Search for T’ $\rightarrow$ tH in SS dilepton final state

Particle Group Meeting

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Benjamin Blancon, Arnab Purohit, Nicolas Chanon

Why T’ (Vector Like Quark)?

- Particularly attractive to solve the hierarchy and CKM unitarity problems.

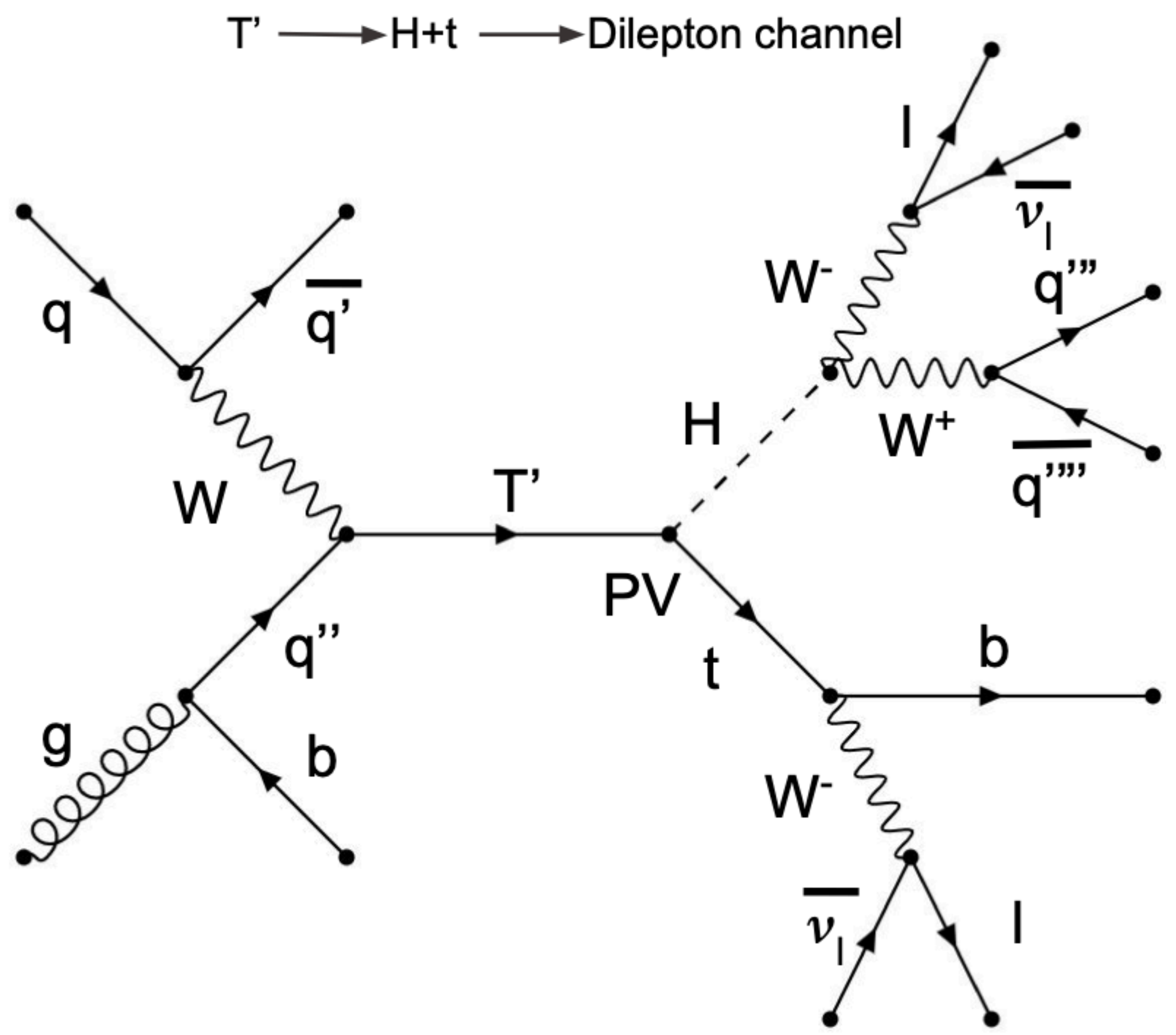
- Quarks for which the left- and right-handed chiral components transform in the same way in the SM electroweak group.

- **VLQ:**
    - Charge +2/3
    - Decay to tH (25%), tZ (25%) and tb (50%)

Introduction

- Search for a single-produced VLQ T' decaying into **top** and **Higgs** in a **SS dilepton** final state.
- **Three** channels considered **(μμ/eμ/ee)**.
- Nominal masses $\mathbf{m_{T'}}$ range: [**600 - 1200 GeV**].
- **Full Run 2** (2016-2018) **UL** data.
- Searching for a resonance in the transverse mass $M_T^{T'}$

$$(M_T^{T'})^2 = \left(\sum_{particles} E_T\right)^2 - \left(\sum_{particles} \vec{p_T}\right)^2$$
$$= \left(E_{T,lep,Higgs} + E_{T,\nu,Higgs} + E_{T,j1,Higgs} + E_{T,j2,Higgs} + E_{T,lep,top} + E_{T,\nu,top} + E_{T,b,top}\right)^2$$
$$- \left(\overrightarrow{p_{T,lep,Higgs}} + \overrightarrow{p_{T,\nu,Higgs}} + \overrightarrow{p_{T,j1,Higgs}} + \overrightarrow{p_{T,j2,Higgs}} + \overrightarrow{p_{T,lep,top}} + \overrightarrow{p_{T,\nu,top}} + \overrightarrow{p_{T,b,top}}\right)^2.$$



Event Selection

- HLT Paths (2018):
  - **HLT_IsoMu24** for muon
  - **HLT_Ele32_WPTight_Gsf** for Electron
- Lepton Selection (2018):

