Higher-Order QCD Predictions for Dark Matter Production in Mono-Z Searches at the LHC

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Johannes Gutenberg University
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In collaboration with **Matthias Neubert, Cen Zhang,**
based on arXiv:1509.05785

DESY，2015-09-30

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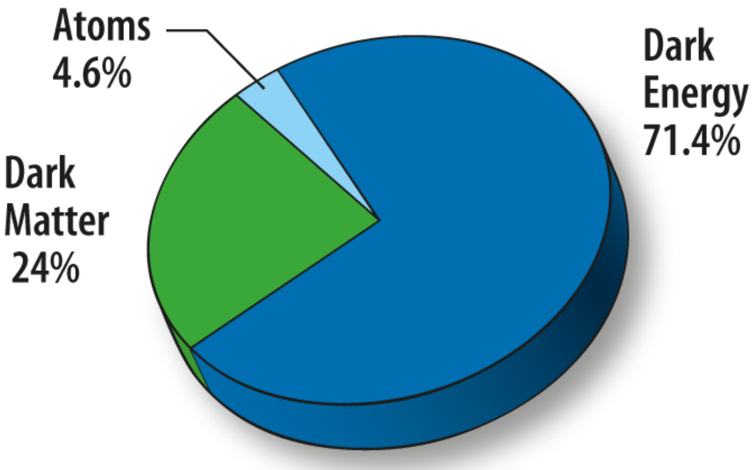
WMAP Nine-year 2013



TODAY

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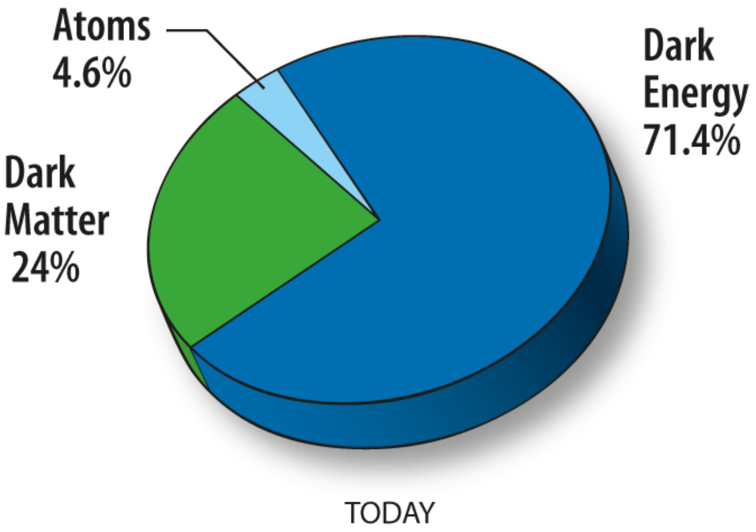

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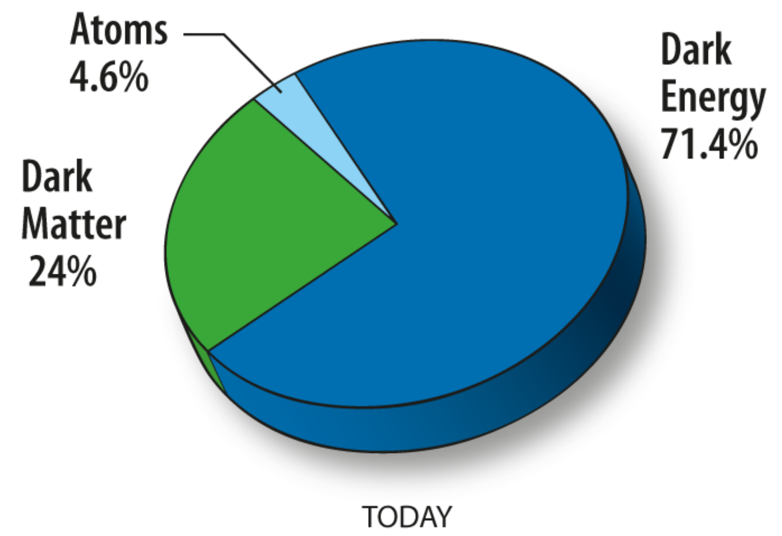

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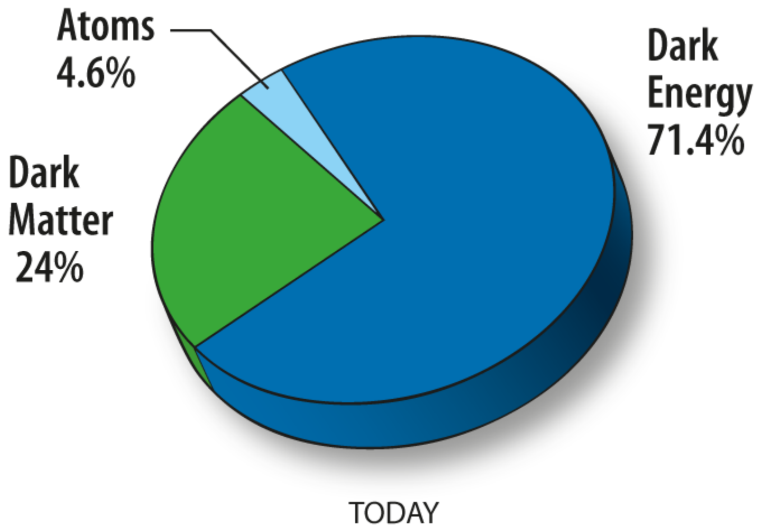

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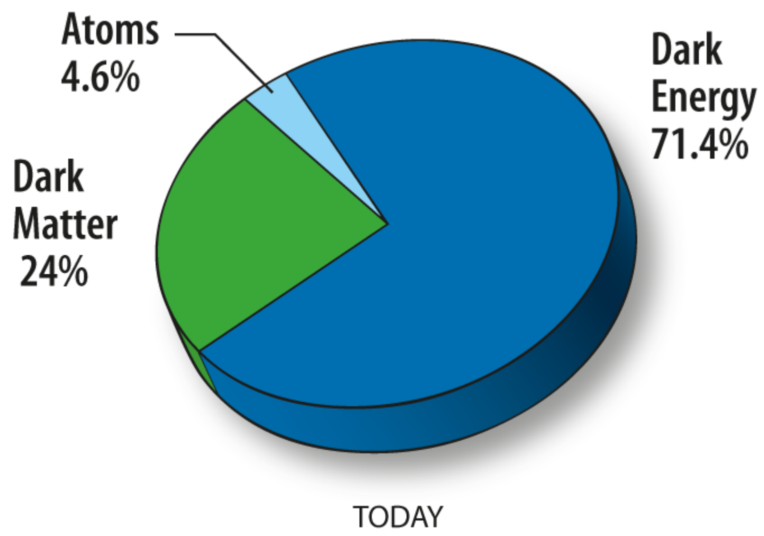

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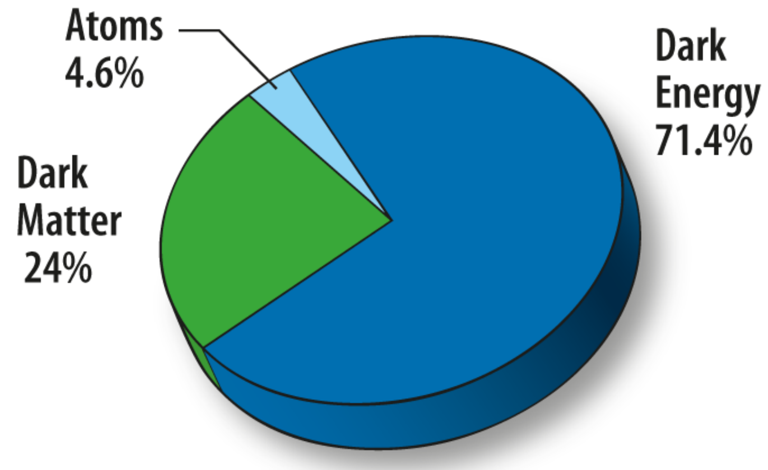

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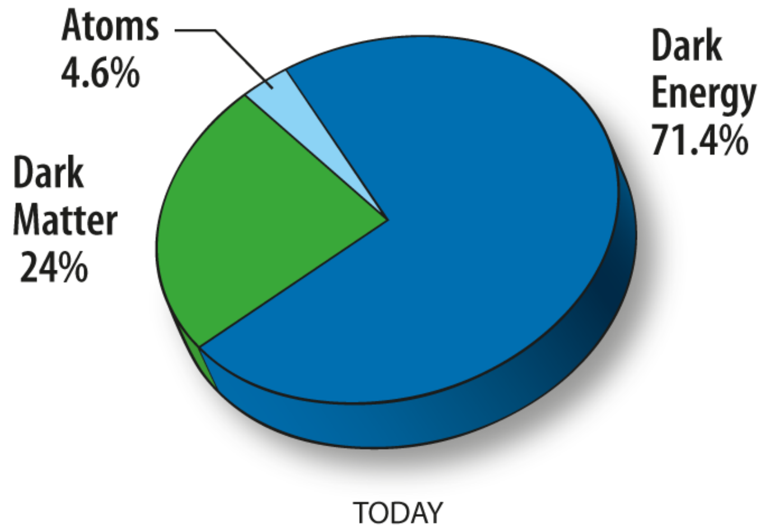

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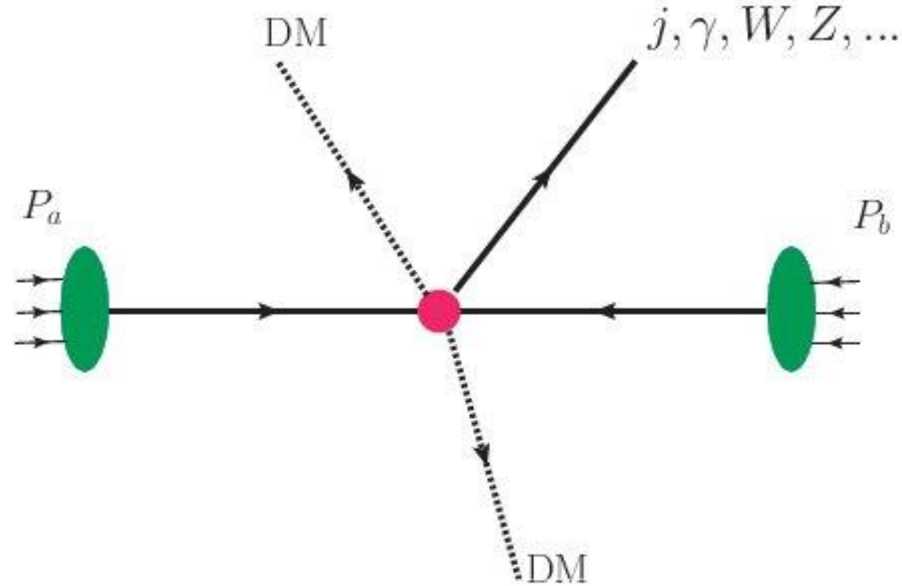
LHC RUN-II

Mono-X production at the LHC



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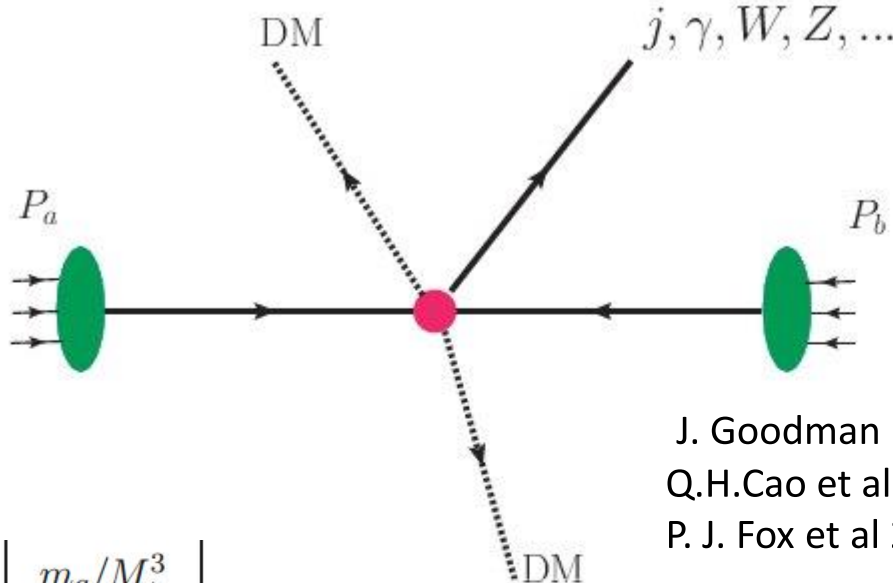

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Effective operators:

D1	$\bar{\chi}\chi\bar{q}q$	m_q/M_*^3
D2	$\bar{\chi}\gamma^5\chi\bar{q}q$	im_q/M_*^3
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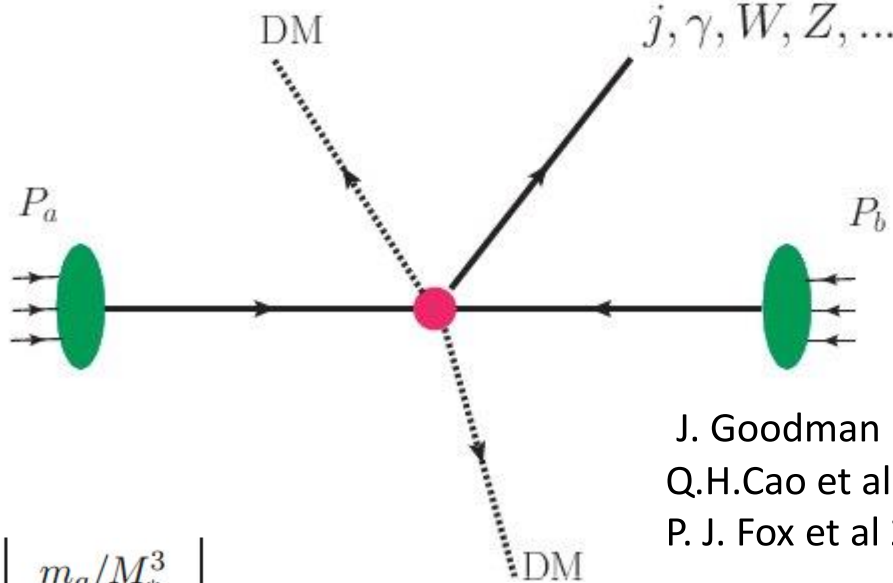

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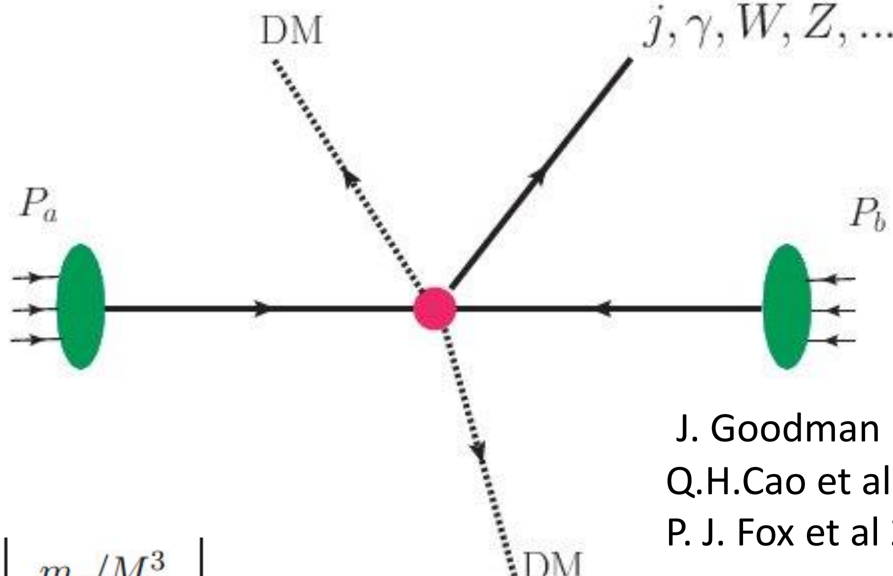

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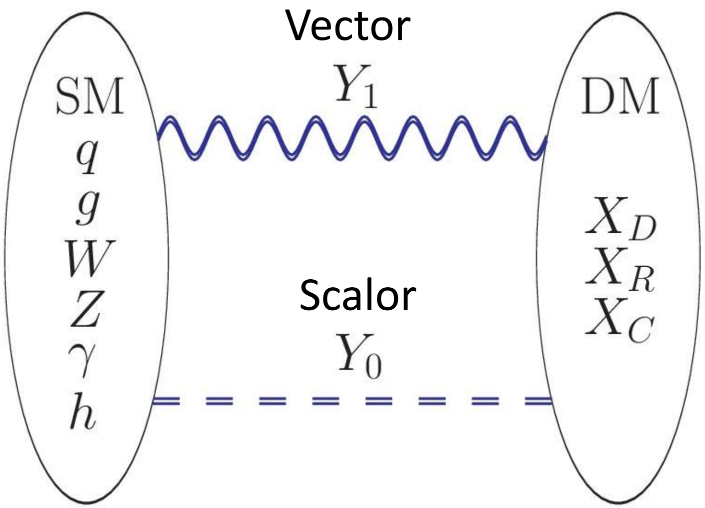

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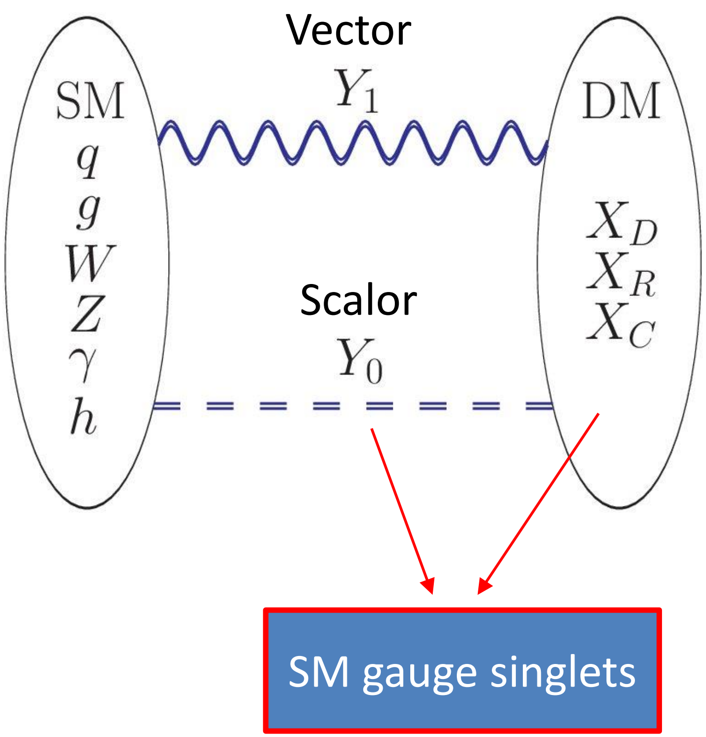

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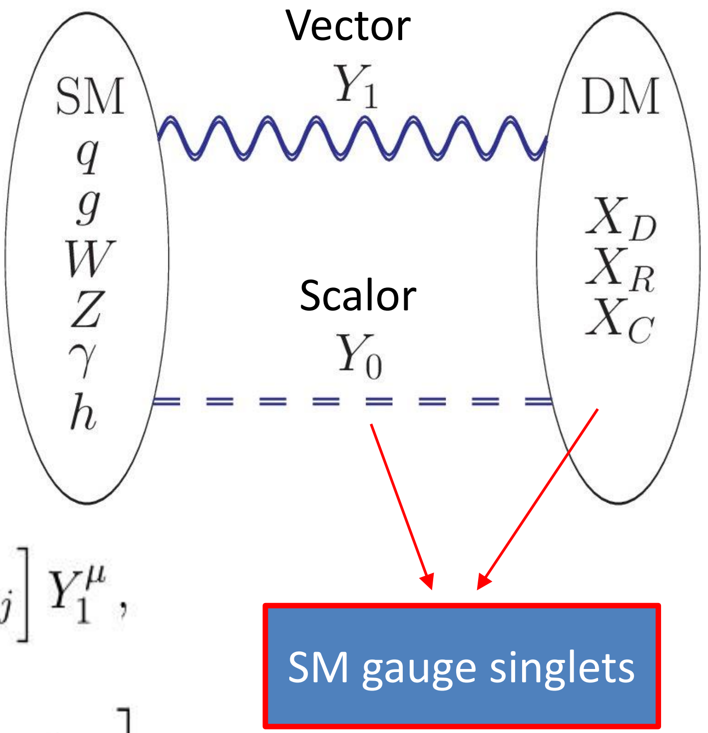

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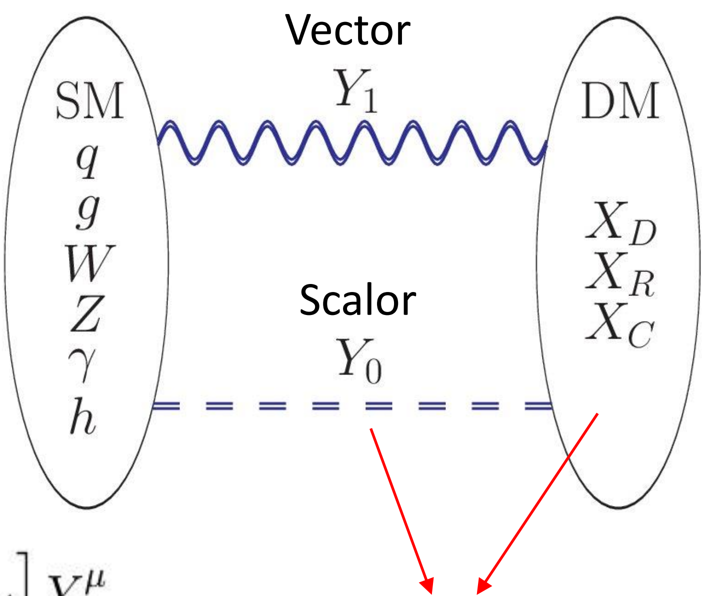

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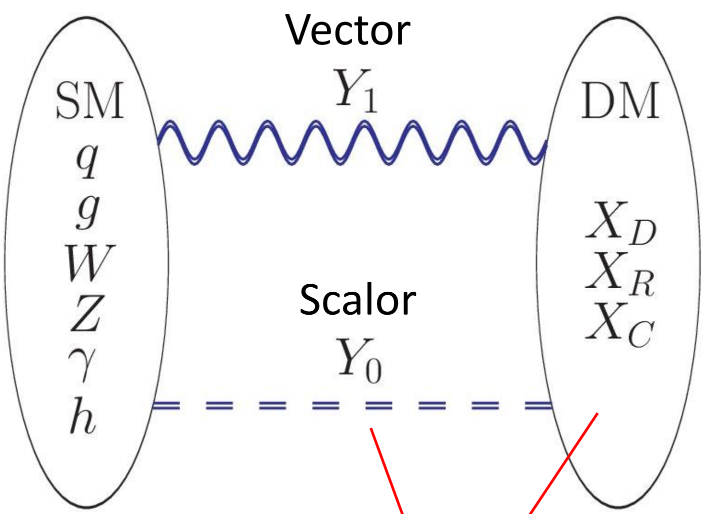

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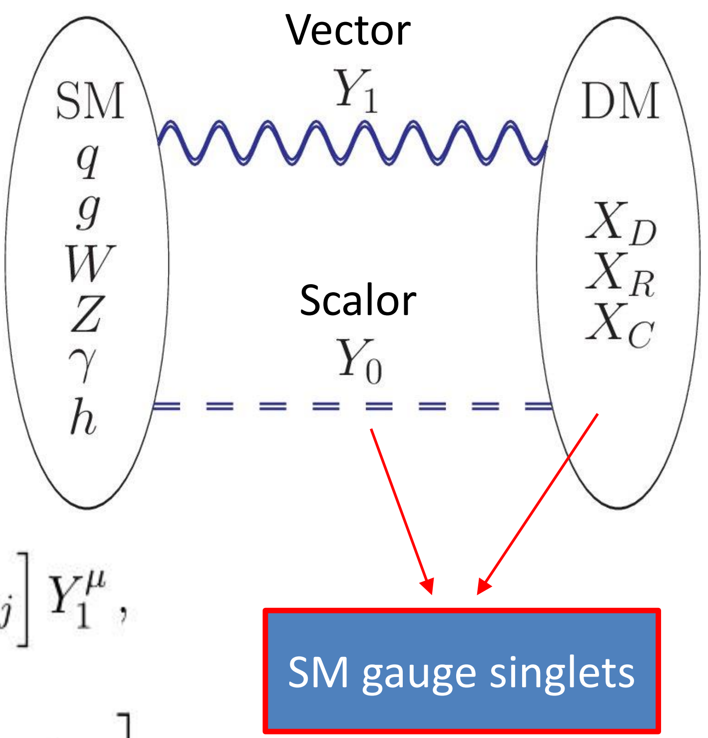

