Searching for New Physics through *dijet* production at the LHC with the SMEFT

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La nostra conoscenza del **protone** nel **Modello Standard** è contaminata da **Nuova Fisica**?

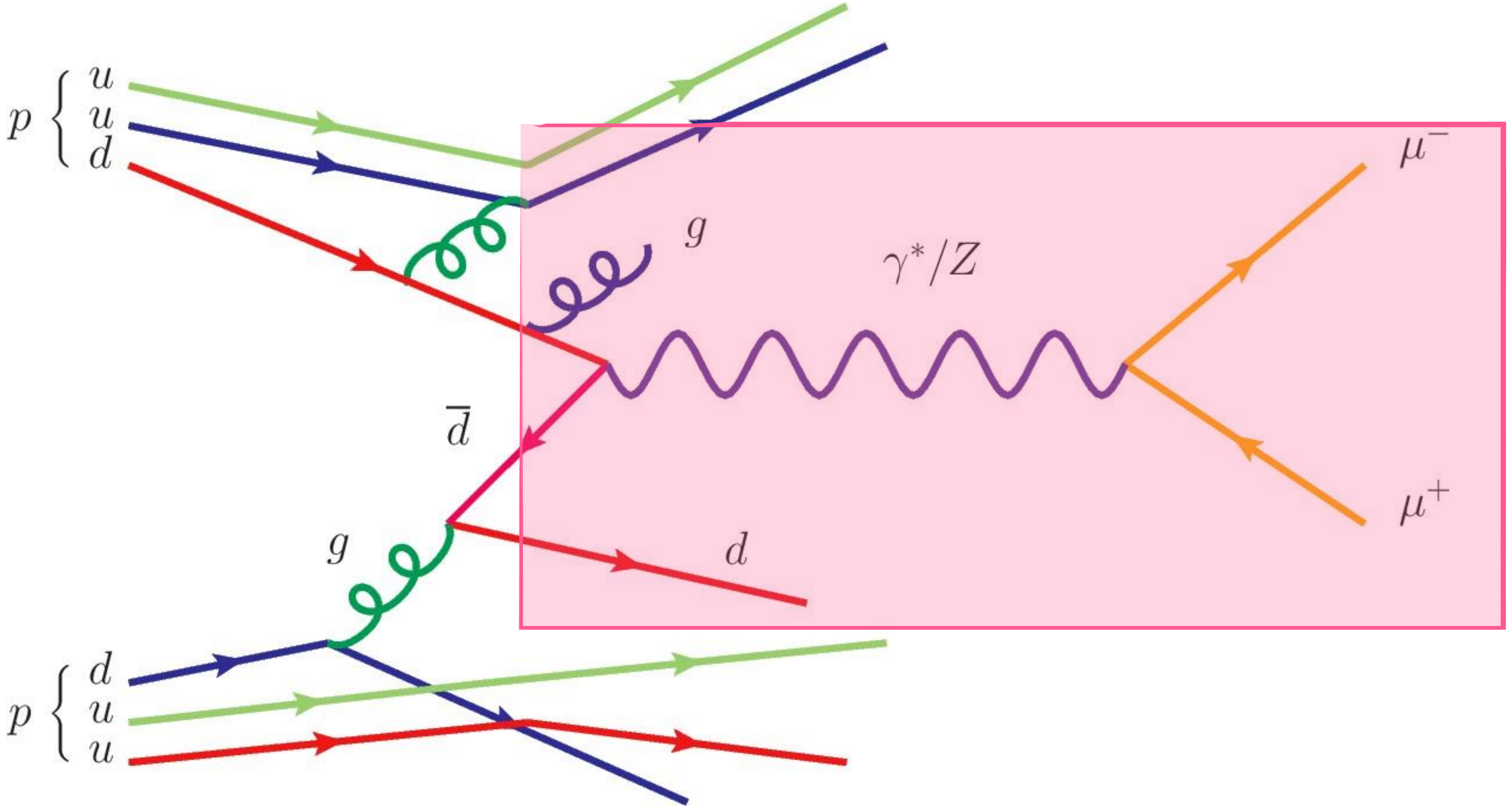
INDICE

STRUTTURA DEL PROTONE NEL MODELLO STANDARD

PREDIZIONI TEORICHE A LHC

$$\sigma^{pp\to ab} = \sum_{i,j=-n_f}^{n_f} \int dz_1\, dz_2\, f_i(z_1,\mu_F)\, f_j(z_2,\mu_F)\, \hat{\sigma}^{ij\to ab}(z_1 z_2 S, \alpha_s(\mu_R), \mu_F) + \mathcal{O}\left(\frac{\Lambda^n}{S^n}\right)$$

Funzioni
Di
Distribuzione
Partonica



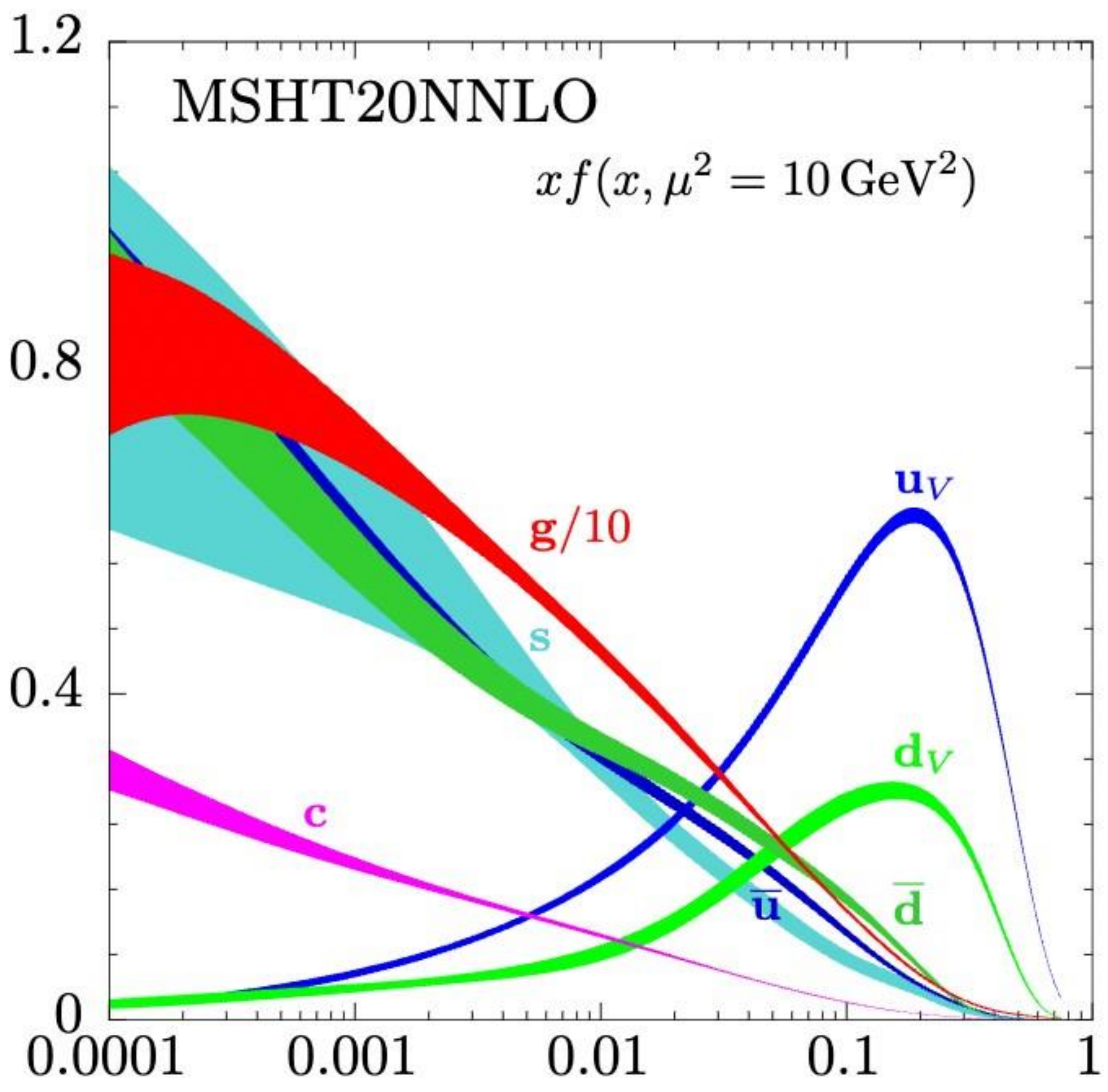
Hard Scattering: Perturbative
QCD + EW

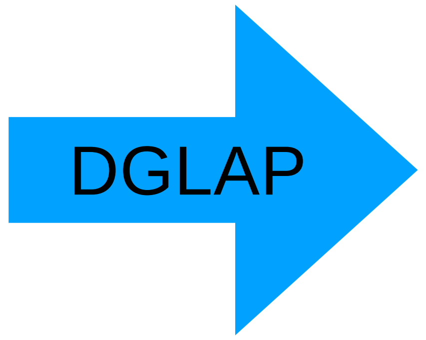
$$d\sigma^{pp\to ab} = \sum_{i,j} \boxed{f_i \otimes f_j} \otimes \boxed{d\hat{\sigma}^{ij\to ab}} + \dots$$

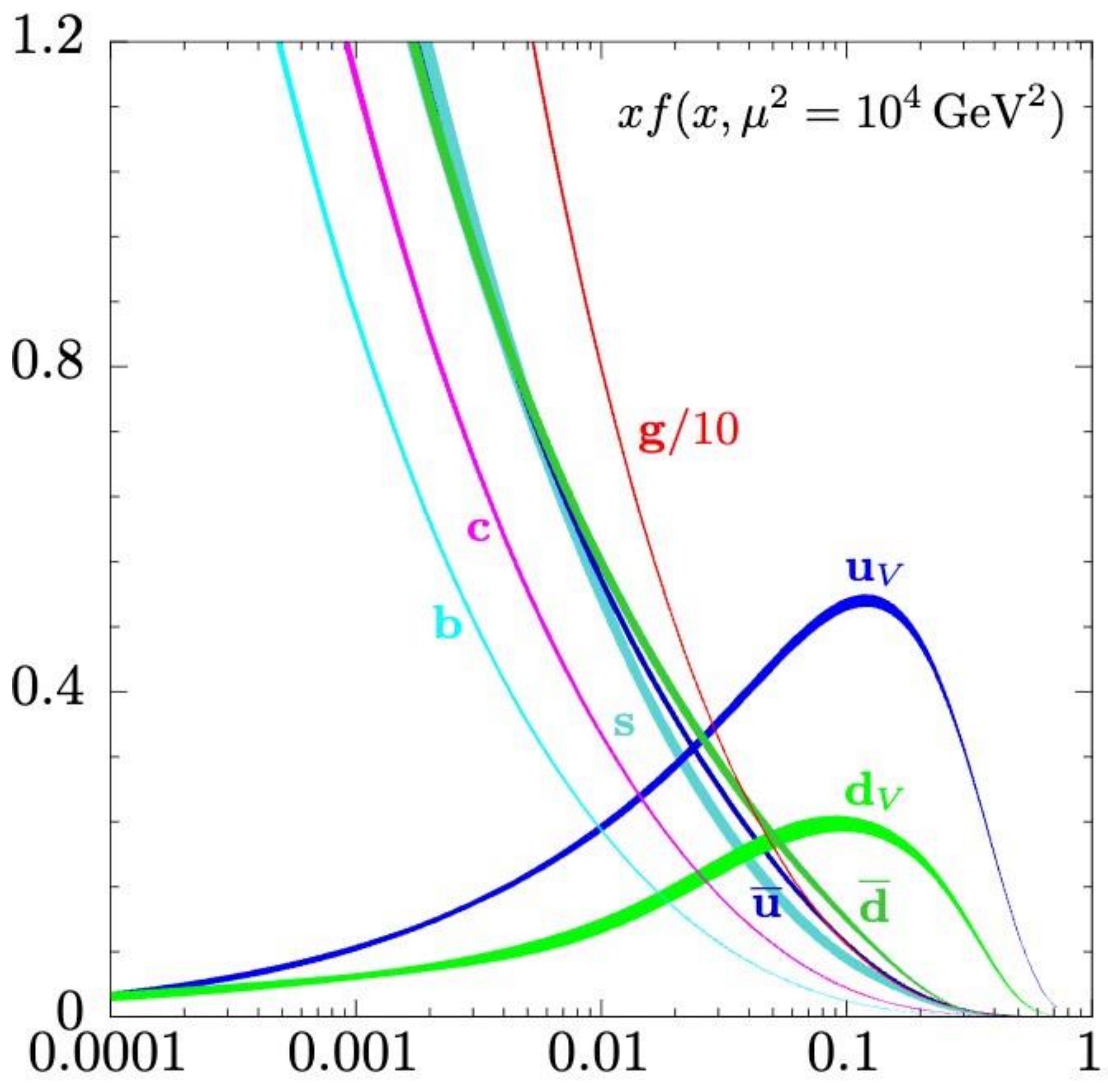
EVOLUZIONE DELLE PDFs CON DGLAP

$$\frac{d}{dt}\begin{pmatrix} q_i(x,t) \\ g(x,t) \end{pmatrix} = \frac{\alpha_s(t)}{2\pi}\int_x^1 \sum_{j=q,\bar{q}} \frac{d\xi}{\xi} \begin{pmatrix} P_{ij}\left(\frac{x}{\xi},\alpha_s(t)\right) & P_{ig}\left(\frac{x}{\xi},\alpha_s(t)\right) \\ P_{gj}\left(\frac{x}{\xi},\alpha_s(t)\right) & P_{gg}\left(\frac{x}{\xi},\alpha_s(t)\right) \end{pmatrix} \otimes \begin{pmatrix} q_j(\xi,t) \\ g(\xi,t) \end{pmatrix}$$

