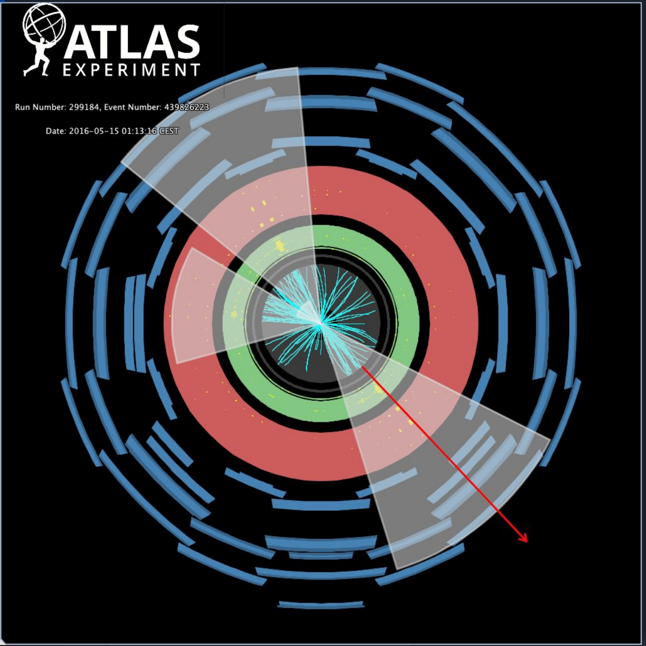


CONF NOTE LINK

Search for non-resonant production of semi-visible jets in ATLAS

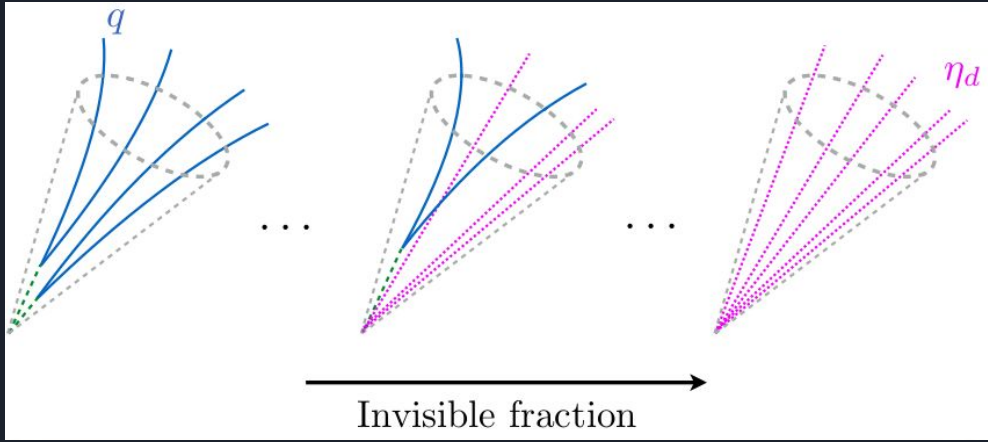
Deepak Kar & Sukanya Sinha

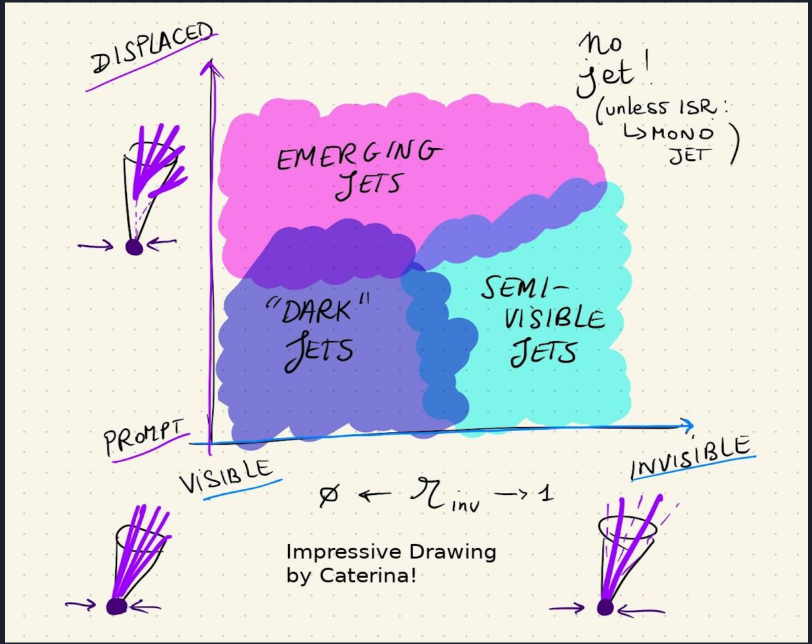
Semi-visible jets workshop,
ETH Zurich

05/07/2022

UNIVERSITY OF THE WITWATERSRAND, JOHANNESBURG

Semi visible jet production

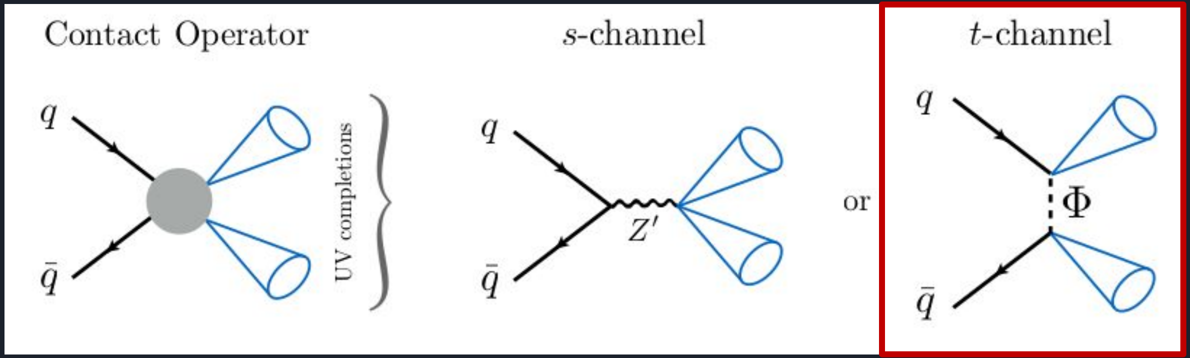




Link to the paper: https://arxiv.org/abs/1707.05326

Model Parameters:

1. M_{Φ} = Mass of Scalar Bi - fundamental
2. r_{inv} = no. of stable invisible hadrons/ no. of hadrons
3. M_d = Mass of dark hadrons
4. Lambda = 2 vertex coupling strength ~ $xs^{1/4}$



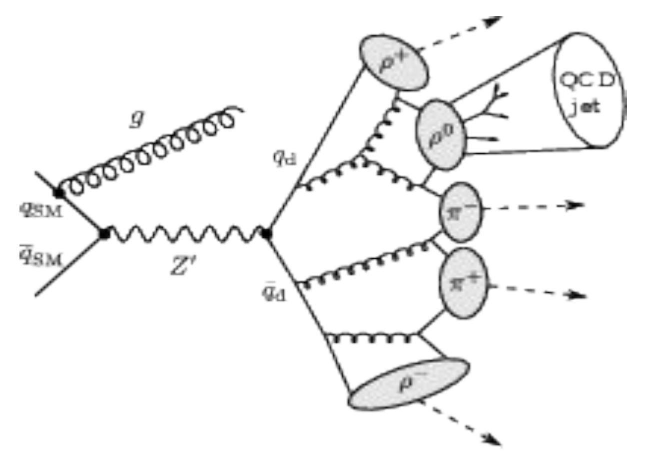
Pythia 8 Hidden Valley Module

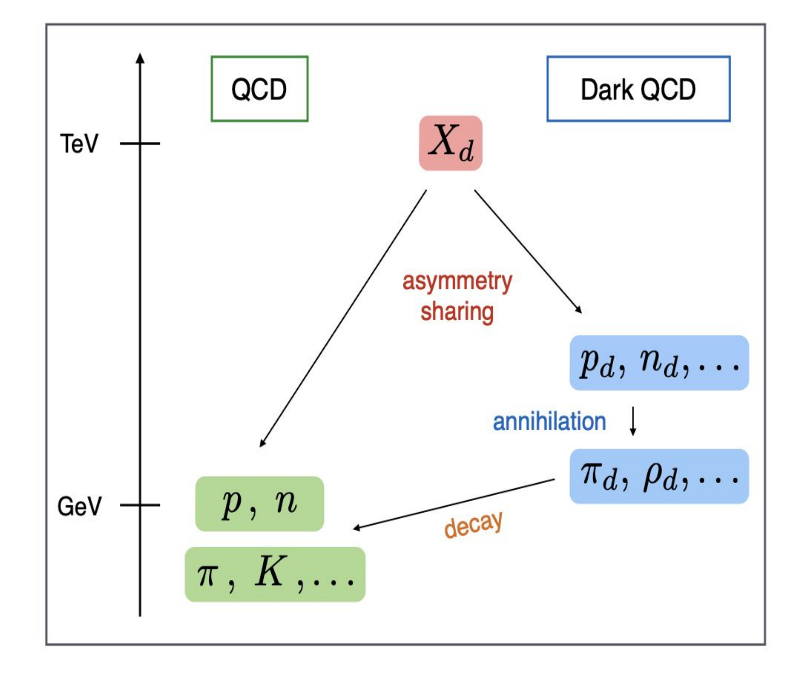
Two different dark quark flavours

- Combine to form π^+, π^-, π^0, and ρ^+, ρ^-, ρ^0 (assumed to be produced thrice as much as pions)
- Only ρ^0 is unstable and (promptly) decays to SM quarks: more likely to decay to b pairs due to need for a mass insertion, to make the angular momentum conservation work out
- Other mesons are (collider-)stable → invisible

Signal xs usually very low compared to BG → More of a topology generator rather than full-blown theory model

Decay chains are rather complex and the showering model is still being developed by the theory community





Baryon and DM asymmetries shared via a mediator X_d → asymmetry in stable dark baryons.

The symmetric relic density annihilated into dark pions → decay into SM particles.

Correct DM relic density obtained when dark baryon masses are in the 10 GeV range.

HV Parameters (why and what)

Parameter	value
HiddenValley:Ngauge	2
HiddenValley:FSR	on
HiddenValley:spinFv	0
HiddenValley:fragment	on
HiddenValley:pTminFSR	1.1
HiddenValley:probVector	0.75
HiddenValley:alphaOrder	1
HiddenValley:Lambda	0.1
HiddenValley:alphaFSR	1.0

All parameters set as per theory paper

Running HV alpha selected, after discussions with theorists in different platforms (Snowmass, LHC DMWG). Advised to be the safest choice for first analysis.

