PHD THESIS DEFENCE

A LEPTON PAIR AND JETS FINAL STATE IN CMS AND UNITARITY INTERPRETATIONS

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OUTLINE

Motivation

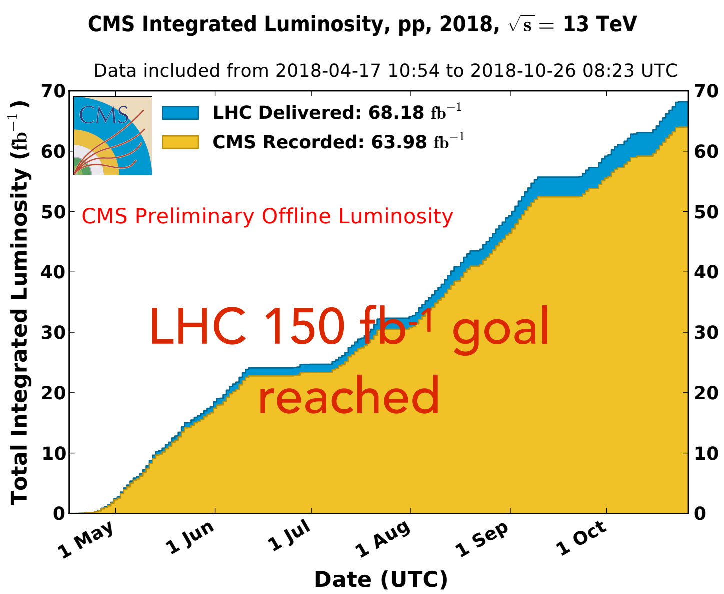
1. Unitarity bounds in effective composite models

2. Experimental searches for exotic particles with CMS at the LHC and future colliders

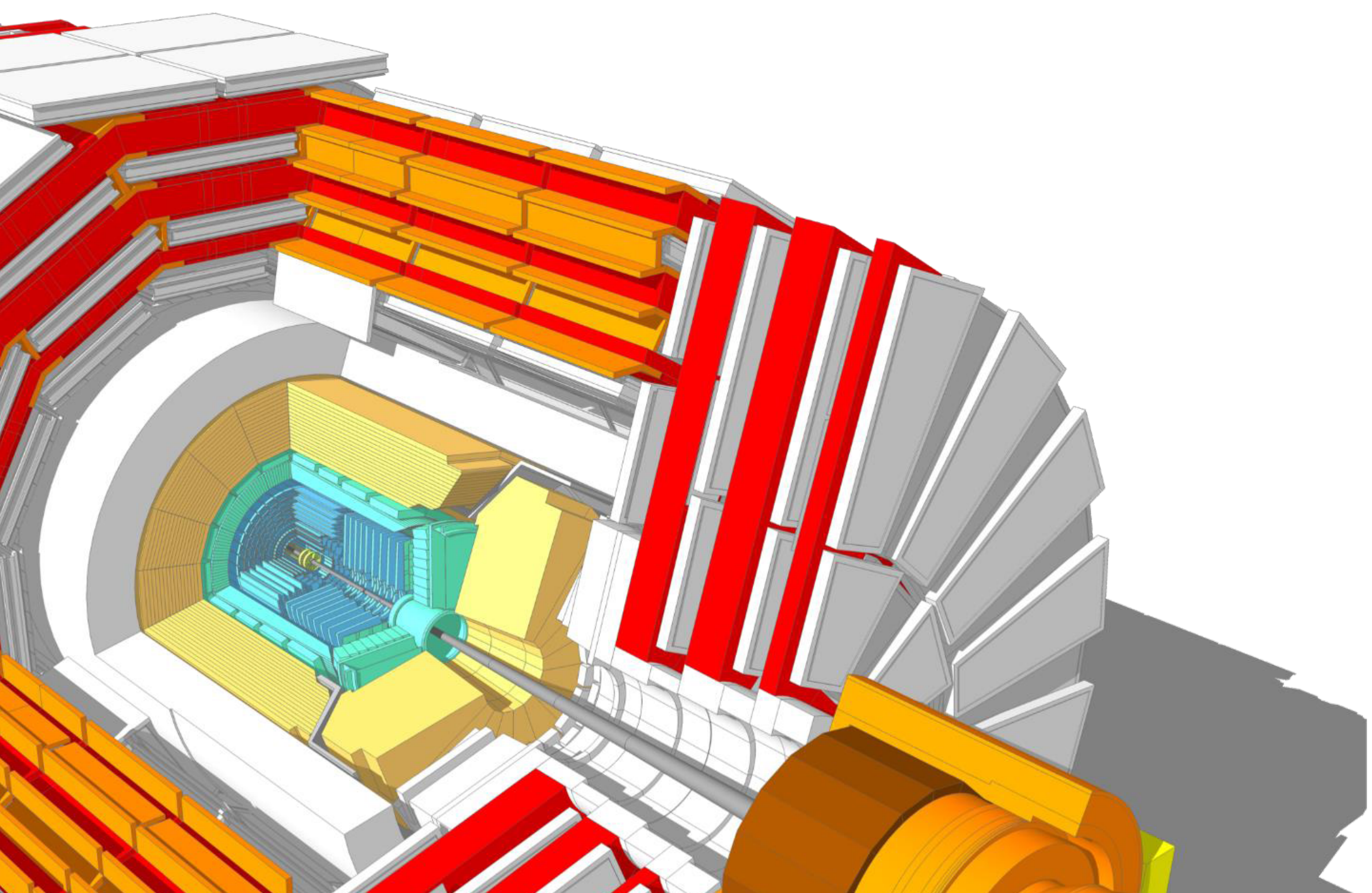
3. Vector-Boson-Scattering measurement in semi-leptonic channel with CMS at the LHC

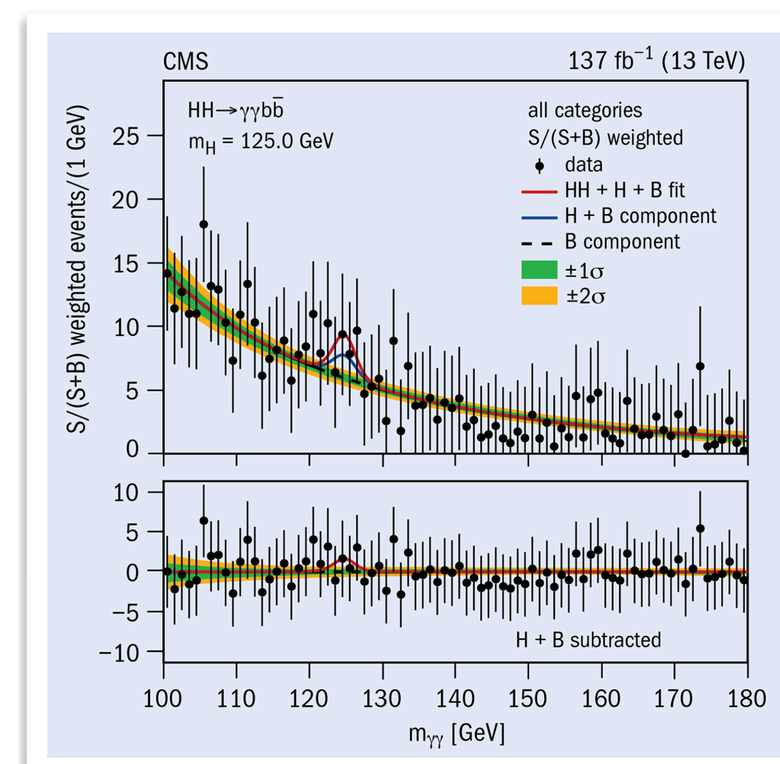
Summary

WHERE ARE WE?



- Almost 10 years from Higgs boson discovery
- Quality and amount of measurements beyond expectations:
  it started with Higgs detection, we target di-Higgs production
- Excellent performance of **LHC** and **CMS detector** at the end of the **LHC Run 2 data taking**



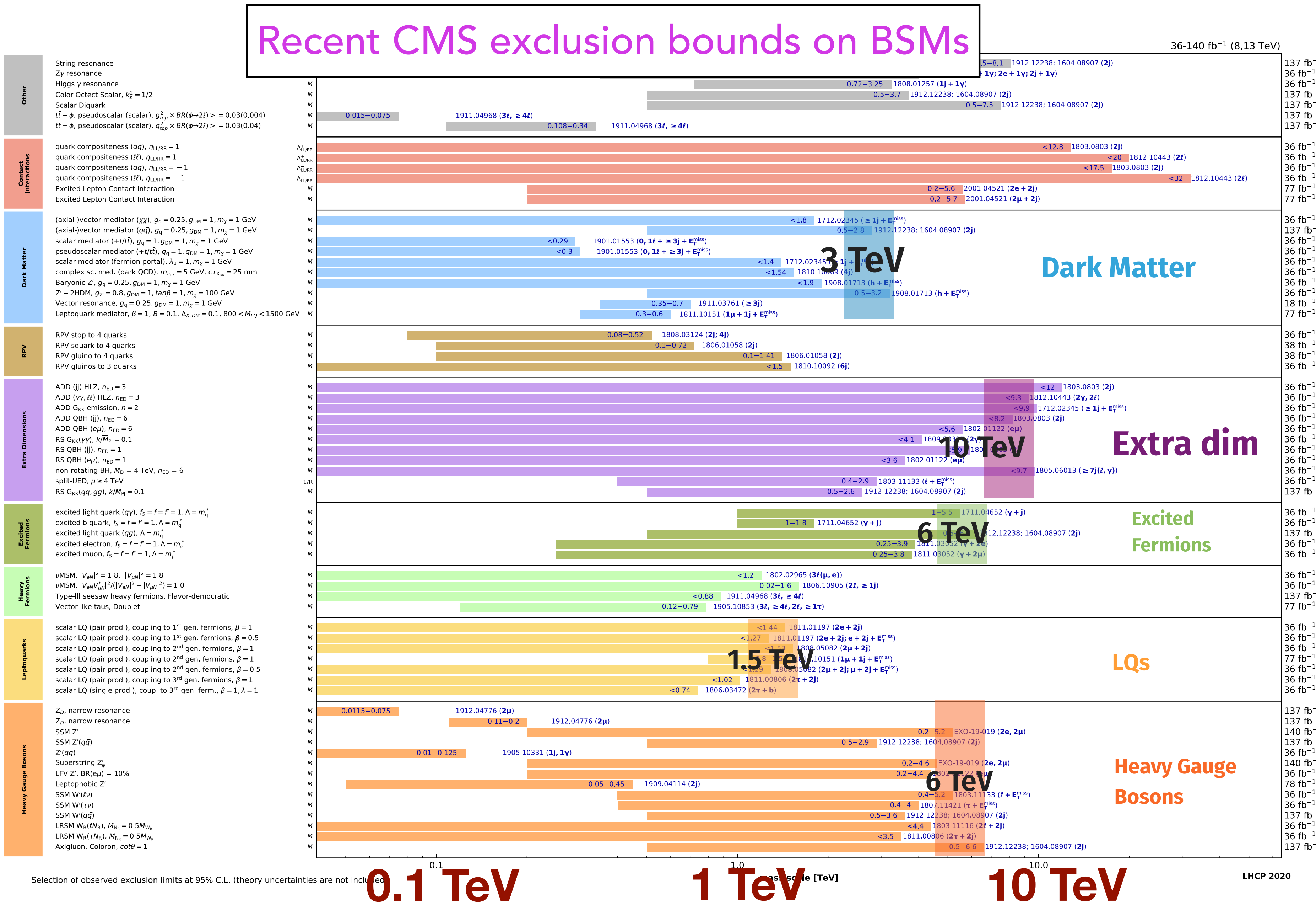


Targeting di-Higgs measurements ArXiv.2011.12373.

WHERE ARE WE?

No **clear*** sign of TeV scale New Physics has been observed in all the LHC data…

Approaching saturation of the energy frontier for the next 30 years.

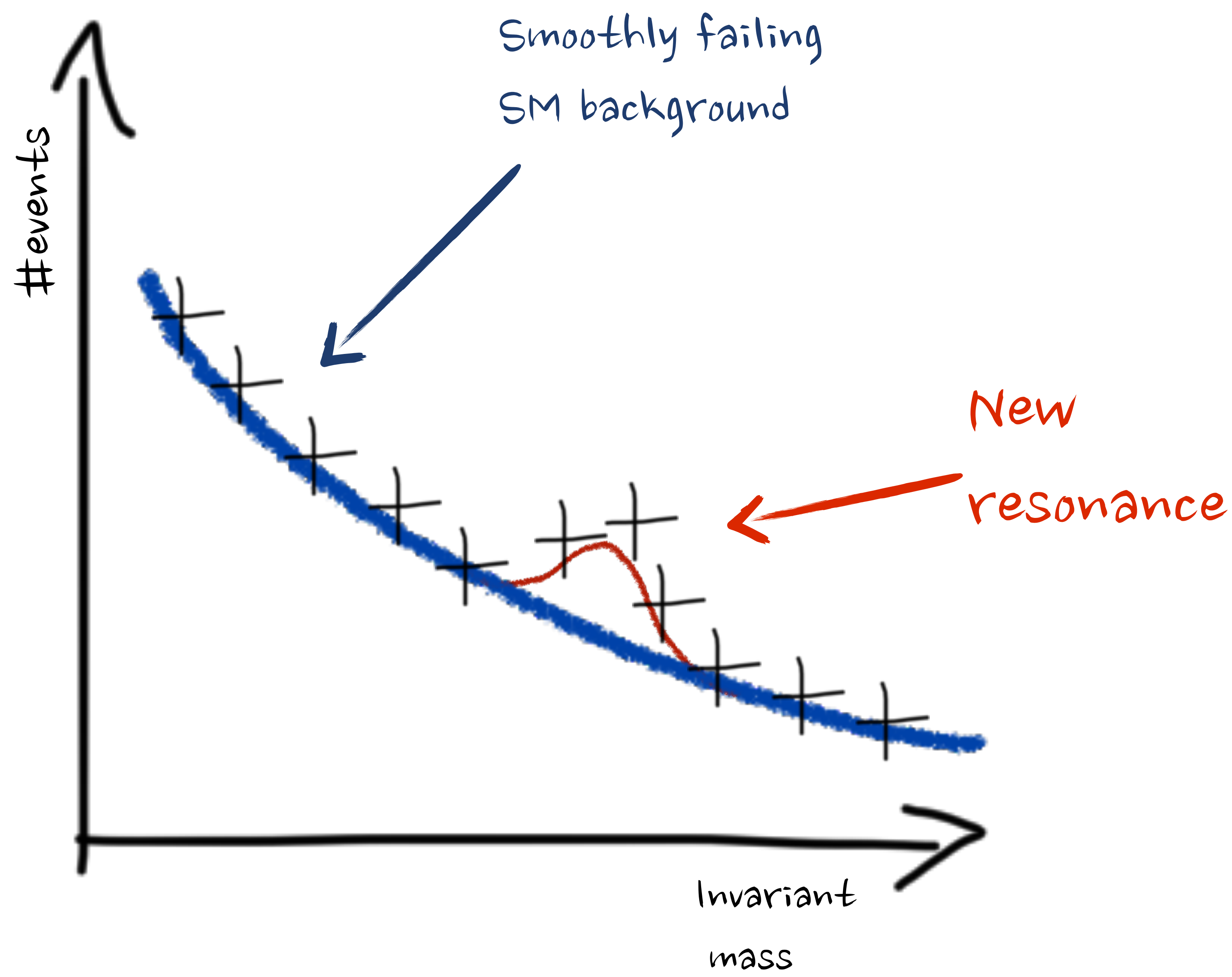


*…until last week [link].

WHAT DO WE DO?

A CARTOON GUIDE TO SEARCH FOR NEW PHYSICS

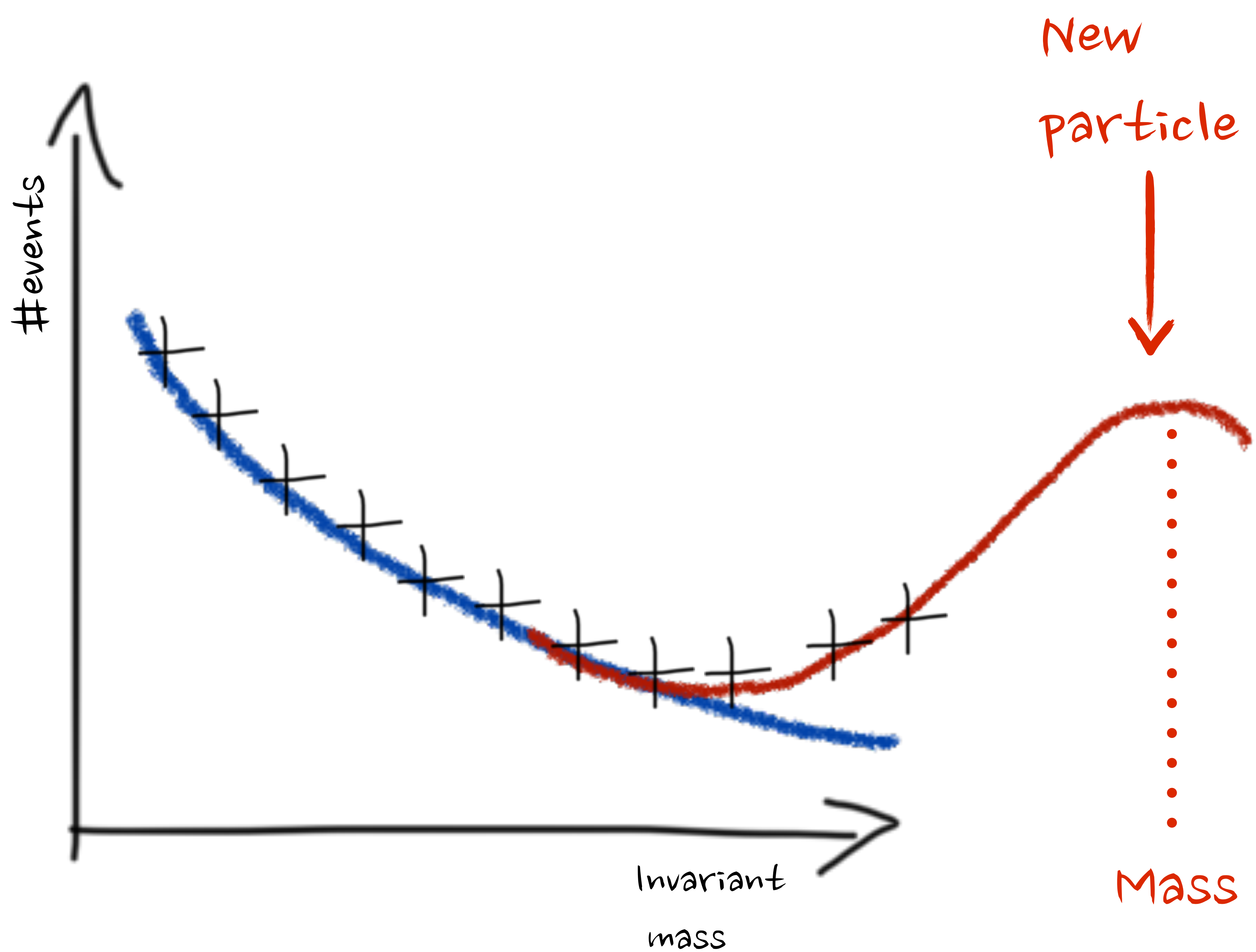
1. Direct searches:



WHAT DO WE DO?

A CARTOON GUIDE TO SEARCH FOR NEW PHYSICS

2. Indirect searches:



EFFECTIVE FIELD THEORY (I)

More generally:
we can invoke some UV theory that we are still not able to catch

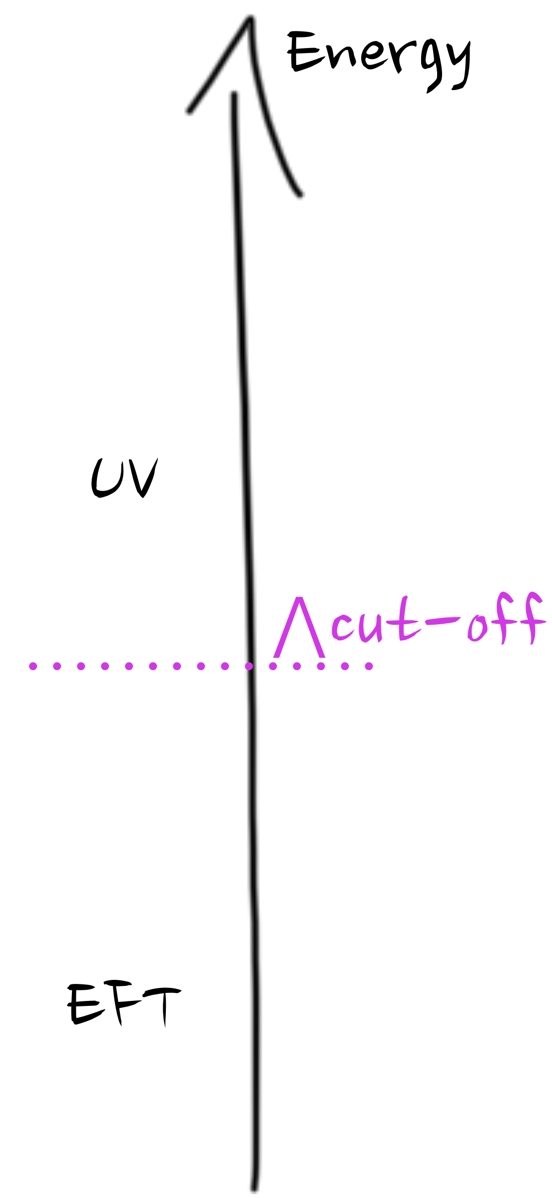
Bottom-up approach: build a Taylor expansion

$$\mathscr{L}_{BSM} \xrightarrow[(E \ll M)]{} \mathscr{L}_{\text{eft}} \simeq \mathscr{L}_4 + \mathscr{L}_5 + \mathscr{L}_6 + \cdots$$

$$\sum_i c_i \frac{\mathcal{O}_i}{\Lambda^2}$$

New BSM couplings
(Wilson coefficients)

BSM scale

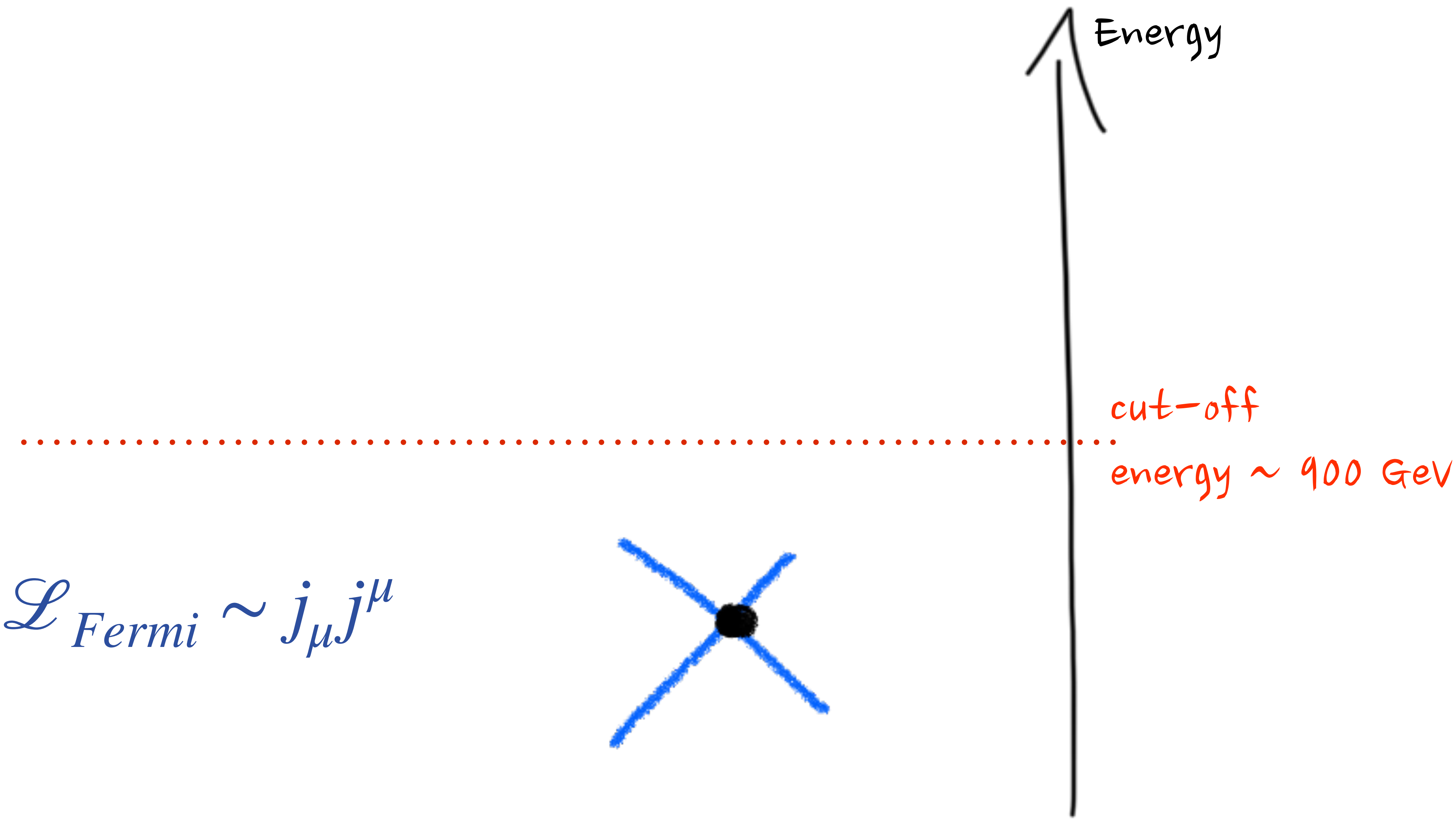


In practice it's an expansion in **fields** and derivatives.

EFFECTIVE FIELD THEORY (II)

Well-known example:
Fermi theory for beta decay

$$\mathscr{L}_{Fermi} \sim j_\mu j^\mu$$



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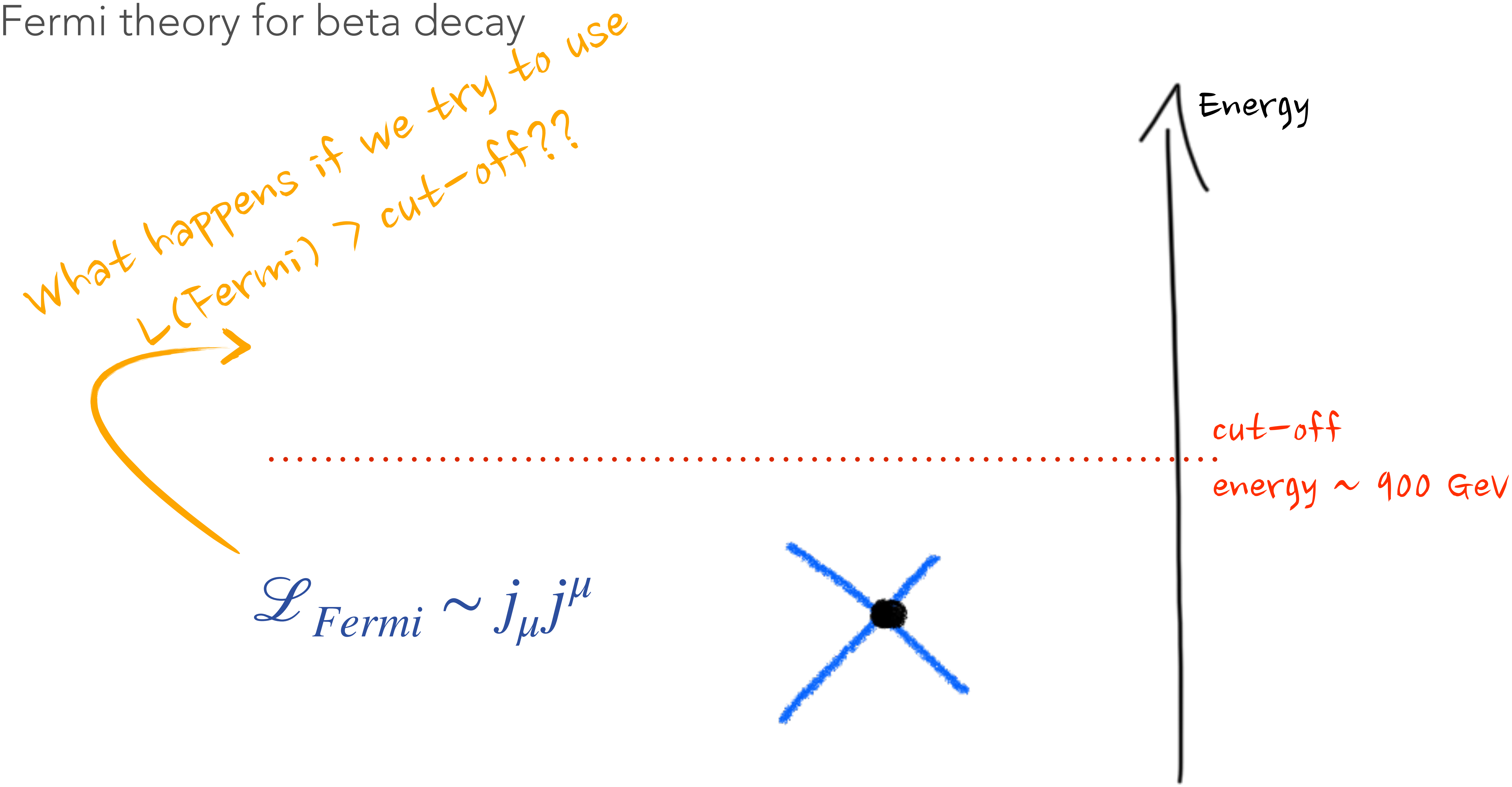


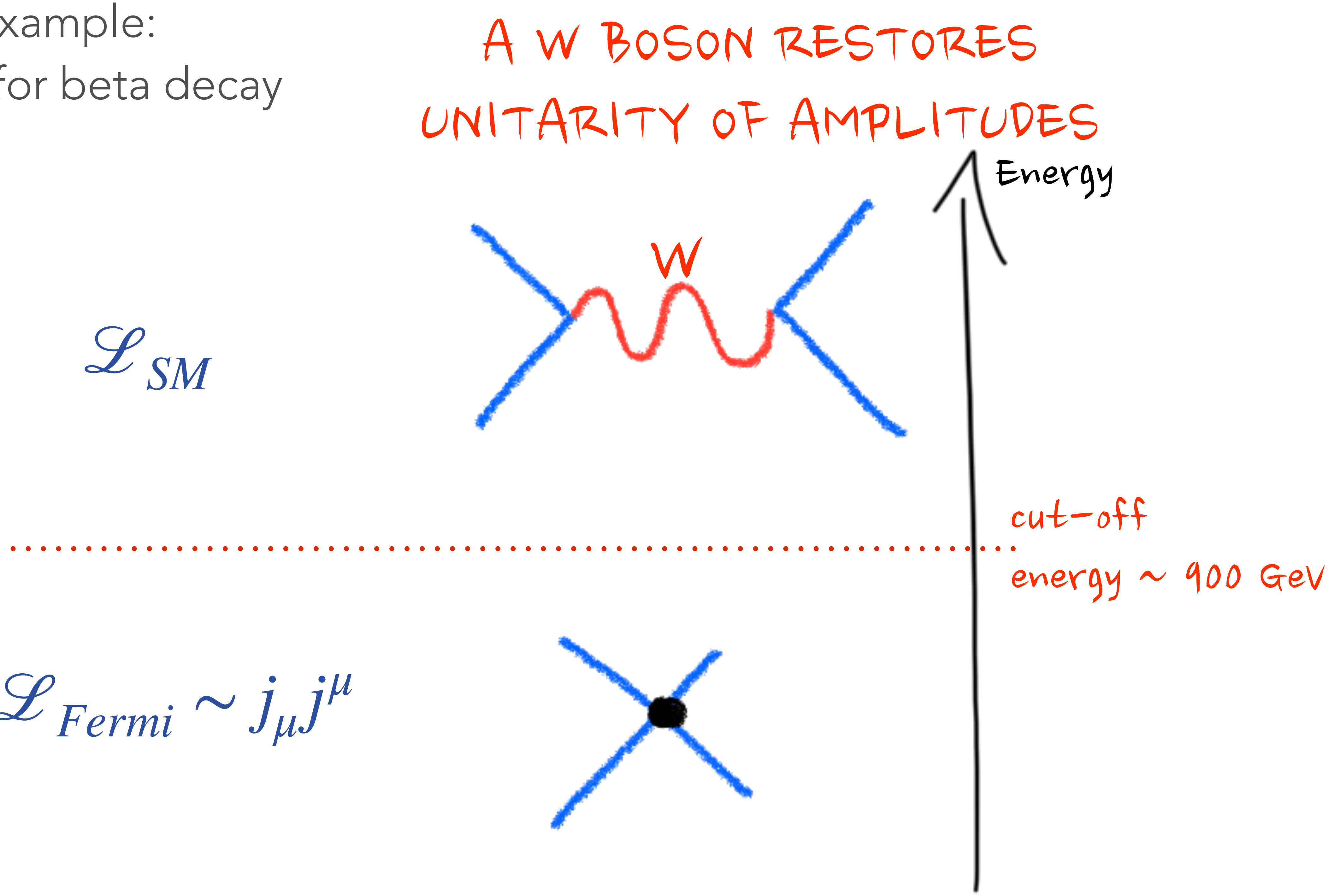
$$\mathscr{L}_{Fermi} \sim j_\mu j^\mu$$

EFFECTIVE FIELD THEORY (II)

Well-known example:
Fermi theory for beta decay

$\mathscr{L}_{SM}$

$\mathscr{L}_{Fermi} \sim j_\mu j^\mu$



Part 1.

Unitarity and effective theories of composite fermions

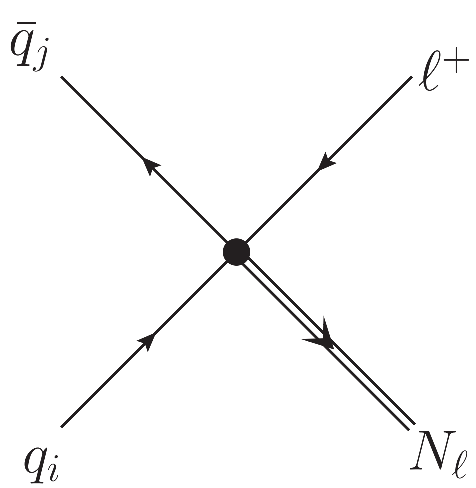
- Compute the cut-off of an EFT prototype, i.e. effective theory of composite fermions
- Test experimental consequences of unitarity bounds

A STRONGLY INTERACTING BSM SCENARIO

- Compositeness of leptons and quarks is one possible scenario beyond the Standard Model
- **Excited leptons and quarks**, e. g. e*, N*, q*, with interactions among lowest-lying and excited states (same constituents) with **effective operators, with masses usually smaller than the scale in which they should show up** $M^* \leq \Lambda$

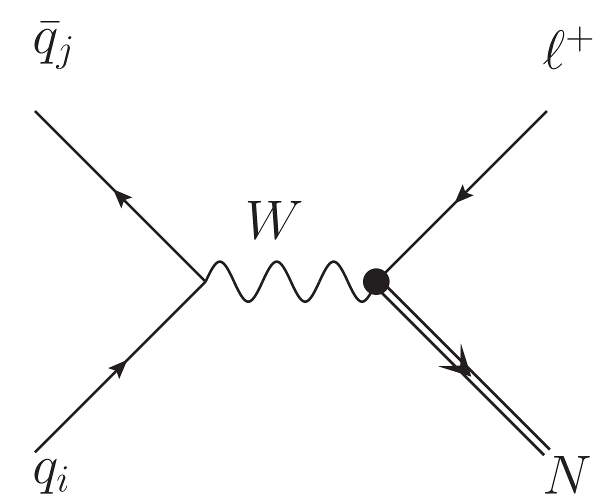
H. Terezawa (PRD 22, 1980); E. Eichten, K. D. Lane, M. E. Peskin (PRL 50, 1983); H. Harari (Phys. Rep., 1984);

Dim-6 contact interactions:



$$\mathscr{L}_C^{(6)} = \frac{4\pi}{\Lambda^2}\frac{1}{2} j^\mu j_\mu,$$

Dimension-5 gauge interactions:



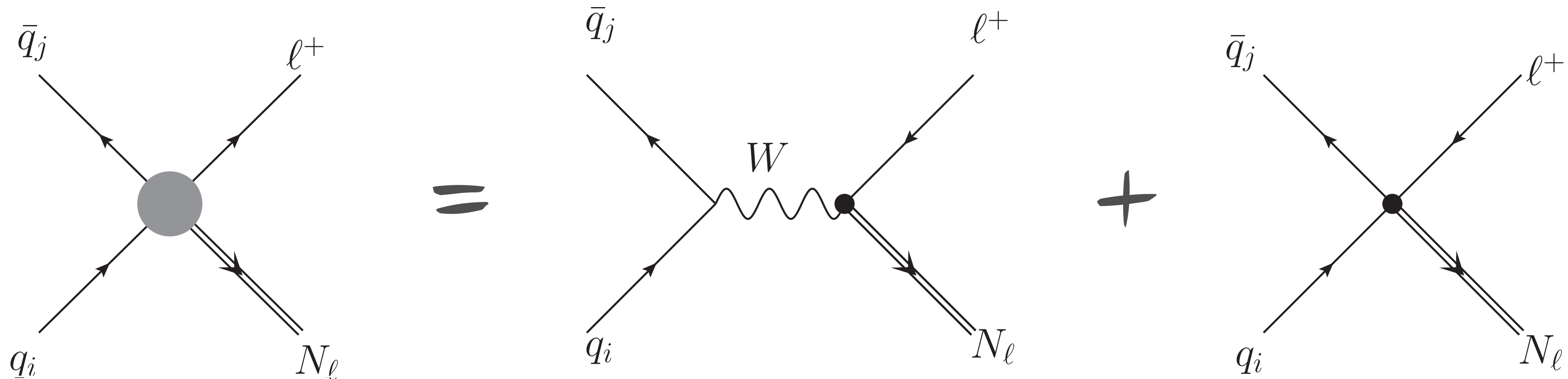
$$\mathscr{L}_G^{(5)} = \frac{1}{2\Lambda}\bar{L}_R^\star \sigma^{\mu\nu}\left(gf\frac{\tau^a}{2}W^a_{\mu\nu} + g'f'\frac{Y}{2}B_{\mu\nu}\right)L_L + h.c.$$

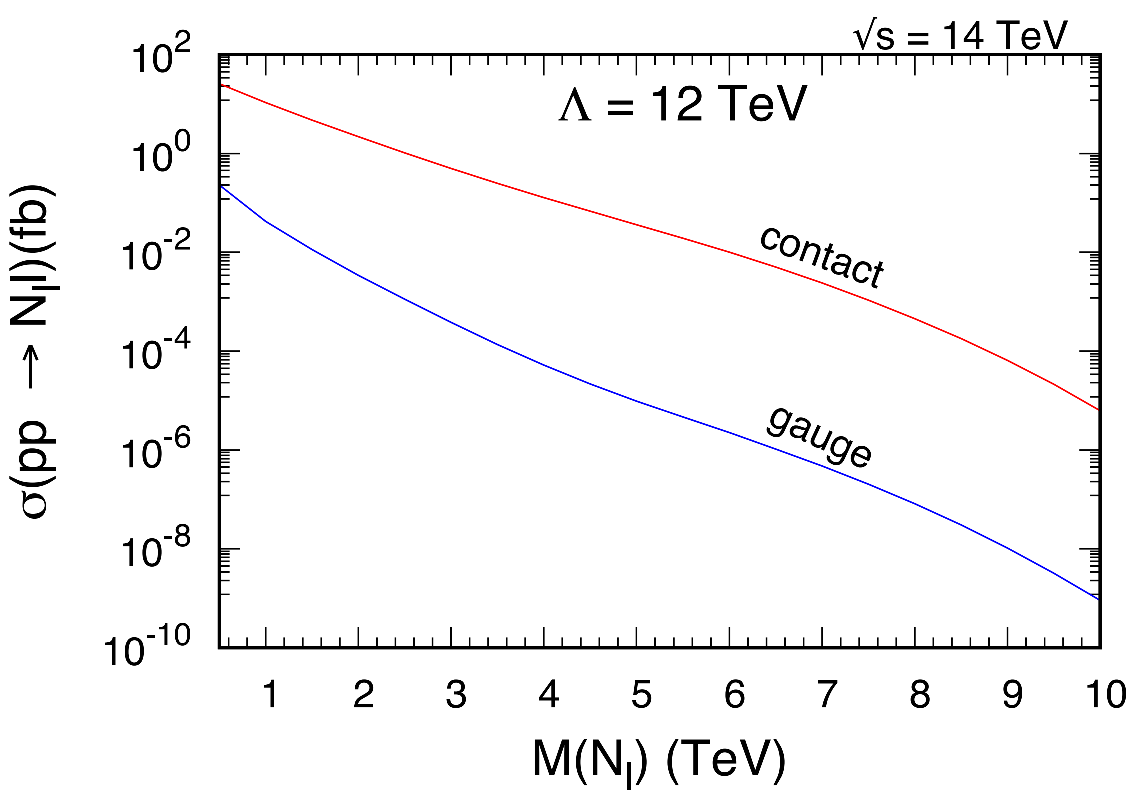
Parameters of the model: Λ, M^* (with $M^* \leq \Lambda$)

(with the other factors usually set to unity f, f′, …)

COMPOSITE MODELS IN COLLIDER SEARCHES (I)

Both **contact** and **gauge** contribute to the total production cross section of the excited leptons



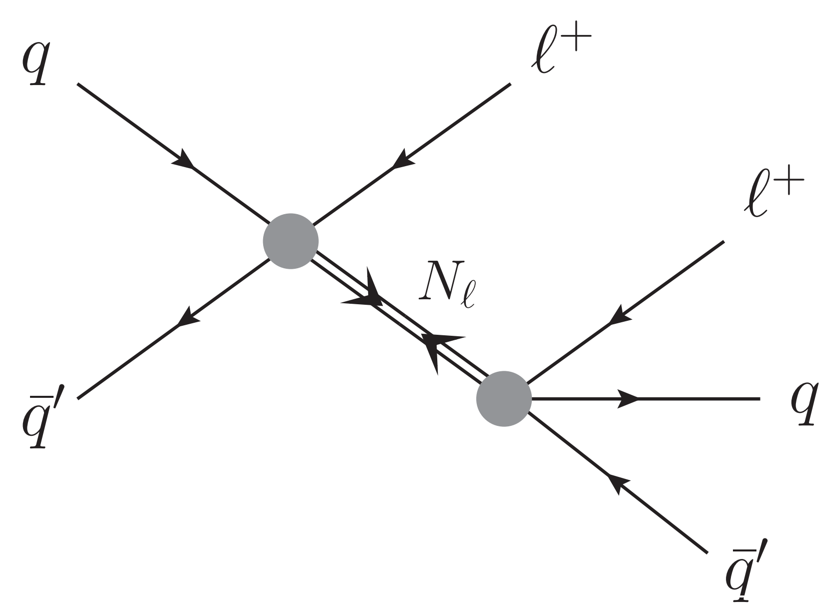


- Production cross sections depend both on **Λ** and **M(N_l)**
- **Contact interaction is dominant**
  (tested up to $\sqrt{s}$ = 100 TeV)

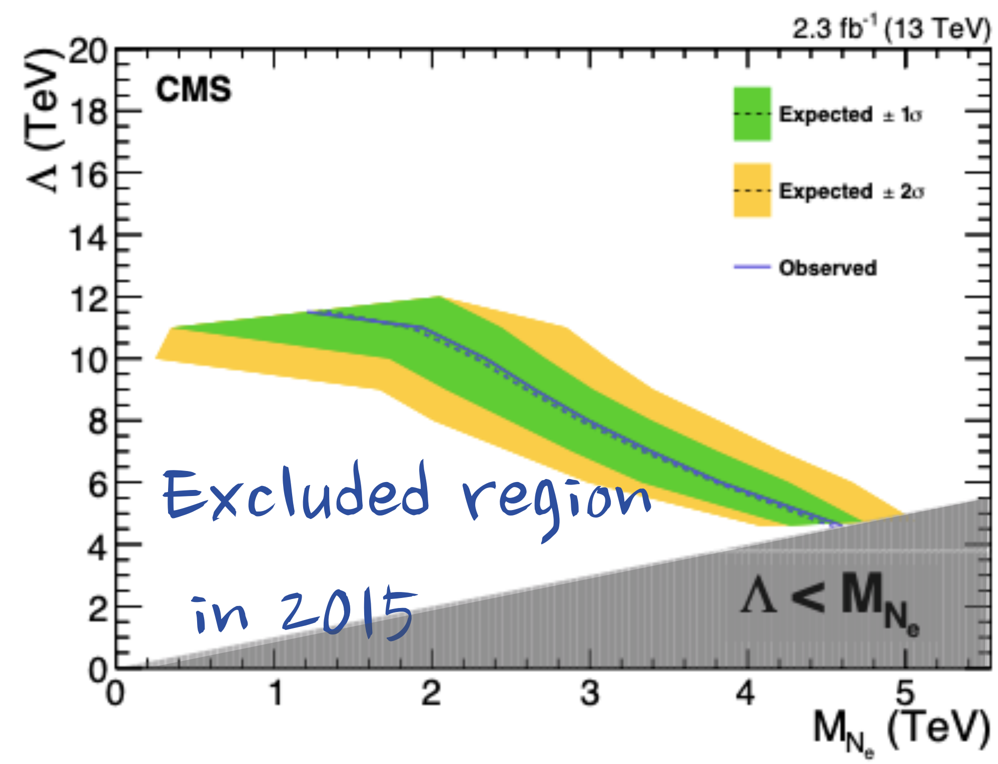
COMPOSITE MODELS IN COLLIDER SEARCHES (II)

Theoretical model widely used by LHC Collaborations.

Majorana Neutrinos (N) (arXiv.1706.08578, PLB 775 (2017))



Possible source of **baryogenesis via leptogenesis** $\Gamma\left(N^* \rightarrow \ell + X\right) \neq \Gamma\left(N^* \rightarrow \bar{\ell} + X\right)$ (arXiv. 1707.00844)



"Brazilian plot" for HCN (arXiv.1510.07988).

