t-channel DM studies in ATLAS

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summarizing the work carried on in the ATLAS mono-jet team

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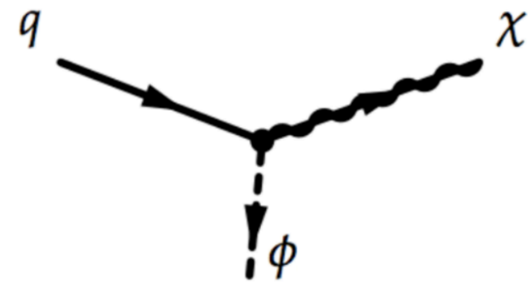
LHC DM WG MEETING 19-09-2016

t-channel DM model



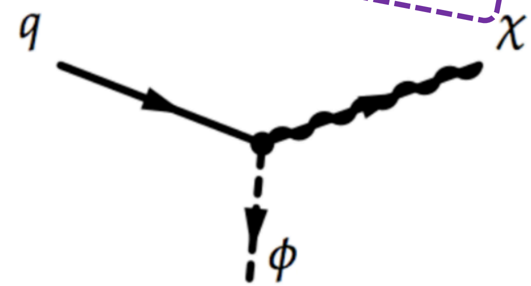
- What is it?
  - Distinctive model for DM production
  - Features a vertex with new coupling g:
    - new mediator(s) ϕ_i, SM quarks, DM χ
- The Lagrangian (general case):

$$\mathcal{L}_{\rm int} = g \sum_{i=1,2,3} (\phi_{(i),L}\bar{Q}_{(i),L} + \phi_{(i),u,R}\bar{u}_{(i),R} + \phi_{(i),d,R}\bar{d}_{(i),R})\chi$$

- Different implementations, common characteristics:
  Bell et al. (1209.0231), Papucci et al. (1402.2285), Wang et al. (1308.0592)
  DM forum report (1507.00966)
  - **mediator** carries non trivial quantum numbers: **coloured, flavoured, charged**
  - **few mediators**, not just one – but usually assume the mediators degenerate in mass
  - mediator can be spin 0 or spin ½
  - DM can be Dirac or Majorana
  - MFV not necessarily assumed (e.g. if coupling to first two generations only)
  - L/R/R+L part of mediator involved in the interaction

+ t-channel DM model

Studied in ATLAS mono-jet analysis



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  - Distinctive model for DM production
  - Features a vertex with new coupling g:
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- The Lagrangian (general case):

$$\mathcal{L}_{\rm int} = g \sum_{i=1,2} (\phi_{(i),L}\bar{Q}_{(i),L} + \phi_{(i),u,R}\bar{u}_{(i),R} + \phi_{(i),d,R}\bar{d}_{(i),R})\chi$$

- Different implementations, common characteristics:

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  DM forum report (1507.00966)

  - **mediator** carries non trivial quantum numbers: **coloured, flavoured, charged**
    - **4 mediators** ϕ_i degenerate in mass
    - ϕ_i scalar, 100% B.R. $\phi_i \rightarrow \chi q$
    - Minimal width
    - LH mediators intearcting (no RH)
  - DM is Dirac spinor
  - MFV not necessarily assumed

$\Rrightarrow$ $\mathbf{M_\phi}$
$\Rrightarrow$ $\mathbf{g}$
$\Rrightarrow$ $\mathbf{m_\chi}$

$$\Gamma(\phi_{(i)} \to \bar{u}_{(i)}\chi) = \frac{g_{(i)}^2}{16\pi M_{\phi_{(i)}}^3}(M_{\phi_{(i)}}^2 - m_{u_{(i)}}^2 - m_\chi^2) \times \sqrt{(M_{\phi_{(i)}}^2 - (m_{u_{(i)}} + m_\chi)^2)(M_{\phi_{(i)}}^2 - (m_{u_{(i)}} - m_\chi)^2)}$$

+ Relic density computation

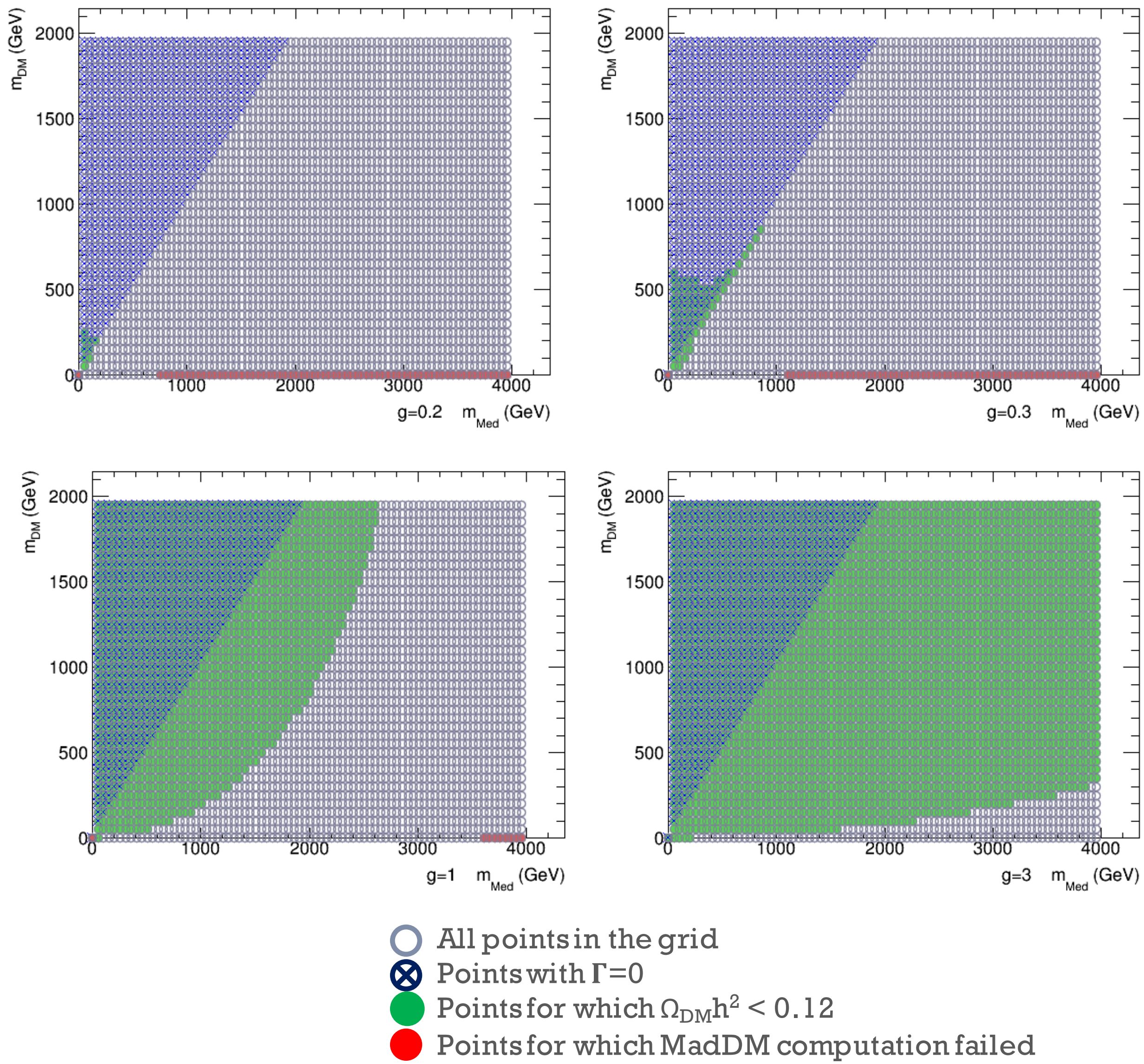
- How interesting is this model in terms of relic density?
  - Assume the t-channel is the only interaction by which DM can annihilate into X before freeze-out
    - one dark matter species (no co-annihilation)
    - X = all other SM and BSM particles
    - consider 2 ⇔ 2 processes

DM DM ⇔ (B)SM (B)SM

- Computation performed with MadDM 2.0.6 (within MG 2.4.3)

⇒ Intermediate couplings regime looks interesting

⇒ Consistent pictures within versions 2.0.5 and 2.0.6 of MadDM



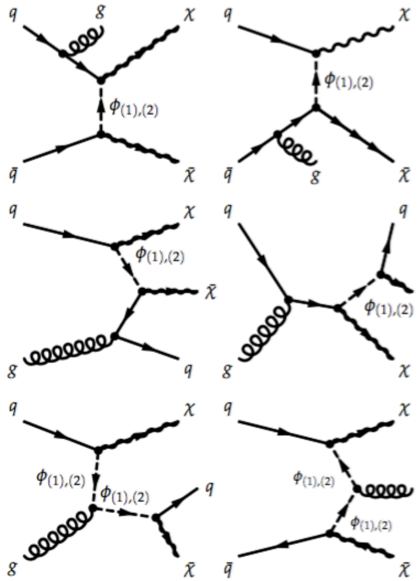
M.G. Ratti, M. McDonald

+ How to generate these signals?

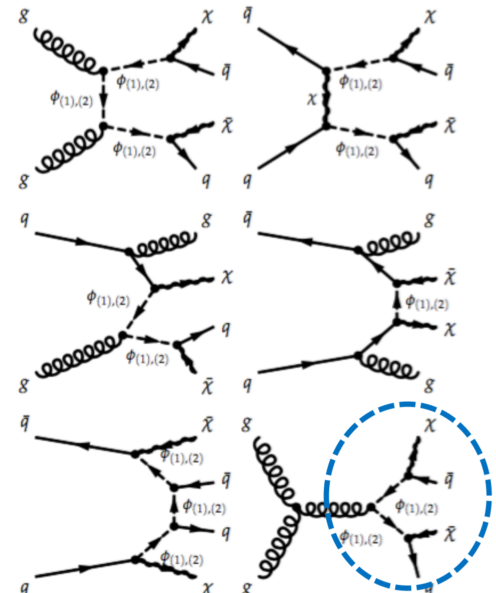
Following Papucci et al. (arXiv: 1402.2285)

- LO matrix element in MadGraph 2.3 + Pythia 8
- "Nominal" generation in MadGraph:
  - pp > dm dm + (0, 1, 2) j

⇛ already a rich phenomenology: 776 Feynman diagrams



Example diagrams for χχ + 1 jet



Example diagrams for χχ + 2 jets

- Nominal setup includes states with intermediate mediators that can go on-shell with no additional generated radiation, but additional radiation can become important

Typical Cross sections (pb) for: m = 100 GeV M= 200 GeV g= 0.1					
	Process	0-j	1-j	2-j	Sum(0,1,2 -j)
nom	pp > dm dm	1.5e-03	7.6e-01	9.1e+01	9.2e+01

increasing →

⇒ generate "split" samples according to the number of mediators in the final state

How to generate these signals?

Following Papucci et al. (arXiv: 1402.2285)

- "Split" generation in MadGraph:
  1. pp > med med + (0, 1, 2) j
  2. pp > dm med + (0, 1, 2) j $ med
  3. pp > dm dm + (0, 1, 2) j $ med

Veto mediators from going on-shell to avoid phase space double counting

Procedure handled in MadGraph by removing core of / entire Breit Wigner resonance $[x_0 - \Gamma\, bwc, x_0 + \Gamma\, bwc]$

- Recombining the split samples:
  - Assume Breit Wigner propagator for the mediator
  - Reweight sample 1 and 2 by a weight w^2 and w respectively:

$$w = \frac{\int_{x_0+\Gamma\, bwc}^{x_0-\Gamma\, bwc} BW(x)\,ds}{\int BW(x)\,ds}$$

$$BW(x) = \frac{1}{\pi\Gamma/2\left(1+\left(\frac{x-x_0}{\Gamma/2}\right)^2\right)}$$

- Examples of recombination
  - Narrow width case

mDM(GeV)	Mmed(GeV)	g	Split	Width/M	BWC	Width*BWC(GeV)	BW weight	Xsec_Py(pb)	BW Xsec(pb)
1	500	0.1	1	1.99e-04	15.0	1.49e+00	9.58e-01	1.48e+00	1.42e+00
1	500	0.1	2	1.99e-04	15.0	1.49e+00	9.79e-01	9.60e-02	9.40e-02
1	500	0.1	3	1.99e-04	15.0	1.49e+00	1.00e+00	1.15e-03	1.15e-03
1	500	0.1	comb	1.99e-04					1.51e+00

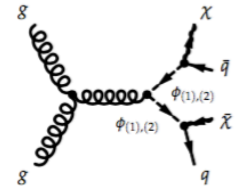
  - Recombination has small effect on the sum
  - Larger width case

mDM(GeV)	Mmed(GeV)	g	Split	Width/M	BWC	Width*BWC(GeV)	BW weight	Xsec_Py(pb)	BW Xsec(pb)
1	500	3.0	1	1.79e-01	1.0	8.95e+01	5.26e-01	1.16e+02	6.09e+01
1	500	3.0	2	1.79e-01	1.0	8.95e+01	7.25e-01	1.04e+02	7.54e+01
1	500	3.0	3	1.79e-01	1.0	8.95e+01	1.00e+00	1.74e+02	1.74e+02
1	500	3.0	comb	1.79e-01					3.10e+02

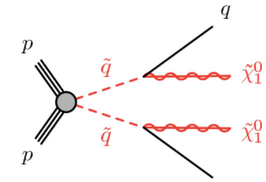
  - Recombination makes sample3 more important wrt to split sample1-2

+ Overlap with MSSM ?

- t-channel DM split sample 1 looking very similar to squark pair production in mssm
  - DM ⇔ neutralino
  - Mediator ⇔ squark

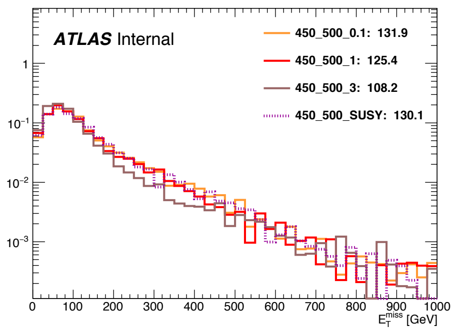


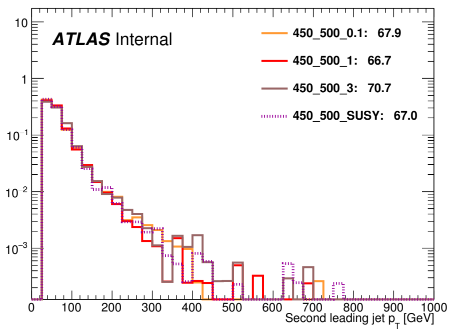
t-channel DM production

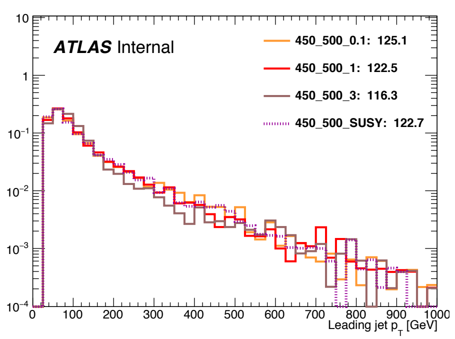


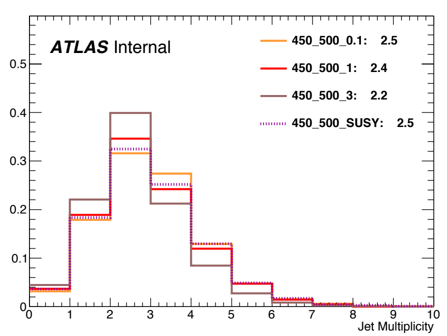
mssm squark pair production

- Quantify overlap of the two simplified models:
  - recovered mssm cross section when g=0.1 in t-channel model **for split sample 1**
  - recovered mssm kinematics for a range of couplings **for split sample 1**