Analysis Samples

Signal: Madgraph + Pythia8 with R_{inv} = 0.2, 0.4, 0.6, 0.8 and M_d = 10 GeV, M_ϕ = 1 - 5 TeV (in 500 GeV intervals)

Background samples:

Process	Generator	ME order	PDF	Parton shower	Tune
Multijet	Pythia 8.230	LO	NNPDF23LO	-	A14
W/Z+jets	Sherpa 2.2.11 [17, 18]	NLO (up to 2 jets)	NNPDF3.0NNLO	Sherpa MEPSatNLO	Sherpa
$t\bar{t}$	Powheg-Box 2	NLO	NNPDF3.0NLO	Pythia 8.230 with NNPDF23LO	A14
Single top	Powheg-Box 2	NLO	NNPDF3.0NLO	Pythia 8.230 with NNPDF23LO	A14
Diboson	Sherpa 2.2.1	NLO (up to 2 jets)	NNPDF3.0NNLO	Sherpa MEPSatNLO	Sherpa

Data samples:

2015: 3.20 \pm 0.07 fb^{-1}
2016: 32.9 \pm 0.72 fb^{-1}
2017: 44.3 \pm 1.06 fb^{-1}
2018: 59.9 \pm 1.19 fb^{-1}

Full Run-2 dataset

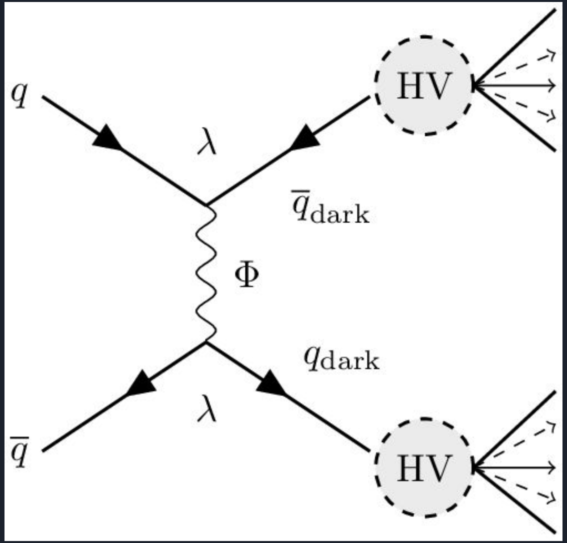
Analysis preselections

1. Looking at events with MET trigger, MET > 200 GeV
2. At least 2 jets with leading jet p_T > 250 GeV, other jet p_T > 30 GeV and |eta| < 2.8
3. No electrons / muons (p_T > 7 GeV)
4. Dead-tile correction, LAr, SCT error veto, NCB treatment for data
5. DeltaPhi(closest jet, MET) < 2.0
6. B-tagged jets < 2
7. Tau jets (p_T > 20 GeV) < 1

The signal events typically have high MET —- better sensitivity for signals with higher mediator masses and R_{inv} fraction (M_{ϕ} > 3 TeV, R_{inv} > 0.4) if search is performed at a high MET range.

MET > 600 GeV and H_T > 600 GeV after the nominal selection defined as signal region (SR).

The corresponding 1L, 1L1B and 2L control regions (CR) defined using leptonic selections (and leptons added back to MET) with same MET and H_T requirements as in SR.



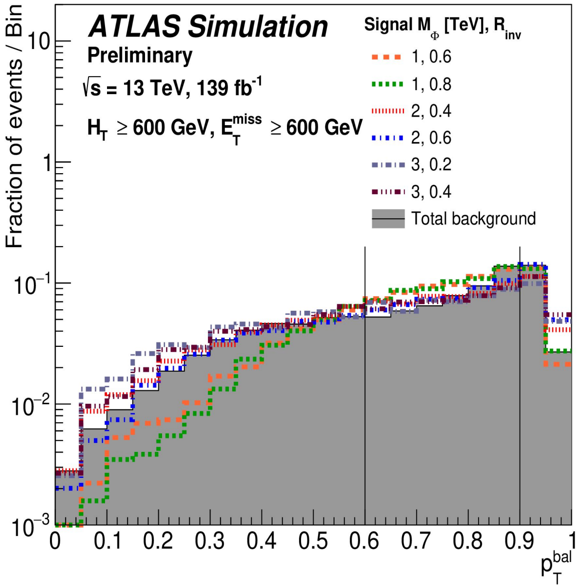
The resultant MET direction is aligned along one of the jets.

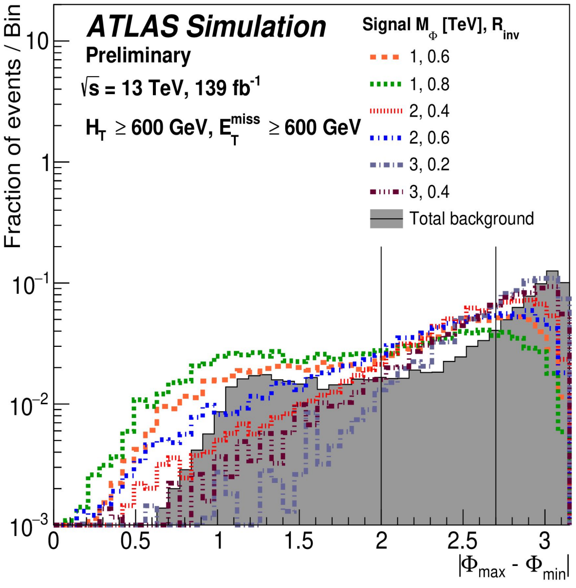
Key Observables

1. the p_{T} balance between the closest jet (j_1) and farthest jet (j_2) from $E_{\mathrm{T}}^{\mathrm{miss}}$ direction, termed as $p_{\mathrm{T}}^{\mathrm{bal}}$:

$$p_{\mathrm{T}}^{\mathrm{bal}} = \frac{|\vec{p}_{\mathrm{T}}(j_1)+\vec{p}_{\mathrm{T}}(j_2)|}{|\vec{p}_{\mathrm{T}}(j_1|+|\vec{p}_{\mathrm{T}}(j_2)|}.$$

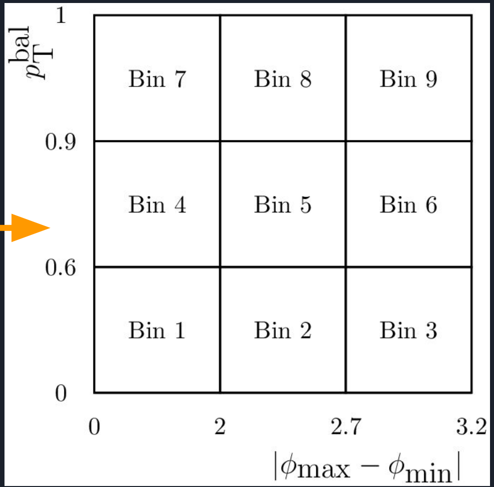
2. the difference in the azimuthal angle between j_1 and j_2 as defined above, termed $|\phi_{\max} - \phi_{\min}|$:





Yields in these nine bins ((3 max-minphi bins)x(3 p_{T} balance bins)) are treated as the observables in different regions.

Contribution of different backgrounds is different for each of the bins, so the signal-depleted but specific background-enriched bins in the SR itself are used to estimate the background.



Systematic Uncertainties

- Largest contribution from theoretical components (~25% on signal cross-sections mostly from scale variations).
    - Apart from usual scale and PDF variations, also included ttbar and single top I/FSR variation, ME and PS variation by using alternate generators, DR/DS subtraction scheme difference for tW.
    - W+jets split into heavy and light flavour, and an extra 30% normalisation uncertainty was used for heavy flavour, since Sherpa 2.2 has been found to underestimate V+heavy-flavour by about a factor of 1.3
    - There is known mismodelling in multijet processes, so a data-otherMC vs multijet reweighting is done in 250 < MET < 300 GeV in 9bin distribution → the reweighting factors are obtained in bin 3,6,9, and applied to 1-3, 4-6, 7-9 respectively.

- Standard experimental uncertainties: JES/JER, MET soft term, luminosity, PU reweighting, flavour tagging, reconstruction/identification/isolation/trigger efficiencies on muon and tau leptons.

Statistical analysis

- To determine individual $N_i \rightarrow$ simultaneous binned maximum likelihood function fit is performed using product of all PDF_i and nine bin yields, using the MC templates
- The fit maximises the likelihood function constructed from the product of all relevant Poisson and Gaussian pdfs. The scale factors for the individual backgrounds, k^{SF} are determined from the fit:

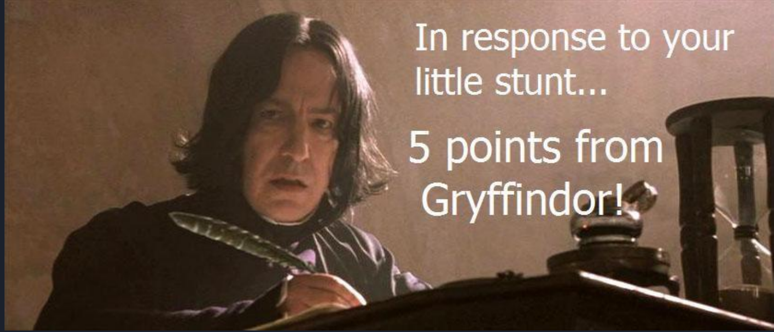
$$\mathcal{L}(\mu, \theta) = \prod_{j \in \text{ 36 bins}} \text{Poisson}(N_j^{\text{obs}} | \mu N_j^{\text{sig}}(\theta) + \sum_{i \in \text{bg}} k_i^{\text{SF}} \times N_{i,j}^{\text{bg}}(\theta)) \times f^{\text{constr}}(\theta)$$

Here, $N_j^{expected}$ is the observed total yield in the bin j, signal strength is \mu, systematic uncertainties in the fit are denoted by nuisance parameters \theta, N_j^{bg}(\theta) is the combined background yield in bin j

The term f_{constr}(\theta) of represents the product of the gaussian constraints applied to each of the nuisance parameters,

$$f_{constr}(\theta) = \prod_{k=1}^{M} G(\theta_k^0 - \theta_k)$$

Fit Strategy

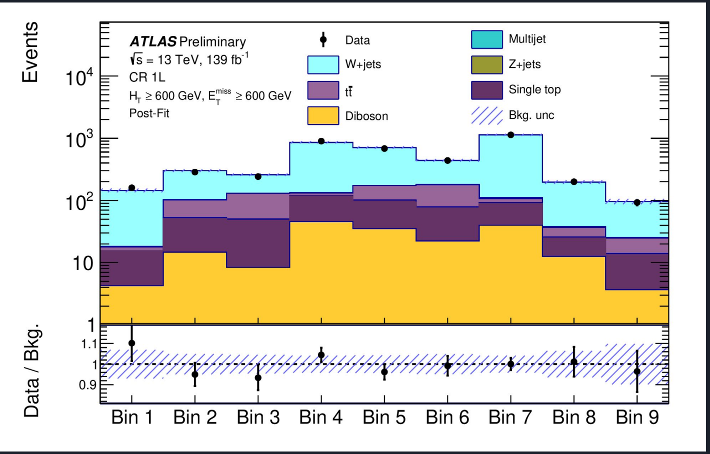


- The signal region (0L SR) 9-binned histograms are fitted simultaneously with 1LCR, 1L1BCR and 2LCR.
- Dedicated systematic uncertainties are applied to the 0L SR, 1L CR, 1L1BCR & 2L CR 9-binned histogram.

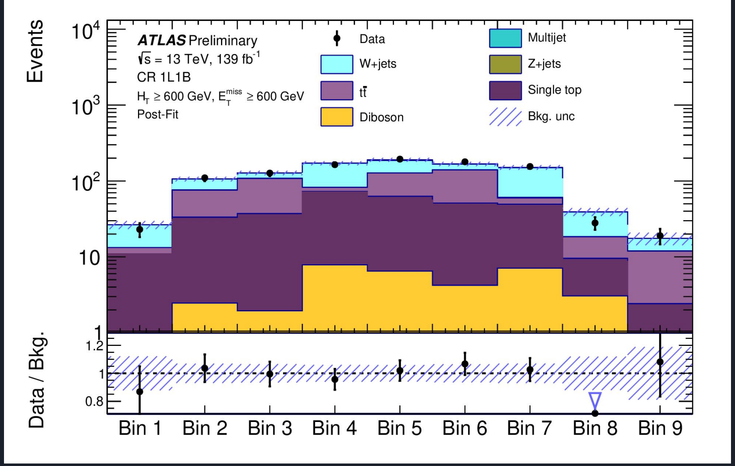
The largest post-fit effects on the shape are signal modelling uncertainties up to 8%, Z+jets modelling uncertainties up to 7%, and top process modelling uncertainties up to 4%. The rest of the contributions are less than 2%.

