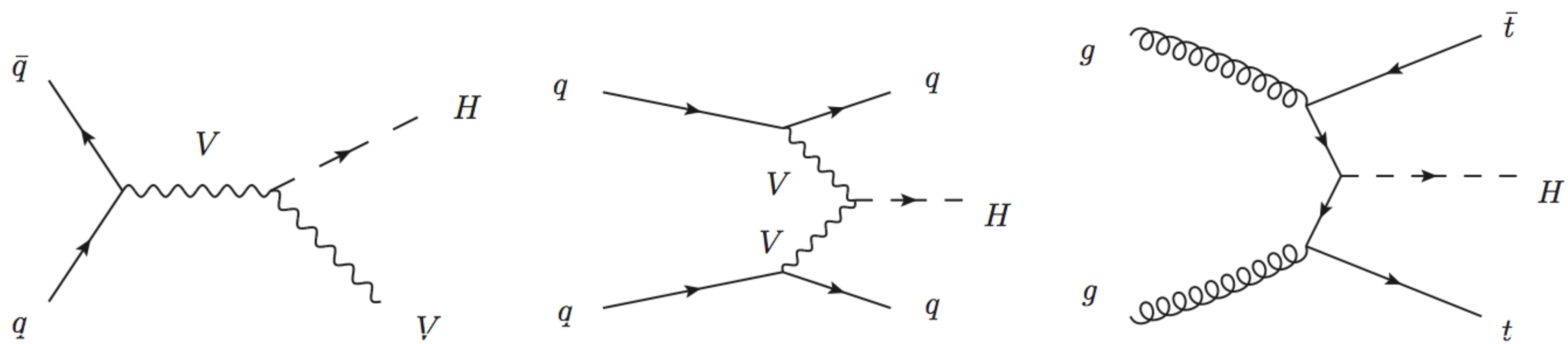
Outline

I. Detector basics
II. Mono-X
III. Invisible Higgs decays
IV. Prospects at future colliders

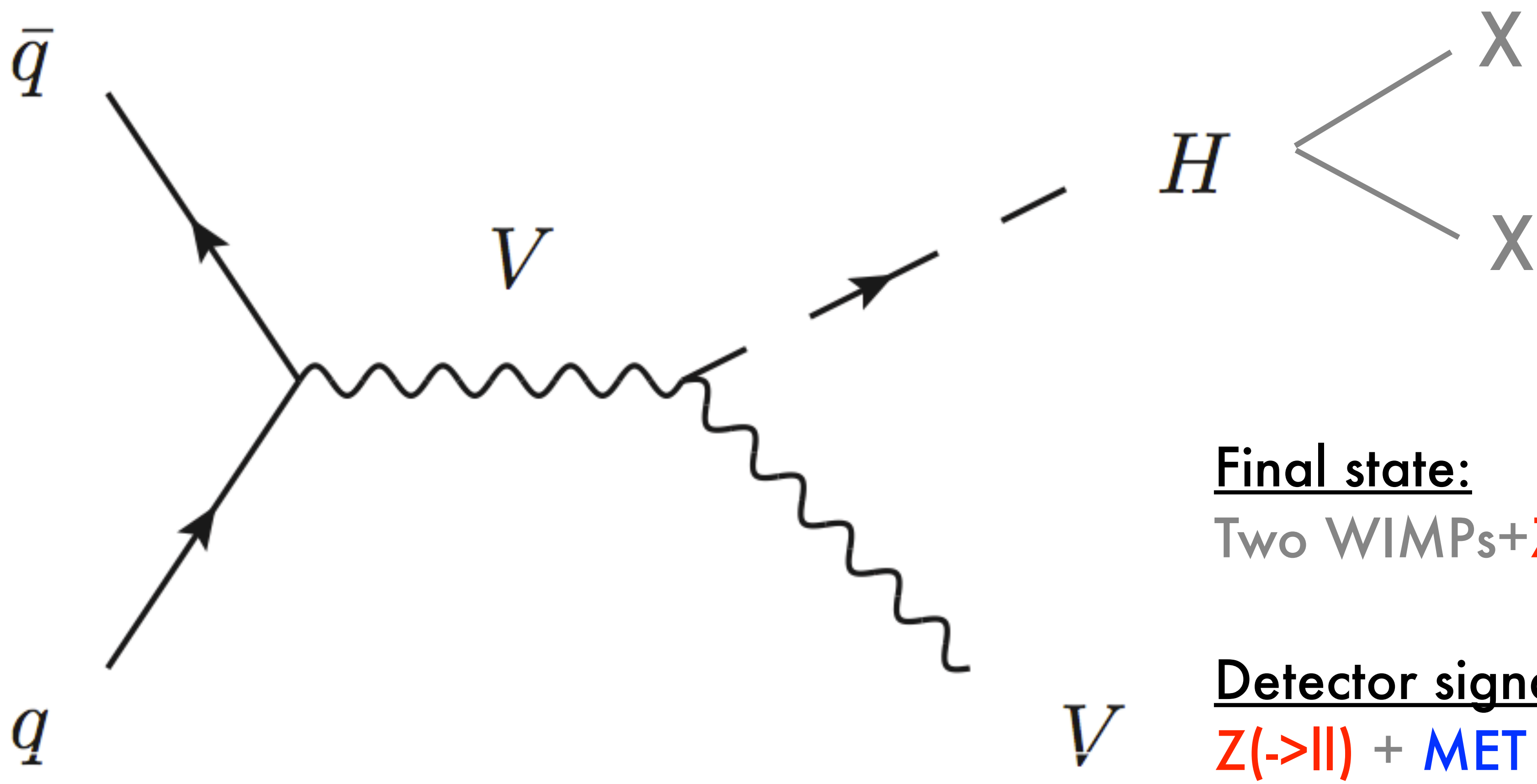
Invisible Higgs

If the Higgs boson decays to DM



Look for V+MET, qq+MET, tt+MET

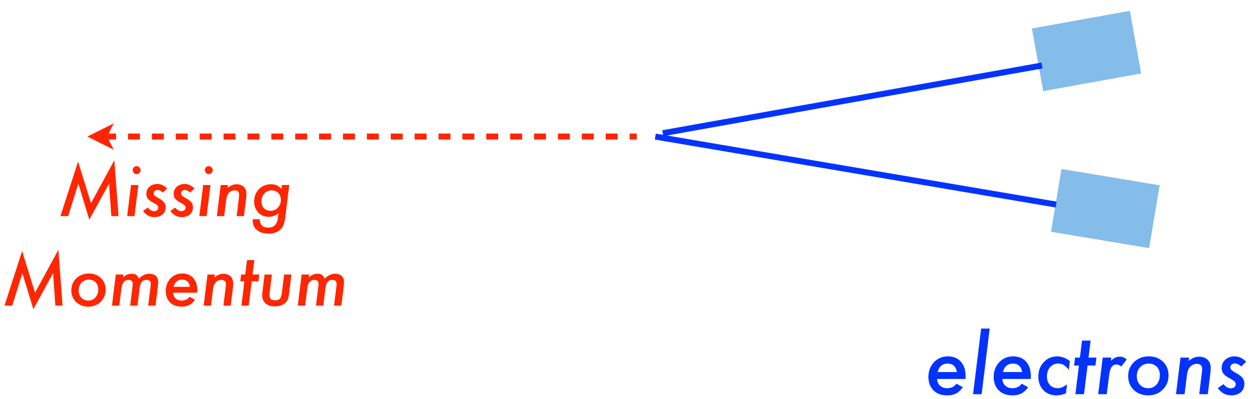
Z+MET



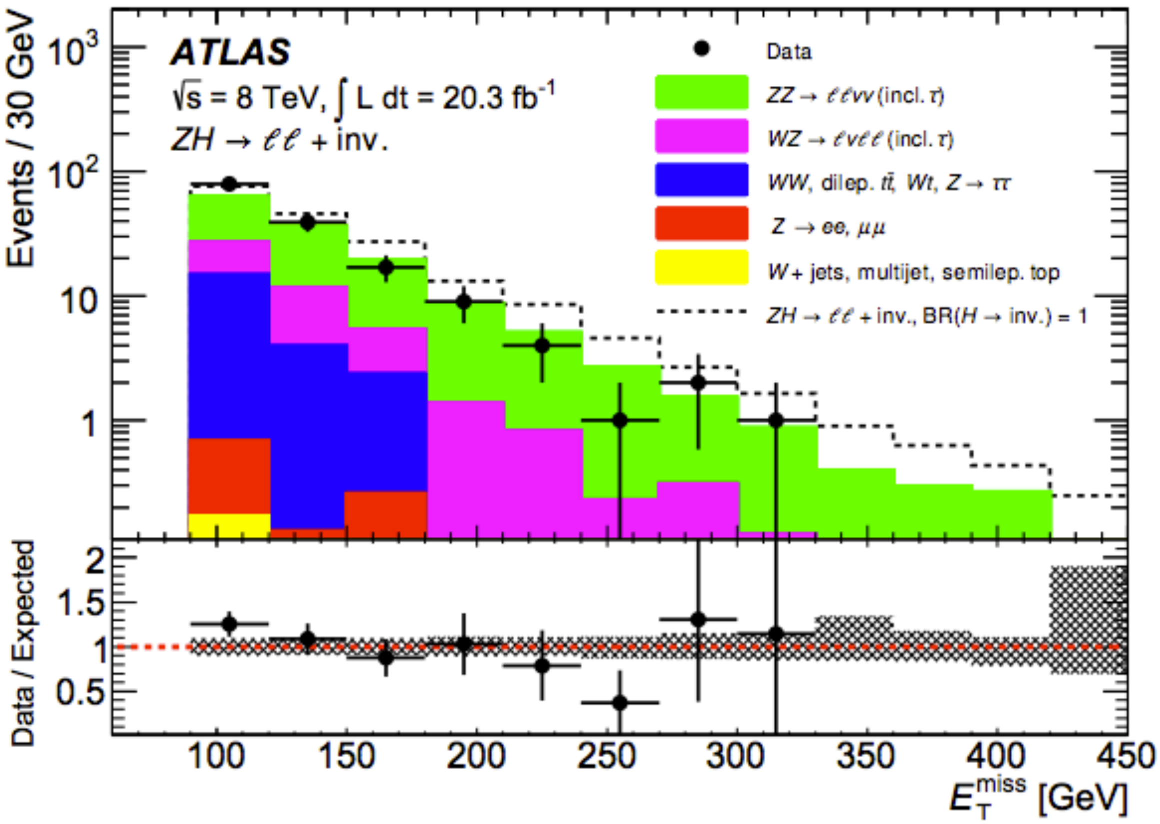
Final state:
Two WIMPs+Z

Detector signature
Z(->ll) + MET

Zh, h invisible