Criterion	Muons		Electrons	
	Fakeable	Tight	Fakeable	Tight
p_T (GeV)	> 30	> 30	> 40	> 40
$\|\eta\|$	< 2.4	< 2.4	< 1.4442 AND (> 1.566 OR < 2.5)	
Identification	Medium ID	Medium ID	Loose ID	Tight ID
Isolation	Loose WP	Tight WP	Loose WP	Tight WP
$\|d_{xy}\|$ (cm)	< 0.05	< 0.05	< 0.05	< 0.05
$\|d_z\|$ (cm)	< 0.1	< 0.1	< 0.1	< 0.1
SIP_{3D}	< 4	< 4	< 4	< 4
Missing inner hits	-	-	$= 0$	$= 0$
Conversion veto	-	-	Yes	Yes
Tight charge	Yes	Yes	Yes	Yes

Tight Isolation: $I_{rel} < I_1$ AND ($p_T^{ratio} > I_2$ OR $p_T^{rel} > I_3$).

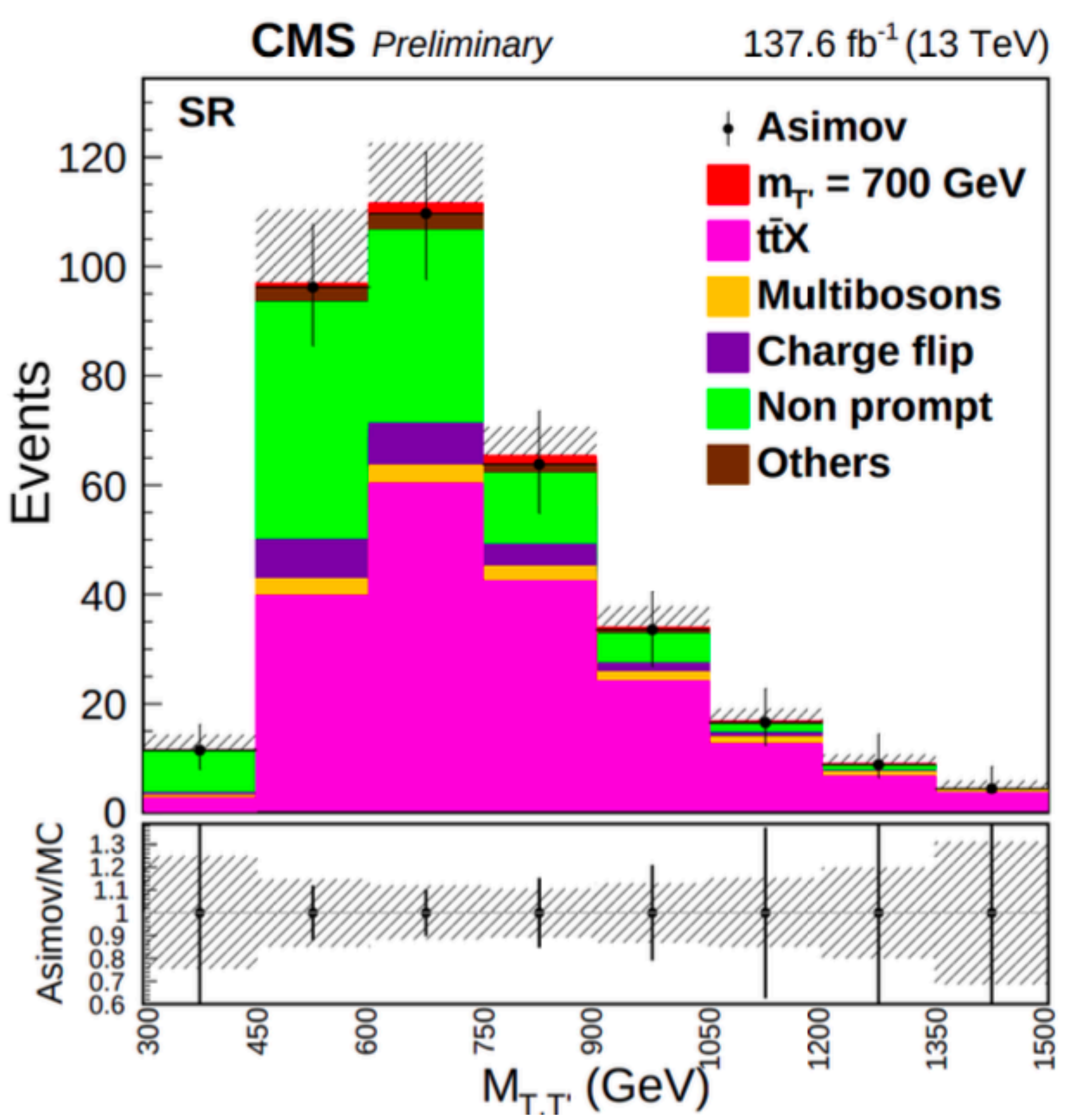
$$p_T^{ratio} = \frac{p_T(l)}{p_T(jet)}, \quad p_T^{rel} = \frac{|(\vec{p}(jet) - \vec{p}(l)) \times \vec{p}(l)|}{|\vec{p}(jet) - \vec{p}(l)|}$$

Isolation	Muon Tight WP		Electron Tight WP	
Year	2016	2017-2018	2016	2017-2018
I_1	0.16	0.11	0.12	0.07
I_2	0.76	0.74	0.80	0.78
I_3	7.2	6.8	7.2	8.0