Scala Adronica: fit globale delle PDFs







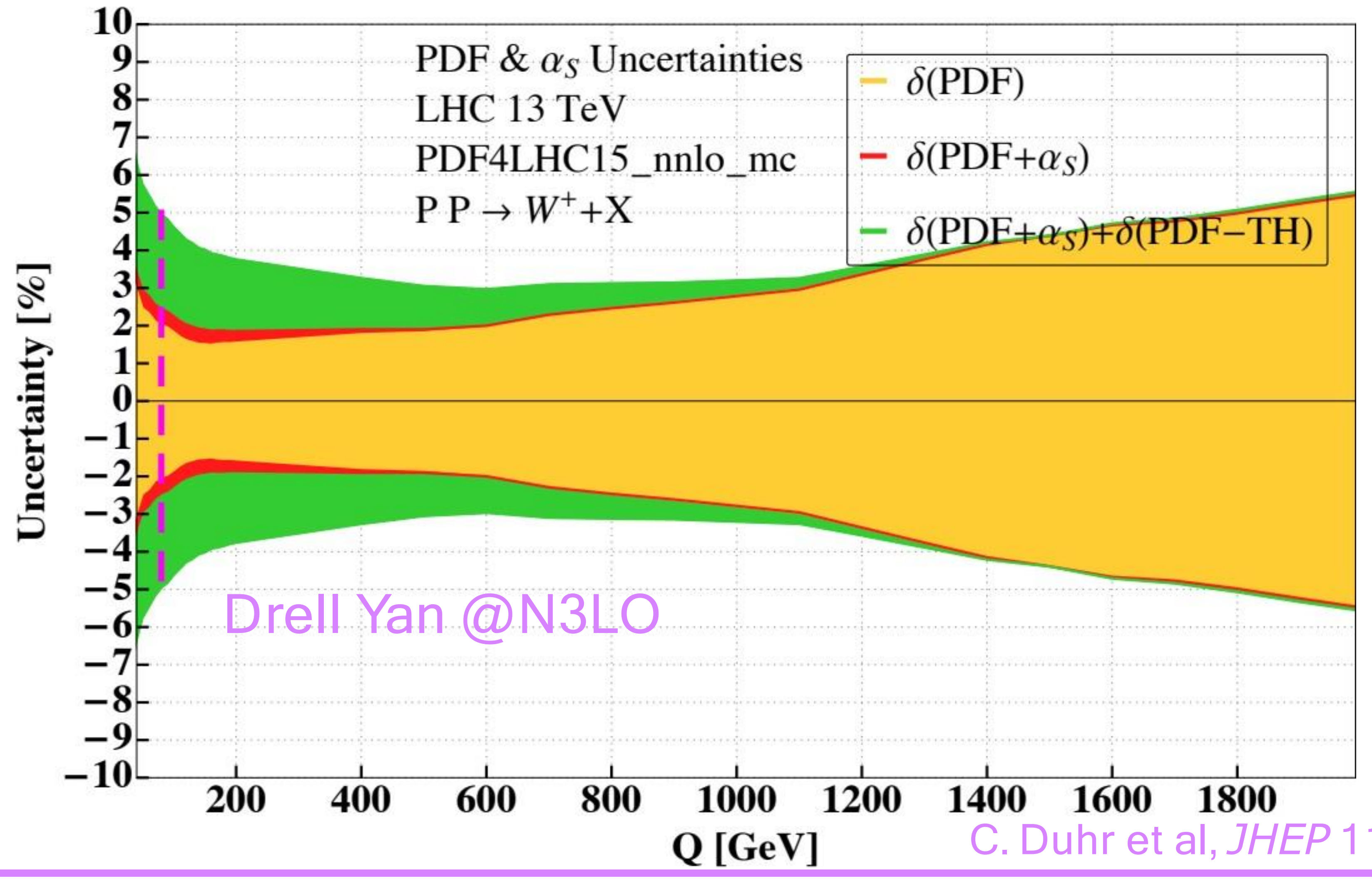
Alta scala di energia: input LHC

PDG 2023

PDFs SONO CRUCIALI PER LA FISICA DI PRECISIONE

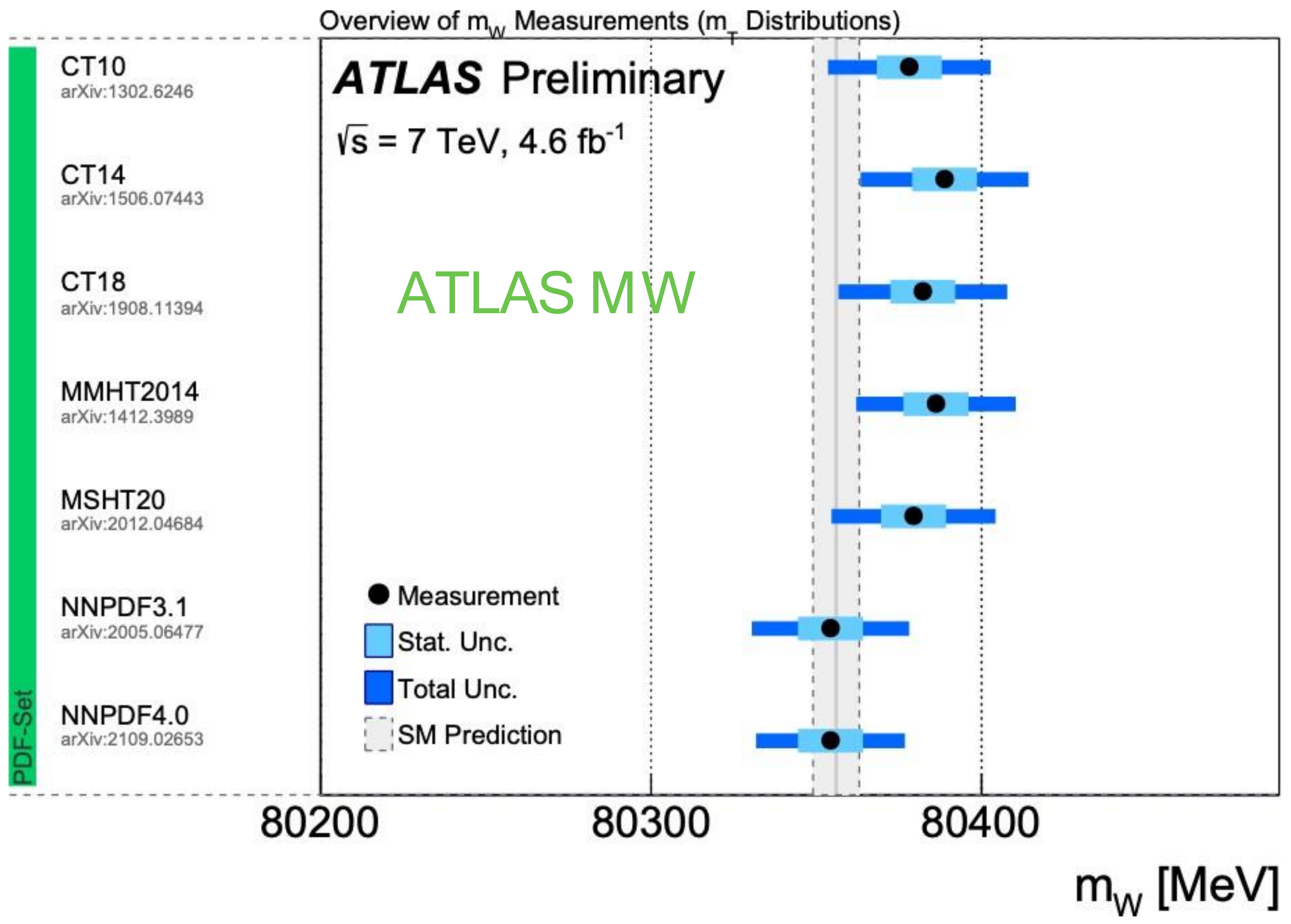
$$d\sigma^{pp\to ab} = \sum_{i,j} \boxed{f_i \otimes f_j} \otimes d\hat{\sigma}^{ij\to ab} + \ldots$$

#1: Incertezze Teoriche delle predizioni SM



C. Duhr et al, *JHEP* 11 (2020) 143

#2: Determinazione dei parametri SM



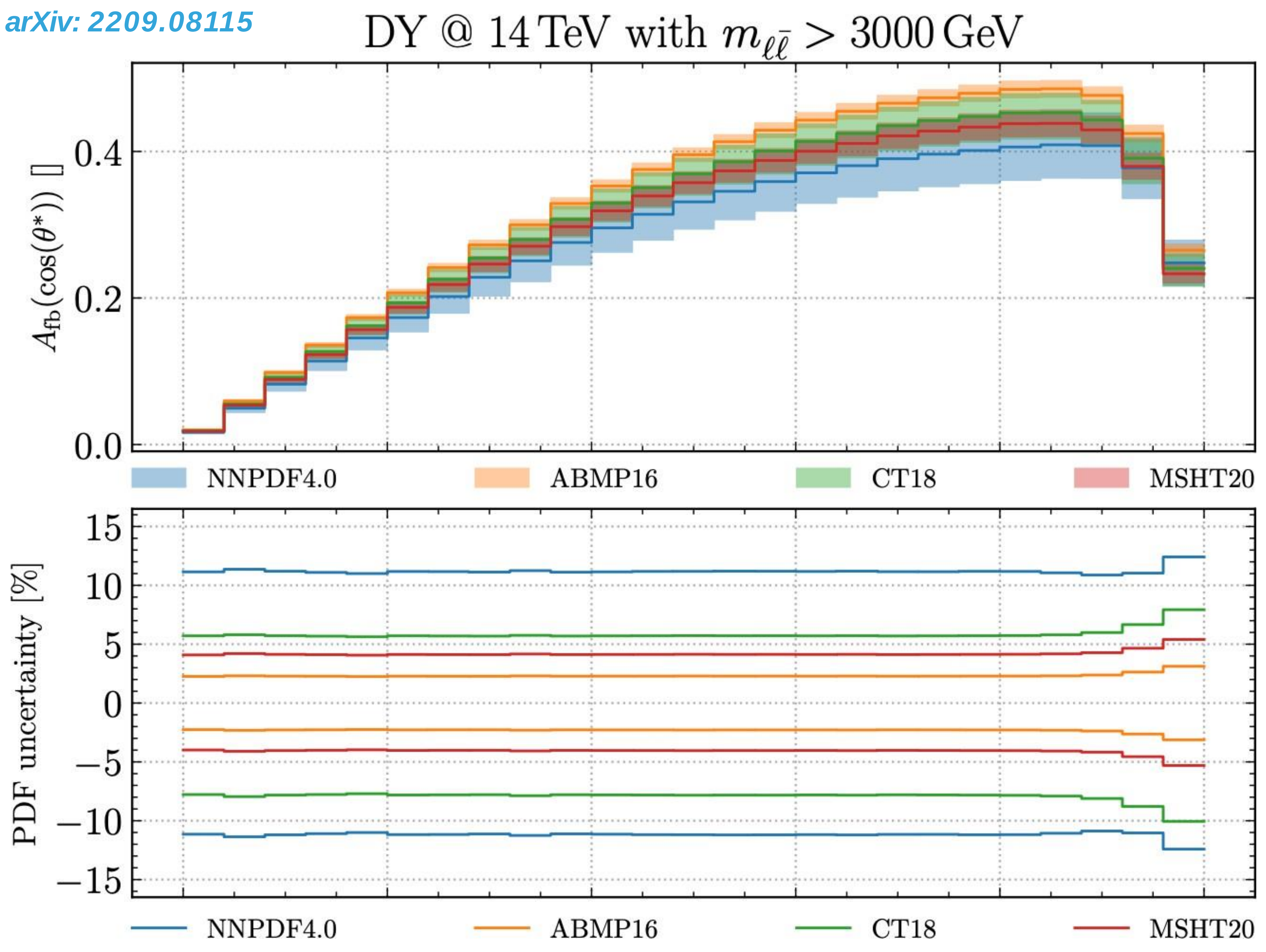
ATLAS-CONF-2023-004

E PER LA RICERCA DI NUOVA FISICA…

$X \approx \frac{M}{\sqrt{S}}$

Stati finali con massa elevata ↔ largo-x PDFs

Ball et al arXiv: 2209.08115



#1: Direct searches: heavy Z' search in DY Forward-Backward asymmetry

ESTRAZIONE DELLE PDFs

TEORIA PERTURBATIVA

$$\sigma(x, Q^2) = \hat{\sigma}_{ij} \otimes f_i \otimes f_j = \int dz_1\, dz_2\, \hat{\sigma}(z_1, z_2, Q^2)\, f_i\left(\frac{x}{z_1}, Q^2\right) f_j\left(\frac{x}{z_2}, Q^2\right)$$

misurato negli esperimenti

sconosciute

Le PDFs sono un set di funzioni indeterminate:

$f_i : [0,1] \to \mathbb{R}$

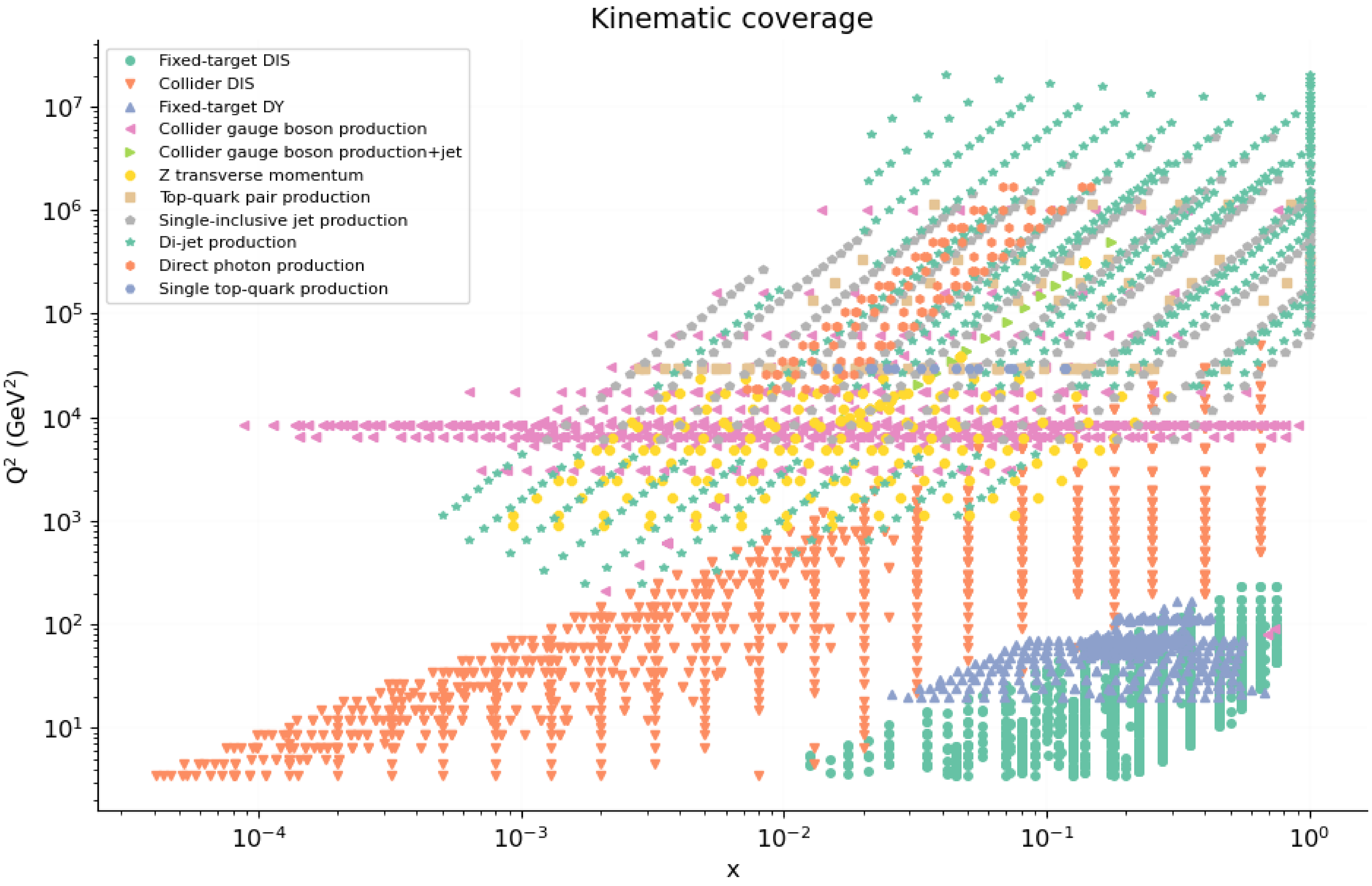
$f_i(x) \sim$ probabilità di estrarre un partone i dal protone con un momento frazionario x

1 - Parametrizzazione (polinomiale o con rete neurale)
2 - Ottimizzazione (minimizzazione del chi2)
3 - Determinazione dei parametri di best fit

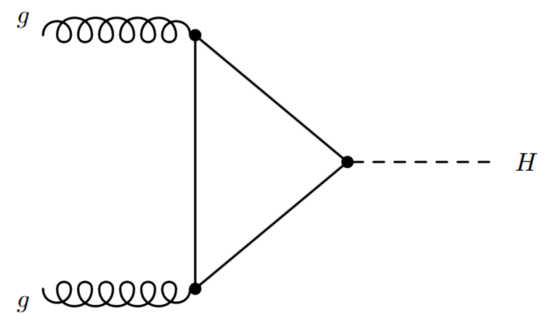
Inoltre, le equazioni DGLAP ci permettono di calcolare le PDFs a tutte le scale:

Q^2, una volta nota una scala iniziale Q_0^2

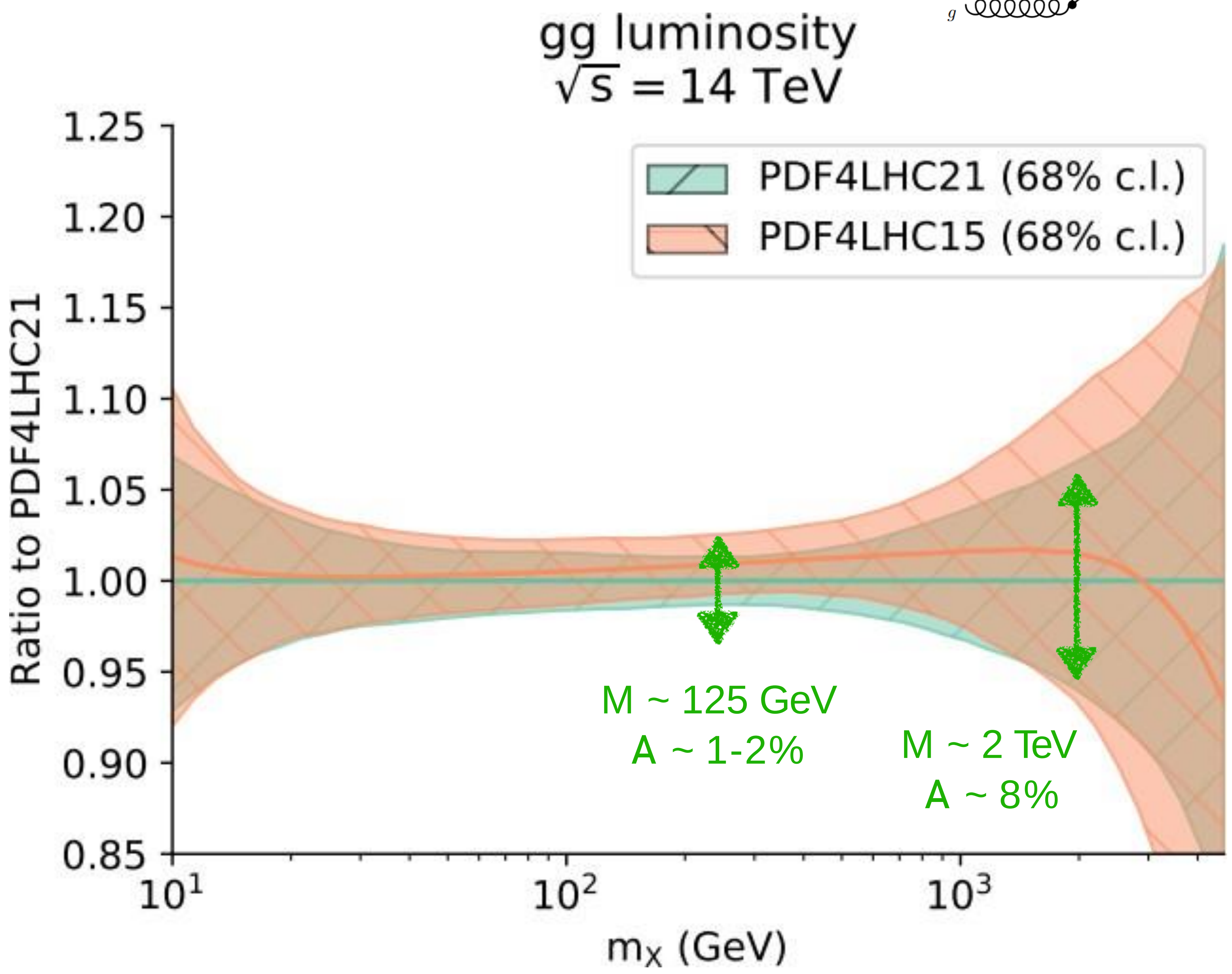
$$f_i(Q^2) = E_{ij}(Q^2 \leftarrow Q_0^2) f_j(Q_0^2)$$


Kinematic coverage
Fixed-target DIS
Collider DIS
Fixed-target DY
Collider gauge boson production
Collider gauge boson production+jet
Z transverse momentum
Top-quark pair production
Single-inclusive jet production
Di-jet production
Direct photon production
Single top-quark production
Q^2 (GeV^2)
10^1
10^2
10^3
10^4
10^5
10^6
10^7
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^0
x

SFIDA TRA PRECISIONE E ACCURATEZZA



Ora che le PDFs hanno raggiunto un alto livello di precisione, è cruciale, al fine di testare Nuova Fisica, che si abbia un livello di accuratezza simile.



PDF4LHC21 study 2203.05506

NUOVA FISICA: SMEFT

STANDARD MODEL EFFECTIVE FIELD THEORY

Partiamo dalla Lagrangiana SMEFT…

$$\mathcal{L}_{SMEFT} = \underbrace{\mathcal{L}_{SM}}_{\text{SM}} + \sum_i^{N_{d6}} \underbrace{\frac{c_i}{\Lambda^2}}_{\text{EFT}_{d6}} \mathcal{O}_i^{(6)} + \sum_i^{N_{d8}} \underbrace{\frac{c_i}{\Lambda^4}}_{\text{EFT}_{d8}} \mathcal{O}_i^{(8)} + \dots$$

Alle sezioni d'urto

correzioni Lineari EFT: interferenza SM-EFT$_{d6}$

Correzioni Quadratiche EFT: EFT$_{d6}$-EFT$_{d6}$

$$\sigma_{SMEFT} \approx \sigma_{SM} \times \left(1 + \sum_i^{N_{d6}} \frac{c_i}{\Lambda^2}\kappa_i + \sum_{i,j}^{N_{d6}} \frac{c_i c_j}{\Lambda^4}\tilde{\kappa}_{ij} \right)$$

INTERPRETAZIONE GLOBALE DELLO SMEFT

Il framework dello smeft connette diversi settori delle osservabili misurate a LHC.

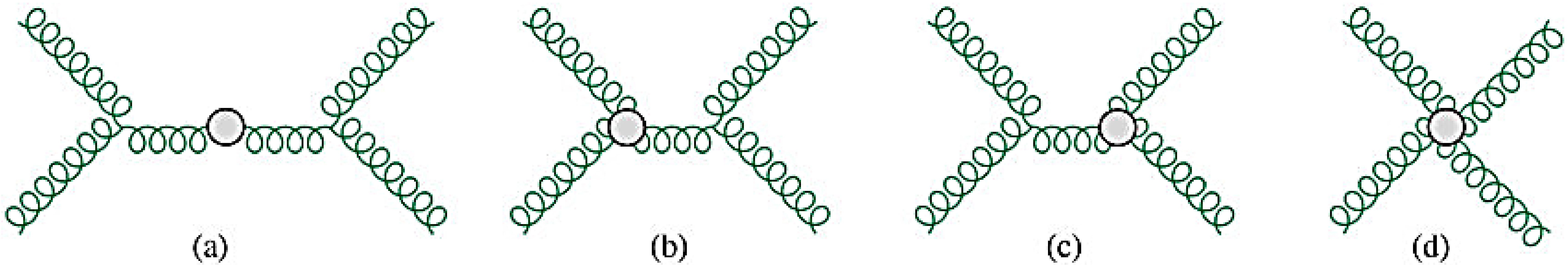
Abbiamo bisogno di usare un approccio globale, includendo più datasets possibili.

→ Interpretazione modello-indipendente della fisica BSM nei dati LHC.

INCLUSIVE JETS

INCLUSIVE DIJETS

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$



$$\sigma = \sigma_{\text{SM}} \times \left(1 + \frac{c_{tG}}{\Lambda^2} a + \frac{c_{tG}^2}{\Lambda^4} b \right)$$

Termini lineari dim-6

Termini quadratici dim 6

ESTRARRE PARAMETRI DAI DATI

$$\chi^2 = \frac{1}{N_{\rm dat}} \sum_{i=1}^{N_{\rm dat}} (T_i(\{\theta\},\{c\}) - D_i)\,{\rm cov}^{-1}_{ij}\,(T_j(\{\theta\},\{c\}) - D_j)$$

$$T_i(\{\theta\},\{c\}) = {\rm PDFs}(\{\theta\},\{c\}) \otimes \hat{\sigma}_i(\{c\})$$

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \sum_i^{N_{d6}} \frac{c_i}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_j^{N_{d8}} \frac{b_j}{\Lambda^4}\mathcal{O}_j^{(8)} + \dots$$

SMEFT WCs

Parametri determinanti le PDFs ad una scala iniziale

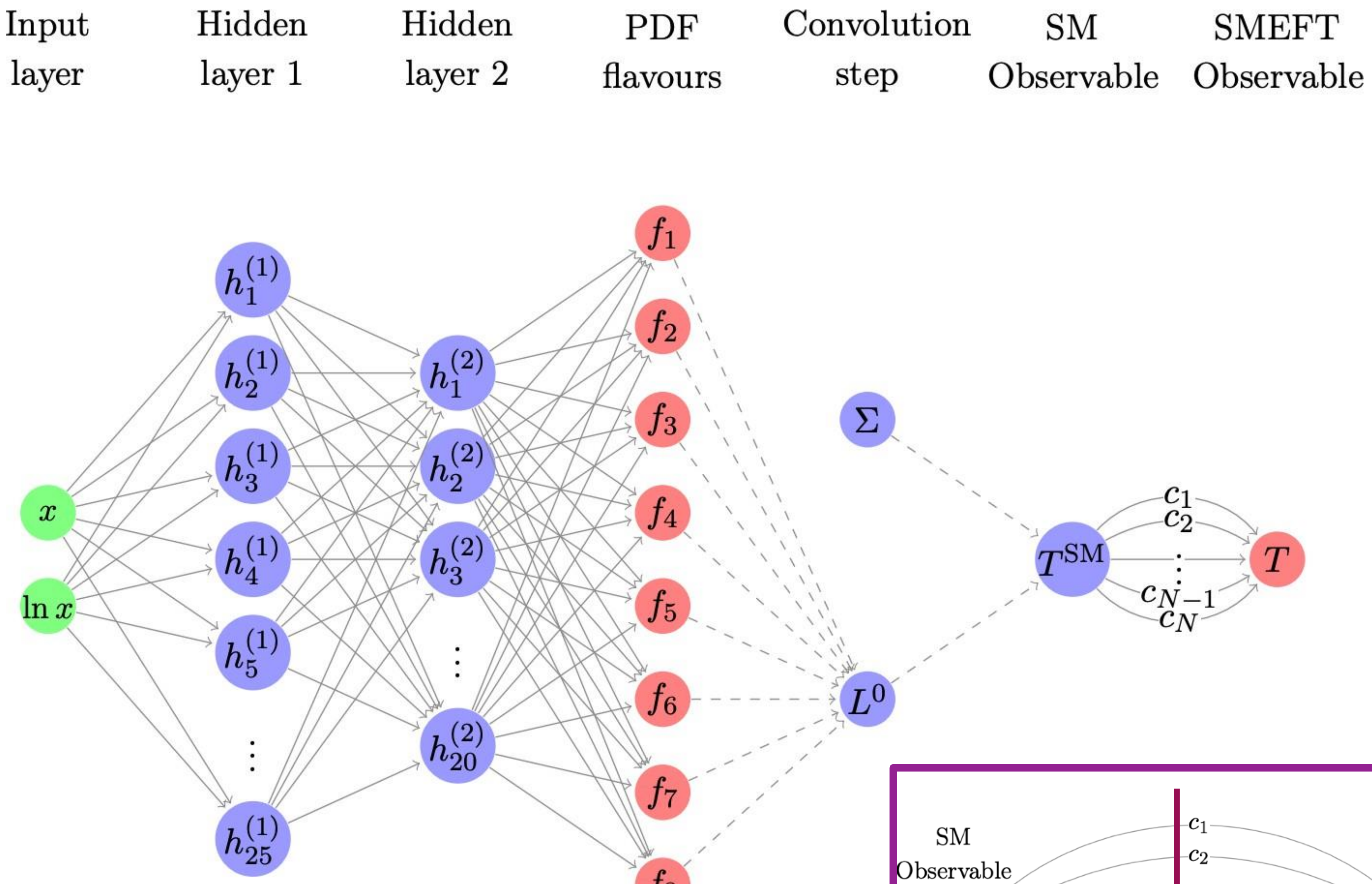
✓ In un fit di PDFs

$$T_i(\{\theta\}) = {\rm PDFs}(\{\theta\},\{c=0\}) \otimes \hat{\sigma}_i(\{c=0\})$$

✓ In un fit di coefficienti di Wilson

$$T_i(\{c\}) = {\rm PDFs}(\{\theta=\bar{\theta}\},\{c=0\}) \otimes \hat{\sigma}_i(\{c\})$$

SIMUNET: UNO STRUMENTO PER FITS SIMULTANEI

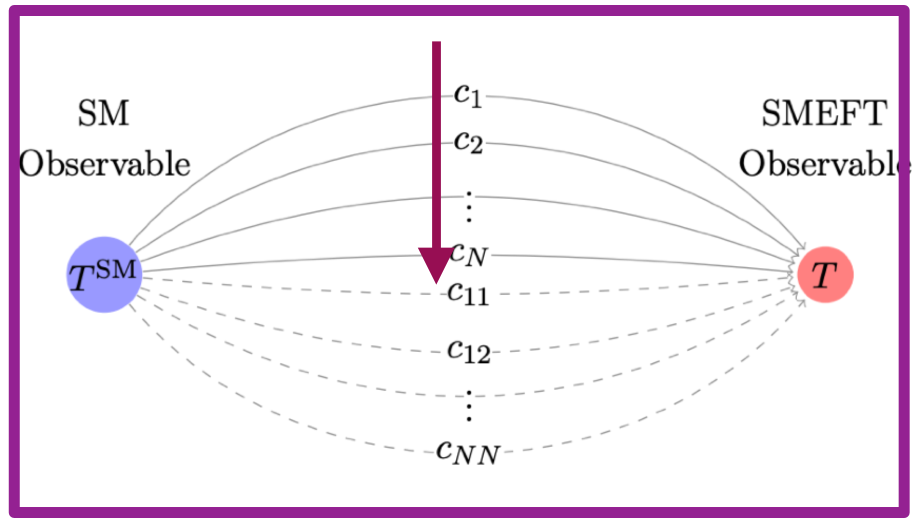


$$T(\hat{\theta}) = \Sigma(\{c_n\}) \cdot L^0(\theta) = T^{\mathrm{SM}}(\theta) \cdot \left(1 + \sum_{n=1}^{N} c_n R_{\mathrm{SMEFT}}^{(n)}\right)$$

$$T^{\mathrm{SM}}(\theta) \;=\; \Sigma^{\mathrm{SM}} \cdot \; L^0(\theta)$$

$$T(\hat{\theta}) = T^{\mathrm{SM}}(\theta) \cdot \left(1 + \sum_{n=1}^{N} c_n R_{\mathrm{SMEFT}}^{(n)} + \sum_{1 \le n \le m \le N} c_{nm} R_{\mathrm{SMEFT}}^{(n,m)}\,,\right)$$

$$c_n c_m$$



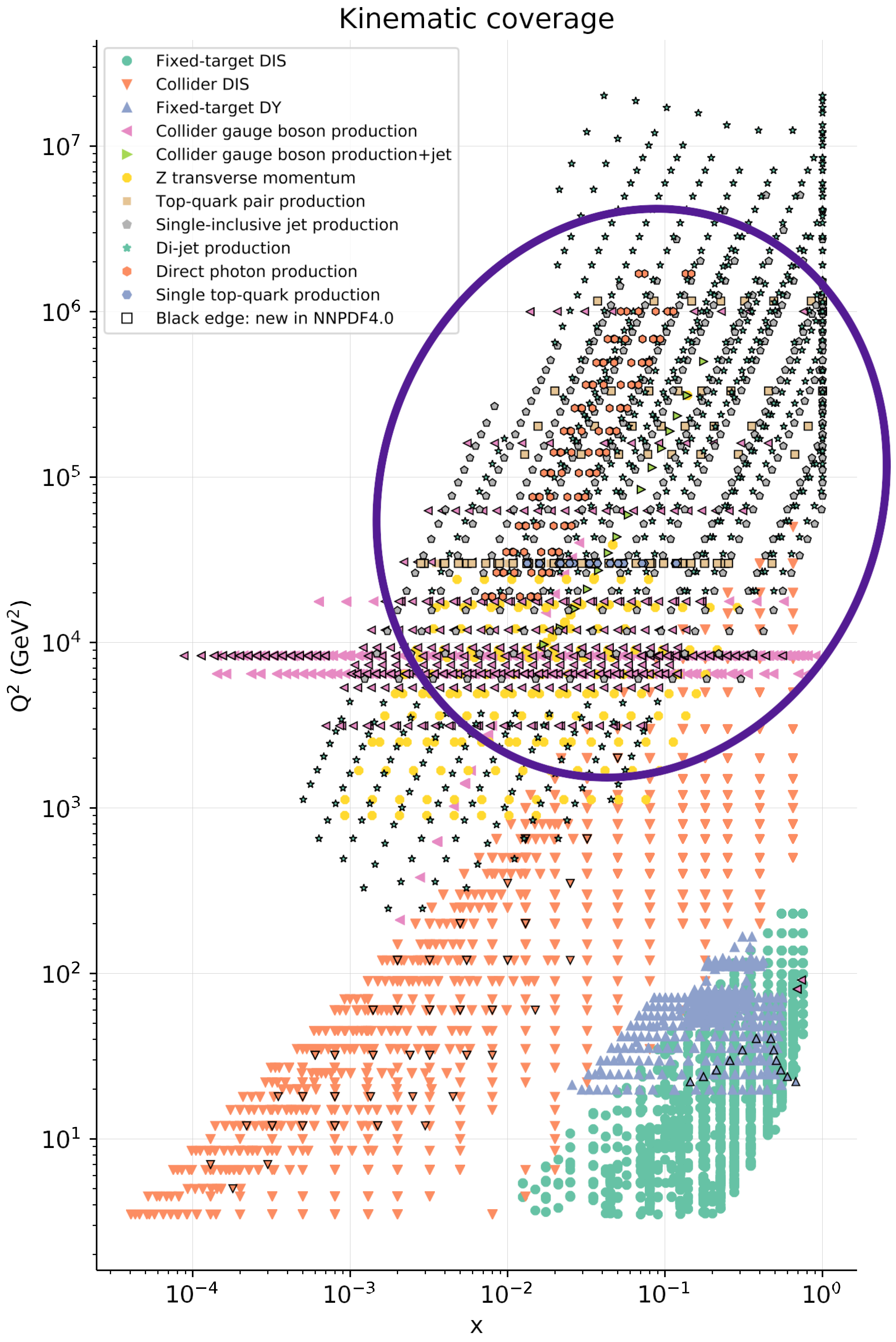
S. Iranipour, MU (arXiv: 2201.07240)
M. Costantini, E Hammou, M. Madigan, L. Mantani, J. Moore, M. Morales, M. Ubiali (arXiv: 2402.03308)

