GRAVITON PRODUCTION AT HADRON COLLIDERS

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June 1st, 2011

based on P. d. A, Kaoru Hagiwara, Qiang Li, Fabio Maltoni, arXiv: 1101.5499

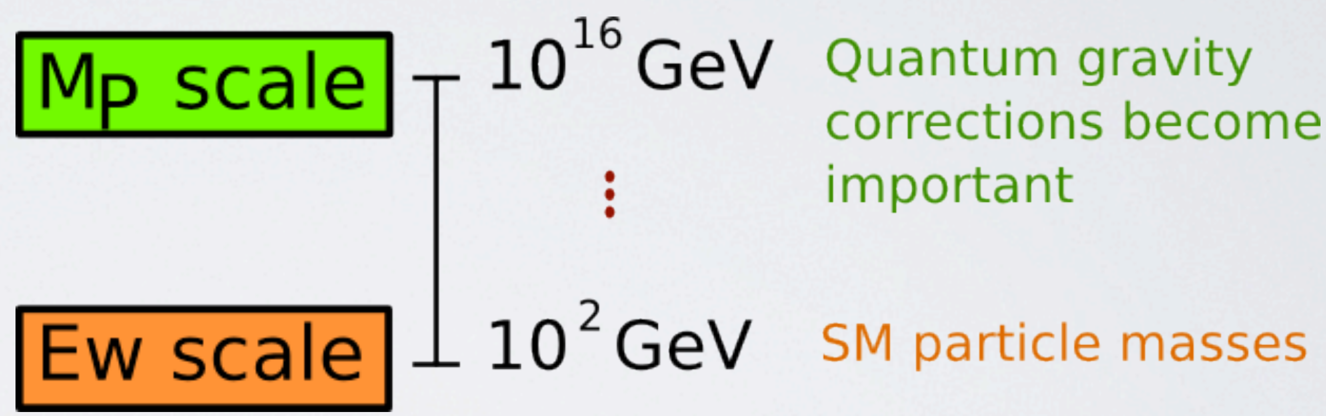
OUTLINE

- Introduction
  - Hierarchy problem
  - Extra dimensional models
- Phenomenology of graviton emission?!?
- Simulating graviton emission in a multi-jet final state
- Results and conclusions

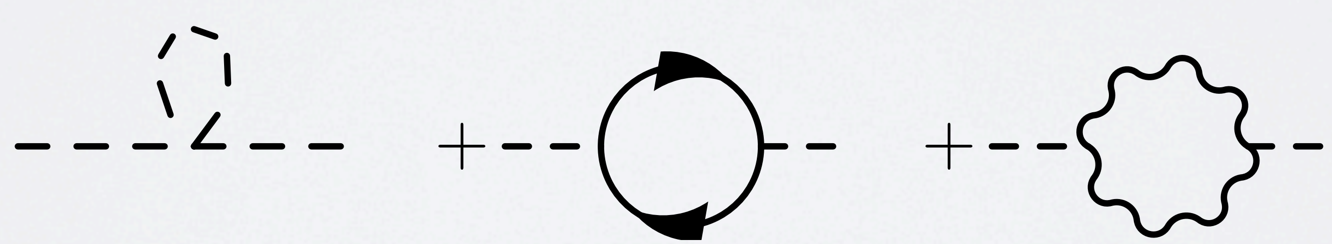
INTRODUCTION

The SM agrees to a great deal with the experimental data we have today, but there are several reasons to expect new physics at TeV scale.

The Hierarchy problem:



Standard Model $\longrightarrow$ Radiative corrections to the Higgs mass:



If $m_H < 200$ GeV $\longrightarrow$ there might be new physics at the TeV scale

PHENOMENOLOGY!

The LHC era! $\left\{ \begin{array}{l} \text{New and interesting pheno at LHC} \\ \text{New expectations for NP} \end{array} \right.$

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The LHC era! { New and interesting pheno at LHC
New expectations for NP

Careful pheno analysis at colliders = Accurate simulation necessary!

- Madgraph/MadEvent = software that allow to generate amplitudes and events for any process in any model

[J. Alwall et al, JHEP 0709:028, 2007]

Spin-2 particles recently incorporated!

[K. Hagiwara, J. Kanzaki, Q. Li and K. Mawatari, arXiv:0805.2554]

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We want to explore theories with spin-2 particles, and look for the phenomenology of graviton emission...

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... several LHC studies in monojet final-state, but what about processes with many jets in the final state?!?

Our aim: study graviton production in a multi-jet final state at hadron colliders for generic models that contain spin-2 particles!

MATCHING SCHEME

- Increasing $\sqrt{s}$ → more events with larger multiplicities

Accurate simulations need to correctly account for the presence of QCD radiation

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ME calculations	Parton Shower simulator
• parton-level description • valid for <u>**hard/separated partons**</u> • needed for multi-jet descriptions	• hadron-level description • valid for <u>**collinear/soft partons**</u> • needed for realistic studies
MadGraph	Pythia / Herwig

Complementary approach → Match them!

HT DISTRIBUTION

Goal: Obtain accurate predictions for non-trivial observables

- Important distributions to be analyzed:
  - P_T graviton and jets
  - η graviton and jets

- H_T = Scalar sum of the P_T of all jets above a threshold P_T^0

$$H_T = \sum P_T(jets)$$

  - H_T has been proven to be larger in signal than in QCD di-jet events
  - It provides a way to discriminate from SM background

PHENOMENOLOGY

In order to obtain accurate predictions for non-trivial observables:

- Generate inclusive sample with MG/ME + Pythia ⟶ matching
- Compare multi-jet matching X mono-jet NLO

Use NLO for normalization, and matching for distributions!

Processes:

- NLO: p p ⟶ G + jet + X (inclusive)
- Matching: p p ⟶ G + n-jets, with n=1,2,3

Which theories to consider ?!?:

BEYOND STANDARD MODEL

Attempt to explain the HP $\longrightarrow$ BSM theories

- **ADD:** model with large extra dimensions
  [N. Arkani-Hamed, S. Dimopoulos, G. Dvali, 1998]

- **RS:** model with a warped extra dimension
  [L. Randall, R. Sundrum, 1999]

- **MGM:** 4D model that contains a massless graviton
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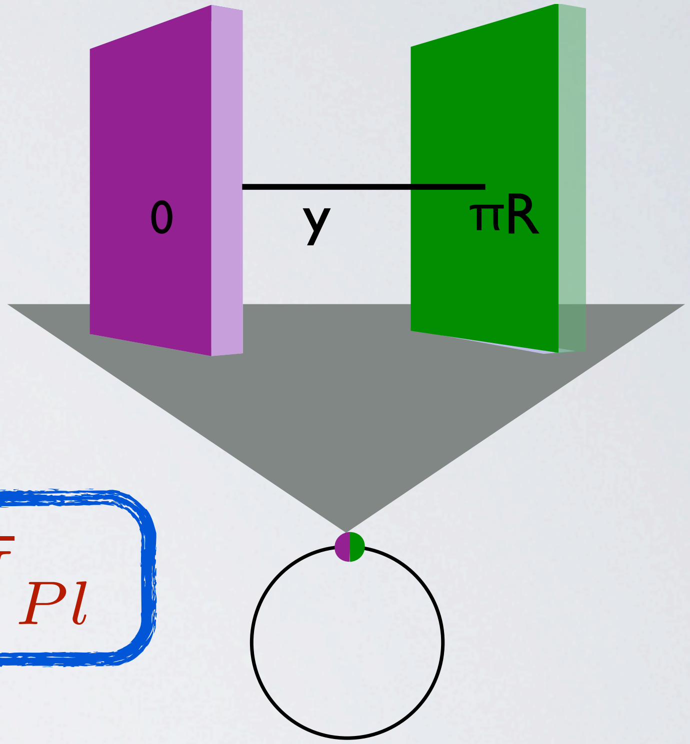
RS MODEL

- RS model = 5 dimensions, warped metric, compactified in a S_1/Z_2

$$\boxed{ds^2 = e^{-2\kappa|y|}\eta_{\mu\nu}dx^\mu dx^\nu + dy^2}$$

$$\boxed{\Lambda = e^{-\kappa\pi R}\overline{M}_{Pl}}$$



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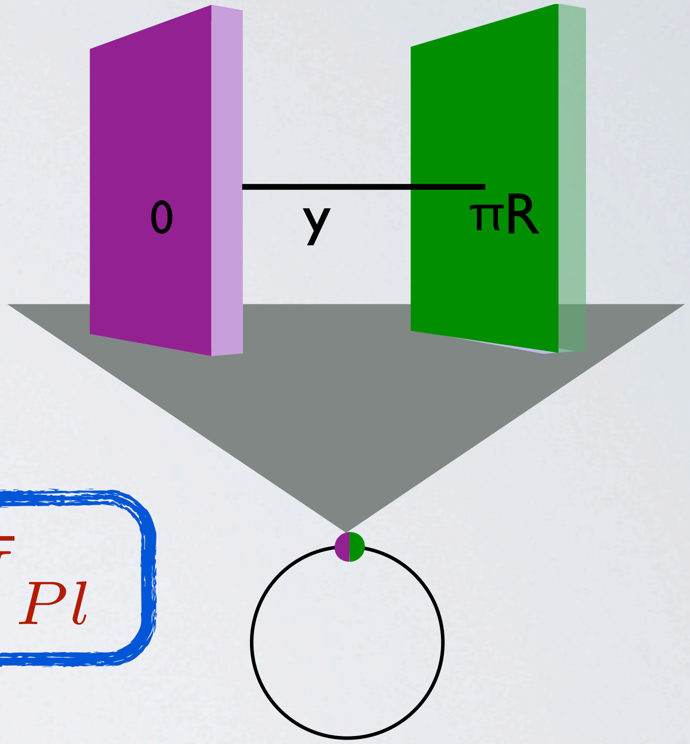