Results…

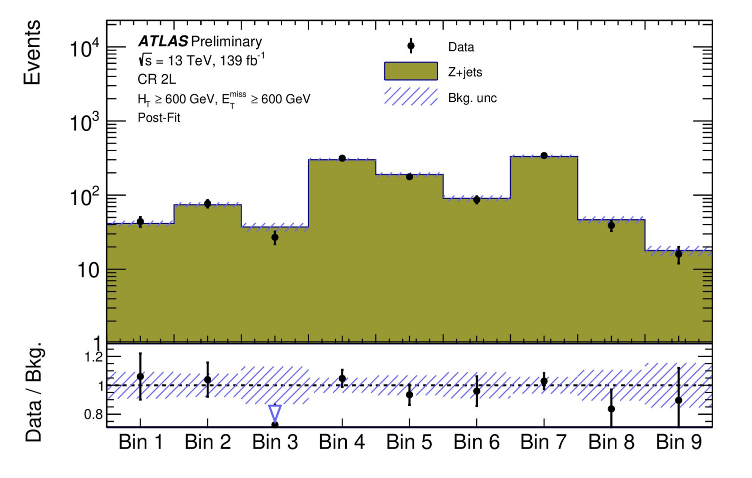
9-bin histograms - CR



CR 1L1B: used to control ttbar / single top background contributions

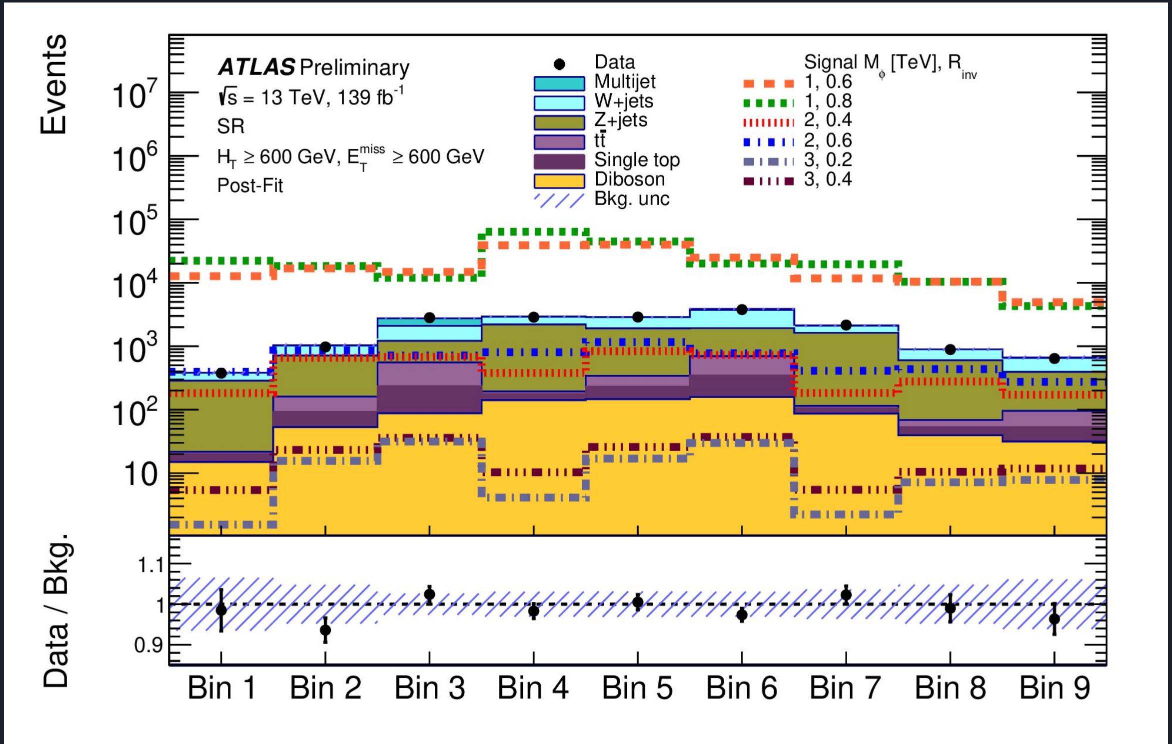


CR 1L: used to control W+jets / single top background contributions



CR 2L: used to control Z+jets background contributions

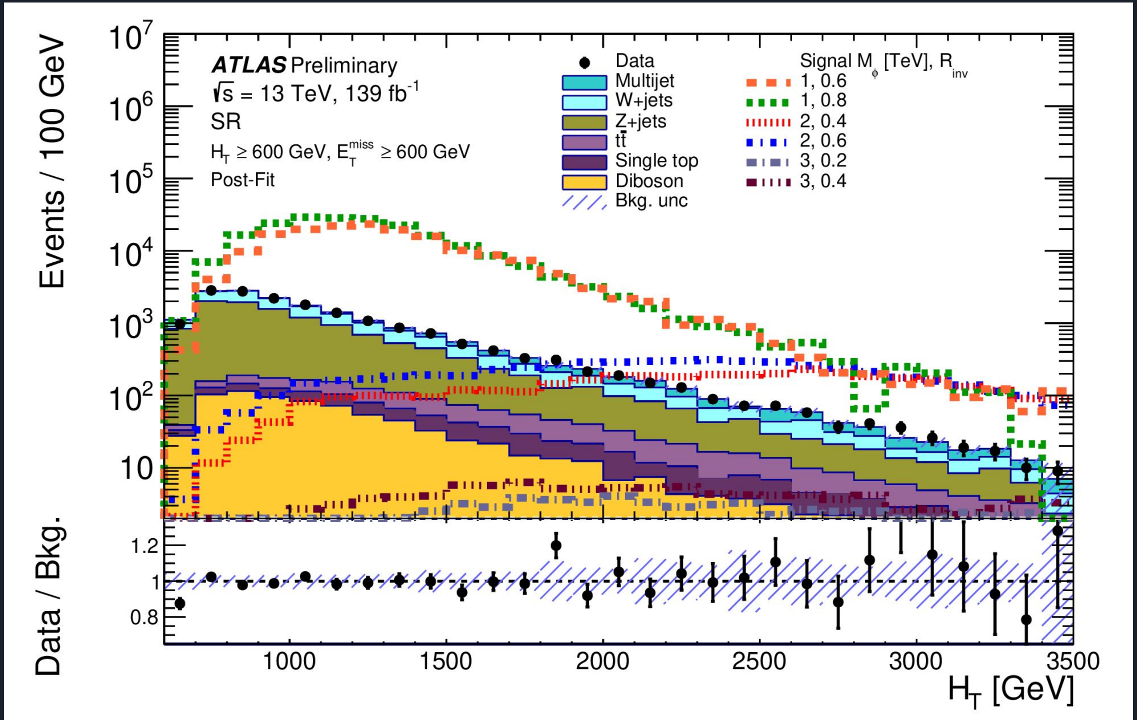
9-bin histograms - SR



We haven't found new physics :-(

Excellent agreement between data and estimated background…

9-bin histograms - Kinematic distributions



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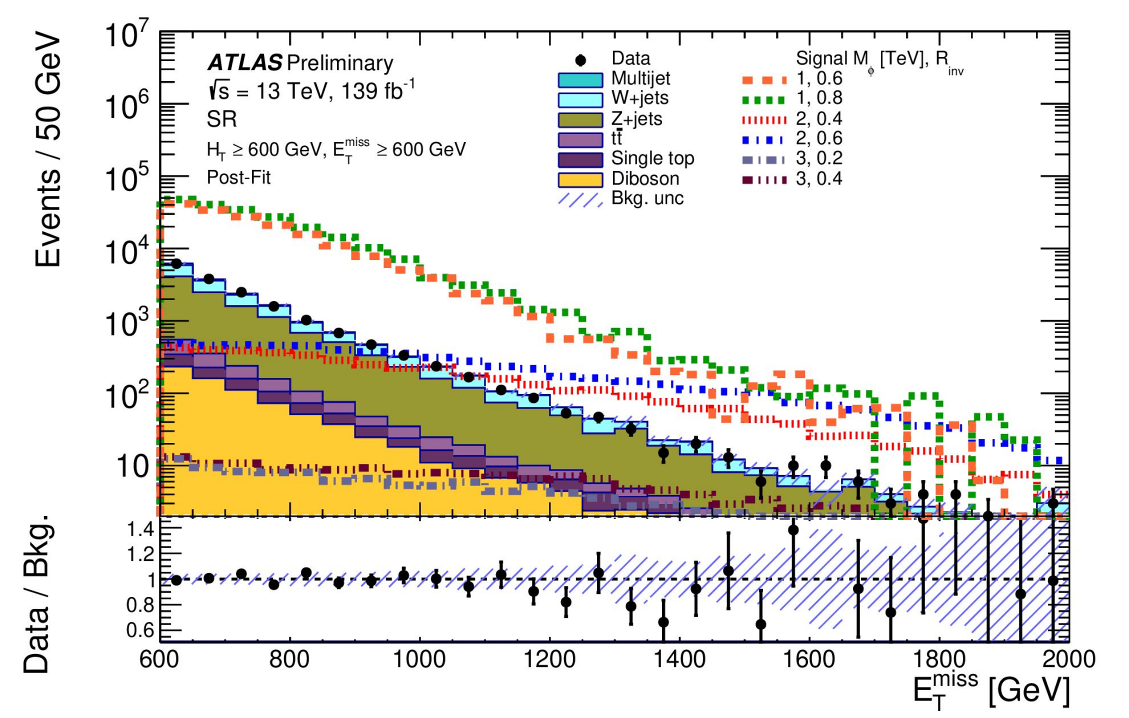
9-bin histograms - Kinematic distributions



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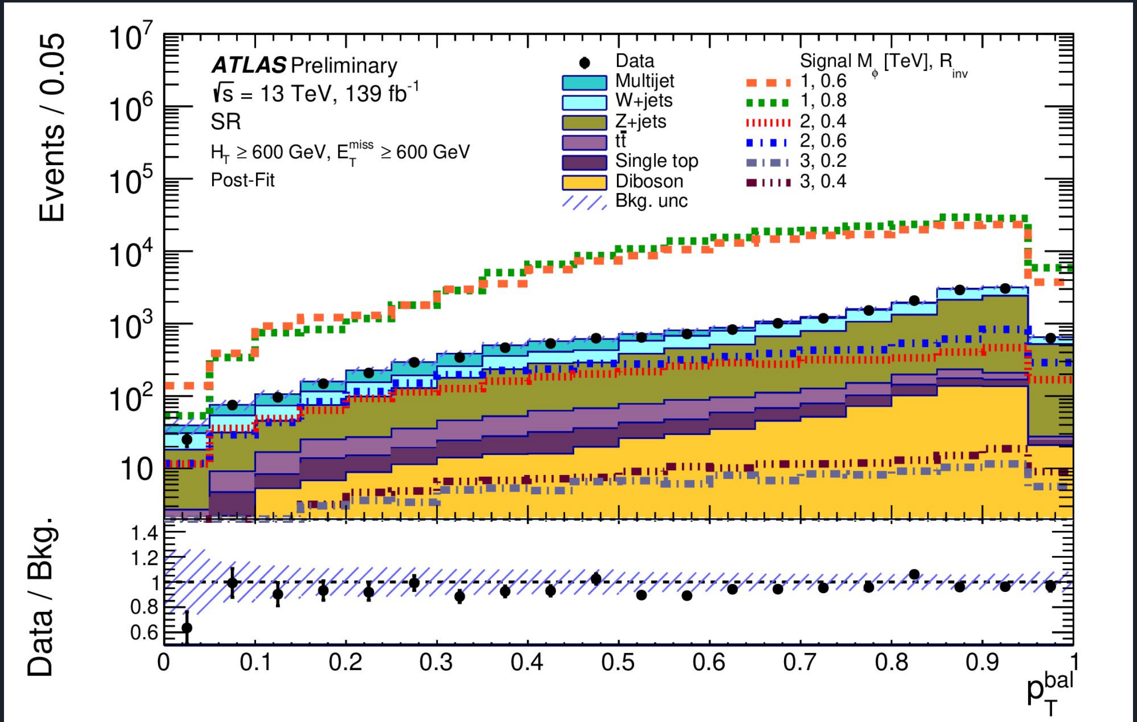

