Selected topics in BSM physics

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Outline

1. Heavy flavour physics:
   1. Rare decays: $B_s \to \mu\mu$
   2. Lepton Flavor Universality tests
2. Vector-like quarks searches
3. Higgs boson and dark matter
4. Z' and W' searches

Heavy flavour physics

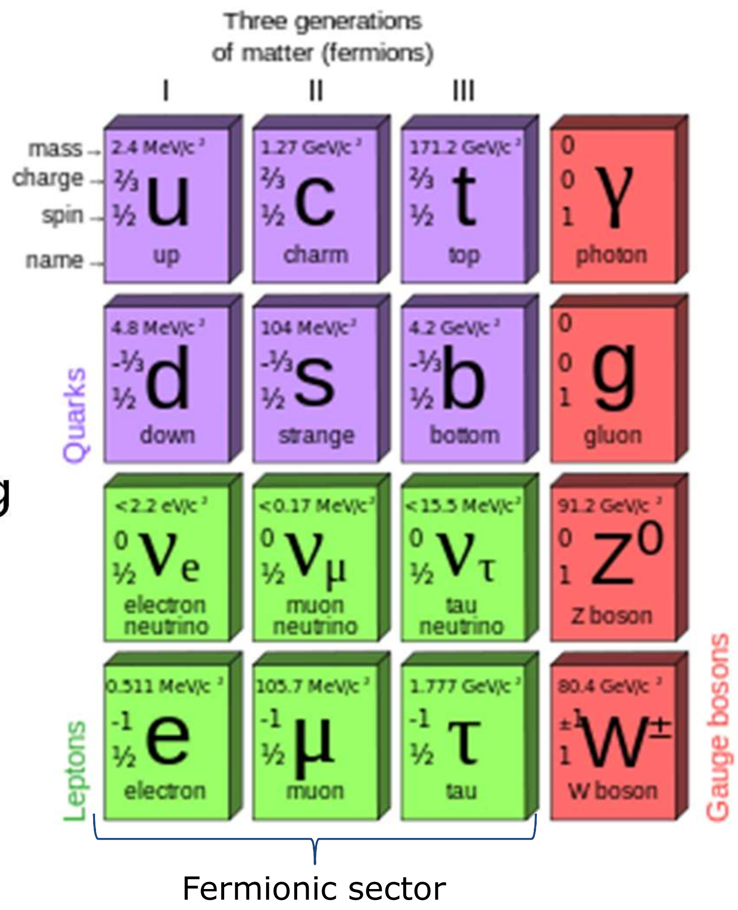
1711.03624
1809.06229

Flavour physics

"Flavor Physics" all the phenomena related to interactions differentiating the various fermion families

Flavour parameters in SM (massless ν):

- 6 quark masses
- 3 lepton masses
- 3 quark mixing angles + 1 phase ⇒ CKM matrix



Gain deeper understanding of the underlying flavour structure of the Standard Model

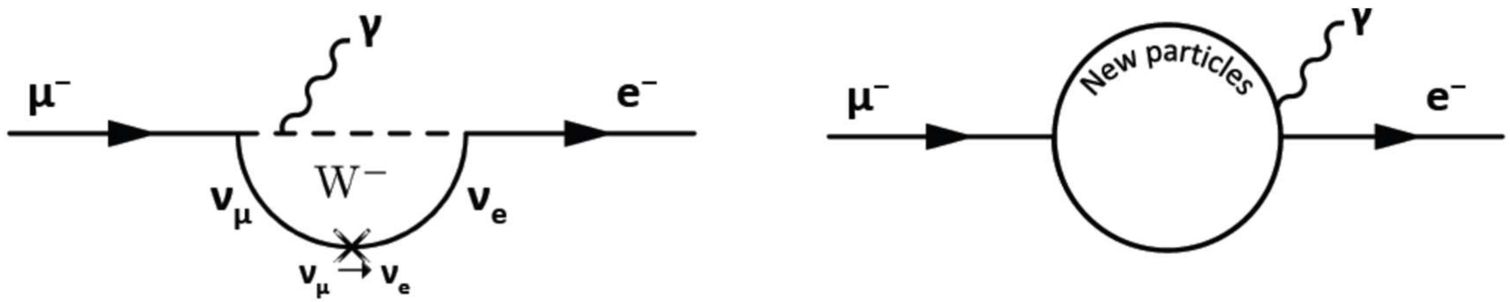
- why 3 families ?
- why so different masses ?

Flavour physics is a wide topic:

- Neutrinos and charged leptons
- Kaon (strange) physics
- Charm and beauty physics
- Top quark physics

Flavour physics

Sensitive to effects of new particles and forces beyond the Standard Model, even particles too massive to be produced



< $1/10^{50}$ muons decay this way

'Indirect' effects of new physics often appear before particles are directly discovered:

- GIM mechanism → predict charm quark existence 4 years before discovery
- CP violation in kaons → prediction of bottom & top quarks
- B meson mixing → top quark much more massive than expected

Rare b-hadron decays

Search for virtual contributions of new heavy particles in loops

Most interesting processes are those highly suppressed in SM

- flavor-changing neutral current (FCNC), forbidden at tree level in SM
- CKM suppressed
- helicity suppressed

Experimental probes with precise theory prediction

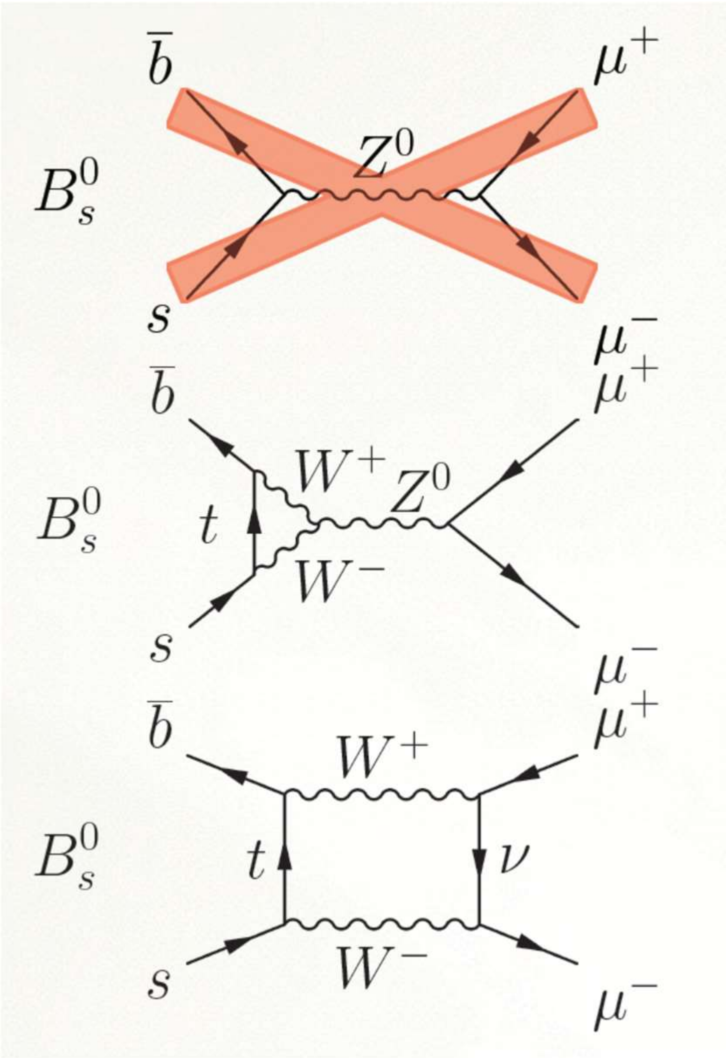
- uncertainty typically dominated by QCD; e.g. prefer leptonic to hadronic final states

Processes that may be modified (enhanced or suppressed) by orders of magnitude by NP

$B^0_{d,s} \to \mu^+\mu^-$

$B^0_{d,s} \to \mu^+\mu^-$ are highly suppressed in SM:

- FCNC processes, only proceed through Z-pengiun, and box diagrams which are higher order process
- Cabibbo suppressed: $|Vtq|^2$
- Helicity suppressed: $\alpha\ [m\mu/mB]^2$
  - Bs is spin zero, and a vector particle mediating the decay always couples to 2 muons of the same chirality. In the limit mμ=0, when chirality=helicity, the muons spins add up, which forbids the decay by spin conservation



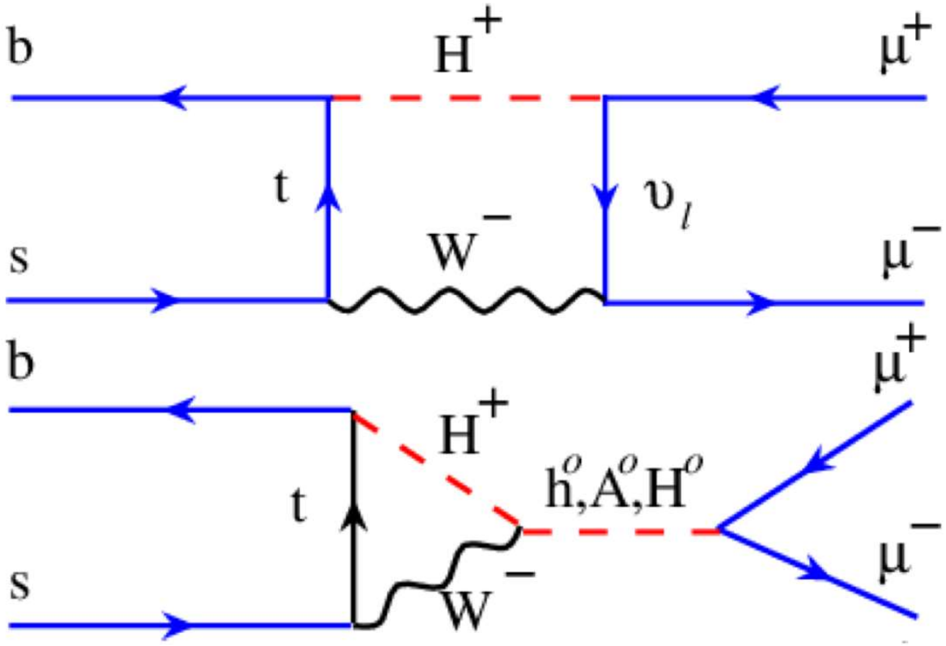
Precise theoretical prediction:

$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = (3.66 \pm 0.23) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$$

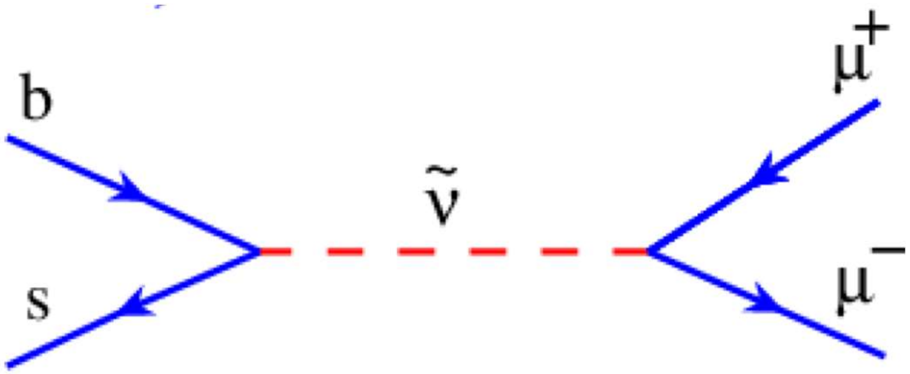
$B^0_{d,s} \to \mu^+\mu^-$: *supersymmetry*

MSSM:

$BR \propto \tan^6\beta$



RPV SUSY:



$B^0_{d,s} \rightarrow \mu^+\mu^-$

Signal:

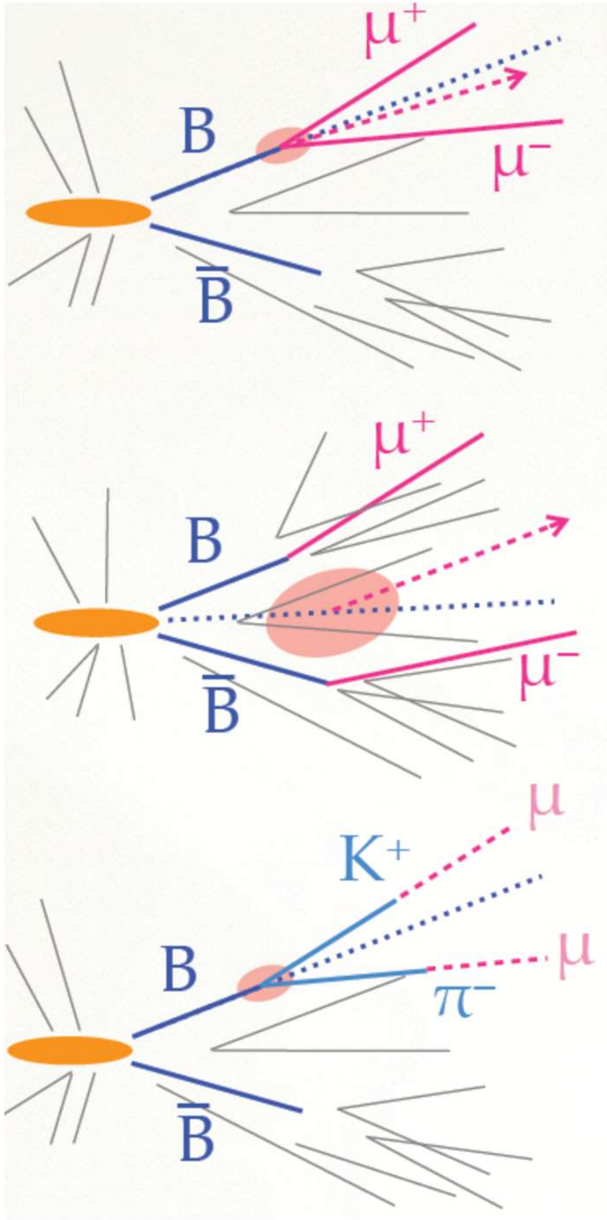
- Two muons from one displaced vertex;
- Momentum aligned with its flight direction;
- Invariant mass peaking at $M(B_{s,d})$.

Background:

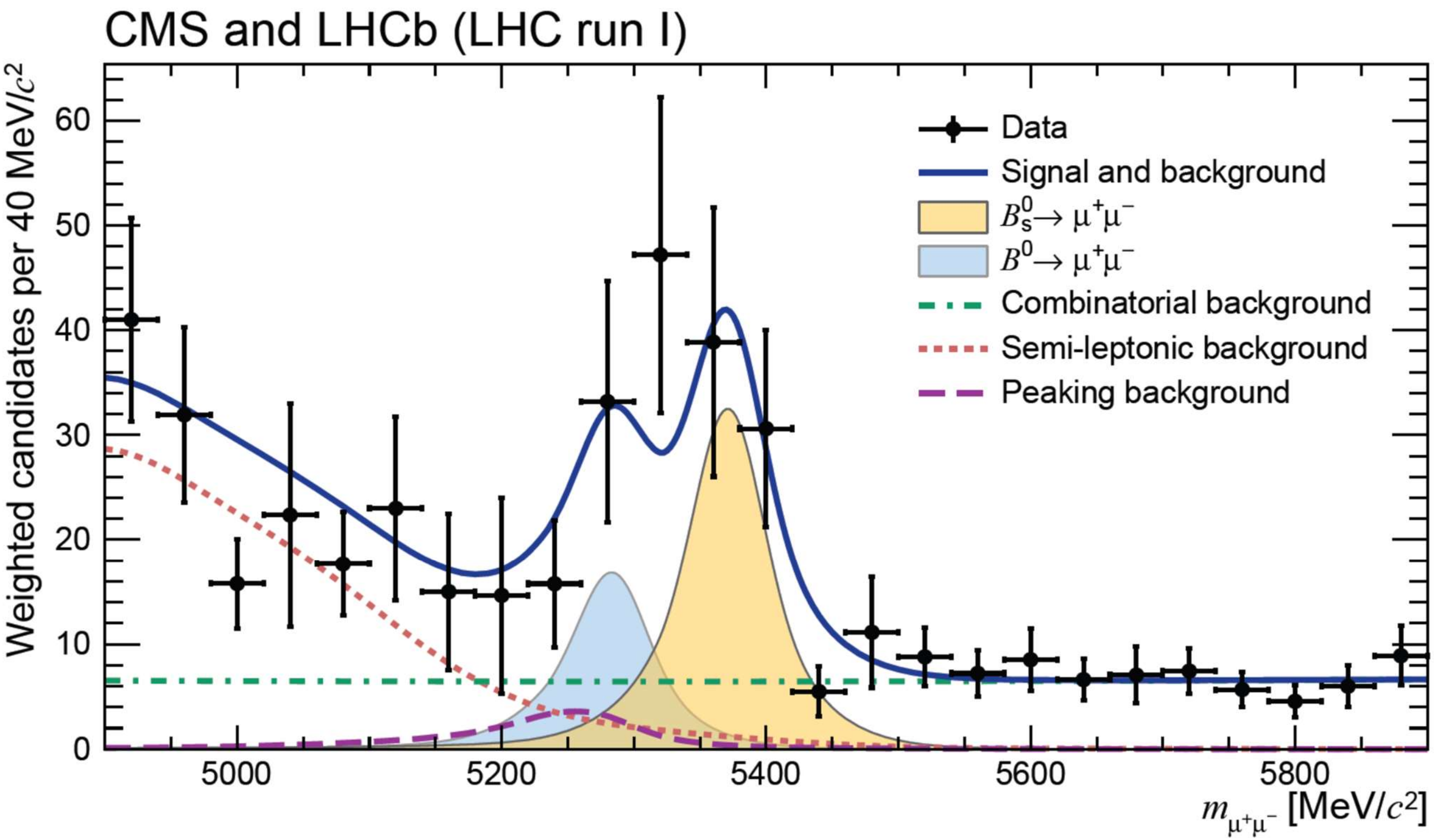
- Two semileptonic B decays
- One semileptonic B + a misidentified lepton
- Rare background from single B meson decays

Main ingredients:

- Huge sample of B mesons
- Efficient trigger
- Powerful selection
  - Vertex resolution
  - Mass resolution
  - Muon ID



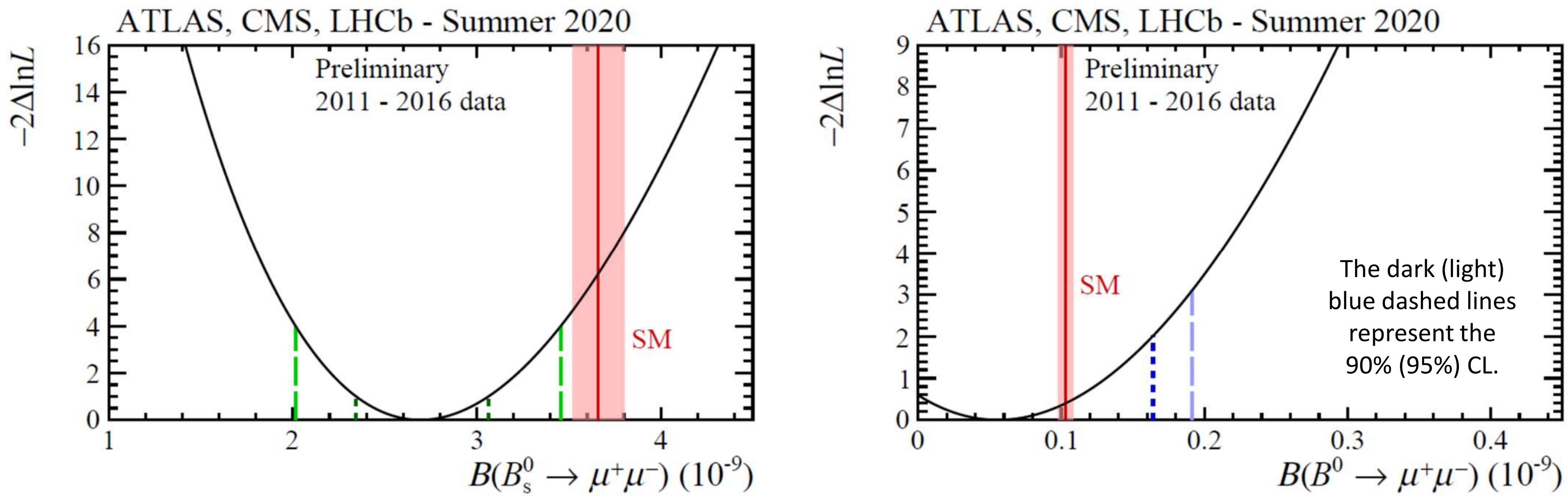
$B^0_{d,s} \rightarrow \mu^+\mu^-$



B_s: 6.2σ (7.4σ expected)

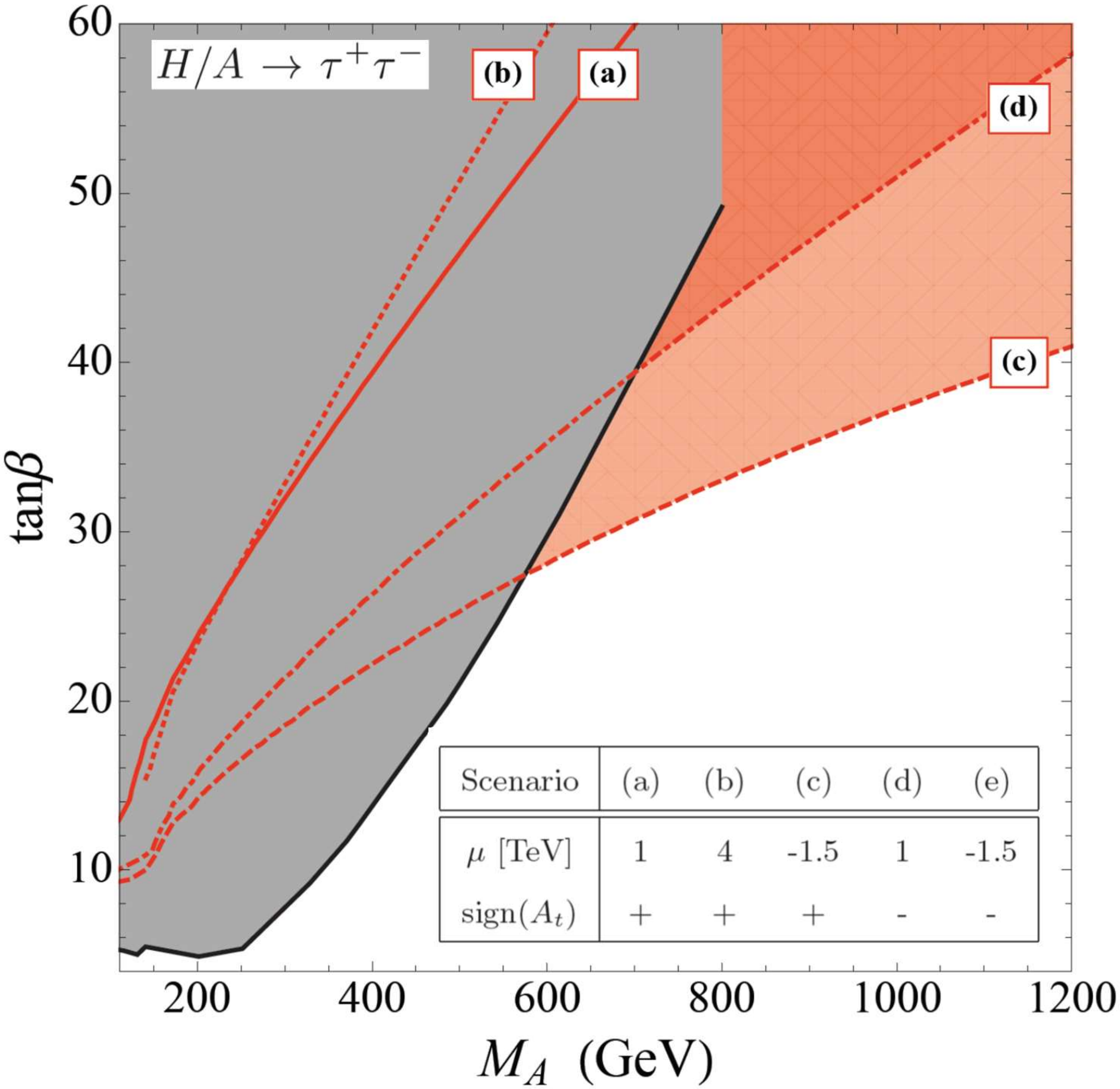
B_d: 3.2σ (0.8σ expected)

$B^0_{d,s} \to \mu^+\mu^-$



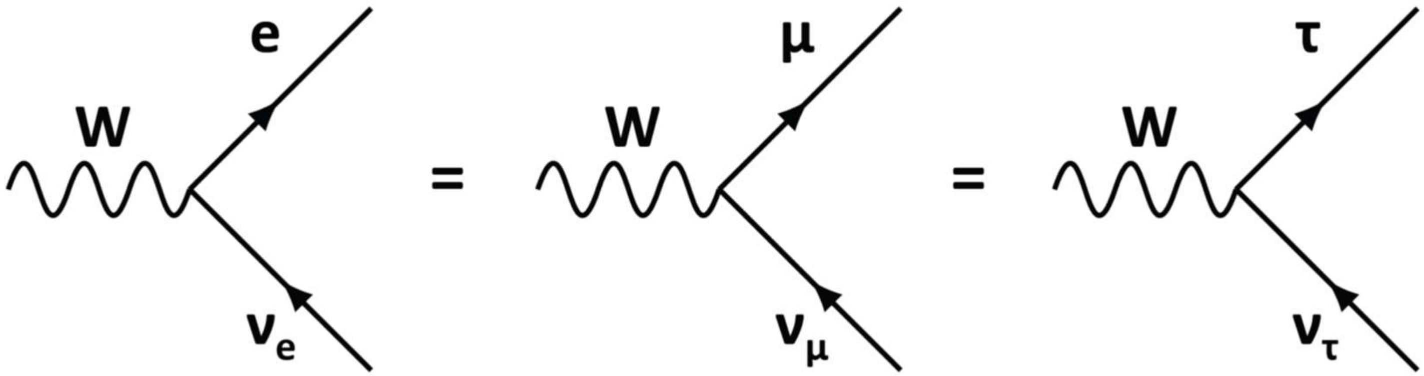
$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = \left(2.69\,^{+0.37}_{-0.35}\right) \times 10^{-9} \text{ and}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (0.6 \pm 0.7) \times 10^{-10}.$$

$B^0_{d,s} \to \mu^+\mu^-$: supersymmetry



Lepton flavour universality

Weak interaction acts equally regardless of lepton flavor



Pillar of standard model – any deviation can **only** be caused by new physics

Theoretically clean… …Experimentally challenging…

Well established in $Z \to \ell\ell$, $\tau \to \ell\nu\nu$, $J/\psi \to \ell\ell$, $\pi \to \ell\nu$, $K \to \pi\ell\nu$

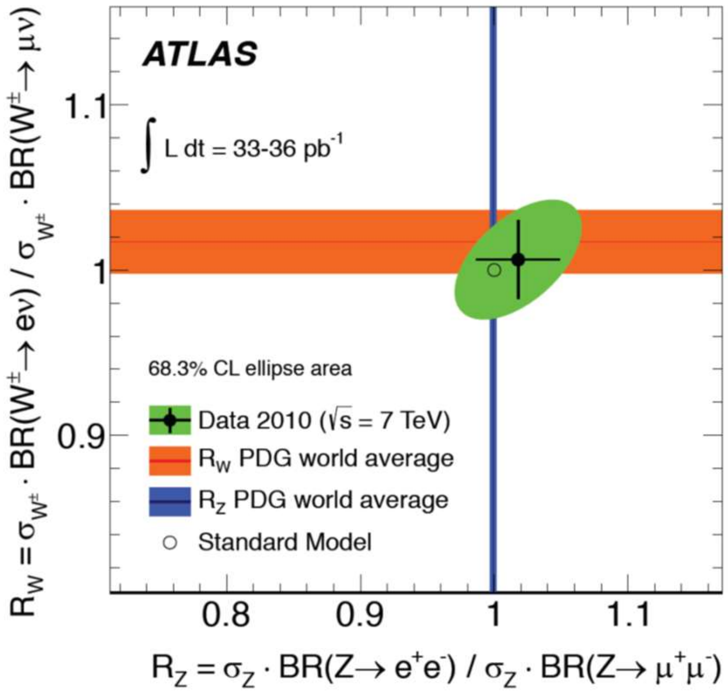
Electroweak sector

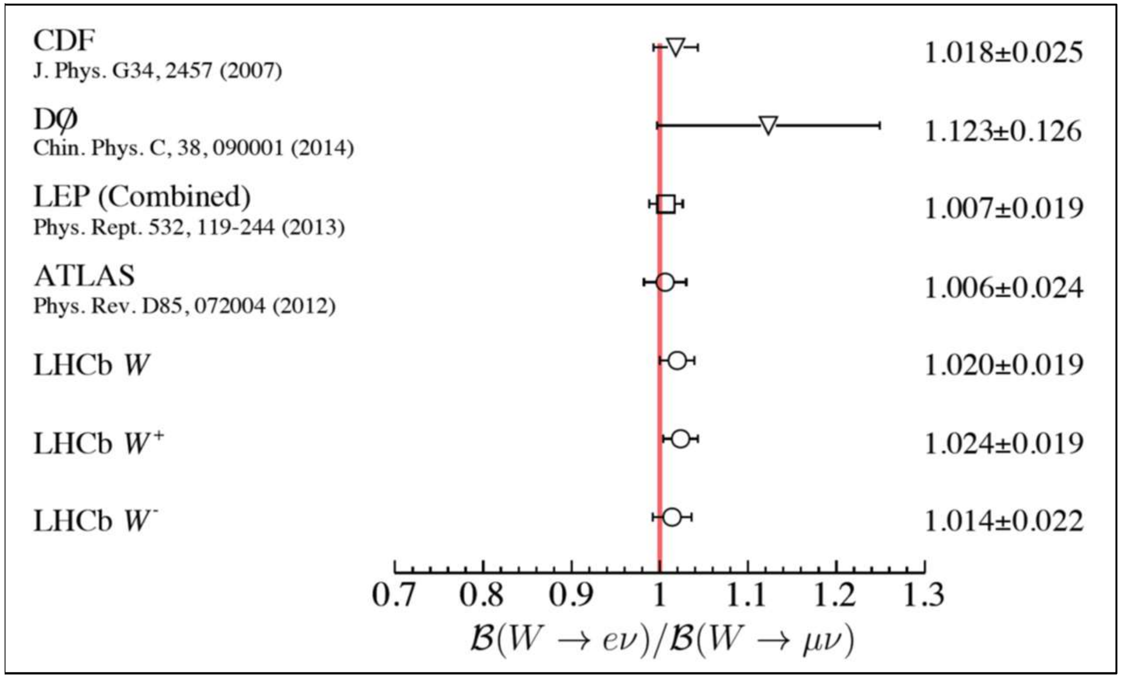
LEP:

$$\frac{\Gamma_{\mu\mu}}{\Gamma_{ee}} = \frac{B(Z \to \mu^+\mu^-)}{B(Z \to e^+e^-)} = 1.0009 \pm 0.0028$$
$$\frac{\Gamma_{\tau\tau}}{\Gamma_{ee}} = \frac{B(Z \to \tau^+\tau^-)}{B(Z \to e^+e^-)} = 1.0019 \pm 0.0032$$

$$\mathcal{B}(W \to \mu\bar{\nu}_\mu) \,/\, \mathcal{B}(W \to e\bar{\nu}_e) = 0.993 \pm 0.019$$
$$\mathcal{B}(W \to \tau\bar{\nu}_\tau) \,/\, \mathcal{B}(W \to e\bar{\nu}_e) = 1.063 \pm 0.027$$
$$\mathcal{B}(W \to \tau\bar{\nu}_\tau) \,/\, \mathcal{B}(W \to \mu\bar{\nu}_\mu) = 1.070 \pm 0.026$$

LHC:





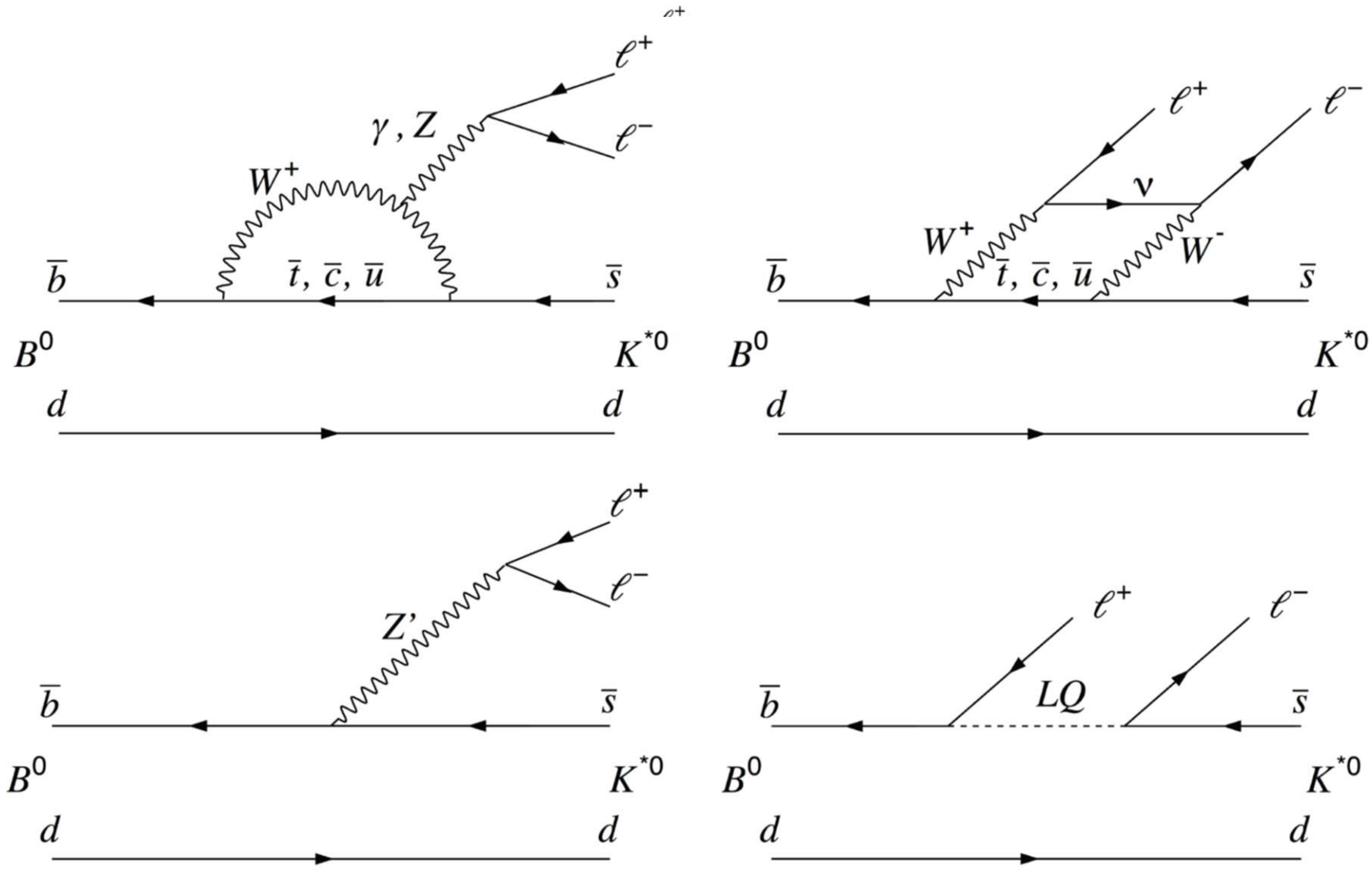
$B_0 \rightarrow K^* l^+ l^-$

Flavour-Changing Neutral-Current quark-transitions

Loop induced process in SM

Rare decays, BR~10^{-6}

$$R_{K^{(*)}} = \frac{BR(B \to K^{(*)}\mu\mu)}{BR(B \to K^{(*)}ee)}$$



$B_0 \rightarrow K^* l^+ l^-$

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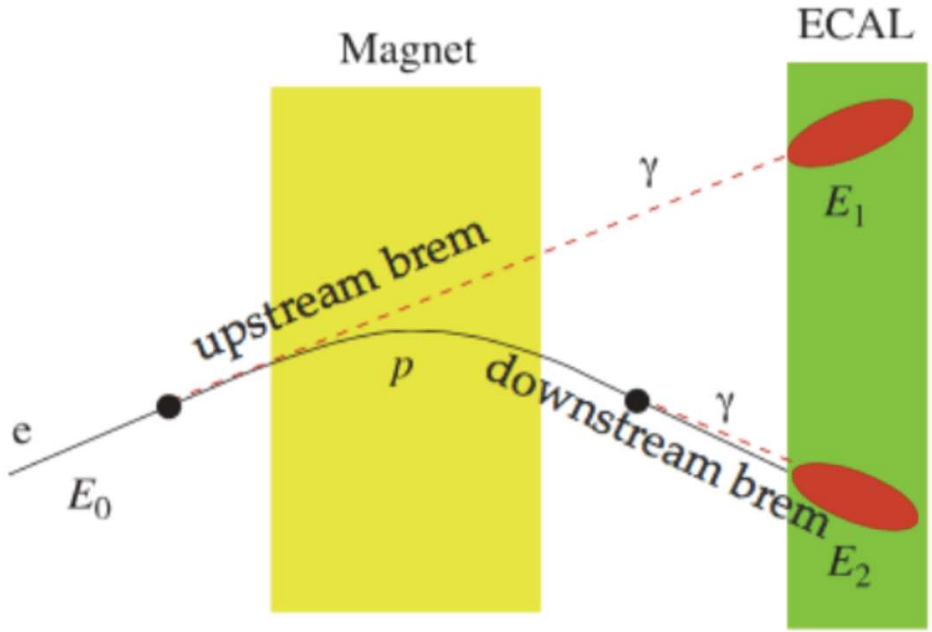
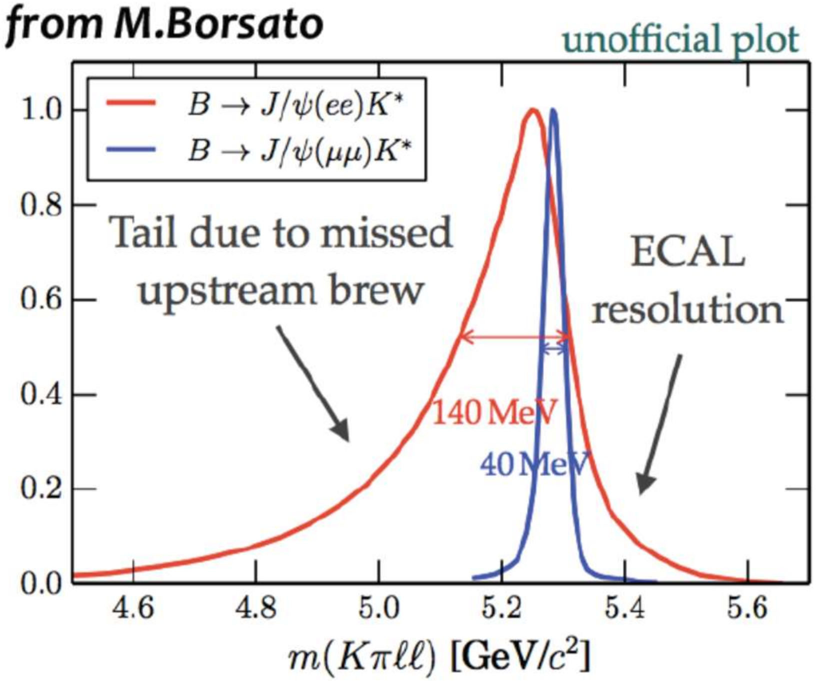


from M.Borsato

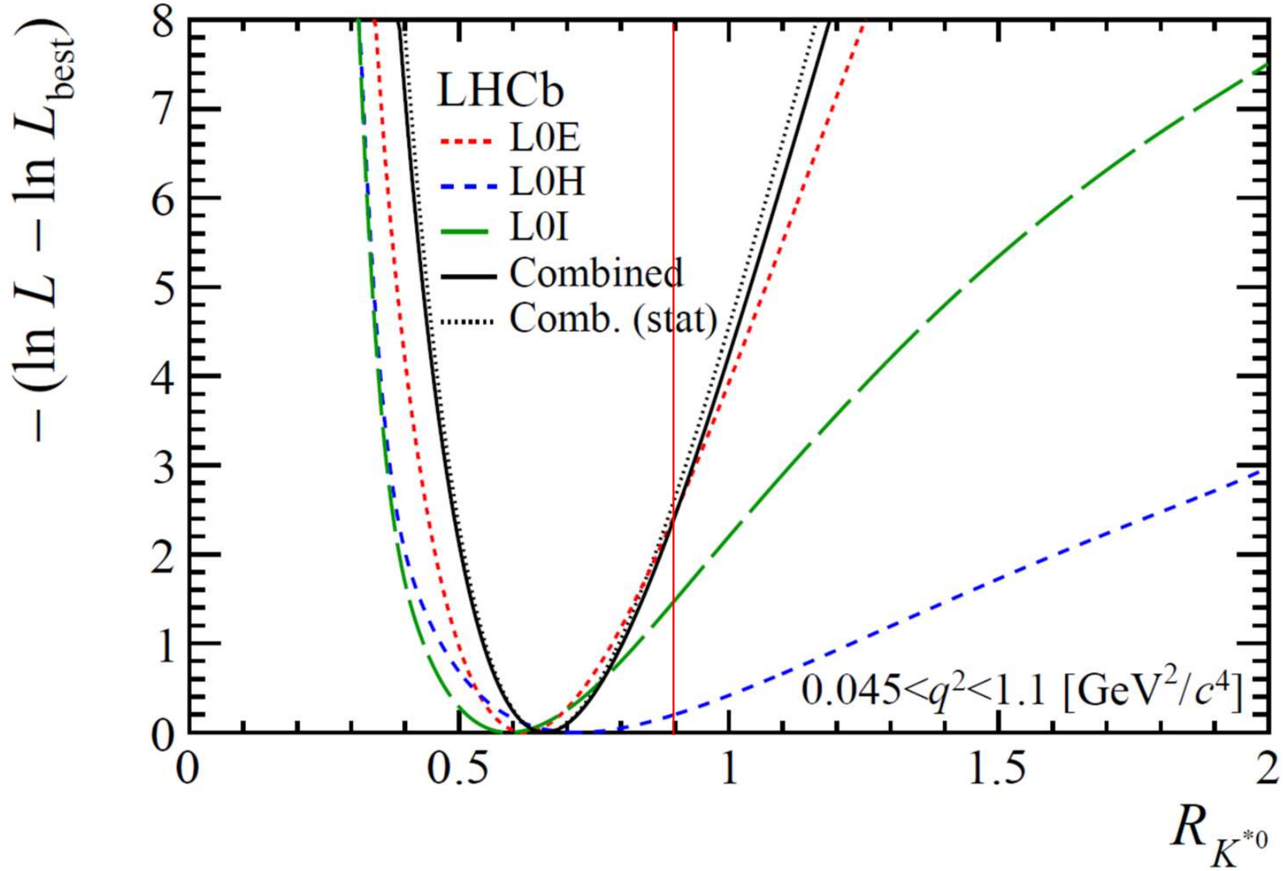


Recovery procedure in place to search for bremsstrahlung-like deposits in the calorimeter

- Limited efficiency but well reproduced in simulation
- Calorimeter resolution (1-2%) worse than spectrometer (~0.5%)

$B_0 \rightarrow K^* l^+ l^-$

$$R_{K^{(*)}} = \frac{BR(B \rightarrow K^{(*)}\mu\mu)}{BR(B \rightarrow K^{(*)}ee)}$$



3 trigger-based categories with different resolutions and different purities

L0E: trigger fired by one of the electrons (E_T>2.5GeV)

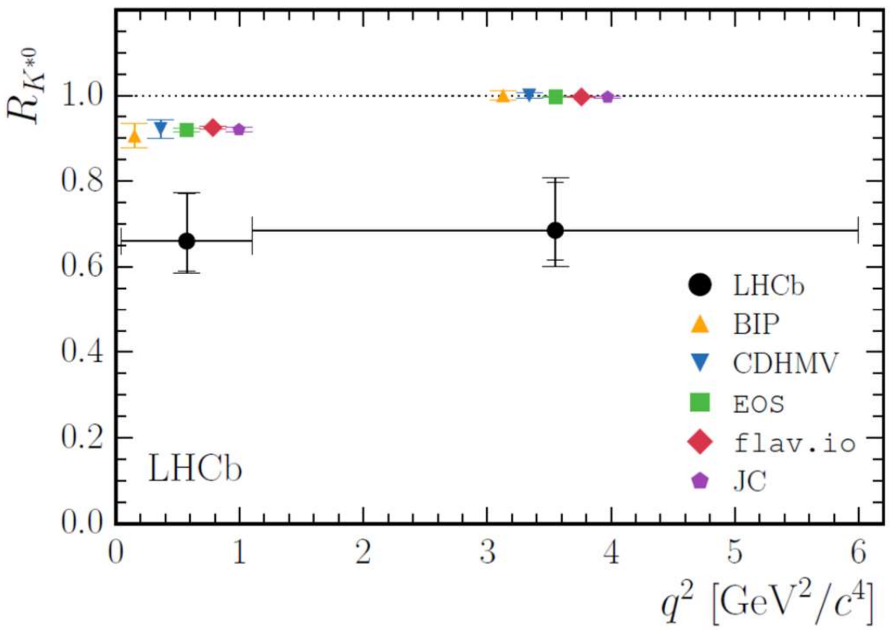
L0H: trigger fired by the κ or the π (E_T>3.5GeV)

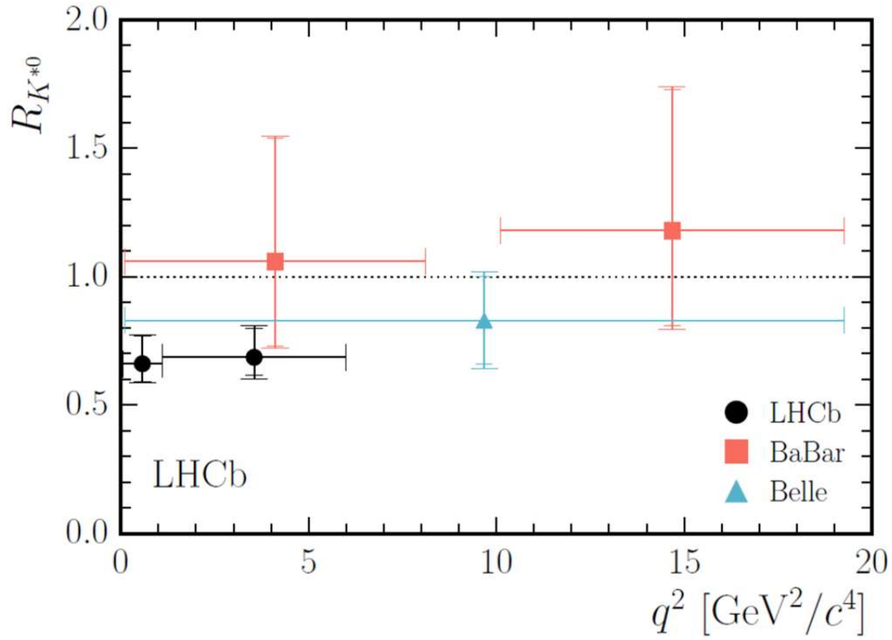
L0I: trigger fired by particles not associated to the signal candidate

$B_0 \rightarrow K^{*} l^{+} l^{-}$

$$R_{K^{(*)}} = \frac{BR(B \rightarrow K^{(*)}\mu\mu)}{BR(B \rightarrow K^{(*)}ee)}$$

$q^2 = M^2(\ell^+\ell^-)$





$$R(K^*) = 0.66^{+0.11}_{-0.07} \pm 0.03 \; (2.1\sigma - 2.3\sigma) \text{ at low } q^2 \in [0.045, 1.1] \text{ GeV}^2/c^4$$
$$R(K^*) = 0.69^{+0.11}_{-0.07} \pm 0.05 \; (2.4\sigma - 2.5\sigma) \text{ at central } q^2 \in [1.1, 6.0] \text{ GeV}^2/c^4$$

Lepton flavour universality

Several anomalies observed in LFU tests

- Statistical fluctuation?
- Issues with SM computations?
- BSM physics?
- Mixture of these effects?

Many models provided by theorists to explain the deviation

- ex: LQ, Z',…

More data will help to decrease statistical uncertainties

- Run 2 data will bring 5 times more statistics

New channels can also be studied (*ex:* $B \to \phi ll$)

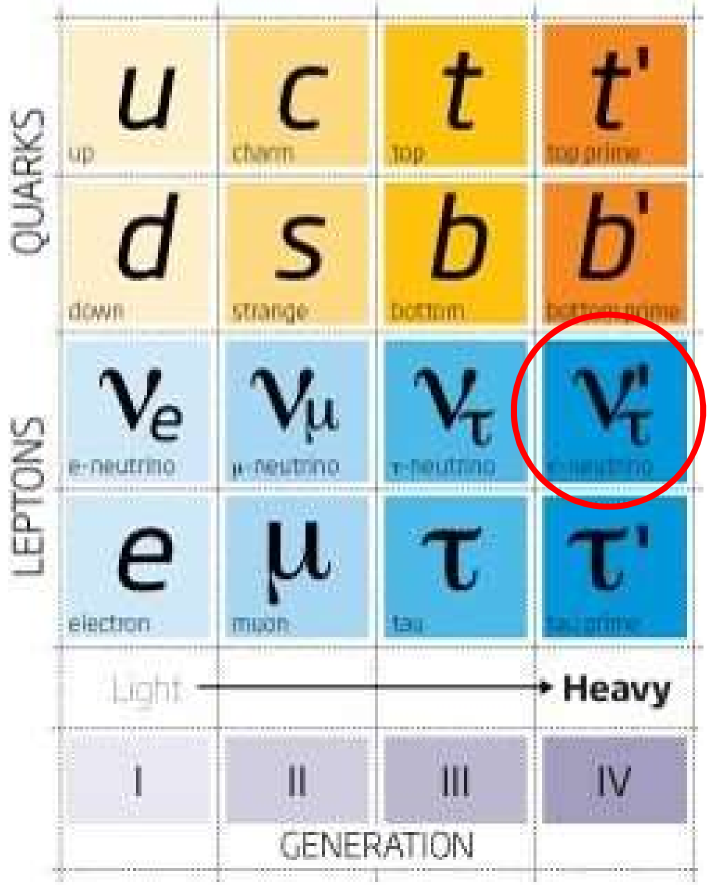
Belle2 is starting with a complementary approach to LHCb

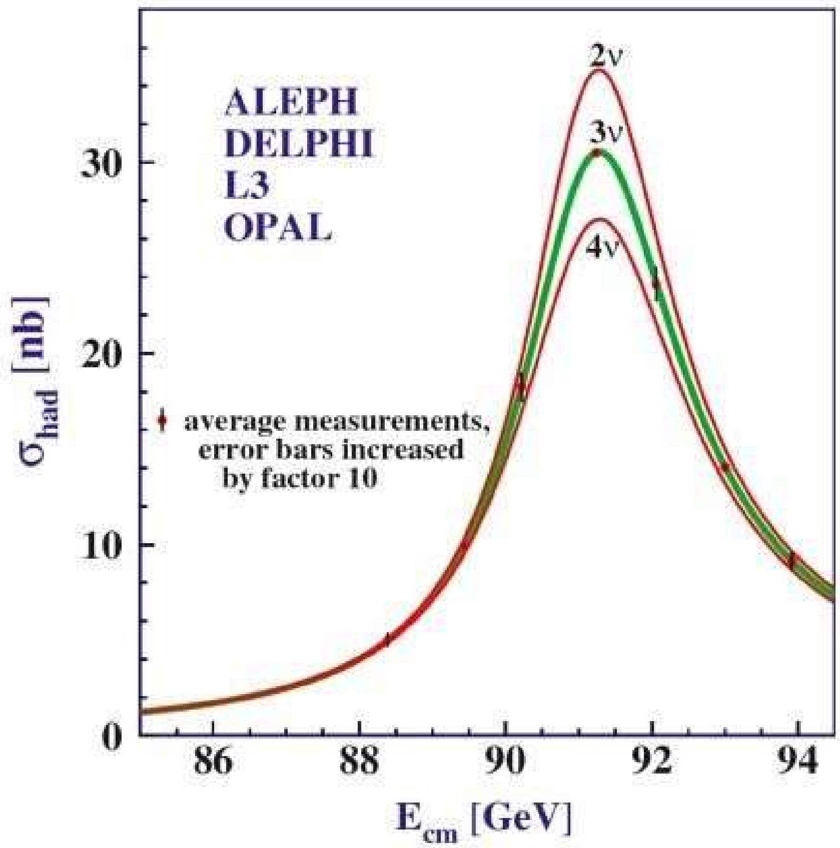
Vector-like quarks

arXiv:1207.5607
arXiv:0907.3155

4^{th} generation

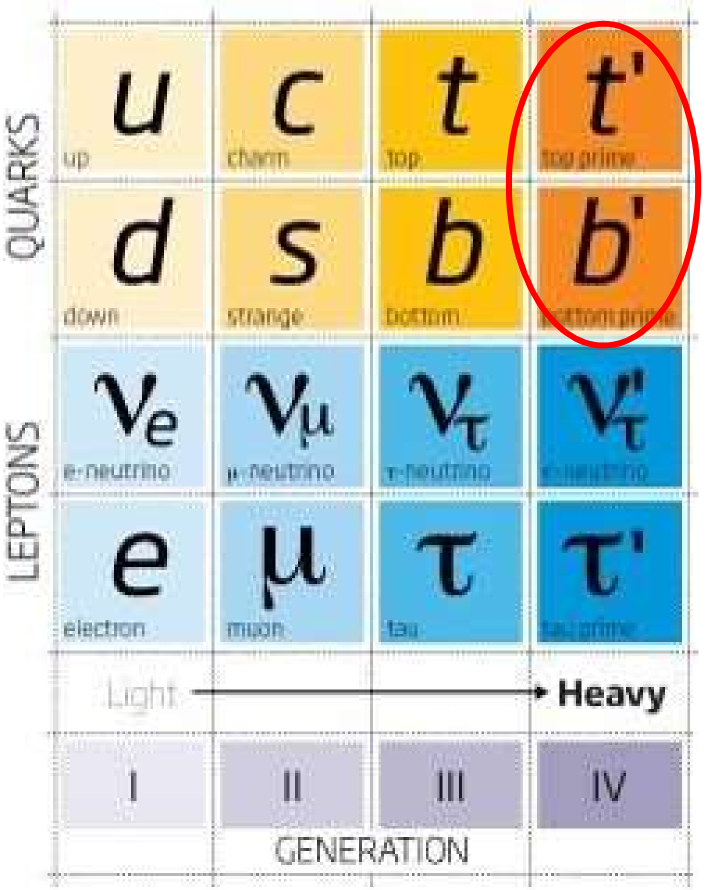
The SM does not predict the number of lepton families

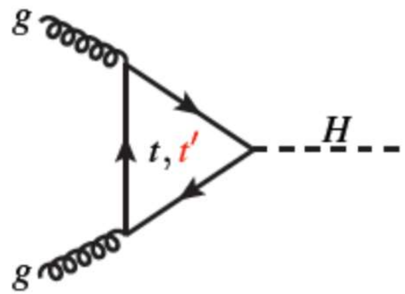




A 4^{th} neutrino coupling to the Z with a mass smaller than $M_Z/2$ is excluded but a fourth lepton family is allowed if it differs from the other families

4th generation





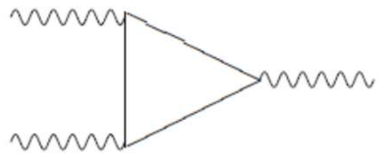
Higgs boson cross section measurements strongly constrain a **chiral** 4th generation of quarks but not a **vector-like** 4^{th} generation

What are Vector-Like Quarks?

Vector-Like Quarks

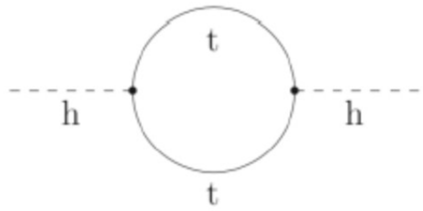
- "Quark": color-triplet spin 1/2 fermions
- "Vector-like": left- and right-handed chirality components transform similarly under SU(2)

A gauge invariant mass term is present: $-M\overline{\Psi}_L\Psi_R$



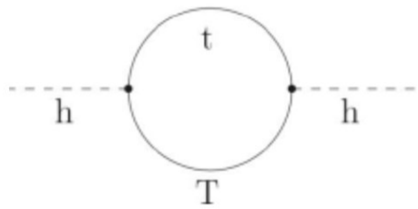
Predicted in many BSM models

- Warped or universal extra-dimensions
- Composite Higgs
- Little Higgs
- E6 grand unification
- …



Introduce new quarks without the need of a new family

- No axial anomaly

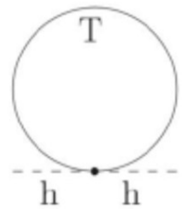


Can mix with their SM counterparts

- FCNC → strong bounds on mixing parameters
- Mixing preferentially to the 3rd generation

Can regulate the Higgs mass-squared divergence

- Attractive solution to the hierarchy problem



Representations

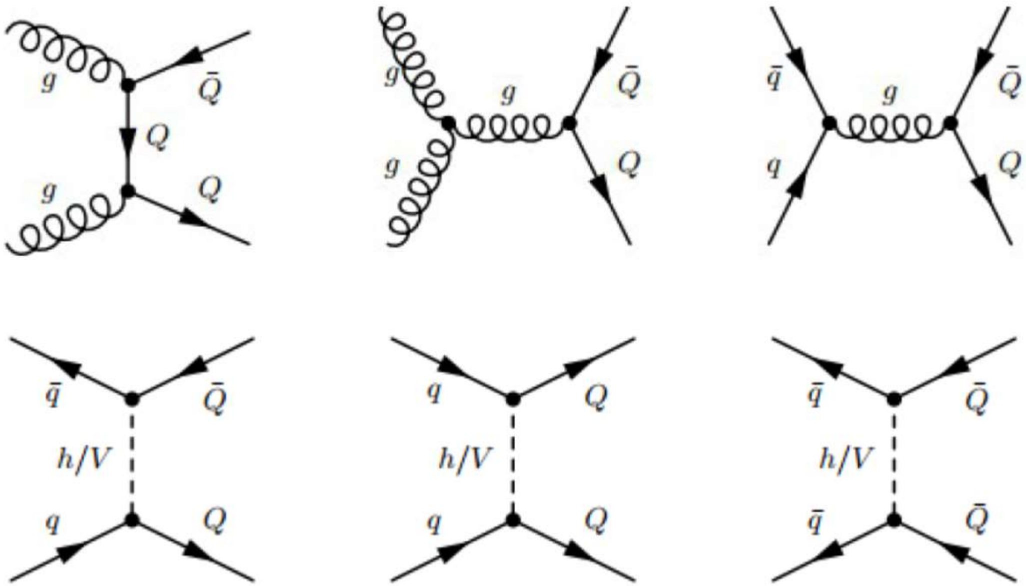
	SM quarks	Singlets		Doublets			Triplets	
	$\begin{pmatrix} u \\ d \end{pmatrix}$ $\begin{pmatrix} c \\ s \end{pmatrix}$ $\begin{pmatrix} t \\ b \end{pmatrix}$	(U)	(D)	$\begin{pmatrix} X \\ U \end{pmatrix}$	$\begin{pmatrix} U \\ D \end{pmatrix}$	$\begin{pmatrix} D \\ Y \end{pmatrix}$	$\begin{pmatrix} X \\ U \\ D \end{pmatrix}$	$\begin{pmatrix} U \\ D \\ Y \end{pmatrix}$
$SU(2)_L$	$q_L = 2$ $q_R = 1$	1		2			3	
$U(1)_Y$	$q_L = 1/6$ $u_R = 2/3$ $d_R = -1/3$	$2/3$	$-1/3$	$7/6$	$1/6$	$-5/6$	$2/3$	$-1/3$
$\mathcal{L}_Y$	$-y_u^i \bar{q}_L^i H^c u_R^i$ $-y_d^i \bar{q}_L^i V_{CKM}^{i,j} H d_R^j$	$-\lambda_u^i \bar{q}_L^i H^c U_R$ $-\lambda_d^i \bar{q}_L^i H D_R$		$-\lambda_u^i \psi_L H^{(c)} u_R^i$ $-\lambda_d^i \psi_L H^{(c)} d_R^i$			$-\lambda_i \bar{q}_L^i \tau^a H^{(c)} \psi_R^a$	
$\mathcal{L}_m$	not allowed	$-M\bar{\psi}\psi$						

For convenience, weak hypercharge is represented at half-scale

Exotic charge partner ($Q = T_z + Y$): $Y_{-4/3}$ or $X_{5/3}$
Other can mix with SM fields with a preference for the 3rd generation
(top partners: U called T or t’ and D called B or b’)

Production

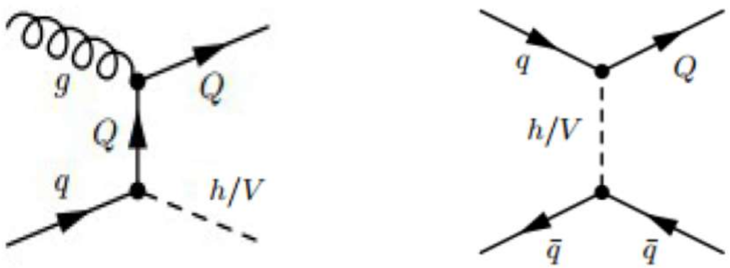
Pair production:



QCD coupling:
- Dominant
- rate model-independent

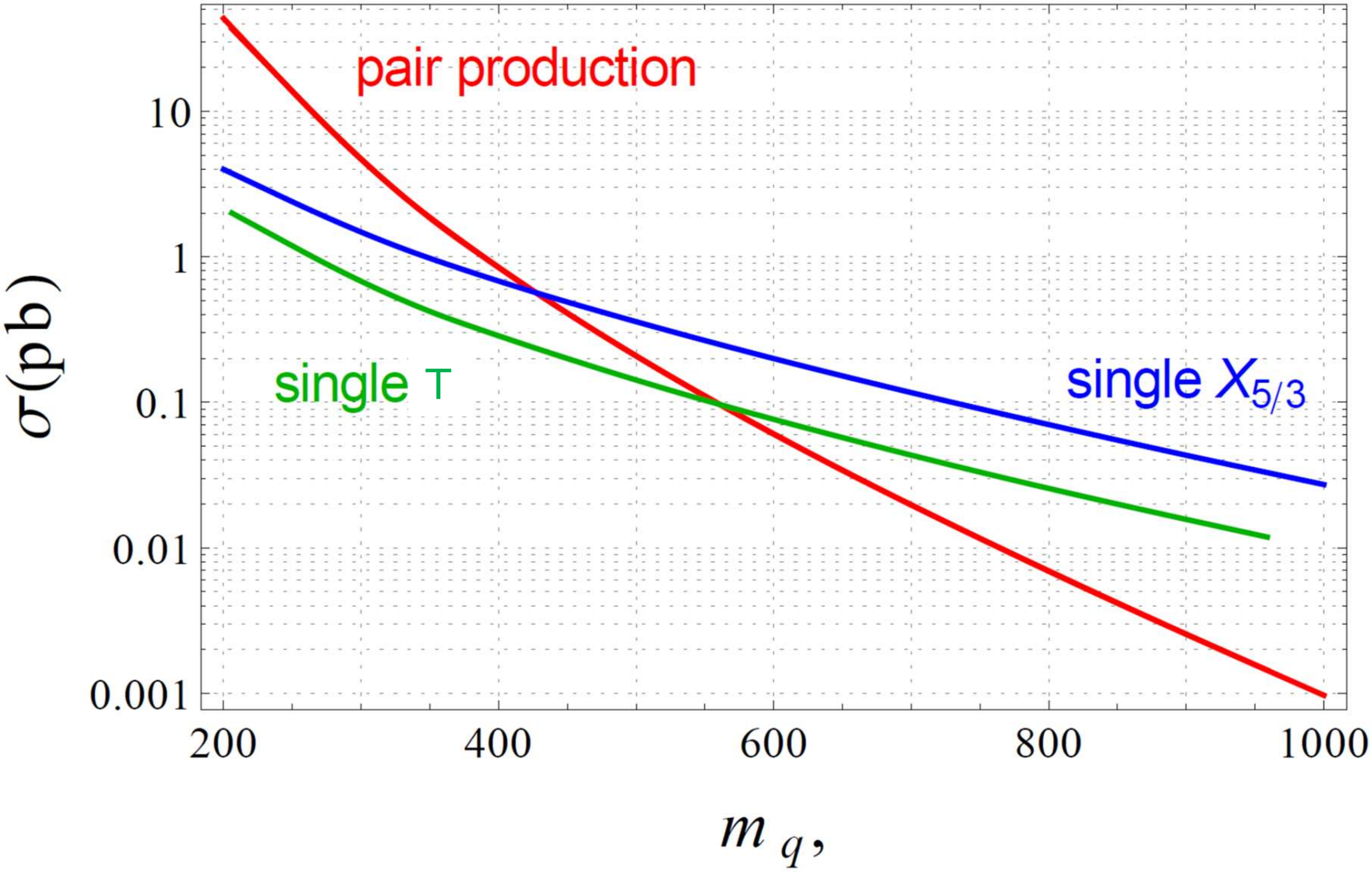
EW coupling:
- rate model-dependent
- suppressed

Single production :



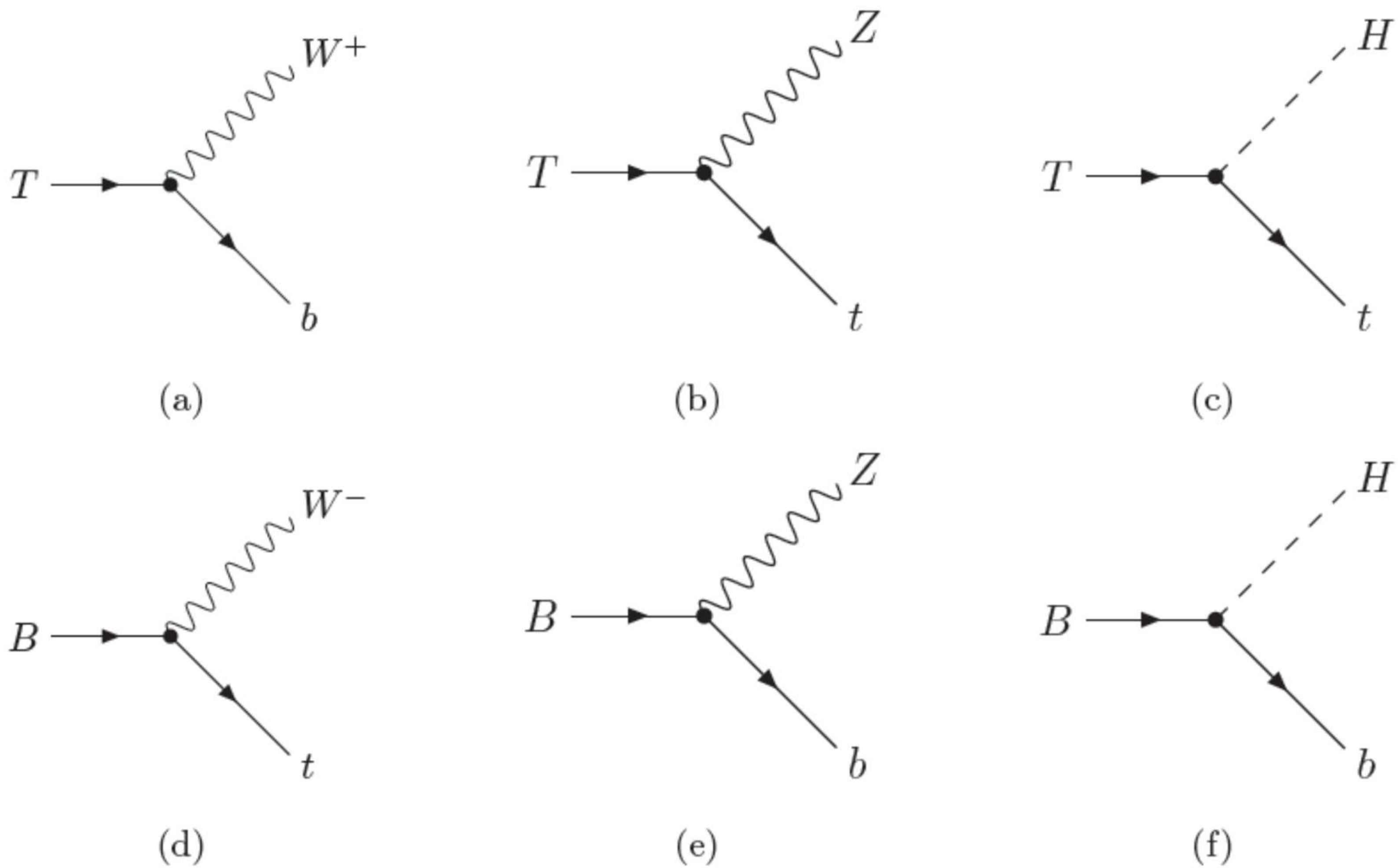
- rate model-dependent

Production



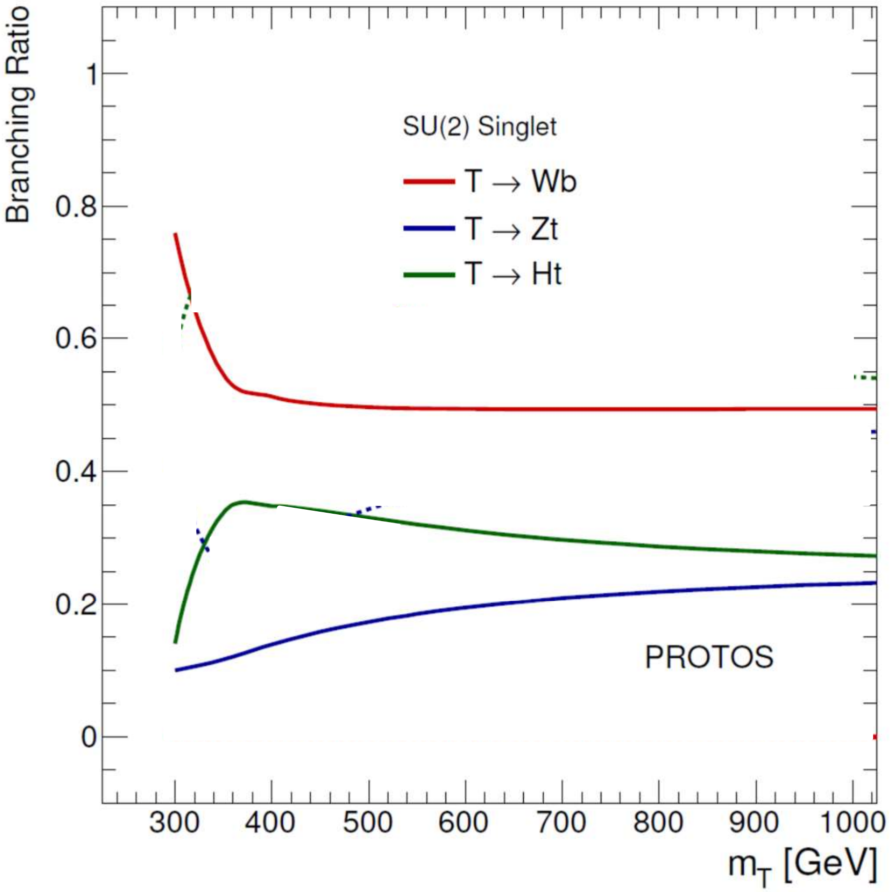
Single production falls slower at high masses

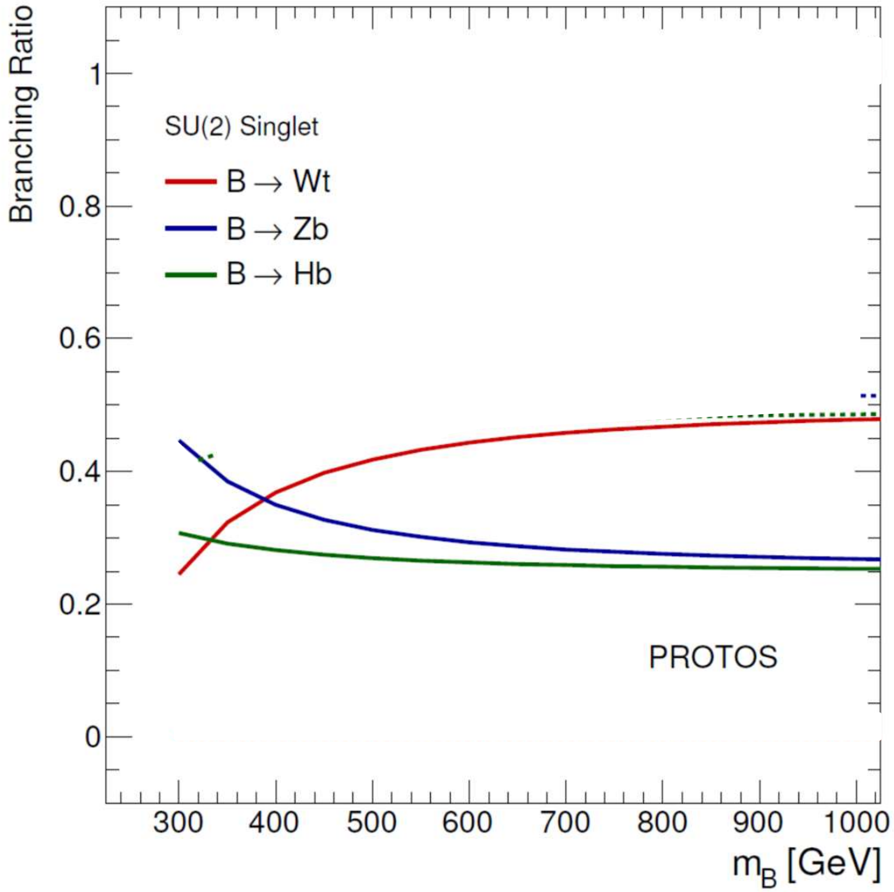
Decays



The decay modes of the vector-like quarks T and B each have a charged current decay mode as would be found with chiral fourth generation SM quarks, but also two neutral current decay modes.