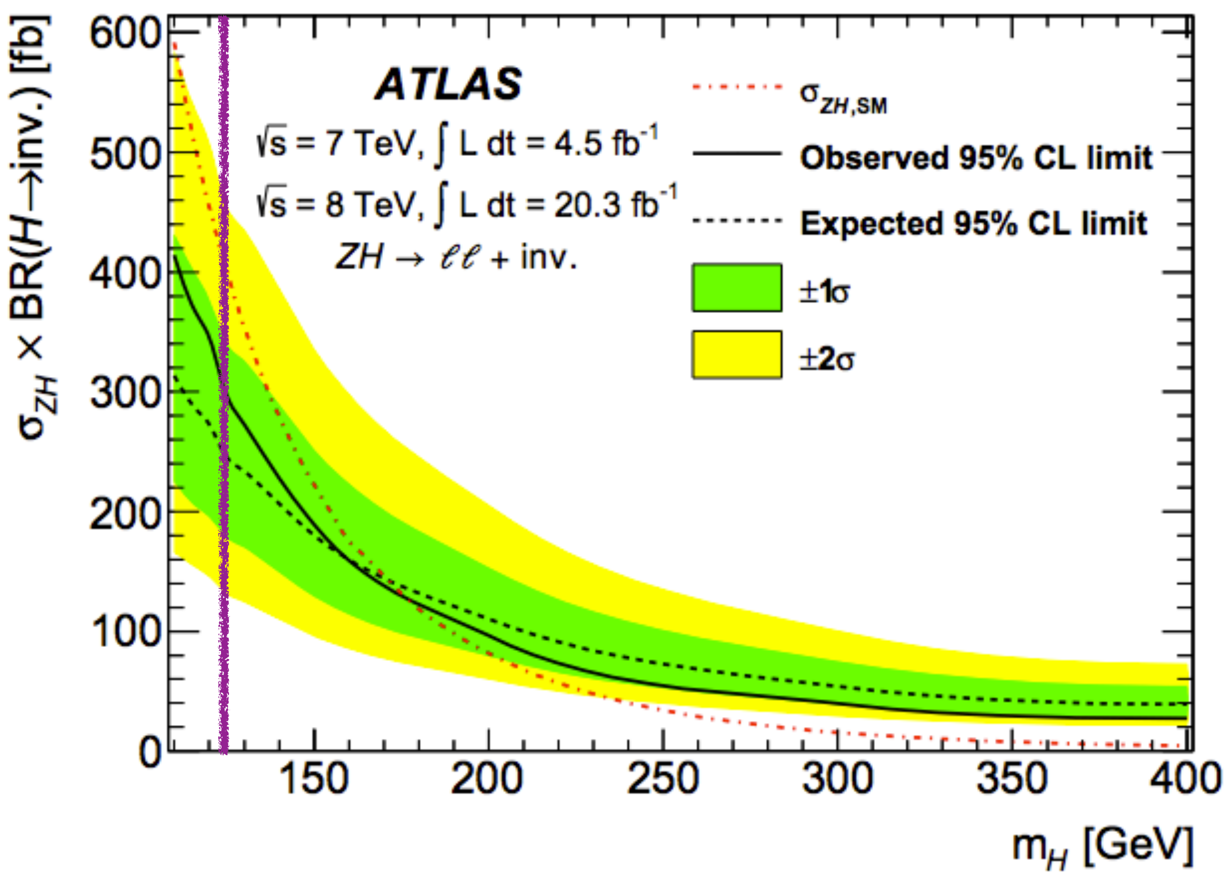


Data



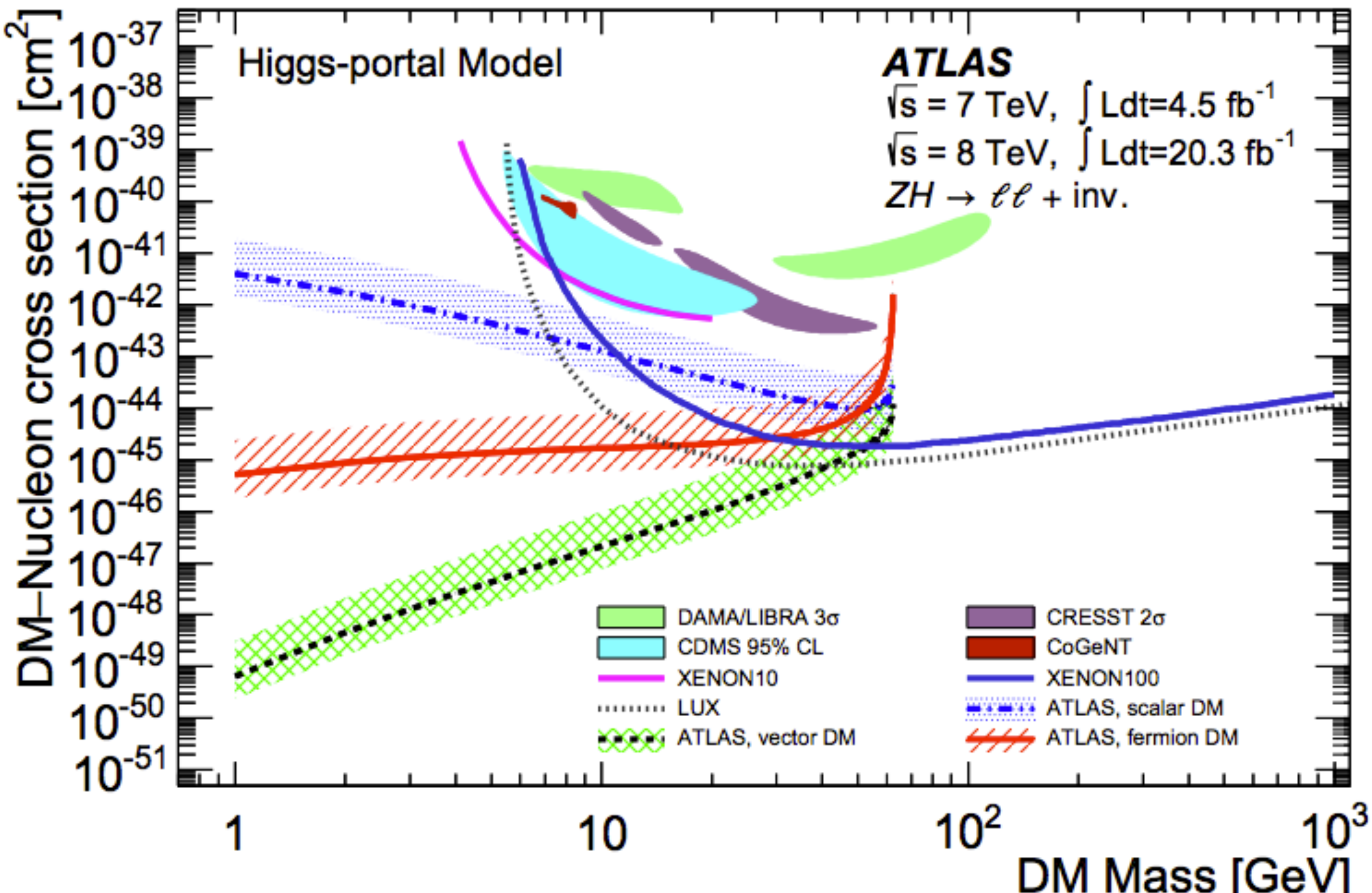
1402.3244

Limits



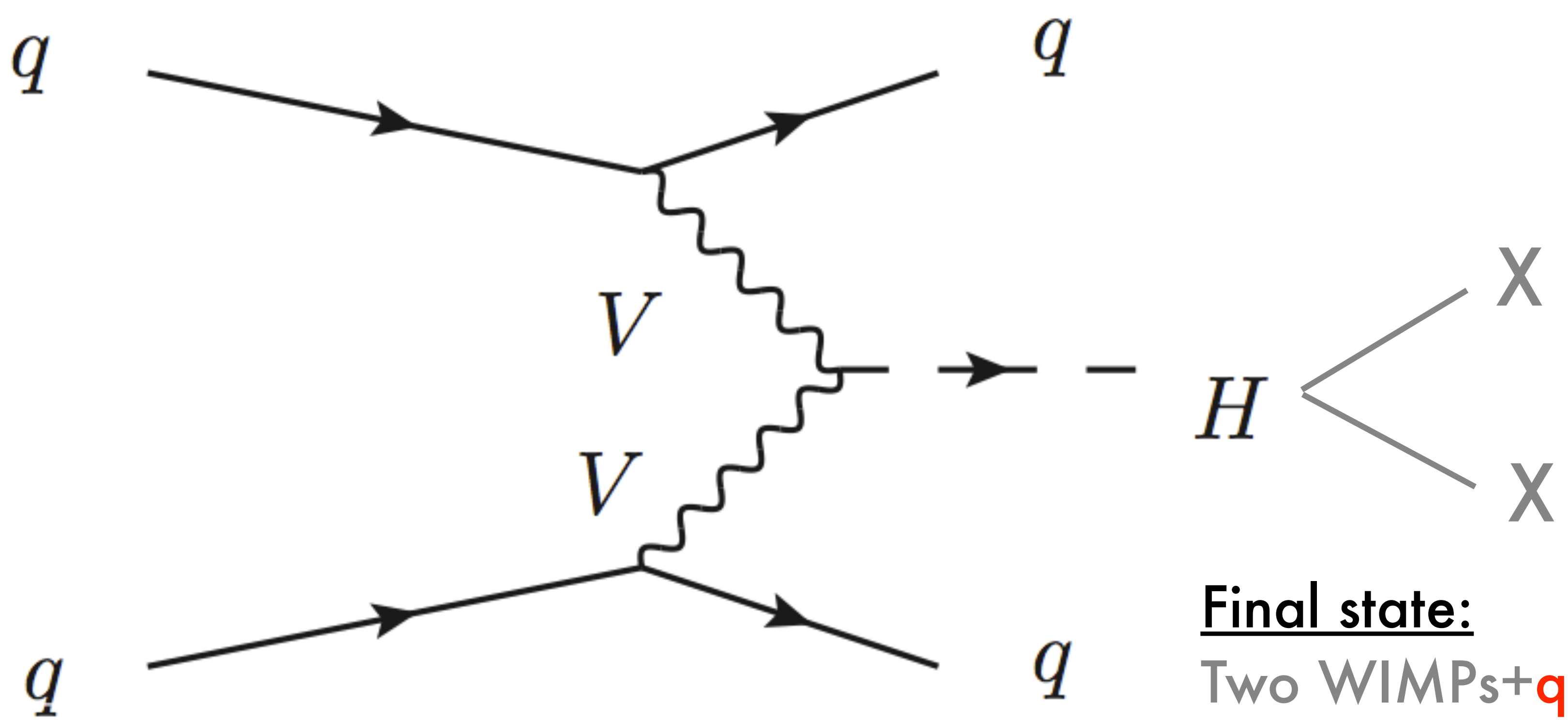
1402.3244

Limits



1402.3244

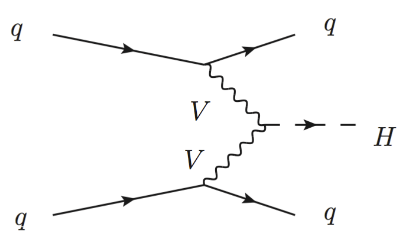
Vector Boson Fusion

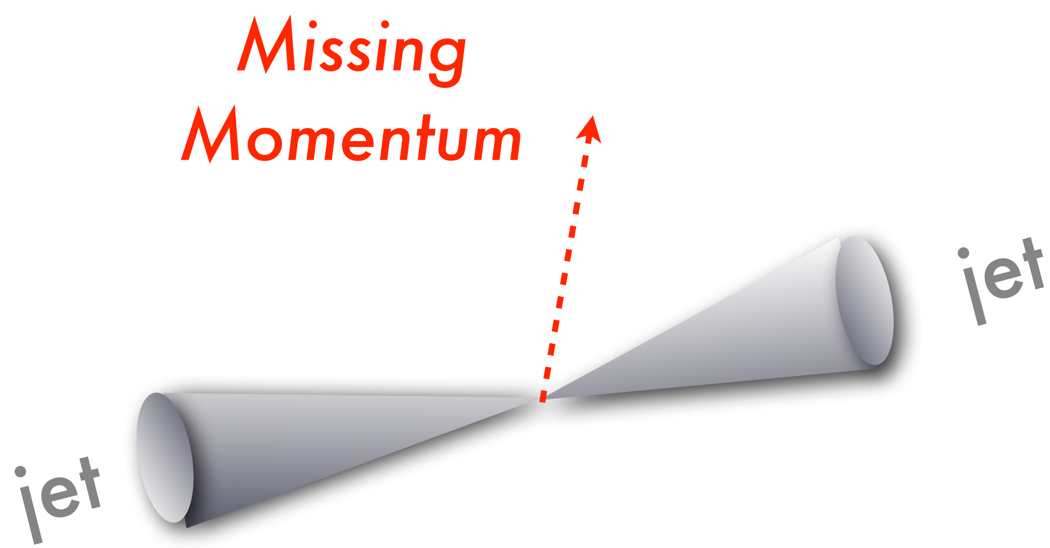


Final state:
Two WIMPs+qq

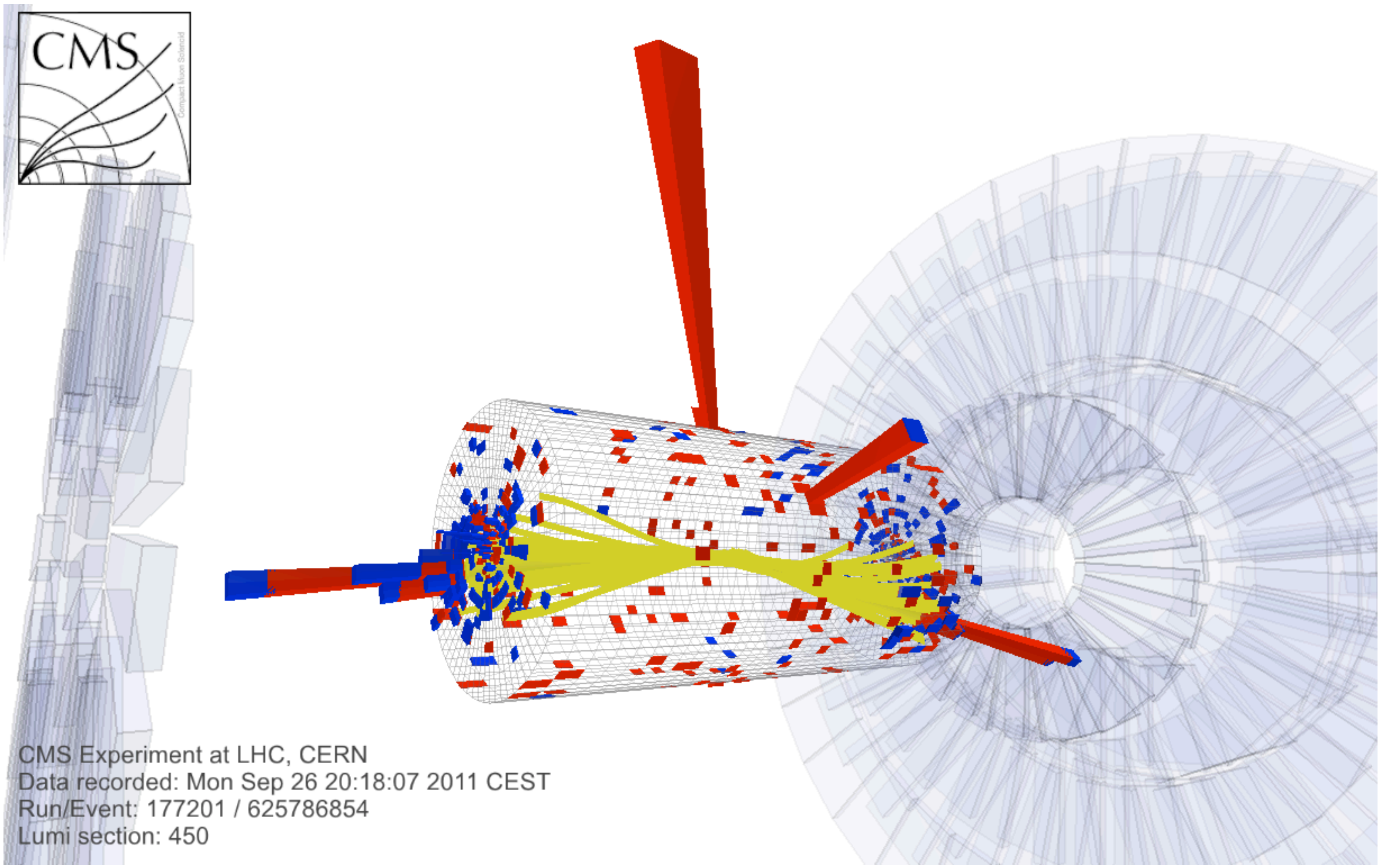
Detector signature
Forward jets + MET

VBF Higgs invisible

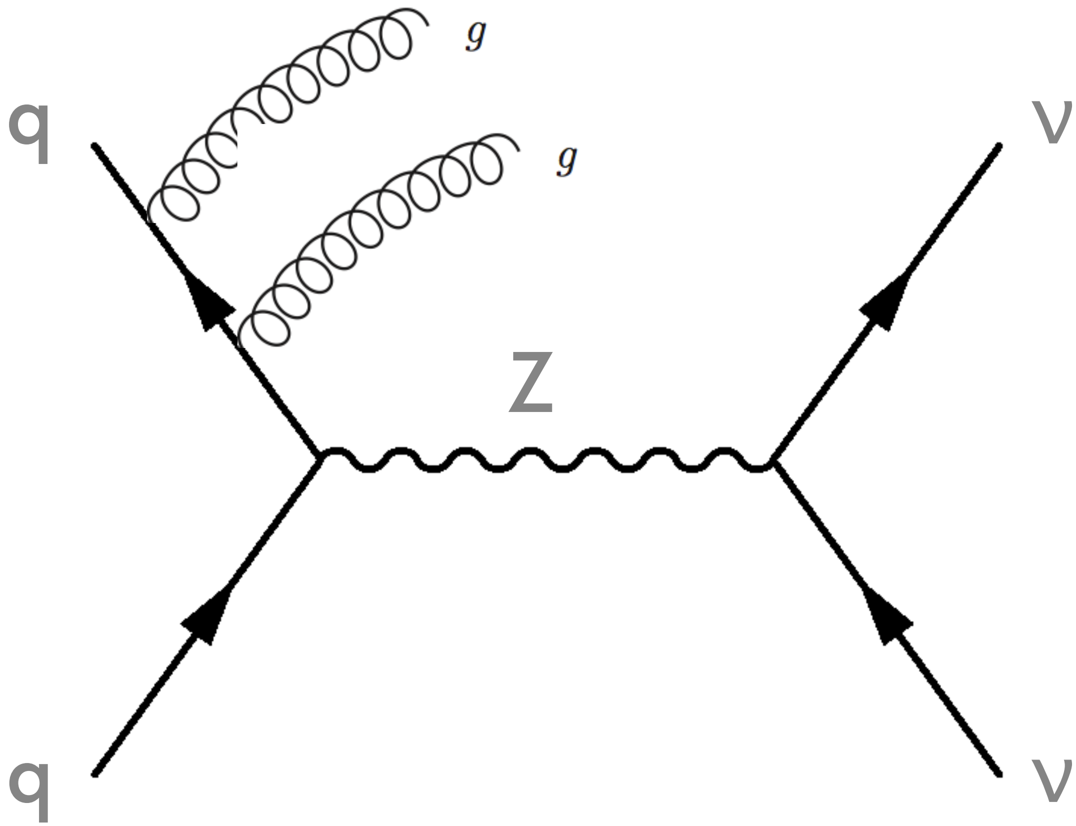




