

Future ee Colliders and Colour Reconnection effects

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Outlook

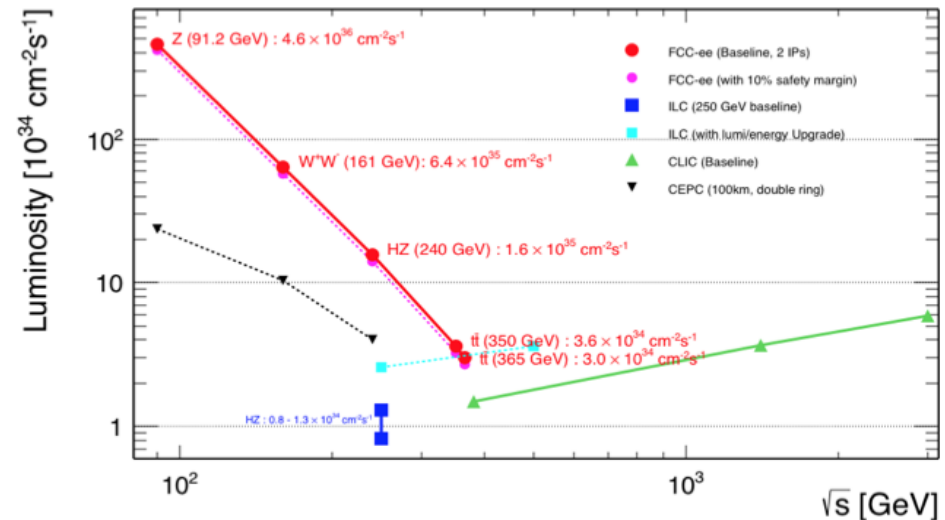
- + Future ee Colliders*
- + Colour Reconnection effects*
- + Results of study CR effects*
- + New models of CR*
- + CR at Future ee Colliders*

Future ee Colliders

Linear or Circular?

Linear: ILC, CLIC

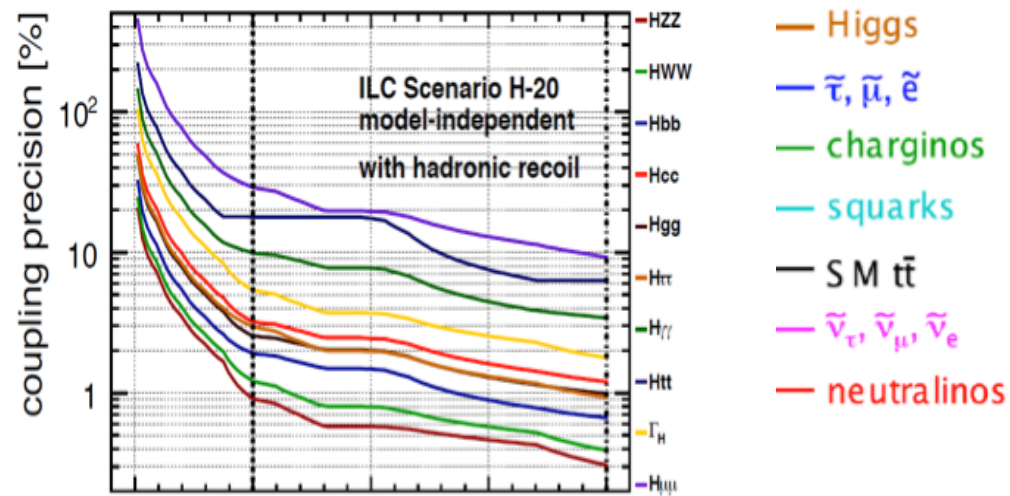
Circular: FCC-ee, CERP



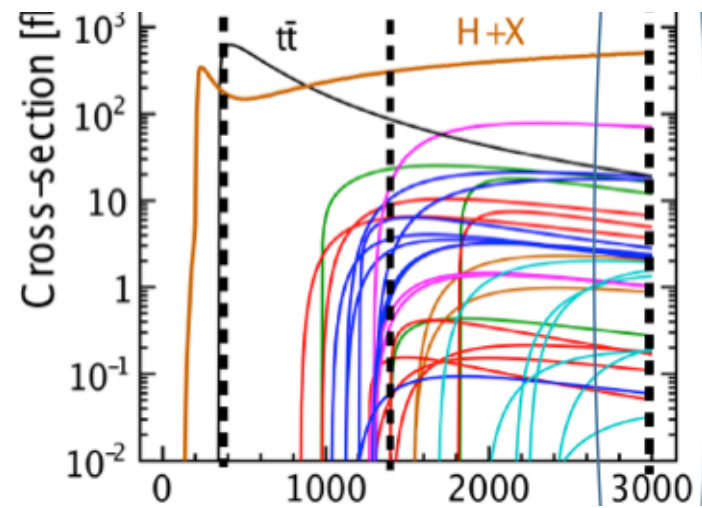
- + A clear advantage of a future circular ee machines is absolute luminosity
- + While with linear colliders are achievable a higher center-of-mass energies due the absence of synchrotron radiation

Future ee Colliders

ILC 250 GeV



CLIC



Future ee Colliders

The FCC-ee - *Future Circular Collider* – will be a unique for searches new physics via high-precision studies of the W, Z, H bosons and top quark with uncertainties at the permil level or below, with huge luminosities (1-100) ab¹ with 4 interaction points, beam energy 90-350 GeV

10⁸ jets from Z and W bosons decays

10⁵ gluon jets from Higgs boson decays



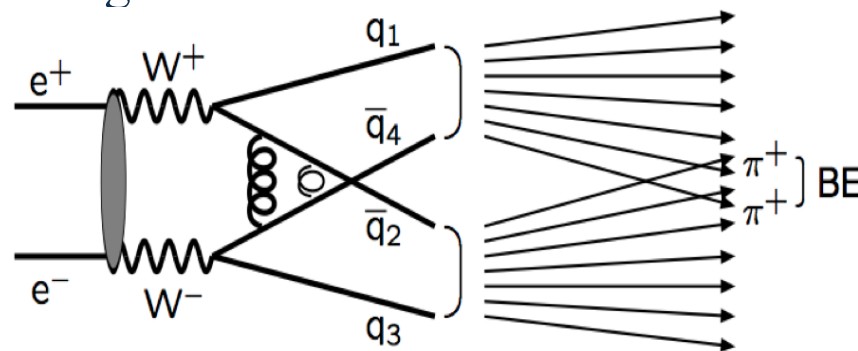
FCC-ee

LHC

\sqrt{s} (GeV):	90 (Z)	125 (eeH)	160 (WW)	240 (HZ)	350 ($t\bar{t}$)	350 (WW→H)
\mathcal{L}/IP (cm ⁻² s ⁻¹)	2.2·10 ³⁶	1.1·10 ³⁶	3.8·10 ³⁵	8.7·10 ³⁴	2.1·10 ³⁴	2.1·10 ³⁴
\mathcal{L}_{int} (ab ⁻¹ /yr/IP)	22	11	3.8	0.87	0.21	0.21
Events/year (4 IPs)	3.7·10 ¹²	1.2·10 ⁴	6.1·10 ⁷	7.0·10 ⁵	4.2·10 ⁵	2.5·10 ⁴
Years needed (4 IPs)	2.5	1.5	1	3	0.5	3