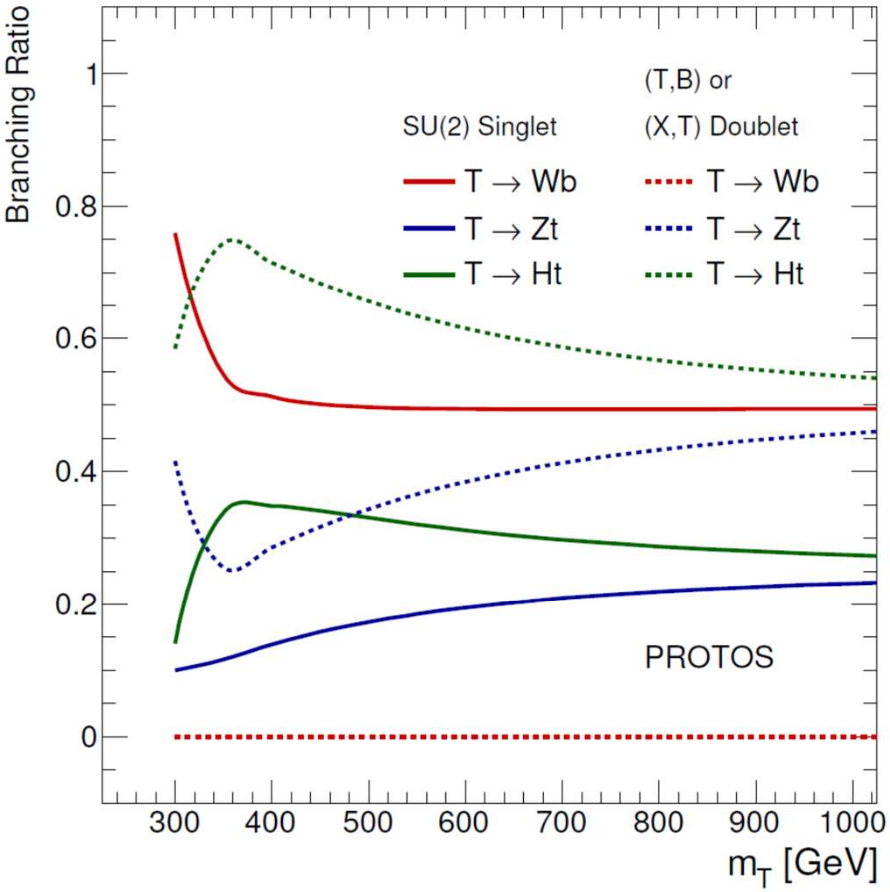
Decays

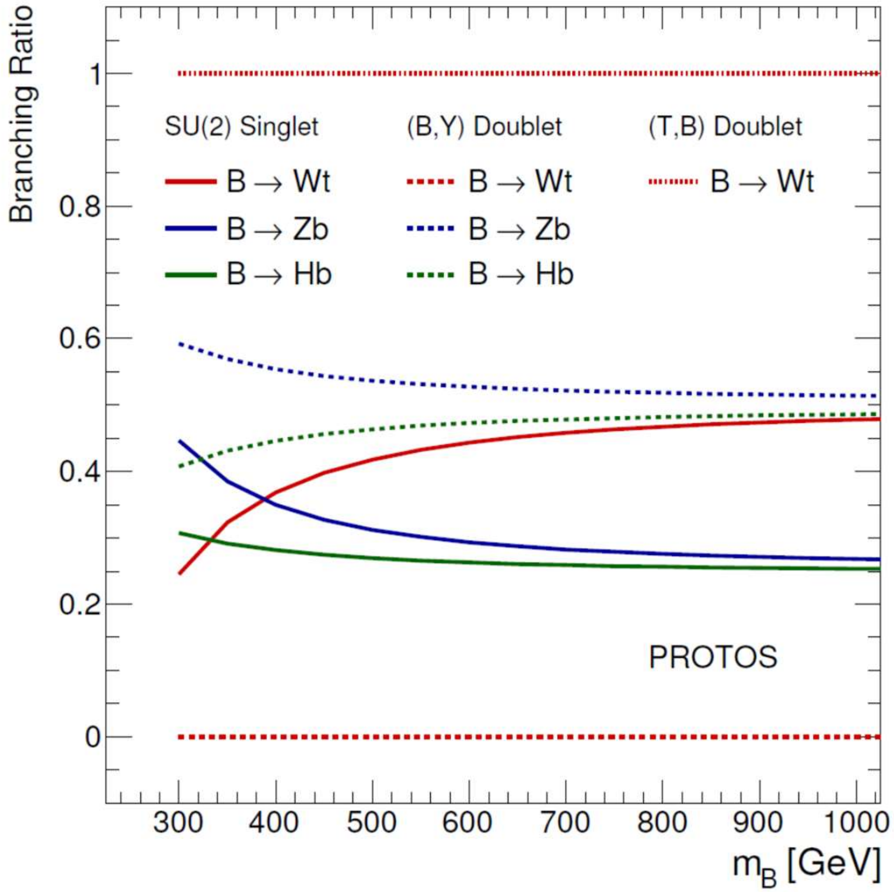




For (T,B) doublet assume VTb << VtB (The top quark mixes preferentially with its partner rather the bottom quark) : T→Wb suppressed

Decays

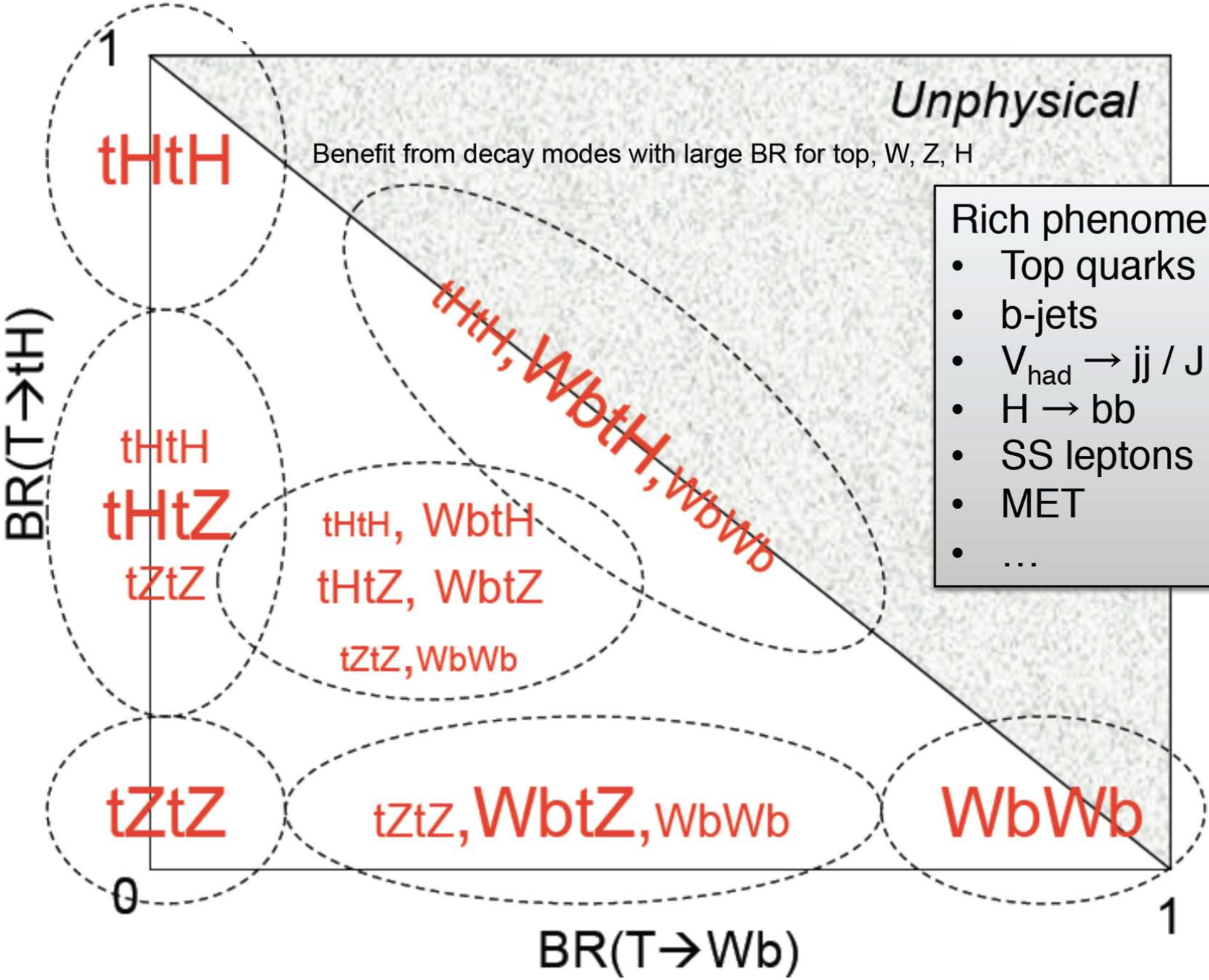




For (T,B) doublet assume VTb << VtB (The top quark mixes preferentially with its partner rather the bottom quark) : T→Wb suppressed

Search strategy for TT pair production

3 decay modes: Wb, Zt and Ht

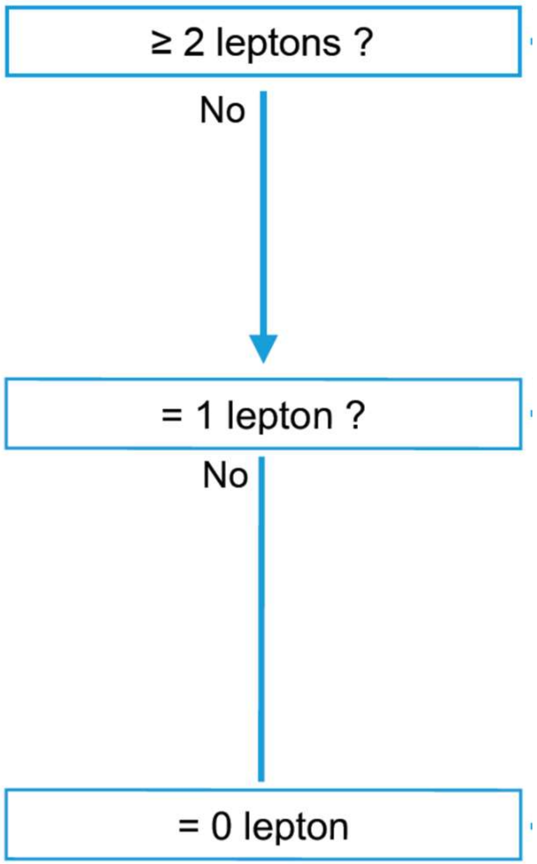


Rich phenomenology:

- Top quarks
- b-jets
- V_{had} → jj / J
- H → bb
- SS leptons
- MET
- …

Search strategy for TT pair production

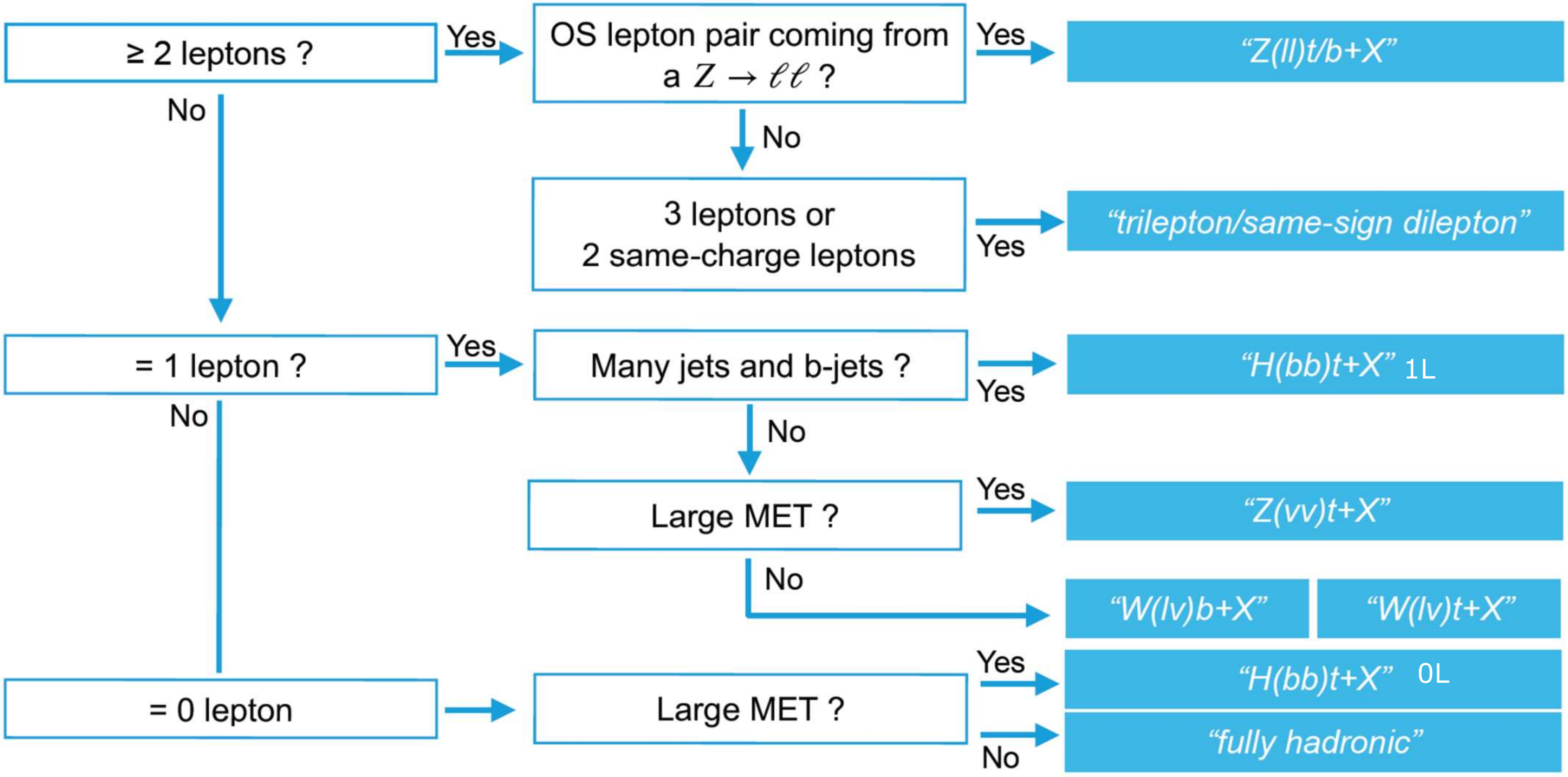
3 decay modes: Wb, Zt and Ht



Also sensitive to BB pair production

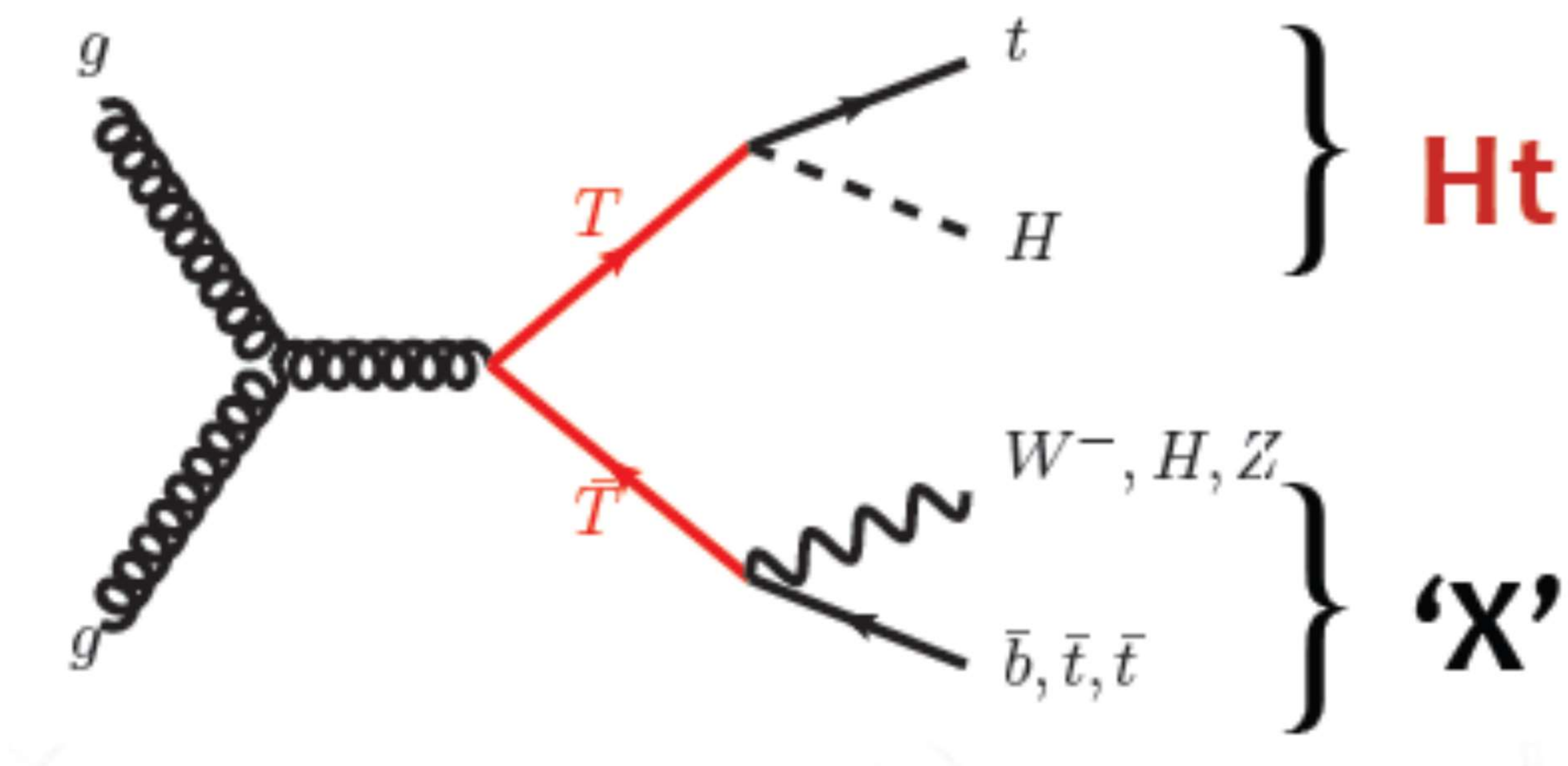
Search strategy for TT pair production

3 decay modes: Wb, Zt and Ht

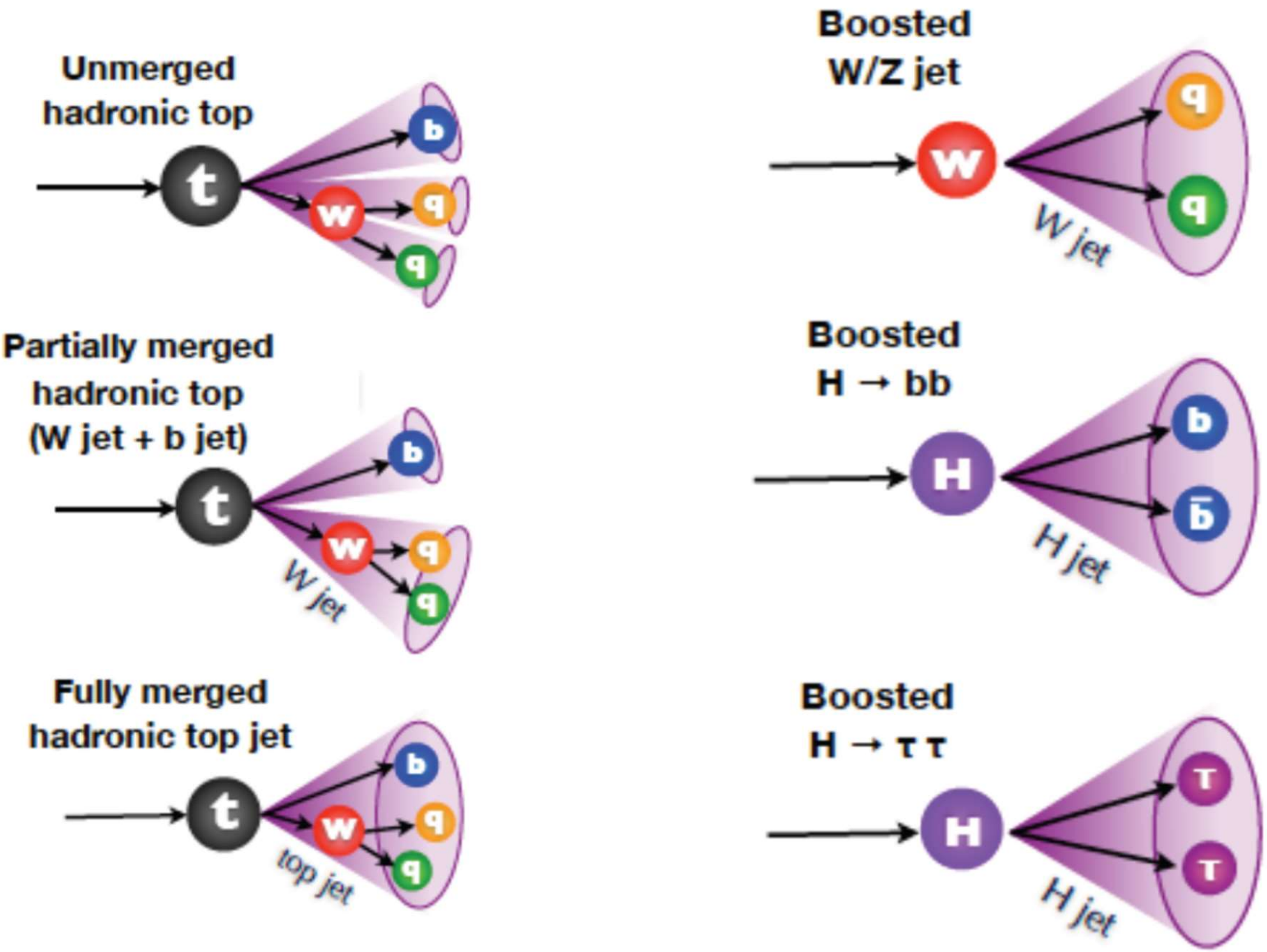


6 analyses in total
Also sensitive to BB pair production

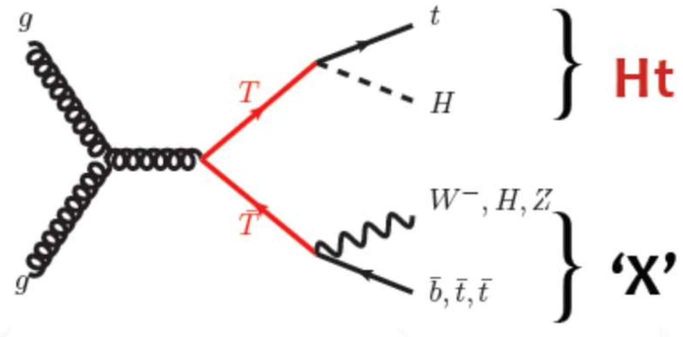
H(bb)t+X analysis



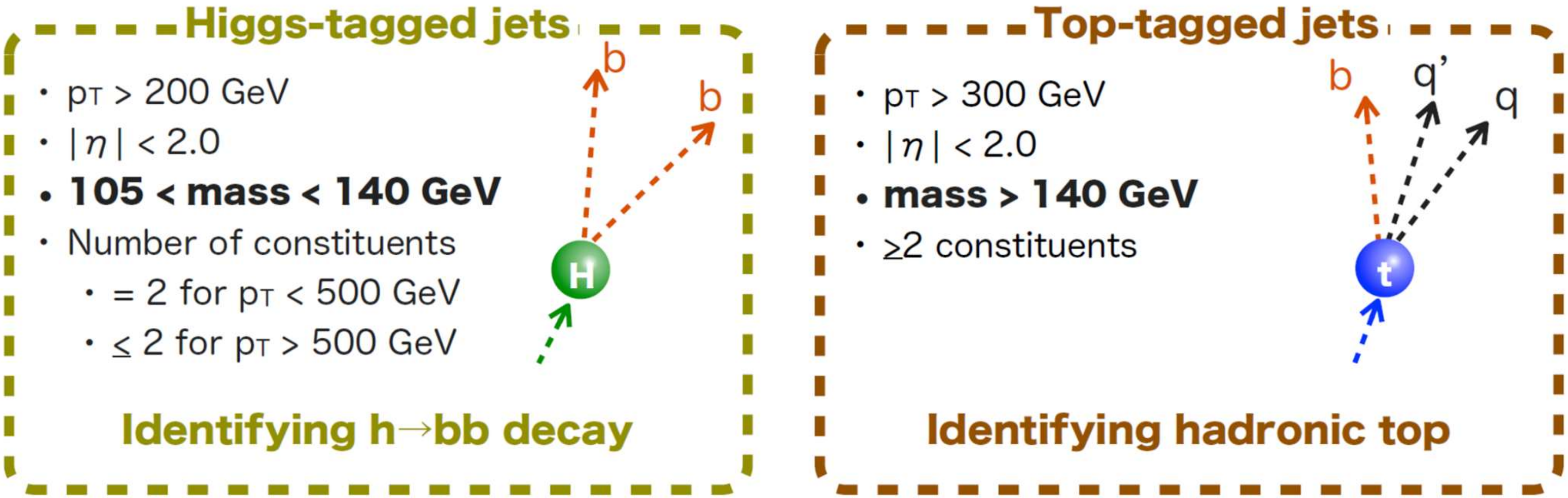
Boosted unstable particles



H(bb)t+X analysis



Higgs as a tool to search for BSM physics
Many b-jets in the final states



D. Yamaguchi

Two channels : 1-lepton vs 0-lepton

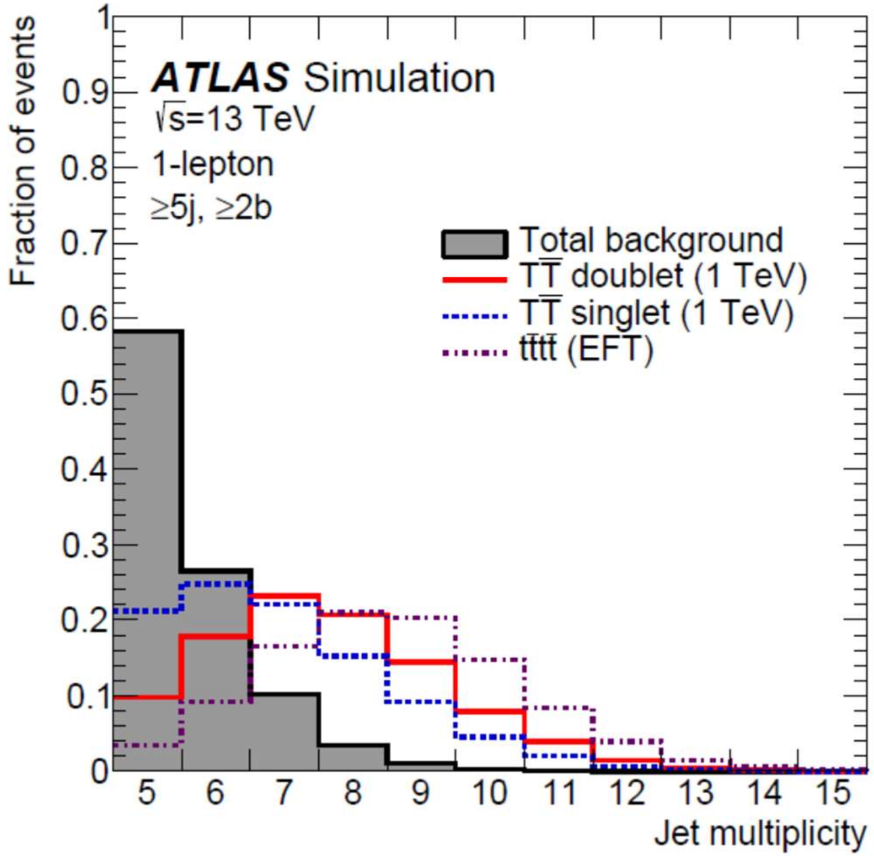
Using reclustered jets (Anti-k_T, R = 1.0) from small-R jets (Anti-k_T, R = 0.4)

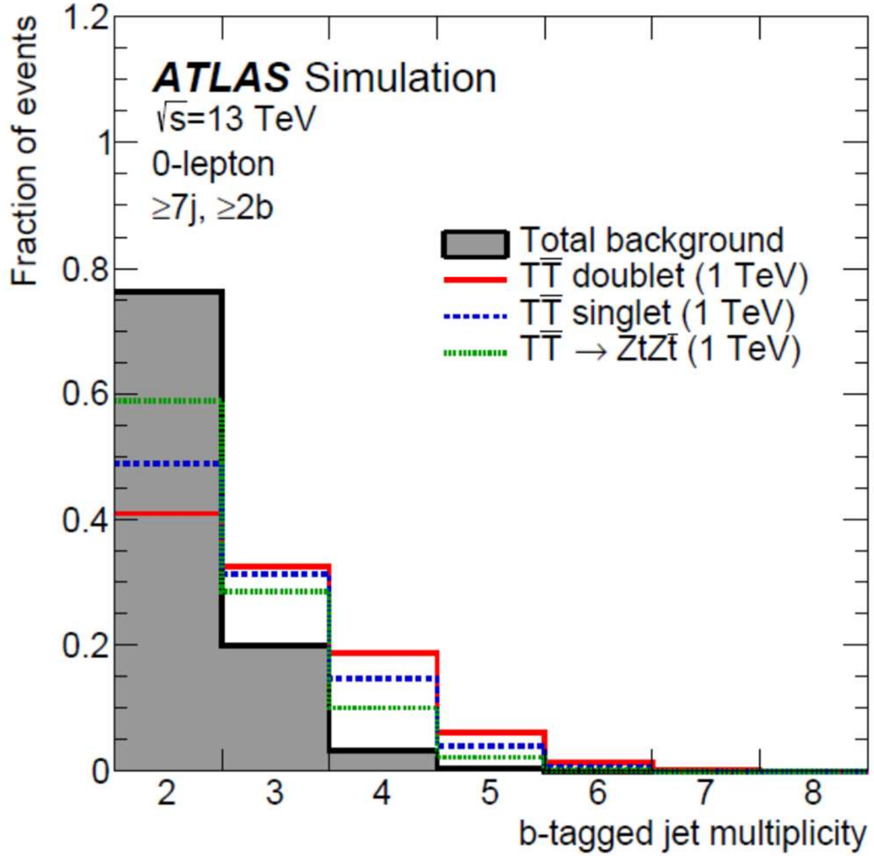
Final signal discrimination based on shape of **effective mass**

