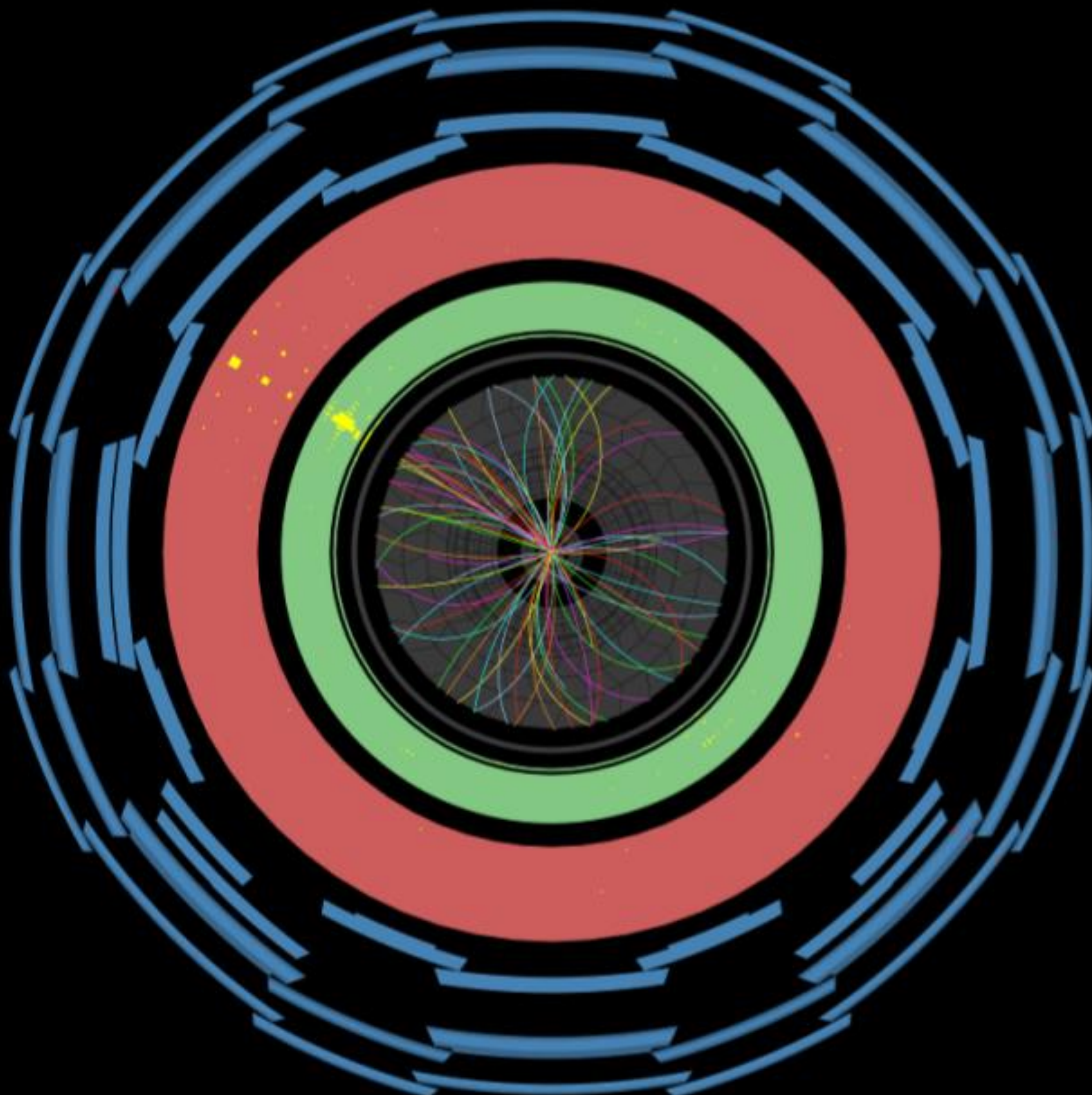
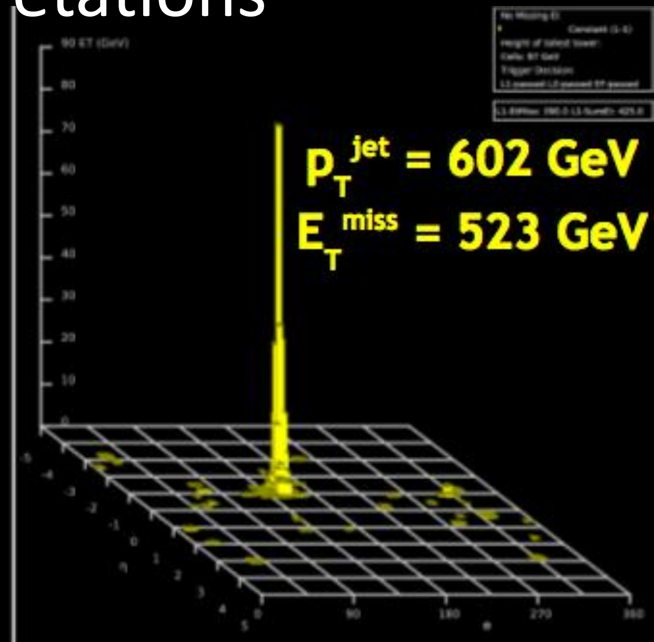
LHC monojet measurements and interpretations