Colour reconnection effects

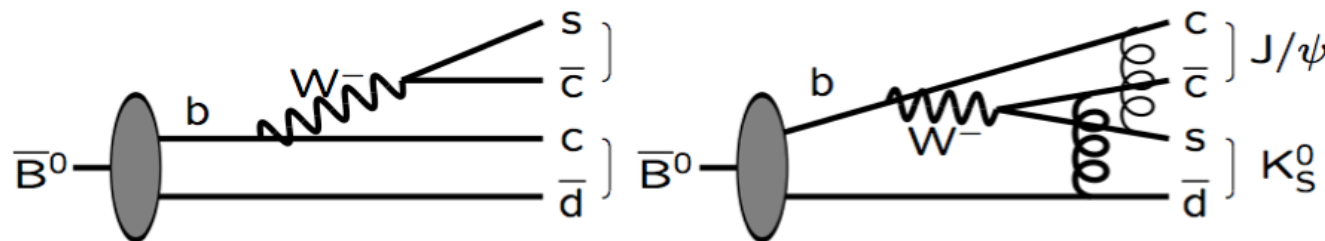
- + Color reconnection is an *ad hoc* mechanism aiming to describe the interactions that can occur between chromoelectric fields during the hadronization transition.
- + CR : top quark, Z, W bosons have widths around 2 GeV and $c\tau=0.1\text{GeV}$ which is smaller than the hadronization times
- + which means inside all the hadronization colour fields, in the evolution of the parton shower, between partons from different hadronic systems by exchanging coloured gluons.



Reconnection exists

$B \rightarrow J/\psi \rightarrow \mu^+ \mu^-$ good way to find B mesons:
H. Fritzsch, Phys. Lett. **B86** (1979) 164, 343

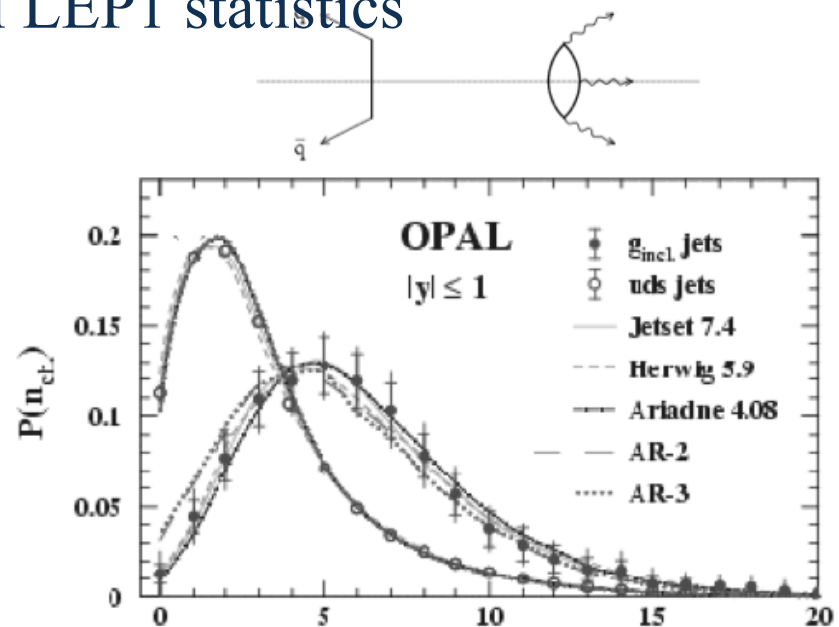
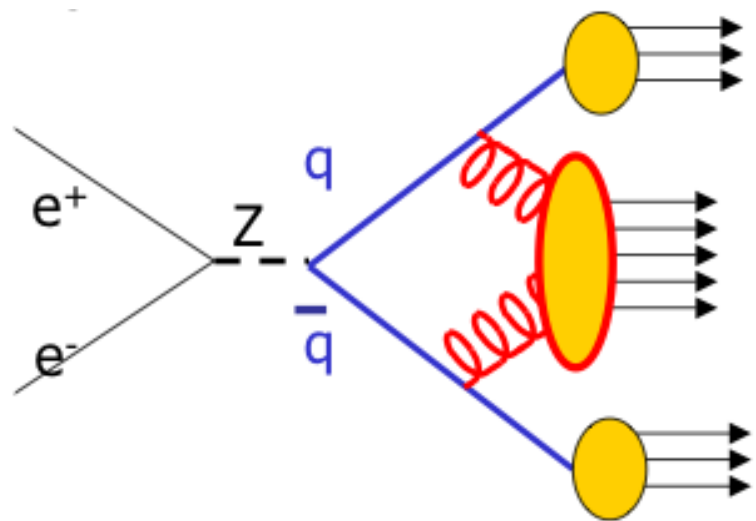
$g^* \rightarrow c\bar{c} \rightarrow J/\psi$ production mechanism in pp (“colour octet”)
H. Fritzsch, Phys. Lett. **B67** (1977) 217



Looking on LEP1 data

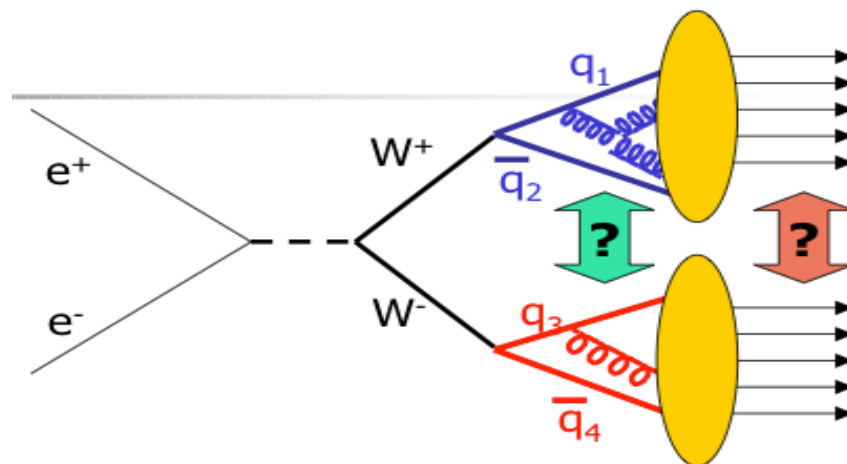
$Z \rightarrow q\bar{q}gg$ form a “glue ring” (Friberg et al. 97)

