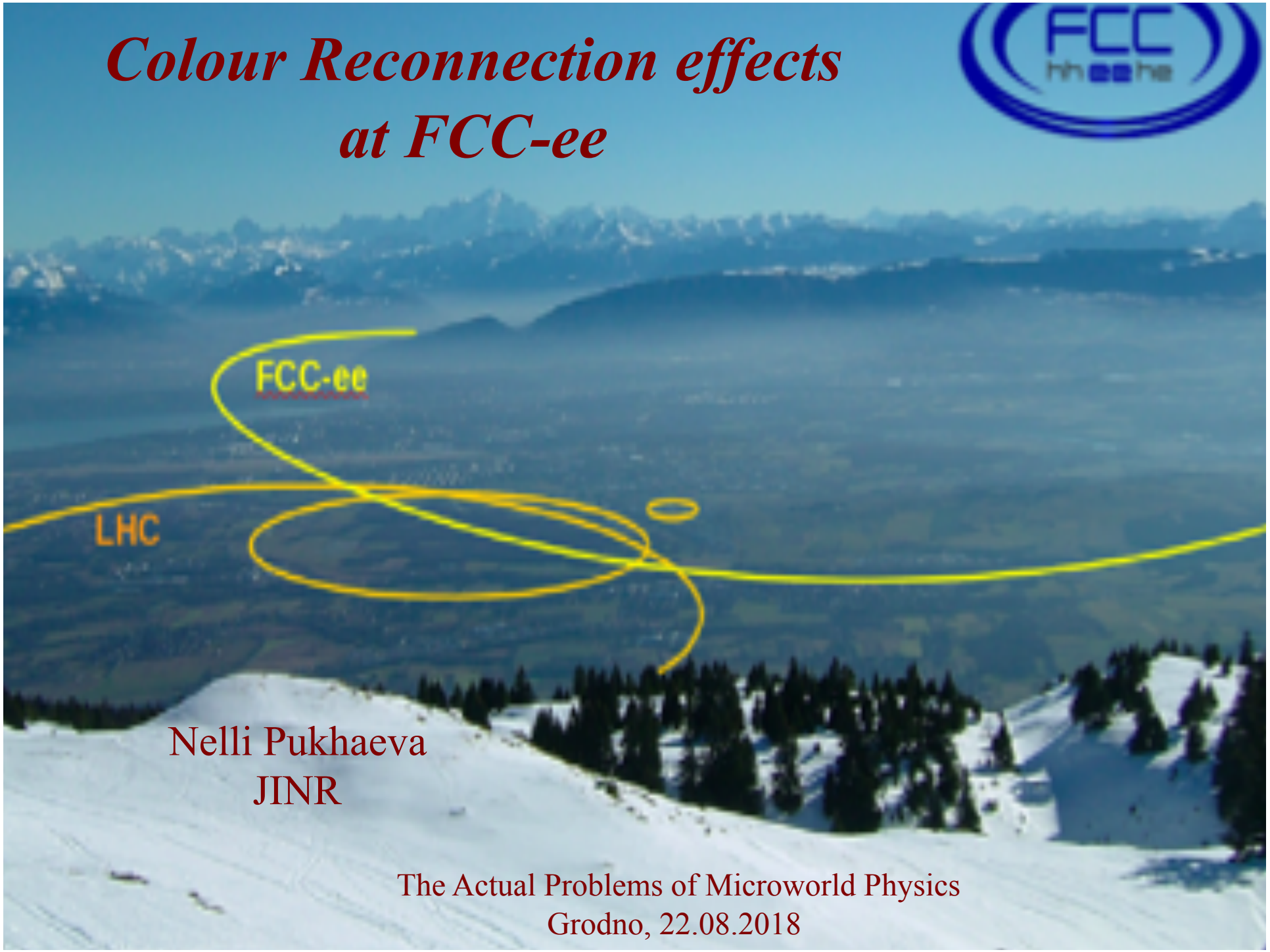
# *Colour Reconnection effects at FCC-ee*