$$m_{\text{eff}} = \sum_{\text{objects}} p_T + E_T^{\text{miss}}$$

H(bb)t+X analysis

Example of discriminating variables

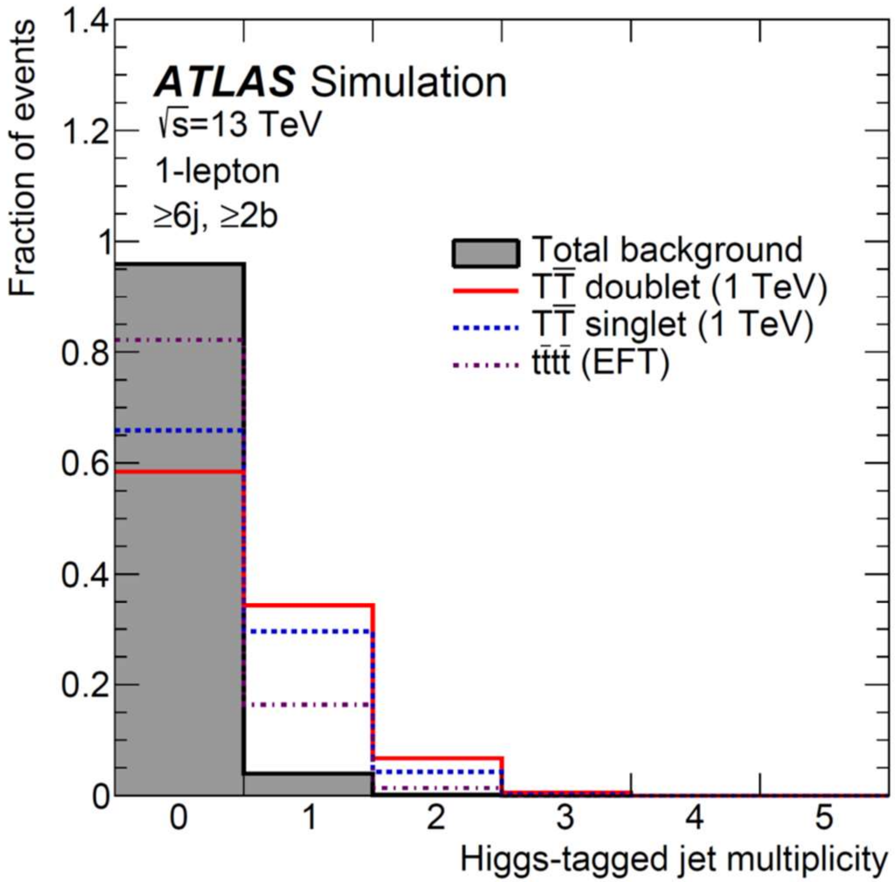


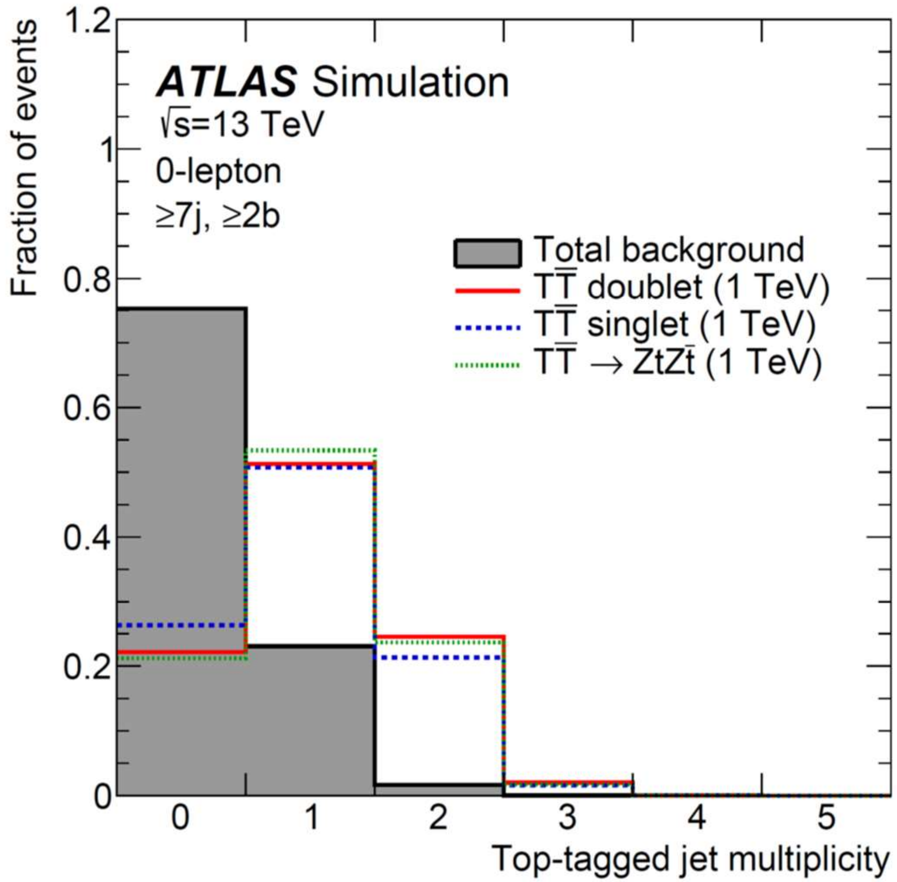


Dominant bkg: $\bar{t}t + b, \bar{t}t + c$

H(bb)t+X analysis

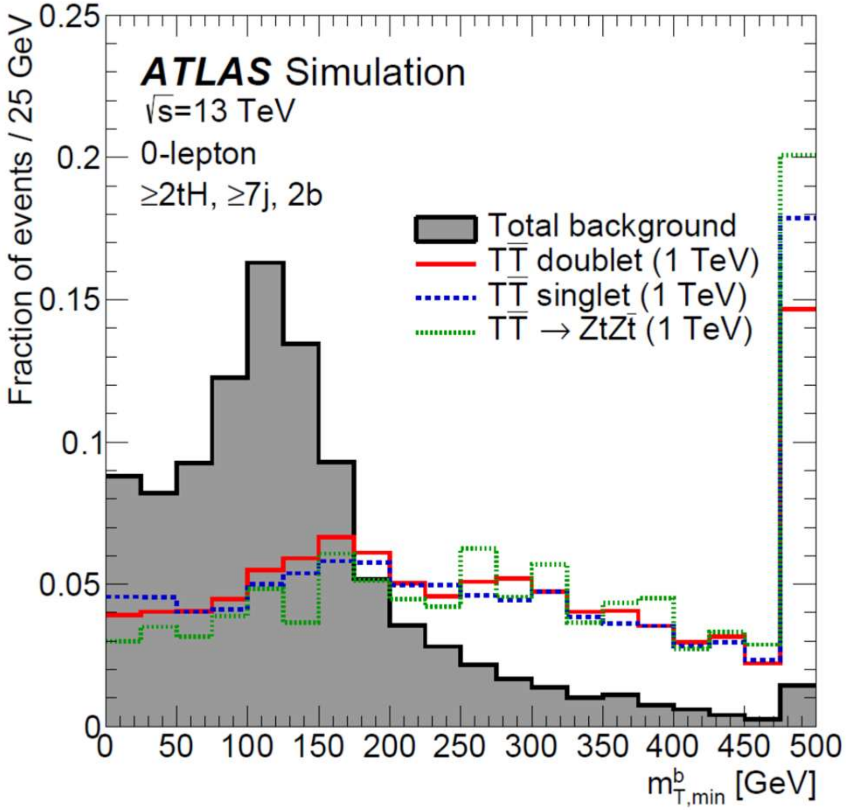
Example of discriminating variables

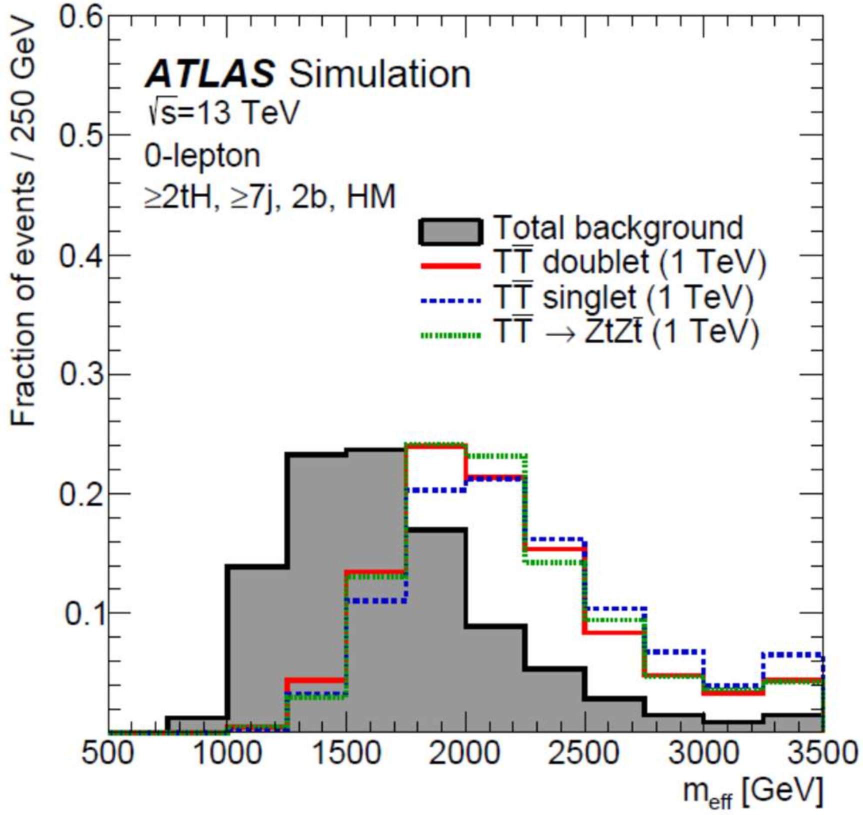




H(bb)t+X analysis

Only 0L channel





$$m^b_{T,\min} = Min(\sqrt{2 p_T^{miss} p_T^b (1-\cos\Delta\phi)})$$

$$m_{\text{eff}} = \sum_{\text{objects}} p_T + E_T^{\text{miss}}$$

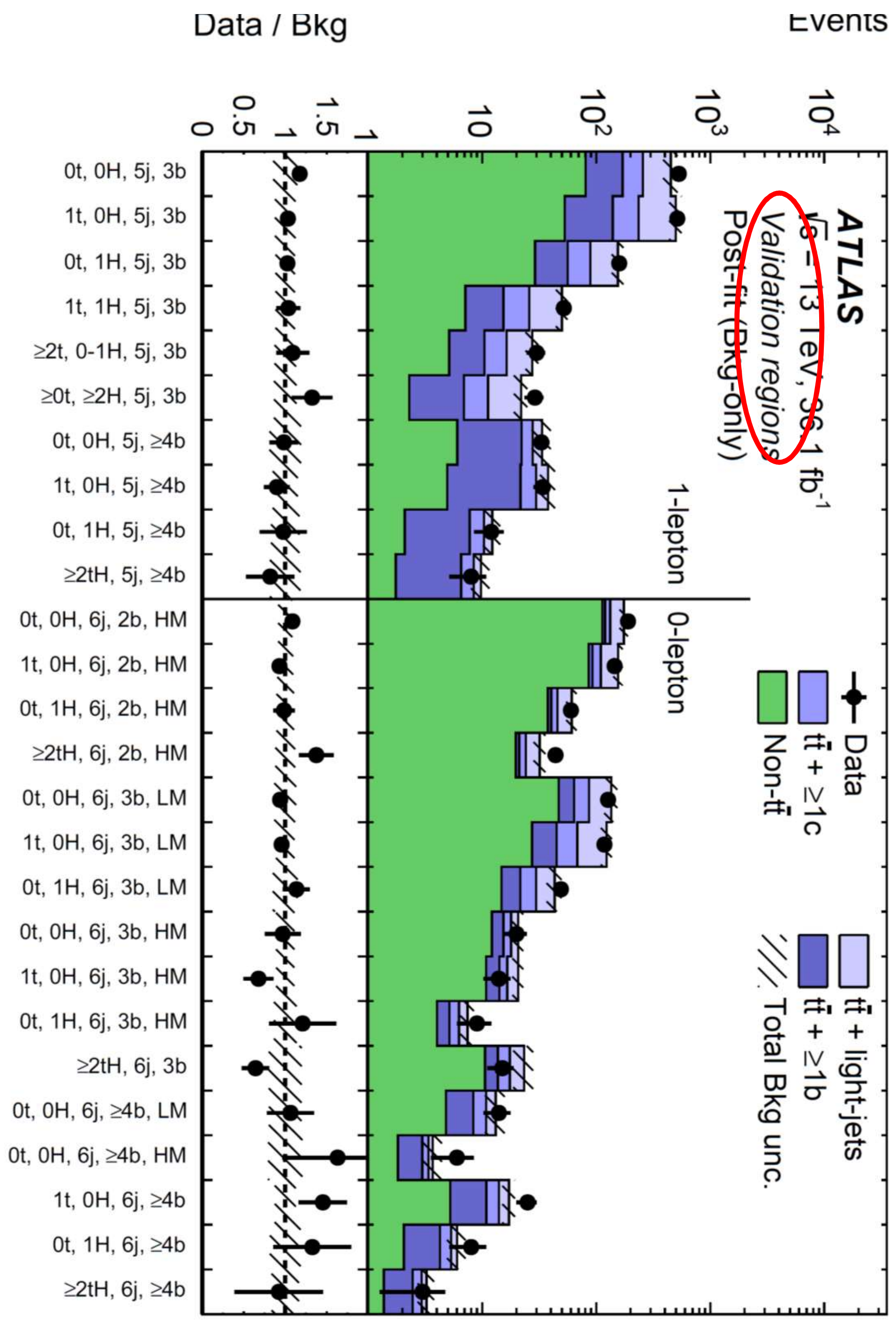
Variable bounded from above by the top quark mass for semileptonic tt bkg events (lost lepton)

H(bb)t+X analysis

Main background: top pair production + heavy flavour jets

Estimated from MC with associated uncertainties profiled by fitting the data

Validation regions with lower jet multiplicity (signal contribution should be negligible)

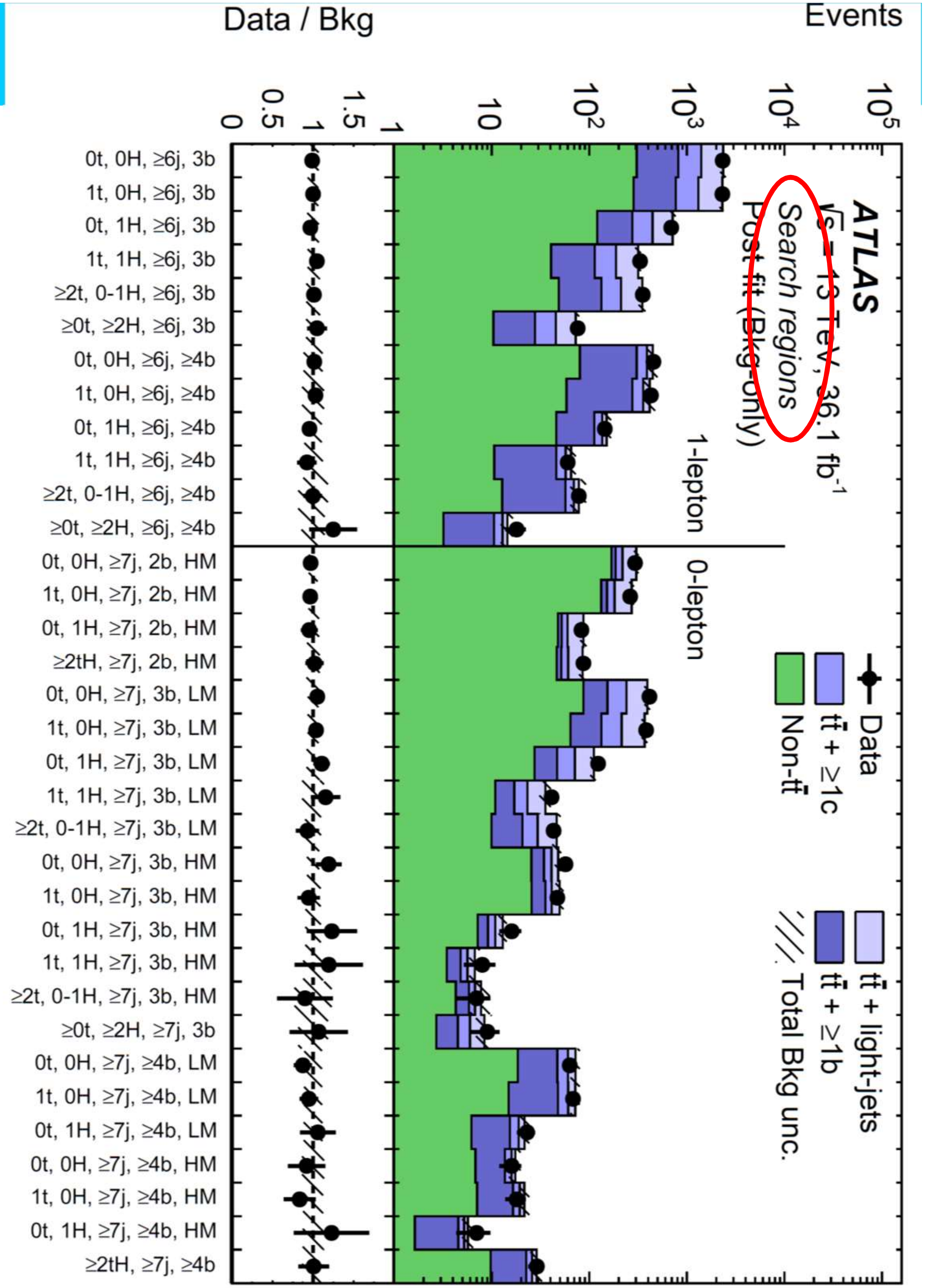


H(bb)t+X analysis

34 signal regions

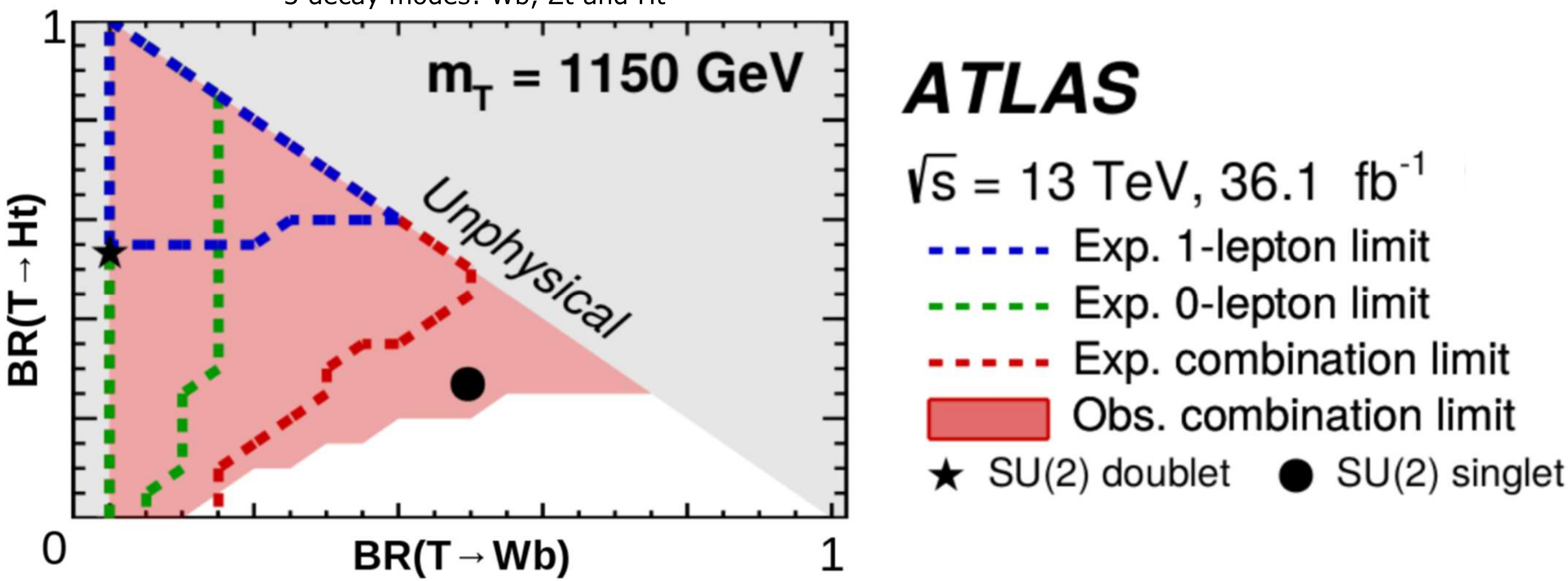
Main background: top pair production + heavy flavour jets

No excess observed



H(bb)t+X analysis

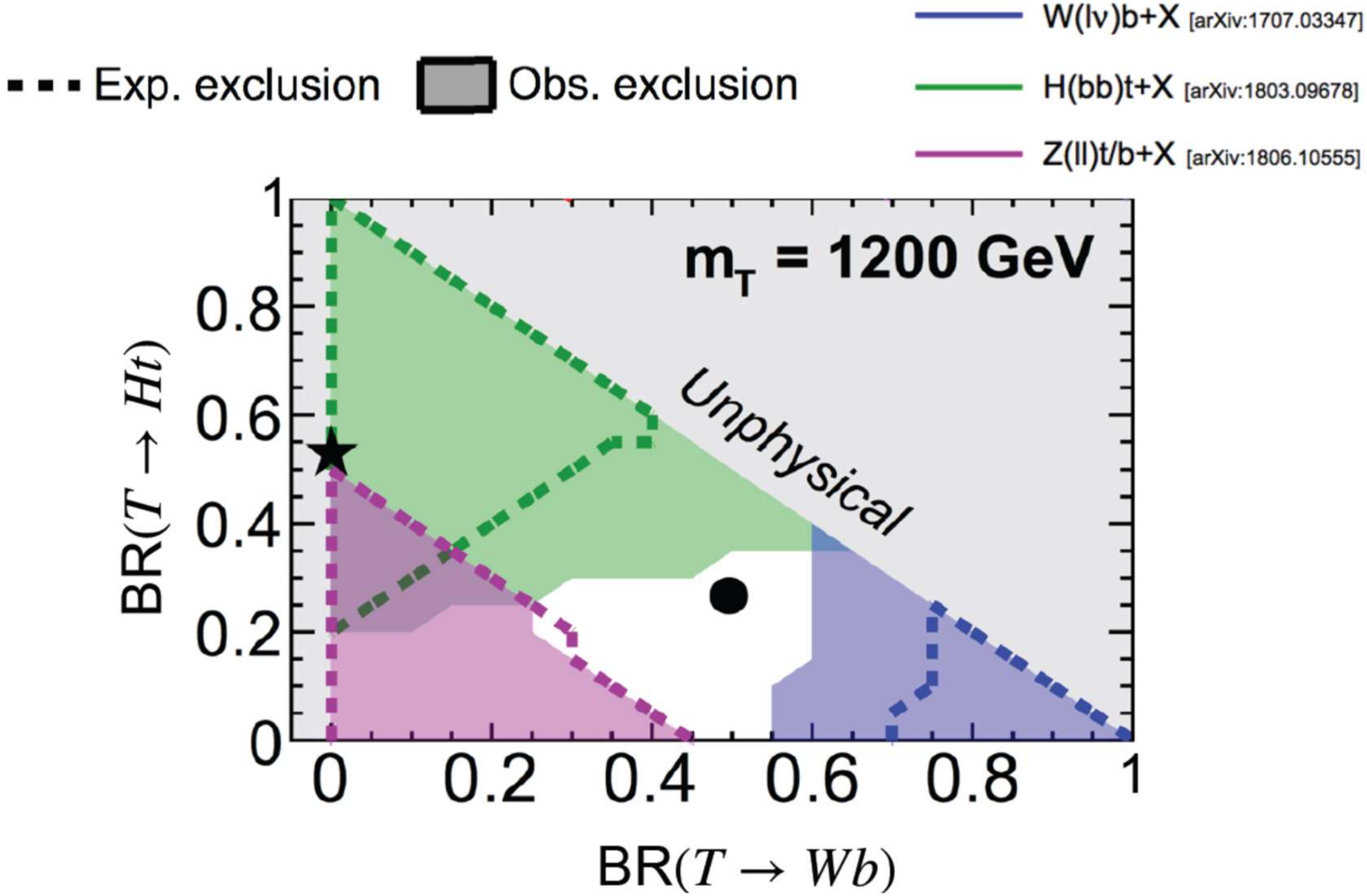
3 decay modes: Wb, Zt and Ht



1-lepton channel : lepton + jets ... sensitive to large BR of T→tH(bb)

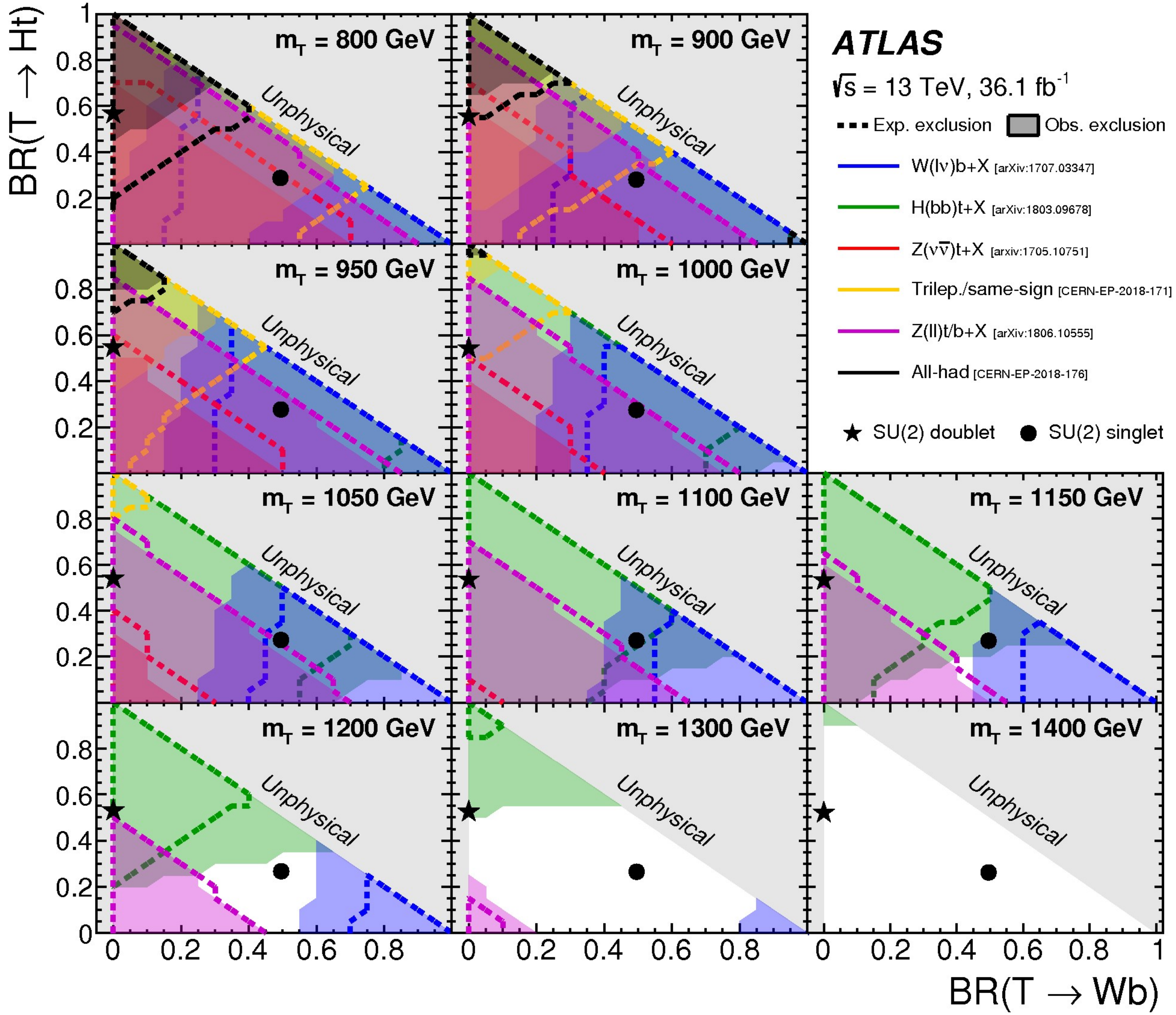
0-lepton channel : jets + E_{Tmiss} ... sensitive to large BR of T→tZ(νν)

Comparison of all analyses

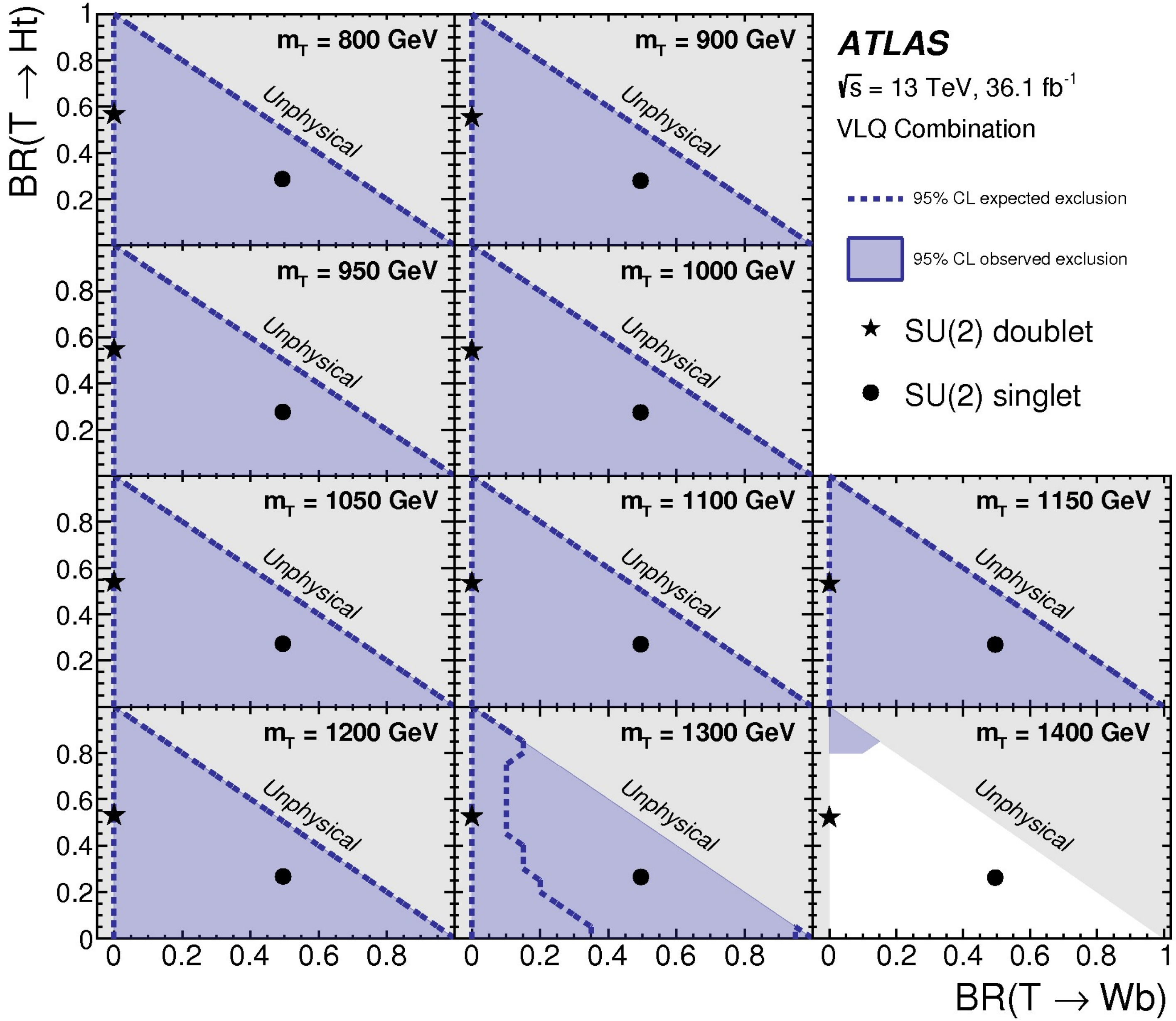


Complementarity between analyses

Comparison of all analyses

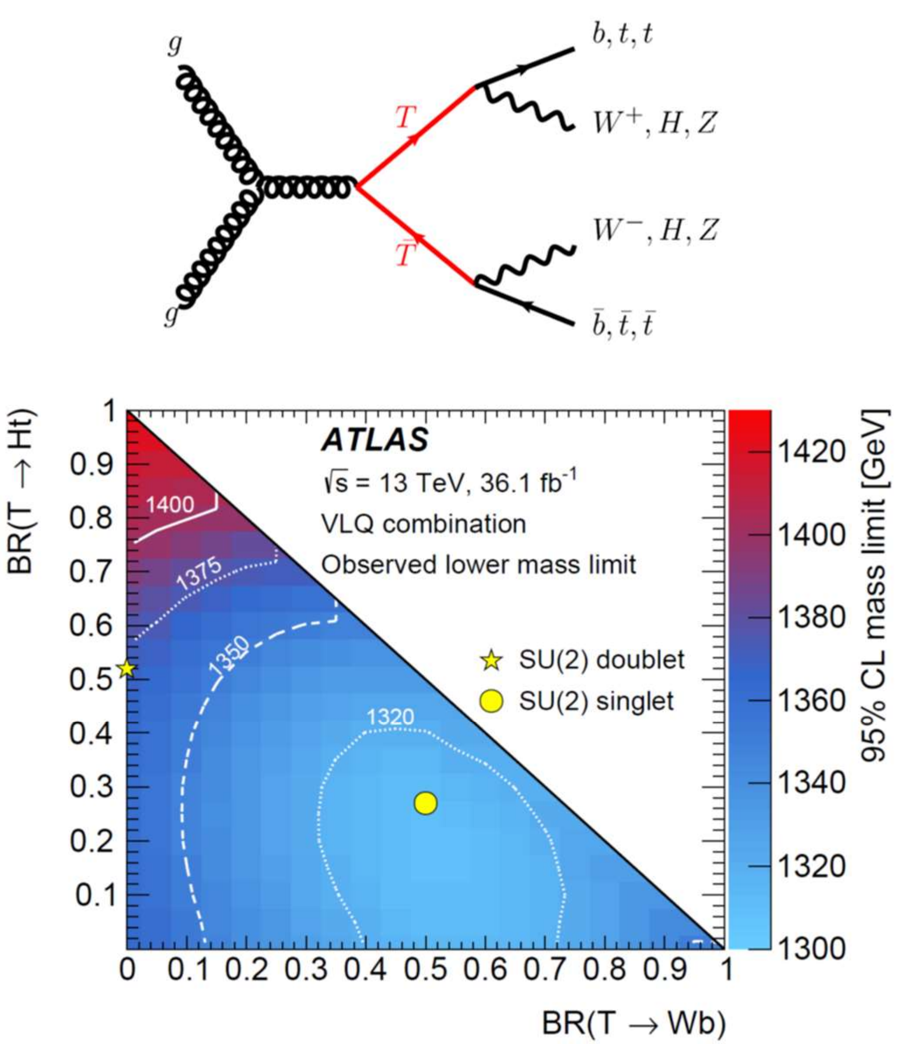


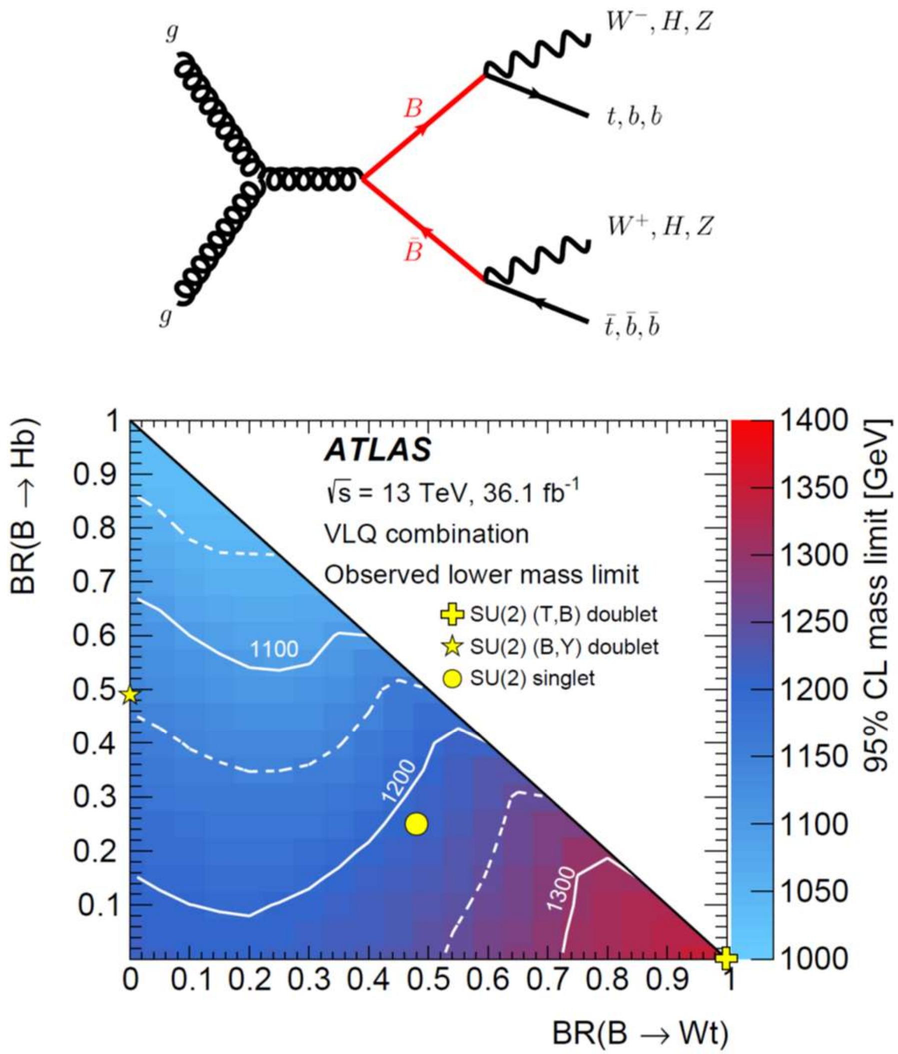
Combination



Strong sensitivity gain !

