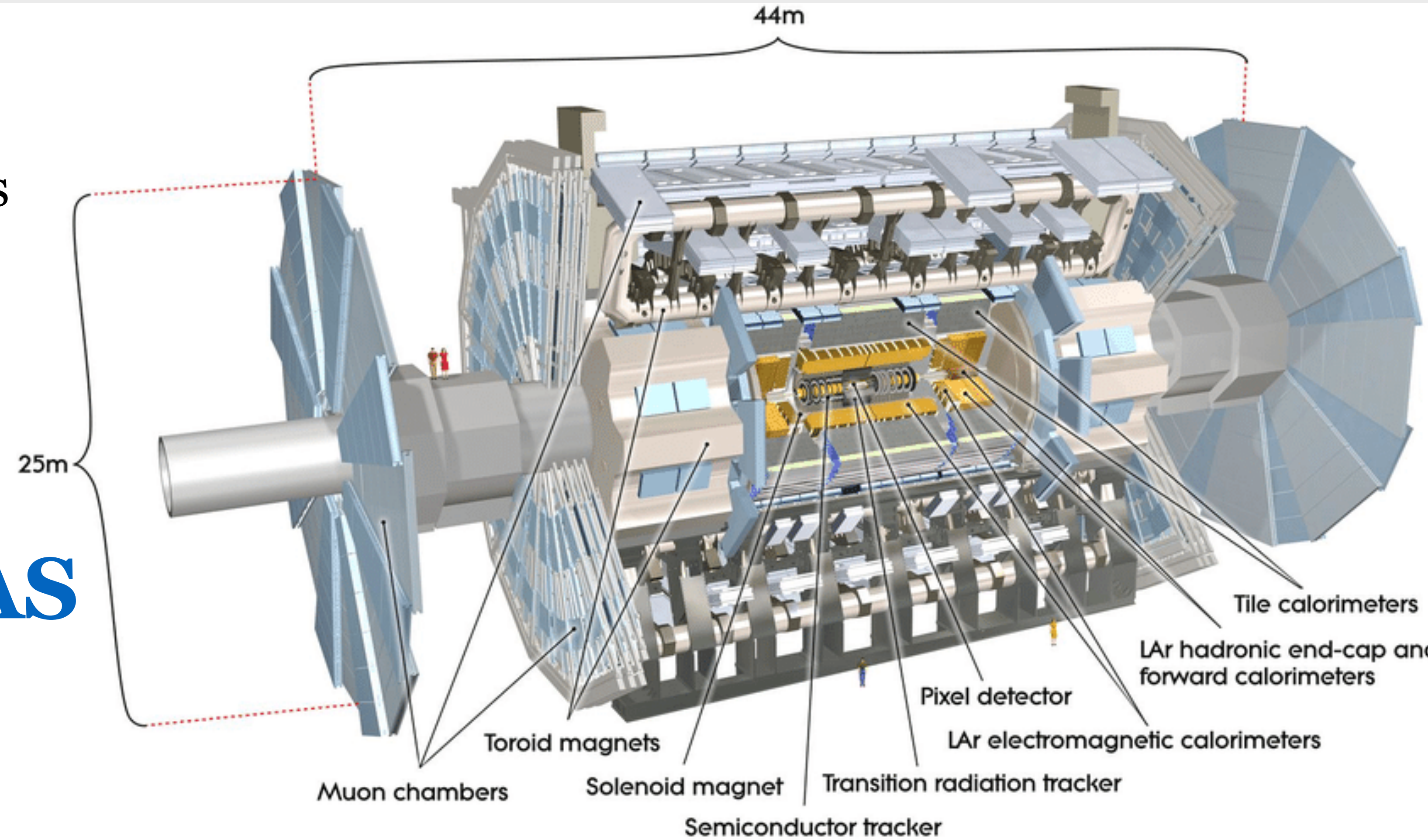
Heavy neutral lepton searches at the LHC

Federico Scutti
University of Melbourne
on behalf of the
ATLAS and CMS collaborations

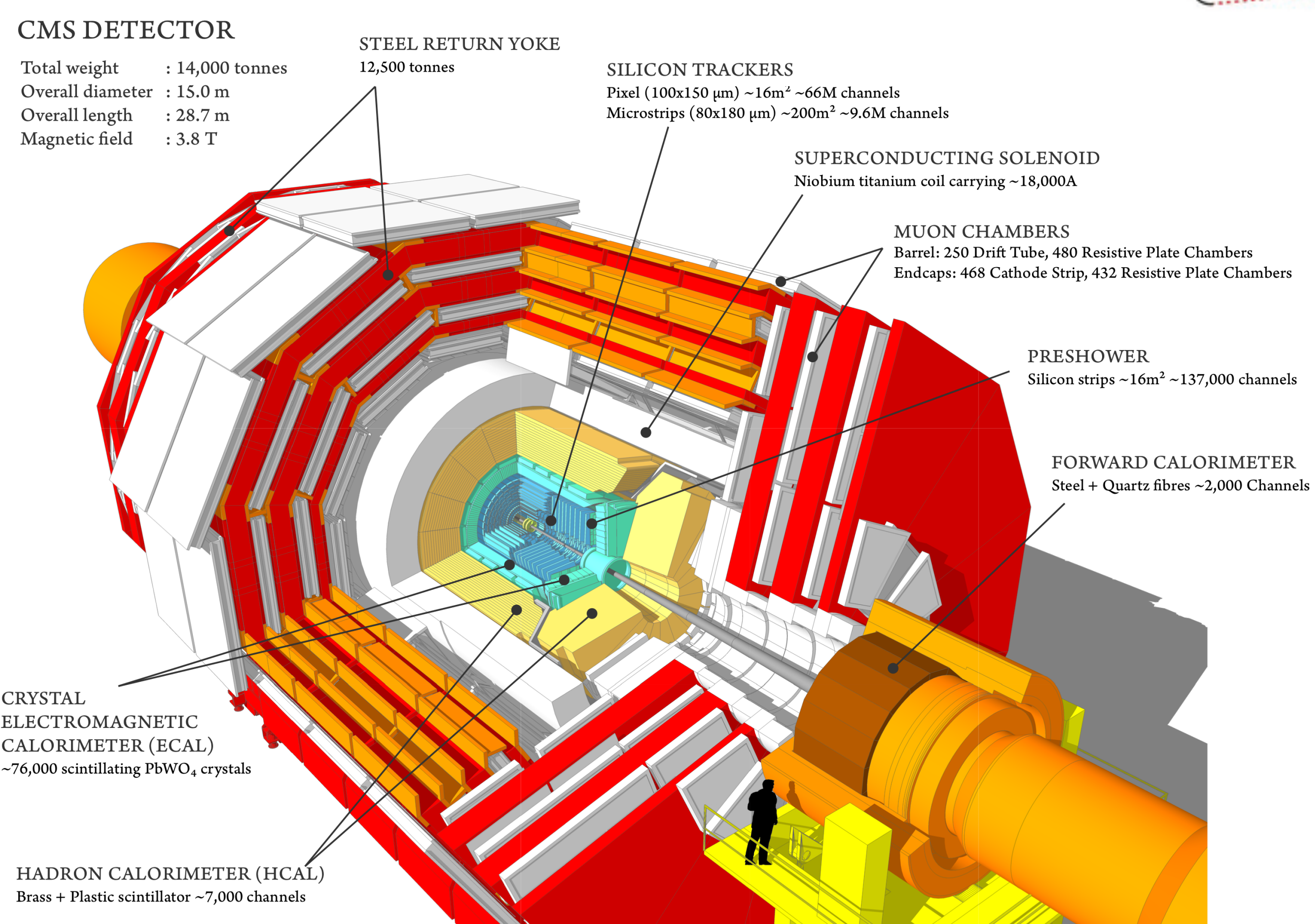
ATLAS and CMS

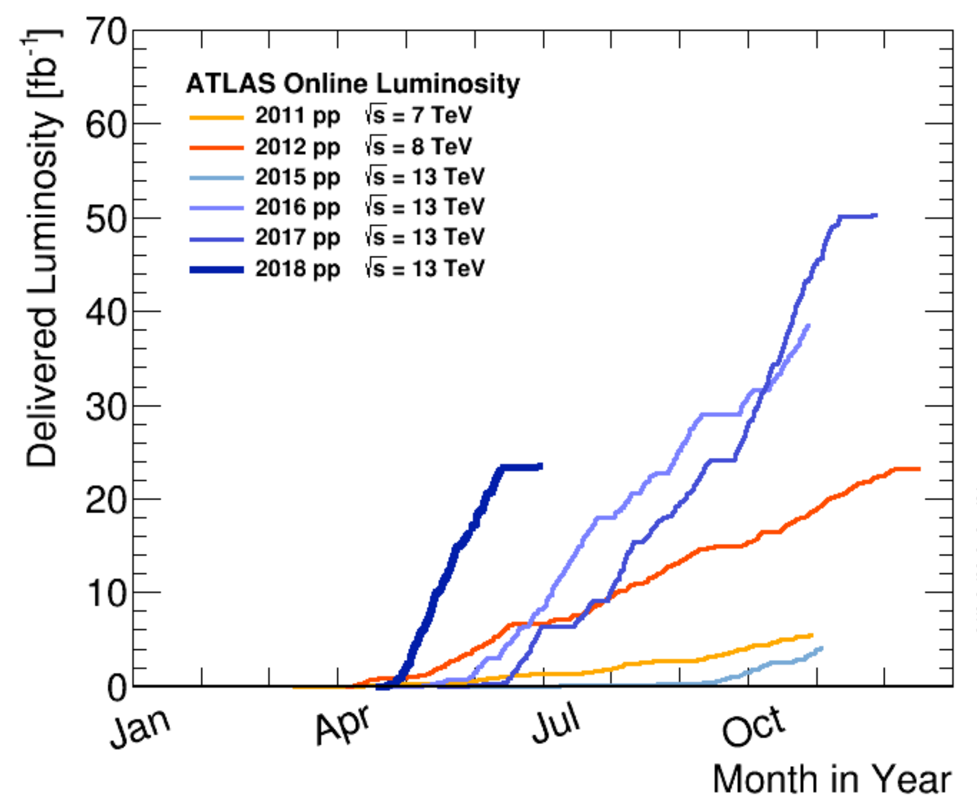
- Multi-purpose experiments surrounding the interaction regions where energetically symmetric proton beams collide.
- pp collisions from LHC at √s = 13 TeV in Run-II.



ATLAS

CMS





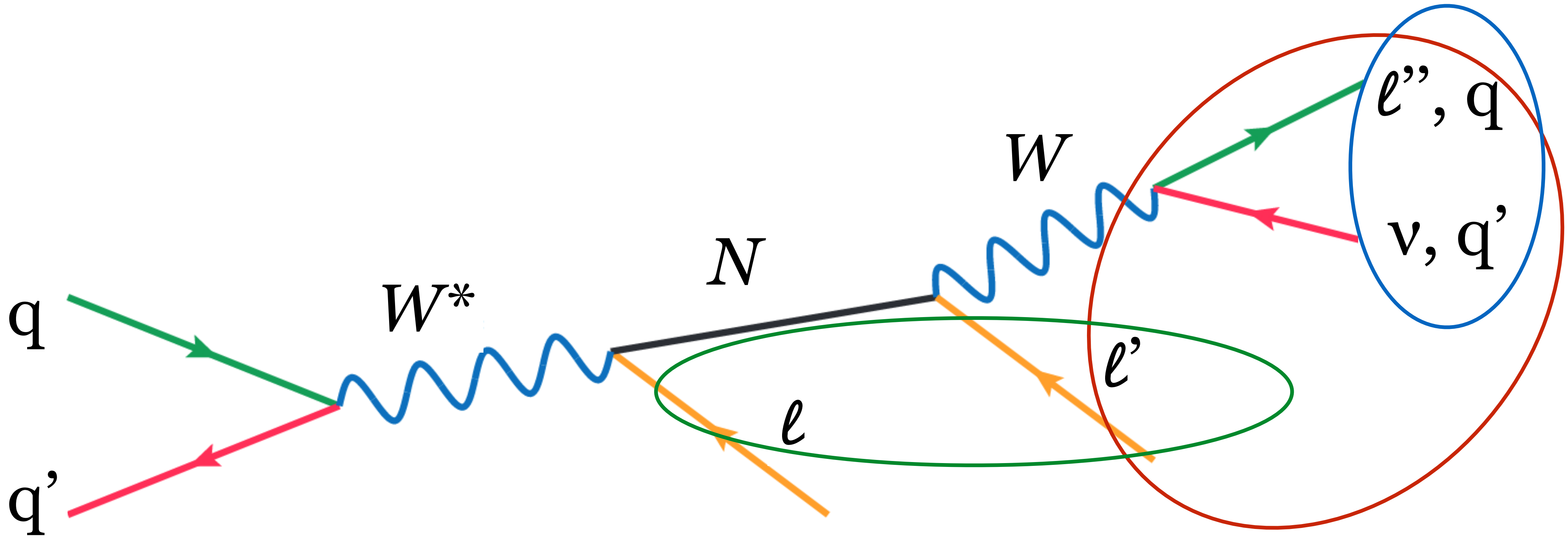
Theory overview: See-Saw models

- Neutrino masses can be accommodated by EWSB, but a ν_R singlet is trivial under the SM gauge group.
- If EWSB holds then Yukawa couplings must be much smaller than for other SM particles, $\lambda_\nu \approx 10^{-12}$.
- Since ν_R is neutral, Majorana mass terms are possible and decoupled from SM EWSB.
- **See-saw mechanisms** based on introducing Majorana masses m_M in addition to Dirac ones m_D.

$$\mathbf{M} = \begin{pmatrix} 0 & m_D \\ m_D & m_M \end{pmatrix} \Rightarrow m_D \ll m_M \Rightarrow m_{\nu,N} = \frac{m_M}{2} \mp \sqrt{\left(\frac{m_M}{2}\right)^2 + m_D^2}$$

- **Type-I**: SU(2) singlet fermion ***N***.
- **Type-II**: SU(2) triplet scalar $\mathbf{\Phi^{0,\pm,\pm\pm}}$.
- **Type-III**: SU(2) triplet fermion $\mathbf{\Sigma^{0,\pm}}$.