PBSP

IL MIO LAVORO

DATI SPERIMENTALI: JETS SINGOLI E DIJETS INCLUSIVI

ESPERIMENTO	ENERGIA	NDATA
CMS	7 TEV	55
CMS	8 TEV	122
CMS	13 TEV	78
ATLAS	7 TEV	90
ATLAS	8 TEV	171
ATLAS	13 TEV	136



IMPLEMENTAZIONE DEI DATI CON LE INCERTEZZE

SISTEMATICHE
STATISTICHE

ADDITIVE
MOLTIPLICATIVE

CORRELATE
NON-CORRELATE

SIMMETRICHE
ANTISIMMETRICHE

«Asymmetric Uncertainties: Sources, Treatment and Potential Dangers», G. D’Agostini

HEPData

Repository for publication-related High-Energy Physics data

PREDIZIONI TEORICHE CON MADGRAPH

MADGRAPH

È un simulatore monte carlo di eventi casuali per qualsiasi processo ai collisori.

$$d\sigma = \frac{1}{2s} \prod_{i=1}^{N} d\Pi_i (2\pi)^4 \delta^{(4)}(p_A + p_B - \sum_i p_i) \cdot |\mathcal{M}|^2 \qquad d\Pi_i = \frac{d^3\mathbf{p}_i}{(2\pi)^3} \frac{1}{2E_i}$$

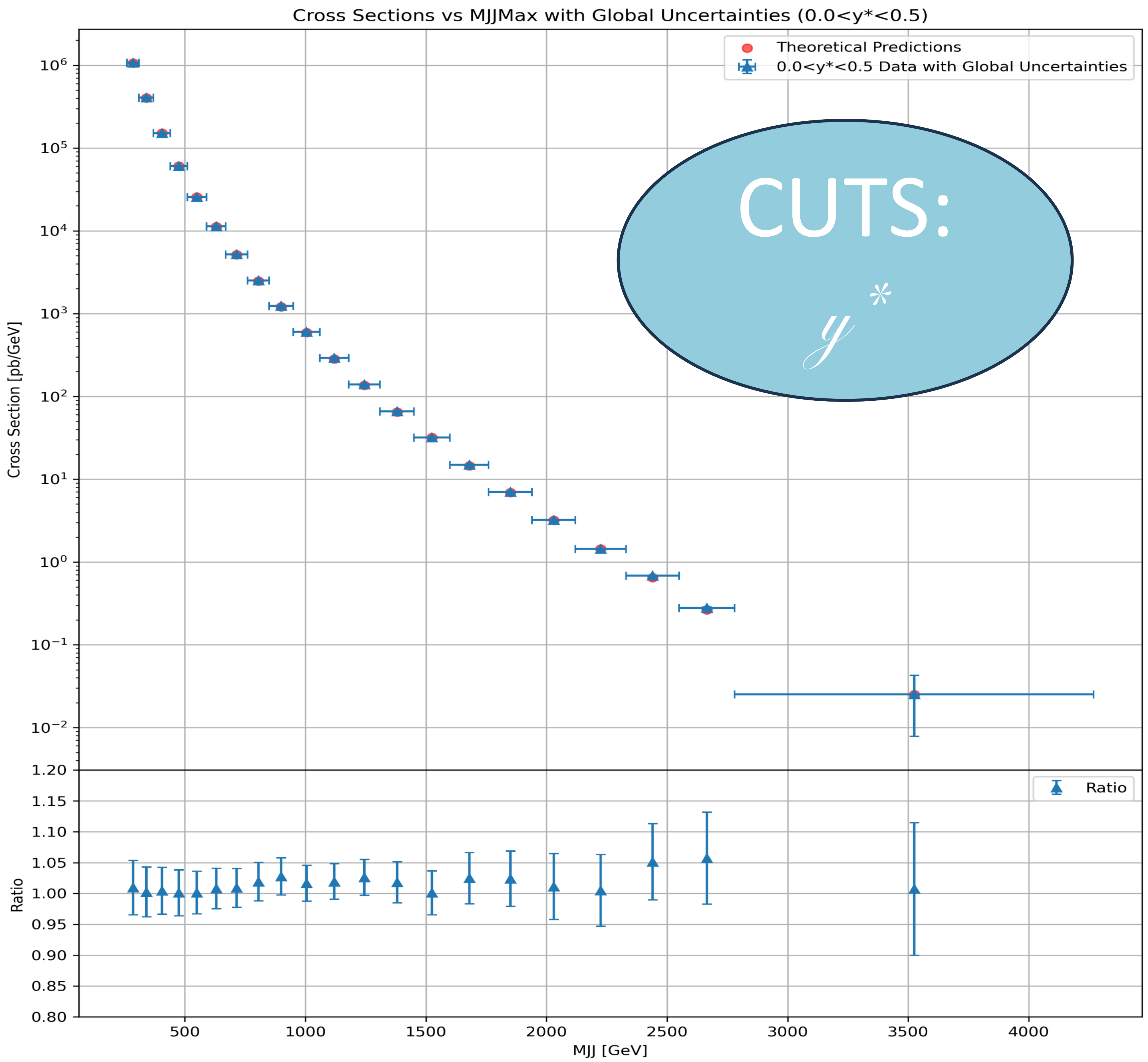
dove **casuale** significa che gli eventi sono ponderati per $|M|^2$
per **evento** si intende un insieme di quadrivettori nello spazio delle fasi.

MODELLO

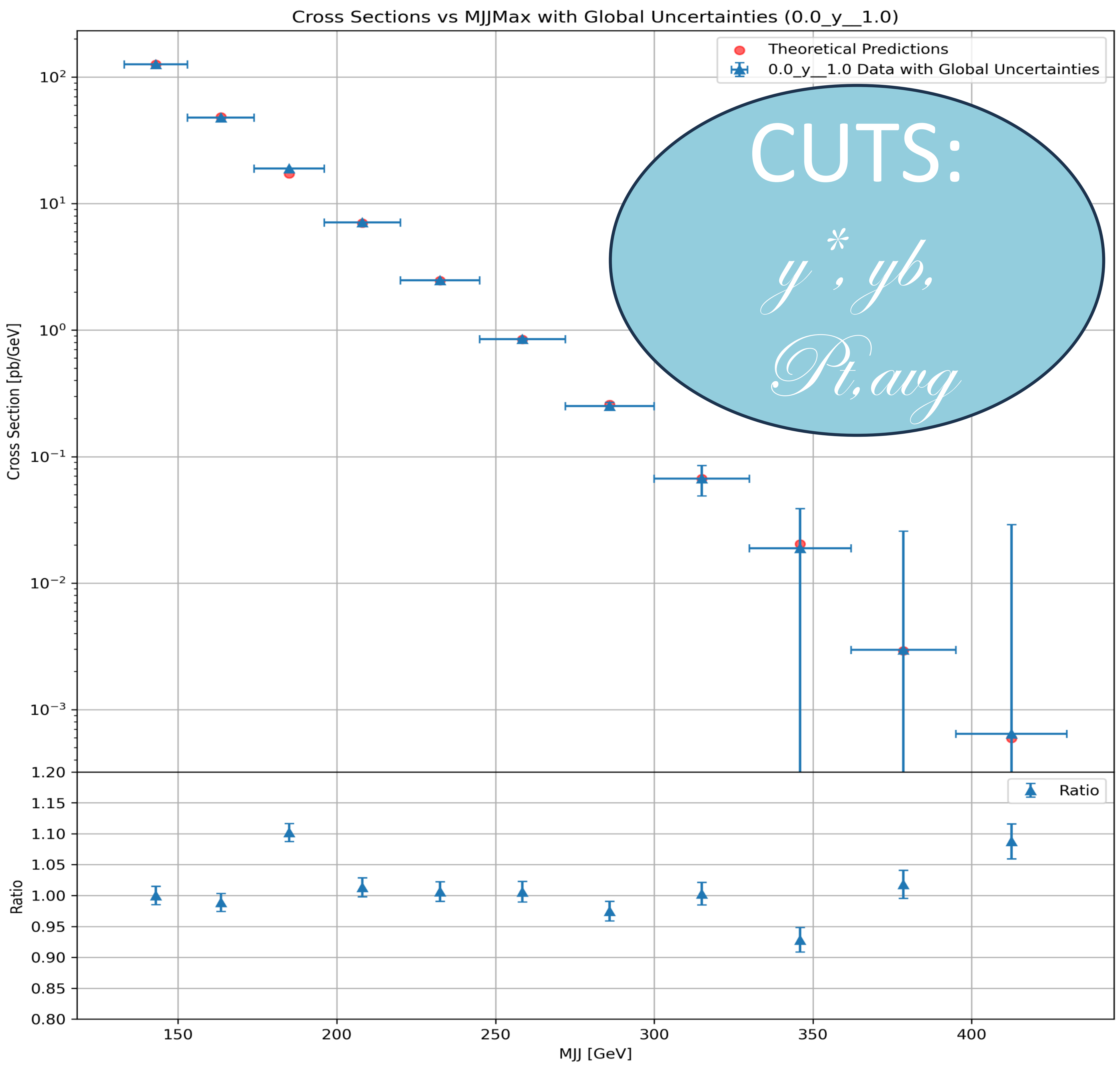
Modello SMEFT, in cui sono inclusi gli operatori gluonici a dim6 e a dim8.