- Graviton propagating on δ
    - KK tower
    - massive graviton

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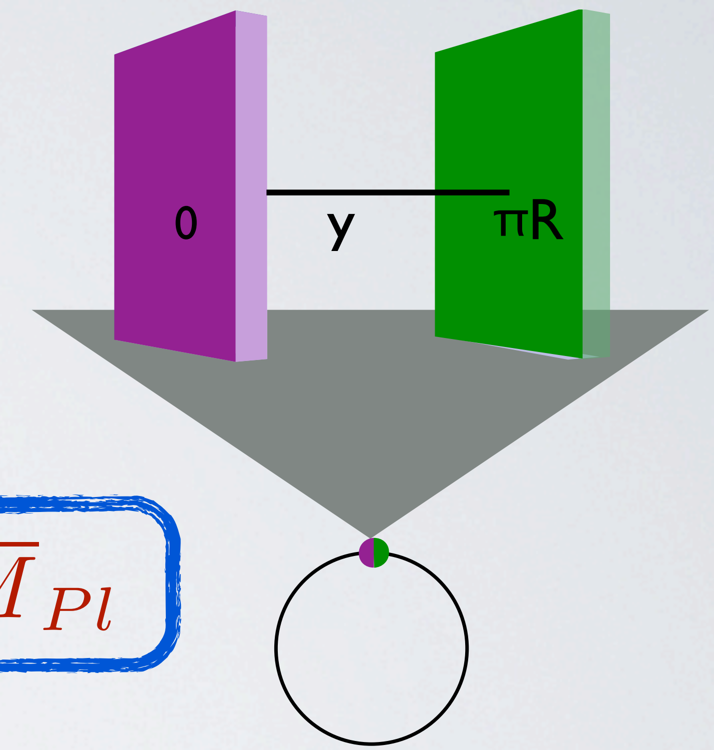
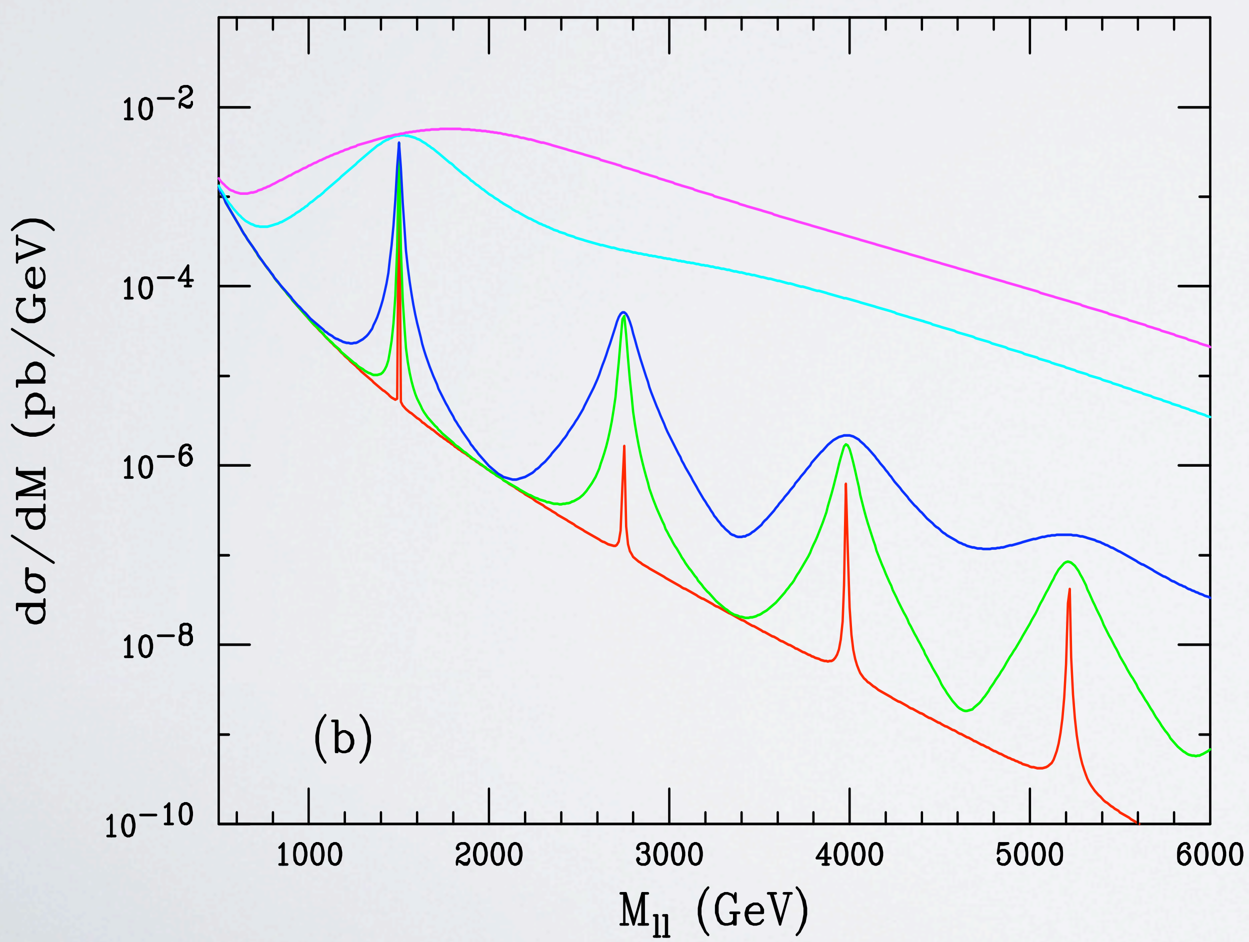


$$\Lambda = e^{-\kappa\pi R}\overline{M}_{Pl}$$

Phenomenology on graviton emission = **decayed product!**



→ [H. Davoudiasl, J. L. Hewett, T. G. Rizzo, Phys. Rev. D63, 075004 (2001)]

RS: FULL INCLUSIVE SAMPLE

- Aim: analyze **jet and graviton distributions** and compare the **shape** of matched results with the ones given by NLO calculation!

To warm up:

HT distribution

- RS model,

  Λ = 3 TeV, and

  M_G = 100 GeV

- Full inclusive sample;
- LO: pp > G,
  Matched: up to 2-jets

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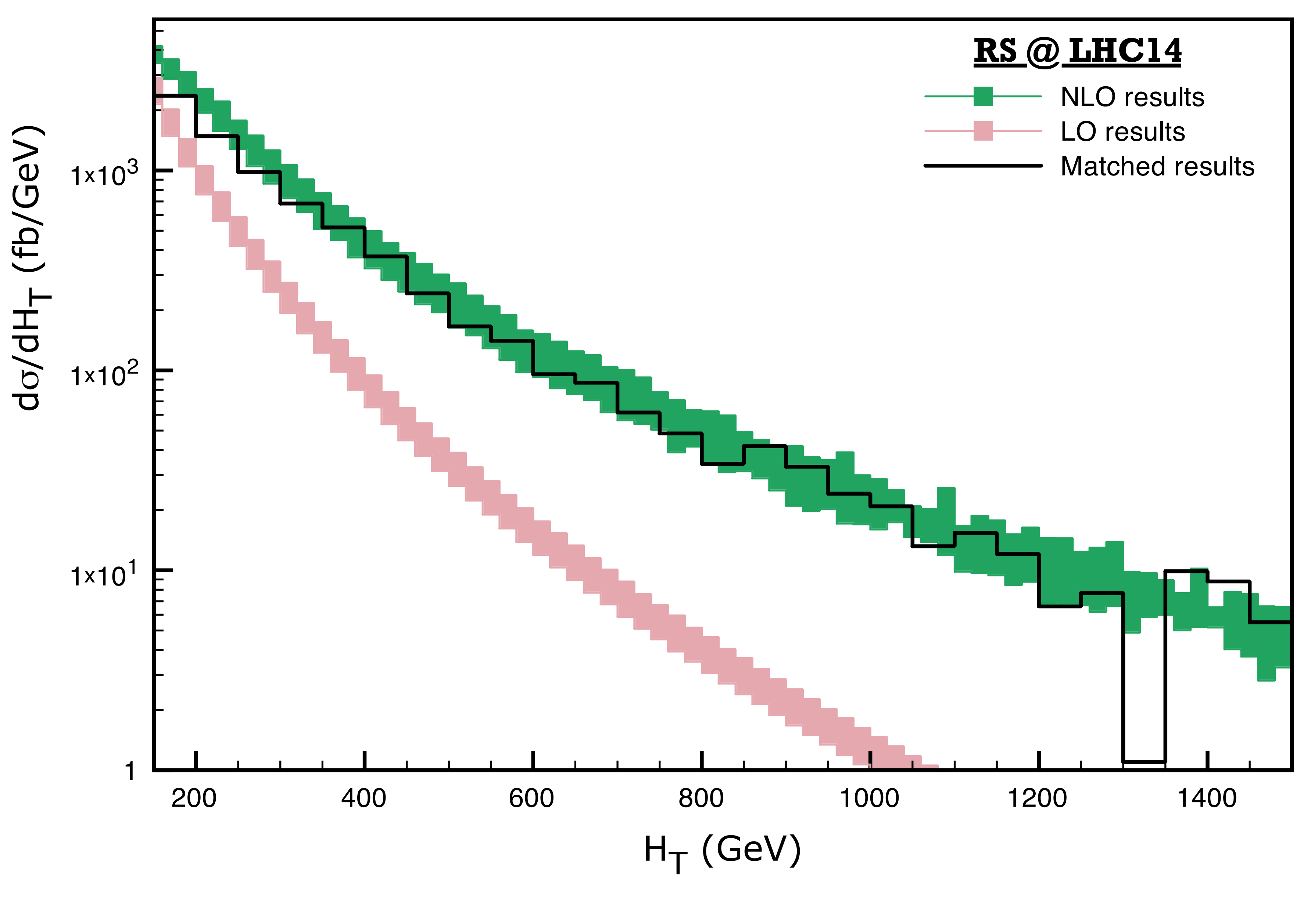

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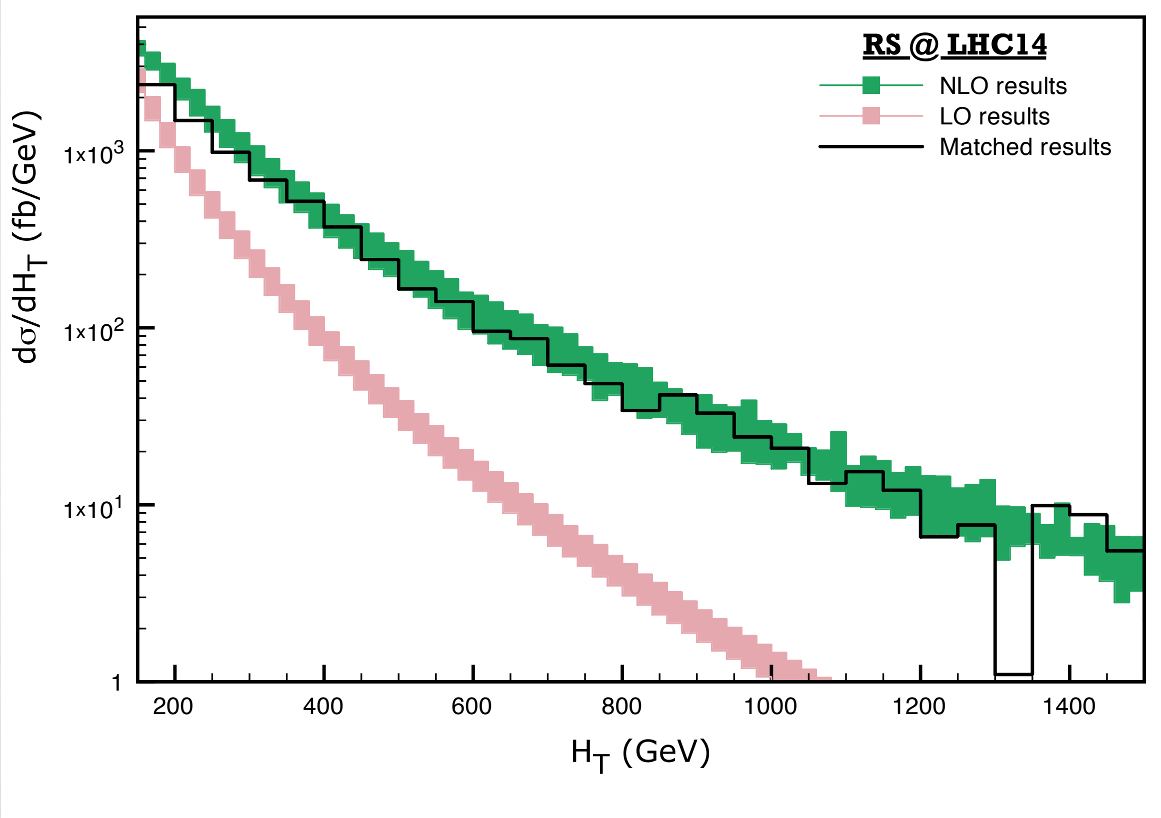