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$$\mathcal{L}_{\rm DM}^{Y_1} = \frac{i}{2}\,g^V_{X_C}\left[X_C^*(\partial_\mu X_C) - (\partial_\mu X_C^*)X_C\right]Y_1^\mu + \overline{X}_D\gamma_\mu(g^V_{X_D} + g^A_{X_D}\gamma_5)X_D\,Y_1^\mu\,,$$

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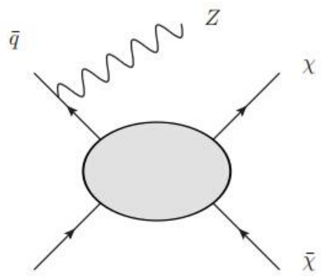

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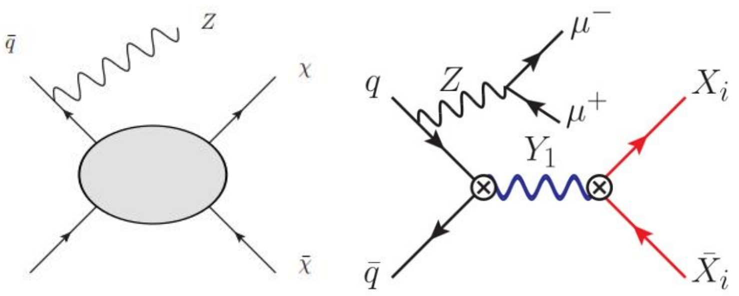

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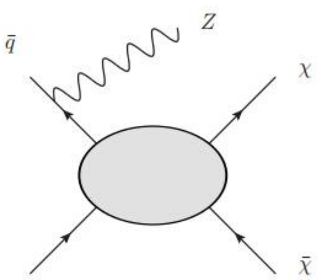

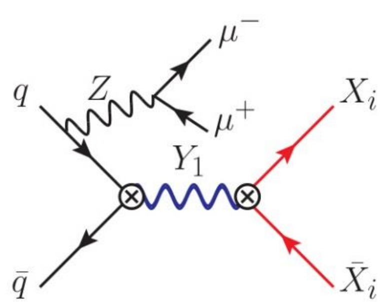

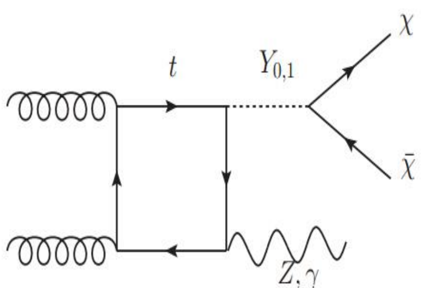

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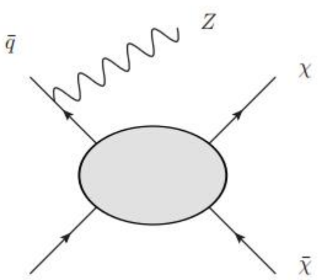

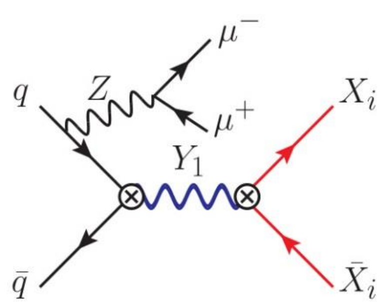

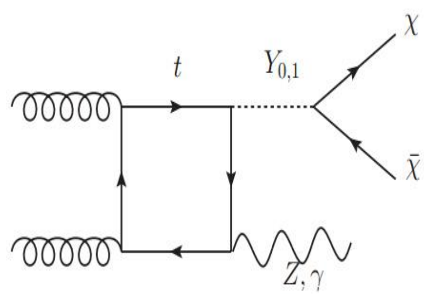

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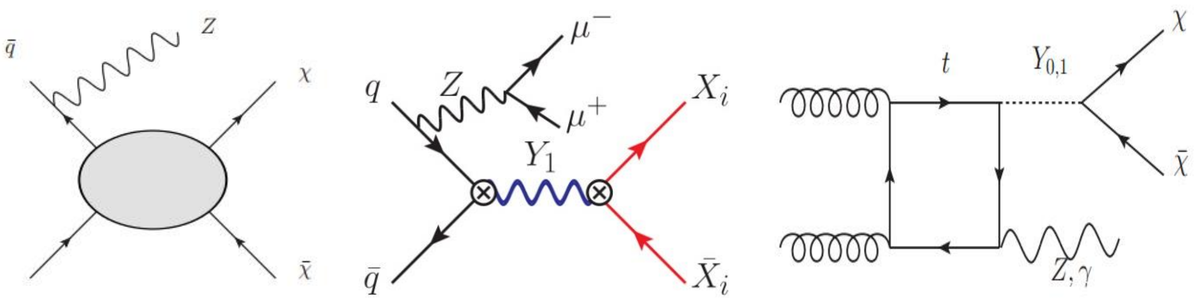

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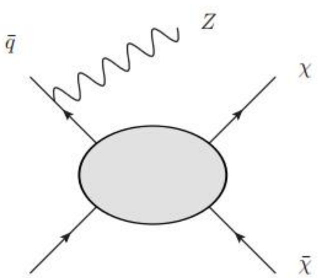

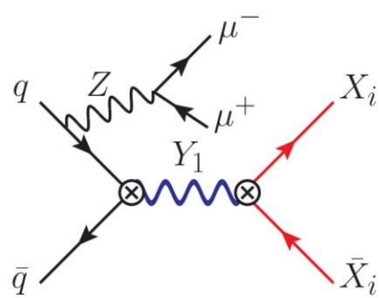

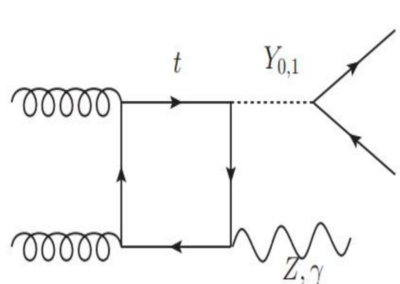

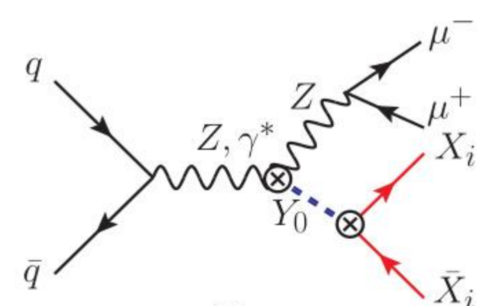

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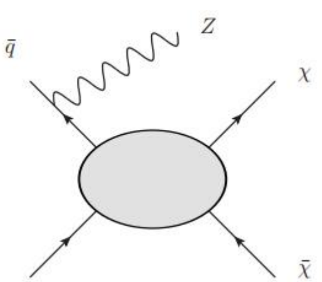
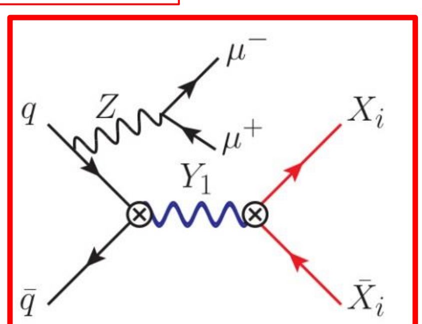
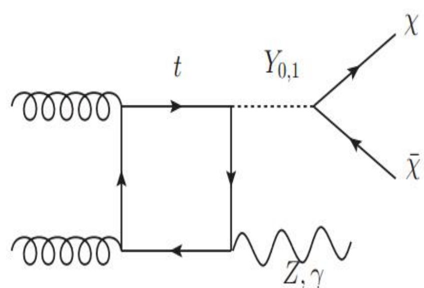
$$\mathcal{L}^{Y_0}_{\mathrm{EW,\,dim\text{-}5}} = \frac{1}{\Lambda}\Big[g^S_{h3}(D^\mu\phi)^\dagger(D_\mu\phi) + g^S_B\, B_{\mu\nu}B^{\mu\nu} + g^P_B\, B_{\mu\nu}\tilde{B}^{\mu\nu} + g^S_W W^i_{\mu\nu}W^{i,\mu\nu} + g^P_W\, W^i_{\mu\nu}\tilde{W}^{i,\mu\nu}\Big]Y_0\,,$$

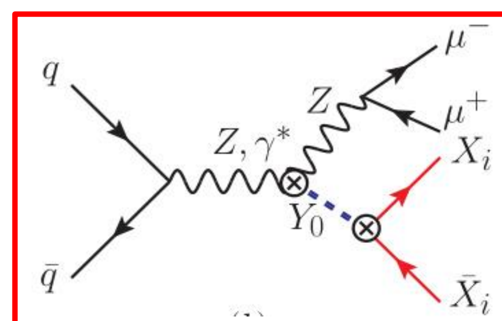
Scenario A

Scenario B









Implementation and validations

- **Our computations are performed in the framework of FeynRules interfaced with MadGraph5_aMC@NLO**
- **We have validated our implementation in several ways.**
  - ✓ **We have calculated the virtual QCD corrections for mono-Z production via the scalar mediator analytically**
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m_{DM} [GeV]	M_{med} [GeV]									
1	10	20	50	100	200	300	500	1000	2000	10000
10	10	15	50	100						10000
50	10		50	95	200	300				10000
150	10				200	295	500	1000		10000
500	10						500	995	2000	10000
1000	10							1000	1995	10000

ATLAS/CMS DM Forum
arXiv:1507.00966

Scenario A_2

Vector mediator, Dirac DM, spin-dependent interaction

$$g_q^A = 0.25,\ \ g_{X_D}^A = 1$$

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Vector mediator, Dirac DM, spin-dependent interaction

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NLO total cross sections (in pb) and K-factors. "e-n" for 10^n

m_{DM} [GeV]	M_{med} [GeV] 10	20 (15)	50	100 (95)	200	300 (295)	500	1000 (995)	2000 (1995)	10000
1	8.5	3.5	1.0	0.35	0.10	4.5e-2	1.3e-2	1.7e-3	1.1e-4	1.3e-8
10	4.6e-2	5.8e-2	0.90	0.34						1.3e-8
50	2.5e-3		2.9e-3	6.6e-3	8.0e-2	4.1e-2				1.2e-8
150	2.0e-4				3.0e-4	8.5e-4	8.8e-3	1.6e-3		1.0e-8
500	3.5e-6						4.5e-6	2.8e-5	7.8e-5	4.1e-9
1000	1e-7							1.4e-7	1.3e-6	9.4e-10
m_{DM} [GeV]	K-factor									
1	1.57	1.46	1.49	1.48	1.42	1.39	1.38	1.35	1.29	1.29
10	1.49	1.50	1.48	1.47						1.29
50	1.41		1.42	1.43	1.42	1.41				1.29
150	1.38				1.38	1.39	1.40	1.36		1.29
500	1.33						1.34	1.36	1.29	1.23
1000	1.21							1.22	1.27	1.09