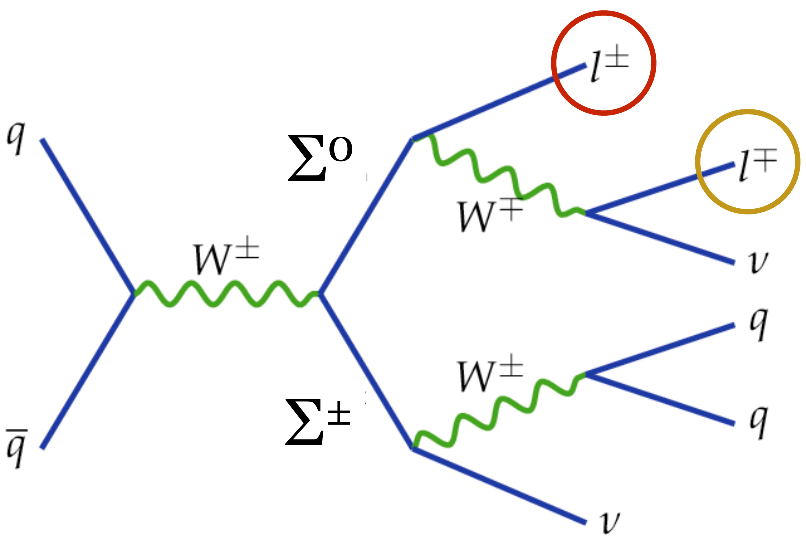
Type-I signatures

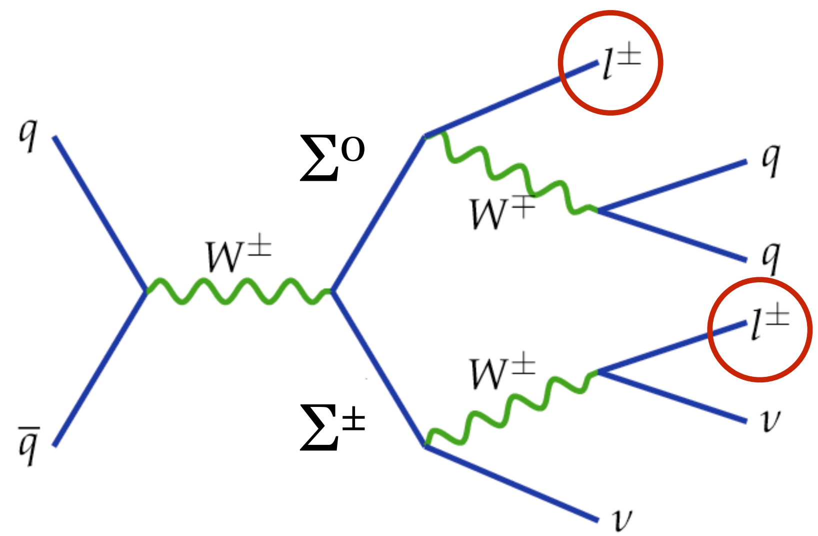


- In minimal Type-I, the heavy neutrino parameters, $\mathbf{m}_N$ and mixing matrix elements $|\mathbf{V}_{\nu N}|^2$ are free.
- Heavy neutrino produced via mixings with SM neutrinos.
- Search strategies based on m_N vs m_W hypothesis.
- **W*** is **on-shell** at very low m_N. **Off-shell** otherwise. Also:
  - $\mathbf{m}_N \ll \mathbf{m}_W$: soft and displaced *N* decay products.
  - $\mathbf{m}_N < / \lesssim / > \mathbf{m}_W$: hierarchies of $p_T(\ell)$ vs $p_T(\ell')$. E.g. ℓ' dominates at high $\mathbf{m}_N$.
  - $\mathbf{m}_N \gg \mathbf{m}_W$: boosted decay products (jets).

Type-III signatures

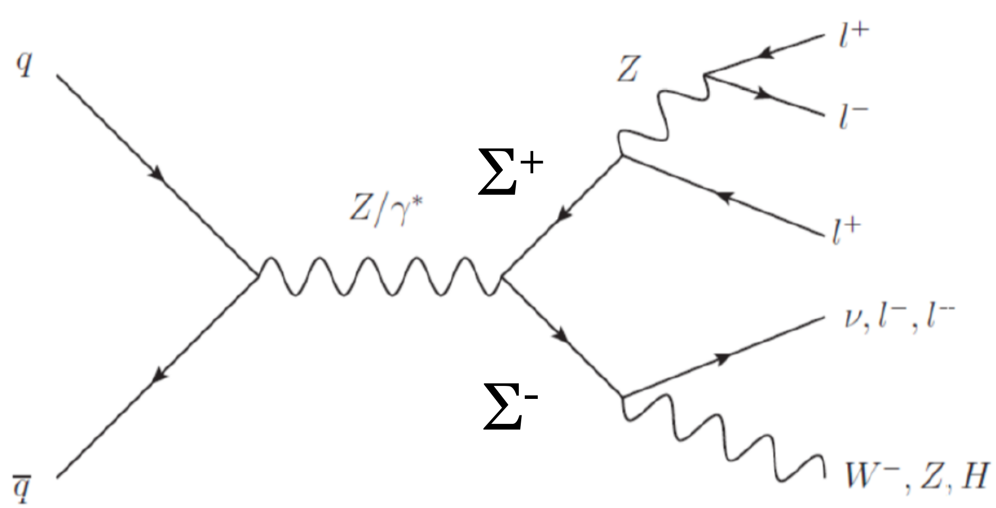
- Mass degenerate Σ^0 and $\Sigma^\pm$ due to gauge invariance. Only one free parameter.
- Production of Σ via gauge interaction.

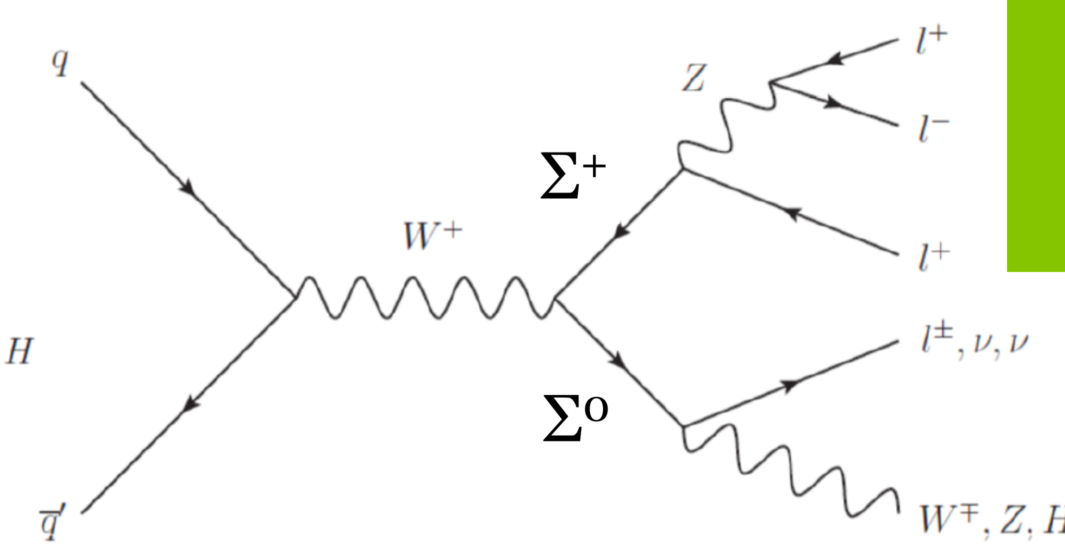




ATLAS

- **pp → $\Sigma^0\Sigma^\pm$ → $\ell\ell$qq**
- Two leptons in final state with same or opposite charge.
- Other decay modes found negligible in final selection.





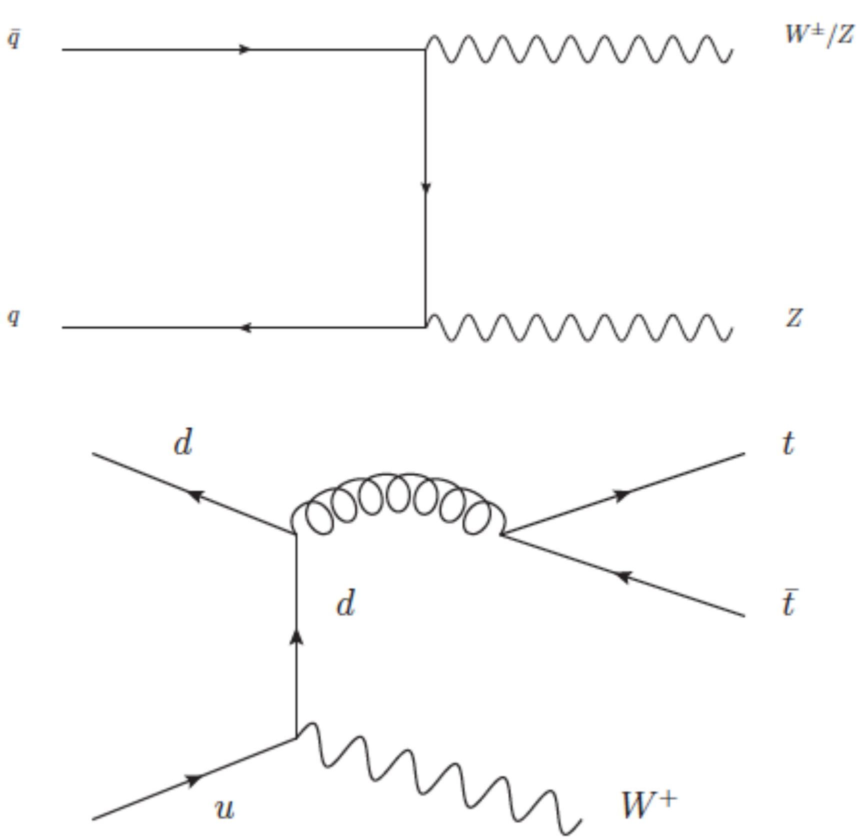
CMS

- **pp → $\Sigma^0\Sigma^\pm$ / $\Sigma^\mp\Sigma^\pm$**
- Purely multi-leptonic
  - $\Sigma^0 \rightarrow W^\mp \ell^\pm$
  - $\Sigma^0 \rightarrow Z$ / $H\nu_\ell$
  - $\Sigma^\pm \rightarrow Z$ / $H \ell^\pm$
  - $\Sigma^\pm \rightarrow W^\pm\nu_\ell$

Backgrounds

Prompt

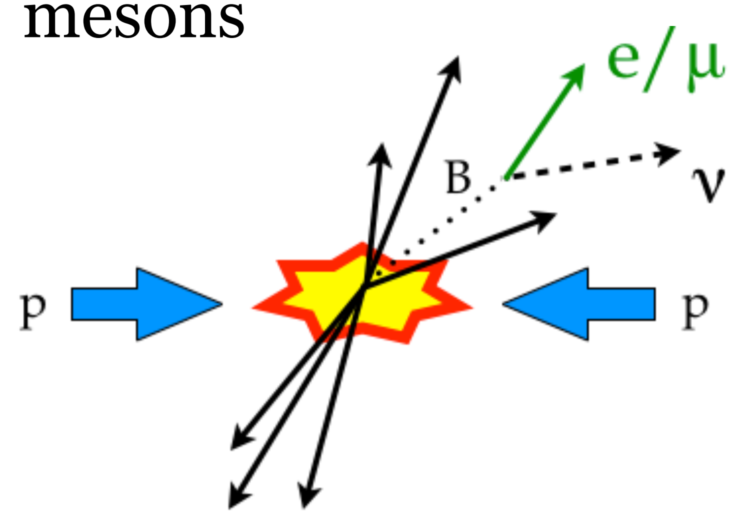
Real prompt leptons:
ZW, ZZ, ttW, ttZ, ttH, $W^{\pm}W^{\pm}$



Estimated with simulation

Mis-ID leptons

- Real electrons or muons from non-prompt decays, e.g. from heavy flavoured mesons

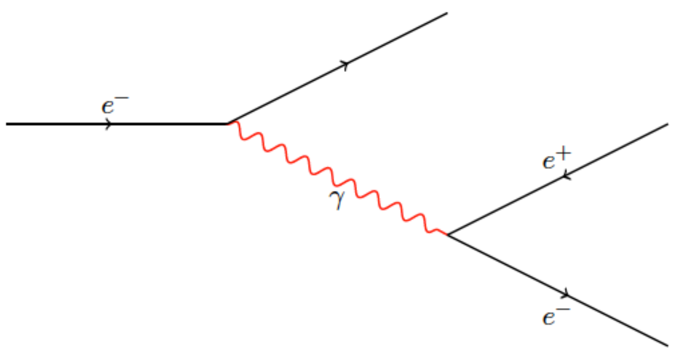


- Jets mis-reconstructed as electrons

Data-driven estimation

Mis-ID charge

Oppositely charged leptons with charge mis-identification:
Z/γ^{*}, ZZ, $W^{\pm}W^{\mp}$, tt



