# ENP Meeting

INFN CSN4 Iniziativa Specifica (Linea 2) ‘Exploring New Physics’

Gennaro Corcella

*INFN - Laboratori Nazionali di Frascati*

Nodi ENP e responsabili:

LNF (Gennaro Corcella)

Napoli (Giulia Ricciardi)

Perugia (Orlando Panella)

Roma I (Marco Bonvini)

Roma II (Alberto Salvio)

Responsabile Nazionale: Gennaro Corcella (2024-26)

20 ricercatori (FTE $\sim$ 15)

Valutazione referee esterni (quality and relevance; plan; method and strategy; impact; team qualification; global evaluation)

Referee 1: A A A A A; Referee 2: A A A A B

In base ai criteri della Commissione IV, ENP in Fascia I

Critica da Referee 2: “proposal is too broad, addresses too many questions...better more coordinated effort in one direction”

# ENP Research topics

## Standard Model precision physics

QCD/EW calculations and MC's for LHC and future colliders
Heavy-quark (top) and Higgs phenomenology

Neutrino physics

## Flavour and BSM

$K$- and $B$-meson decays

Effective Field Theories and BSM

331, supersymmetry, composite models

Axions, dark sectors and solutions to strong $CP$ problem

## Non-perturbative field theory and hadron physics

Lattice and holographic QCD for $g-2$

Lattice methods for phase transitions and gravitational waves

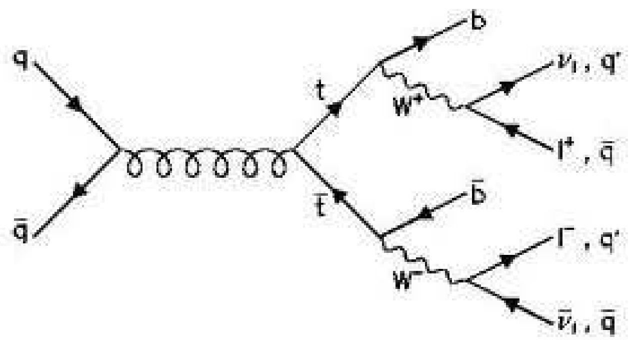
Exotic hadron phenomenology

# ENP: LNF node G.Corcella (Ric.II livello 100%); E.Bagnaschi (Ric.III livello 75%); D.Sengupta (Ass.Ric. 100%)

Standard Model phenomenology: interpretation of the top mass (G.C. and D. Sengupta)

Top-mass measurements rely on MC showers, not (N)NLO calculations ('MC mass')

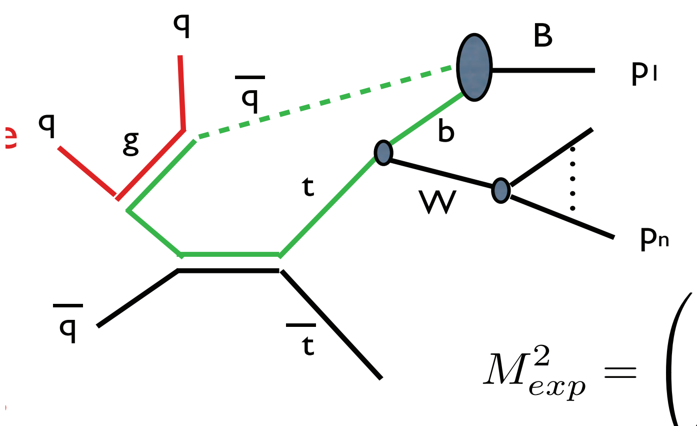
Measured mass close to $m_{\rm pole}$: top-decay kinematics is driven by $m_{\rm pole}$



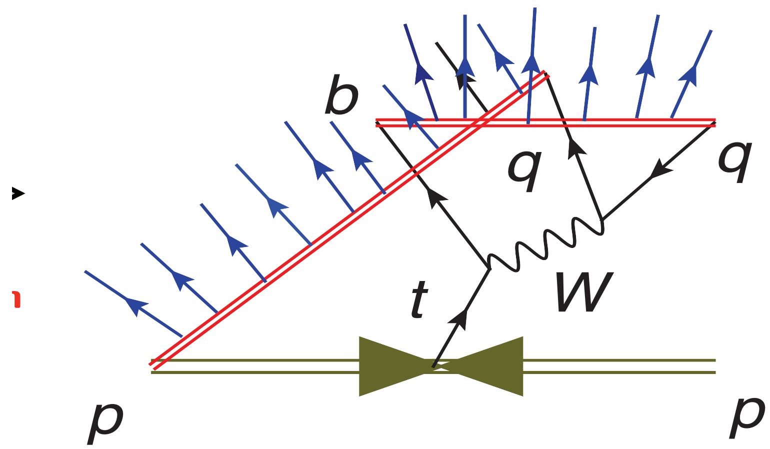

$$\frac{1}{[(p_W+p_b)^2-m_t^2]^2+m_t^2\Gamma_t^2}\sim\frac{1}{\pi}\,\delta[(p_W+p_b)^2-m_t^2]\ \text{for}\ \Gamma_t\ll m_t$$

