Search for new physics using MonoJet & Mono-Light Z′ signatures with CMS at LHC

(USLUA meeting- Fermilab)

Abhishikth Mallampalli

People involved

Run-II monojet / mono-V analysis (common AN)

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CMS Run2 MonoJet/mono-V Team

Search for dark matter recoiling from a Narrow Jet at 13 TeV

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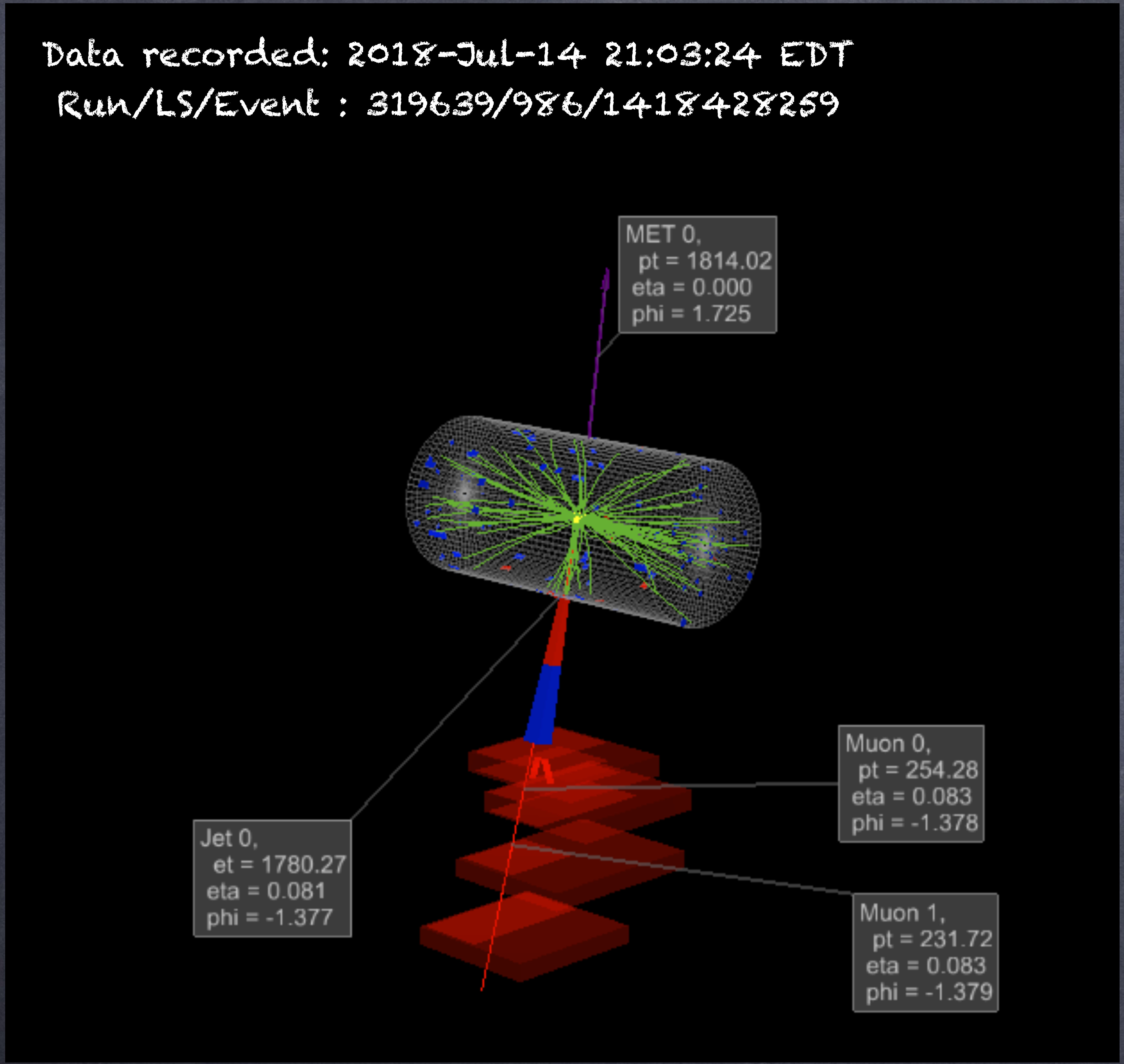
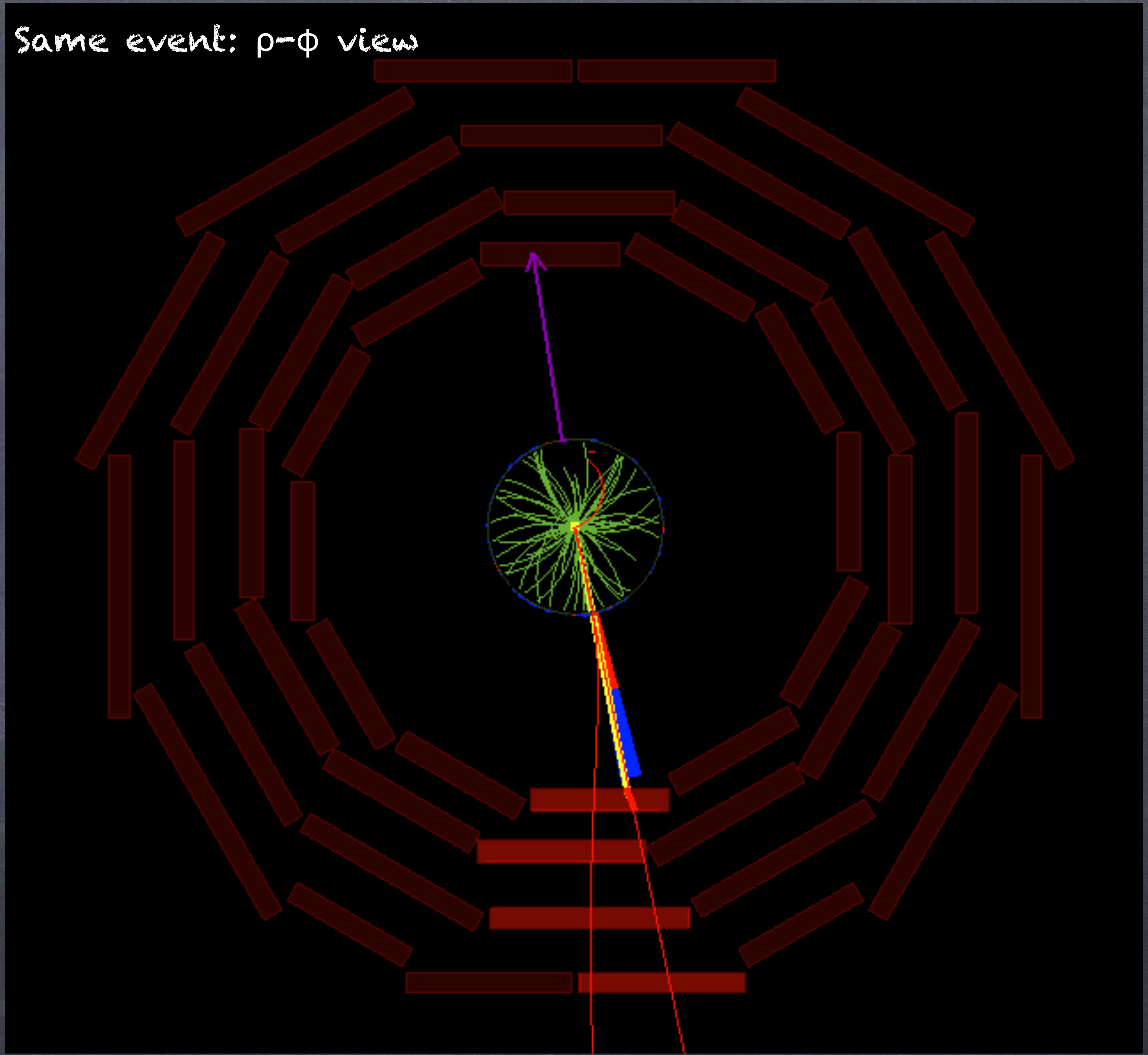
Mono- Light Z′ search

MonoJet

Published: paper, arXiv

MonoJet Event

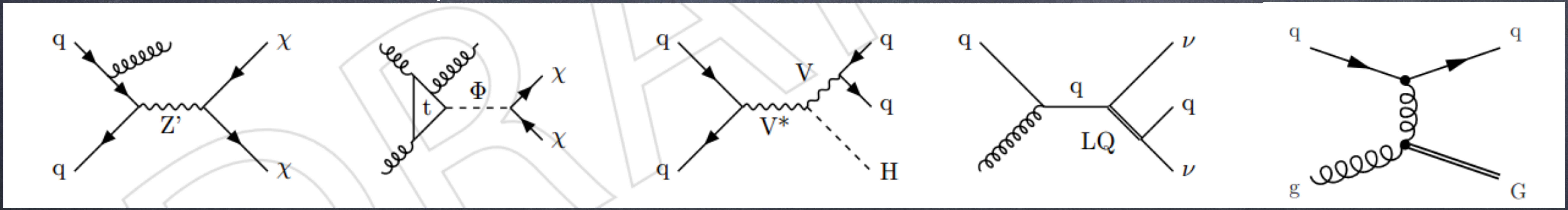




What could be causing this signature?

- Many theories beyond SM eg. Dark matter, Invisible Higgs decays, Leptoquarks, ADD(extra-dimensions) etc.

DM scenarios



Simplified DM Spin-1 mediator | Simplified DM Spin-0 mediator | Invisible Higgs decays | Leptoquark | Graviton(ADD)

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What could be causing this signature?

- Standard model processes which have this event topology:
  - Z+jets: Z(->vv)+jets – main irredicible bkg, Z(->ll) minor bkg.
  - W+jets: lepton not identified or reconstructed
  - γ+jets: γ mis-measured or undetected
  - Top: Suppressed by using bjet vetos
  - Diboson: WW,WZ,ZZ–one decays leptonically, other hadronically (W,Z around 70% decay to jets)
  - QCD: small fraction have large MET but overall rate of QCD events is large (large meaning~ 10^7 see the xsec # backup slide..most of pp are QCD)

Electroweak bkg estimation

$$L_c(\vec{\mu}^{Z\to\nu\nu}, \vec{\mu}, \vec{\theta}) = \prod_i \text{Poisson}\left(d_i^{\gamma} \,|\, B_i^{\gamma}(\vec{\theta}) + \frac{\mu_i^{Z\to\nu\nu}}{R_i^{\gamma}(\vec{\theta})}\right)$$

$$\times \prod_i \text{Poisson}\left(d_i^{Z} \,|\, B_i^{Z}(\vec{\theta}) + \frac{\mu_i^{Z\to\nu\nu}}{R_i^{Z}(\vec{\theta})}\right)$$

$$\times \prod_i \text{Poisson}\left(d_i^{W} \,|\, B_i^{W}(\vec{\theta}) + \frac{f_i(\vec{\theta})\mu_i^{Z\to\nu\nu}}{R_i^{W}(\vec{\theta})}\right)$$

$$\times \prod_i \text{Poisson}\left(d_i \,|\, B_i(\vec{\theta}) + (1 + f_i(\vec{\theta}))\mu_i^{Z\to\nu\nu} + \mu S_i(\vec{\theta})\right)$$