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JINR

The Actual Problems of Microworld Physics
Grodno, 22.08.2018

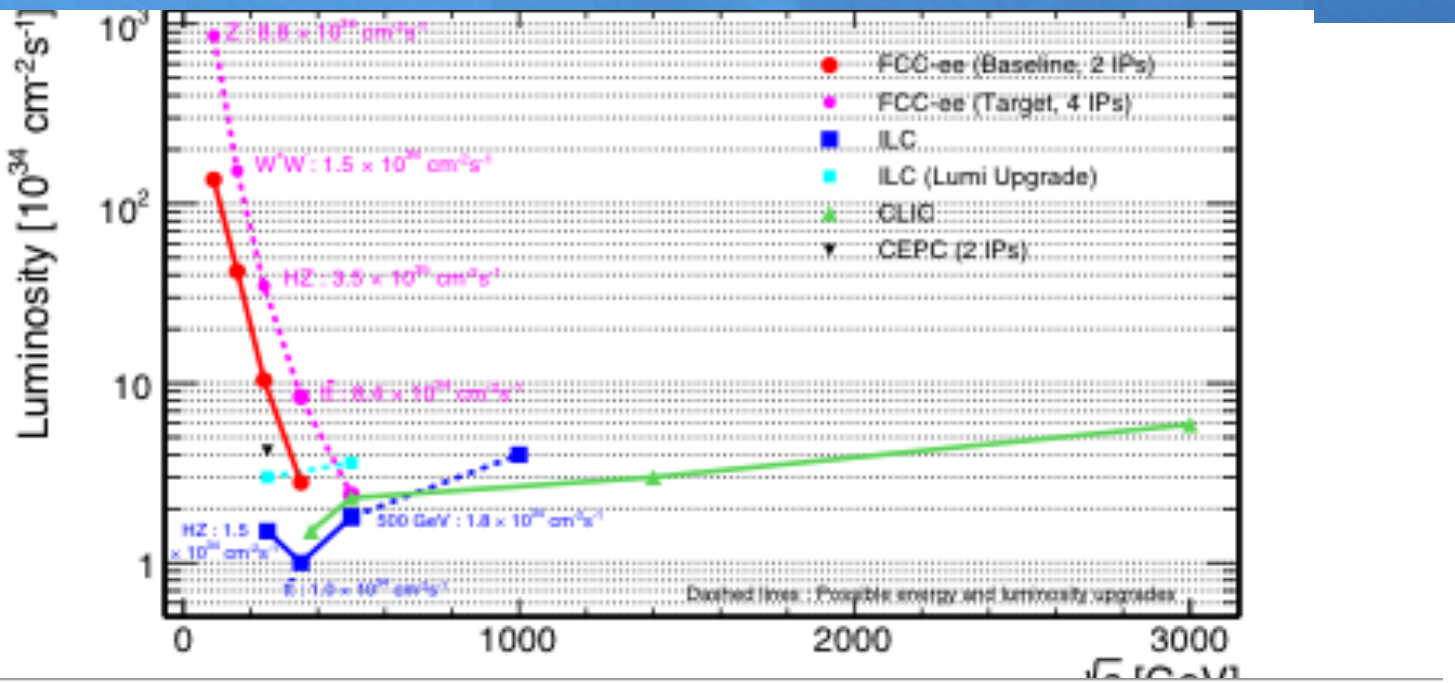
# *Outlook*

- *FCC-ee at CERN*
- *Colour Reconnection effects*
- *Results of study CR effects*
- *New models of CR*
- *CR at FCC-ee*


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) ab^1
+ with 4 interaction points, beam energy 90-350 GeV
+ 10^8 jets from Z and W bosons decays
+ 10^5 gluon jets from Higgs boson decays

# *FCC-ee*



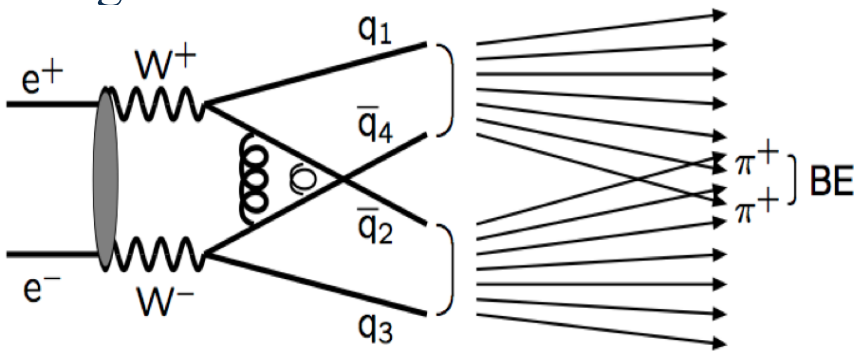

| $\sqrt{s}$ (GeV): | 90 (Z) | 125 (eeH) | 160 (WW) | 240 (HZ) | 350 ($t\bar{t}$) | 350 (WW→H) |
|---|---|---|---|---|---|---|
| $\mathscr{L}$/IP ($cm^{-2}\,s^{-1}$) | $2.2{\cdot}10^{36}$ | $1.1{\cdot}10^{36}$ | $3.8{\cdot}10^{35}$ | $8.7{\cdot}10^{34}$ | $2.1{\cdot}10^{34}$ | $2.1{\cdot}10^{34}$ |
| $\mathscr{L}_{int}$ ($ab^{-1}$/yr/IP) | 22 | 11 | 3.8 | 0.87 | 0.21 | 0.21 |
| Events/year (4 IPs) | $3.7{\cdot}10^{12}$ | $1.2{\cdot}10^{4}$ | $6.1{\cdot}10^{7}$ | $7.0{\cdot}10^{5}$ | $4.2{\cdot}10^{5}$ | $2.5{\cdot}10^{4}$ |
| 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 $c\tau$= 0.1GeV which is smaller than the hadronization times

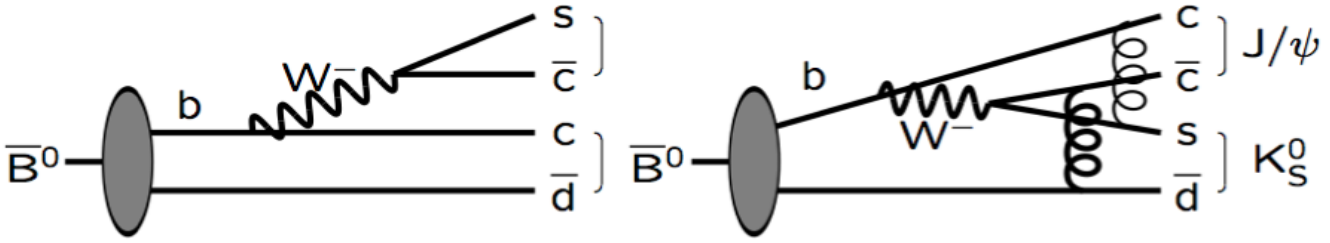
- which means inside all the hadronization colour fields, in the evolution of the parton shower, between partons from different hadronic systems by exchanging coloured gluons.