Results

1. Large NLO/LO K-factor
2. Matching normalized to NLO

k-factor	Norm. factor
1.65	1.73

3. Excellent shape agreement (NLO x Match)
4. Clearly LO results is not enough

RS: SEMI-INCLUSIVE SAMPLE

- Semi-inclusive graviton production @ LHC

- Processes:

  - LO: $p\,p \longrightarrow G + \text{jet}$
  - Matching: $p\,p \longrightarrow G + \text{n-jets}$, with n=1,2,3

- Cuts:

	P_T^{miss}	$P_T^{1st\ jet}$	η	Q_{match}
LHC	> 500 GeV	> 50 GeV	< 4.5	> 50 GeV
Tevatron	> 120 GeV	> 20 GeV	< 4.5	> 30 GeV

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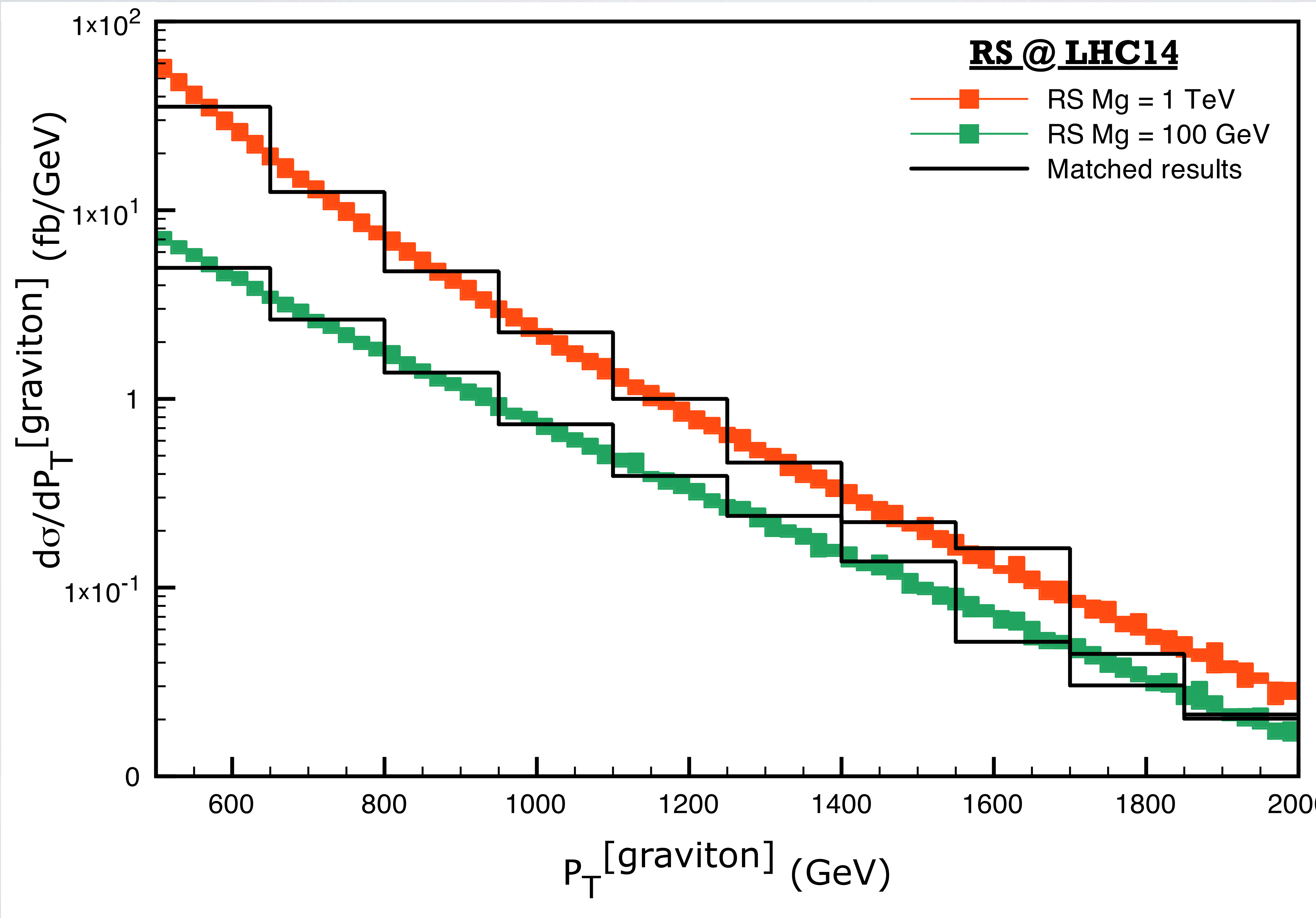

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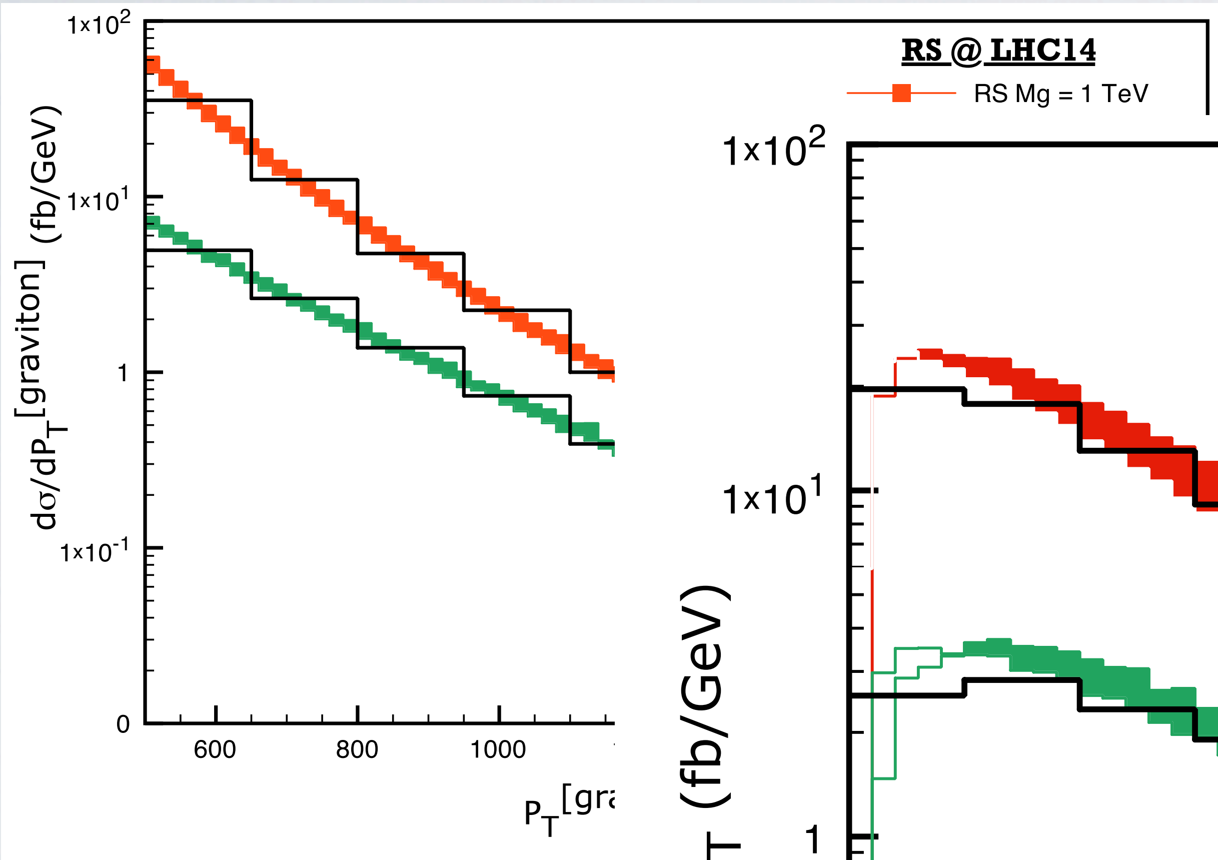