Reconstructed mass $p^2=(p_{b-\rm jet}+p_\nu+p_\ell)^2$ (with cuts on jets and leptons) with on-shell tops should be close to the pole mass, up to widths, NP and higher-order corrections

Colour-reconnection effects can spoil this picture




$$M^2_{exp}=\left(\sum_{i=1,\ldots,n}p_i\right)^2$$




Left: M.L.Mangano, TOP 2013 workshop, Right: S.Argyropoulos, LNF'15 workshop

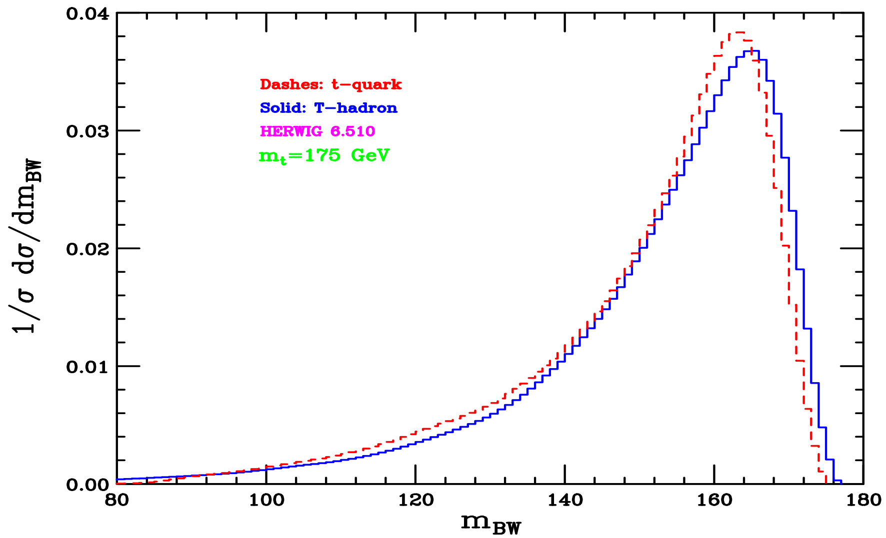
More generally: $m_{t,\mathrm{exp}} = m_{t,\mathrm{pole}} \pm \Delta m_t$ $\Delta m_t$ uncertainty/discrepancy

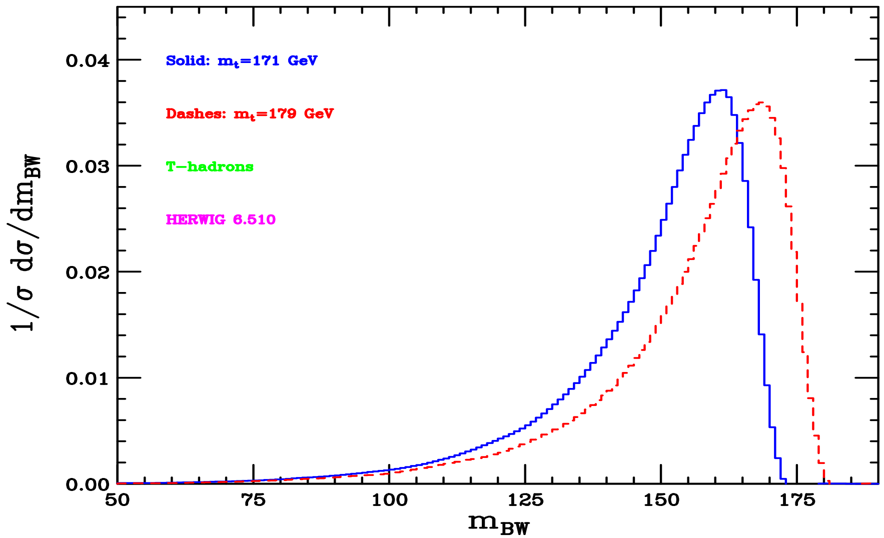
Much work carried out within SCET (A.Hoang et al) to assess $\Delta m_t$: results widely depend on accuracy and observable considered (300-900 MeV)

Other approaches (P.Nason et al) concentrate on uncertainty due to NP/width effects assuming that the measured mass mimics $m_{t,\mathrm{pole}}$