MADGRAPH: SM

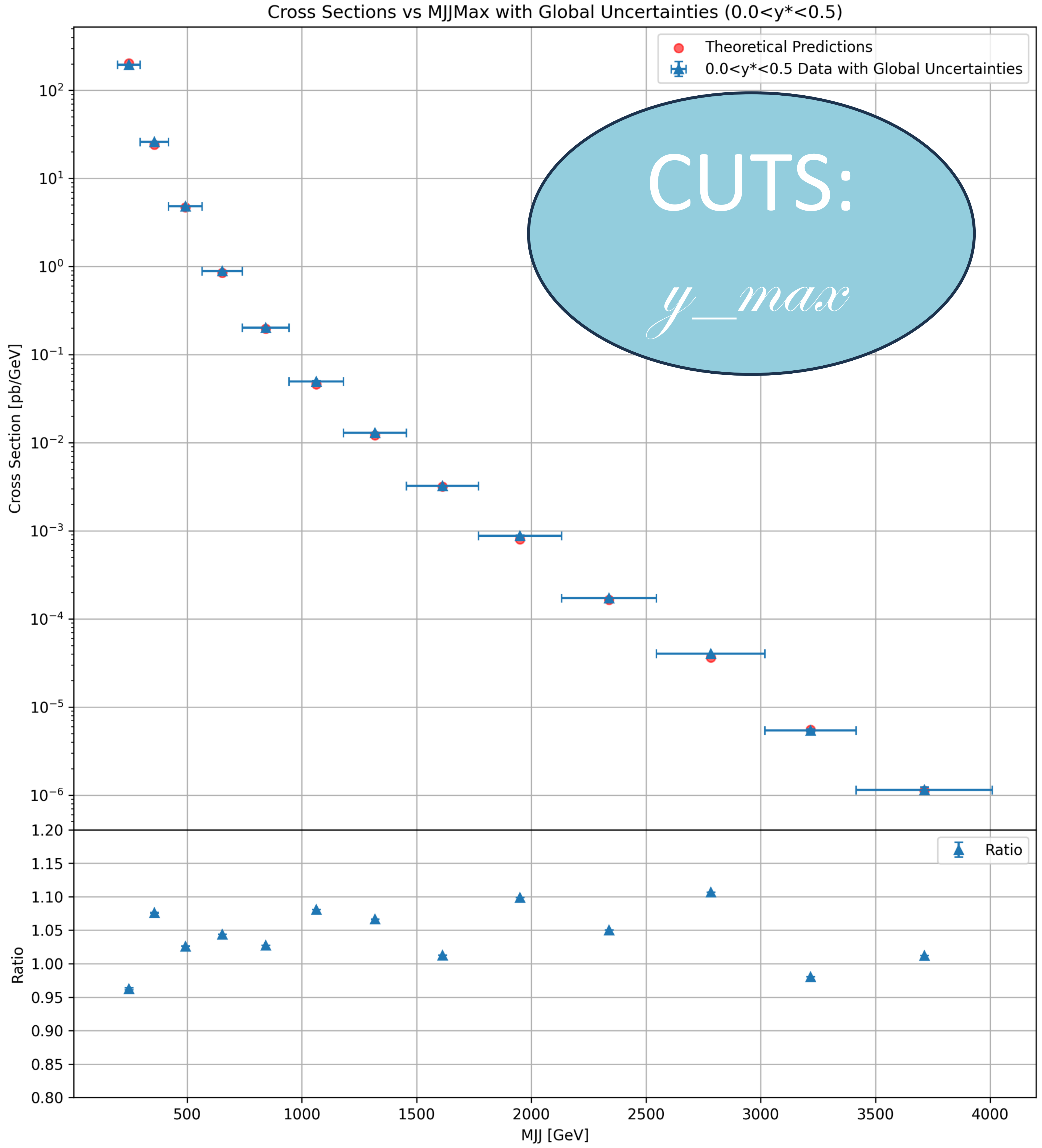
ATLAS 7 TEV DIJET



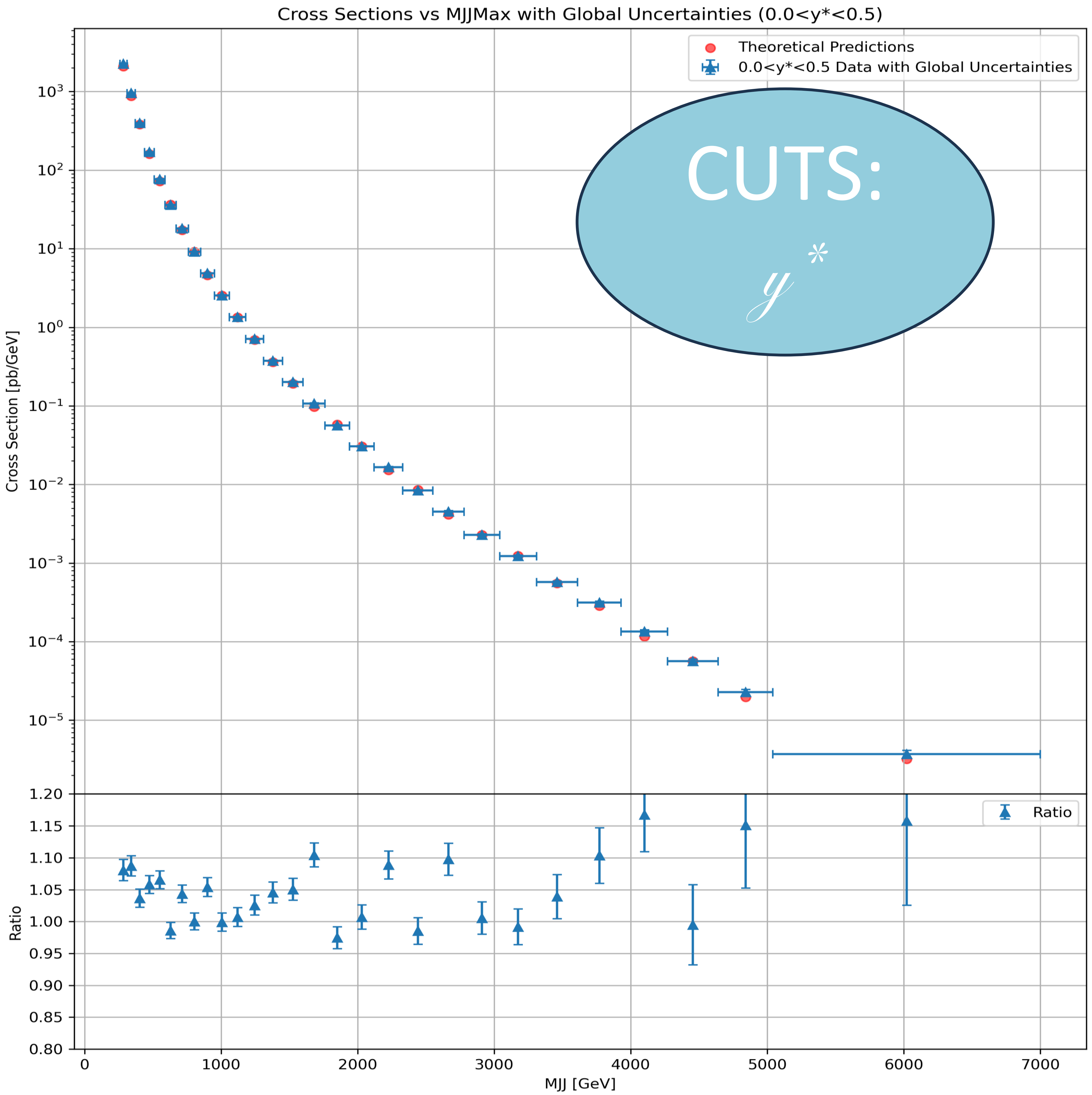
CMS 8 TEV DIJET



CMS 7 TEV DIJET



ATLAS 13 TEV DIJET

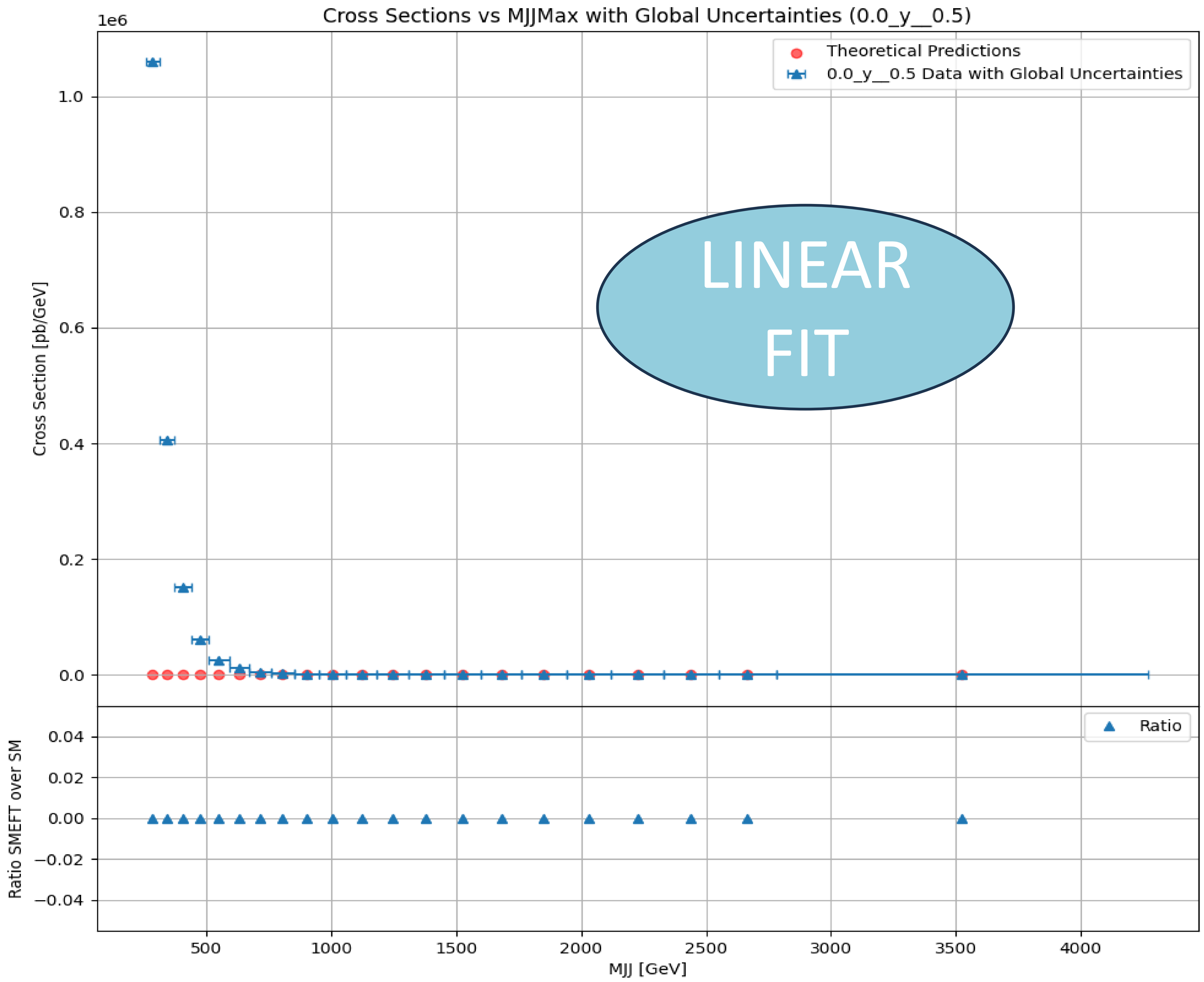


MADGRAPH: contributo SMEFT Lineare

$$\sigma = \sigma_{\text{SM}} \times \left(1 + \frac{c_{tG}}{\Lambda^2}a + \frac{c_{tG}^2}{\Lambda^4}b\right)$$

Termini lineari dim 6

Termini quadratici dim 6



PERCHÈ L'INTERFERENZA È NULLA?

$$d\sigma^{(0)} = \frac{9}{2}\frac{(st+tu+su)^3}{(stu)^2},$$

$$d\sigma^{(1)} = 0,$$

$$d\sigma^{(2)} = \frac{-13851}{512M^4}(st+tu+su),$$

$$d\sigma^{(3)} = \frac{243}{32M^6}(stu),$$

$$d\sigma^{(4)} = \frac{135}{64M^8}(st+tu+su)^2, \qquad (3.2)$$

"DIMENSION-6 GLUON OPERATORS AS PROBES OF NEW PHYSICS"
E.H. S I M M O N S, 1989

Non-interference statement

Four-point amplitudes with at least one transverse polarized gauge boson do not interfere at tree level in the massless limit.

Lately, similar reasoning has been applied to electroweak diboson production in the high energy limit (Azatov et. al. '16).

"On interference and non-interference in the SMEFT"

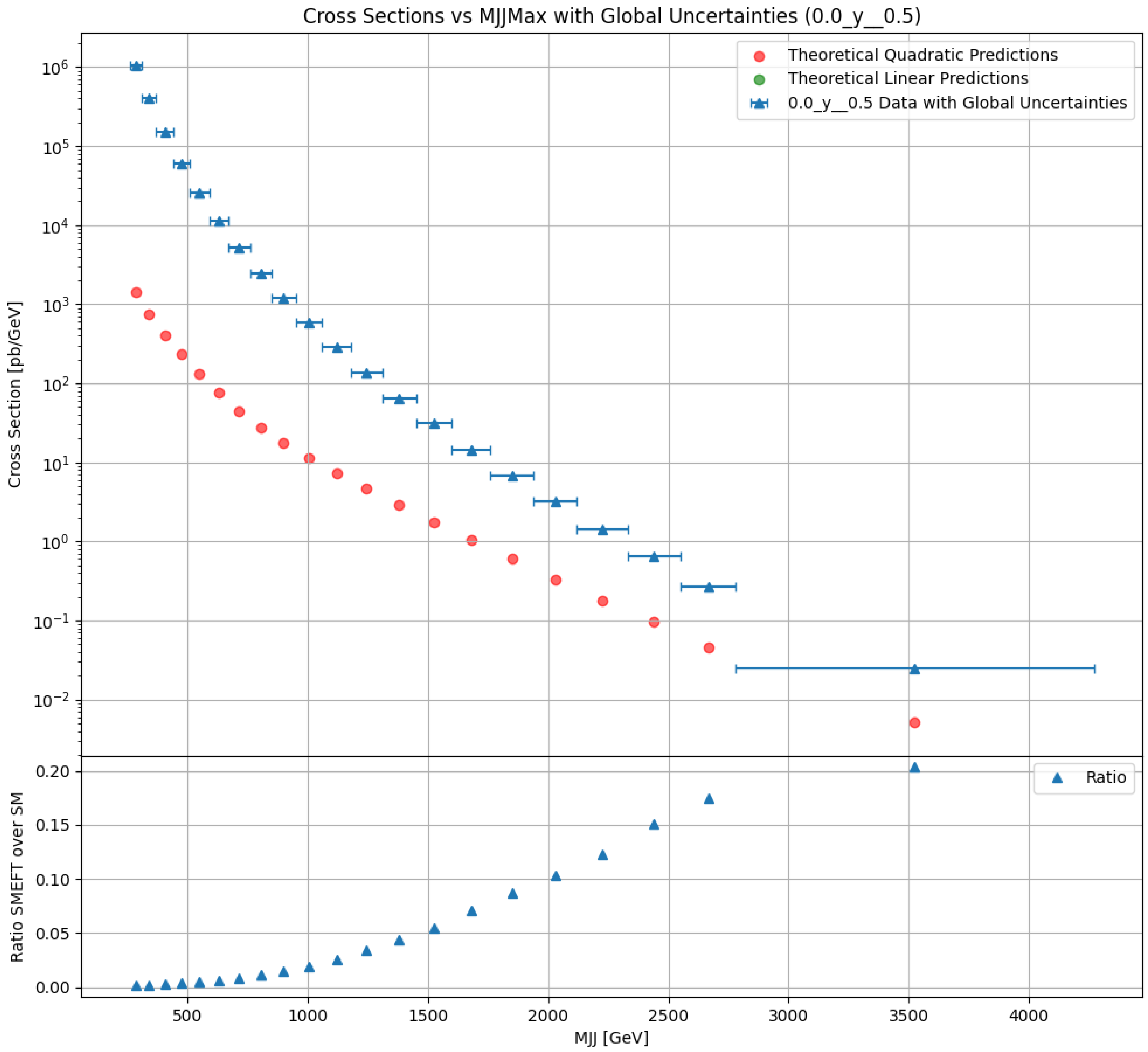
A.Halset & M.Trott

MADGRAPH: contributo SMEFT Quadratico

$$\sigma = \sigma_{\rm SM} \times \left(1 + \frac{c_{tG}}{\Lambda^2} a + \frac{c_{tG}^2}{\Lambda^4} b \right)$$