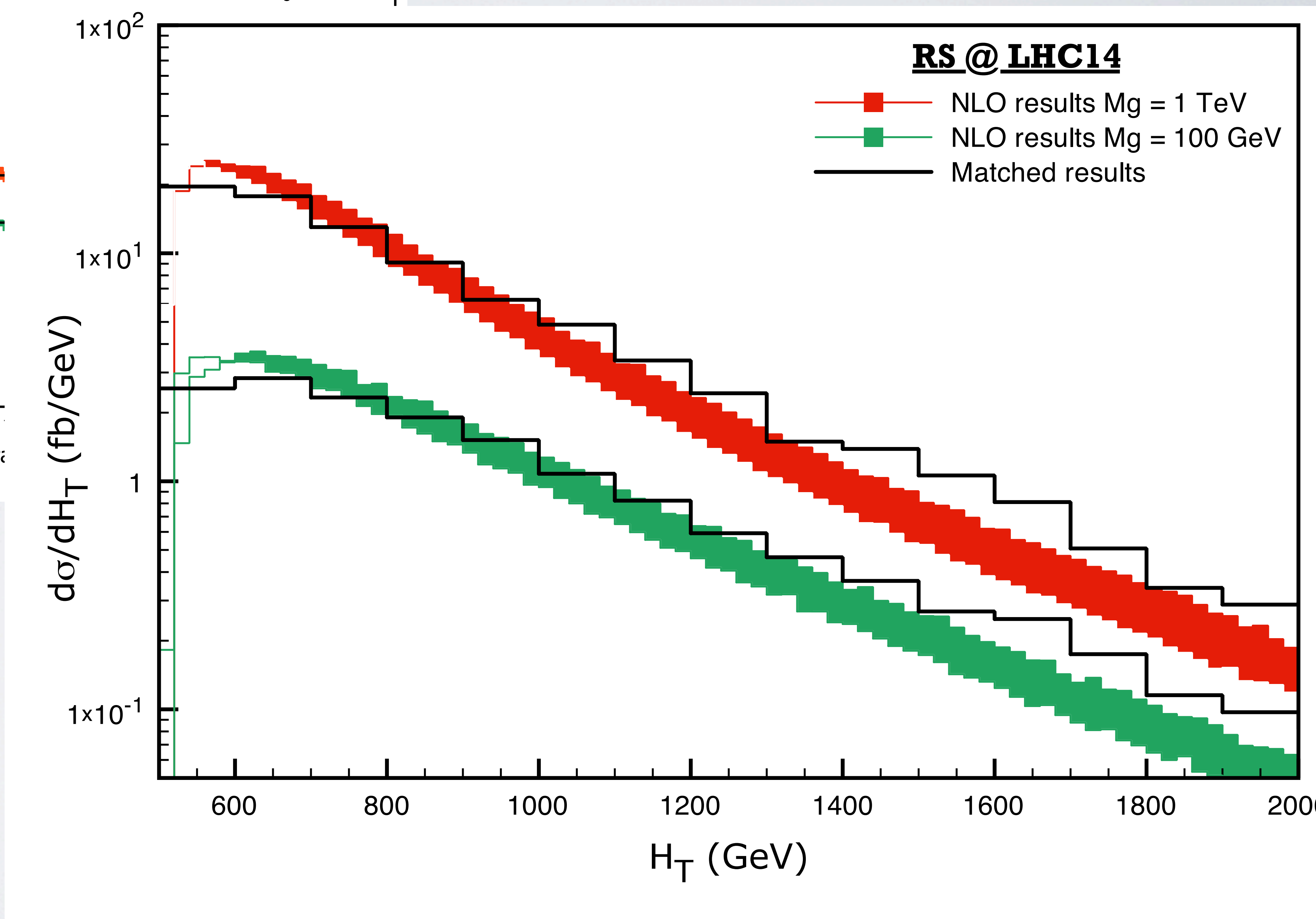

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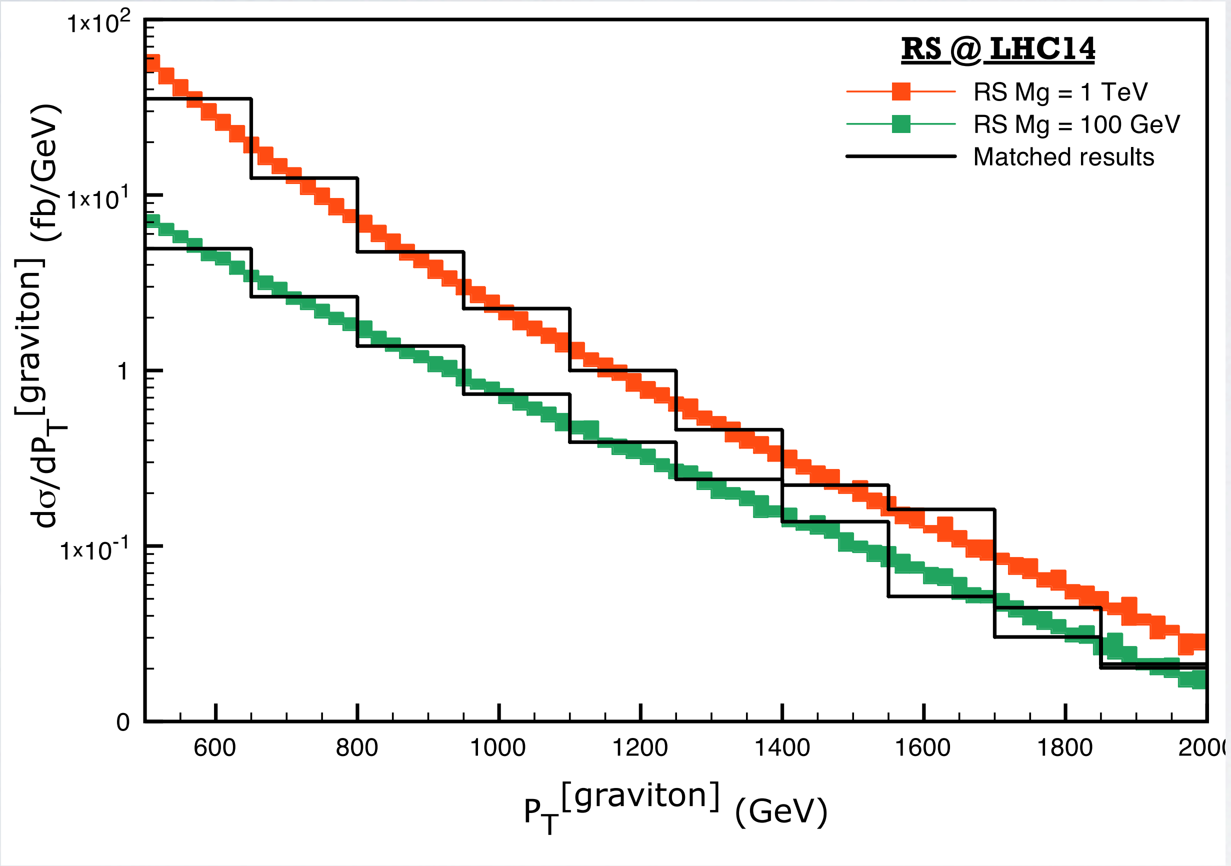

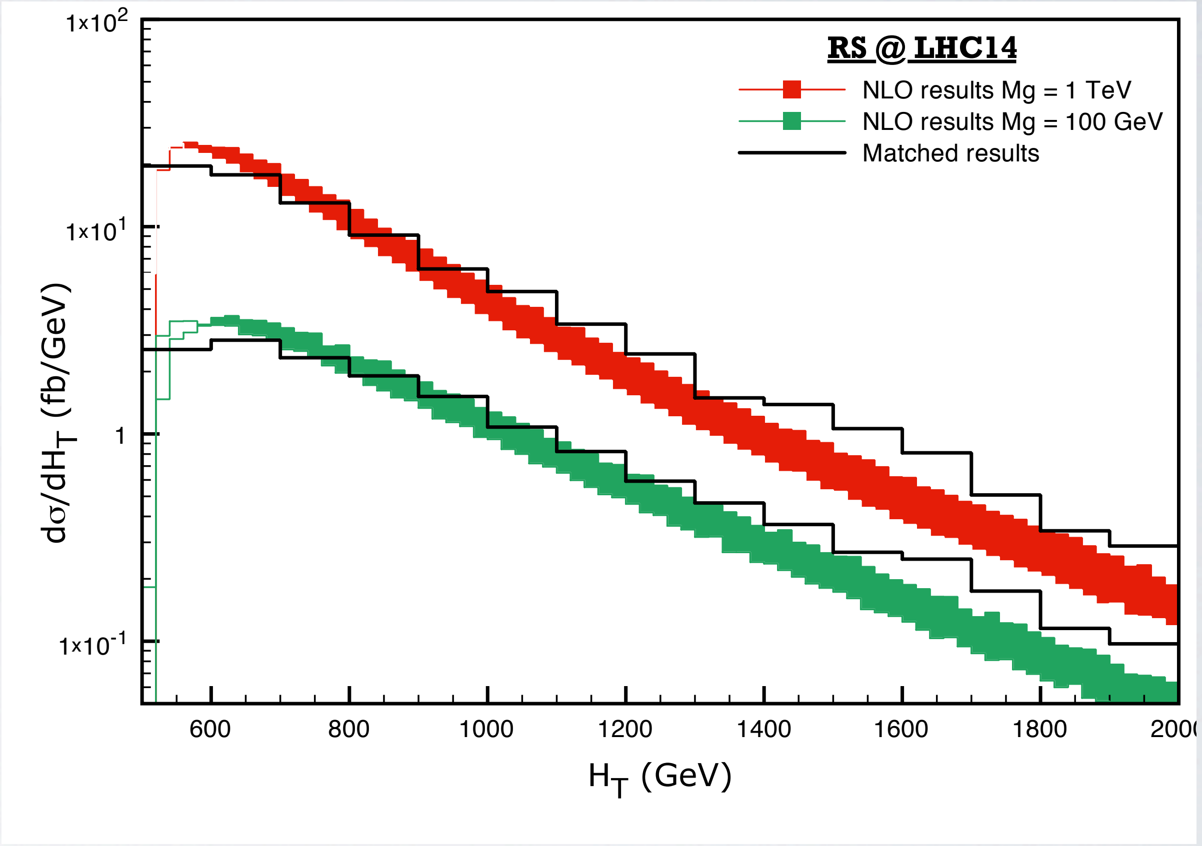

Results

- Matching normalized with NLO (Norm. factors = 1.99, 1.81)
- Excellent shape agreement $\longrightarrow$ PT miss
- Harder distribution for high HT values

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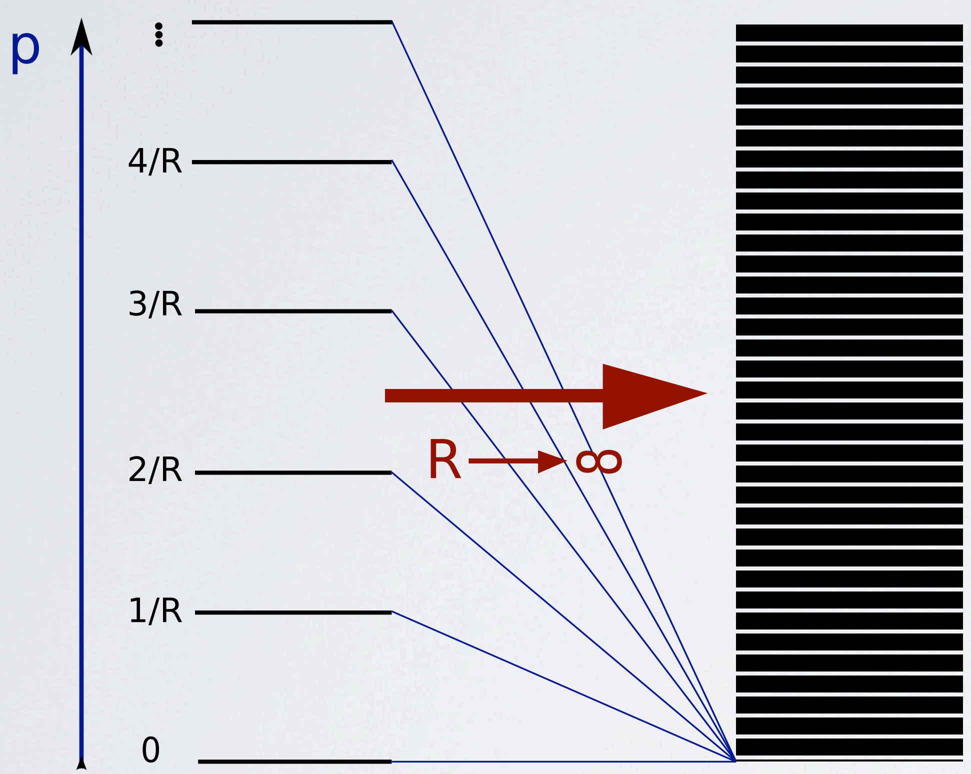
ADD MODEL