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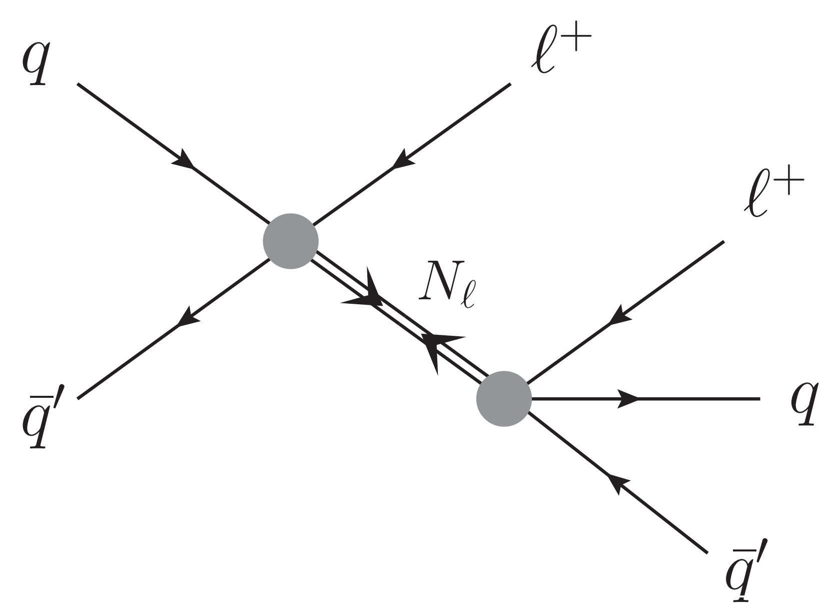

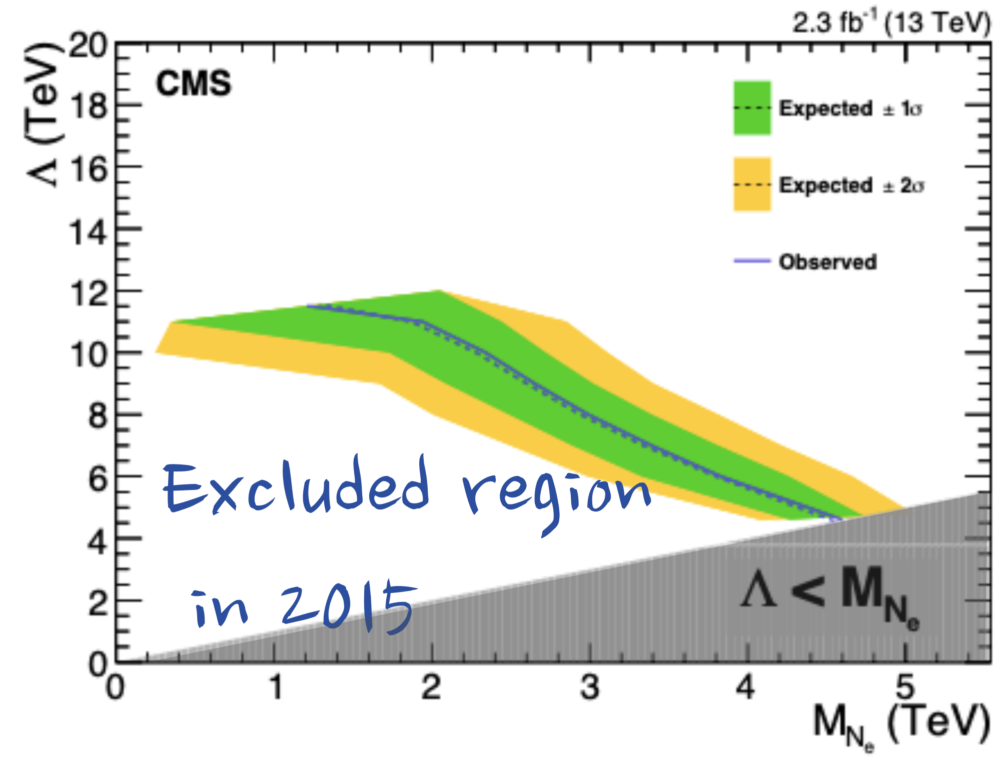

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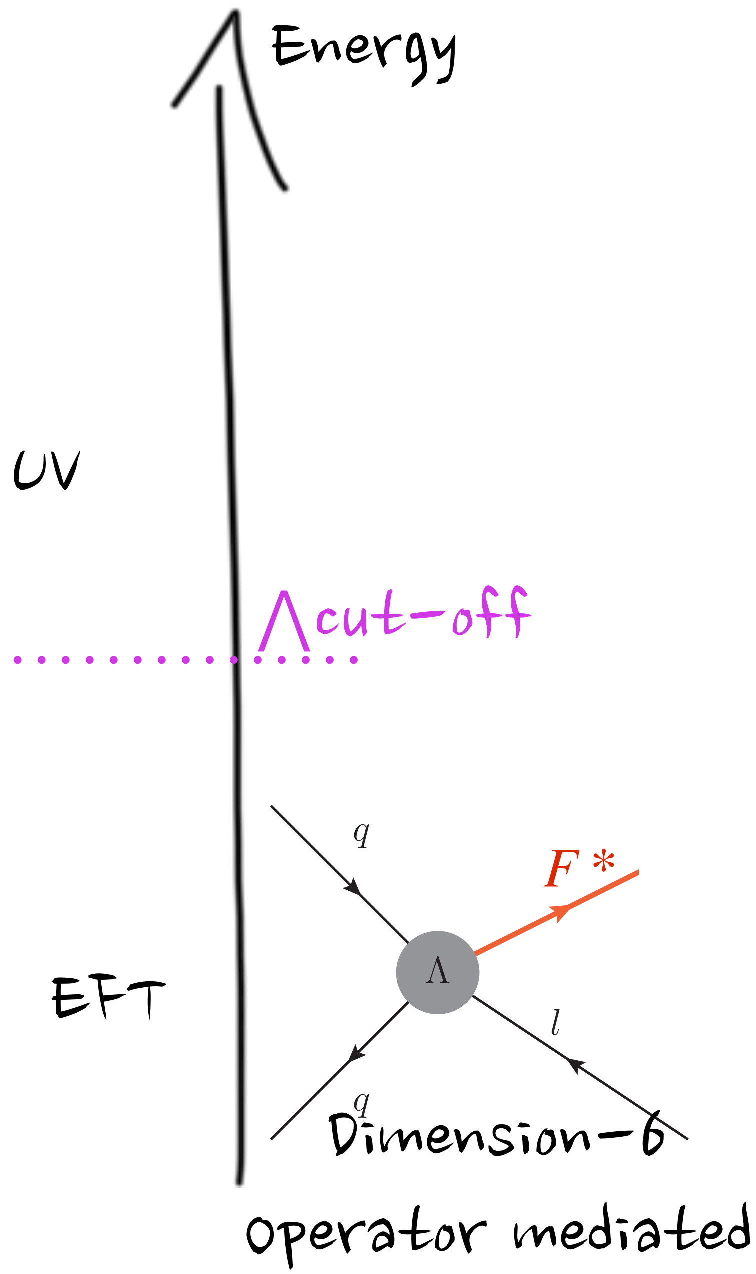
The limits on largest mass are quoted from **Exp-limits|95%CL with: $\mathbf{M^* = \Lambda}$**

- for 2015 CMS data analysis exclusion up to $\mathbf{\Lambda = M(N_e) \simeq M(N_\mu) \simeq 4.6\,TeV}$
- How do we know that the limit is in a **valid region for the EFT?**

PERTURBATIVE UNITARITY BOUND FOR EFFECTIVE COMPOSITE FERMIONS (I)*



- Dominant production for excited leptons at the LHC: $q\bar{q}' \to N_\ell \ell$

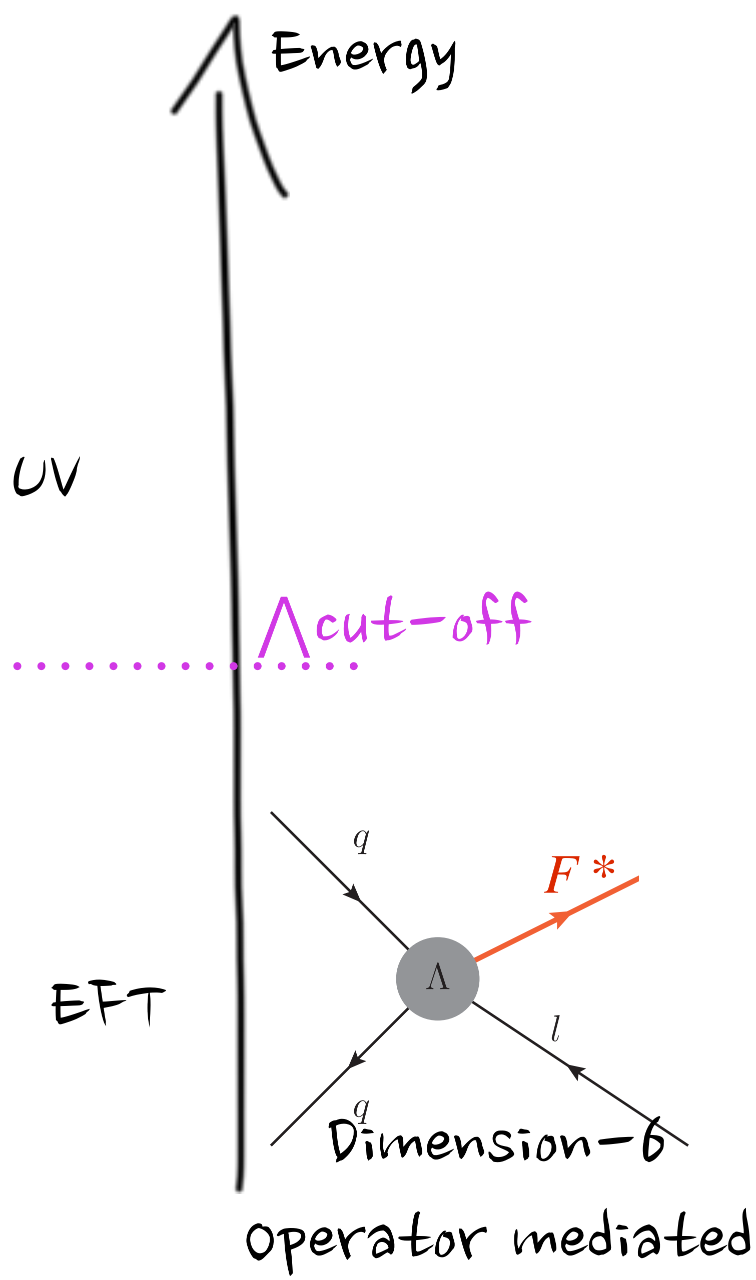
- The production cross-section of the Contact Interaction **(dimension-6) Lagrangian** grows rapidly with collision energy:

$$\mathcal{O}_6 = \frac{g_*^2}{\Lambda^2}(\bar{q}\gamma^\mu P_L q')(\bar{F}^*\gamma_\mu P_L l) \quad \Rightarrow \hat{\sigma} \simeq \frac{g_*^4}{192\pi\Lambda^2}\frac{E^2}{\Lambda^2}$$

- The probability for the transition can be > 1! There must be some cut-off for the validity of this EFT.

*"**Perturbative unitarity bounds for effective composite models**", **Biondini, Leonardi, Panella, Presilla** (ArXiv.1903.12285, PLB)

PERTURBATIVE UNITARITY BOUND FOR EFFECTIVE COMPOSITE FERMIONS (II)*



From Optical Theorem in proton-proton collisions, we can obtain a perturbative unitarity bound for the EFT production process:

$$\Lambda \geq \left(\frac{\hat{s}}{3}\right)^{\frac{1}{2}}\left(1+\frac{M^{*2}}{2\hat{s}}\right)^{1/4}\left(1-\frac{M^{*2}}{\hat{s}}\right)^{1/2}$$

Excited Fermion mass (M^*)

EFT scale (Λ)

C.o.M. energy of parton system ($\hat{s}$)

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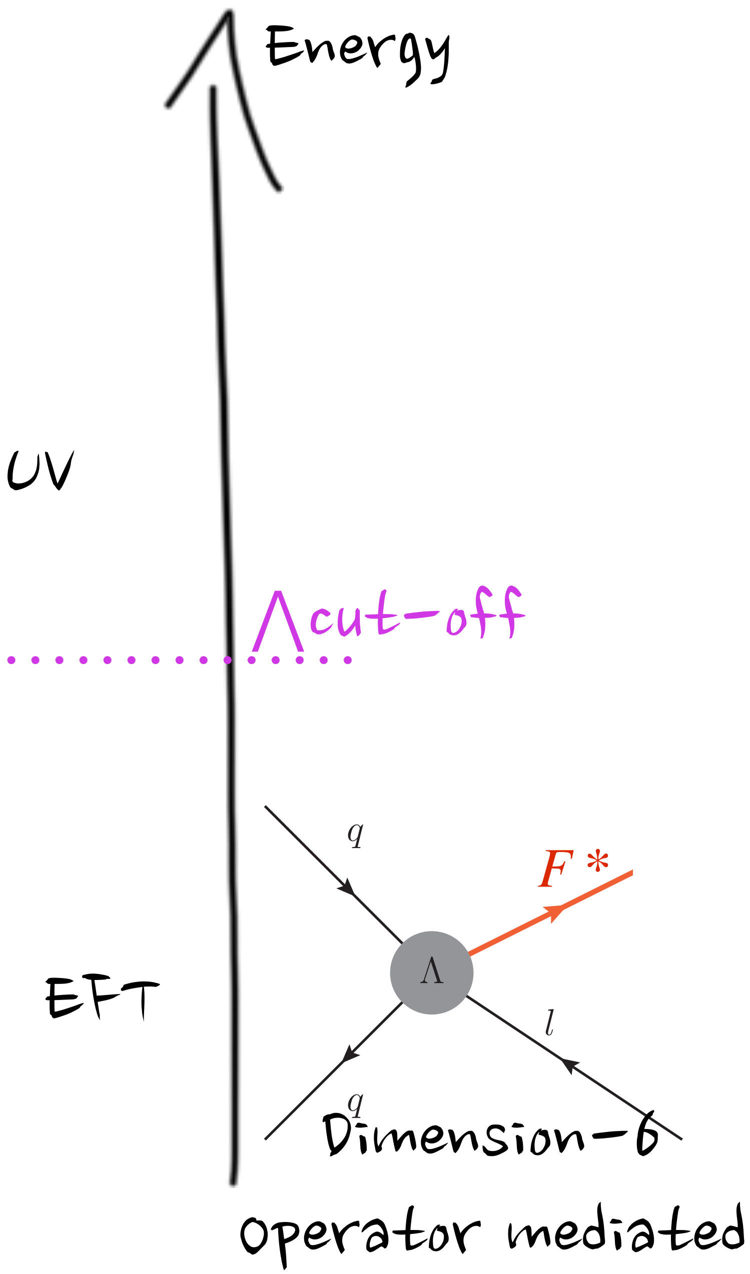

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EFT scale

C.o.M. energy of parton system

fixing $(\hat{s}, M^*)$ we know the allowed Λ values for the EFT

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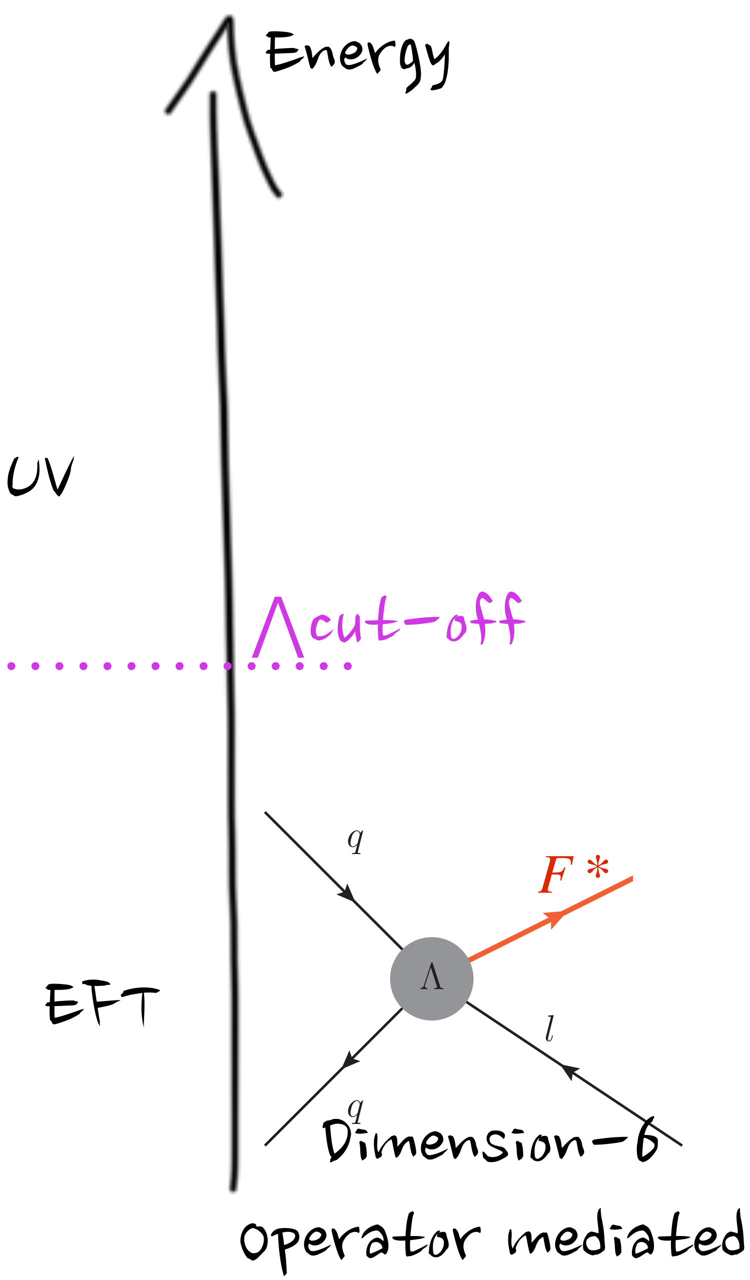

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Excited Fermion mass

EFT scale

C.o.M. energy of parton system

Physical Interpretation

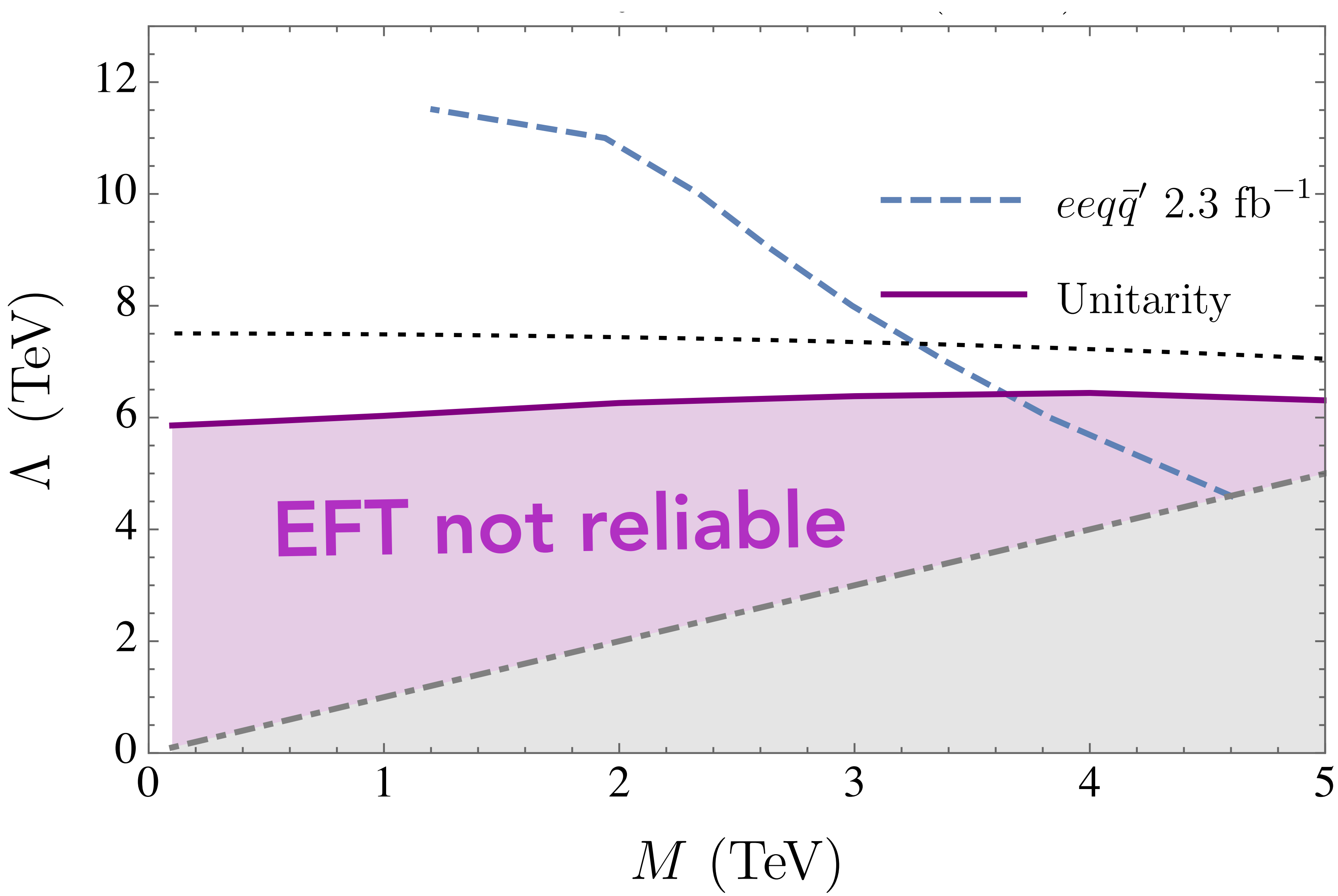
A modification to $\mathcal{O}_6$ must appear before the bound is violated:

- **UV completion of a new dynamics, or**
- **higher terms in the operator expansion.**

*"Perturbative unitarity bounds for effective composite models", Biondini, Leonardi, Panella, Presilla (ArXiv.1903.12285, PLB)

IMPACT OF THE BOUND ON COLLIDER SEARCHES

EXAMPLE FROM CMS RUN2 ANALYSIS



***blue dashed:**
CMS Observed limit in 2015

***black dotted:**
saturation of the bound ($\hat{s} = s$)

***purple level curves:**
100% of MC events satisfying unitarity condition
[same approach in Endo, Yamamoto - 1403.6610]

IMPACT OF THE BOUND ON COLLIDER SEARCHES

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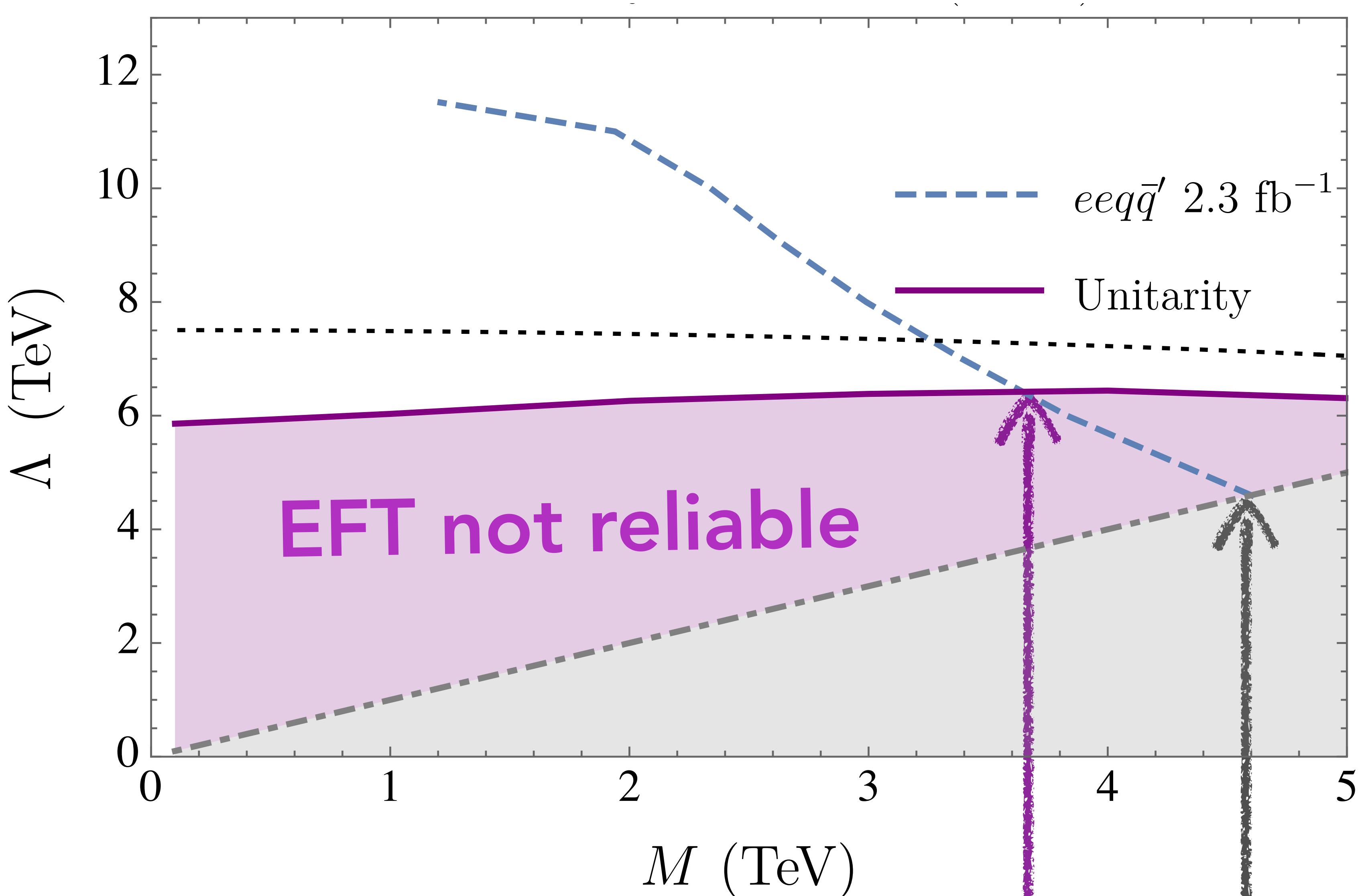

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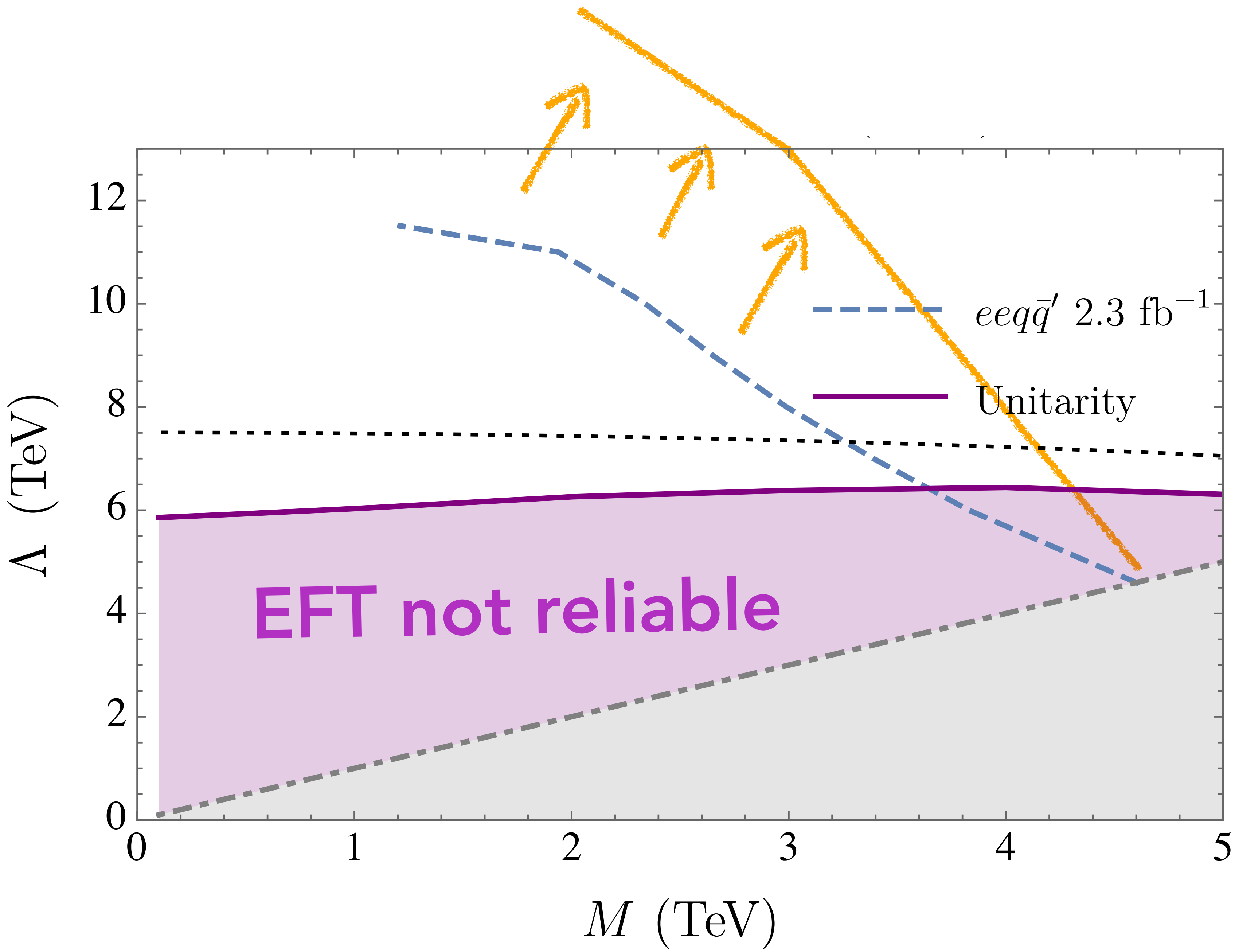
HIGHEST MASS REACH ASSUMING ALL UNITARY EVENTS:
$\Lambda = 6\, TeV, M = 3.6\, TeV$

HOW CMS QUOTES RESULTS:
$\Lambda = M = 4.6\, TeV$

IMPACT OF THE BOUND ON COLLIDER SEARCHES

EXAMPLE FROM CMS RUN2 ANALYSIS



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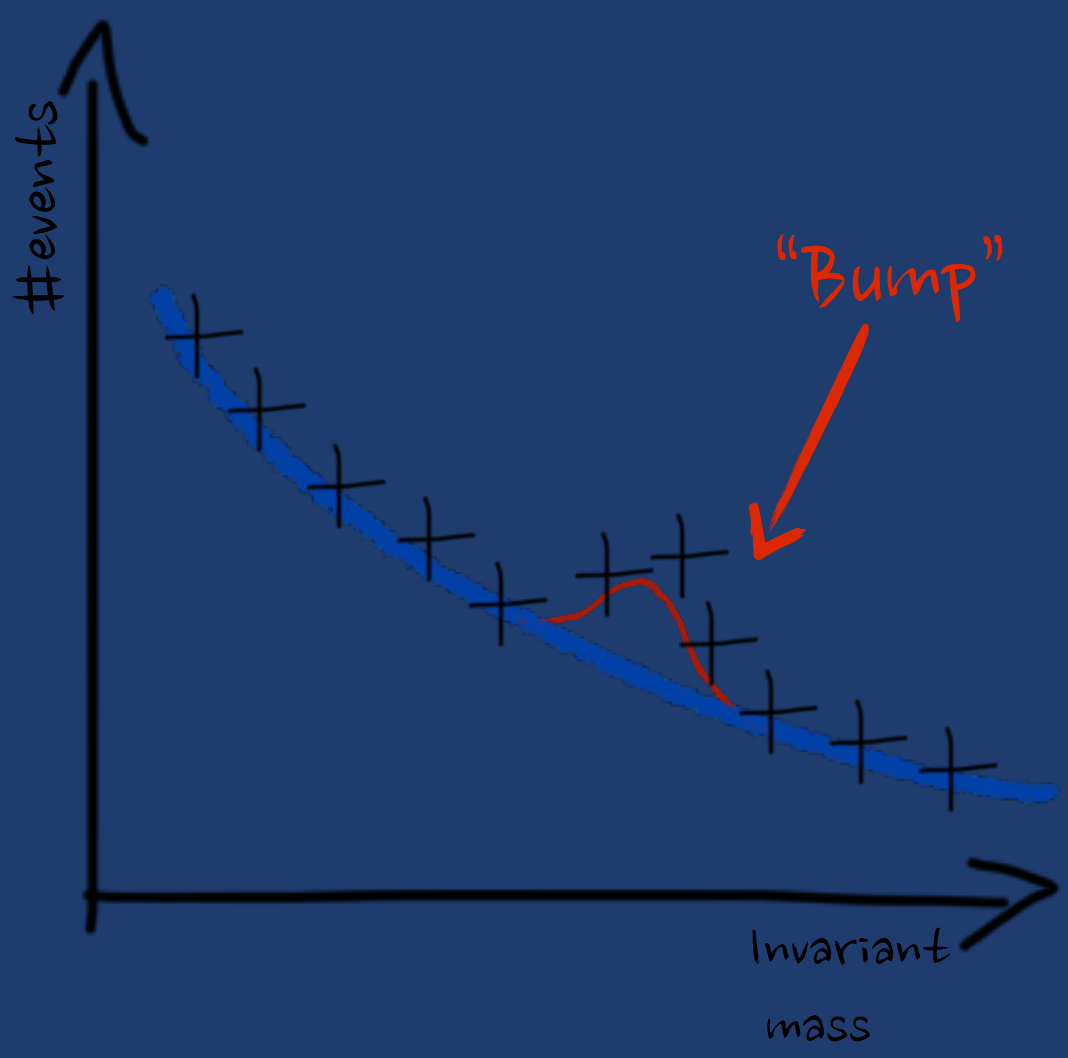
UNITARITY CAN HAVE A KEY ROLE IN THE OPTIMISATION OF THE SEARCH

Part 2.

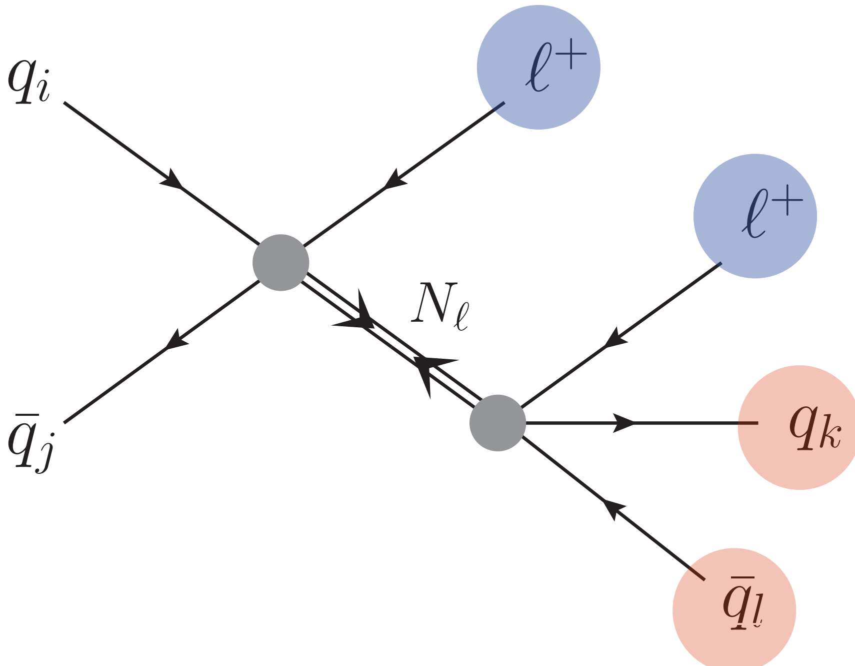
Heavy Majorana neutrinos at the LHC and beyond

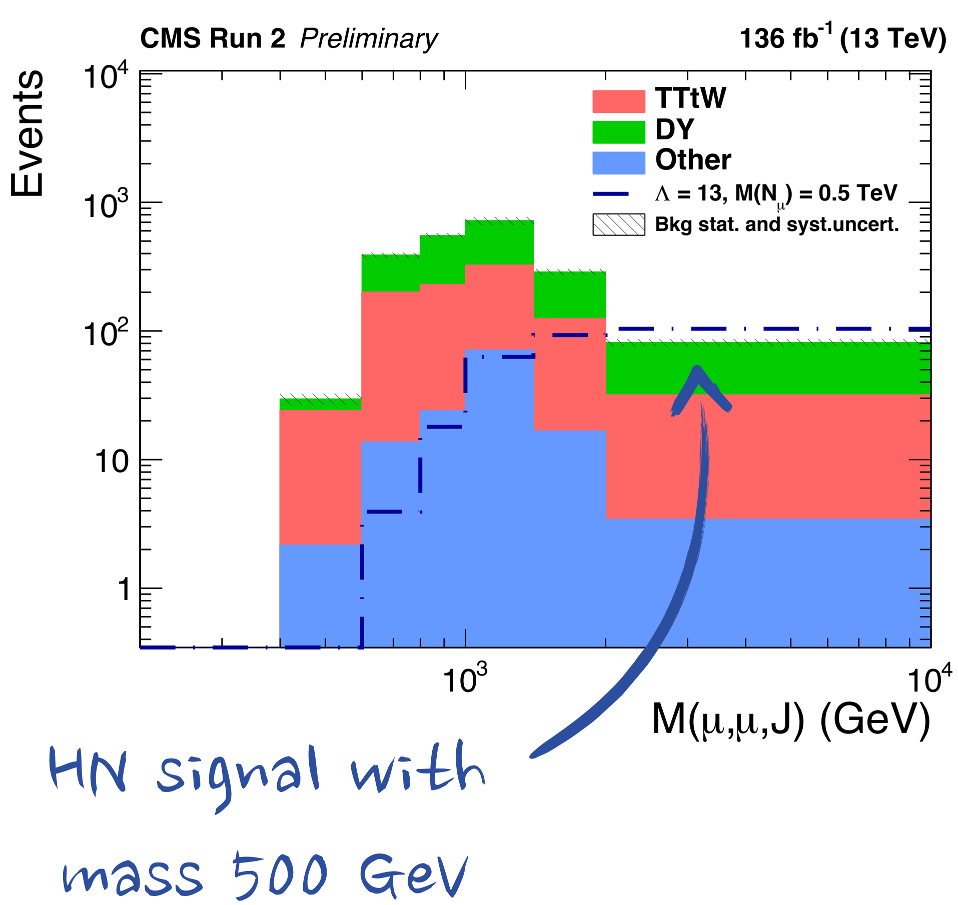


Experimental search for resonances at large mass:

- Study kinematics, topology and theory constraints on the signal process
- Find an optimal selection to maximise signal efficiency and background rejection
- Estimate the background sources: the "bump" often lies in a poorly populated background region

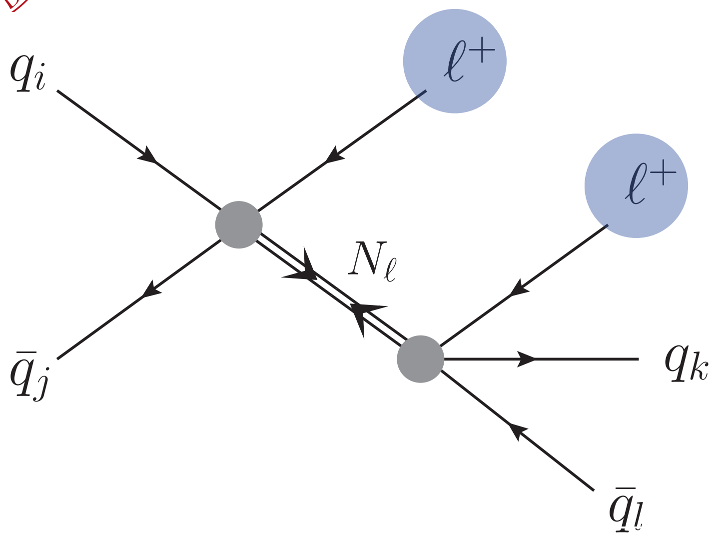
HEAVY COMPOSITE NEUTRINO AND DI-LEPTON DI-JET SIGNATURE





- Majorana neutrinos with masses from 0.5 to 8 TeV could be detected at the Run2
- **Two high-p_T same-flavour and same-sign leptons in the final state** (electrons or muons)
- **Two high-p_T quarks in the final state.**
- **The invariant mass of the dilepton system and the leading "Fat Jet" is chosen as a discriminant variable** Unambiguous connection with the heavy neutrino mass (ArXiv.1510.07988)

LEPTON SELECTION



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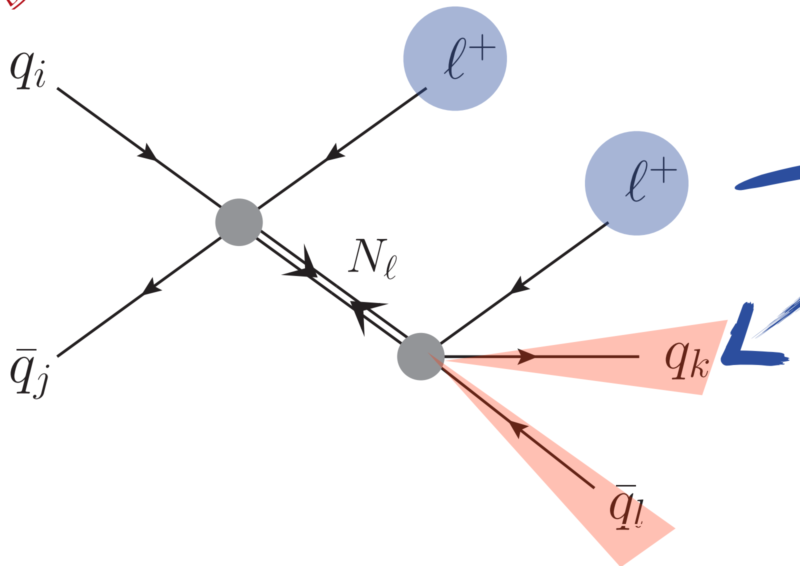
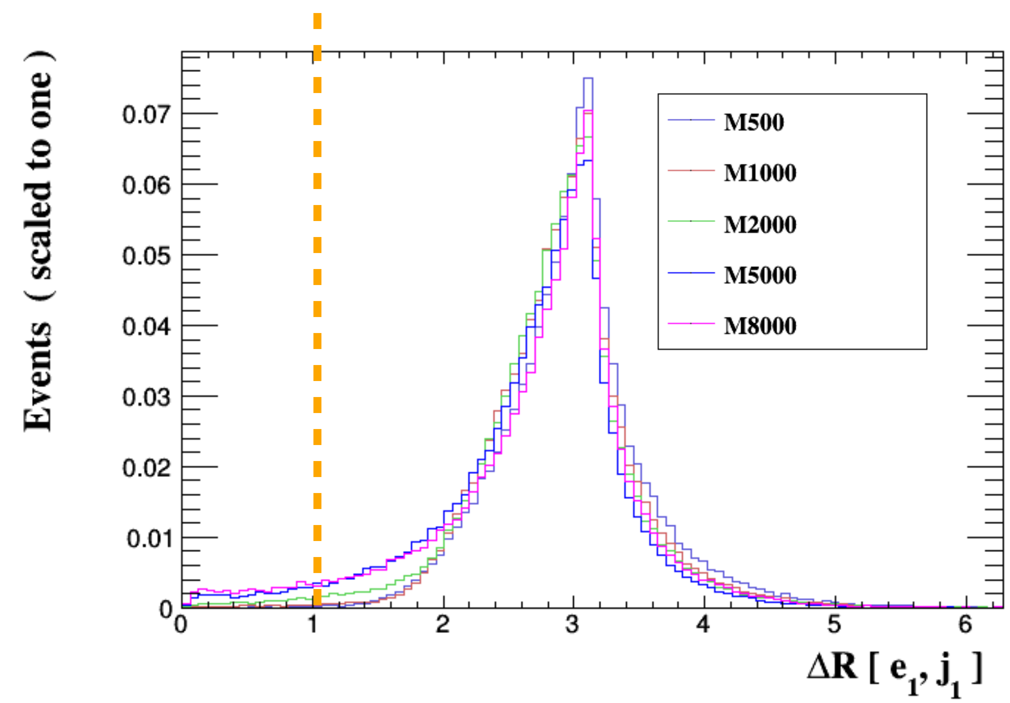


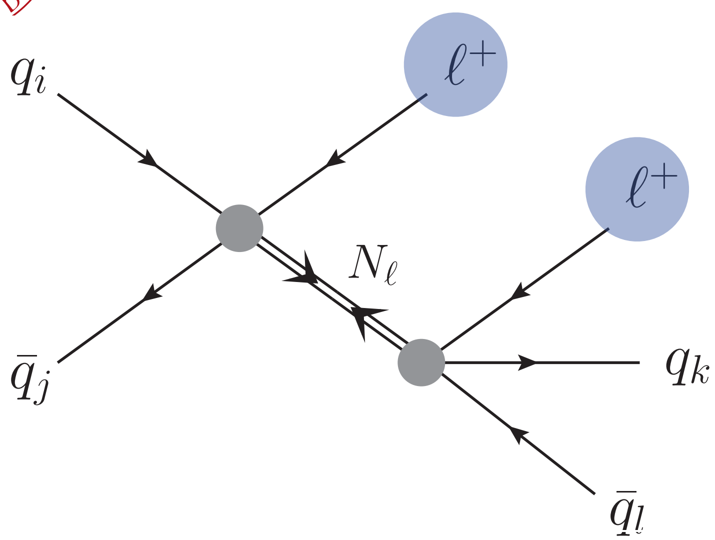
ΔR
separation

- **Isolation from hadronic activity.**

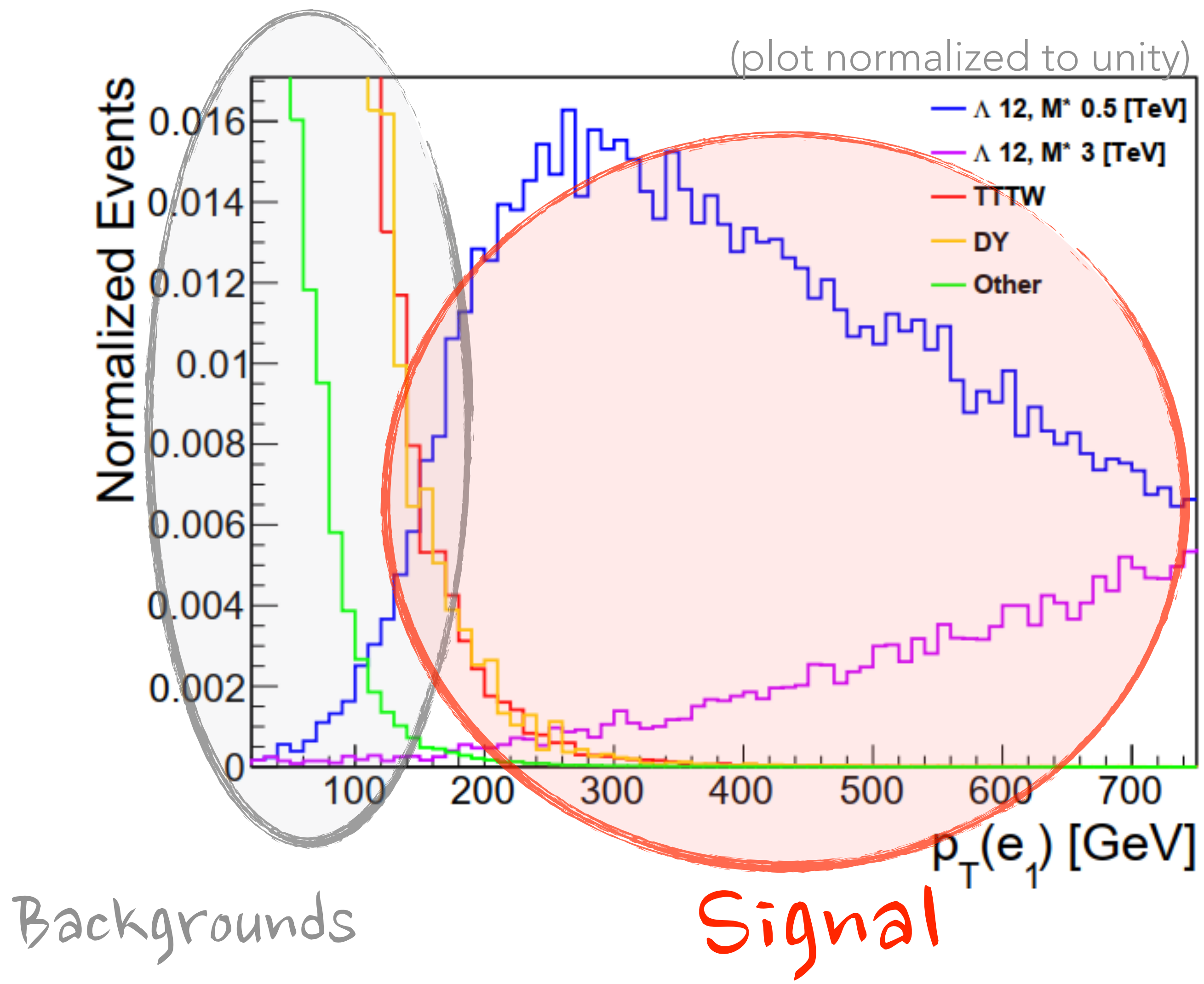


Leptons are well spatially separated from jets

LEPTON SELECTION

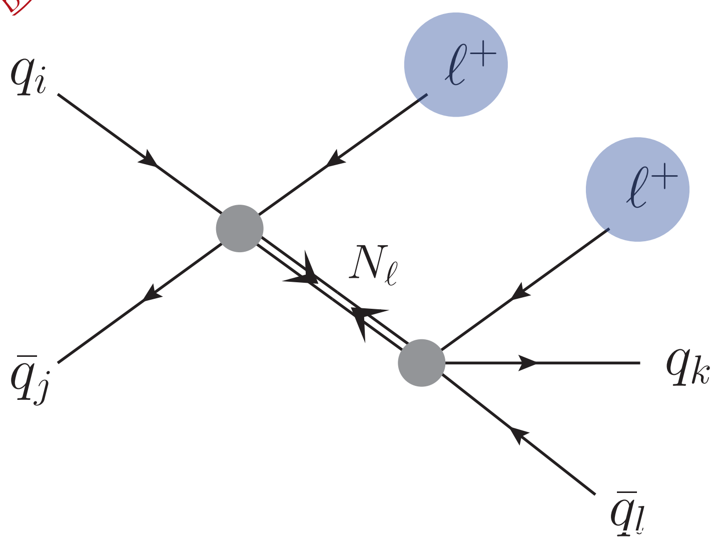


- **Isolation from hadronic activity.**
- **Kinematic region.**



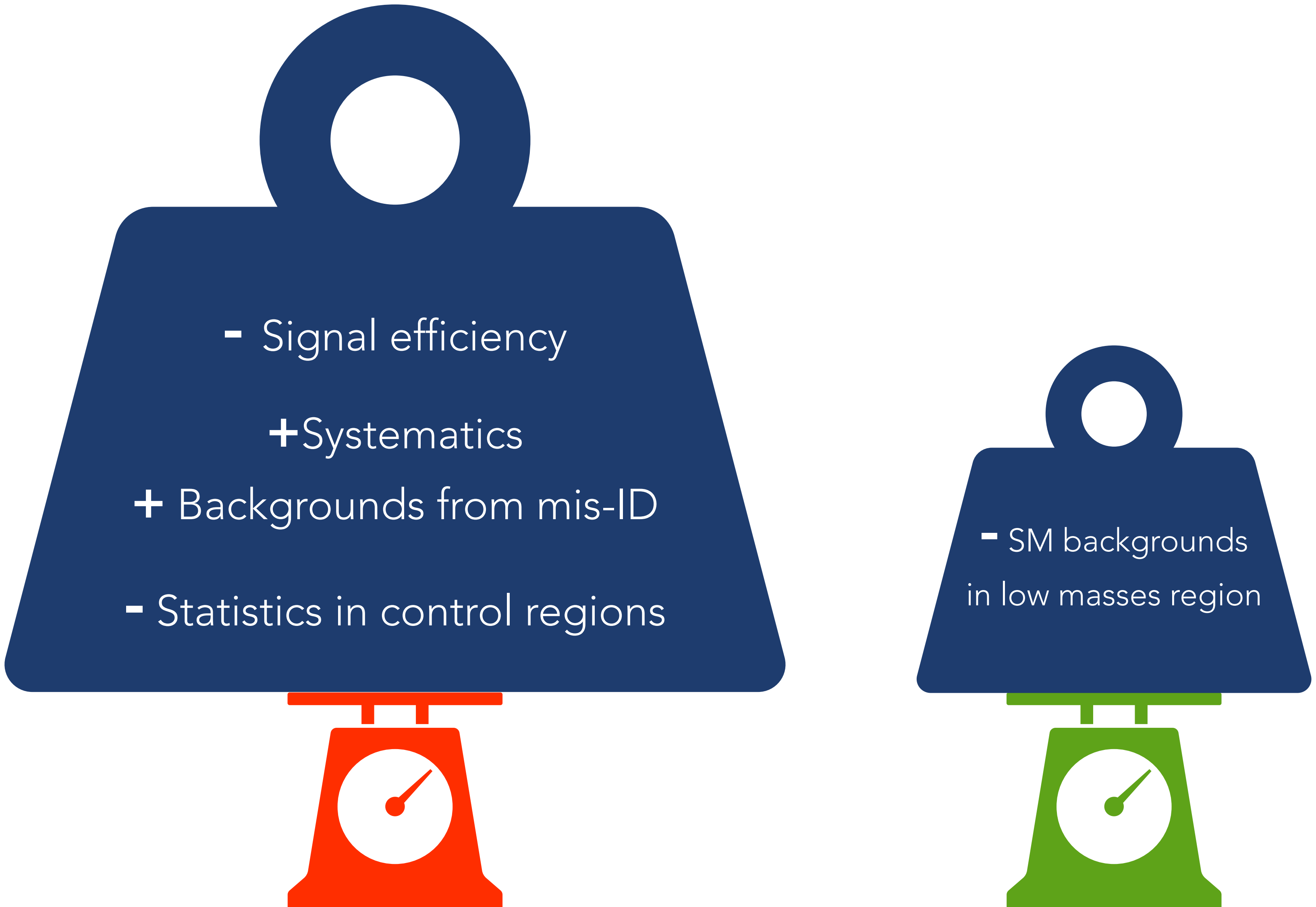
The kinematic of the signal is different from the backgrounds