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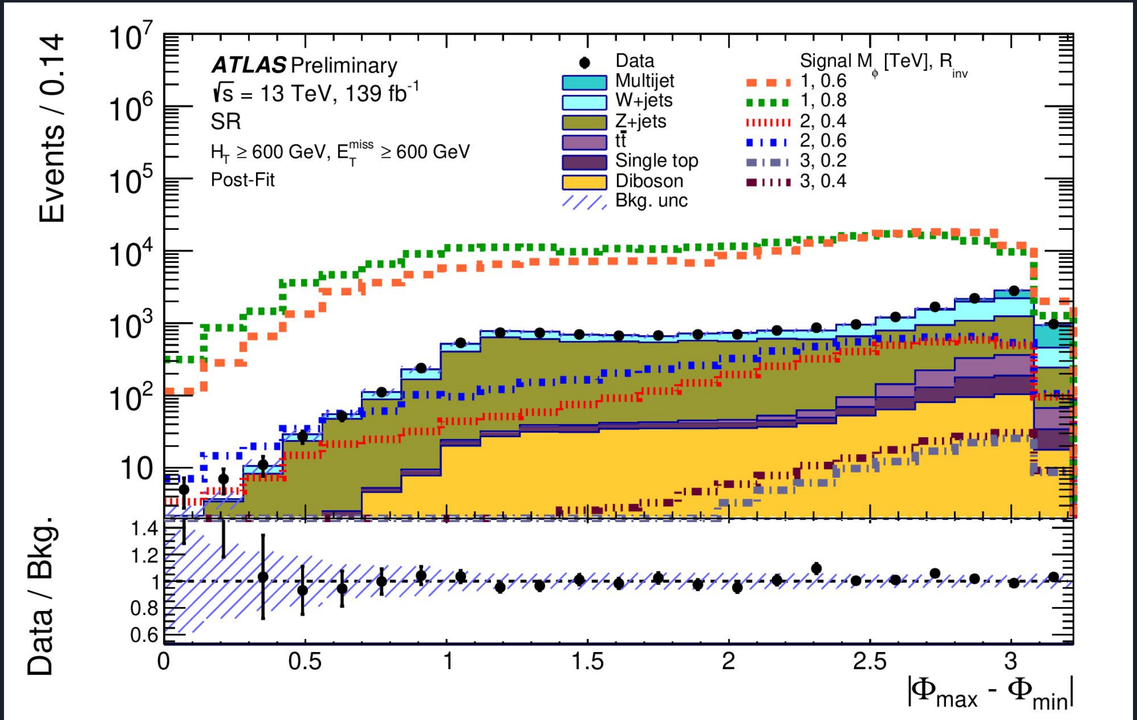
9-bin histograms - Kinematic distributions



We haven't found new physics :-(

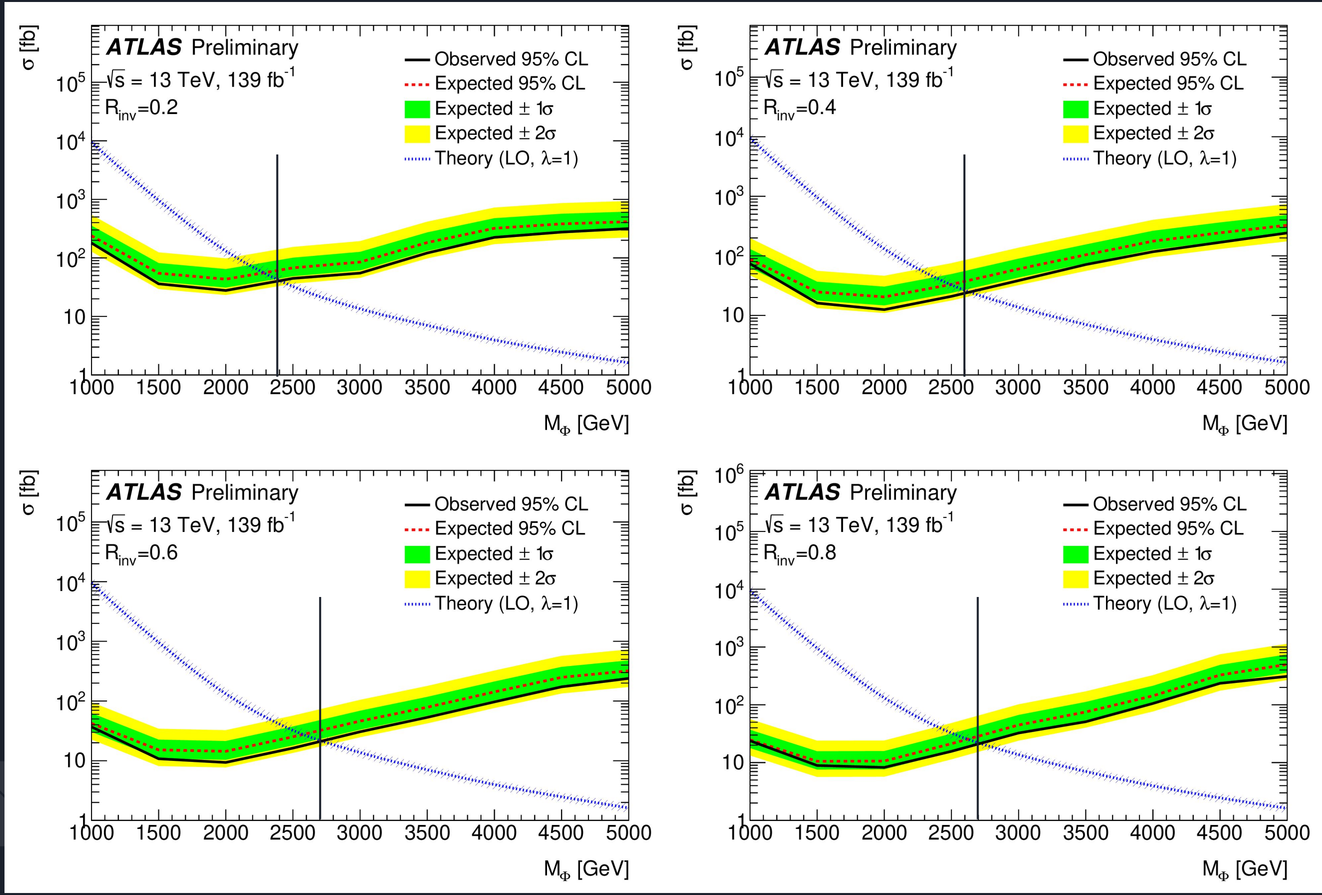
Excellent agreement between data and estimated background...

Some tables to stare at....

Process	k_i^{SF}
Z+jets	1.18 ± 0.05
W+jets	1.09 ± 0.04
Top processes	0.64 ± 0.04
Multijet	1.10 ± 0.04

	SR	CR 1L	CR 1L1B	CR2L
Z+jets	8490 ± 260	11.6 ± 1.4	2.2 ± 0.6	1120 ± 40
W+jets	5820 ± 300	3190 ± 170	351 ± 41	-
$t\bar{t}$	920 ± 70	350 ± 29	304 ± 24	-
Single top	533 ± 47	358 ± 29	290 ± 25	-
Multijet	850 ± 100	28 ± 11	7.7 ± 3.1	-
Diboson	757 ± 10	187 ± 9	34.5 ± 2.8	-
Total background	17 370 ± 280	4120 ± 100	990 ± 35	1120 ± 40
Data	17 388	4136	999	1124
Signal:				
M_ϕ=1 TeV, R_{inv}=0.6	180 000 ± 40 000	-	-	-
M_ϕ=1 TeV, R_{inv}=0.8	220 000 ± 50 000	-	-	-
M_ϕ=2 TeV, R_{inv}=0.4	4100 ± 900	-	-	-
M_ϕ=2 TeV, R_{inv}=0.6	5800 ± 1300	-	-	-
M_ϕ=3 TeV, R_{inv}=0.2	117 ± 26	-	-	-
M_ϕ=3 TeV, R_{inv}=0.4	170 ± 40	-	-	-

95% CL Limits on mediator mass

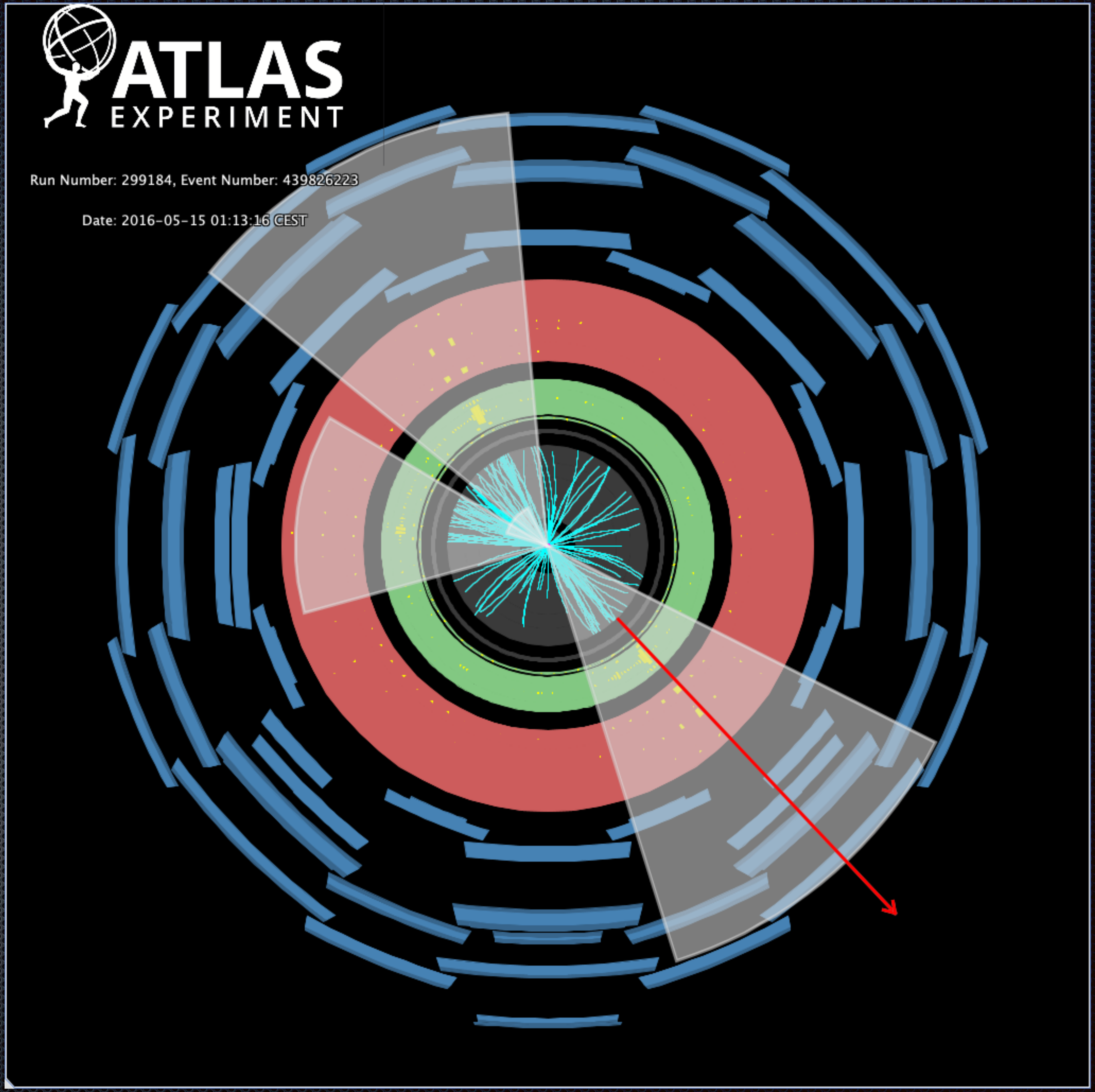


Assuming unity coupling between q - ϕ - q_d, can exclude mediator masses upto 2.7 TeV, subject to values of R_{inv}