i = recoil bins

$d_i^{\gamma/Z/W}$ = data # in CR

$B_i^{\gamma/Z/W}$ = bkg. # in CR

$\vec{\theta}$ = uncertainties

$R_i^{\gamma/Z/W}$ = Trans. Factor = SR/CR

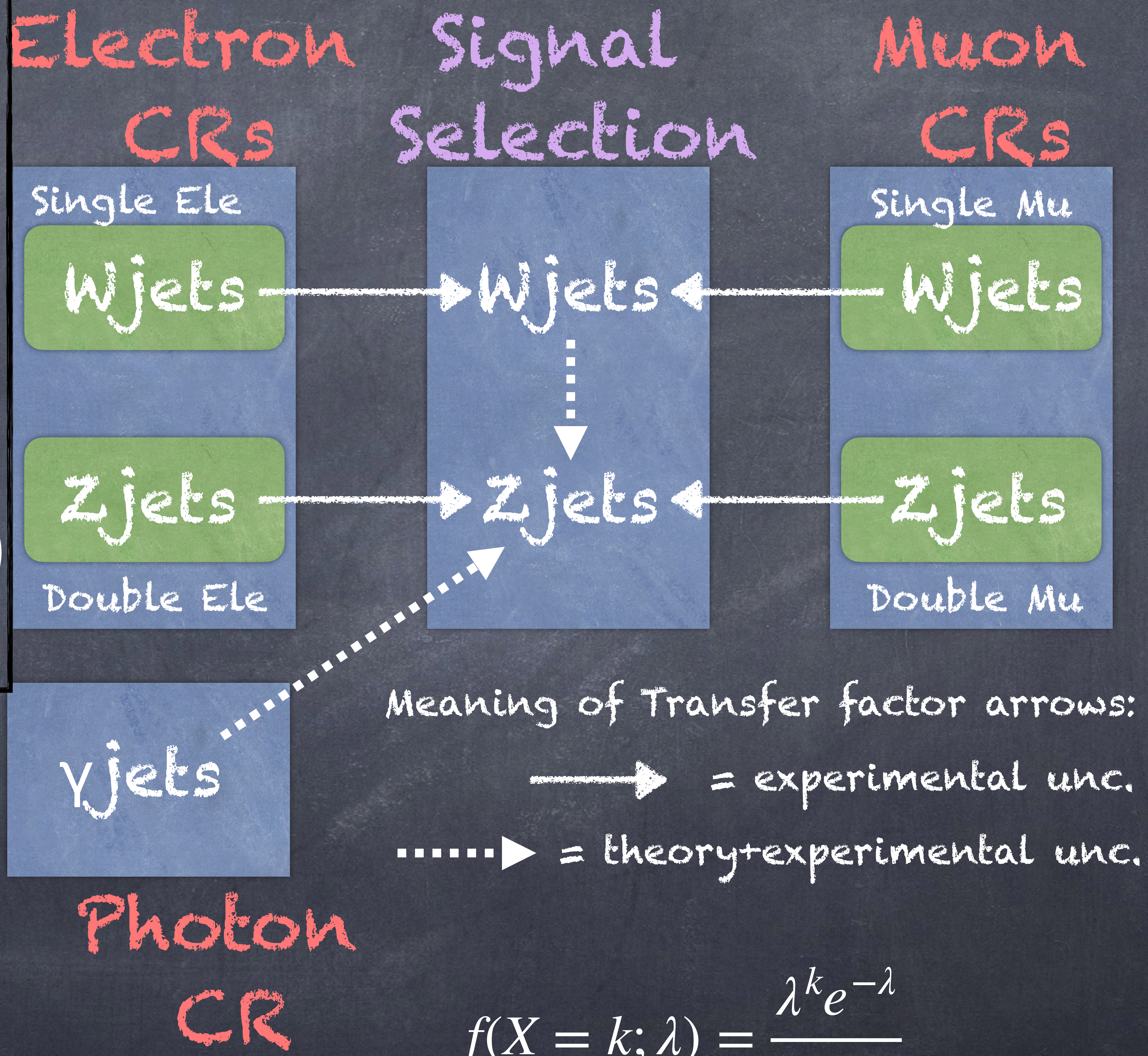
$f_i(\vec{\theta})$ = W/Z in SR

$S_i(\vec{\theta})$ = nominal signal in SR

μ = signal strength

$\vec{\mu}^{Z\to\nu\nu}$ = Z->νν in SR

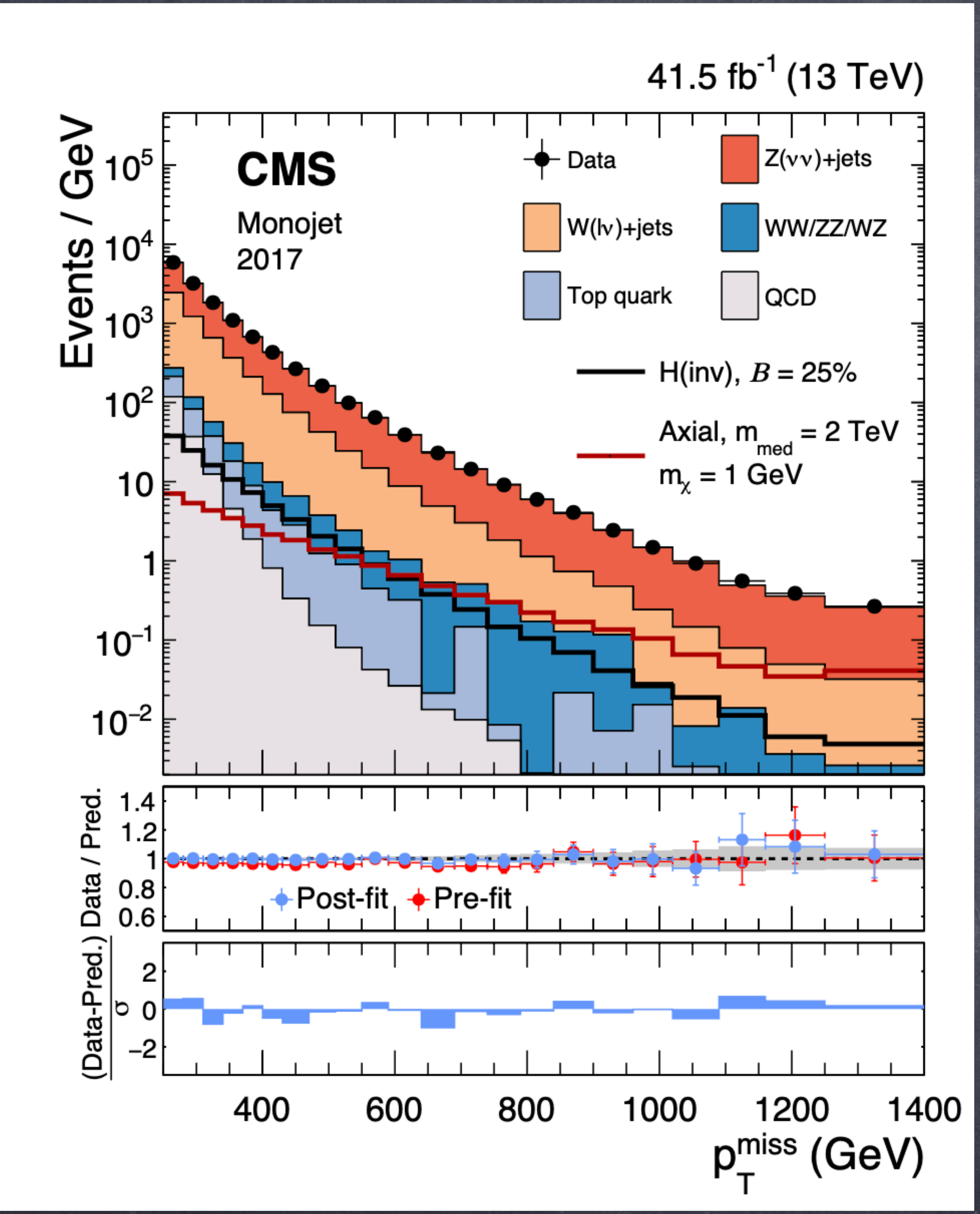
→ Freely floating



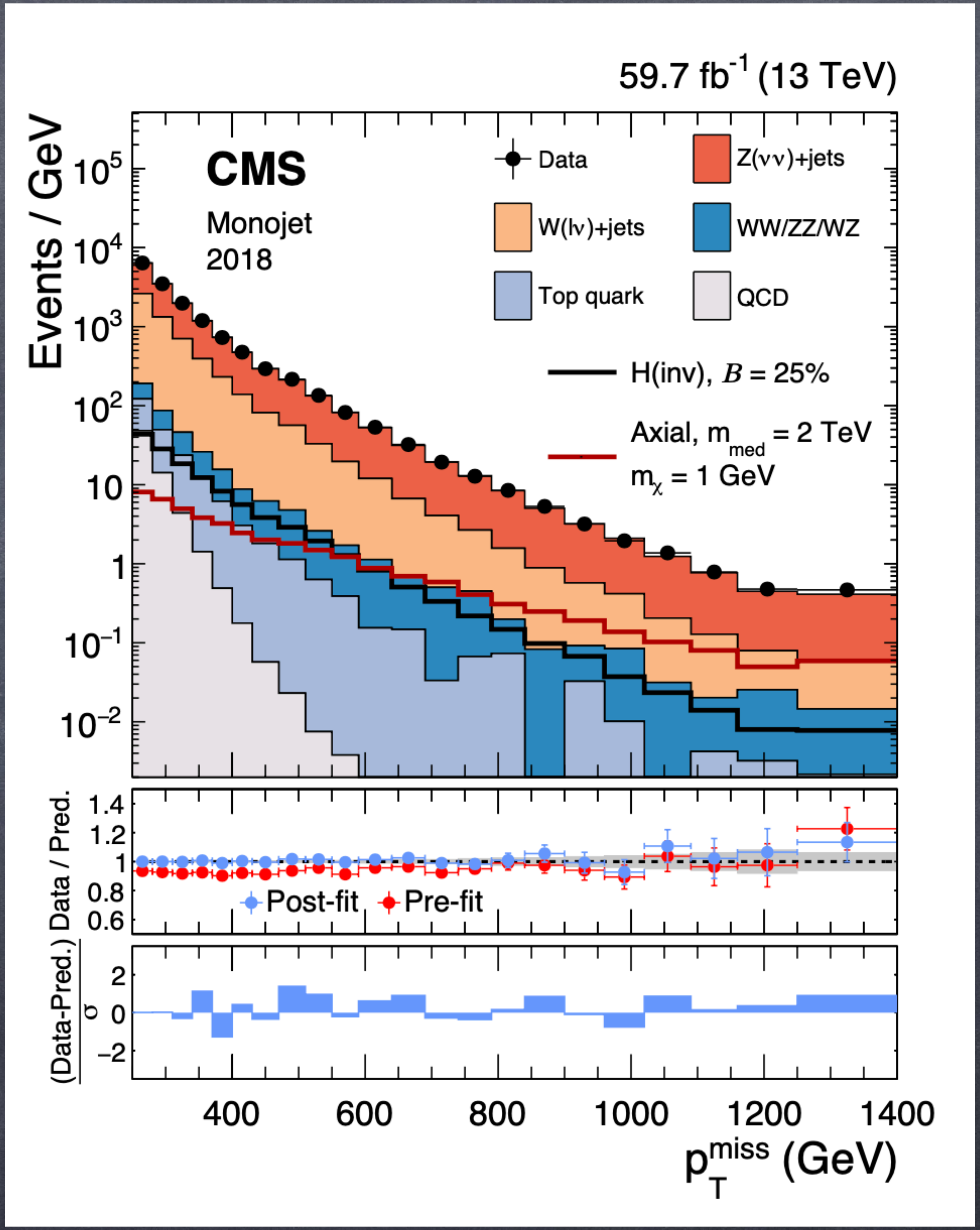
$$f(X = k; \lambda) = \frac{\lambda^k e^{-\lambda}}{k!}$$