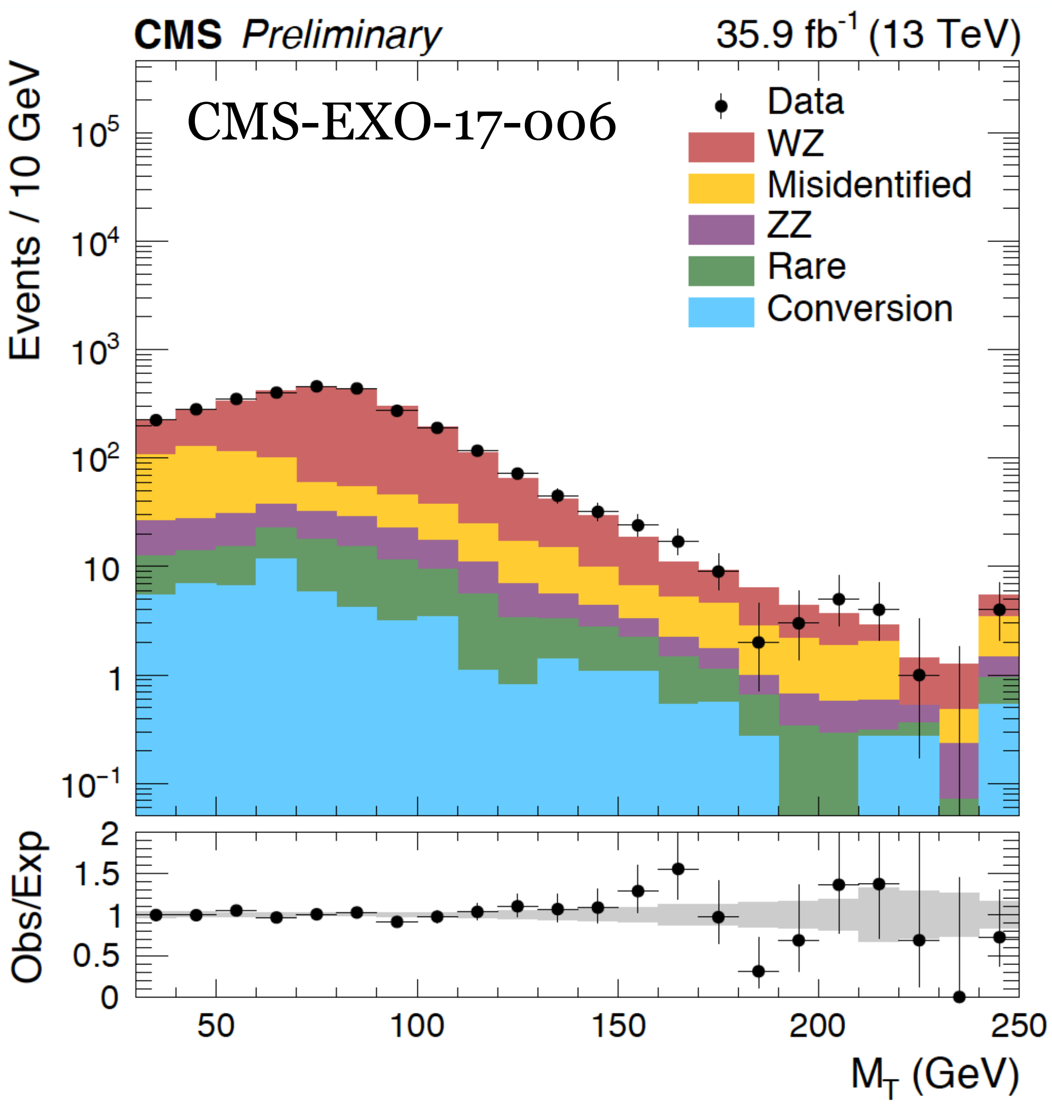
Mis-ID probability estimated from data

Background estimation

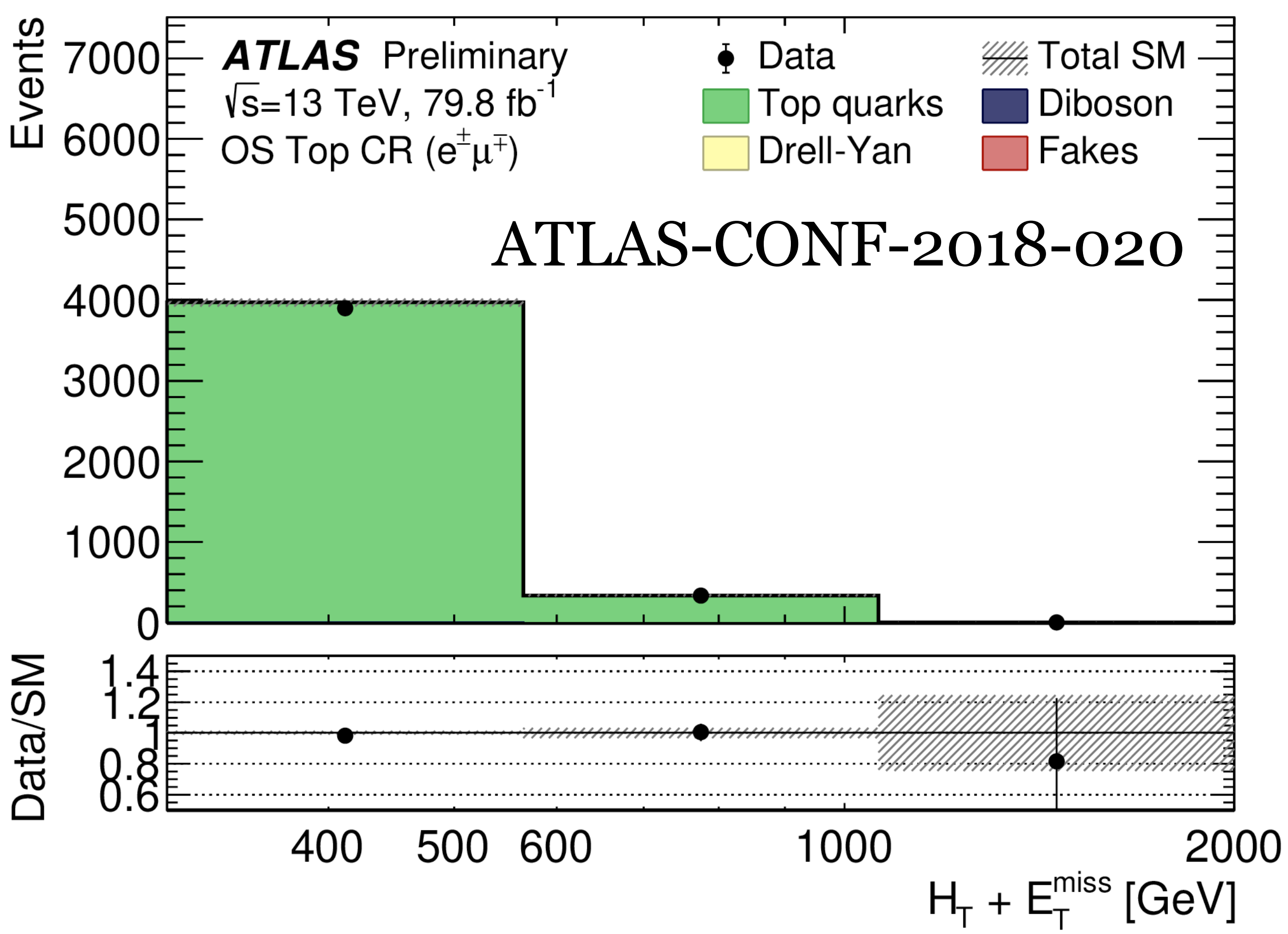
Prompt leptons

- Prompt contributions are estimated using simulated samples.
- Usually simulated @NLO accuracy
- Major contributions are normalised in dedicated control regions.
- Derive correction factors or include the control regions in the fit.

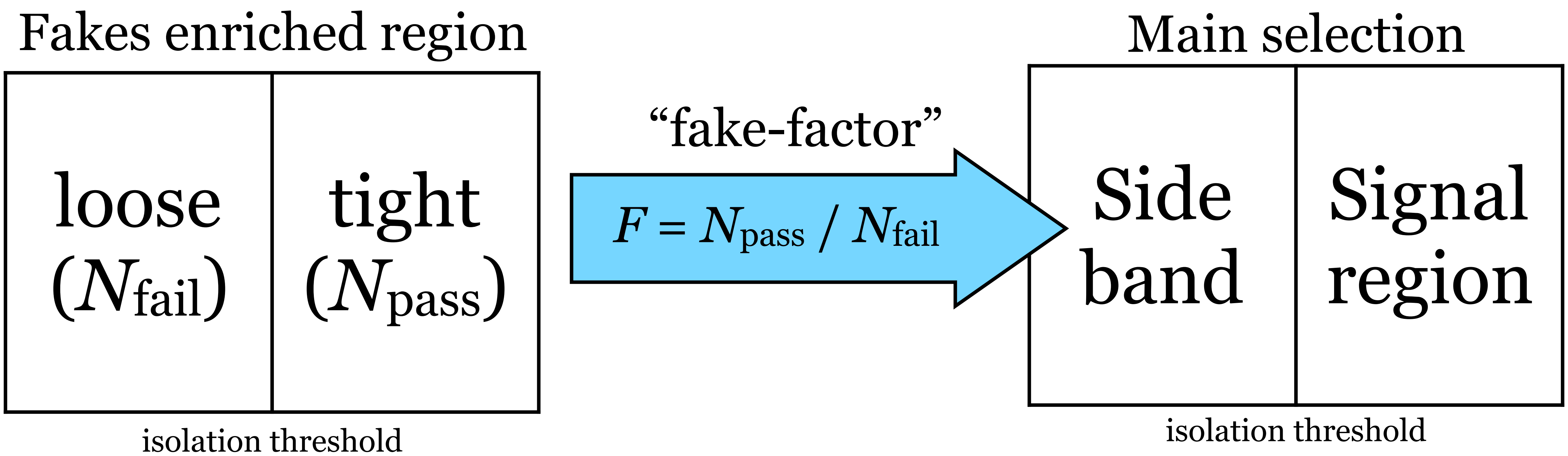
WZ →3ℓν control region

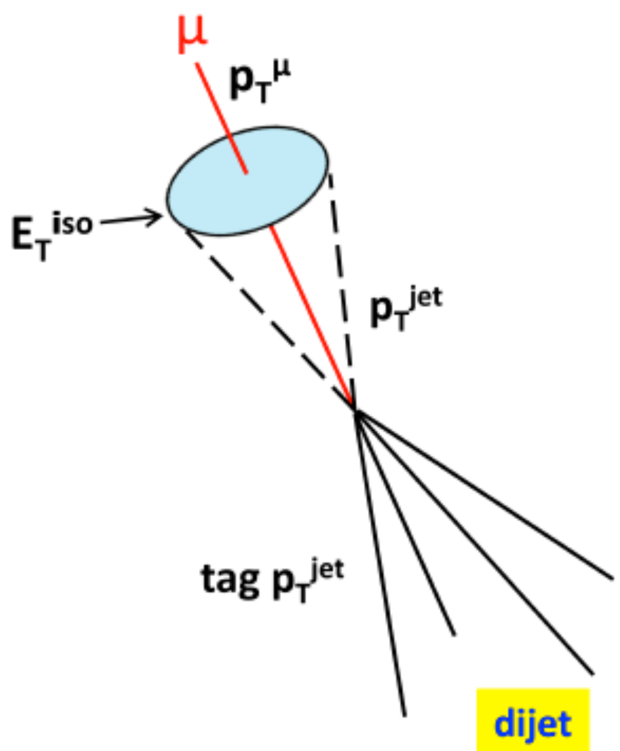


Top control region



Mis-identified leptons





Tag-and-probe selections on di-jet events

- Signal region extrapolation: e.g. two lepton case:

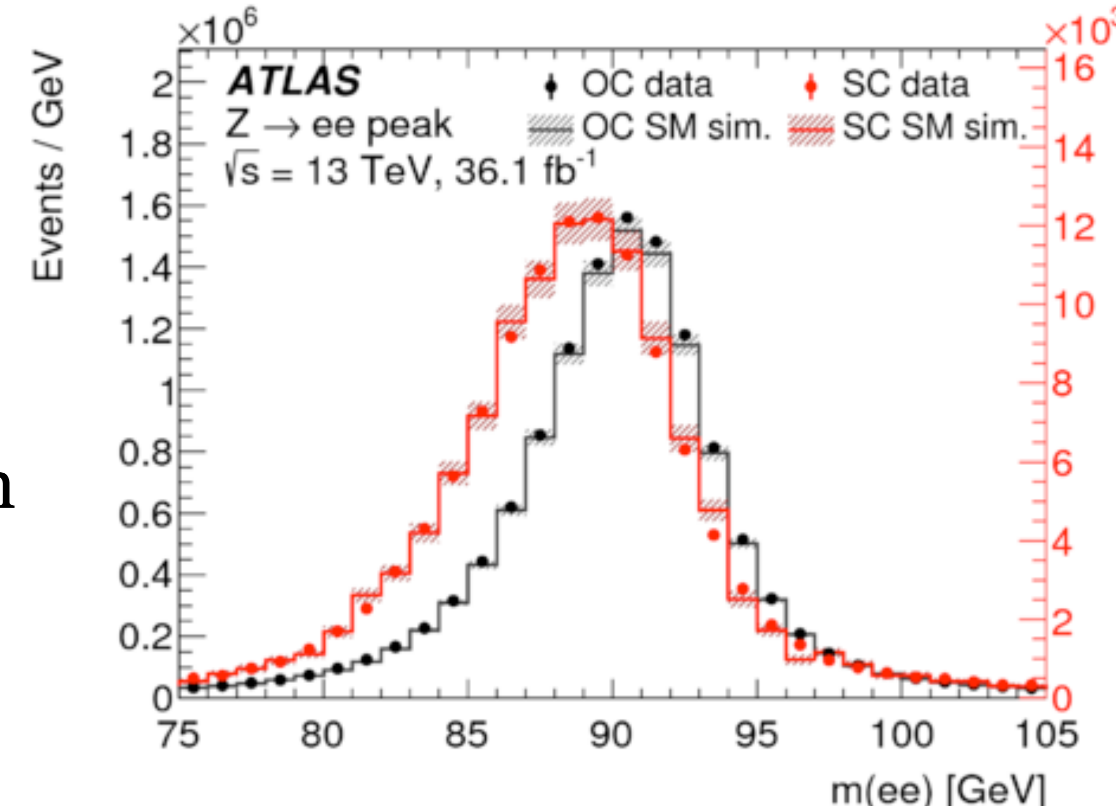
$$N_{TT}^{\text{fakes}} = \left[\sum_{TL} F_2 + \sum_{LT} F_1 - \sum_{LL} F_1 F_2\right]_{\text{data}} - \left[\sum_{TL} F_2 + \sum_{LT} F_1 - \sum_{LL} F_1 F_2\right]_{\text{prompt simulation}}$$

- Can be extended for more than two leptons
- Parameterisation of F based on lepton kinematic