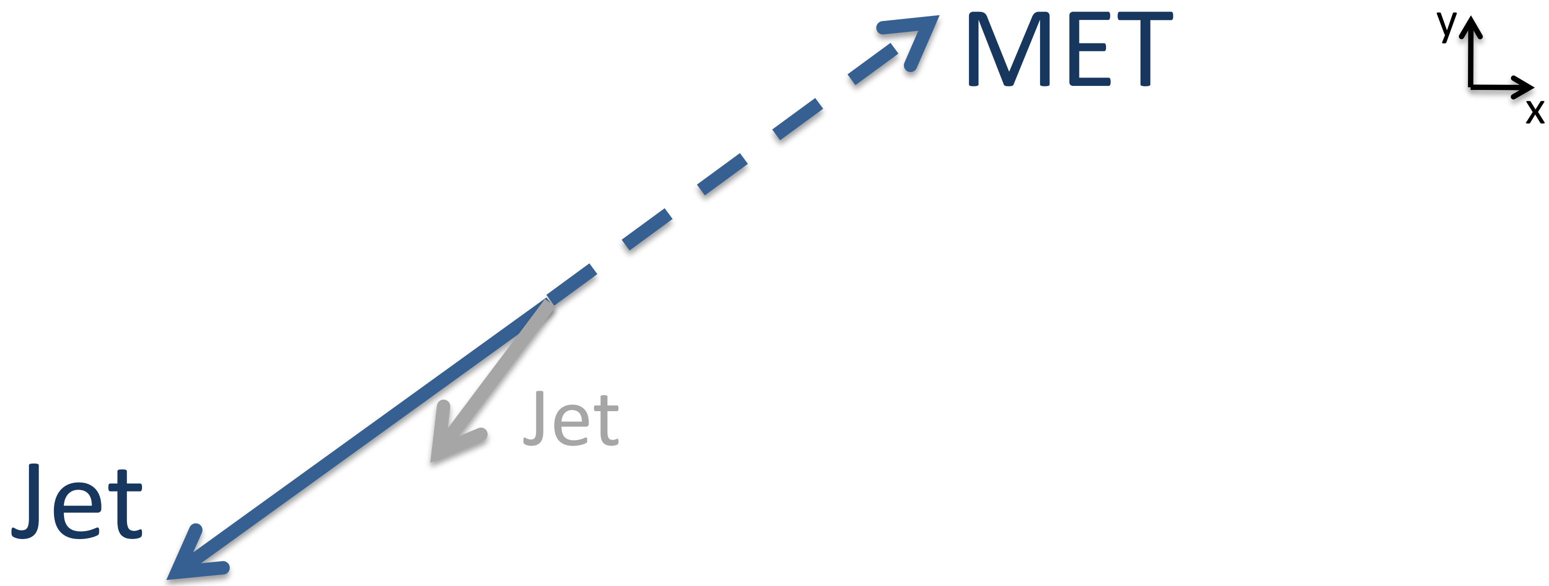


- Measurements by ATLAS and CMS
- ADD interpretations
- WIMP interpretations

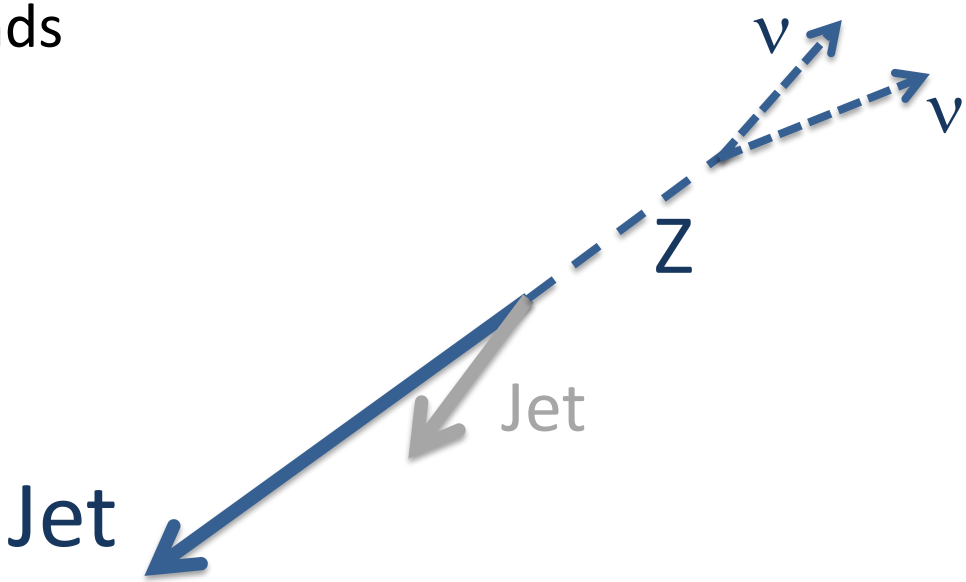
David Berge, CERN, ATLAS

Final state

Signal

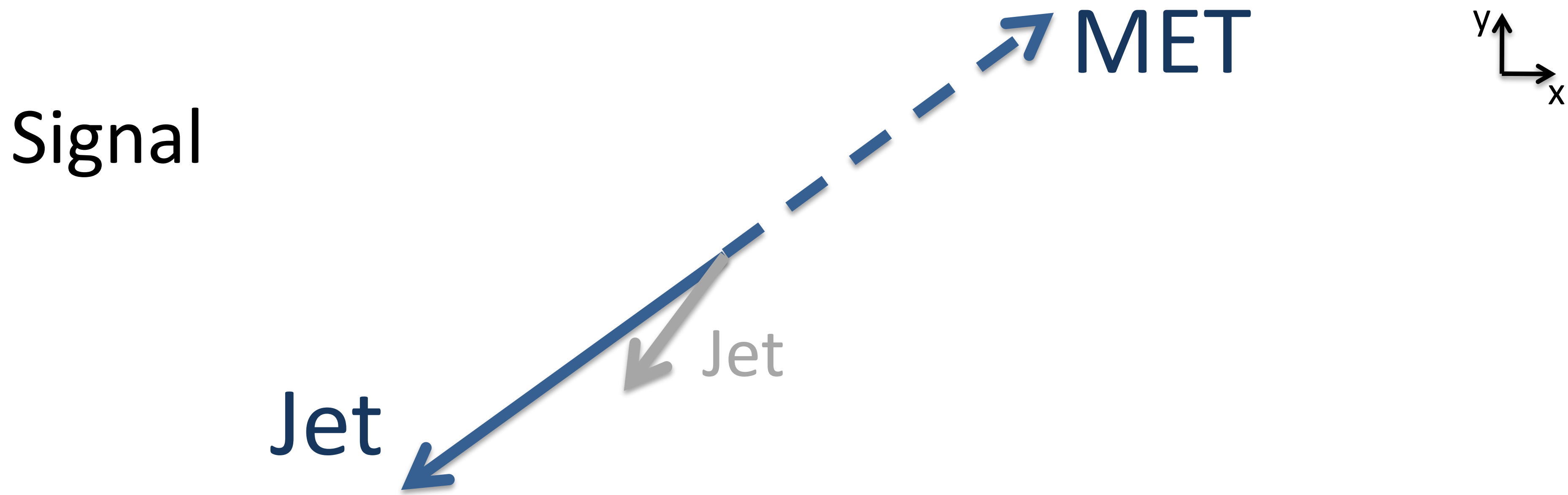


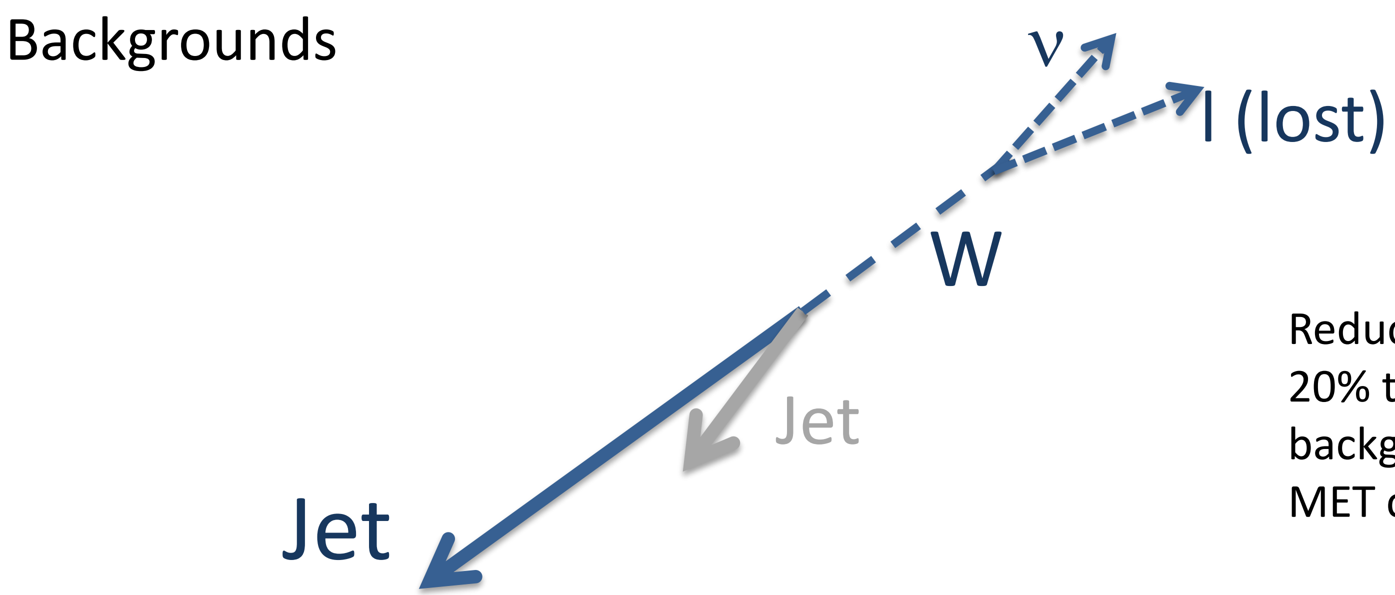
Backgrounds



Irreducible SM background, 50% to 80% of total background depending on MET cuts.

Final state



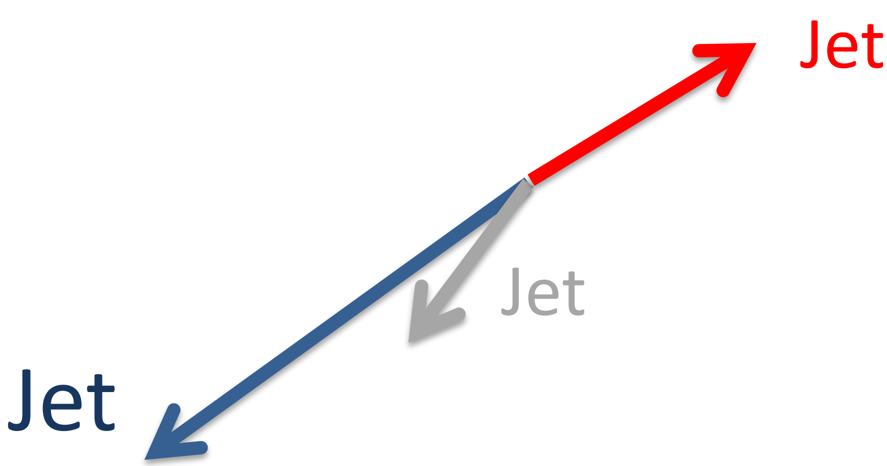


Reducible SM background, 20% to 50% of total background depending on MET cuts.

Final state

Signal

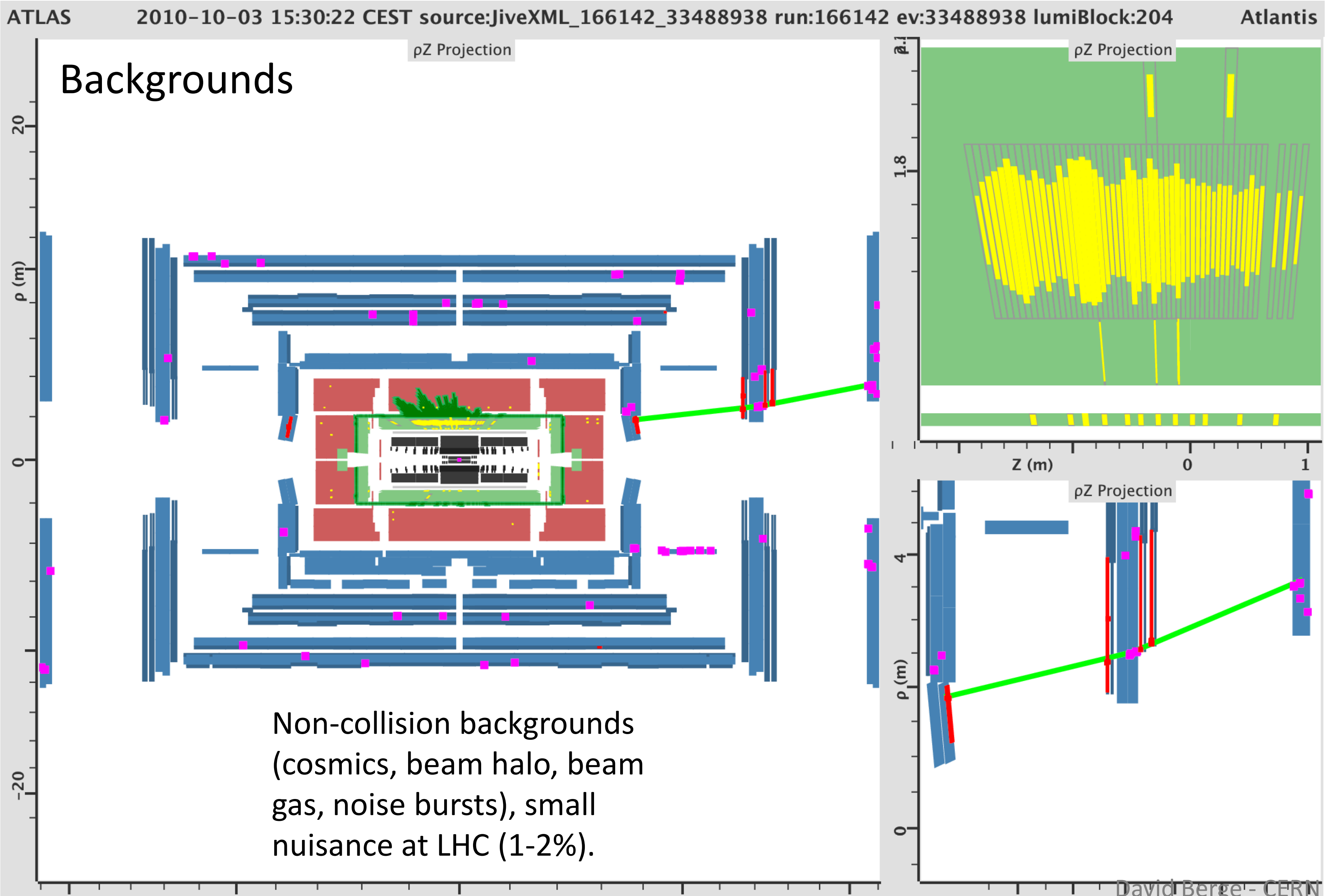
Backgrounds



QCD background from jet mismeasurement, almost negligible due to $\Delta\phi$ cuts (1-2%).

Final state

ATLAS-CONF-2011-137



Backgrounds

Non-collision backgrounds (cosmics, beam halo, beam gas, noise bursts), small nuisance at LHC (1-2%).

2010 Data ($35pb^{-1}$) – Journal Publications

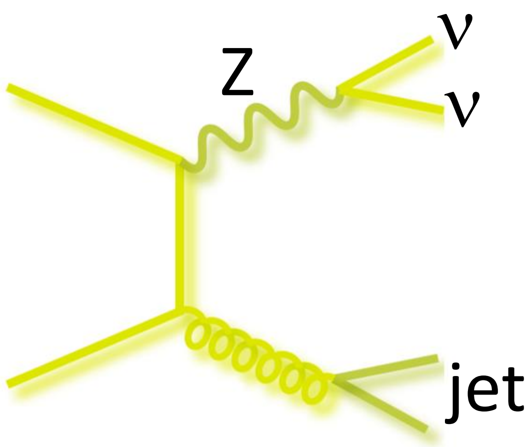
ATLAS	CMS
• http://arxiv.org/abs/1106.5327 • Isolated lepton veto (20 / 10 GeV for e / μ) • Low pt: – Lead jet pt > 120 GeV, $\|\eta\| < 2.0$ – 2nd jet veto pt < 30 GeV, $\|\eta\| < 4.5$ – MET > 120 GeV • Hight pt: – Lead jet pt > 250 GeV, $\|\eta\| < 2.0$ – 2nd jet veto < 60 GeV, $\|\eta\| < 4.5$ – 3rd jet veto < 30 GeV, $\|\eta\| < 4.5$ – MET > 220 GeV – $\Delta\phi$(j2,MET) > 0.5 • ADD limits	• http://arxiv.org/abs/1106.4775 • Isolated lepton veto (20 GeV for both e / μ) • MET > 150 GeV • Lead jet pt > 110 GeV, $\|\eta\| <$ 2.4 • No 2nd jet veto, but N_{jets} <3 and $\Delta\phi$ (j1,j2) < 2.0 • 3rd jet pt < 30 GeV • τ veto • ADD and unparticle limits

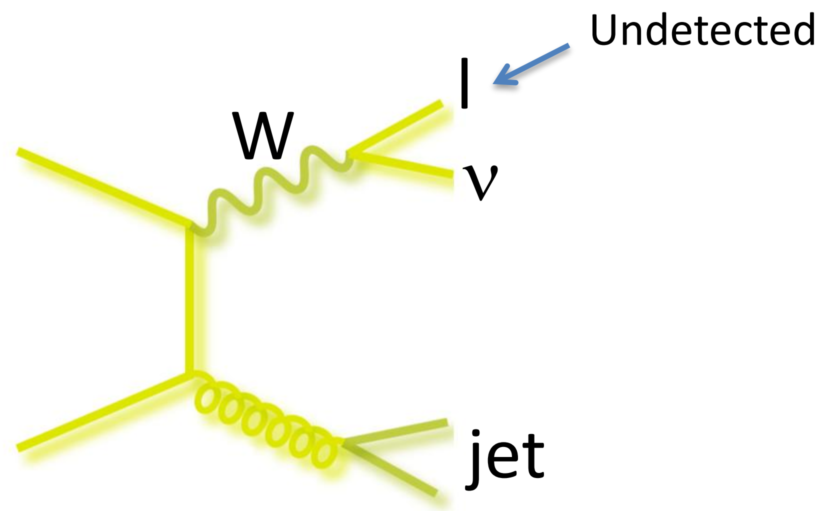
2011 Data ($1.1fb^{-1}$) – Conference Notes