However, the story does not end here…

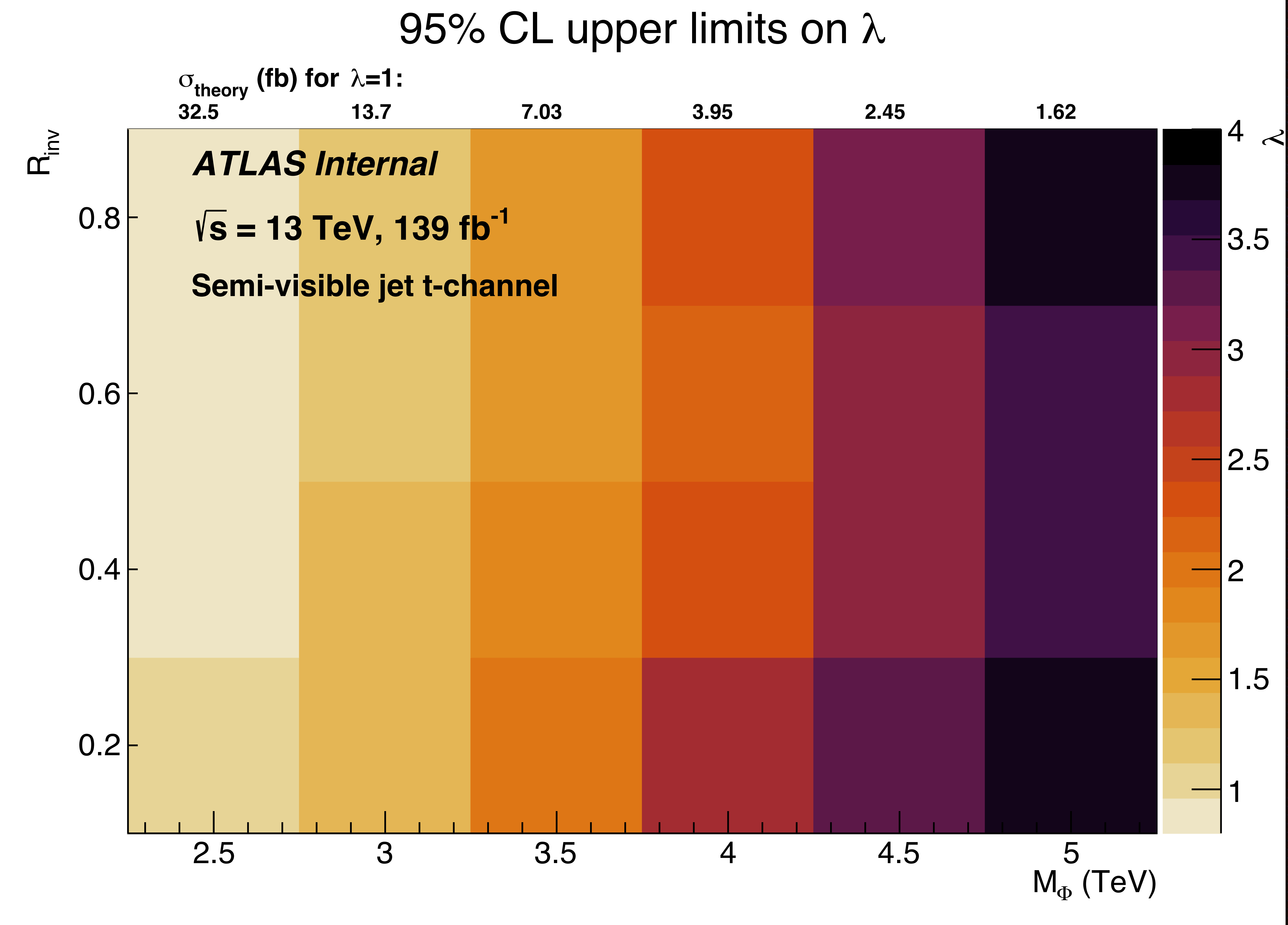
Sorry for the interruption …

How would a signal event look?



More Results

For mediator mass of 2.5 TeV or higher van also express the limits in terms of the q-q_d-ϕ vertex coupling strength λ, with the XS scaling as λ^4

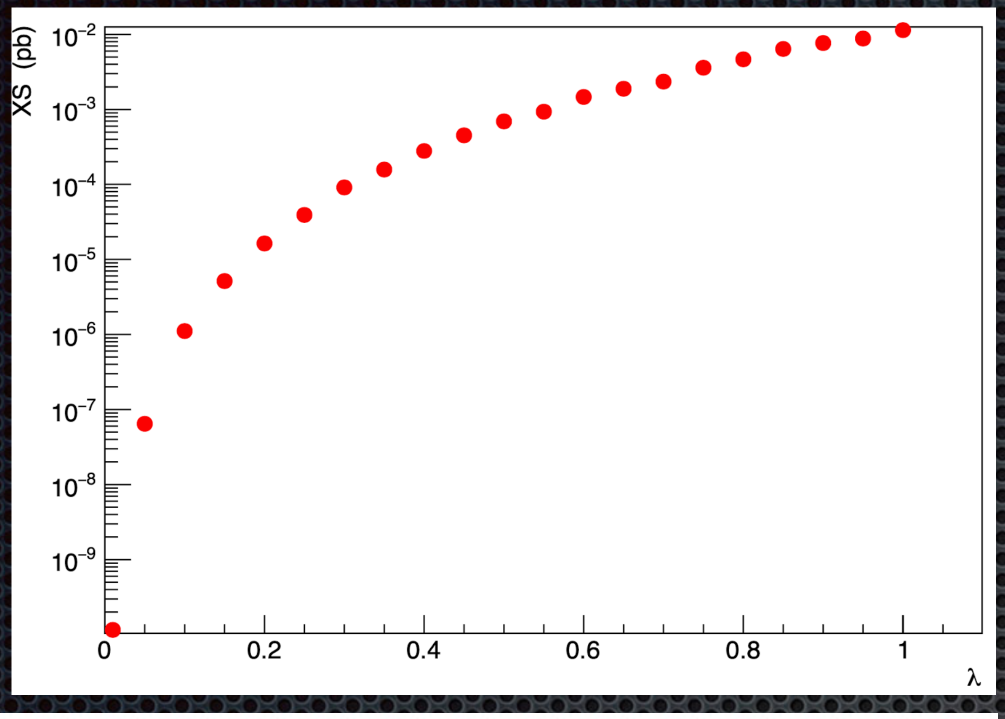


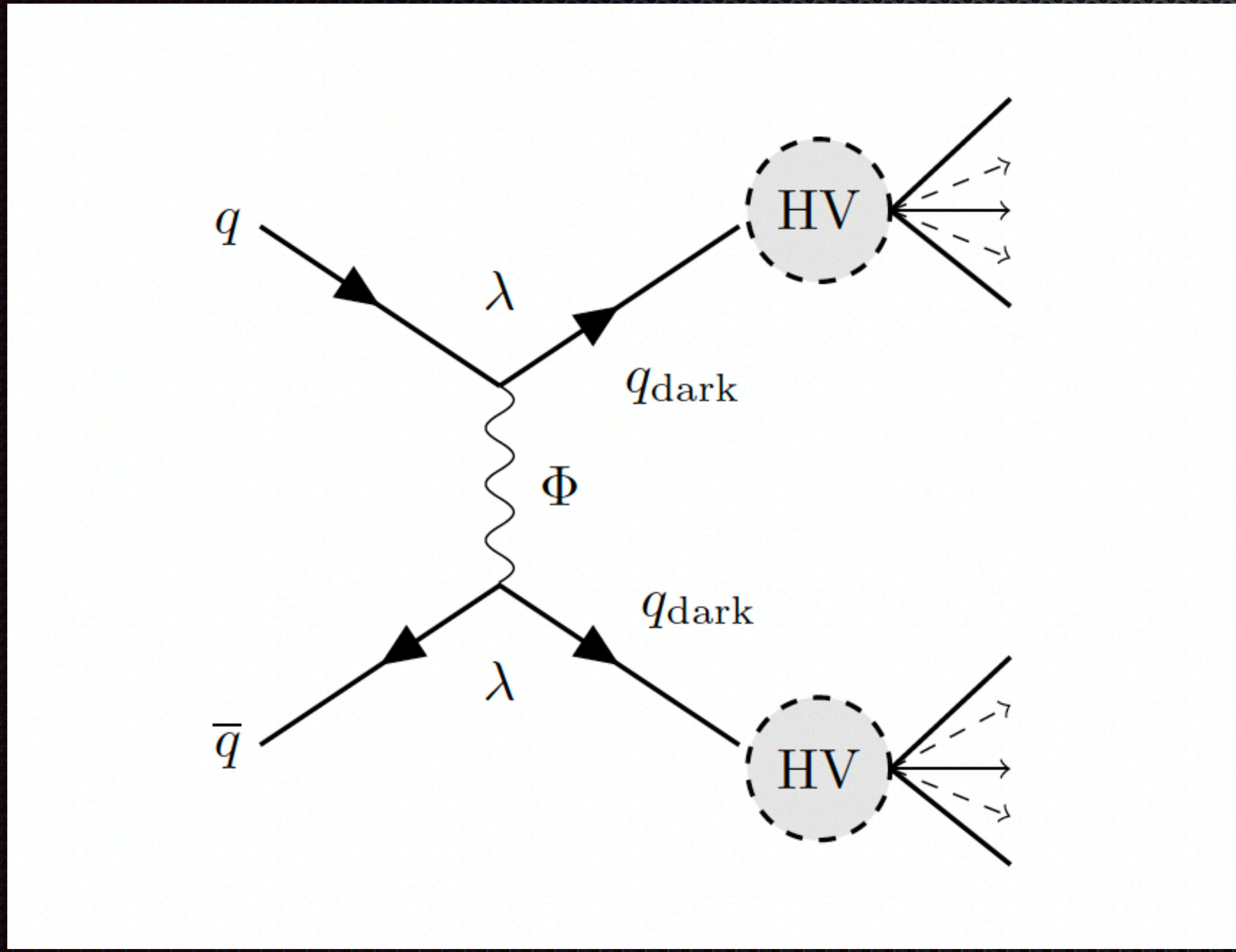
Discussion

Why 2.5 TeV?