Mis-identified charge

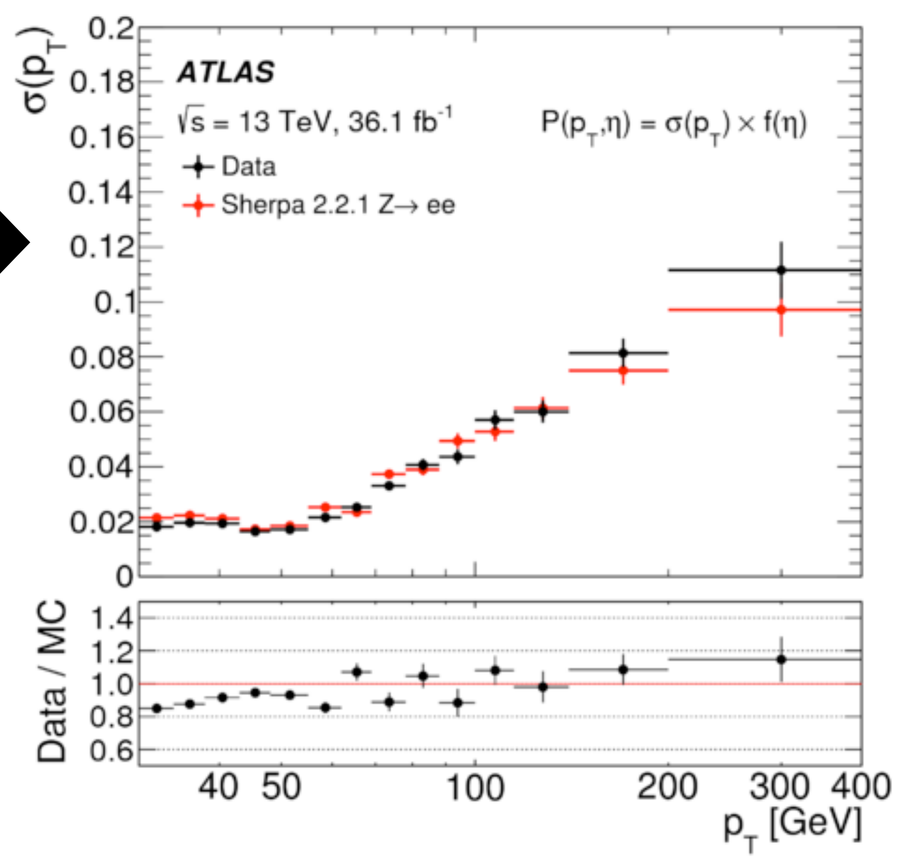
ATLAS example: ATLAS-CONF-2018-020

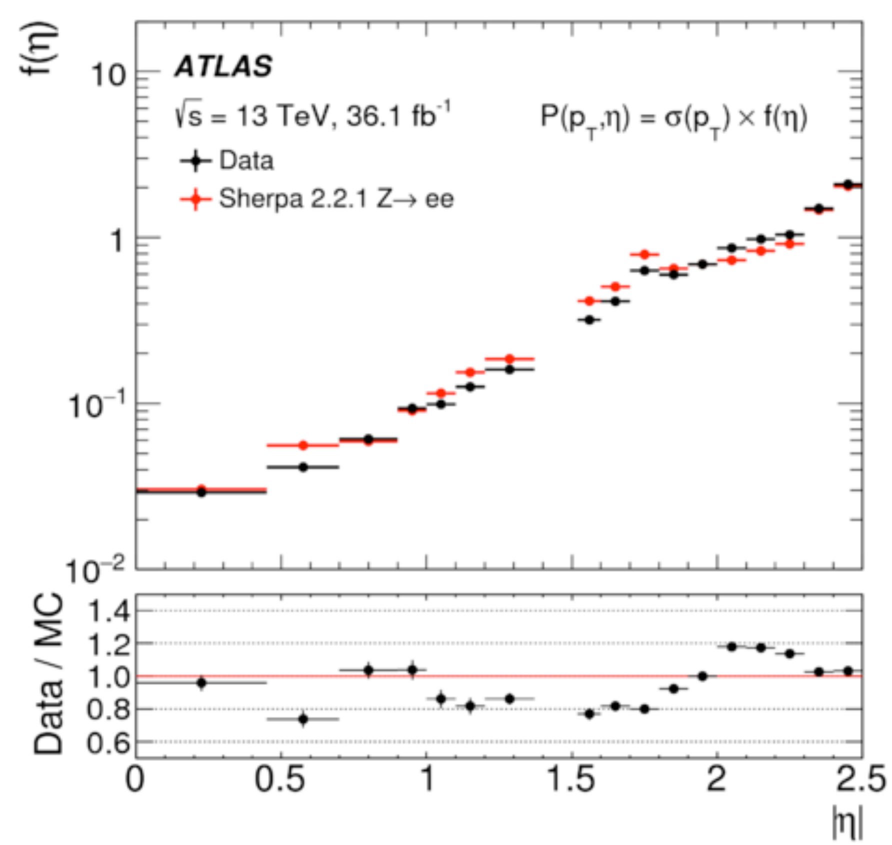
- $Z \rightarrow ee$ events used from data and simulation.
- Fit simultaneously opposite and same -charge events and separately for data and simulation.
- Derive parameterised probabilities and measure a correction based on data/simulation trends.
- Correction is applied to any simulated electron with mis-identified charge.



Mis-id probability: $P(p_T,\eta)=\sigma(p_T)\times f(\eta)$

corrections



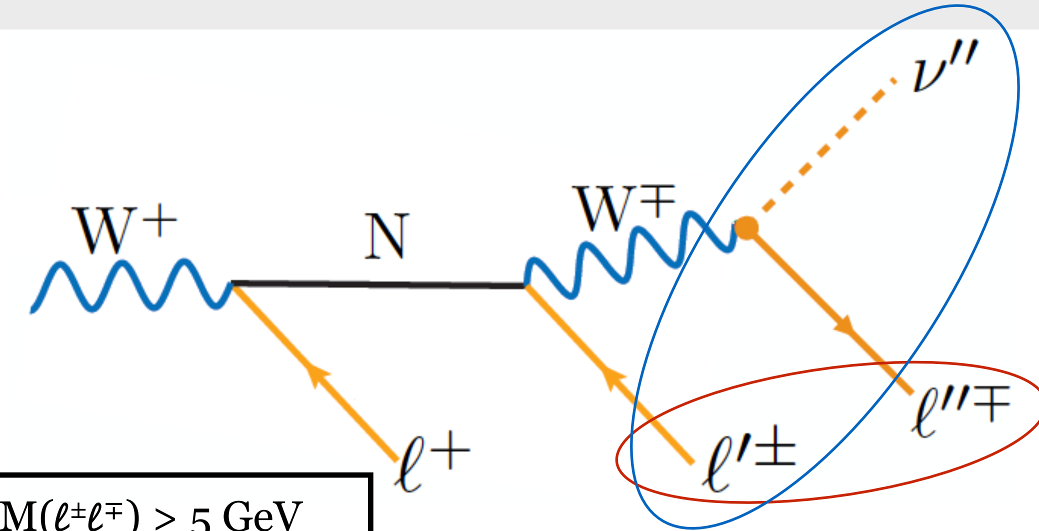


Type-I searches

Type-I - trilepton channel

CMS: 1802.02965

- Any mix of charge and flavour for *e* and μ.
- No mass peak due to neutrinos in W decays.
- Veto events with same-sign three leptons, b-jets or with lepton invariant masses consistent with m_Z.
- Binned in $p_T(\ell_{lead})$, $M(\ell^\pm\ell^\mp\ell^\pm)$, **$M_{min}(\ell^\pm\ell^\mp)$**, **$M_T(\ell',E_T^{miss})$**.