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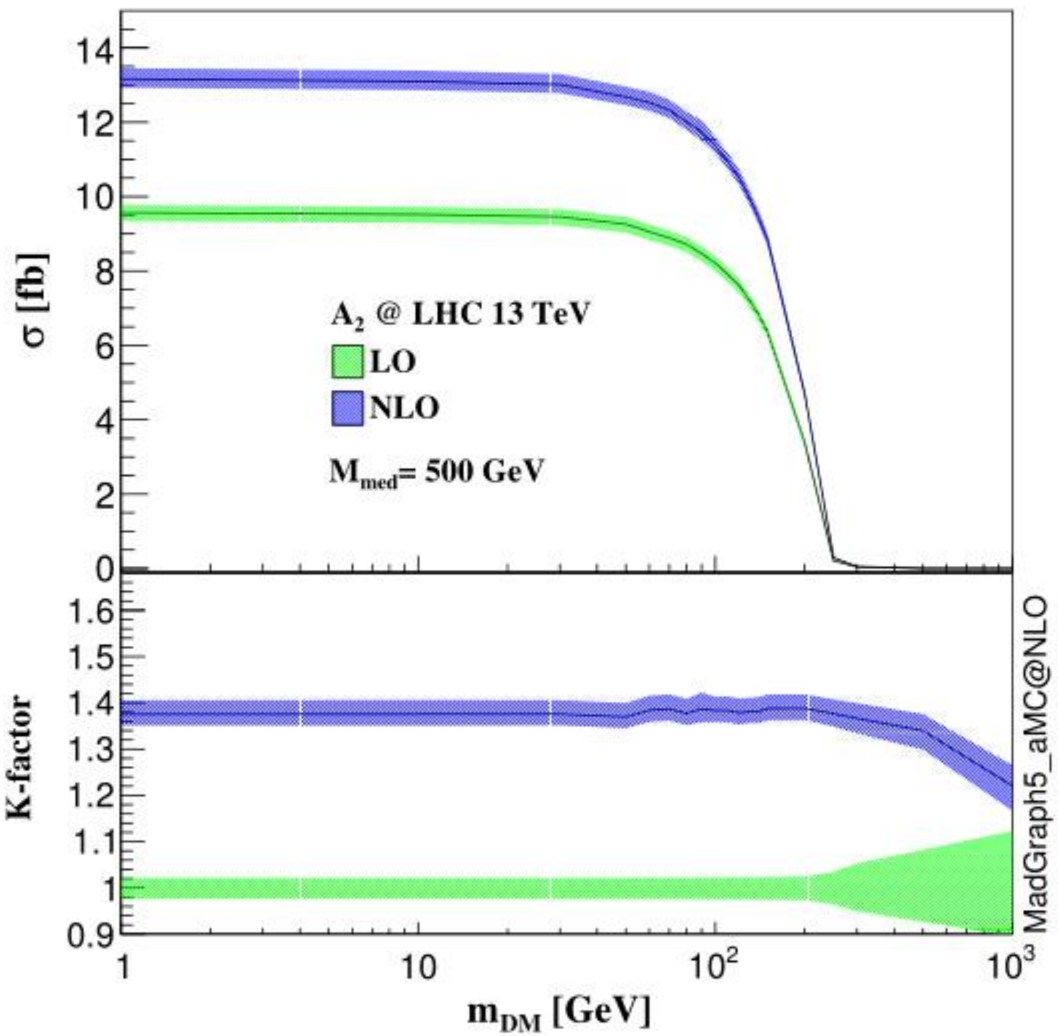
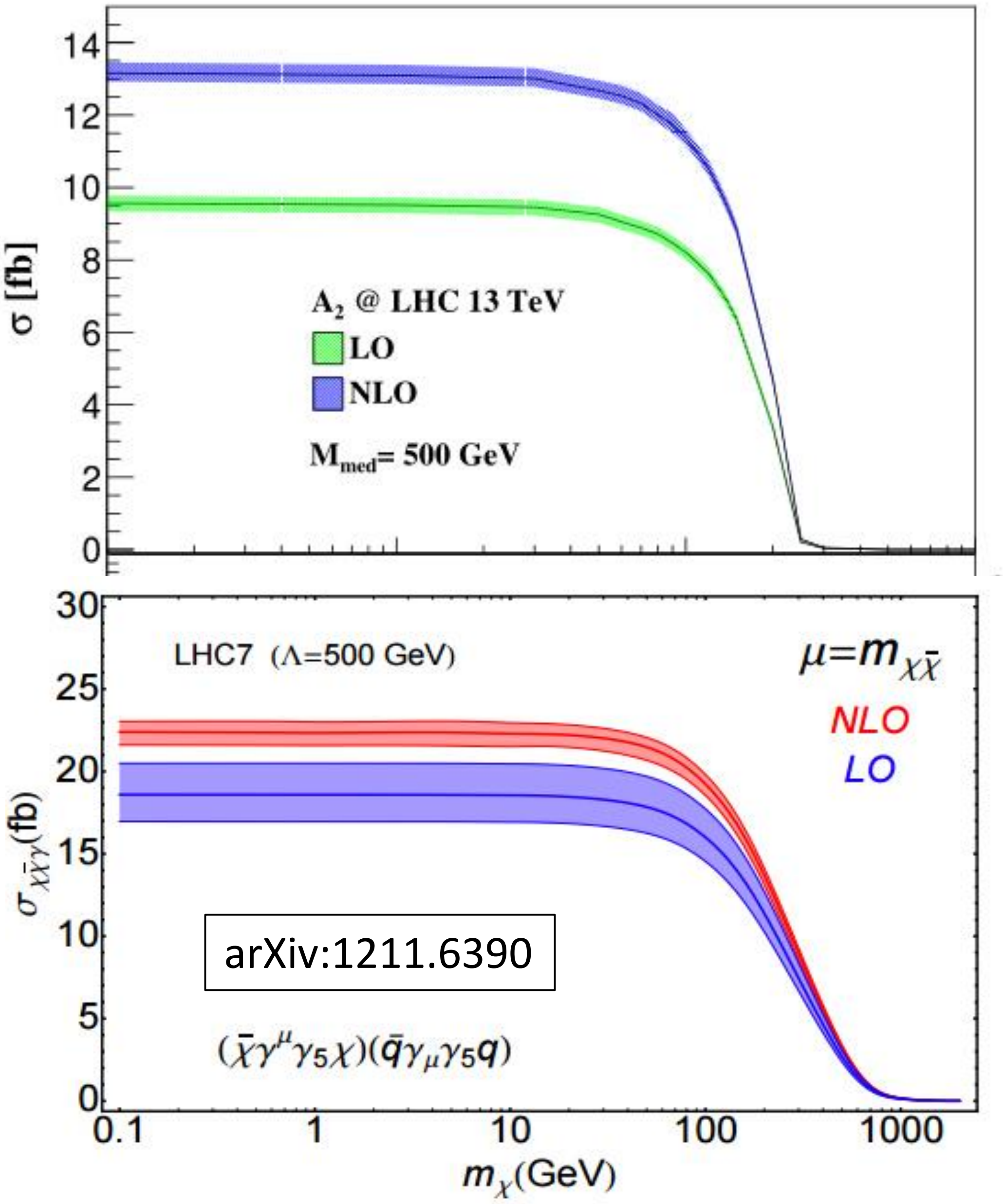


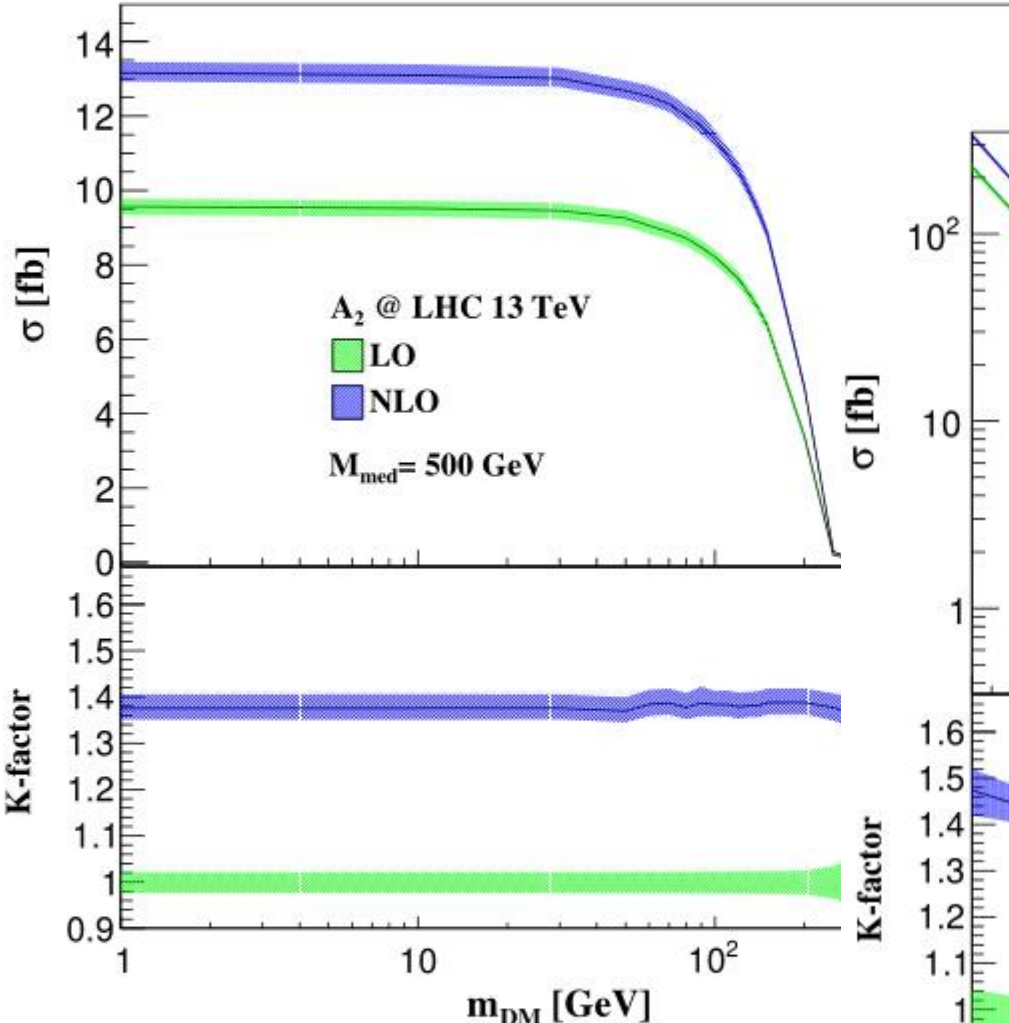
σ [fb]
14
12
10
8
6
4
2
0
A₂ @ LHC 13 TeV
LO
NLO
M_med= 500 GeV
K-factor
1.6
1.5
1.4
1.3
1.2
1.1
1
0.9
MadGraph5_aMC@NLO
1
10
10²
10³
m_DM [GeV]

Scenario A_2

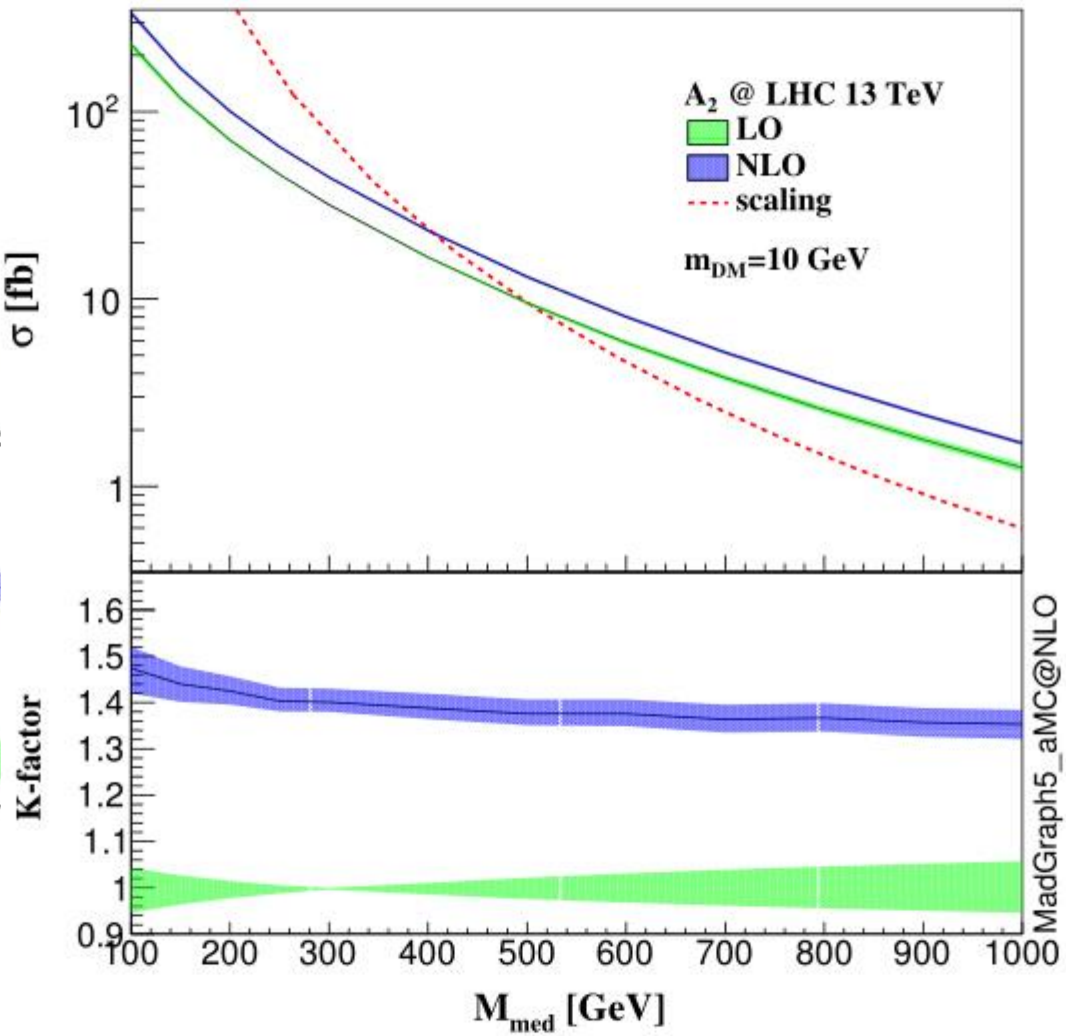


14
12
10
8
6
4
2
0
σ [fb]
A₂ @ LHC 13 TeV
LO
NLO
M_med= 500 GeV
30
25
20
15
10
5
0
0.1
1
10
100
1000
m_χ(GeV)
LHC7 (Λ=500 GeV)
μ=m_χχ̄
NLO
LO
arXiv:1211.6390
(χ̄γ^μγ₅χ)(q̄γ_μγ₅q)