# *Reconnection exists*

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

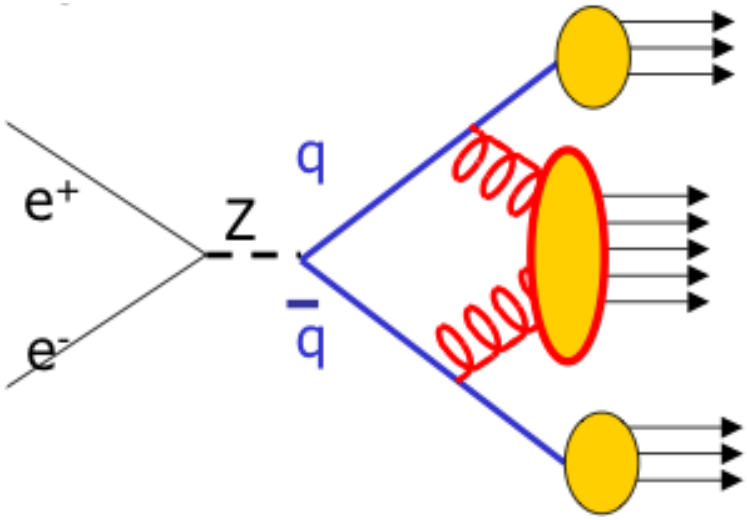
$g^* \to c\bar{c} \to J/\psi$ production mechanism in pp ("colour octet")
H. Fritzsch, Phys. Lett. **B67** (1977) 217

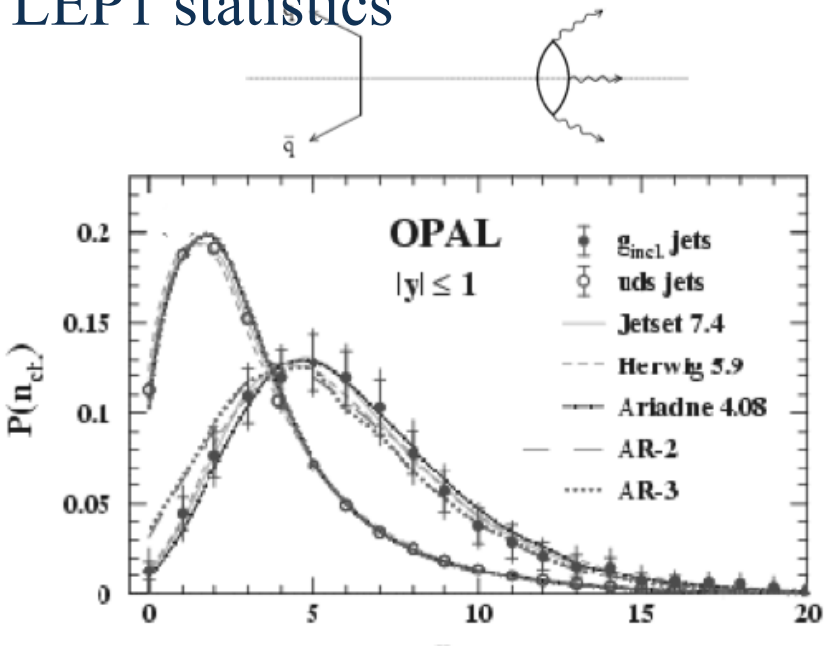


# *Looking on LEP1 data*

Z->qqgg form a “glue ring” (Friberg et al. 97)