Split sample 1: m_{DM}=450 GeV, M_{med}=500 GeV

MadGraph level cross section (pb)

m=450 M=500 g=0.1					
Split	Process	0-j	1-j	2-j	Sum(0,1,2 -j)
1	pp > sq sq	1.4e+00	4.9e-01	1.1e-01	2.0e+00
2	pp > sq dm $ sq	9.6e-03	3.9e-03	1.0e-03	1.5e-02
3	pp > dm dm $ sq	1.4e-05	5.4e-06	4.3e-06	2.4e-05
nom	pp > dm dm	1.4e-05	1.7e-04	6.9e-03	7.0e-03

m=450 M=500 g=1					
Split	Process	0-j	1-j	2-j	Sum(0,1,2 -j)
1	pp > sq sq	1.8e+00	5.5e-01	1.2e-01	2.5e+00
2	pp > sq dm $ sq	9.6e-01	3.0e-01	6.3e-02	1.3e+00
3	pp > dm dm $ sq	1.4e-01	2.3e-02	3.7e-03	1.7e-01
nom	pp > dm dm	1.4e-01	3.7e-02	2.7e-02	2.1e-01

m=450 M=500 g=3					
Split	Process	0-j	1-j	2-j	Sum(0,1,2 -j)
1	pp > sq sq	4.0e+01	6.6e+00	1.8e+00	4.8e+01
2	pp > sq dm $ sq	8.7e+00	1.1e+01	2.5e+00	2.3e+01
3	pp > dm dm $ sq	1.1e+01	1.8e+00	5.8e-01	1.4e+01
nom	pp > dm dm	1.1e+01	2.0e+00	2.2e+00	1.6e+01

m=450 M=500 g=SUSY				
Process	0-j	1-j	2-j	Sum(0,1,2 -j)
pp > sq sq	1.4e+00	4.9e-01	1.1e-01	2.0e+00

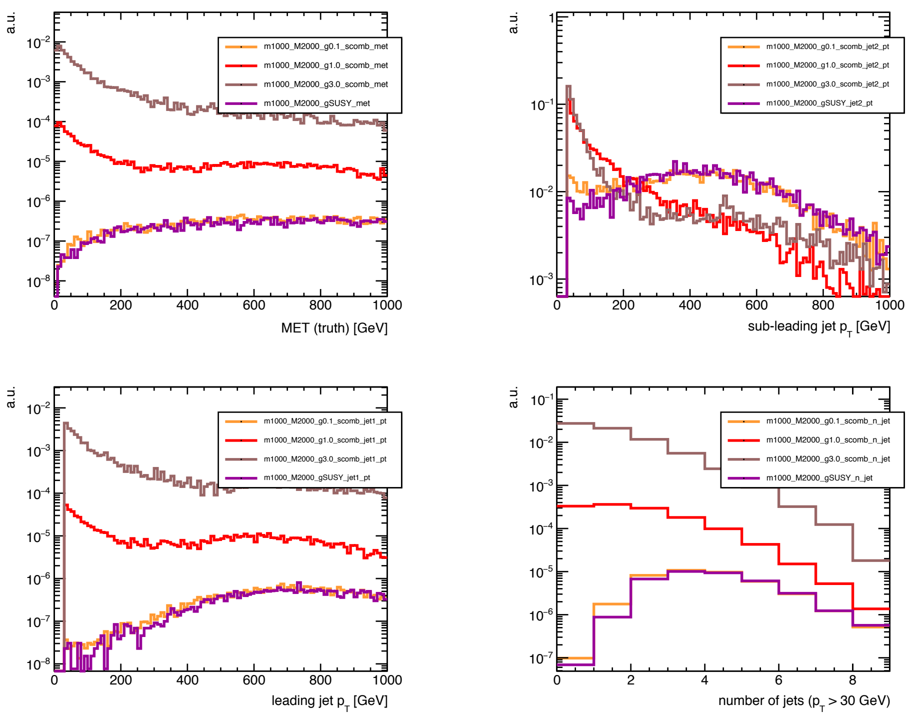
Private mssm production, switched off RH squarks

(validated with official ATLAS MC production)

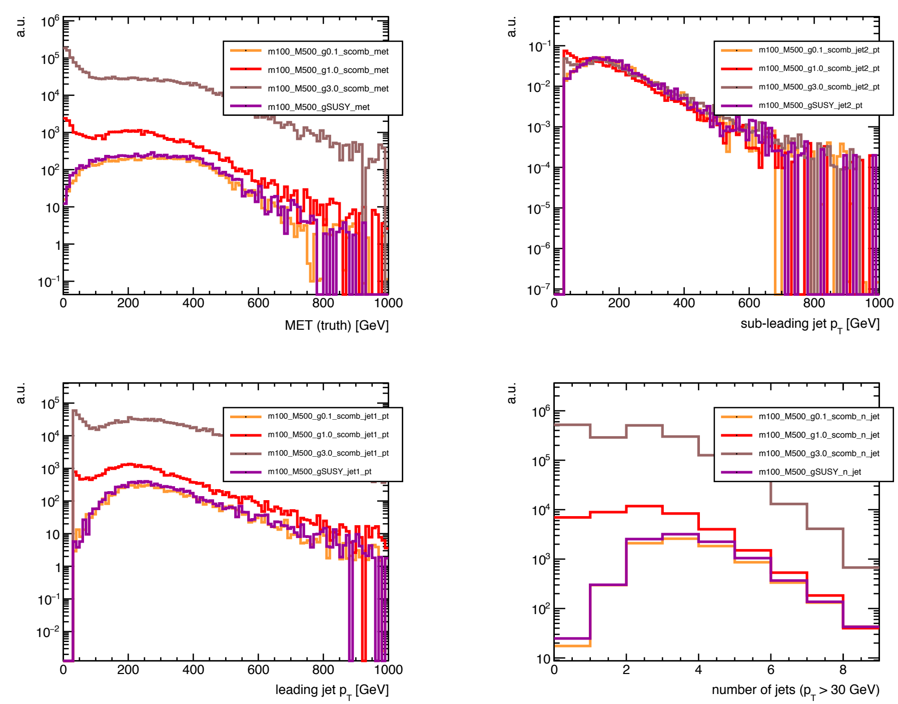
Overlap with MSSM ?

- However g is a free parameter in the DM model:
  - at higher g the other split samples become more important
  - according to the mass range, the kinematics can change significantly

Combined sample: m_{DM}=1 GeV, M_{med}=2000 GeV



Combined sample: m_{DM}=1 GeV M_{med}= 500 GeV



- For g>0.1 0-jet and 1-jet contributions become more important

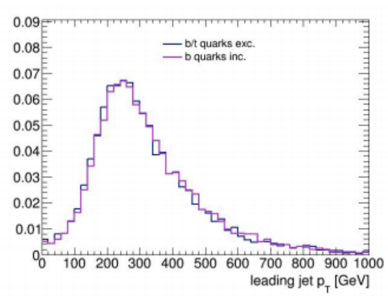
+ b/inclusive vs exclusive MC?

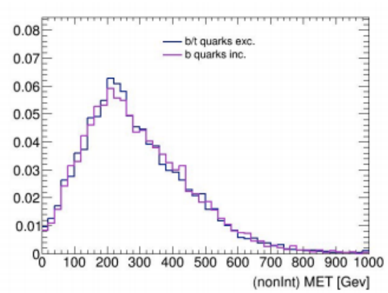
- Studied change in cross-section and kinematics when including/excluding b-flavoured mediators

m_χ, M, $g_{q\chi}$	σ_1 [fb] (b exc.)	σ_2 [fb] (b exc.)	σ_3 [fb] (b exc.)	σ_{total} [fb] (b exc.)	σ_1 [fb] (b inc.)	σ_2 [fb] (b inc.)	σ_3 [fb] (b inc.)	σ_{total} [fb] (b inc.)
1, 10, 0.25	5.49E+09	2.74E+08	5.54E+05	5.77E+09	6.88E+09	3.05E+08	6.01E+05	7.18E+09
1, 500, 0.25	6.33E+02	3.66E+02	1.19E+01	1.01E+03	8.13E+02	3.97E+02	1.22E+01	1.22E+03
1, 1500, 0.25	8.01E-02	9.66E-01	2.07E-01	1.25E+00	1.01E-01	9.91E-01	1.44E-01	1.24E+00
100, 1500, 0.1	7.95E-02	1.72E-01	9.05E-03	2.61E-01	1.02E-01	1.83E-01	9.20E-03	2.94E-01
100, 1500, 0.5	8.16E-02	3.65E+00	4.17E+00	7.90E+00	1.02E-01	3.73E+00	4.21E+00	8.04E+00
100, 1500, 1	1.21E-01	1.46E+01	6.59E+01	8.05E+01	1.48E-01	1.49E+01	6.66E+01	8.16E+01

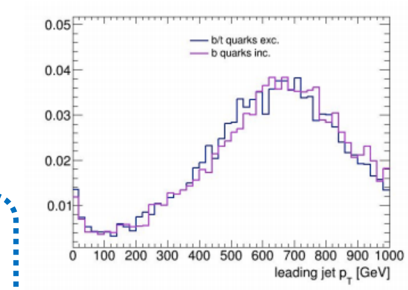
- Change in total cross section is at most O(10%)

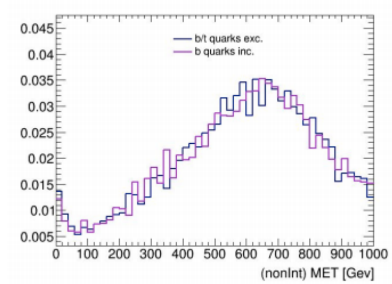
m_{DM}=1 GeV
M_{med}=500 GeV
g=0.25





m_{DM}=100 GeV
M_{med}=1500 GeV
g=0.1



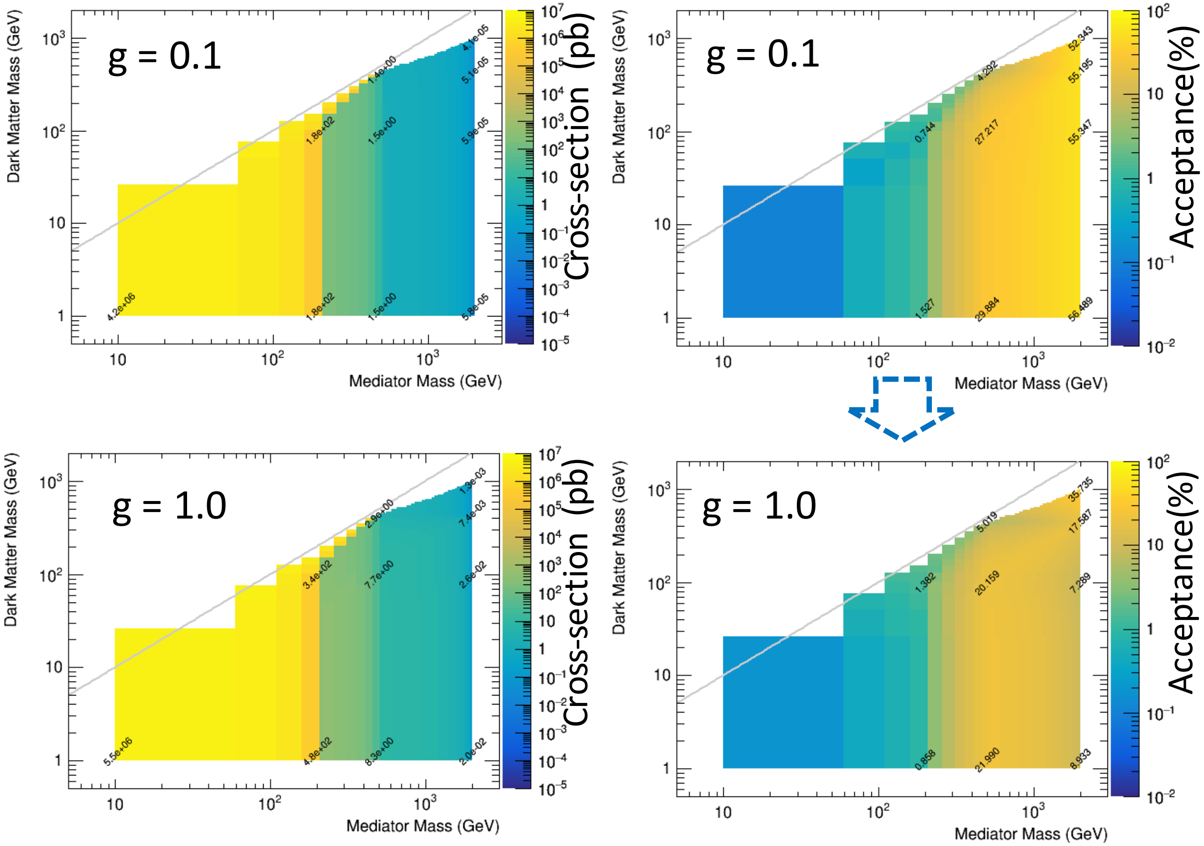


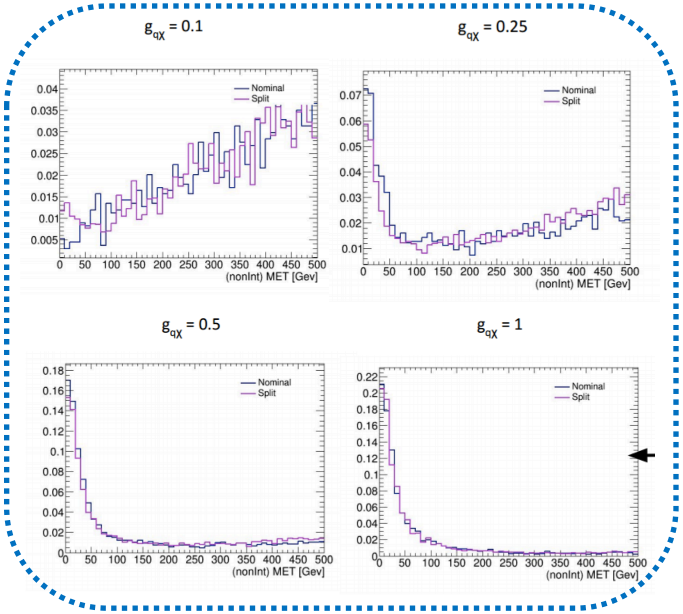
- Kinematics are very similar

⇒ Can use rescaling for setting limits

Cross section, Acceptance trends

- Reasonable trends as a function of mediator masses and couplings





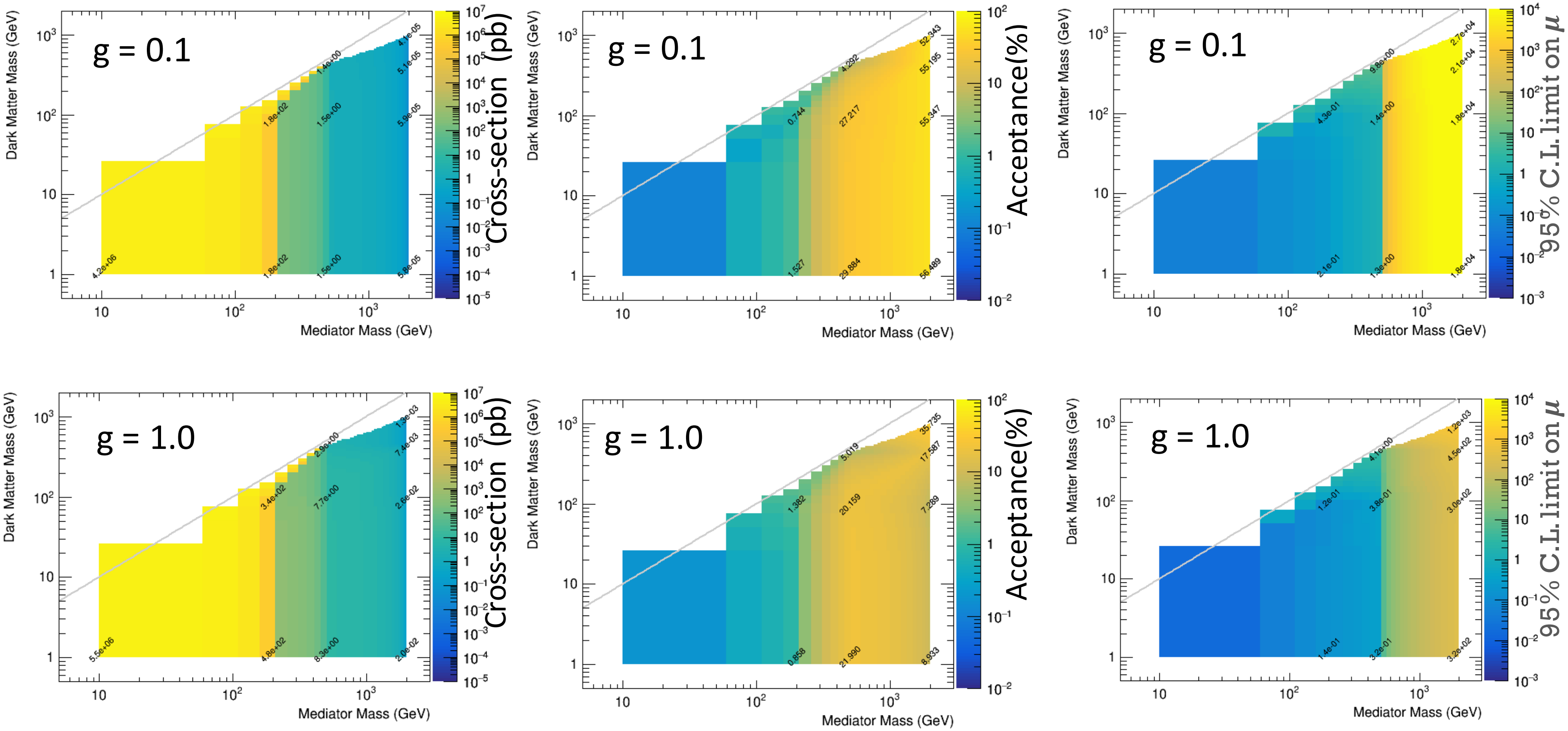
Significant dependence on the coupling, as opposed to s-channel
$\Rightarrow$ need to request few samples for each mass-mass point