Discussion

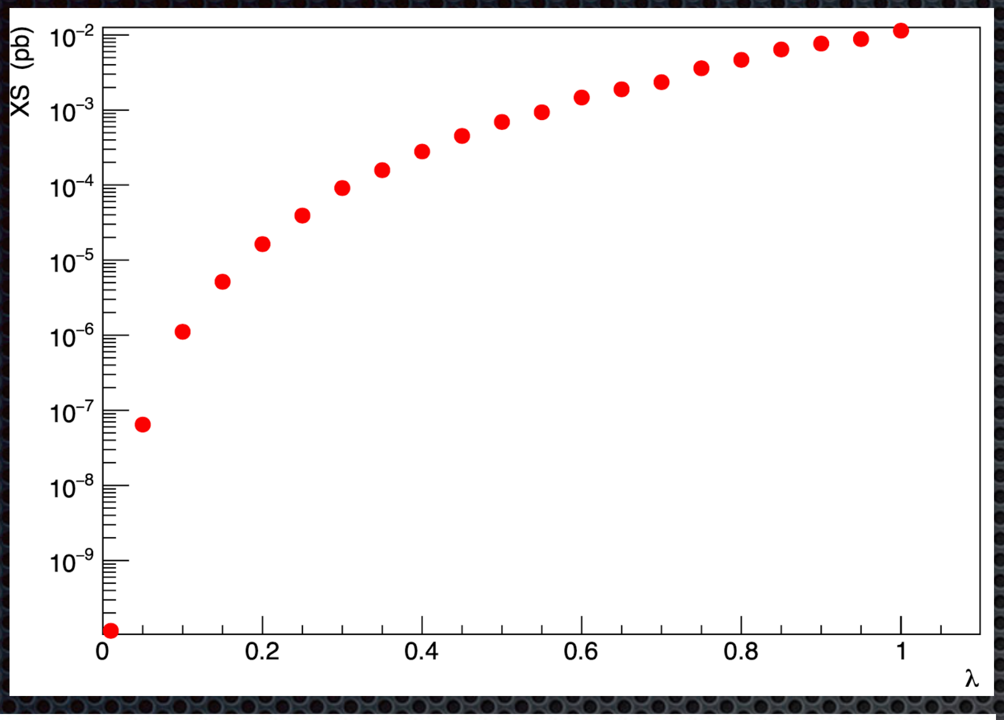
Why 2.5 TeV?

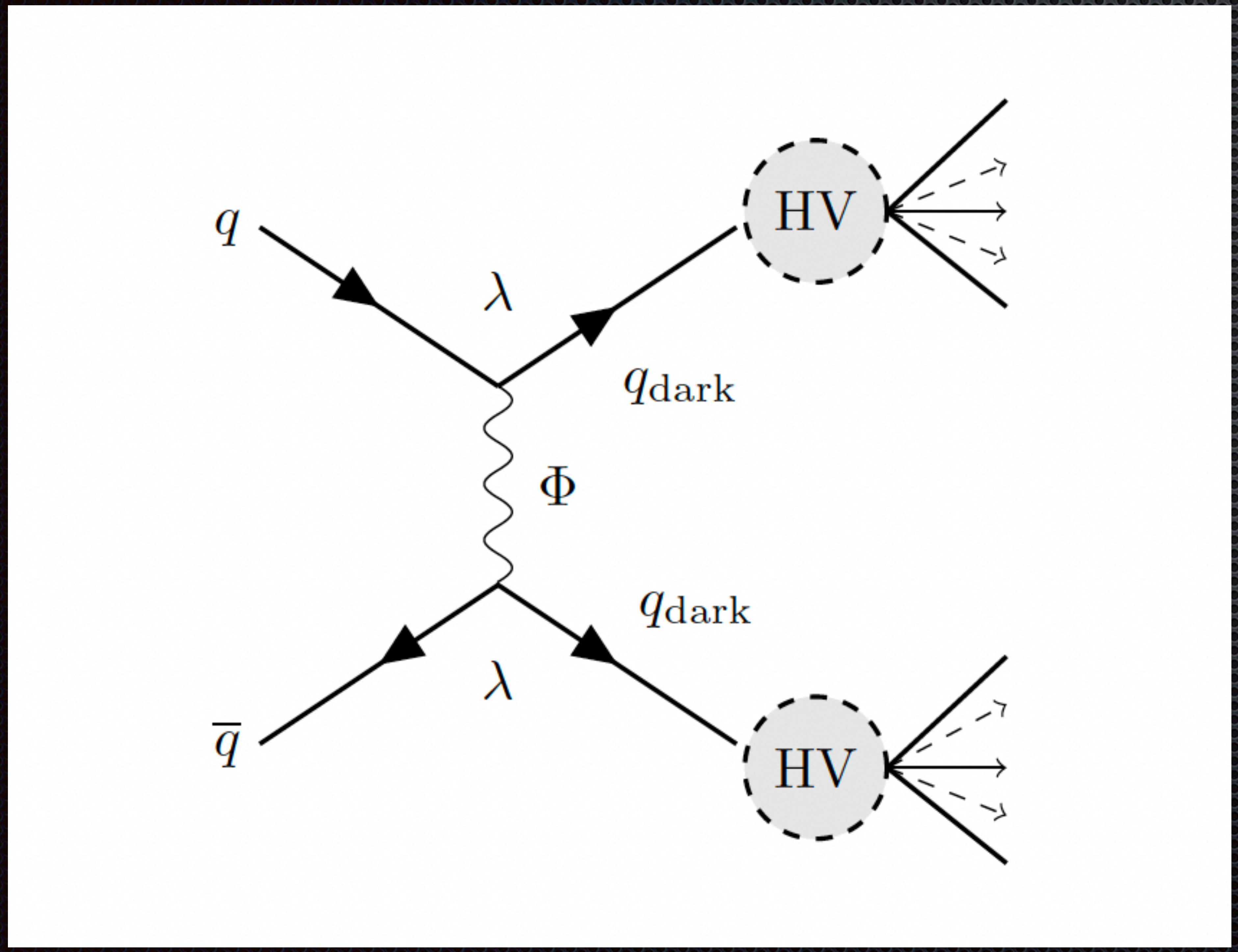


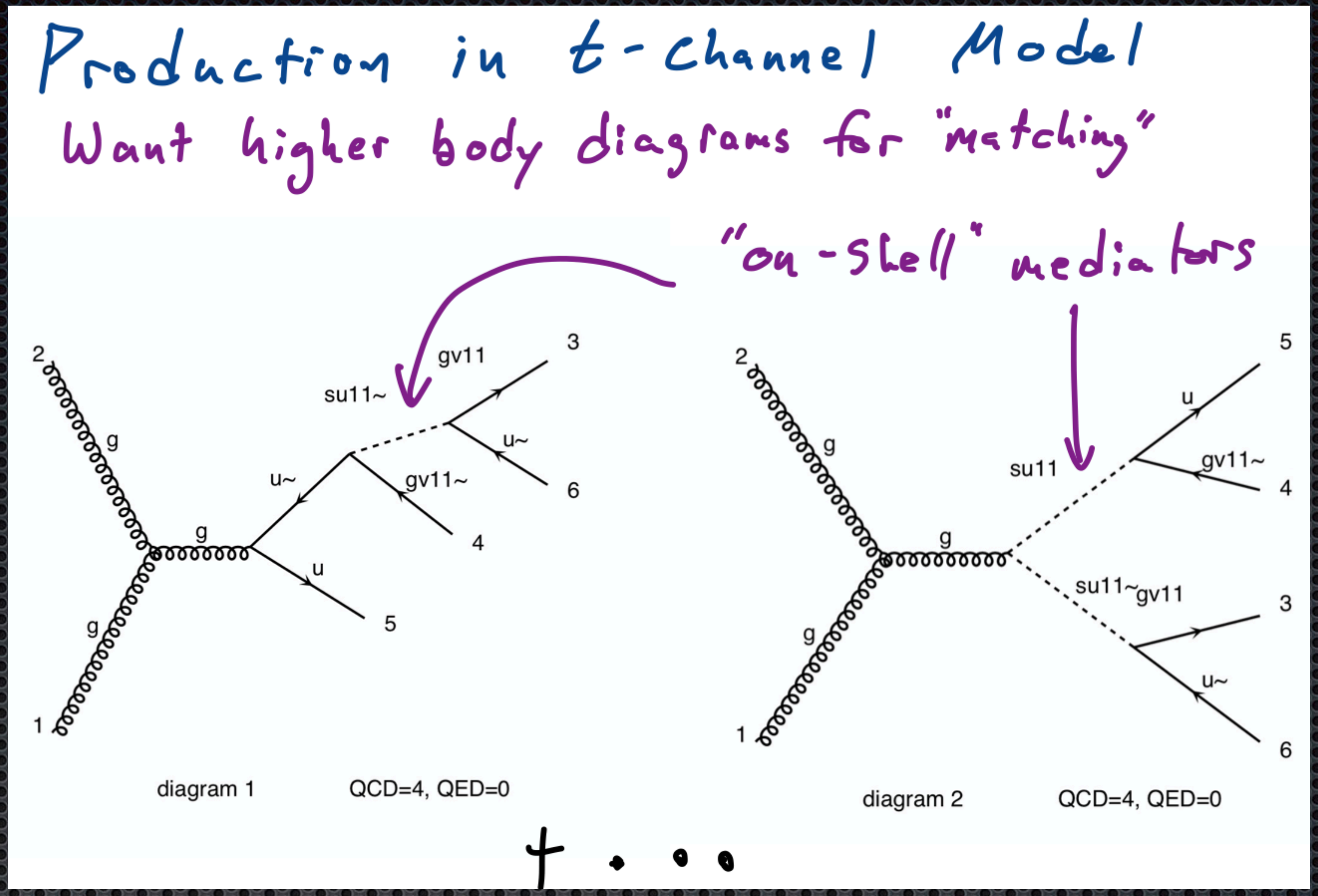


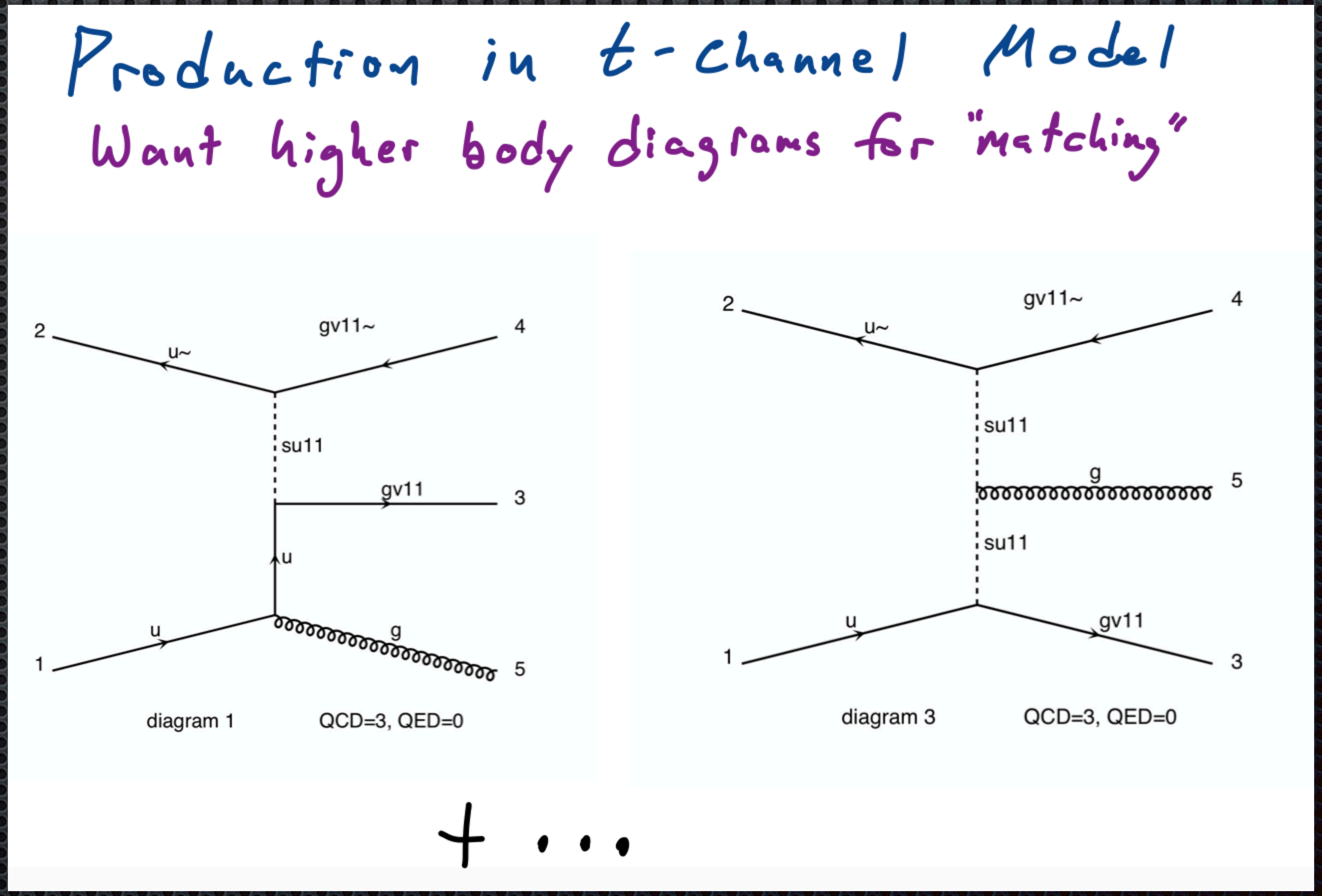
Discussion

Why 2.5 TeV?