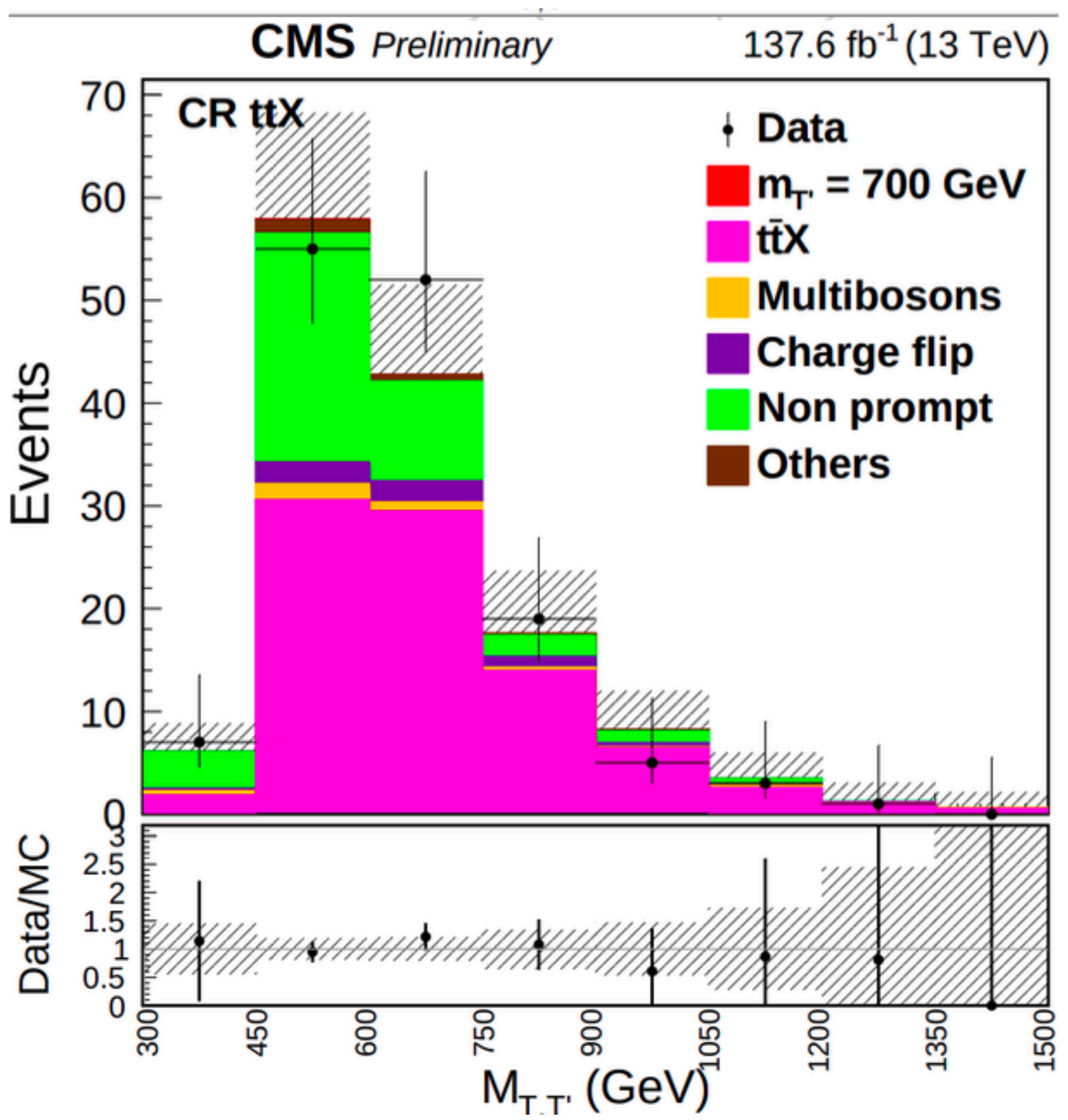
Results

- Profile likelihood fit is performed using **Combine** package.