LEPTON SELECTION

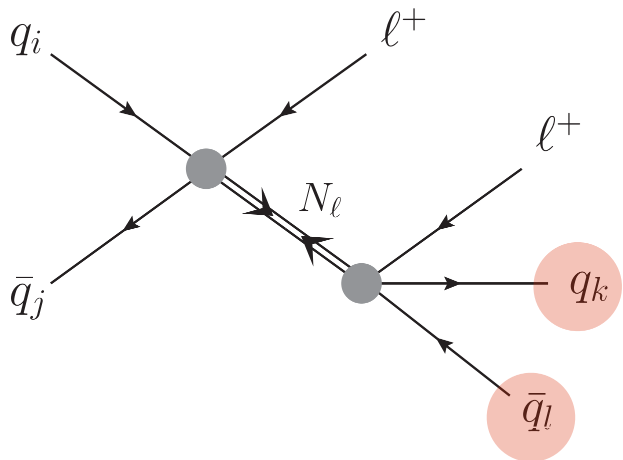


Possibility to choose both SAME-SIGN and OPPOSITE-SIGN leptons to maximise acceptance

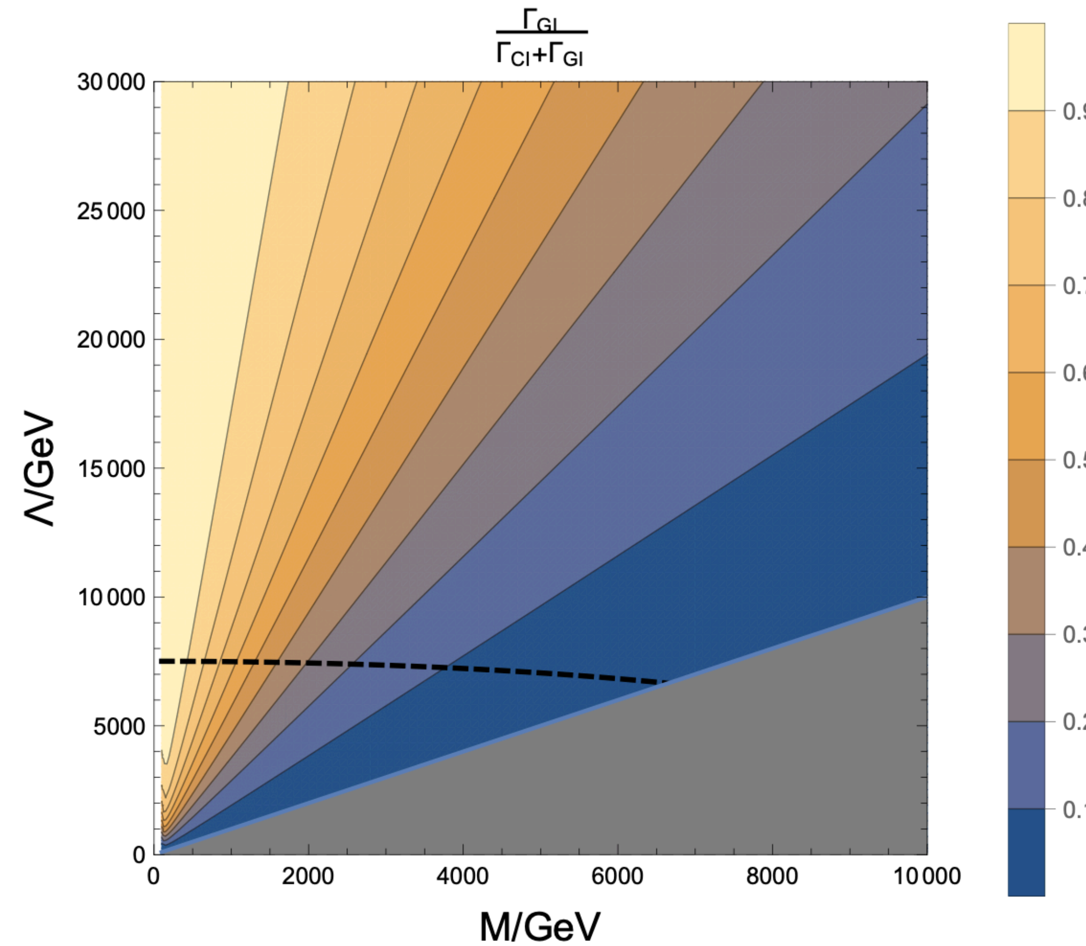
- **Isolation from hadronic activity.**
- **Kinematic region.**
- **Charge selection.**

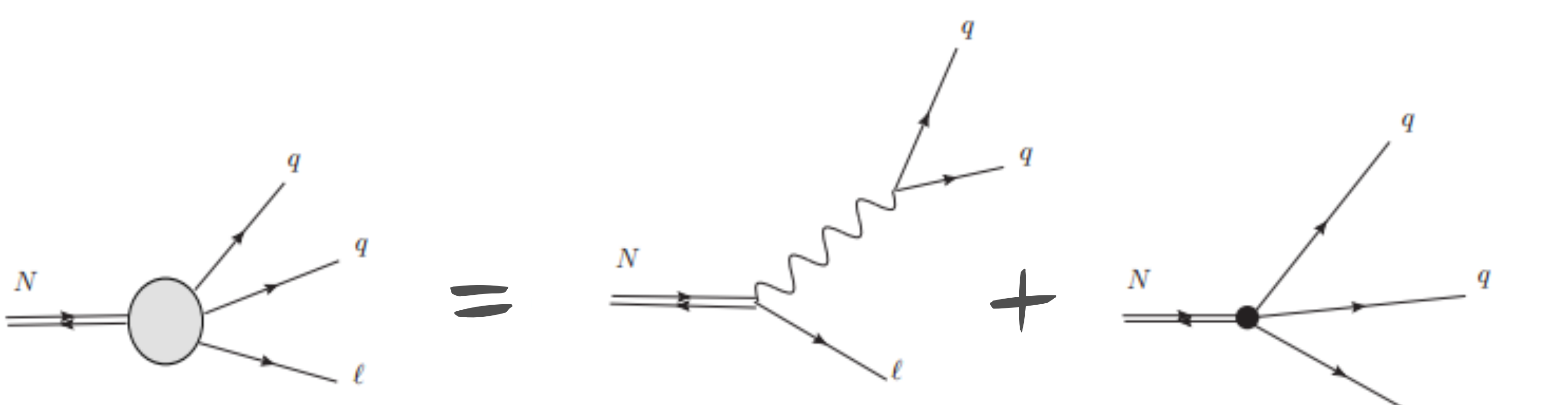


JETS SELECTION



In the decay process there is an interplay of **contact** and **gauge** depending on **Λ** and **M**
→ **different decay topologies**





Gauge

Contact

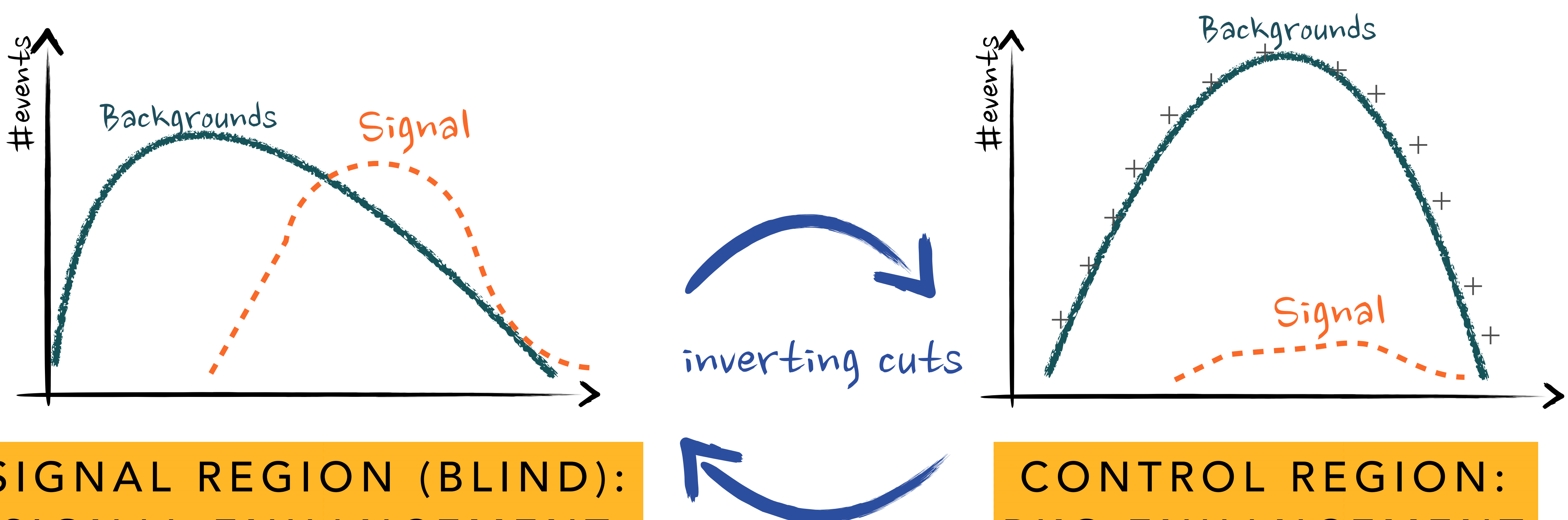
The quarks tend to overlap
→ one **fat jet** in the final state

No preferred topology
→ two/three jets reconstructed

REQUIRING AT LEAST ONE "FAT" JET MAXIMIZES SIGNAL ACCEPTANCE AND PURITY

BACKGROUND ESTIMATE STRATEGY

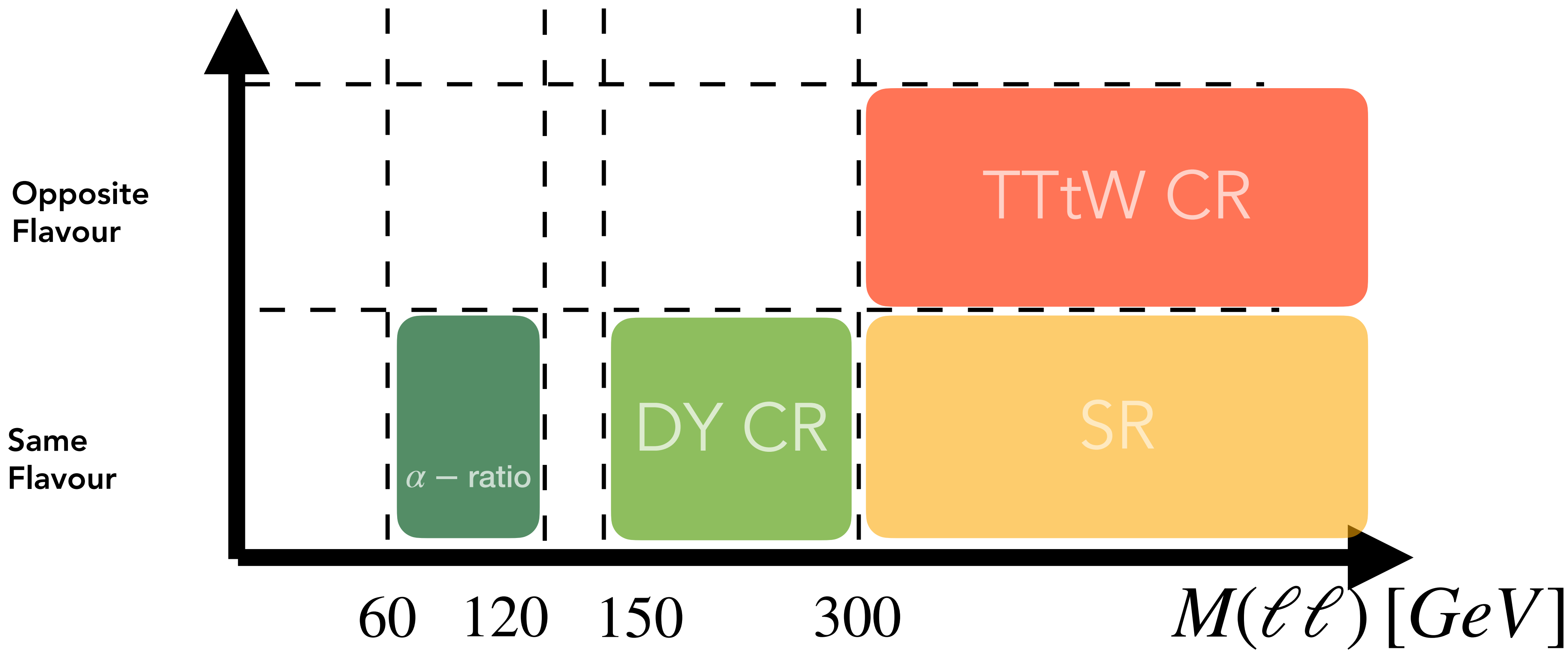
Small background contribution, and subject to statistical fluctuations => Need to devise strategies to **study the background in a large statistics region** (CONTROL REGION) with **different kinematical regime from the signal region**

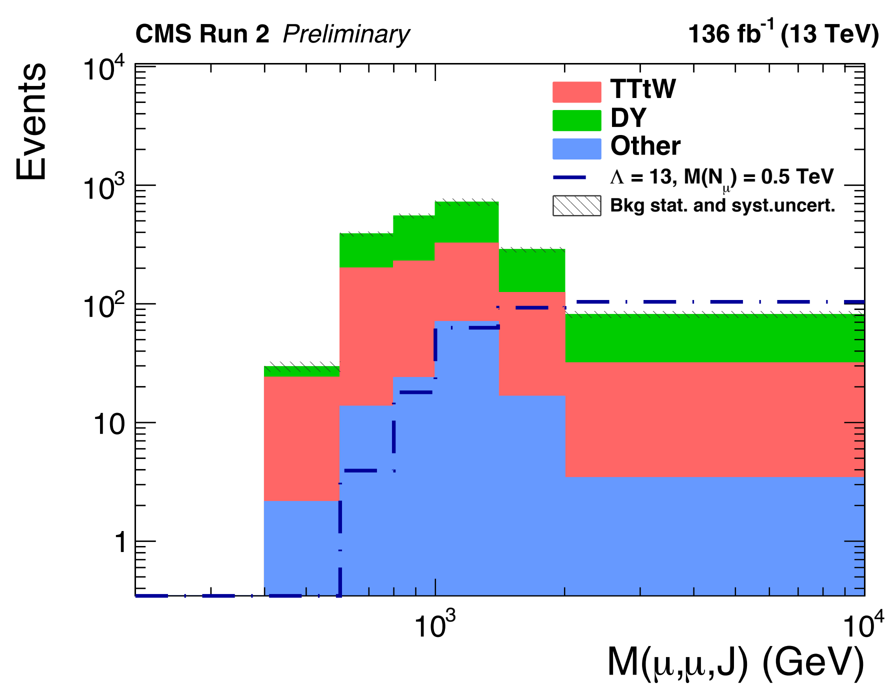


SIGNAL REGION (BLIND): SIGNAL ENHANCEMENT

CONTROL REGION: BKG ENHANCEMENT

BACKGROUND ESTIMATE STRATEGY



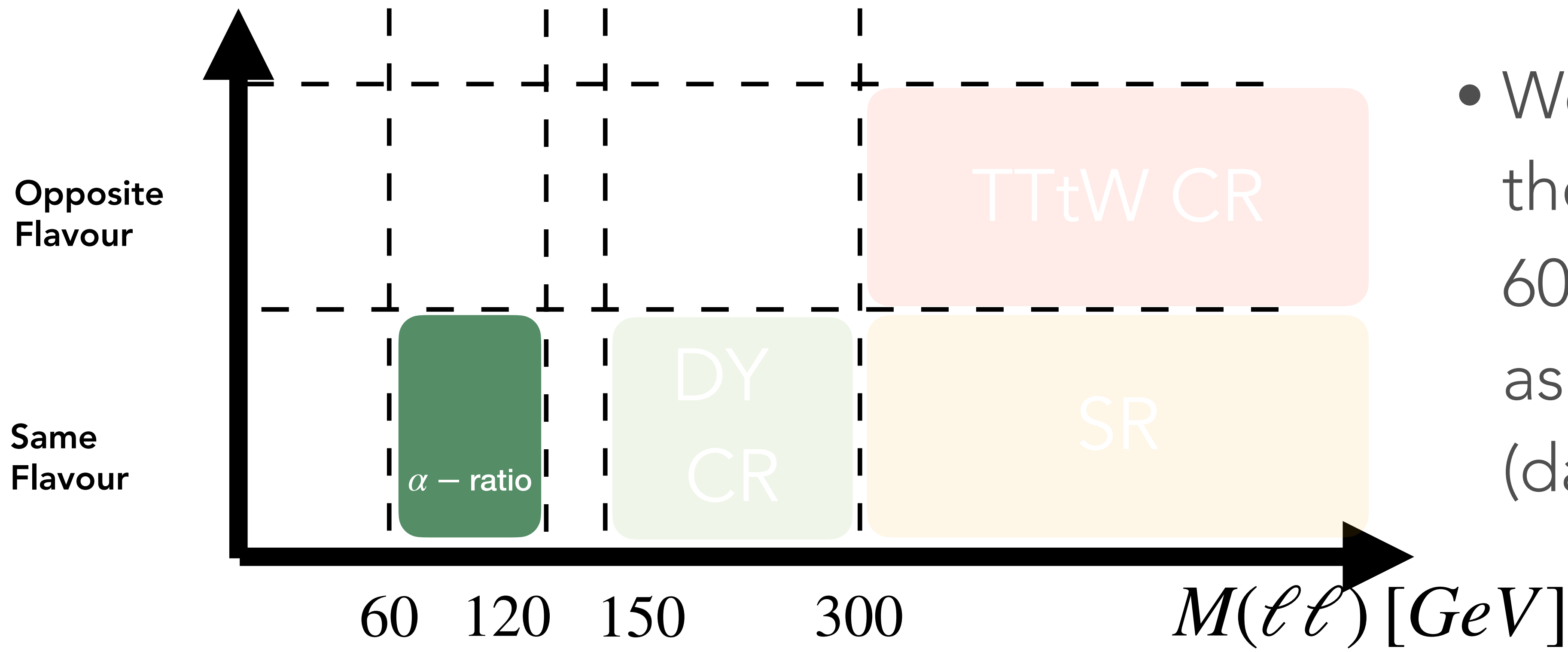


Major backgrounds for this analysis are:

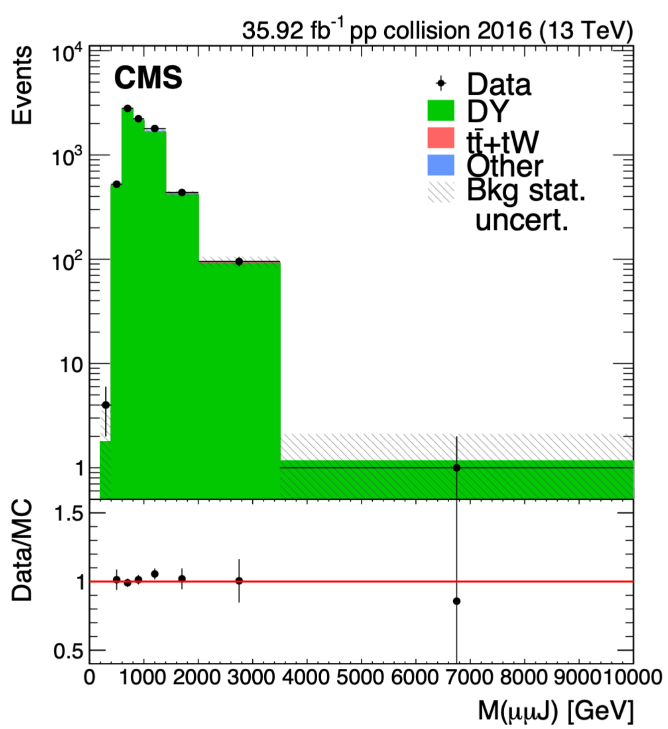
- Drell-Yan process
- "TTtW" = $t\bar{t}$ + single-top
- OTHER (QCD multi-jets, multi-boson)

BACKGROUND ESTIMATE: DRELL-YAN

DETERMINE THE APPROPRIATE PHASE SPACE TO CONTROL THE BACKGROUND CONTAMINATION:



- We evaluate a SF around the Z peak $60 < M(\ell\ell) < 120$ GeV, as the ratio of the events (data-nonDY)/DY



BACKGROUND ESTIMATE: DRELL-YAN

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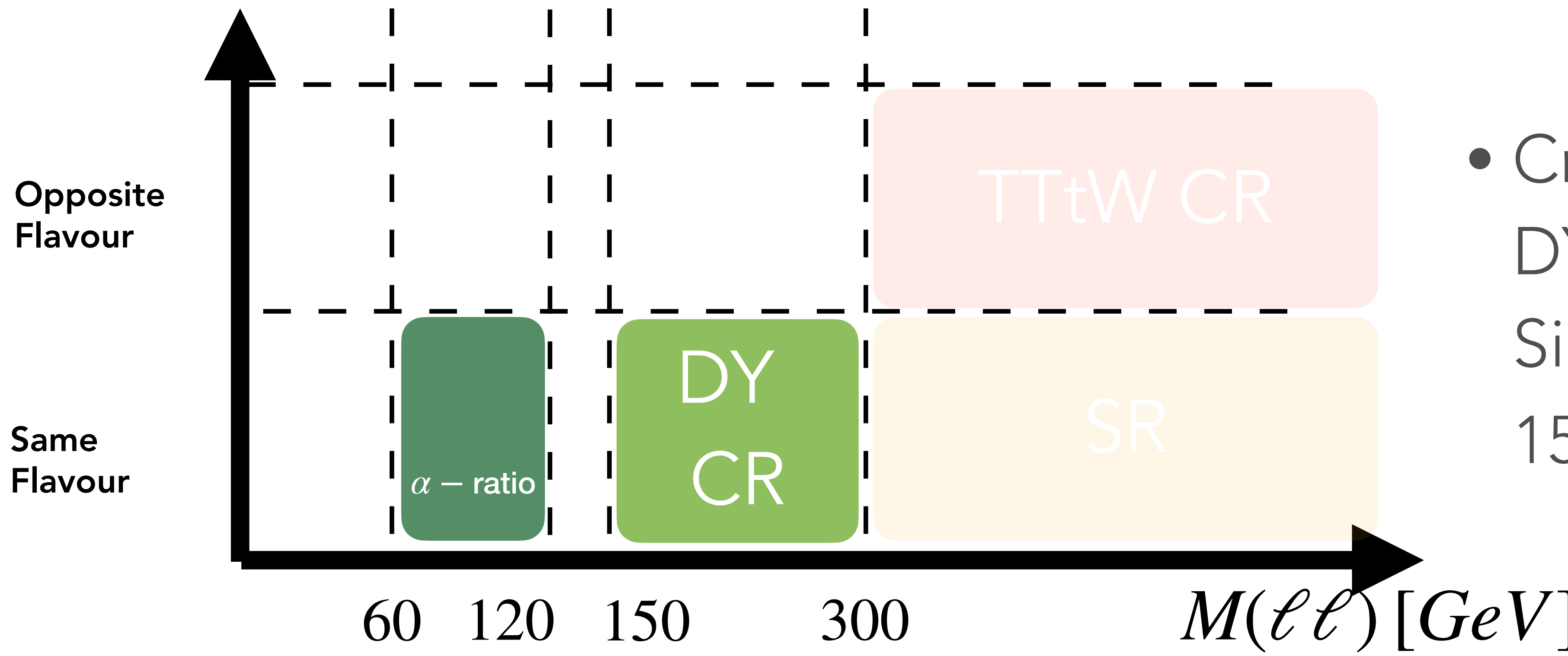
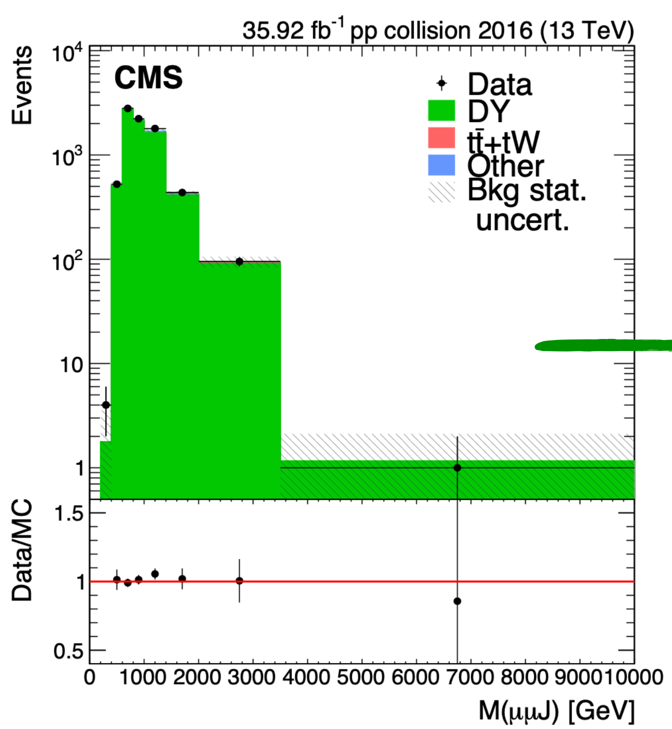
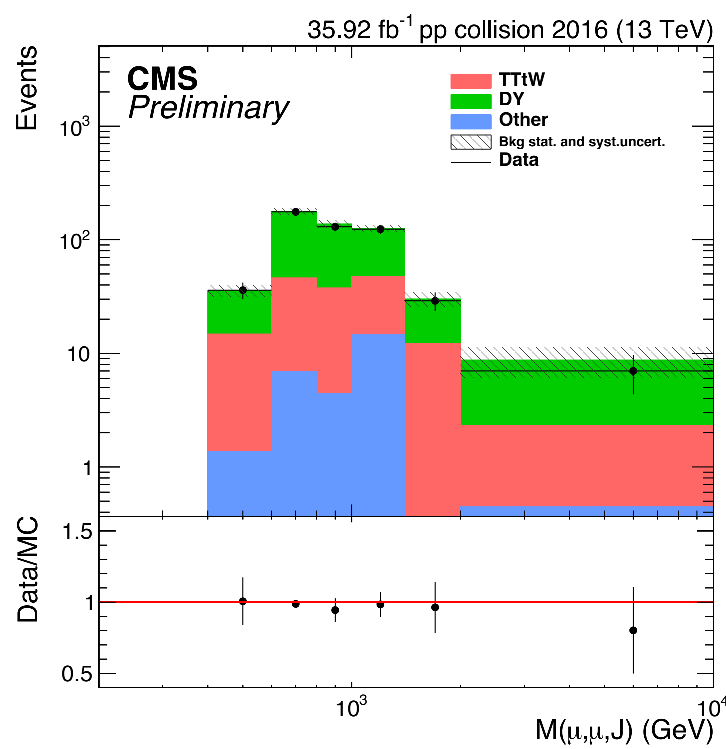


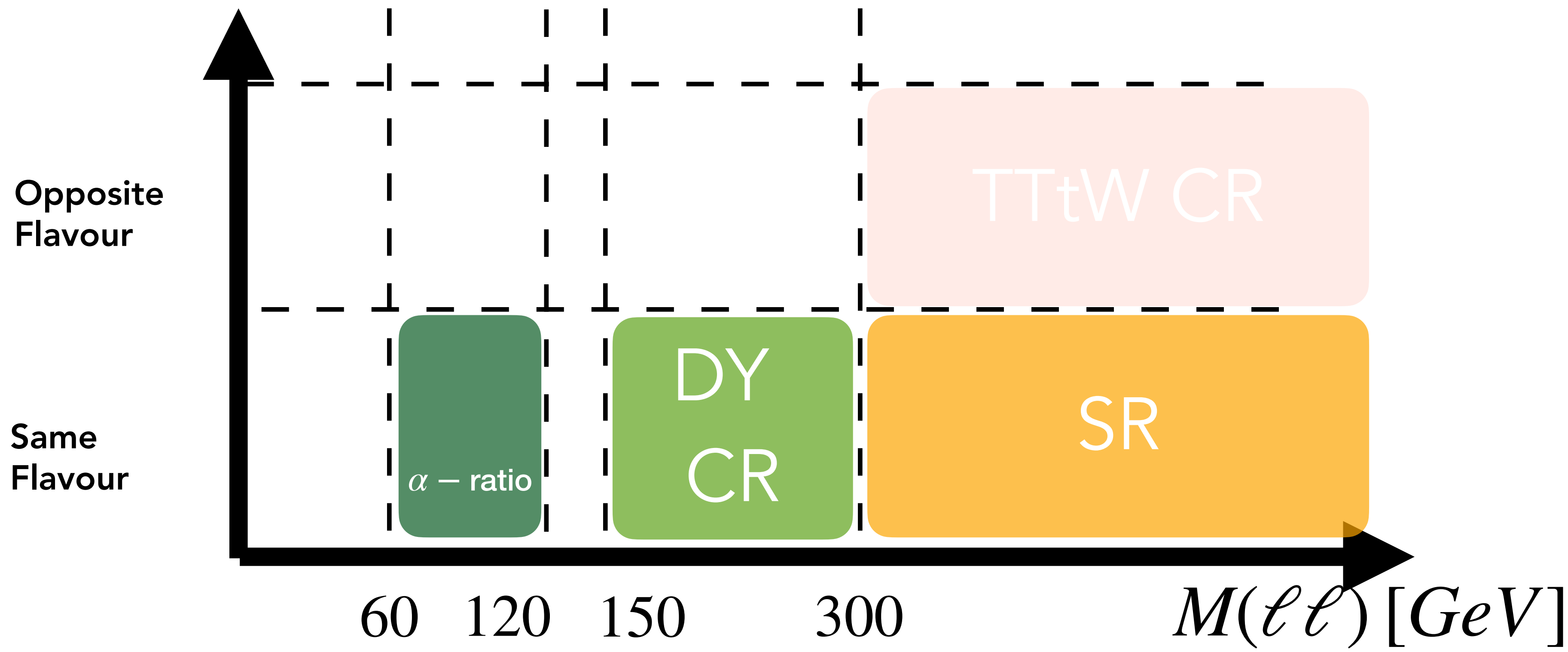
- Cross-check the corrected DY in a region closer to the Signal region
  $150 < M(\ell\ell) < 300$ GeV

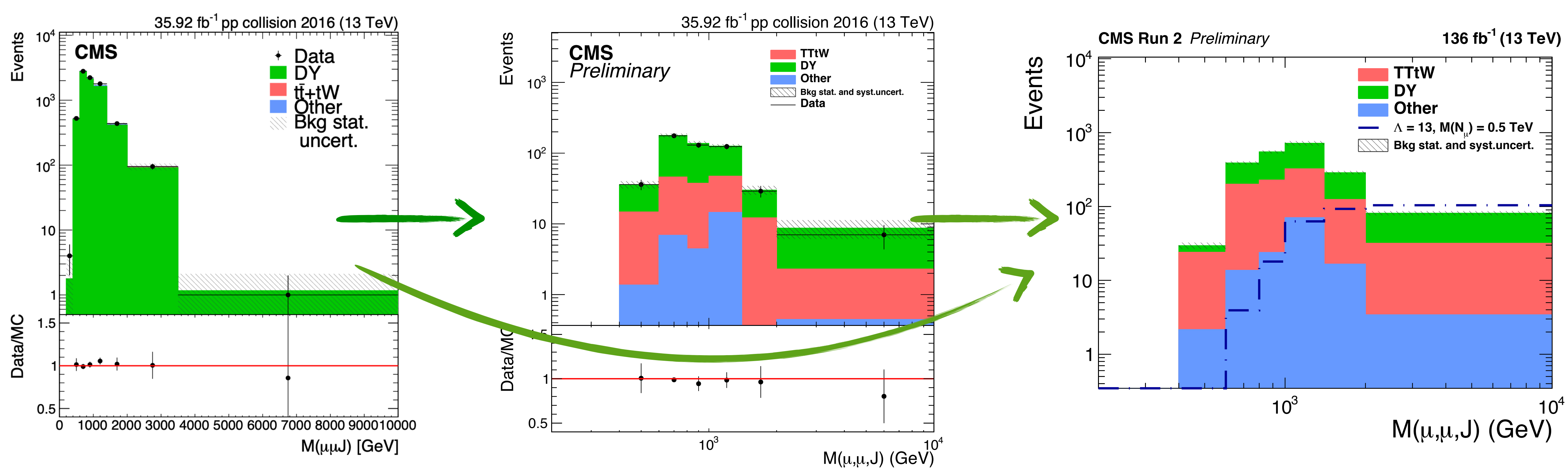




BACKGROUND ESTIMATE: DRELL-YAN

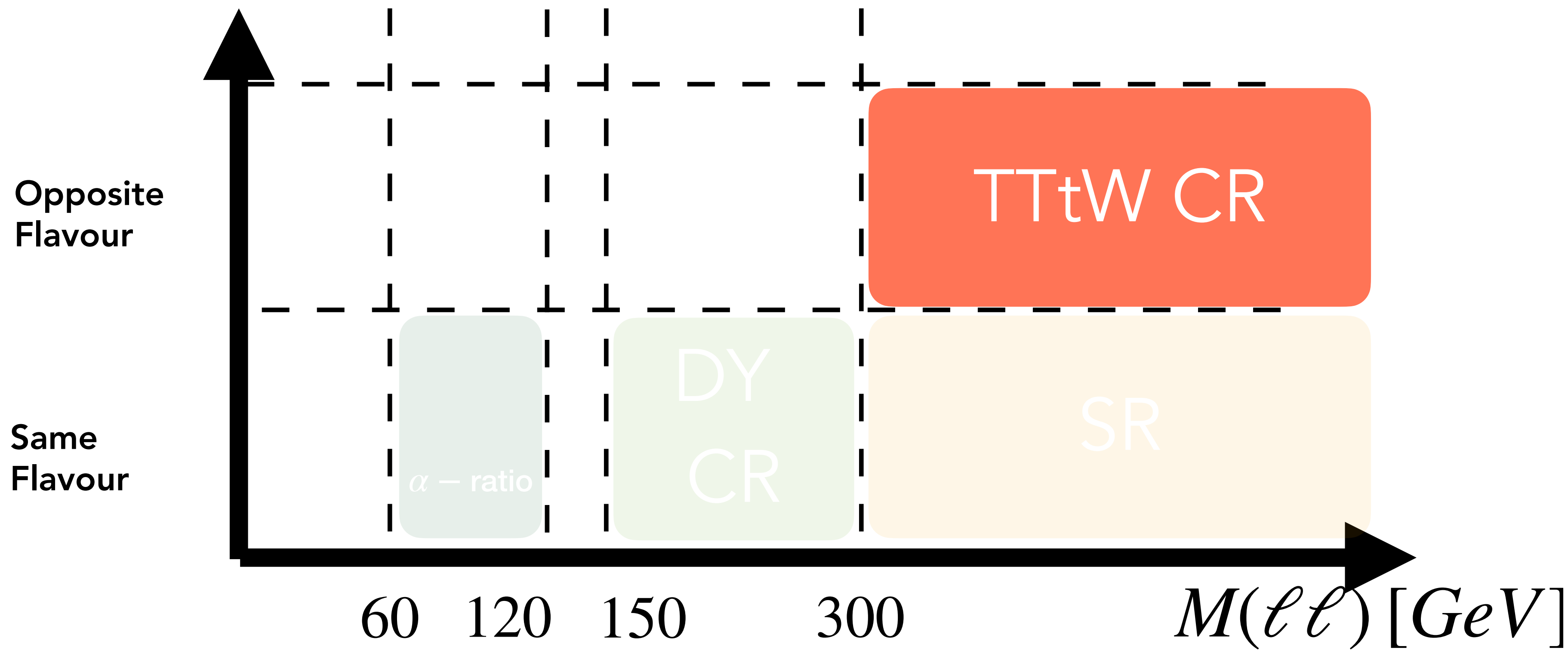
DETERMINE THE APPROPRIATE PHASE SPACE TO CONTROL THE BACKGROUND CONTAMINATION:

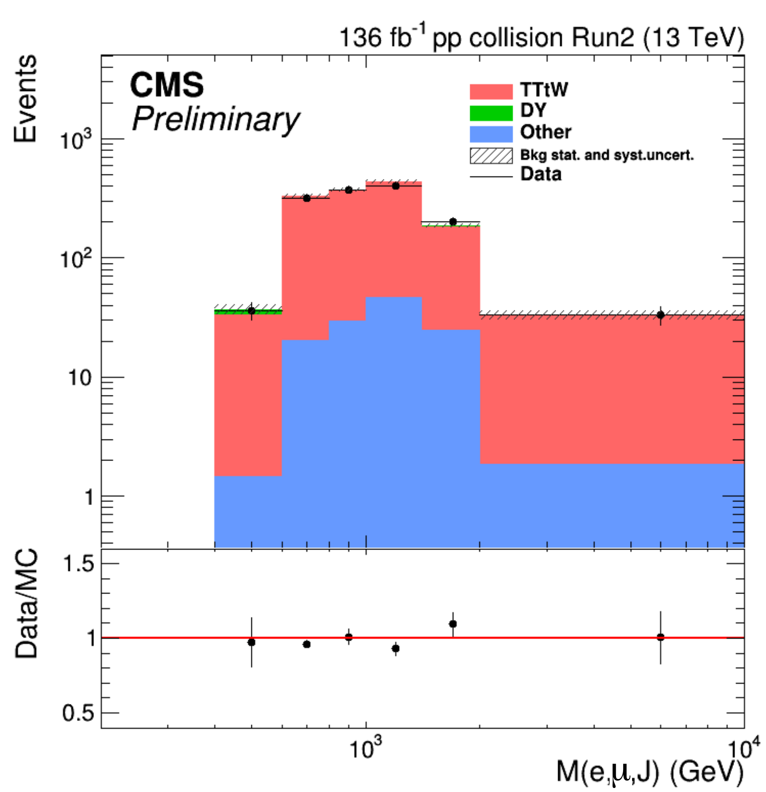




BACKGROUND ESTIMATE: TOP

DETERMINE THE APPROPRIATE PHASE SPACE TO CONTROL THE BACKGROUND CONTAMINATION:

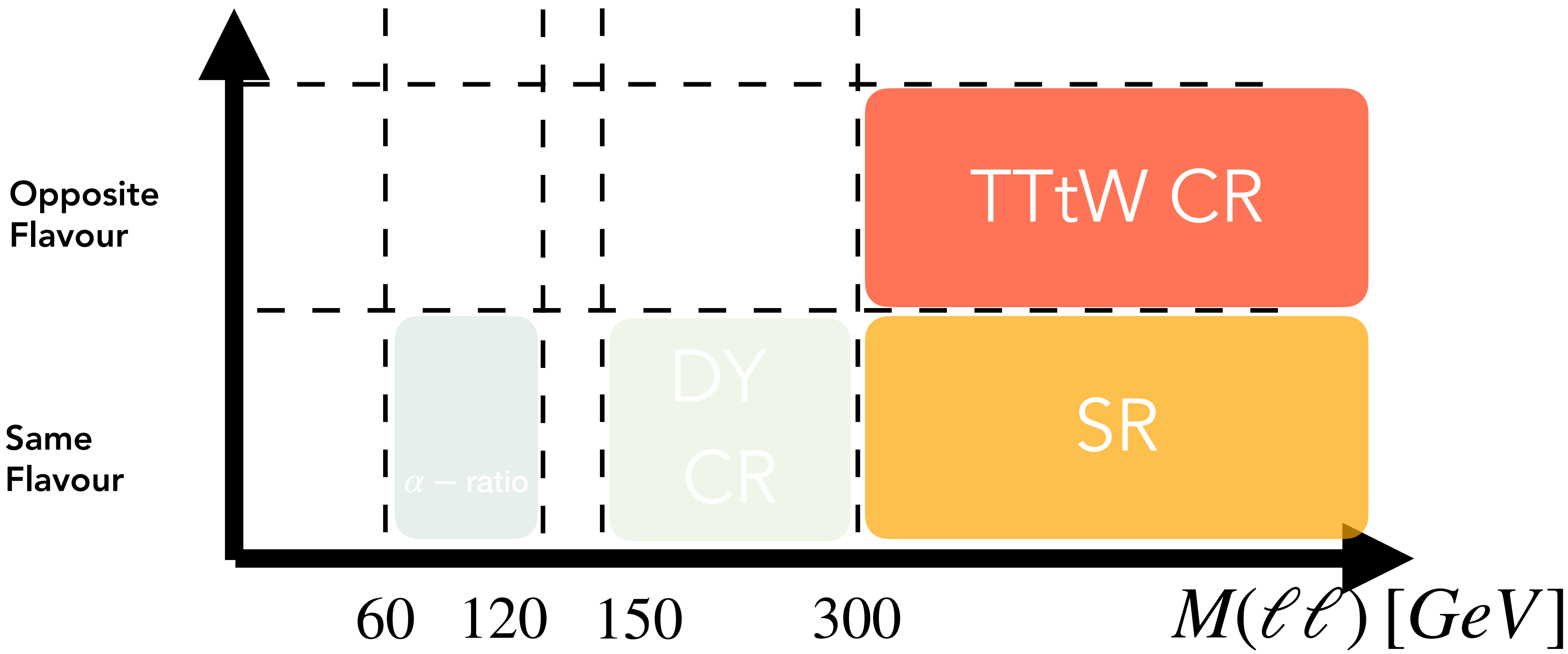


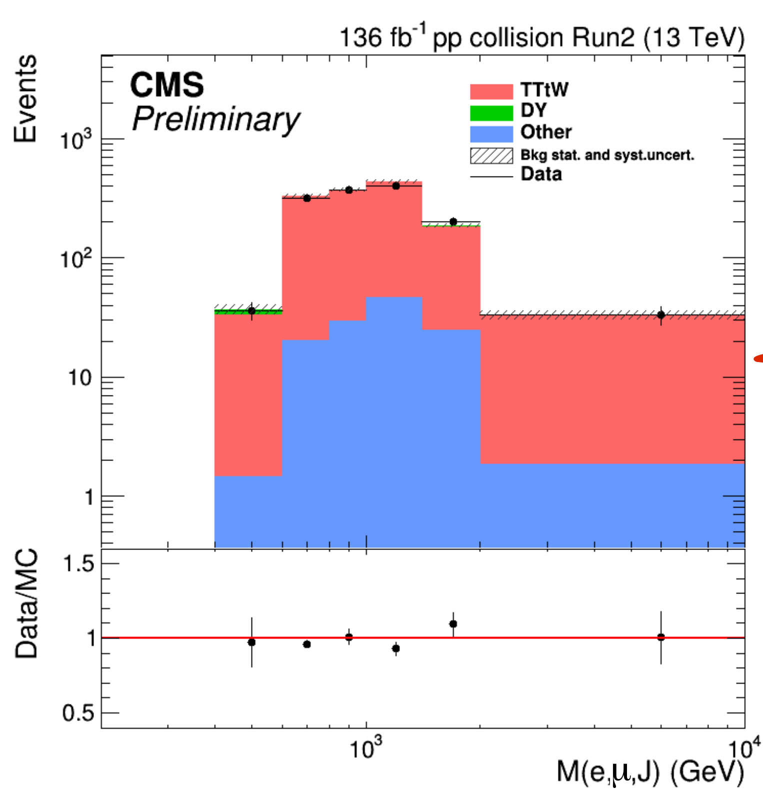


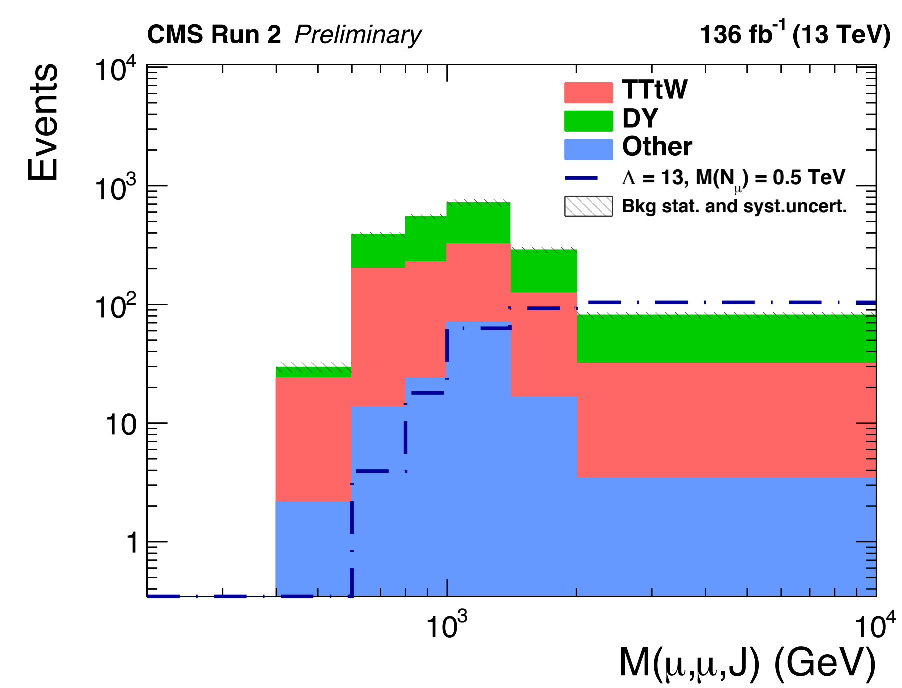
- The background from $t\bar{t}$ and single-top processes is estimated directly from MC simulation.
- $M(e\mu J)$ **as CR to validate the MC prediction**: *Flavour-symmetric processes with branching ratio to a pair of leptons of different flavour* $e\mu$ *twice as large as the branching ratio to* ee .