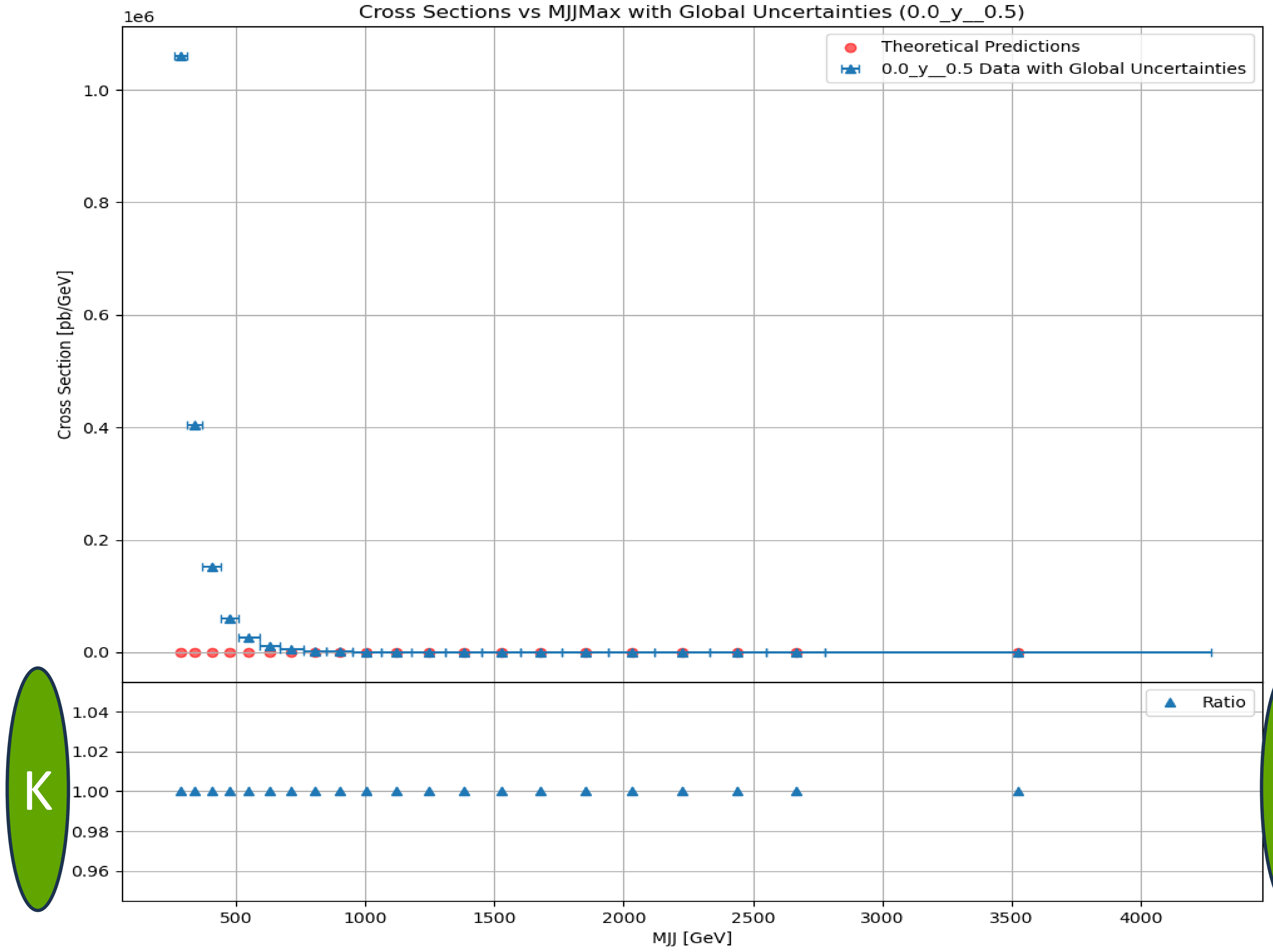
Termini lineari dim-6

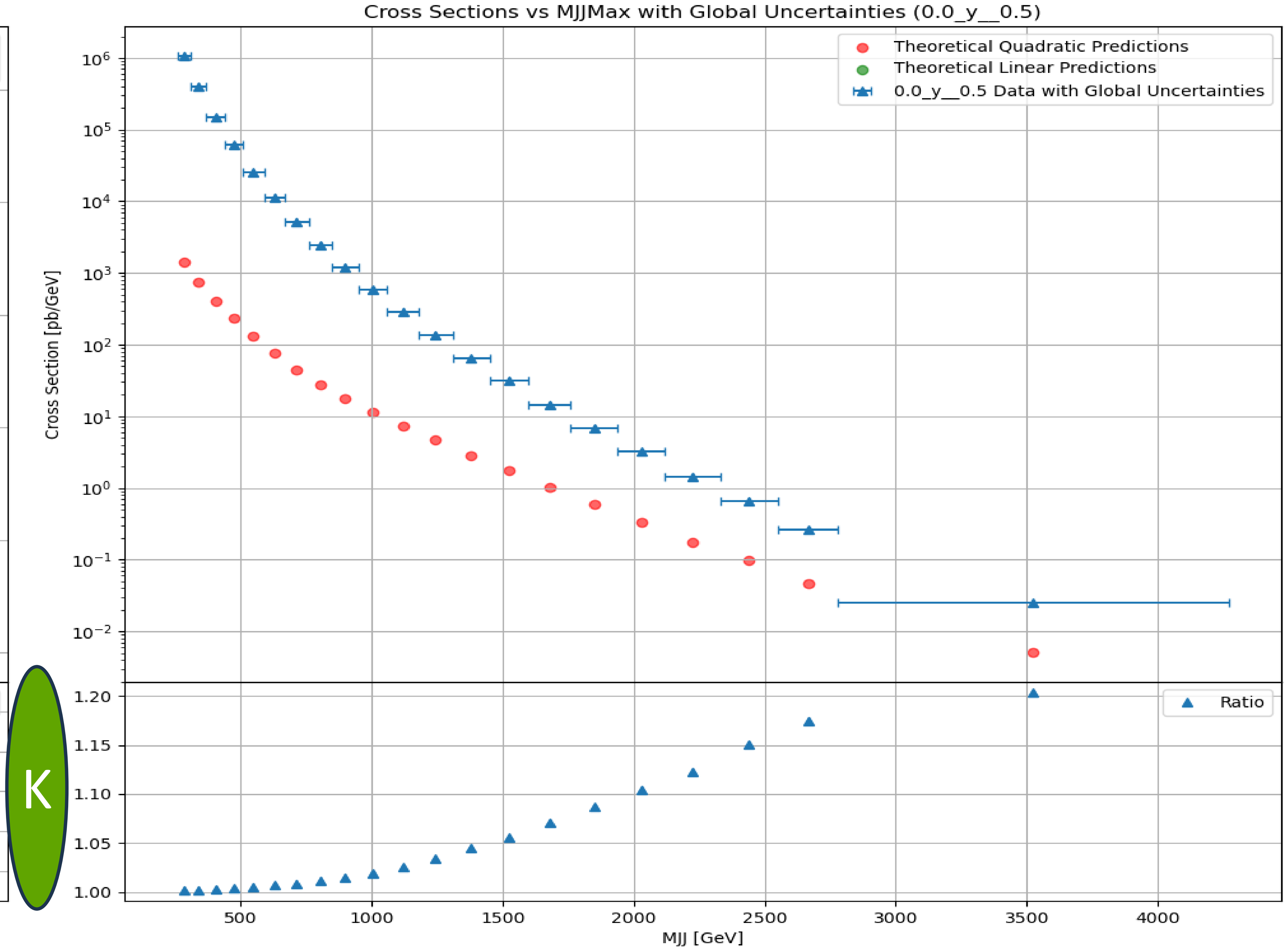
Termini quadratici dim-6



K FACTORS

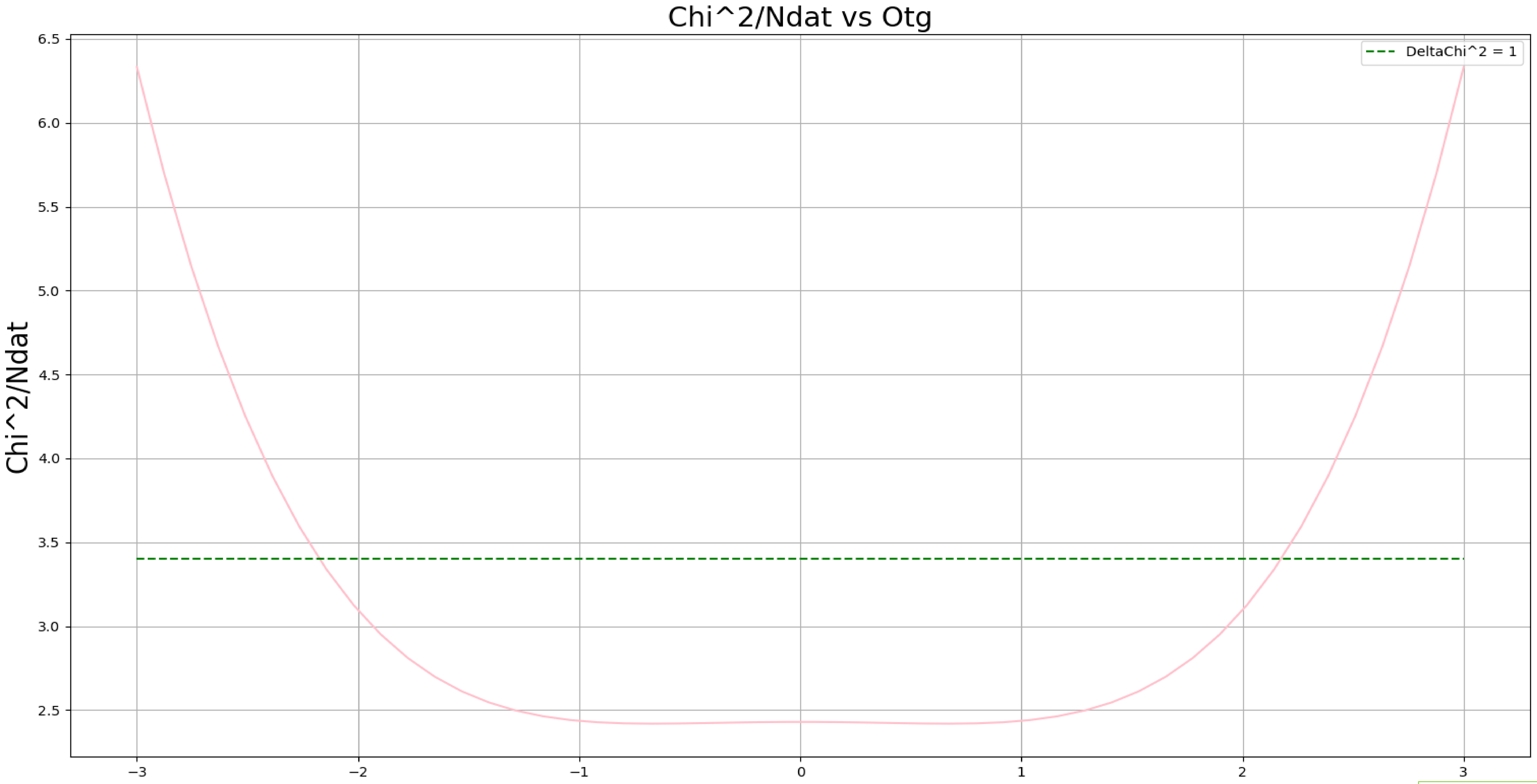
$$K = \frac{\text{SM\_preds} + \text{LINEAR SMEFT\_preds} + \text{QUADRATIC SMEFT\_preds}}{\text{SM\_preds}}$$





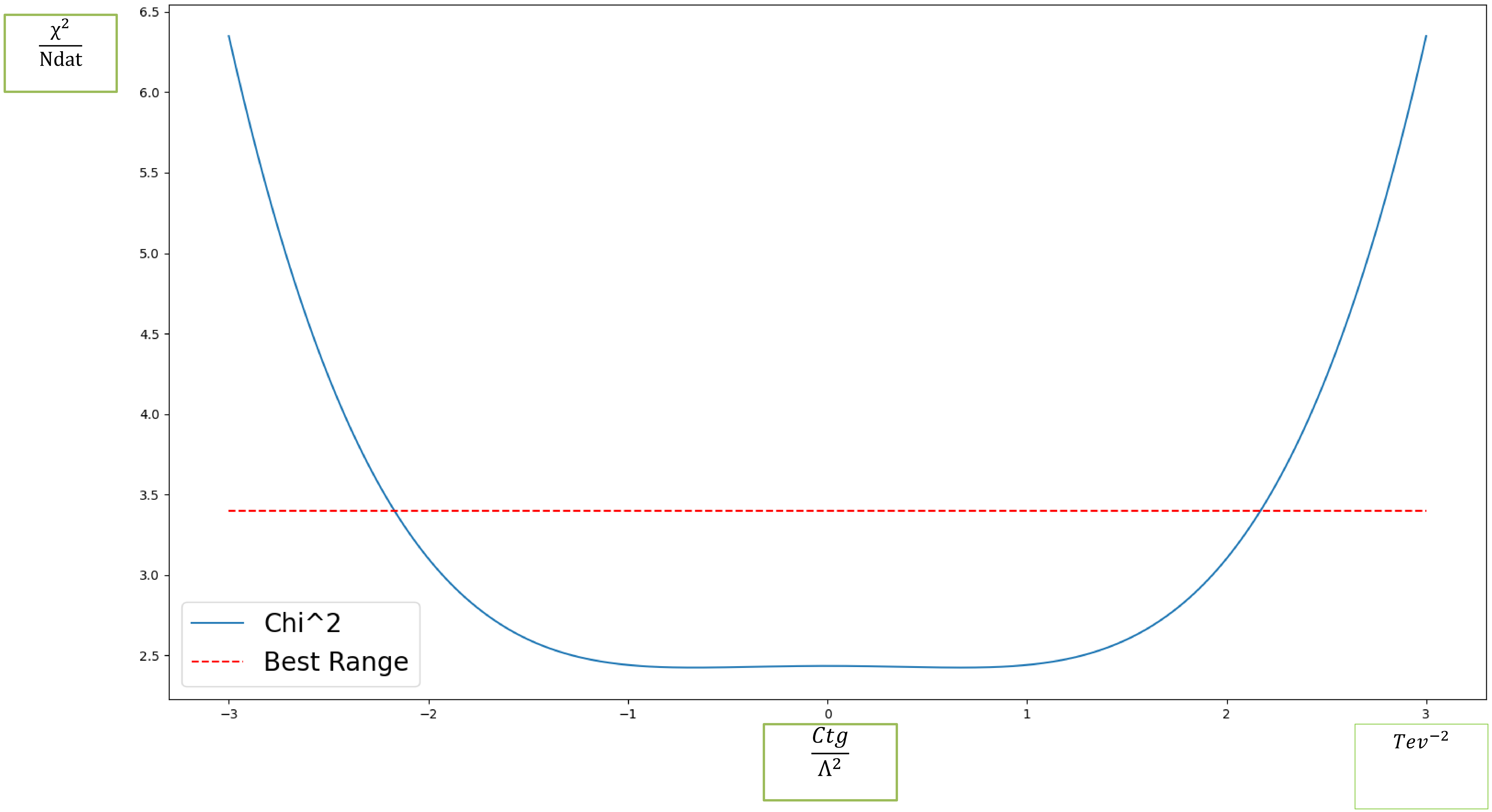
Naive X^2 and Otg

$$\chi^2 = \sum_{i=1}^{k} \frac{(o_i - e_i)^2}{e_i}$$



$\frac{Ctg}{\Lambda^2}$ Tev^{-2}

ULTRANEST

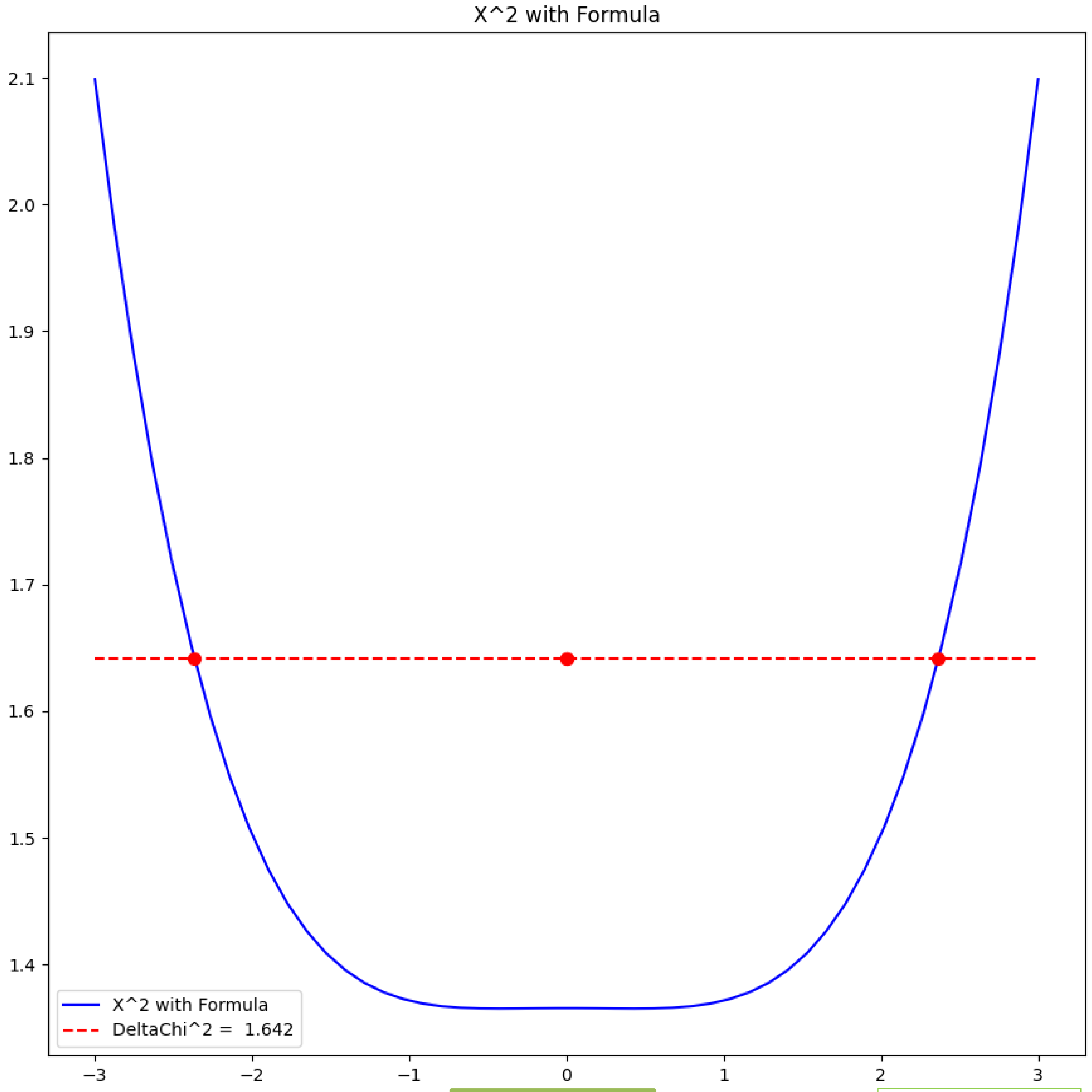


$\frac{\chi^2}{\text{Ndat}}$
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
Chi^2
Best Range
−3
−2
−1
0
1
2
3
$\frac{Ctg}{\Lambda^2}$
Tev^{-2}

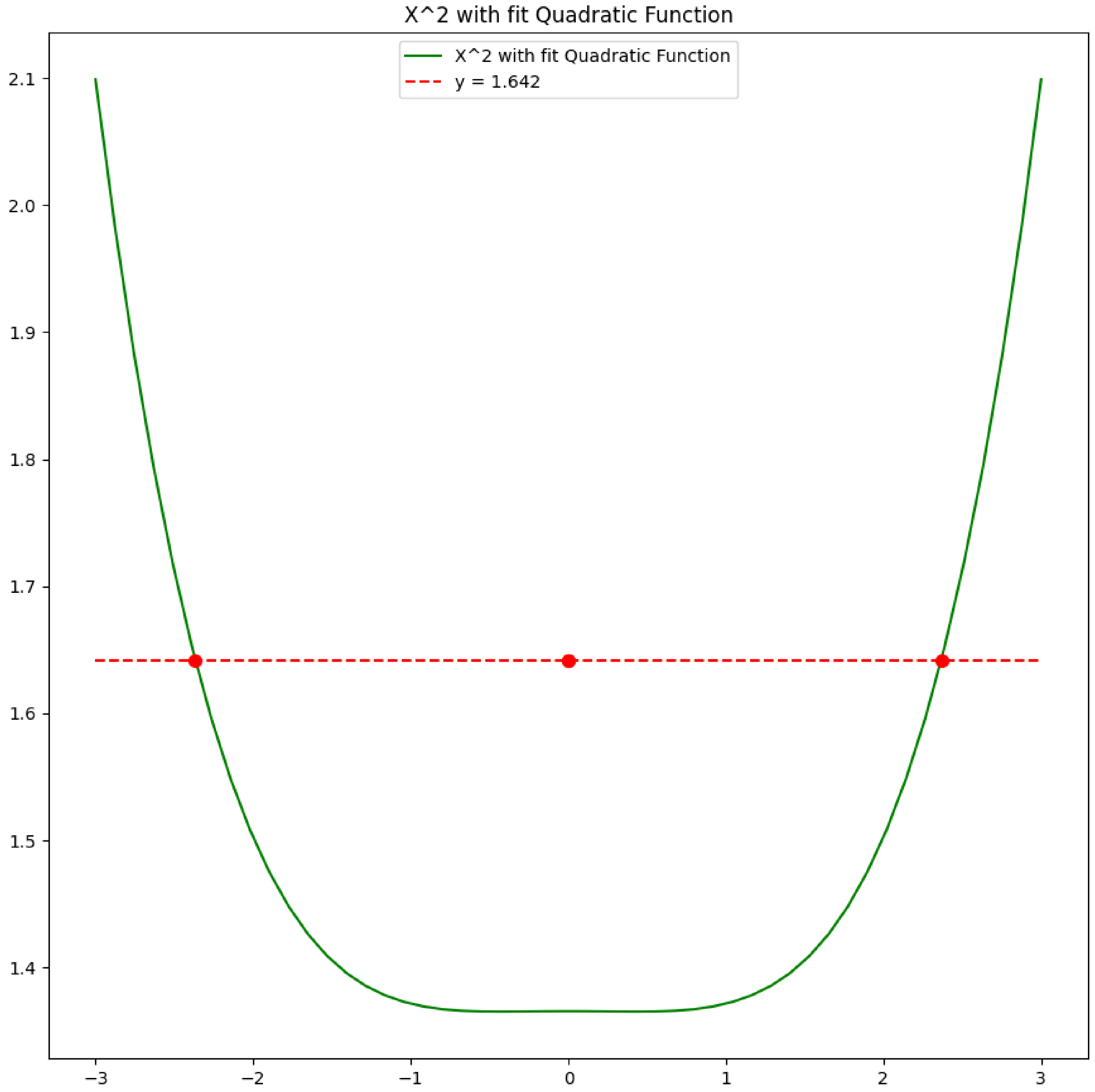
X^2 vs Otg

$$\chi^2(\mathbf{c}) = \frac{1}{n_{\mathrm{dat}}} \sum_{i,j=1}^{n_{\mathrm{dat}}} \left(\sigma_{i,\mathrm{SMEFT}}(\mathbf{c}) - \sigma_{i,\mathrm{exp}}\right) \left(\mathrm{cov}^{-1}\right)_{ij} \left(\sigma_{j,\mathrm{SMEFT}}(\mathbf{c}) - \sigma_{j,\mathrm{exp}}\right)$$

$\frac{\chi^2}{\mathrm{Ndat}}$



$\frac{Ctg}{\Lambda^2}$ Tev^{-2}



$\frac{Ctg}{\Lambda^2}$ Tev^{-2}

CONCLUSIONI E PROSSIMI PASSI

- Ho organizzato i dati sperimentali di single jets e dijets;
- Ho prodotto le predizioni teoriche di dijets in SM e SMEFT;
- Ho dimostrato perché l'interferenza con SM, per i termini lineari SMEFT a dim6, è zero;
- Ho calcolato il χ^2, considerando tutti i datasets di dijets;
- Fits simultaneo e contaminato di dijets con SIMUnet;
- Fits simultaneo e contaminato di singoli jets inclusivi con SIMUnet;

GRAZIE PER L'ATTENZIONE!