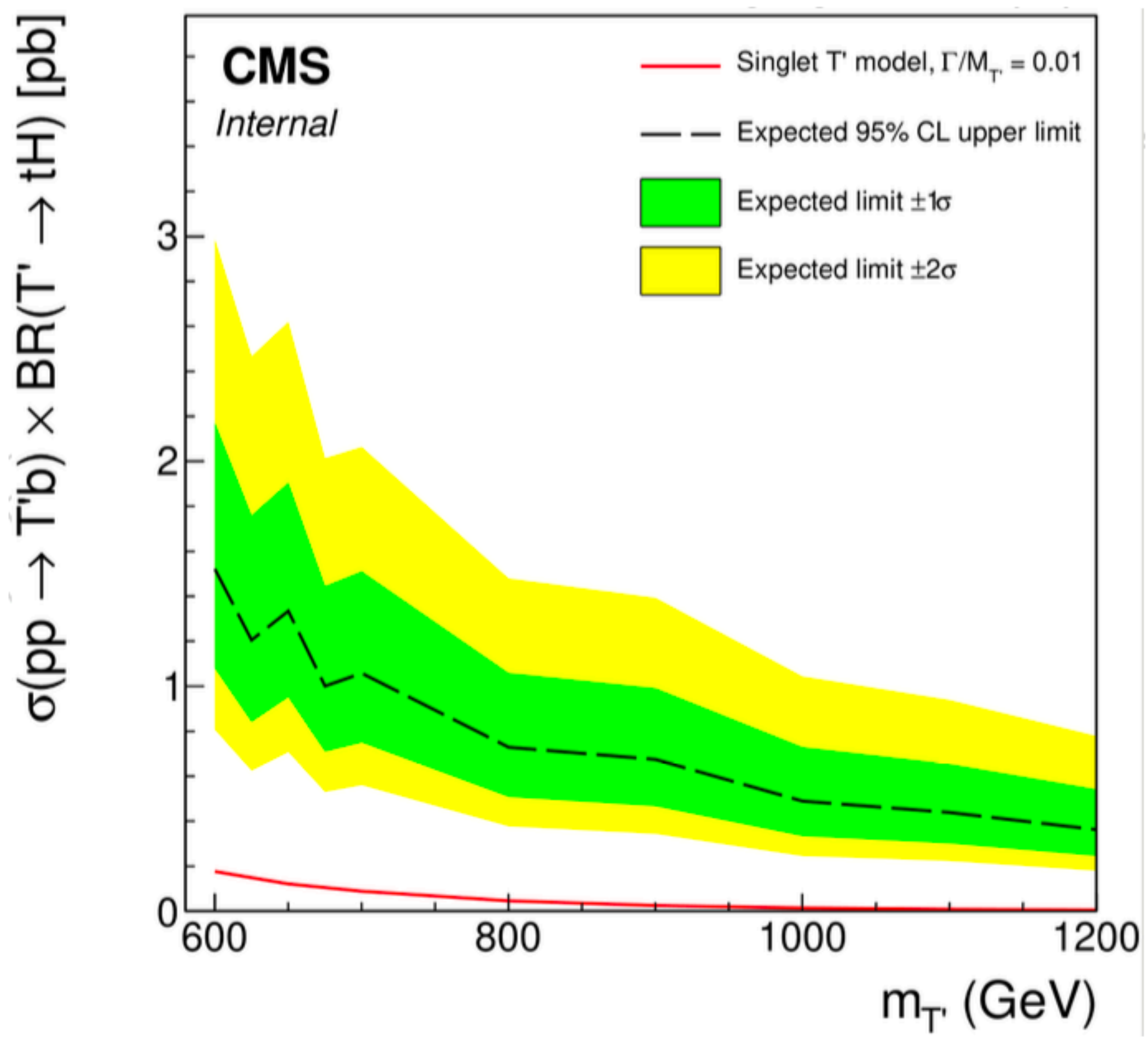
Signal Region



ttX Region



- **Expected UL at 95% CL of the cross section multiplied by the BR of the T' → *Ht* decay.**



Object Review

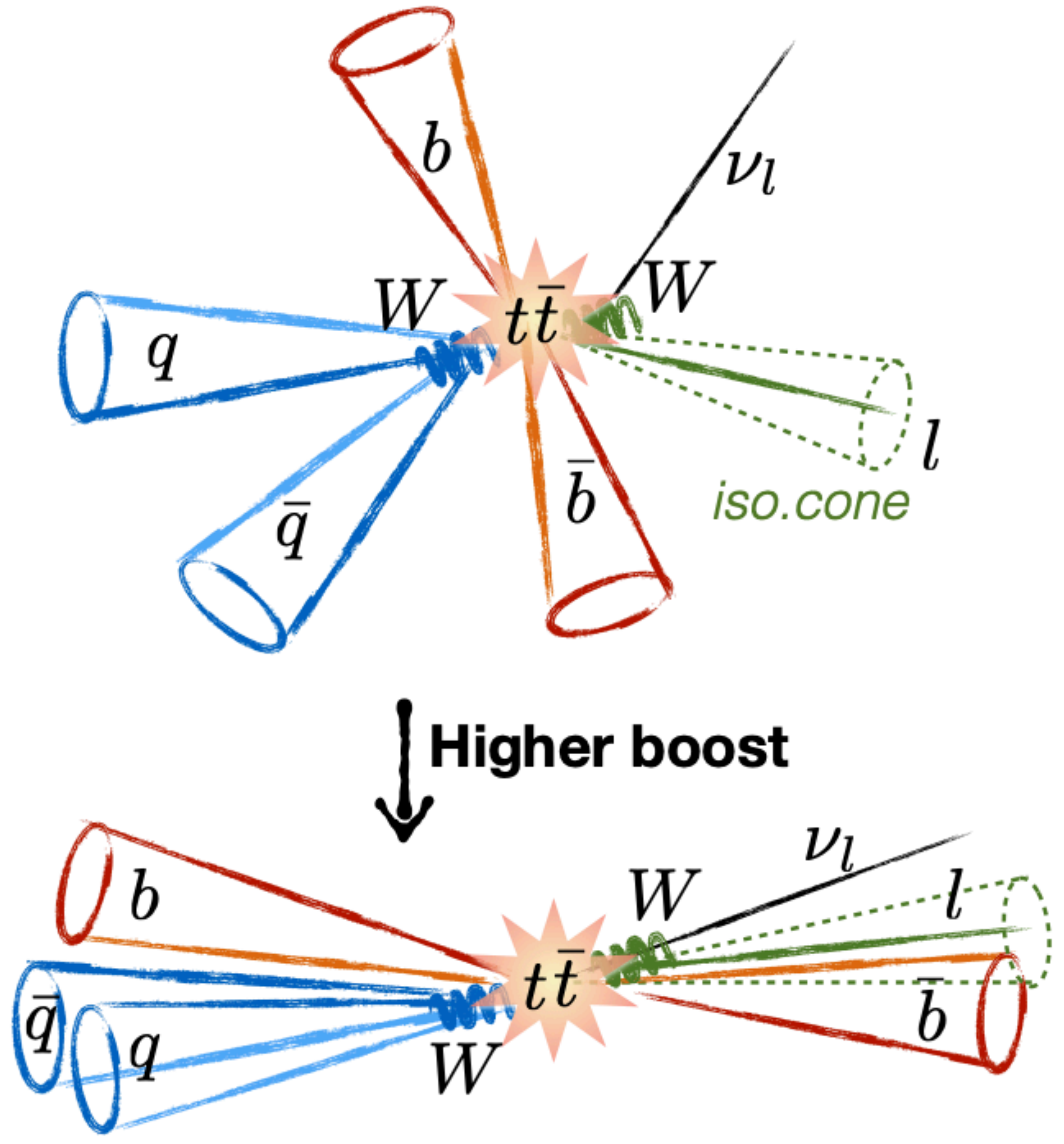
- Status of the Object reviews:

Explicit green-lights from experts

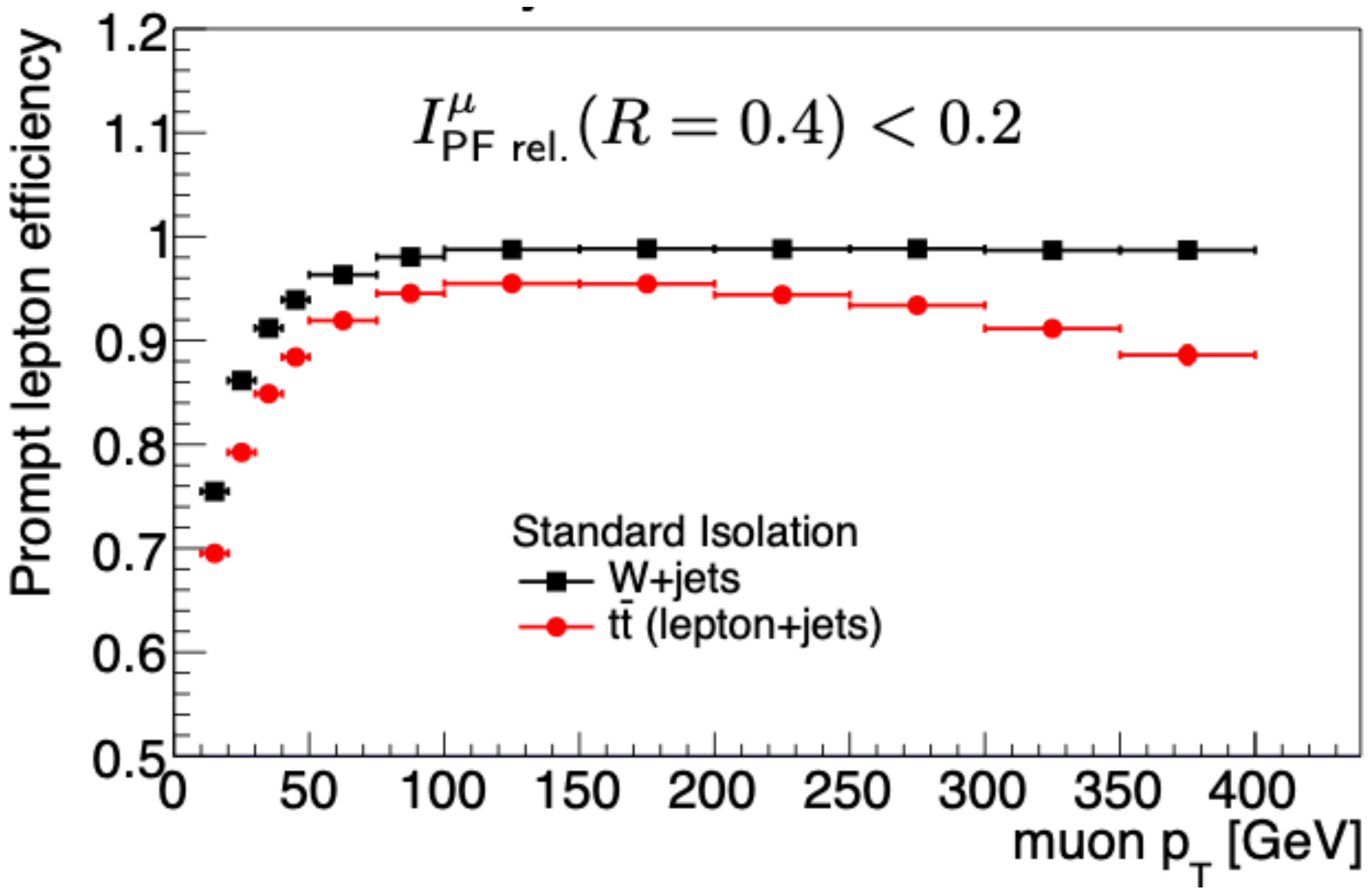
Category	Name	Status
Conveners		Ongoing.
INT	Agostino De Iorio	Green light
PPD	Antimo Cagnotta & Fabio Iemmi	Green light
GEN	Elise Jourd'huy	Green light
TRIG		Ongoing.
EGM		Ongoing.
MUO		Ongoing.
TAU		Green light
JME		Ongoing.
BTV	Amitav Mitra & Mary Hadley	Green light
STAT		Green light

- **TRIG, EGM and MUO comments are related to the extra isolation cut (multiIso) which we are applying in our analysis as we have relatively boosted leptons.**
  - In this multi-isolation, the cone is varies as a function of the p_T of the lepton.
  - We are checking the impact of replacing this extra isolation cut with the standard isolation in our selection.
- **The JME object review is related to one missing uncertainty (JER).**
  - We have already added this in our analysis framework.
  - In the next iteration of our results we are expecting to include it.

Isolation



- The SFs are not available for Multi-isolation
- We have switched to Standard Isolation.
  - It is not good for boosted scenario. Removes a lot of signal events. Significance degraded. (results in the next slides.)
- We have used Mini-Isolation and Lepton-MVA.



Results with Standard Isolation

- First reproduced Benjamin's results (from his thesis). They are comparable within <1%.   0.266 σ in comparison to 0.267 σ