Combination

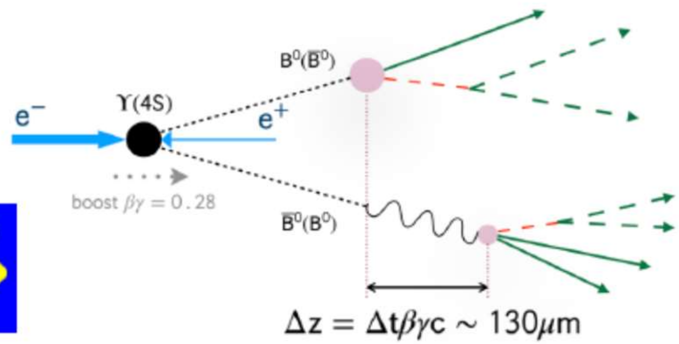


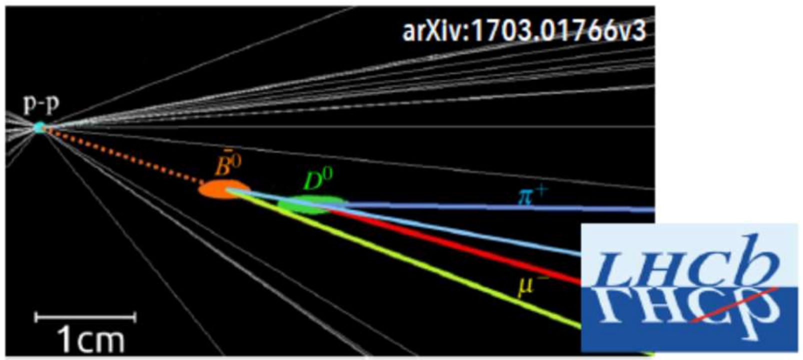


Higgs boson and dark matter

BELLE II AND LHCb

Belle II $e^+e^- \to \Upsilon(4S) \to B\bar{B}$	**LHCb** $pp \to B\bar{B}X$
Two B's and nothing else **Higher tagging efficiency**	Large pp background
Small cross section $\sigma_{bb} \sim 1$ nb but $\sigma_{bb}/\sigma_{tot} \sim 1/4$	Large cross section $\sigma_{bb} \sim 248\ \mu b$ but $\sigma_{bb}/\sigma_{tot} \sim 10^{-2}$
Mostly $B^{+/0}$	Not only $B^{+/0}$: B_s, B_c, Λ_b **Better on heavy hadrons**
Efficient, simple trigger	Complex triggers
Momentum conservation, ~ hermetic detector	p_T conservation, no hermeticity
Similar performance for and e and μ **LFU tests**	Better performance for μ than for e **Higher sensitivity for modes with muons**
High neutrals efficiencies	Poor neutrals efficiencies
B meson decay lengths: hundreds of μm	B meson decay lengths: mm **Good separation between vertices**





Dark matter

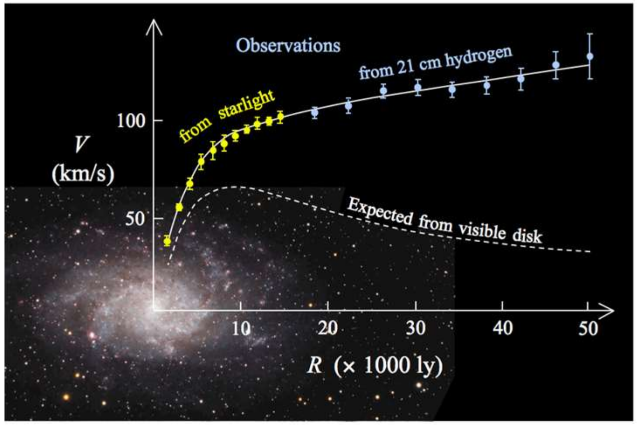
Existence of dark matter known through its gravitational interactions

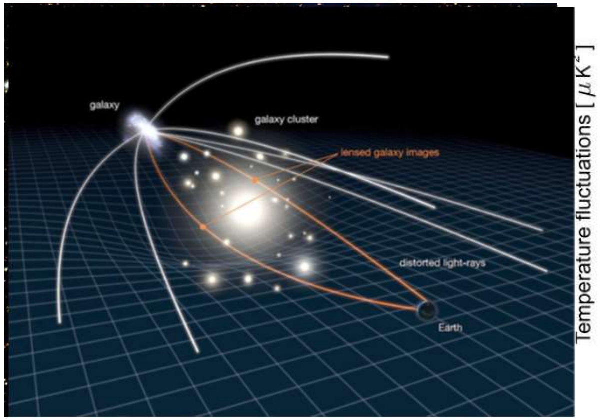
- Galactic rotation
- Weak lensing
- CMB

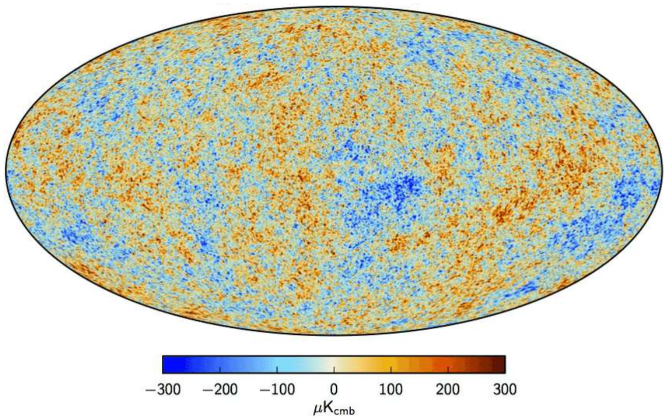
But the underlying nature of dark matter (DM) remains unknown

There is a well established case for weakly interacting dark matter particles (WIMPs)

Such particles may be produced in high energy pp collisions at the LHC and in particular through decays of the Higgs boson

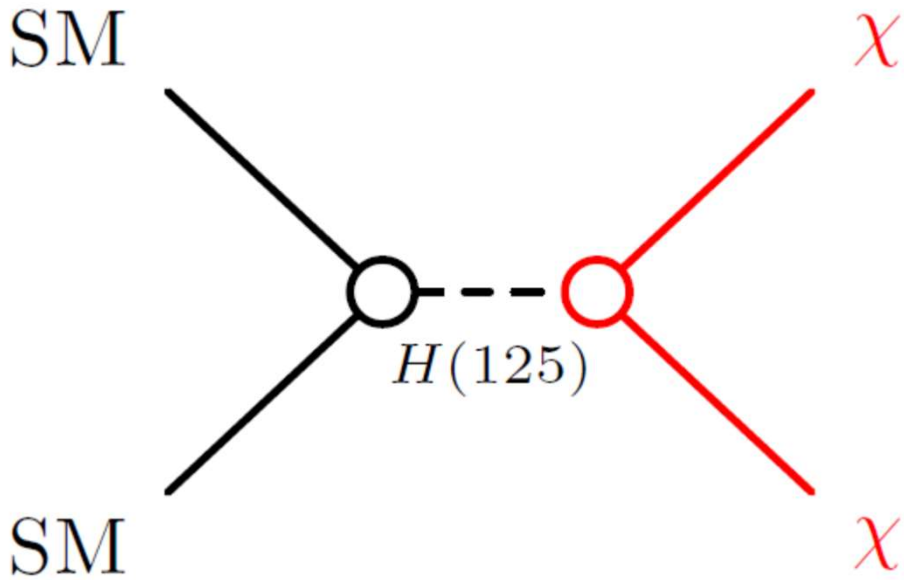






Higgs portal

Higgs portal model: Higgs boson mediates the interaction between DM and SM
Two free parameters: dark matter mass and coupling between the Higgs boson and dark matter



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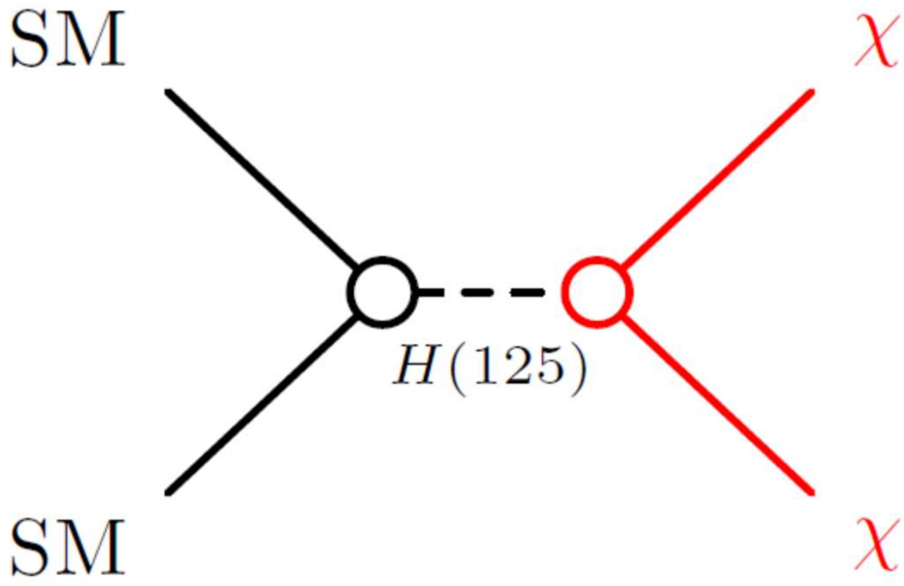


In the SM, H ⟶ invisible only from H ⟶ ZZ ⟶νν νν

B(H ⟶ inv) = 0.026x0.20^2 = 0.1%

Any deviation would indicate BSM physics!

Powerful channel for DM searches if m_{DM}<m_H=2

Higgs portal with scalar DM

$$\Delta\mathcal{L}_S = -\frac{1}{2}m_S^2 S^2 - \frac{1}{4}\lambda_S S^4 - \frac{1}{4}\lambda_{hSS} H^\dagger H S^2$$

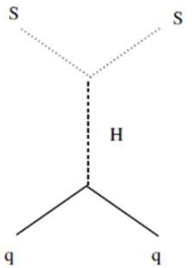
Invisible branching ratio:

$$\Gamma^{\mathrm{inv}}_{h\to SS} = \frac{\lambda_{hSS}^2 v^2 \beta_S}{64\pi m_h}$$

with

$$\beta_X = \sqrt{1 - 4M_X^2/m_h^2}$$

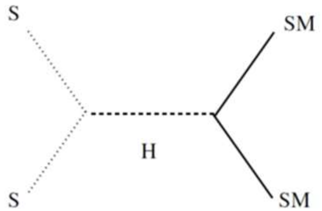
The spin–independent DM–nucleon interaction:



$$\sigma^{SI}_{S-N} = \frac{\lambda_{hSS}^2}{16\pi m_h^4}\frac{m_N^4 f_N^2}{(M_S + m_N)^2}$$

f_N is a nuclear form factor parameterizing the Higgs–nucleon coupling

Annihilation cross-section into light fermion:

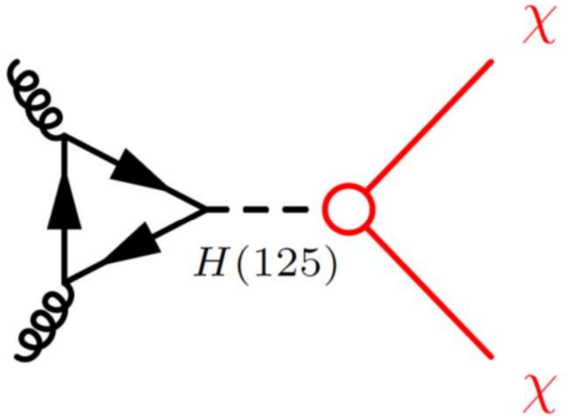


$$\langle\sigma^S_{\mathrm{ferm}} v_r\rangle = \frac{\lambda_{hSS}^2 m_{\mathrm{ferm}}^2}{16\pi}\frac{1}{(4M_S^2 - m_h^2)^2}$$

v_r is the DM relative velocity.

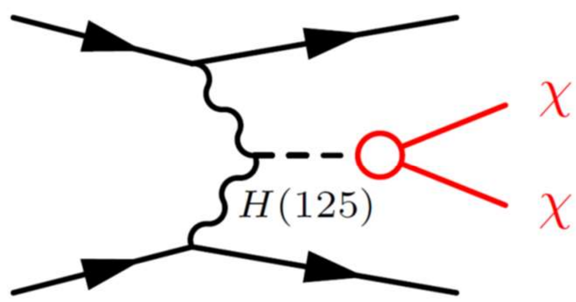
Overview of search channels for H→invisible

Gluon fusion: 49 pb



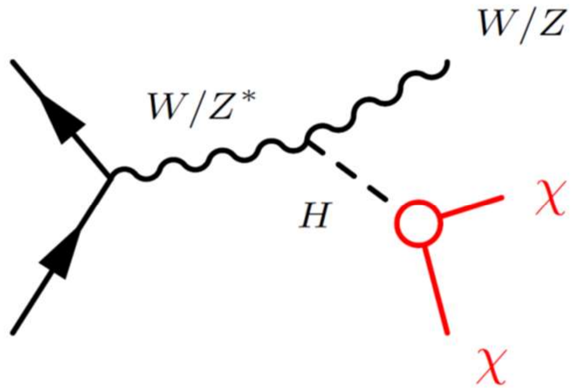
- Need ISR ($\Rightarrow$ jet+$E_{\mathrm{T}}^{\mathrm{miss}}$) to trigger and tag
- Same final state as mono-jet search
- Least sensitive signature

VBF: 3.8 pb



- Tag using forward jets with large $\Delta\eta(jj)$
- Low background, $S/B \sim 0.5$ ($\mathcal{B}_{\mathrm{inv}} = 1$)
- Most sensitive signature

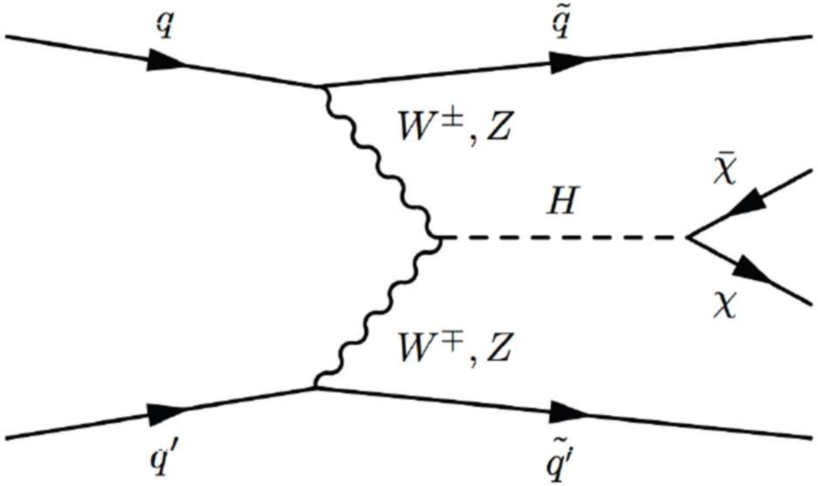
VH: 2.3 pb

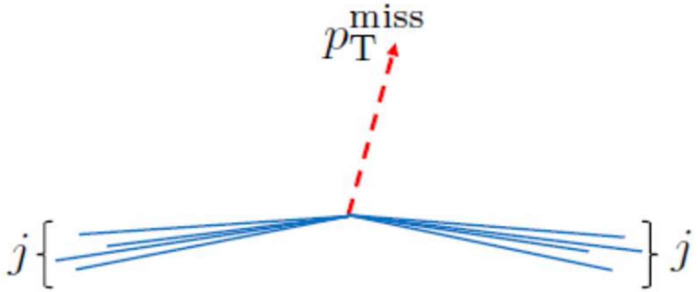


- Tag using $Z \to \ell\ell$ or jets from $V(\mathrm{had})$
- Same final state as $V + E_{\mathrm{T}}^{\mathrm{miss}}$ search
- Intermediate sensitivity

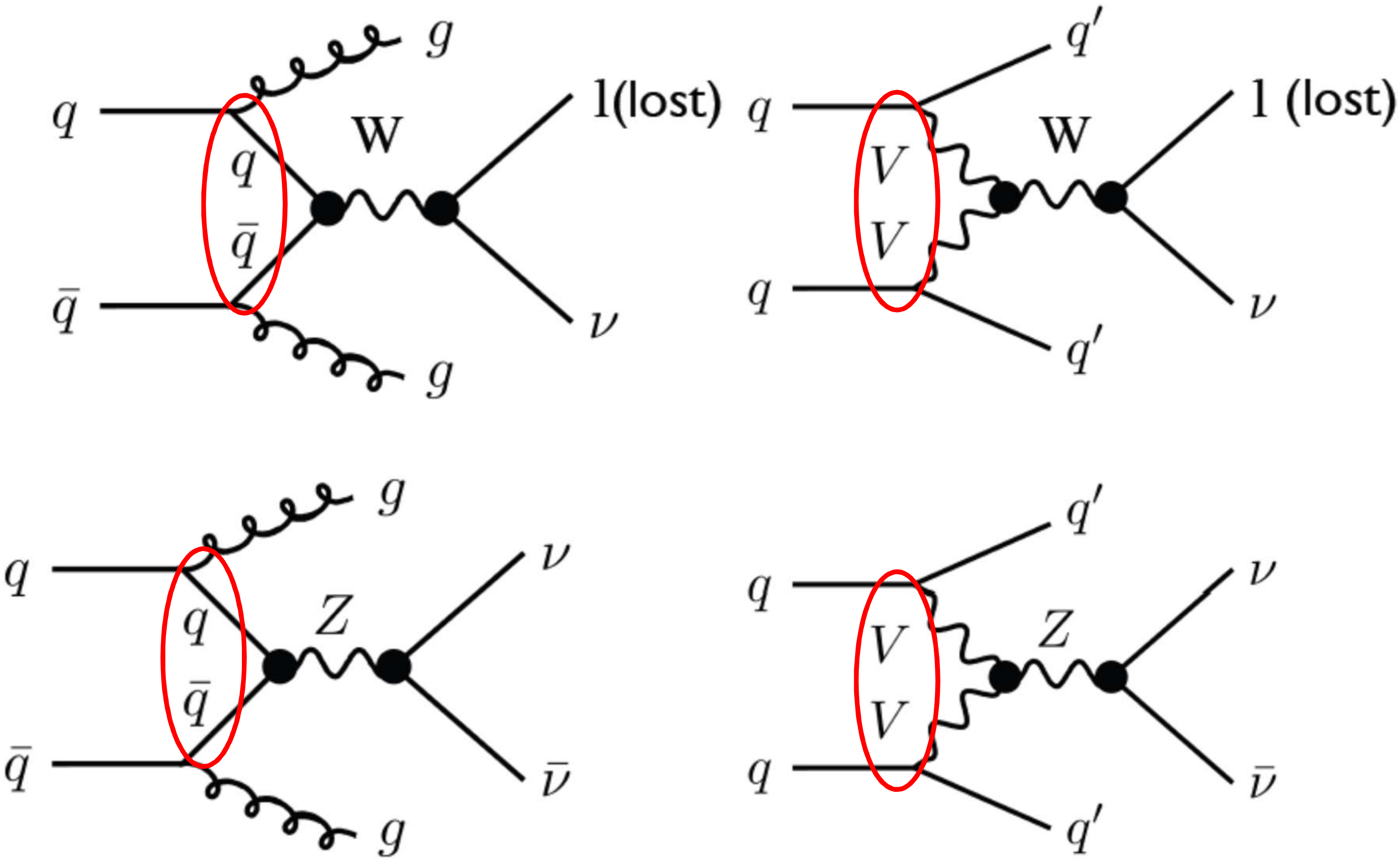
VBF channel

Selection based on Missing ET and two VBF jets (large $|\Delta\eta|$ and large m_{jj})





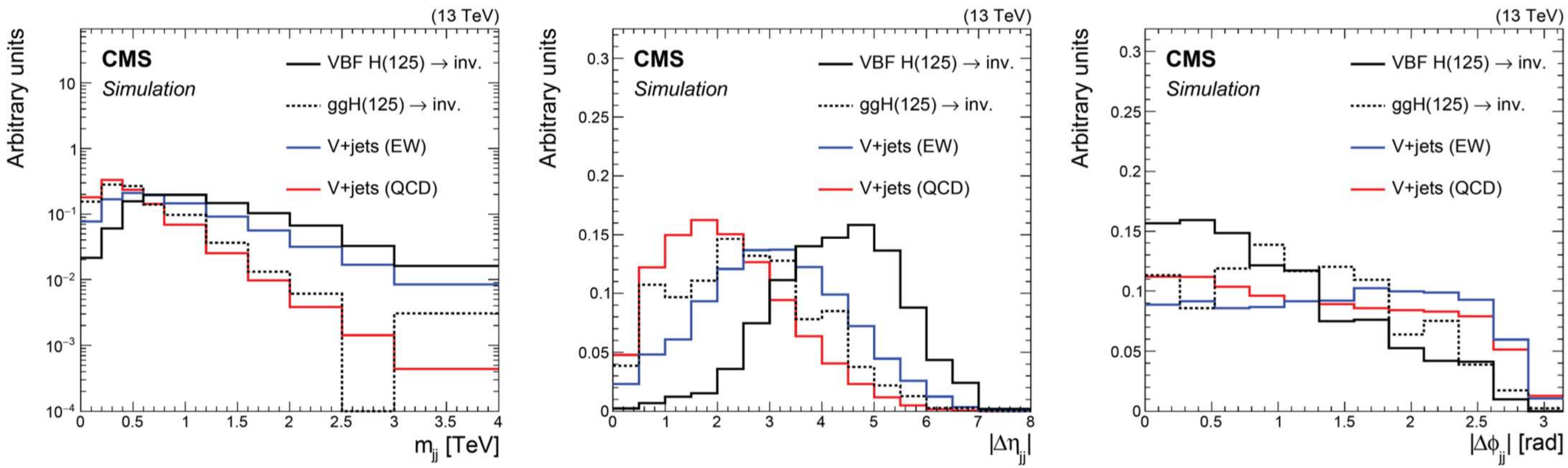
Background



Use Control Regions with same kinematic selections but different lepton requirement to constrain background in Signal Region

Analysis selection

Observable	Shape analysis	Cut-and-count analysis	Target background
Leading (subleading) jet	$p_T > 80\,(40)$ GeV, $\lvert\eta\rvert < 4.7$		All
p_T^{miss}	>250 GeV		QCD multijet, $t\bar{t}$, γ+jets, W+jets
$\Delta\phi(\vec{p}_T^{\,miss}, \vec{p}_T^{\,jet})$	>0.5 rad		QCD multijet, γ+jets
Muons (electrons)	$N_{\mu,e} = 0$ with $p_T > 10$ GeV, $\lvert\eta\rvert < 2.4\,(2.5)$		W+jets, $Z(\ell\ell)$+jets
τ_h candidates	$N_{\tau_h} = 0$ with $p_T > 18$ GeV, $\lvert\eta\rvert < 2.3$		W+jets, $Z(\ell\ell)$+jets
Photons	$N_\gamma = 0$ with $p_T > 15$ GeV, $\lvert\eta\rvert < 2.5$		γ+jets, $V\gamma$
b quark jet	$N_{jet} = 0$ with $p_T > 20$ GeV, CSVv2 > 0.848		$t\bar{t}$, single top quark
$\eta_{j1}\,\eta_{j2}$	<0		$Z(\nu\bar{\nu})$+jets, $W(\ell\nu)$+jets
$\lvert\Delta\phi_{jj}\rvert$	<1.5 rad		$Z(\nu\bar{\nu})$+jets, $W(\ell\nu)$+jets
$\lvert\Delta\eta_{jj}\rvert$	>1	>4	$Z(\nu\bar{\nu})$+jets, $W(\ell\nu)$+jets
m_{jj}	>200 GeV	>1.3 TeV	$Z(\nu\bar{\nu})$+jets, $W(\ell\nu)$+jets

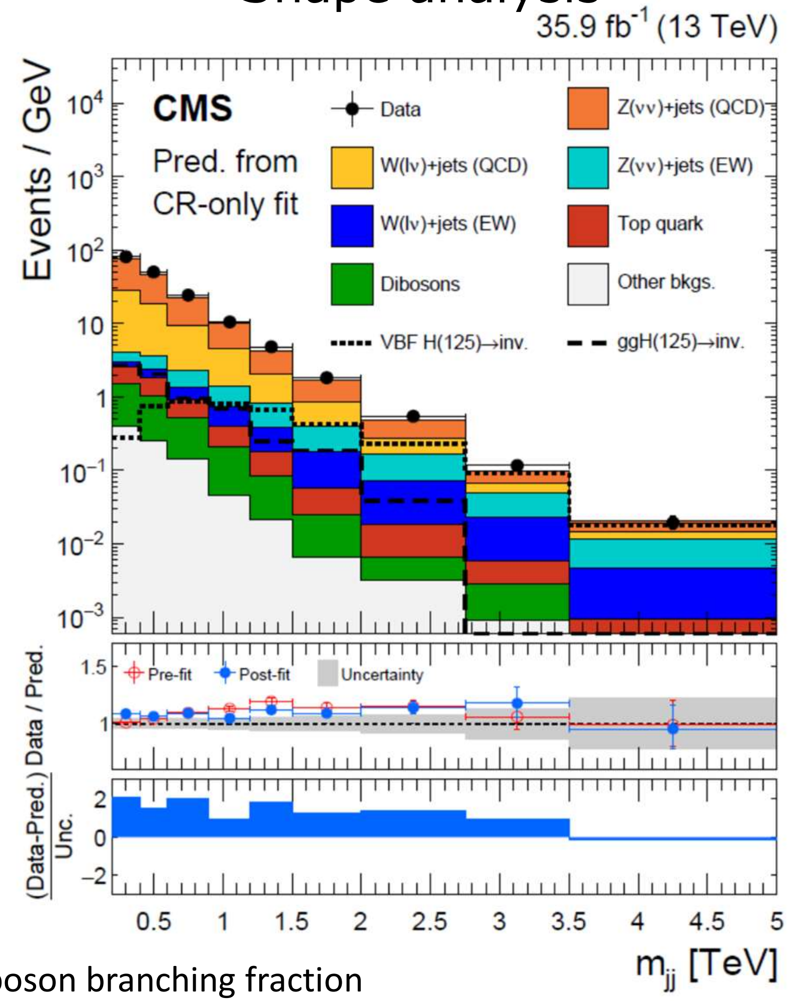


Results

Cut-and-count

Process	Signal region
$Z(\nu\nu)$ (QCD)	810 ± 71
$Z(\nu\nu)$ (EW)	269 ± 33
$Z(\ell\ell)$ (QCD)	—
$Z(\ell\ell)$ (EW)	—
$W(\ell\nu)$ (QCD)	499 ± 33
$W(\ell\nu)$ (EW)	141 ± 11
Top quark	37.8 ± 8.8
Dibosons	18.6 ± 6.2
Others	3.3 ± 2.3
Total bkg.	1779 ± 96
Signal $m_H = 125\,\text{GeV}$	743 ± 129 $\mathcal{B}(H \to inv) = 1$
Data	2035

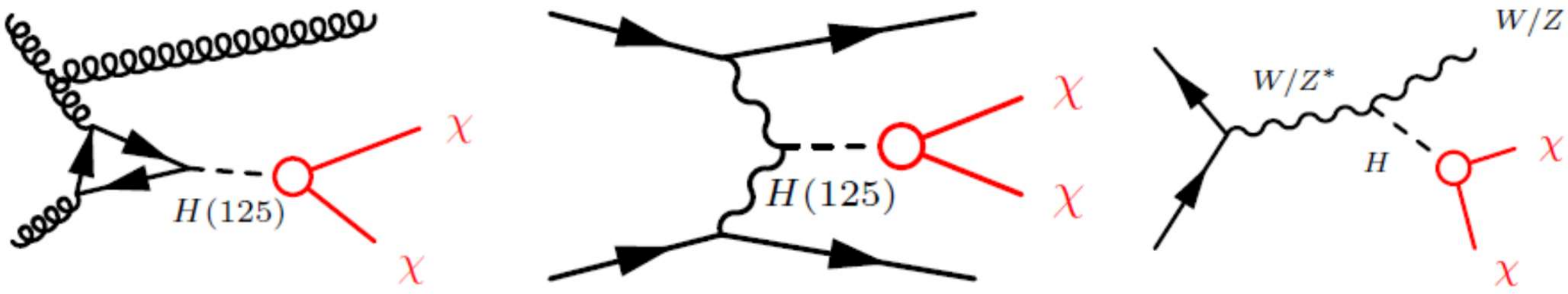
Shape analysis



upper limits on the invisible Higgs boson branching fraction

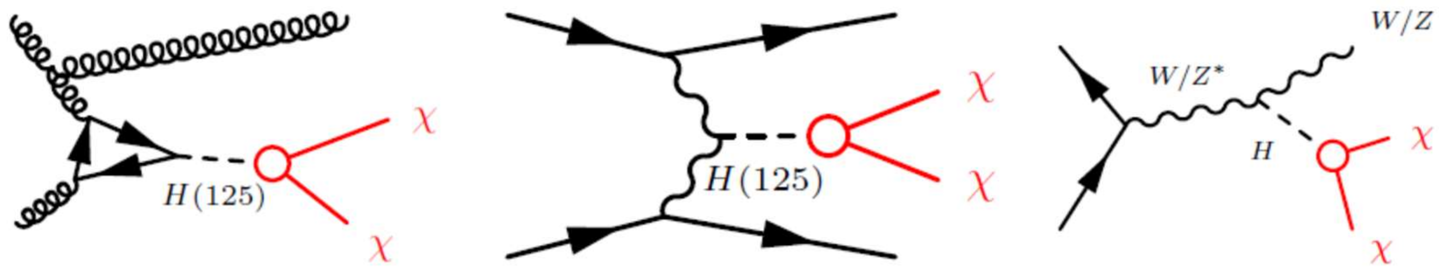
Analysis	Observed limit	Expected limit
Shape	0.33	0.25
CC	0.58	0.30

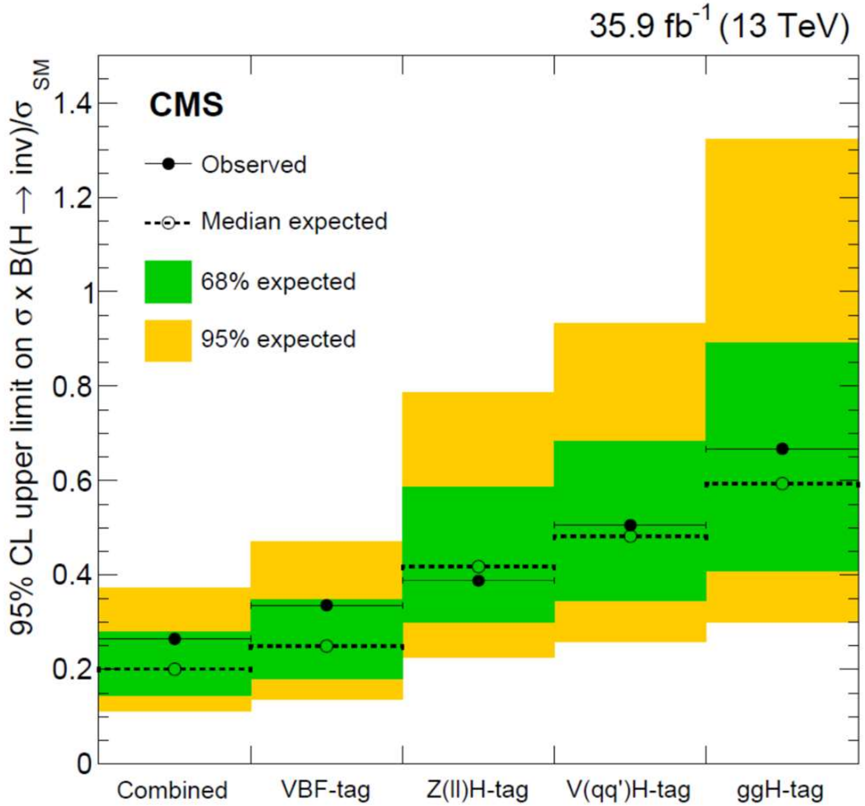
Combination

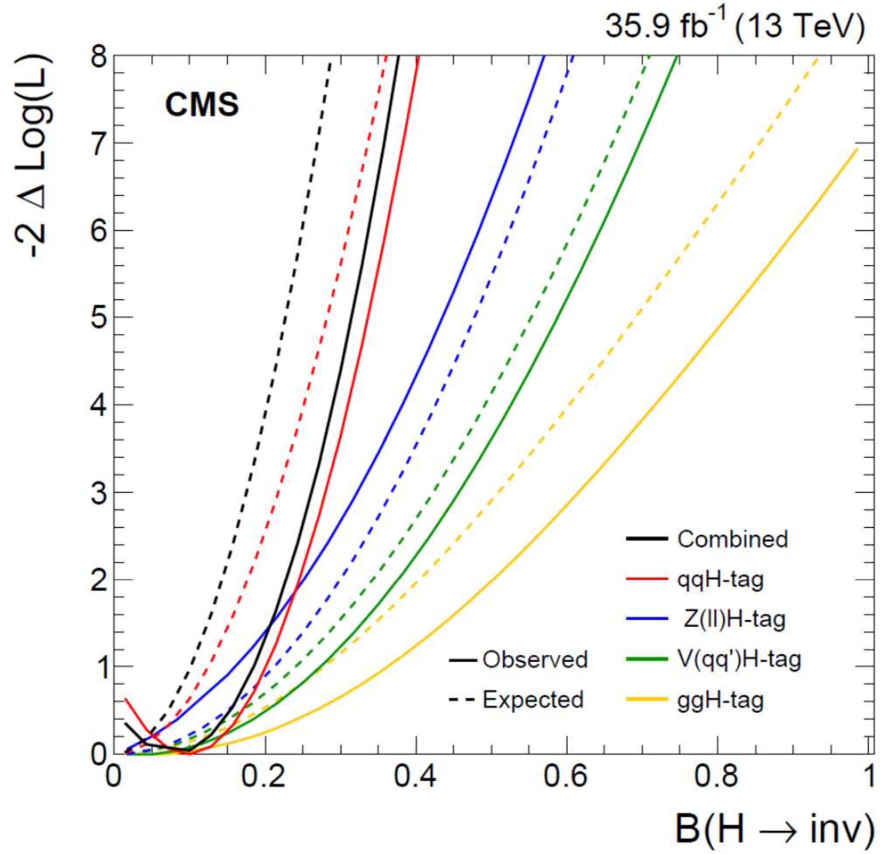


Analysis	Final state	Signal composition	Observed limit	Expected limit
qqH-tagged	VBF-jets + p_T^{miss}	52% qqH, 48% ggH	0.28	0.21
VH-tagged	$Z(\ell\ell) + p_T^{miss}$	79% qqZH, 21% ggZH	0.40	0.42
	$V(qq') + p_T^{miss}$	39% ggH, 6% qqH, 33% WH, 22% ZH	0.50	0.48
ggH-tagged	jets + p_T^{miss}	80% ggH, 12% qqH, 5% WH, 3% ZH	0.66	0.59