OPAL: 439 events in the full LEP1 statistics



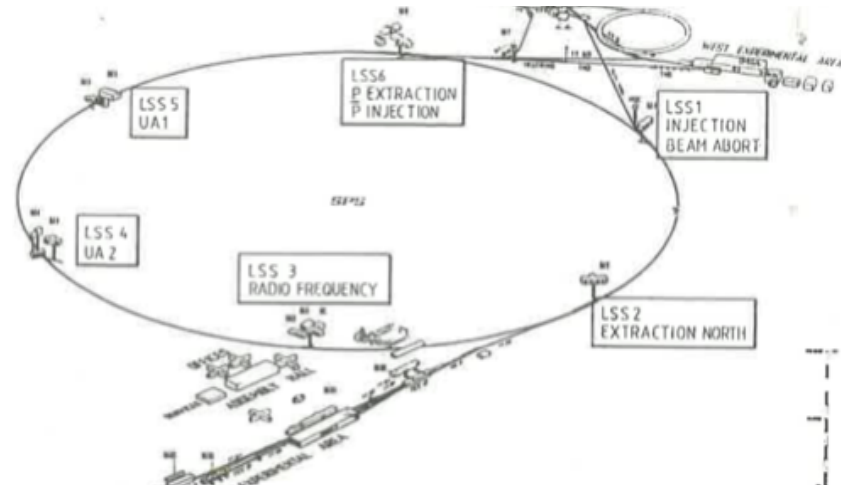
CR effects in WW events

- + In the absence of colour reconnection, from the fragmentation of two colour singlet strings each of which is stretched between the two quarks from a W boson.
- + However, interactions may occur between the decay products of the two W bosons.
- + This “cross-talk” is due relatively short distance separating the decay of the W bosons (in order of 0.1 fm)



The W boson

- + Discovered in UA1 and UA2 at CERN SpS in 1983
- + Charge : $\pm 1e$
- + Width : 2.085 ± 0.042 GeV
- + Spin : 1
- + Mass : 80.385 ± 0.015 GeV
- + Decay Channels : e, μ, τ BR $\sim 11\%$ each
hadrons : BR $\sim 67\%$

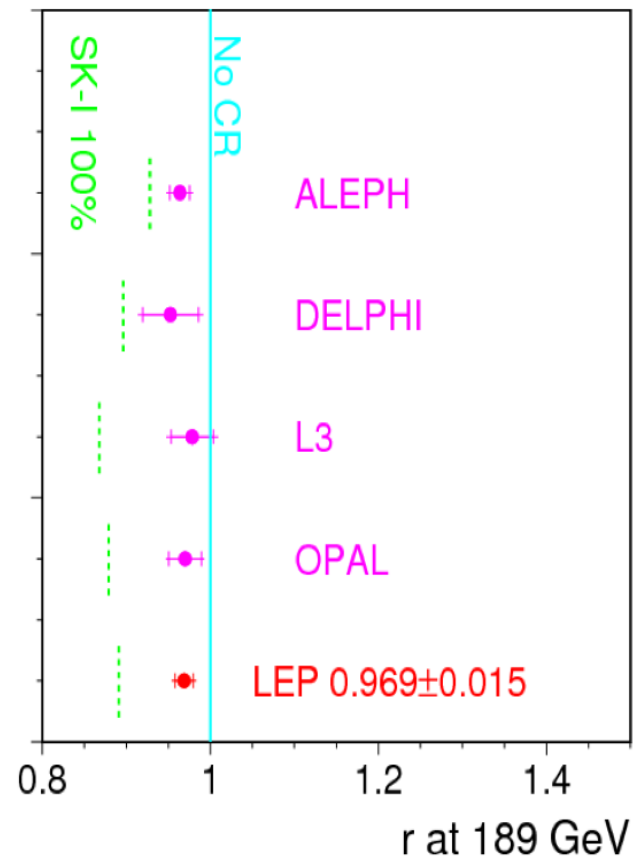
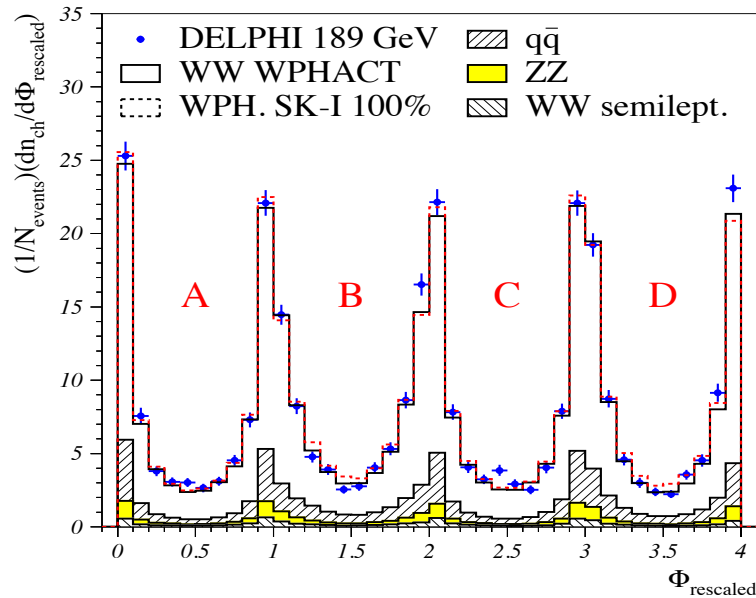


Systematics of WW at LEP2

Source	qqlv	qqqq	combined
Hadronisation	13	19	14
QED(ISR/FSR)	8	5	7
Detector	10	8	10
Colour Reconnection	0	35	9
Bose-Einstein Correlation	0	7	2
LEP Beam Energy	9	9	10
Other	3	11	4
Total Systematics	21	44	22
Statistical	30	40	25
Total	36	59	33

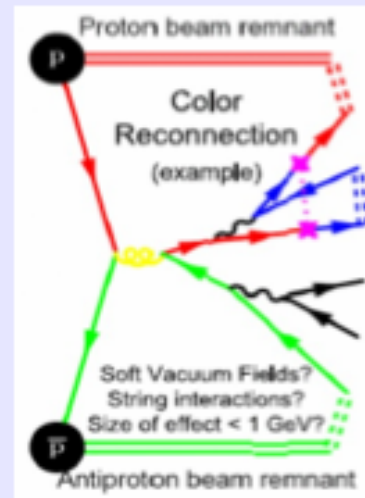
The conclusion of the LEP2

- + Best LEP2 fit (topology + mass): 51% of 189 GeV events reconnected in SKI model.
- + No-CR excluded at 99.5% CL