Poisson distribution

Data/Simulation comparison for 2017/2018



2017



2018

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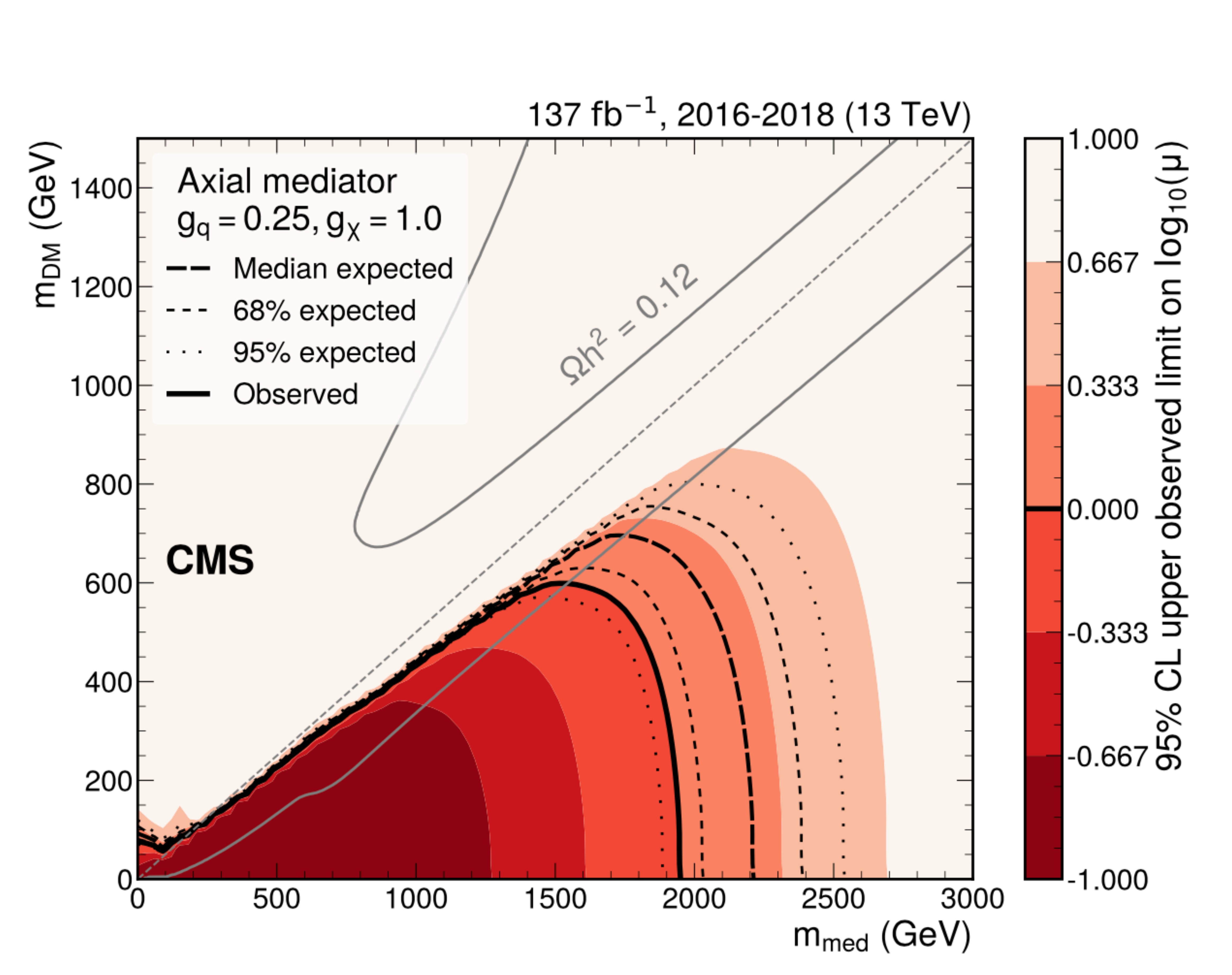
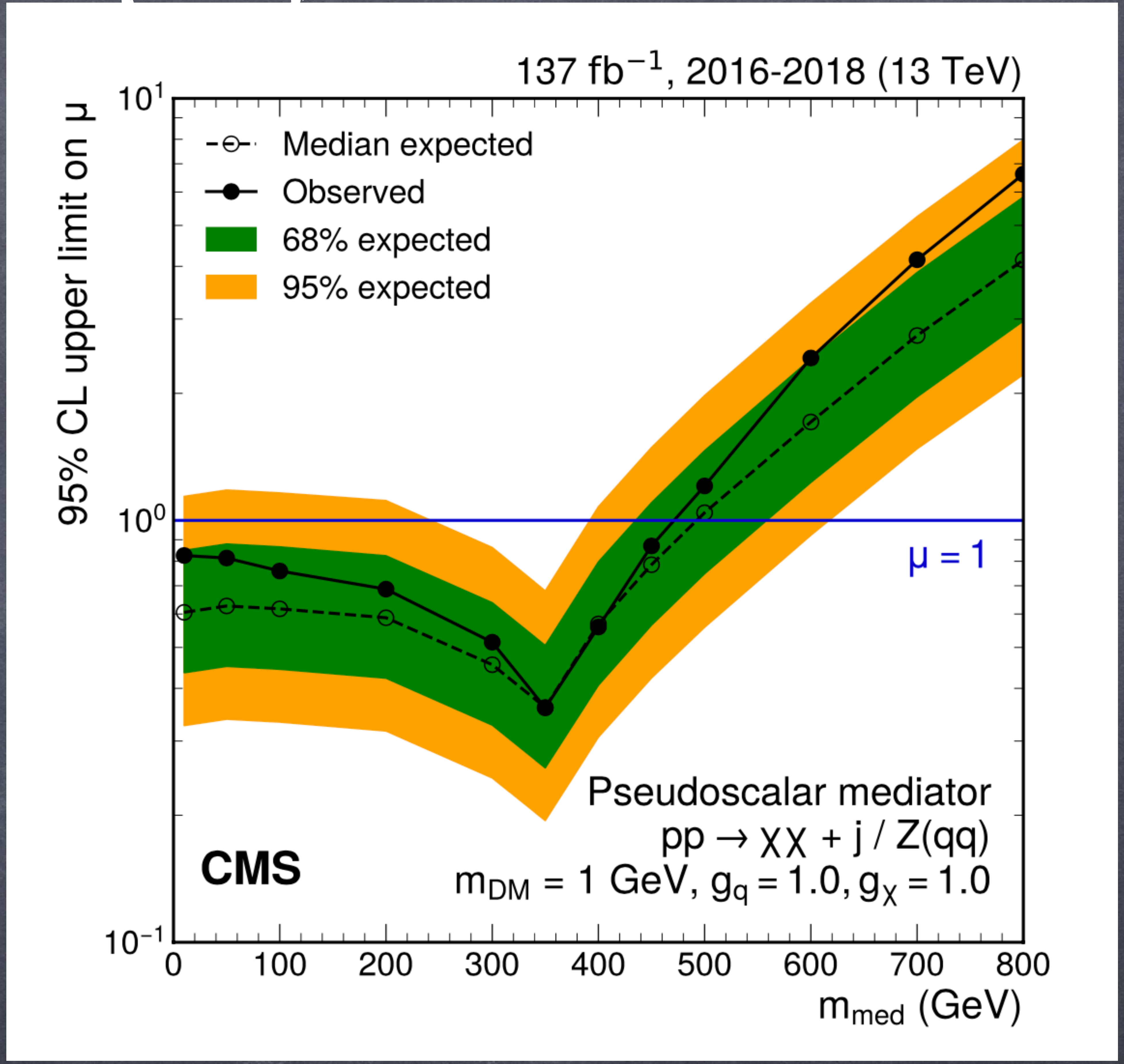
Results: Dark Matter simplified models



Axial Vector mediator

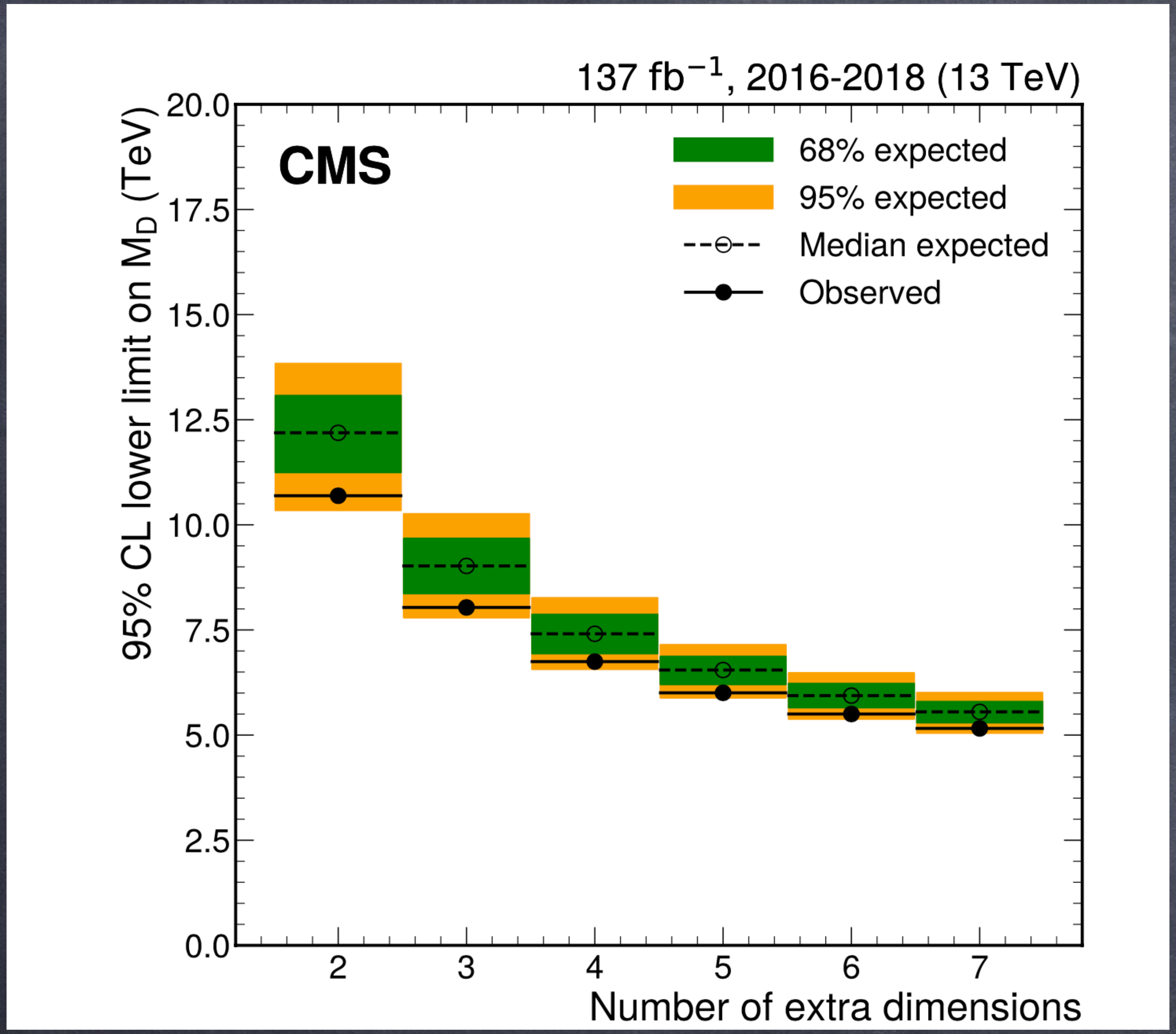


Pseudoscalar mediator

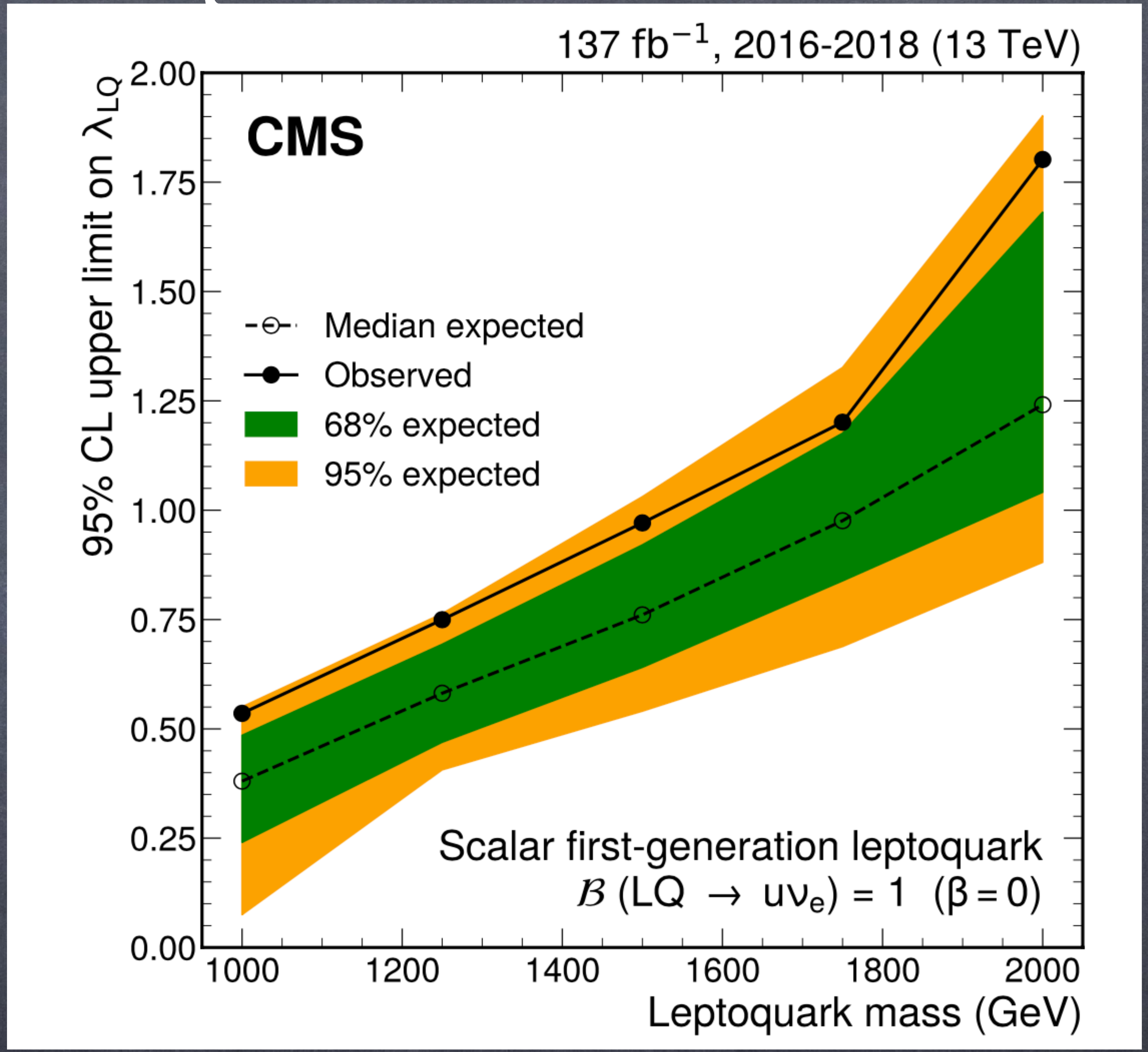
Axial Vector: For ~ 1 GeV DM, exclusion upto 1.95 TeV for the couplings specified