- ADD model $\longrightarrow$ D = 4 + δ dimensions, flat metric, spatial and compact



$$\boxed{M_{Pl}^2 = M_\star^{\delta+2} V_\delta}$$

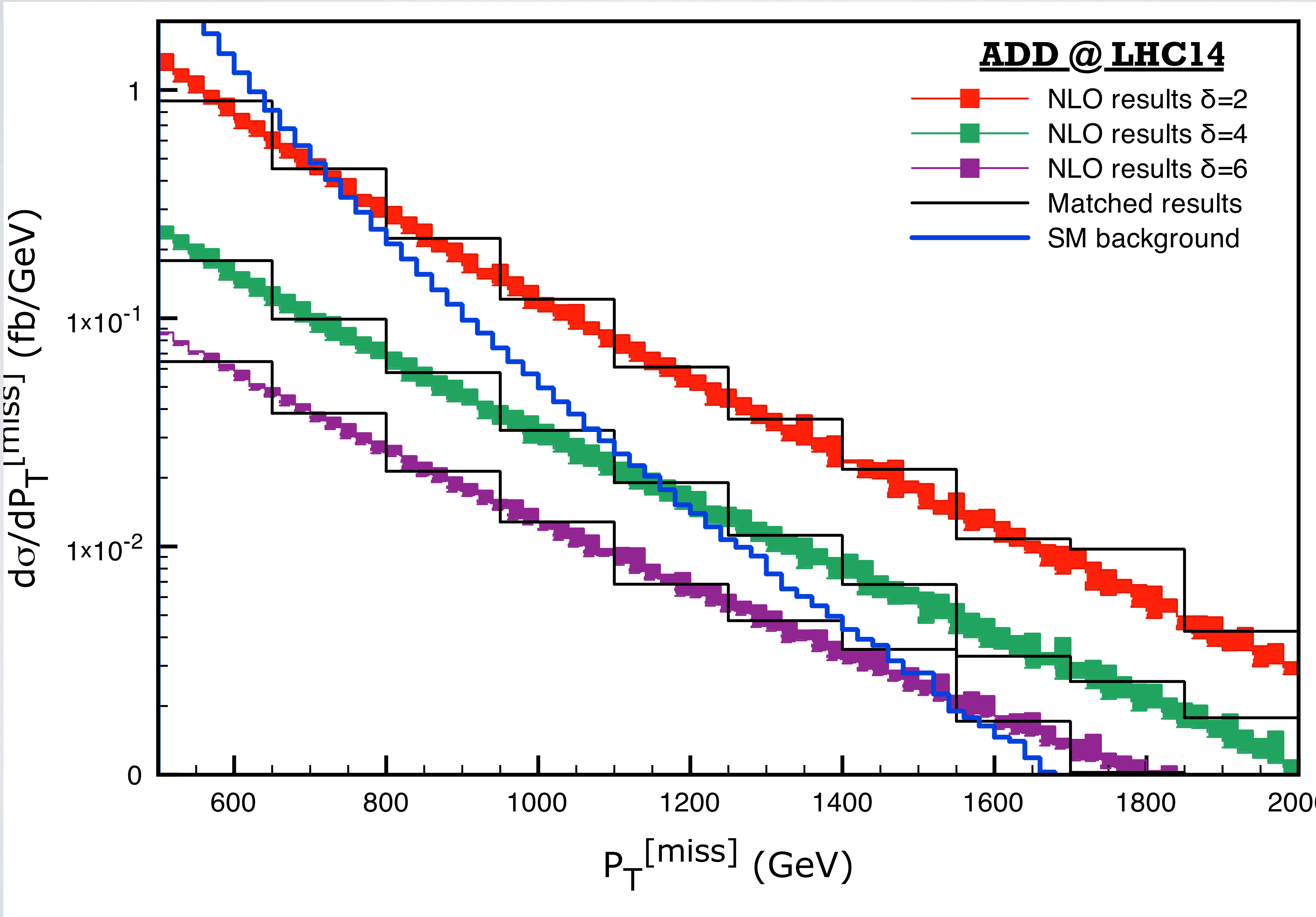
- Field propagating on δ ⟶ KK tower:
  - massive graviton
  - couples to SM particles:

[T. Han, J. D. Lykken, R. J. Zhang, Phys. Rev. D 59, 105006 (1999)]
[G. F. Giudice, R. Rattazzi, J. D. Wells, Nucl. Phys. B 544, 3 (1999)]

$$\mathcal{L}_{int} = -\frac{1}{\Lambda} \sum_n G_{\mu\nu}^{(n)} T_{SM}^{\mu\nu}$$

$\boxed{\text{Phenomenology on graviton emission} = \textbf{missing energy!}}$

ADD: SEMI-INCLUSIVE SAMPLE



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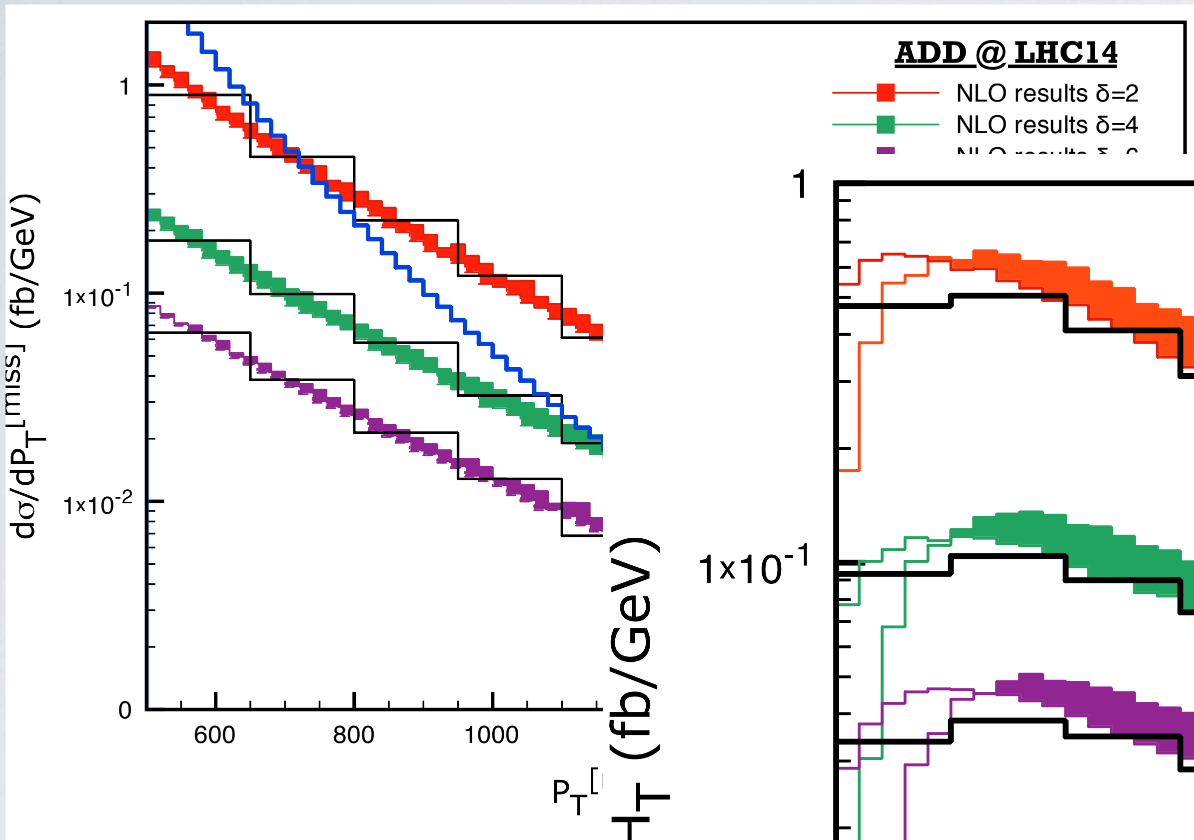