Tevatron results

- + Study with the Perugia tune, which gives 1.3 GeV



to the top mass systematics of order

$$\text{CR(sys)} \approx 0.5 \text{ GeV}$$

generator : $\Delta(m_t) = 0.25 \text{ GeV}$ (HERWIG-PYTHIA)

ISR/FSR : $\Delta(m_t) = 0.15 \text{ GeV}$

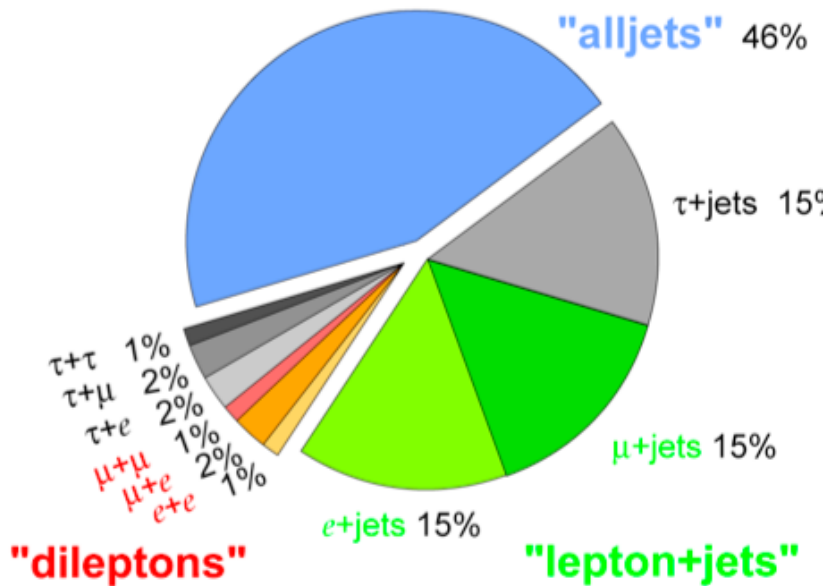
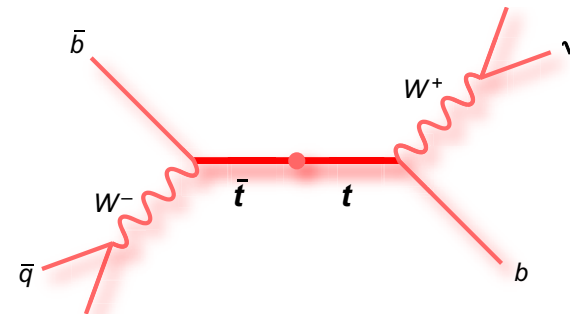
Jets (OOC+JES) : $\Delta(m_t) = 0.43 \text{ GeV}$

b-jets : $\Delta(m_t) = 0.16 \text{ GeV}$

Color reconnection: $\Delta(m_t) = 0.37 \text{ GeV}$

Top BR and Decays

BR

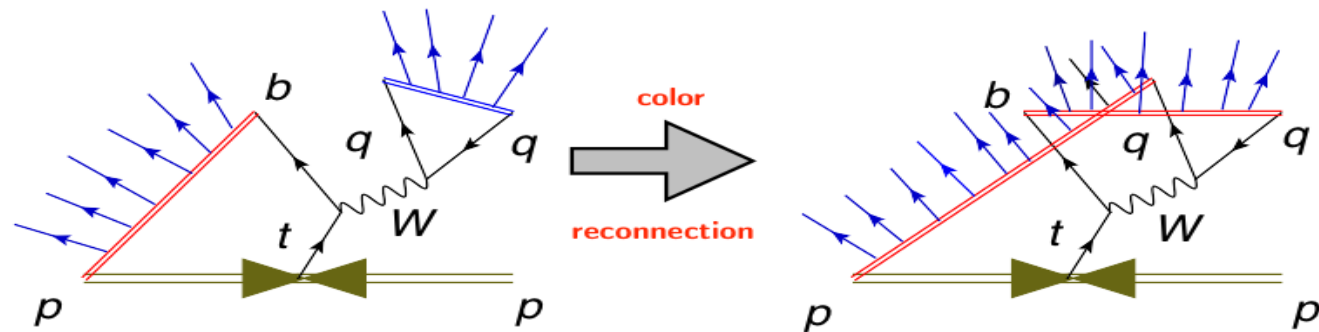
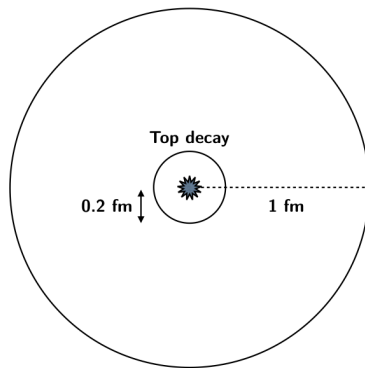
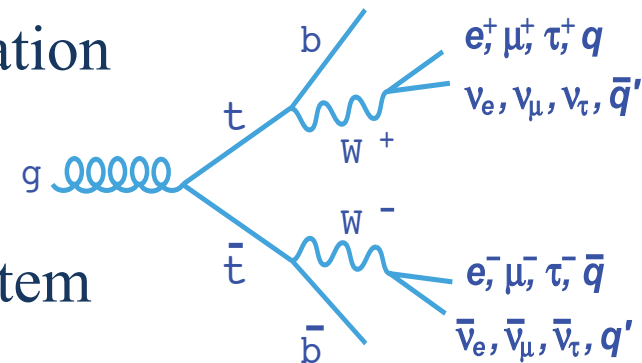