Pseudoscalar: For ~ 1 GeV DM, exclusion upto 470 GeV for the couplings specified

Results: ADD and Leptoquark models



ADD extra dimensions



Scalar 1st gen. Leptoquark

ADD: fundamental Planck scale below 10.7(2 extra dim.) to 5.2 TeV(7 extra dim.) can be excluded

Leptoquark: excluded for leptoquarks SM fermions coupling larger than 0.5 to 1.8, for leptoquark masses between 1.0 and 2.0 TeV

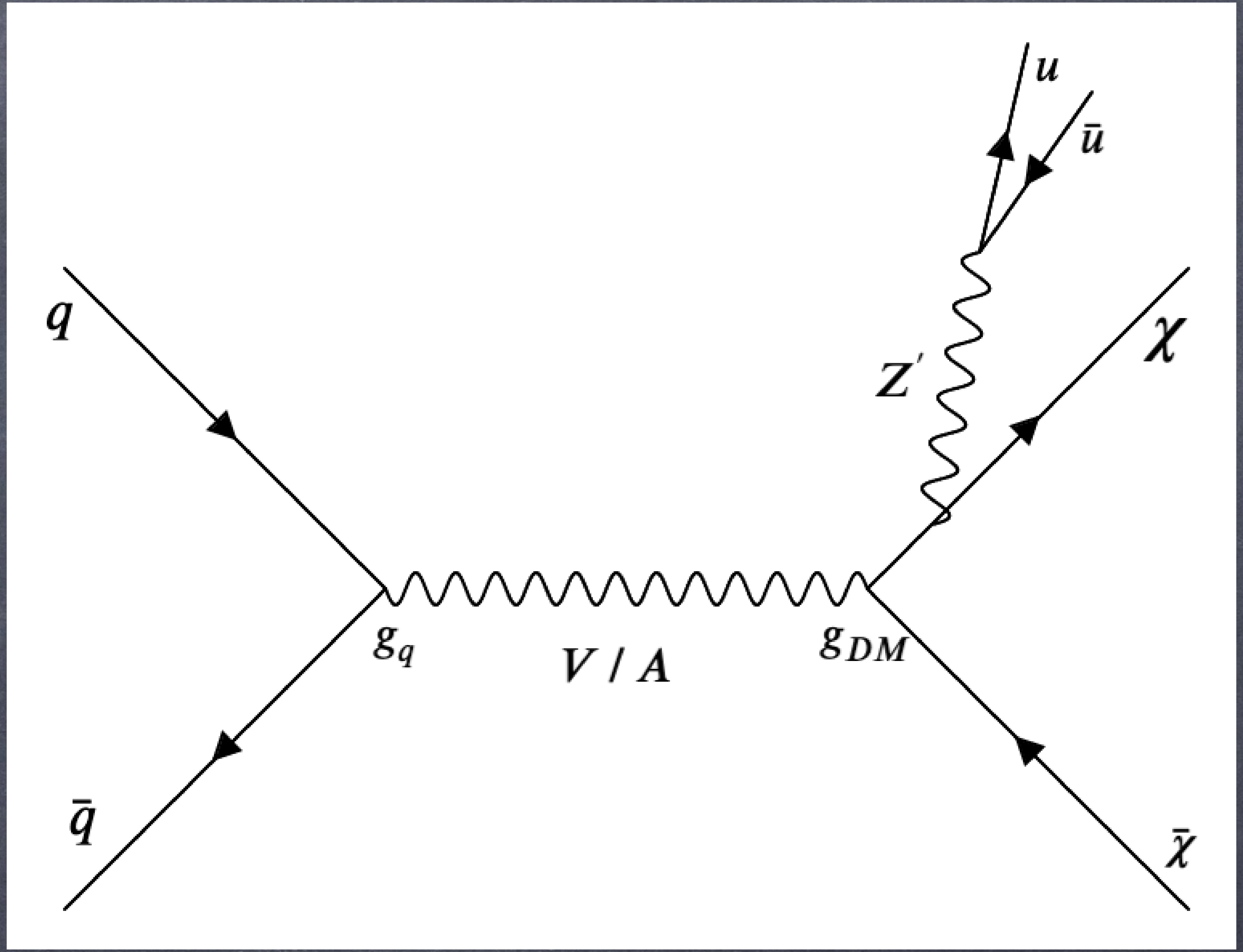
Mono-Light Z′

Undergoing review

What are we looking for?

- ~1 GeV scale dark Z': decays primarily to light quarks ($u\bar{u}$, $d\bar{d}$)
- The boosted Z′ has some interesting properties:
  - Narrow cone
  - 2 prong object
  - Small # charged particles

  } compared to an average QCD jet
- Free parameters: Dark matter mass($m_\chi = 1GeV - 1TeV$), mediator mass(TeV scale), Z' mass