- Cross section decreasing with increasing masses
- Increasing with increasing couplings

- Acceptance of mono-jet selection [MET>250GeV, leading jet p_T>250 GeV and $|\eta|$<2.4, Njets$\leqq$4, $|\Delta\phi$(jet,MET)$|$>0.4, no e/mu]
- Higher for lower couplings: due to change in the kinematics

Cross section, Acceptance, Sensitivity trends

- Reasonable trends as a function of mediator masses and couplings



- Cross section decreasing with increasing masses
- Increasing with increasing couplings

- Acceptance of mono-jet selection [MET>250GeV, leading jet p_T>250 GeV and $|\eta|<2.4$, Njets≦4, $|\Delta\phi$ (jet,MET)$|>0.4$, no e/mu]
- Higher for lower couplings

- Back-of-envelope sensitivity: limit on signal strength

  $\mu \sim 2\ \sigma^{Bkg}_{(Mo2016)} / \ N^{sig}_{(Mo2016)}$
- Higher exclusion at higher couplings

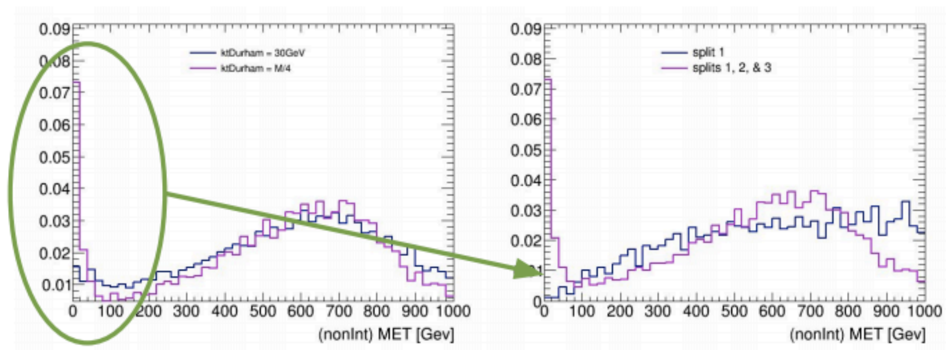
Merging MadGraph and Pythia

- Tested CKKW-L merging between MadGraph and Pythia: key parameter is the merging scale
  - would like to have a single merging strategy for the entire grid
  - not an easy task given the wide range of masses, couplings and the three split processes

- Check two possible strategies:
  a) Mediator mass related scale, e.g. $M_{med}/4$, $M_{med}/8$
    - Similar choice done in SUSY for squark squark generation => good for split sample 1
    - Not so good for split sample 3

  b) Jet pt related scale, e.g. analysis-jet-pt-cut/2
    - makes sure that there is enough fixed order calculation in order to describe the process of interest

m_χ = 1 GeV, M = 1.5 TeV, $g_{q\chi}$ = 0.25, ktDurham = M/4

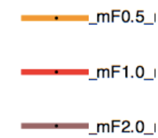


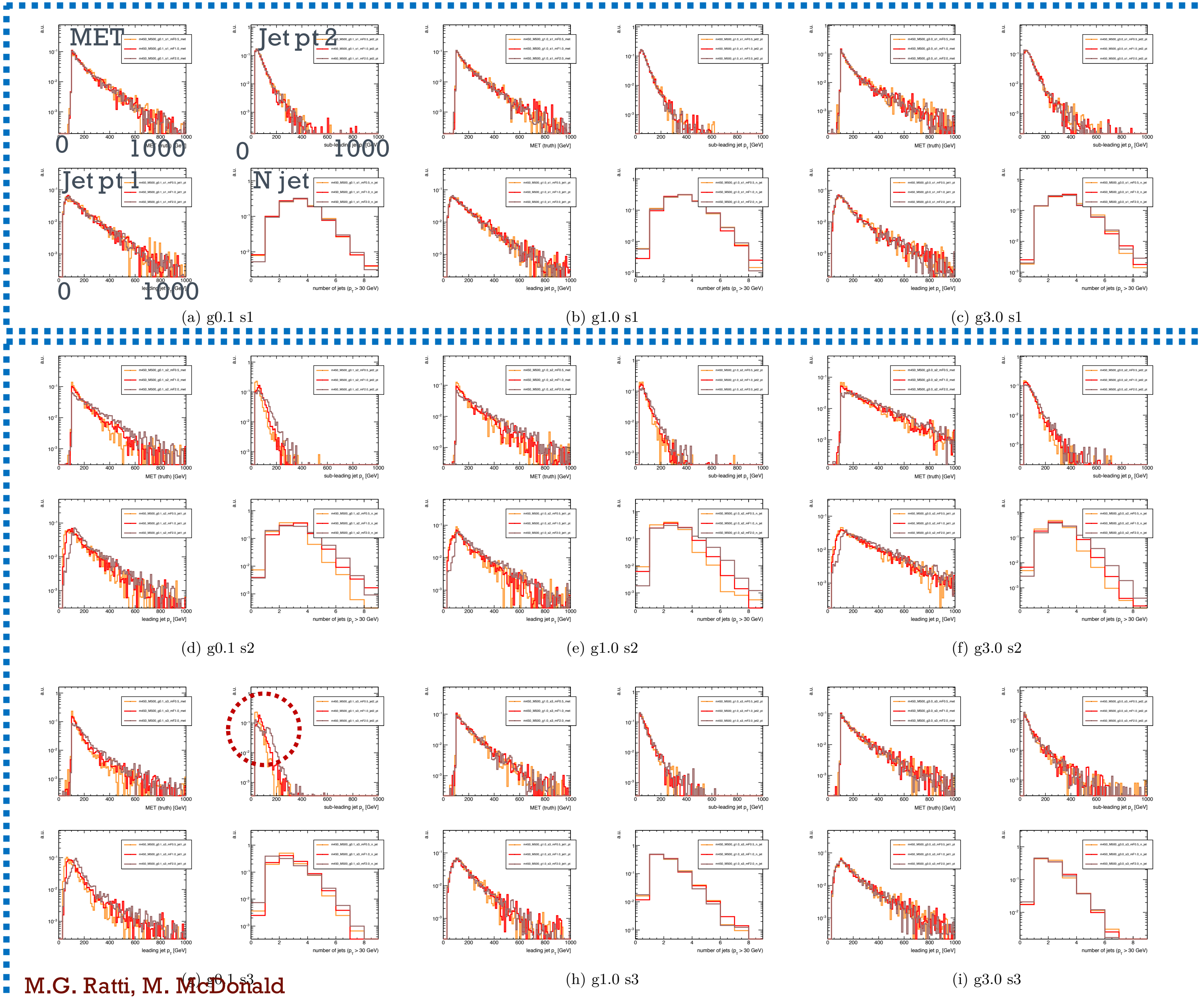
- Too much soft activity at low pt

- Assess which strategy is more reasonable by checking that:
  - the relevant kinematic shapes (met, leading and subleading jet pt) do not vary too much by varying the scale by a factor 0.5 or 2
  - the cross section and acceptances also do not vary too much

- Focus on two mass-mass regimes:
  - (relatively) compressed case: m_{DM} = 450 GeV, M_{Med}=500 GeV
  - non-compressed : m_{DM} = 100 GeV, M_{Med}=2000 GeV

Compressed regime, scale = $M_{Med}/8$





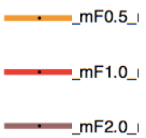
OK:

- Just very small variation due to up and down scale variation

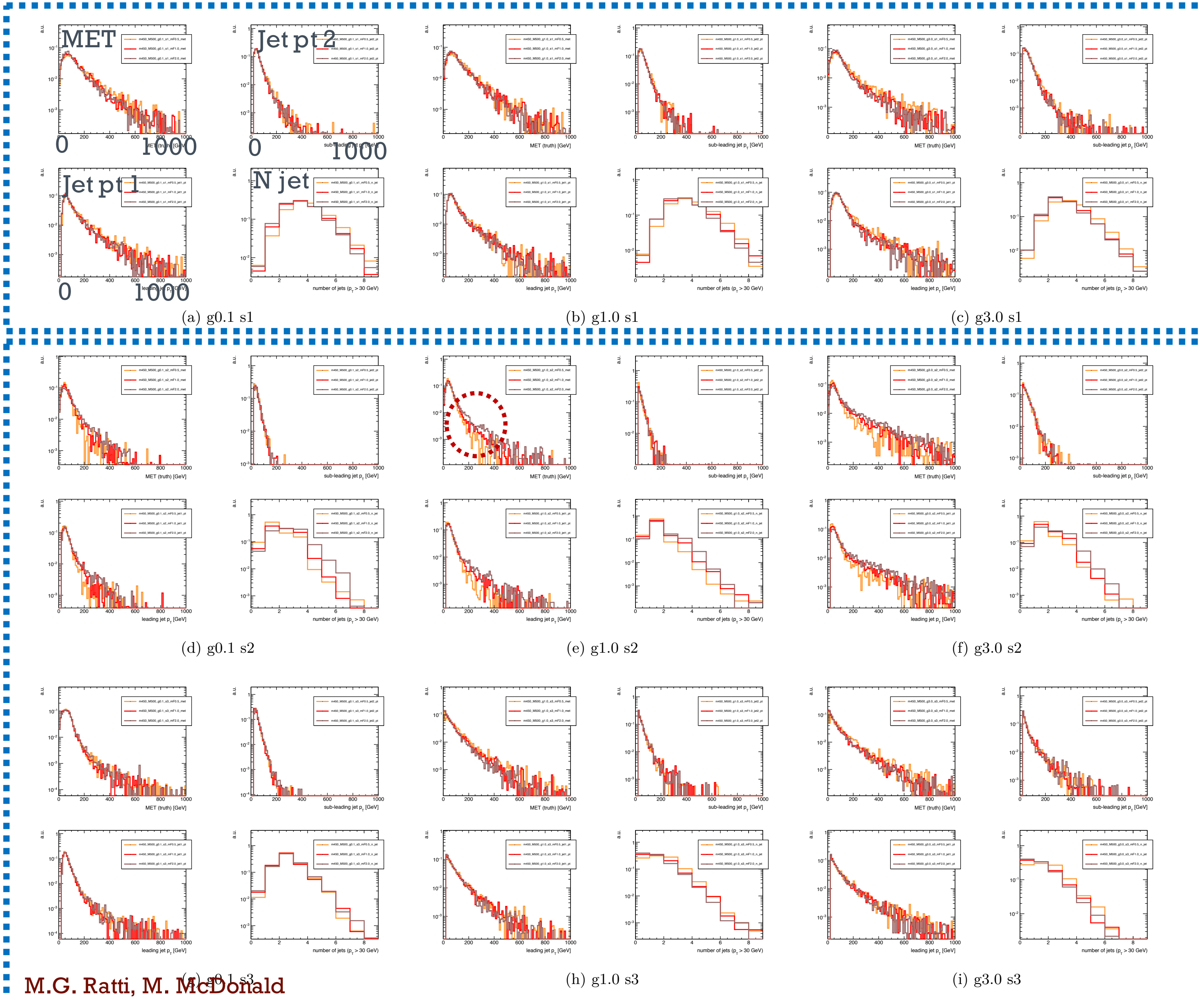
~OK:

- Only some remaining structure

Caveat:
MET filter at 100 GeV applied



+ Compressed regime, scale = 15 GeV



(a) g0.1 s1 (b) g1.0 s1 (c) g3.0 s1

(d) g0.1 s2 (e) g1.0 s2 (f) g3.0 s2

(g) g0.1 s3 (h) g1.0 s3 (i) g3.0 s3

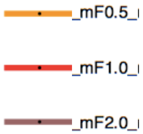
OK:

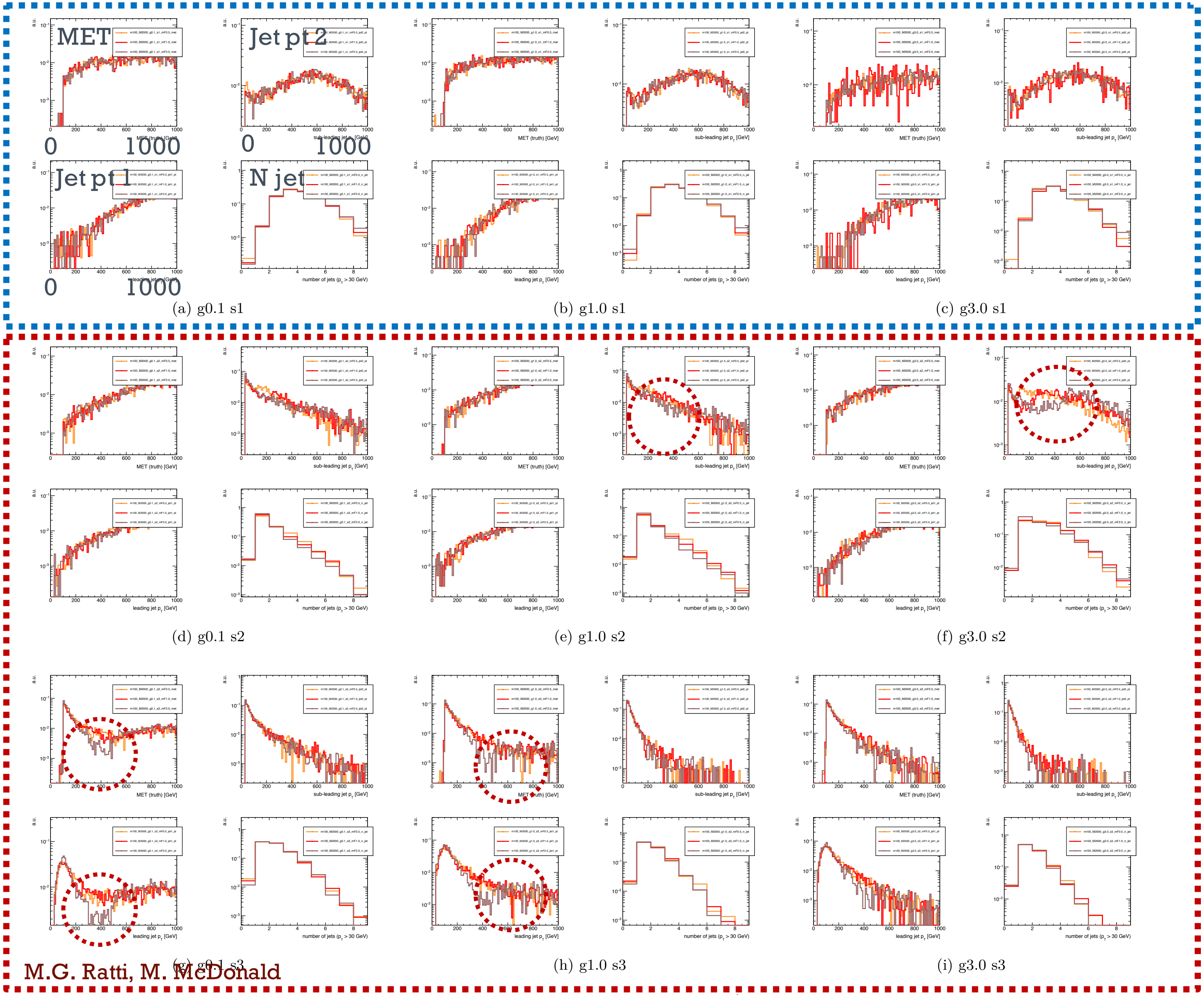
- Just very small variation due to up and down scale variation

~OK:

- Only some remaining structure

Non-compressed regime, scale = $M_{Med}/8$





~OK:

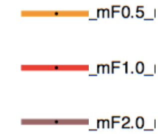
- Jacobian peak described pretty well in most cases
- In general not sizeable variations with the merging scale