ATLAS	CMS
• http://cdsweb.cern.ch/record/1369187 • Isolated lepton veto (20 / 10 GeV for e / μ) • Low pt: – Lead jet pt > 120 GeV, $\lvert\eta\rvert < 2.0$ – 2nd jet veto pt < 30 GeV, $\lvert\eta\rvert < 4.5$ – MET > 120 GeV • Hight pt: – Lead jet pt > 250 GeV, $\lvert\eta\rvert < 2.0$ – 2nd jet veto < 60 GeV, $\lvert\eta\rvert < 4.5$ – 3rd jet veto < 30 GeV, $\lvert\eta\rvert < 4.5$ – MET > 220 GeV – $\Delta\phi$(j2,MET) > 0.5 • **Very hight pt:** – Lead jet **pt > 350 GeV**, $\lvert\eta\rvert < 2.0$ – 2nd jet veto < 60 GeV, $\lvert\eta\rvert < 4.5$ – 3rd jet veto < 30 GeV, $\lvert\eta\rvert < 4.5$ – **MET > 300 GeV** – $\Delta\phi$(j2,MET) > 0.5 • ADD limits	• http://cdsweb.cern.ch/record/1376675 • Isolated lepton veto (20 GeV for both e / μ) • **Low to high MET:** – **MET > 200 GeV** – **MET > 250 GeV** – **MET > 300 GeV** – **MET > 350 GeV** – **MET > 400 GeV** • Lead jet pt > 110 GeV, $\lvert\eta\rvert < 2.4$ • No 2nd jet veto, but N_{jets} <3 and $\Delta\phi$ (j1,j2) < 2.0 • 3rd jet pt < 30 GeV • τ veto • ADD limits

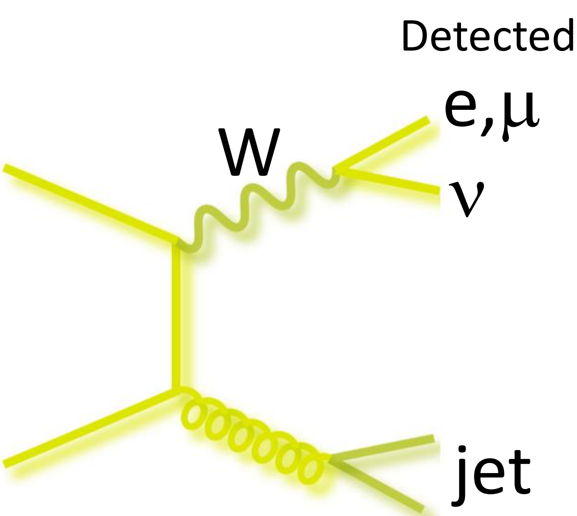
Electroweak Backgrounds

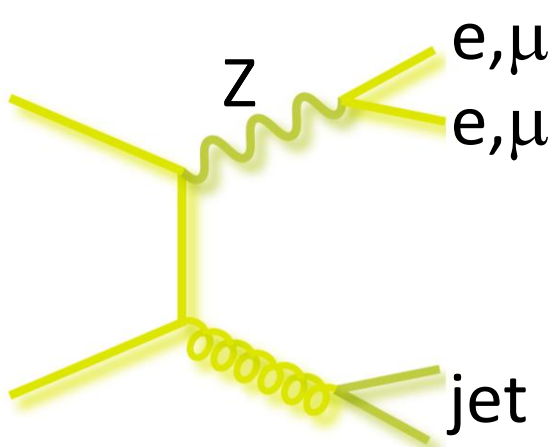
Main backgrounds:





Data driven estimates:





- **CR:** invert lepton veto
- **ATLAS:** subtract ttbar MC, take scale factor data/MC in CR to rescale MC in SR
- **CMS:** same for W+jets, for Z+jets they are taking the Z->ll data estimate, plus acceptance & efficiency differences from MC and rescale for BR's

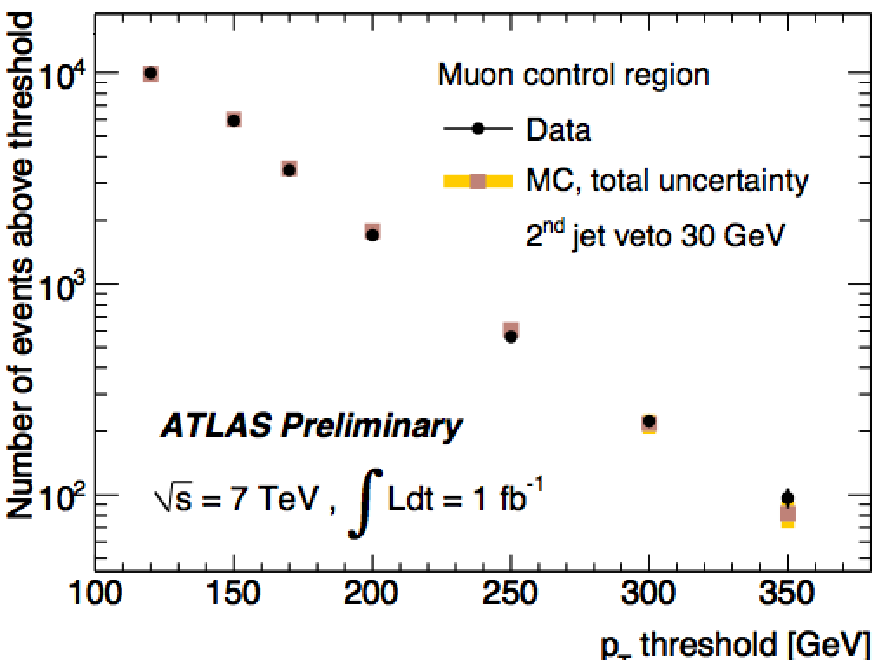
Electroweak Backgrounds ATLAS

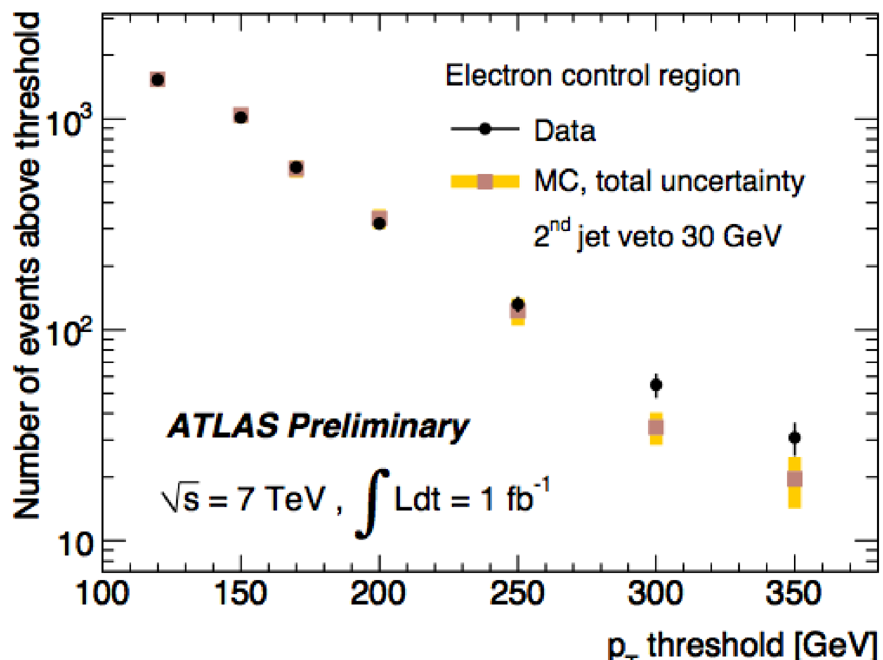
- Keep signal selection of large MET and a single jet, add a single lepton requirement (e 20 GeV, μ 10 GeV)
- This is found to result in approx: 80% W->e,μ ν, 15% W->τ ν, 5% ttbar (for the latter the MC estimate is subtracted, with assumed 20% total systematic uncertainty – 2% on the result)
- Muon sample:
  - Data / MC scale in control region to normalise W->$\mu\nu$+jets, Z->$\nu\nu$+jets, Z->$\mu\mu$+jets MC in signal region
- Electron sample:
  - Data / MC scale in control region to normalise W->eν+jets, W->$\tau\nu$+jets, Z->$\tau\tau$+jets MC in signal region

Electroweak Backgrounds ATLAS

- Scale factor cross checks: no dependence on kinematic cuts found
- Within statistics scale factors from direct Z or W selection (plus a high-pt jet and large MET in the W selection) agree
- Systematic uncertainty on bg estimate:
  - Uncertainties on lepton ID (4%), ttbar MC (2%), statistics in CR summed in quadrature

Control regions after scaling, data versus sum of MC:





Electroweak Backgrounds CMS

Estimation of invisible Z background from Z→ll and W→lν

Z→νν from Z→ll

$$N(Z \to \nu\nu) = \frac{N_Z^{obs} - N_Z^{bgd}}{A_Z \bullet \varepsilon_Z} \bullet R\left(\frac{Z \to \nu\nu}{Z \to ll}\right)$$

~ 6

- use same dataset (Jet/Met) as signal region
- select 2 well reconstructed and isolated muons with; $p_T > 20$, $|\eta| < 2.1$, opposite sign charge
- dimuon mass 81-101 GeV
- apply search selection with Met defined as vector sum of p_T of muons
- correct for acceptance and reconstruction efficiencies
- negligible background
- take R from theory

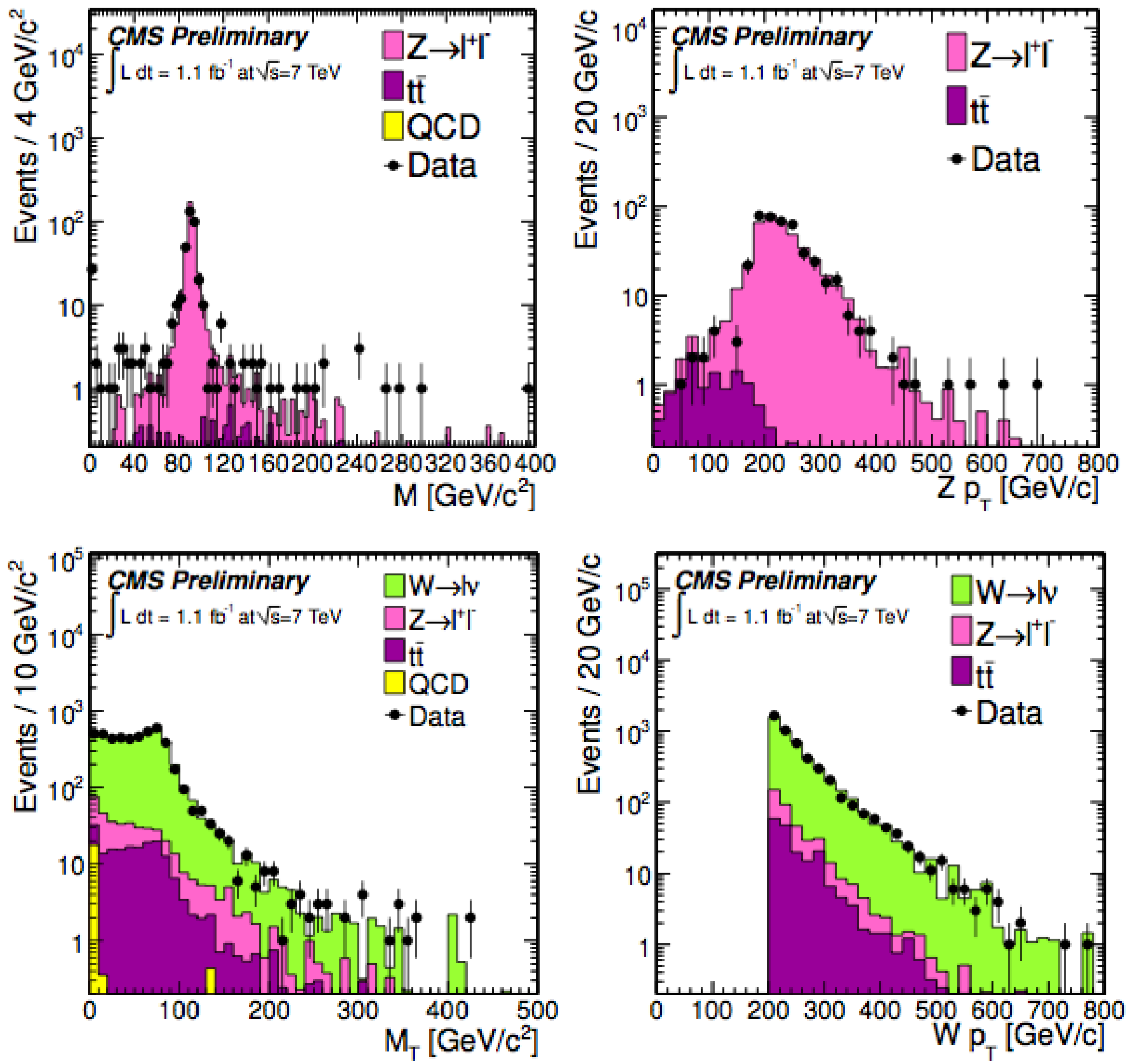
Z→νν from W→lν

$$N(Z \to \nu\nu) = \frac{N_W^{obs} - N_W^{bgd}}{A_W \bullet \varepsilon_W} \bullet R\left(\frac{Z \to \nu\nu}{W \to l\nu}\right)$$