VBF Higgs event (h->gg)



Backgrounds



Final state:

jets + MET

Process:

Z to ν ν, with jets

Background estimate

Signal

0 leptons
2 jets
MET

Z->vv

Control

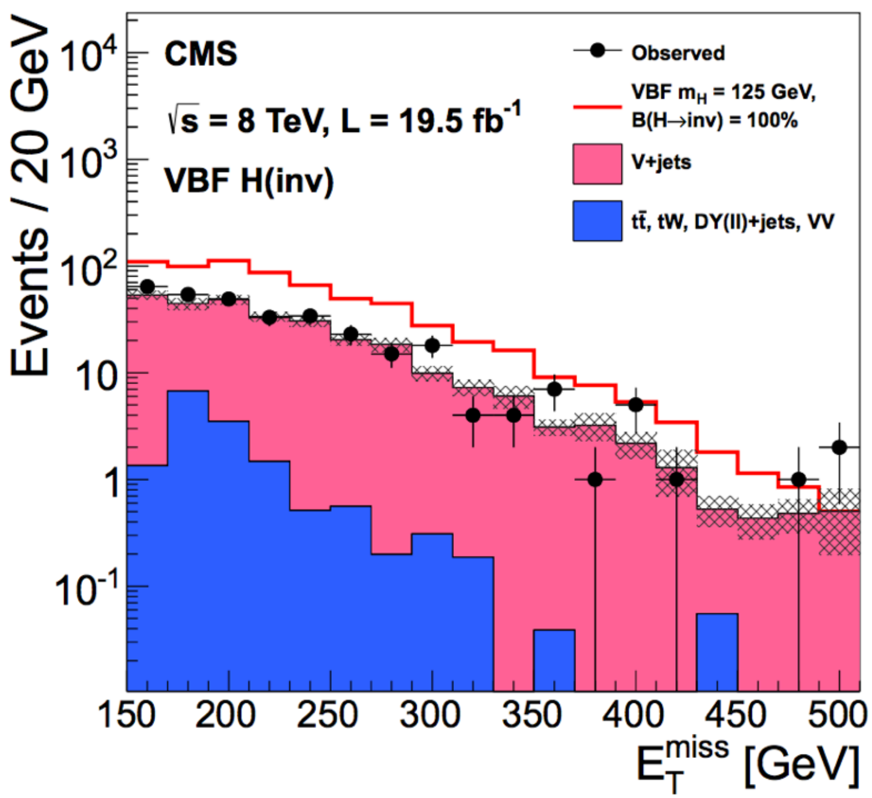
2 lepton
2 jets
MET

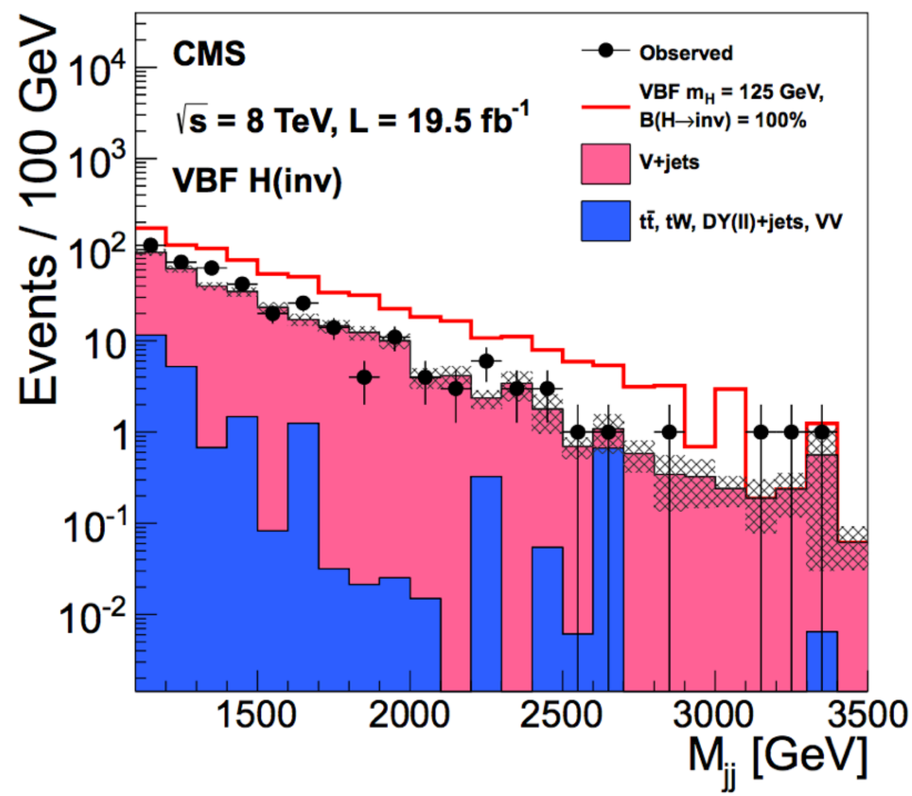
Z->ll

Yields

Process	Event yields
$Z(\nu\nu)$+jets	$99 \pm 29\,(\text{stat.}) \pm 25\,(\text{syst.})$
$W(\mu\nu)$+jets	$67 \pm 5\,(\text{stat.}) \pm 16\,(\text{syst.})$
$W(e\nu)$+jets	$63 \pm 9\,(\text{stat.}) \pm 18\,(\text{syst.})$
$W(\tau_h\nu)$+jets	$53 \pm 18\,(\text{stat.}) \pm 18\,(\text{syst.})$
QCD multijet	$31 \pm 2\,(\text{stat.}) \pm 23\,(\text{syst.})$
Sum ($t\bar{t}$, single top quark, VV, DY)	$20.0 \pm 8.2\,(\text{syst.})$
Total background	$332 \pm 36\,(\text{stat.}) \pm 46\,(\text{syst.})$
VBF H(inv.)	$210 \pm 30\,(\text{syst.})$
ggF H(inv.)	$14 \pm 11\,(\text{syst.})$
Observed data	390
S/B (%)	70