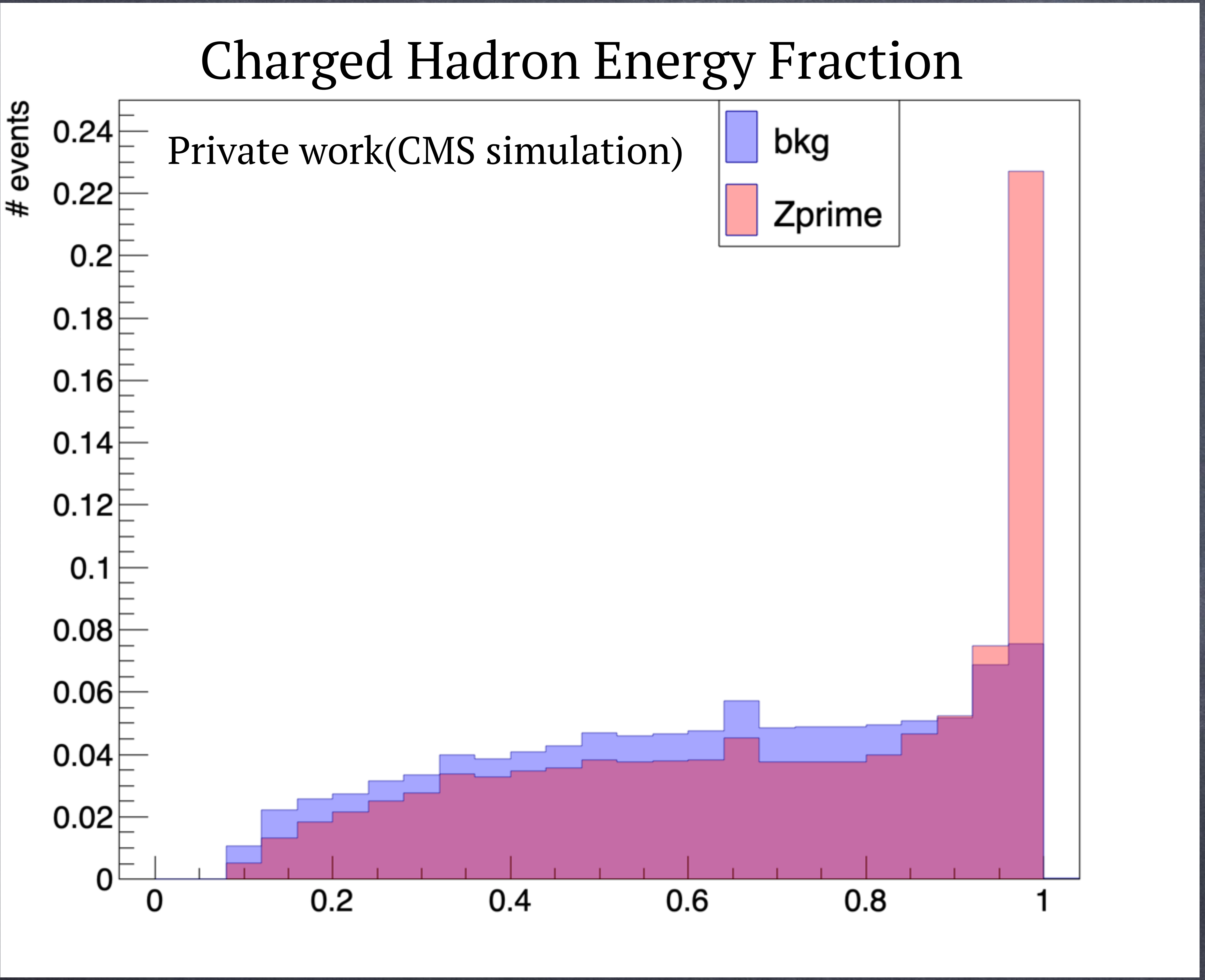


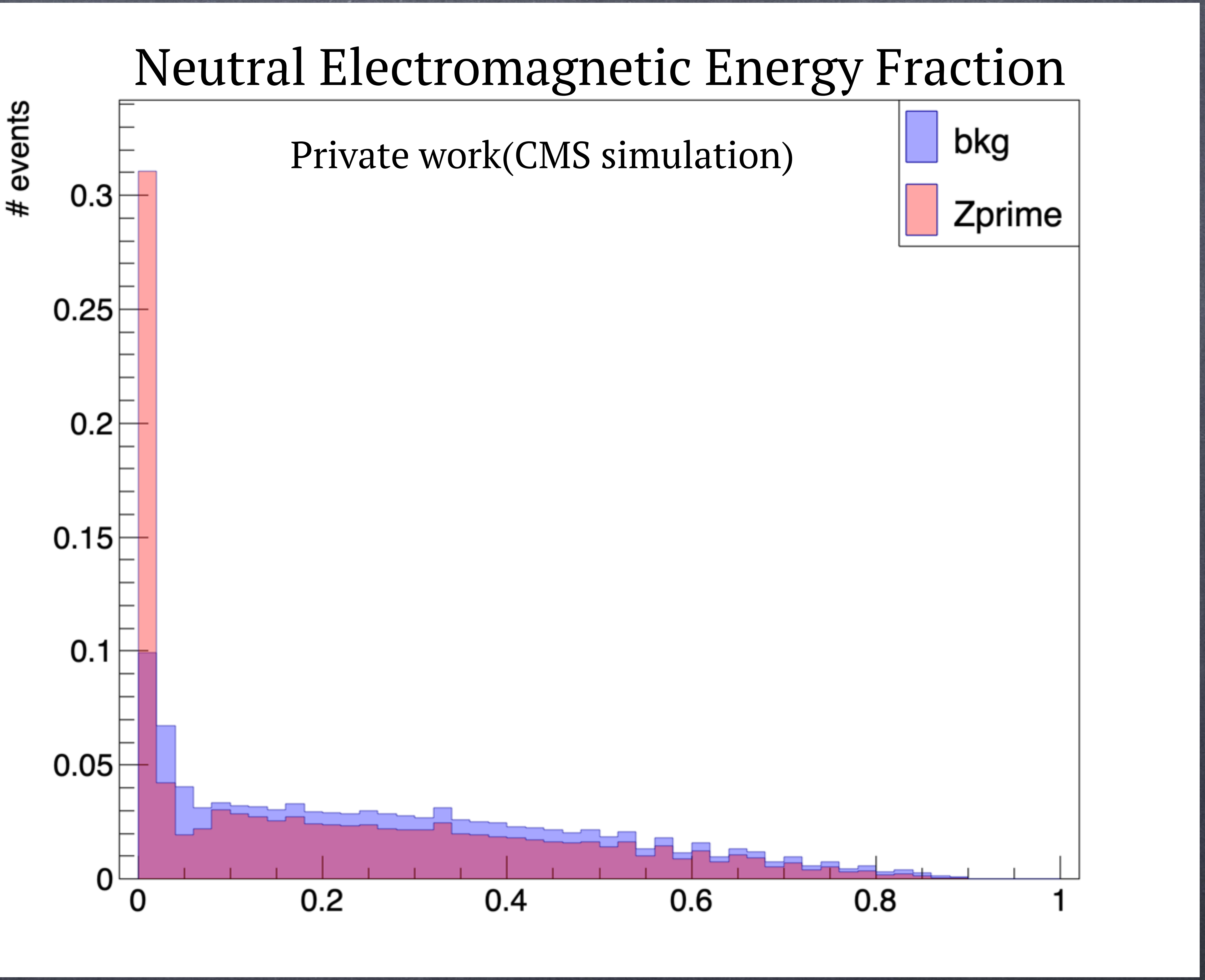
$g_q = 0.25$

$g_{DM} = 1$

V/A = vector/axial mediator

Some interesting variables





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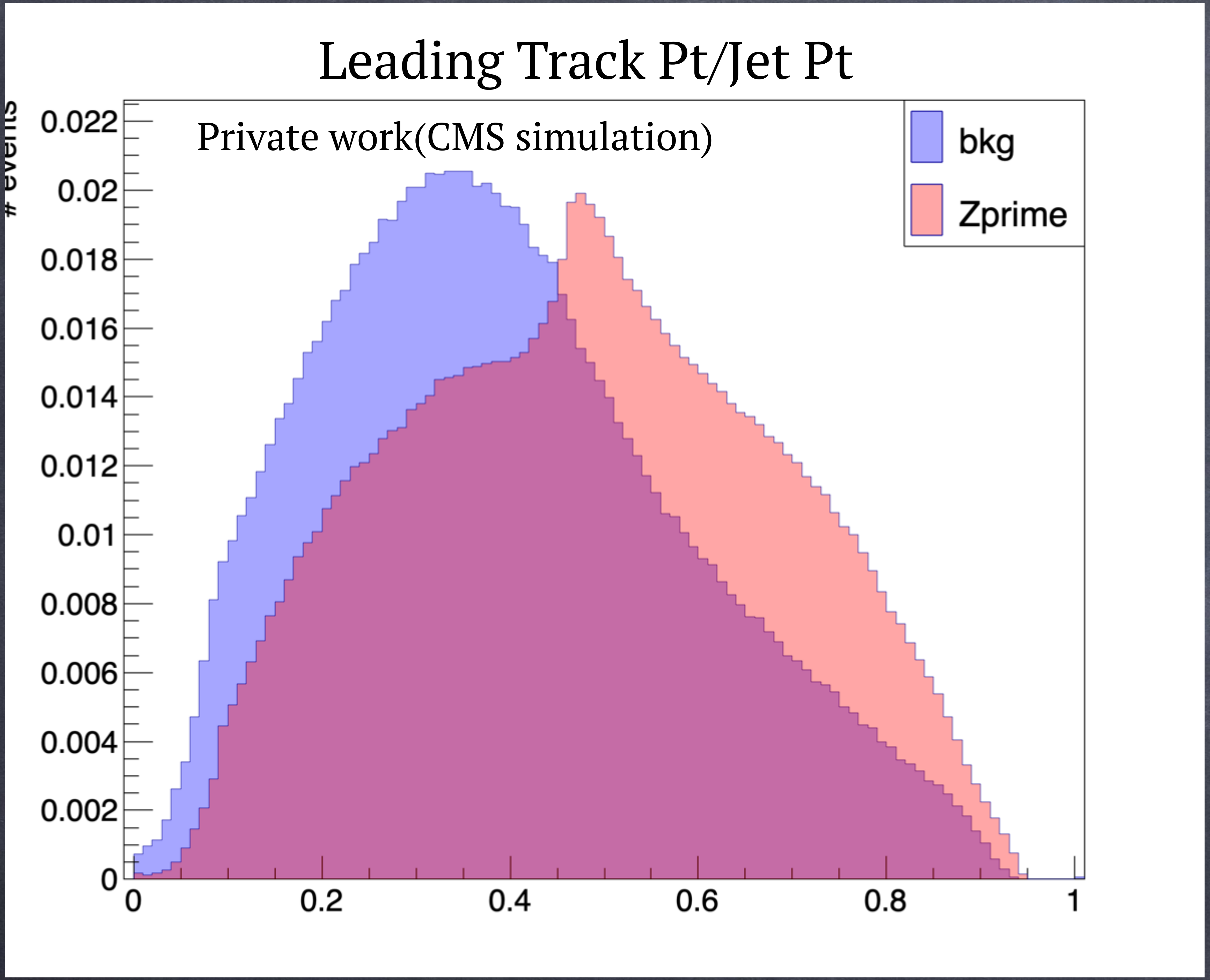
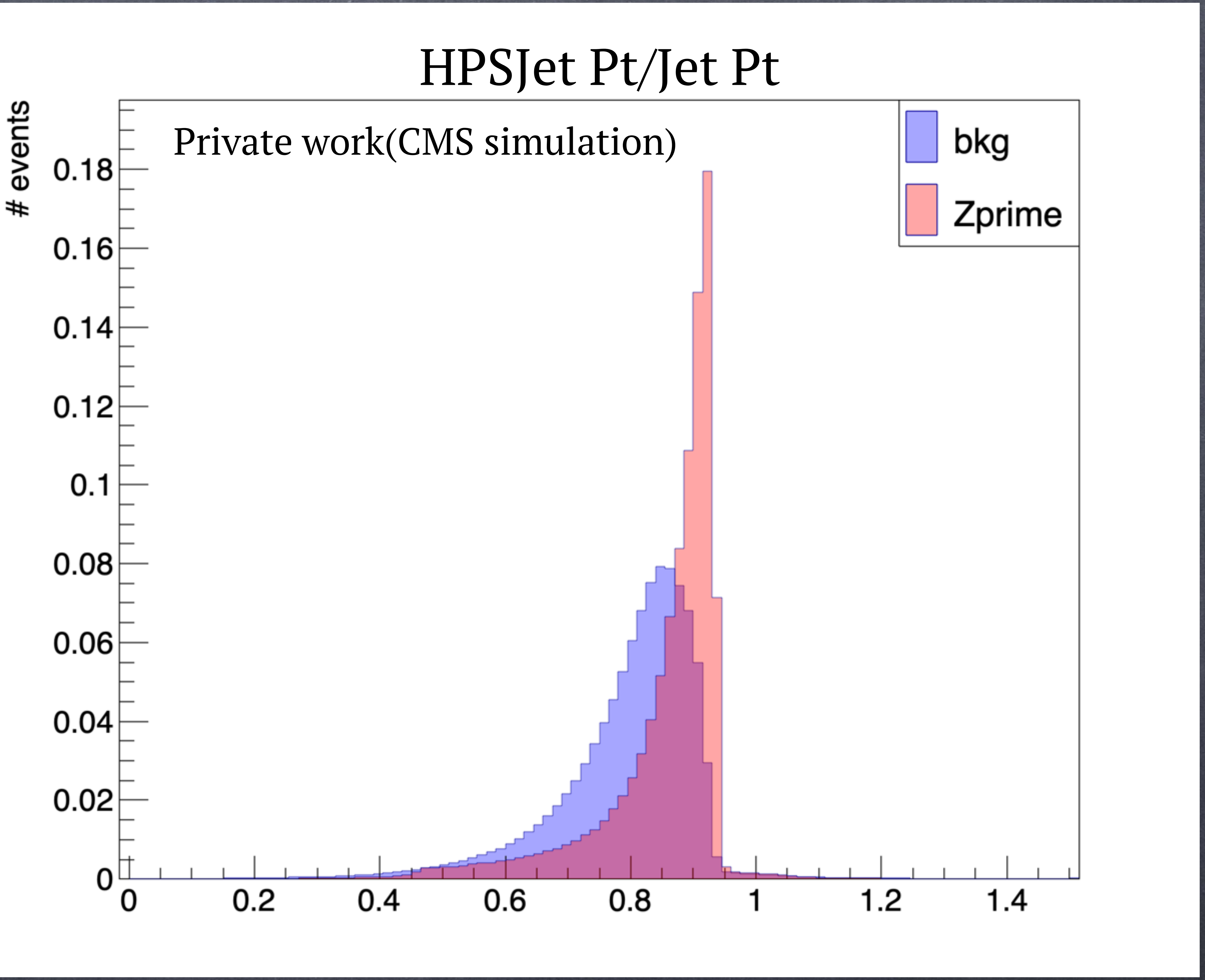
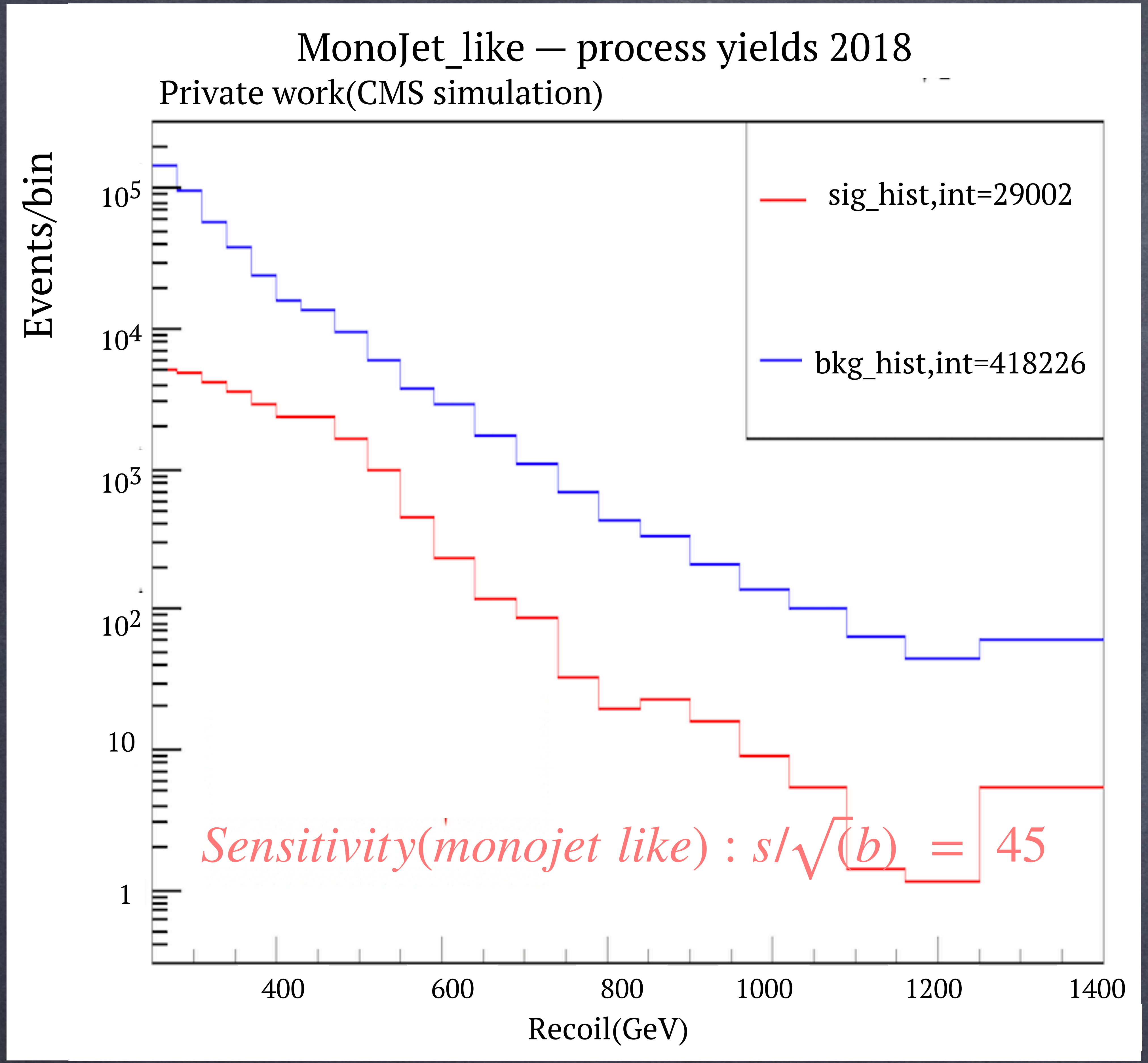
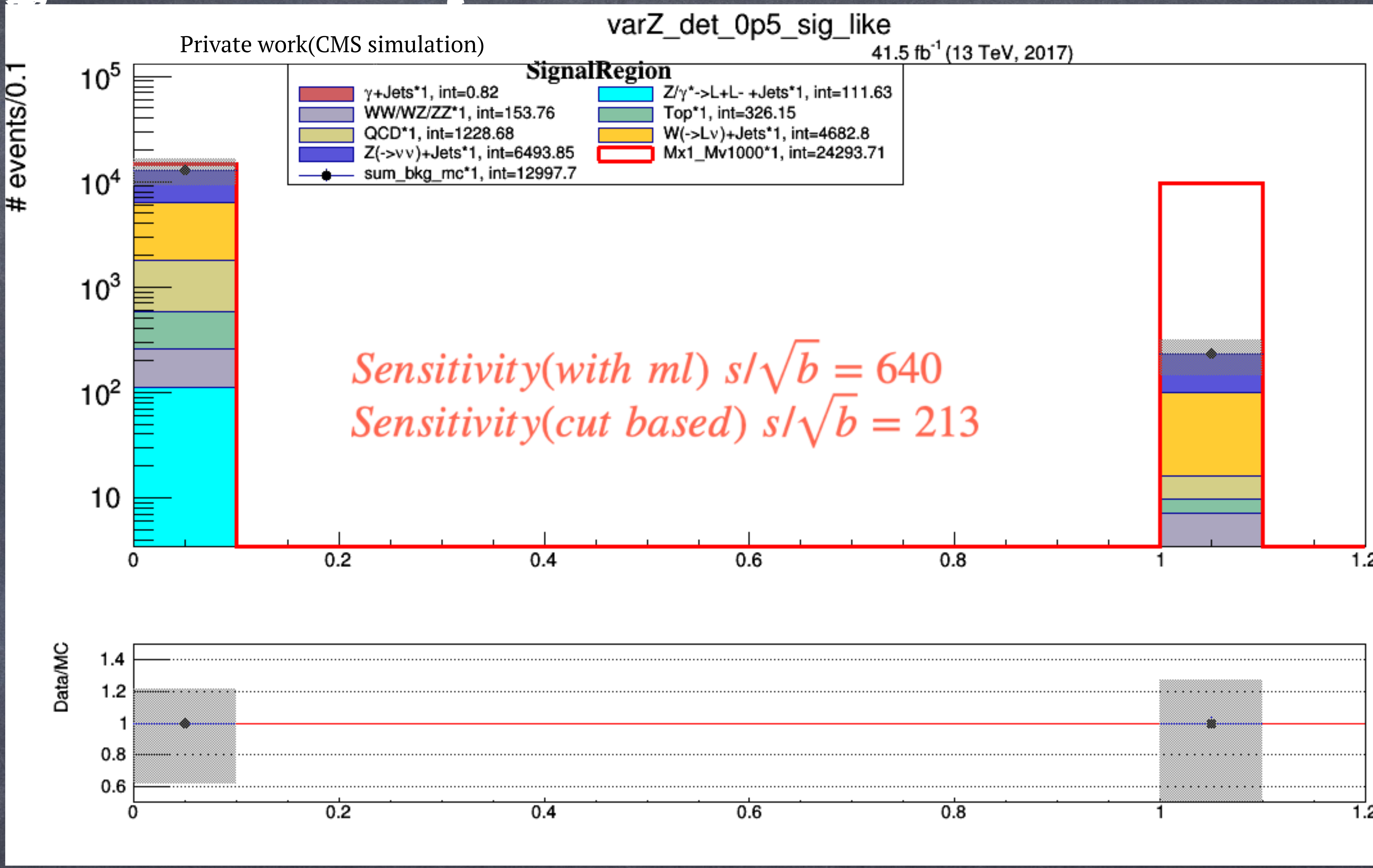
Some interesting variables