- use same dataset (Jet/Met) as signal region
- select 1 well reconstructed and isolated muon with; $p_T > 20$, $|\eta| < 2.1$
- transverse mass (M_T) 50 - 100 GeV
- apply search selection with Met defined as vector sum of Met and muon
- correct for acceptance and reconstruction efficiencies
- correct for background
- take R from theory, correct for the difference in p_T spectra of bosons at high p_T

Electroweak Backgrounds CMS

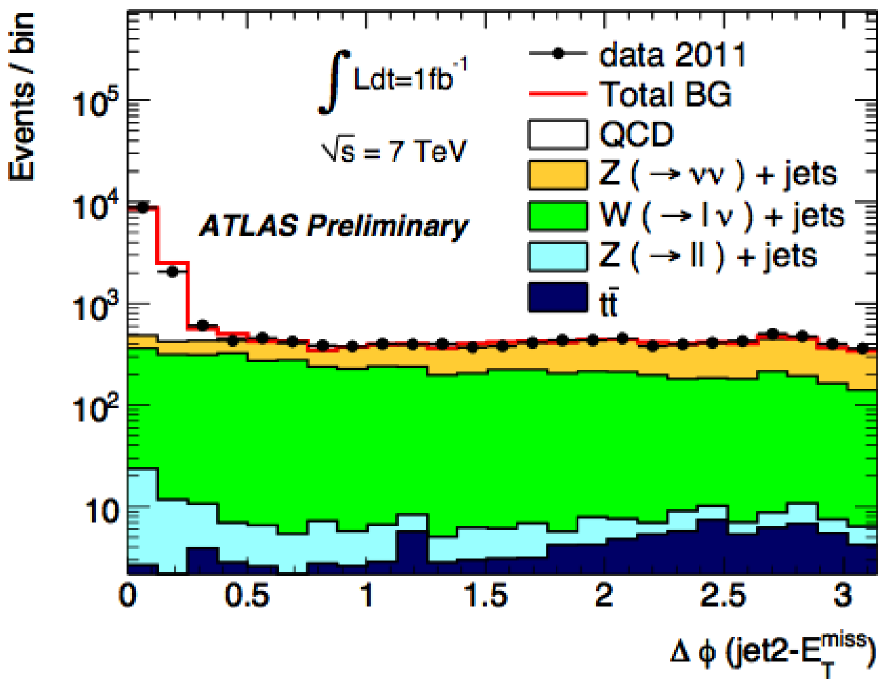
- Z and W background samples
- MC normalised to data
- Data estimate / scale factors only done for muons

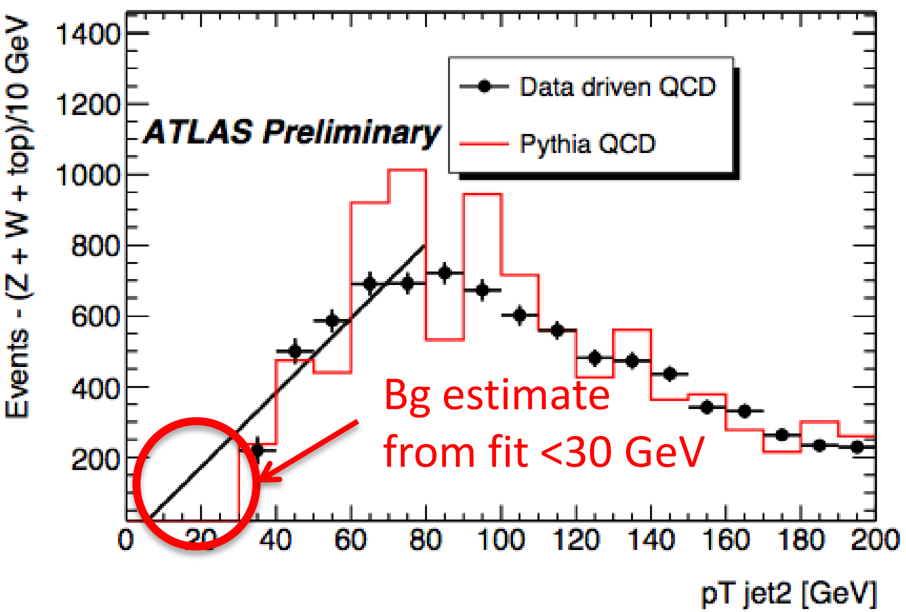


Remaining Backgrounds

- QCD multijets
  - CMS from MC
  - ATLAS from data where sufficient statistics, else negligible
- Ttbar from MC (negligible in all cases)
- Noncollision backgrounds
  - Ignored by CMS, estimated from data by us
  - Data estimates: jets in unpaired and empty crossings in 2010, David's beam-halo tagger in 2011…

ATLAS QCD estimate: drop jet veto and $\Delta\phi$ cut, subtract other bg from MC, fit data in $\Delta\phi$<0.5





Remaining Backgrounds

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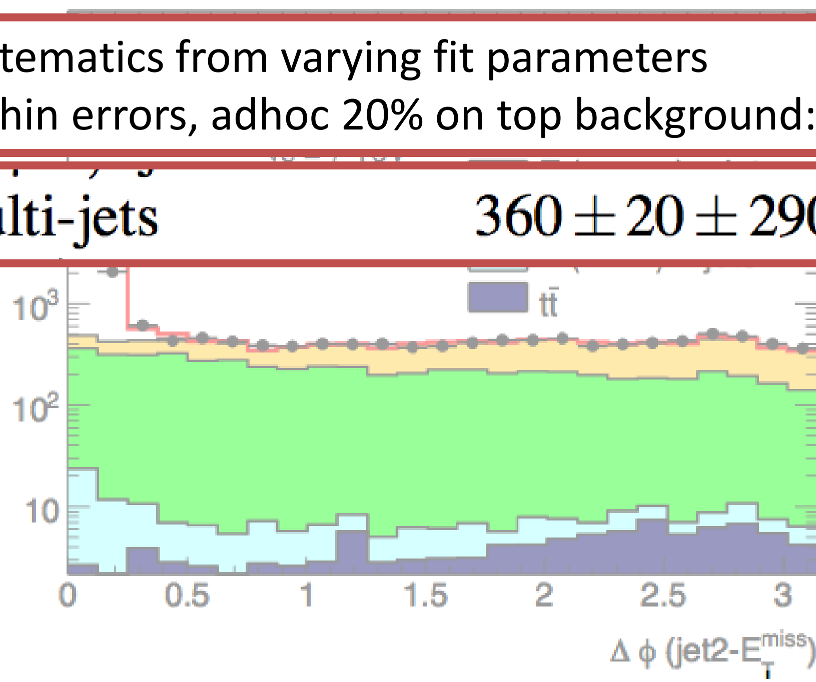
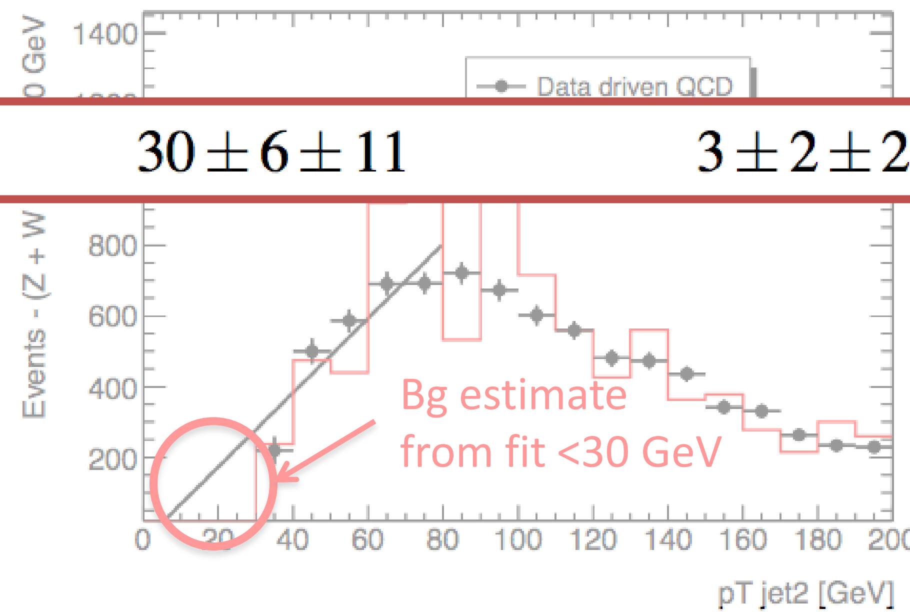
- Noncollision backgrounds
  - Ignored by CMS, estimated from data by us
  - Data estimates: jets in unpaired and empty crossings in 2010, David's beam-halo tagger in 2011…

ATLAS QCD estimate: drop jet veto and Δϕ cut, subtract other bg from MC, fit data in Δϕ<0.5

Systematics from varying fit parameters within errors, adhoc 20% on top background:

Multi-jets	$360 \pm 20 \pm 290$	$30 \pm 6 \pm 11$	$3 \pm 2 \pm 2$





Grand total ATLAS

	Background Predictions $\pm$ (stat.) $\pm$ (syst.)		
	LowPt Selection	HighPt Selection	veryHighPt selection
$Z\ (\rightarrow \nu\bar{\nu})$+jets	$7700 \pm 90 \pm 400$	$610 \pm 27 \pm 47$	$124 \pm 12 \pm 15$
$W(\rightarrow \tau\nu)$+jets	$3300 \pm 90 \pm 220$	$180 \pm 16 \pm 22$	$36 \pm 7 \pm 8$
$W(\rightarrow e\nu)$+jets	$1370 \pm 60 \pm 90$	$68 \pm 10 \pm 8$	$8 \pm 1 \pm 2$
$W(\rightarrow \mu\nu)$+jets	$1890 \pm 70 \pm 100$	$113 \pm 14 \pm 9$	$18 \pm 4 \pm 2$
Multi-jets	$360 \pm 20 \pm 290$	$30 \pm 6 \pm 11$	$3 \pm 2 \pm 2$
$Z/\gamma^*(\rightarrow \tau^+\tau^-)$+jets	$59 \pm 3 \pm 4$	$2.0 \pm 0.6 \pm 0.2$	-
$Z/\gamma^*(\rightarrow \mu^+\mu^-)$+jets	$45 \pm 3 \pm 2$	$2.0 \pm 0.6 \pm 0.1$	-
$t\bar{t}$	$17 \pm 1 \pm 3$	$1.7 \pm 0.3 \pm 0.3$	-
γ+jet	-	-	-
$Z/\gamma^*(\rightarrow e^+e^-)$+jets	-	-	-
Non-collision Background	$370 \pm 40 \pm 170$	$8.0 \pm 3.3 \pm 4.1$	$4.0 \pm 3.2 \pm 2.1$
Total Background	$15100 \pm 170 \pm 680$	$1010 \pm 37 \pm 65$	$193 \pm 15 \pm 20$
Events in Data (1.00 fb^{-1})	15740	965	167