BACKGROUND ESTIMATE: TOP

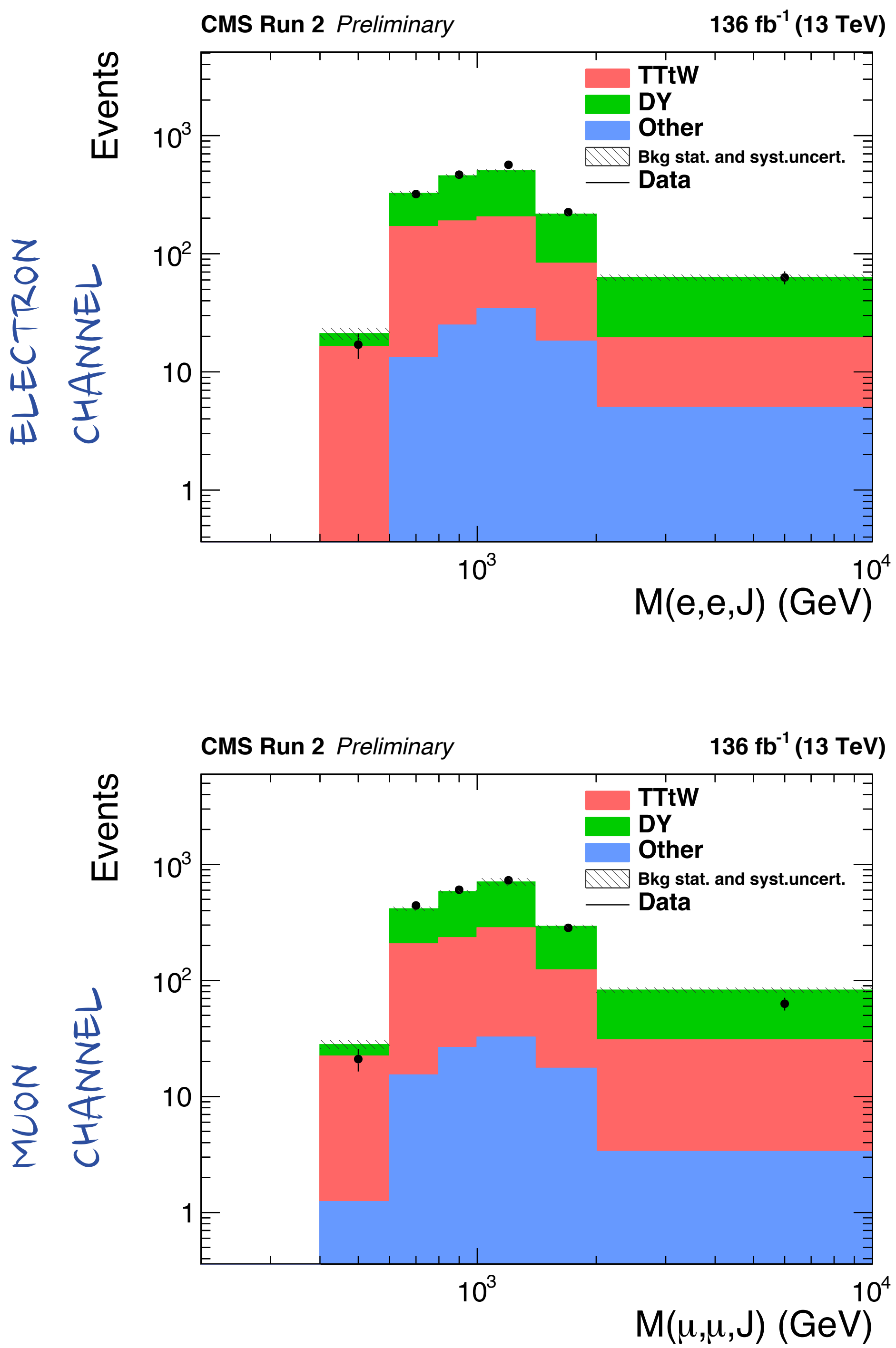
DETERMINE THE APPROPRIATE PHASE SPACE TO CONTROL THE BACKGROUND CONTAMINATION:





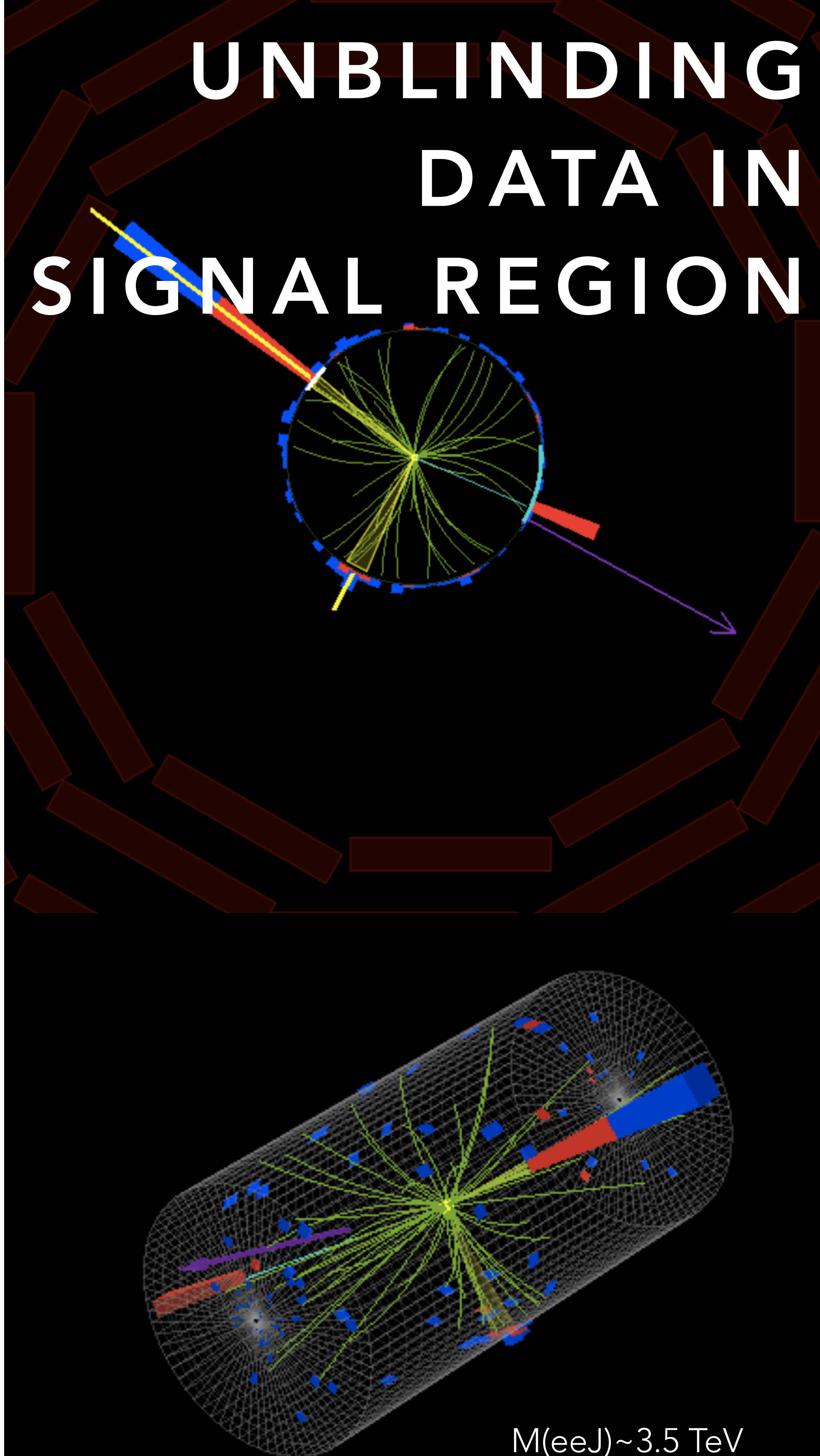


Finally comparing the Run2 CMS DATA with the background estimate



THE DATA DO NOT SHOW ANY SIGNIFICANT DEVIATION FROM THE STANDARD MODEL BACKGROUNDS :(

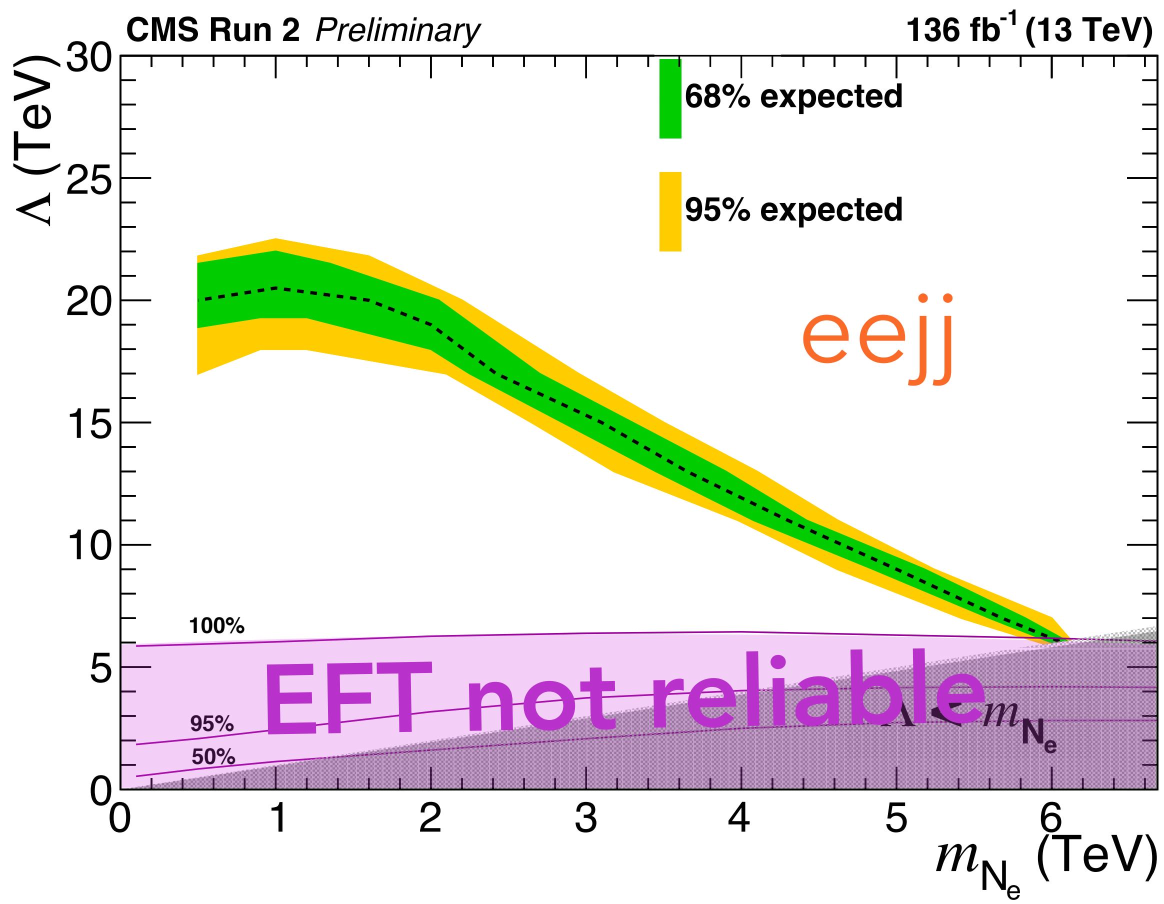
UNBLINDING DATA IN SIGNAL REGION

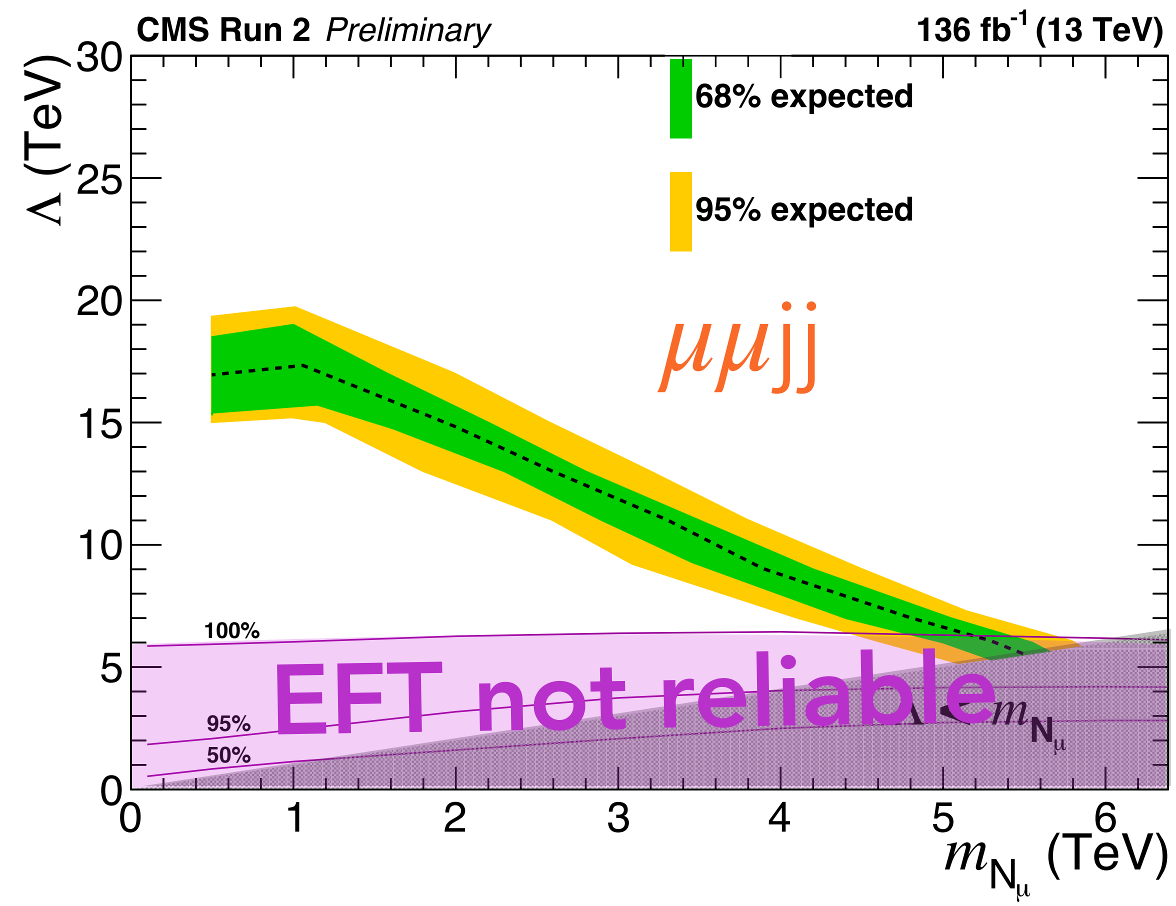


Display of high-energetic event collected in 2017 by CMS.

FINAL RESULT

Experimental limits on the **compositeness scale** Λ for the $ee q\bar{q}'$(left) and the $\mu\mu q\bar{q}'$(right) final states, **as a function of the mass** of the HCMN





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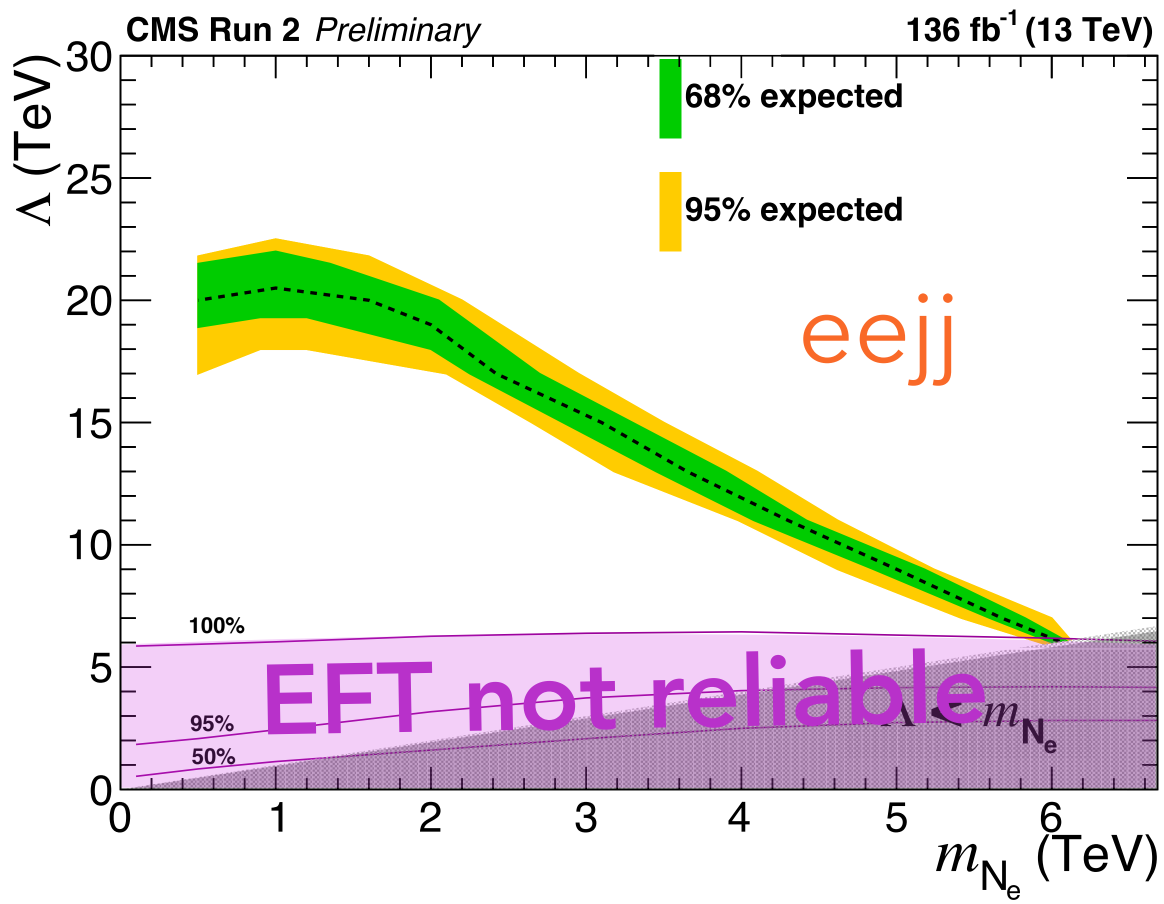
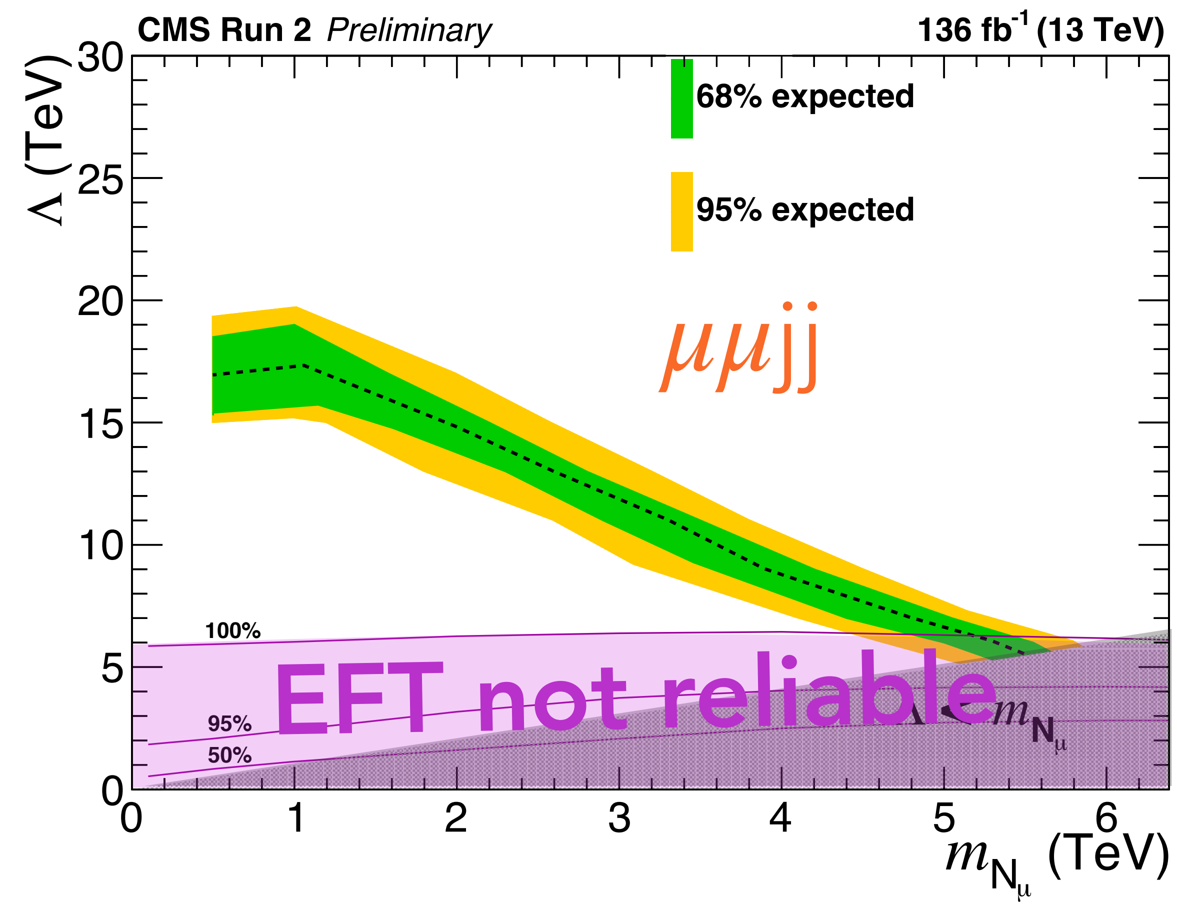
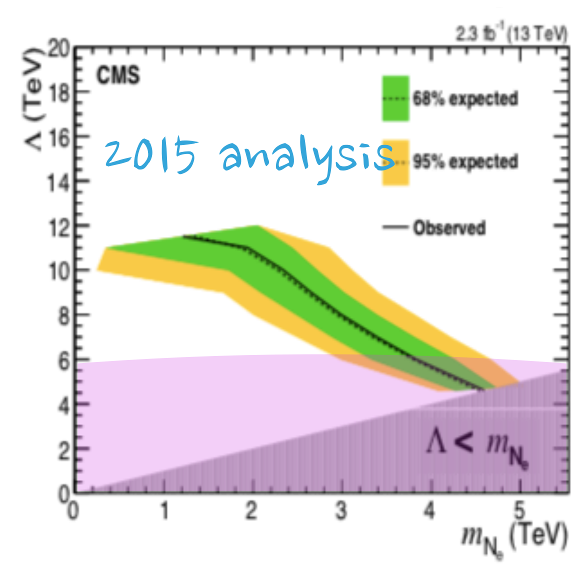


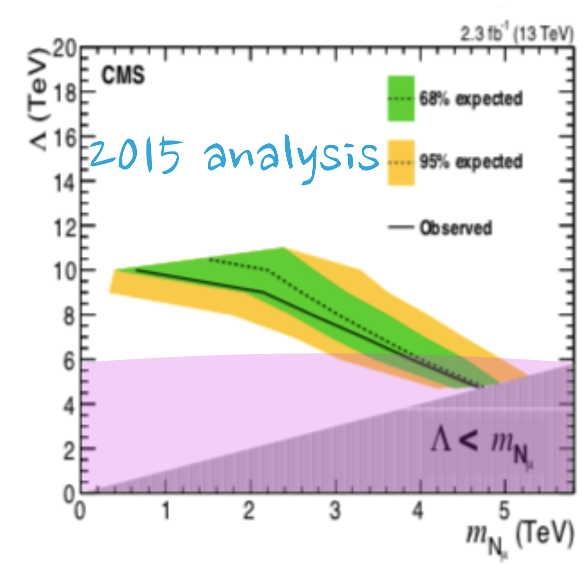


Wider phase space covered in the (Λ, M(N$_l$)) plane wrt to previous Run2

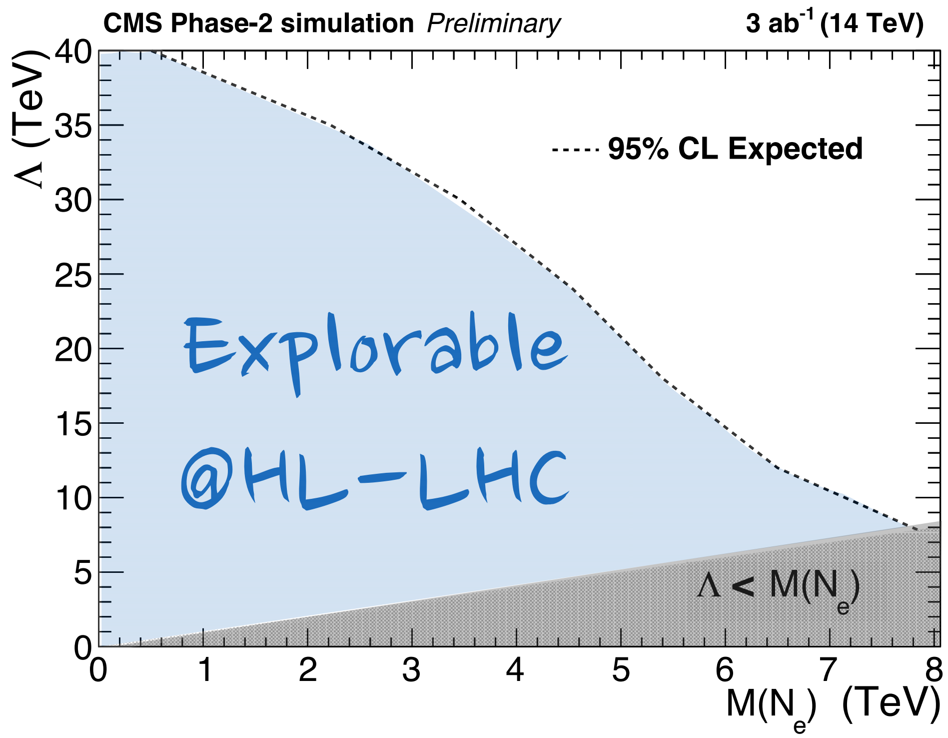
+

Unitarity constraints applied for the first time (ArXiv.1903.12285)

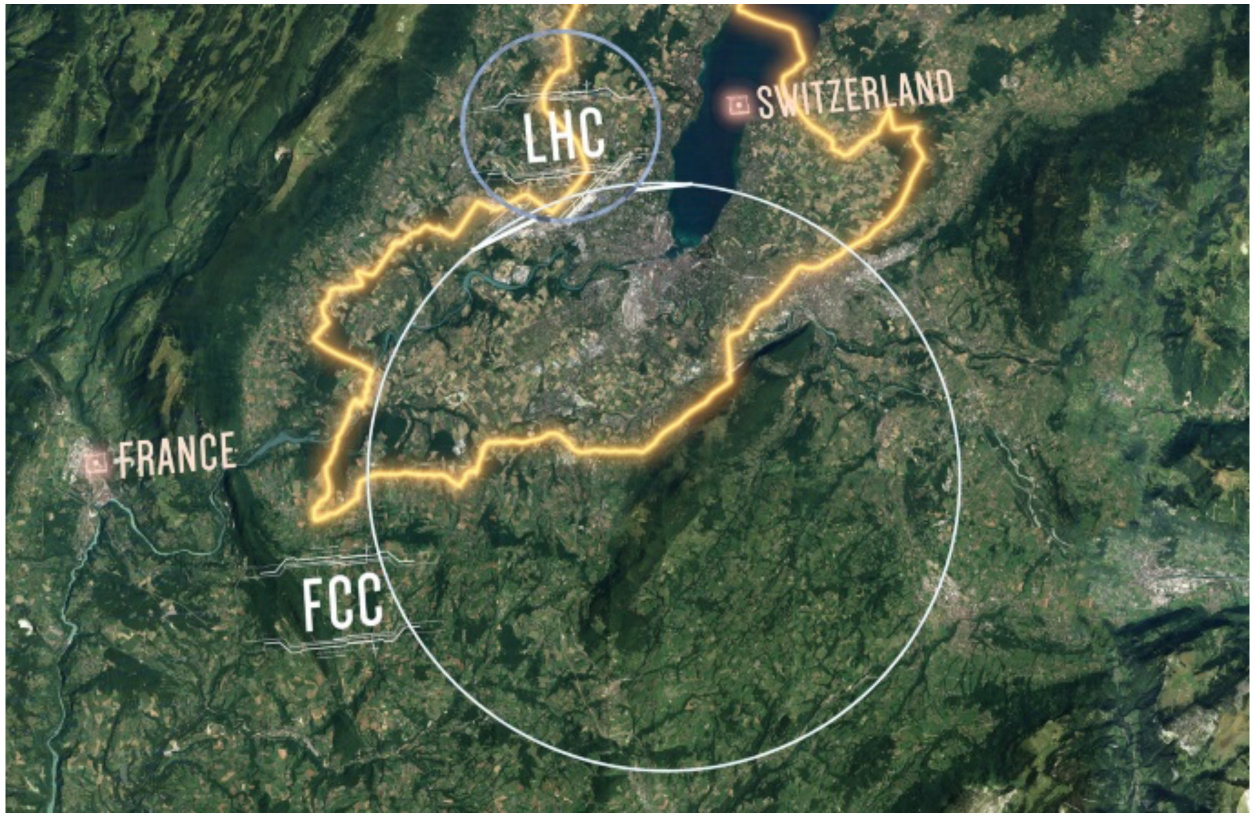




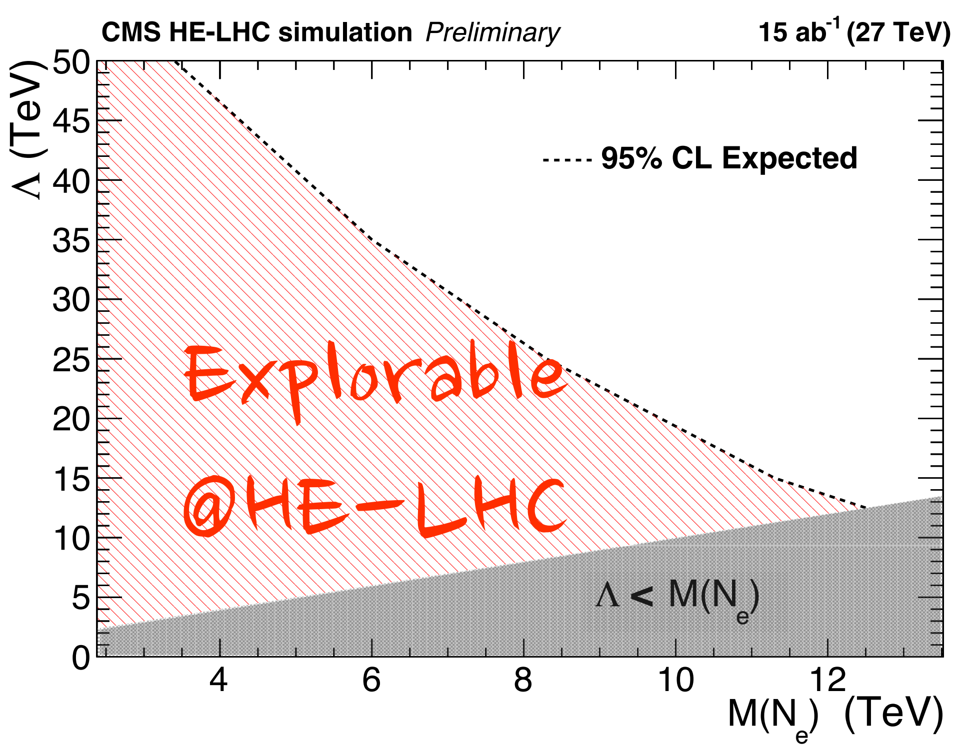
FUTURE PROSPECTS



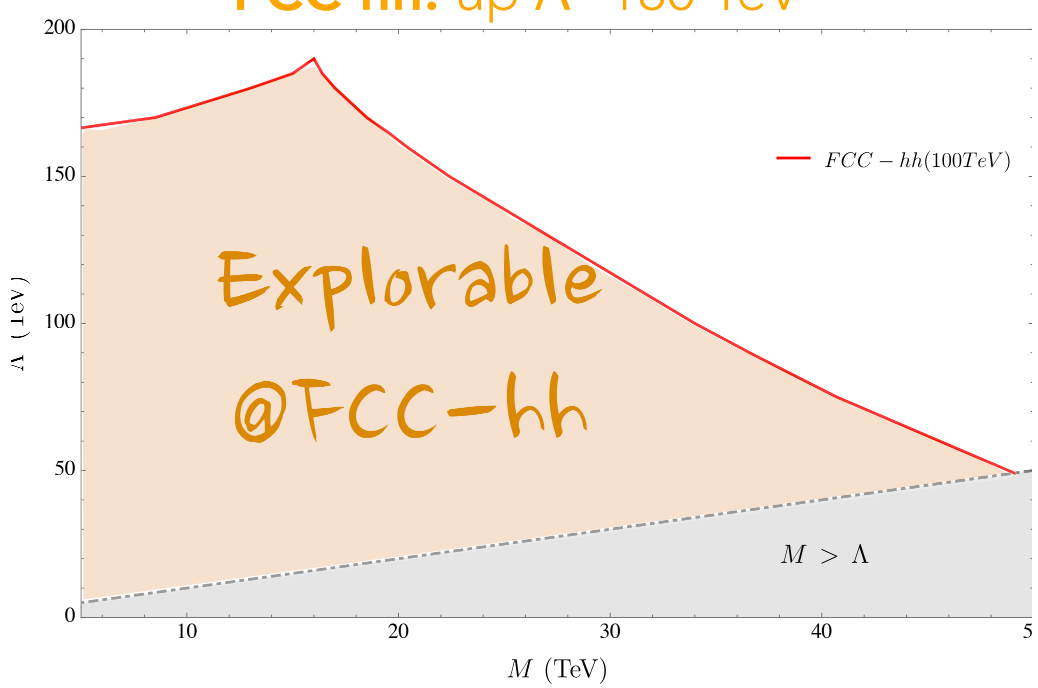
HL-LHC: with 20 times statistics **doubling Λ reach**



HE-LHC:
twice energetic and 60 times more statistics
=>**M(N) up to 12 TeV, Λ up to 55 TeV**

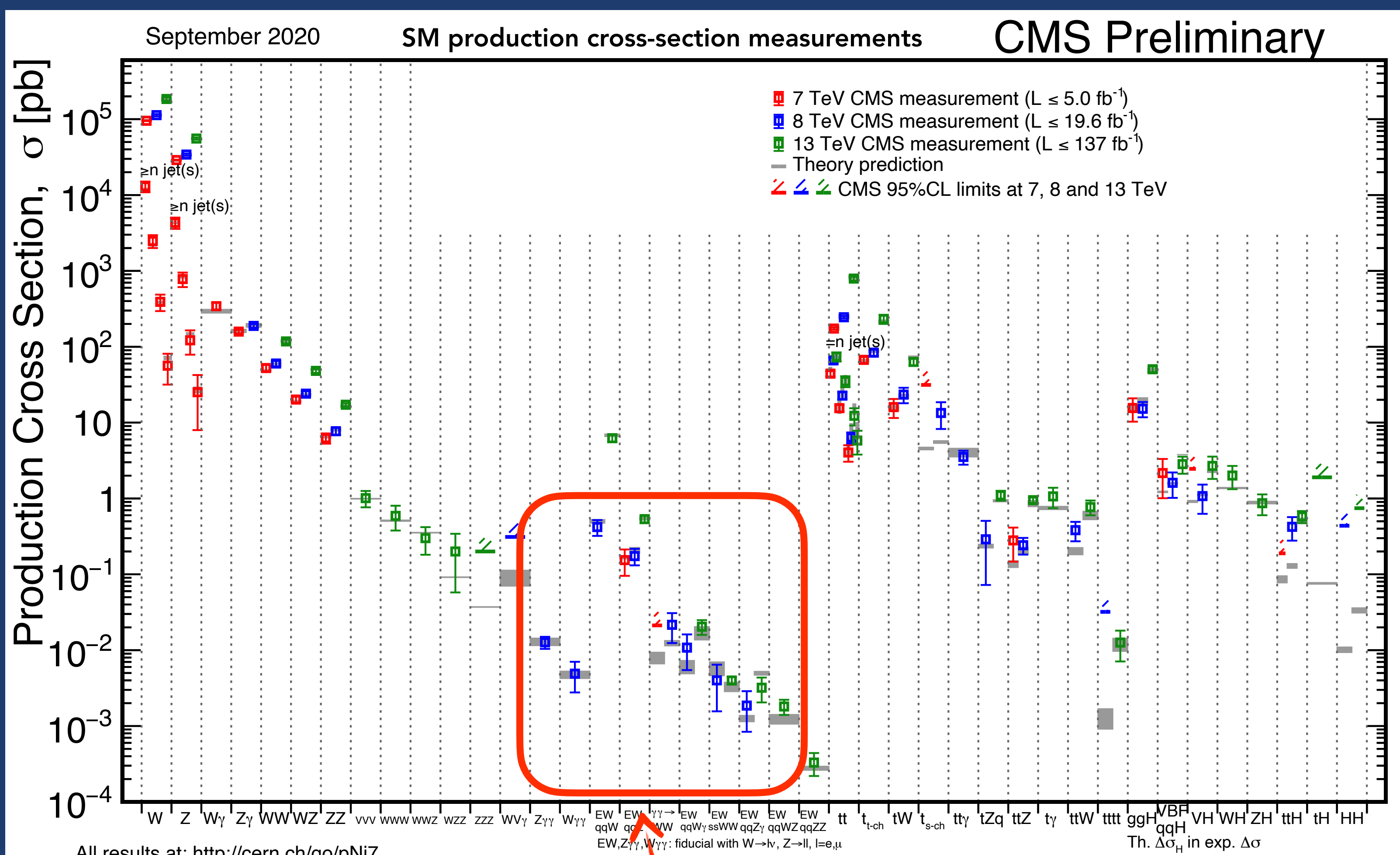


FCC-hh: up Λ~180 TeV



Part 3.

Dilepton and jets final state with Vector Boson Scattering



VBS EW processes measured

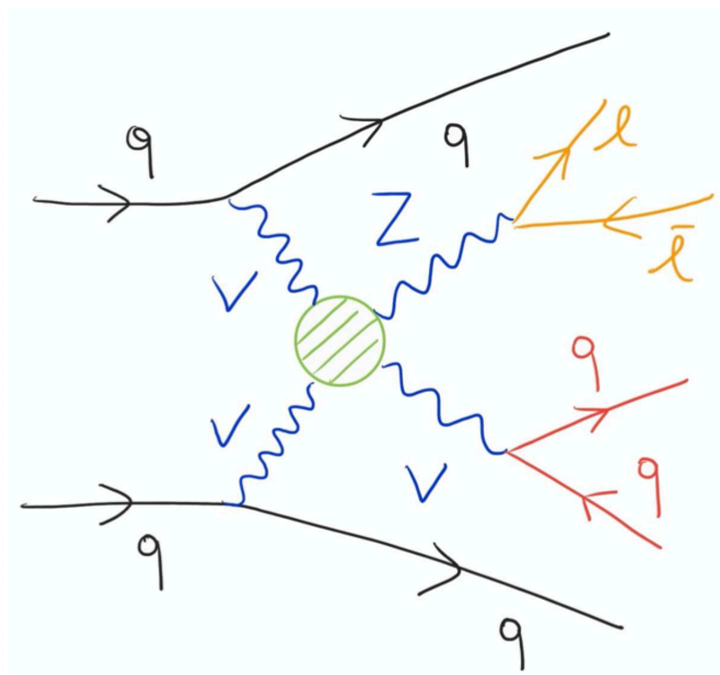
Precision measurement of a rare process:

$\sigma(pp \rightarrow VZ \rightarrow 2\ell + 4q) \approx 10^{-3} pb$

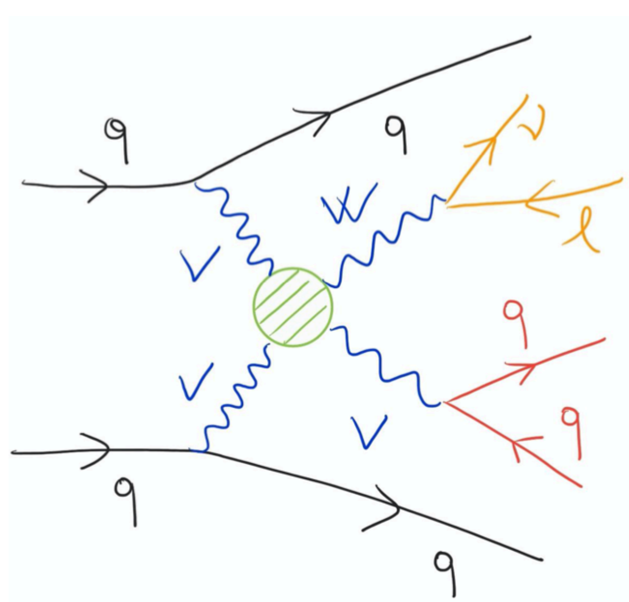
- Fine control of background sources in control regions: nearly identical profile of the process of interest.
- Tailored algorithm for object selection.
- Exploit machine learning techniques.

VBS SEMI-LEPTONIC FINAL STATE

VV scattering is a **purely EWK process** with 6 fermions in the final state where one **V boson decays leptonically** and **the other hadronically.**



FOCUS OF THE THESIS

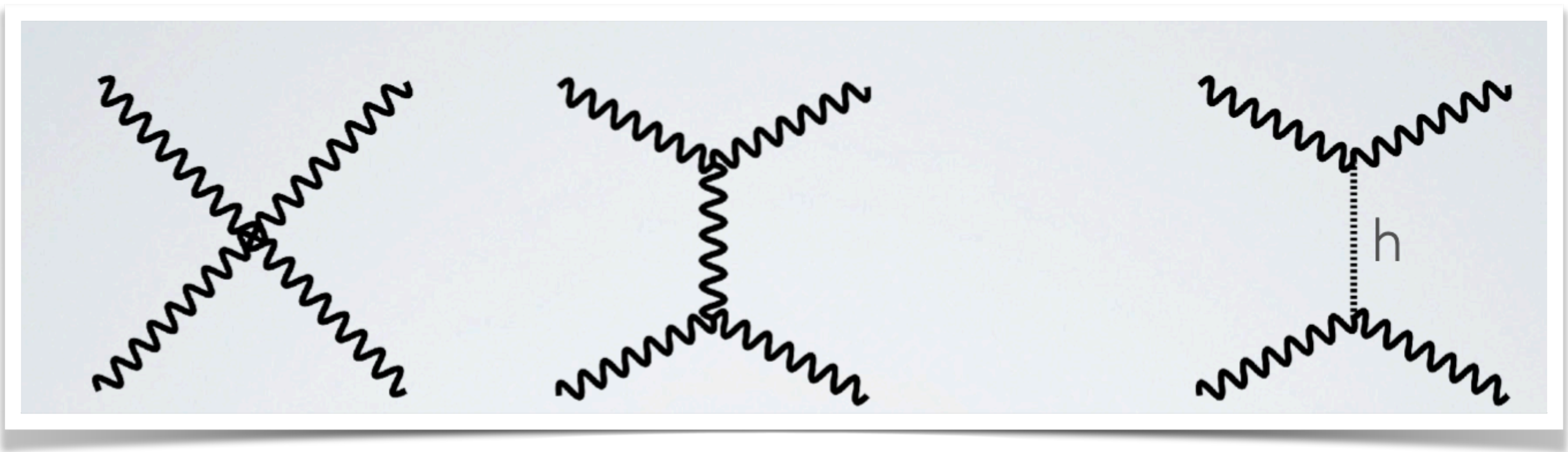


Why a relevant measure?

- Studies of gauge invariance: this process is gauge invariant thanks to very delicate cancellations between diagrams
- **At the heart of EWSB:** containing triple and quartic gauge couplings => good sensitivity to EFT operators
- **Unitarity Studies: would violate unitarity without the Higgs (delayed unitarity?)**

VBS & UNITARITY OF THE SM

SCATTERING $Z_L Z_L \Longleftrightarrow W^+_L W^-_L$



$M = c\ \text{Energy}^2 + \ldots$

$M = -c\ \text{Energy}^2 + \ldots$

Higgs exchange cancels high energy growth if its couplings are SM-like, matrix element is unitary if $m_H \lesssim 1\,\text{TeV}$ (Lee, Quigg, Thacker bound)

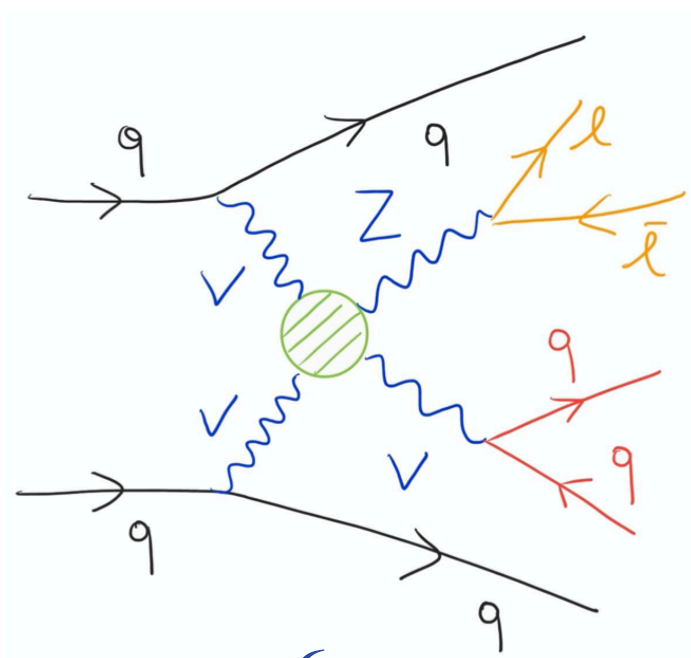
DILEPTON + JETS PROCESSES WITHIN THE SM

Good balance between:

✓ Benefit from the large hadronic branching fraction of W or Z boson

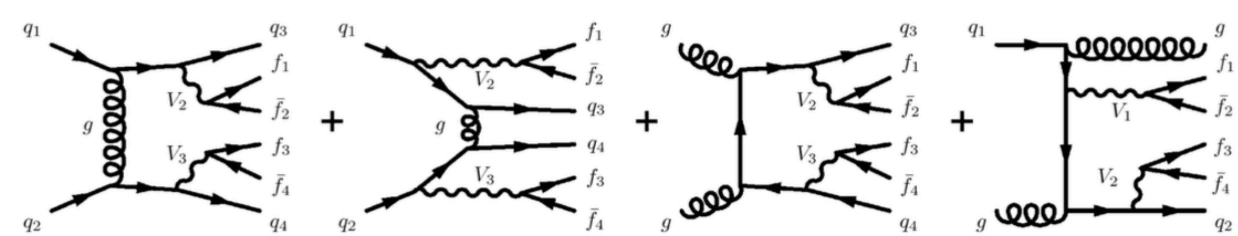
✳ Larger irreducible backgrounds

SIGNAL

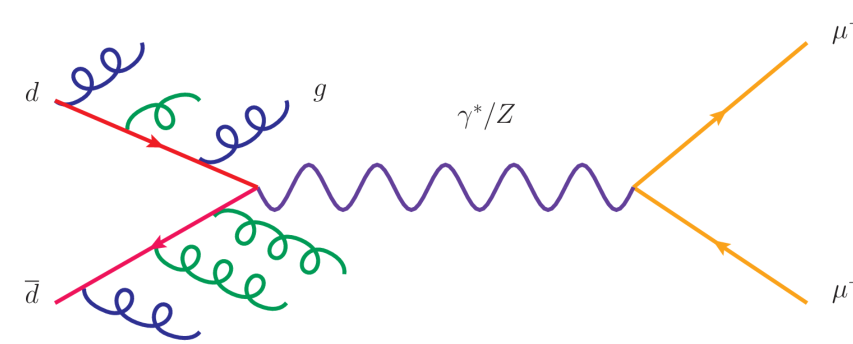


$\mathcal{O}(\alpha_{EW}^6)$

IRREDUCIBLE BACKGROUNDS



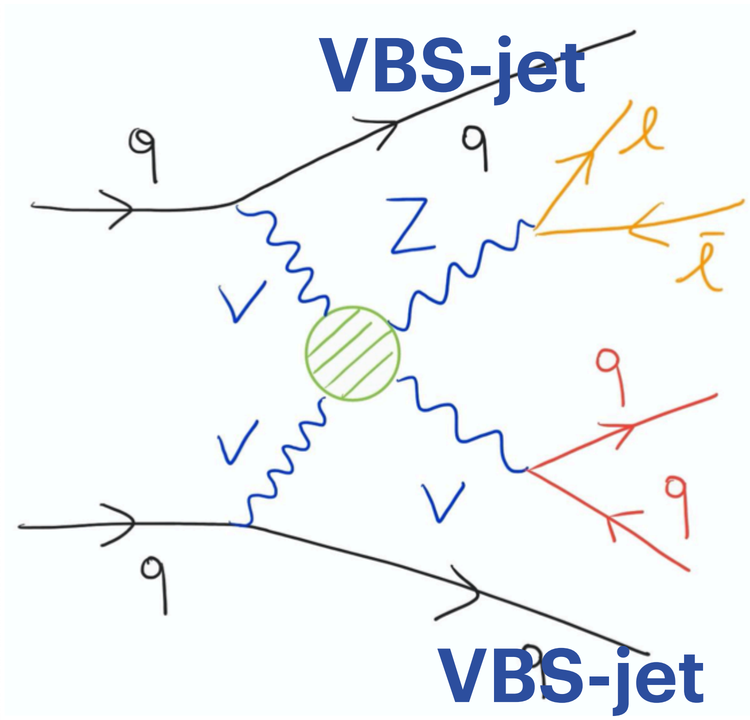
$\mathcal{O}(\alpha_{EW}^4 \alpha_S^2)$ QCD-VV production
(negligible interference with the signal)



$\mathcal{O}(\alpha_{EW}^2 \alpha_S^4)$ DY+jets

VBS TOPOLOGY

HIGH JET-MULTIPLICITY AT THE RECONSTRUCTED LEVEL



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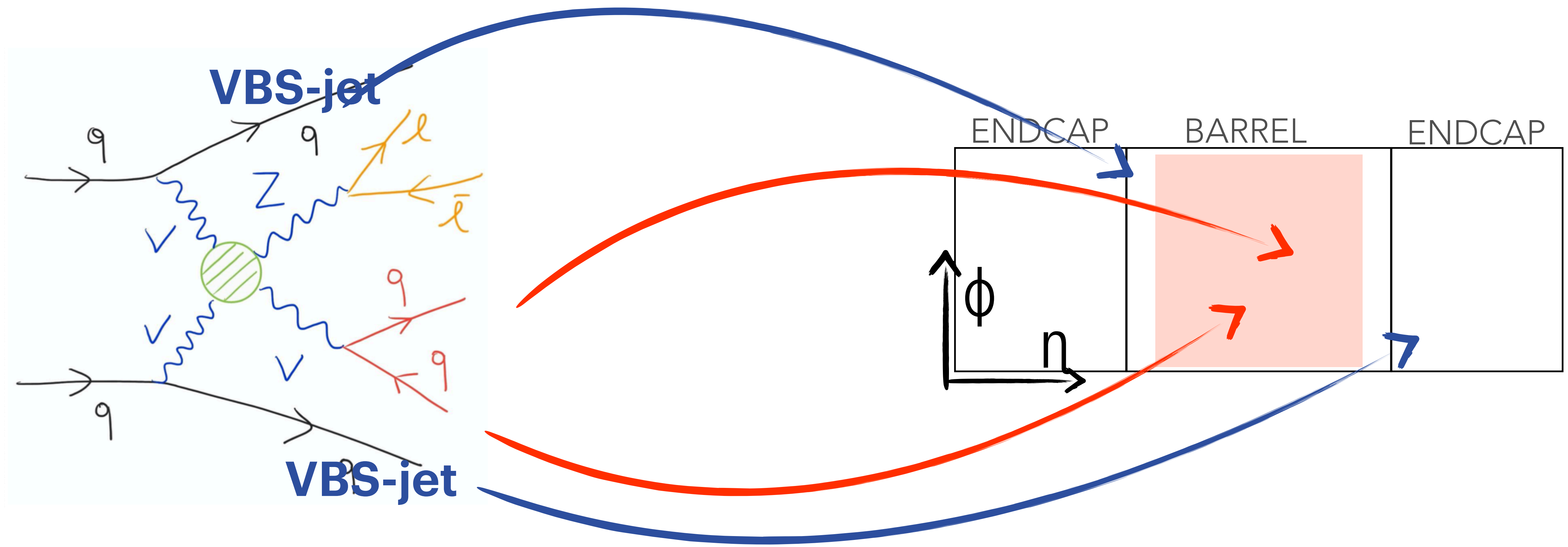
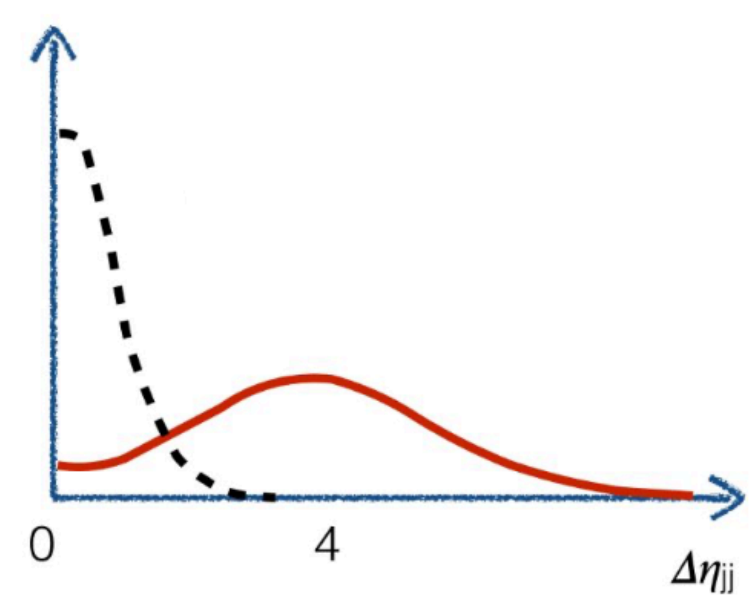


- **Large pseudorapidity separation between the VBS-jets** - for the low QCD activity btw partons (no colo flow at LO arXiv. 1805.09335)



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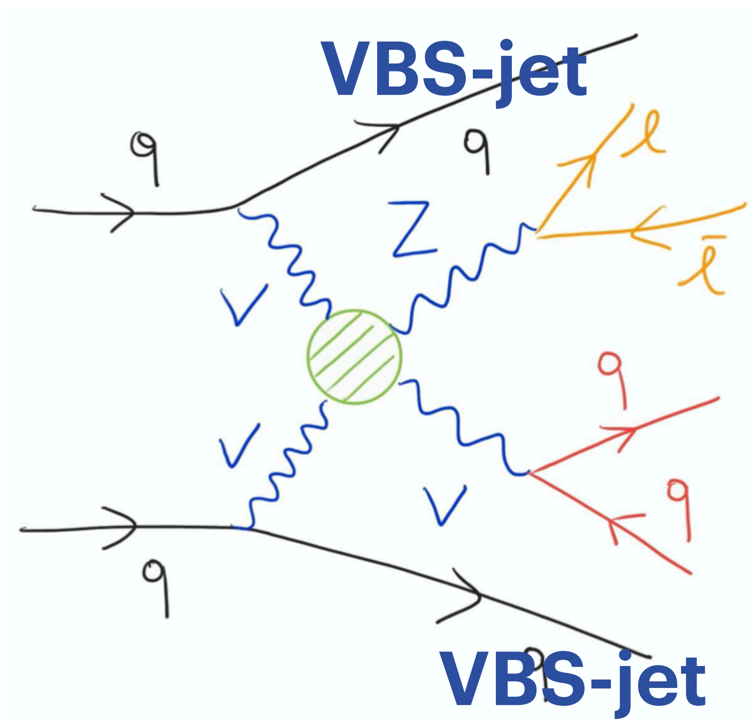