Scenario A_2



σ [fb]
K-factor
m_DM [GeV]
A_2 @ LHC 13 TeV
LO
NLO
M_med= 500 GeV



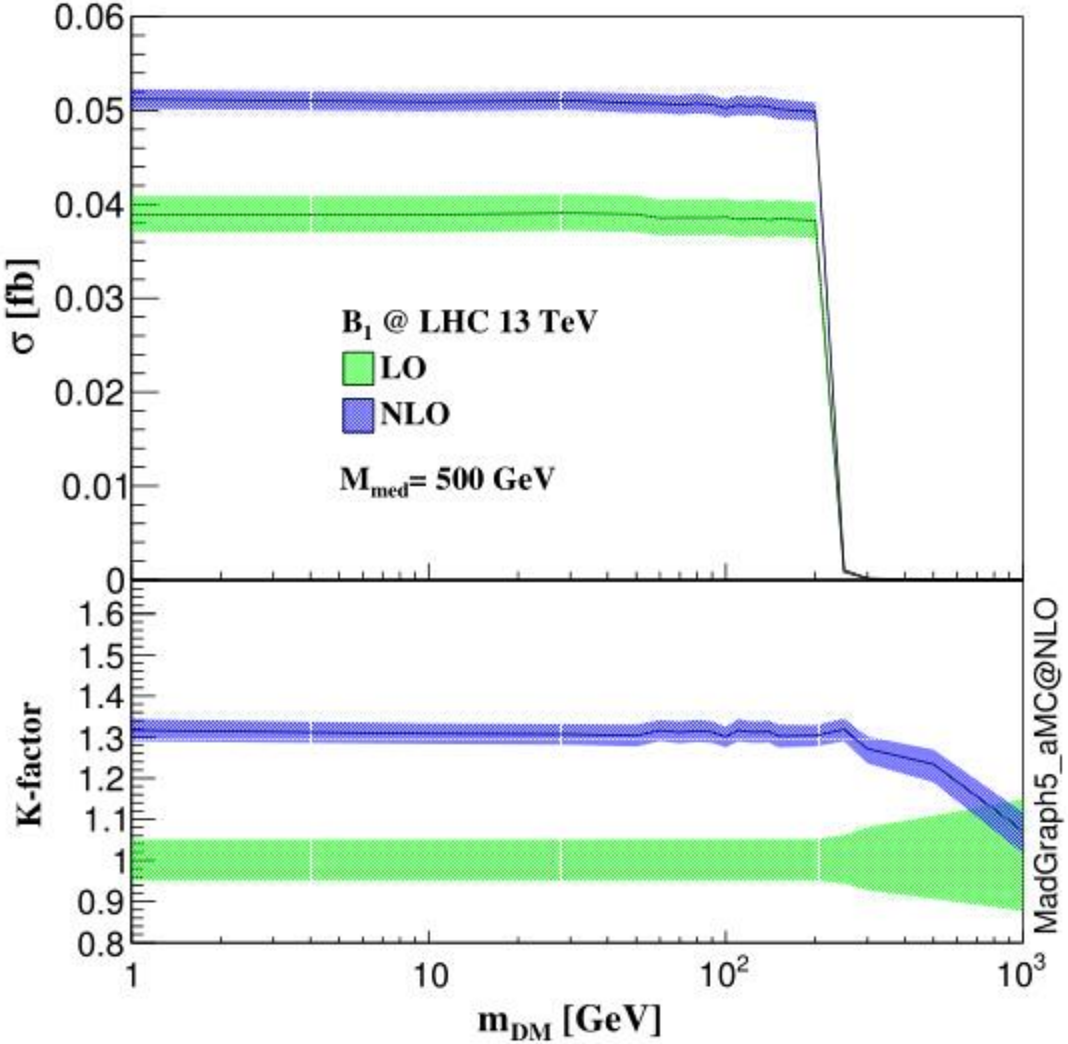
σ [fb]
K-factor
M_med [GeV]
A_2 @ LHC 13 TeV
LO
NLO
scaling
m_DM=10 GeV
MadGraph5_aMC@NLO

Scenario B_1

Scalor mediator, Dirac DM, CP-even interaction

$$\frac{1}{\Lambda} g_W^S W_{i,\mu\nu} W^{i,\mu\nu} Y_0$$

$$g_W^S = 0.25,\ g_{X_D}^S = 1,\ \Lambda = 3\ \text{TeV}$$



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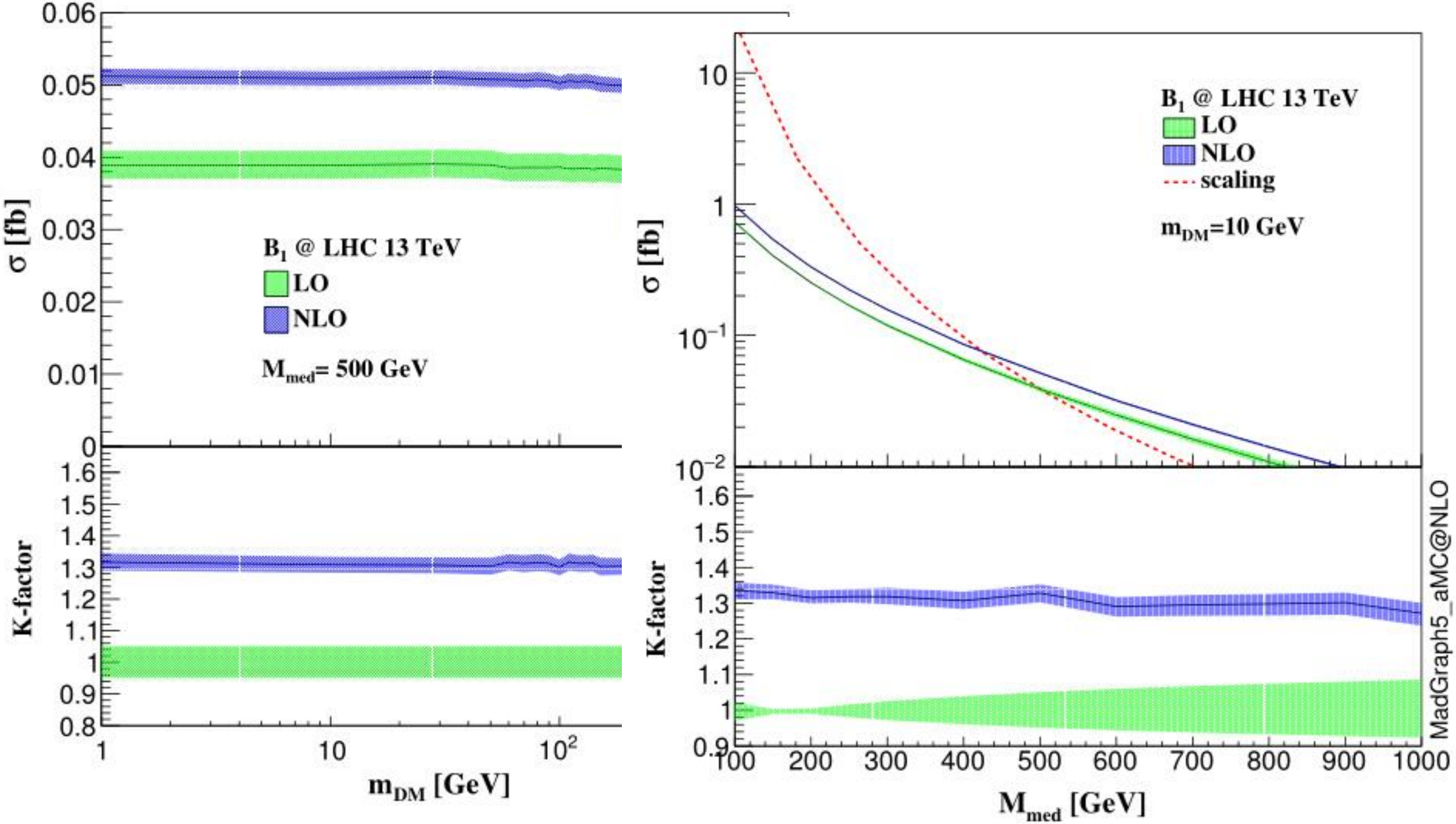
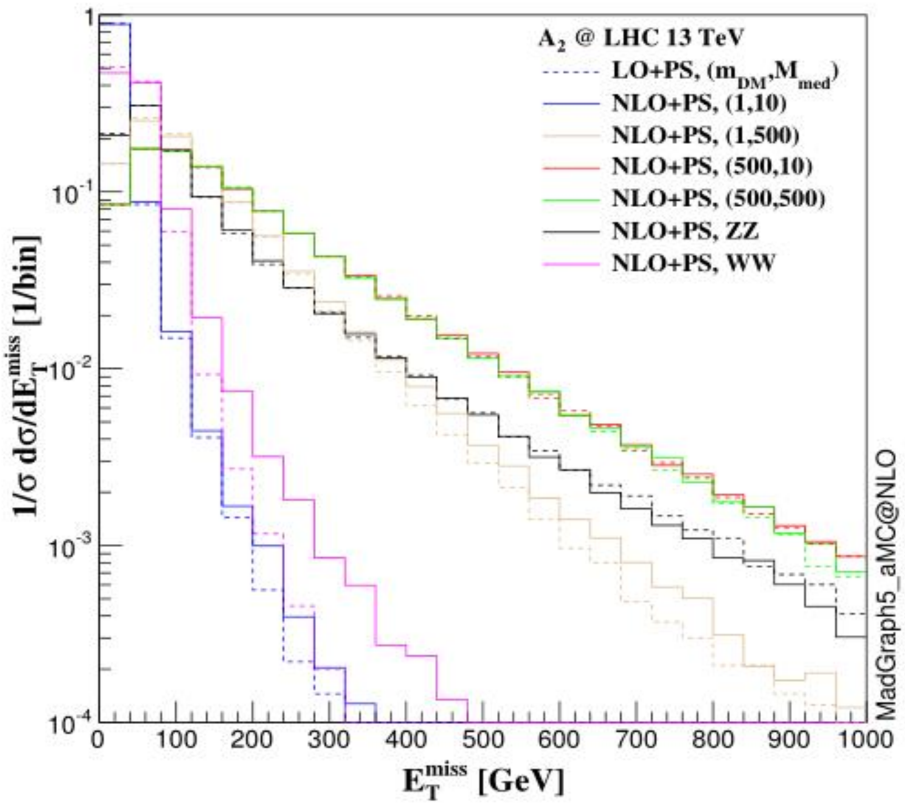
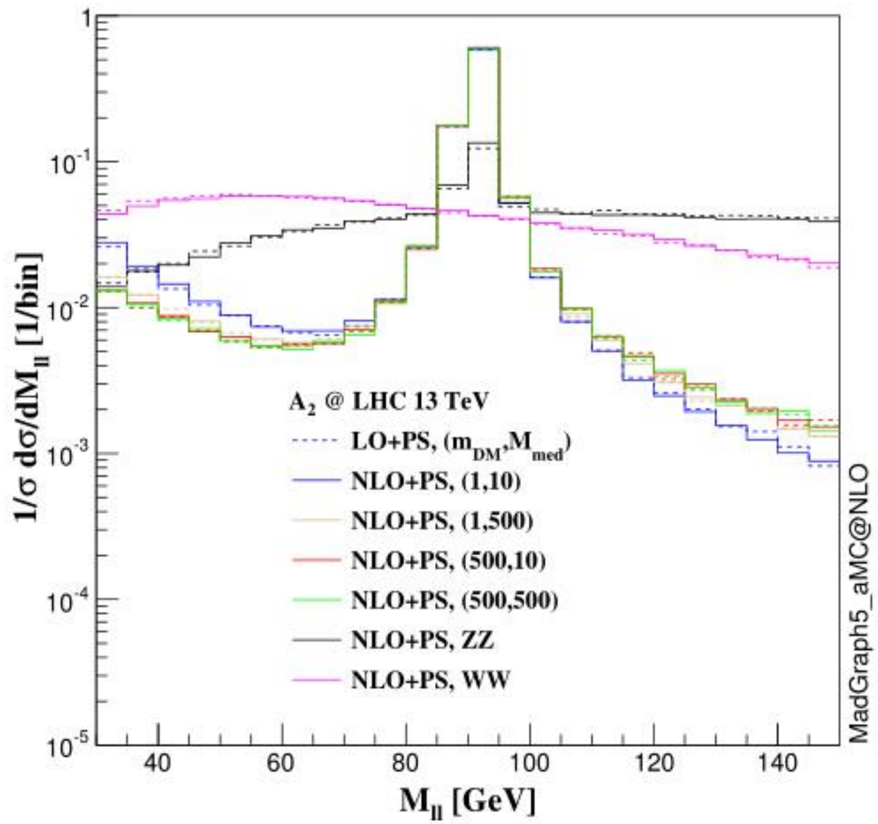
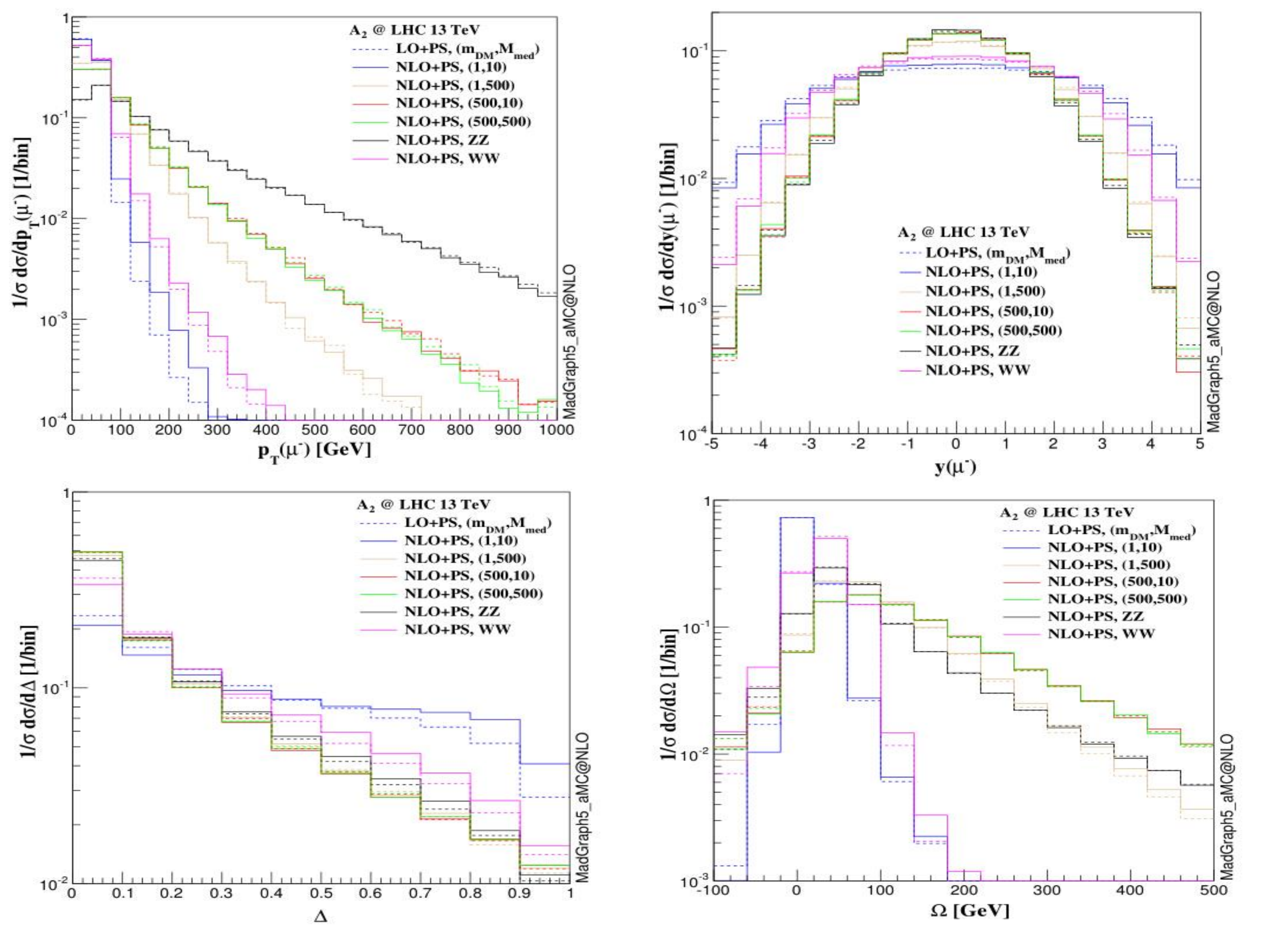