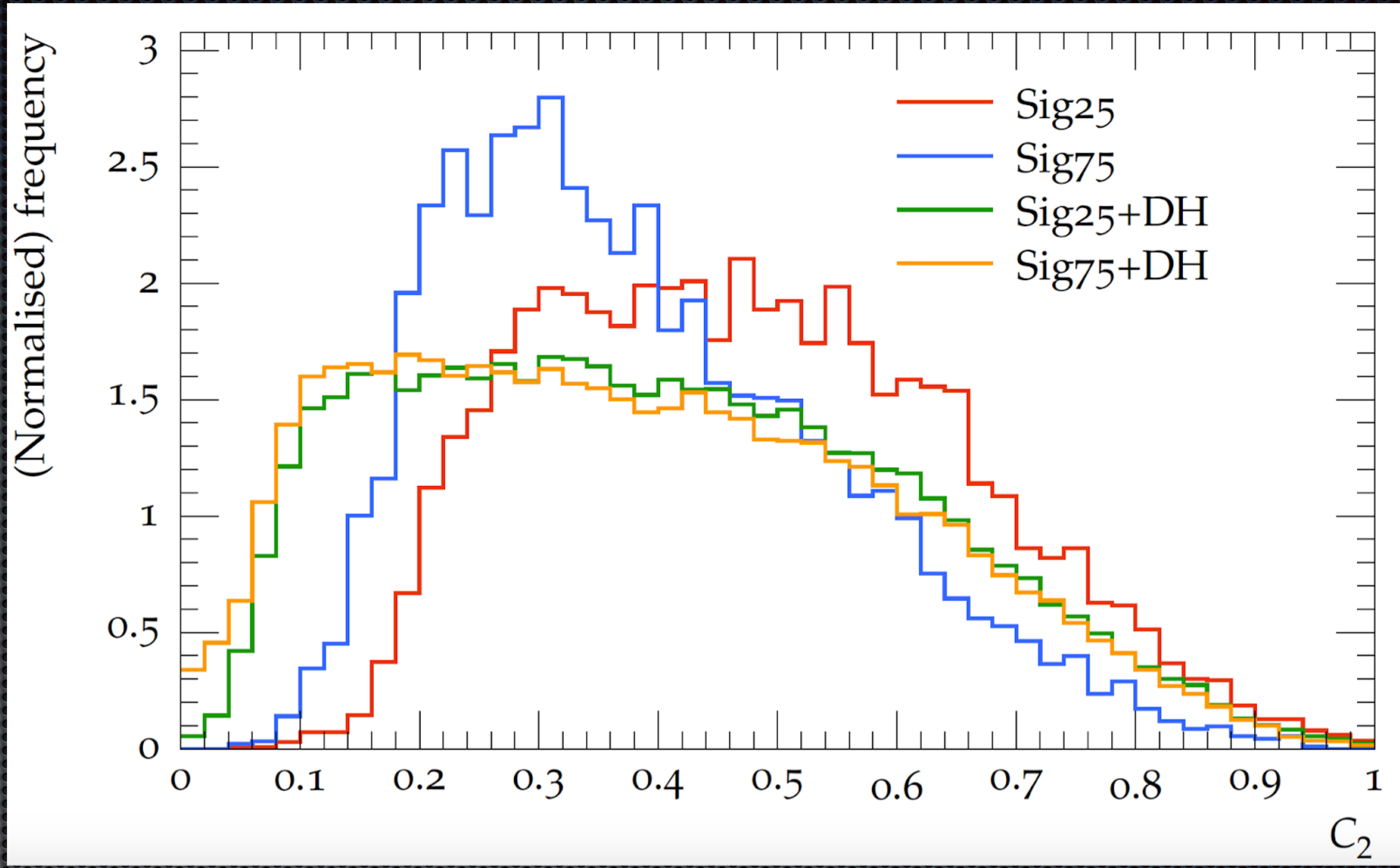
Diagrams with intermediate state mediator particles → produced essentially on-shell (they include the full propagator structure so they in principle can go off-shell, but this is suppressed).

Does not matter for a signature based search!

Blatantly stolen from Tim Cohen

What’s next? A very biased roadmap …

JSS in SVJ



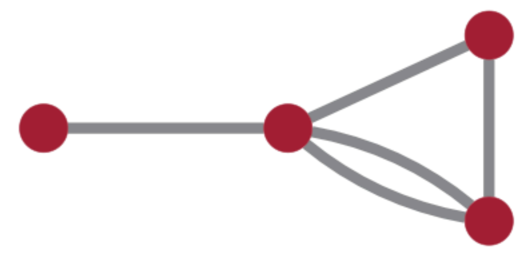
Substructure becomes less two-pronged with visible and dark hadrons in them, and the absence of the dark hadrons create the two-pronged structure → The substructure is created by the interspersing of visible hadrons with dark hadrons.

Can use ML algorithms, jet images …

SciPostPhys.10.4.084

Beyond traditional JSS (with Andy Buckley)

Energy flow polynomials (EFPs):



$$= \sum_{i_1=1}^{M} \sum_{i_2=1}^{M} \sum_{i_3=1}^{M} \sum_{i_4=1}^{M} z_{i_1} z_{i_2} z_{i_3} z_{i_4} \theta_{i_1 i_2} \theta_{i_2 i_3} \theta_{i_2 i_4}^2 \theta_{i_3 i_4}$$

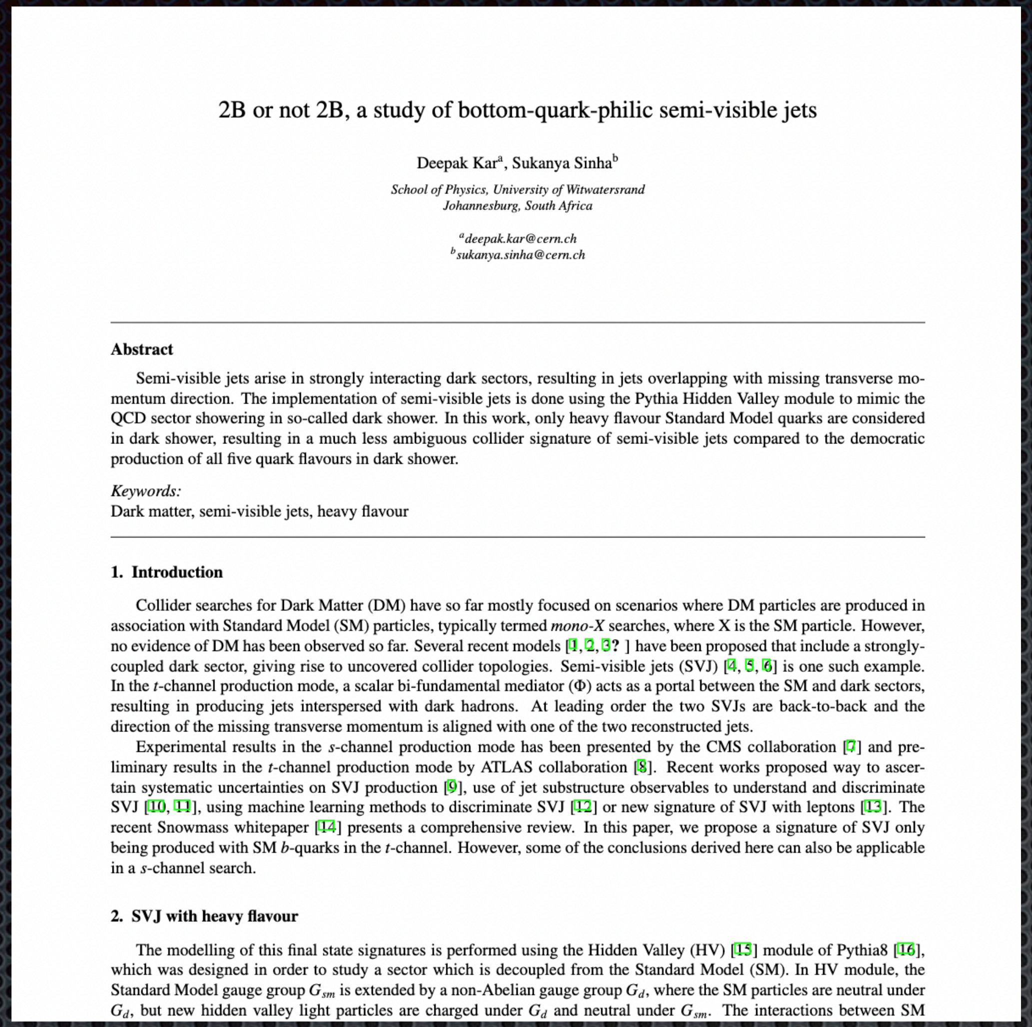
EFP: https://arxiv.org/abs/1712.07124

EFPs form a linear basis of all IRC-safe observables, making them suitable to construct new of JSS observables

Certain EFP diagrams seem to have some bins that multijet background does not populate at all, in which the SVJ signal dominates…

Coming soon to arXiv

B-philic SVJ



2B or not 2B, a study of bottom-quark-philic semi-visible jets

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Abstract

Semi-visible jets arise in strongly interacting dark sectors, resulting in jets overlapping with missing transverse momentum direction. The implementation of semi-visible jets is done using the Pythia Hidden Valley module to mimic the QCD sector showering in so-called dark shower. In this work, only heavy flavour Standard Model quarks are considered in dark shower, resulting in a much less ambiguous collider signature of semi-visible jets compared to the democratic production of all five quark flavours in dark shower.

Keywords:
Dark matter, semi-visible jets, heavy flavour

1. Introduction

Collider searches for Dark Matter (DM) have so far mostly focused on scenarios where DM particles are produced in association with Standard Model (SM) particles, typically termed *mono-X* searches, where X is the SM particle. However, no evidence of DM has been observed so far. Several recent models [1, 2, 3**?**] have been proposed that include a strongly-coupled dark sector, giving rise to uncovered collider topologies. Semi-visible jets (SVJ) [4, 5, 6] is one such example. In the t-channel production mode, a scalar bi-fundamental mediator (Φ) acts as a portal between the SM and dark sectors, resulting in producing jets interspersed with dark hadrons. At leading order the two SVJs are back-to-back and the direction of the missing transverse momentum is aligned with one of the two reconstructed jets.