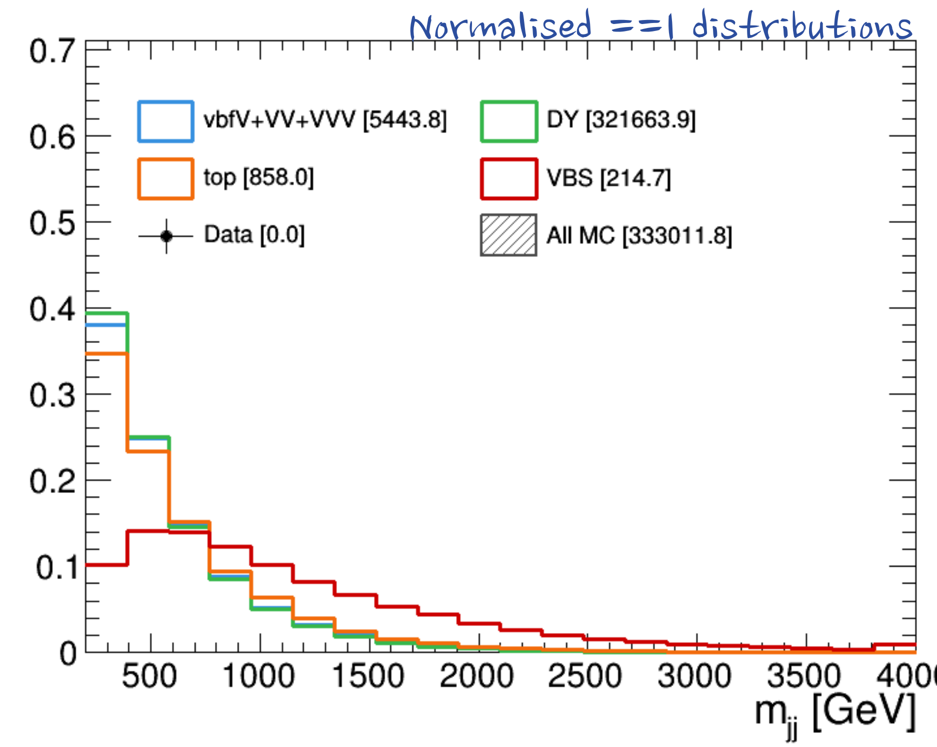

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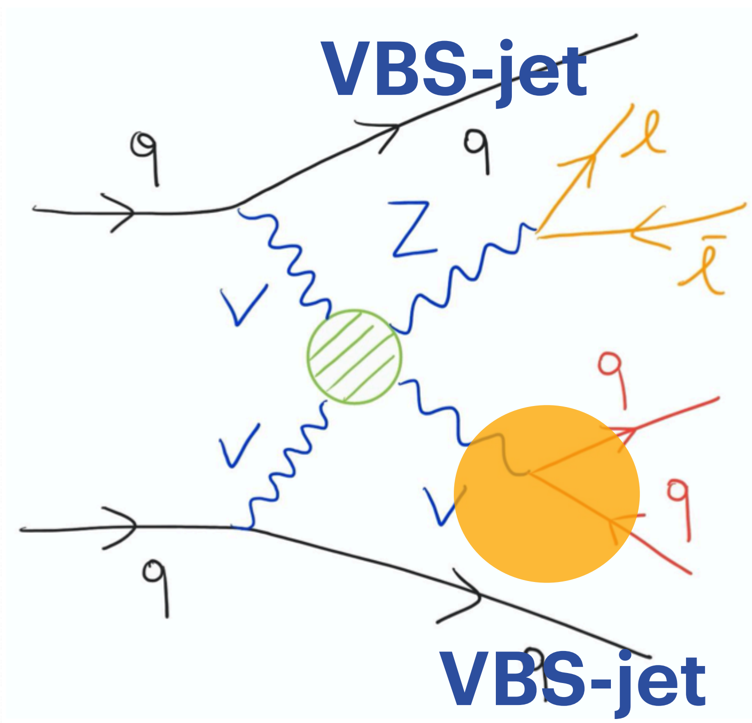
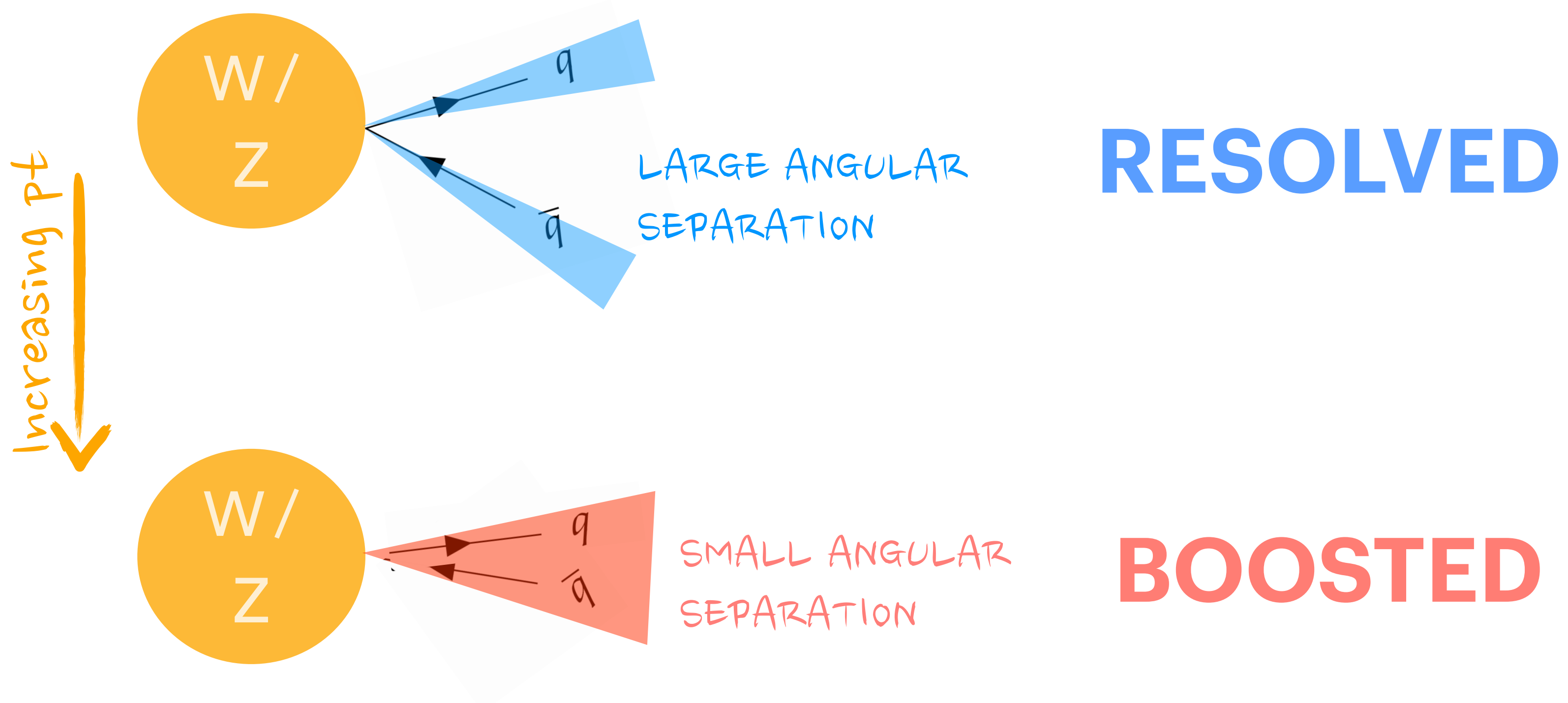


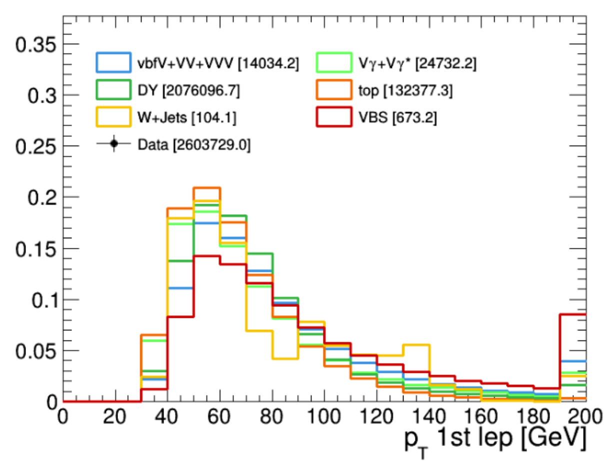


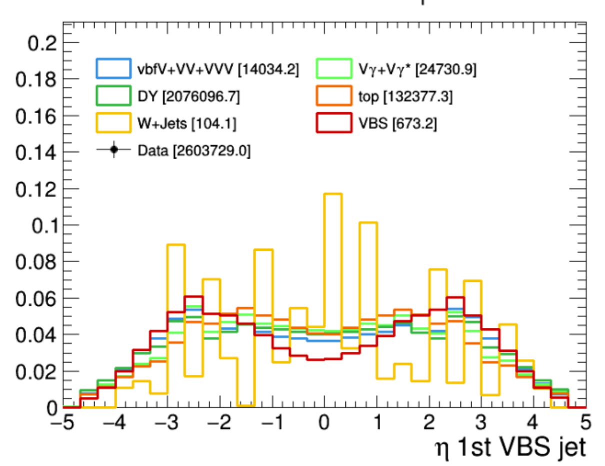
- **Large pseudorapidity separation between the VBS-jets** - for the low QCD activity btw partons (no colo flow at LO arXiv. 1805.09335)
- VBS-jets in **forward** detector region: highest invariant-mass in the event
- **V boson**, central, and highly Lorentz-boosted

A PLAYGROUND FOR DNN

Exploit multi-variate techniques to optimise the sensitivity to the EW Vector Boson Scattering process.

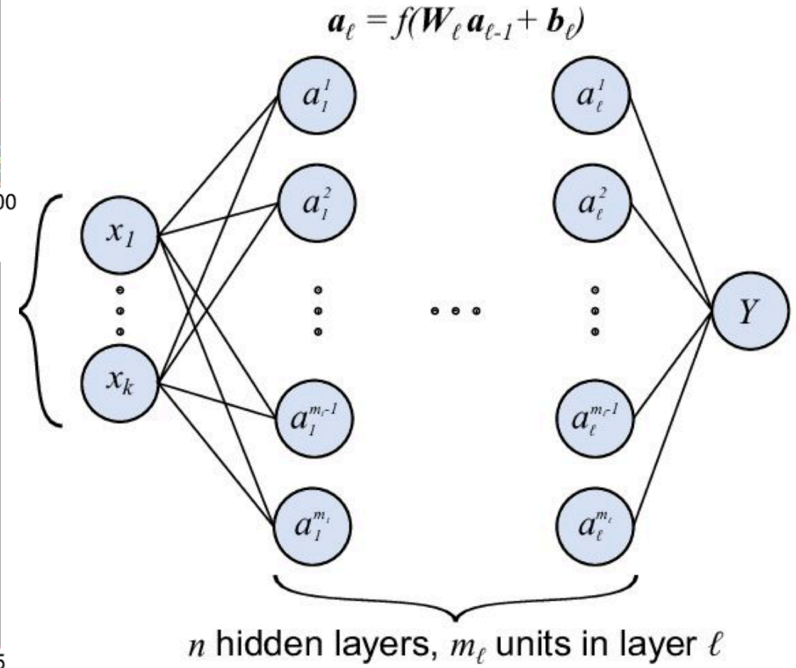
INPUT VARIABLES



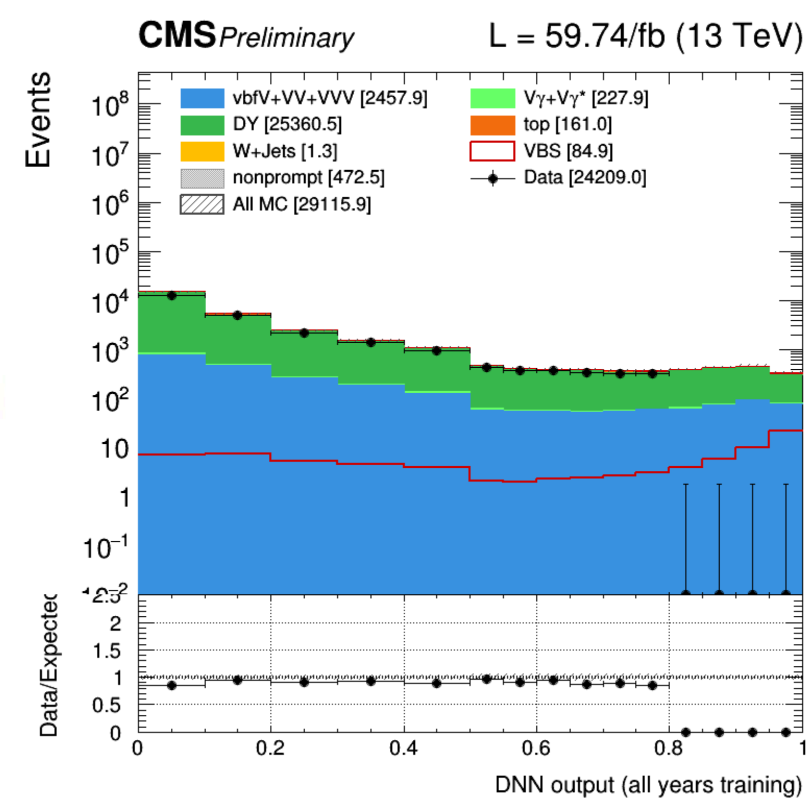


…+ more high- and low-level features

Fully-connected Deep Neural Network



BINARY CLASSIFIER



- Basic approach: all Backgrounds vs Signal

(events weighted by cross-section and analysis scale-factors)

- Training performed on events in signal region

DNN: PERFORMANCES AND FEATURES

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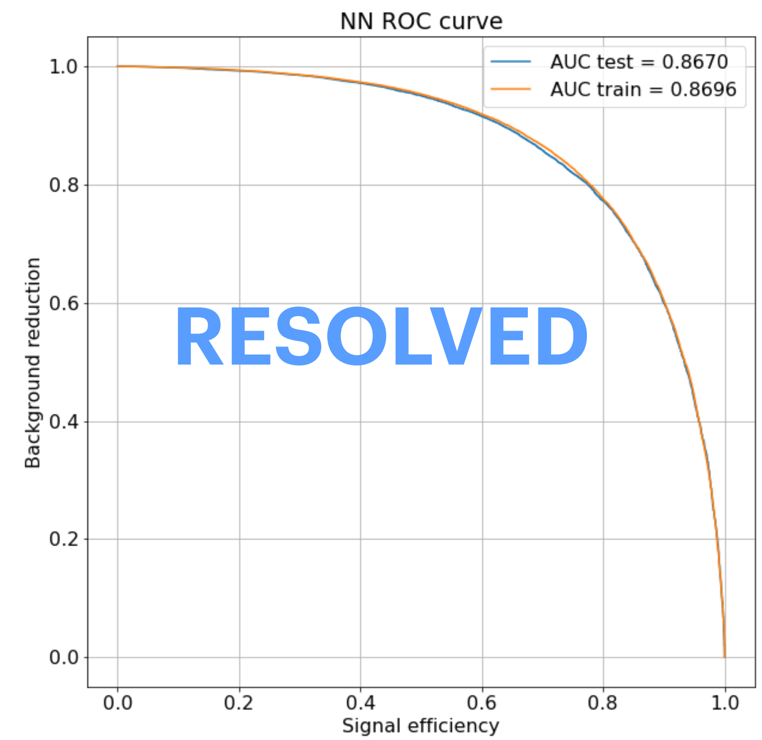
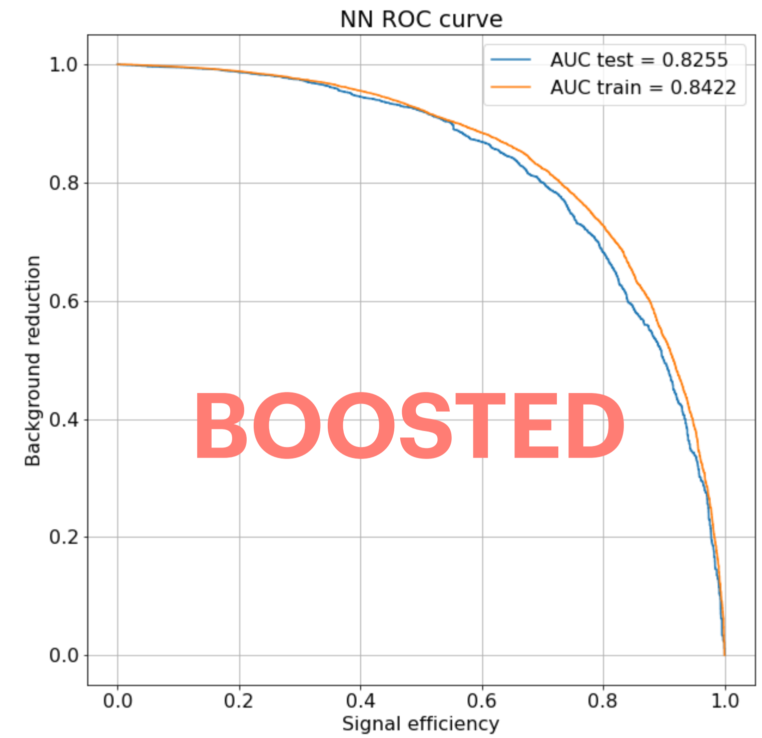
- Two distinct "signal regions":
  - One classifier for Resolved and one for Boosted, **similar performances**



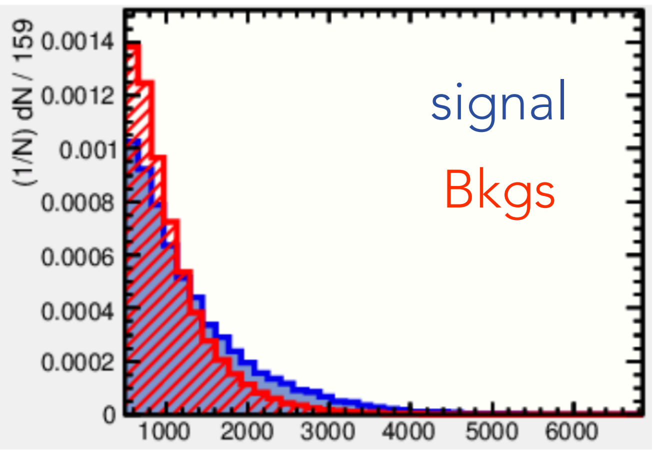


Area Under ROC curve (AUC) ~ 0.8
→ good discrimination power

DNN: PERFORMANCES AND FEATURES

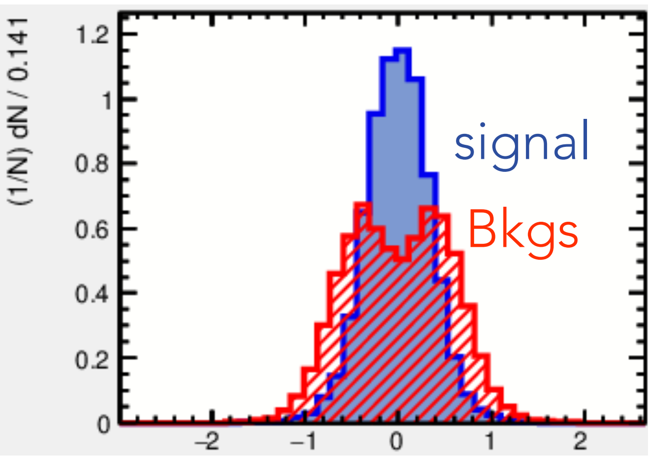
- Two distinct "signal regions":
  - One classifier for Resolved and one for Boosted, **similar performances**
- Optimised the input variables for each classifier

Invariant mass of the "VBS-jets"

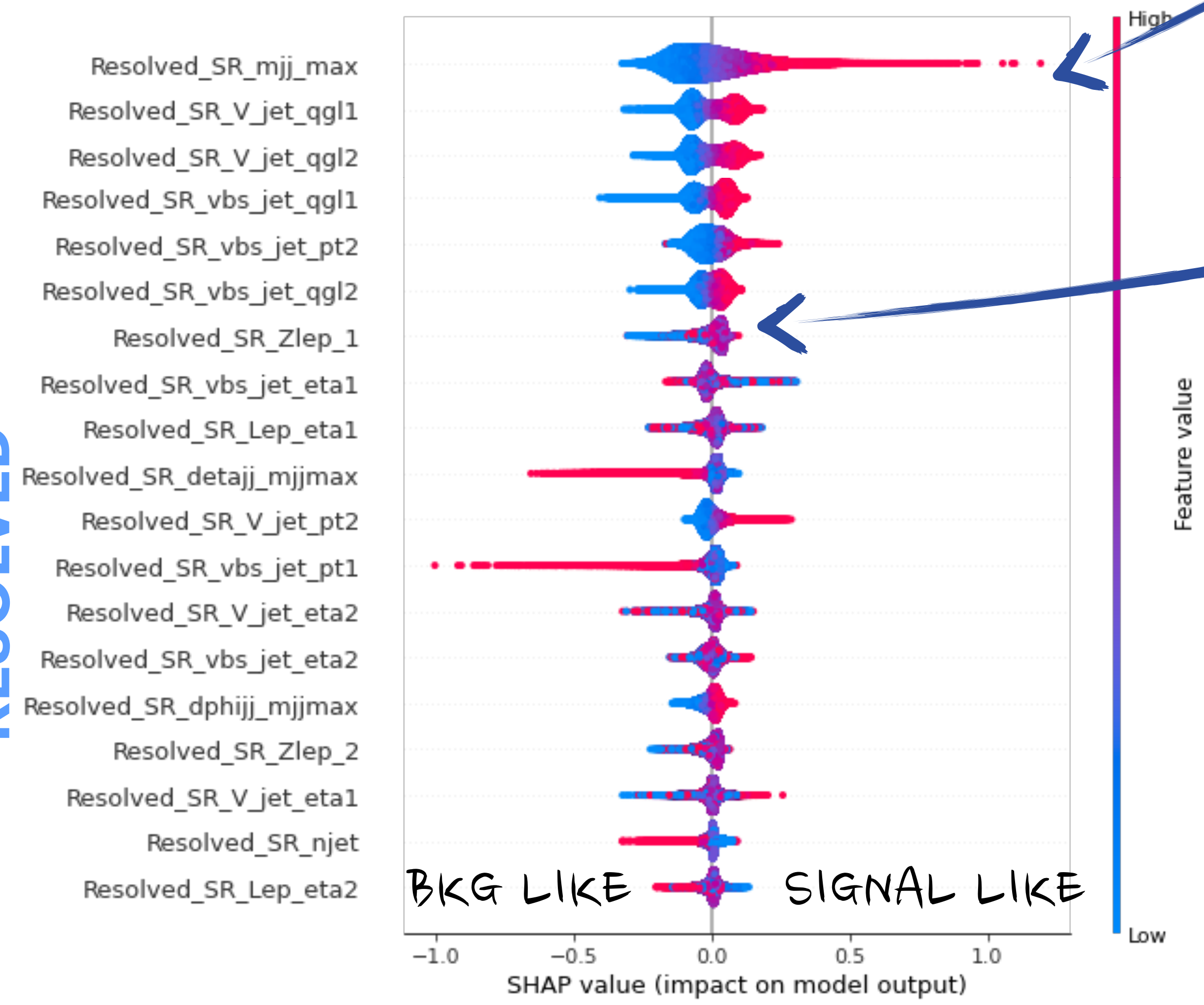


"Zeppenfeld" variables

$$Z = \frac{\eta_i - <\eta>}{\Delta\eta}$$



RESOLVED



Discrimination power of input variables calculated with SHAP method (borrowed by game theory) and sorted by importance.

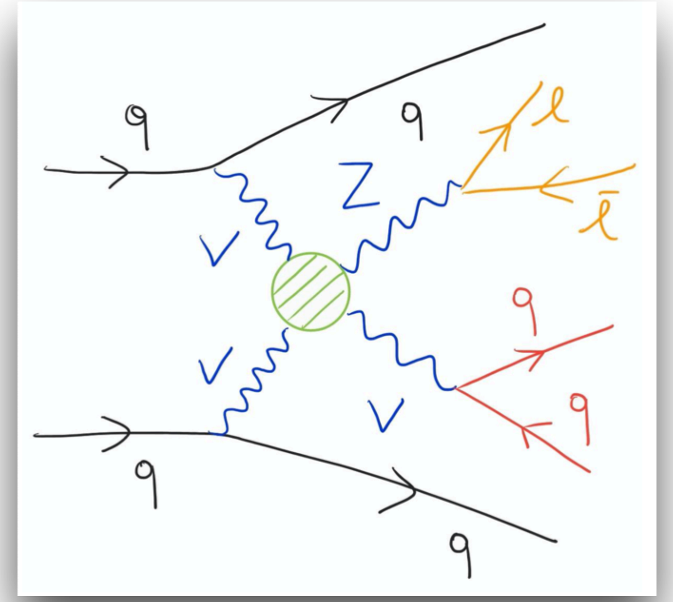
The contribute of a given input with the respect to the others : optimisation of the number of input variables + visualisation of physics behind ranking

RESULTS AND PERSPECTIVES FROM VBS SEMI-LEPTONIC (I)

Expected statistical significance for the combination of Boosted and Resolved category:

(2.30 ± 0.18) σ

(2.08σ resolved +1.19σ boosted)



Main systematic uncertainties for the measurement comes from MC modelling of QCD scale and Parton-Showering uncertainties and MC statistical error.

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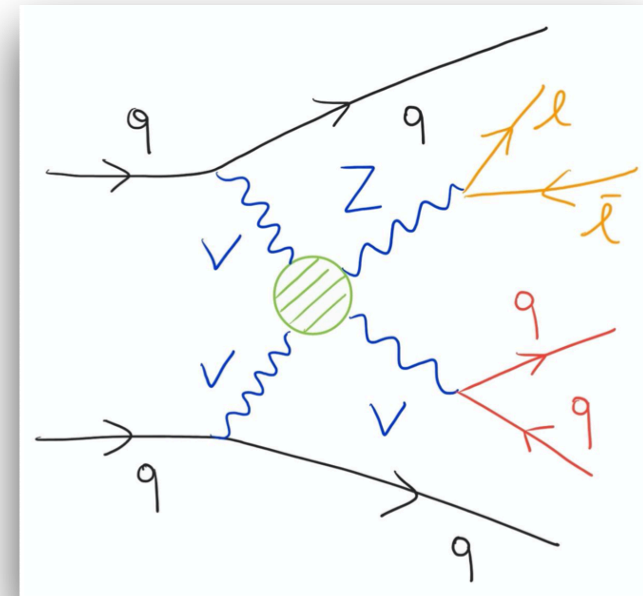

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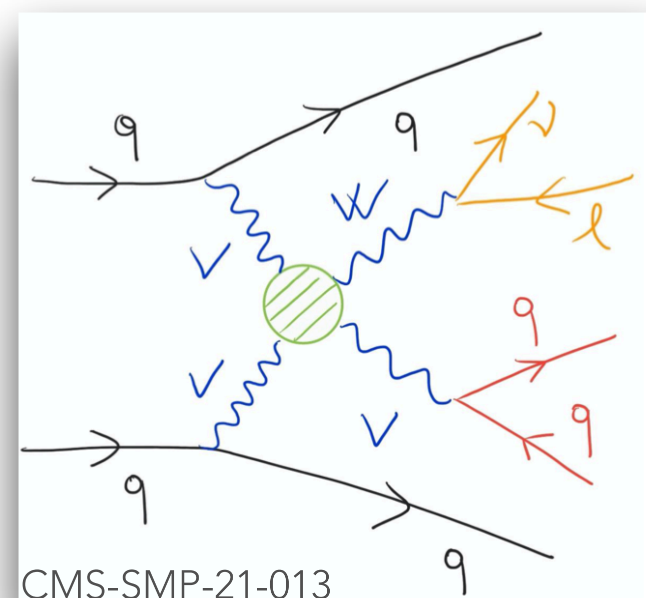
+



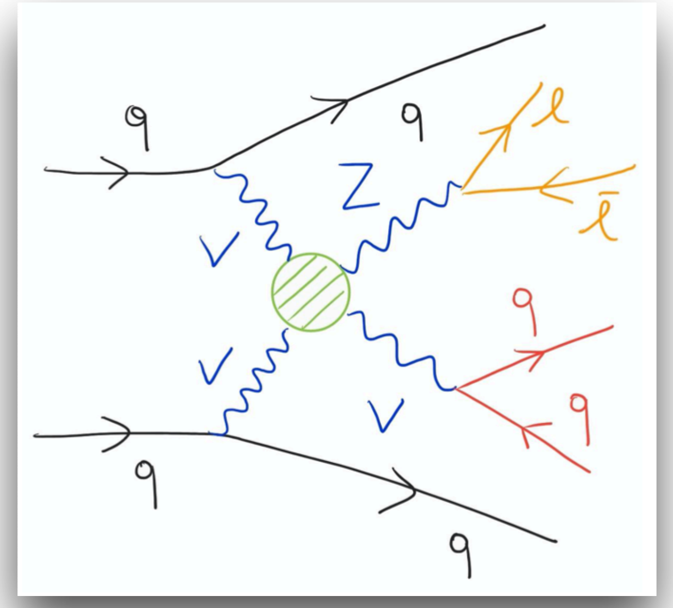
To the same EW order we have also WV semi-leptonic final state, for which we can reach:

(4.30 ± 0.28) σ

REAL CHANCE TO PERFORM THE FIRST OBSERVATION OF THE VBS SEMI-LEPTONIC FINAL STATE!

RESULTS AND PERSPECTIVES FROM VBS SEMI-LEPTONIC (II)

Expected statistical significance for the combination of Boosted and Resolved category:



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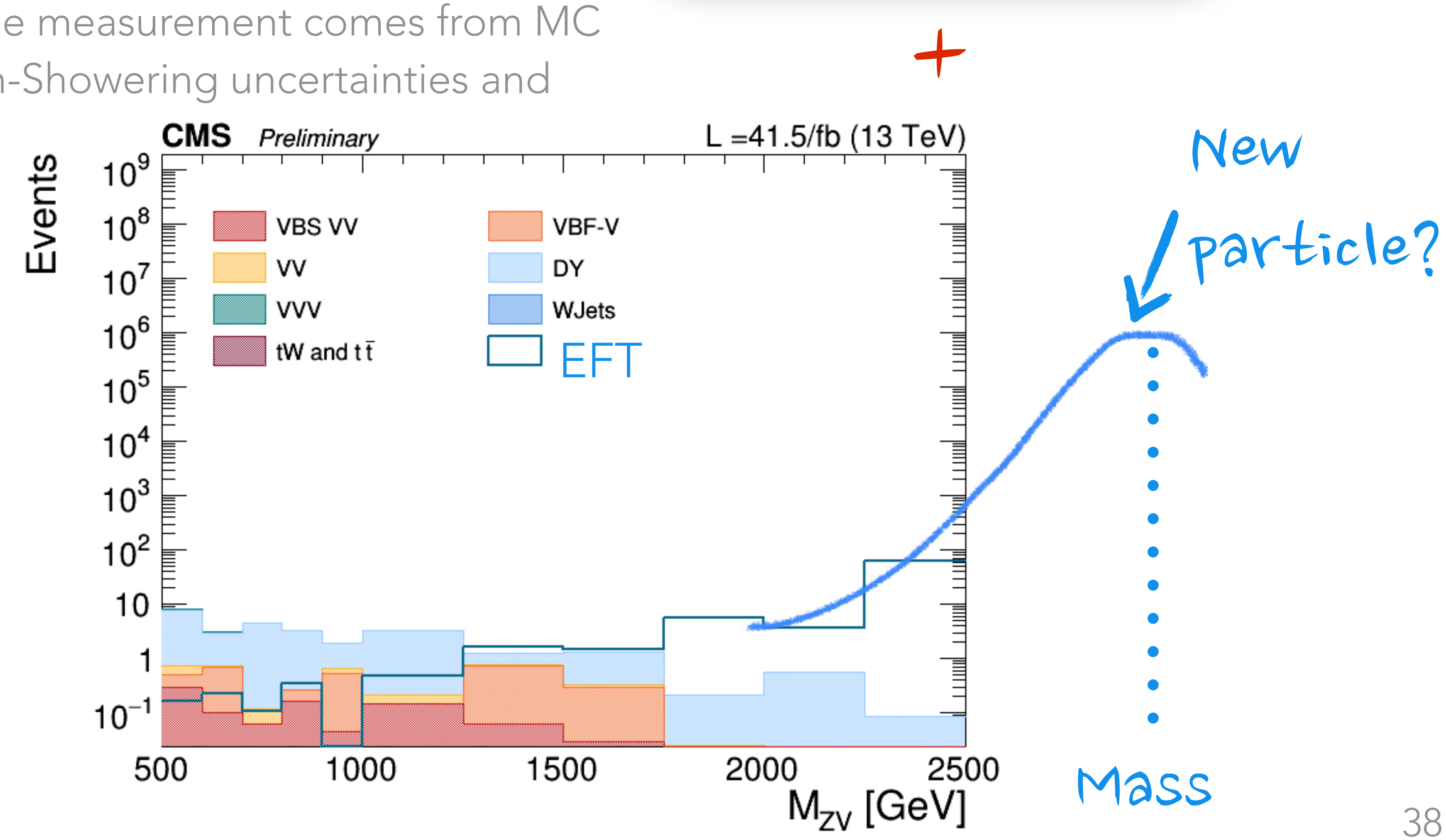
EFT interpretation of the results:

$$\mathscr{L}_{eff} = \mathscr{L}_{SM} + \sum_{n=1}^{\infty} \sum_{i} \left(\frac{c_i^{(n)}}{\Lambda^n} \right)_i^{(n+4)}$$



SUMMARY

Effective Theories and their connections to Standard Model and Beyond the Standard Model physics: **phenomenology and experimental measurements at the LHC in the final state with two leptons and jets.**

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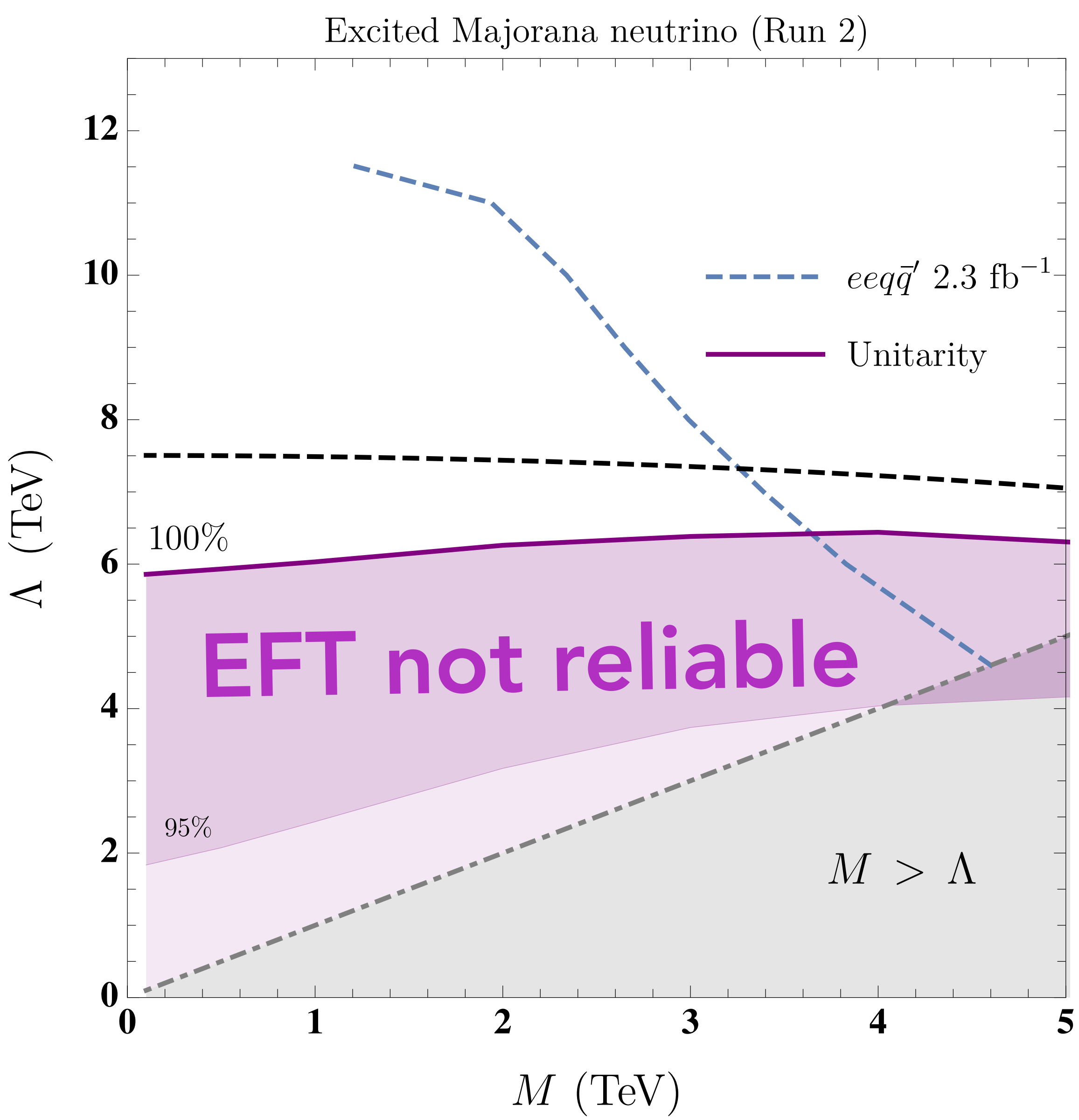
Unitarity bounds and implications in hadron collider searches for New Physics in compositeness scenarios:

- The restriction of the parameter space of the model is relevant and deserves some attention from experimental community!



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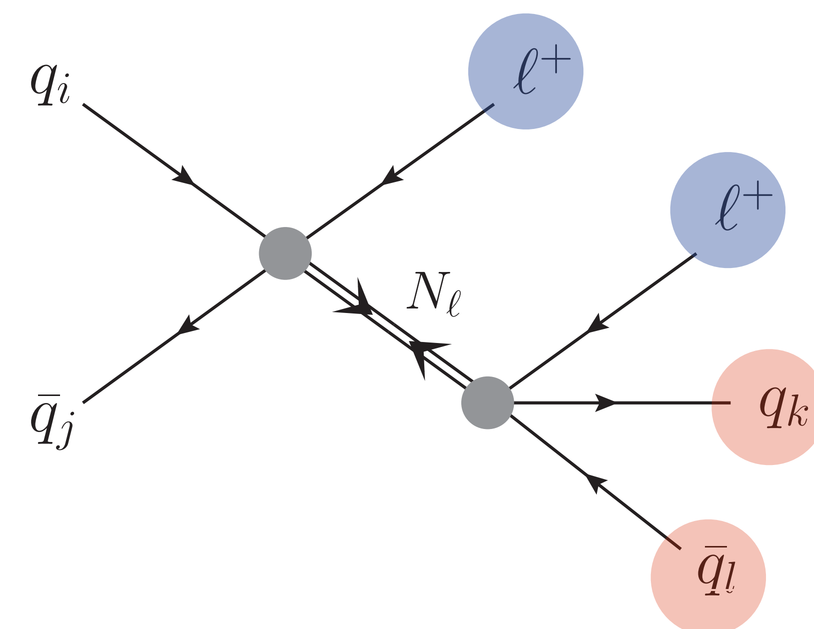

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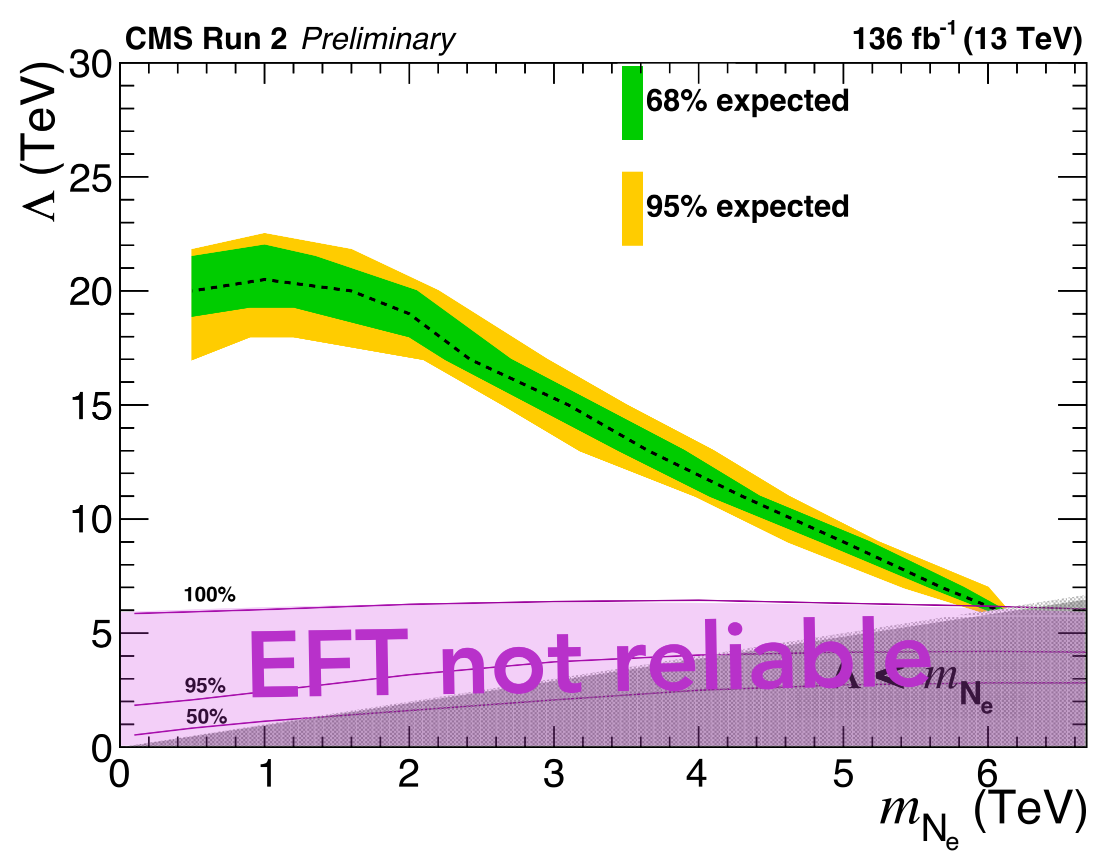
- LHC Run 2 data analysis with 13 TeV proton-proton collisions show no evidence of the presence of an **Heavy Composite Majorana Neutrino**



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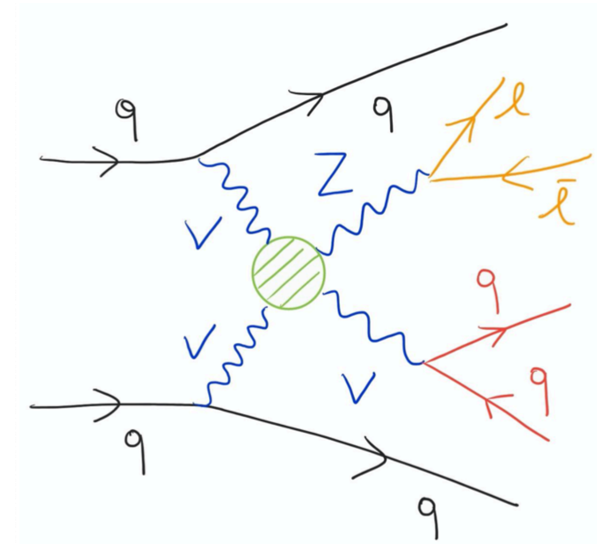

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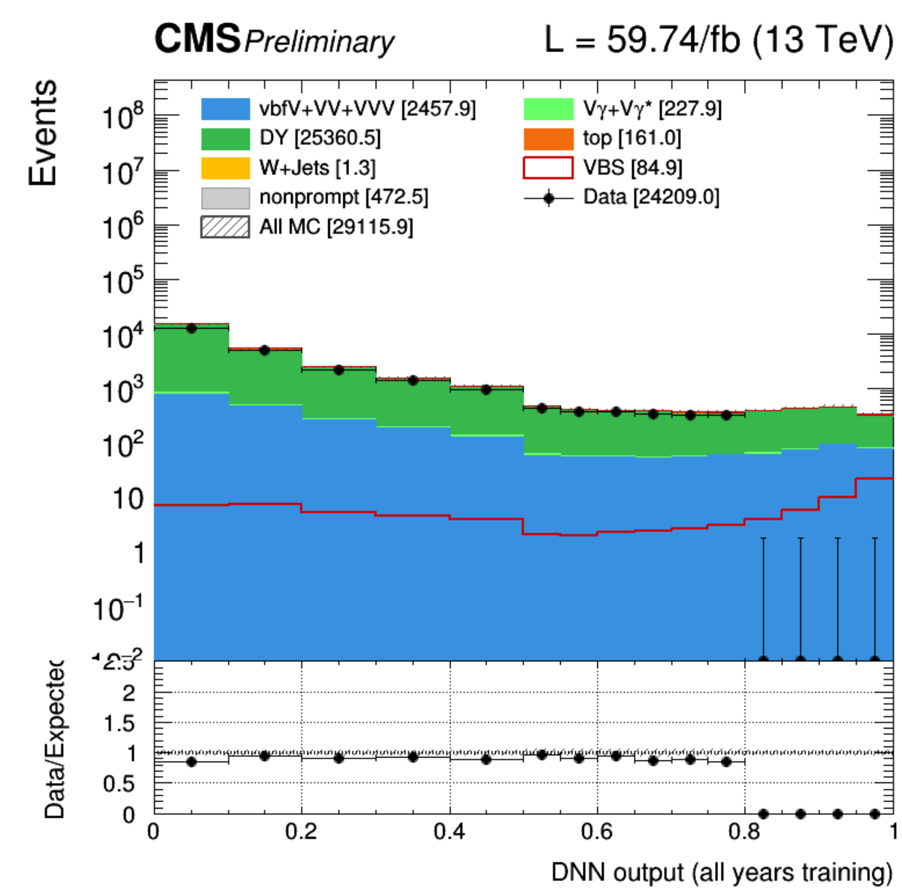


Rare processes with dominant backgrounds are not totally beyond our possibilities:

- The observation of **Vector Boson Scattering** process in the semi-leptonic final state is behind the corner

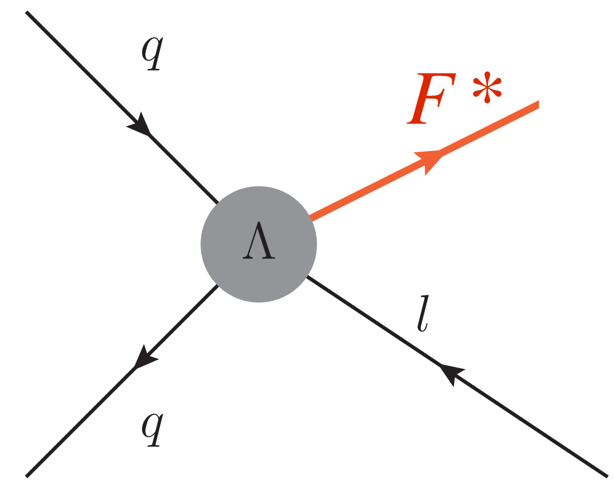
Backup.

-THANK YOU FOR LISTENING!

THE PHILOSOPHY OF THE PERTURBATIVE UNITARITY BOUND

"Perturbative unitarity bounds for effective composite models"
- Biondini, Leonardi, Panella, Presilla (ArXiv.1903.12285, PLB)

- The unitary bound is imposed on the production subprocess $q\bar{q}' \to N_\ell \ell$ considering only the dominant CI contribution
- We assume that only one dimension-6 operator describes the interactions among SM quarks/leptons and excited fermions



$$\mathcal{O}_6 = \frac{g_*^2}{\Lambda^2}\bar{q}\gamma^\mu P_L q' \bar{F}^* \gamma_\mu P_L l \quad \Rightarrow \hat{\sigma} \simeq \frac{g_*^4}{192\pi\Lambda^2}\frac{E^2}{\Lambda^2}$$

- If we insist on keeping **only** $\mathcal{O}_6$, we neglect additional operators (dim-8) that would be important for E/Λ not very small, **we can obtain a constraint** in terms of the E in the collision ($E = \sqrt{\hat{s}}$), the mass of the F^* and the large scale Λ with perturbative unitarity

Physical Interpretation: a modification to $\mathcal{O}_6$ must appear before the bound is violated

- UV completion of a new dynamics
- higher terms in the operator expansion.

PERTURBATIVE UNITARITY IN EFFECTIVE THEORIES OF COMPOSITE FERMIONS

- From **optical theorem**:

$$\sum_{f \neq i} \beta_i \beta_f |T^j_{i \to f}|^2 \leq 1\,, \quad \beta = \frac{\sqrt{\left[\hat{s} - (m_1 - m_2)^2\right]\left[\hat{s} - (m_1 + m_2)^2\right]}}{\hat{s}} \tag{a}$$

- $T_{i \to f}(\theta)$ is expressed in terms of definite helicity states $\lambda_{i,f} = \pm 1/2 \Longrightarrow$ possible combinations: $(+,+), (-,-), (+,-), (-,+)$

- Total angular momentum $j = 1$ gives non-zero amplitudes:

$$T^{j=1}_{(-,+)\to(-,+)} = -\frac{\hat{\mathbf{s}} g_*^2}{12\pi\Lambda^2}\left(1 - \frac{M^2}{\hat{\mathbf{s}}}\right)^{\frac{1}{2}}$$

$$T^{j=1}_{(-,+)\to(+,+)} = \frac{\sqrt{\hat{s}} M g_*^2}{12\sqrt{2}\pi\Lambda^2}\left(1 - \frac{M^2}{\hat{s}}\right)^{\frac{1}{2}} \tag{b}$$

- The unitarity condition becomes then:

$$\Lambda \geq \left(\frac{\hat{s}}{3}\right)^{\frac{1}{2}}\left(1 + \frac{M^2}{2\hat{s}}\right)^{1/4}\left(1 - \frac{M^2}{\hat{s}}\right)^{1/2} \tag{c}$$

PERTURBATIVE UNITARITY IN EFFECTIVE THEORIES OF COMPOSITE FERMIONS

How to implement the bound in experimental analyses?

- The unitarity bound can be used to find some $\hat{s}_{\text{uni}}$ as a function of model parameter space (Λ, M)
- **Events for which** $\hat{s} > \hat{s}_{uni}$ **cannot be trusted**:

$\sqrt{\hat{s}} < \sqrt{\hat{s}_{\text{uni}}}$: $\mathcal{O}_6$

$\sqrt{\hat{s}} > \sqrt{\hat{s}_{\text{uni}}}$: $\mathcal{O}_6$ not reliable

- A possibile strategy: **set the experimental limit on the signal restricted** to the validity of the EFT with $\mathcal{O}_6$

$$\sigma^{\text{sig}}_{\text{EFT}}\Big|_{\sqrt{\hat{s}}<\sqrt{\hat{s}_{\text{uni}}}} < \sigma^{\text{sig}}_{\text{EFT}}$$

- Systematically underestimates the cross-section and thus provides a **conservative**, **but correct**, exclusion limit.