Decays

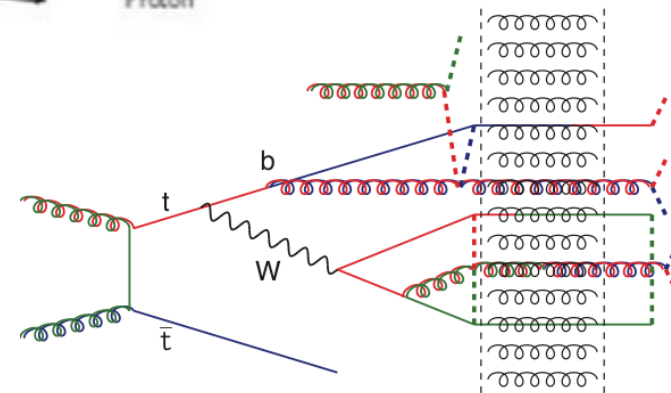
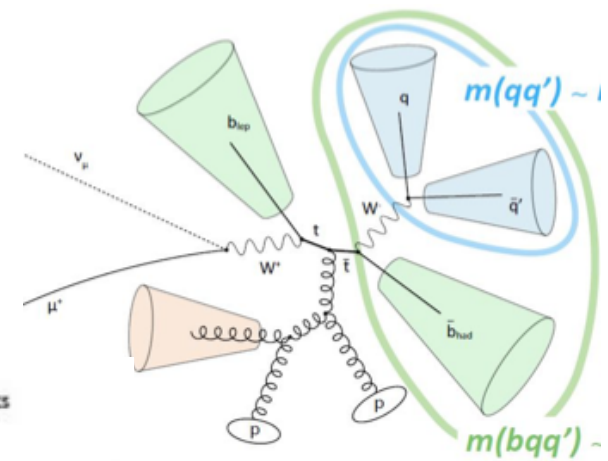
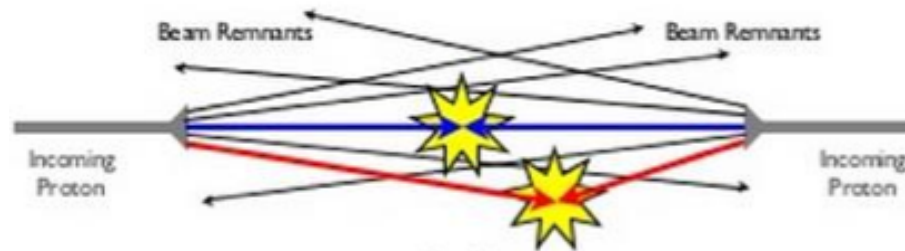
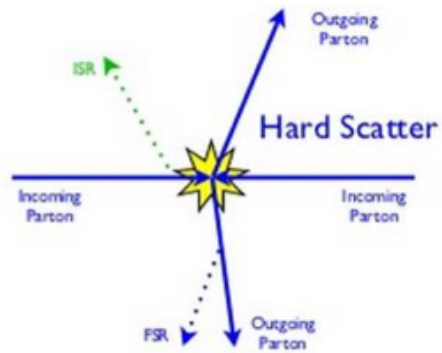
$\bar{c}s$	electron+jets	muon+jets	tau+jets	all-hadronic	
$\bar{u}d$					
τ^-	$e\tau$	$\mu\tau$	$\tau\tau$		
μ^-	$e\mu$	$\mu\mu$	$\mu\tau$	muon+jets	
e^-	$e\tau$	$e\mu$	$e\tau$	electron+jets	
W decay	e^+	μ^+	τ^+	$u\bar{d}$	$c\bar{s}$

CR at Top decays

- Interactions and interference between the top decay products during the hadronization
- Important effect for the top mass measurements
- CR affects the reconstruction of top system



Top decay in pp events



Atlas results:

Model with “no-CR” - unphysical

New (toy models)

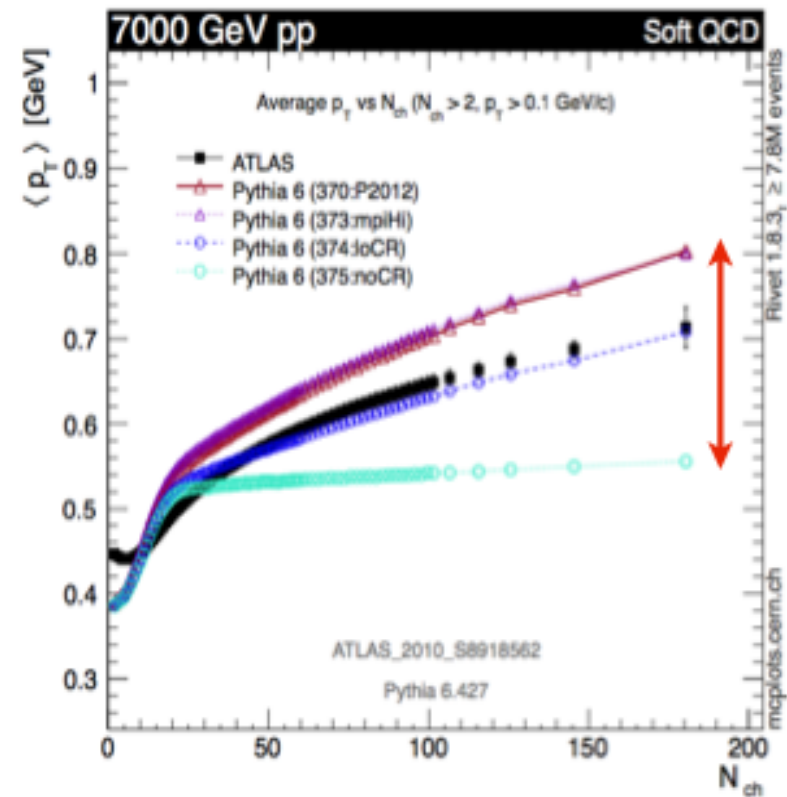
- forced random
- forced nearest
- forced farthest
- forced smallest $\Delta\lambda$
- smallest $\Delta\lambda$

only top events
default CR afterburner

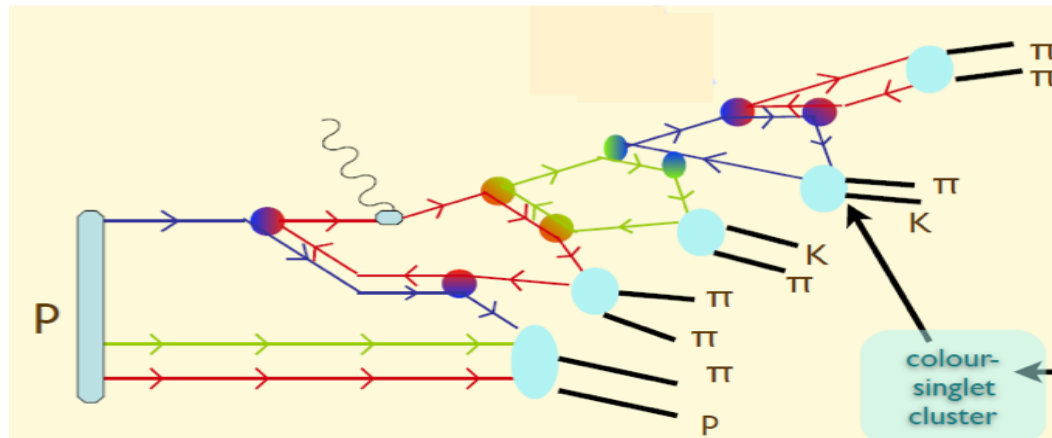
New (more sophisticated)

- swap
- move
- swap + flip
- move + flip

all events



Colour reconnection pp



sub-leading color effects
in the perturbative part
of the calculation

Interaction between
colour fields during
the hadronization

Parameter	Definition
MPI Parameters	
MultipartonInteractions:pT0Ref	p_T regularisation parameter
MultipartonInteractions:expPow	Exponent of matter overlap function
MPI based CR model (CR0)	
ColourReconnection:range	CR strength
QCD-based model (CR1)	
ColourReconnection:m0	Mass parameter of order λ_{QCD} used in the string length measure
ColourReconnection:junctionCorrection	Multiplicative correction to string length above
Gluon-move scheme (CR2)	
ColourReconnection:m2Lambda	Equivalent to m_0 for QCD-based model
ColourReconnection:fracGluon	Average fraction of gluons that undergo a colour reconnection
ColourReconnection:dLambdaCut	Minimal value for decrease in string length

Table 1: Tuning parameters and their definitions. The **MultipartonInteractions:expPow** can only be used with an exponential MPI matter overlap function (**MultipartonInteractions:bProfile** = 3). The parameters specific to a CR model are stated together. CR1 model was used with **ColourReconnection:allowDoubleJunRem** = **off** setting, as recommended by the authors.