OPAL: 439 events in the full LEP1 statistics



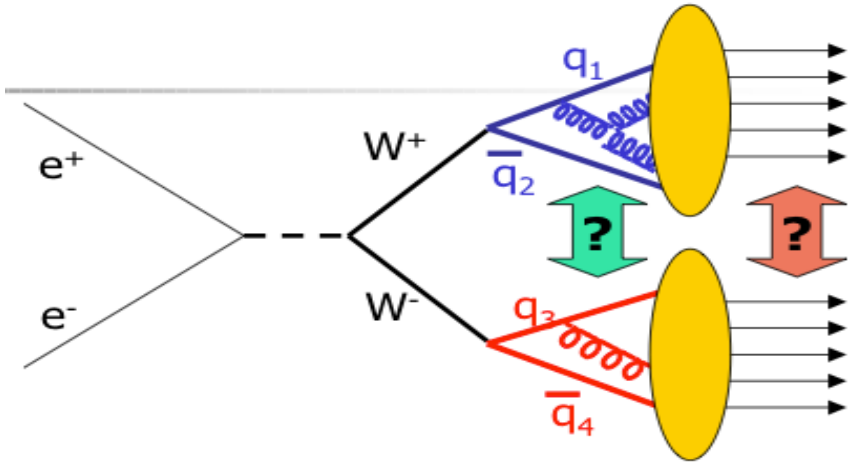



# *Systematics of WW at LEP2*

| Source | qqlν | 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 |

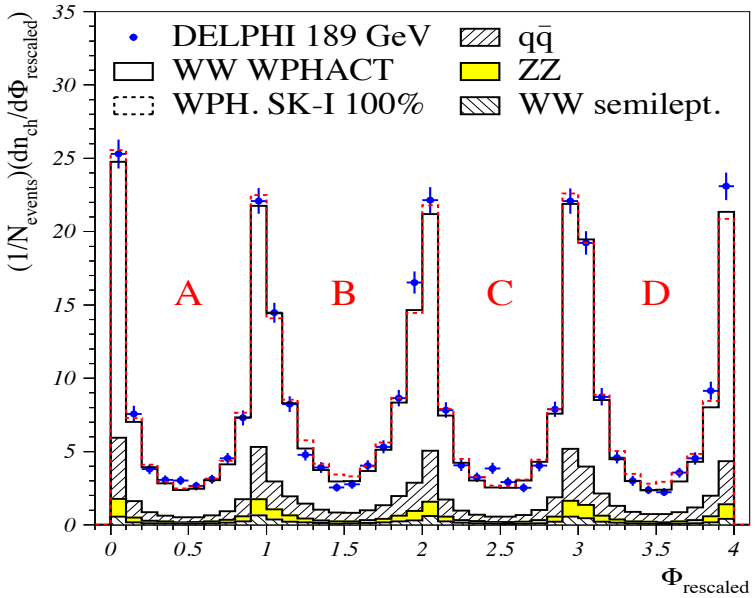
# *CR effects in WW events*

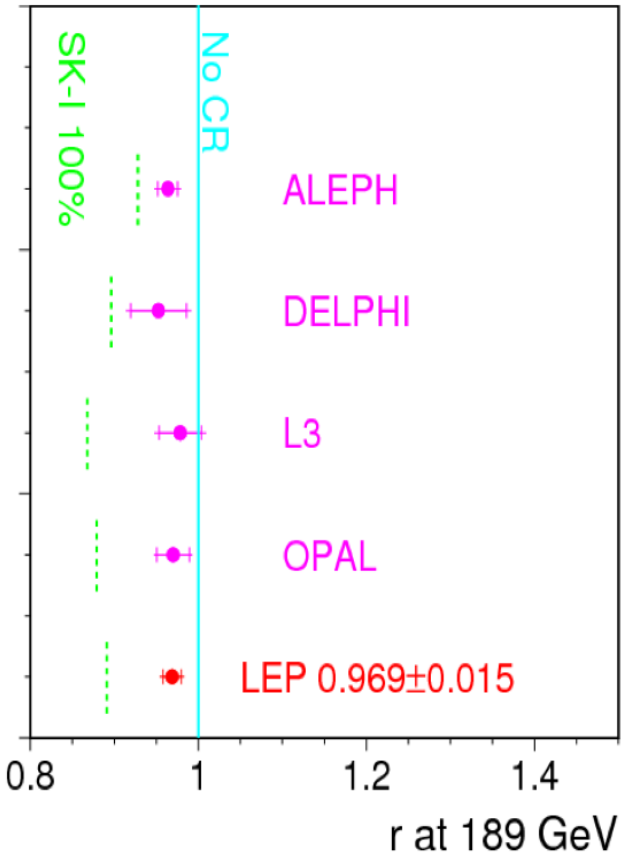
- In the absence of colour reconnection, from the fragmentation of two colour singlet strings each of which is stretched between the two quarks from a W boson.
- However, interactions may occur between the decay products of the two W bosons.
- This “cross-talk” is due relatively short distance separating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



# *The conclusion of the LEP2*

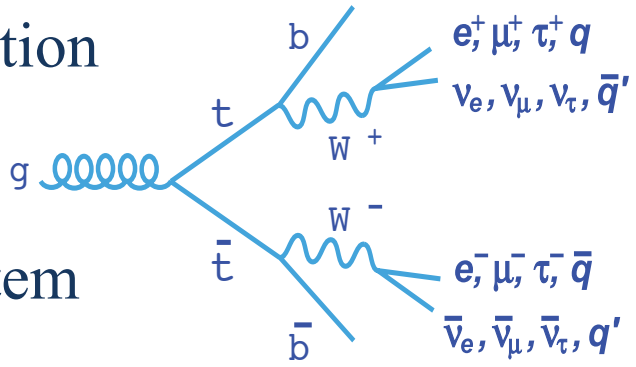
- Best LEP2 fit (topology + mass): 51% of 189 GeV events reconnected in SKI model.
- No-CR excluded at 99.5% CL