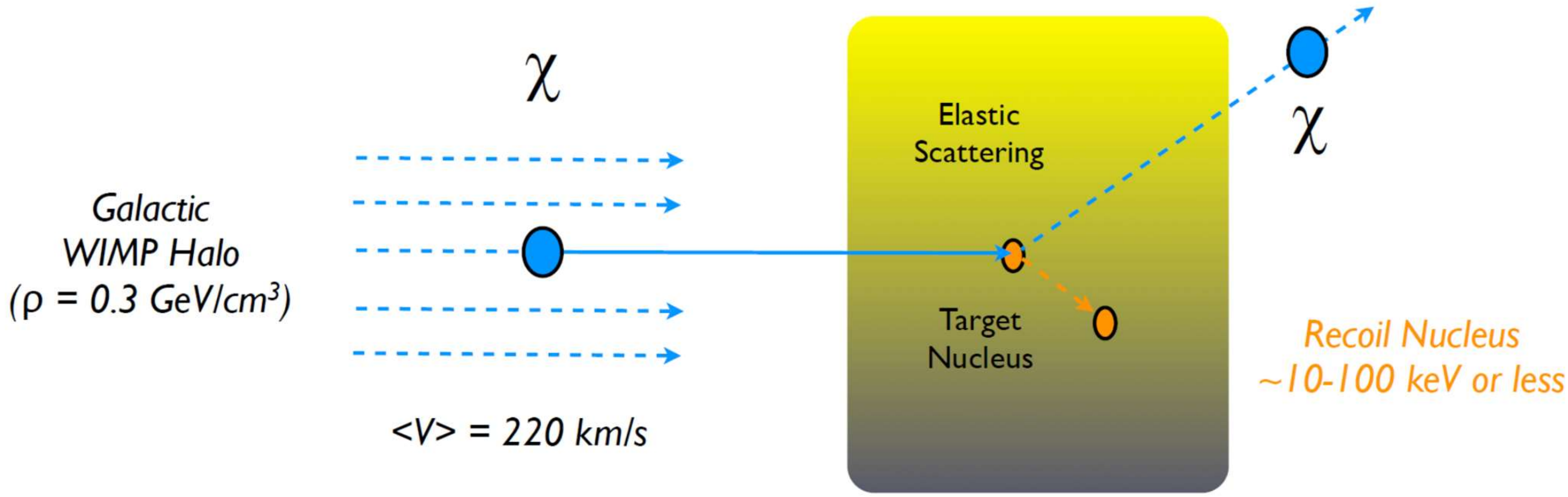
Combination







Direct detection

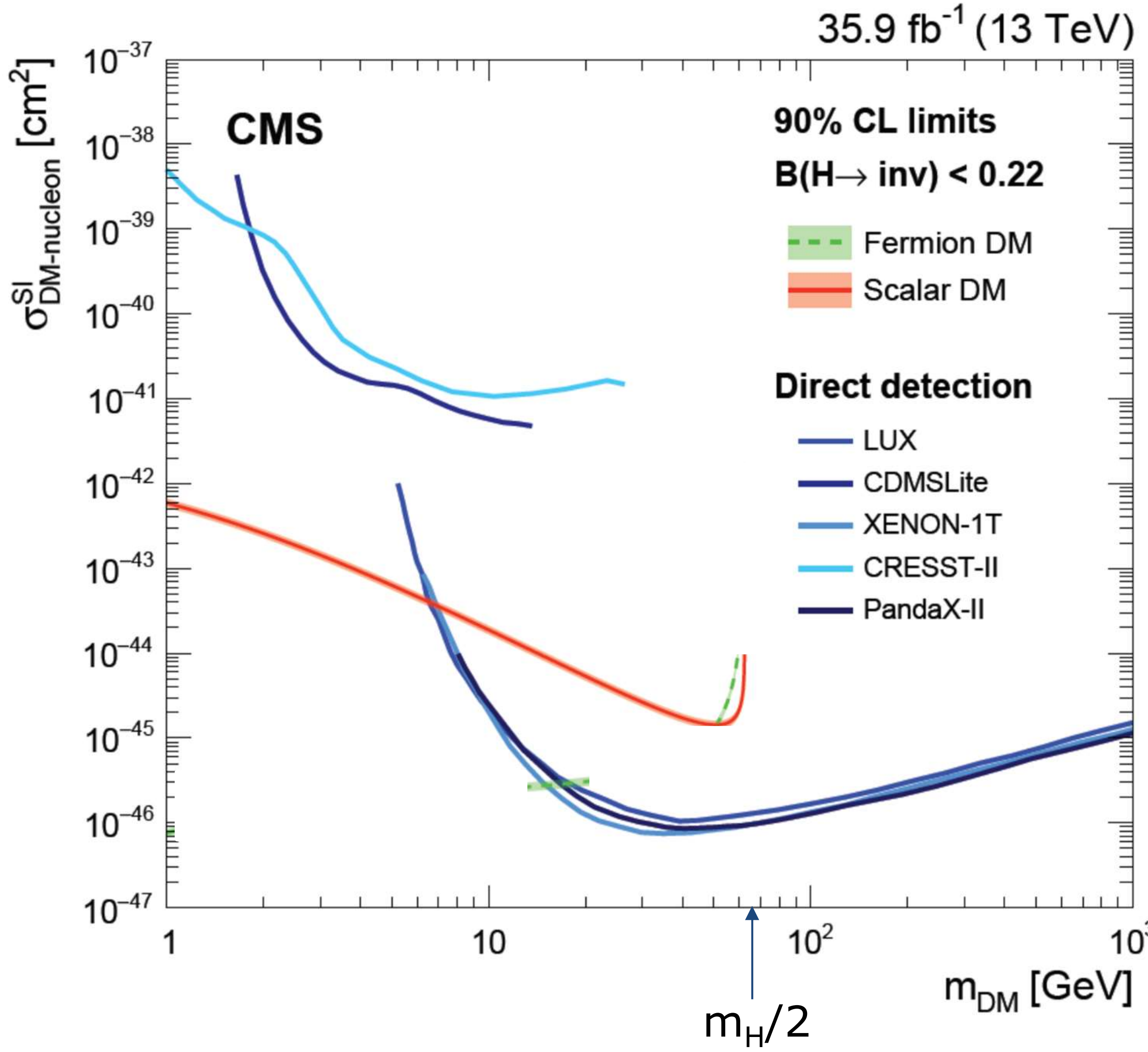


$\sigma_{\chi N}$ *probed to-date* ~ 10^{-44} *cm*^{2}

What is measured (with different target nuclei and detectors) : energy of the recoiling nucleus

What are the challenges: very small energy, very large backgrounds and very small rate

Comparison with direct detection



Z' and W' searches

arXiv:1010.6058

New gauge bosons

The SM gauge group $SU(3)_C x SU(2)_L x U(1)_Y$ can be extended to solve some of the puzzles not explained by the SM, possibly leading to

- An additional heavy neutral boson Z'
- An additional heavy charged boson W'

Simplest extension:

$$SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)'.$$

A massive spin-1 Z' arises from the breaking at the TeV scale of the U(1)' group

The new boson has couplings to SM fermions given by the coefficients g_f^V and g_f^A of the Lagrangian interaction term

$$\mathcal{L}_{NC} = \frac{g'}{2} Z'_\mu \bar{f} \gamma^\mu (g_V^f - g_A^f \gamma^5) f.$$

Models

E6 GUT

- $E_6 \to SO(10)\times U(1)_\psi \to SU(5) \times U(1)_\chi \times U(1)_\psi$
- $SU(5) \to SU(3)c \times SU(2)_L \times U(1)_Y$
- $Z' = Z'_\psi \cos\theta + Z'_\chi \sin\theta$ (can be at the TeV scale)
- The value of θ determine the Z' couplings to fermions

Left-right symmetric model

- $SU(2)_L\times SU(2)_R\times U(1)_{B-L} \to SU(2)_L\times U(1)_{3R}\times U(1)_{B-L} \to SU(2)_L\times U(1)_Y$
- Both W' and Z'
- $Z' = Z'_{3R} \cos\phi + Z'_{B-L} \sin\phi$

Sequential Standard Model (SSM)

- Spin 1 heavy boson with SM-like couplings
- Mainly used as a benchmark model

Composite Higgs

- Analogue of ρ of QCD

Warped extra dimension

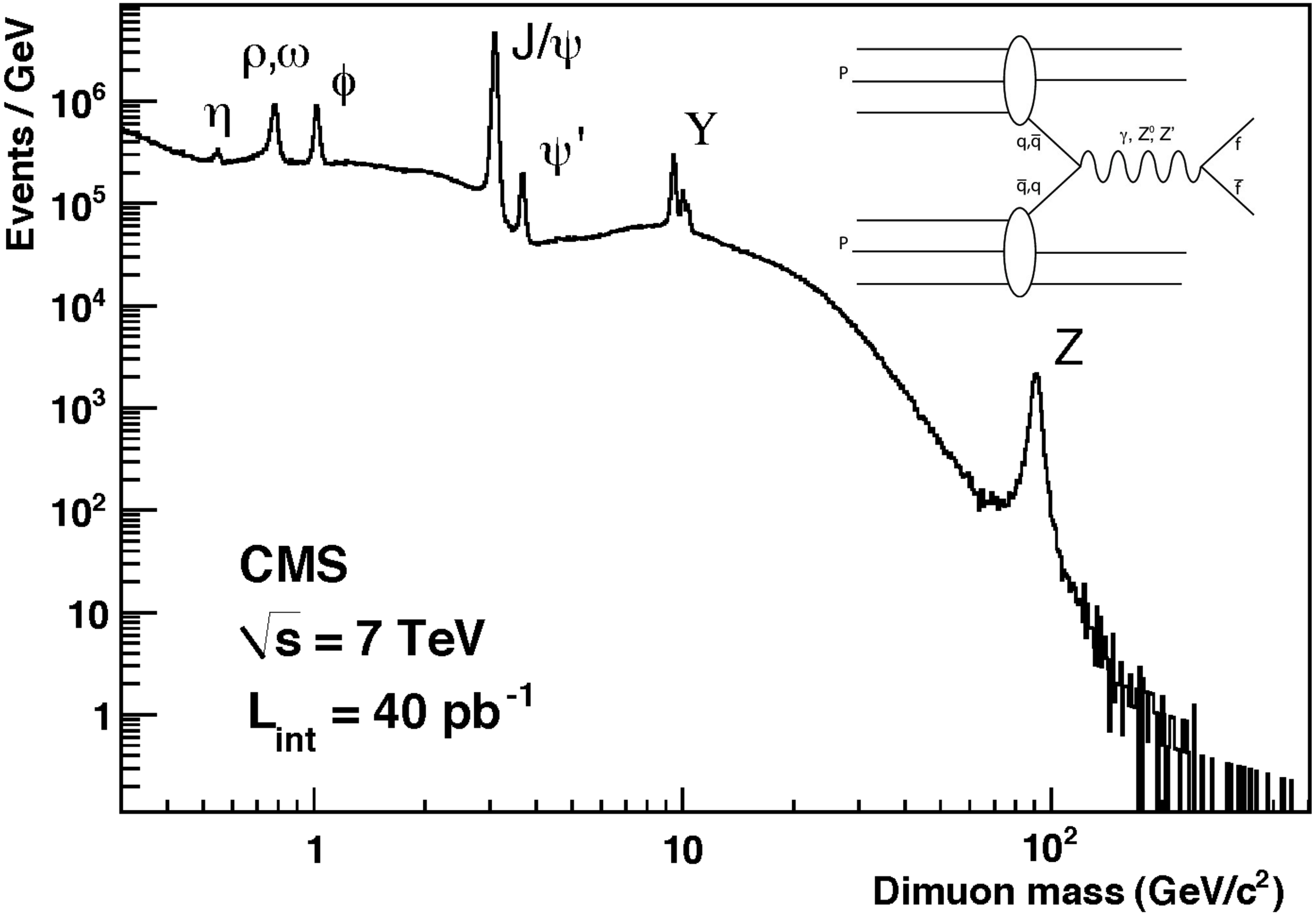
- Excited Kaluza-Klein mode of the graviton (spin-2) can give similar signatures

Z' Models

$U'(1)$ model	Mixing angle	$\mathcal{B}(\ell^+\ell^-)$	c_u	c_d	c_u/c_d	$\Gamma_{Z'}/M_{Z'}$
E_6						
$U(1)_\chi$	0	0.061	6.46×10^{-4}	3.23×10^{-3}	0.20	0.0117
$U(1)_\psi$	0.5π	0.044	7.90×10^{-4}	7.90×10^{-4}	1.00	0.0053
$U(1)_\eta$	-0.29π	0.037	1.05×10^{-3}	6.59×10^{-4}	1.59	0.0064
$U(1)_S$	0.129π	0.066	1.18×10^{-4}	3.79×10^{-3}	0.31	0.0117
$U(1)_N$	0.42π	0.056	5.94×10^{-4}	1.48×10^{-3}	0.40	0.0064
LR						
$U(1)_R$	0	0.048	4.21×10^{-3}	4.21×10^{-3}	1.00	0.0247
$U(1)_{B-L}$	0.5π	0.154	3.02×10^{-3}	3.02×10^{-3}	1.00	0.0150
$U(1)_{LR}$	-0.128π	0.025	1.39×10^{-3}	2.44×10^{-3}	0.57	0.0207
$U(1)_Y$	0.25π	0.125	1.04×10^{-2}	3.07×10^{-3}	3.39	0.0235
GSM						
$U(1)_{SM}$(SSM)	-0.072π	0.031	2.43×10^{-3}	3.13×10^{-3}	0.78	0.0297
$U(1)_{T3L}$	0	0.042	6.02×10^{-3}	6.02×10^{-3}	1.00	0.0450
$U(1)_Q$	0.5π	0.125	6.42×10^{-2}	1.60×10^{-2}	4.01	0.1225

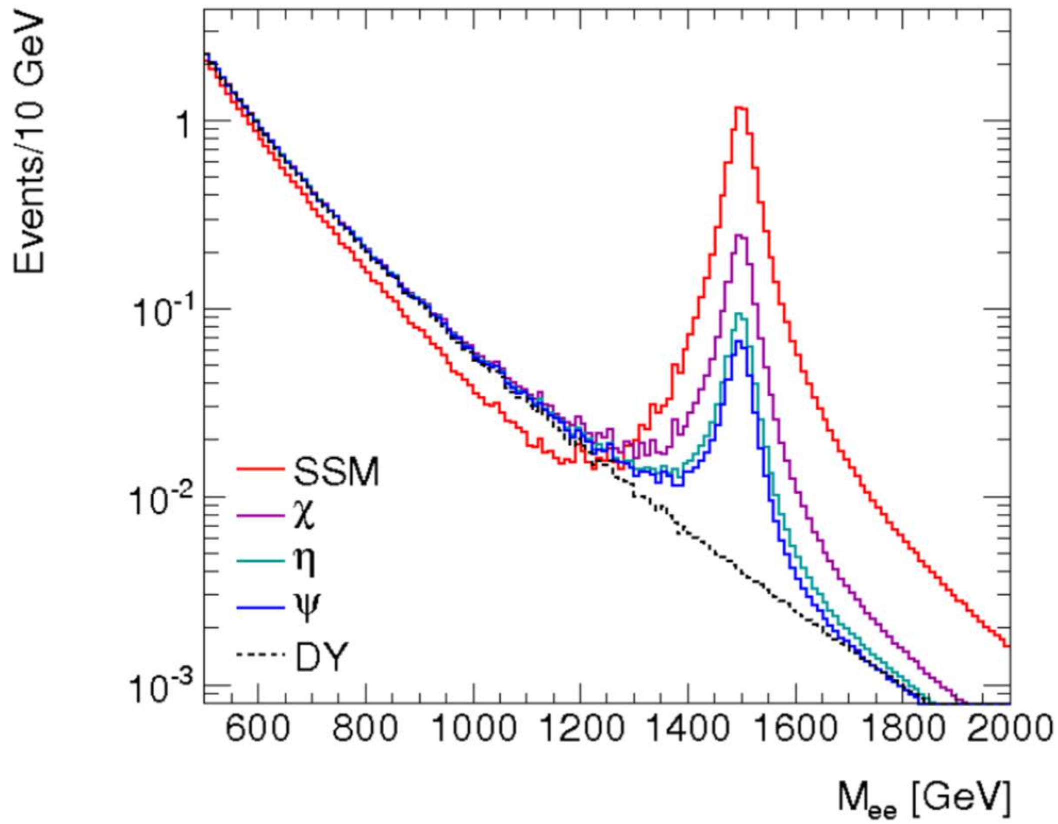
Search for dilepton resonances

$$M = \sqrt{2E_1E_2(1 - cos\theta)}$$



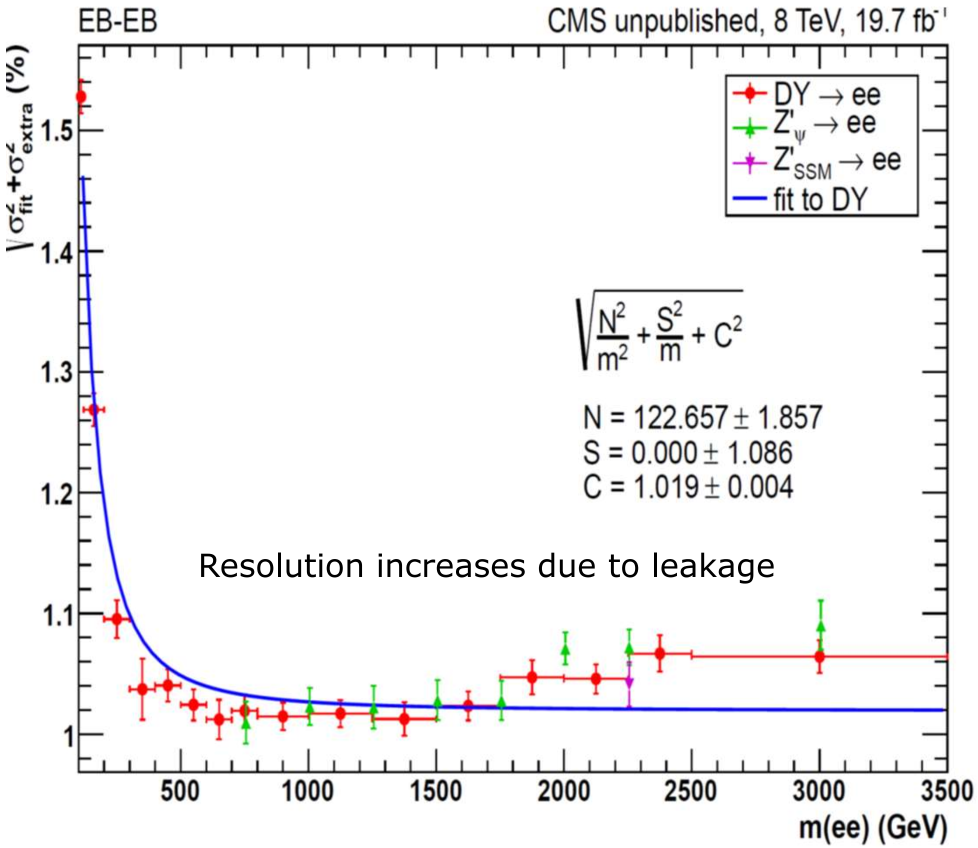
Search for dilepton resonances

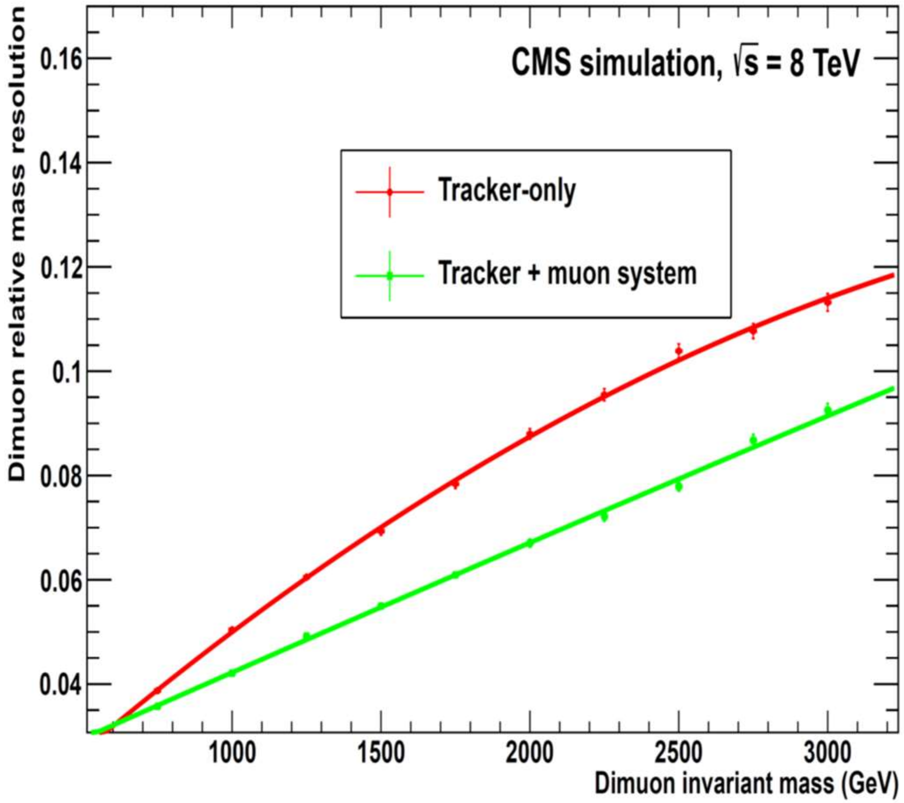
$$M = \sqrt{2E_1E_2(1 - cos\theta)}$$



Clear experimental signature
– 2 high pt leptons (electron or muon) with large invariant mass
- τ allows to probe couplings to 3rd generation leptons

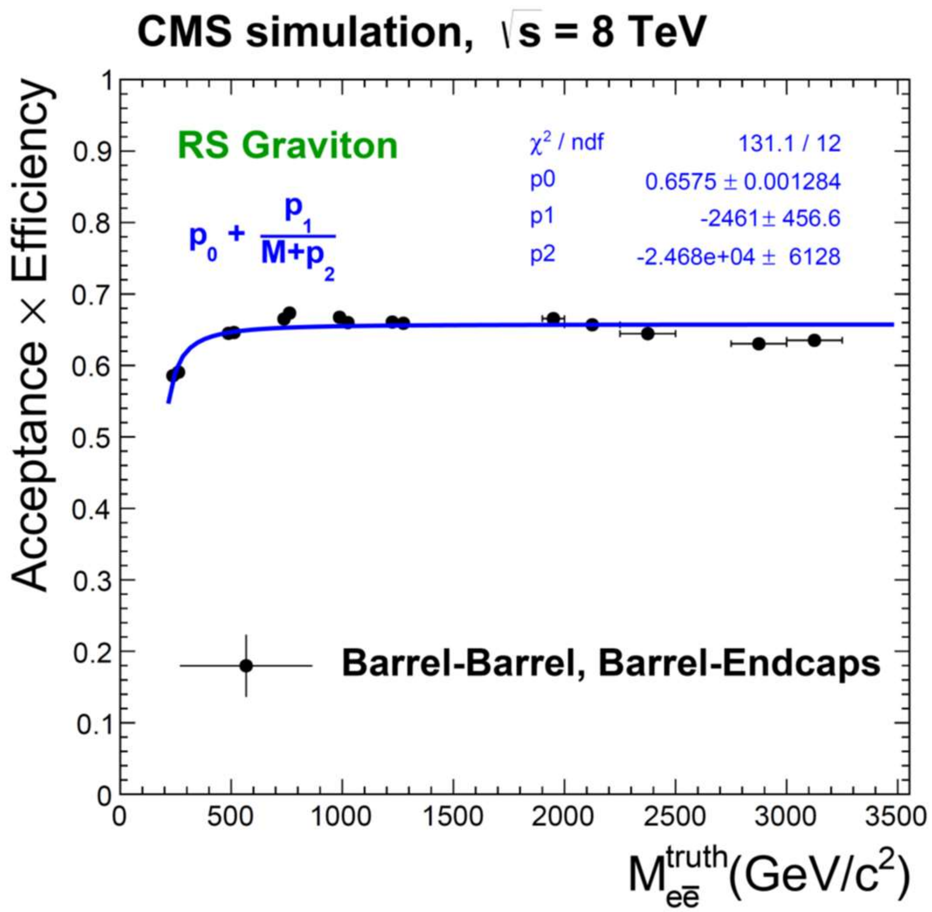
Resolution

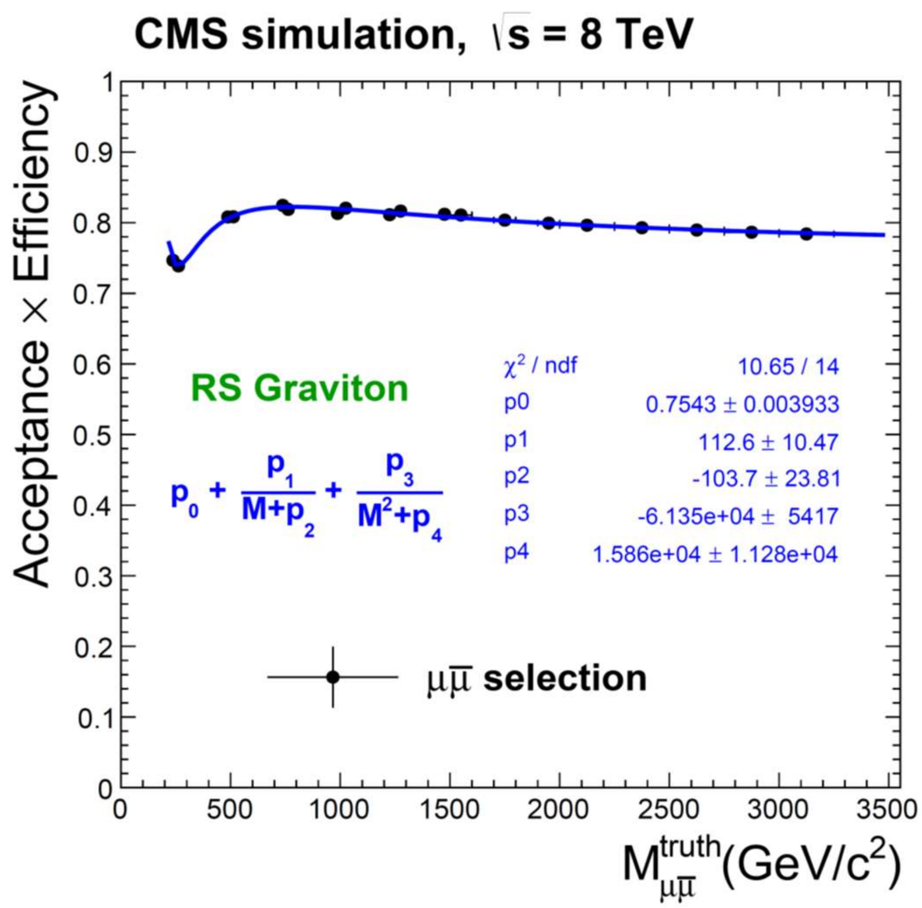




Better mass resolution for electrons compared to muons

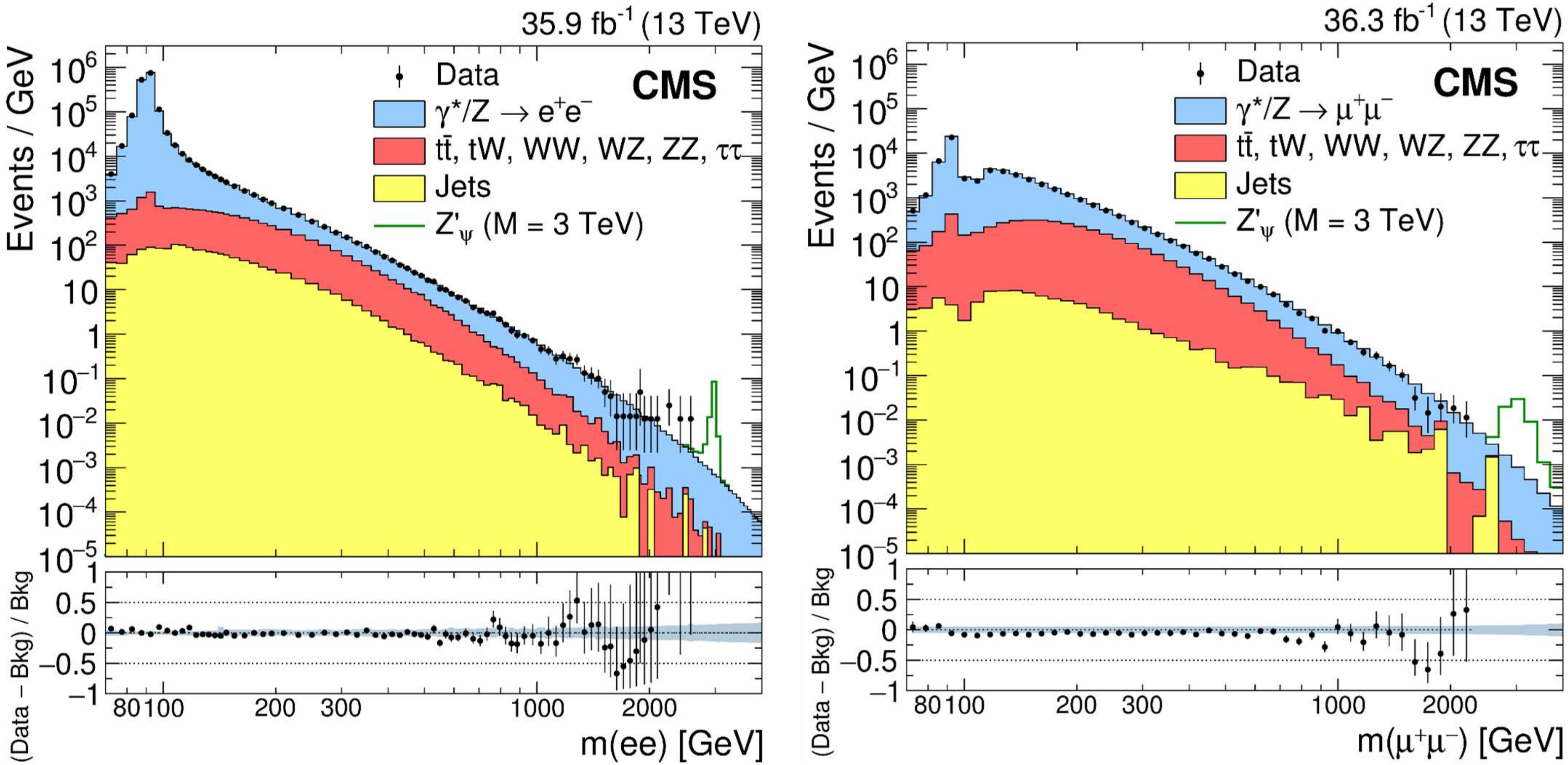
Efficiency





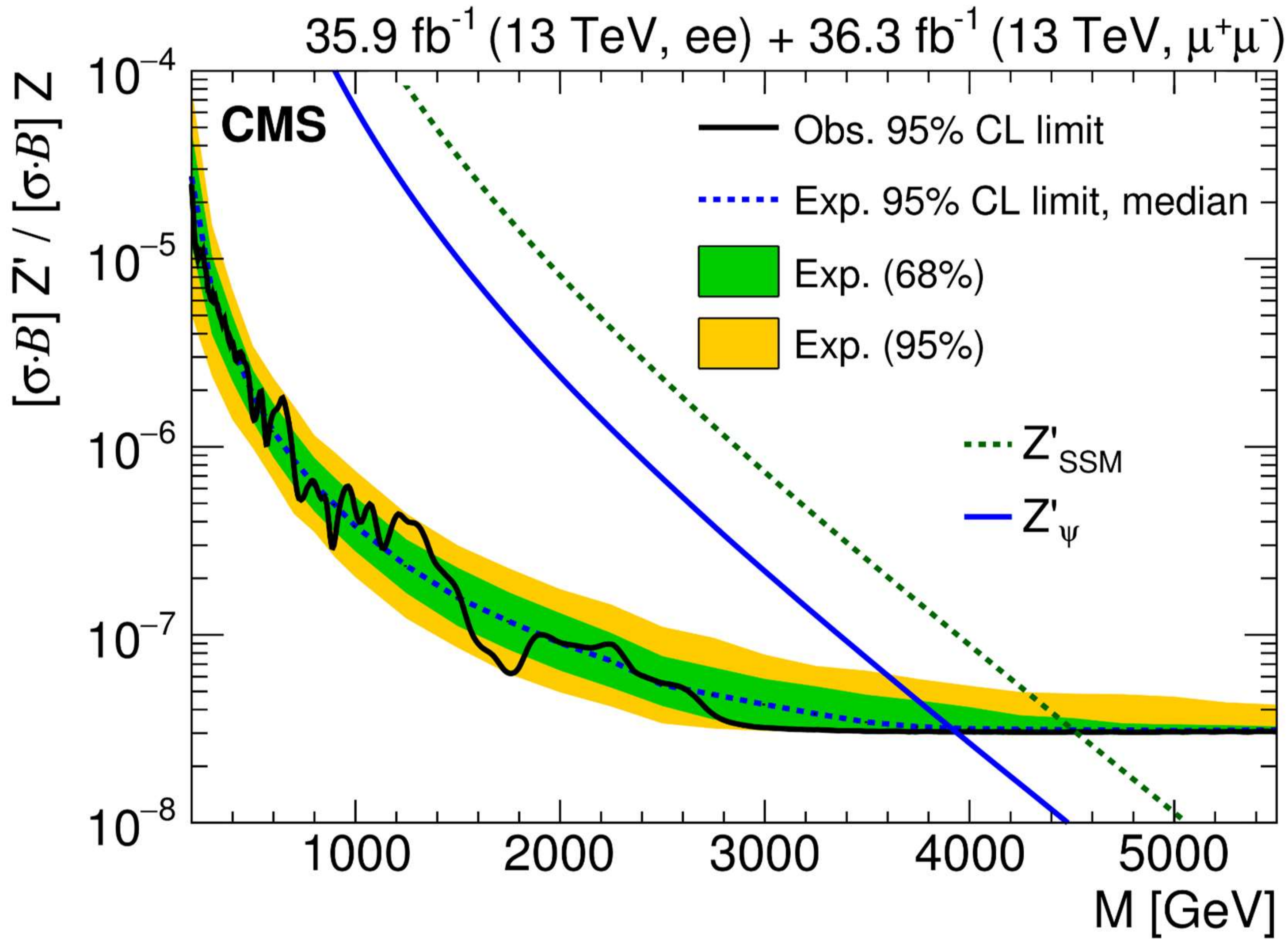
But higher efficiency for muons

Mass spectra



The MC background is normalized to the Z peak

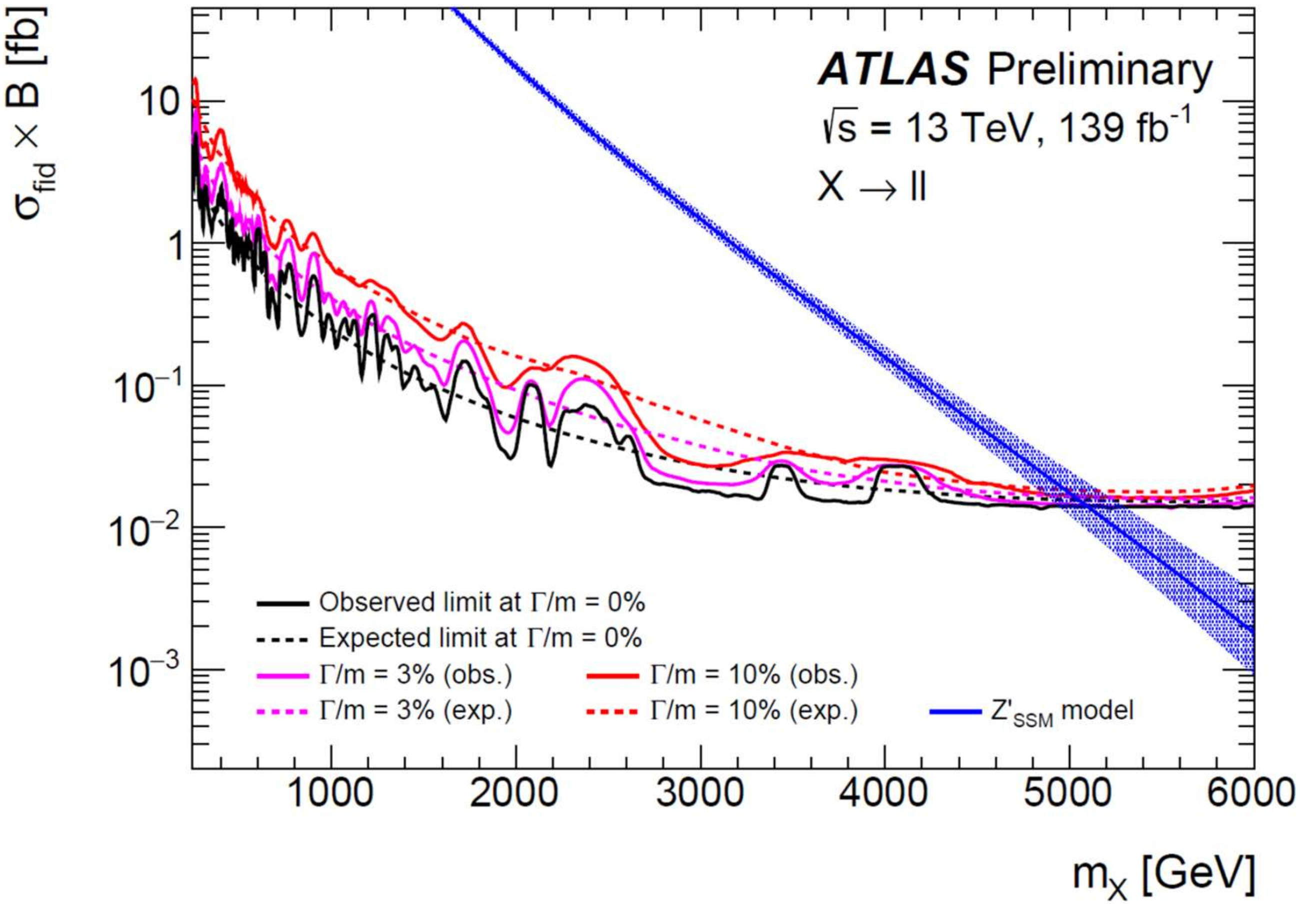
Limits



Results are interpreted in the ratio of the signal cross section/Z cross section so one is insensitive to the uncertainty on the luminosity

The statistical analysis from the electron channel and muon channel are combined in order to place stronger limits on the lower bounds of the Z′ mass