Atlas study of CR

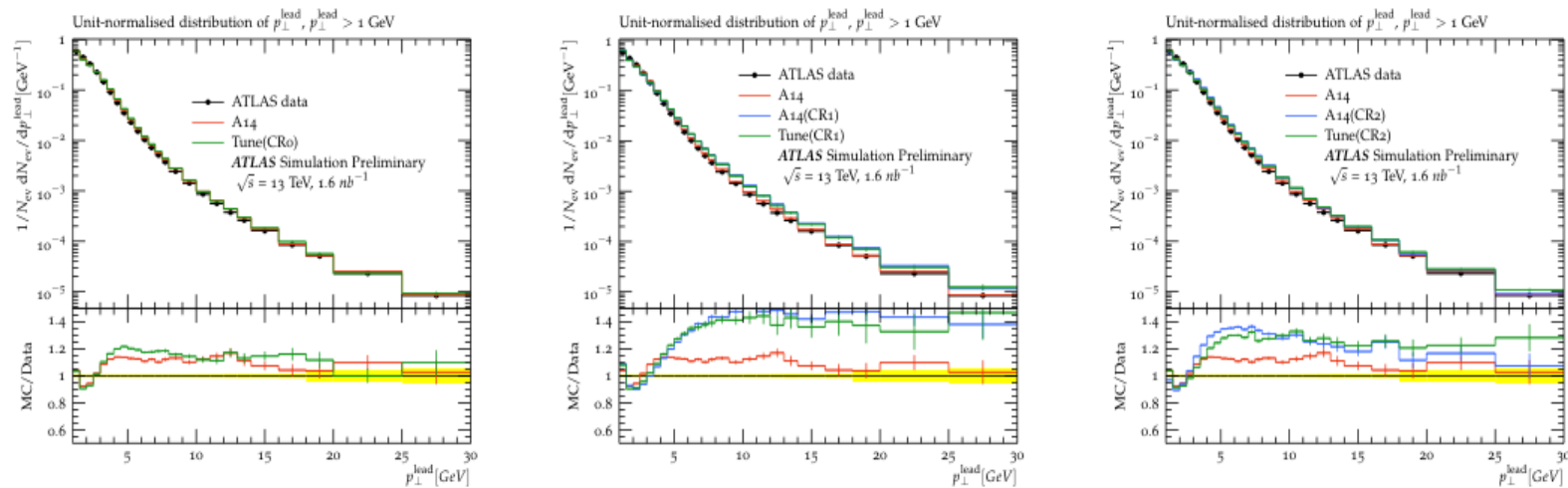
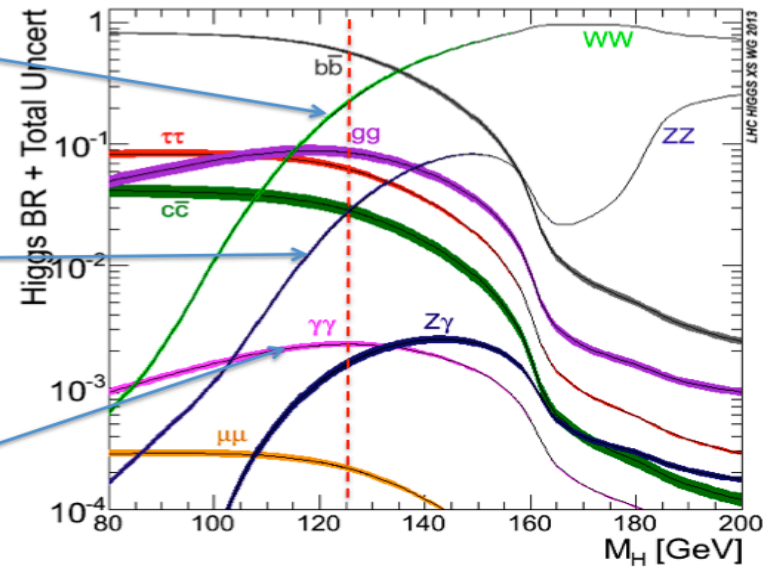
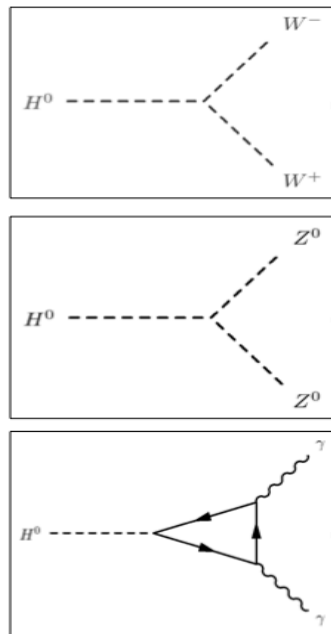
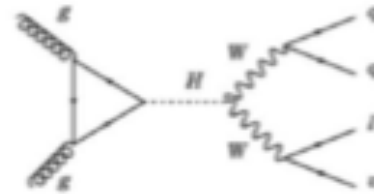


Figure 4: Predictions using the A14 tuned parameter settings (red), A14 tuned parameter settings with only CR model changed (blue), and a new set of tuned parameters with the new CR model (green) for CR0, CR1 and CR2 settings (left to right) are compared with leading charged particle p_T distribution with ATLAS data from Run 2 [7]. The yellow shaded areas at the ratio plot in the bottom represent the uncertainty on the data.