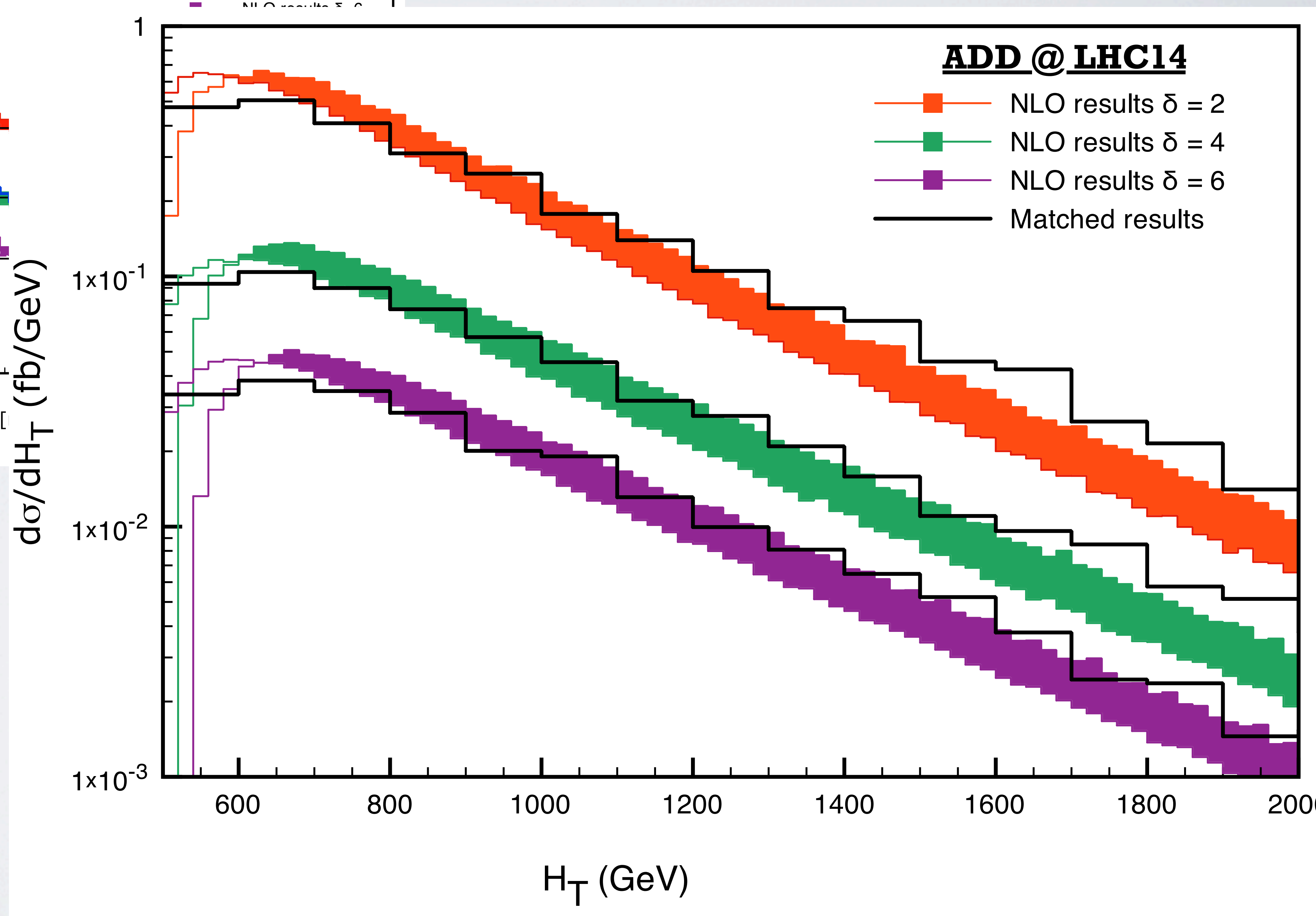

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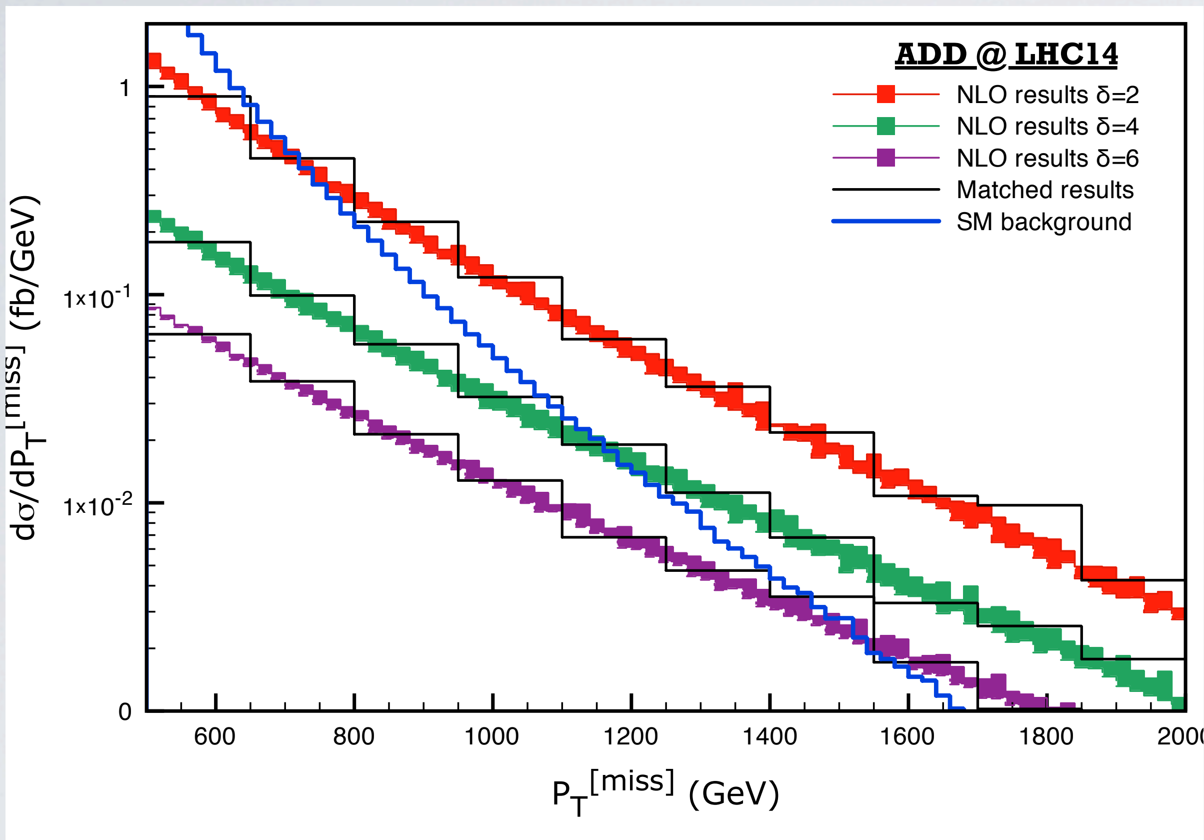
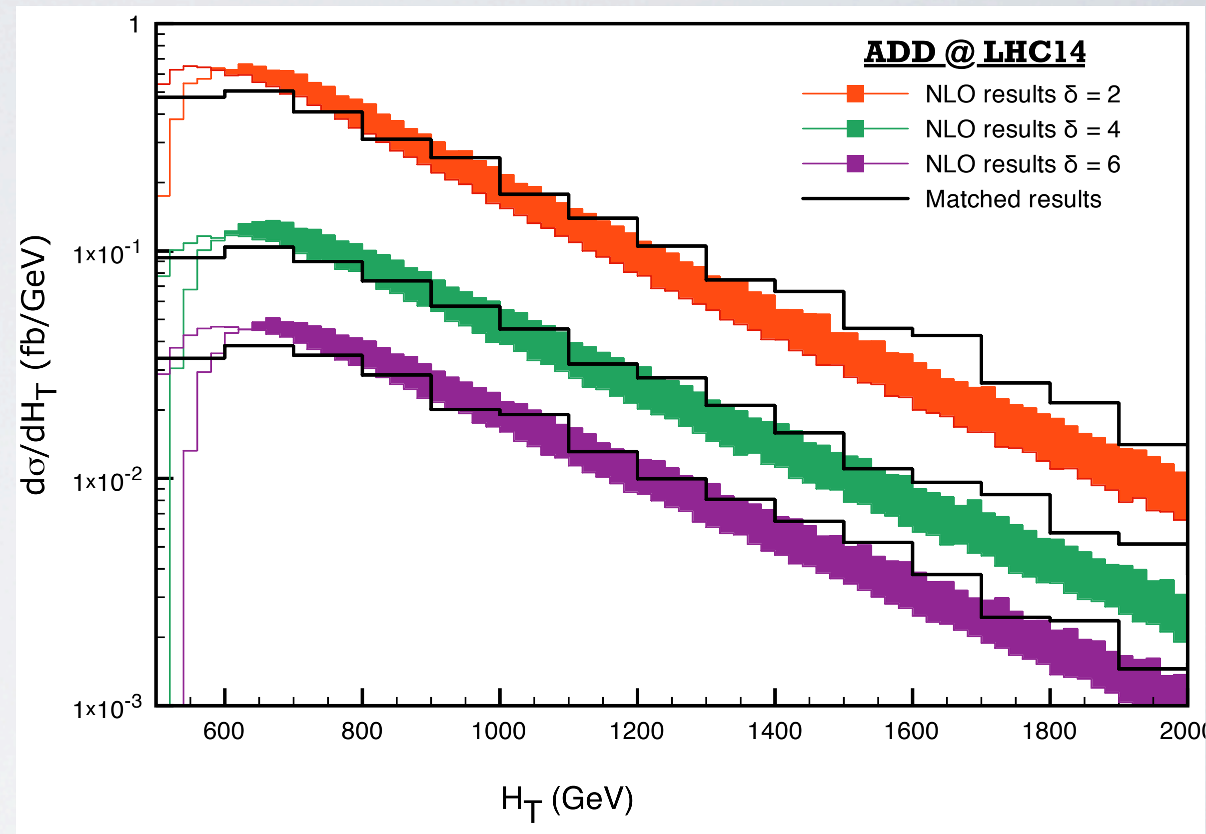




Results

- Matching normalized with NLO:
  - Norm. factors = 2.05, 2.34, 2.49
- Excellent shape agreement ⟶ PT miss
- Harder distribution for high HT values
- Irreducible background has different shape!

SUMMARY SPIN-2 PRODUCTION

- Simulations with spin-2 particles in MG/ME: ready for phenomenology!

- Phenomenology of p p $\longrightarrow$ G + n-jets

  Detailed comparison between **NLO and MLM-matching**:

  ✓ done for ADD, RS and MGM

  ✓ Good agreement for graviton/missing P_T, 1st and 2nd jet P_T, graviton and jet pseudo-rapidities

  ✓ Harder distributions for large matched H_T (matching is computed up to 3 extra partons)

- Upshot: matched samples (normalized to NLO) give a theoretically accurate and experimental friendly way to simulate events at the LHC

- More information on: [P. d. A, Kaoru Hagiwara, Qiang Li, Fabio Maltoni, **arXiv: 1101.5499**]

Thank you!!