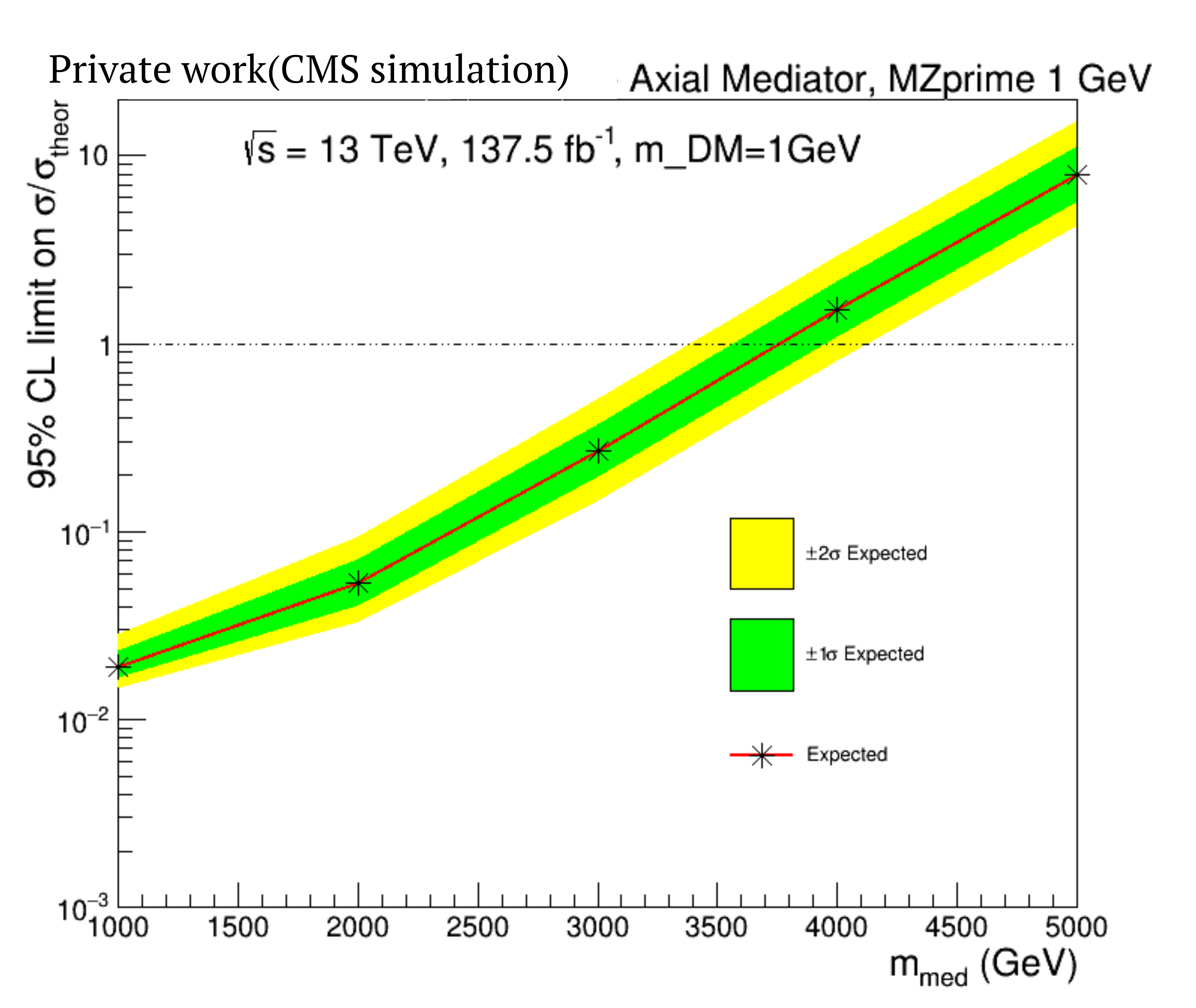
Sensitivity comparison



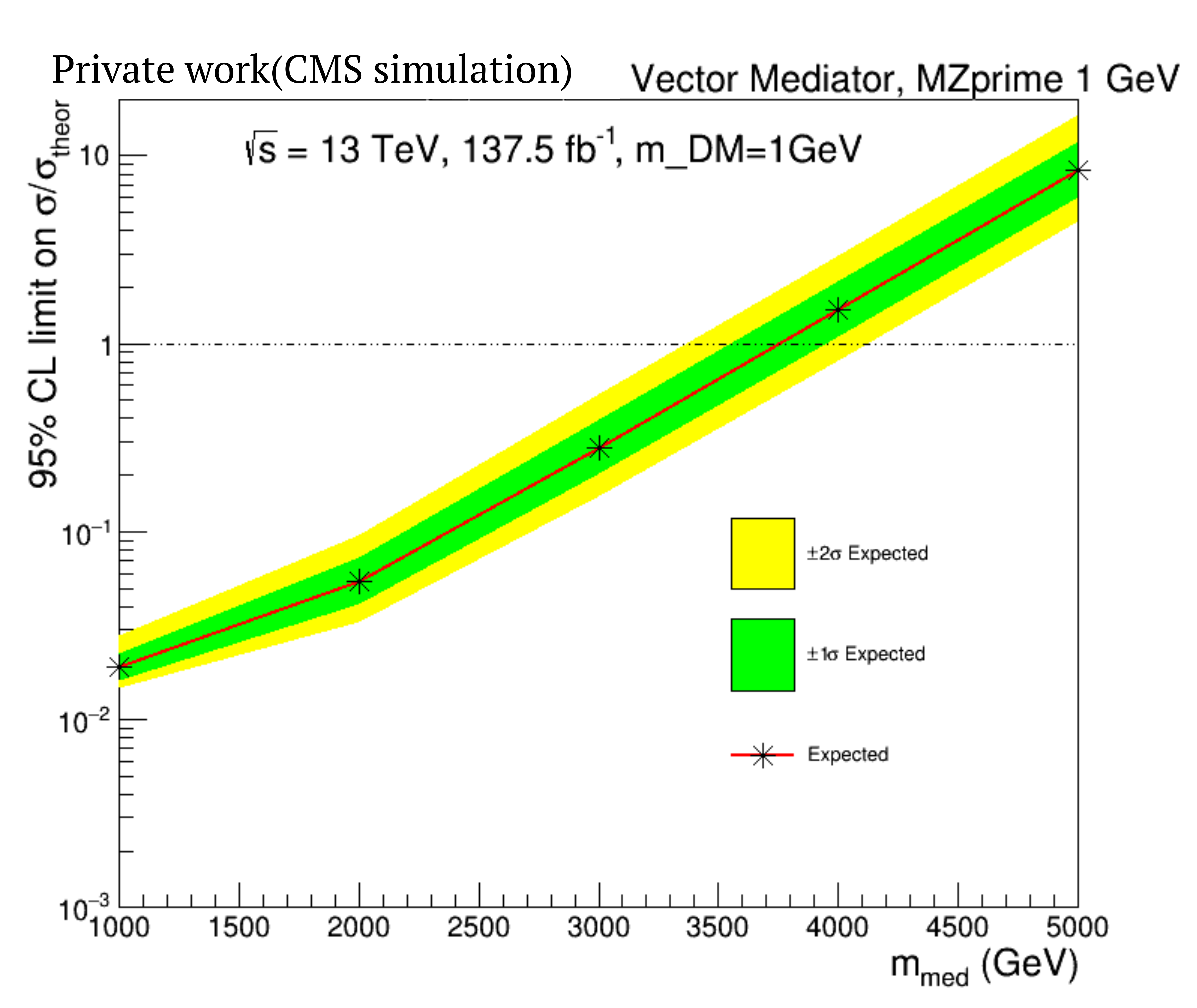


Significant improvement in sensitivity when using MonoLightZ' strategy(HPSJet+ML) compared to MonoJet strategy(using Ak4Jets) and also compared to cut based approach(using HPSJets without ML)

Expected Results



Axial Mediator



Vector Mediator

Summary

Several new physics models explored using Mono-Jet search

In Mono-Z' search, using special properties of the jet to get significantly improved results using Machine learning

Thank You

Backup

MonoJet

Systematic Uncertainties

On Transfer factors

Theory

QCD: Fact. & renorm. scales, Pt shape & process dependance, PDF

EW: Effects of unknown Sudakov logs, Missing NNLO effects, Effects of NLL Sudakov approx.

Other: Unfactorized mixed QCD-EW corrections

Experimental

e^-: Trigger, Reco efficiency, ID eff., veto

μ^-:, Reco eff., ID eff., Isolation eff., veto

γ^-: Trigger, ID eff., P_T scale

Other: MET Trigger, τ^- veto, prefiring

On simulation based processes

Theory

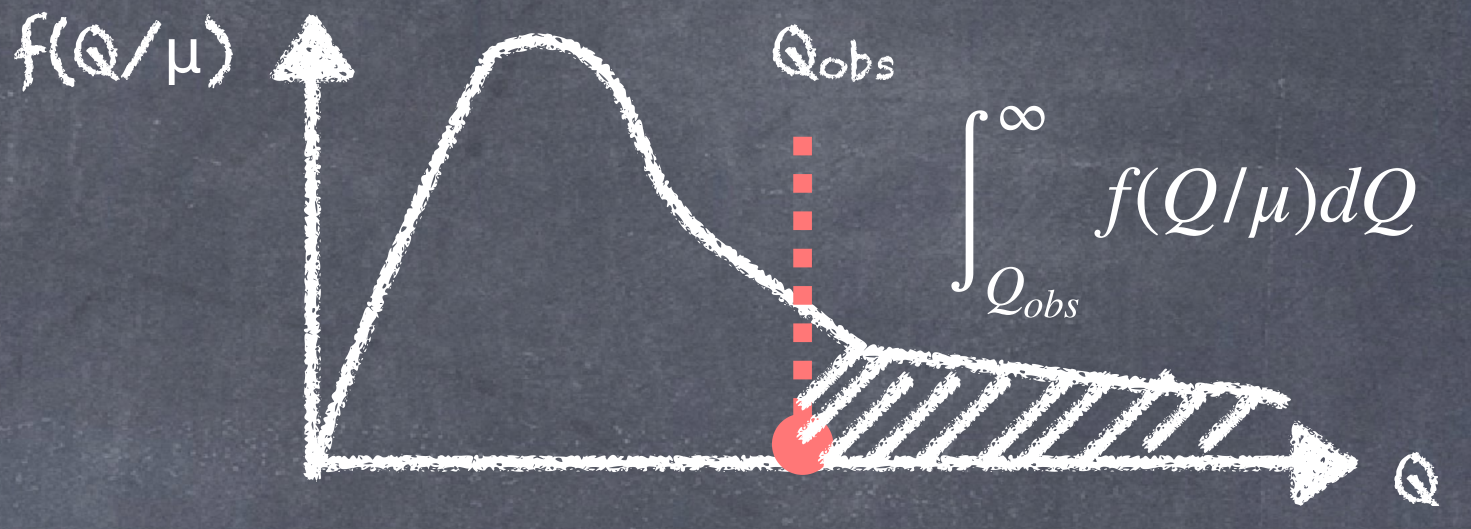
Top p_T reweight, Top norm,
Diboson mixed EW-QCD corr.,
Diboson norm,
Z(ll)+jets norm,