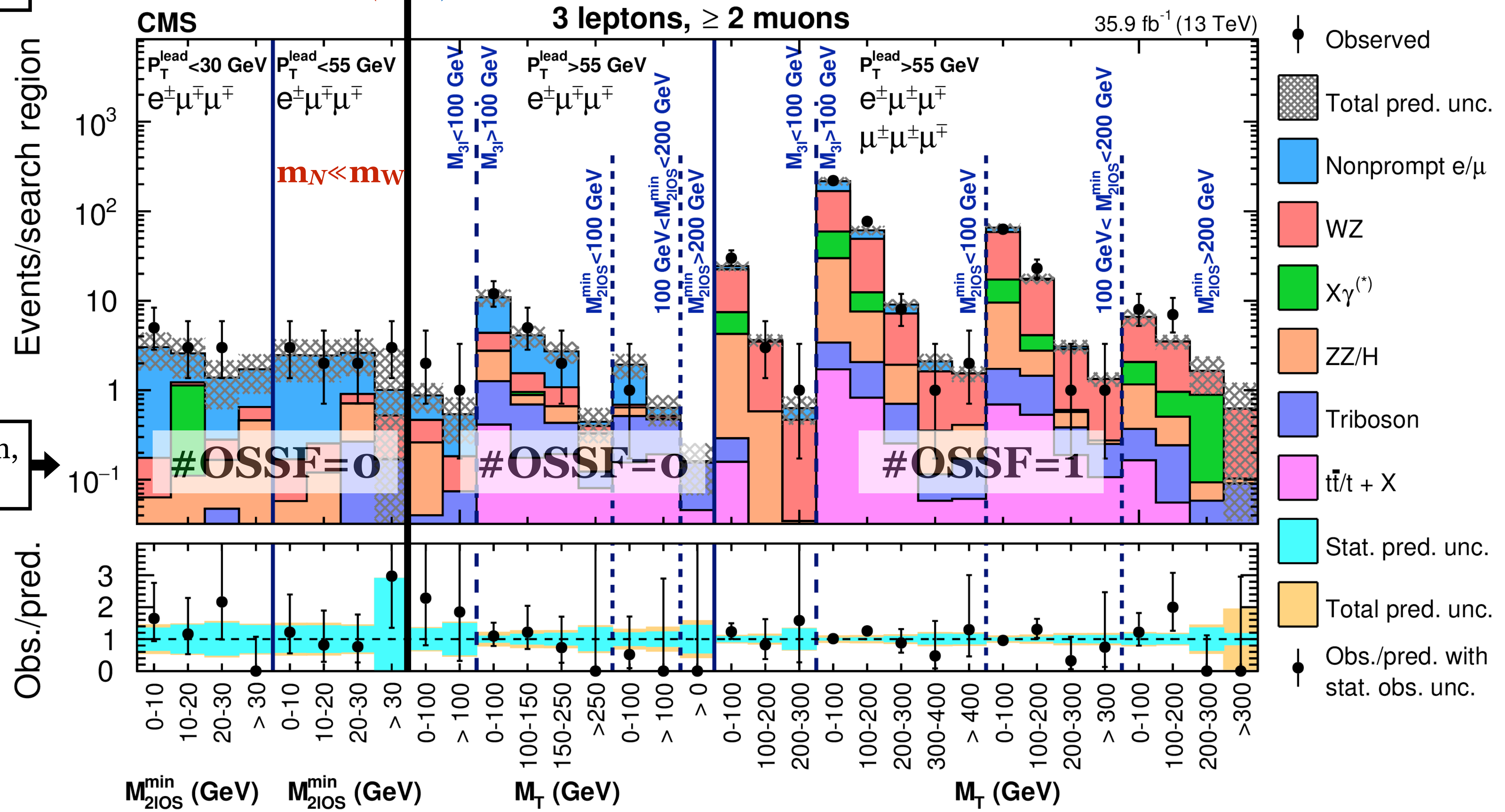


$M(\ell^\pm\ell^\mp\ell^\pm) < 80$ GeV, $E_T^{miss} < 75$ GeV

$m_N < m_W$ | $m_N > m_W$

$M(\ell^\pm\ell^\mp) > 5$ GeV

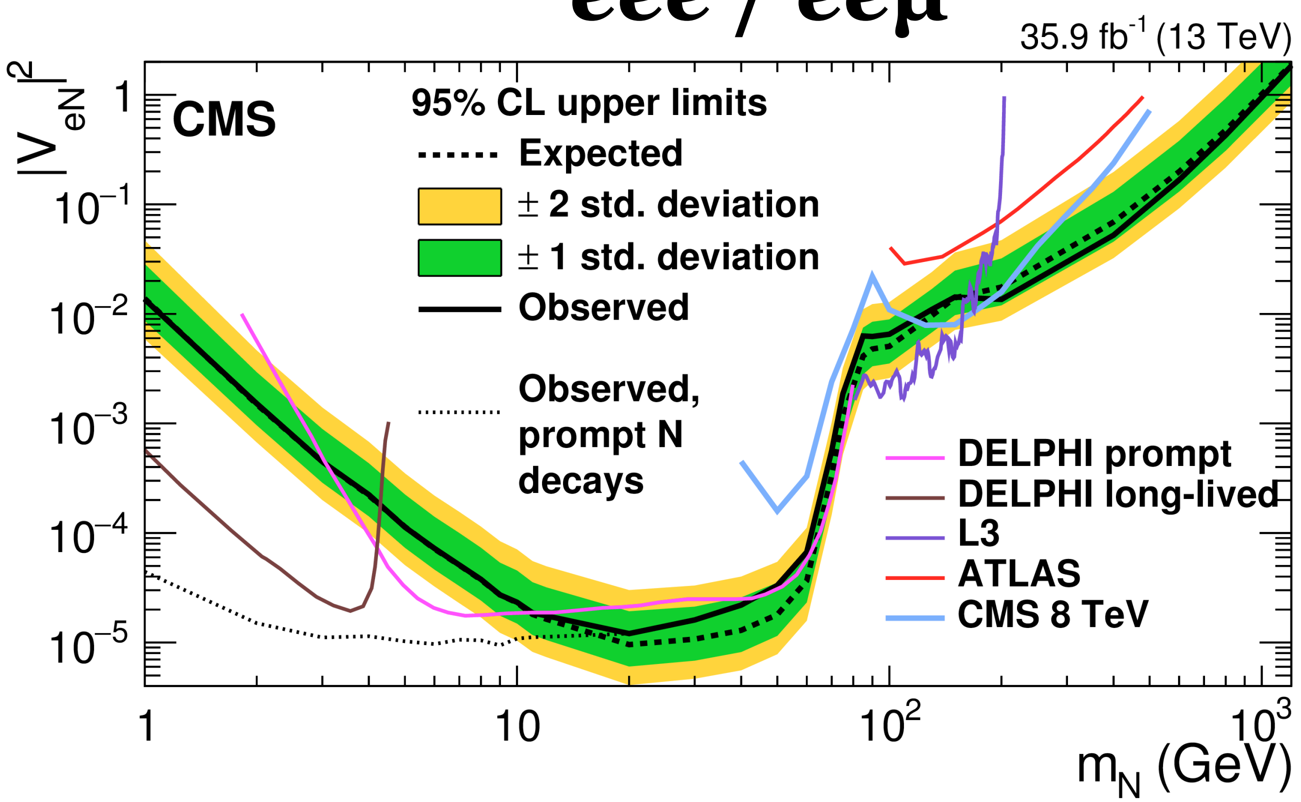
OSSF: opposite-sign, same-flavour



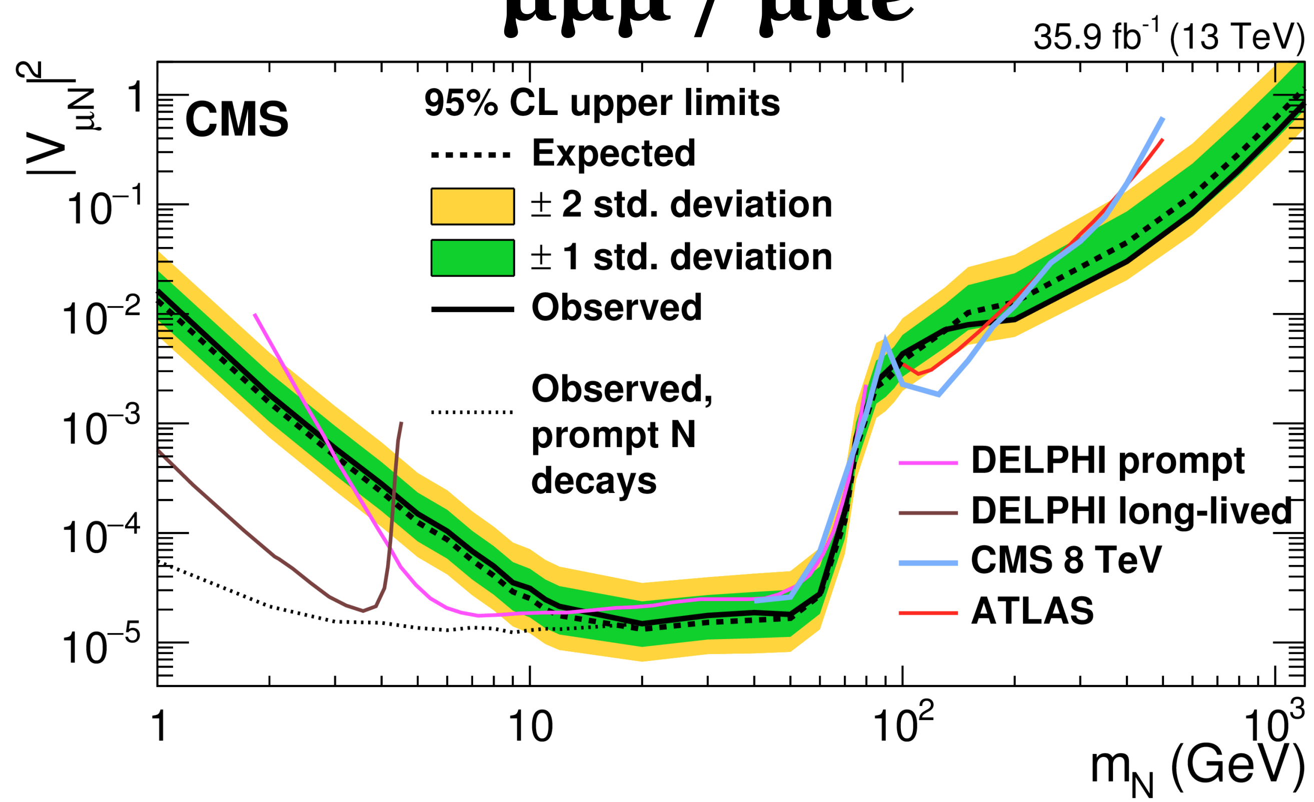
Type-I - trilepton channel

CMS: 1802.02965

eee / eeμ



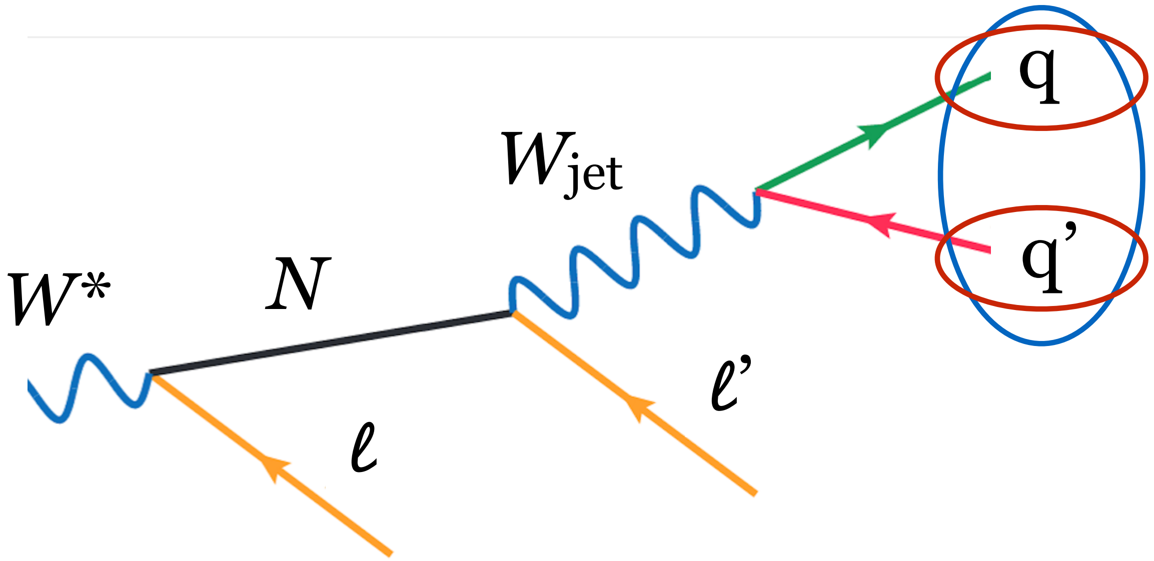
μμμ / μμe



- Elements of the mixing matrix $|V_{\nu N}|$ are varied independently and are non-zero for a single flavour at a time.
- Displaced *N* decays occur for $m_N \lesssim 20$ GeV.
  - $\tau_N \sim |V_{\nu N}|^{-2}\, m_N^{-5}$.
  - Efficiency correction taken into account at lower masses.

Type-I - dilepton channel

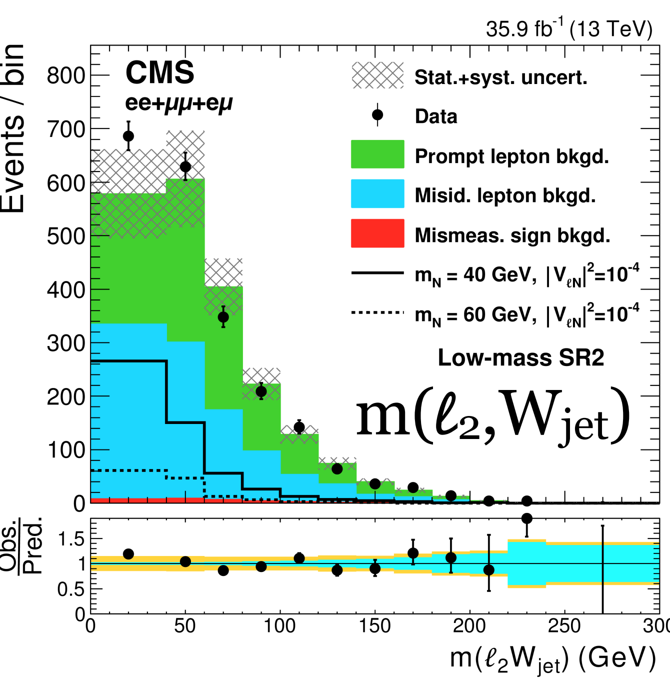
CMS: 1806.10905



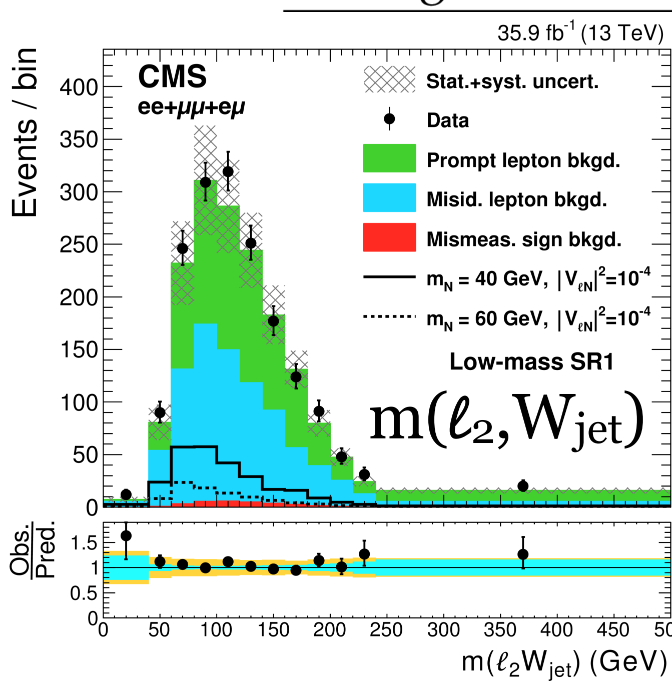
	Hierarchy	N res. jets	N merg. jets
low-mass SR2	$m_N < m_W$	1	0
low-mass SR1	$m_N \lesssim m_W$	≥2	0
high-mass SR1	$m_N > m_W$	≥2	0
high-mass SR2	$m_N \gg m_W$	≥0	≥1

- Includes gg/qq' → $N\ell^\pm$ and qγ → $Nq'\ell^\pm$
- Same-sign dileptons only.
- $p_T(\ell) \gtrsim 20$ GeV.
- All e/μ combinations.
- Optimised using W_{jet} and ℓ kinematics.

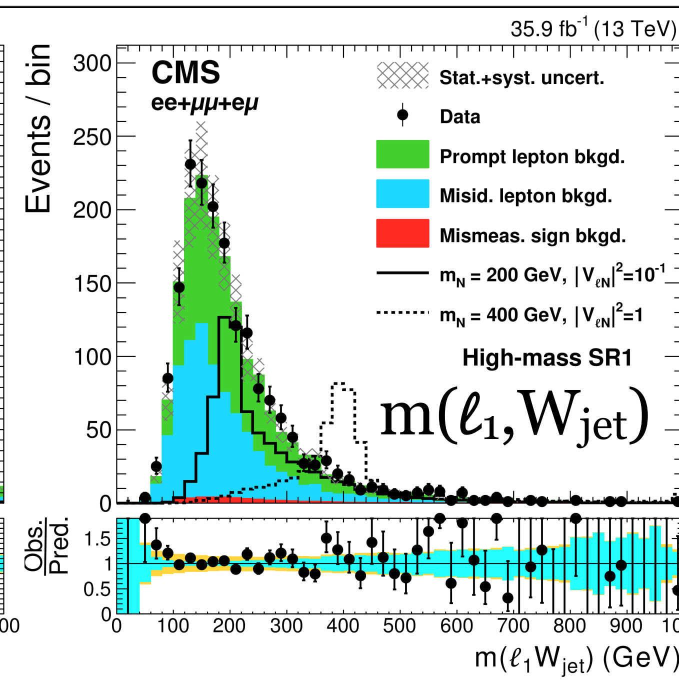
Region	p_T^{miss} (GeV)	$(p_T^{miss})^2/S_T$ (GeV)	$m(\ell^\pm\ell^\pm W_{jet})$ (GeV)	$m(W_{jet})$ (GeV)	p_T^j (GeV)
Low-mass SR1+SR2	<80	—	<300	—	>20
High-mass SR1	—	<15	—	30–150	>25
High-mass SR2	—	<15	—	40–130	>200