Kinematic distributions

- We present distributions of six observables: the missing transverse energy E_T^{miss}, the dilepton invariant mass M_{ll}, the muon transverse momentum $p_T(\mu^-)$ and rapidity $y(\mu^-)$, $\Delta = \left|E_T^{miss} - p_T^Z\right|/p_T^Z$ and $\Omega = -\overrightarrow{p_T^{miss}} \cdot \overrightarrow{p_T^Z}/p_T^Z$.
- We also show the SM backgrounds of $pp \to ZZ \to \bar{\nu}\nu\mu^+\mu^-$ and of $pp \to W^+W^- \to \bar{\nu}\nu\mu^+\mu^-$ for comparison.



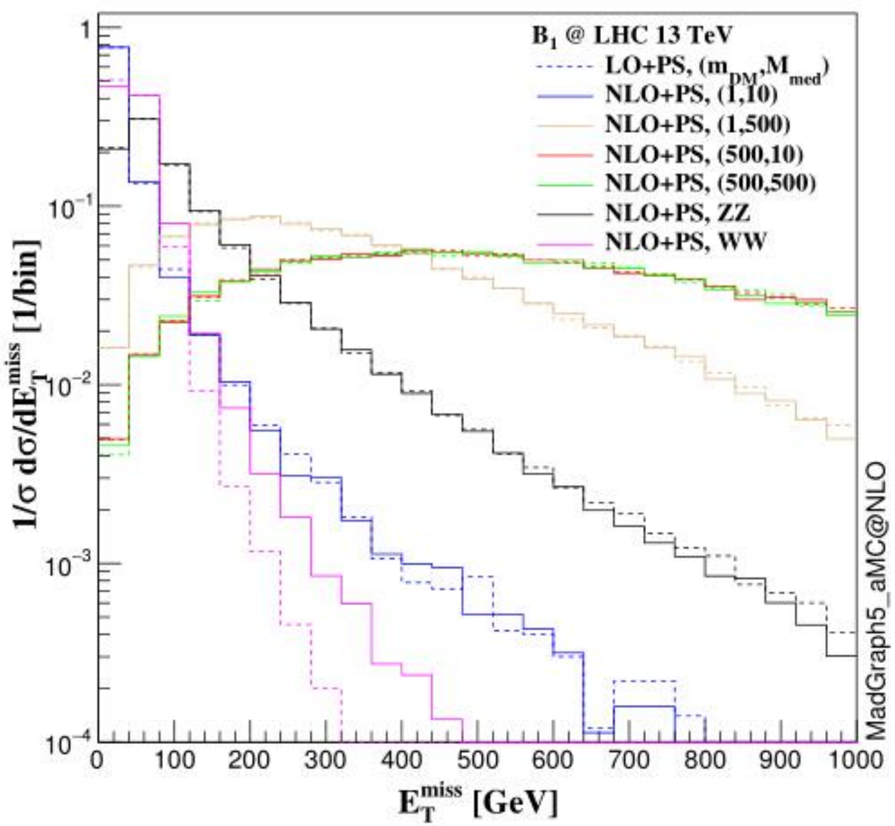


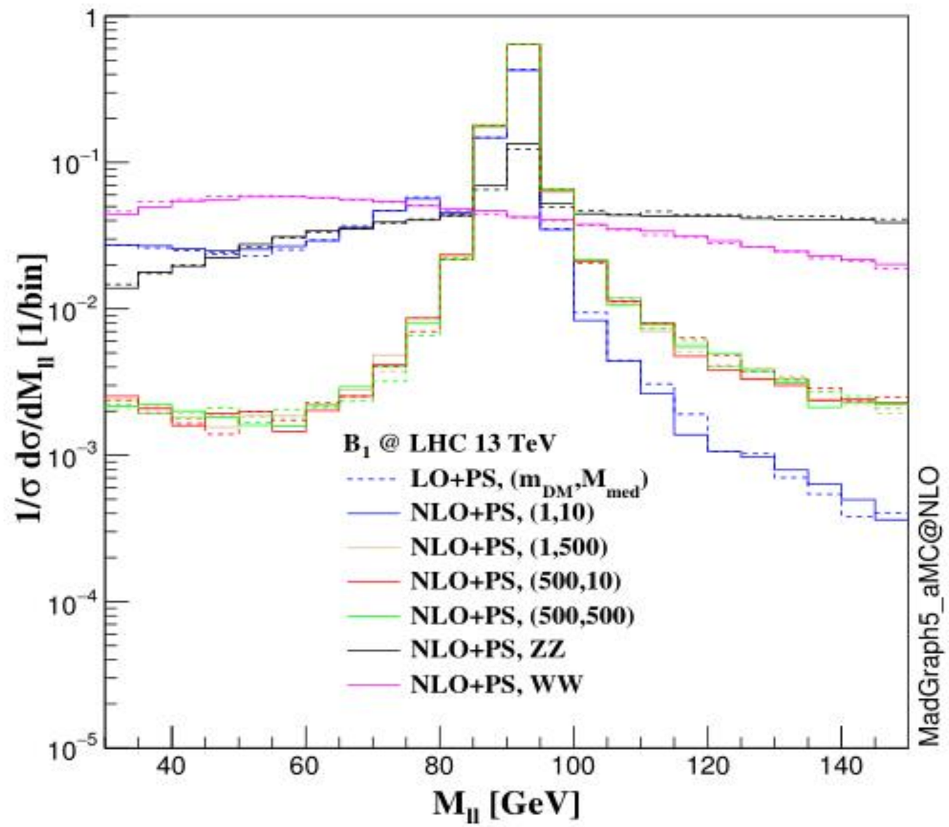


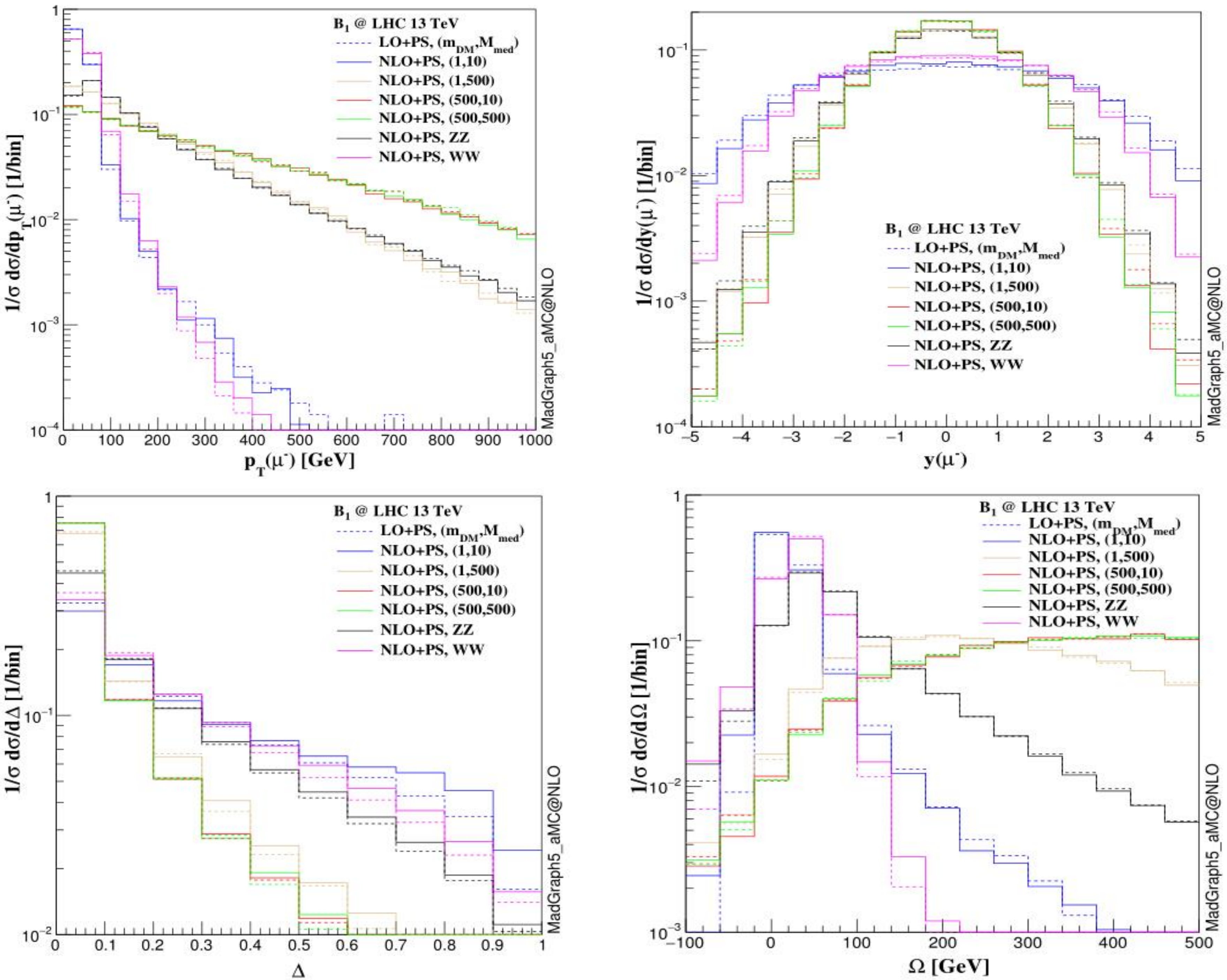
A2 @ LHC 13 TeV
LO+PS, (mDM,Mmed)
NLO+PS, (1,10)
NLO+PS, (1,500)
NLO+PS, (500,10)
NLO+PS, (500,500)
NLO+PS, ZZ
NLO+PS, WW
1/σ dσ/dpT(μ-) [1/bin]
pT(μ-) [GeV]
1/σ dσ/dy(μ-) [1/bin]
y(μ-)
1/σ dσ/dΔ [1/bin]
Δ
1/σ dσ/dΩ [1/bin]
Ω [GeV]
MadGraph5_aMC@NLO