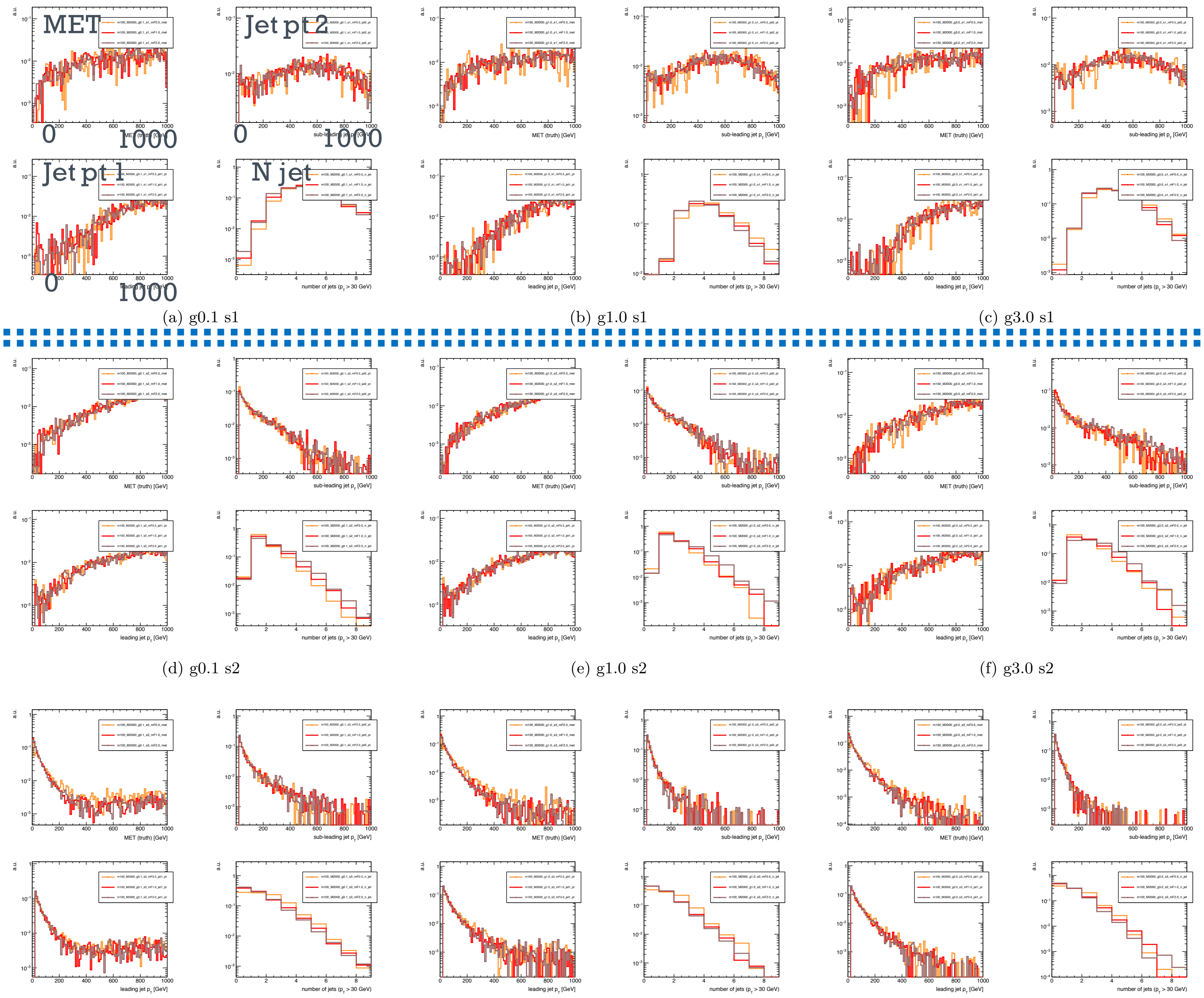
Not always OK:

- Up variation shows unwanted structure in regions interesting for the analysis

Caveat: MET filter at 100 GeV applied

+ Non-compressed regime, scale = 15 GeV





(a) g0.1 s1 (b) g1.0 s1 (c) g3.0 s1

(d) g0.1 s2 (e) g1.0 s2 (f) g3.0 s2

(g) g0.1 s3 (h) g1.0 s3 (i) g3.0 s3

~OK:

- Jacobian peak described pretty well in most cases
- In general not sizeable variations with the merging scale

~OK

- Structures do not show up

Cross section variations: scale = 15 GeV vs $M_{Med}/8$

Compressed regime:
m_{DM}=450 GeV M_{med}= 500 GeV

N.B. Met Filter applied

		Merging scale at 15 GeV			Merging Scale at Med/8		
g	Split	Xsec_Py(pb)	Low Var(%)	Up Var(%)	Xsec_Py(pb)	Low Var(%)	Up Var(%)
0,1	1	1,41E+00	-20,79	12,23	1,47E+00	4,62	-0,75
0,1	2	2,90E-02	-42,61	41,71	2,52E-02	62,77	-47,83
0,1	3	4,96E-04	-3,10	-17,08	1,15E-04	243,64	-81,79
1	1	1,74E+00	-19,98	10,25	1,88E+00	-1,60	-0,69
1	2	1,29E+00	-16,37	11,71	1,37E+00	5,75	-10,85
1	3	1,42E-01	-27,07	15,19	1,51E-01	7,07	-3,64
3	1	3,28E+01	-28,80	18,75	3,98E+01	-3,57	2,69
3	2	1,65E+01	-26,65	27,63	2,14E+01	-0,61	-10,04
3	3	1,09E+01	-30,63	15,71	1,21E+01	2,88	-1,07

Non-compressed regime:
m_{DM}=100 GeV M_{med}= 2000 GeV

N.B. Met Filter applied

		Merging scale at 15 GeV			Merging Scale at Med/8		
g	Split	Xsec_Py(pb)	Low Var(%)	Up Var(%)	Xsec_Py(pb)	Low Var(%)	Up Var(%)
0,1	1	3,43E-05	-9,19	9,95	3,55E-05	0,82	1,69
0,1	2	2,66E-05	-15,90	14,51	2,53E-05	10,79	-9,17
0,1	3	2,65E-06	-28,14	16,31	2,93E-06	3,20	-3,95
1	1	1,21E-04	-28,09	7,95	1,40E-04	-5,15	1,43
1	2	2,63E-03	-14,28	15,76	2,50E-03	11,15	-9,15
1	3	2,26E-02	-33,60	17,31	2,55E-02	1,96	-2,39
3	1	8,03E-03	-26,65	10,76	9,99E-03	-10,08	-2,20
3	2	5,26E-02	-42,08	13,43	4,76E-02	9,11	-19,47
3	3	1,74E+00	-34,16	16,19	1,97E+00	1,87	-1,82

- $M_{med}/8$ strategy has in general smaller or comparable up and down variations as compared to 15 GeV strategy
- But some huge variations in split sample 3 => confined at low coupling
  - ⇒ Still need to assess the variations on the combined samples

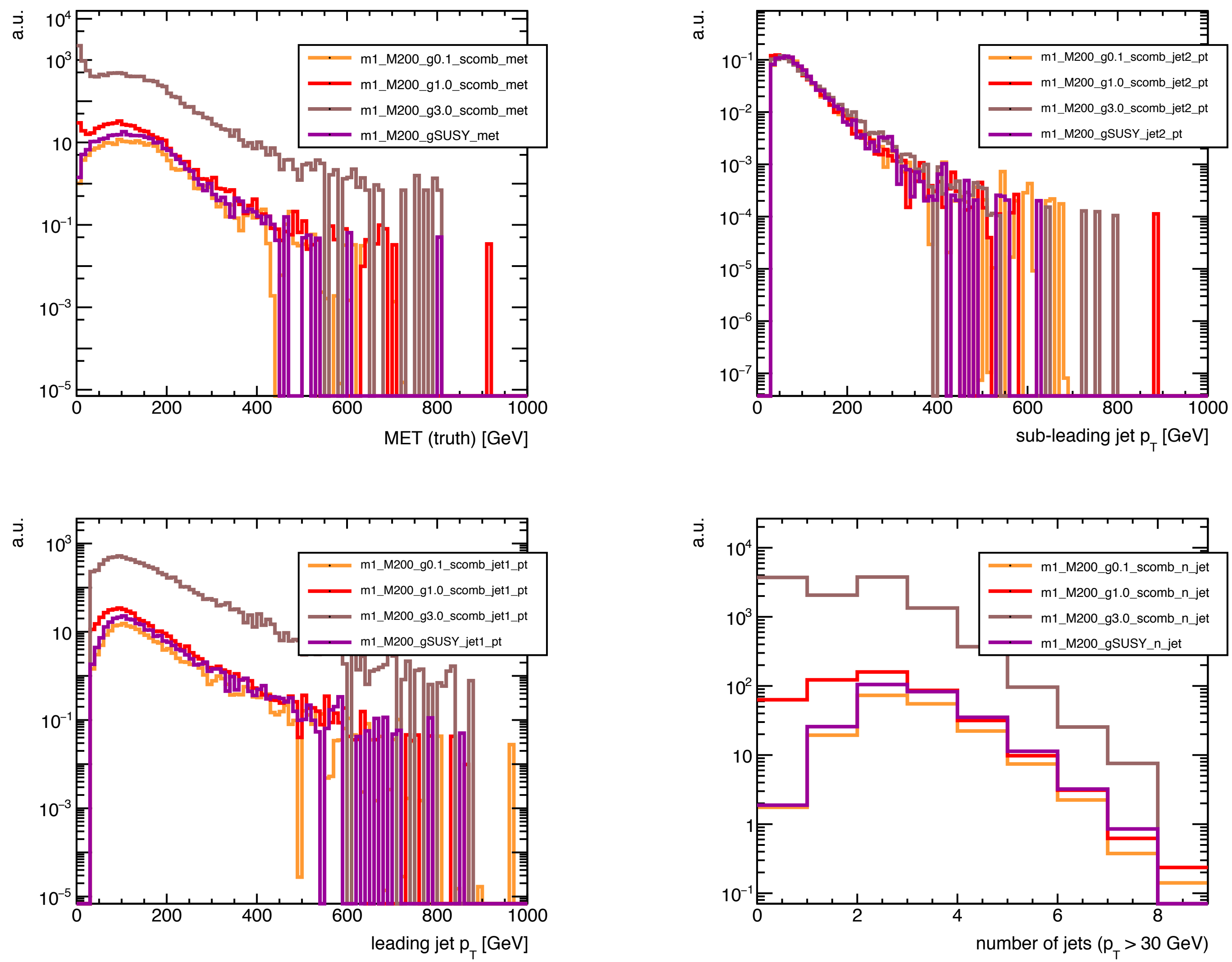
Conclusions and Open Points

- Performed extensive studies on the t-channel DM simplified model
  - studied relation with relic density
  - quantified similarities and differences wrt mssm squark pair production
- Good progress in MC generation
  - importance of split generation for correct cross section and jet multiplicity
  - relevance of coupling dependence on kinematics and cross sections
- Open points / improvements
  - choice of merging scale:
    - if single scale, low merging scale looks safer
    - investigate different merging scales for different split processes?
  - more refined sensitivity studies for grid optimization towards MC request

BACK-UP

+ SUSY vs Combined DM comparison

- Compare SUSY with DM (combined samples) for different values of g=0.1,1,3 (private production)



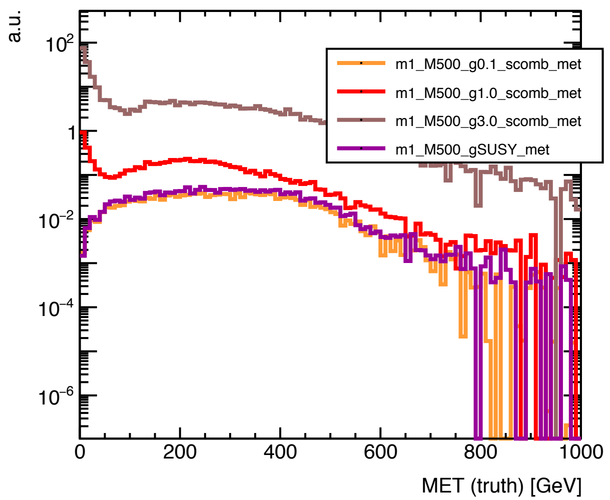
$m_{DM}=1, M_{med}=200$

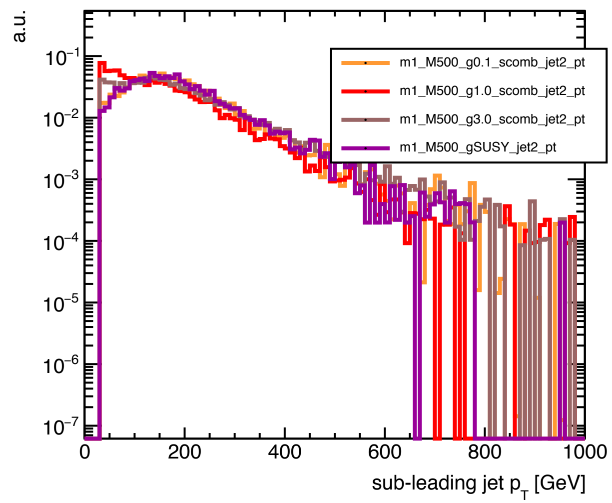
- At g=0.1 mssm kinematics are recovered
- At g=1 1-jet contribution becomes more important

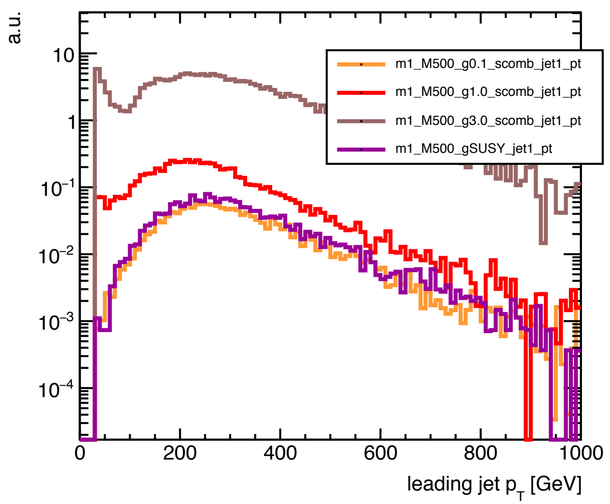
+ SUSY vs Combined DM comparison

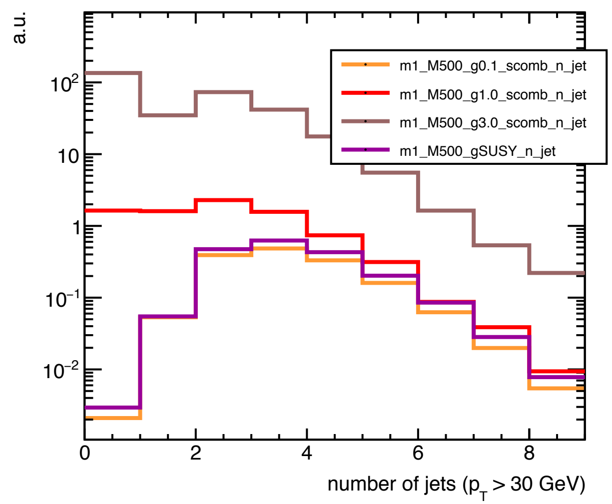
- Compare SUSY with DM (combined samples) for different values of g=0.1,1,3 (private production)