Experimental

Luminosity, e^- & MET trigger,
Jet/MET energy calibration,
μ^- ID, reco & iso eff.,
e^- reco and ID eff. ,
b-jet veto, QCD,
Fake muons, Jet-to-e^- fakes,γ-to-e^- fakes

Setting Limits on Signal models

- No significant excess in data compared to the expected. So we set limits on signal strengths for different BSM scenarios



A pdf of test statistic for a given value of μ

- Some terminology:
  - p value: probab. of getting value more extreme than observed
  - Likelihood: $\mathscr{L}(\vec{\alpha}) \propto p(data\,|\,\vec{\alpha})\,.\,\Pi(\vec{\theta}_0\,|\,\vec{\theta})$

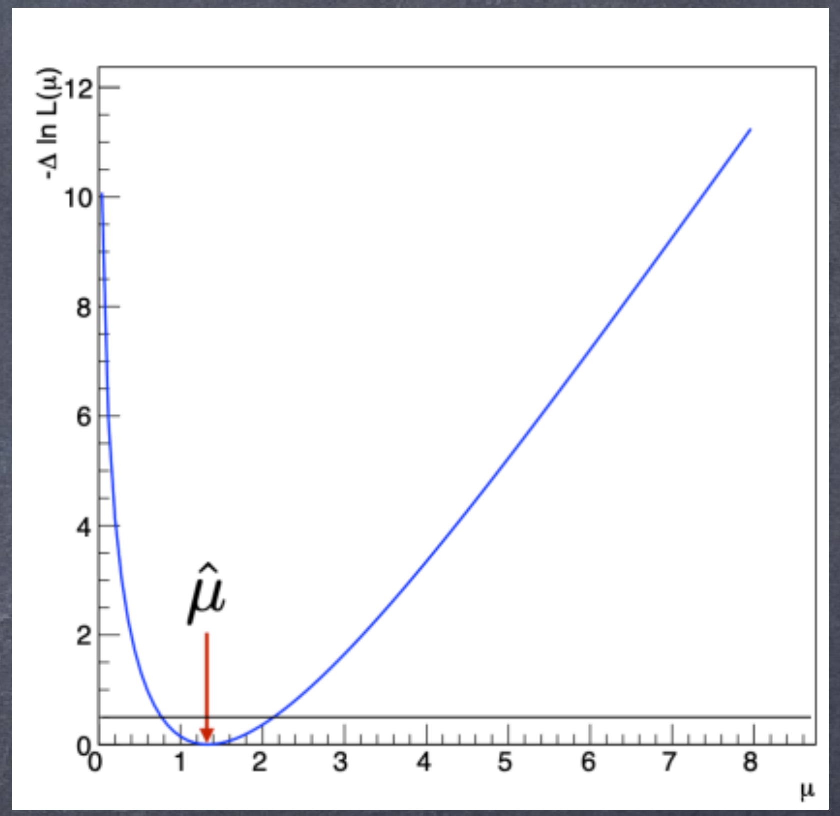
  where likelihood parameters $\vec{\alpha} = (\vec{\mu}, \vec{\theta})$ and

  constraint term $\Pi(\vec{\theta}_0\,|\,\vec{\theta})$

  $\vec{\mu}$ = Parameters of interest, $\vec{\theta}$ = Nuisance parameters,

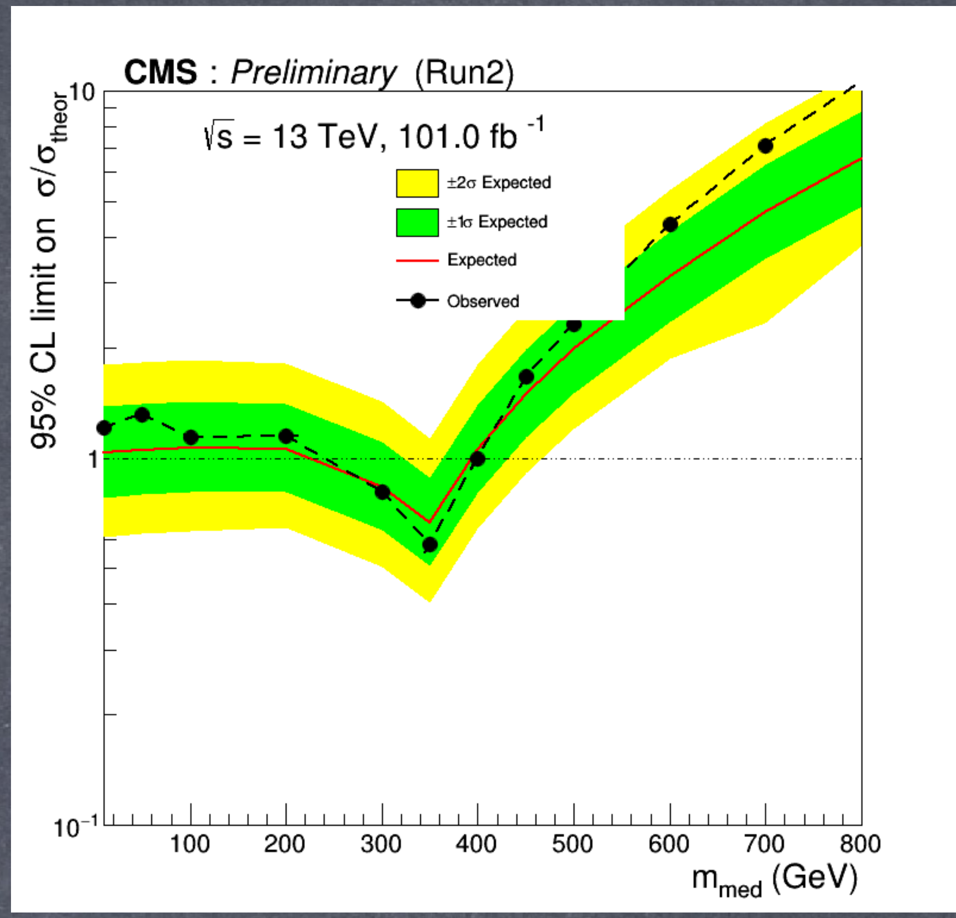
  $\vec{\theta}_0$ = Measured/nominal value

  - Test statistic used : Profile Likelihood ratio



$$q_\mu = \begin{cases} -2\ln\frac{L(\mu,\hat{\theta}_\mu)}{L(0,\hat{\theta}_0)} & \hat{\mu} < 0 \\ -2\ln\frac{L(\mu,\hat{\theta}_\mu)}{L(\hat{\mu},\hat{\theta})} & 0 \le \hat{\mu} \le \mu \\ 0 & \hat{\mu} > \mu \end{cases}$$

Setting Limits on Signal models



- We use the CLs criterion $CL_s = CL_{s+b}/CL_b$

  where CL_{s+b} = p value under sig+bkg hypothesis

  and CL_b = p value under bkg. only hypothesis

- A signal hypothesis with a given μ is excluded at 95% CL if $CL_s \leq 0.05$

- Can use asymptotic approximation or generate toy datasets to get the test statistic distributions

- In the exclusion plots, green bands ~ ± 1σ, yellow bands ~ ±2σ variation in the upper limits

```
 -- AsymptoticLimits ( CLs ) --
Observed Limit: r < 10.8183
Expected  2.5%: r < 7.0537
Expected 16.0%: r < 9.8108
Expected 50.0%: r < 14.5625
Expected 84.0%: r < 22.3988
Expected 97.5%: r < 33.5971
```

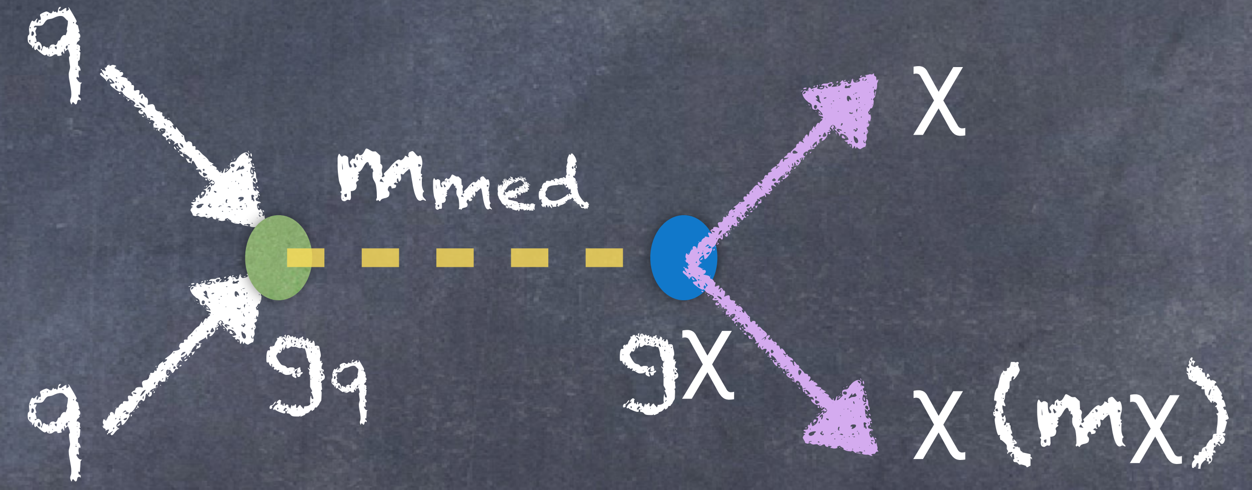
Dark Matter Models

- DM has not been observed in any particle experiments so far except maybe DAMA-LIBRA experiment(but this result is not yet confirmed)
- Possible signatures of DM at CMS include: Missing Transverse Momentum(MET), Disappearing tracks, Metastable charged particles etc.

Vector	Axial-Vector
$g_q \sum_q V_\mu \bar{q} \gamma^\mu q$	$g_q \sum_q A_\mu \bar{q} \gamma^\mu \gamma_5 q$
Scalar	**Pseudo-Scalar**
$\frac{g_q}{\sqrt{2}} \sum_q \Phi y_q \bar{q} q$	$\frac{i g_q}{\sqrt{2}} \sum_q A y_q \bar{q} \gamma_5 q$

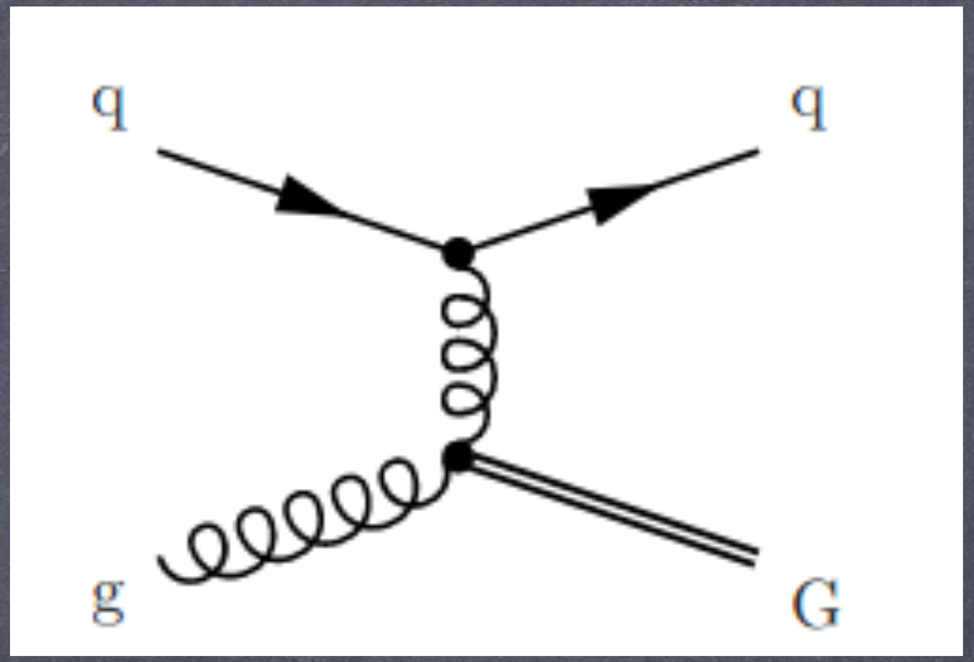
$$y_q = \sqrt{2} m_q / \nu, \quad \nu = 246 GeV$$

(Vacuum expectation value of SM Higgs boson)



Extra spacetime dimensions

- Hierarchy problem in SM - difference in strengths of gravity and the other forces
- Theory proposed by Arkani-Hamed, Dimopulous, Dvali(ADD) suggests gravitons could be escaping into other dimensions making gravity weaker
- Signal parameters:
  - d : number of extra dimensions
  - M_D : (Fundamental Planck scale in 4+d dim)