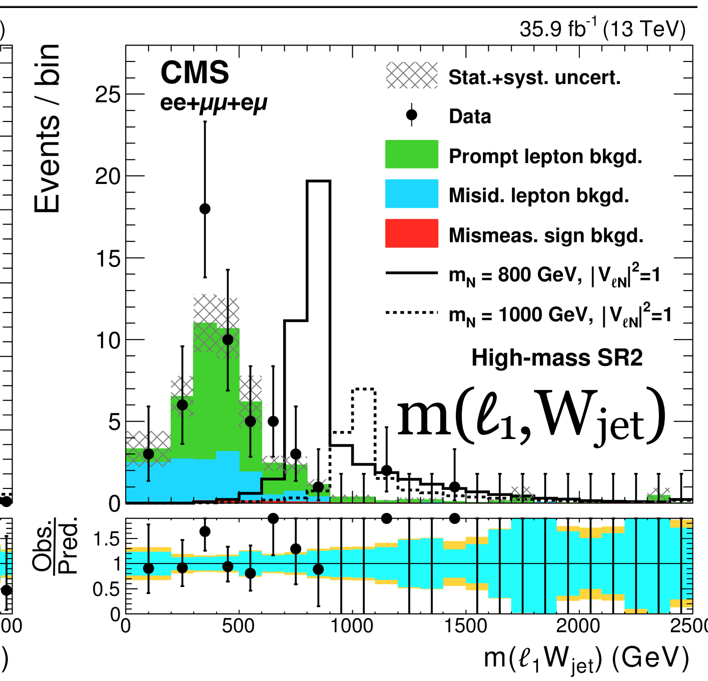
Low-mass SR2



Low-mass SR1



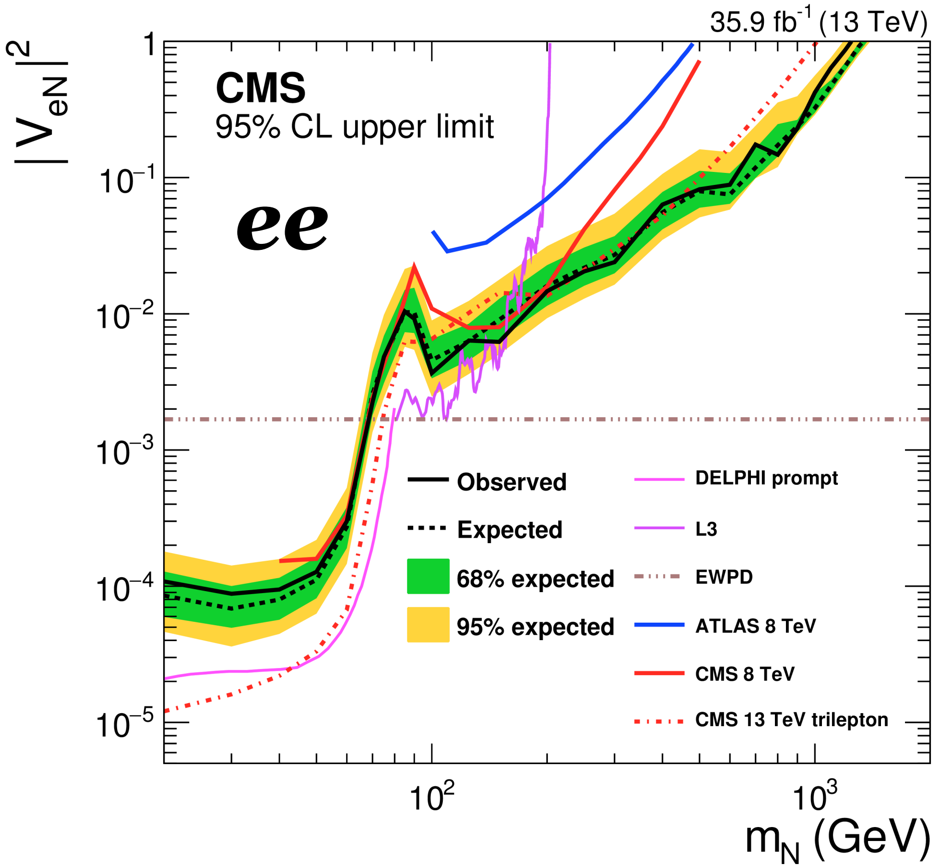
High-mass SR1

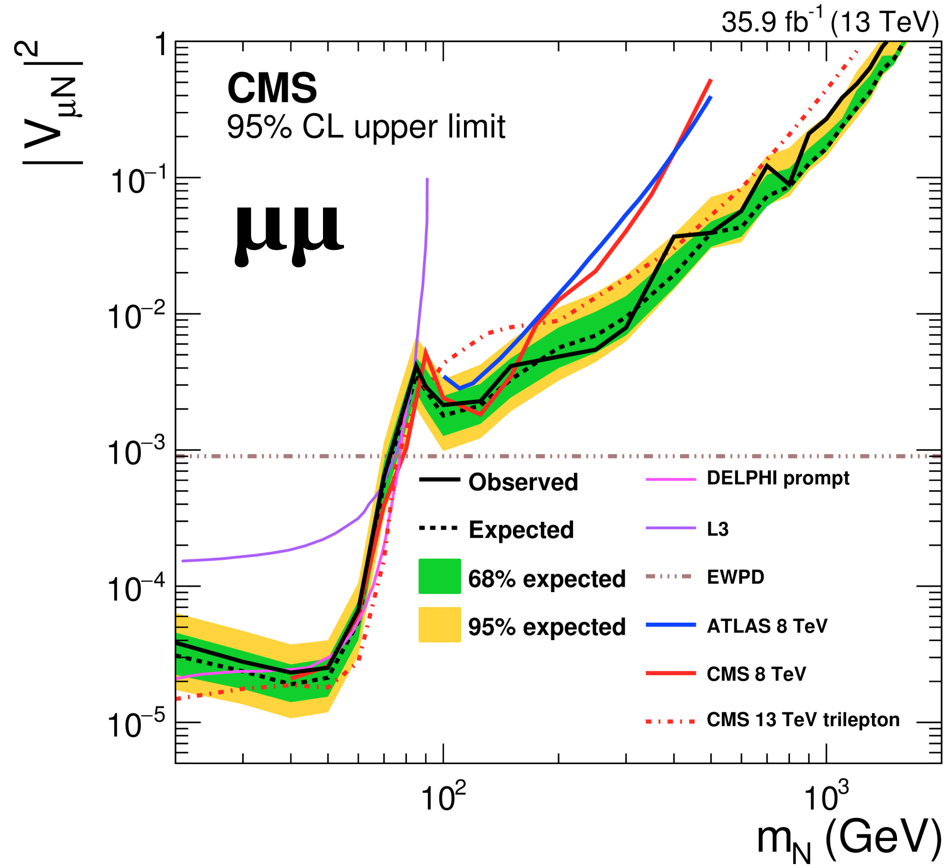


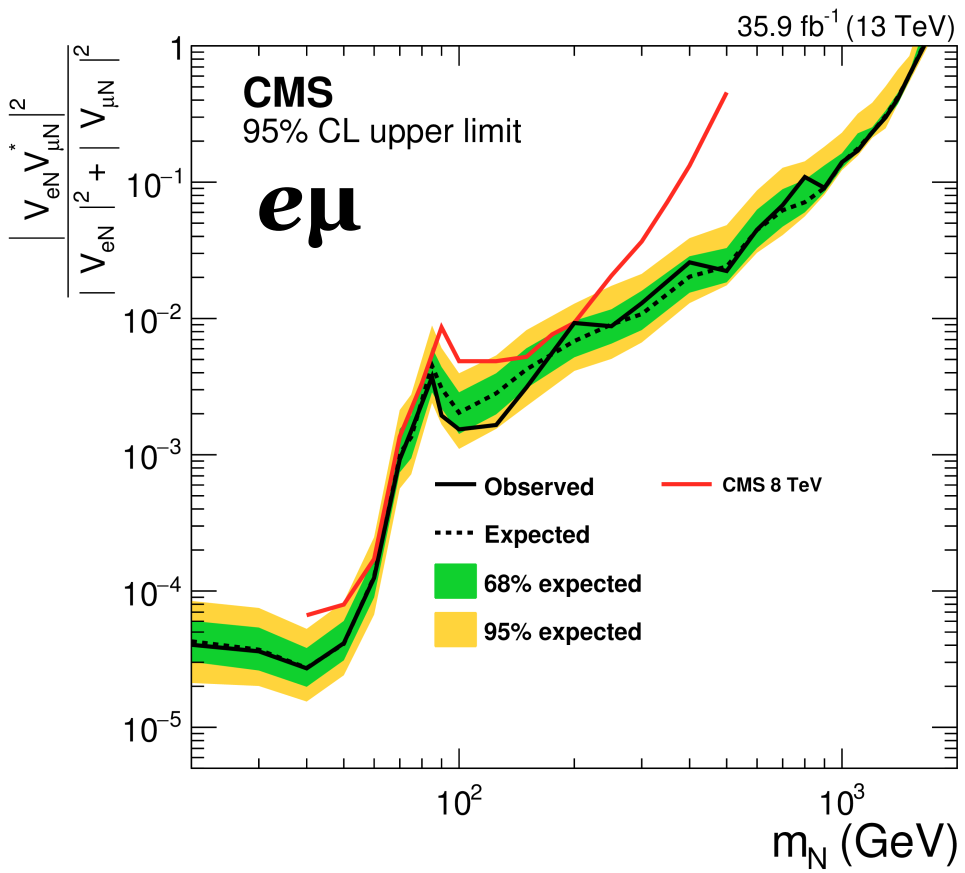
High-mass SR2

Type-I - dilepton channel

CMS: 1806.10905







- High-mass limit dominated by dilepton channel over trilepton: BR(W→qq') > BR(W→ℓν).
- Low-mass sensitivity dominated by trilepton: minimum $p_T(\ell)$ < minimum p_T(jet).

Type-III searches

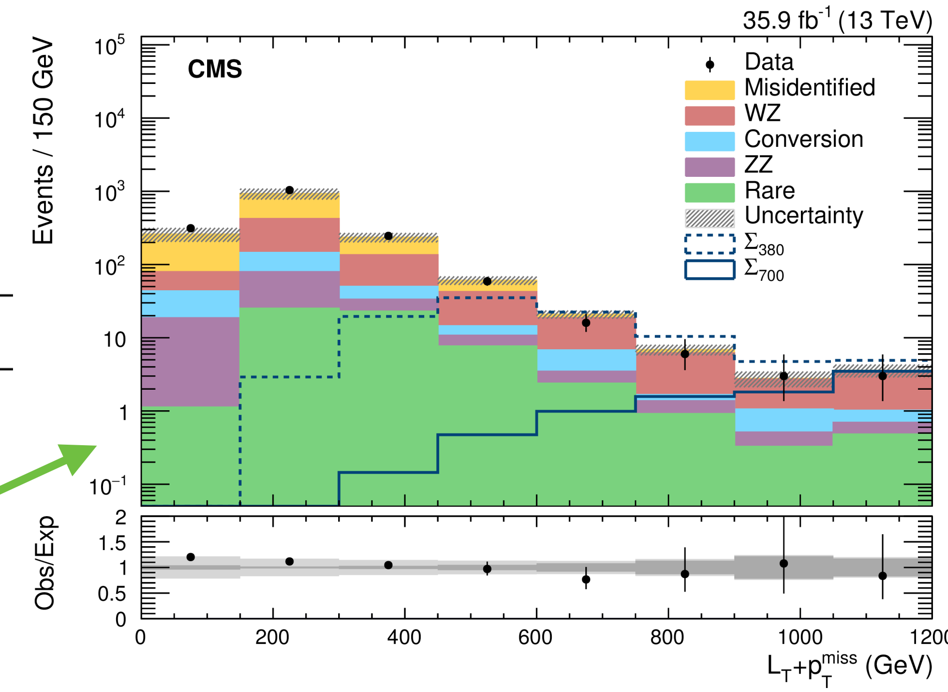
Type-III - multilepton channel

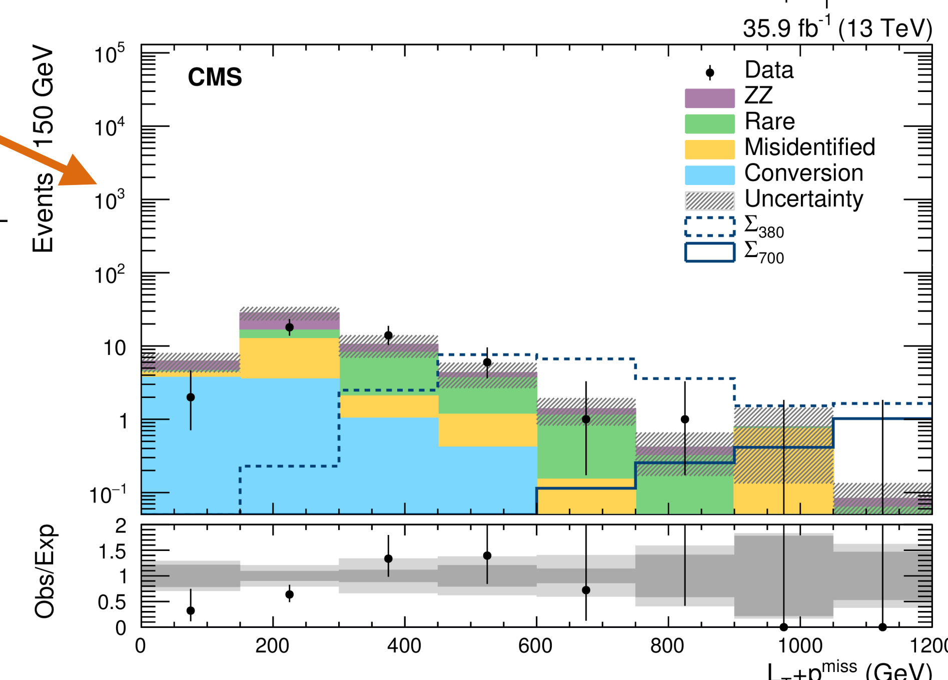
CMS: 1708.07962

- **pp** → **Σ⁰ Σ± / Σ∓ Σ±** → Complicated decay chain leads to 27 different channels.
- Scalar sum of $p_T(\ell)$, called L_T, and E_T^{miss} are combined as primary discriminant. Contribution from neutrinos and charged leptons.
- Count lepton multiplicities based on charge product and multiplicity of same-flavour pairs.
- Categorisation for $N_{leptons}$ = 3 and ≥ 4.
- $p_T(\ell)$ > 25, 15, 10 GeV.

$N_{leptons}$	OSSF & mass	Variable	p_T^{miss} requirement
3	OSSF1, on-Z	M_T	$p_T^{miss} > 100$ GeV
	OSSF1, above-Z	$L_T+p_T^{miss}$	—
3	OSSF1, below-Z	$L_T+p_T^{miss}$	$p_T^{miss} > 50$ GeV
	OSSF0	$L_T+p_T^{miss}$	—
≥ 4	OSSF1	$L_T+p_T^{miss}$	—
	OSSF2	$L_T+p_T^{miss}$	$p_T^{miss} > 50$ GeV if on-Z