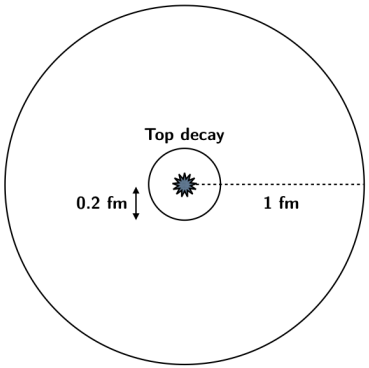


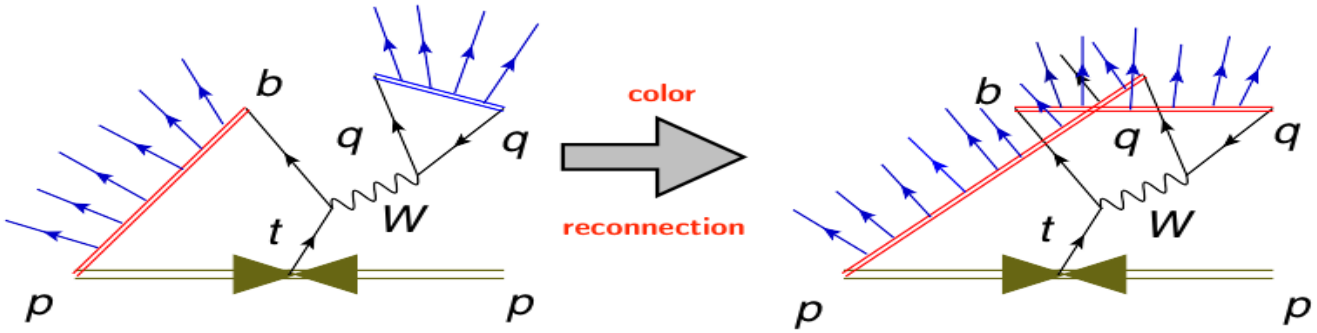



# *CR at Top decays*

- 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

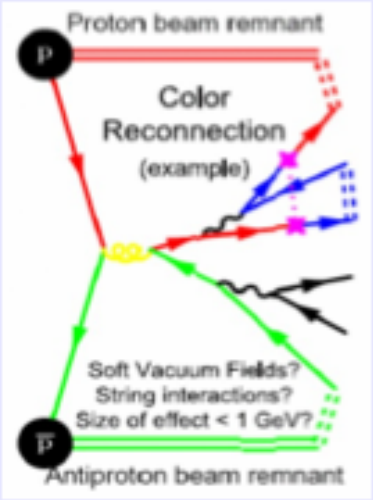


# *Tevatron results*

+ Study withthe Perugiao tune, which gives 1.3 GeV




to the top mass systematics of order

CR(sys)≈ 0.5 GeV

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

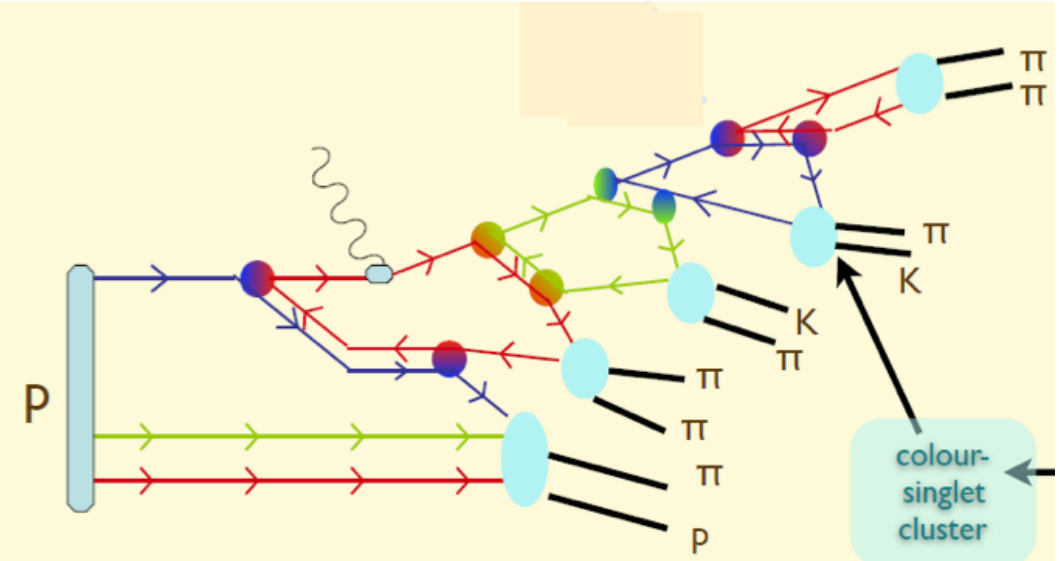
ISR/FSR : $\Delta(m_t) = 0.15$ GeV

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

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

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

# Colour reconnection

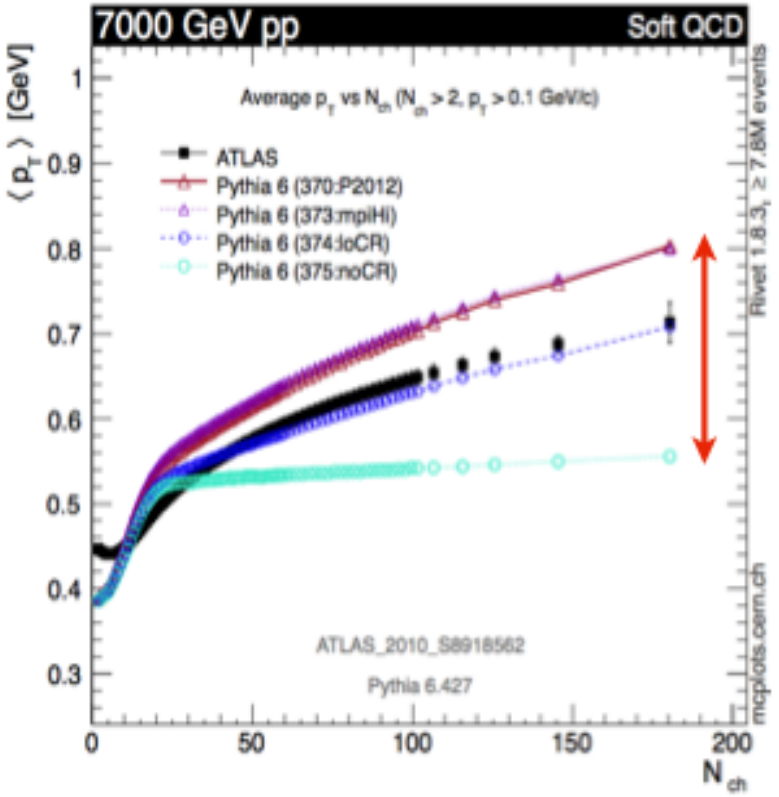



sub-leading color effects in the perturbative part of the calculation

Interaction between colour fields during the hadronization transition

# *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**

# *Atlas study of CR*

| Parameter | Definition |
|---|---|
| MPI Parameters | |
| **`MultipartonInteractions:pT0Ref`** | $p_{\mathrm{T}}$ 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 $\lambda_{QCD}$ used in the string length measure |
| **`ColourReconnection:junctionCorrection`** | Multiplicative correction to string length above |
| Gluon-move scheme (CR2) | |
| **`ColourReconnection:m2Lambda`** | Equivalent to m0 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 was used with **`ColourReconnection:allowDoubleJunRem = off`** setting