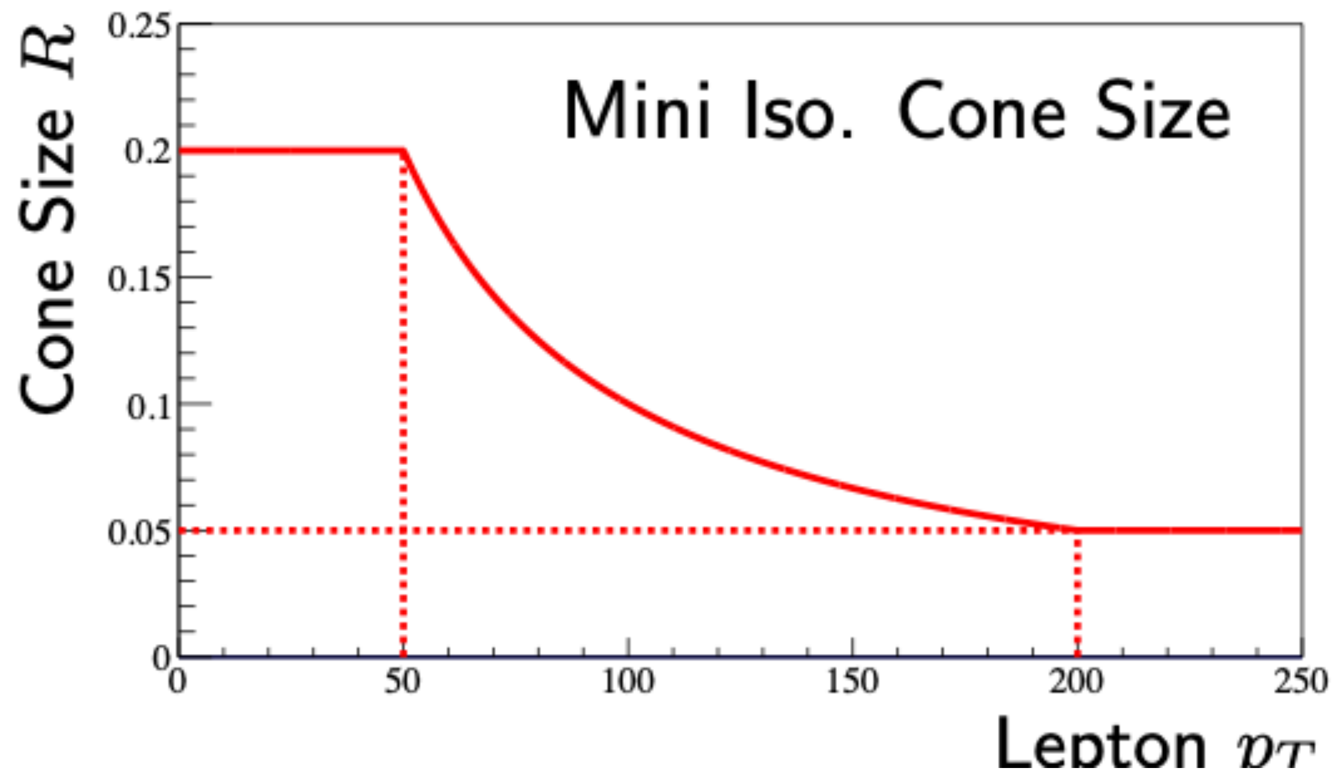
		Signal	ttX	Multiboson	Flip	Fake	Other Bkgs
Arnab	ee	0.347	13.292	1.653	4.395	8.266	1.821
	em	1.042	34.883	4.339	6.695	33.024	2.658
	mm	0.603	22.964	1.426	0.0	31.321	1.599
	Tot	1.991 -6%	71.138 +11%	7.418	11.089	71.611 +69%	6.078
Benjamin	ee	0.265	10.503	1.215	3.215	4.904	1.169
	em	1.038	31.181	3.710	4.750	18.120	2.047
	mm	0.803	22.378	0.954	0.0	19.097	1.355
	Tot	2.106	64.063	5.878	7.965	42.121	4.571

0.187 σ

0.267 σ

35% reduction on significance at $M_{T'}$ = 700 GeV. It is even worse at 1 TeV, **> 50 %**

Different Isolation variables available in CMS



- For boosted two-body decay:

$$\Delta R_{\text{daughters}} \approx \frac{2m_{\text{mother}}}{p_{T,\text{mother}}}$$

- Mini isolation: use cone size of

$$R = \begin{cases} 0.2, & p_{T,\text{lep}} \leq 50 \text{ GeV} \\ \frac{10 \text{ GeV}}{p_{T,\text{lep}}}, & p_{T,\text{lep}} \in (50 \text{ GeV}, 200 \text{ GeV}) \\ 0.05, & p_{T,\text{lep}} \geq 200 \text{ GeV} \end{cases}$$

Different Isolation variables available in CMS

Lepton MVA ID

Variables also used in Multi-Iso

Variables	Description
p_T	**Transverse momentum**
$\|\eta\|$	**Pseudorapidity** (absolute value)
relIso0p3	**Relative isolation**, scalar p_T sum of PF objects in dR = 0.3
miniRelIsoCharged	**Relative mini isolation** with p_T-dependent cone size including charged (or neutral) PF objects
miniRelIsoNeutral	
jetNDauChargedMVASel	Properties w.r.t. the **closest jet** (in dR = 0.4) using JEC applied only to its hadronic component: number of charged particles in the jet; fraction of the lepton momentum in transverse direction to the jet axis; ratio between the lepton and jet p_Ts; b tagging probability (***DeepCSV*** ➜ ***DeepJet***).
jetPtRelv2	
min(jetPtRatio,1.5)	
jetBTag	
sip3d	**Impact parameters**: 3D signed impact parameter significance; transverse and longitudinal impact parameters w.r.t. primary vertex
log(|dxy|)	
log(|dz|)	
MVA ID score (electrons) / segmentCompatibility (muons)	POG electron **MVA ID discriminant** (***ElectronMVAEstimatorRun2Spring16GeneralPurposeV1Values*** ➜ ***ElectronMVAEstimatorRun2Fall17NoIsoV2Values***) / **compatibility of track segments** in the muon system with the expected pattern of a minimum ionizing particle

Results with Different-Isolation

- We are trying several variations other than multi-isolation.