Statistical error is statistics in MC, systematics is lepton ID, ttbar subtraction, statstics in CR

Grand total CMS

Requirement	W+jets	Z(νν)+j	Z+j	$t\bar{t}$	t	QCD	Total BG	Data
$E_T^{miss} > 200$ GeV, jet cleaning	13689	5182	1103	2837	213	2588	25613	24428
$p_T(j_1) > 110$ GeV/c, $\|\eta(j_1)\| < 2.4$	13080	4936	1056	2601	195	2558	24425	23623
$N_{Jets} \leq 2$	8553	3686	725	299	46.4	768	14078	14544
$\Delta\phi(j_1, j_2) < 2.5$	7448	3446	659	253	40.0	19.2	11865	12345
Lepton Removal	2174	3328	16.1	47.9	6.7	0.5	5573	5965
$E_T^{miss} > 250$ GeV	639	1192	4.0	14.1	1.9	0.5	1851	1930
$E_T^{miss} > 300$ GeV	200	483	0.9	4.6	0.6	0.1	689	708
$E_T^{miss} > 350$ GeV	67.8	217	0.3	1.7	0.2	0.1	288	293
$E_T^{miss} > 400$ GeV	36.2	105	0.1	0.9	0.1	0.1	142	151

Total background uncertainties 2011

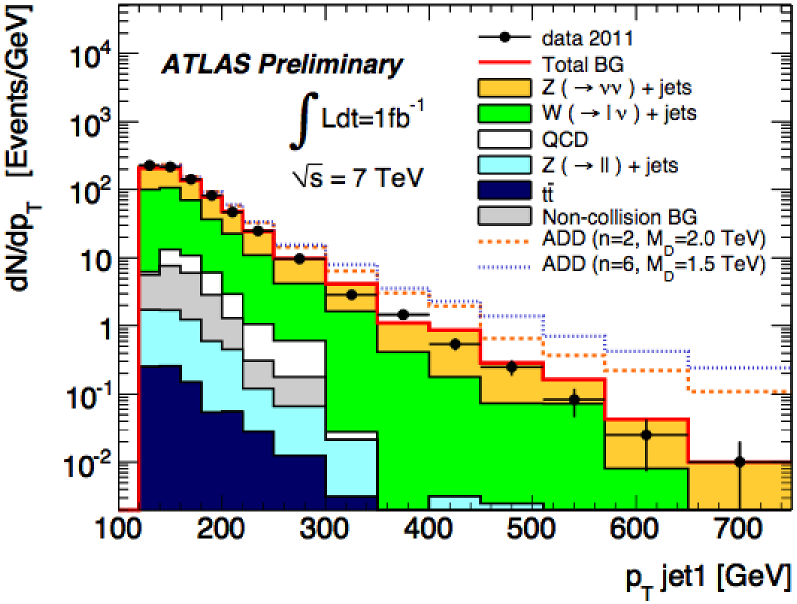
CMS only quote total (stat+syst) uncertainties for the 200 GeV MET analysis

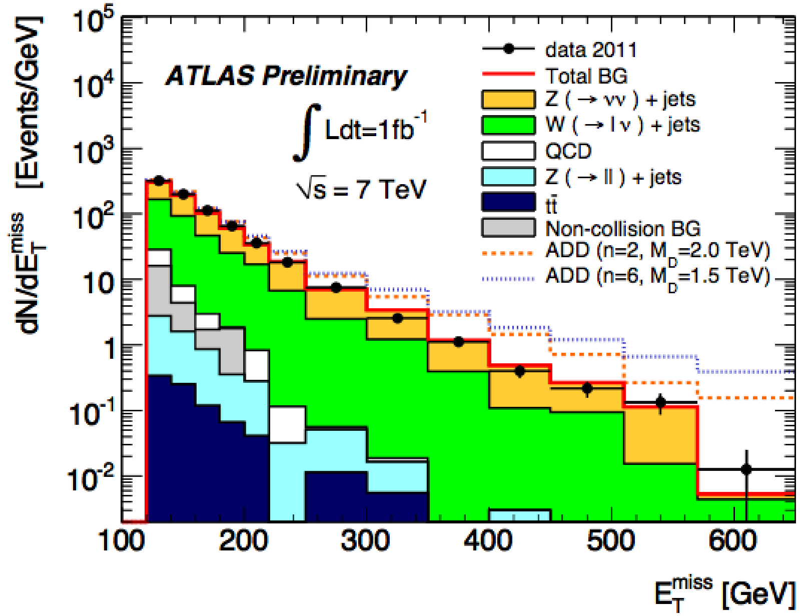
	ATLAS lowpt	ATLAS highpt	ATLAS veryhighpt	CMS 200 GeV MET
Statistical error	1.1%	3.7%	7.8%	
Systematic error	4.5%	6.4%	10%	
Total error	4.6%	7.4%	12.7%	5.5%

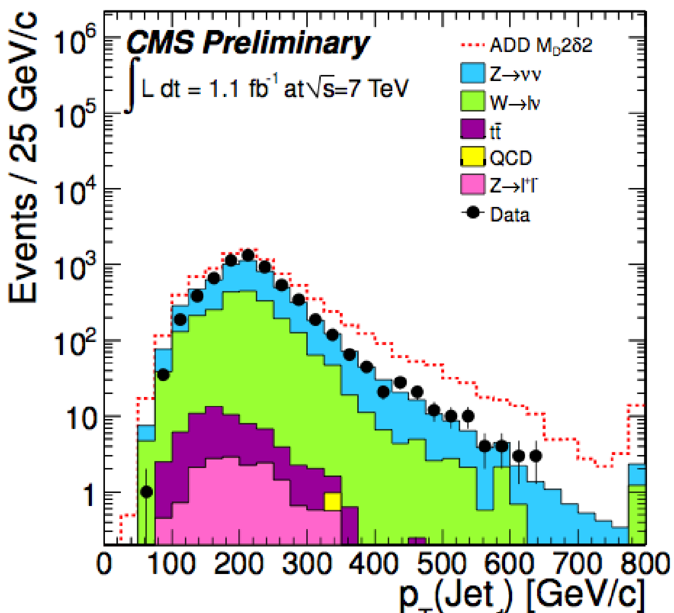
Signal systematic uncertainties

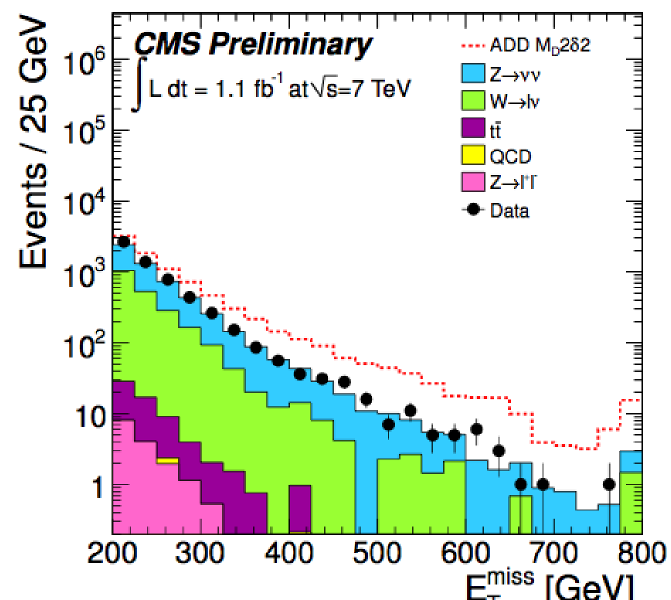
	ATLAS low/high pt	CMS low/high pt
PDF	6% / 7%	1-3% / 3-8%
ISR / FSR	13%	<2%
Q^2 scale	11%	-
JES	5% / 6%	8-11% / 10-20%
JER	3% / 1%	-
Pile-up	3% / 2%	3%
Luminosity	3%	5%
Total	20% / 20%	12% / 22% (take largest quote everywhere)

Results

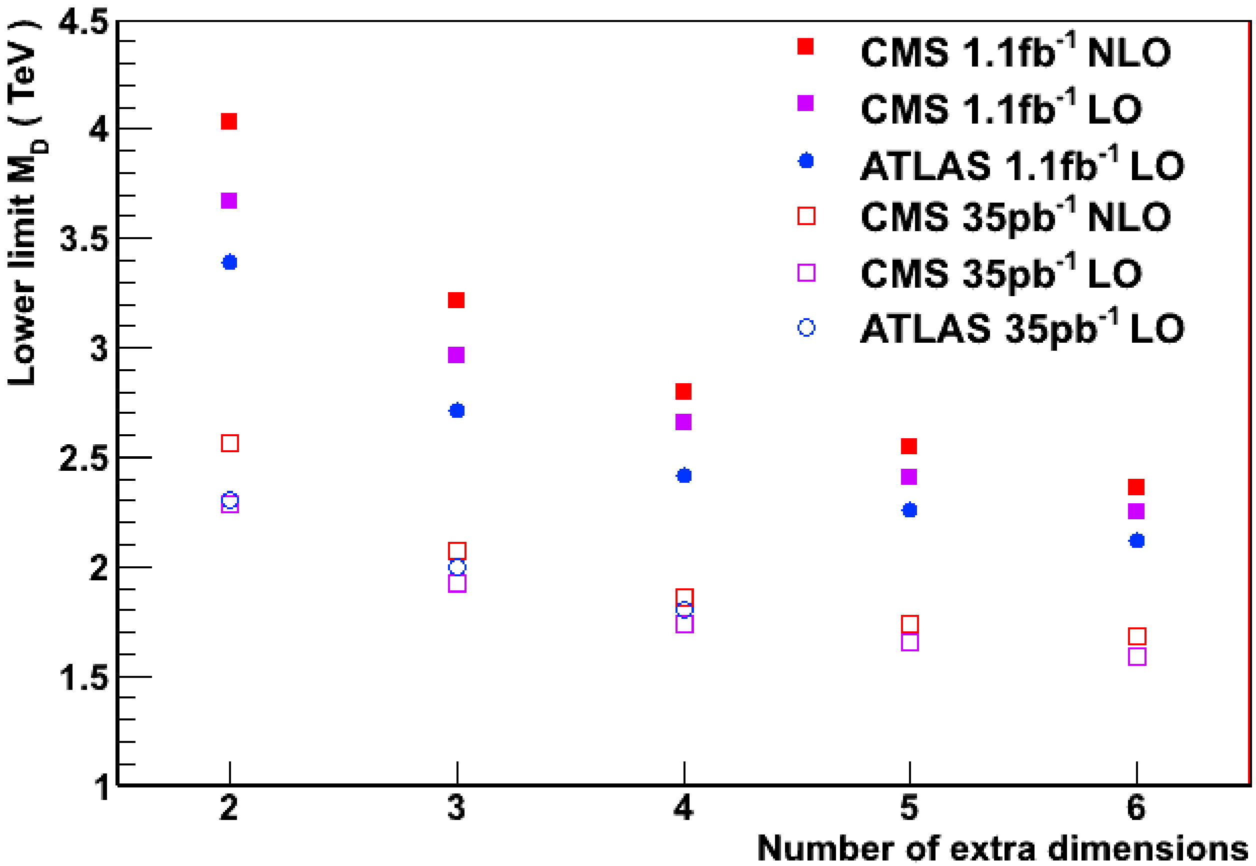

ATLAS Preliminary
∫Ldt=1fb^-1
√s = 7 TeV
data 2011
Total BG
Z (→ νν) + jets
W (→ l ν) + jets
QCD
Z (→ ll) + jets
tt̄
Non-collision BG
ADD (n=2, M_D=2.0 TeV)
ADD (n=6, M_D=1.5 TeV)
dN/dp_T [Events/GeV]
p_T jet1 [GeV]