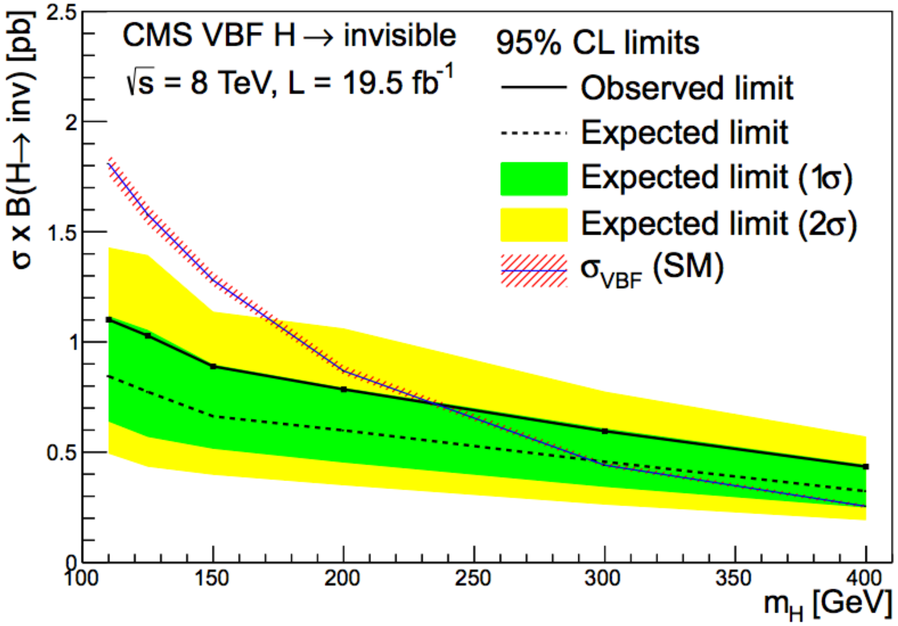
Data

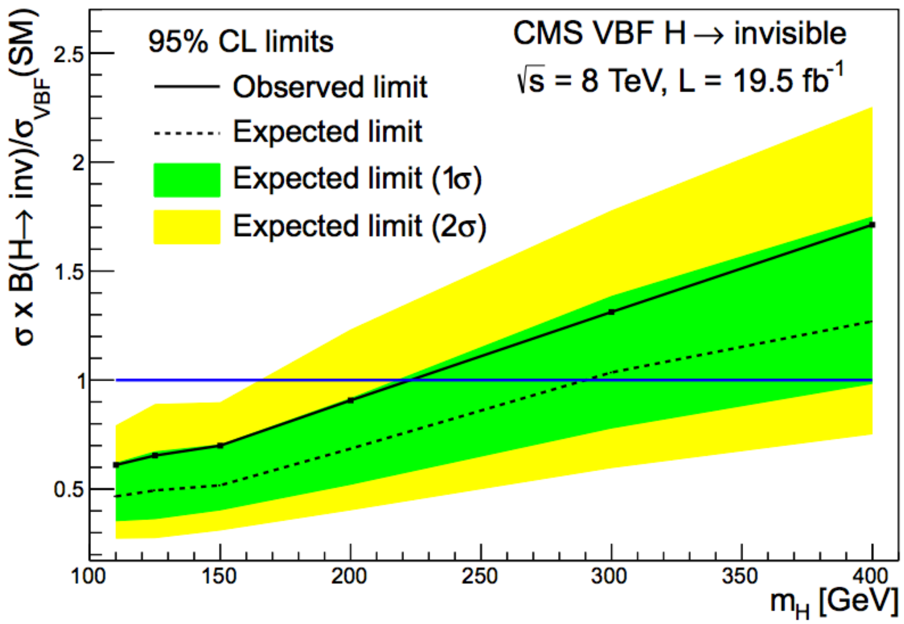




1404.1344

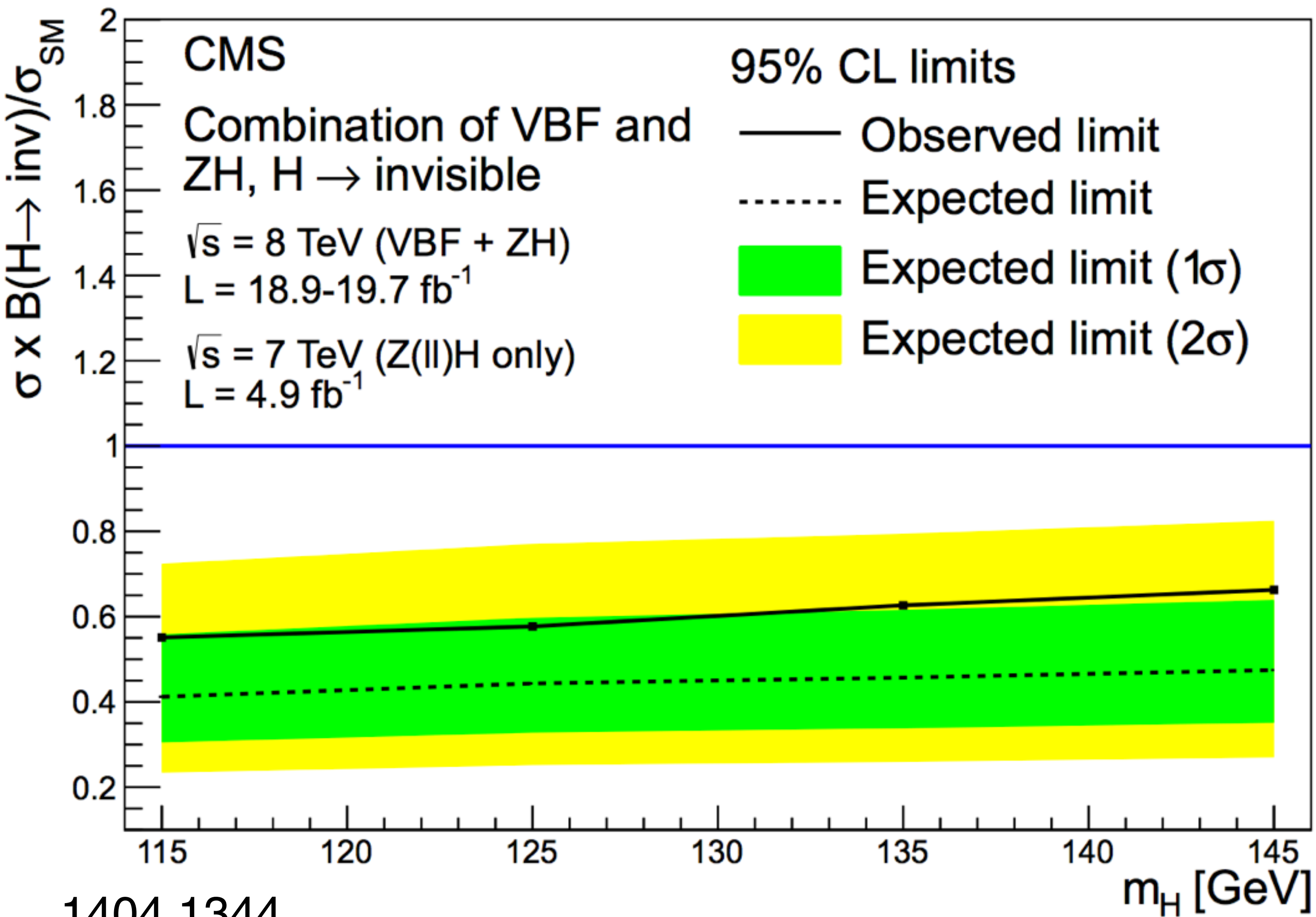
Limits





1404.1344

Limits



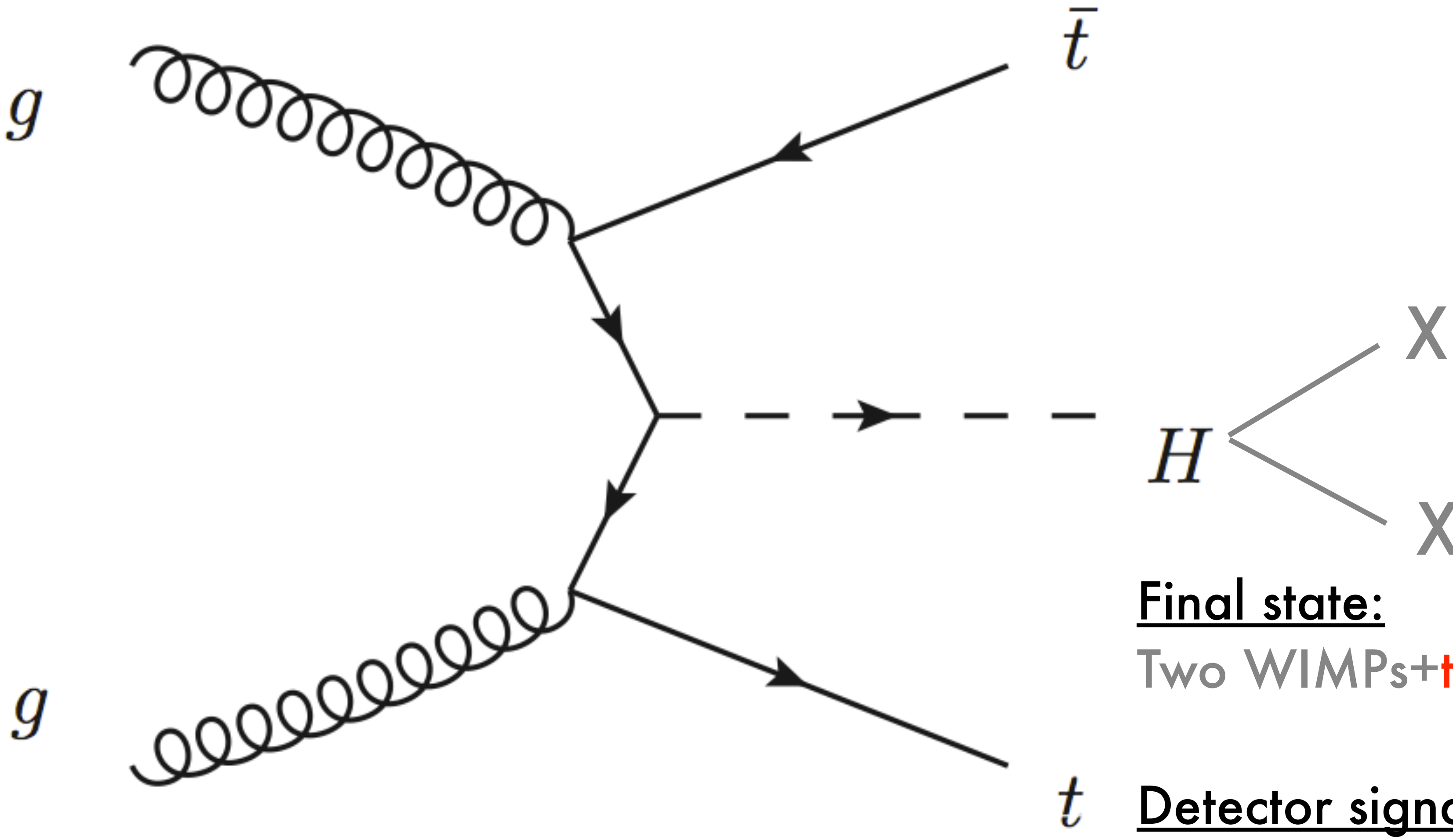
1404.1344

Limits combined

m_H (GeV)	Observed (expected) upper limits on $\sigma \cdot \mathcal{B}(H \to inv)/\sigma_{SM}$		
	VBF	ZH	VBF+ZH
115	0.63 (0.48)	0.76 (0.72)	0.55 (0.41)