Different Iso		Signal	ttX	Multiboson	Flip	Fake	Other Bkgs	Significance
Multi-Iso	Tot	2.106	64.063	5.878	7.965	42.121	4.571	0.267
Std-Iso	Tot	1.991	71.138	7.418	11.089	71.611	6.078	0.187
Mini-Iso	Tot	2.991	65.08	6.318	8.95	45.611	6.078	0.214
Lepton-MVA Tight	Tot	2.014	63.463	5.948	10.078	50.873	5.78	0.227
Lepton-MVA Medium	Tot	2.289	64.584	6.133	11.073	51.08	4.433	0.264

For the results with Lepton-MVA, we have considered di-lepton trigger paths as well.
We are is progress to produce the results for higher mass points.

Back up

Analysis Note: AN-2022/174, PAS: B2G-24-017

Multi-Isolation

- The relative mini isolation I^{rel}_{mini} [54] is defined as follows:

$$I^{rel}_{mini} = \frac{\sum_R \left(p_T(h^{\pm})\right) + \max\left(0, \sum_R \left(p_T(h^0) + p_T(\gamma) - \rho A \frac{R^2}{0.3}\right)\right)}{p_T(l)}, \tag{1}$$

  where ρ is the pileup energy density, $A(e)$ the effective area defined in Tab. 18, and where $\sum_R \left(p_T(h^{\pm})\right)$, $\sum_R \left(p_T(h^0)\right)$, and $\sum_R \left(p_T(\gamma)\right)$ refer to the sum of the transverse momentum of the respective charged hadrons, neutral hadrons, and photons, within a cone R depending on the electron p_T:

$$R = \frac{10}{\min\left(\max\left(p_T(l), 50\right), 200\right)}. \tag{2}$$

  Requiring I^{rel}_{mini} below a given threshold ensures that the electron is locally isolated, even in topologies where its transverse momentum exceeds a hundred of GeV. The impact of pileup is mitigated, using the effective area correction. This criterion is applied on top of the cut-based ID criterion.

- p_T^{ratio} is defined as follows:

$$p_T^{ratio} = \frac{p_T(e)}{p_T(jet)}, \tag{3}$$

Multi-Isolation

- p_T^{rel} is defined as follows:

$$p_T^{rel} = \frac{|(\overrightarrow{p}(jet) - \overrightarrow{p}(l)) \times \overrightarrow{p}(l)|}{|\overrightarrow{p}(jet) - \overrightarrow{p}(l)|}. \quad (4)$$

  Requiring p_T^{rel} above a given threshold allows recovering electrons from accidental overlap with jets. If the jet and the electron are spatially separated, the numerator will be indeed large and the denominator small. The jet energy corrections are only applied to the hadronic part of the jet.

An electron is considered isolated if the following conditions are satisfied:

$$I_{mini}^{rel} < I_1 \text{ AND } \left(p_T^{ratio} > I_2 \text{ OR } p_T^{rel} > I_3\right). \quad (5)$$

Isolation	Muon WP		Electron WP	
Year	2016	2017-2018	2016	2017-2018
I_1	0.16	0.11	0.12	0.07
I_2	0.76	0.74	0.80	0.78
I_3	7.2	6.8	7.2	8.0

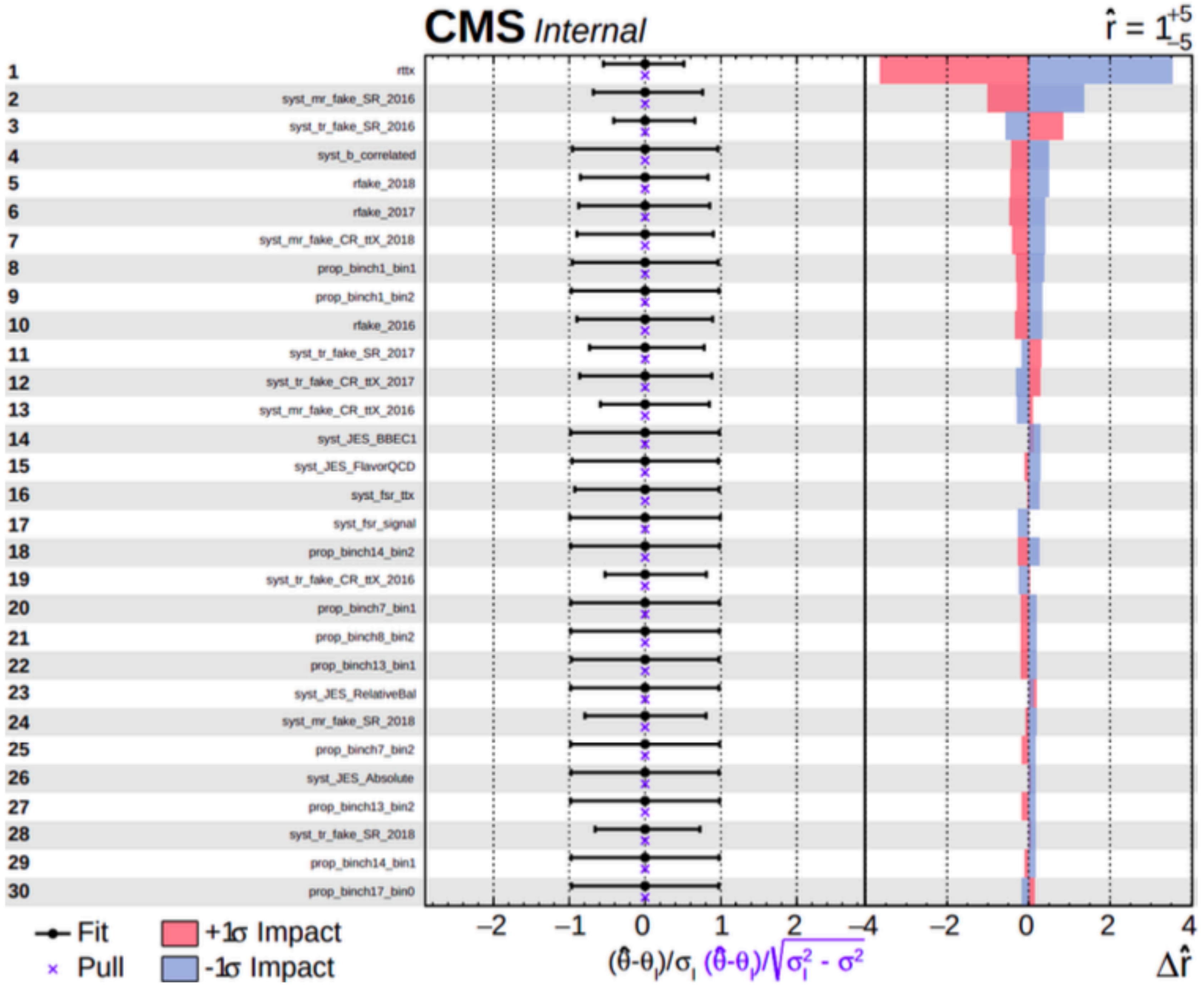
Table 19: Isolation WPs for both electrons and muons for 2016, 2017 and 2018.