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

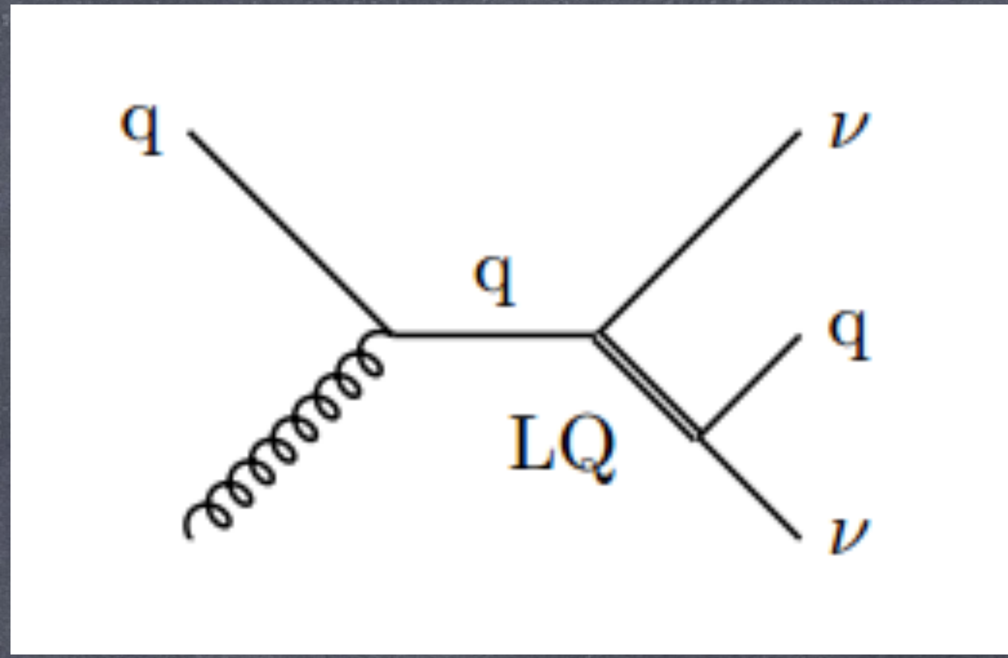
$$M_{Pl} \sim 10^{18} GeV$$

$$R \sim 10^{\frac{30}{d}-17} \left(\frac{TeV}{M_D}\right)^{\frac{d+2}{d}} cms$$

Leptoquark(LQ)

- LQs : hypothetical color-triplet bosons[can be spin0(scalar LQ) or spin1(vector LQ)]
- Predicted by many extensions to SM eg. Grand Unified Theories(GUT),

  technicolor schemes, composite models.

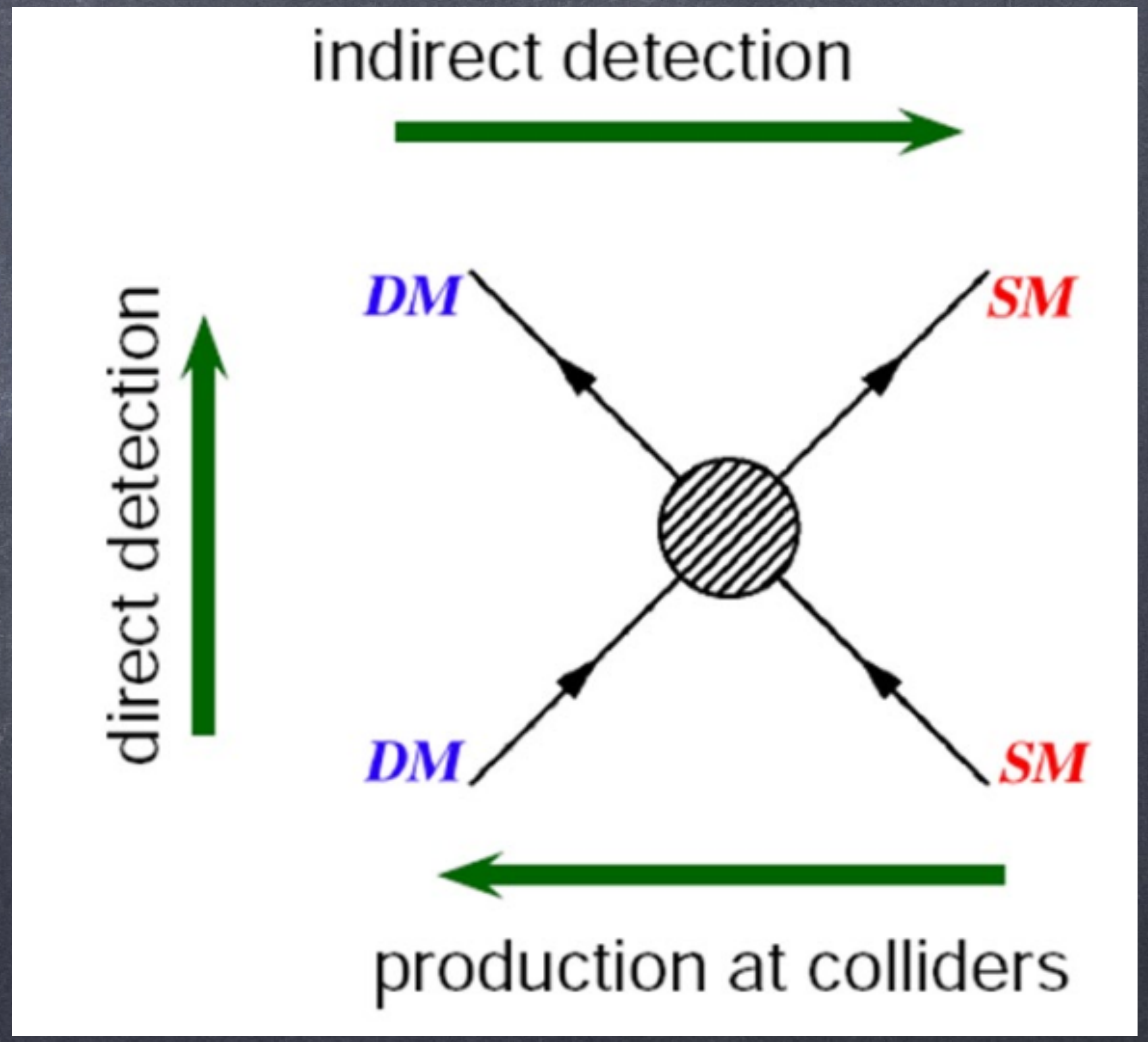


- Fractional electric charge , Baryon and Lepton number
- Existing experimental limits on flavor changing neutral currents and other rare processes disfavour leptoquarks coupling to more than 1 SM generation
- Here we consider scalar 1st generation LQ, also assume β=BR(LQ->ue^-)=0 making BR(LQ->$u\nu_e$)=1
- Signal Parameters: LQ mass and coupling value of LQ-quark-neutrino vertex

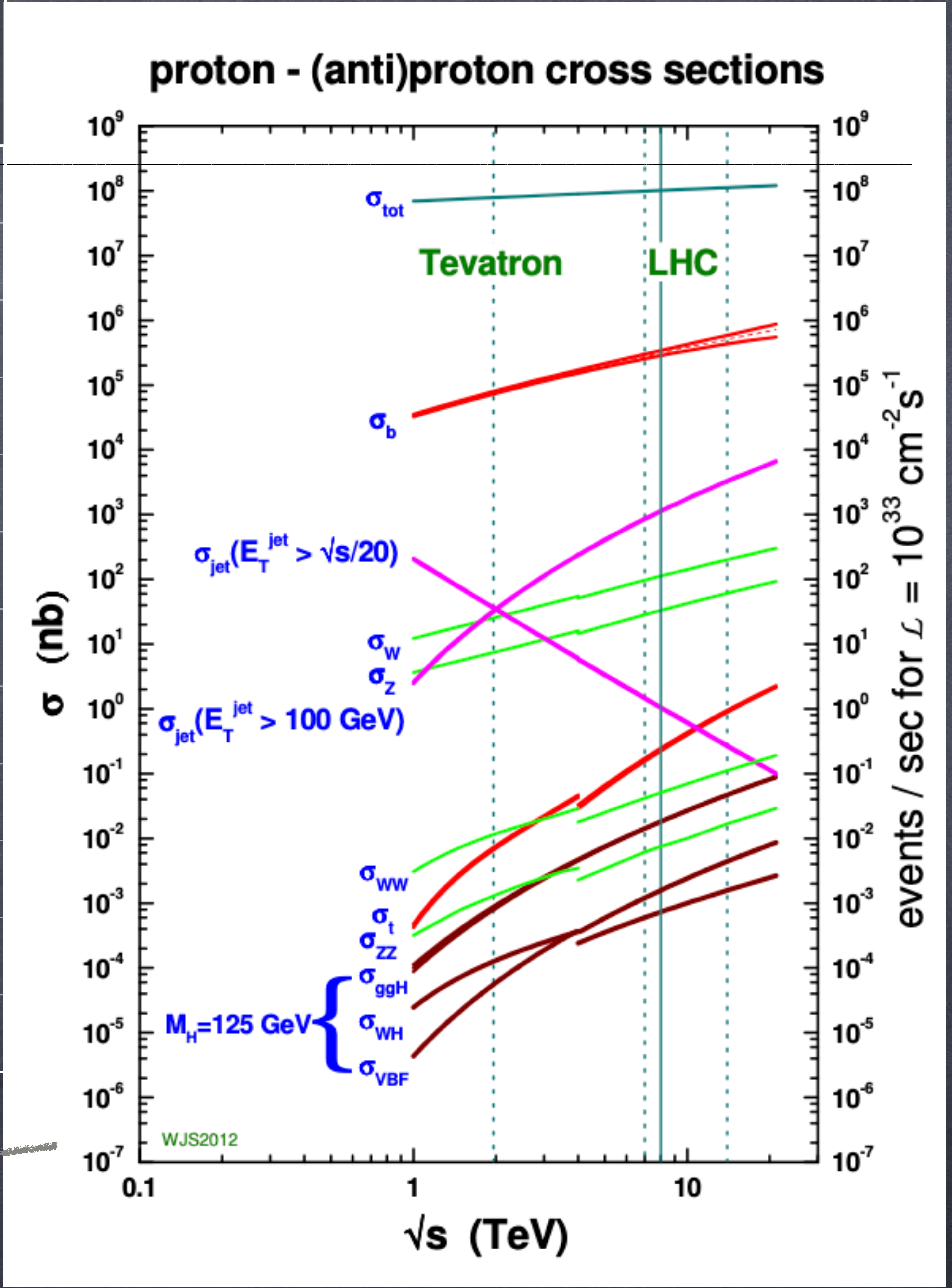
Dark Matter

- Strong astrophysical evidence for Dark Matter eg. Rotation curves of galaxies, gravitational lensing, Cosmic Microwave Background radiation, bullet cluster etc.
- There are alternative explanations for some of these phenomena like MOND(Modified Newtonian Dynamics) but they dont explain all these phenomena like DM does
- Based on these evidences the properties that DM possesses: Dark(no electric charge or colour charge), Massive, Stable(or lifetime)
- What could DM be? MACHOS? Standard Model(SM) neutrinos?
- Some particles proposed as solutions to some other problems in SM are possible DM candidates eg. Sterile Neutrinos, Supersymmetry scenarios, Axions
- Many experiments exploring different search strategies today

Bullet cluster



Particle	Xsec(pb)	approx. # events produced(not reconstructed) in Run2 $140\ fb^{-1} = 140 * 10^3\ pb^{-1}$
pp inelastic	$8 * 10^{10}$	$1.1 * 10^{16}$
pp elastic	$2 * 10^{10}$	$2.8 * 10^{15}$
b	$4 * 10^8$	$5.6 * 10^{13}$
W	$2 * 10^5$	$2.8 * 10^{10}$
Z	$6 * 10^4$	$8 * 10^9$
Top	10^3	$1.4 * 10^8$
Higgs(125 GeV)	50	$7 * 10^6$
DM(Pseudoscalar)	$0.007 - 5$	$10^3 - 7 * 10^5$
DM(scalar)	$0.001 - 2$	$140 - 2.8 * 10^5$
ADD	$0.0009 - 1.15$	$126 - 1.6 * 10^5$
1st gen. scalar LQ	$0.001 - 0.2$	$140 - 2.8 * 10^4$
Mono-Light Z'	$10^{-5} - 1.5$	$1.4 - 3.2 * 10^5$



These cross sections are calculated either at NLO or NNLO pQCD, using MSTW2008 (NLO or NNLO) parton distributions, with the exception of the total hadronic cross section which is based on a parametrisation of the Particle Data Group.

W.J. Stirling

Mono-Light Z′

Machine learning model performance