125	0.65 (0.49)	0.81 (0.83)	0.58 (0.44)
135	0.67 (0.50)	1.00 (0.88)	0.63 (0.46)
145	0.69 (0.51)	1.10 (0.95)	0.66 (0.47)
200	0.91 (0.69)	—	—
300	1.31 (1.04)	—	—

1404.1344

$t\bar{t}H$



Final state:

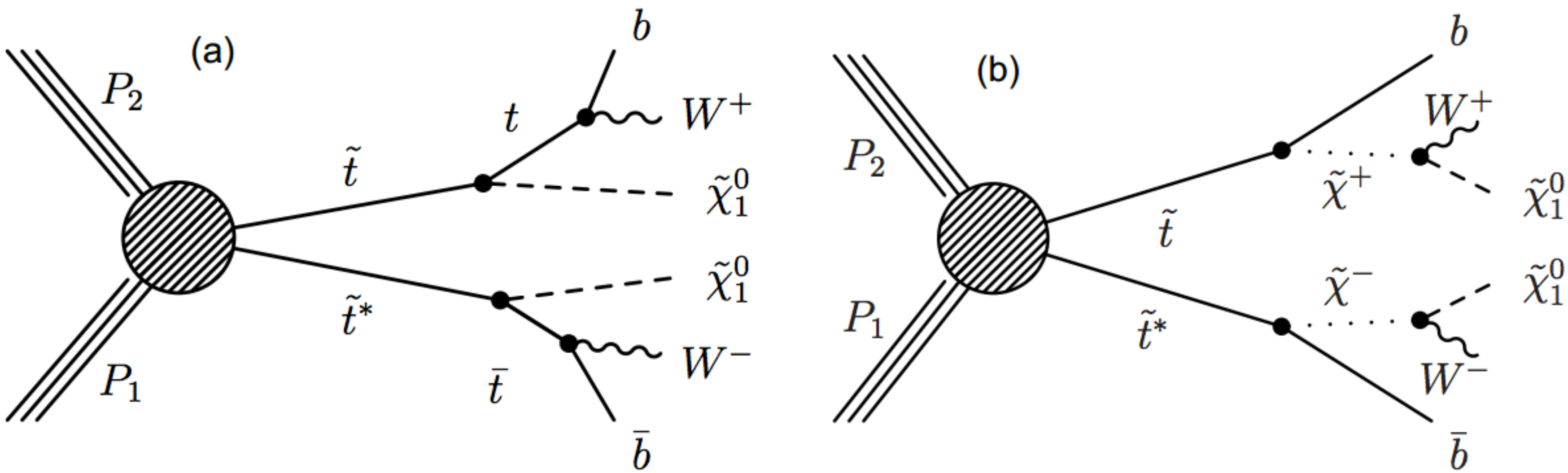
Two WIMPs+$t\bar{t}$

Detector signature

$t\bar{t}$ + MET

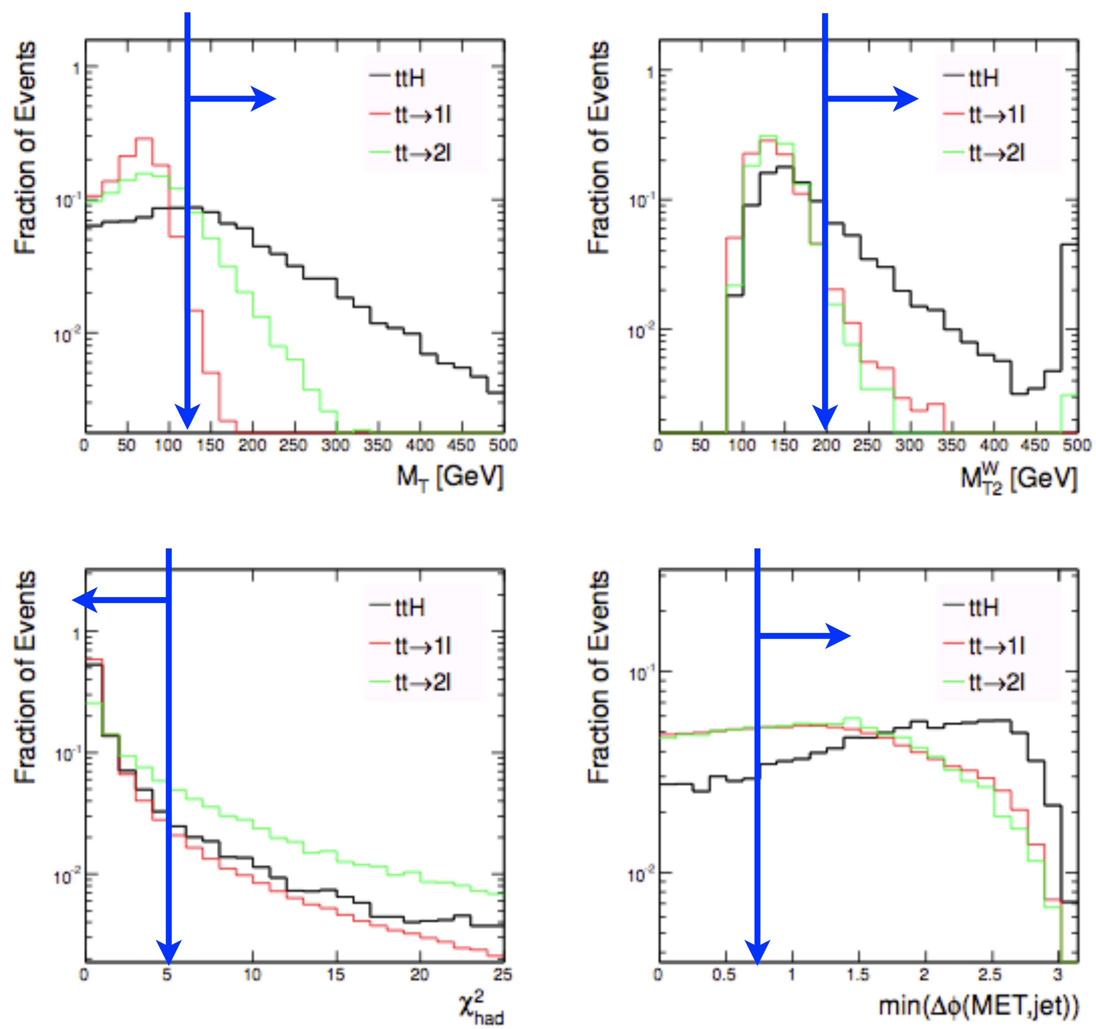
CMS search

CMS looked for this



Final state: bWbW + XX

Also works for ttH!