IMPLEMENTATION OF THE UNITARITY BOUND

Practical implementation for **comparison with existing measurements:**

- $\hat{s} = x_1 x_2 s$,
  $\sqrt{s}$ = machine c.m.
- 10^5 MC events with CalcHEP@LO
- MadAnalyses retrieves $\hat{s}$ from LHEs
- For each event: $(\hat{s}, M, \Lambda)$ and apply the analytical relation of the bound
- Plot a level curve with the percentage of MC events satisfying the bound

MC GENERATION: 10^5 EVENTS

↓ **LHE**

$\hat{s}$ DISTRIBUTION

↓ $(\hat{s}, M, \Lambda)$

$\forall$ MC EVENT

$$\frac{g_*^4\, \hat{s}\,(2\hat{s} + M^2)}{288\pi^2\Lambda^4}\left(1 - \frac{M^2}{\hat{s}}\right)^2 \leq 1$$

IMPLEMENTATION OF THE BOUND (II)

Semi-analytic validation

In proton-proton collisions:

$$\sigma = \frac{1}{s}\sum_{ij}\int_{M^2}^{s} d\hat{s}\int_{\hat{s}/s}^{1} f_i\left(x,Q^2\right) f_j\left(\frac{\hat{s}}{sx},Q^2\right)\hat{\sigma}(M,\Lambda,\hat{s})$$

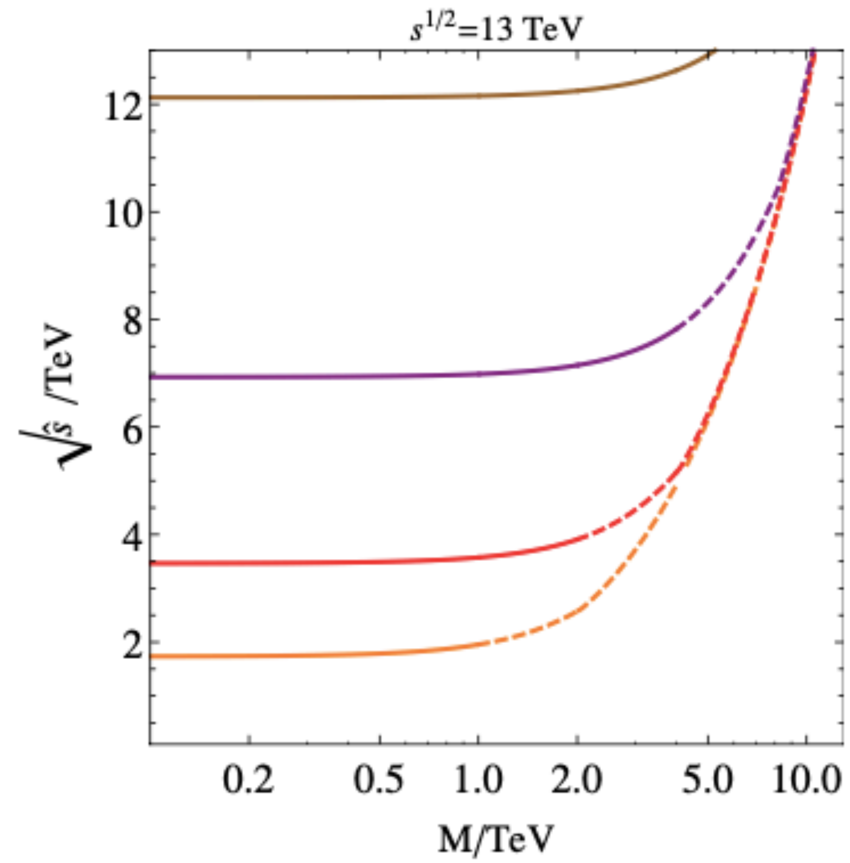
Integrating (with LHAPDF NNPFD3.0 libraries) we compute the distribution:

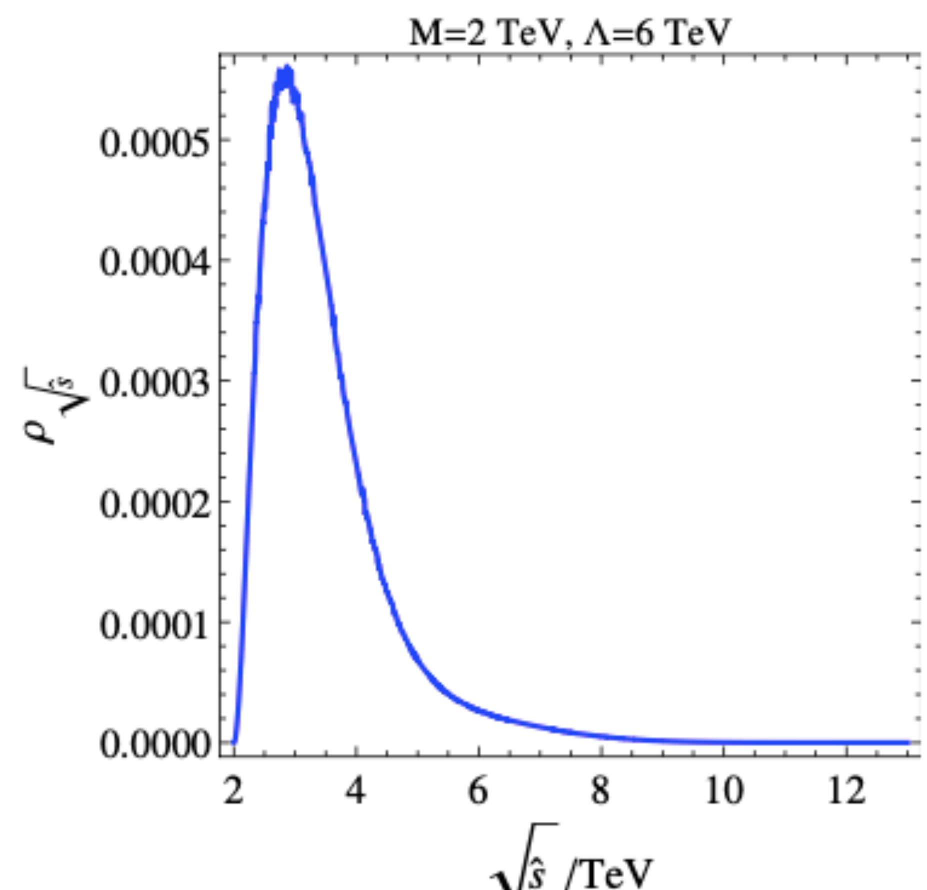
$$\rho \equiv \frac{1}{\sigma}\frac{d\sigma}{ds}, \text{ with normalisation } \int_M^s \rho d\hat{\mathbf{s}} = 1.$$

The unitarity condition can be used to restrict the extreme of integration $\hat{\mathrm{s}}_{max}(M,\Lambda,s) \le s$:

$$\textbf{Fraction of events} = \int_M^{\hat{\mathrm{s}}\,\mathrm{max}} \rho_s d\hat{\mathbf{s}}$$

<u>Validation</u>: this fraction matches the level curves obtained with the method of the previous slide.





BONUS: DIFFERENT APPROACHES TO UNITARITY

The approach we adopted is just one of the many present in the literature (cut-off):

Suppression of the pathologic behaviour of EFT amplitudes

- **"Cut-off":**
  limits the theory up to the unitarity violation scale

$$\hat{A} = A \quad \text{for } s \leq \Lambda^2$$

- **Form factors:**
  smoother suppression with a continuous function

$$\hat{A} = A f^{FF} \quad \text{with } f^{FF} = (1 + s/\Lambda^2)^{-\xi}$$

- **Kink:** mix of the previous two

$$\hat{A} = A f^{kink} \quad \text{with}$$

$$f^{\text{Kink}} = \begin{cases} 1 & \text{if } s \leq \Lambda^2 \\ (s/\Lambda^2)^{-\xi} & \text{if } s > \Lambda^2 \end{cases}$$

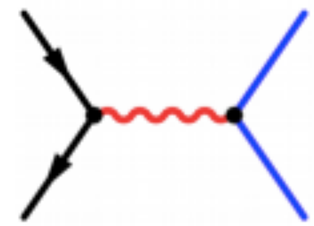
- **K-matrix unitarization:** unitarity directly imposed at partial wave level

$$\hat{A}(s) = \frac{A(s)}{1 - iA(s)}$$

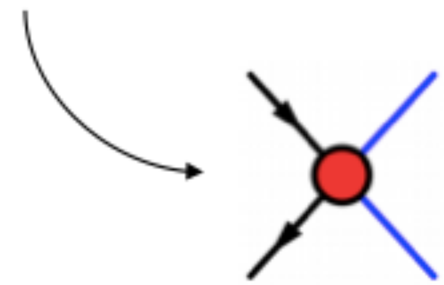
- **T-matrix unitarization, Inverse Amplitude Method, …**

BONUS: A LESSON FROM DM*

- Generic form of the operators in the EFT containing only the DM and the SM particles, with no assumptions on the underlying dynamics



$$\sim \frac{g_\chi g_q}{Q_{\rm tr}^2 - M^2} = -\frac{g_\chi g_q}{M^2}\left(1 + \frac{Q_{\rm tr}^2}{M^2} + \frac{Q_{\rm tr}^4}{M} + \dots\right)$$



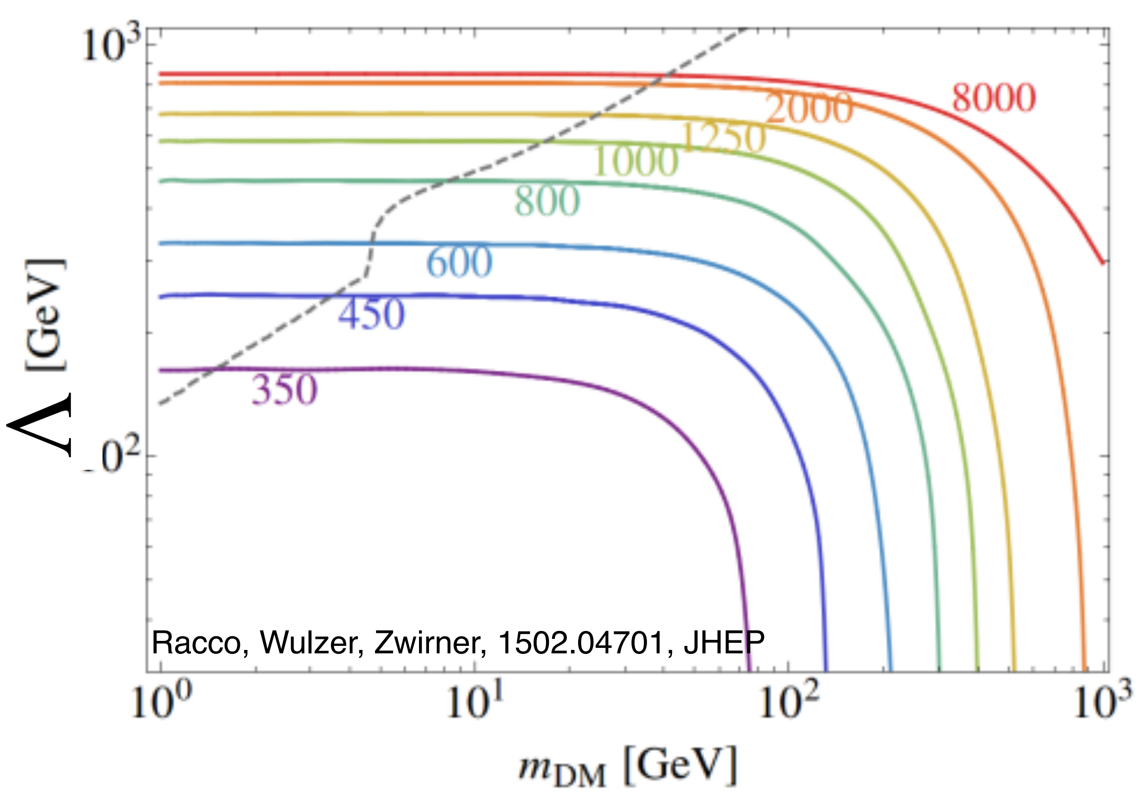
$$= \frac{1}{\Lambda^2}(\bar\chi\Gamma_a\chi)(\bar q\Gamma_b q)$$

- Considering the recast of ATLAS Cut&Count mono-jet search

- Similar condition using the centre of mass energy of the hard process:

$$E_{\rm cm}^2 \equiv \left(p_\chi + p_{\bar\chi} + p_T^{jet}\right)^2 < \Lambda_{\rm cut}^2$$

- **Λ_{cut} regarded as one of the free parameters:**
  scan in $(m_{DM}, \Lambda, \Lambda_{cut})$



Deterioration of the bound for smaller Λ_{cut}:

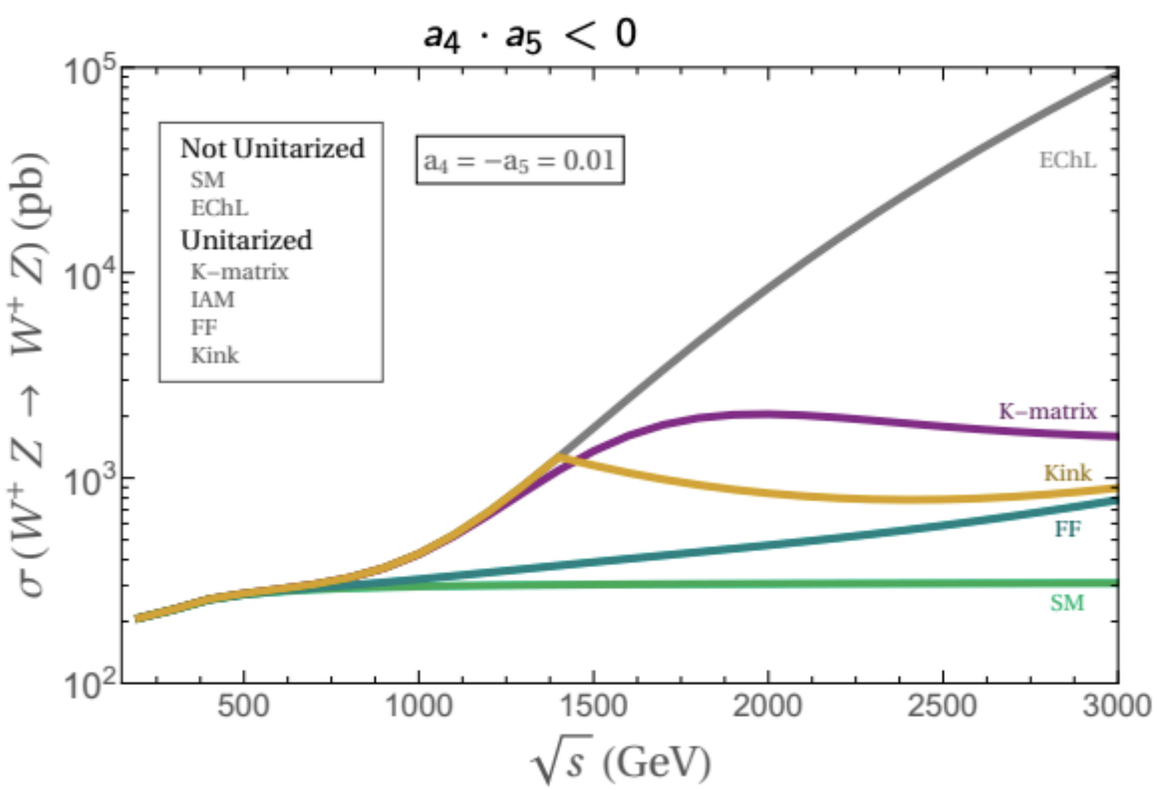
- Cross-section of the process decreases
- **Smaller kinematical range**
  =>low p_T^{jet} improves the mass reach for any value of Λ_{cut}
  (OPTIMISATION OF THE ANALYSIS!)

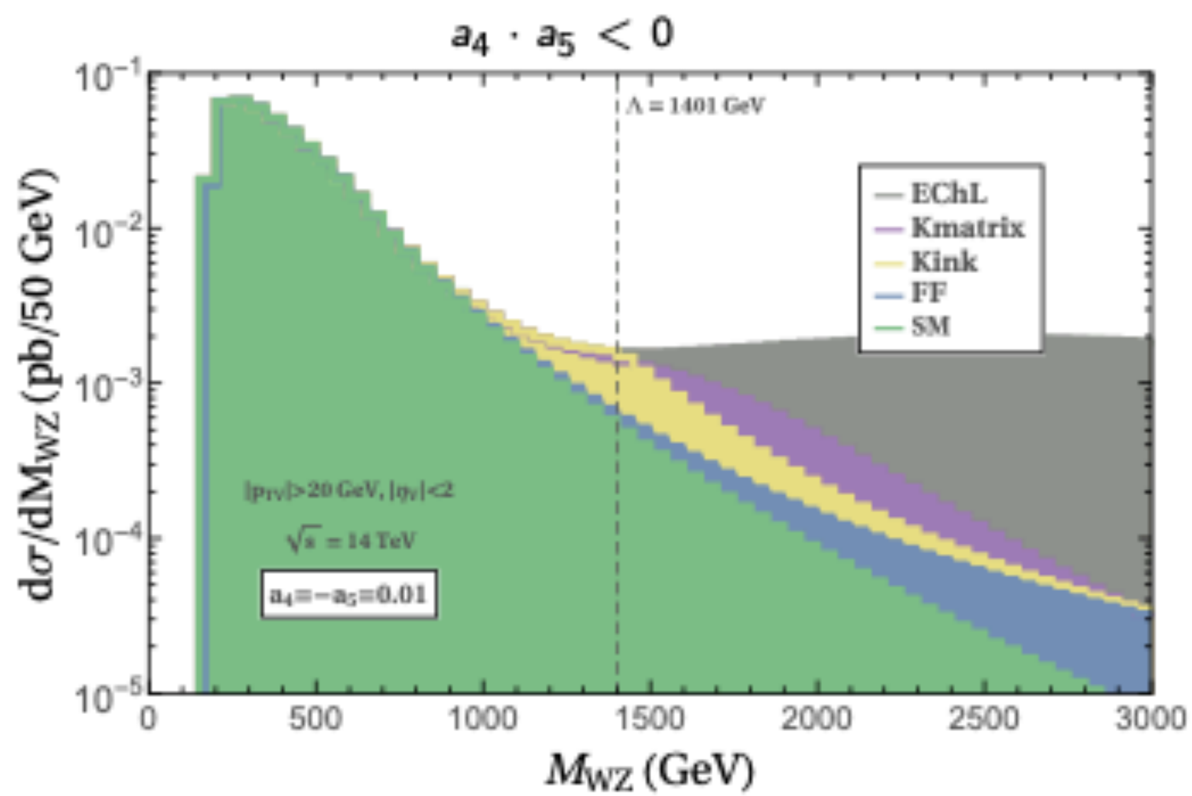
* ArXiv. 1502.04701, "EFT approach in Dark Matter searches" - E. Morgante

BONUS:

COMPARISON BTW DIFFERENT METHODS*

- Study of several unitarization methods applied to the VBS subprocess pp→WZjj using HEFT approach ("non linear EChL")
- **Different unitarization procedures lead to different predictions:**





The experimental constraints interpreted using one method or another will be different:

Bounds on non-unitary theory can over-constrain
(& viceversa)

$$\sigma_{EChL} > \sigma_{K\text{-}matrix} > \sigma_{Kink} > \sigma_{FF}$$

*ArXiv. 1907.06668, "Unitarization effects in EFT predictions of VBS @LHC" - R. Morales

UNITARITY BOUND FOR GAUGE INTERACTIONS

The bound for GI:

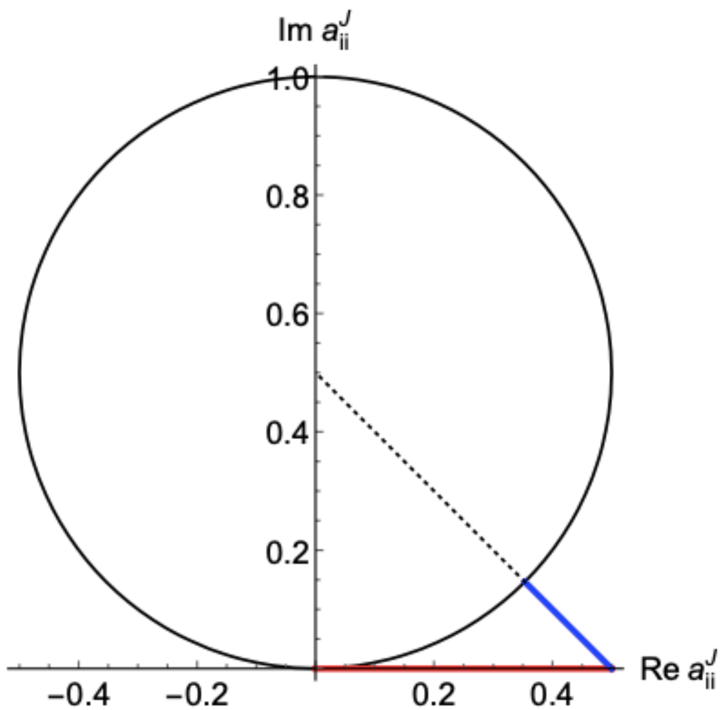
$$\mathscr{L}^{(5)}_{\rm G1} = \frac{gf}{\sqrt{2}\Lambda}\bar{N}\sigma^{\mu\nu}\left(\partial_\mu W^+_\nu\right)P_L\ell + \text{ h.c.}, \quad f \equiv 1, \quad \frac{gf}{\sqrt{2}} \approx 1$$

$$T^{j=1}_{(-,+)\to(-,+)} = -\frac{ig^2}{24\pi\Lambda}\frac{\hat{s}^{3/2}}{\hat{s}-m_W^2}\left(1-\frac{M^2}{s}\right)^{\frac{1}{2}}$$

$$T^{j=1}_{(-,+)\to(+,+)} = \frac{ig^2}{24\sqrt{2}\pi\Lambda}\frac{\hat{s}M}{\hat{s}-m_W^2}\left(1-\frac{M^2}{\hat{s}}\right)^{\frac{1}{2}}$$

$$\frac{g^4}{1152\pi^2\Lambda^2}\frac{\hat{s}^2\left(2\hat{s}+M^2\right)}{\left(\hat{s}-m_W^2\right)^2}\left(1-\frac{M^2}{\hat{s}}\right)^2 \leq 1$$

DERIVATION OF THE BOUND



40% correction needed for restoring unitarity

ariXiv. 1604.05746

Unitarity is just a fancy way of saying probabilities add up to 1!

From $S^\dagger S = 1$ follows the optical theorem.

What is the information in the unitarity condition applied to a certain process?

Considering the elastic scattering regime:

$$Im\ a^J_{ii} \geq |a^J_{ii}|^2 \implies (Re\ a^J_{ii})^2 + (Im\ a^J_{ii} - 1/2)^2 \leq 1/4$$

Loop corrections must be important around the unitarity violation

(Schwartz-"QFT and the SM")

AN OLD LESSON

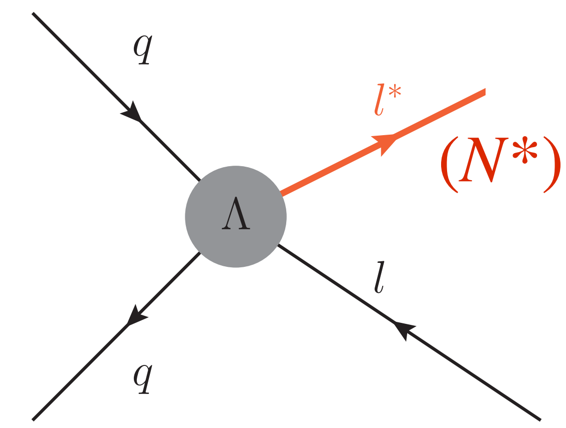
Fermi theory: Dim-6 operators violate unitarity around 350 GeV.
Restored: W boson at 80 GeV.

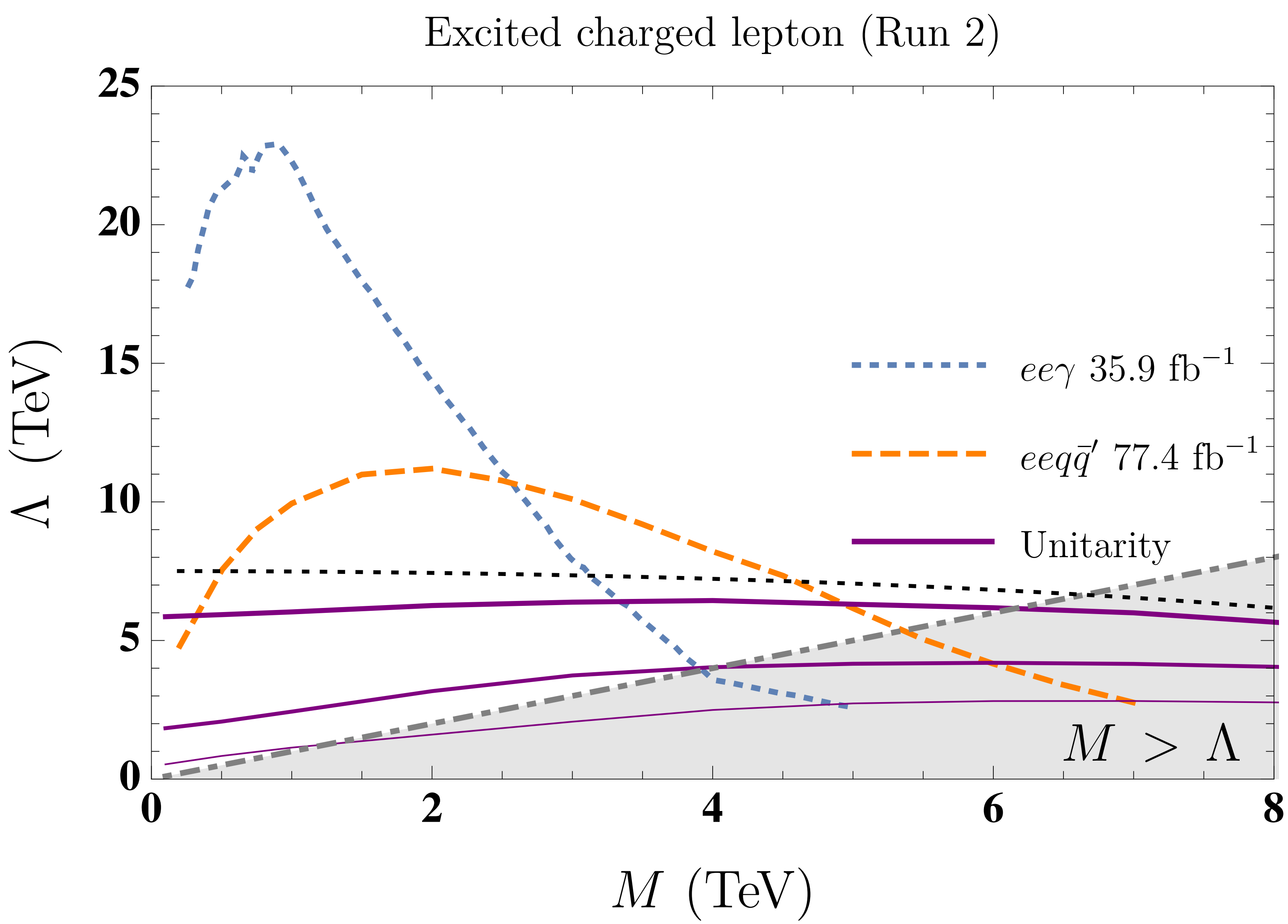
Light pion effective theory: Pion scattering violates unitarity around 1.2 GeV.
Restored: Axial and vector resonances at 800 MeV.

Electroweak Theory: WW scattering requires new physics around 1 TeV.
Restored: SM Higgs boson at 125.5 GeV.

BOUNDS FOR EXCITED CHARGED LEPTONS

Charged leptons (e*, μ*, q*) are produced in with the **same vertex with CI**
➔ the bound can be directly compared to more experimental results





M ≤ 4 TeV and M ≤ 5.5 TeV

***Unitarity bound 100%:**
M ≤ 3.4 TeV and M ≤ 5.0 TeV

***Unitarity bound 95%:**
M ≤4 TeV and M ≤6.0 TeV

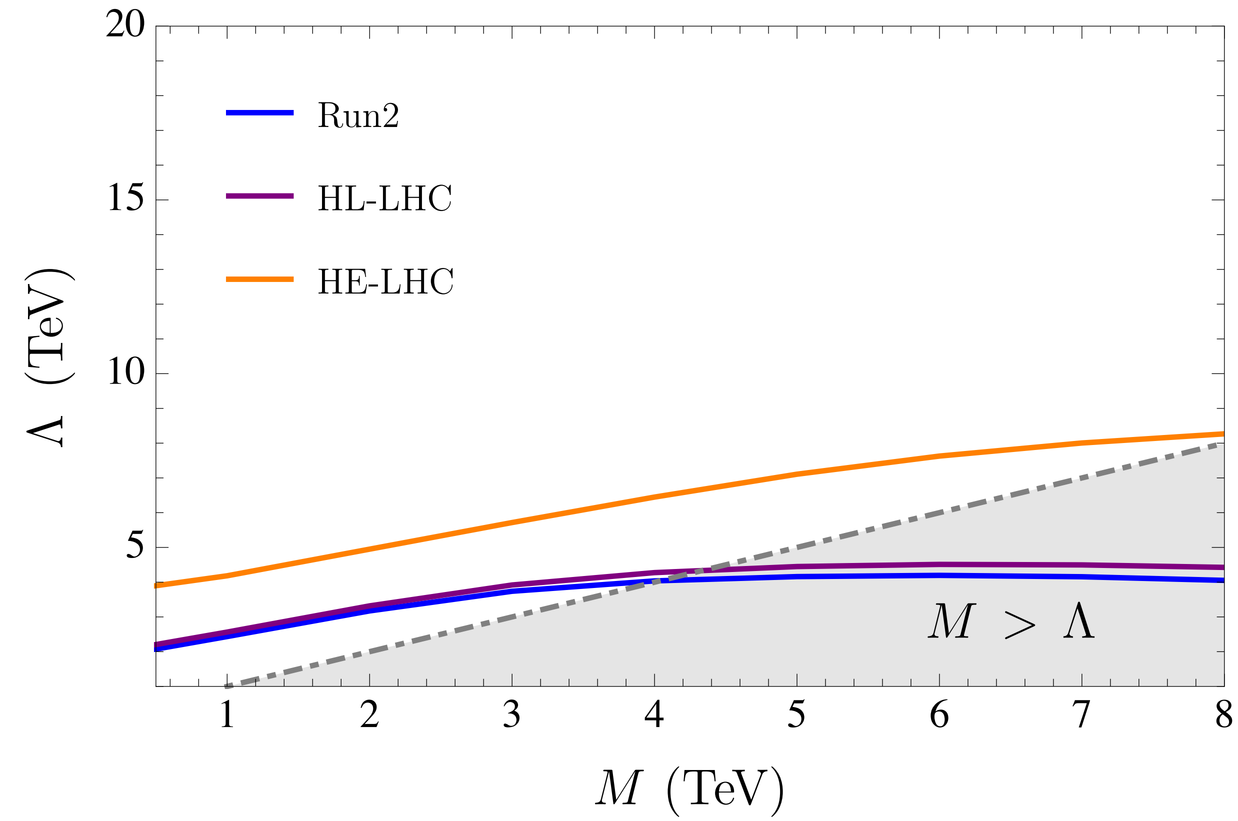
***Unitarity bound 50%:**
M ≤5 TeV and M ≤7.0 TeV

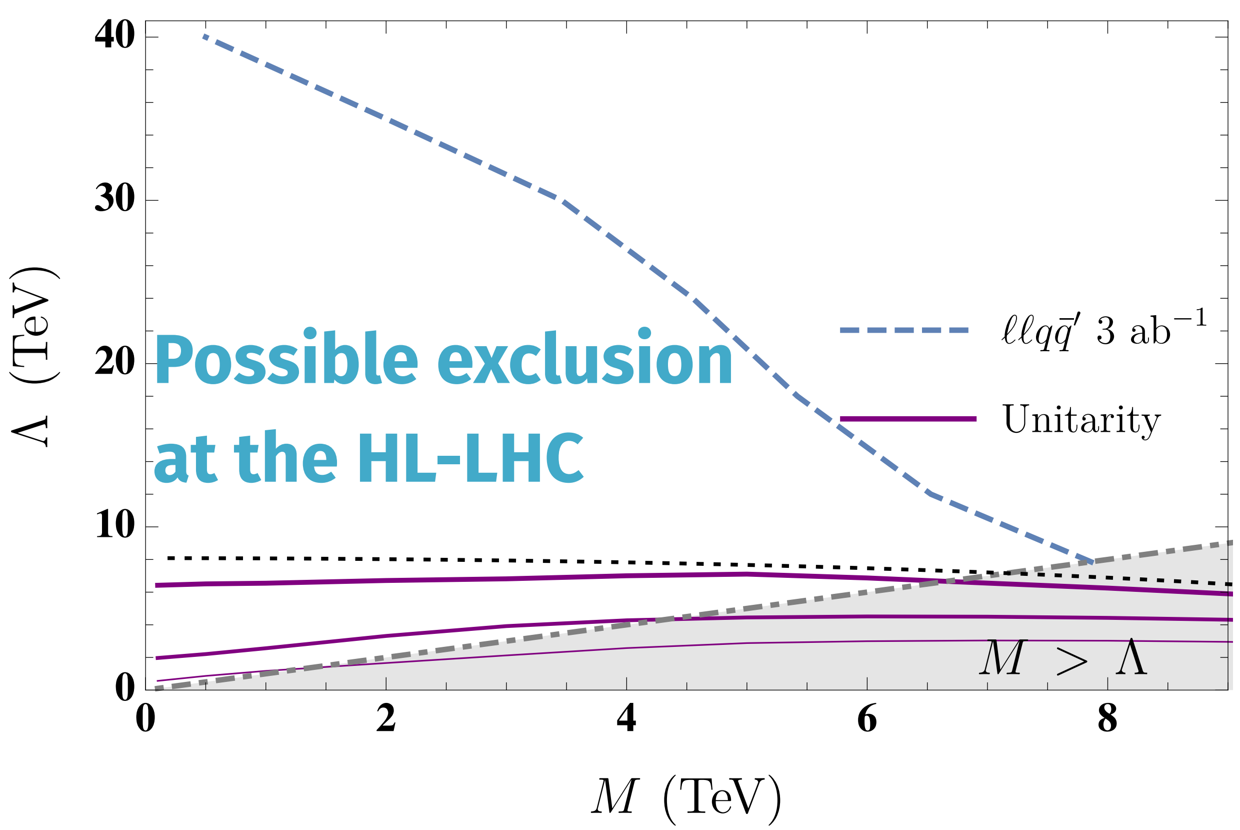
Only (EXO-18-013/EXO-18-004) CMS searches quoted in the plot.

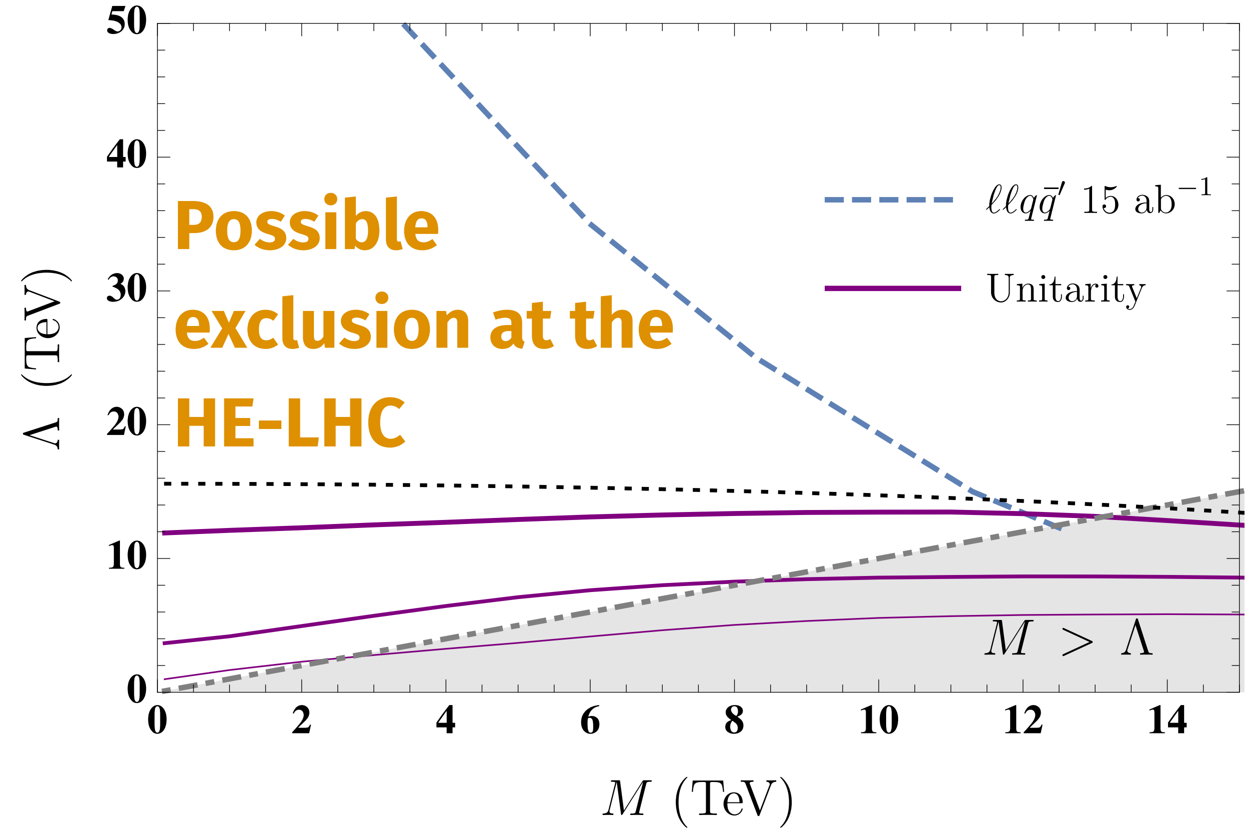
BOUNDS FOR HL/HE-LHC

The bound is applied to **HL-LHC** (13 TeV, 3 ab^{-1}) and **HE-LHC** (27 TeV, 15 ab^{-1}) projection studies ("Yellow Report", arXiv:1902.10229).

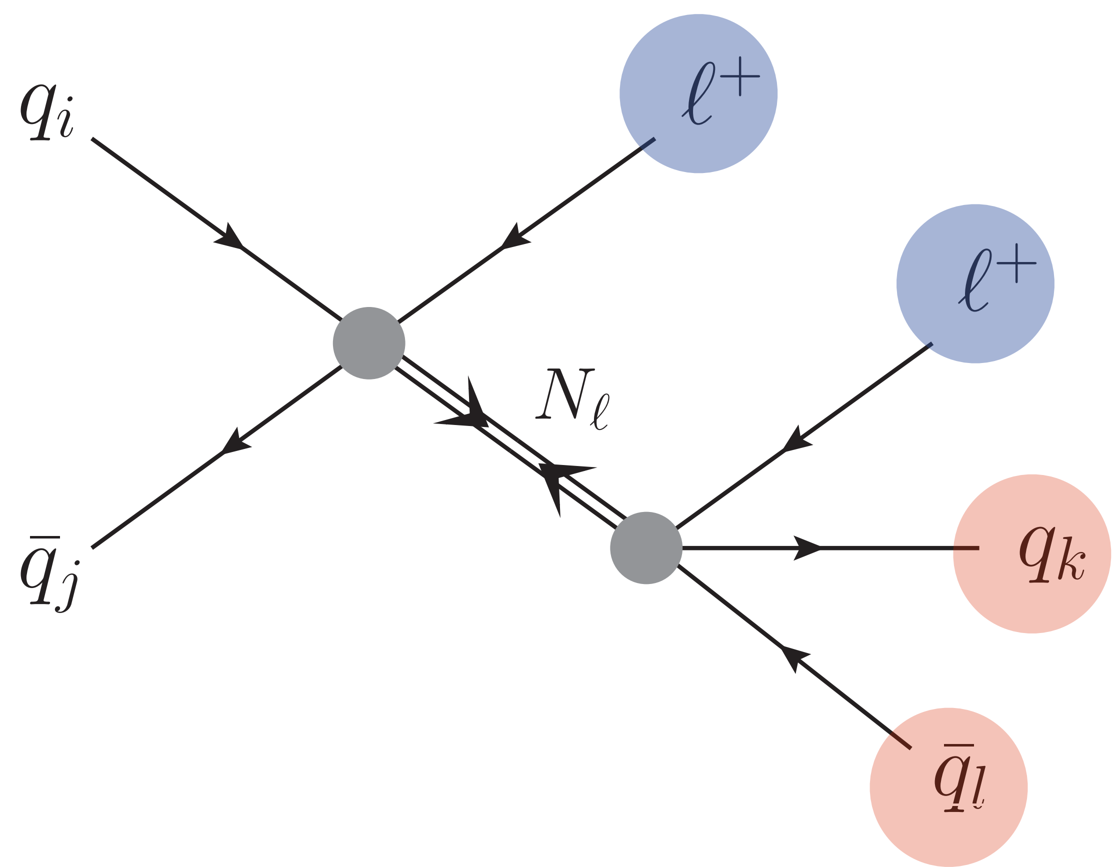
As the collision energy increases the unitarity bound becomes stronger, since the c.m. energy of the process tends to be larger.







PART2. HEAVY COMPOSITE NEUTRINO AND DI-LEPTON DI-JET SIGNATURE



- Heavy Majorana neutrino in the mass range 0.5 to 8 TeV could be detected at the LHC in Run2 data
- **Two high-p_T same-flavour and same-sign isolated leptons in the final state** (electrons or muons, two independent channels).
- **Two high-p_T quarks in the final state.**

Summary of the selections:

$eeq\bar{q}'$ selection:
- 2 electrons
- $pT(e_1) > 150$ GeV, $pT(e_2) > 100$ GeV and $|\eta| < 2.4$
- $M(e_1,e_2)>300$GeV
- AT LEAST 1 Fat Jet ,with pT >190 GeV and $|\eta|<2.4$

$\mu\mu q\bar{q}'$ selection:
- 2 muons
- $pT(\mu_1) > 150$ GeV, $pT(\mu_2) > 100$ GeV and $|\eta| < 2.4$
- $M(\mu_1,\mu_2)>300$GeV
- AT LEAST 1 Fat Jet, with pT >190 GeV and $|\eta|<2.4$

HCMN: SELECTION CUTS

$ee q\bar{q}'$ **selection**:

- N==2 high-pt electrons: pT(e1) > 150 GeV, pT(e2) > 100 GeV and |η| < 2.4
- M(e1,e2)>300GeV
- N(FatJet)≥1 ("JetPUPPIAK8") ,with pT >190 GeV and |η|<2.4

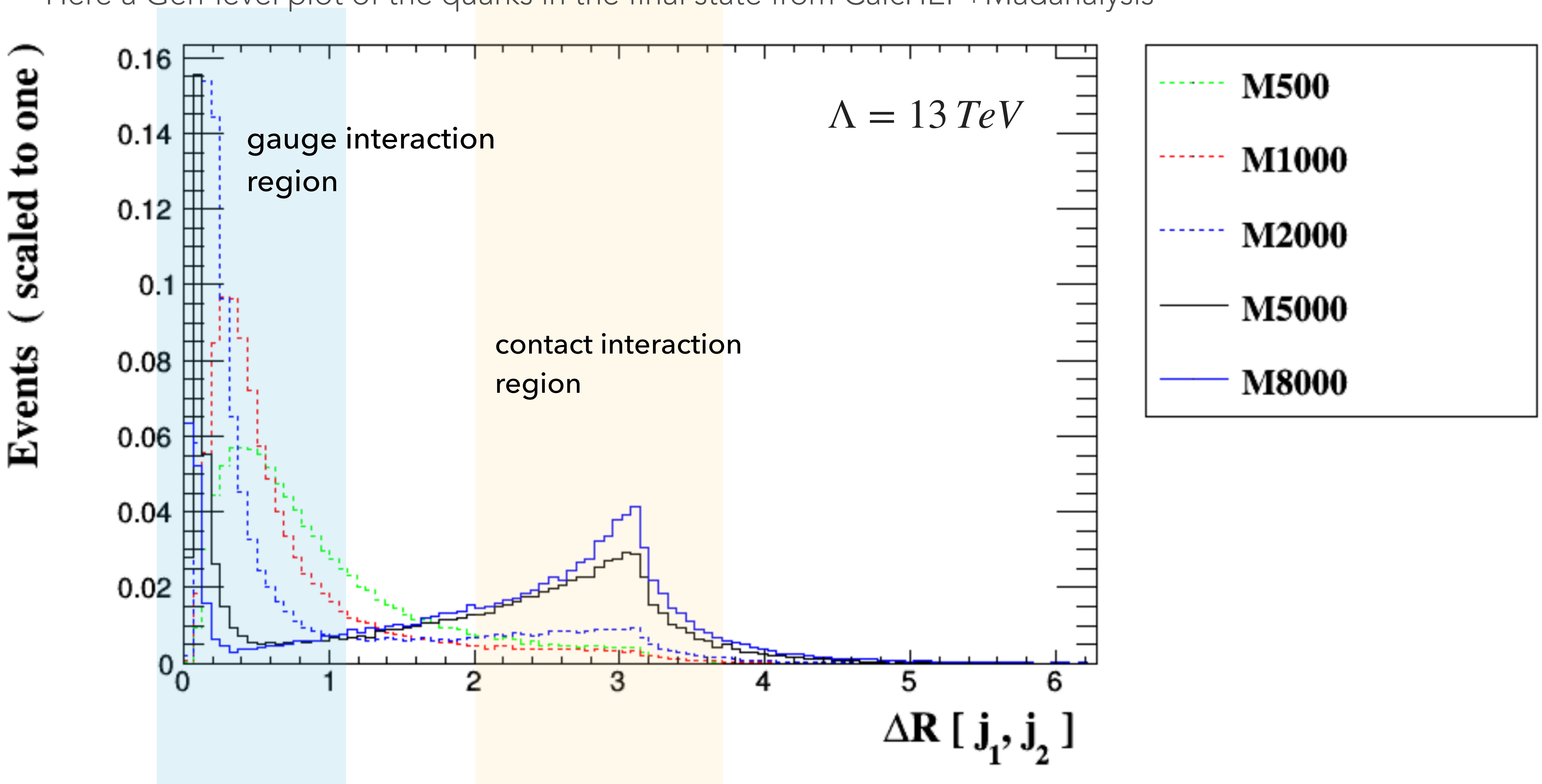
$\mu\mu q\bar{q}'$ **selection**:

- N==2 high-pt muons: pT(μ1) > 150 GeV, pT(μ2) > 100 GeV and |η| < 2.4
- M(μ1,μ2)>300GeV
- N(FatJet)≥1 ("JetPUPPIAK8") ,with pT >190 GeV and |η|<2.4

JET SELECTION (1)

- Let's recall the kinematic of the decay products: remember the GI and the CI are both always present in the decay, but with different mixtures

- Here a Gen-level plot of the quarks in the final state from CalcHEP+Madanalysis



JET SELECTION (2)

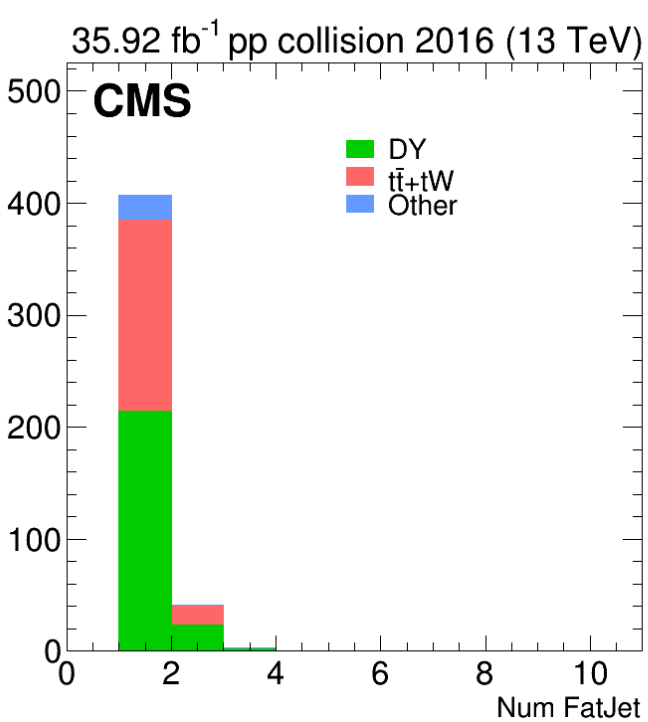
- **Since both GI and CI are mixed in the final state the best choice to grab both with high efficiency and have less background contamination is to choose a large radius jet.**

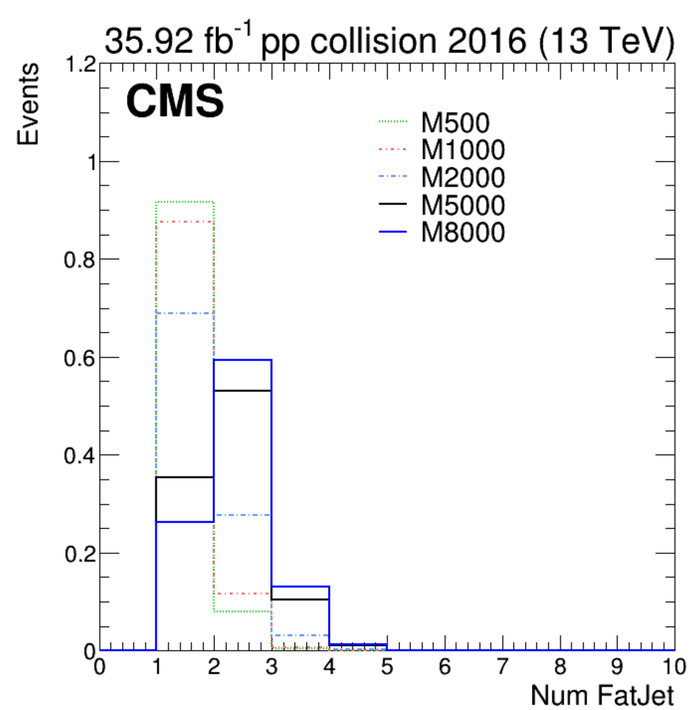
- We have also looked at how many times the fat jet actually captures the signal quarks matching with gen information

		q1&q2	q1 || q2
M500	Jet 1	75%	17%
M500	Jet ≥2	20%	10%
M5000	Jet 1	21%	77%
M5000	Jet ≥2	0%	75%

Table with fraction of events where both final state quarks or one of the two is matched in the leading fat jet or subleading. Behaviour for different masses with different contribution of GI and CI

This motivates also the choice of N(jets)≥1

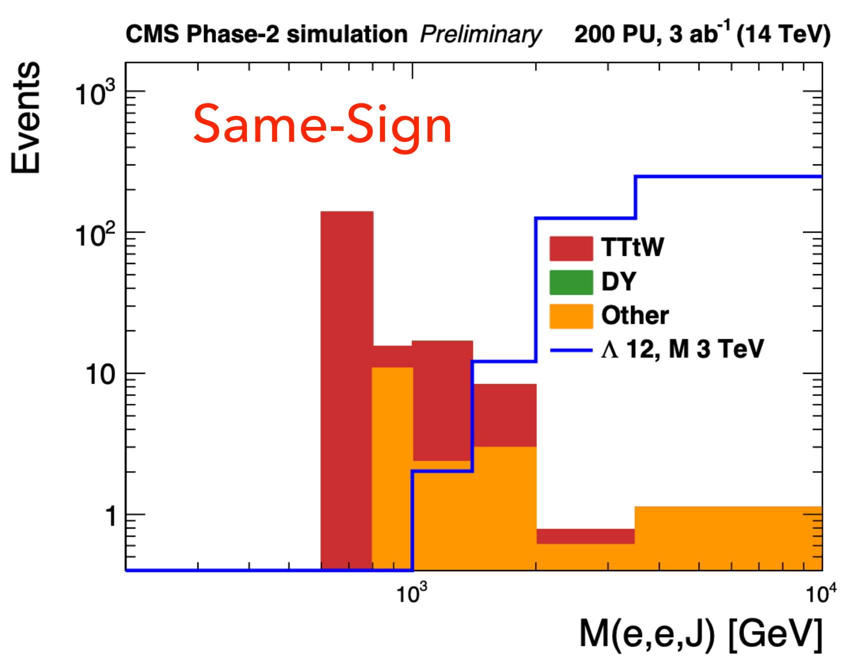


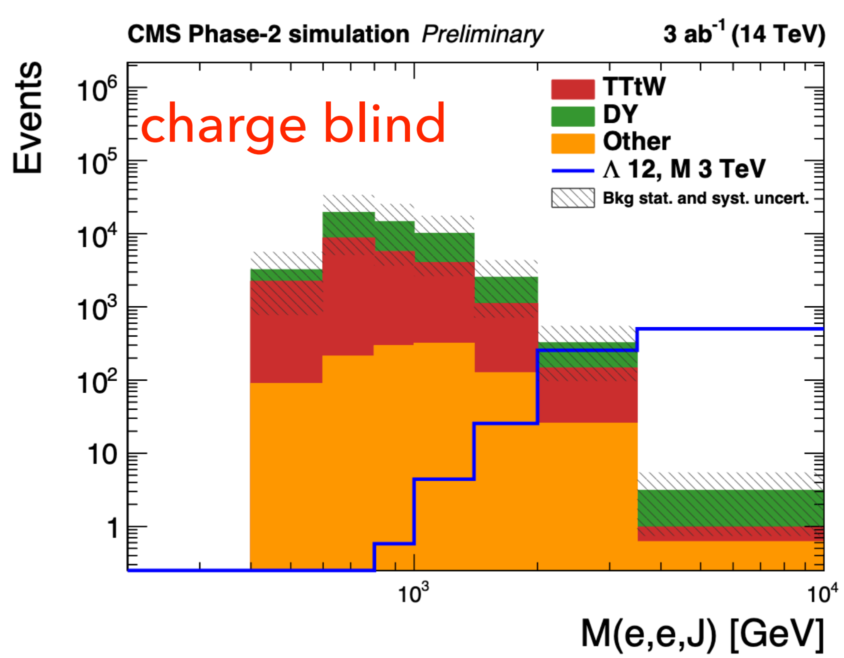


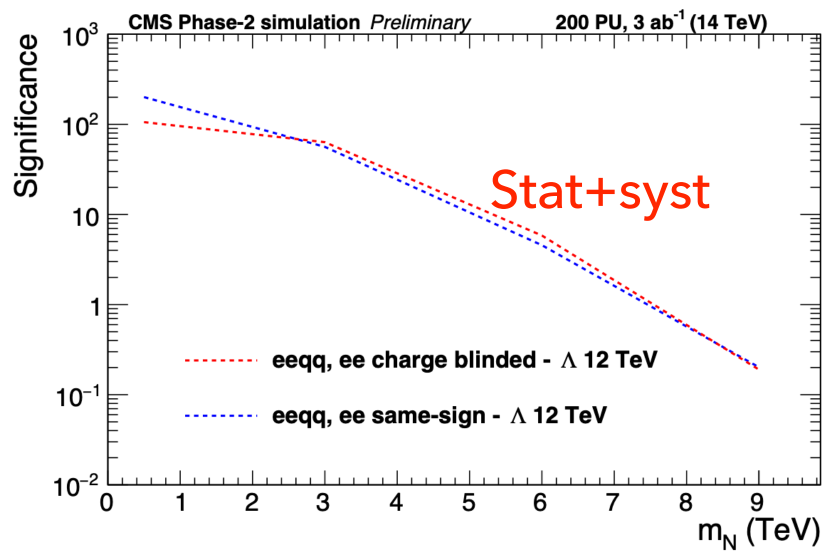
#AK8 jets in the event.
Bkg stacked on the left, signal normalised
to 1 on the right.