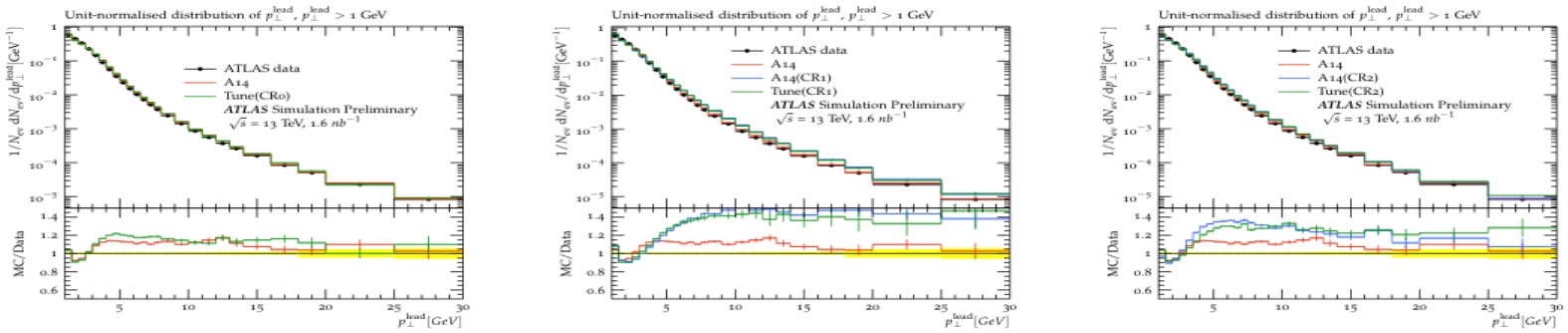
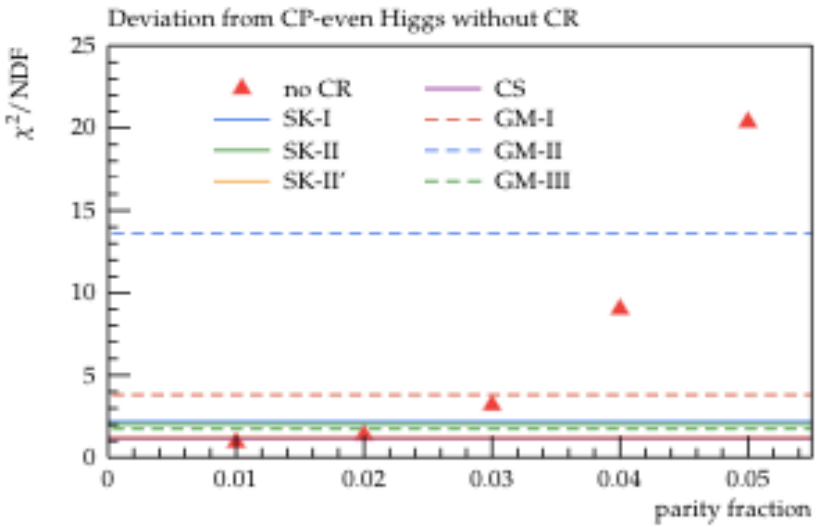



Figure 4: Predictions using the A14 tuned parameter settings (red), A14 tuned parameter settings with only CR model changed (blue), and a new set of tuned parameters with the new CR model (green) for CR0, CR1 and CR2 settings (left to right) are compared with leading charged particle $p_{\mathrm{T}}$ 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.

# *CR in H->WW*

- CR includes the big uncertainty
- CR can shift jet directions – necessary CR well understood
- Results of Higgs Parity measurement in WW->qqqq

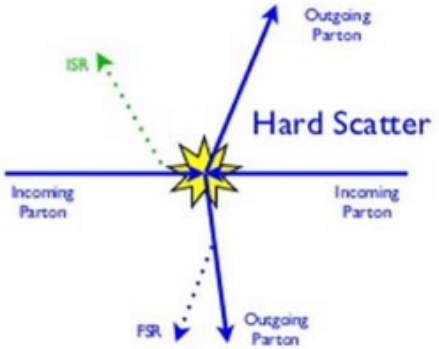


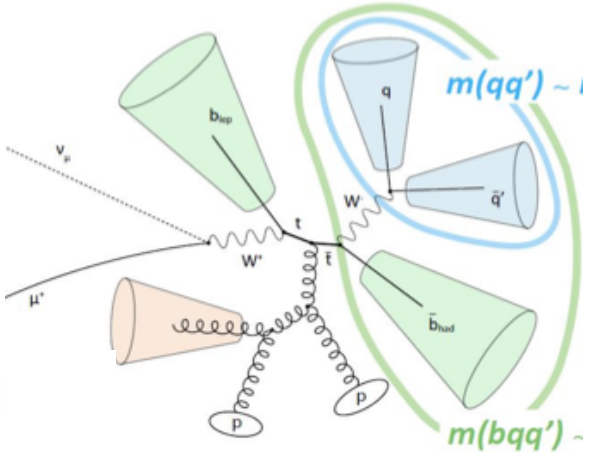
# *CR models*

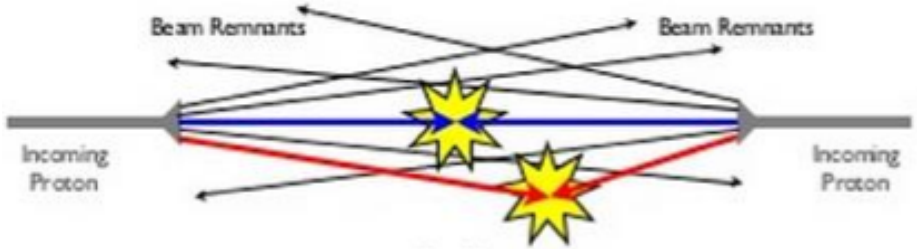
The CR effects were search firstly at LEP2 in ee->WW->qqqq events, a number of models were developed:

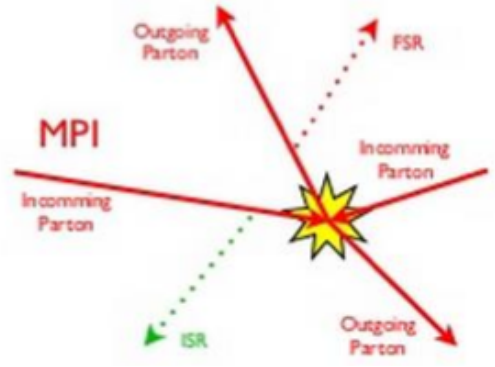
- main in the PYTHIA – SKI, SKII
- in HERWIG – Plain CR considers all quark ends of clusters and reconnects clusters – probability p_reco and Statistical CR
- for HERA – new models in terms of CR from the Uppsala group which described DIS and rapidity gaps
- MPI – multiparton intersction model in PYTHIA 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

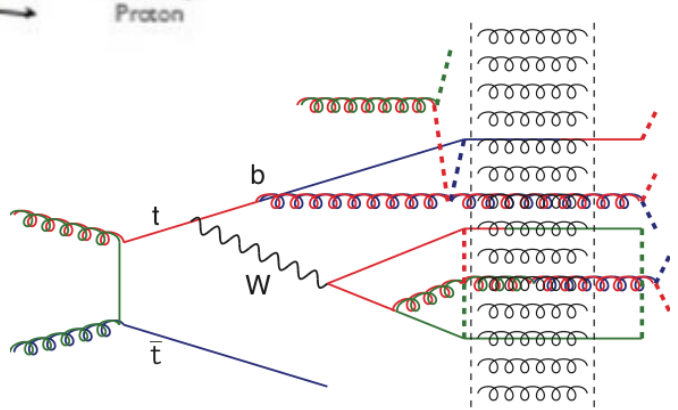
# *Top decay in pp events*



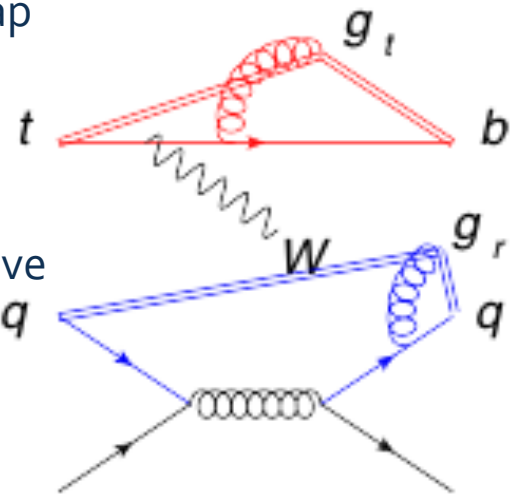



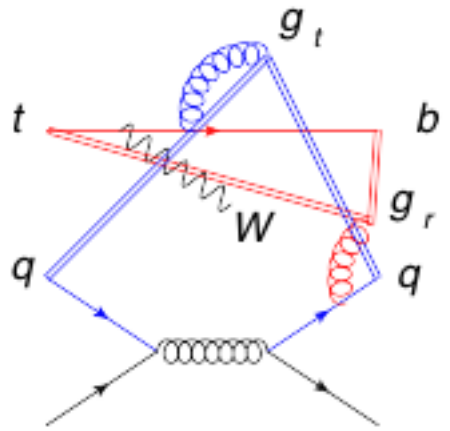
# *How CR is mode:*

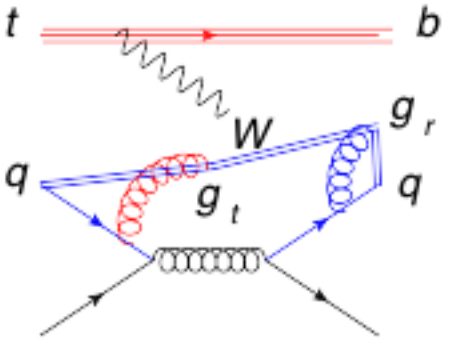
Color Swap

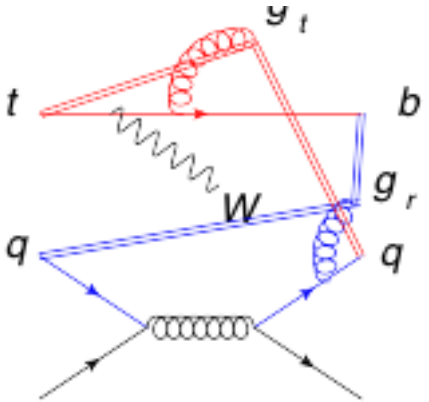
Gluon Move

Color Flip



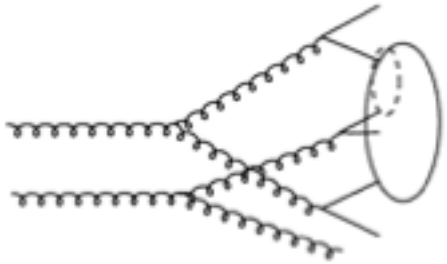




| Model | $\Delta m_{top}^{rescaled}$ [GeV] |
|---|---|
| default | +0.239 |
| forced random (min) | -0.524 |
| move | +0.239 |
| swap (max) | +0.273 |