OSSFn = number of opposite-sign, same-flavour pairs

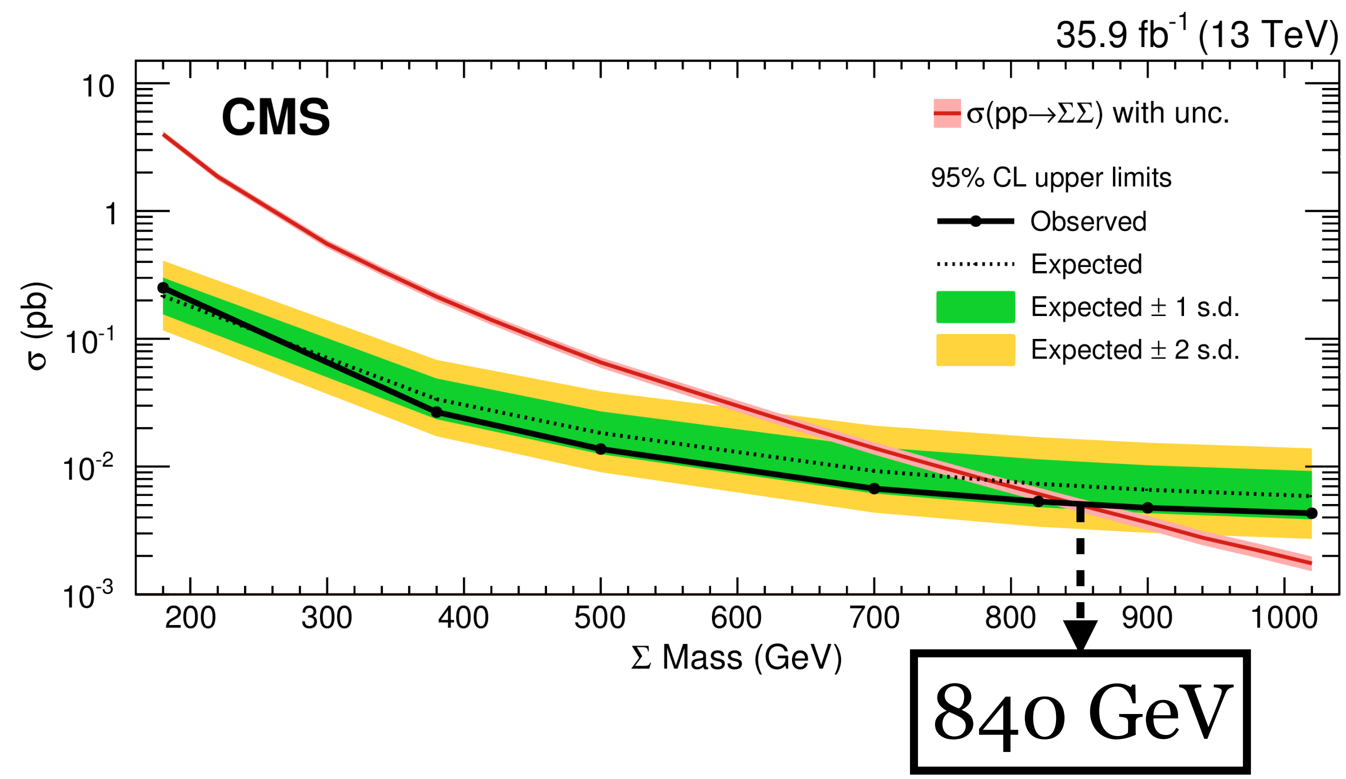


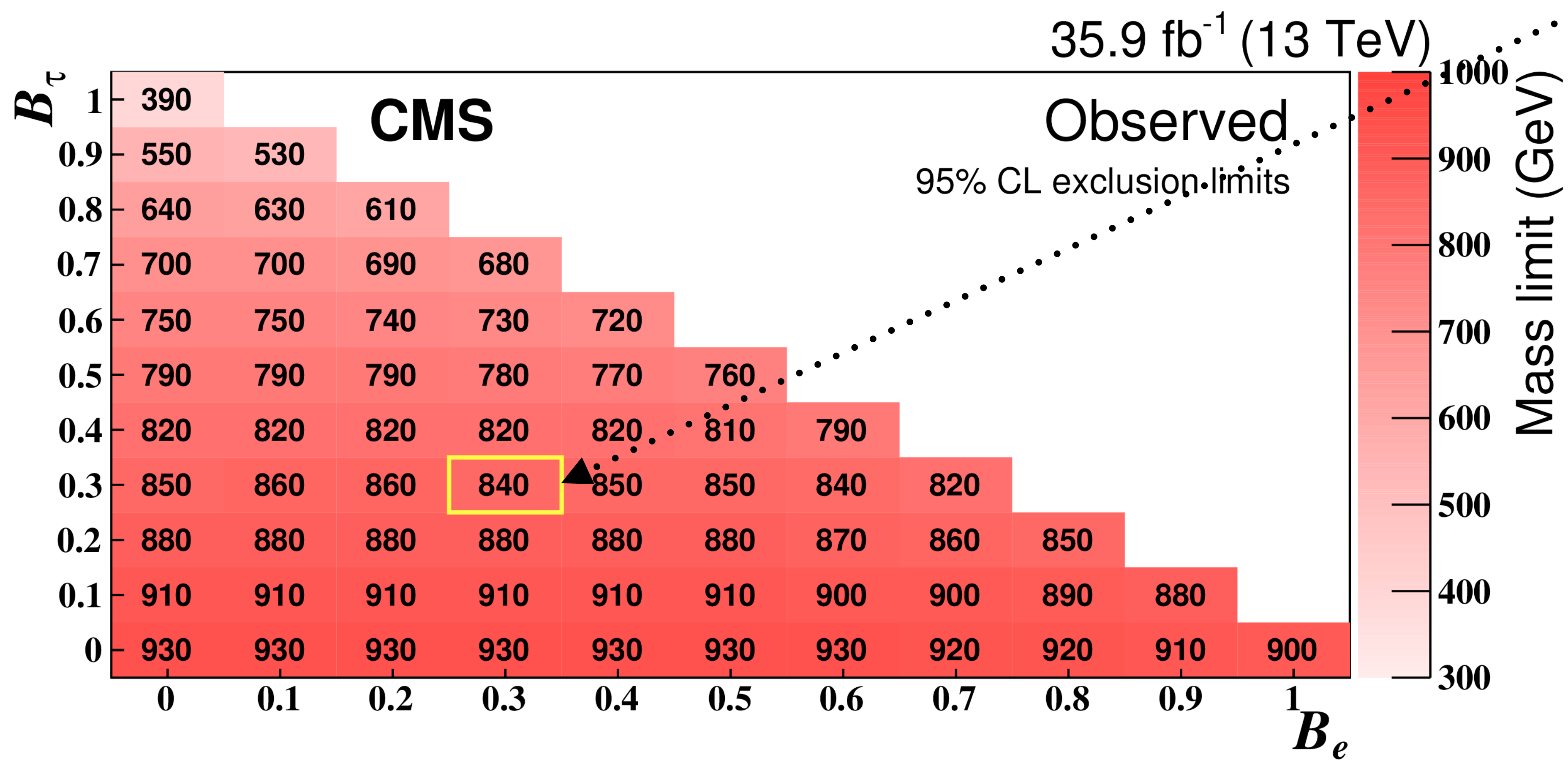


Type-III - multilepton channel

CMS: 1708.07962

- Upper limits on the cross-section for $pp \to \Sigma^0 \Sigma^\pm / \Sigma^\mp \Sigma^\pm$
- "Flavour democratic" scenario: branching ratios to all leptons equal.
- 2d limits on $BR_\ell \sim |V_\ell|^2 / (|V_\mu|^2 + |V_e|^2 + |V_\tau|^2)$ where V_ℓ is a mixing angle b/w the heavy and light fermions.
- Taus included via their leptonic decay.



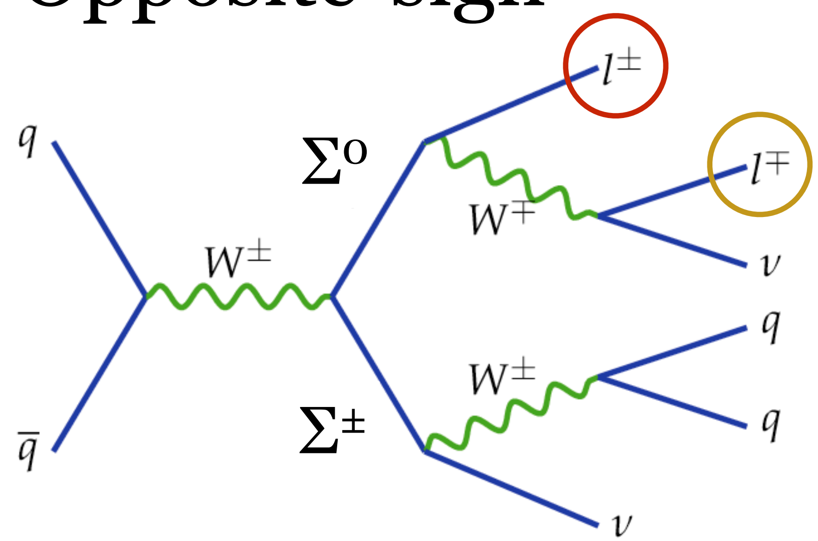


Type-III - dilepton channel

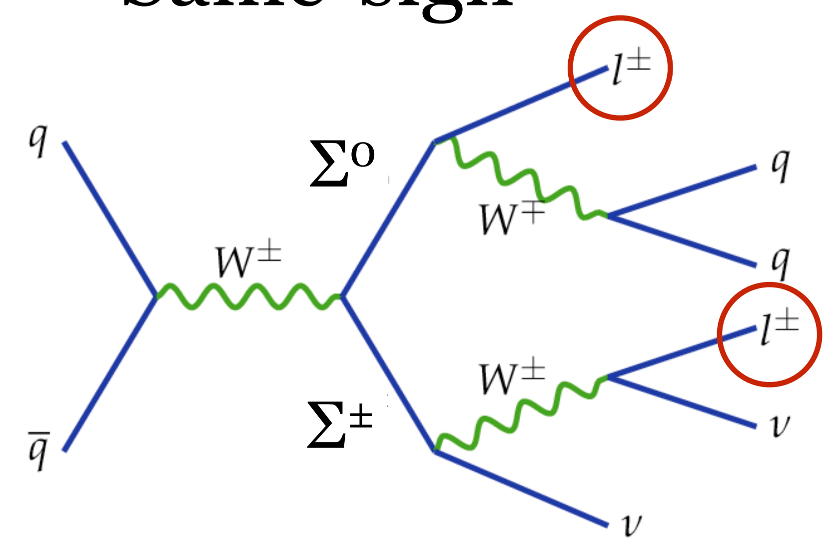
ATLAS: ATLAS-CONF-2018-020

- **pp → Σ⁰ Σ±**
- Opposite and same -sign optimised independently.
- Two resolved jets in final state. M(j,j) consistent with W mass and E_T^{miss}.
- Scalar sum of $p_T(\ell)$, called H_T, and E_T^{miss} are combined as primary discriminant.

Opposite-sign



Same-sign

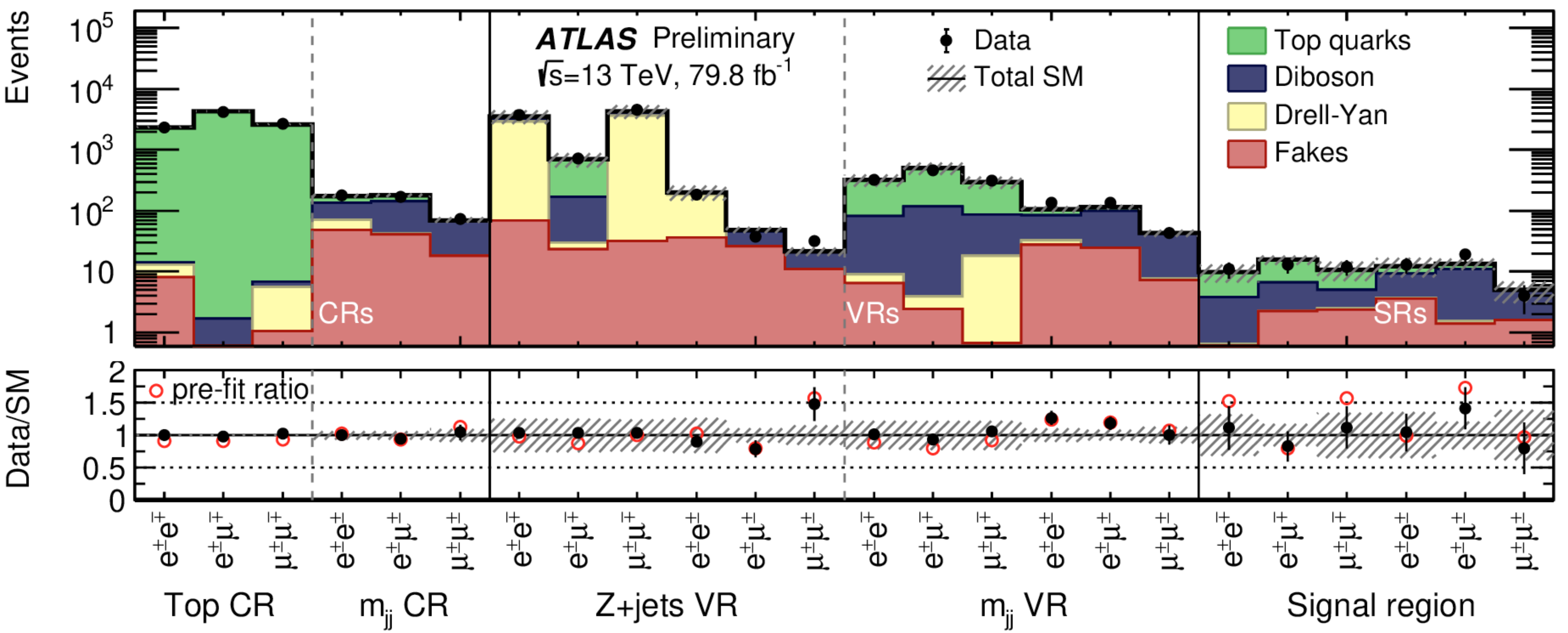


	OS ($\ell^+\ell^- = e^+e^-, e^\pm\mu^\mp, \mu^+\mu^-$)				**SS** ($\ell^\pm\ell^\pm = e^\pm e^\pm, e^\pm\mu^\pm, \mu^\pm\mu^\pm$)			
	Top CR	Z+jets VR	m_{jj} VR	SR	Z+jets VR	m_{jj} VR	m_{jj} CR	SR
N(jet)	≥ 2	≥ 2	≥ 2	≥ 2	≥ 2	≥ 2	≥ 2	≥ 2
N(b-jet)	$\mathbf{\geq 2}$	0	0	0	0	0	0	0
m_{jj} [GeV]	[60, 100)	[60, 100)	$\mathbf{[35, 60) \cup [100, 125)}$	[60, 100)	[60, 100)	$\mathbf{[0, 60) \cup [100, 300)}$	$\mathbf{[0, 60) \cup [100, 300)}$	[60, 100)
$m_{\ell\ell}$[GeV]	[110, ∞)	**[70, 110)**	[110, ∞)	[110, ∞)	**[70, 100)**	[100, ∞)	[100, ∞)	[100, ∞)
Sig(E_T^{miss})	≥ 5	≥ 5	$\mathbf{\geq 10}$	$\mathbf{\geq 10}$	≥ 5	≥ 5	≥ 5	$\mathbf{\geq 7.5}$
$\Delta\phi(E_T^{miss}, l)_{min}$				$\mathbf{\geq 1}$				
$p_T(jj)$ [GeV]				**[100, ∞)**				**[60, ∞)**
$p_T(\ell\ell)$ [GeV]				**[100, ∞)**				**[100, ∞)**
$H_T + E_T^{miss}$ [GeV]	[300, ∞)	[300, ∞)	[300, ∞)	[300, ∞)		**[500, ∞)**	**[300, 500)**	[300, ∞)