Full run 2 result

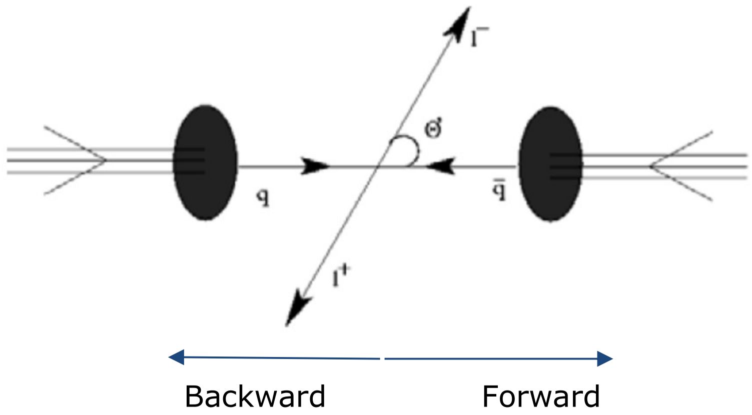


Model	Lower limits on $m_{Z'}$ [TeV]					
	ee		$\mu\mu$		$\ell\ell$	
	obs	exp	obs	exp	obs	exp
Z'_ψ	4.3	4.3	4.0	3.8	4.5	4.5
Z'_χ	4.6	4.6	4.2	4.1	4.8	4.7
Z'_{SSM}	4.9	4.9	4.5	4.4	5.1	5.0

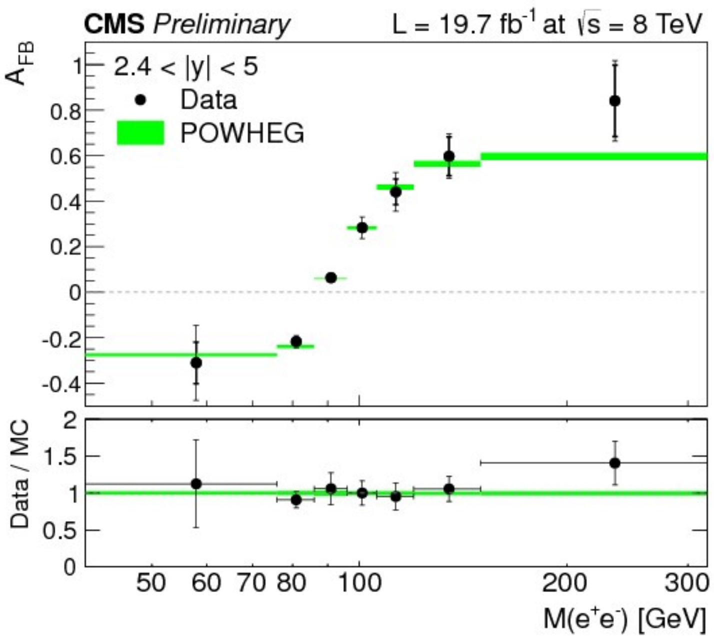
Distinguishing models

In the Z/Z′ rest frame:

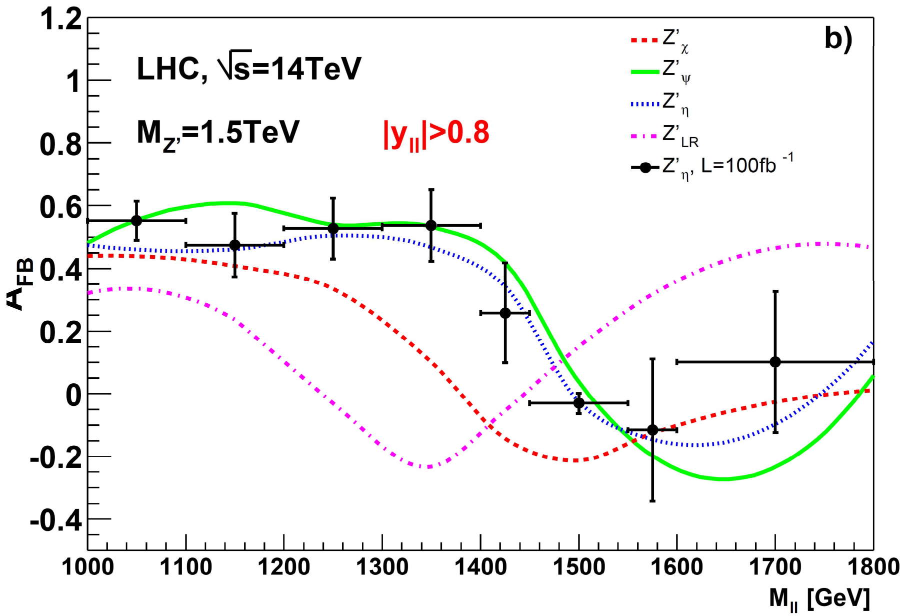
$$A_{FB} = \frac{N_F - N_B}{N_F + N_B}$$



Quark direction infers from the Z′ direction since the quarks have in average higher x than antiquarks



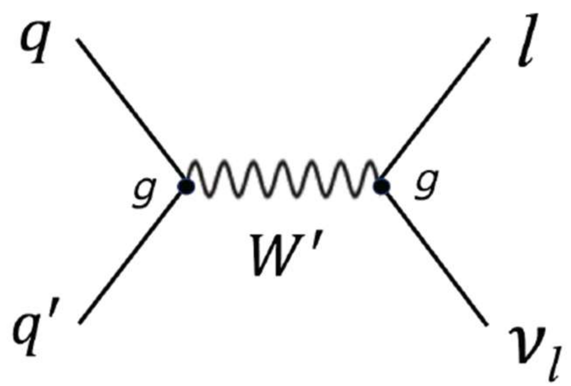
Forward backward asymmetry measurement



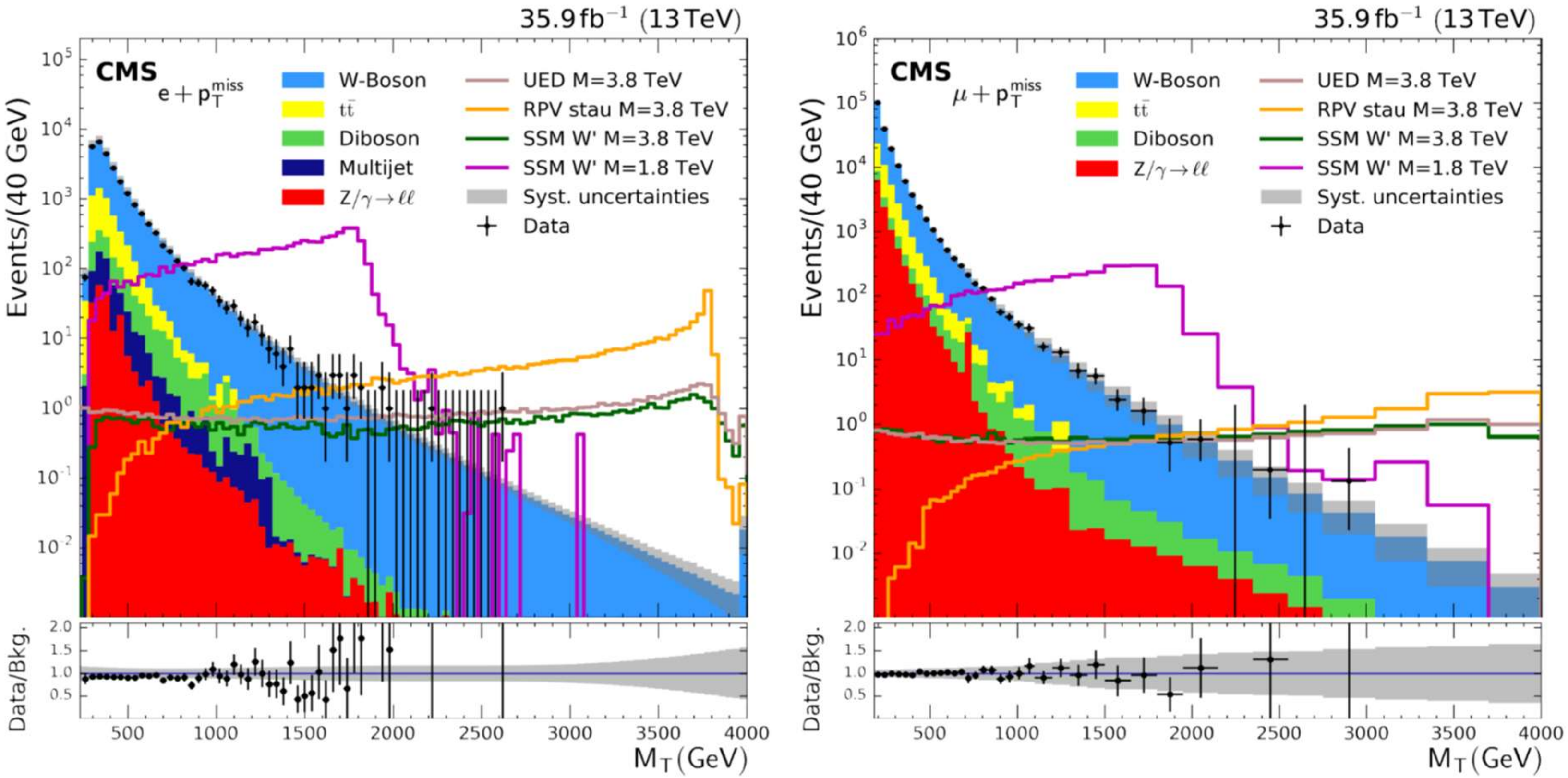
Search for W' → lν

Signature: high pT electron + high Etmiss

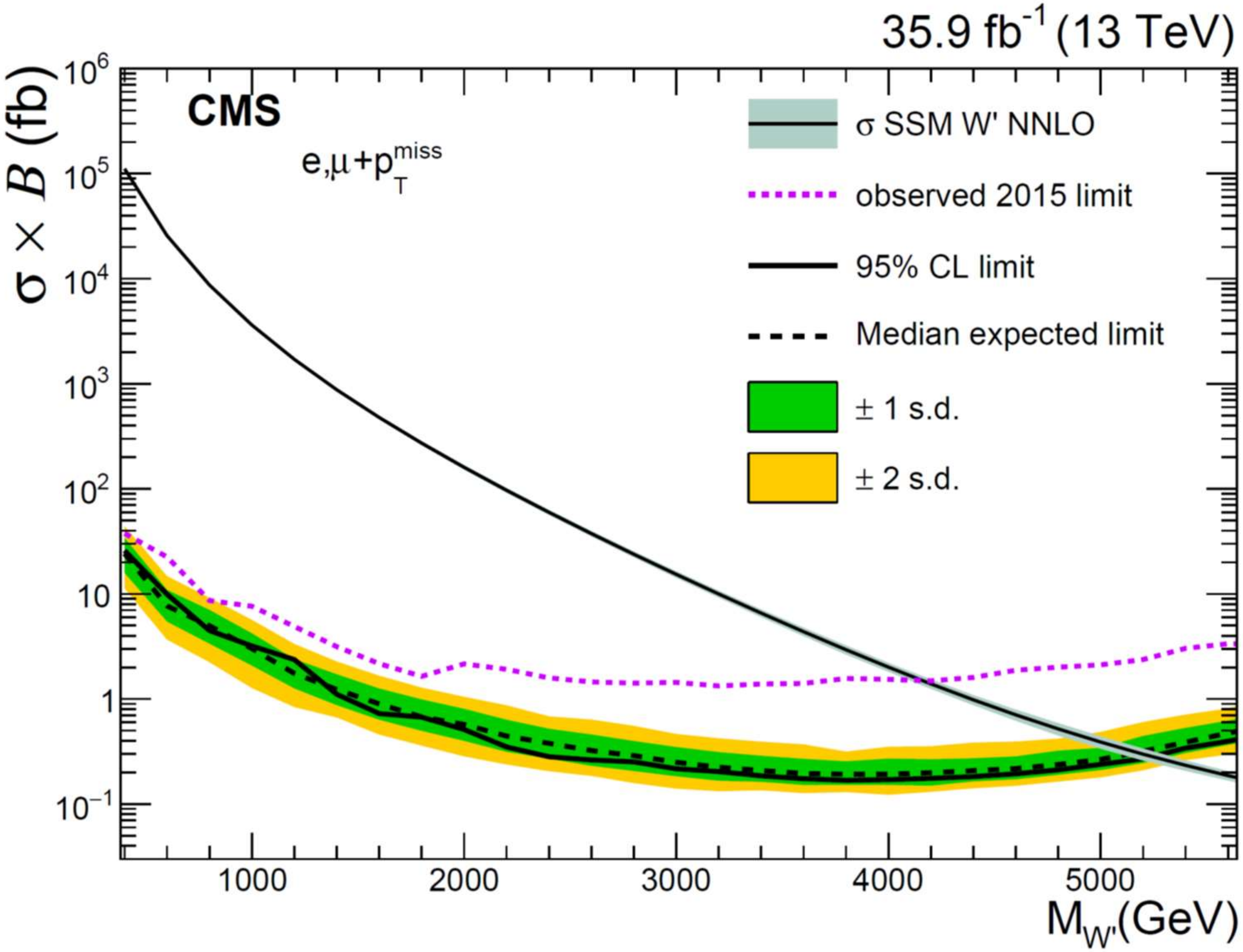
→ peak in transverse mass distribution



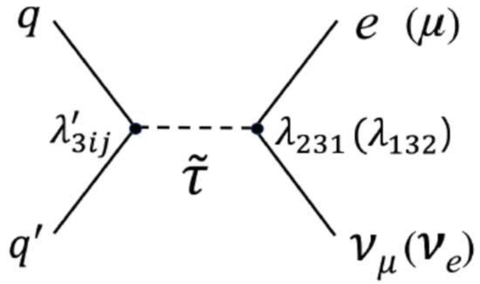
$$M_T = \sqrt{2 p_T^{\ell} \; p_T^{miss} \left(1 - \cos[\Delta\phi(\ell, \vec{p}_T^{\,miss})]\right)},$$



Search for W' → lν

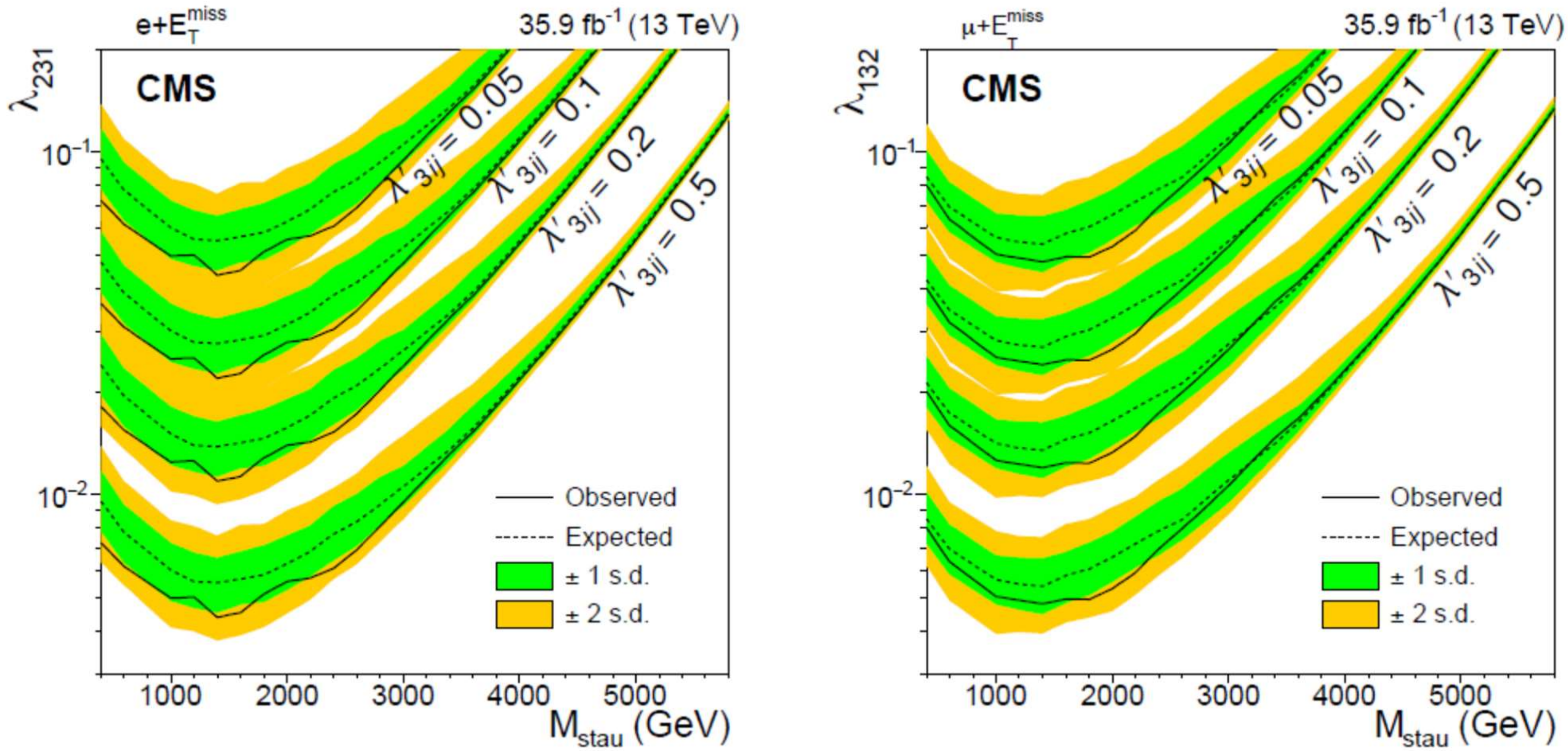


Search for W' → lν: RPV SUSY interpretation



$$W_{\Delta L=1} = \frac{1}{2}\lambda^{ijk} L_i L_j \overline{e}_k + \lambda'^{ijk} L_i Q_j \overline{d}_k + \mu'^{i} L_i H_u$$

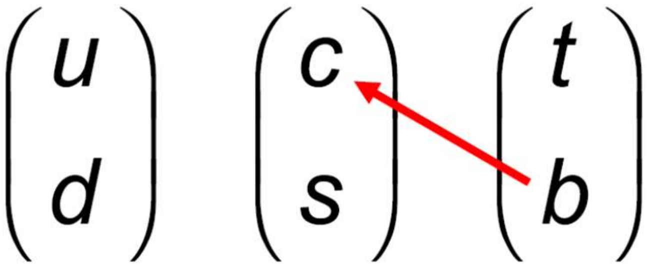
$$W_{\Delta B=1} = \frac{1}{2}\lambda''^{ijk} \overline{u}_i \overline{d}_j \overline{d}_k$$




That's all Folks!

The b quark

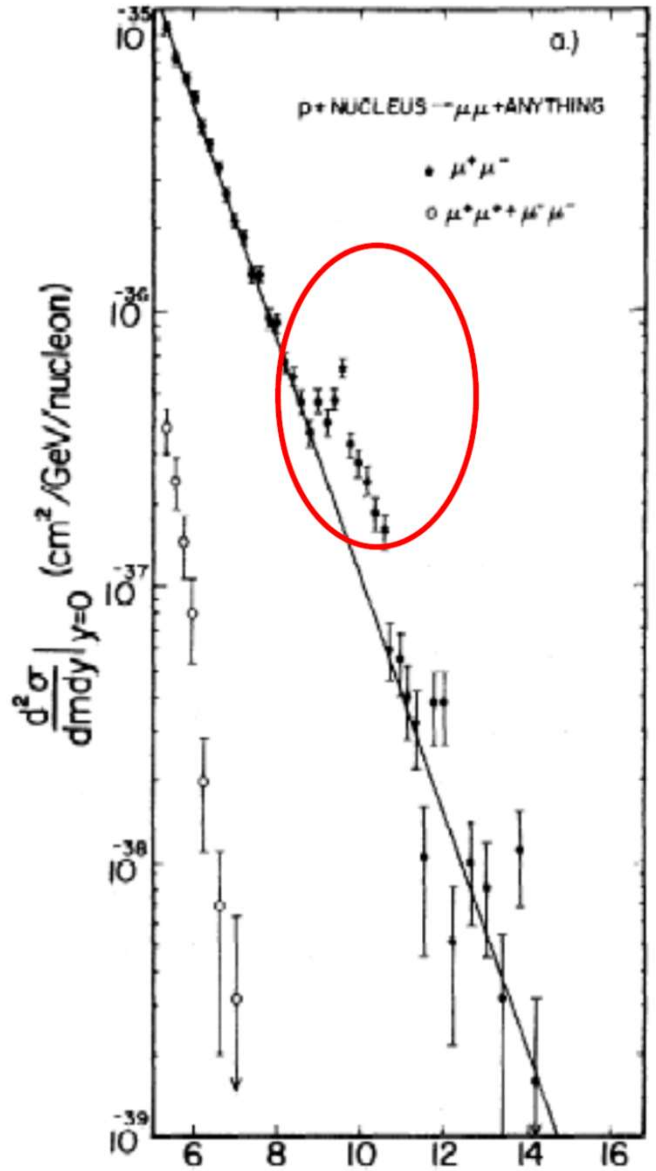
- The heaviest quark that forms bound states (mB ~ 5.3 GeV)
- Decays outside its family



⟹ large lifetime ~ 1.5 ps

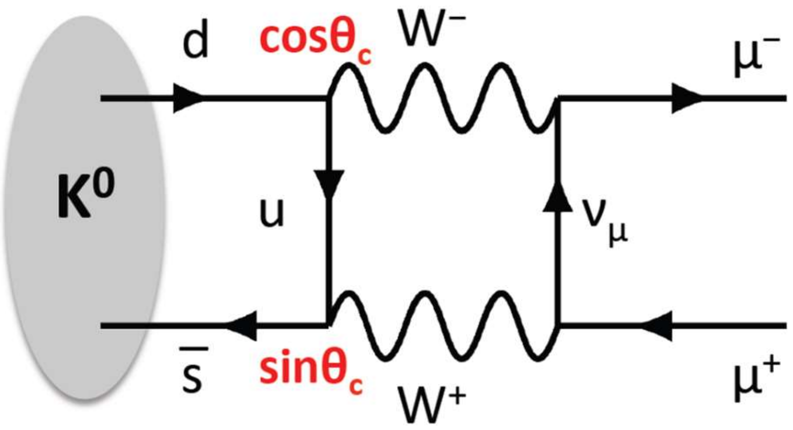
⟹ very large number of decays modes

⟹ large CP violation effects



1977 Fermilab

GIM mechanism (1970)

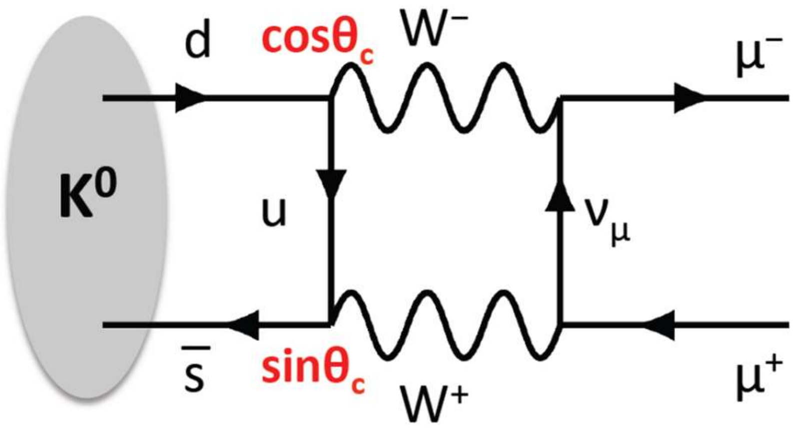


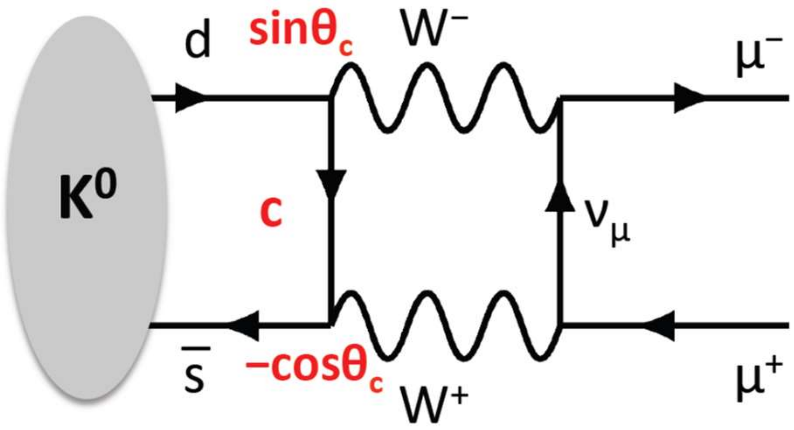
$$\frac{\mathcal{B}(K^0 \to \mu^+\mu^-)}{\mathcal{B}(K^+ \to \mu^+\nu_\mu)} = \frac{7\times 10^{-9}}{0.64} \simeq 10^{-8}$$

Process $K^0 \to \mu^+\mu^-$ apparently highly suppressed (based on exp.) – but why?

$$\begin{pmatrix} d' \\ s' \end{pmatrix} = \begin{pmatrix} \cos\theta_C & \sin\theta_C \\ -\sin\theta_C & \cos\theta_C \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix}$$

GIM mechanism (1970)





$$\frac{\mathcal{B}(K^0 \to \mu^+\mu^-)}{\mathcal{B}(K^+ \to \mu^+\nu_\mu)} = \frac{7 \times 10^{-9}}{0.64} \simeq 10^{-8}$$

Process $K^0 \to \mu^+\mu^-$ apparently highly suppressed (based on exp.) – but why?

Add charm quark ⇒ add second diagram with similar amplitude but opposite sign

⇒ total amplitude highly suppressed!

Cancellation not perfect because u and c quarks have different mass.

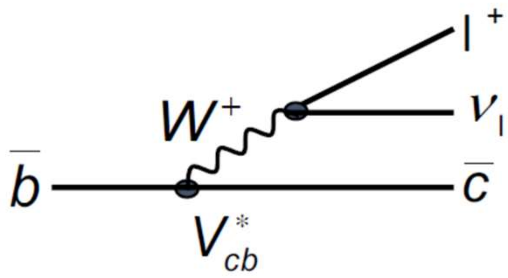
$$\begin{pmatrix} d' \\ s' \end{pmatrix} = \begin{pmatrix} \cos\theta_C & \sin\theta_C \\ -\sin\theta_C & \cos\theta_C \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix}$$

J/ψ meson (cc bound state) discovered simultaneously at BNL and SLAC in 1974

FCNC suppressed in the SM

The QCD challenge

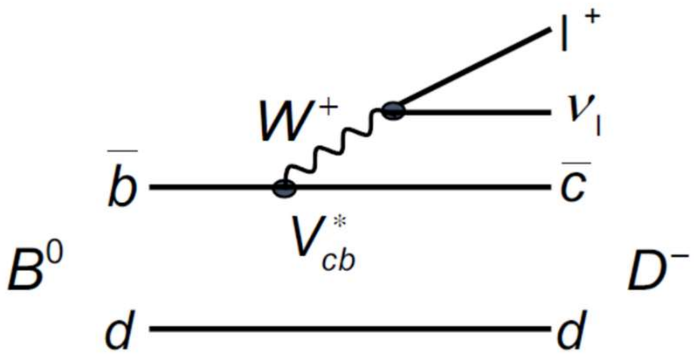
Quarks change flavour through the charged weak interaction



The QCD challenge

Quarks change flavour through the charged weak interaction

But… they are bound by the strong interaction into hadrons

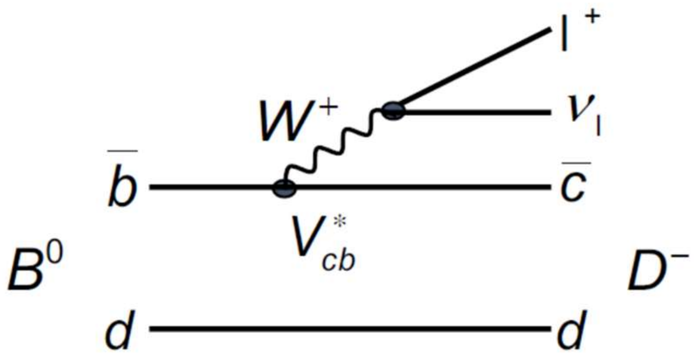


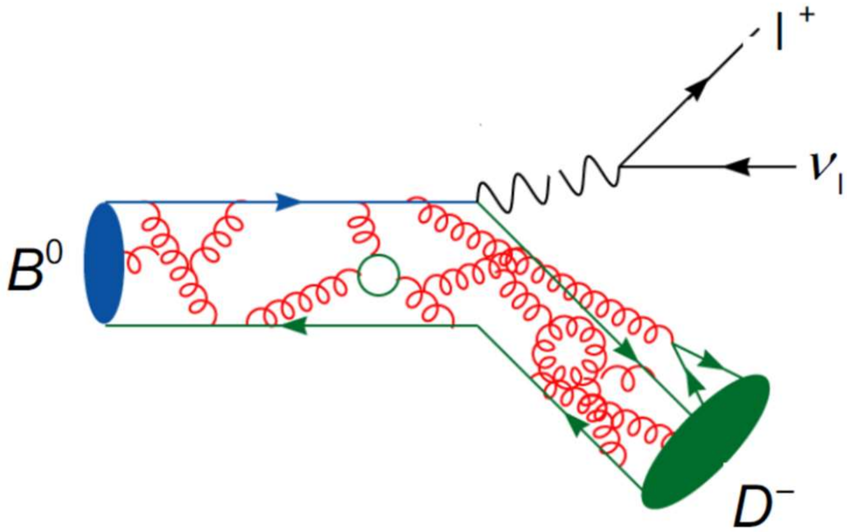
⇒ Many possible quark combinations, many possible decays to different final states

The QCD challenge

Quarks change flavour through the charged weak interaction

But… they are bound by the strong interaction into hadrons





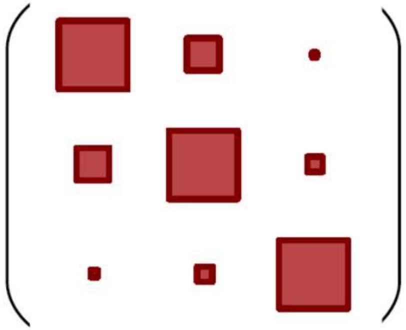
⇒ Many possible quark combinations, many possible decays to different final states

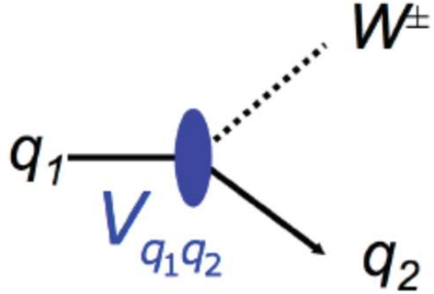
⇒ Cannot observe weak interaction in isolation – need to take into account non-perturbative QCD effects

CKM or quark mixing matrix

In the basis dealing with mass eigenstates:

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \sim$$





Unitary:

$$V^\dagger V = \mathbb{1}$$

Only 4 independent parameters (3 angles + 1 phase)

$$V = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4).$$

$\lambda \sim 0.22$ $A \sim 0.8$ $\rho = 0.2$ $\eta = 0.35$

The $b \to d$ unitarity triangle

One of the unitarity condition gives

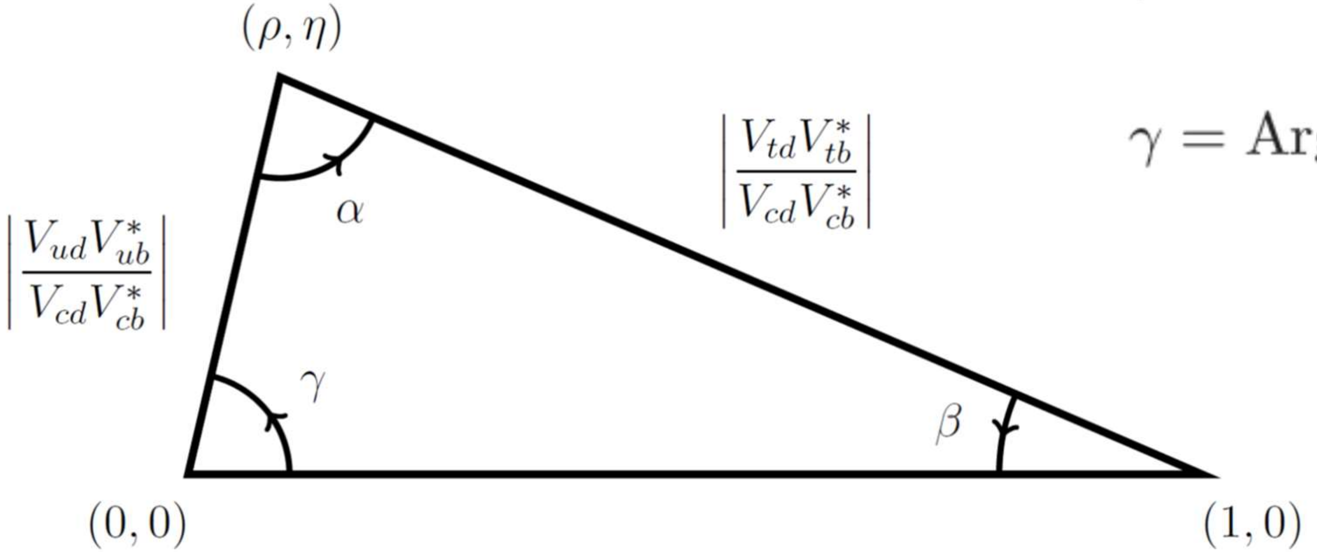
$$\sum_i V_{id} V_{ib}^* = 0$$

$$\bar{\rho} + i\bar{\eta} = -\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}$$

$$\alpha = \mathrm{Arg}\frac{-V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}$$

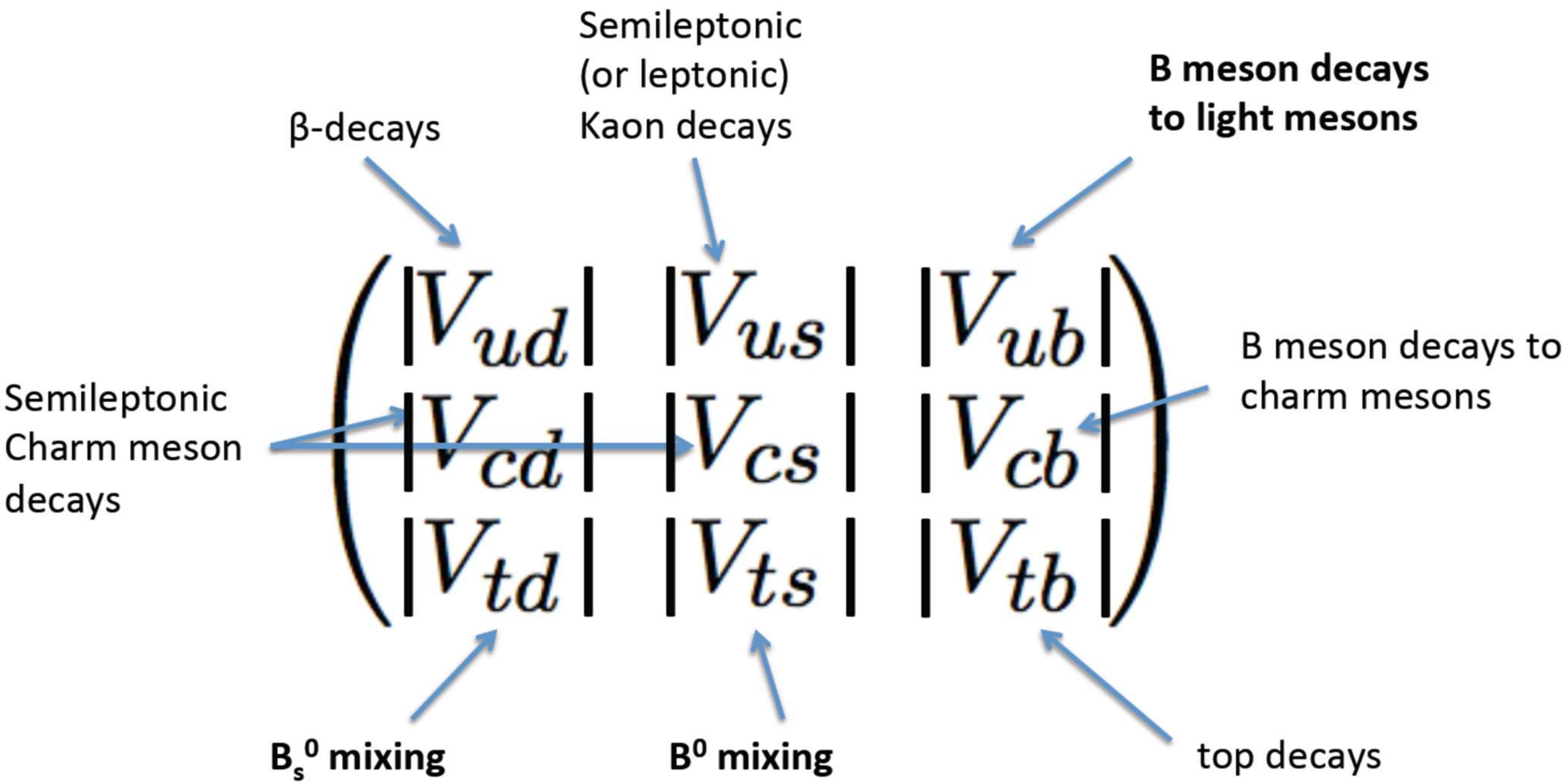
$$\beta = \mathrm{Arg}\frac{-V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}$$

$$\gamma = \mathrm{Arg}\frac{-V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}$$