ATLAS Preliminary
∫Ldt=1fb^-1
√s = 7 TeV
data 2011
Total BG
Z (→ νν) + jets
W (→ l ν) + jets
QCD
Z (→ ll) + jets
tt̄
Non-collision BG
ADD (n=2, M_D=2.0 TeV)
ADD (n=6, M_D=1.5 TeV)
dN/dE_T^miss [Events/GeV]
E_T^miss [GeV]


CMS Preliminary
∫L dt = 1.1 fb^-1 at √s=7 TeV
ADD M_D2δ2
Z→νν
W→lν
tt̄
QCD
Z→l+l-
Data
Events / 25 GeV/c
p_T(Jet_1) [GeV/c]


CMS Preliminary
∫L dt = 1.1 fb^-1 at √s=7 TeV
ADD M_D2δ2
Z→νν
W→lν
tt̄
QCD
Z→l+l-
Data
Events / 25 GeV
E_T^miss [GeV]

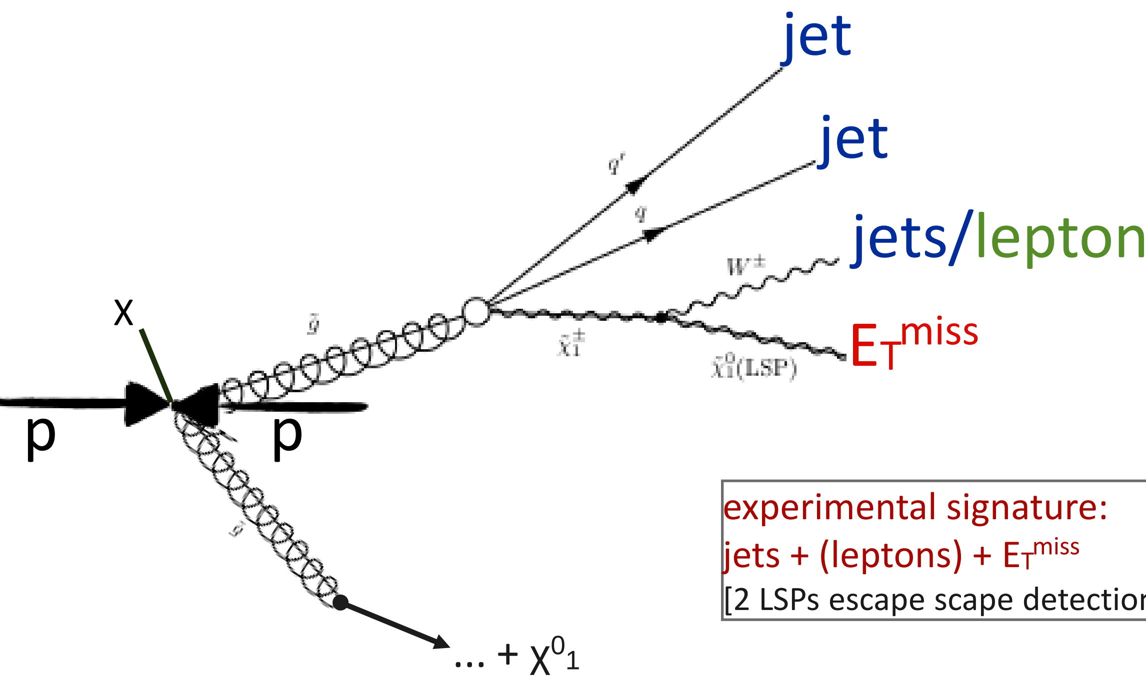
ADD Limits Overview



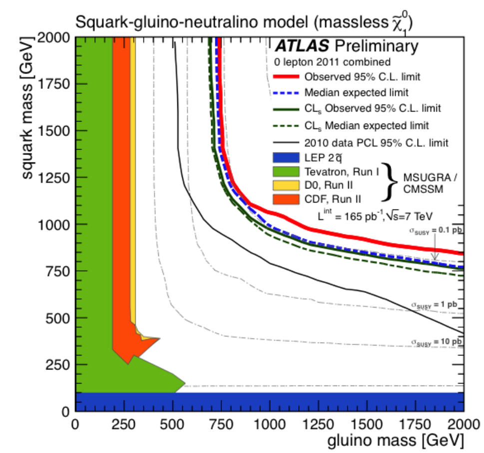
- CMS are taking sizeable K factors into account (1.5 for $\delta = \{2,3\}$, 1.4 for $\delta = \{4,5\}$, ATLAS doesn't
- LO limits better for CMS due to larger MET cut
- We have discussed ultraviolet behavior of ADD
  - Effective theory used to compute ADD cross sections
  - Only valid if event scale below M_D
  - In 2010 we didn't quote $\delta=\{5,6\}$ M_D values because of this, in 2011 we decided to quote both M_D (with and without suppression of region s-hat > M_D^2)
- ATLAS quotes fiducial cross section limits for all 3 selections (both at detector level, but also unfolded)

1: “Standard” Dark Matter Searches at Colliders

One possibility: search for large missing ET in cascade decays



experimental signature:
jets + (leptons) + E_T^{miss}
[2 LSPs escape scape detection]

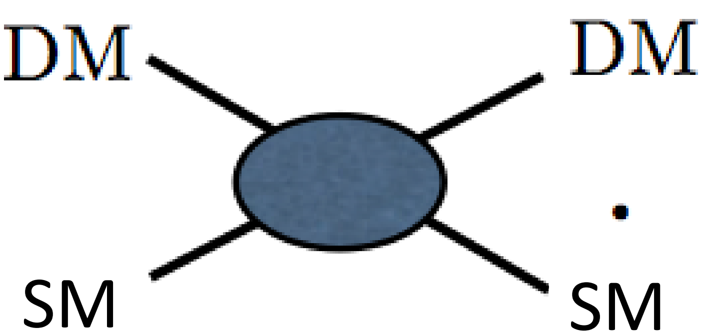


2: Generic WIMP Searches at Colliders

- Consider WIMP pair production at colliders, idea goes back to:
  - First paper
  - Maverick Dark Matter (Kolb, Hooper etc)
- Latest papers about ATLAS $1fb^{-1}$ result:
  - arxiv:1109.4398 (FNAL crew)
  - arxiv:1108.1196 (UCI crew)

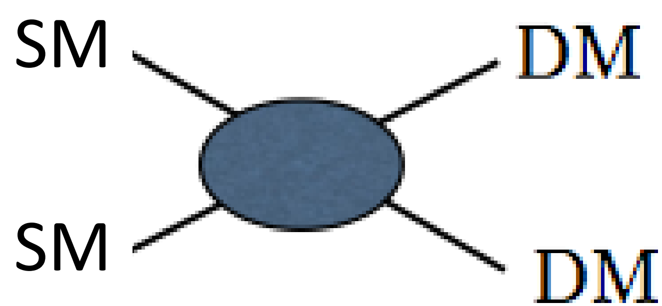
- All based on the idea:

Direct DM searches:



If this interaction exists…

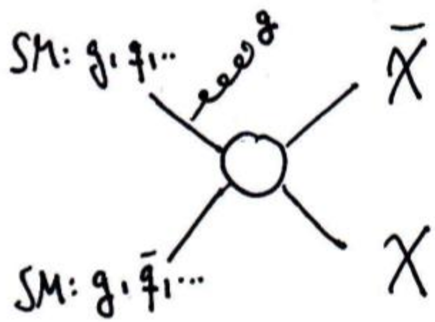
Colliders:



… this one must exist, too.

Generic WIMP Searches at Colliders

Search for WIMP pair production



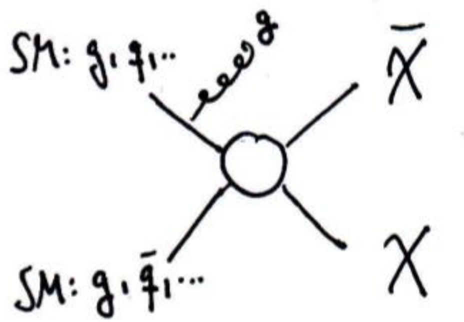
➡ Monojet searches…

Assume:

- WIMP exists and can be pair produced
- Dark Matter candidate the only particle within reach
- Effective field theory approach, integrate out new heavy mediator
- WIMP—SM coupling set by m_χ and suppression scale Λ
- Require hard jet to recoil against WIMPs thereby creating missing ET (otherwise no trigger)

Generic WIMP Searches at Colliders

Search for WIMP pair production



<u>Assume:</u>

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- WIMP—SM coupling set by m_χ and suppression scale Λ
- Require hard jet to recoil against WIMPs thereby creating missing ET (otherwise no trigger)

➡ Monojet searches…

Contact operators e.g. vector coupling:

$$O_V = \frac{(\bar{\chi}\gamma_\mu \chi)(\bar{f}\gamma^\mu f)}{\Lambda^2}$$

Production cross section dependence:

$$\sigma(\Lambda^{-4}, m_\chi)$$

Supression scale: $\Lambda = \frac{M}{\sqrt{g_\chi g_f}}$

Generic WIMP Searches at Colliders

Parametrise WIMP-SM interactions with various dim-6 operators:

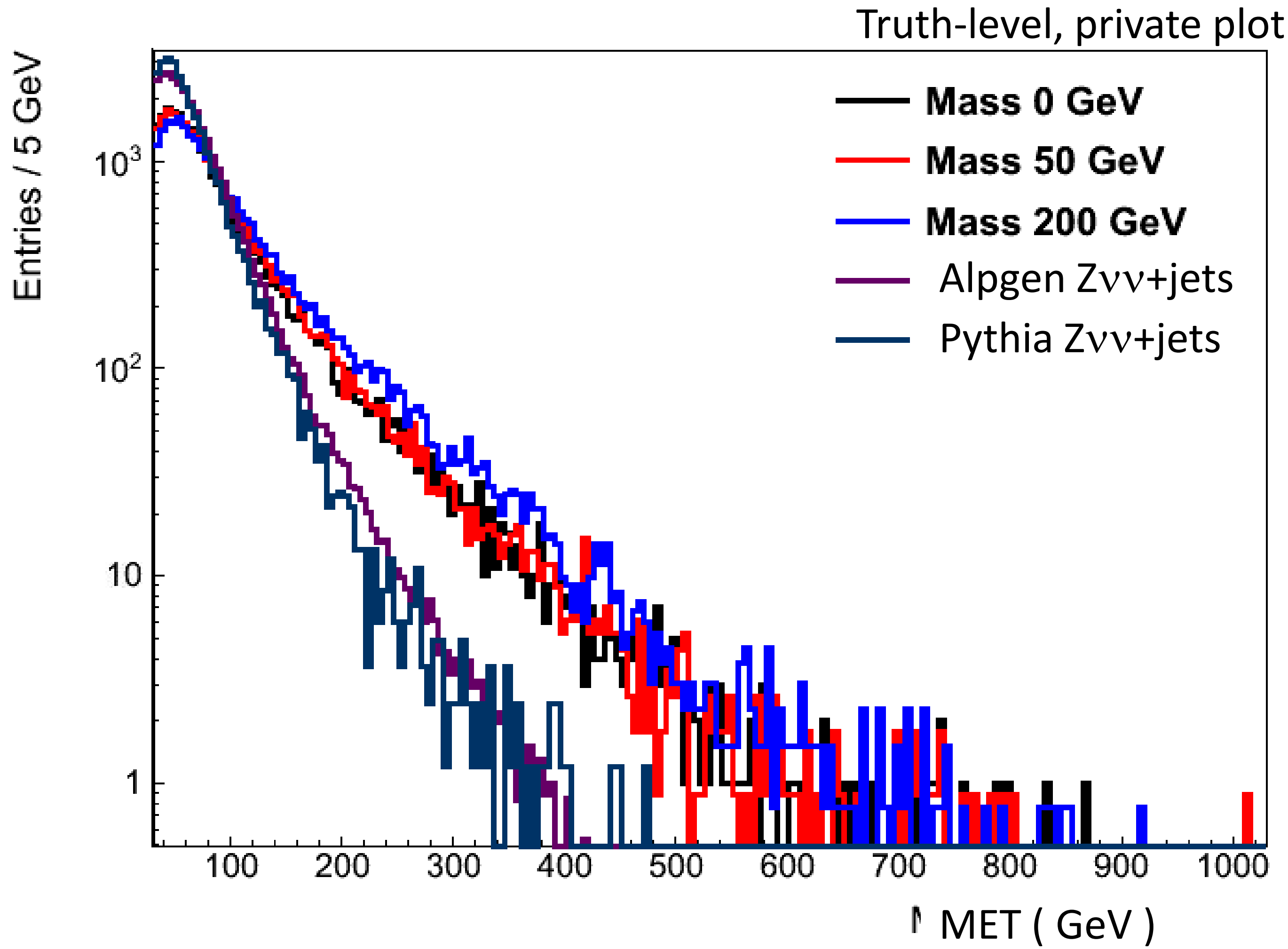
$$L_{Eff} = G_\chi \ \bar{\chi}\Gamma_\chi\chi \ \bar{q}\Gamma_q q$$