Higgs decays

BR $H \rightarrow WW$ 21%

Simulation of high-energy physics process



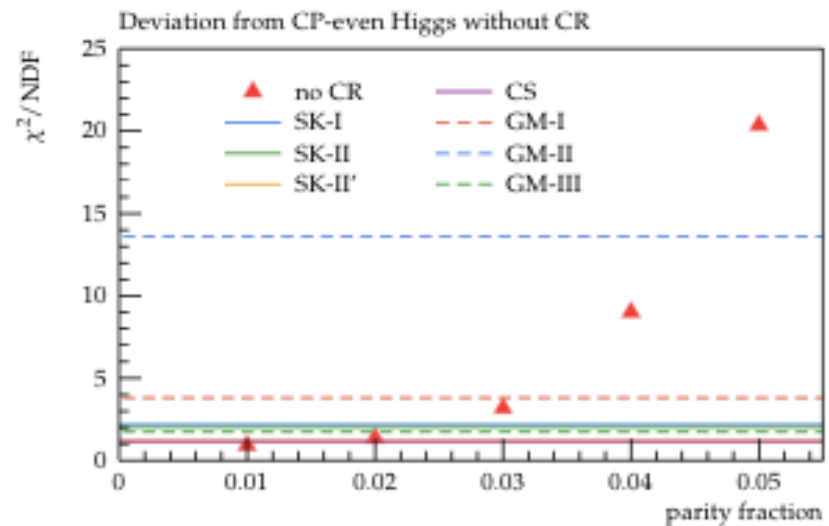
LHC HIGGS XS WG 2013

CR in $H \rightarrow WW$

- + CR includes the big uncertainty
- + CR can shift jet directions – necessary CR well understood
- + Results of Higgs Parity

measurement

in $WW \rightarrow qqqq$



CR models

The CR effects were search firstly at LEP2 in $ee \rightarrow WW \rightarrow qqqq$ events, a number of models were developed:

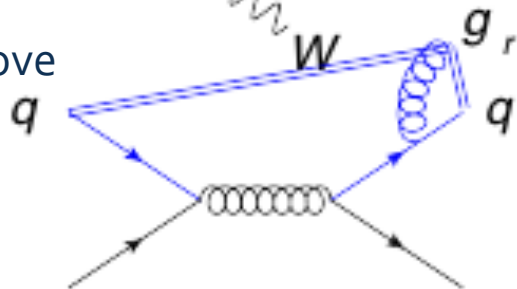
- + main in the PYTHIA – SKI, SKII
- + in HERWIG – Plain CR considers all quark ends of clusters and reconnects clusters – probability p_{reco} and Statistical CR
- + for HERA – new models in terms of CR from the Uppsala group which described DIS and rapidity gaps
- + MPI – multiparton intersction model in PYTHIA for hadronic collisions, which explain the increasing transverse momentum p_{t} with increasing charged multiplicity n_{ch}
- + “gluon move” model – GM in PYTHIA 8
- + a new QCD-based CR model – CS – Y-shaped topology
- + Rope Hadronization model – with effects on flavour composition, can explain QGP-like features in systems as small as pp

How looks CR models:

Color Swap

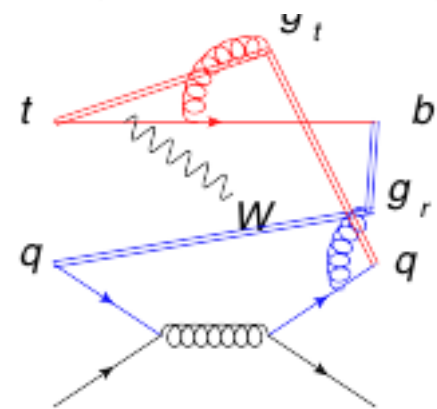
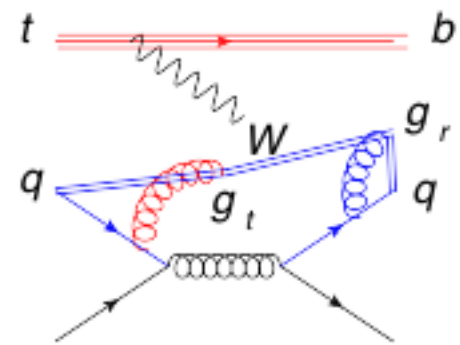
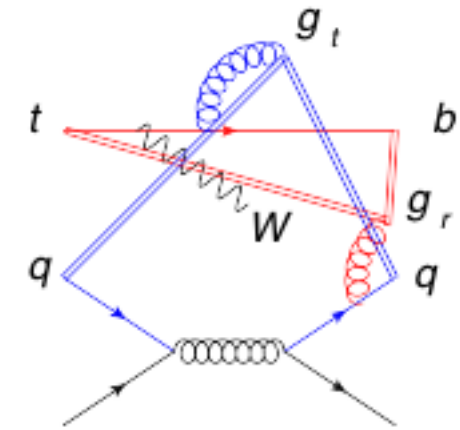


Gluon Move



Color Flip

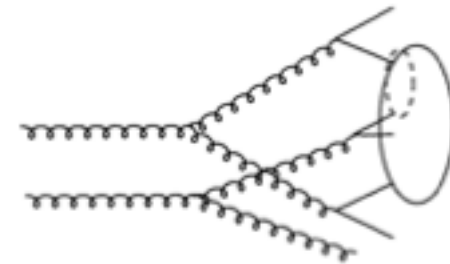
Model	$\Delta m_{\text{top}}^{\text{rescaled}}$ [GeV]
default	+0.239
forced random (min)	-0.524
move	+0.239
swap (max)	+0.273



CR in models

+ Herwig:

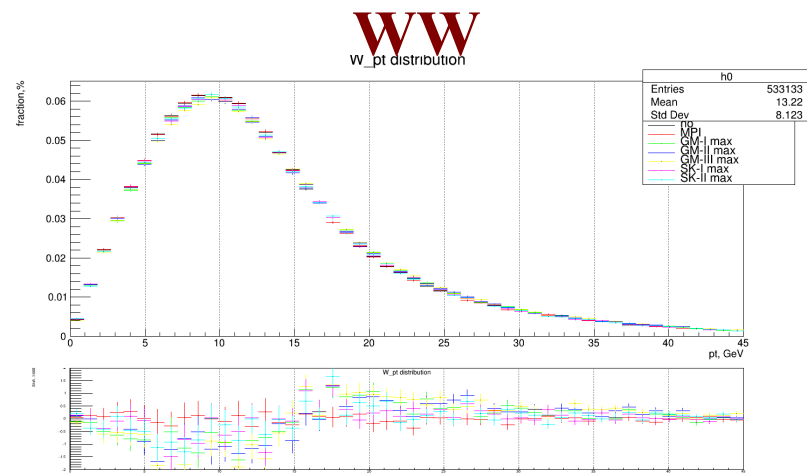
- + based on space-time structure of event at the end of parton shower
- + perform a reconnection $(ij)(kl) \rightarrow (ik)(jl)$
- + accept with probability $1/9$