$m_{DM}=1, M_{med}=500$





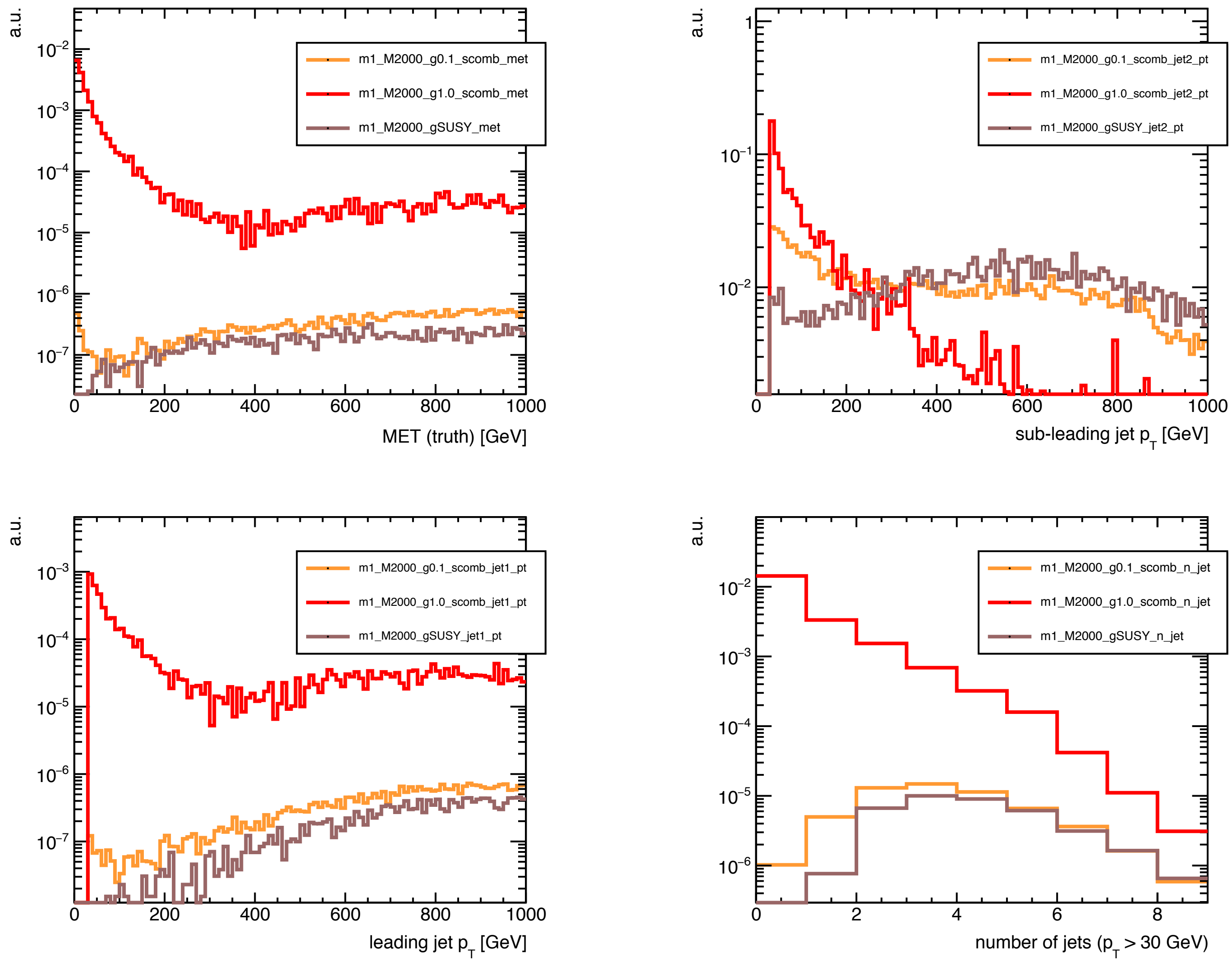




- At g=0.1 mssm kinematics are recovered
- At g=1 1-jet contribution becomes more important

+ SUSY vs Combined DM comparison

- Compare SUSY with DM (combined samples) for different values of g=0.1,1,3 (private production)

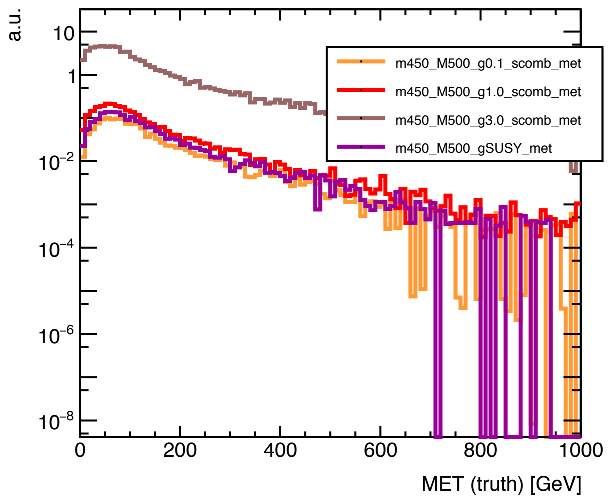


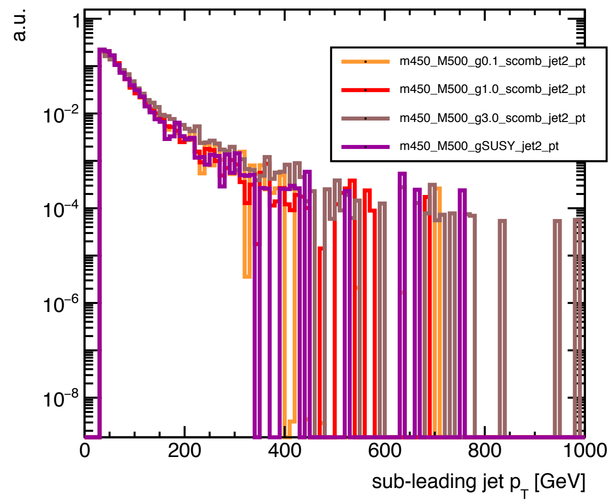
$m_{DM}=1, M_{med}=2000$

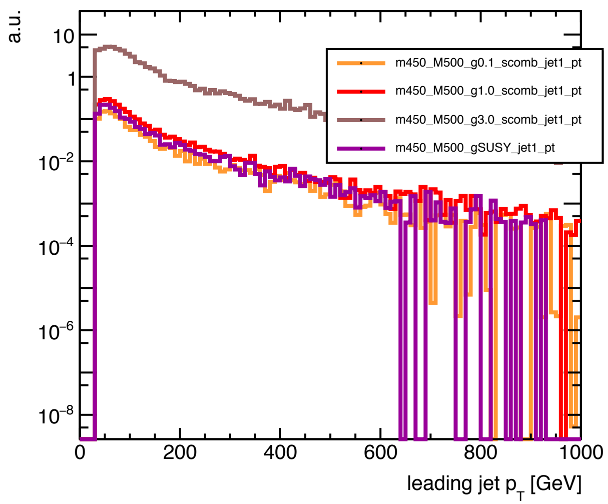
- At g=0.1 mssm kinematics are recovered
- At g=1 1-jet contribution becomes much more important

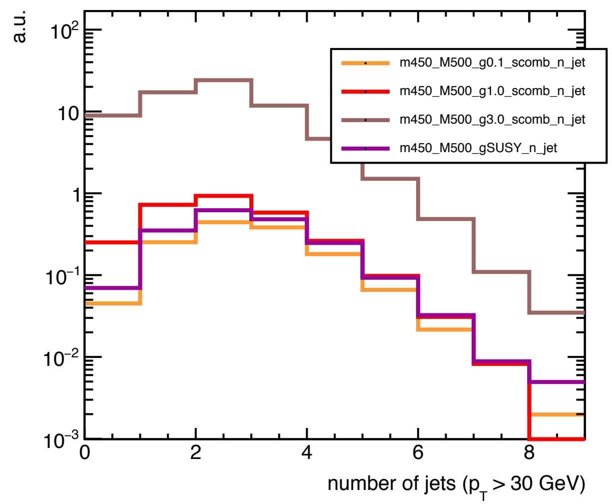
+ SUSY vs Combined DM comparison

- Compare SUSY with DM (combined samples) for different values of g=0.1,1,3 (private production)







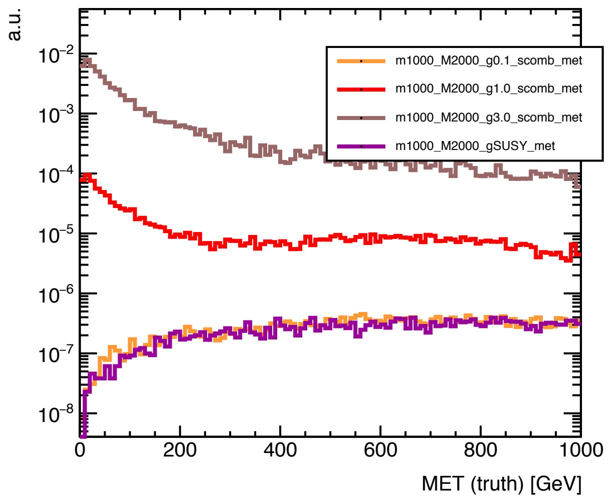


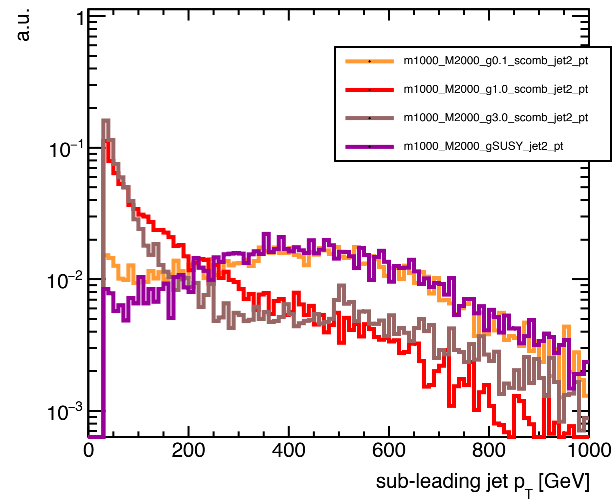
$m_{DM}=450, M_{med}=500$

- At g=0.1 mssm kinematics are recovered
- At higher couplings kinematics do not seem to change significantly

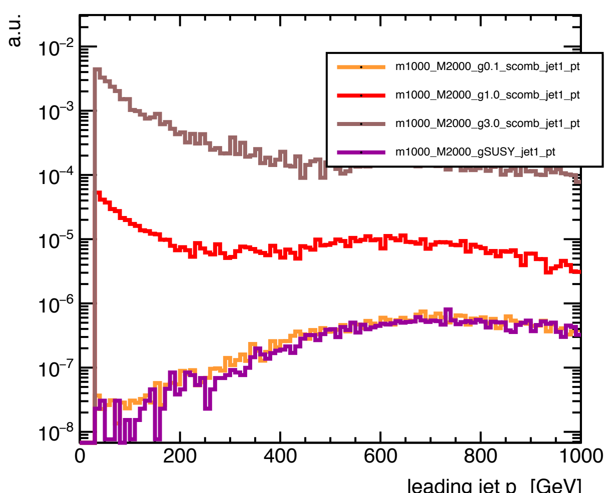
+ SUSY vs Combined DM comparison

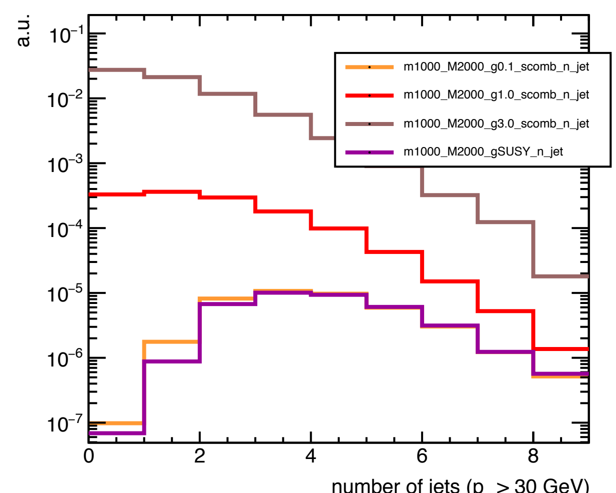
- Compare SUSY with DM (combined samples) for different values of g=0.1,1,3 (private production)





m_{DM}=1000, M_{med}=2000

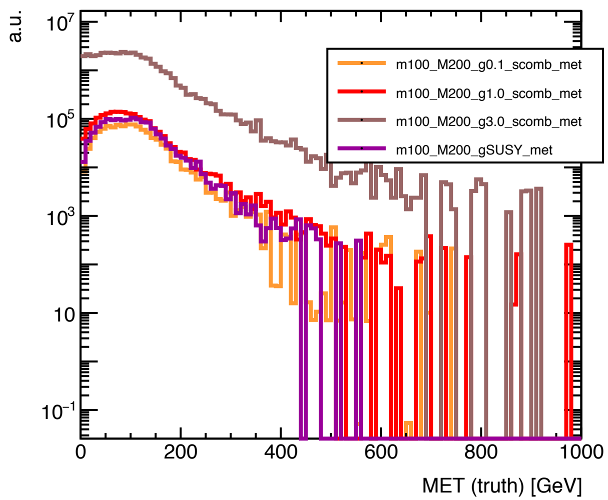


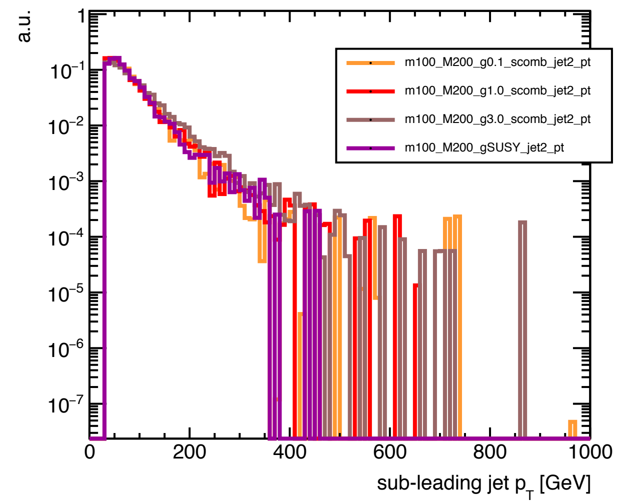


- At g=0.1 mssm kinematics are recovered
- At g=1 1-jet contribution becomes dominant

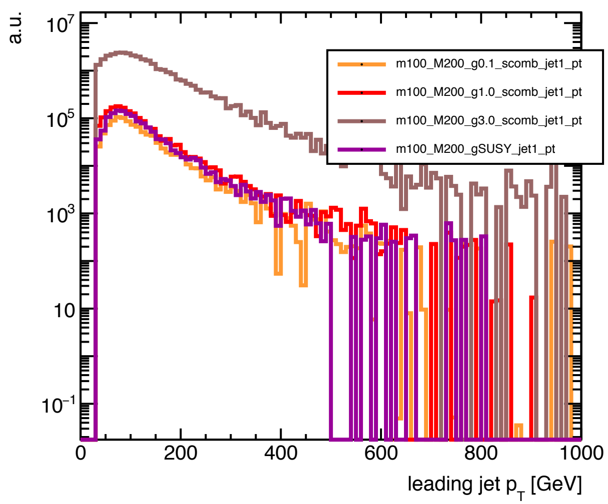
SUSY vs Combined DM comparison

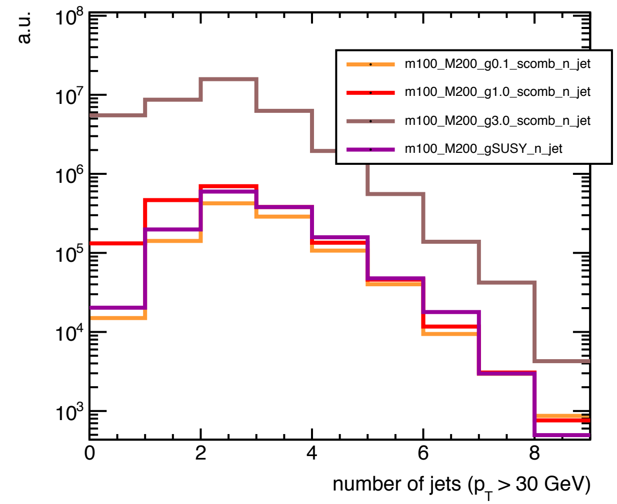
- Compare SUSY with DM (combined samples) for different values of g=0.1,1,3 (private production)





m_{DM}=100, M_{med}=200

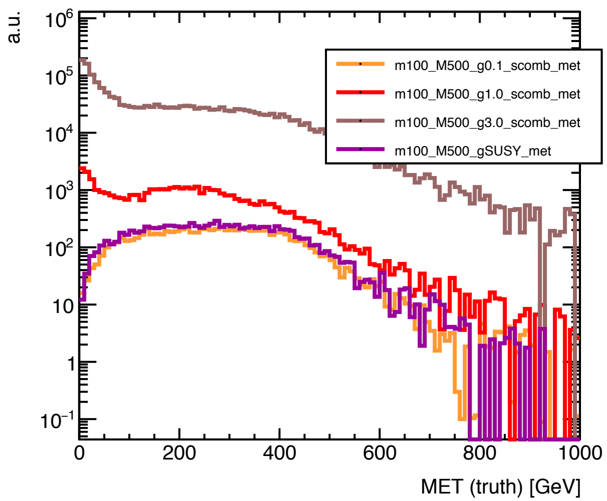


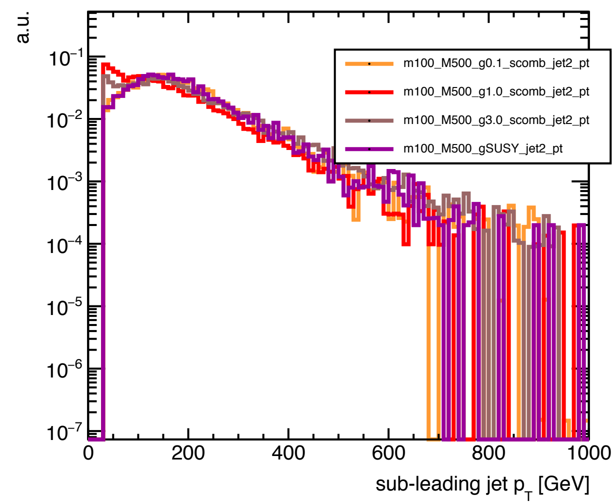


- At g=0.1 mssm kinematics are recovered
- At g=1 1-jet contribution becomes more important