LEPTONS CHARGE SELECTION

- Since we are looking for Majorana neutrinos the first comments concerns the charge of the leptons.
  - It is clear that in case of an excess that would be the first thing we check to characterize the signature
- However, there are consequences of using the lepton charge information that affect this analysis in opposite ways: **charge-blind analysis is the best choice as extracted from considering all uncertainties**
- Requiring the charge ID of high-pt lepton (>100 GeV):
  - reduces signal efficiency (is also not very pure)
  - adds a new background contribution from charge mid-ID
  - adds additional SF and systematics
  - also reduces the statistics of the background control regions
  - Reduces the SM background contribution (which sits mostly at low masses)
- Study was performed in PAS FTR-18-006 with a kinematical selection close to 2016 (not reoptimized): there is very minor advantage in the SS selection even with the larger statistics of the Phase2. Note that the systematics from the charge-ID are not included

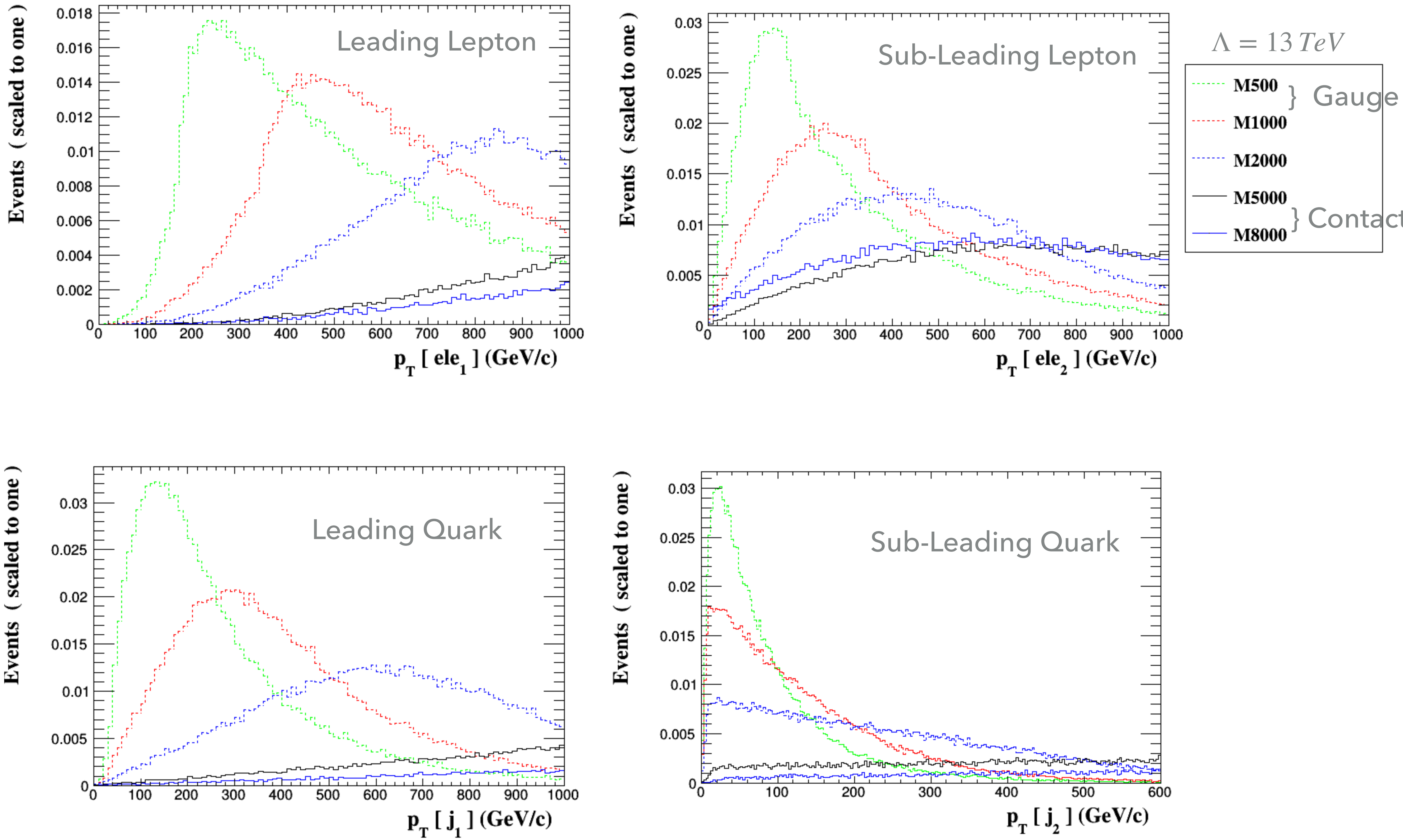






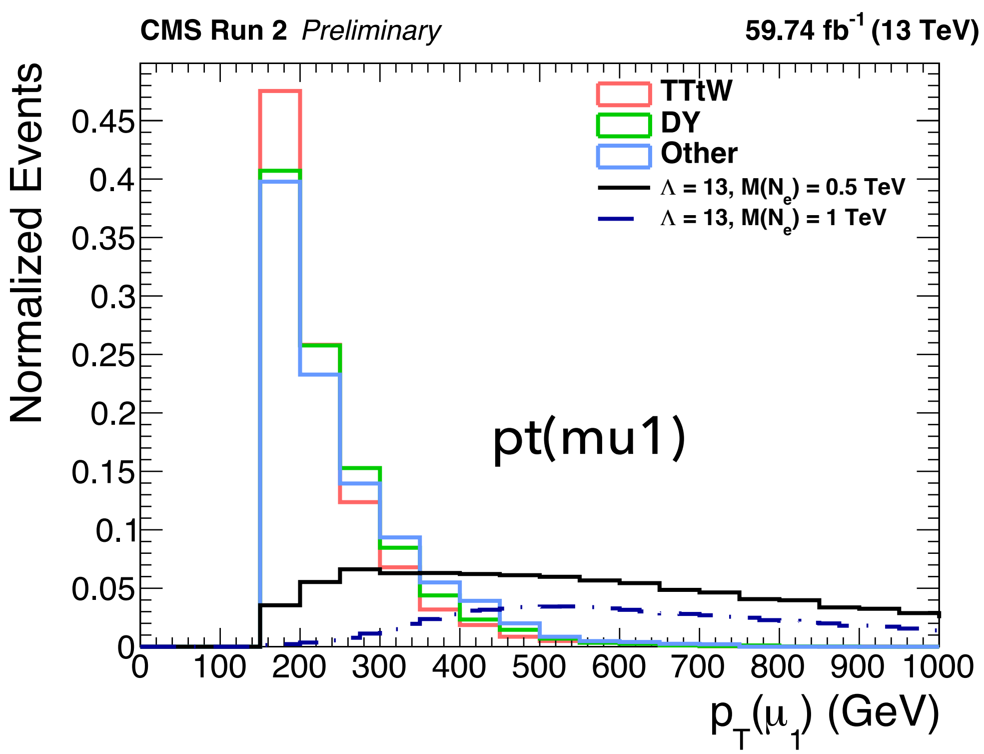
FTR-18-006

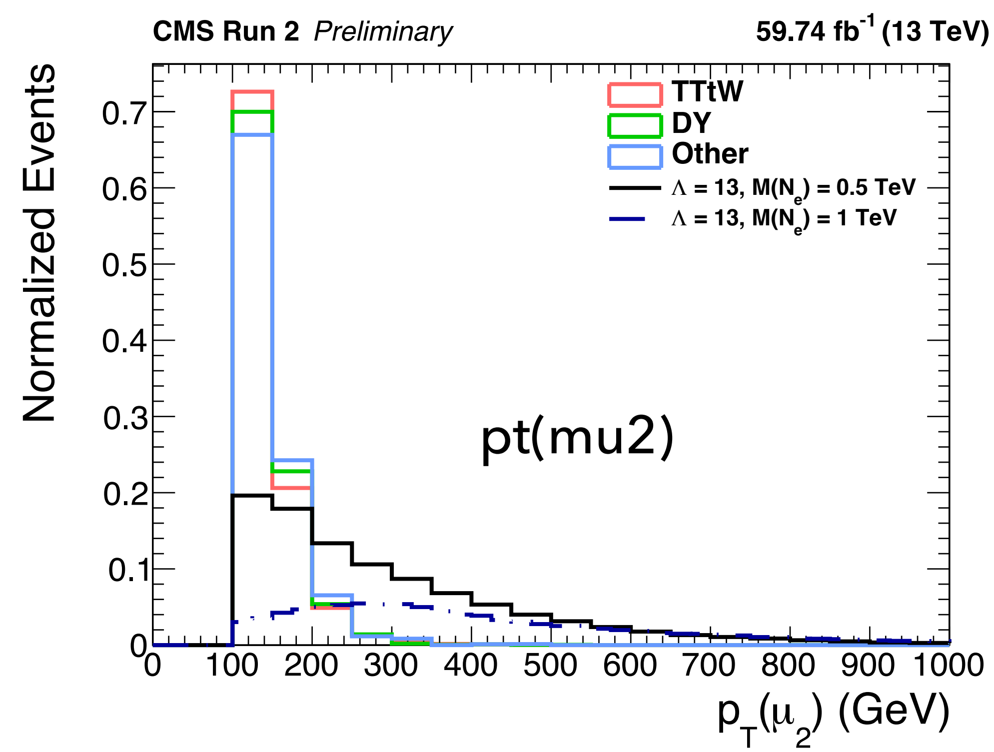
SIGNAL KINEMATIC (GEN LEVEL) - PT DISTRIBUTIONS

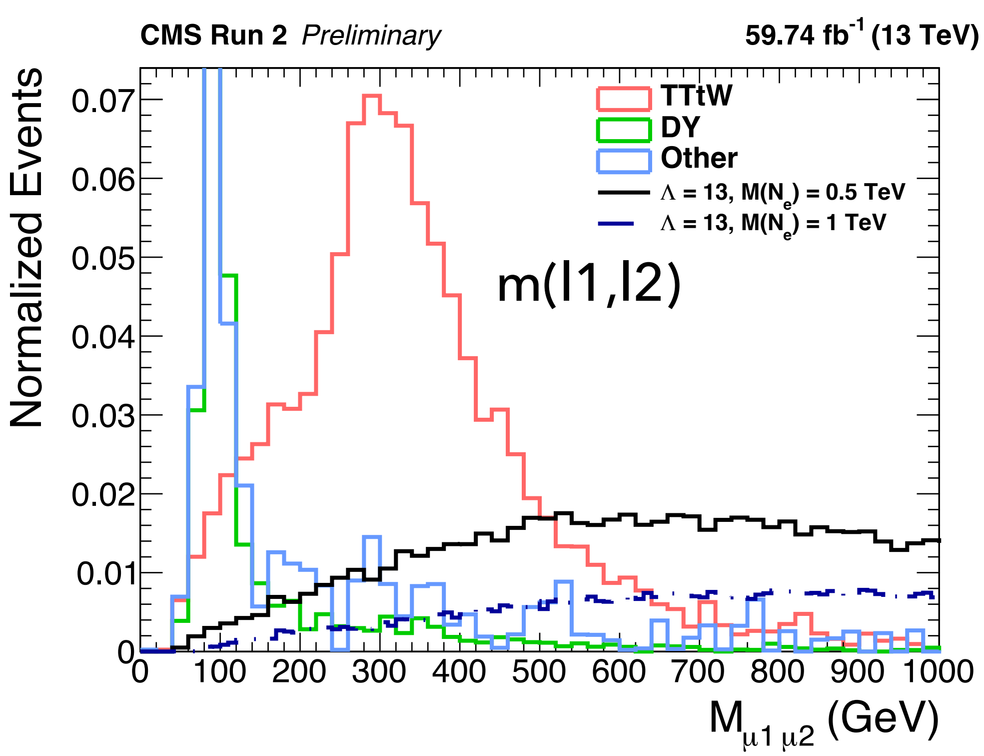


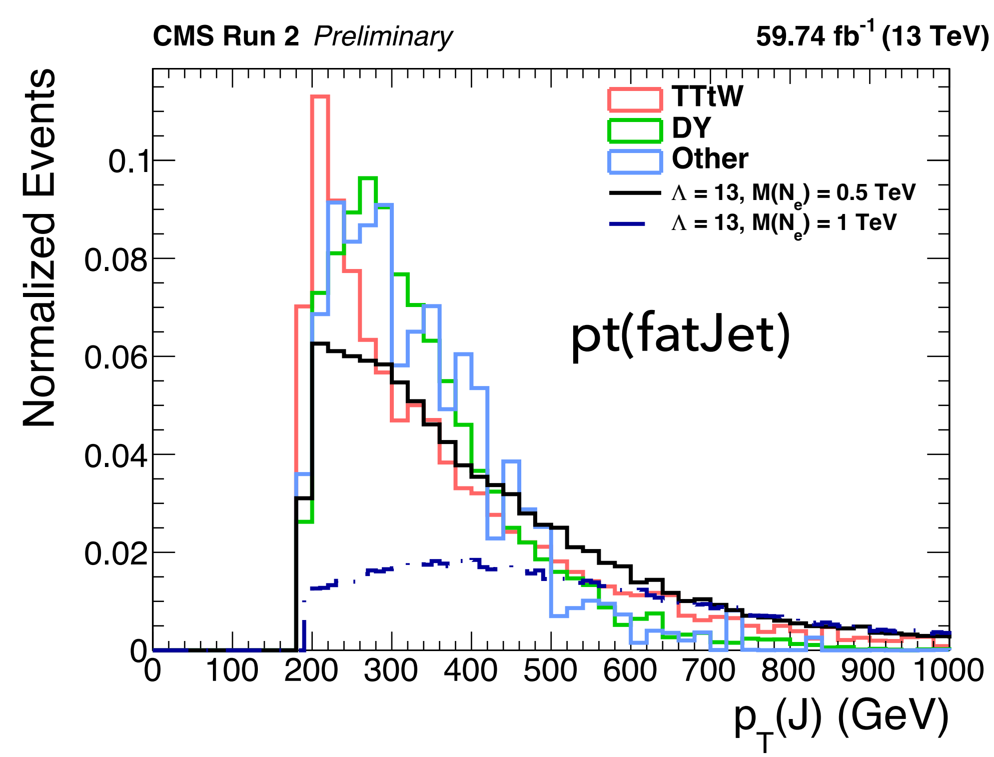
KINEMATICAL DISTRIBUTIONS (2)

- Choice of cut estimated with a figure of merit for S/B significance
- Reduction of background contribution (wrt 2015) keeping signal efficiency

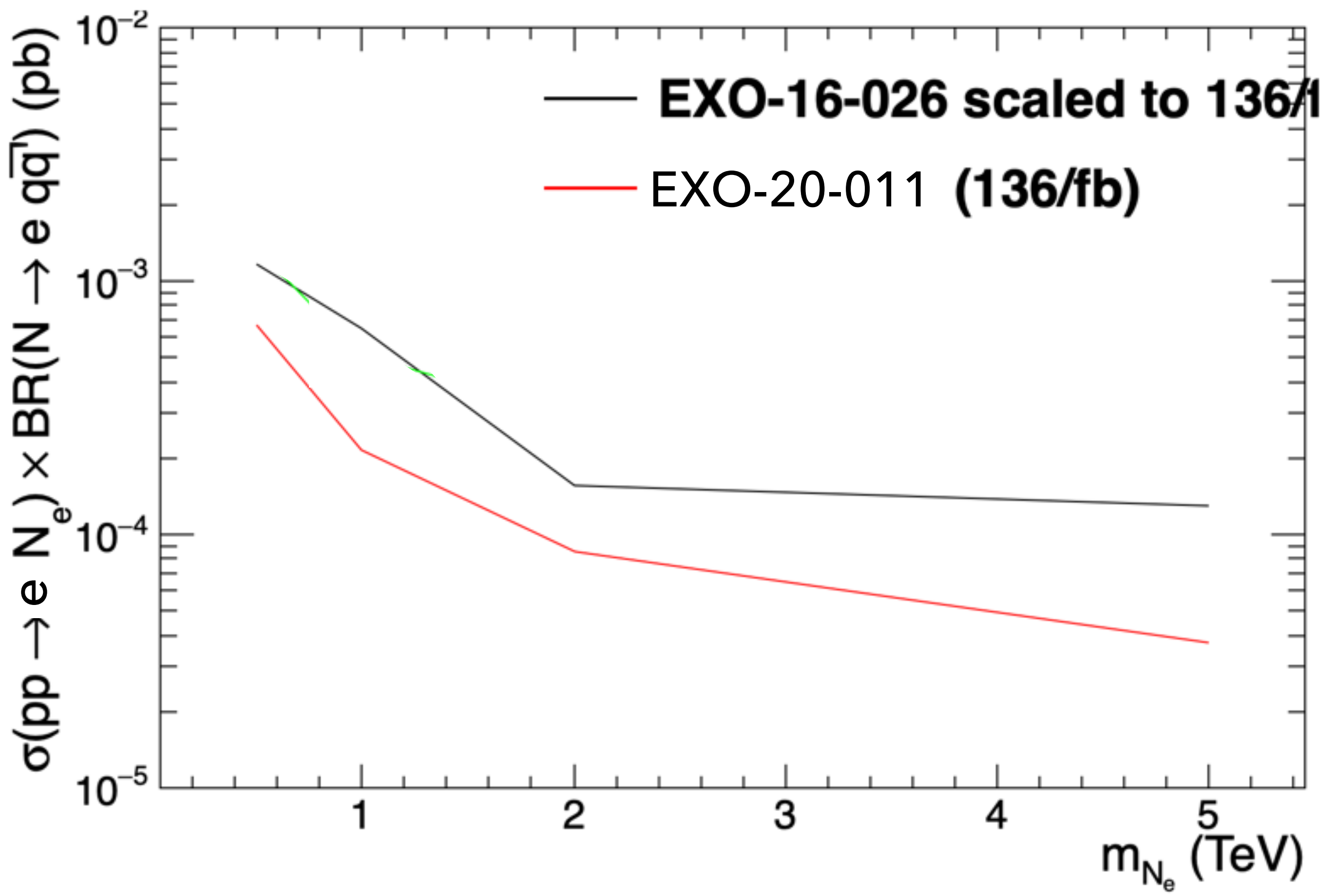




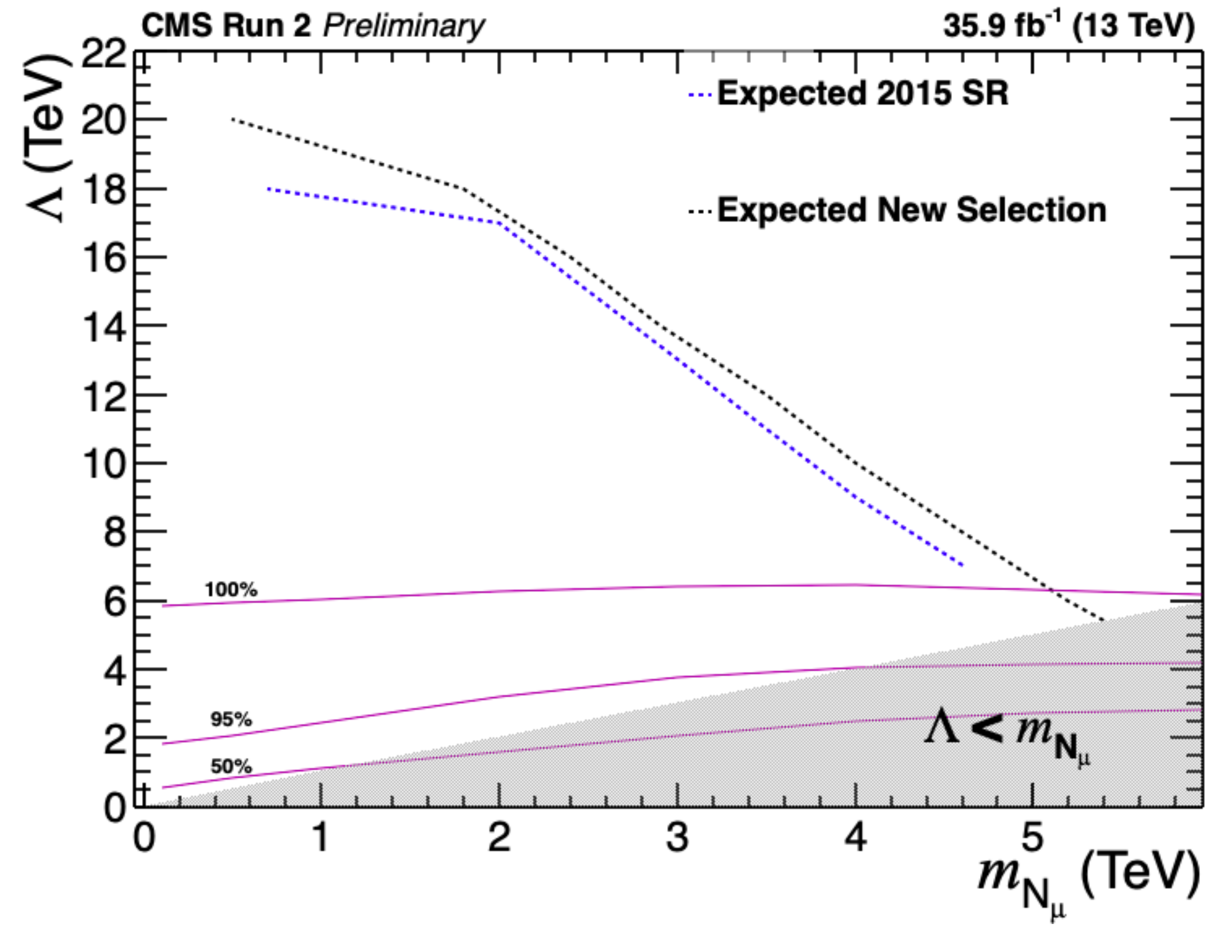




IMPROVEMENT WITH NEW SELECTION



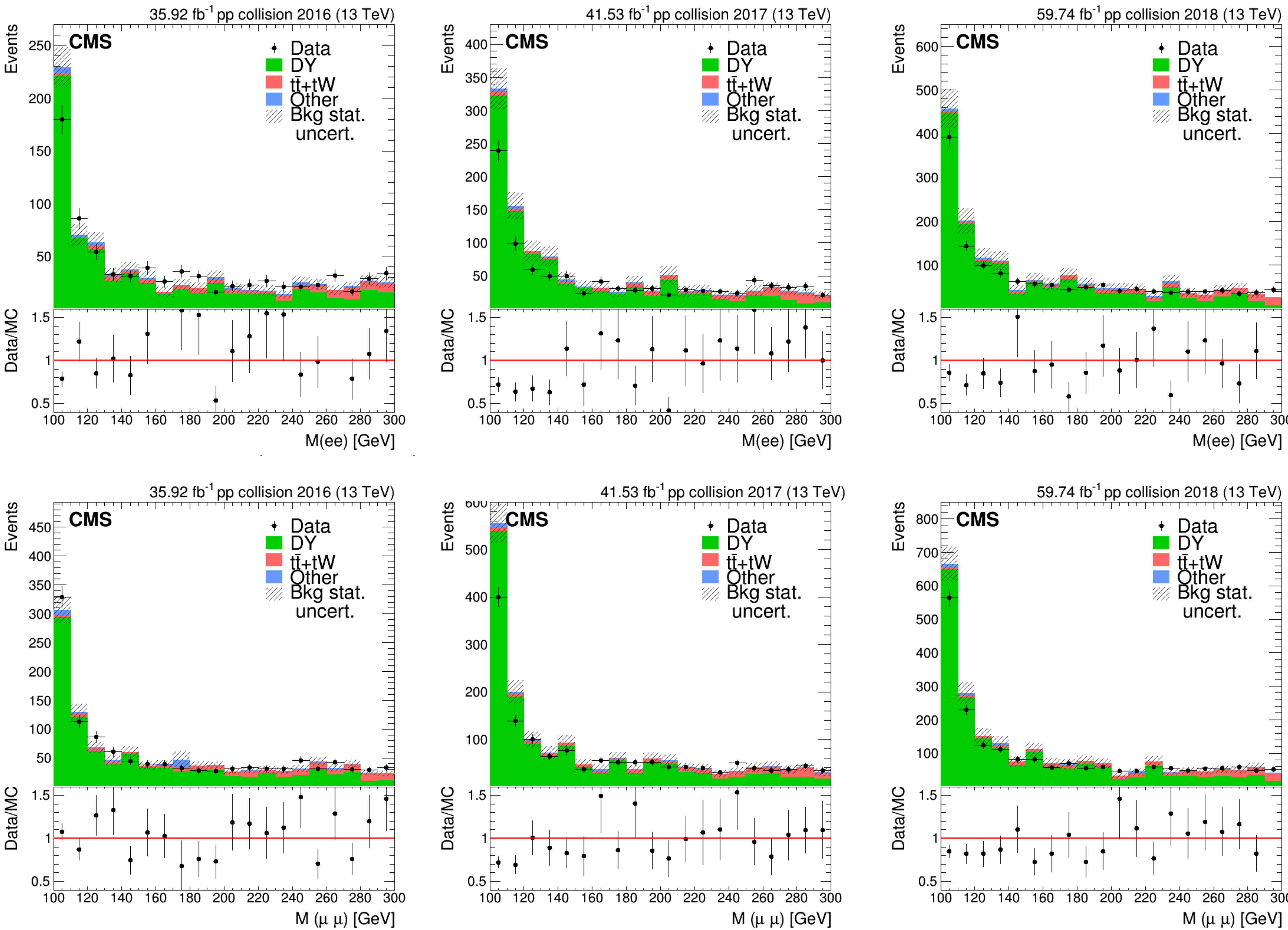
Expected limits comparison in the electron channel for the present analysis and EXO-20-016



Comparison on the 2D parameters space explored with 36/fb and muon channel

- Improvement wrt 2015 analysis not only in higher mass reach but also at larger lambda at low masses (stat only comparison)
  - background reduction of about factor 2

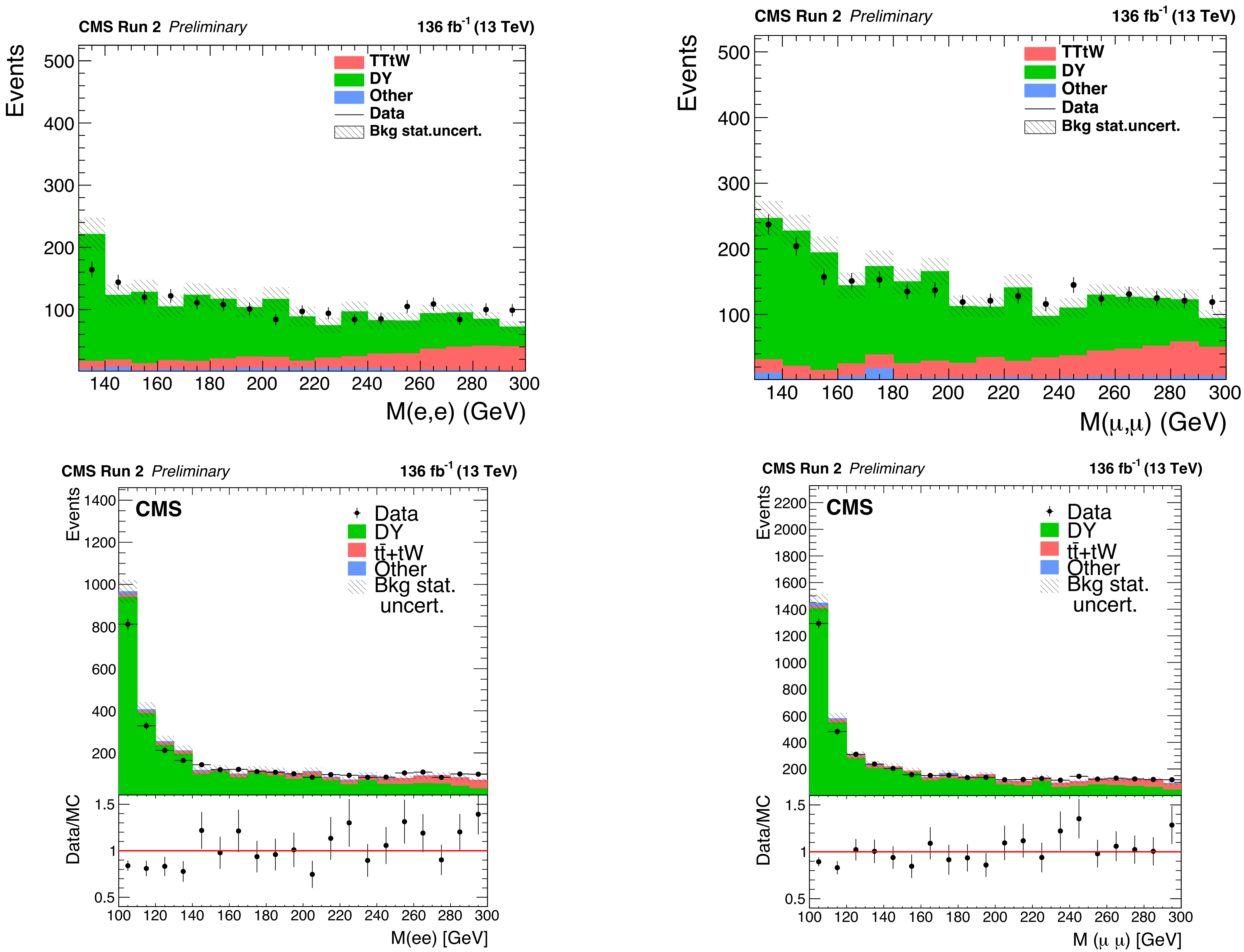
DRELL-YAN CONTROL REGION



ee

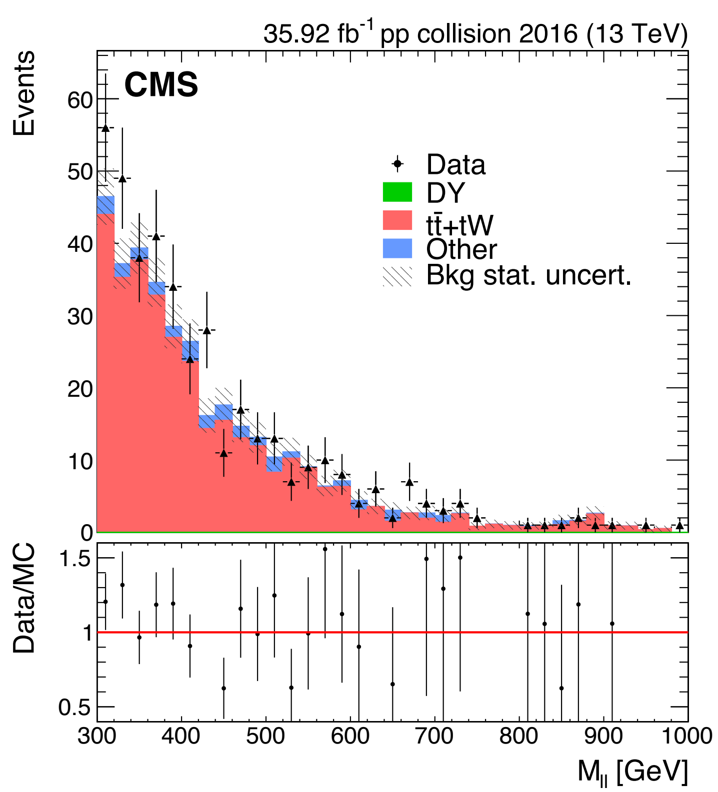
μμ

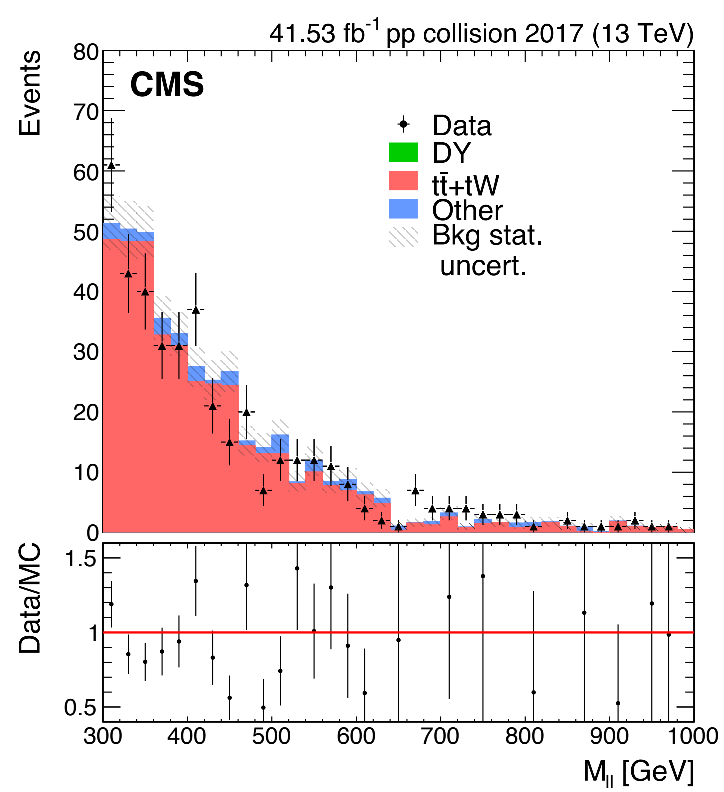
DRELL YAN BACKGROUND CONTROL REGION

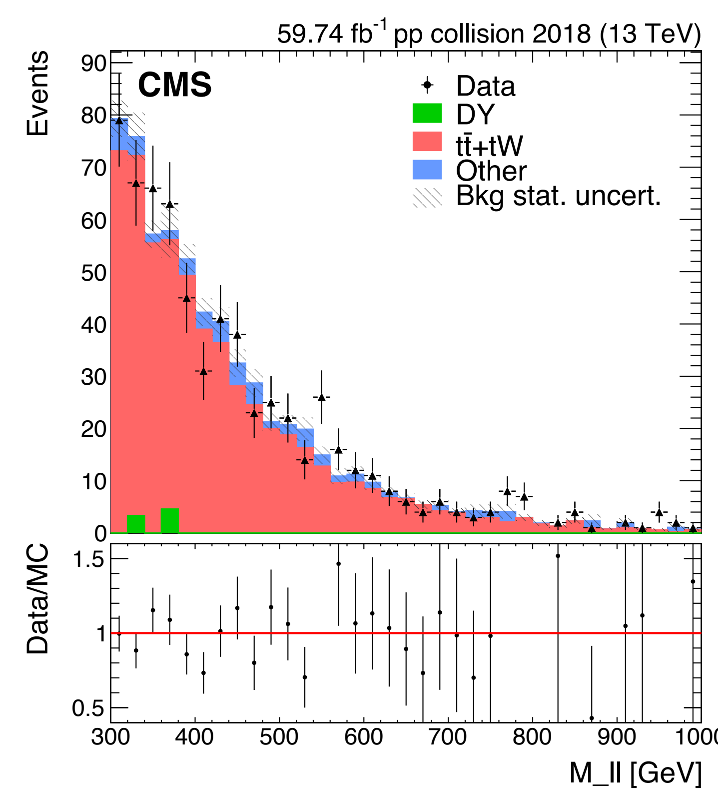


TT+TW BACKGROUND ESTIMATE

- The background from TT and ST processes is estimated directly from MC simulation.
- We define a CR to validate the MC prediction with data requiring the SR selection and a pair of leptons of different flavor (e-μ)
    - 1μ + 1e (no sign requirements) with pT > 150 GeV pT > 100 GeV respectively.
- **The TTtW contribution here is fit simultaneously with the SR in the limit extraction**

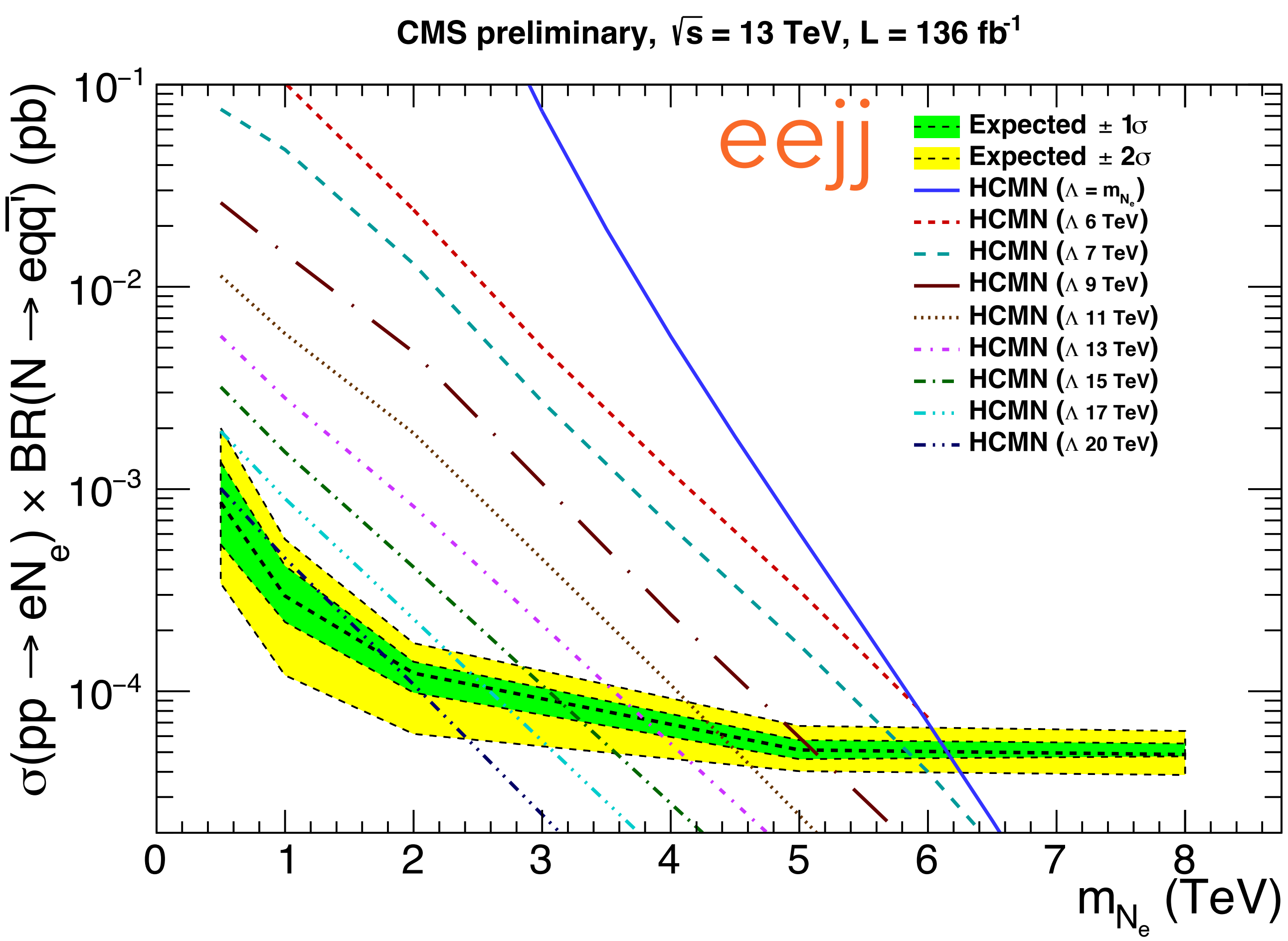




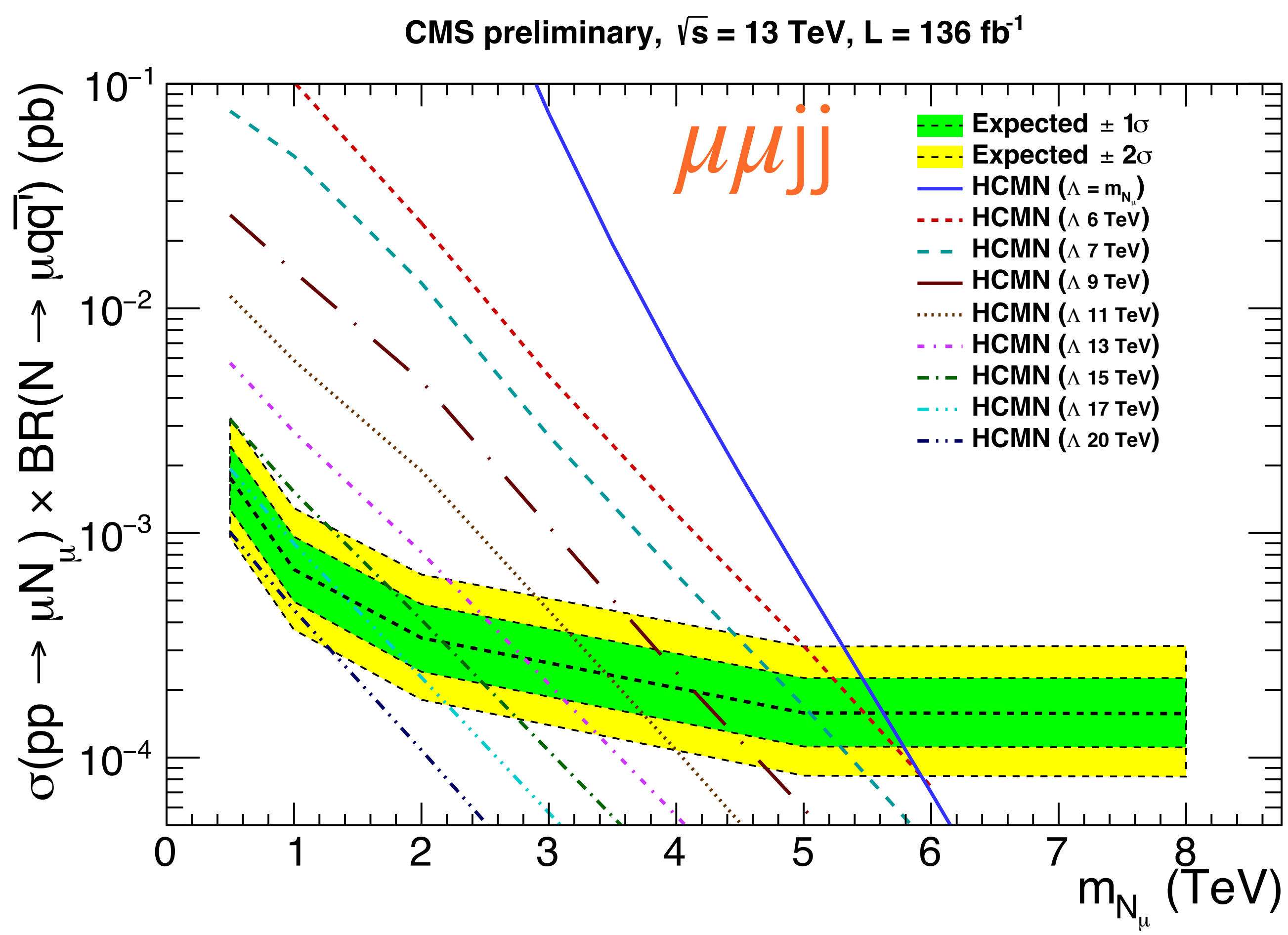


EXPECTED LIMITS ON CROSS-SECTION

The expected 95% CL upper limits on $\sigma(pp \rightarrow lN_l) \times B(N_l \rightarrow lq\bar{q}')$ for the $eeq\bar{q}'$(left) and the $\mu\mu q\bar{q}'$ (right) final states, as a function of the mass of the HCMN



Limits obtained with toys.

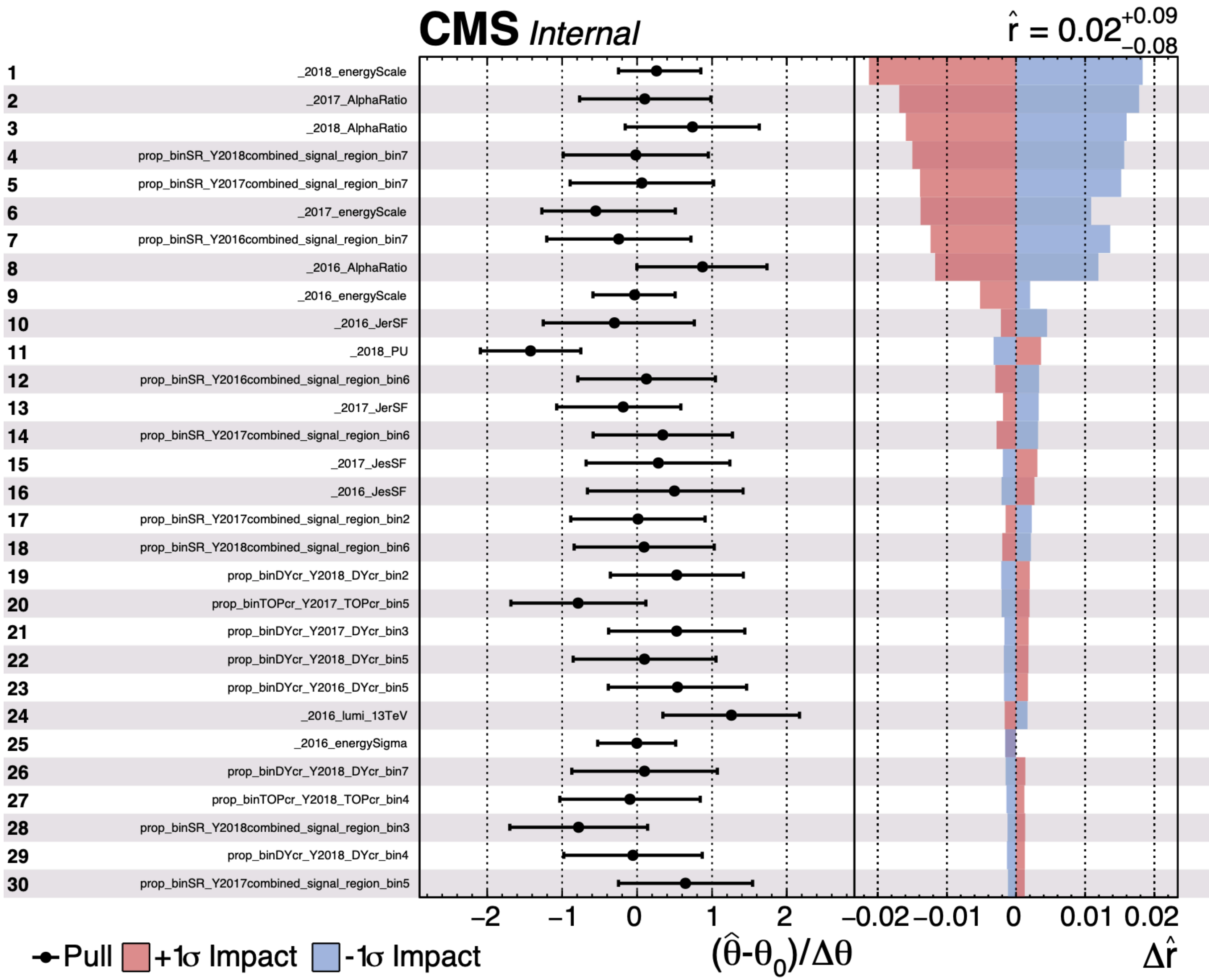


Limits obtained with Asymptotic Approximation and checked with toys.