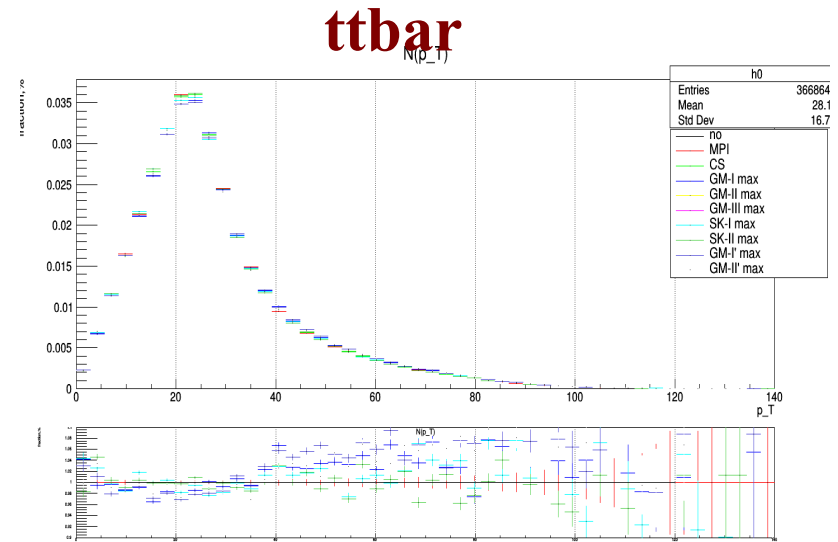
+ Sherpa:

- + Model 1: reconnections that minimize “color length”
- + Model 2: random assignment of parton into color singlets

Results of simulations - Pythia8



SKI $dM_w = 24$ MeV, $dN_{ch} = 0.6$
 SKII $dM_w = 6$ MeV $dN_{ch} = 0.2$
 CS $dM_w = 6$ MeV $dN_{ch} = 0.5$
 GMI $dM_w = 31$ MeV $dN_{ch} = 1.2$
 GMII $dM_w = 41$ MeV $dN_{ch} = 0.5$
 GMIII $dM_w = 43$ MeV $dN_{ch} = 2.0$



SKI $dM_{top} = -160$ MeV, $dN_{ch} = 0.2$
 SKII $dM_{top} = 20$ MeV $dN_{ch} = 0.1$
 CS $dM_{top} = -30$ MeV $dN_{ch} = 0.9$
 GMI $dM_{top} = 100$ MeV $dN_{ch} = 2.3$
 GMII $dM_{top} = 200$ MeV $dN_{ch} = 0.4$
 GMIII $dM_{top} = 180$ MeV $dN_{ch} = 3.1$

CR at FCC-ee

- + The CR issues will reappear at FCC-ee for W boson mass
- + top quark study
- + The CR understanding is interesting itself
- + In SM $M(H)=125\text{GeV}$ is a pure CP-even state, but it can be a CP-odd admixture, then it is important to set stringent limits
- + Possible to study angular correlations in $H \rightarrow WW \rightarrow qqqq$ decays – CR can shift jet directions – necessary CR well understood

E_{cm} (GeV)	$\langle \delta \overline{m}_W \rangle$ (MeV)						
	I	II	II'	GM-I	GM-II	GM-III	CS
170	+18	-14	-6	-41	+49	+2	+7
240	+95	+29	+25	-74	+400	+104	+9
350	+72	+18	+16	-50	+369	+60	+4

Future ee Colliders

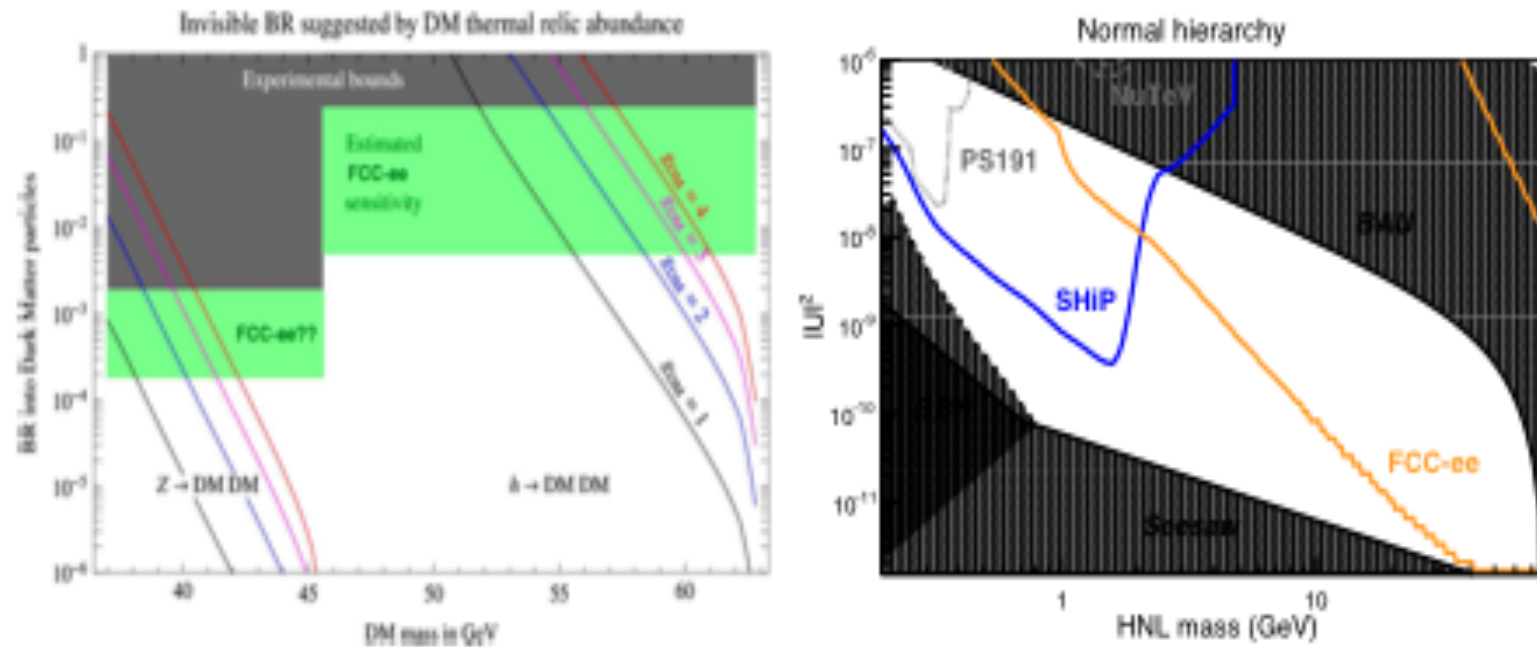


Figure 5: Regions of FCC-ee sensitivity for: (i) Rare Z and H decays into DM pairs in the $\text{BR}_{Z,H \rightarrow \text{DM DM}}$ vs. m_{DM} plane (left) [21], and (ii) sterile neutrinos as a function of their mass and mixing to light neutrinos (normal hierarchy) for 10^{13} Z decays (right) [22].



Thanks for attentions