ADD KK SUMMATION

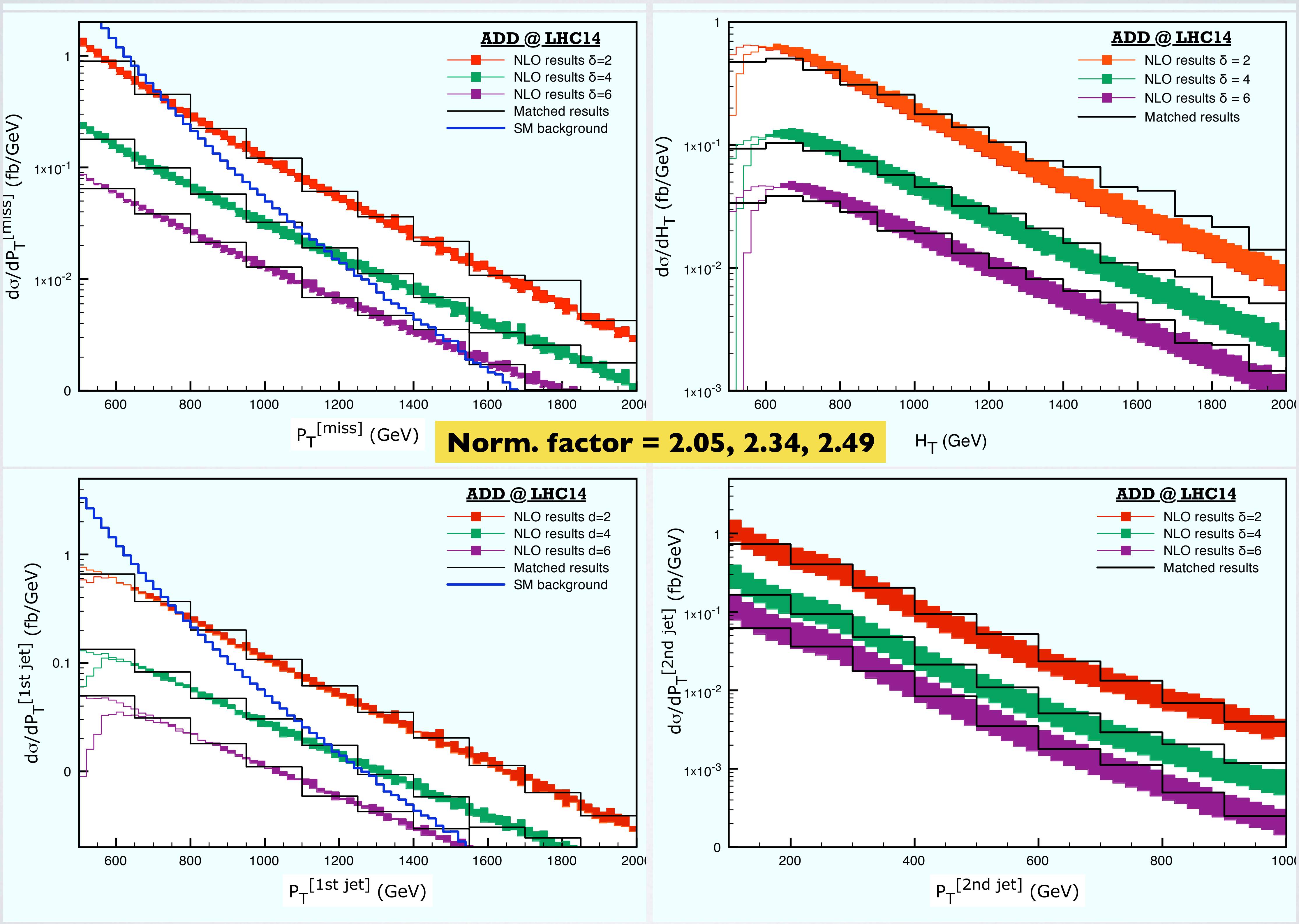
- In the ADD model the individual KK resonances have masses equal to m=n/R.
- The mass gap between neighboring modes Δm is small for δ not too large. Quantitatively one finds Δm≈ 20 keV, 7 MeV and 0.1 GeV for MS = 1 TeV and δ =4, 6 and 8.

[T. Han, J. D. Lykken, R. J. Zhang, Phys. Rev. D 59, 105006 (1999)]
[G. F. Giudice, R. Rattazzi, J. D. Wells, Nucl. Phys. B 544, 3 (1999)]

- The discrete mass spectrum can be approximated by a continuum with a density of states dN = ρ(m)dm, where

$$\rho(m) = \frac{2\pi^{\delta/2}}{\Gamma(\delta/2)} \frac{\overline{M}_{Pl}^2}{M_S^{2+\delta}} m^{\delta-1}$$

ADD @ LHC



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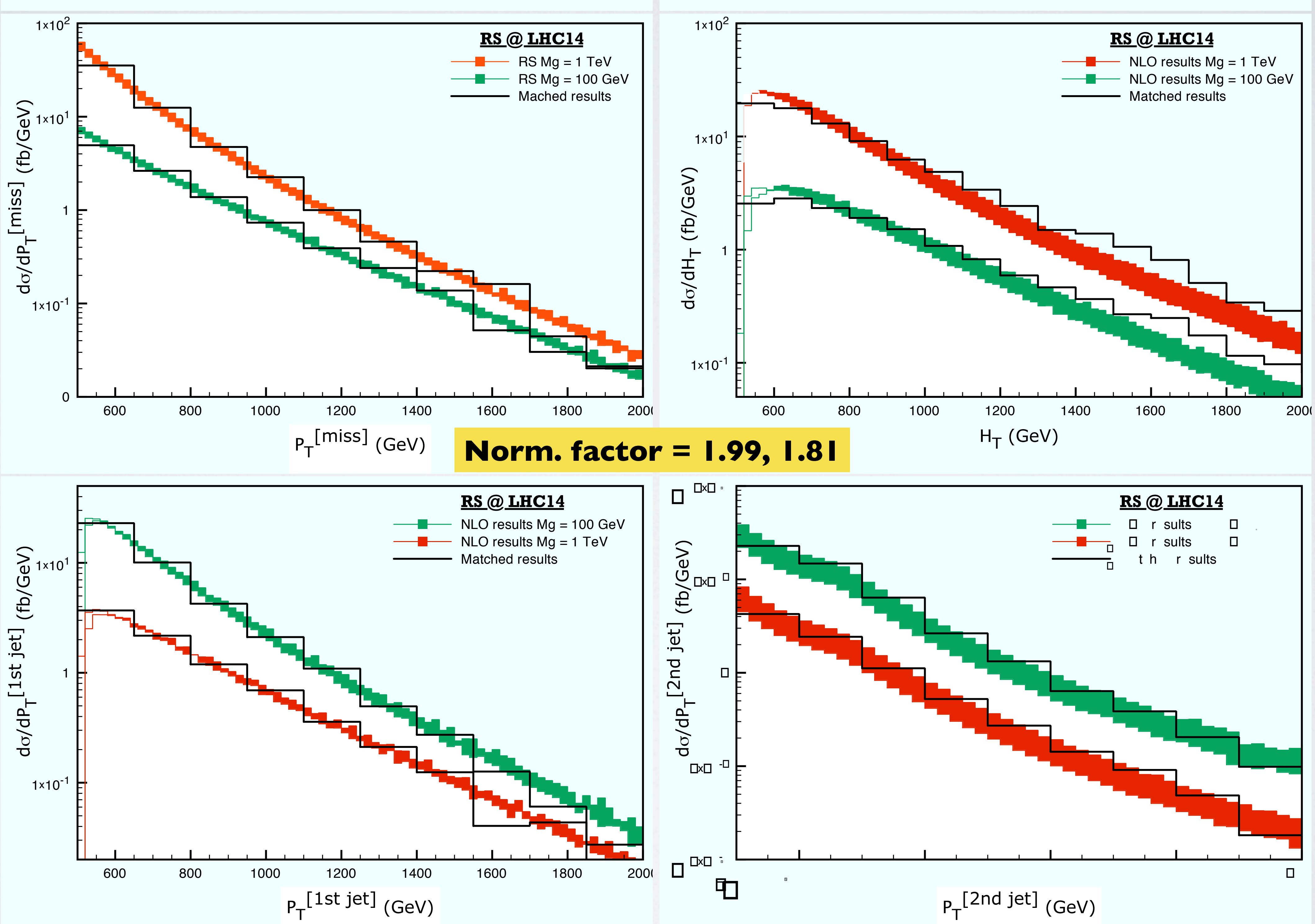
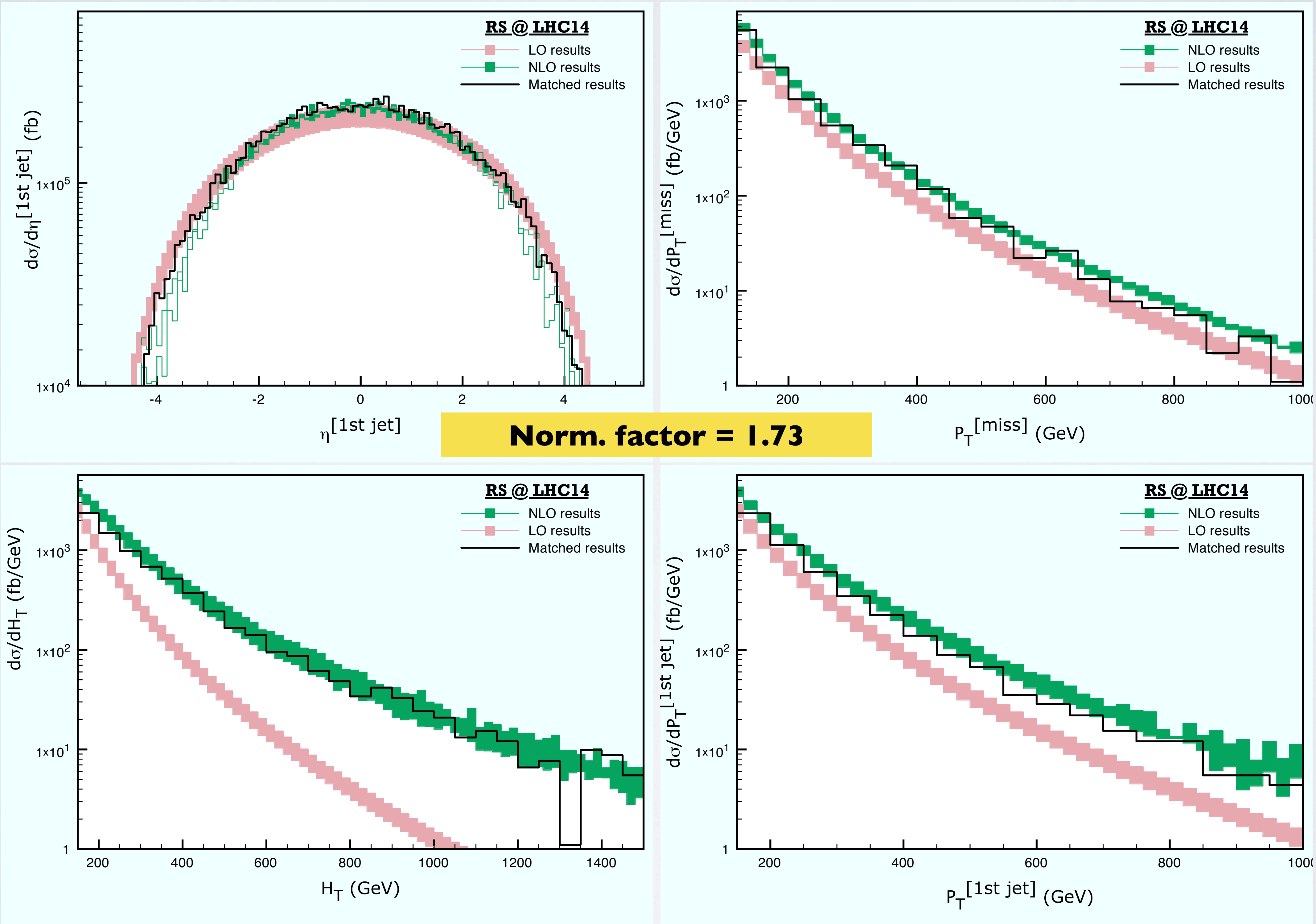
RS @ LHC