$$\Gamma_{\chi,q} \in \{1, \gamma^5, \gamma^\mu, \gamma^\mu\gamma^5, \sigma^{\mu\nu}\}$$

arxiv:1108.1196

Expected signal MET distributions

Vector operator, histograms scaled to the same area



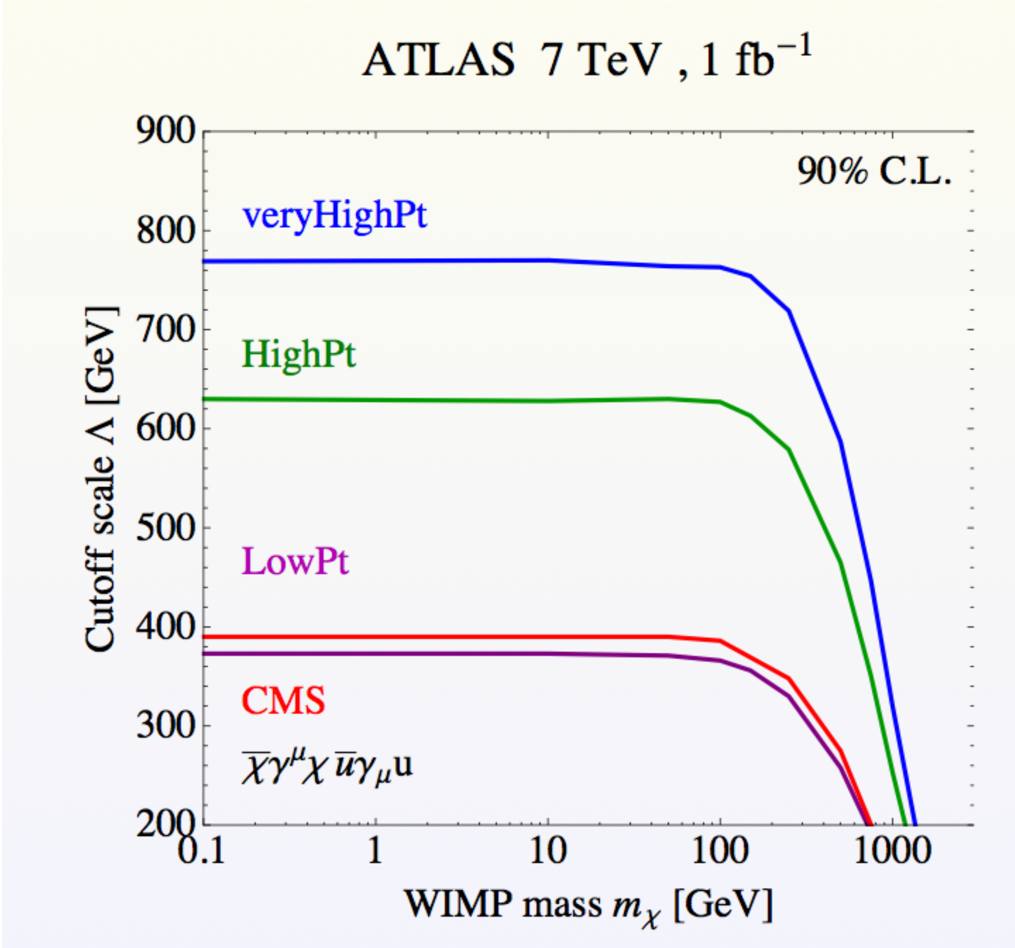
Expect harder MET spectrum even for m_χ= 0 GeV!

Limits on suppression scale Λ

- Take vector operator as example

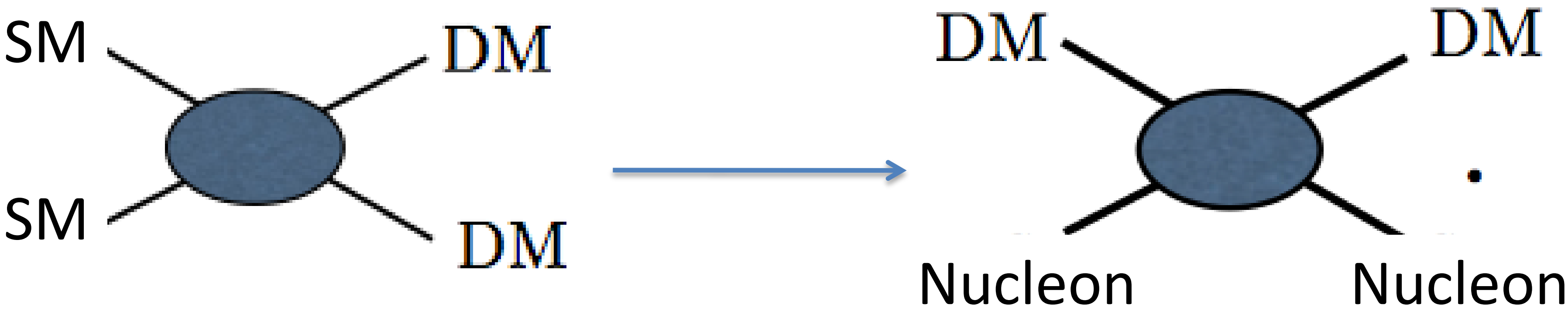
$$\frac{(\bar{\chi}\gamma^{\mu}\chi)(\bar{u}\gamma_{\mu}u)}{\Lambda^2}$$

- Convert cross section limits into limit on Λ for particular m_χ



arXiv:1109.4398

Limits in direct detection plane



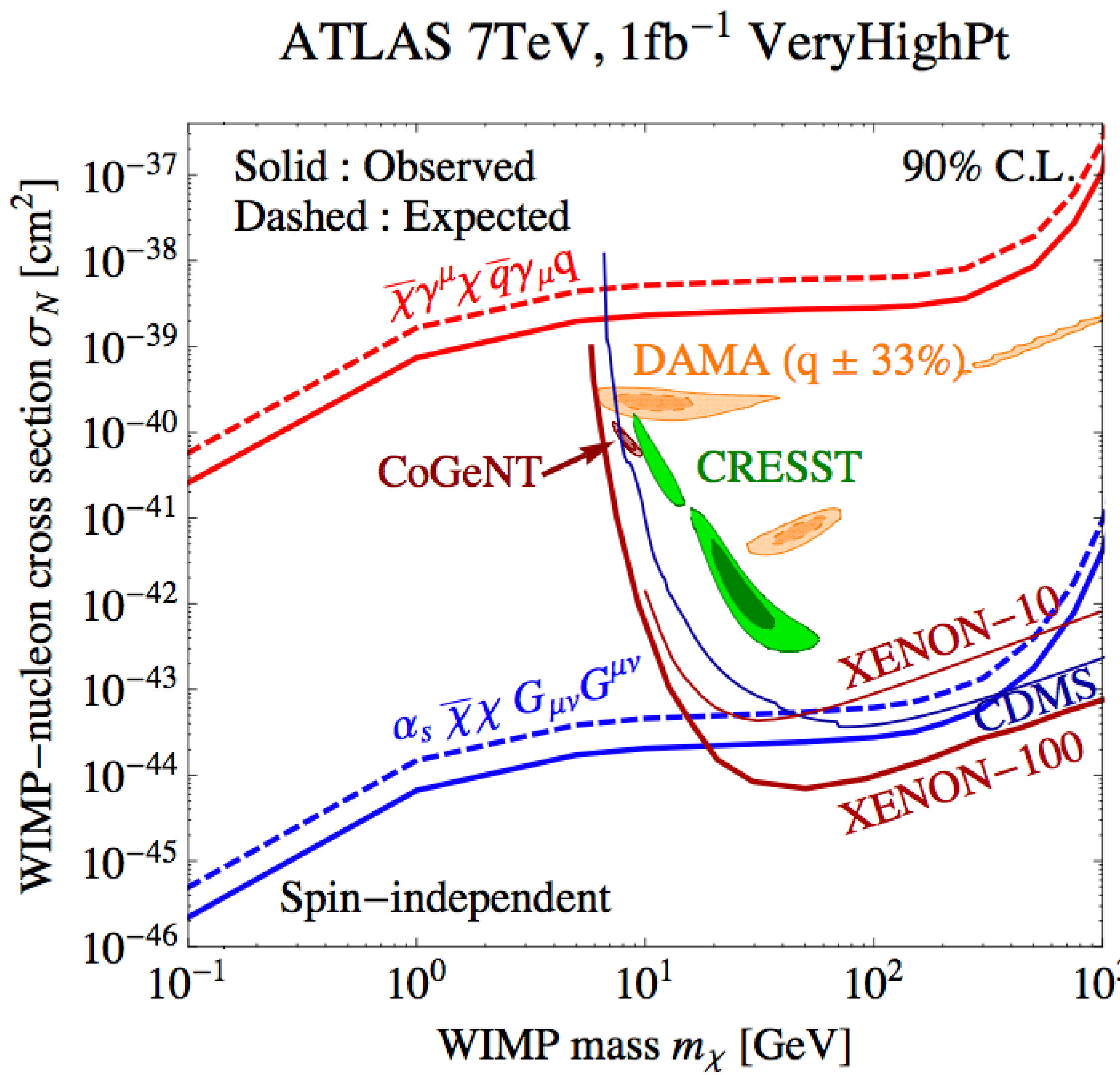
Now convert the high-energy limit on Λ into limits on $\sigma_{\chi\text{-Nucleon}}$, by converting quark-level to Nucleon-level matrix elements.