Stat. + Syst. limits on cross-section for Full Run 2.

IMPACT OF SYSTEMATICS ON HCN RESULT

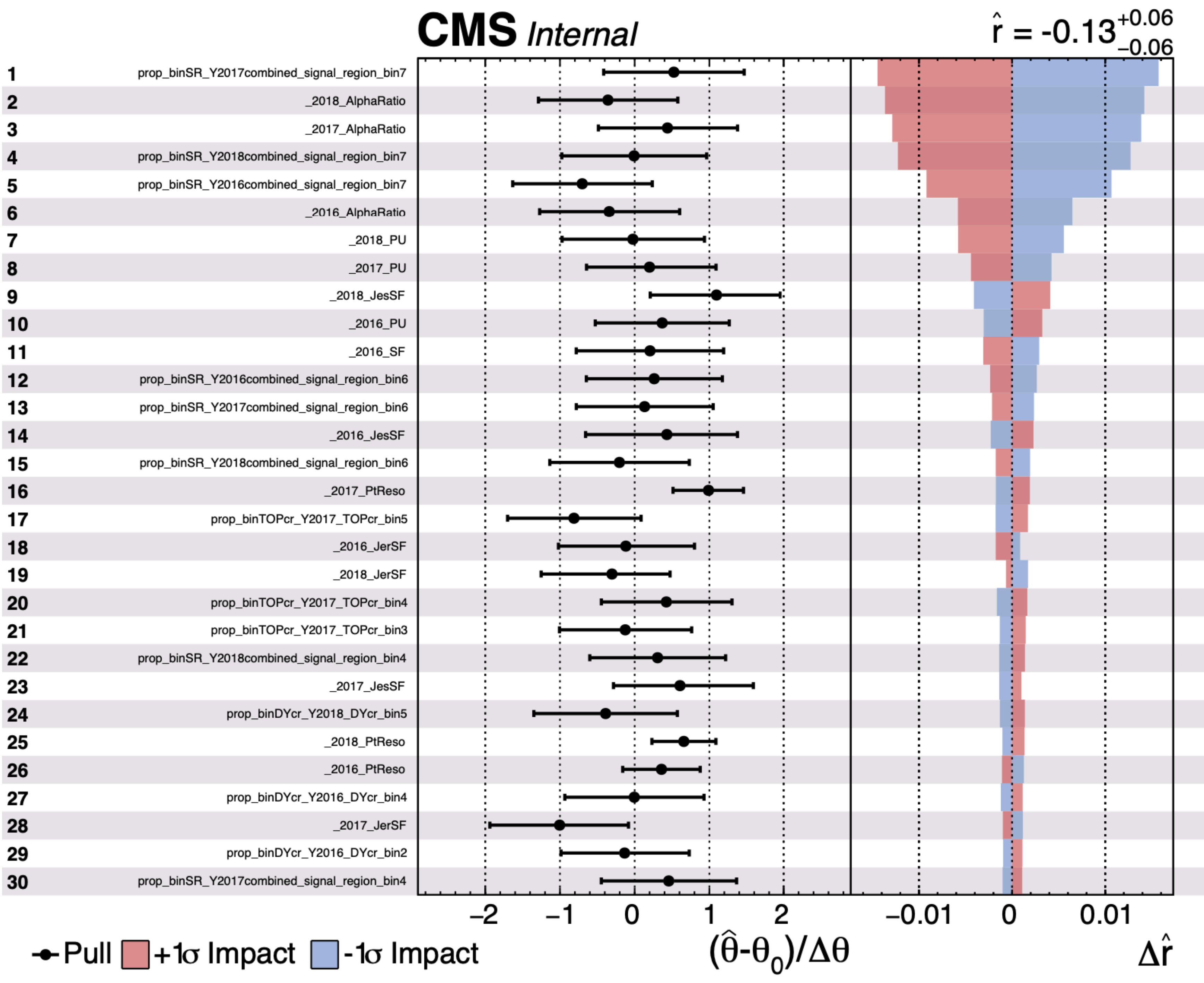
- Electron channel: main systematic uncertainties ordered by magnitude of their effect on the fit to data.



- "Prop_bin*"= MC statistics of the bin indicated
- "*_AlphaRatio"= DY estimation method systematics

IMPACT OF SYSTEMATICS ON HCN RESULT

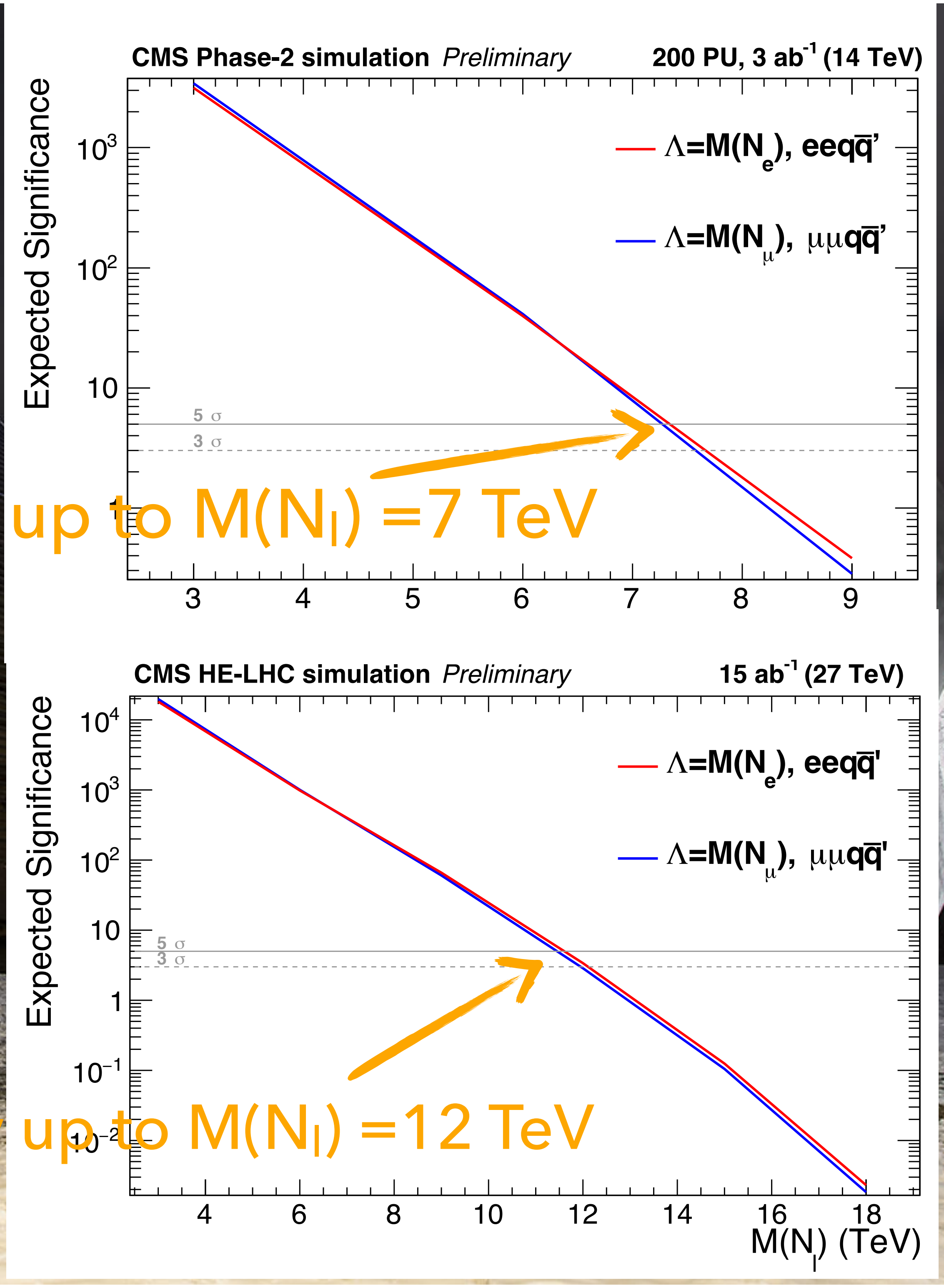
- Muon channel: main systematic uncertainties ordered by magnitude of their effect on the fit to data.



- "Prop_bin*"= MC statistics of the bin indicated
- "*_AlphaRatio"= DY estimation method systematics

FUTURE PROSPECTS

- The results are expressed in terms of sensitivity for a discovery or extensions of the excluded region.
- The expected statistical significance for both the eeqq̄′ and μμqq̄′ channel for the case Λ = M(Nl)



PART3.MVA

- BDT and DNN around same efficiency, better control of overtraining on DNN
  - Framework in place to integrate DNN : we focus on DNN for now
- Training
  - One model for each category
  - Trained on Full run 2 in SR
- Samples reweighted to avoid unbalance: 1:1 ratio S/B
  - scaled to year lumi and conserving each bkg ratio
  - 80%/20% train/test ratio
- Bayesian optimization (with early stopping)
  - # layer, neuron by layer, starting learning rate, regularization (l1, l2, dropout)
  - maximizing test AUC penalized by gap between training and testing
- Overtraining checked by comparing train and test curves and KS tests

The Architecture

- Fully connected network
  - ReLU activation functions
  - batch normalization, l1l2 regu, dropout
  - Adam optimizer
- Optimized hyperparameters

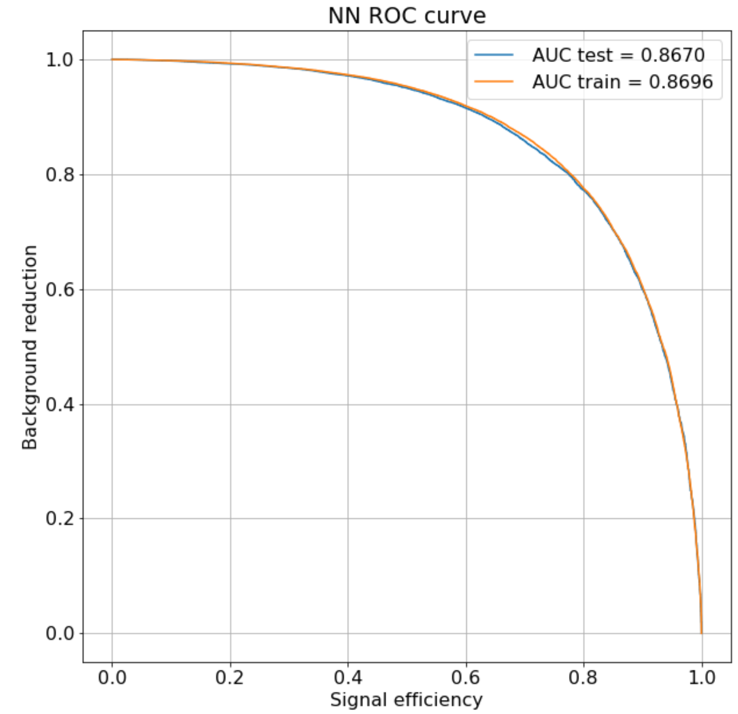
model	n layer	n neurons	l1	l2	dropout	starting lr
SR Resolved	3	280	0	0.01	0.5	0.003
SR Boosted	2	100	0	0.05	0.37	0.0006

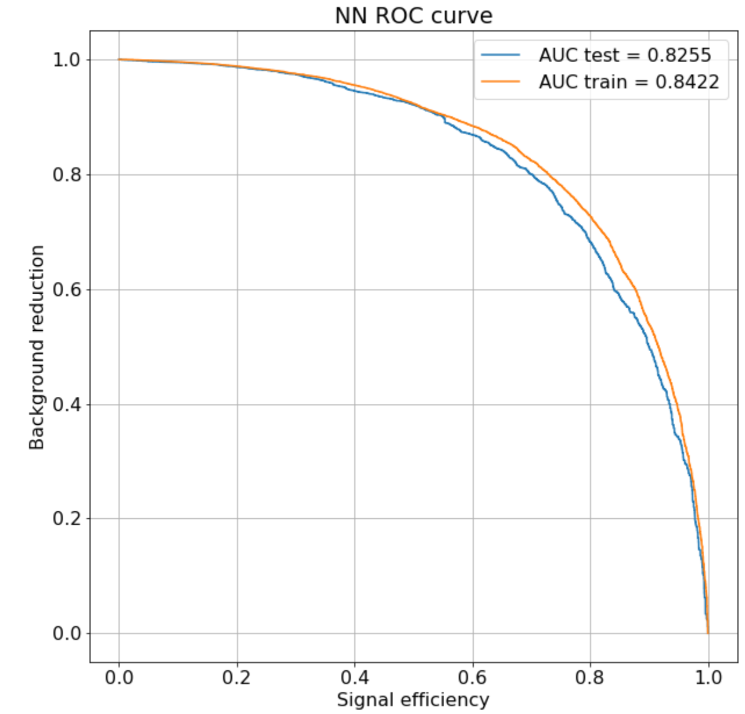
D N N

RESOLVED

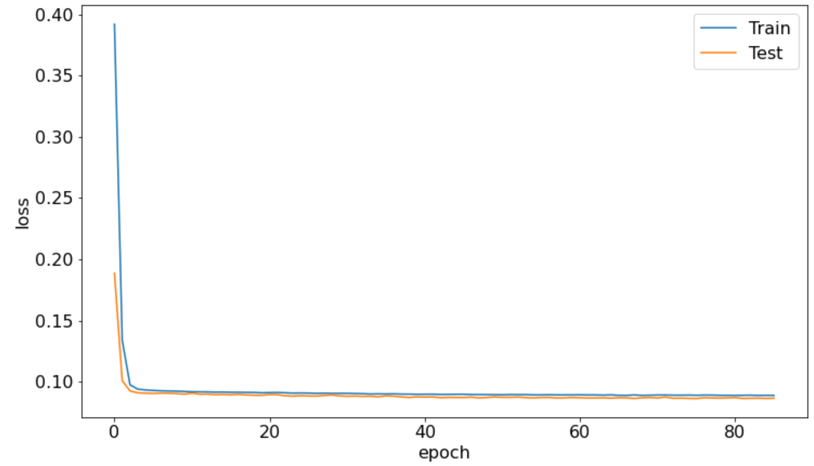
BOOSTED

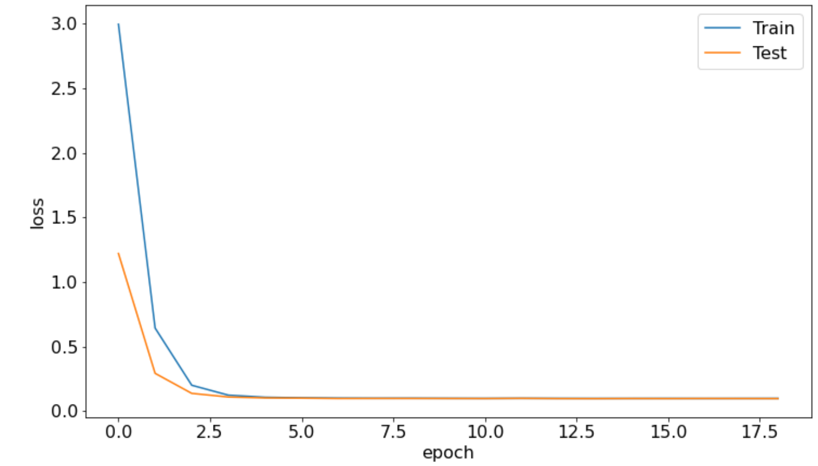
AUC

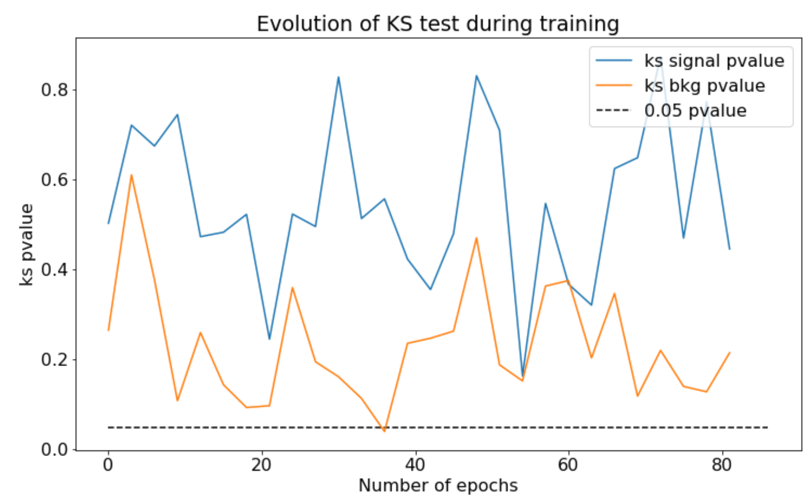




Training monitoring







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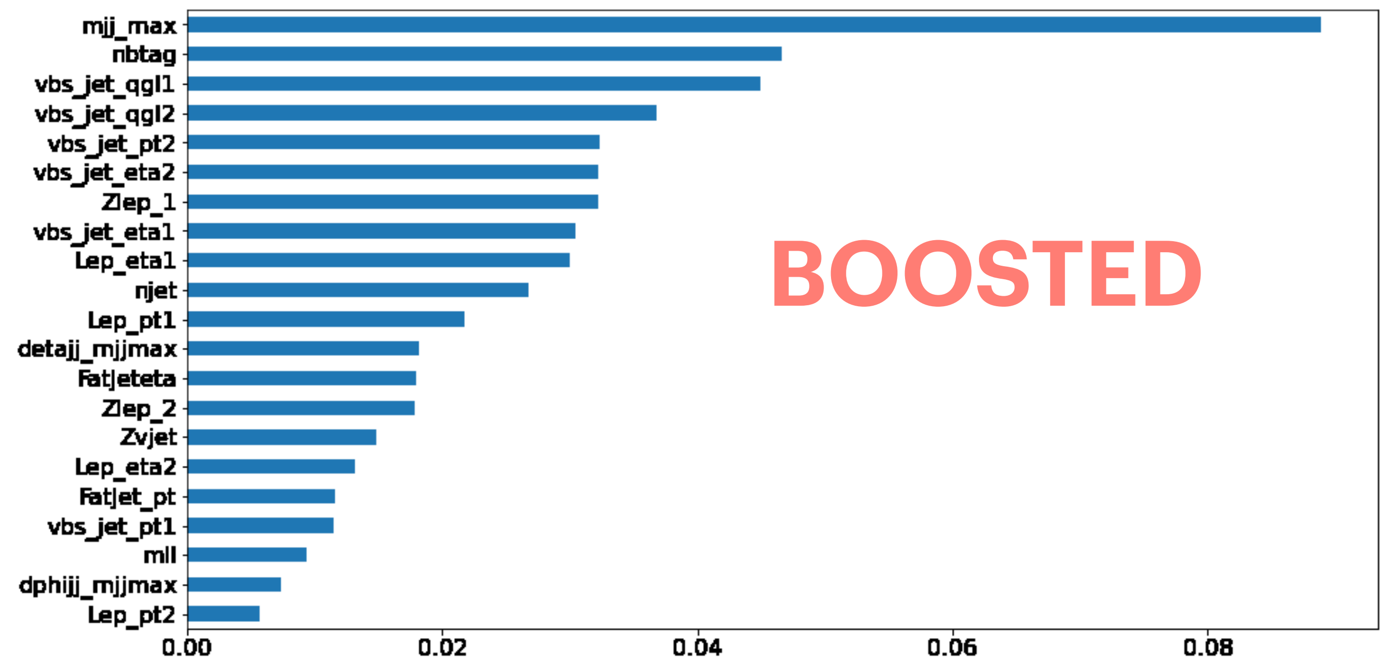
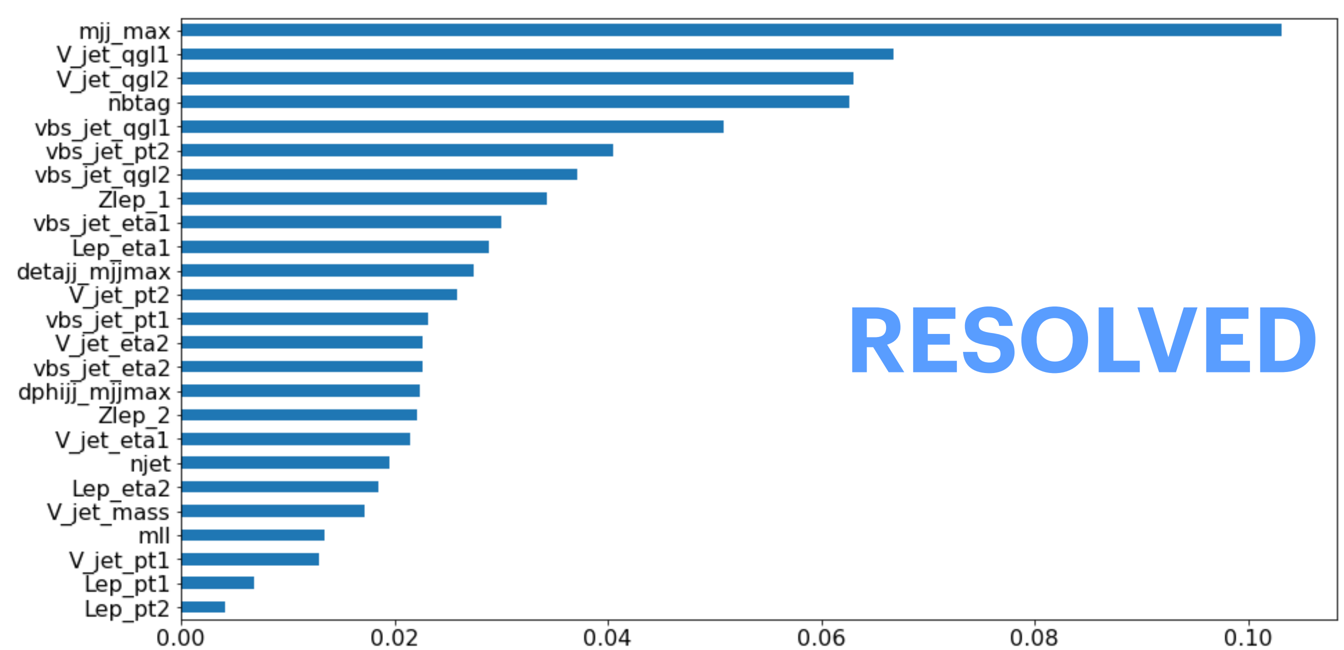
DNN: INPUT VARIABLES IMPORTANCE

- Lepton leading and subleading pt, eta, Zeppenfeld and mll
- VBS leading and subleading jets pt, eta, qgl, deta, dphi, mjj
- number of jets (over 30 GeV)



- Boosted only: Fat Jet pt, eta, Zeppenfeld
- Resolved only: V jets pt, eta, qgl
- nobtag region: number of jets btagged
- Many variables used, may need some pruning



SHAP METHOD

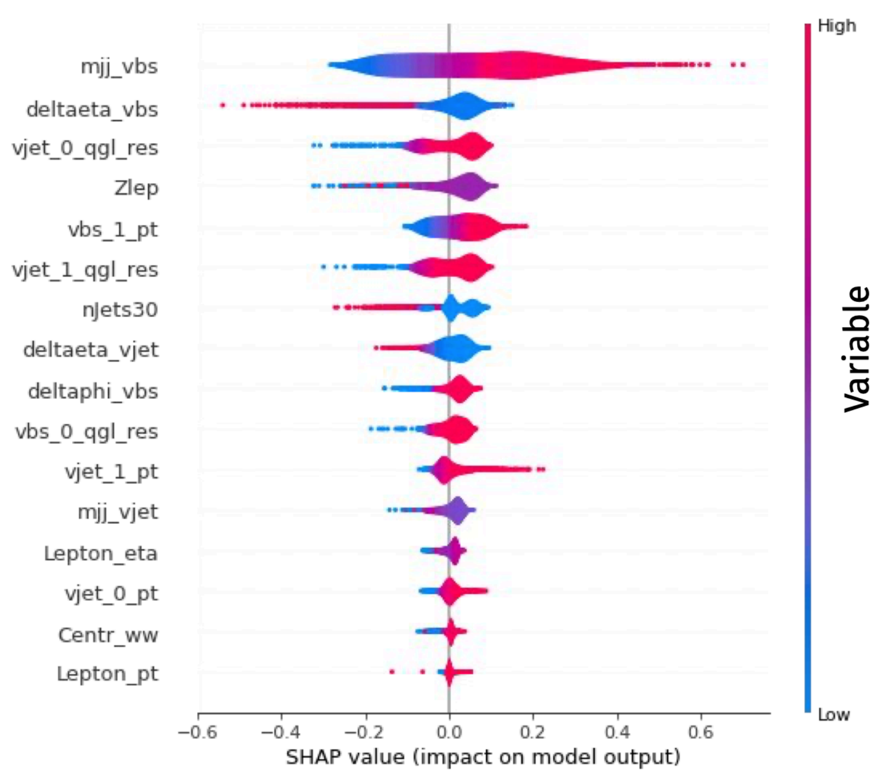
- SHAP (SHapley Additive exPlanations) is a method to explain individual predictions from a general machine learning model.
- It is an explanation metric computed **event by event**
- The aim is to explain the output of the model f(x) as a **linear** sum of the **SHAP value of each input ϕ**

$$f(x) = \phi_0 + \sum_{j=1}^{M} \phi_j x'_j = E_X(\hat{f}(X)) + \sum_{j=1}^{M} \phi_j$$

- SHAP values are then **analyzed on a set of events**

- SHAP is based on the game theoretically optimal Shapley Values.
- *"The Shapley value is the average marginal contribution of a feature value across all possible combinations"* -> It represents the contribute of a given input with the respect of the others
- Computing pure shapley values is computational expensive
  - approximate solutions exists for different types of practical models like DNNs
  - SHAP library implementation

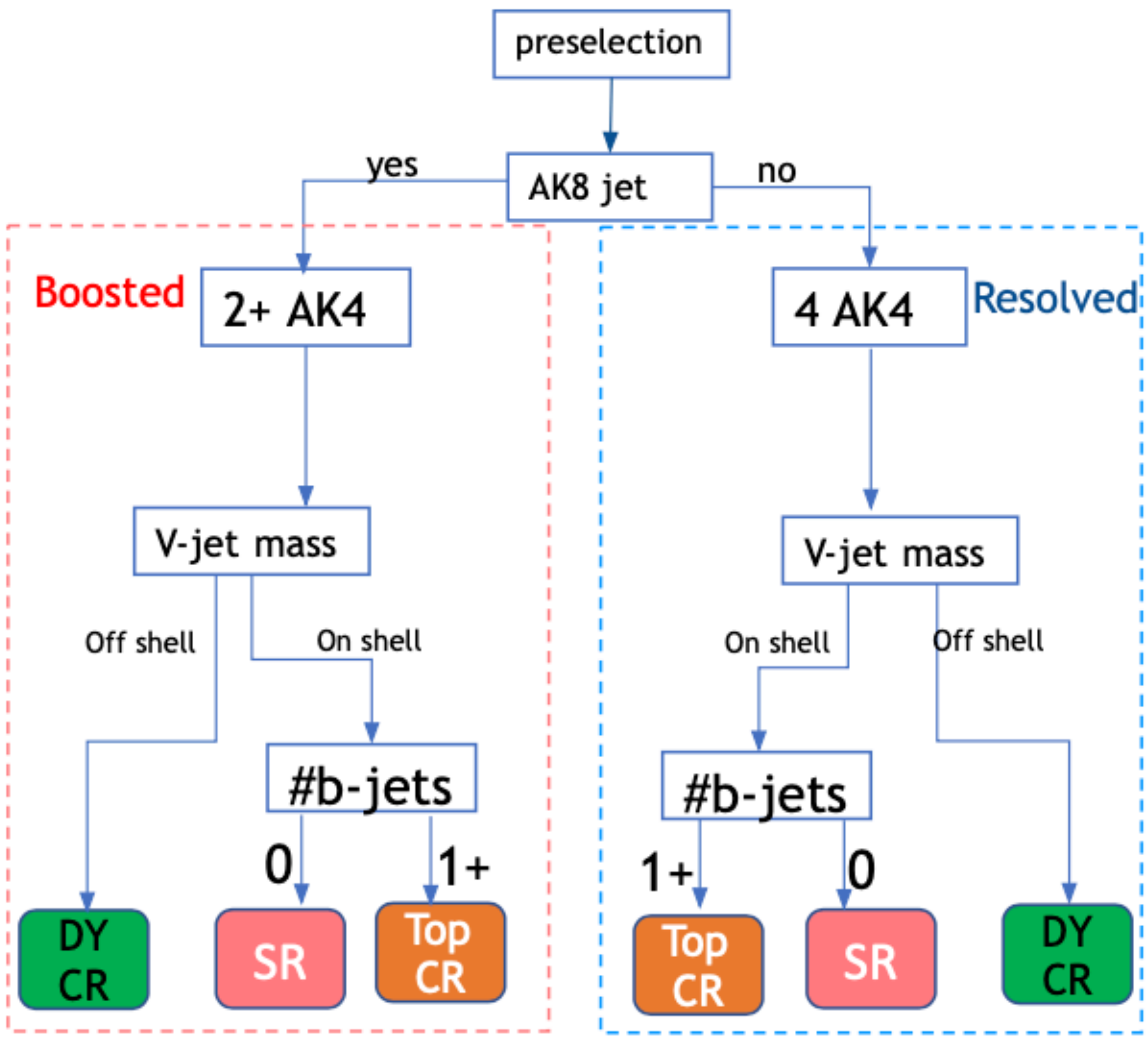
Resolved model



The SHAP value attributed to each input of the model is **analyzed** for a set of 5k events and plotted.

- If the value of a variable for an event has a positive (negative) shap value, it means that value makes the event signal (bkg) like
- The width of the distribution shows the frequency of the specific SHAP value
- The color represents the normalized value of the input variable. E.g. High = max(variable), Low = min(variable)
- Variables are **ranked** by the mean of the |SHAP value|
- A wider distribution shows that the input variable have more **discrimination power**

IRREDUCIBLE BACKGROUNDS CONTROL



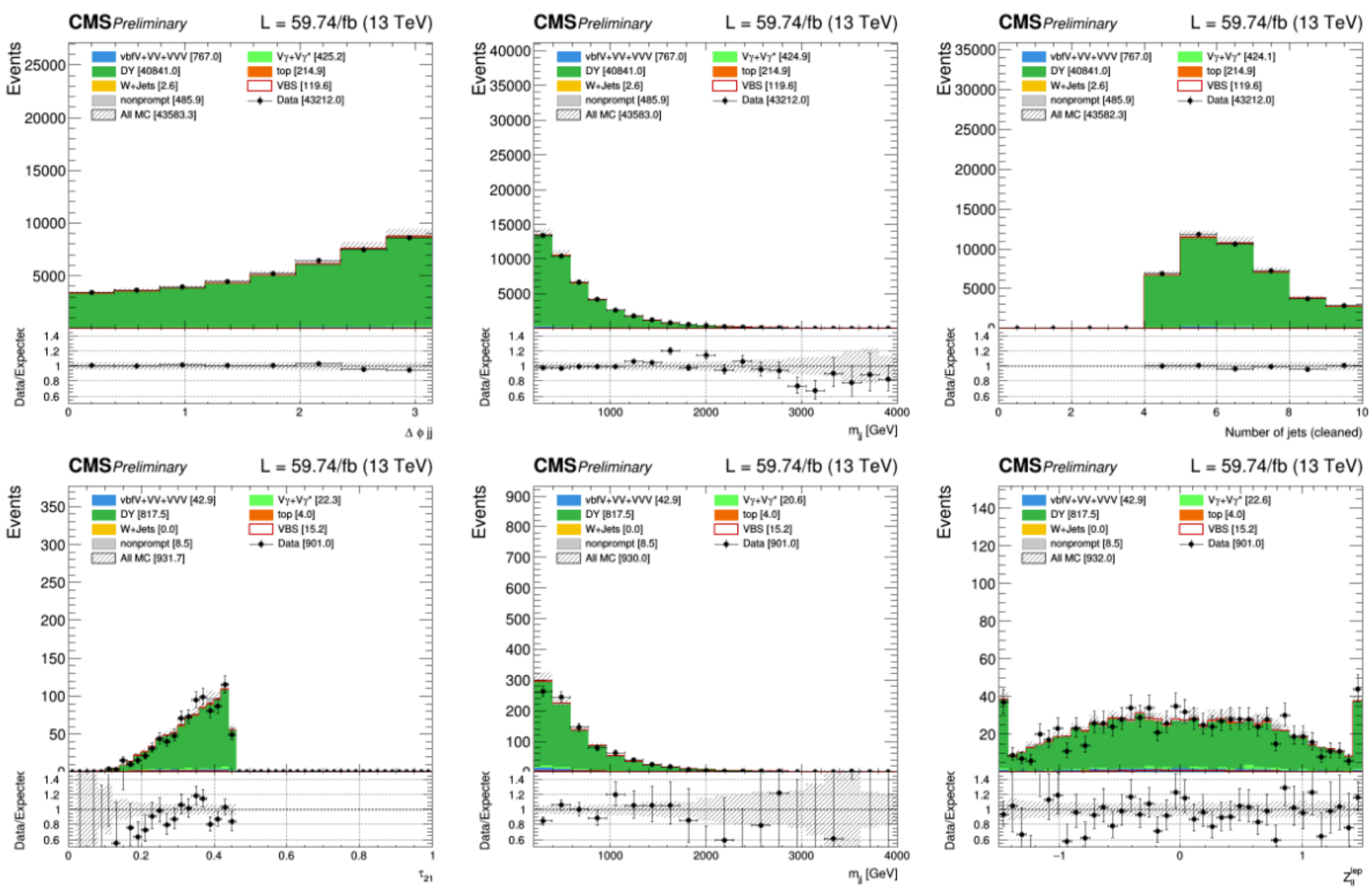
- Preselection:
  - 2 leptons, pt > 35 (20) Gev, |η| < 2.5, mll in [76,106] GeV
  - # AK4 >=2, mjj >200 Gev, dηjj >2
- V mass:
  - On shell [65,105]
  - Off shell [40,65] or [65,250]

- How important is to control background sources
- The mass of the reconstructed hadronically decaying vector boson is used to define a V+jets control regions in both WV (W+jets) and ZV (DY+jets) channels, for resolved and boosted categories.
- The final fit is performed combining all the regions

DYJETS CR

(2018 HERE, 16 AND IN 17 SIMILAR TREND)

- Vjets_mass <65 GeV || >105 GeV
- 2leptons with SS/SF
- $m_{\ell\ell} \in [76; 106]\, GeV$



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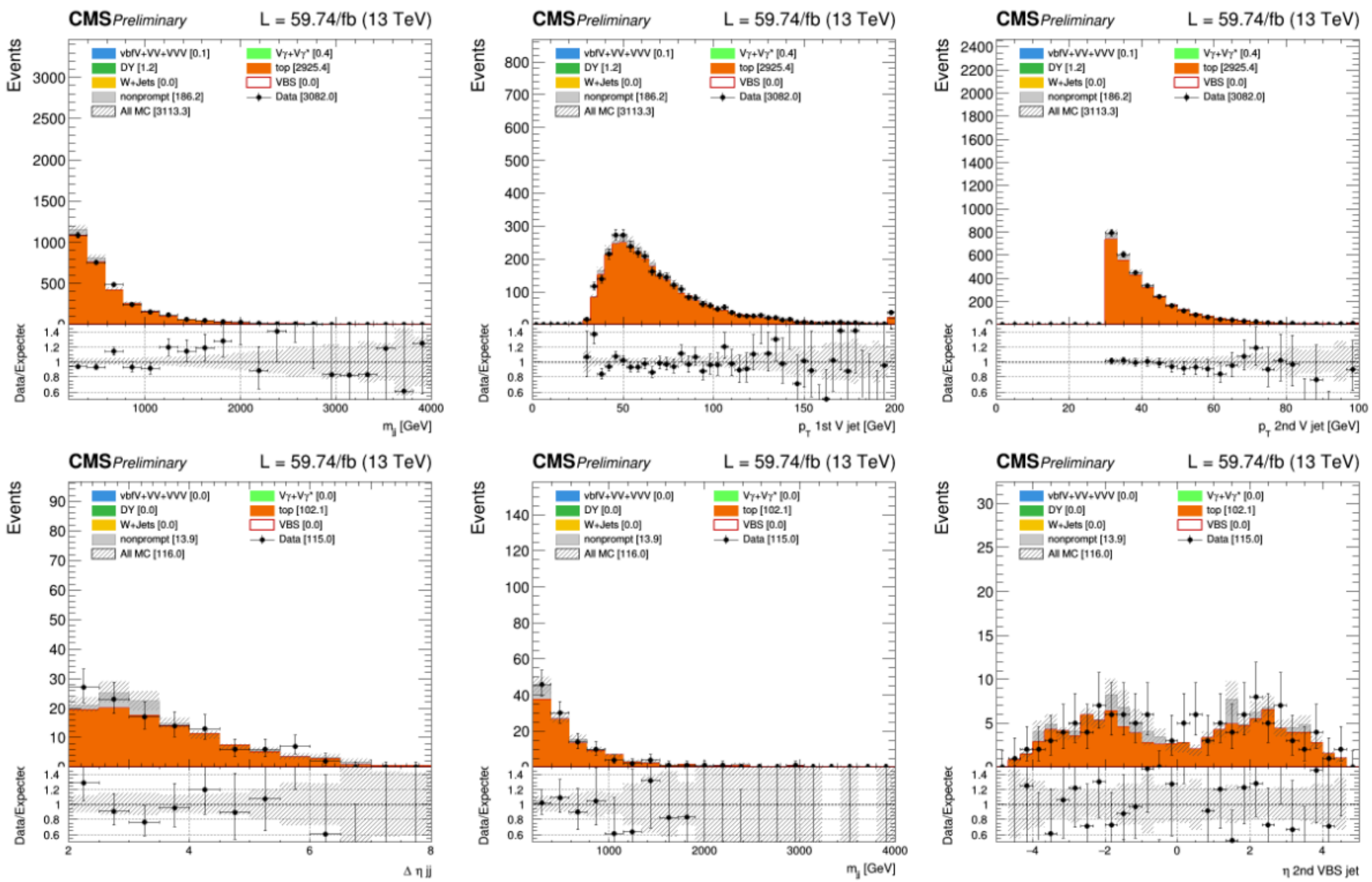
TOP CR

(2018 HERE, 16 AND IN 17 SIMILAR TREND)

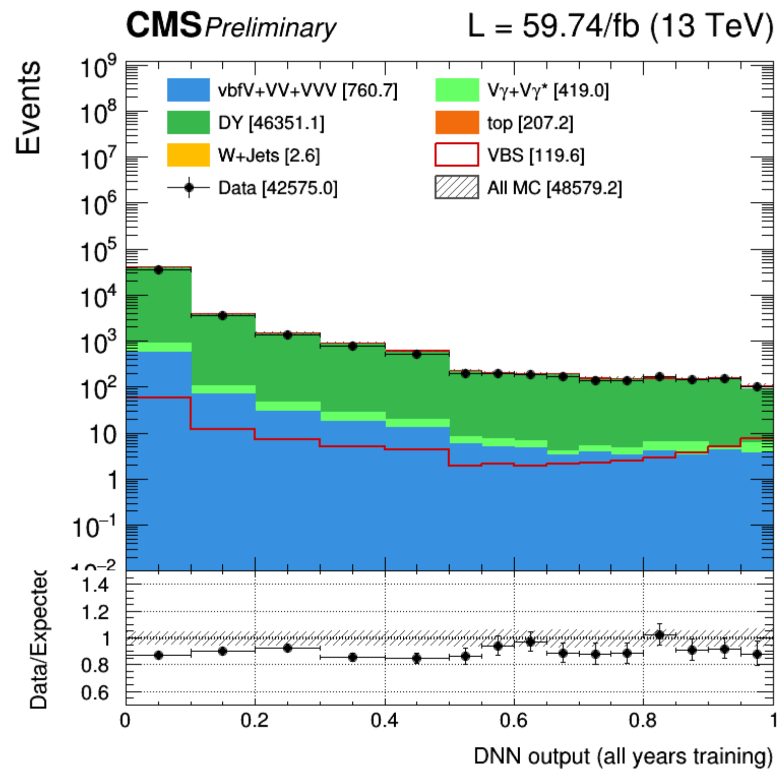
- $VJ_{smass} \in [65; 105]\, GeV$
- 2leptons with OS/OF
- $m_{\ell\ell} \in [76; 106]\, GeV$

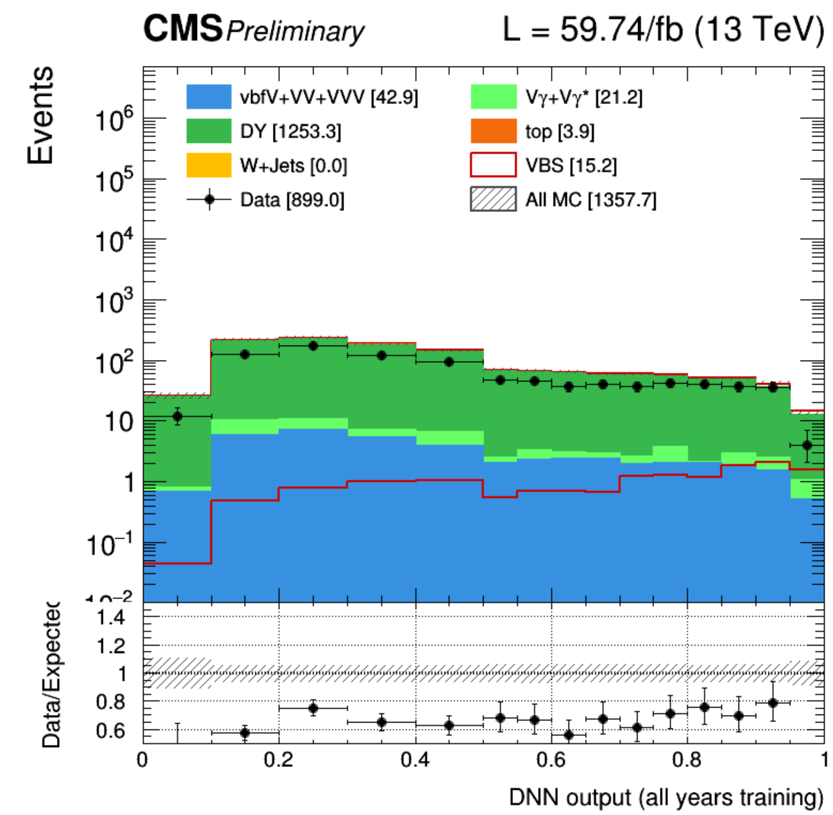


RESOLVED BOOSTED

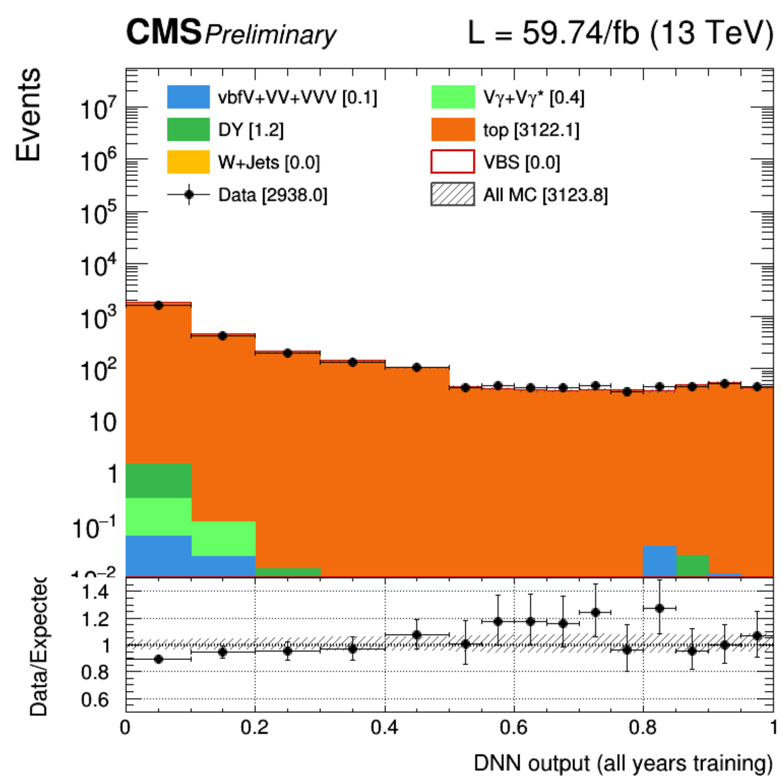
DNN OUTPUT IN CR

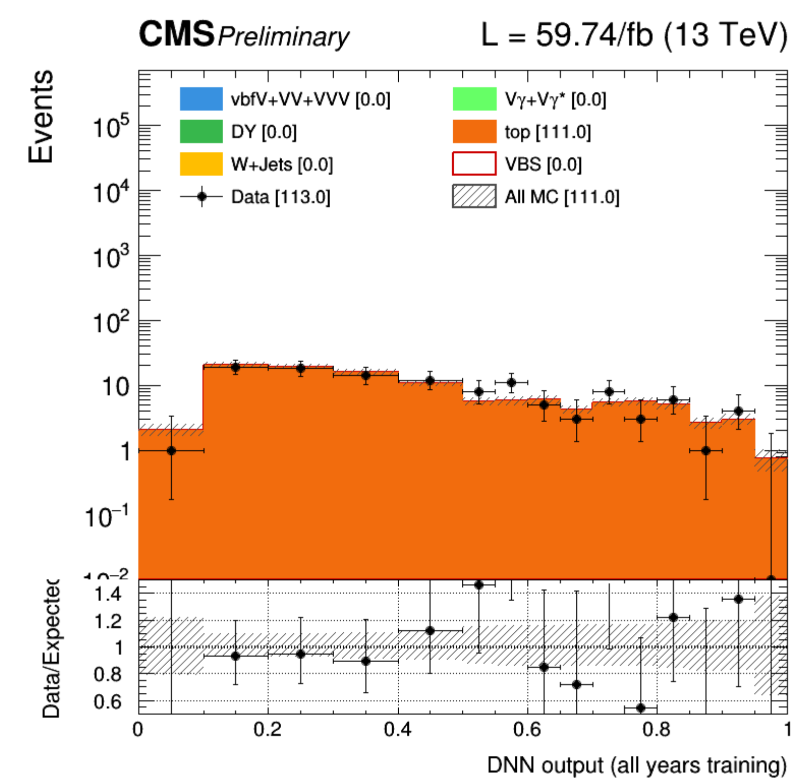
DY





Top



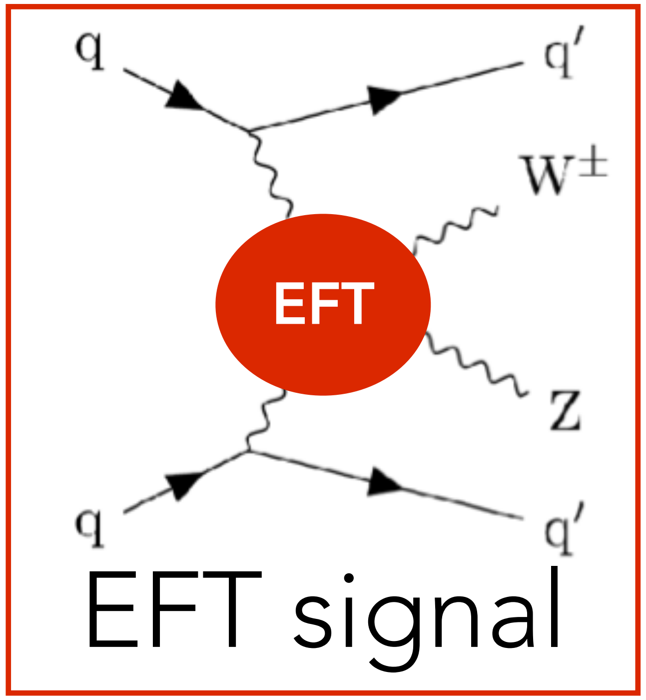


Except for normalization, the agreement is correct (mostly flat across the range).

- EFT interpretation of the results:

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_{n=1}^{\infty} \sum_{i} \left(\frac{c_i^{(n)}}{\Lambda^n} \right)_i^{(n+4)}$$

- Often EFT signal in the tails of the distributions (with the standard EFT samples)



$$\mathcal{O}_{T_5} = \mathrm{Tr}\left[W_{\mu\nu}W^{\mu\nu}\right] \times B_{\alpha\beta}B^{\alpha\beta}$$
$$\mathcal{O}_{T_6} = \mathrm{Tr}\left[W_{\alpha\nu}W^{\mu\beta}\right] \times B_{\mu\beta}B^{\alpha\nu}$$
$$\mathcal{O}_{T_7} = \mathrm{Tr}\left[W_{\alpha\nu}W^{\mu\beta}\right] \times B_{\beta\nu}B^{\nu\alpha}$$
$$\mathcal{O}_{T_8} = B_{\mu\nu}B^{\mu\nu}B_{\alpha\beta}B^{\alpha\beta}$$
$$\mathcal{O}_{T_9} = B_{\alpha\mu}B^{\mu\beta}B_{\beta\nu}B^{\nu\alpha}$$