+ SUSY vs Combined DM comparison

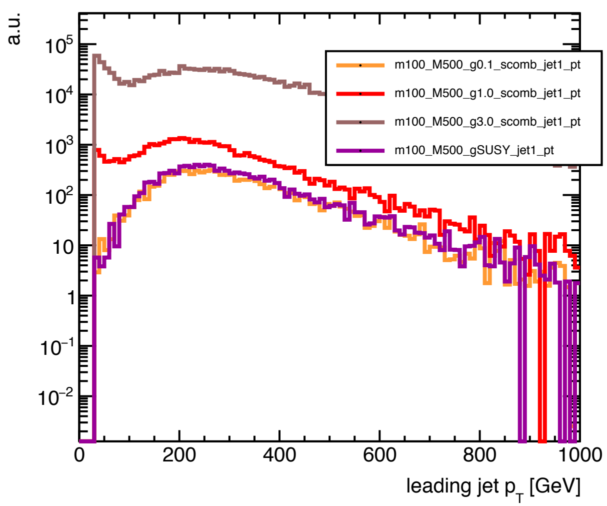
- Compare SUSY with DM (combined samples) for different values of g=0.1,1,3 (private production)

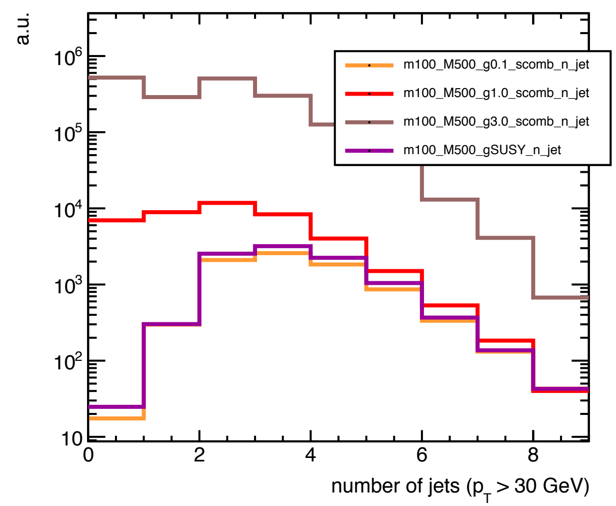




$m_{DM}=100, M_{med}=500$

- At g=0.1 mssm kinematics are recovered
- At g=1 1-jet contribution becomes more important

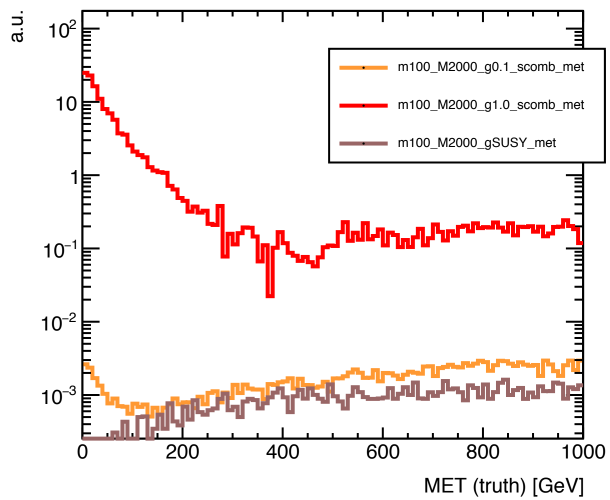


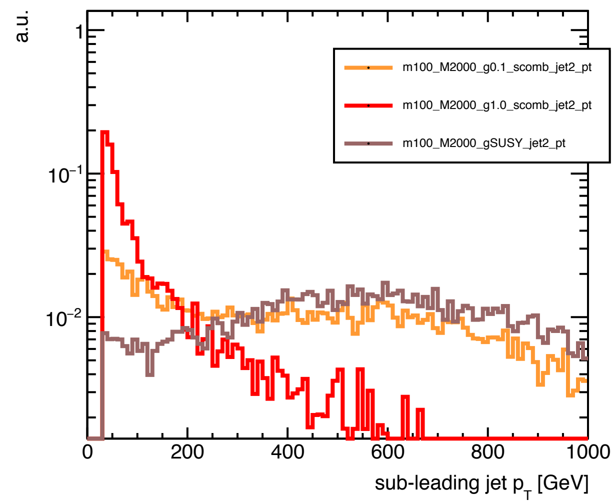


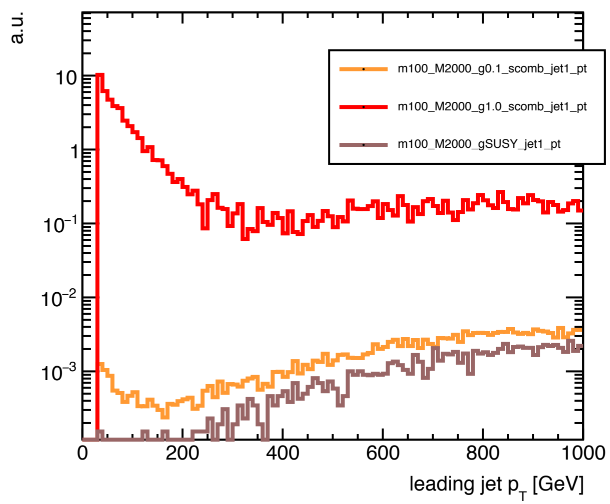
SUSY vs Combined DM comparison

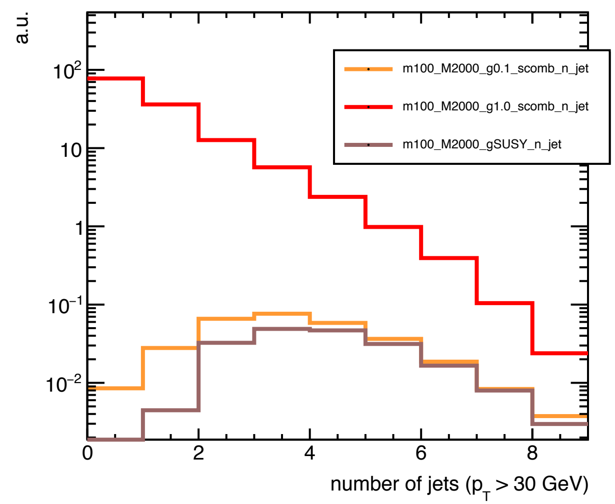
- Compare SUSY with DM (combined samples) for different values of g=0.1,1,3 (private production)

m_{DM}=100, M_{med}=2000





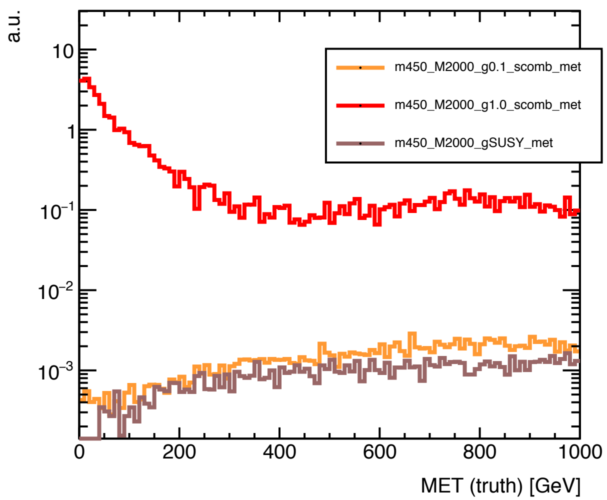


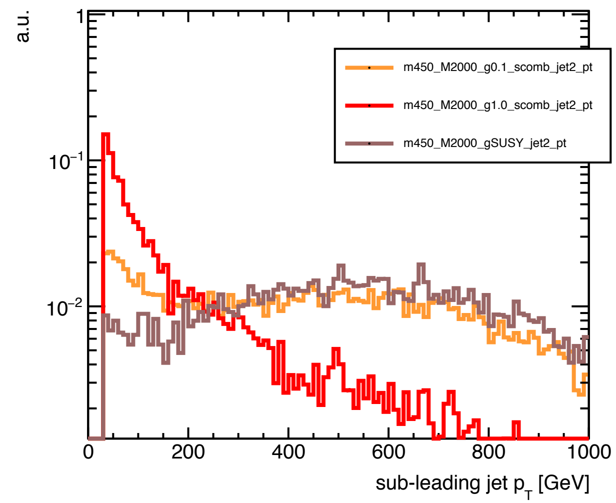


- At g=0.1 mssm kinematics are approx recovered
- At g=1 1-jet contribution becomes much more important

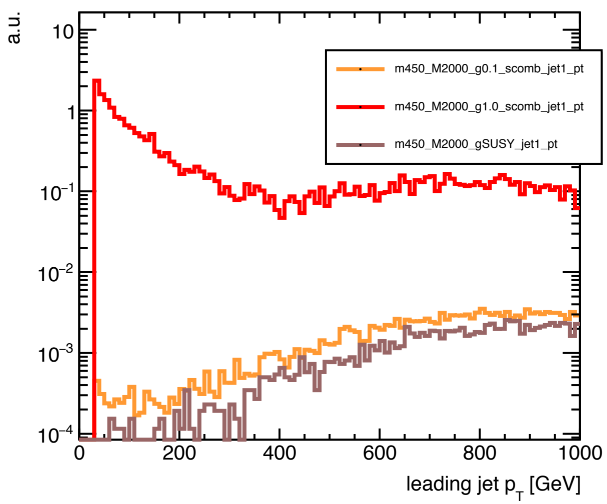
+ SUSY vs Combined DM comparison

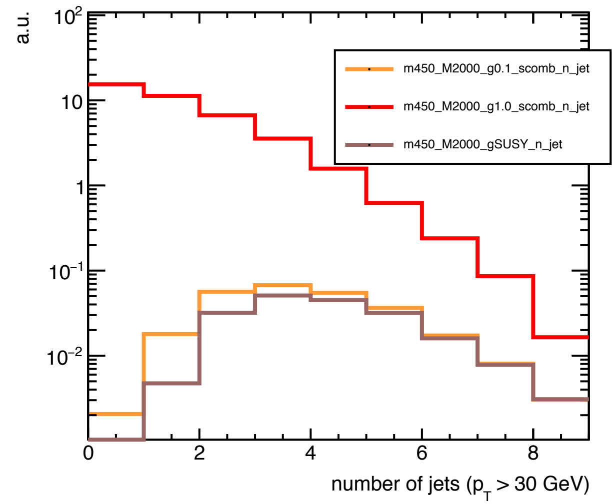
- Compare SUSY with DM (combined samples) for different values of g=0.1,1,3 (private production)





m_{DM}=450, M_{med}=2000





- At g=0.1 mssm kinematics are approx recovered
- Some residual difference in showering ?
- At g=1 1-jet contribution becomes much more important

MadGraph-level cross sections (pb) for 0-1-2 parton

m= 100 M= 200 g= 0.1					
Split	Process	0-j	1-j	2-j	Sum(0,1,2 -j)
1	pp > sq sq	1.7e+02	9.8e+01	4.0e+01	3.1e+02
2	pp > sq dm $ sq	1.0e+00	5.7e+00	3.2e+00	1.0e+01
3	pp > dm dm $ sq	1.5e-03	1.5e-02	4.6e-02	6.3e-02
nom	pp > dm dm	1.5e-03	7.6e-01	9.1e+01	9.2e+01

m= 1000 M= 2000 g= 0.1					
Split	Process	0-j	1-j	2-j	Sum(0,1,2 -j)
1	pp > sq sq	3.6e-05	2.1e-06	7.1e-08	3.9e-05
2	pp > sq dm $ sq	5.4e-06	1.5e-06	7.5e-08	7.0e-06
3	pp > dm dm $ sq	7.3e-08	7.2e-08	1.3e-08	1.6e-07
nom	pp > dm dm	7.3e-08	3.9e-06	1.9e-05	2.3e-05

m= 100 M= 200 g= 1					
Split	Process	0-j	1-j	2-j	Sum(0,1,2 -j)
1	pp > sq sq	2.1e+02	1.1e+02	4.2e+01	3.6e+02
2	pp > sq dm $ sq	1.0e+02	6.2e+01	2.1e+01	1.9e+02
3	pp > dm dm $ sq	1.5e+01	3.7e+00	1.1e+00	2.0e+01
nom	pp > dm dm	1.5e+01	7.8e+01	1.4e+02	2.4e+02

m= 1000 M= 2000 g= 1					
Split	Process	0-j	1-j	2-j	Sum(0,1,2 -j)
1	pp > sq sq	1.0e-04	3.1e-06	9.6e-08	1.0e-04
2	pp > sq dm $ sq	5.4e-04	6.5e-05	2.0e-06	6.1e-04
3	pp > dm dm $ sq	7.3e-04	6.1e-05	5.1e-06	8.0e-04
nom	pp > dm dm	7.3e-04	4.0e-04	7.8e-05	1.2e-03

m= 100 M= 200 g= 3					
Split	Process	0-j	1-j	2-j	Sum(0,1,2 -j)
1	pp > sq sq	3.7e+03	9.8e+02	3.5e+02	5.0e+03
2	pp > sq dm $ sq	9.3e+02	1.8e+03	6.2e+02	3.4e+03
3	pp > dm dm $ sq	1.2e+03	2.8e+02	1.9e+02	1.7e+03
nom	pp > dm dm	1.2e+03	8.5e+02	2.6e+03	4.7e+03

m= 1000 M= 2000 g= 3					
Split	Process	0-j	1-j	2-j	Sum(0,1,2 -j)
1	pp > sq sq	6.0e-03	9.8e-05	4.3e-05	6.1e-03
2	pp > sq dm $ sq	4.9e-03	4.5e-03	1.4e-04	9.6e-03
3	pp > dm dm $ sq	5.9e-02	1.6e-03	4.9e-04	6.1e-02
nom	pp > dm dm	5.9e-02	4.2e-03	4.1e-03	6.7e-02

m= 100 M= 200 g= SUSY				
Process	0-j	1-j	2-j	Sum(0,1,2 -j)
pp > sq sq	1.7e+02	9.9e+01	4.0e+01	3.1e+02

m= 1000 M= 2000 g= SUSY				
Process	0-j	1-j	2-j	Sum(0,1,2 -j)
pp > sq sq	3.6e-05	2.1e-06	7.1e-08	3.9e-05

- Split1 dominant at low coupling; the higher the coupling the more important get split2-3
- SUSY cross section at MG level recovered for g=0.1
- Nominal cross section smaller than sum of split1-2-3
- Cross section doesn't increase with higher parton multiplicity in split 1-2-3, UNLIKE in the nominal

➔ Same considerations apply for other points investigated

MadGraph Setup – Example Process card

- DM t-channel:
  - Split sample approach important especially in the compressed scenario (m_{Med}- m_{DM} small)
  - Split sample 1 is the one similar to SUSY
  - b/t quarks/mediators not coupled
  - Model contains only Left part of mediators

```
import model dmS_T -modelname

define p = g d u s c d~ u~ s~ c~
define j = g d u s c d~ u~ s~ c~
define med = etad etadbar etau etaubar etac etacbar etas etasbar
define dm = chi chi~
```

Split sample 1

```
generate p p > med med / a h z w+ w- NP=2 QCD=2 @1
add process p p > j med med / a h z w+ w- NP=2 QCD=3 @2
add process p p > j j med med / a h z w+ w- NP=4 QCD=4 @3
```

Split Sample 2

```
generate p p > dm med / a h z w+ w- $med @1
add process p p > j dm med / a h z w+ w- $med @2
add process p p > j j dm med / a h z w+ w- $med @3
```

Split Sample 3

```
generate p p > chi chi~ / a h z w+ w- $med @1
add process p p > j chi chi~ / a h z w+ w- $med @2
add process p p > j j chi chi~ / a h z w+ w- $med NP=4 QCD=2 @3
```

Nominal (no split)

```
generate p p > chi chi~
add process  p p > chi chi~ j
add process  p p > chi chi~ j j
```

- SUSY strong production:
  - mssm
  - gluino and other susy particles decoupled
  - b/t quarks/squarks not coupled
  - Take only Left part of susylq

```
import model mssm
define p = g u c d s u~ c~ d~ s~
define j = g u c d s u~ c~ d~ s~
define susyweak = el- el+ er- er+ mul- mul+ mur- mur+ \
ta1- ta1+ ta2- t a2+ n1 n2 n3 n4 x1- x1+ x2- x2+ \
sve sve~ svm svm~ svt svt~
define susylq = ul dl cl sl
define susylq~ = ul~ dl~ cl~ sl~

generate p p > susylq susylq~ $ go susyweak @1
add process p p > susylq susylq~ j $ go susyweak @2
add process p p > susylq susylq~ j j $ go susyweak @3
```