RS @ LHC14
RS Mg = 1 TeV
RS Mg = 100 GeV
Mached results
dσ/dP_T[miss] (fb/GeV)
P_T[miss] (GeV)
NLO results Mg = 1 TeV
NLO results Mg = 100 GeV
Matched results
dσ/dH_T (fb/GeV)
H_T (GeV)
Norm. factor = 1.99, 1.81
NLO results Mg = 100 GeV
NLO results Mg = 1 TeV
dσ/dP_T[1st jet] (fb/GeV)
P_T[1st jet] (GeV)
dσ/dP_T[2nd jet] (fb/GeV)
P_T[2nd jet] (GeV)

FULL INCLUSIVE RS @ LHC14



PSEUDO-RAPIDITY RESULTS

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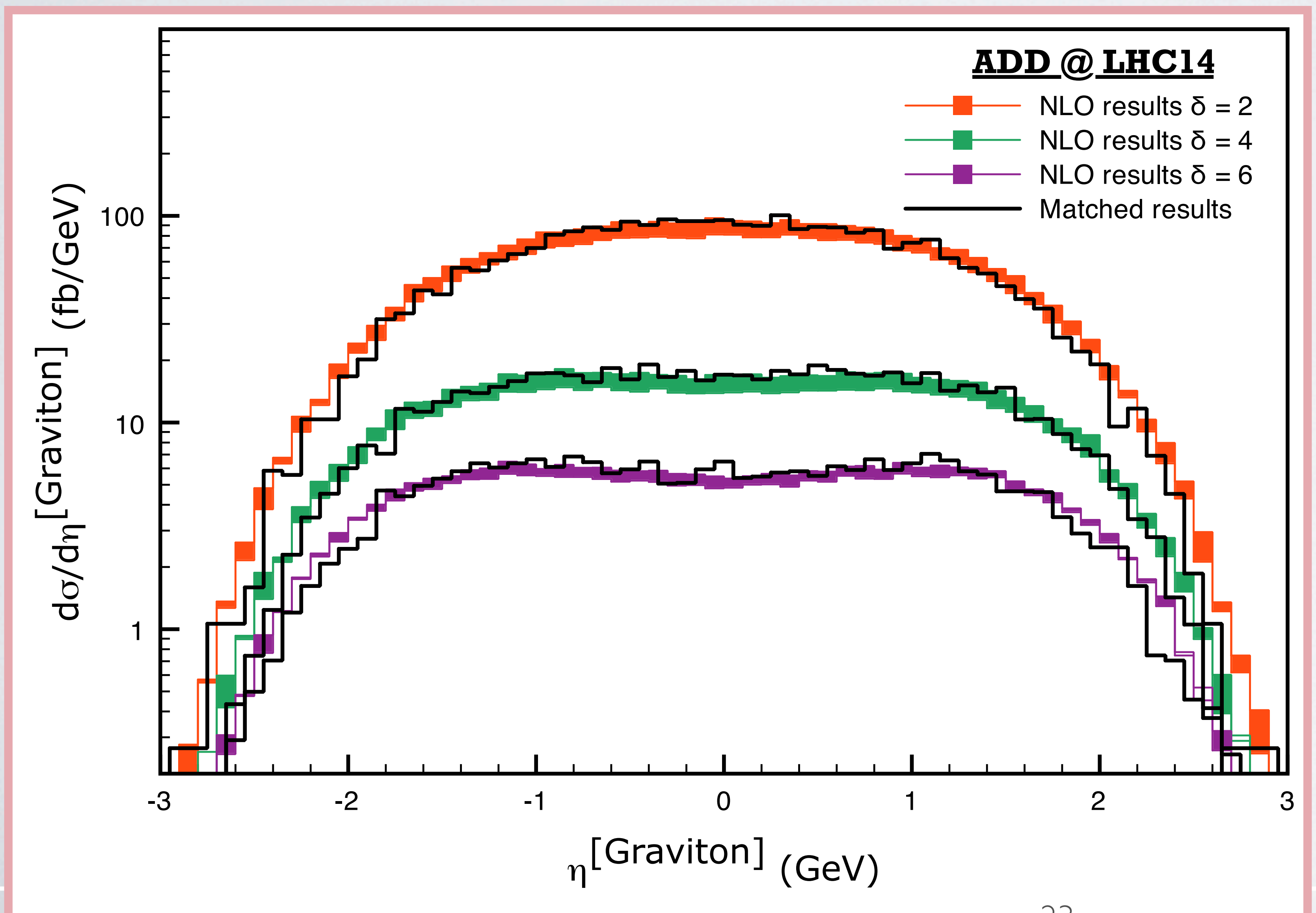

ADD

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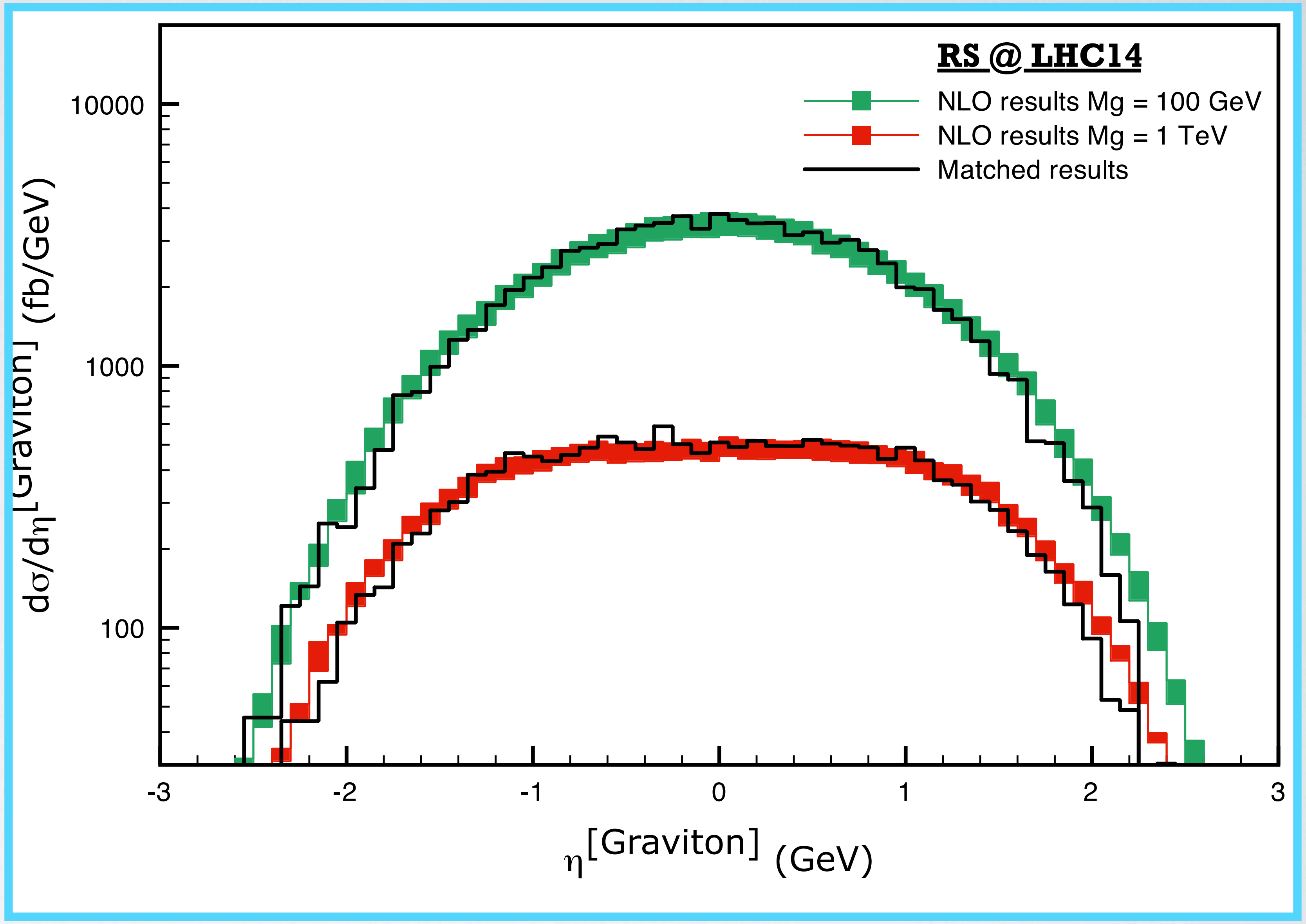

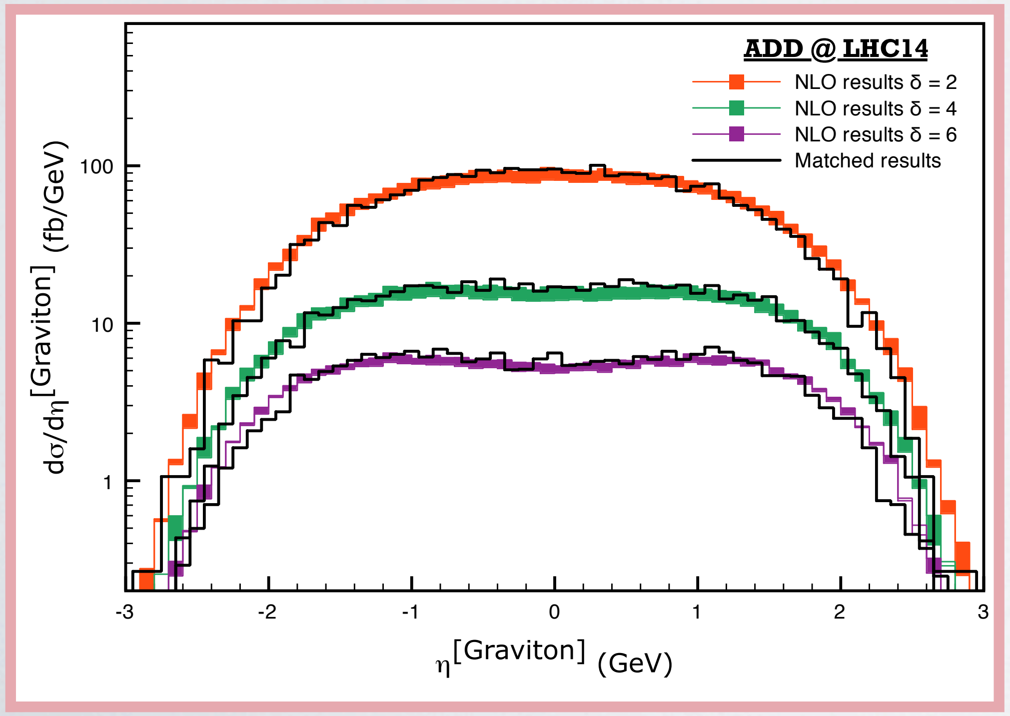

ADD

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