Kinematic distributions

Scenario B_1







B_1 @ LHC 13 TeV
LO+PS, (m_{DM},M_{med})
NLO+PS, (1,10)
NLO+PS, (1,500)
NLO+PS, (500,10)
NLO+PS, (500,500)
NLO+PS, ZZ
NLO+PS, WW
$1/\sigma\ d\sigma/dp_T(\mu^-)$ [1/bin]
$p_T(\mu^-)$ [GeV]
$1/\sigma\ d\sigma/dy(\mu^-)$ [1/bin]
$y(\mu^-)$
$1/\sigma\ d\sigma/d\Delta$ [1/bin]
Δ
$1/\sigma\ d\sigma/d\Omega$ [1/bin]
Ω [GeV]
MadGraph5_aMC@NLO

Discovery potential at the 13 TeV LHC

Basic cuts: $p_T(\mu^\pm) > 20 \text{ GeV}\,, \qquad |y(\mu^\pm)| < 2.5$

Advanced cuts: $E_T^{\text{miss}} > 100 \text{ GeV}\,, \quad M_{ll} \in [85 \text{ GeV}, 100 \text{ GeV}]\,, \quad \Delta < 0.4\,, \quad \Omega > 80 \text{ GeV}\,.$

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M_{med} [GeV]	Basic cuts	E_T^{miss}	M_{ll}	Δ	Ω	ϵ_{cut}
Benchmark scenario A_2						
100	326	275	158	53.7	20.4	0.061
200	97.7	86.6	59.1	28.0	11.7	0.117
500	12.9	12.0	9.39	5.76	2.73	0.209
1000	1.68	1.59	1.32	0.890	0.451	0.265
ZZ	4747	3688	2101	1379	16.0	$3.24 \cdot 10^{-3}$
WW	988	479	82.6	10.6	0.487	$4.31 \cdot 10^{-4}$
Benchmark scenario B_1						
100	0.966	0.897	0.684	0.466	0.238	0.245
200	0.331	0.319	0.281	0.228	0.129	0.388
500	$5.09 \cdot 10^{-2}$	$5.02 \cdot 10^{-2}$	$4.81 \cdot 10^{-2}$	$4.35 \cdot 10^{-2}$	$2.78 \cdot 10^{-2}$	0.546
1000	$6.81 \cdot 10^{-3}$	$6.77 \cdot 10^{-3}$	$6.63 \cdot 10^{-3}$	$6.23 \cdot 10^{-3}$	$4.24 \cdot 10^{-3}$	0.622
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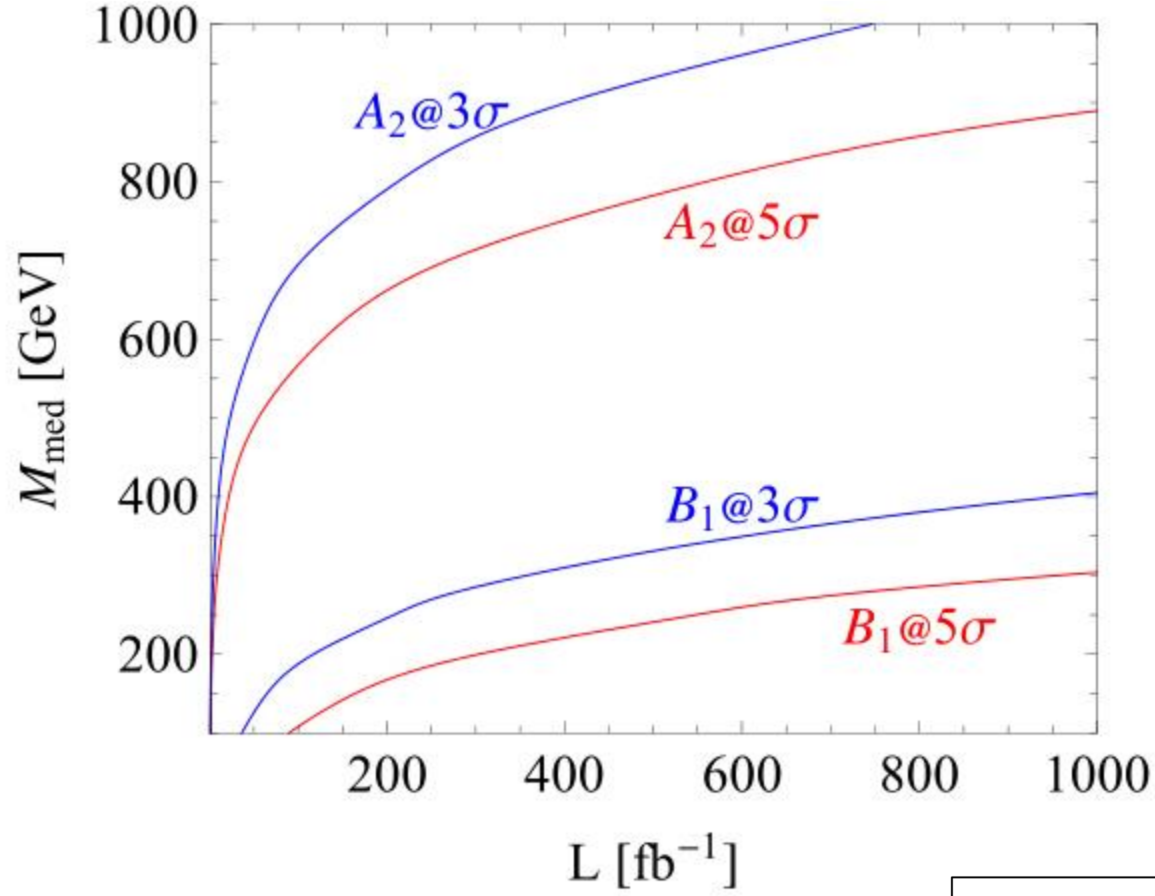
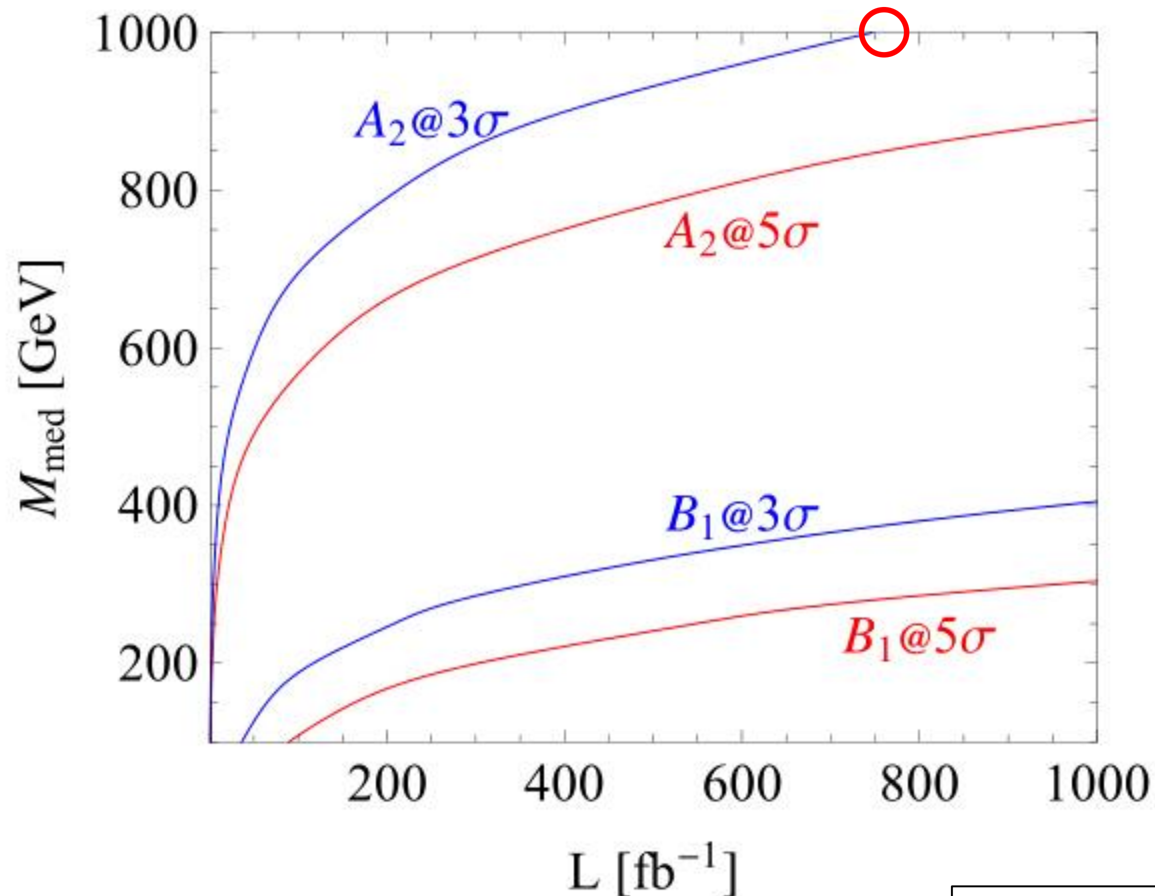
Discovery potential at the 13 TeV LHC



$m_{DM} = 10$ GeV
$\Lambda = 1$ TeV.

Discovery potential at the 13 TeV LHC

$750\ fb^{-1}$



$m_{DM} = 10$ GeV
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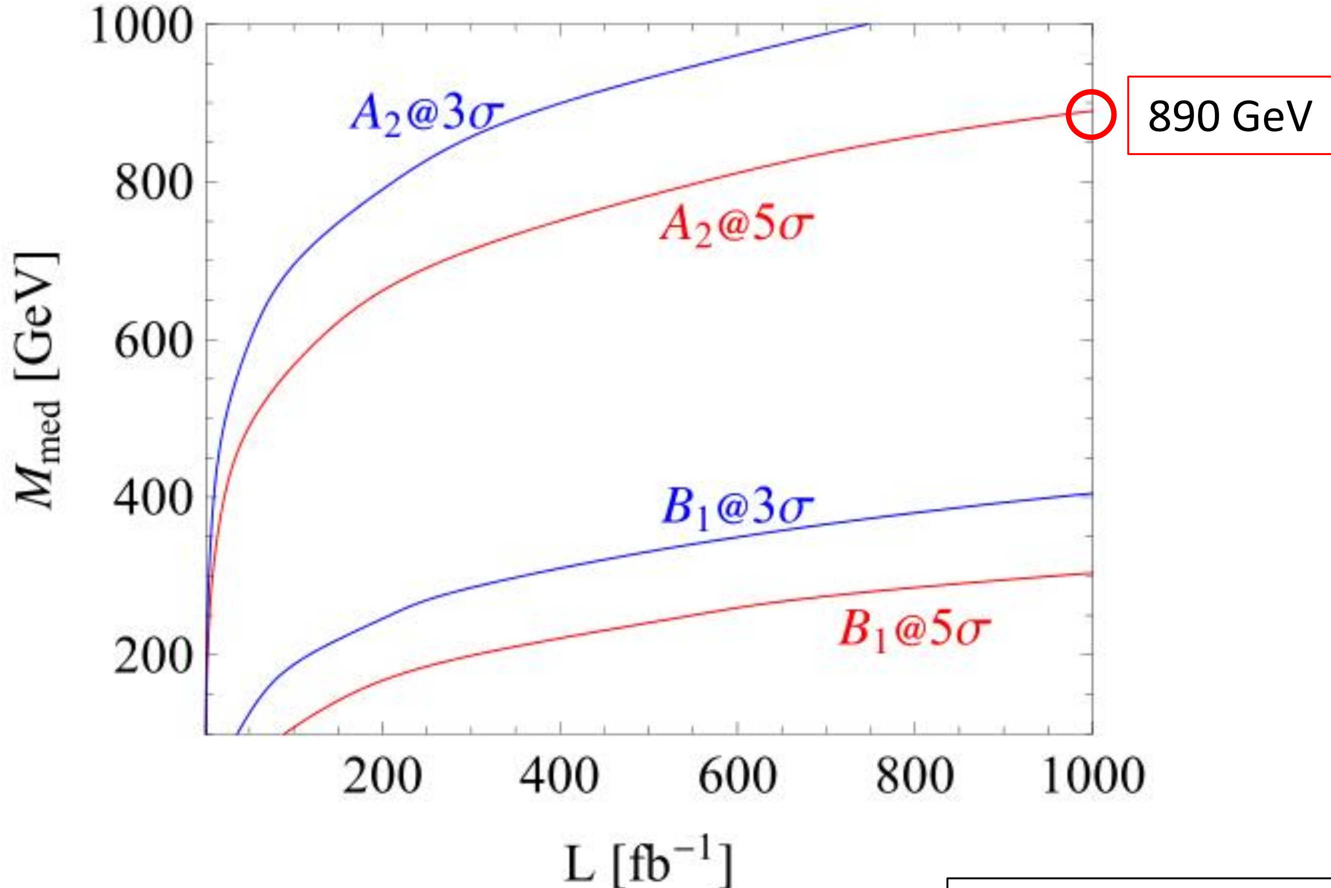
Discovery potential at the 13 TeV LHC