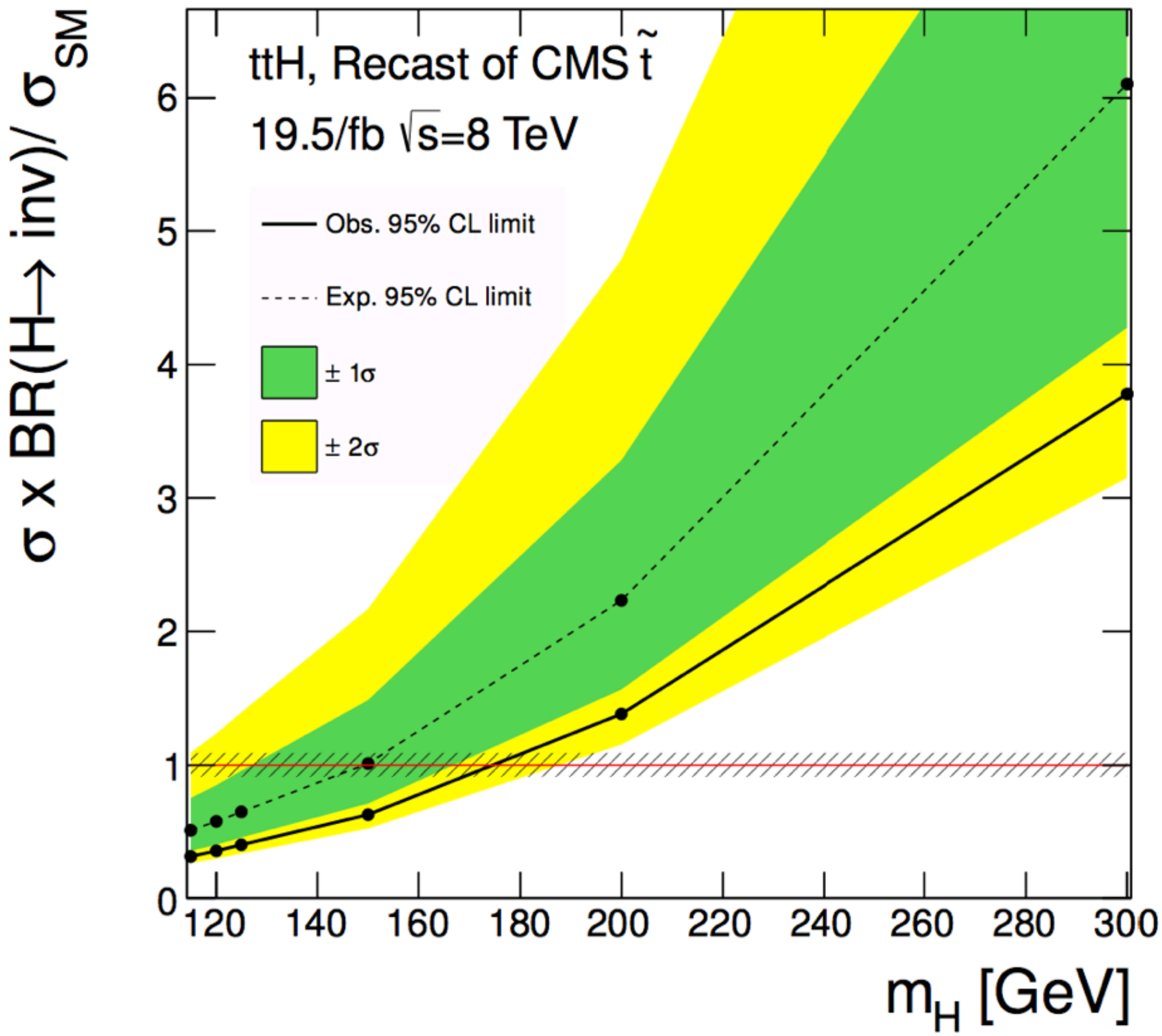
1408.0011

Large S/B

$t\bar{t} \to \ell\ell$	3.2 ± 1.4
1ℓ top	3.0 ± 2.2
$W + \text{jets}$	1.5 ± 0.5
Rare	1.8 ± 0.9
Total	9.5 ± 2.8
Data	3
ttH	11.4

1408.0011

Limit



< 0.40, 95%CL
at mh=125

1408.0011

Combination

Exp.	Mode	Dataset	Background	Obs.	Signal
ATLAS [13]	$Zh \to \ell\ell + E_T^{miss}$	7 TeV	25.4 ± 1.9	28	8.9
	$Zh \to \ell\ell + E_T^{miss}$	8 TeV	138 ± 10	152	44
CMS [14]	$Zh \to \ell\ell + E_T^{miss}$	7 TeV	19.7 ± 9.8	19	5.4
		8 TeV	89.0 ± 8.5	82	25.0
	$Zh \to \ell\ell + j + E_T^{miss}$	7 TeV	5.4 ± 1.6	5	0.9
		8 TeV	24.4 ± 10.0	28	4.1
CMS[14]	$Zh \to bb + E_T^{miss}$	8 TeV, low p_T^H	40.5 ± 4.1	38	1.6
		8 TeV, med p_T^H	64.8 ± 181.3	61	3.6
		8 TeV, high p_T^H	181.3 ± 9.8	204	12.6
CMS[14]	$qqH \to jj + E_T^{miss}$	8 TeV	332 ± 58	390	224
CMS recast[15]	$t\bar{t}H \to 1\ell + 4j + E_T^{miss}$	8 TeV	9.5 ± 2.8	3	11.4

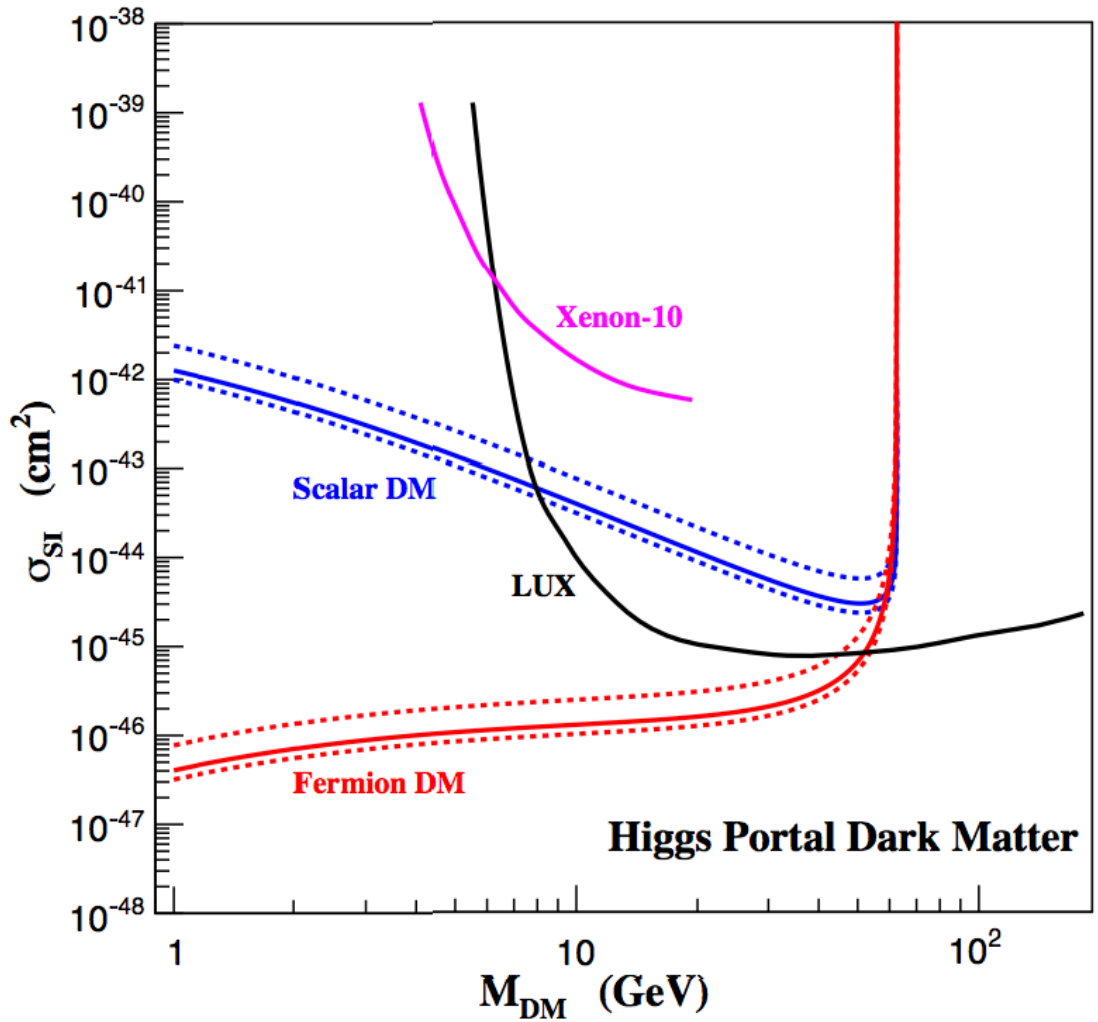
1408.0011

Combined limits

Exp.	Mode	Obs. (Exp.) limit
ATLAS [13]	$Zh \to \ell\ell + E_{\mathrm{T}}^{\mathrm{miss}}$	1.04 (0.81)
CMS [14]	$Zh \to \ell\ell + E_{\mathrm{T}}^{\mathrm{miss}}$	1.02 (1.19)
CMS [14]	$Zh \to bb + E_{\mathrm{T}}^{\mathrm{miss}}$	3.15 (2.69)
CMS [14]	$qqH \to jj + E_{\mathrm{T}}^{\mathrm{miss}}$	0.76 (0.57)
CMS recast[15]	$t\bar{t}H \to 1\ell 4j + E_{\mathrm{T}}^{\mathrm{miss}}$	0.40 (0.65)
CMS[14, 15]	$qqH + t\bar{t}H$	0.45 (0.47)
All[13, 14]	All but $t\bar{t}H$	0.63 (0.46)
All[13–15]	All	0.40 (0.40)