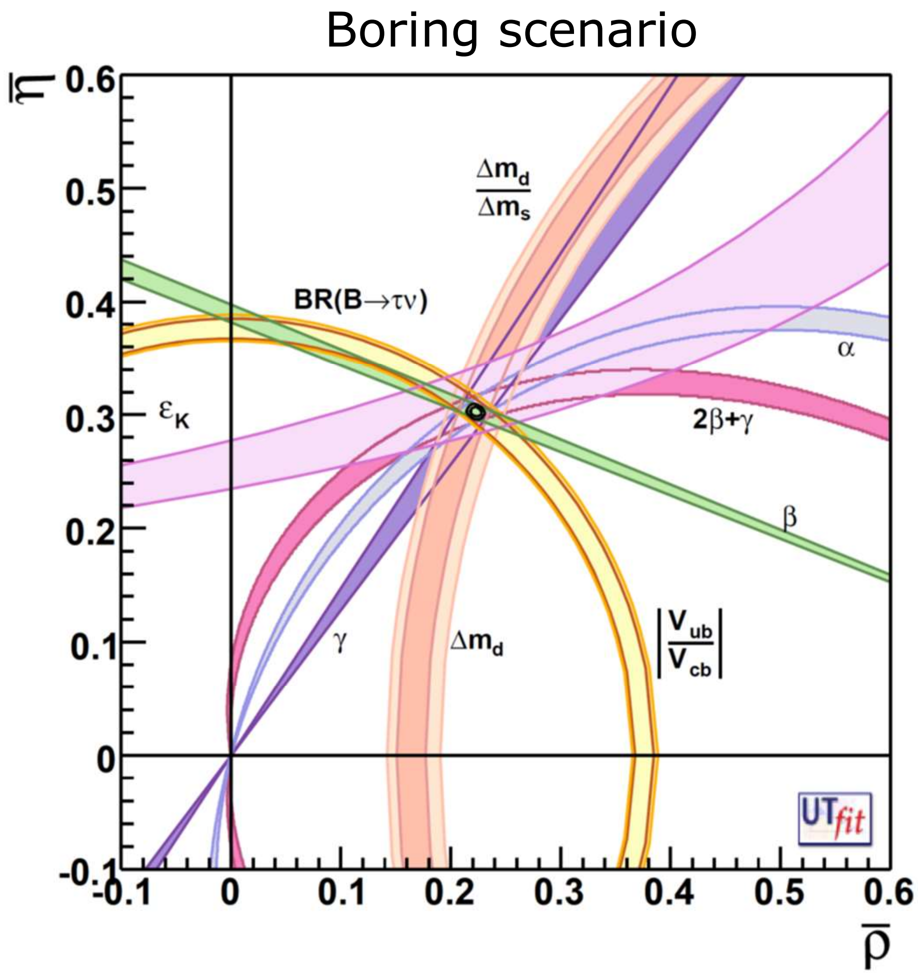
Area of the triangle proportional to CPV

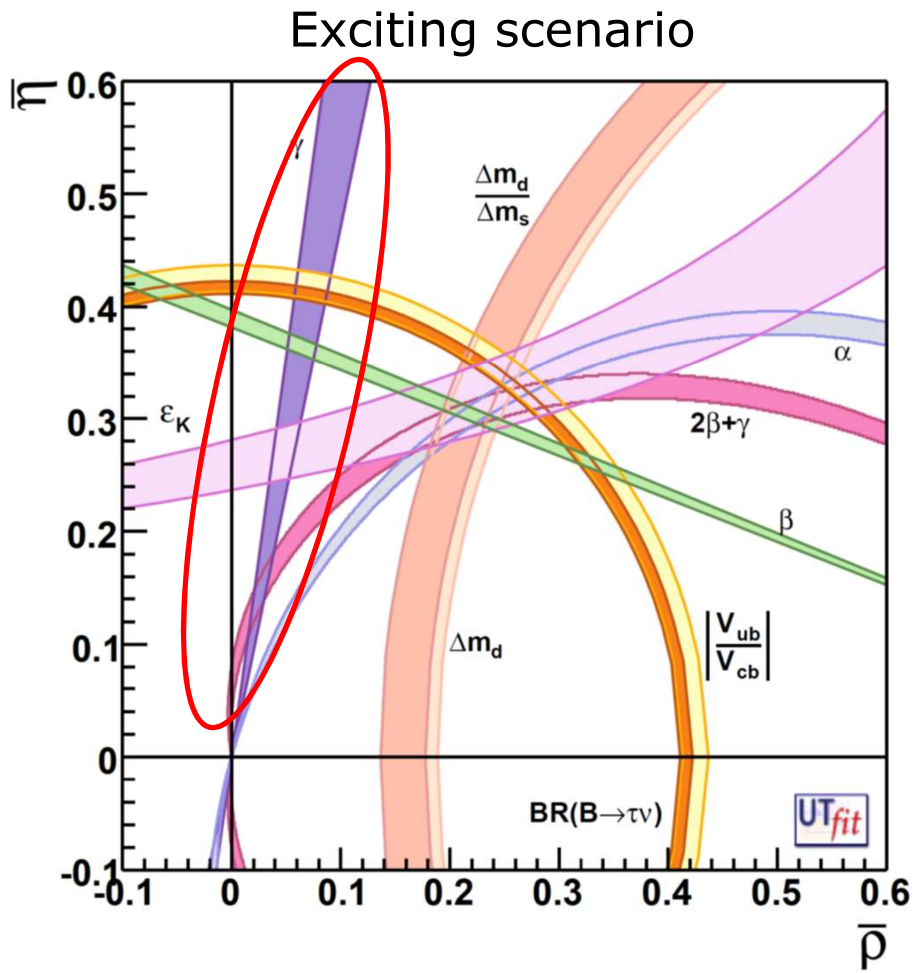
Testing the CKM mechanism



Back to the future

Projection from 2007





arXiv:0710.3799

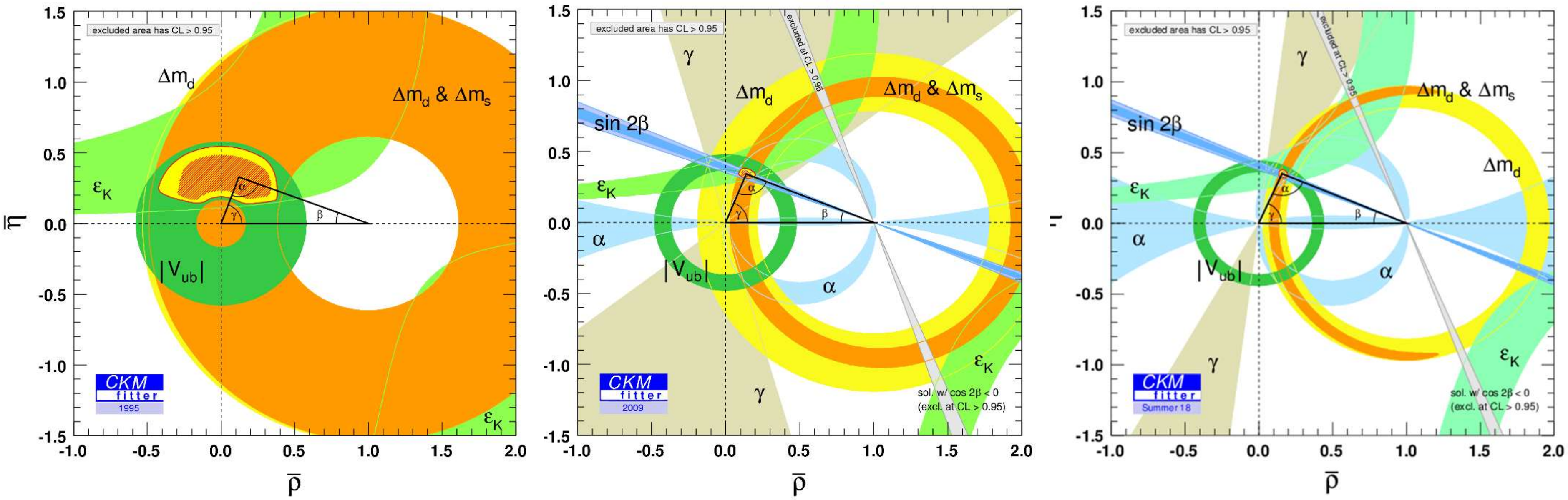
The b → d unitarity triangle

Wide program of measurements to over-constrain the SM parameter-space

1995:
top discovery

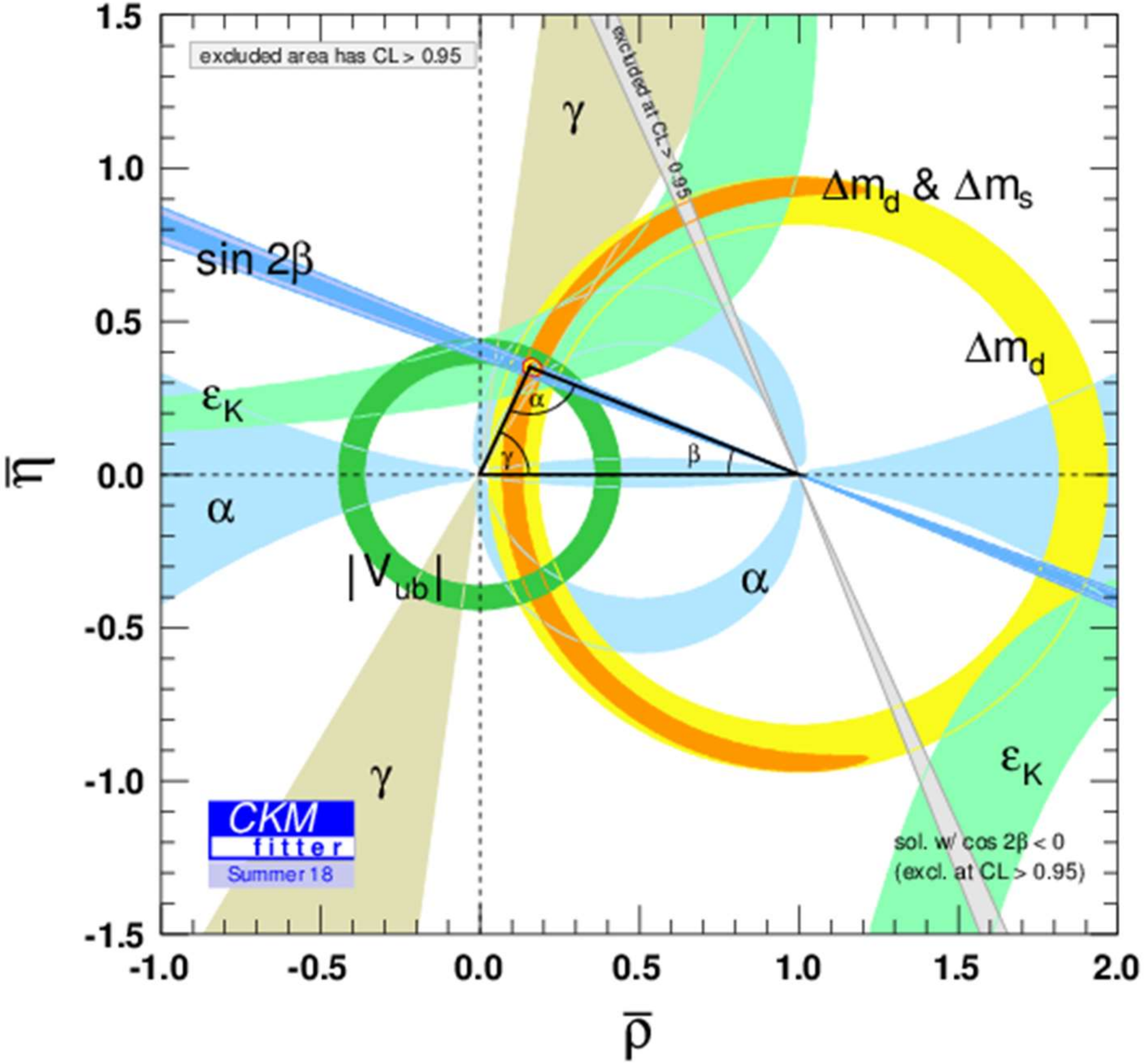
2009:
End of B-factories

2019:



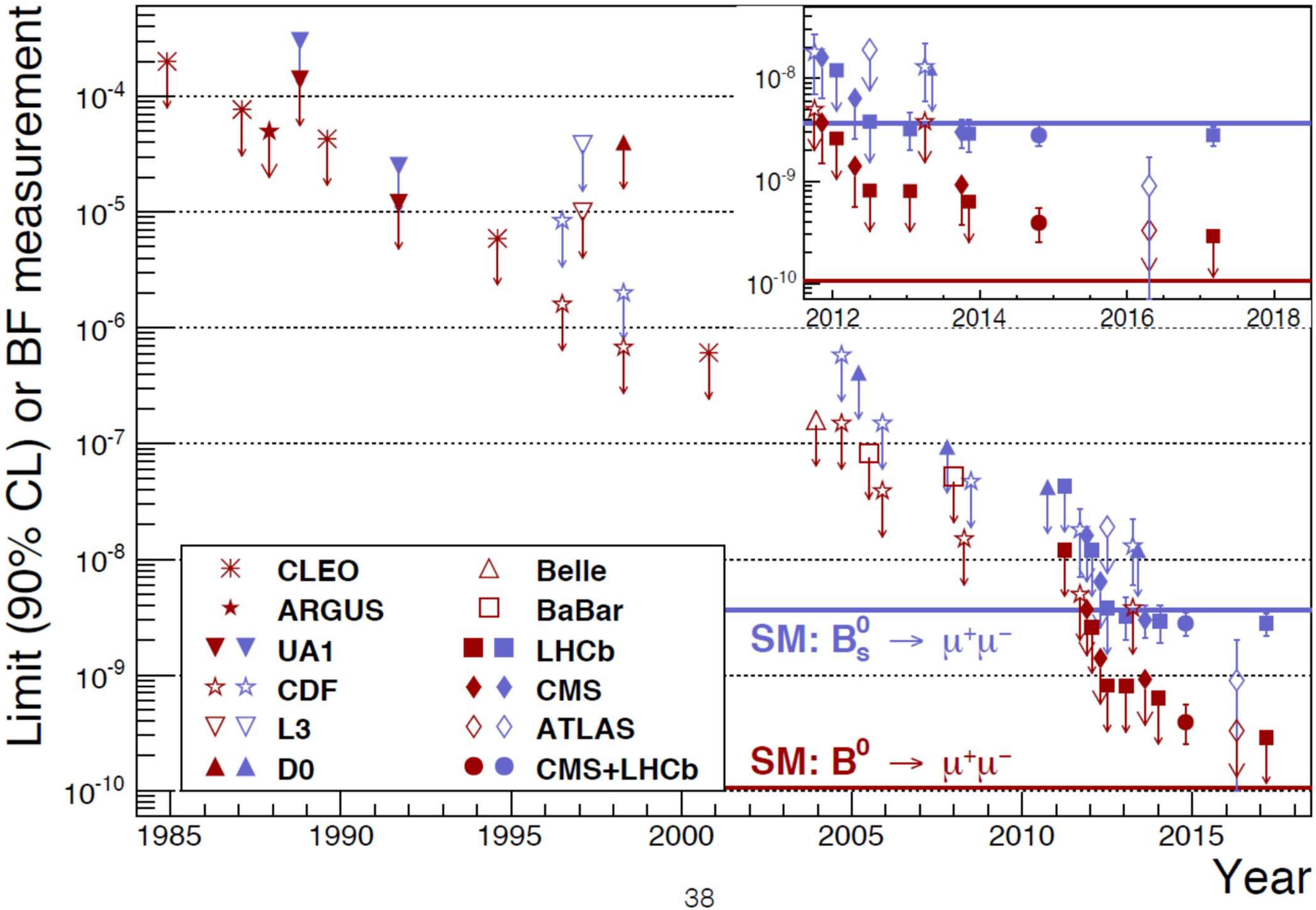
With the current precision, CP violation well described by the CKM mechanism

The $b \to d$ unitarity triangle



γ is angle with largest uncertainty

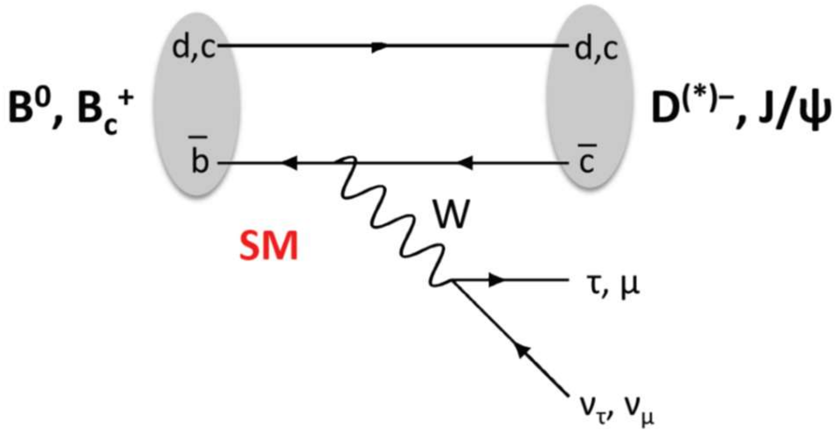
$B^0_{d,s} \rightarrow \mu^+\mu^-$



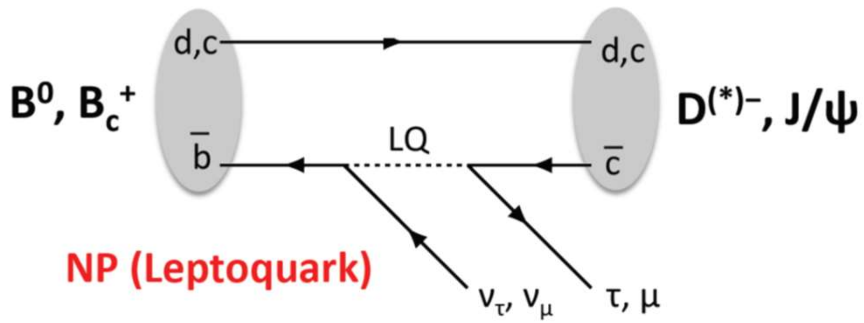
$B \to D^{(*)}l\nu$

Compare $l=\mu,\tau$ rates for $B \to Dl\nu$

$$R_{D^{(*)}} = \frac{\Gamma(\bar{B} \to D^{(*)}\tau\bar{\nu})}{\Gamma(\bar{B} \to D^{(*)}\ell\bar{\nu})}$$

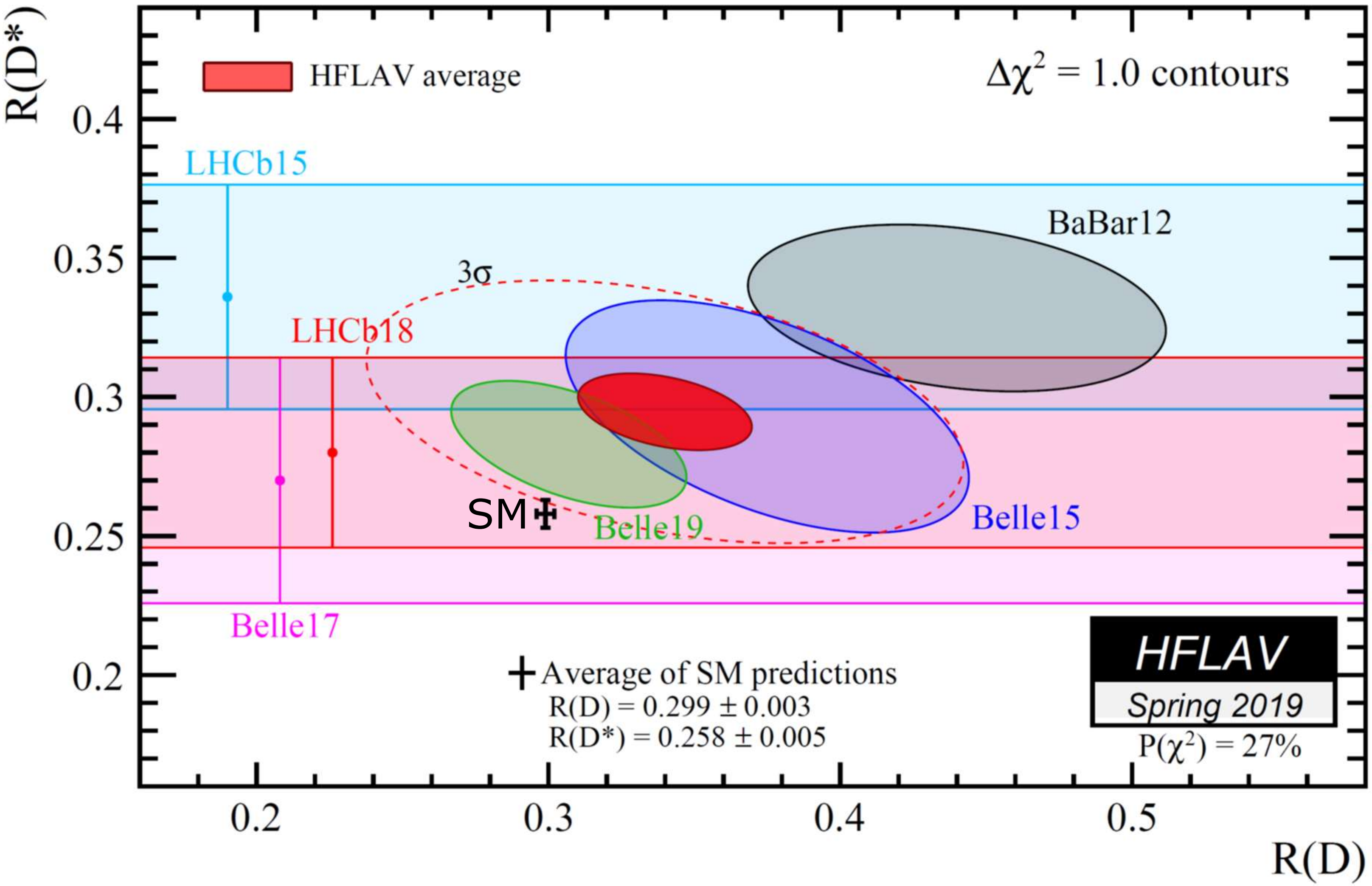


Tree-level in SM, but can have NP contributions (e.g. leptoquark or charged Higgs)



Leptoquark:
- hypothetical particles with non-zero baryon and lepton quantum numbers
- Appear in many BSM models, e. g. GUTs

$B \to D^{(*)} l\nu$



SM prediction deviates from unity due to different μ/τ masses (available phase space)

Combined significance of ~3σ

Vector-like quarks

The left-handed and right-handed chiralities of a vector-like fermion ψ transform in the same way under the SM gauge groups $SU(3)_c \times SU(2)_L \times U(1)_Y$

Why are they called "vector-like"?

$$\mathcal{L}_W = \frac{g}{\sqrt{2}} \left(J^{\mu+} W^+_\mu + J^{\mu-} W^-_\mu \right)$$

Charged current Lagrangian

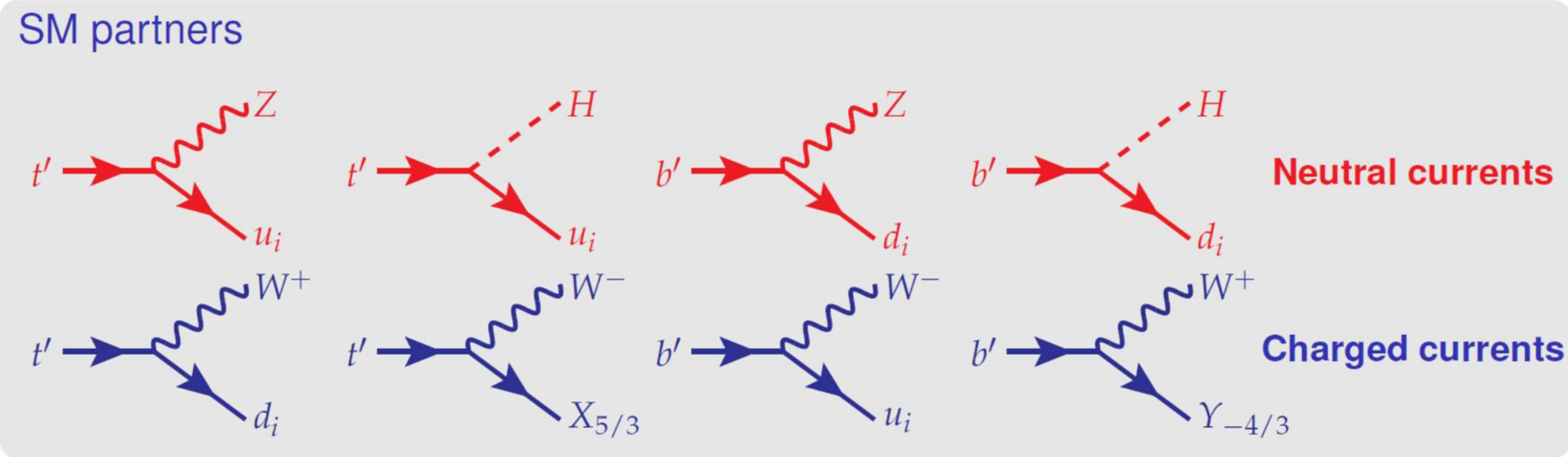
- SM chiral quarks: ONLY left-handed charged currents

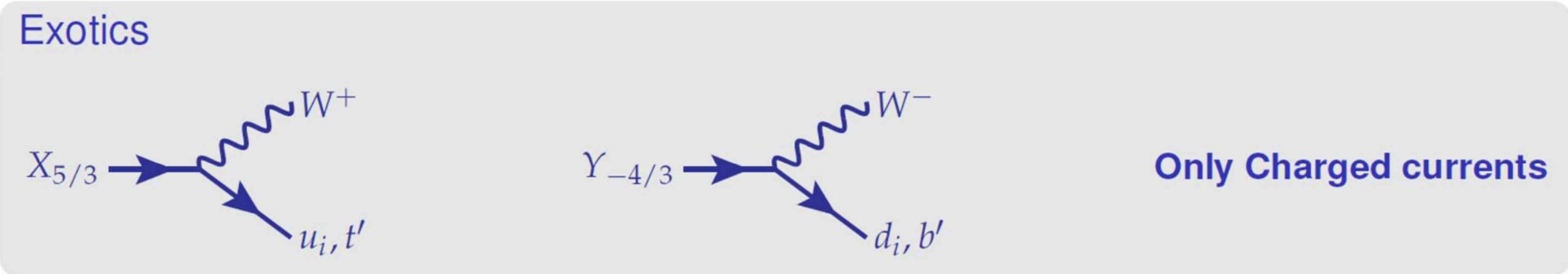
$$J^{\mu+} = J^{\mu+}_L + J^{\mu+}_R \quad \text{with} \quad \begin{cases} J^{\mu+}_L = \bar{u}_L \gamma^\mu d_L = \bar{u}\gamma^\mu (1-\gamma^5) d = V - A \\ J^{\mu+}_R = 0 \end{cases}$$

- vector-like quarks: BOTH left-handed and right-handed charged currents

$$J^{\mu+} = J^{\mu+}_L + J^{\mu+}_R = \bar{u}_L \gamma^\mu d_L + \bar{u}_R \gamma^\mu d_R = \bar{u}\gamma^\mu d = V$$

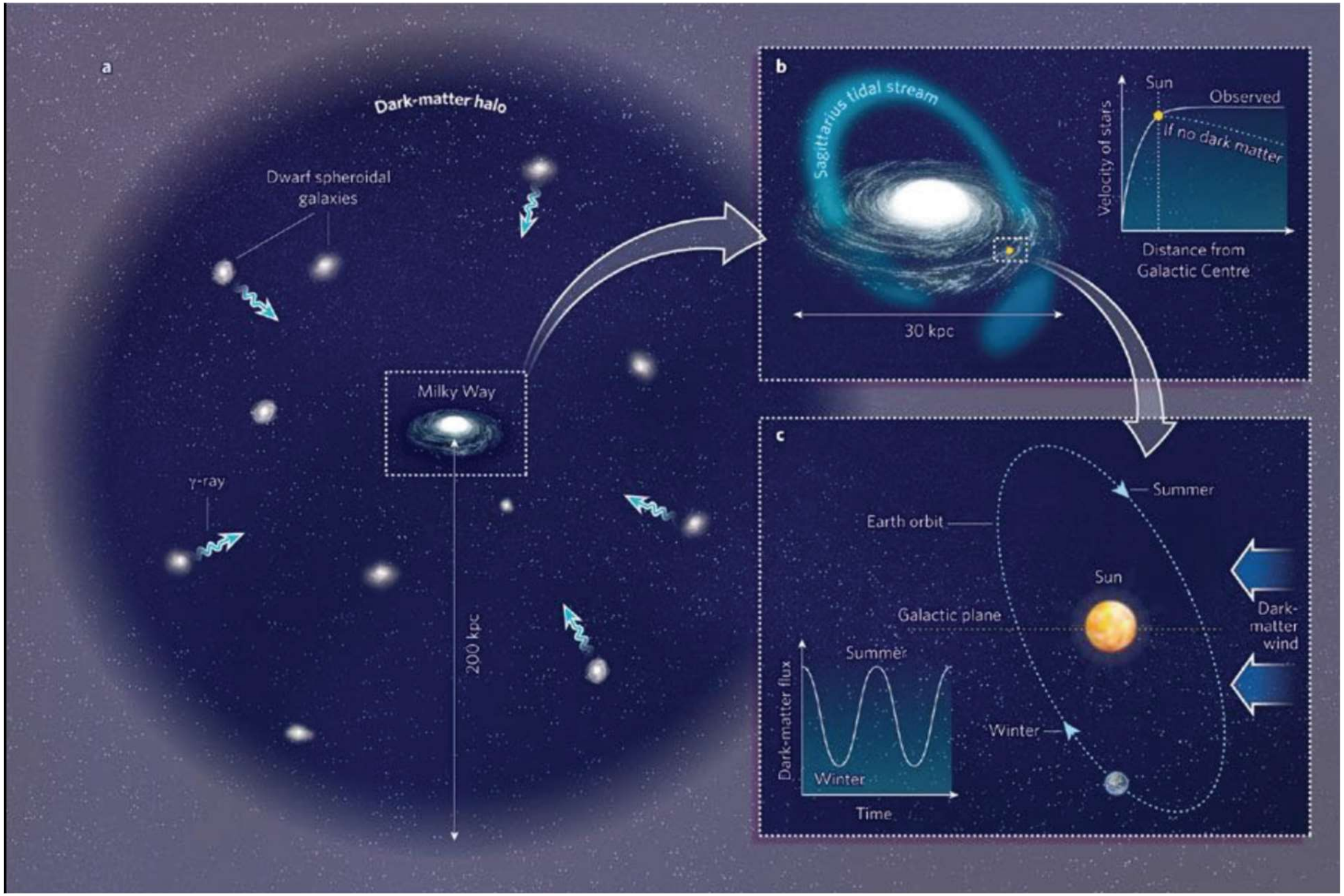
Vector-like quarks





Not all decays may be kinematically allowed

it depends on **representations** and **mass differences**


a
Dark-matter halo
Dwarf spheroidal galaxies
Milky Way
γ-ray
200 kpc
b
Sagittarius tidal stream
30 kpc
Sun
Observed
If no dark matter
Velocity of stars
Distance from Galactic Centre
c
Summer
Earth orbit
Sun
Galactic plane
Dark-matter wind
Winter
Dark-matter flux
Summer
Winter
Time

Belle(II), LHCb side by side

Belle (II)

$e^+e^- \to \Upsilon(4S) \to b\bar{b}$

at $\Upsilon(4S)$: 2 B's (B^0 or B^+) and nothing else ⇒ clean events

(flavour tagging, B tagging, missing energy)

$\sigma_{b\bar{b}} \sim 1$ nb ⇒ 1 fb^{-1} produces 10^6 $B\bar{B}$

$\sigma_{b\bar{b}}/\sigma_{total} \sim 1/4$

LHCb

$pp \to b\bar{b}X$

production of B^+, B^0, B_s, B_c, Λ_b...
but also a lot of other particles in the event

⇒ lower reconstruction efficiencies

$\sigma_{b\bar{b}}$ much higher than at the $\Upsilon(4S)$

	$\sqrt{s}$ [GeV]	$\sigma_{b\bar{b}}$ [nb]	$\sigma_{b\bar{b}}$ / σ_{tot}
HERA pA	42 GeV	~30	~10^{-6}
Tevatron	2 TeV	5000	~10^{-3}
LHC	8 TeV	~3×10^5	~ 5×10^{-3}
	14 TeV	~6×10^5	~10^{-2}

$b\bar{b}$ production cross-section at LHCb ~ 500,000 × BaBar/Belle !!

$\sigma_{b\bar{b}}/\sigma_{total}$ much lower than at the $\Upsilon(4S)$

⇒ lower trigger efficiencies

B mesons live relativey long

Belle (II): mean decay length $\beta\gamma c\tau \sim 200\ \mu m$

LHCb: **mean decay length $\beta\gamma c\tau \sim 7$ mm** (displaced vertices)

data taking period(s)

Belle (II): [1999-2010] = 1 ab^{-1}
[2019-...] = ...

LHCb: [run I: 2010-2012] = 3 fb^{-1},
[run II: 2015-2018] = 6 fb^{-1}

(near) future

Belle (II): [Belle II from 2019] → 50 ab^{-1}

LHCb: [LHCb upgrade from 2021]

Mixing

y: Yukawa coupling
M: bare VLQ mass

$$\mathcal{L}_{\text{mass}} = -\begin{pmatrix} \bar{t}^0_L & \bar{T}^0_L \end{pmatrix} \begin{pmatrix} y^u_{33}\frac{v}{\sqrt{2}} & y^u_{34}\frac{v}{\sqrt{2}} \\ y^u_{43}\frac{v}{\sqrt{2}} & M^0 \end{pmatrix} \begin{pmatrix} t^0_R \\ T^0_R \end{pmatrix}$$

Weak eigenstate basis

Mass eigenstate basis

$$\begin{pmatrix} t_{L,R} \\ T_{L,R} \end{pmatrix} = \begin{pmatrix} c^u_{L,R} & -s^u_{L,R}e^{i\phi_u} \\ s^u_{L,R}e^{i\phi_u} & c^u_{L,R} \end{pmatrix} \begin{pmatrix} t^0_{L,R} \\ T^0_{L,R} \end{pmatrix}$$

ϕ complex phase

$s^u_{L,R} \equiv \sin\theta^u_{L,R}$

$c^u_{L,R} \equiv \cos\theta^u_{L,R}$

$$\tan 2\theta^q_L = \frac{\sqrt{2}|y^q_{34}|vM^0}{(M^0)^2 - |y^q_{33}|^2v^2/2 - |y^q_{34}|^2v^2/2} \quad \text{(singlets, triplets)},$$

$$\tan 2\theta^q_R = \frac{\sqrt{2}|y^q_{43}|vM^0}{(M^0)^2 - |y^q_{33}|^2v^2/2 - |y^q_{43}|^2v^2/2} \quad \text{(doublets)},$$

For large M_0, mixing proportional to m/M_0
→ Larger mixing for 3rd generation