MadGraph Setup – Example Run card

- List of the key parameters:

```
nn23lo1  =  pdlabel     ! PDF set
247000   =  lhaid       ! if pdlabel=lhapdf, this is the lhapdf number

 0      =  ickkw          ! 0 no matching, 1 MLM, 2 CKKW matching
 3.0    =  lhe_version     ! Change the way clustering information pass to shower.
 20.0   =  ptj           ! minimum pt for the jets
 125.0 =    ktdurham
 0.4    =   dparameter
 0.0    =  xqcut     ! minimum kt jet measure between partons

 15.0   =  bwcutoff       ! (M+/-bwcutoff*Gamma)
 4      =  maxjetflavor      ! Maximum jet pdg code
```

- KtDurham and ptj values under discussion

- Bwcutoff
  - Needed for split samples 2/3, measures how large is the region where MG vetoes on-shell mediators
  - default value is 15 => lowered when the width of the mediator is large

Pythia Setup - Merging

- Pythia setup and MG+Pythia interface handled in both cases with:
  - include("MC15JobOptions/Pythia8_A14_NNPDF23LO_EvtGen_Common.py")
  - include("MC15JobOptions/Pythia8_MadGraph.py")
- Merging Process:
  - SUSY strong production:

```
Merging:Process                    | pp>{ul,1000002}{ul~,-1000002}{dl,1000001}{dl~,-1000001}
                                        {sl,1000003}{sl~,-1000003}{cl,1000004}{cl~,-1000004} |
```

  - DM t-channel (split sample 1):

```
Merging:Process      Split sample 1          | pp>{etad,9000006}{etad~,-9000006}{etau,9000007}{etau~,-9000007}
                                                  {etas,9000008}{etas~,-9000008}{etac,9000009}{etac~,-9000009} |

| Merging:Process        Split Sample 2        | pp>{chi,1000022}{chi~,-1000022} |
| Merging:Process   (tried the two listed here)  | pp>{chi,1000022}{chi~,-1000022}{etad,9000006}{etad~,-9000006}{etau,9000007}
                                               {etau~,-9000007}{etas,9000008}{etas~,-9000008}{etac,9000009}{etac~,-9000009} |

| Merging:Process      Split sample 3     | pp>{chi,1000022}{chi~,-1000022} |          void           |

| Merging:Process      Nominal (no split) | pp>{chi,1000022}{chi~,-1000022} |          void           |
```

- Matching CKKW-L in both SUSY and DM :

Name	Now	Default	Min	Max
Merging:doKTMerging	on	off		
Merging:Dparameter	0.40000	1.00000		
Merging:mayRemoveDecayProducts	on	off		
Merging:nJetMax	2	0	0	
Merging:nQuarksMerge	4	5	2	5
Merging:TMS	125.00000	0.0		

TMS = ktDurham

+ Feynman Diagrams

⊙ Summary for process pp>sq sq (0-jet)

- There are three kinds of processes involved (some g/NP dependent, some not):
  - *A.* $gg - sq\overline{sq}$ 1 - QCD=2 NP=0
  - *B.* $q\bar{q} - sq\overline{sq}$ 1 - QCD=0 NP=2, 2 - QCD=0 NP=2
  - *C.* $qq' - sq\overline{sq}$ 1 - QCD=0 NP=2

- A. is independent on the new coupling and the associated cross section is the same in dmS_T g=0.1,1,3 => dominant contribution in 0-jet case

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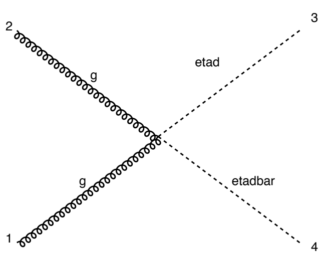

diagram 1 NP=0, QCD=2, QED=0

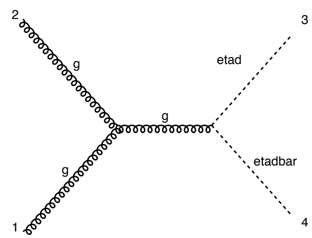

diagram 2 NP=0, QCD=2, QED=0

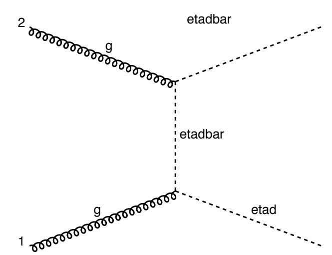

diagram 3 NP=0, QCD=2, QED=0

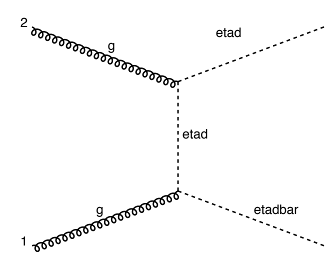

diagram 4 NP=0, QCD=2, QED=0

- B – partially dependent on g

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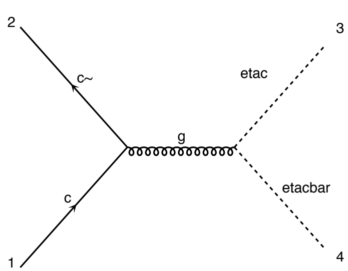


diagram 1 NP=0, QCD=2, QED=0

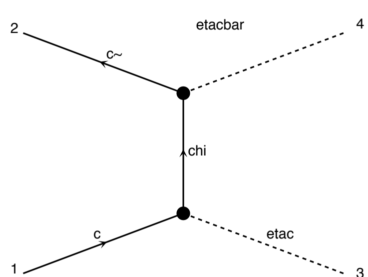


diagram 2 NP=2, QCD=0, QED=0

- C is the most dependent on g, gives an increasingly important contribution at higher g

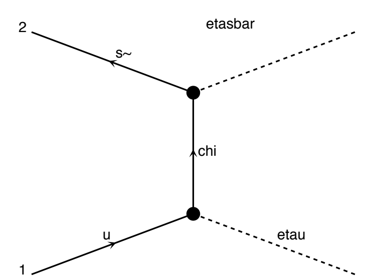
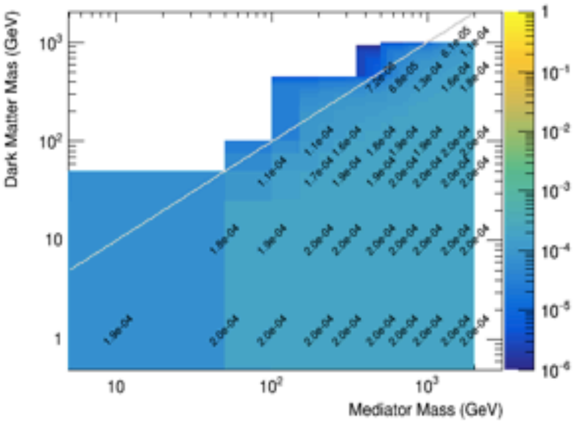


diagram 1 NP=2, QCD=0, QED=0

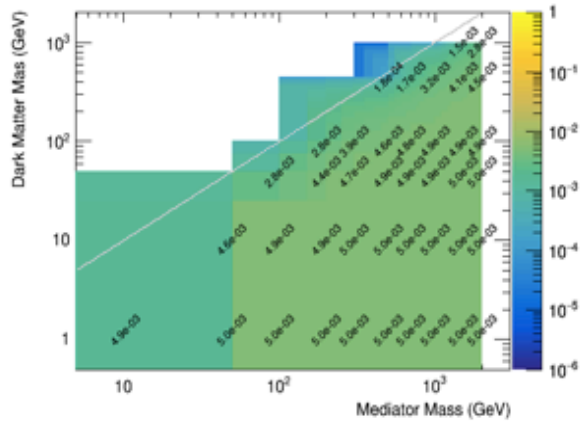
+ Relative width of the mediator

- Relative width: Γ_{Med}/m_{med} , computed for u-type mediator, similar for d/c/s-types
- Biggest dependce on g (rather uniform in m_{med}, m_{DM})

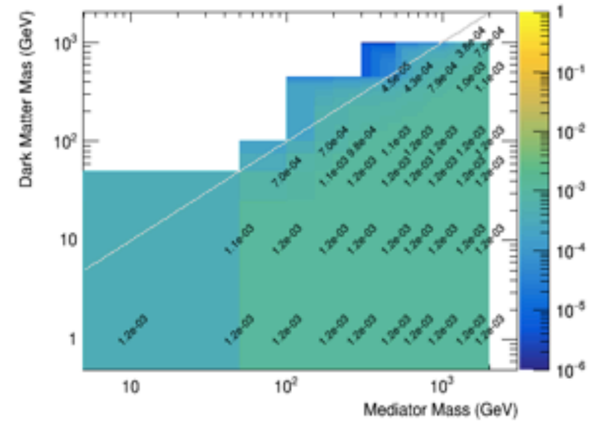
g = 0.1



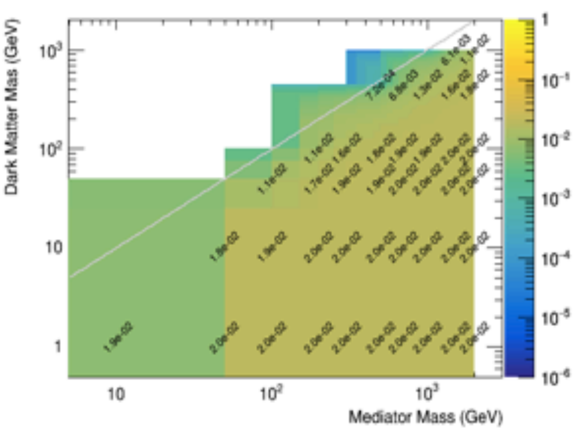
g = 0.25



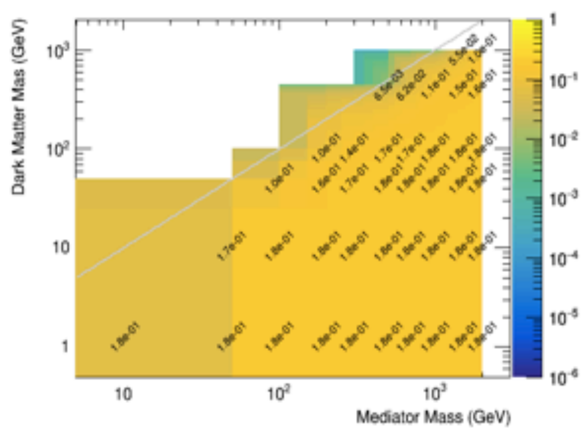
g = 0.50



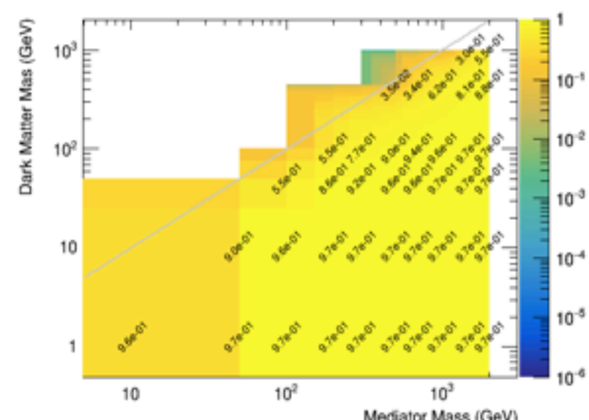
g = 1.0



g = 3.0



g = 7.0

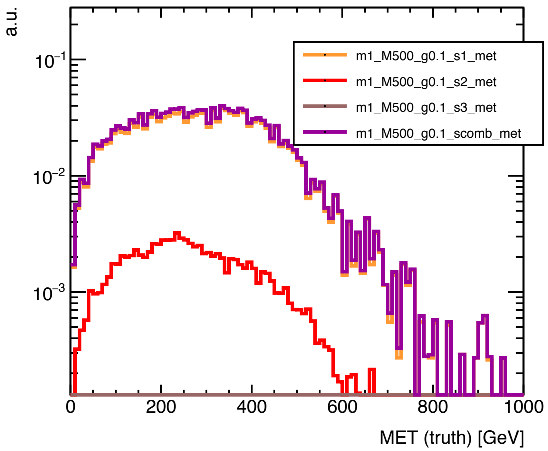


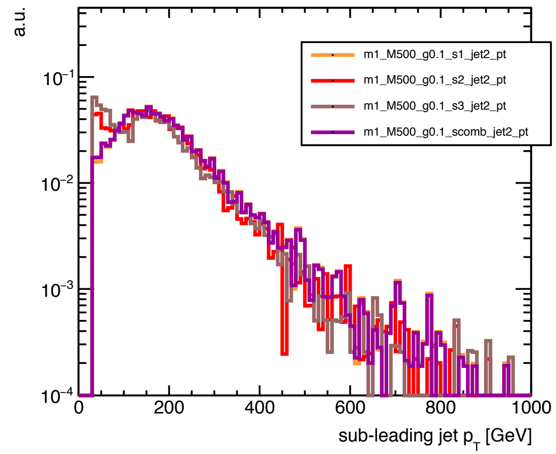
Width very large here, narrow width approximation probably doesn't apply, Papucci's recombination difficult

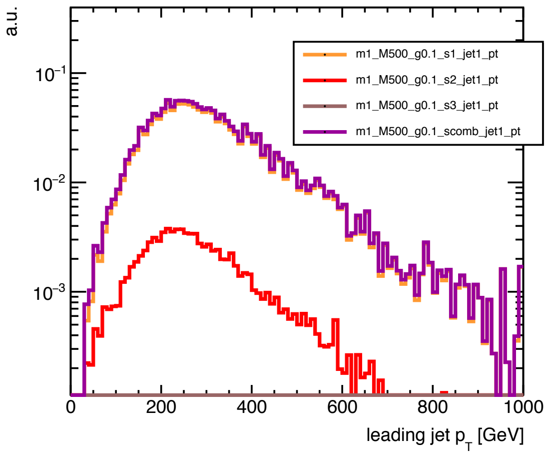
Recombination – Split vs Combined

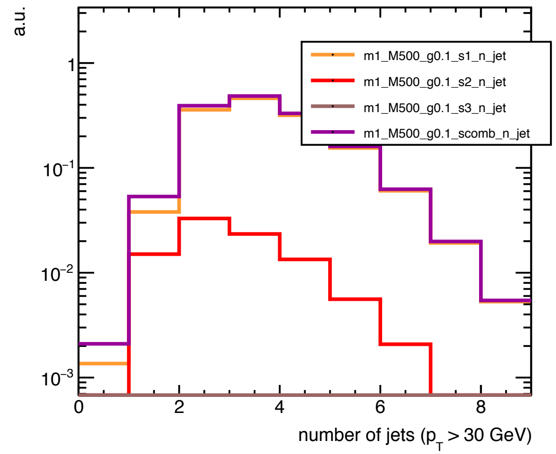
m=1, M=500

- How split1 kinematics are changed by split2-3 processes?
  - At **low coupling g=0.1**









Weight of events in split sample i:
$BW\_w_i \times \sigma_i$ (MG+Pythia) $\times MC\_w / \sum MC\_w$

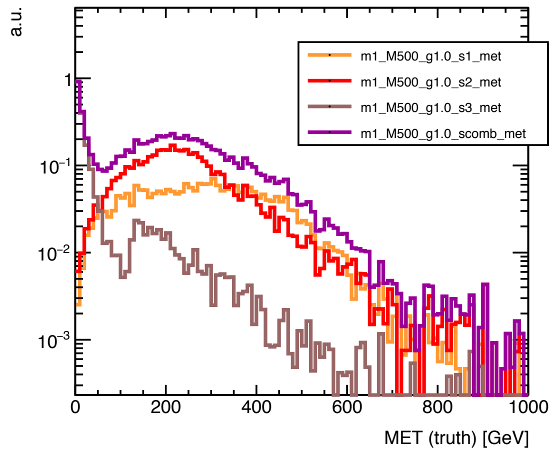
Combined histo obtained by sum of the three histos:
$h_{comb} = h_1 + h_2 + h_3$

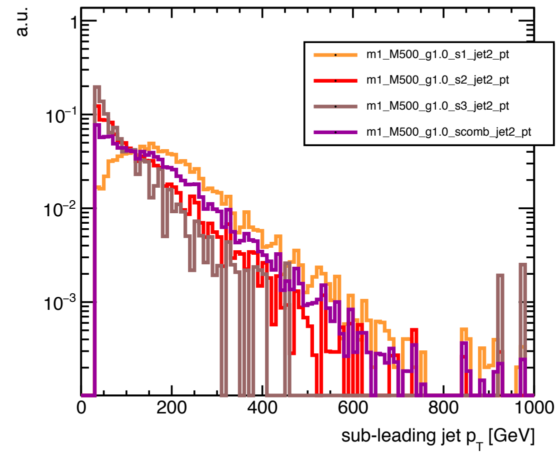
- Kinematics are not changed much
- Very high MET and hard leading jet
- High jet multiplicity