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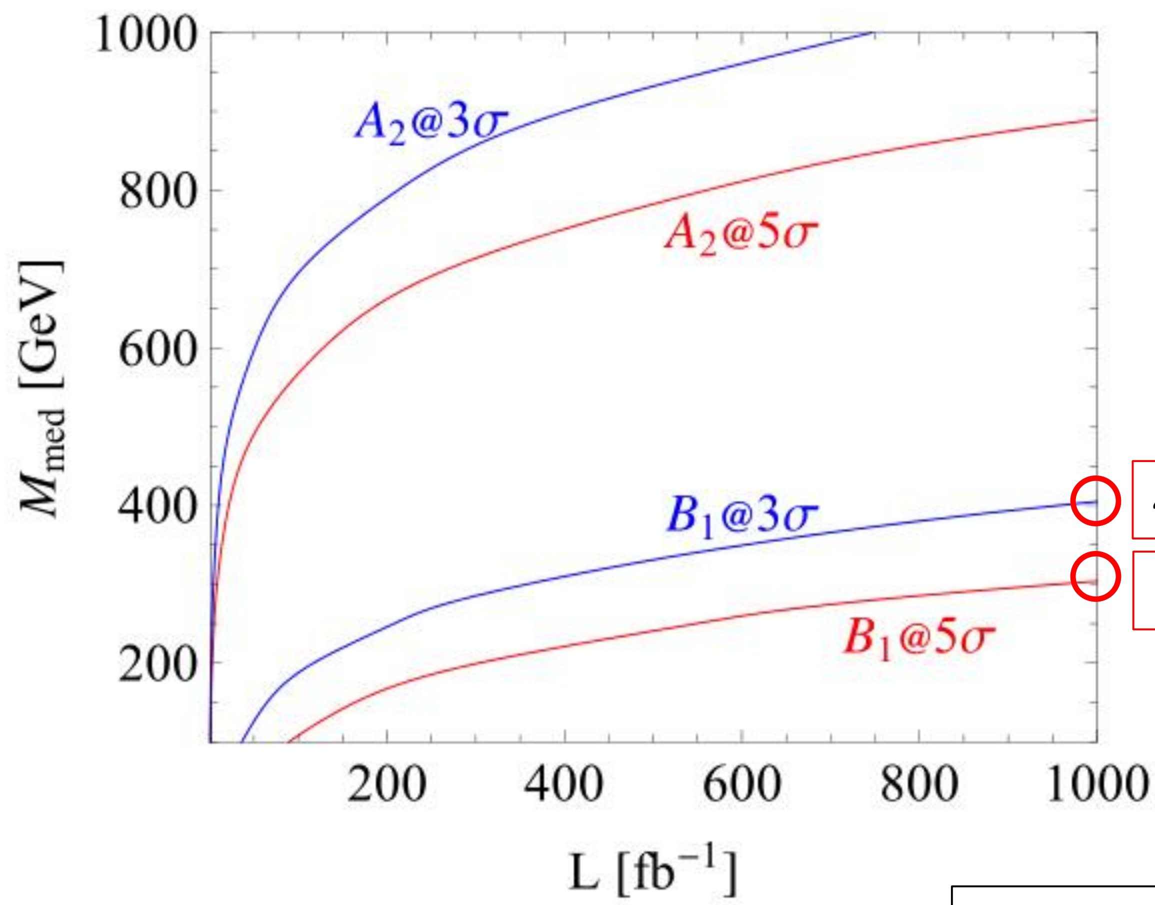
Discovery potential at the 13 TeV LHC



400 GeV

300 GeV

$m_{DM} = 10$ GeV
$\Lambda = 1$ TeV.

Summary

- **We have implemented a class of simplified models for DM production via s-channel vector or scalar mediators in the FeynRules/MadGraph5_aMC@NLO framework.**
- **We have presented the first NLO QCD predictions for mono-Z signals in simplified models including parton-shower effects.**
- **The K-factors vary in the range of about 1.3 – 1.5, which shows that the NLO corrections have a noticeable impact on the mono-Z signal and should not be ignored.**
- **The theoretical predictions of the cross sections become more reliable at NLO and in many cases the scale uncertainties are reduced.**

Summary

- **We have studied various kinematic distributions in order to better understand the feature of the mono-Z signal.**
- **We have also estimated the discovery potential of the mono-Z signal at the 13 TeV LHC.**
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http://feynrules.irmp.ucl.ac.be/wiki/DMsimp

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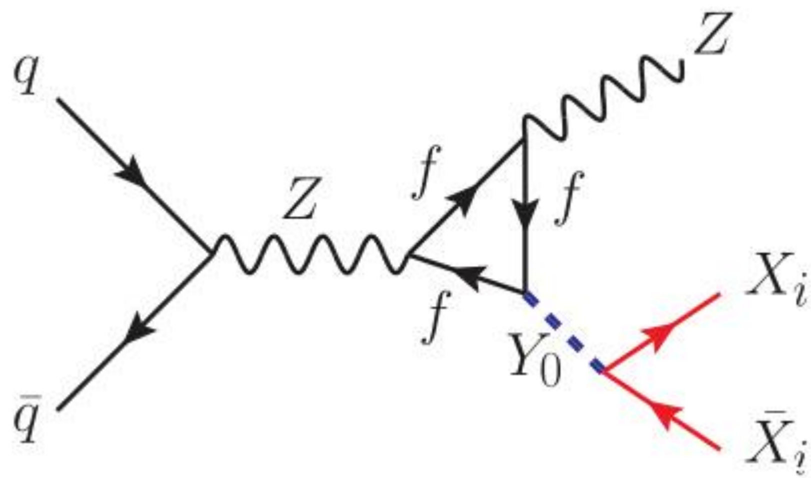
Thank you for your attention!

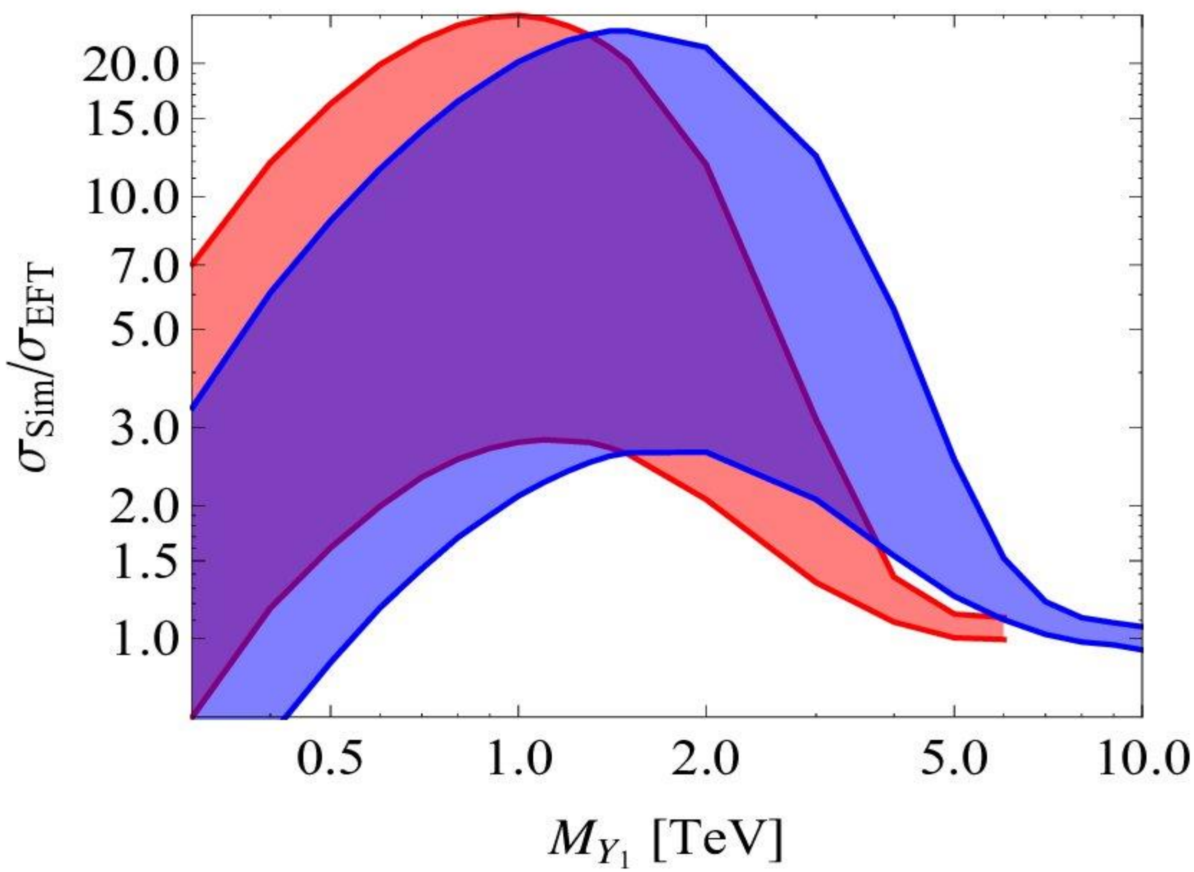
Back up

The loop diagram inducing the dim-5 operator



Compare EFT and Simplified model

Ratio of the mono-Z production cross sections at the 8 TeV (red) and 13 TeV (blue) LHC. The upper and lower limits of the bands correspond to the cases where $\Gamma_{Y1} = M_{Y1}/8\pi$ and $\Gamma_{Y1} = M_{Y1}/3$, respectively. The DM mass is chosen to be m_{DM} = 100 GeV.



Benchmark scenario B_1

	$M_{\rm med}$ [GeV]									
	10	20	50	100	200	300	500	1000	2000	10000
$m_{\rm DM}$ [GeV]		(15)		(95)		(295)		(995)	(1995)	
1	1.2e-2	7.2e-3	2.5e-3	9.8e-4	3.3e-4	1.5e-4	5.1e-5	6.9e-6	3.2e-7	3.1e-11
10	8.8e-5	1.1e-4	2.5e-3	9.7e-4						3.0e-11
50	6.5e-6		7.5e-6	1.6e-5	3.3e-4	1.6e-4				3.2e-11
150	5.8e-7				8.5e-7	2.4e-6	5.1e-5	6.7e-6		2.5e-11
500	9.5e-9						1.3e-8	8.8e-8	2.8e-7	8.6e-12
1000	9.7e-9							1.1e-7	2.9e-7	8.7e-12
$m_{\rm DM}$ [GeV]	K-factor									
1	1.43	1.42	1.39	1.35	1.33	1.30	1.32	1.31	1.17	1.21
10	1.37	1.37	1.37	1.33						1.17
50	1.32		1.31	1.32	1.32	1.32				1.29
150	1.31				1.32	1.32	1.31	1.28		1.22
500	1.23						1.25	1.27	1.18	1.10
1000	1.25							1.26	1.17	1.13