Type-III - dilepton channel

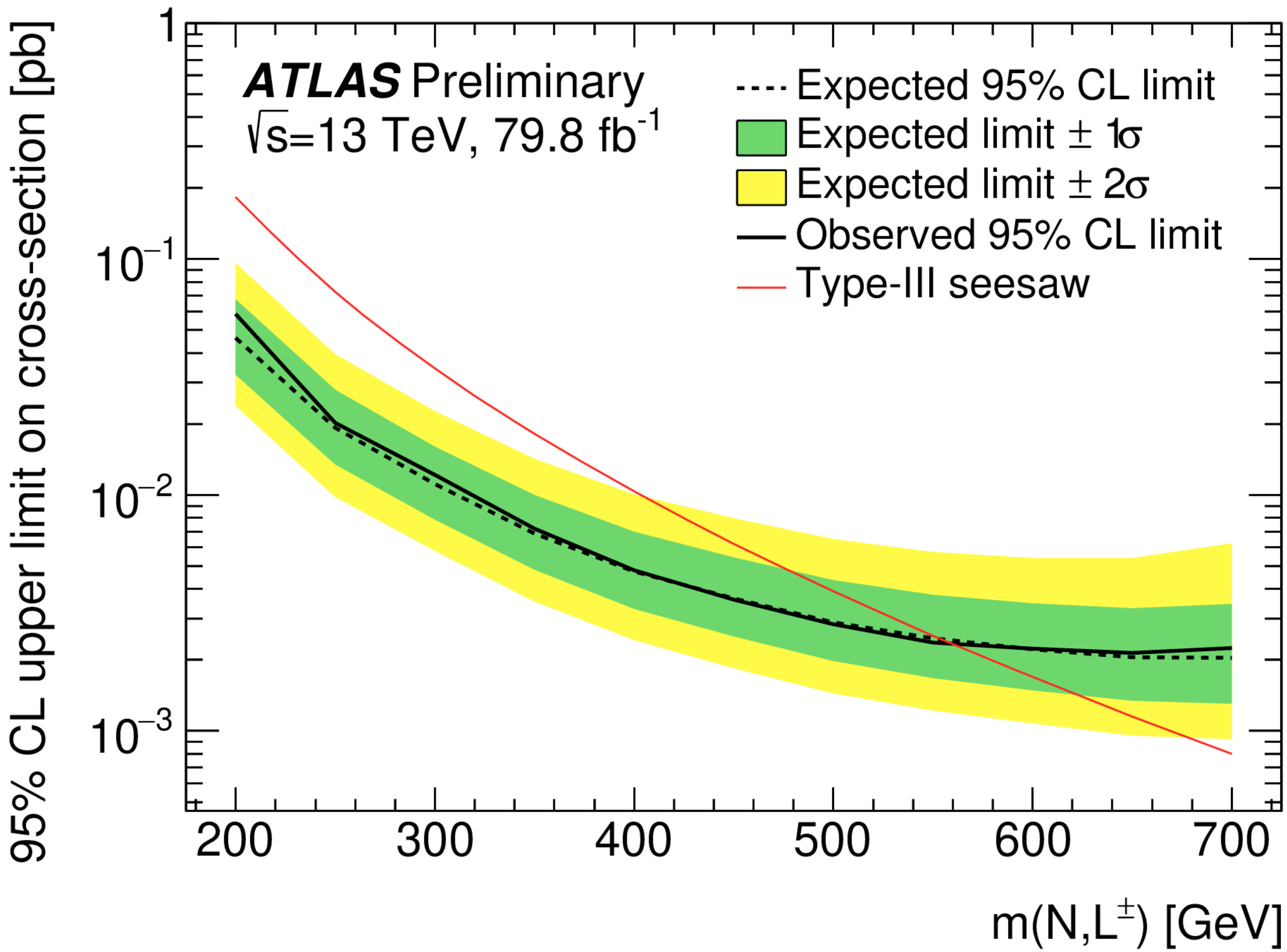
ATLAS: ATLAS-CONF-2018-020

- Full shape information used in the final fit.
- CRs used to normalise simulated backgrounds directly in the fit procedure.
- Independent validation regions defined to validate the modelling.
- Z+jets validation regions to validate charge misidentification modelling.



Type-III - dilepton channel

ATLAS: ATLAS-CONF-2018-020



- All channels are combined to derive the final limit.
- Assume "flavour democratic" scenario with equal branching ratios to all leptonic decays.

Conclusions

- The see-saw mechanism is a promising paradigm for neutrino mass generations embedded in many theories of new physics.

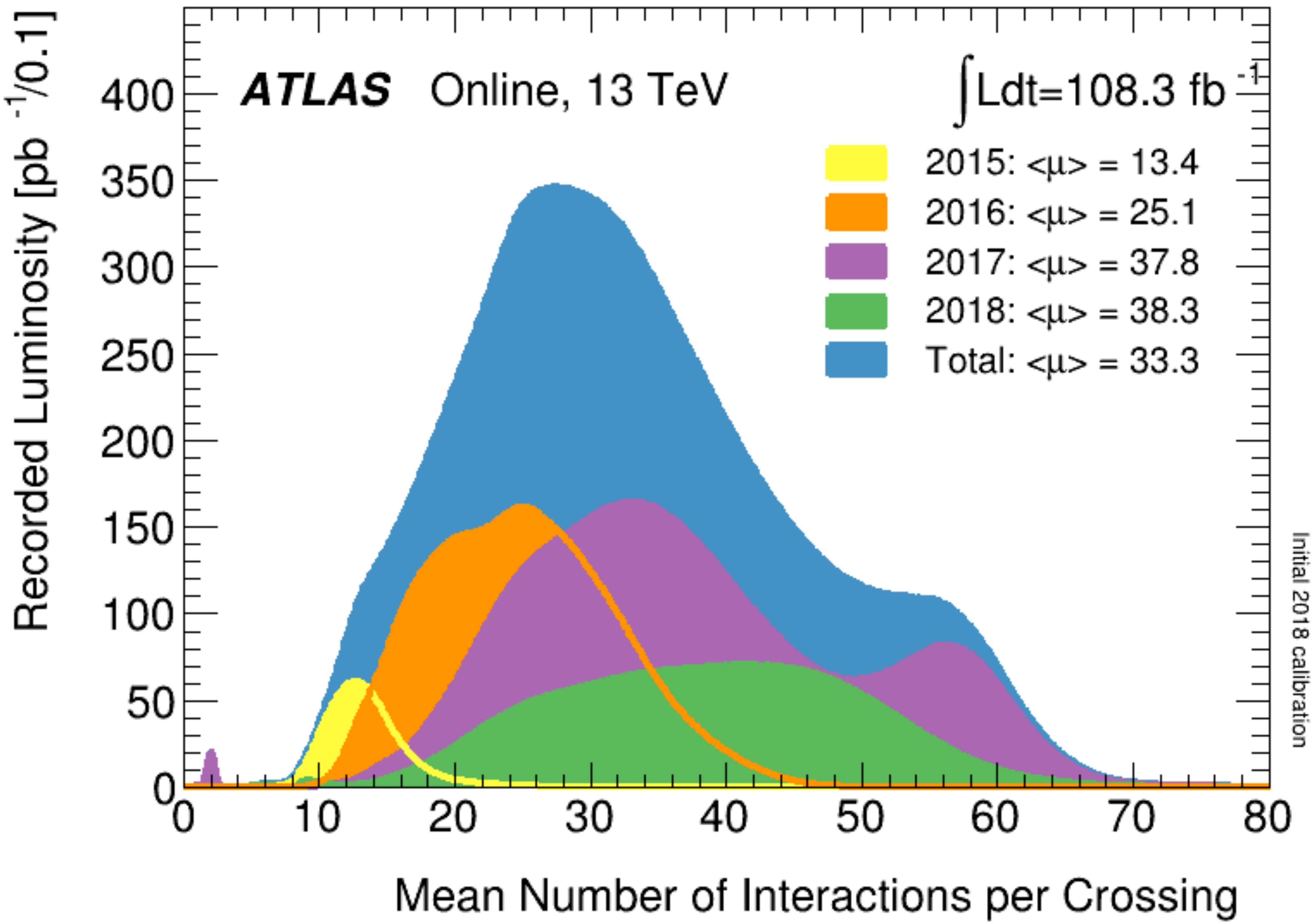
- Collider experiments do have access to different incarnations of it: Type-I/II/III.

- ATLAS and CMS have a rich plan for the end of Run-II. Stay tuned!

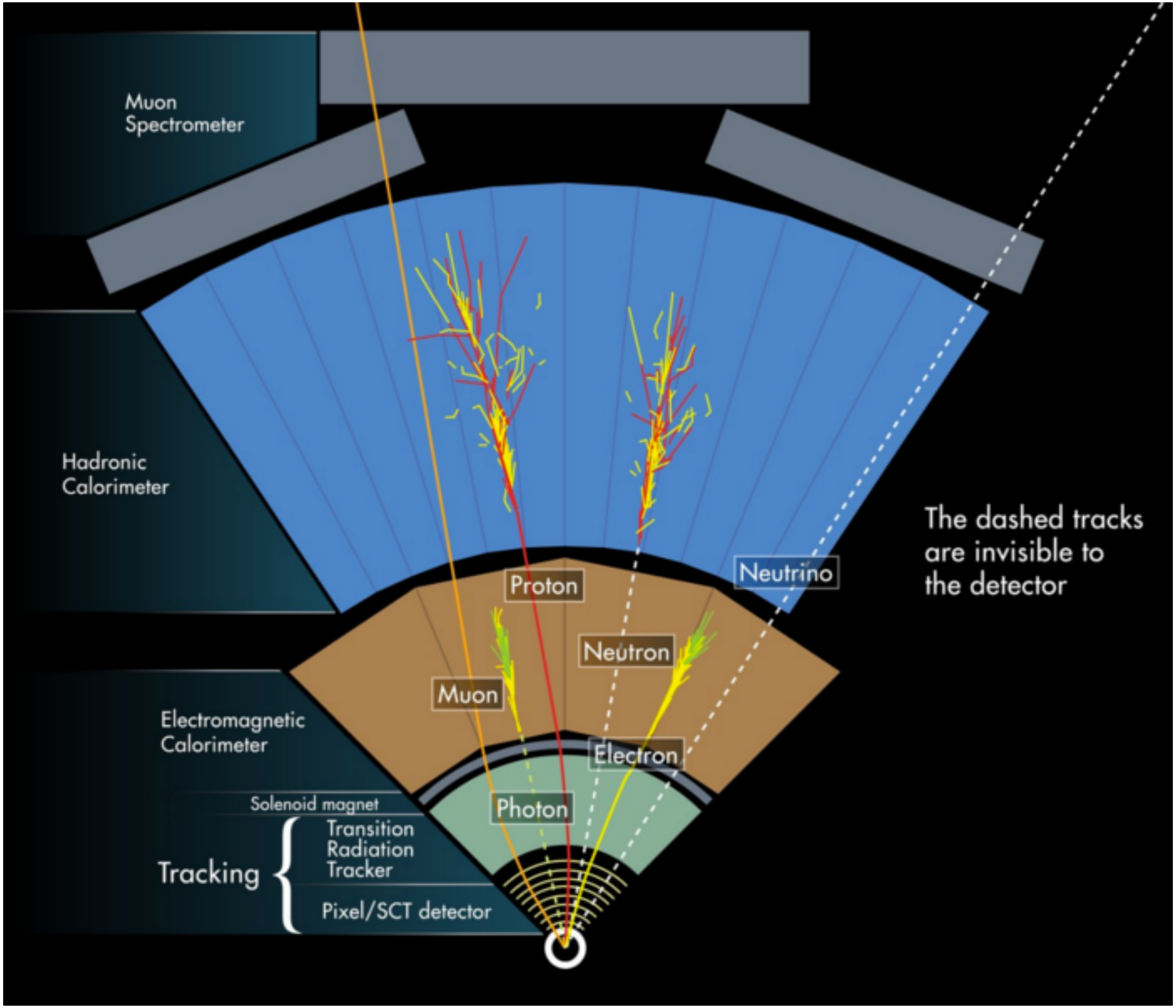
Thank you!

Backup

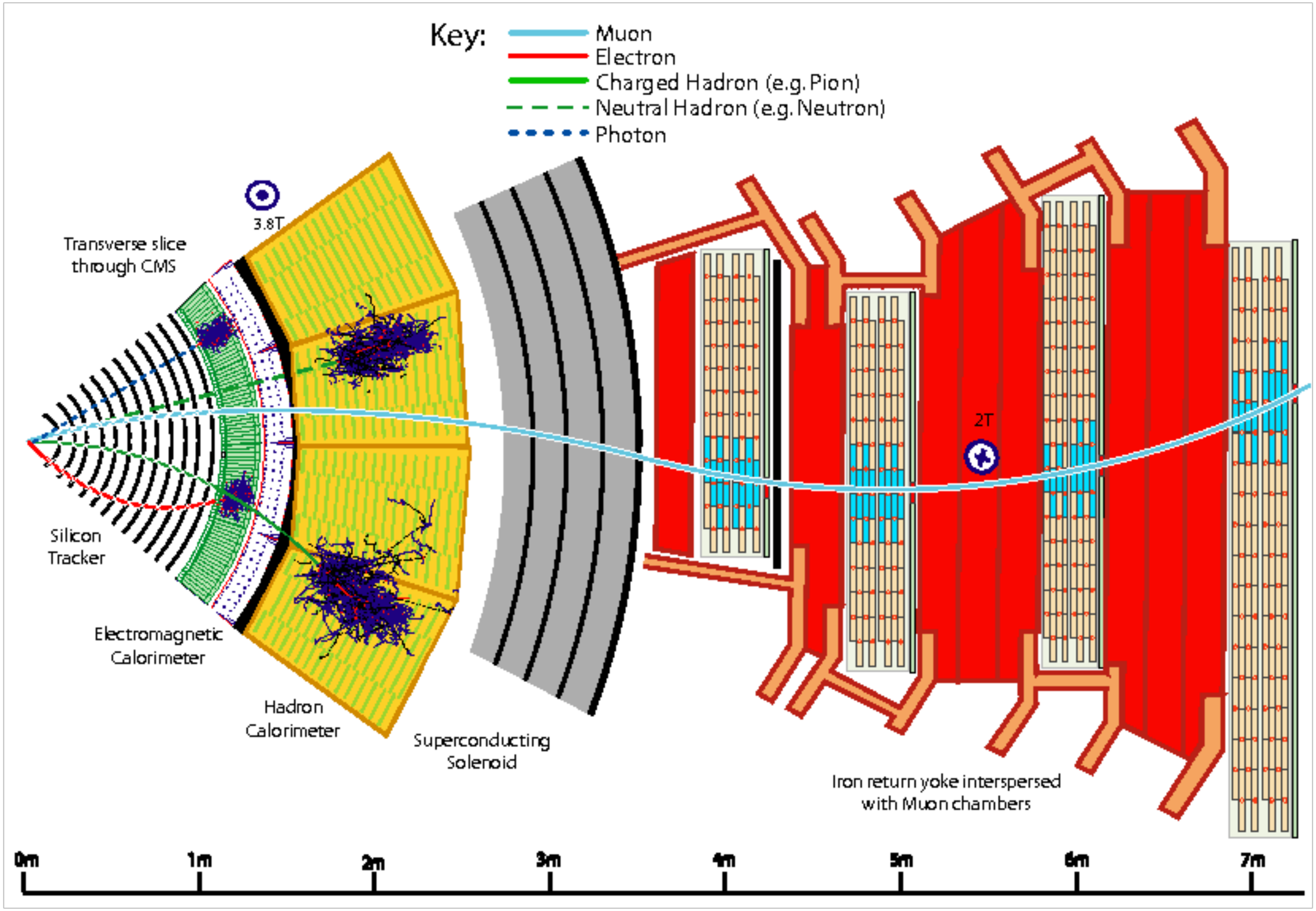
ATLAS and CMS



ATLAS and CMS



ATLAS and CMS



ATLAS and CMS