1408.0011

Interpretation



1408.0011

Outline

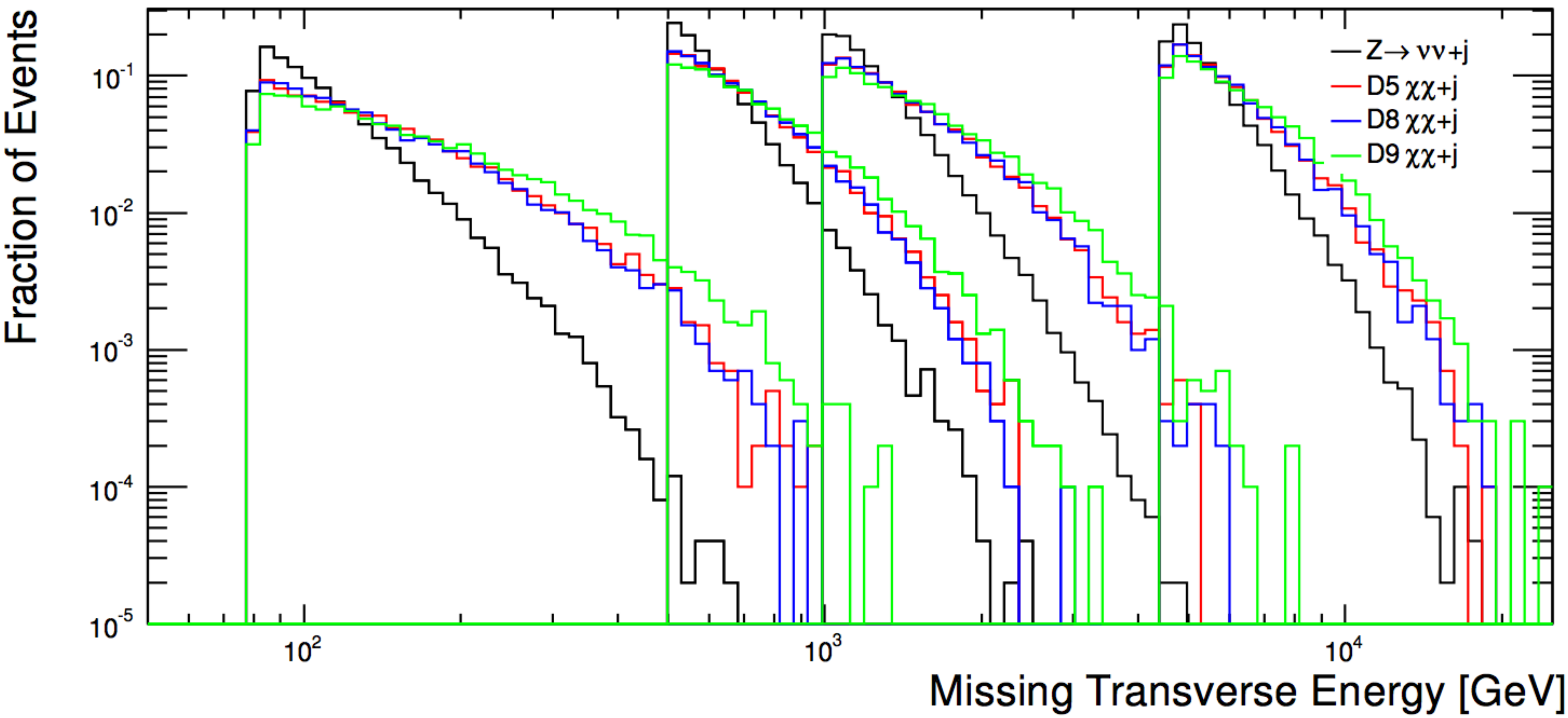
I. Detector basics
II. Mono-X
III. Invisible Higgs decays
IV. Prospects at future colliders

Facilities

$\sqrt{s}$ [TeV]	$\not{E}_T$ [GeV]	$\mathcal{L}$ [fb^{-1}]	N_{D5}	N_{bg}
7	350	4.9	73.3	1970 ± 160
14	550	300	2500	2200 ± 180
14	1100	3000	3200	1760 ± 143
33	2750	3000	$8.2 \cdot 10^4$	1870 ± 150
100	5500	3000	$3.4 \cdot 10^6$	2310 ± 190

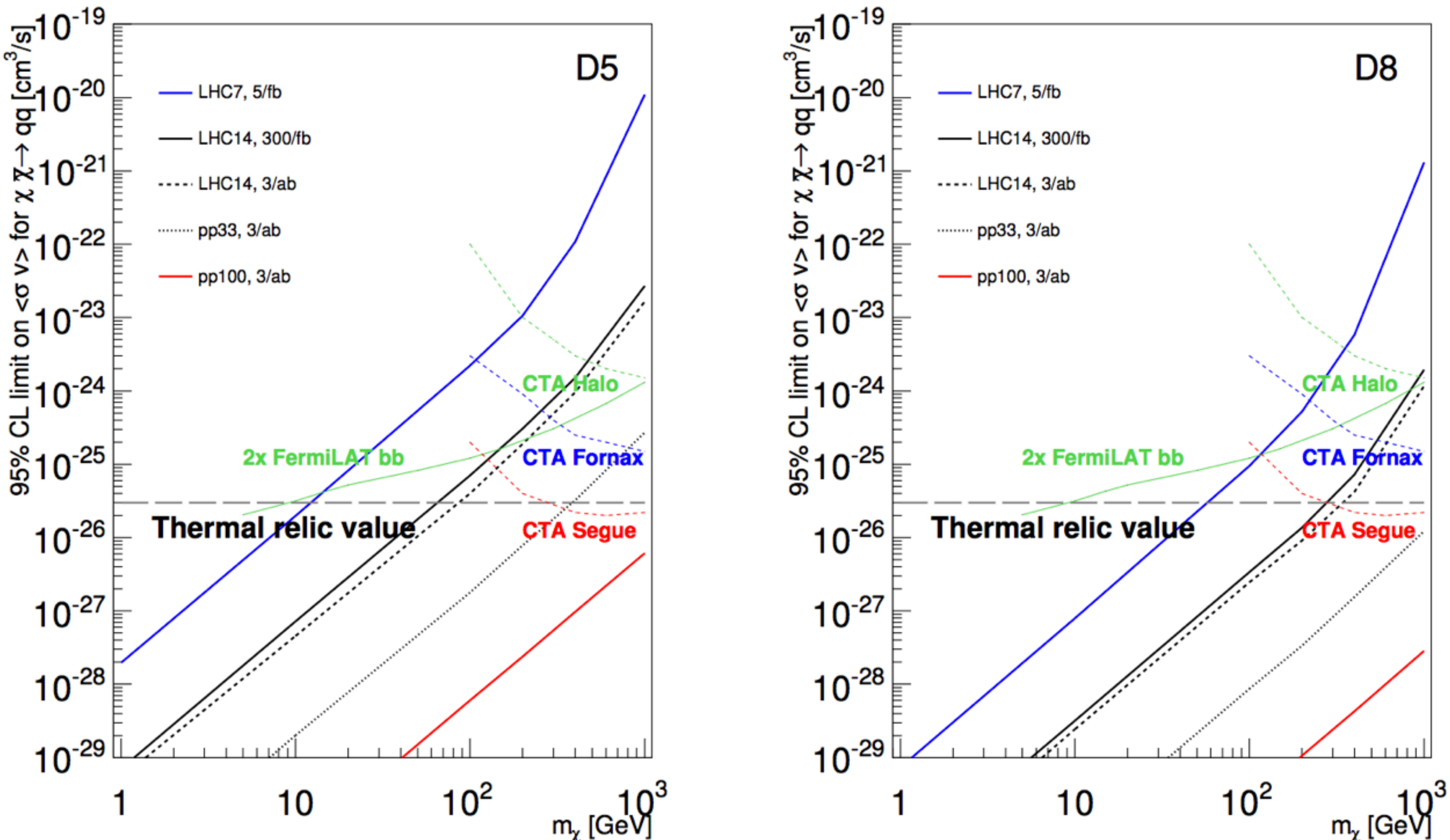
1307.5327

MET cuts



1307.5327

Limits



1307.5327

Invisible Higgs

$\int \mathcal{L} dt$ (fb^{-1})	BR_{inv}	
300	$< 23 - 32\%$	ATLAS
3000	$< 8 - 16\%$	ATLAS
300	$< 17 - 28\%$	CMS
3000	$< 6 - 17\%$	CMS

1310.8361

Invisible Higgs

Facility	ILC			ILC(LumiUp)	TLEP (4 IP)		CLIC		
$\sqrt{s}$ (GeV)	250	500	1000	250/500/1000	240	350	350	1400	3000
$\int \mathcal{L} dt$ (fb^{-1})	250	+500	+1000	1150+1600+2500‡	10000	+2600	500	+1500	+2000
$P(e^-, e^+)$	$(-0.8, +0.3)$	$(-0.8, +0.3)$	$(-0.8, +0.2)$	(same)	$(0, 0)$	$(0, 0)$	$(0, 0)$	$(-0.8, 0)$	$(-0.8, 0)$
BR_{inv}	0.9%	$< 0.9\%$	$< 0.9\%$	0.4%	0.19%	$< 0.19\%$			

1310.8361

Fin