Experimental results in the s-channel production mode has been presented by the CMS collaboration [7] and preliminary results in the t-channel production mode by ATLAS collaboration [8]. Recent works proposed way to ascertain systematic uncertainties on SVJ production [9], use of jet substructure observables to understand and discriminate SVJ [10, 11], using machine learning methods to discriminate SVJ [12] or new signature of SVJ with leptons [13]. The recent Snowmass whitepaper [14] presents a comprehensive review. In this paper, we propose a signature of SVJ only being produced with SM b-quarks in the t-channel. However, some of the conclusions derived here can also be applicable in a s-channel search.

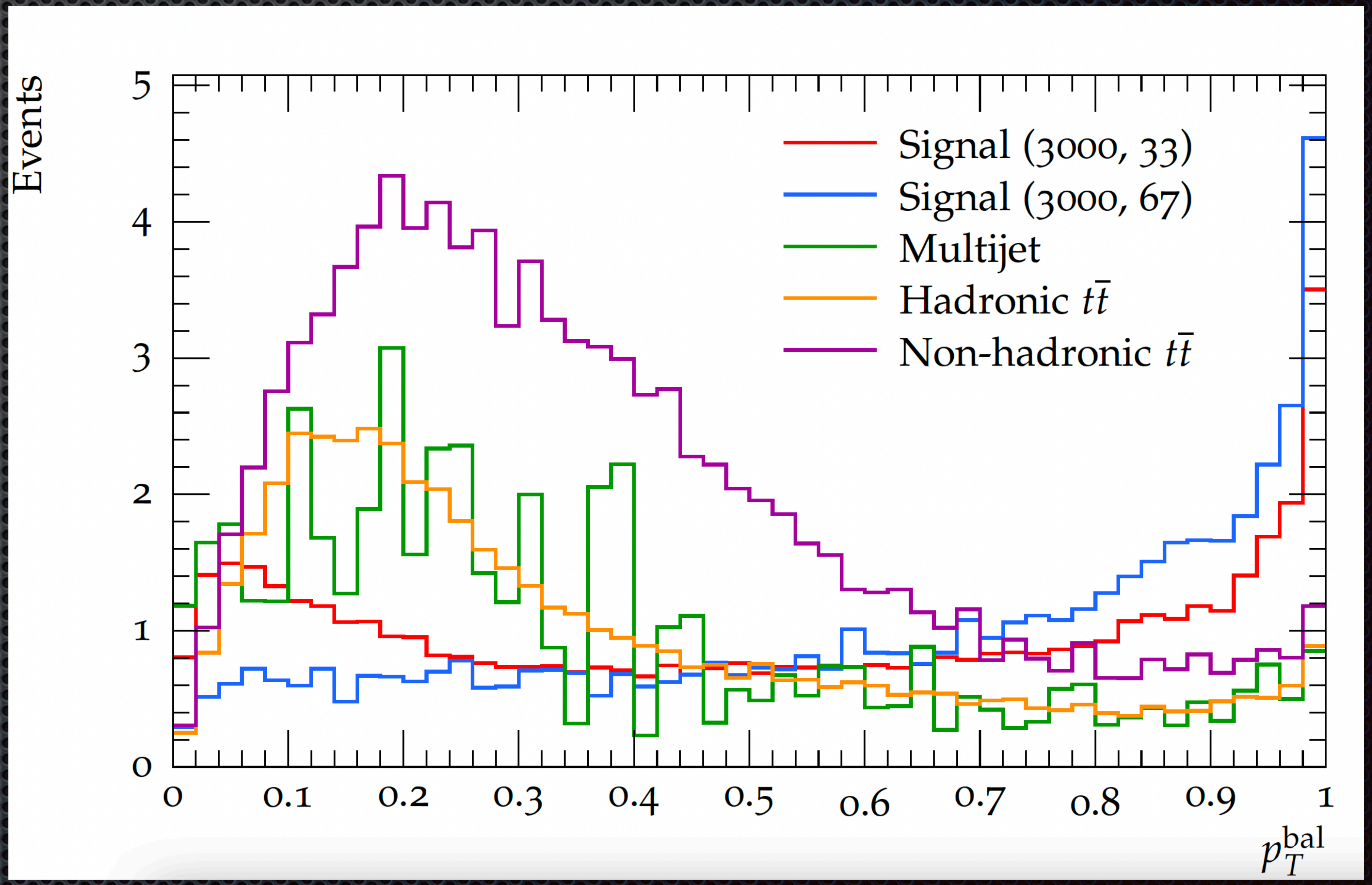
2. SVJ with heavy flavour

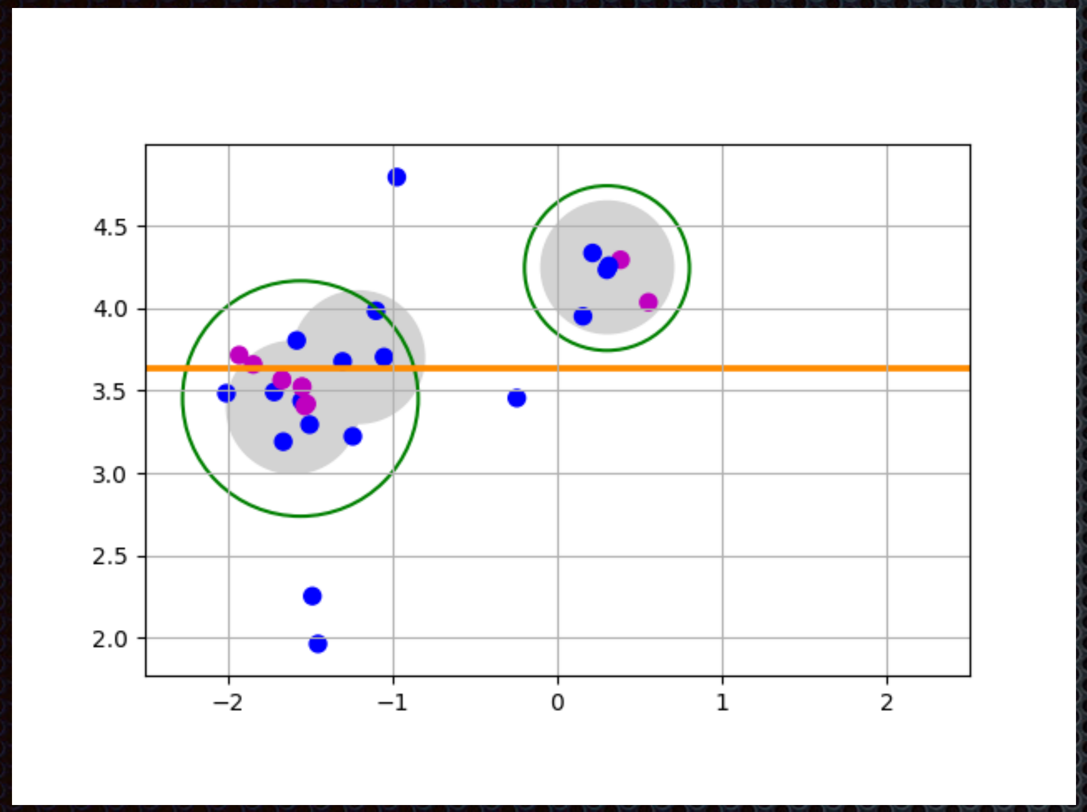
The modelling of this final state signatures is performed using the Hidden Valley (HV) [15] module of Pythia8 [16], which was designed in order to study a sector which is decoupled from the Standard Model (SM). In HV module, the Standard Model gauge group G_{sm} is extended by a non-Abelian gauge group G_d, where the SM particles are neutral under G_d, but new hidden valley light particles are charged under G_d and neutral under G_{sm}. The interactions between SM

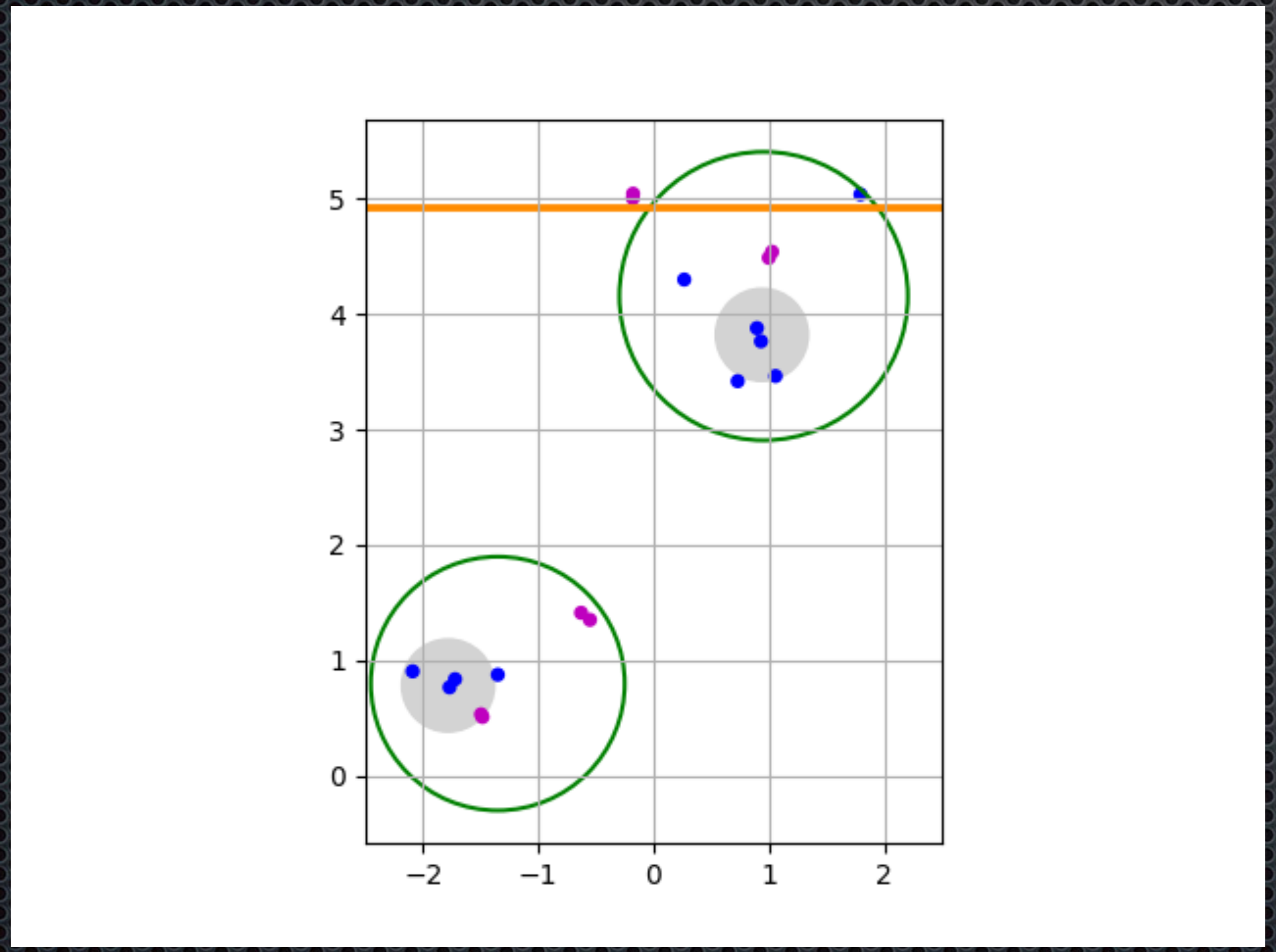
Can get good signal to background Discrimination after a set of selections …

Theoretically well motivated!

Extra handle on SVJs in collider search







Better reconstruction with Variable Radius jets

VR: https://arxiv.org/abs/0903.0392

Coming tonight to arXiv