BACKUP

RUNCARD

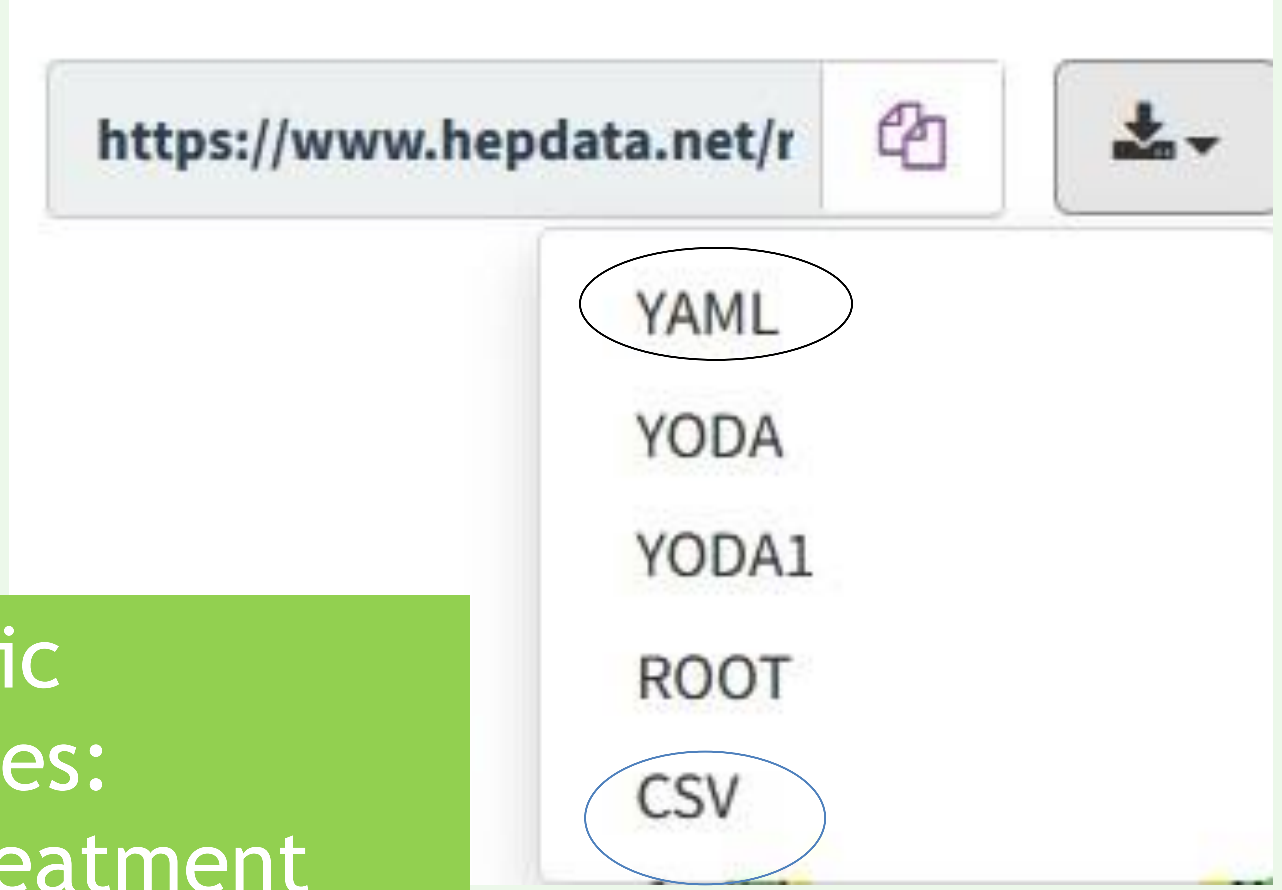
```
import model gluon_dim8_UFO-massless
generate p p > j j NP=0 QCD==2
output ATLAS_DIJET_7TEV_R06_Y_0.0_0.5_mjj_260.0_310.0
launch
set run_tag ATLAS_DIJET_7TEV_R06_Y_0.0_0.5_mjj_260.0_310.0
set nevents 10000
set cG 0.0
set cG1 0.0
set cG2 0.0
set cG3 0.0
set cG4 0.0
set cG5 0.0
set cG6 0.0
set cG7 0.0
set cG8 0.0
set cG9 0.0
set ebeam1 3500.0
set ebeam2 3500.0
set pdlabel lhapdf
set lhaid 331100
set dynamical_scale_choice 4
set ptj1min 50.0
set ptj2min 50.0
set mmjj 260.0
set mmjjmax 310.0
set drjj 0.6
set etaj 3.0
set etajmin 0.0
set use_syst False
```

```
import model gluon_dim8_UFO-massless
generate p p > j j NP^2==4
output ATLAS_DIJET_7TEV_R06_Y_0.0_0.5_mjj_260.0_310.0
launch
set run_tag ATLAS_DIJET_7TEV_R06_Y_0.0_0.5_mjj_260.0_310.0
set nevents 10000
set cG 1.0
set cG1 0.0
set cG2 0.0
set cG3 0.0
set cG4 0.0
set cG5 0.0
set cG6 0.0
set cG7 0.0
set cG8 0.0
set cG9 0.0
set ebeam1 3500.0
set ebeam2 3500.0
set pdlabel lhapdf
set lhaid 331100
set dynamical_scale_choice 4
set ptj1min 100.0
set ptj2min 50.0
set mmjj 260.0
set mmjjmax 310.0
set drjj 0.6
set etaj 3.0
set etajmin 0.0
set use_syst False
```

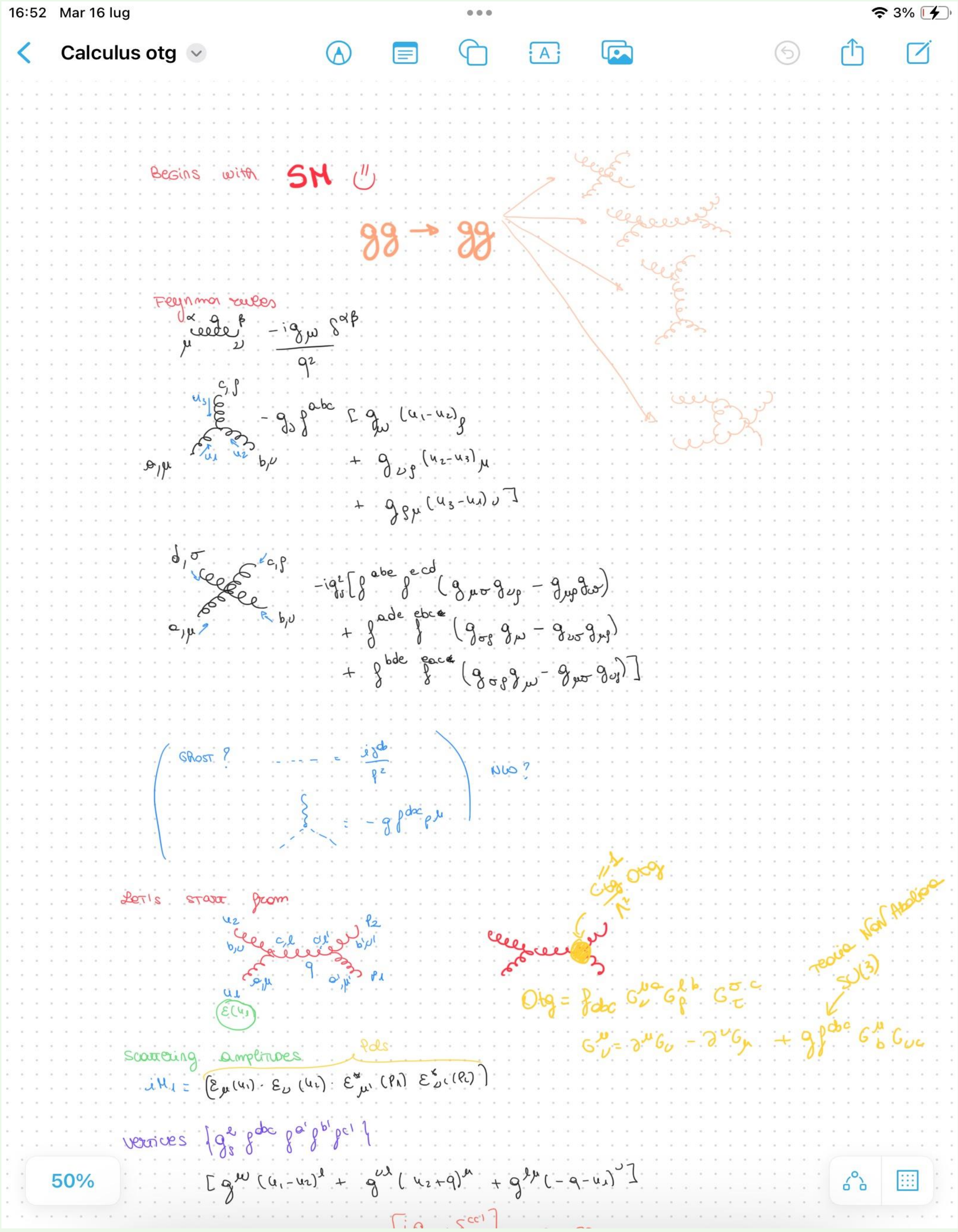
INCERTEZZE e MATRICE DI COVARIANZA

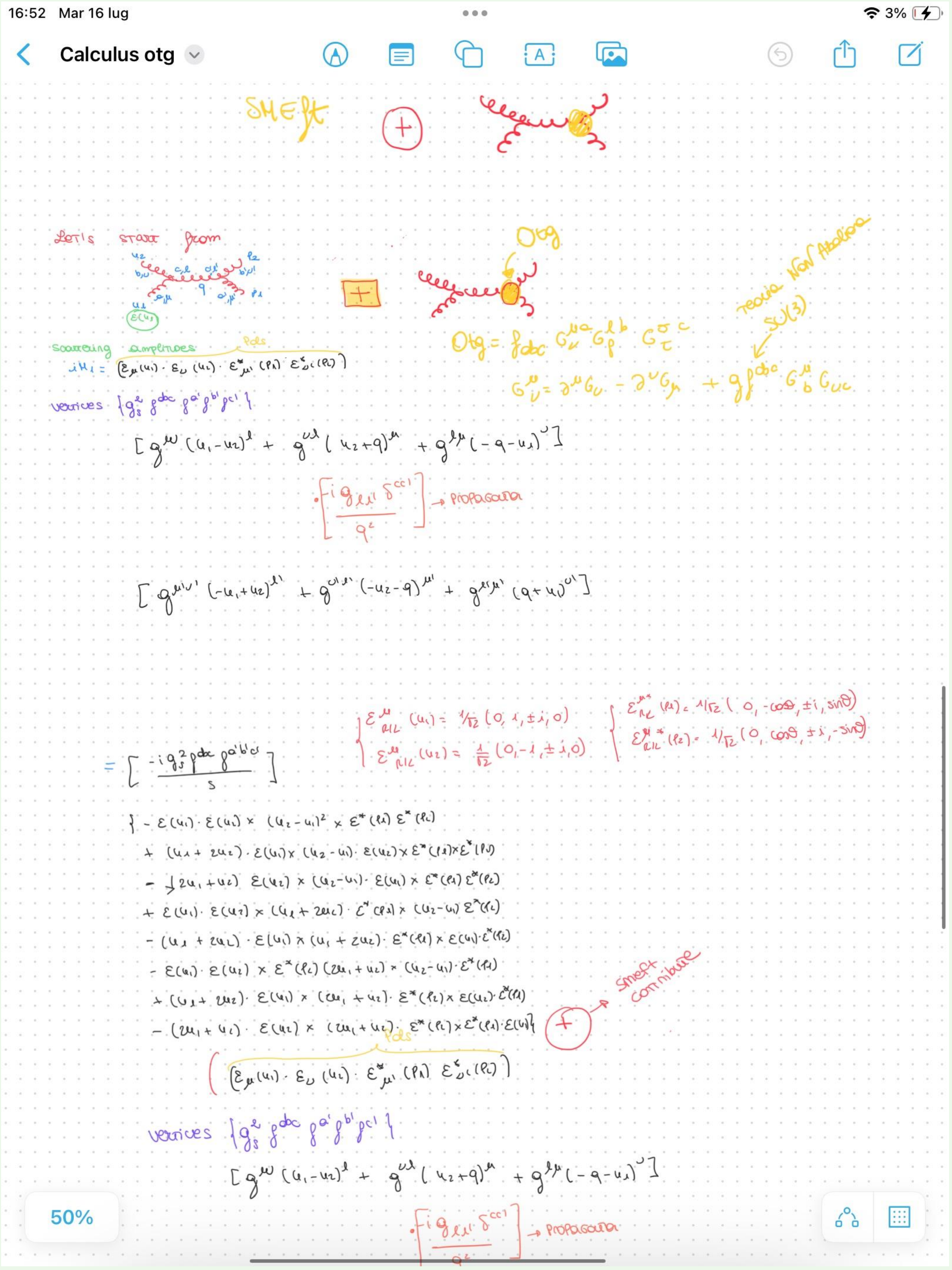
```
def extract_errors_from_yaml(yaml_file_path):
with open(yaml_file_path, 'r') as file:
 yaml_content = yaml.safe_load(file)
errors_by_value = {}
 for dependent_variable in yaml_content.get('dependent_variables', []):
 for value in dependent_variable.get('values', []):
 value_key = value.get('value')
  if value_key is not None:
if value_key not in errors_by_value:
  errors_by_value[value_key] = []
  for error in value.get('errors', []):
if 'symerror' in error:
 label = error.get('label', '')
if label == 'sys':
 errors_by_value[value_key].append(float(error['symerror'].rstrip('%')))
 elif 'asymerror' in error:
  asym_error_minus = -float(error['asymerror']['minus'].rstrip('%'))
 asym_error_plus = float(error['asymerror']['plus'].rstrip('%'))
 semi_value = (asym_error_plus +  asym_error_minus) * 0.5
average = (asym_error_plus - asym_error_minus) * 0.5
 errors_by_value[value_key].append(sqrt(average**2 + 2*(semi_value)**2))
return errors_by_value
```