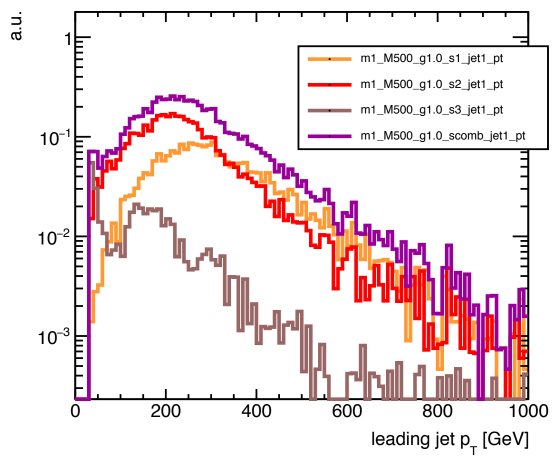
Recombination – Split vs Combined

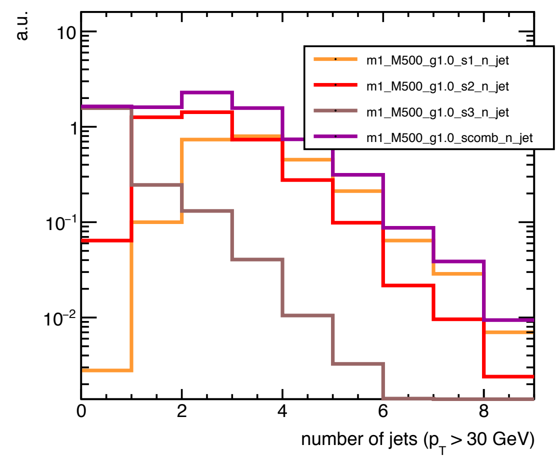
m=1, M=500

- How split1 kinematics are changed by split2-3 processes?
  - At **intermediate coupling g=1.0**









Weight of events in split sample *i*:
$BW\_w_i \times \sigma_i$ (MG+Pythia) $\times MC\_w / \sum MC\_w$

Combined histo obtained by sum of the three histos:
$h_{comb} = h_1 + h_2 + h_3$

- Split sample 2 and 3 become more important
- MET and jet pt get softer:
  - Is this a real feature or a problem in the matching scale?
- Jet multiplicity decreases

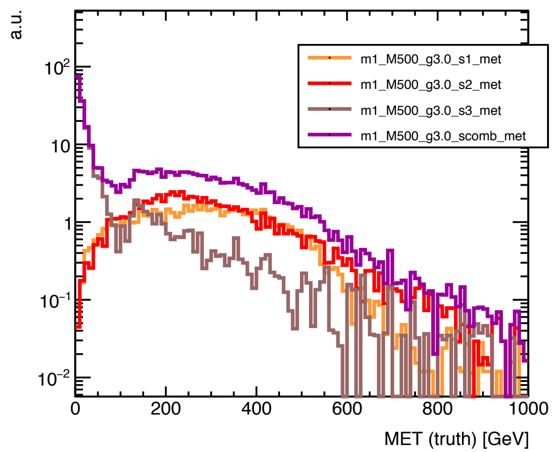
+ Recombination – Split vs Combined

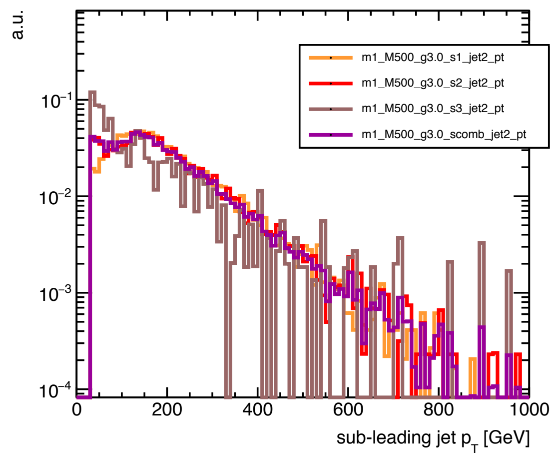
m=1, M=500

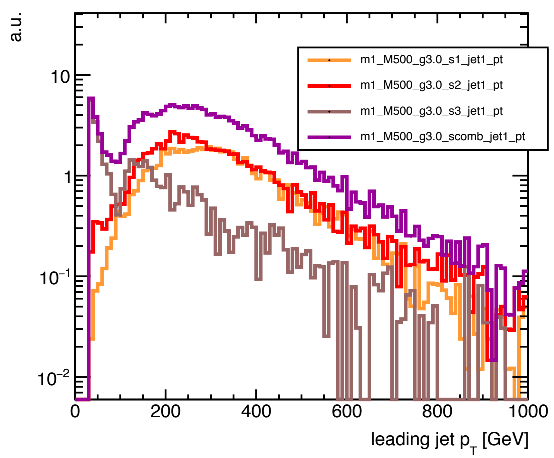
- How split1 kinematics are changed by split2-3 processes?
  - At **higher coupling g=3.0**

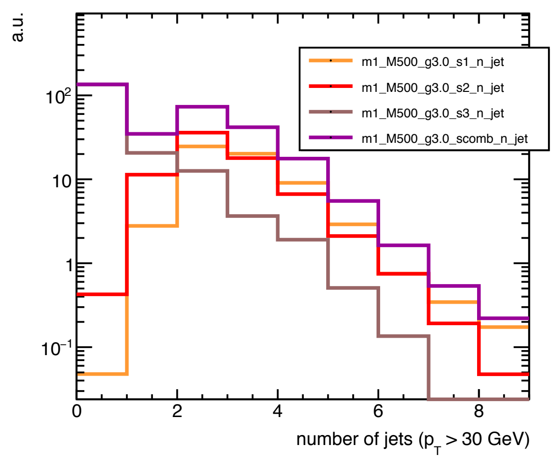
Weight of events in split sample *i*:
$BW\_w_i \times \sigma_i$ (MG+Pythia) $\times MC\_w / \sum MC\_w$

Combined histo obtained by sum of the three histos:
$h_{comb} = h_1 + h_2 + h_3$







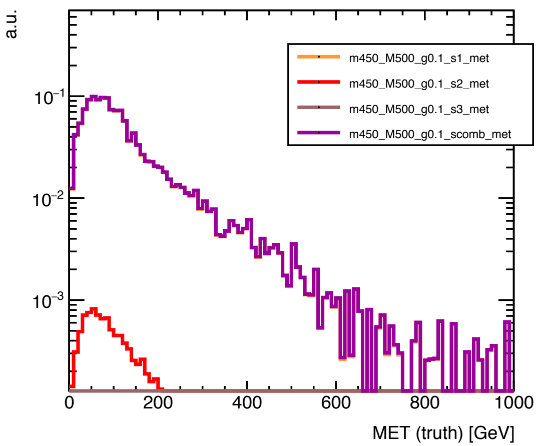


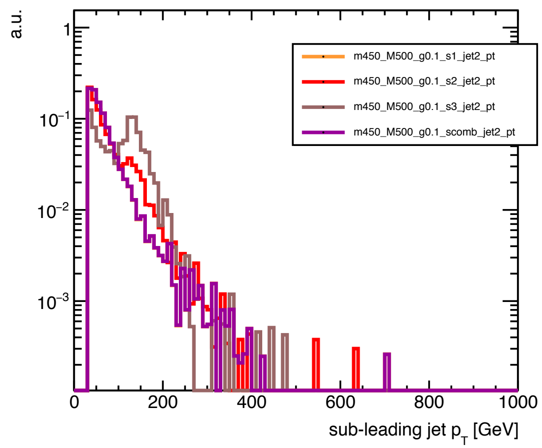
- Split 3 becomes even more important
- MET and jet pt get softer
  - Is this a real feature or a problem in the matching scale?
- Jet multiplicity decreases even more
  - Many 0-jet events

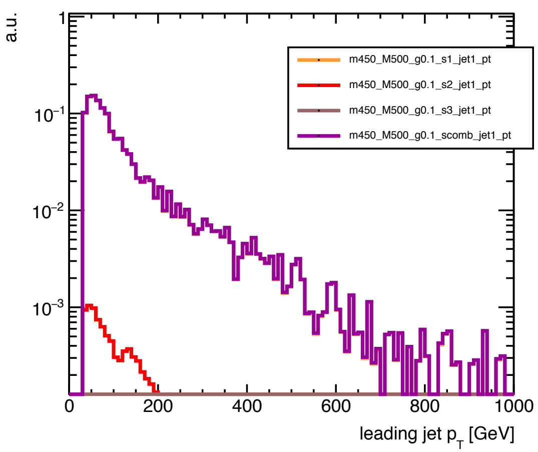
Recombination – Split vs Combined

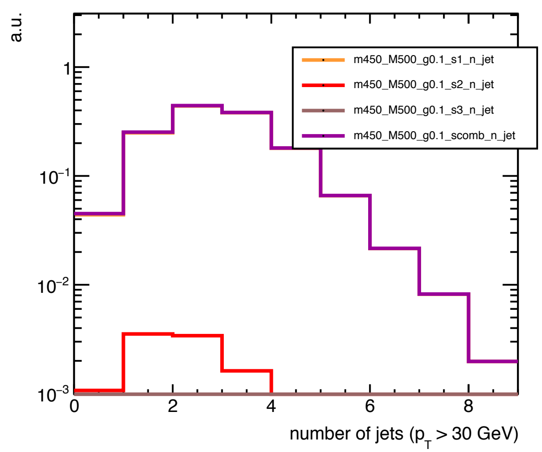
m=450, M=500

- How split1 kinematics are changed by split2-3 processes?
  - At **low coupling g=0.1**









Weight of events in split sample i:
BW_w$_i$ x σ_i (MG+Pythia)
x MC_w/ $\sum$MC_w

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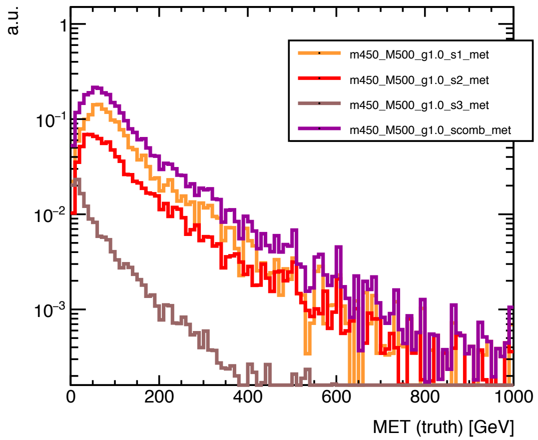
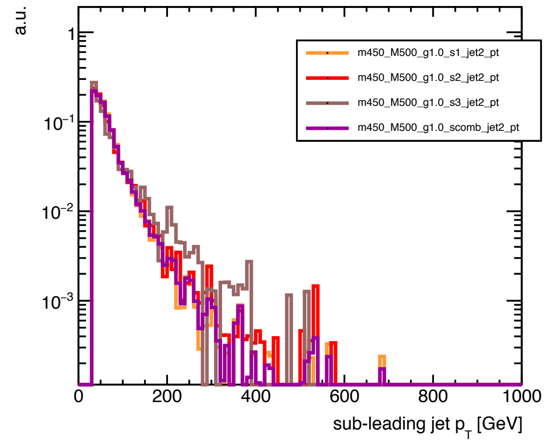
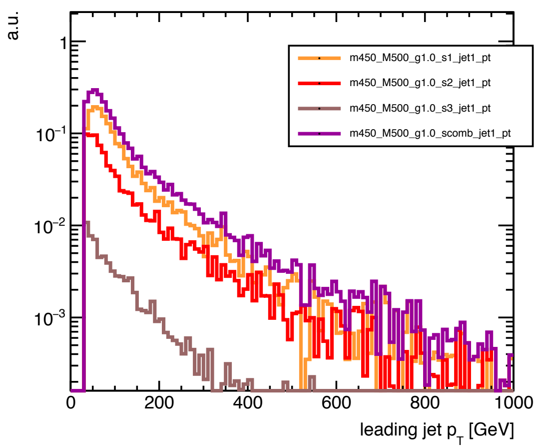
Recombination – Split vs Combined

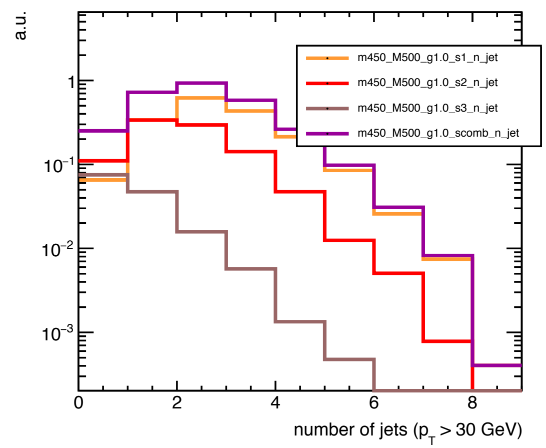
m=450, M=500

- How split1 kinematics are changed by split2-3 processes?
  - At **intermediate coupling g=1.0**









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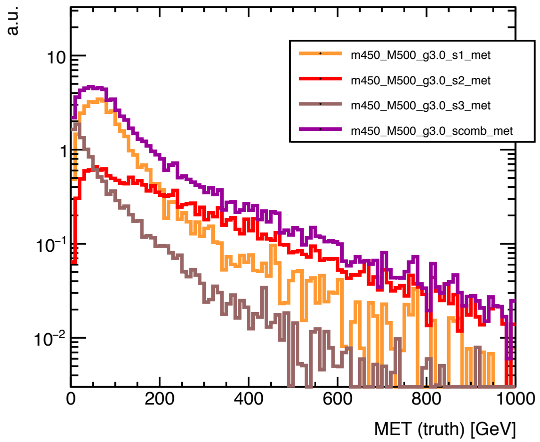
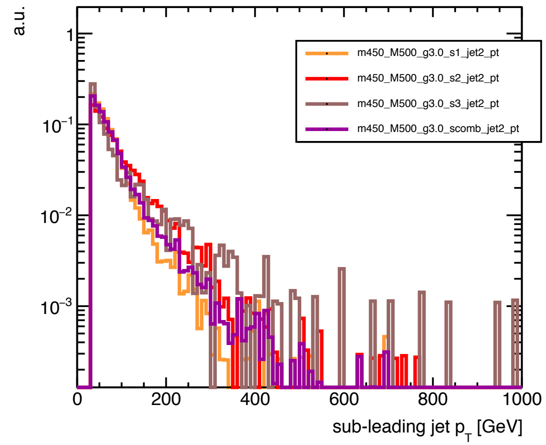
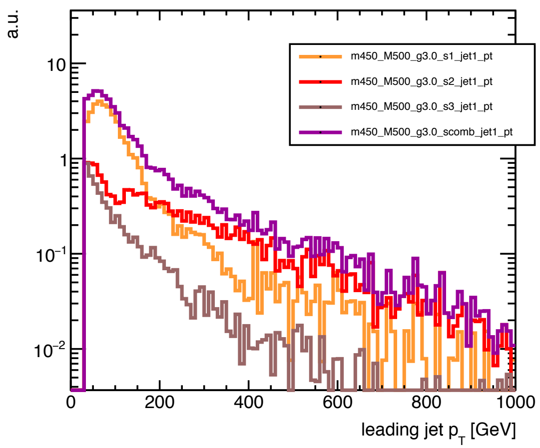
Recombination – Split vs Combined

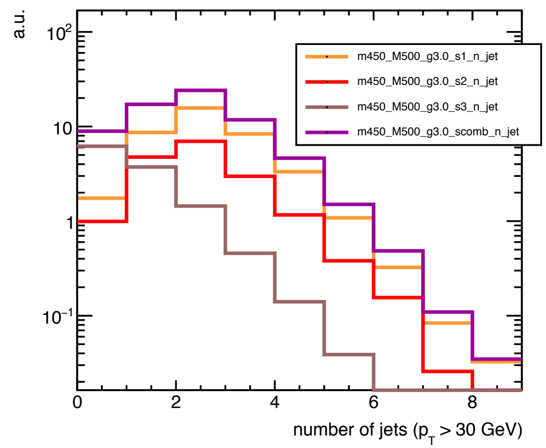
m=450, M=500

- How split1 kinematics are changed by split2-3 processes?
  - At **higher coupling g=3.0**









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