# *CR in models*

## + Herwig:

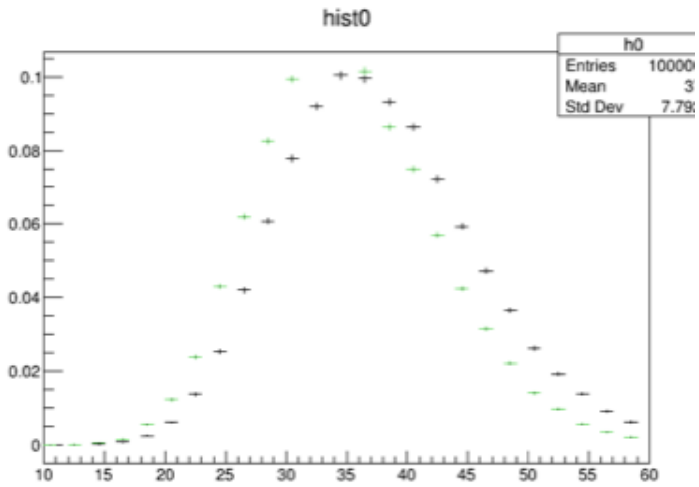
- + based on space-time structure of event at the end of parton shower
- + perform a reconnection (ij)(kl) ->(ik)(jl)
- + accept with probability 1/9



## + Sherpa:

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

# *Results of simulations*




| | no | GM-I | GM-II | GM-III | SK-I | SK-II |
|---|---|---|---|---|---|---|
| MW | 80.383 | 80.383 | 80.383 | 80.384 | 80.382 | 80.381 |
| MT | 173.298 | 173.296 | 173.298 | 173.295 | 173.297 | 173.298 |
| Ch. mult(MT) | 58.950 | 56.489 | 58.078 | 55.219 | 58.997 | 58.964 |

# *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)=125GeV is a pure CP-even state, but in can be an CP-odd admixture, then it is important to set stringent limits
- Possible to study angular correlations in H->WW->qqqq decays – CR can shift jet directions – necessary CR well understood

| $E_{\rm cm}$ | $\langle \delta \overline{m}_{\rm W} \rangle$ (MeV) | | | | | | |
|---|---|---|---|---|---|---|---|
| (GeV) | 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 |

# *FCC-ee*

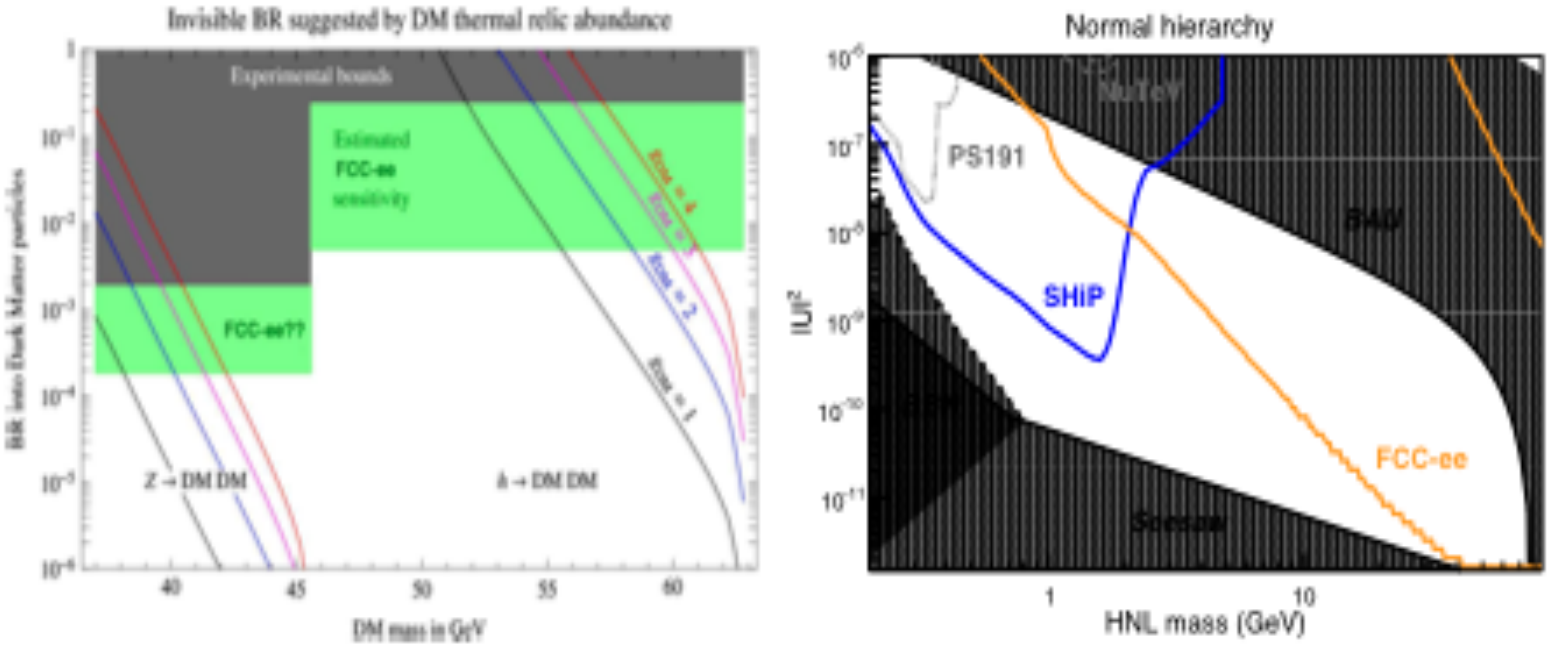



Figure 5: Regions of FCC-ee sensitivity for: (i) Rare Z and H decays into DM pairs in the $BR_{Z,H\to DM\,DM}$ vs. $m_{DM}$ plane (left) [21], and (ii) sterile neutrinos as a function of their mass and mixing to light neutrinos (normal hierarchy) for $10^{13}$ Z decays (right) [22].

*Thanks for attentions*