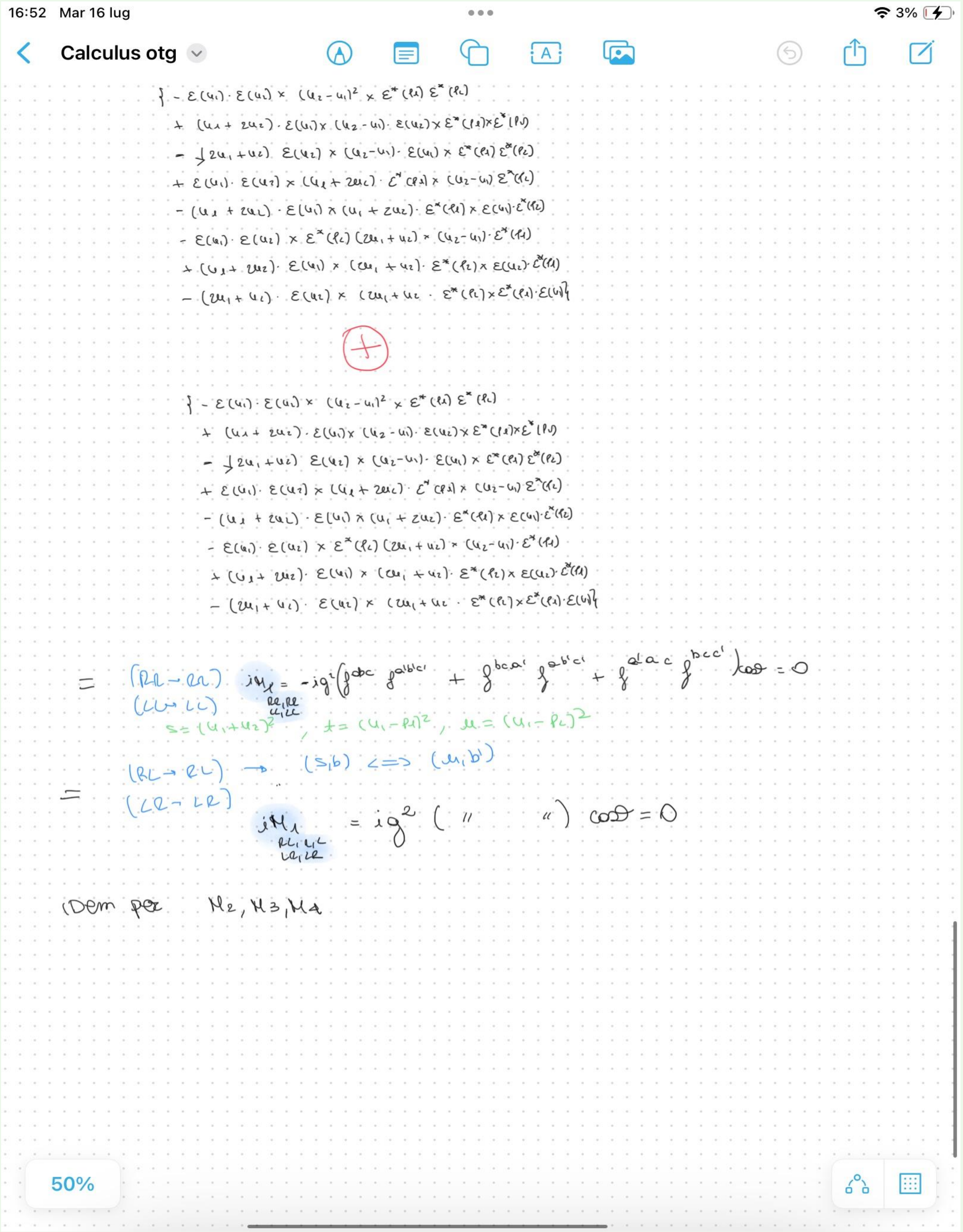
«Asymmetric Uncertainties: Sources, Treatment and Potential Dangers», G. D'Agostini




```
result_matrix = np.zeros((n,n))for i in range(n):
  for j in range(n):
 val_i = data.iloc[i].values[0]
 val_j = data.iloc[j].values[0]
 result_matrix[i, j] = val_i * val_j
  if i!=j:          result_matrix[j, i] = result_matrix[i, j]
 elif i == j:          result_matrix[i, j] = result_matrix[i,i]**2
```


16:52 Mar 16 lug
Calculus otg
Begins with SM
gg → gg
Feynman rules
Ghost ?
NLO ?
Let's start from
Otg
Scattering amplitudes
Pols
Vertices
50%

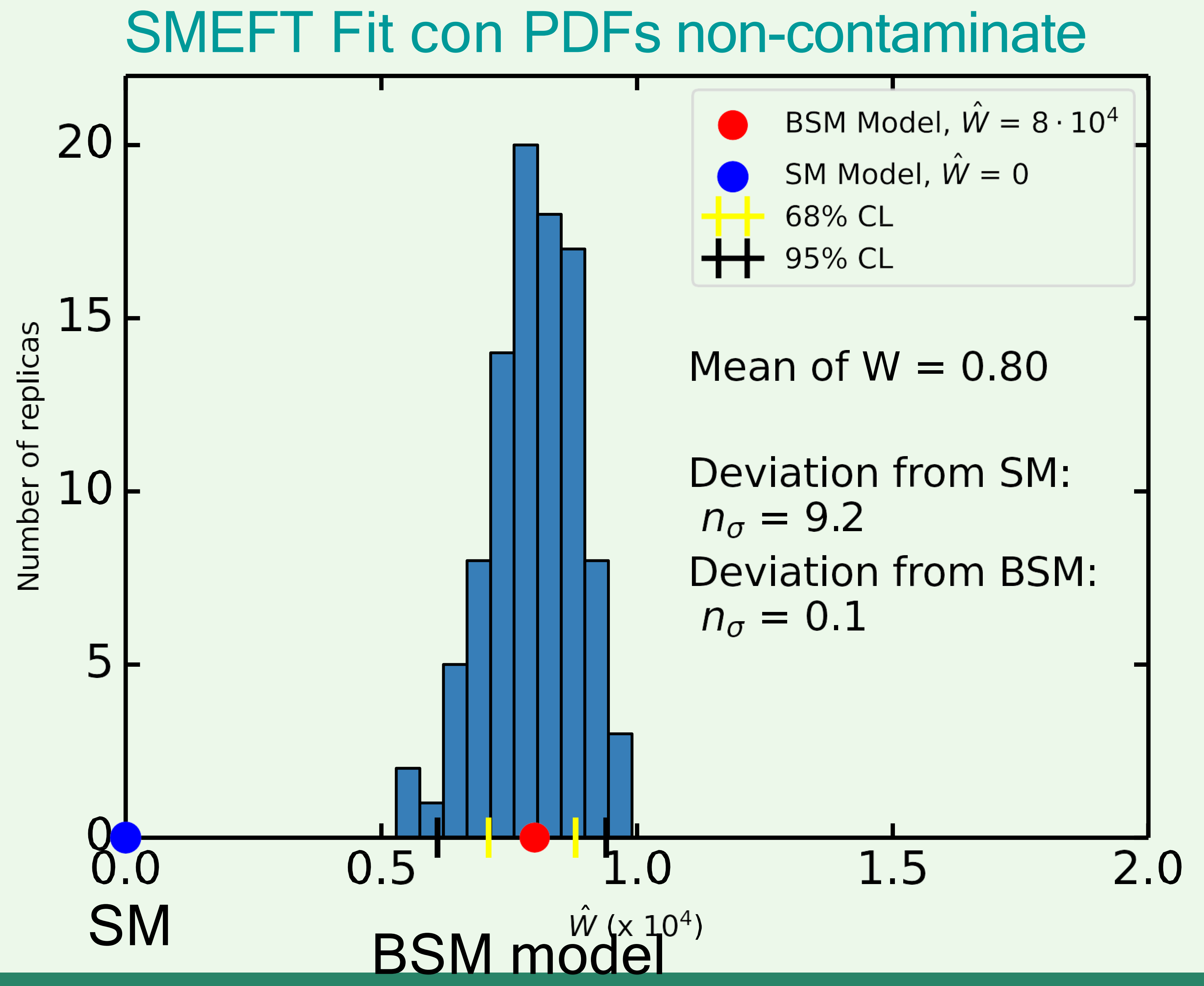

16:52 Mar 16 lug
Calculus otg
SMEFT
Let's start from
Otg
Scattering amplitudes
Pols
Vertices
Propagator
Teoria Non Abeliana
SU(3)
SMEFT contribute
50%

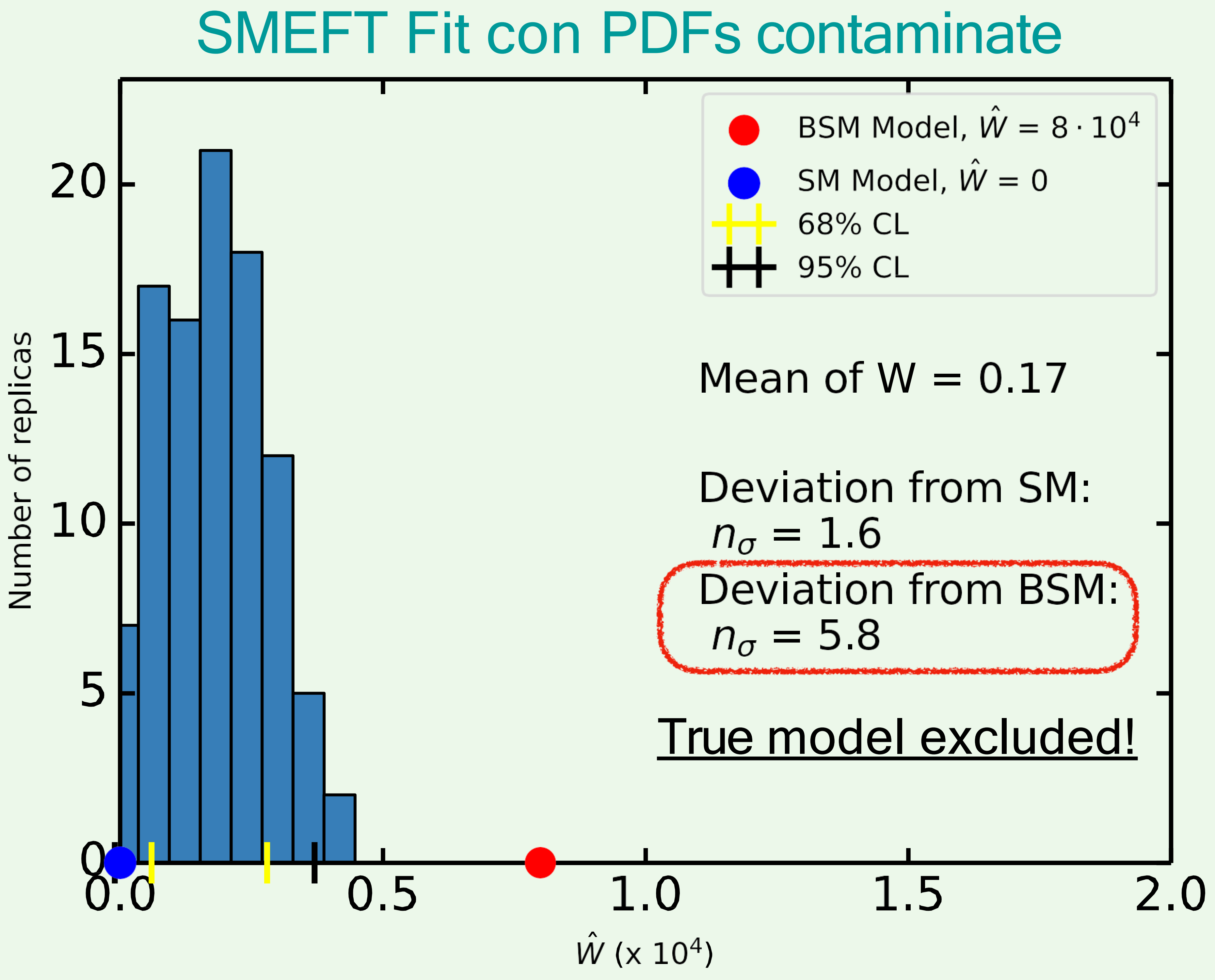

16:52 Mar 16 lug
Calculus otg
Dem per M2, M3, M4
50%

FIT DIJET CONTAMINATO

https://indico.cern.ch/event/1339526/contributions/5907802/attachments/2877580/5039763/HEFT_Hammou.pdf

Impatto della contaminazione dei PDFs fits negli SMEFT fits e viceversa



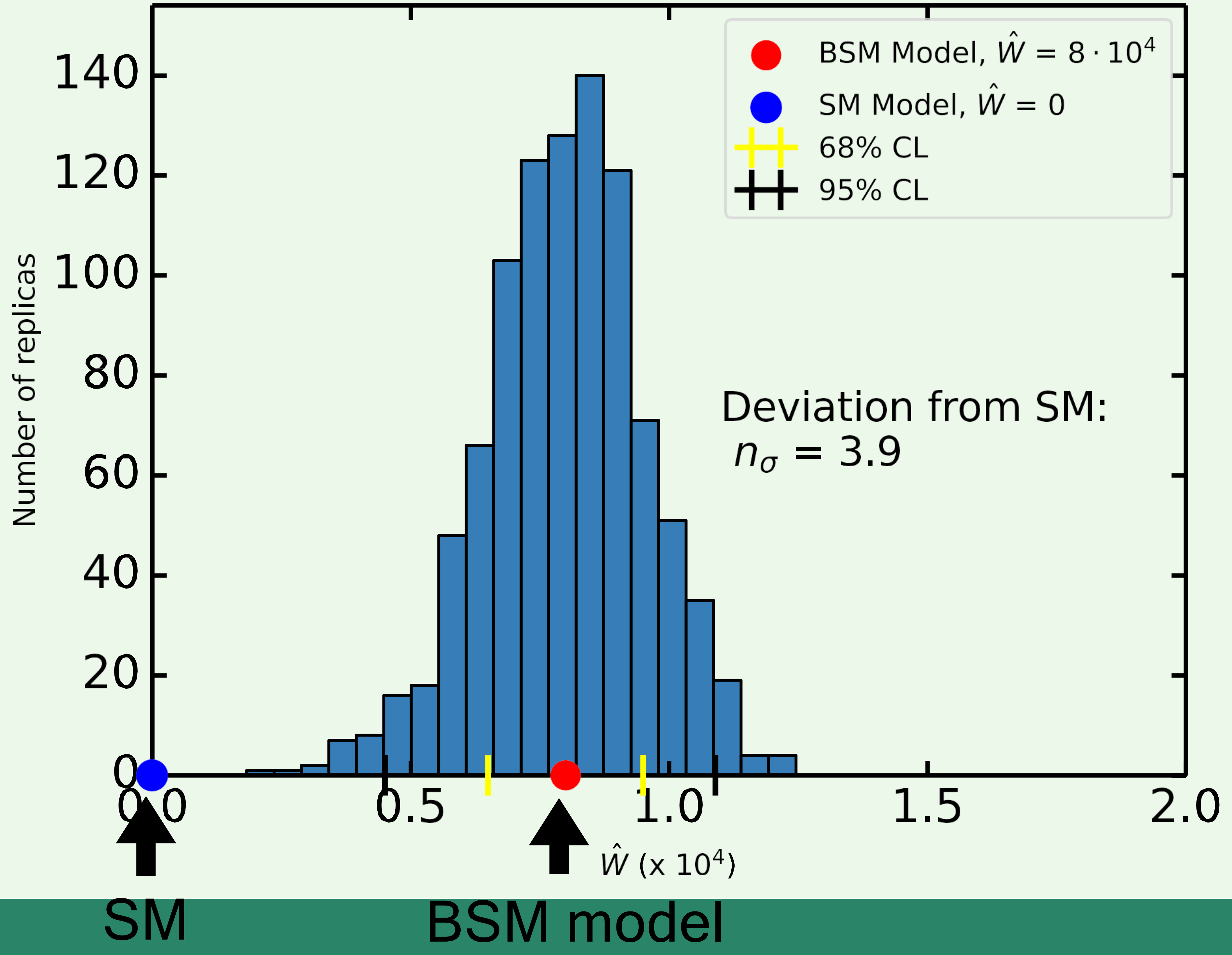


FIT DIJET SIMULTANEO

https://indico.cern.ch/event/1339526/contributions/5907802/attachments/2877580/5039763/HEFT_Hammou.pdf

Districare la contaminazione dei fits PDFs

SMEFT Fit



PDF Fit