Results

- Profile likelihood fit is performed using **Combine** package.

Systematic uncertainty source	Correlation between regions	Correlation between years	Correlation between processes
Luminosity, corr. component	✓	✓	Total except DD processes
Luminosity, uncorr. component	✓	-	Total except DD processes
Pileup	✓	✓	Total except DD processes
Pileup JetID	✓	✓	Total except DD processes
L1 Trigger ECAL prefiring	✓	✓	Total except DD processes
B-tagging (bottom), corr. component	✓	✓	Total except DD processes
B-tagging (bottom), uncorr. component	✓	-	Total except DD processes
B-tagging (light), corr. component	✓	✓	Total except DD processes
B-tagging (light), uncorr. component	✓	-	Total except DD processes
Electron trigger, syst. component	✓	✓	Total except DD processes
Electron trigger, stat. component	✓	-	Total except DD processes
Electron reconstruction	✓	✓	Total except DD processes
Electron ID	✓	✓	Total except DD processes
Muon trigger, syst. component	✓	✓	Total except DD processes
Muon trigger, stat. component	✓	-	Total except DD processes
Muon reconstruction, syst. component	✓	✓	Total except DD processes
Muon reconstruction, stat. component	✓	-	Total except DD processes
Muon ID, syst. component	✓	✓	Total except DD processes
Muon ID, stat. component	✓	-	Total except DD processes
Muon isolation, syst. component	✓	✓	Total except DD processes
Muon isolation, stat. component	✓	-	Total except DD processes
JES Absolute, corr. component	✓	✓	Total except DD processes
JES Absolute, uncorr. component	✓	-	Total except DD processes
JES BBEC1, corr. component	✓	✓	Total except DD processes
JES BBEC1, uncorr. component	✓	-	Total except DD processes
JES FlavorQCD	✓	✓	Total except DD processes
JES RelativeSample	✓	-	Total except DD processes
JES RelativeBal	✓	✓	Total except DD processes
MC modeling MR	✓	-	Total except DD processes
MC modeling MR/Target region	Total except DD processes	-	Total except DD processes
Top quark p_T reweighting	✓	✓	Total except DD processes
PDF	✓	✓	Total except DD processes
Renormalization and factorization scale	✓	✓	Total except DD processes
ISR	✓	✓	Total except DD processes
FSR	✓	✓	Total except DD processes
Normalization of backgrounds	✓	✓	-

DRAFT



Analysis regions

Preselection (Cut 0)

Muon	Pt > 30 GeV, |η| < 2.4, tight ID, optimized selection on isolation, distance to Primary Vertex (PV), 3D Impact parameter significance (SIP_{3D}) and charge misreconstruction veto.
Electron	Pt > 40 GeV, |η| < 2.5, tight ID, optimized selection on isolation, distance to PV, SIP_{3D}, number of hits, photon conversion veto and charge misreconstruction veto.
Jet	Pt > 30 GeV, |η| < 2.4, tight ID and removed overlap between the jets and the leptons in a cone of ΔR < 0.4.
B-jet	Pt > 30 GeV, |η| < 2.4, tight ID and medium DeepJet WP. Identical overlap condition as the jets.

Signal Selection:

- The two leptons must be back-to-back.
- The T' has a large mass so we expect the 2 leptons and the b-jet to have high p_T.
- The top quark must have a non-hadronic decay.

Cut 1: $\Delta R(l_1, l_2) > 1.8$.
Cut 2: $p_T^{l_1} + p_T^{l_2} > 160\ GeV$
Cut 3: $\min(|M_{3j} - M_{top}| > 34\ GeV)$

- Falling $M_T^{T'}$ distribution needed to estimate the background.
- Background efficiency in each $M_T^{T'}$ bin should be the same after each cut to keep the same shape.
- Solution: cut optimization using quantiles of the background yield.

Background: (two types)

- **Fake leptons:** The largest contributor to this category is the $t\bar{t}1l$ process (63.3% of the fake leptons in the SR, with a contribution of the $t\bar{t}X$, $t\bar{t}2l$, *tX*(*W/q*), and multiboson processes of 17.9%, 10.1%, 6.4%, and 2.3% respectively).
- **Flip leptons:** leptons whose charge has been misidentified. The largest contributor to this category is the $t\bar{t}2l$ process (95.3% of the flip leptons in the SR).

$t\bar{t}X$ Control region:

- targets the *ttX* processes.
- Reverted cut 3.
- one of the two top quarks decaying hadronically.

$t\bar{t}2l$ Measurement region:

- targets the charge flip process.
- Cut 0 is modified to require 2 OS leptons.
- a top quark pair is produced with both top quarks decaying leptonically.

$t\bar{t}1l$ Measurement region:

- targets the non prompt process.
- Cut 0 is modified to require one of the SS leptons must pass the fakeable requirements but fail the tight requirements.