<u>Caveats:</u>

- Important uncertainty: hadronic matrix elements
- SI vs SD interactions depending on operator
- Simple transfer of LHC measurement to direct-detection plane doesn't always work, e.g.
    - Light mediators
    - Non-flavour-universal interaction

Spin independent Nucleon-WIMP scattering cross section

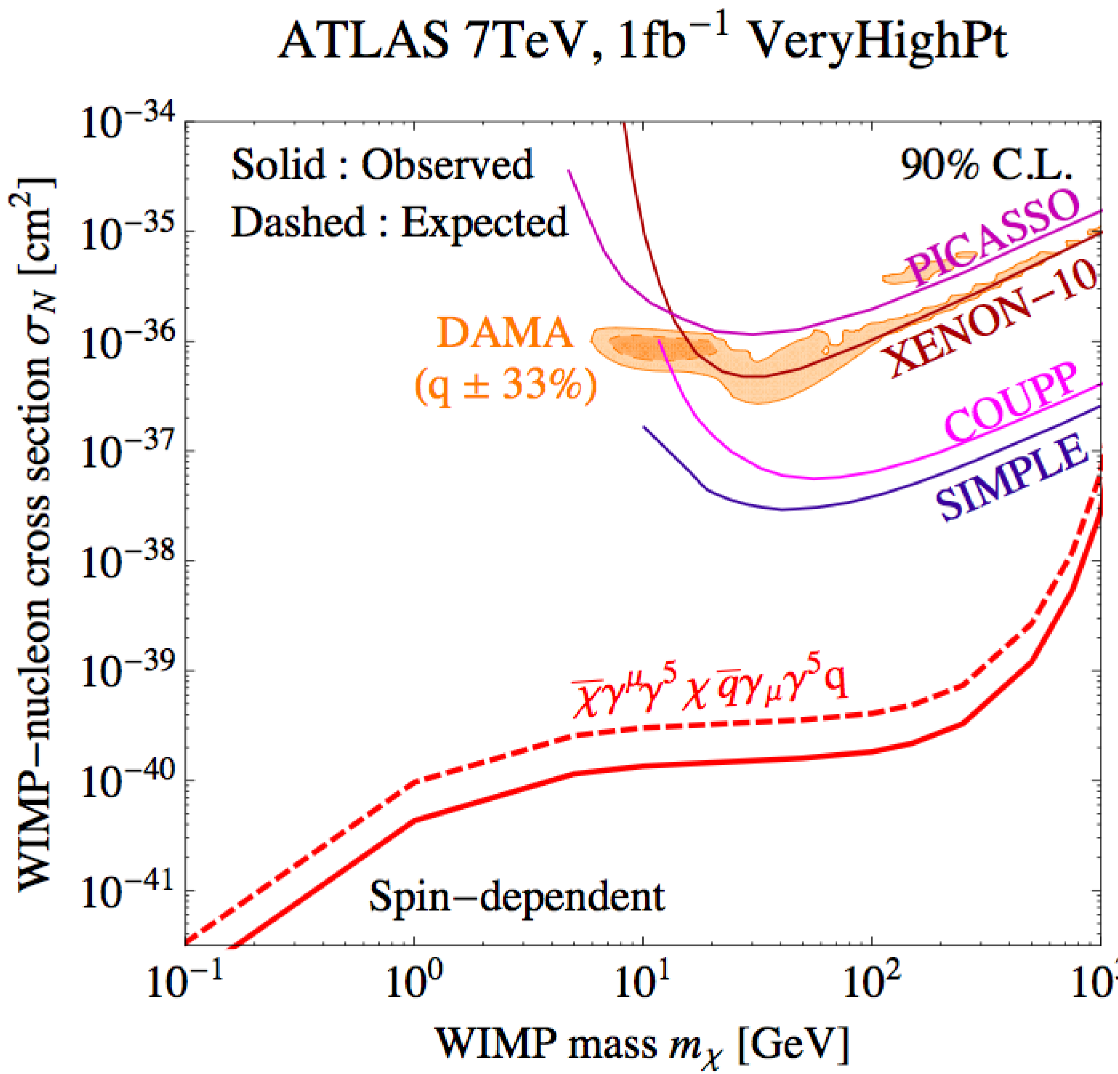
- LHC measurement translates into at least one line per operator (and are only correct for heavy mediators)
- Low-mass LHC reach complementary to DD experiments
- LHC limits don't suffer from astrophysical uncertainties



arXiv:1109.4398

Spin dependent Nucleon-WIMP scattering cross section

- LHC measurement translates into at least one line per operator (and are only correct for heavy mediators)
- Low-mass LHC reach complementary to DD experiments
- LHC limits don't suffer from astrophysical uncertainties

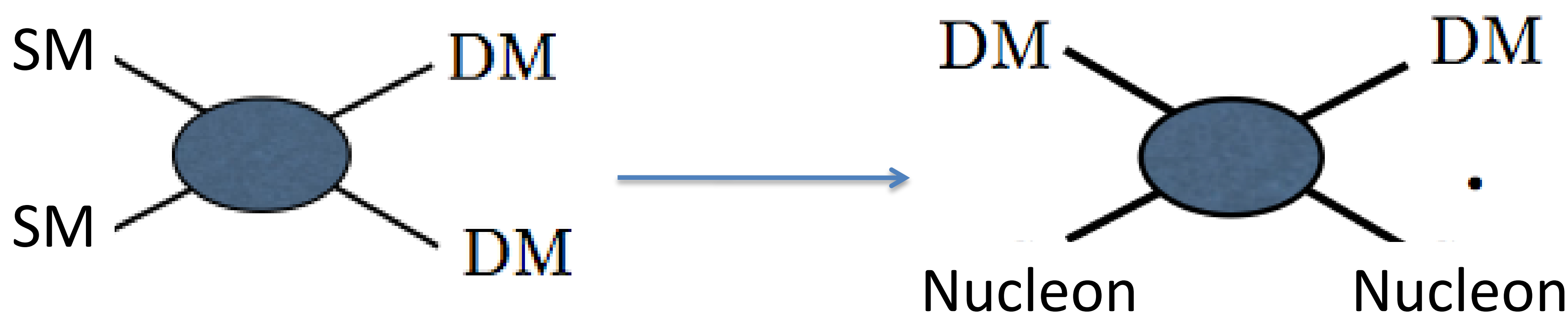


arXiv:1109.4398

ATLAS Monojet Outlook

- 5.2 fb^{-1} now delivered, 5fb^{-1} recorded by ATLAS, some 4.5 fb^{-1} will pass quality cuts and appear in the next monojet paper (planned for Moriond)
- Additional interpretations besides ADD are planned to be included (e.g. EFT approach for WIMP pairs)

Limits in direct detection plane



Now convert the high-energy limit on Λ into limits on $\sigma_{\chi\text{-Nucleon}}$, by converting quark-level to Nucleon-level matrix elements:

$$B_u^p = B_d^n = 8.22 \pm 2.26\,,$$
$$B_d^p = B_u^n = 6.62 \pm 1.92\,,$$
$$B_s^p = B_s^n = 3.36 \pm 1.45$$

$$f_u^p = f_d^n = 2$$
$$f_d^p = f_u^n = 1$$

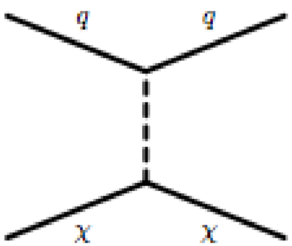
$$\mathcal{O}_1 = \frac{i\, g_\chi\, g_q}{q^2 - M^2} (\bar{q}q)(\bar{\chi}\chi)\,,$$
$$\mathcal{O}_2 = \frac{i\, g_\chi\, g_q}{q^2 - M^2} (\bar{q}\gamma_\mu q)(\bar{\chi}\gamma^\mu\chi)$$

$$\Rightarrow$$

$$\sigma_1^{Nq} = \frac{\mu^2}{\pi\Lambda^4} B_{Nq}^2\,,$$
$$\sigma_2^{Nq} = \frac{\mu^2}{\pi\Lambda^4} f_{Nq}^2\,,$$

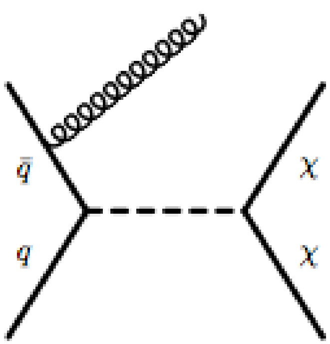
Cross Sections

- The direct detection cross section ($q \sim 100$ MeV):



$$\sigma_{DD} \sim g_\chi^2 \, g_q^2 \, \frac{\mu^2}{M^4} \qquad \mu = \frac{m_\chi m_N}{m_N + m_\chi}$$

- Mono-jet + $\not{E}_T$ ($q \sim 10 - 100$ GeV):



$$\sigma_{1j} \sim \begin{cases} \alpha_s \, g_\chi^2 \, g_q^2 \, \frac{1}{p_T^2} & M \lesssim 100 \text{ GeV} \\ \alpha_s \, g_\chi^2 \, g_q^2 \, \frac{p_T^2}{M^4} & M \gtrsim 100 \text{ GeV} \end{cases}$$

Roni Harnik

Back of an Envelope:

Consider a heavy mediator:

assume $p_T < M$ (just a contact operator)

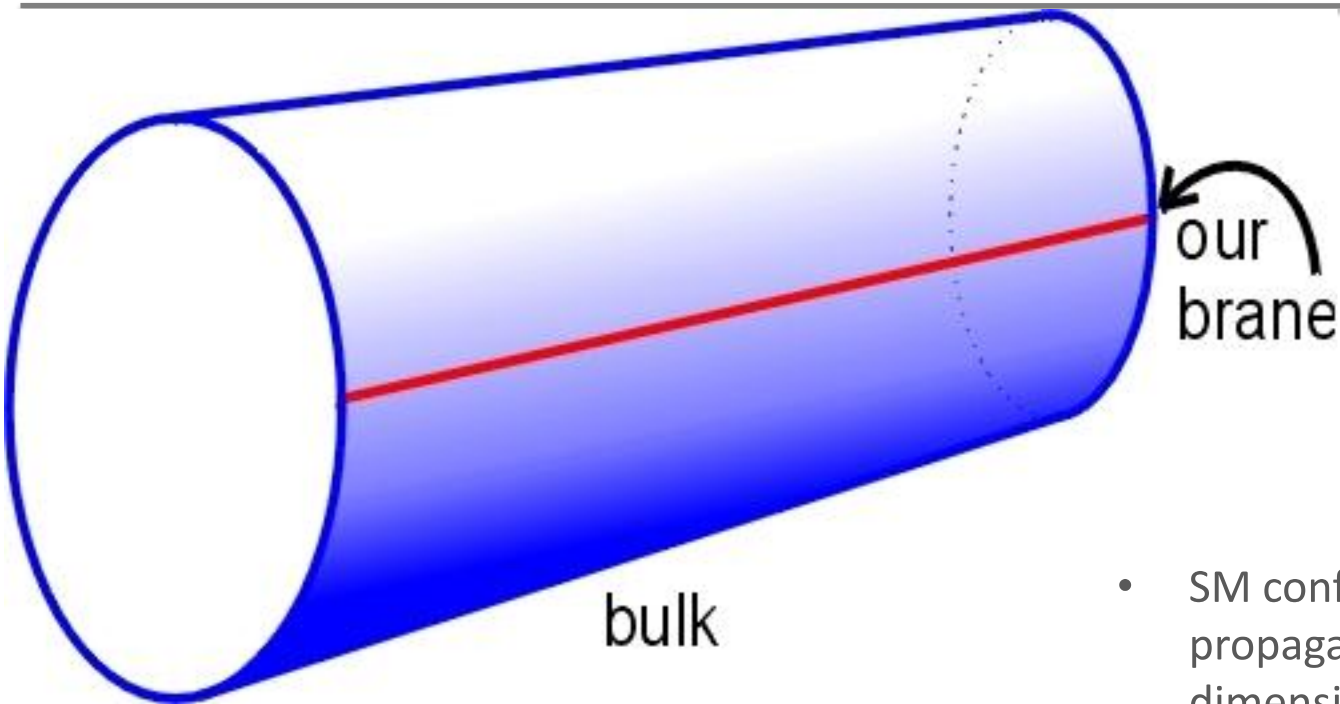
$$\sigma_{1j} \sim \alpha_s g_\chi^2 g_q^2 \frac{p_T^2}{M^4} \qquad \sigma_{\rm DD} \sim g_\chi^2 g_q^2 \frac{\mu^2}{M^4}$$

$$(p_T \sim 100\,{\rm GeV}) \qquad (\mu \sim 1\,{\rm GeV})$$

$$\frac{\sigma_{1j}}{\sigma_{DD}} \sim \mathcal{O}(1000)$$

Roni Harnik

Interpretations: ADD



$$M_{Pl}{}^2 \sim M_D{}^{2+n} R^n$$

- SM confined to brane, graviton propagates in the bulk (4+n dimensions)
- Extra dimensions are compactified, lead to Kaluza-Klein towers of massive graviton modes
- Signatures: monojet (graviton emission), non-resonant diphoton or dilepton production (virtual graviton exchange)