Our work: simulate fictitious top hadrons as a shortcut to make the MC mass a hadron mass, connectable to any quark-mass definition (lattice, NRQCD)

$e^+e^- \to t\bar{t} \to T\bar{T} \to (BW^+)(\bar{B}W^-)X$ vs $e^+e^- \to t\bar{t} \to (bW^+)(\bar{b}W^-) \to (BW^+)(\bar{B}W^-)X'$




$\langle m_{BW} \rangle = a m_{t,T} + b$ with $m_T = f(m_{t,\mathrm{pole}})$ from lattice/NRQCD $\Rightarrow \Delta m_t$

Possible interactions with ENP nodes with expertise in lattice

Impact on stability issue (A.Salvio et al '13 assumes $\Delta m_t \simeq 300$ MeV)

## Heavy quark fragmentation and effective coupling (G.C. and E.Bagnaschi)

$B$-hadron production in $e^+e^-$: $e^+e^- \to Z(p_Z) \to b(p_b)\bar{b}(p_{\bar{b}})X \to B(p_B)\bar{B}(p_{\bar{B}})X'$

$$\sigma(e^+e^- \to B) = \sigma(e^+e^- \to b\bar{b}) \otimes D_{np}(b \to B) \;\;;\;\; x_b = \frac{2p_b \cdot p_Z}{m_Z^2} \simeq \frac{2E_b}{m_Z}$$

$$\frac{1}{\sigma_0}\frac{d\sigma}{dx_b} = \delta(1-x_b) + \frac{\alpha_S(\mu)}{2\pi}\left\{\left[P_{qq}(x_b)\ln\frac{m_Z^2}{m_b^2} + A(x_b)\right] + \mathcal{O}\left[\left(\frac{m_b^2}{m_Z^2}\right)^p\right]\right\} + \mathcal{O}(\alpha_S^2)$$

$P_{qq}(x)$ and $A(x)$ contain terms $\sim 1/(1-x)_+$ and $\sim [\ln(1-x)/(1-x)]_+$

Perturbative fragmentation (Mele–Nason '91): massless coefficient function and process-independent massive perturbative fragmentation function (like PDFs)

$$\frac{1}{\sigma_0}\frac{d\sigma}{dx_b}(x_b, m_b \neq 0) = \frac{1}{\sigma_0}\sum_i \int_{x_b}^1 \frac{dz}{z}\frac{d\hat{\sigma}_i^{\rm MS}}{dz}(m_Z, m_i = 0, \mu_F) D_i^{\rm MS}\left(\frac{x_b}{z}, \mu_F, m_b\right) + \mathcal{O}\left[\left(\frac{m_b^2}{m_Z^2}\right)^p\right]$$

$D_i(x_b, \mu_F, m_b)$: perturbative fragmentation function (PFF) for $i \to b$

$\ln(m_Z^2/m_b^2)$ resummed via DGLAP and $D_{ini}$; threshold resummation in $N$-space

State of the art: $e^+e^-$ NNLO+NNLL (Bonino et al '23, Czakon et al '23)

Top decay NNLO+(N)NLL, Higgs decay/DIS NLO+NLL (extension to NNLO+NNLL?)

NP corrections: $D_{np} = N x^\alpha (1-x)$ (Bonino); $D_{np} = a_0\delta(1-x) + \sum_3^{31} a_i z^i (1-z)$ (Czakon)

Parameters $\alpha$ and $a_i$ after fitting in with experimental data

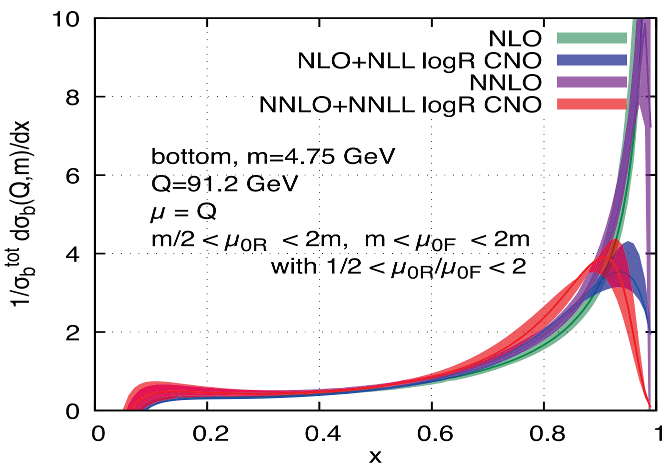
## Problems with Landau pole in threshold-resummed coefficient function and $D_{ini}$ ($\Delta$)

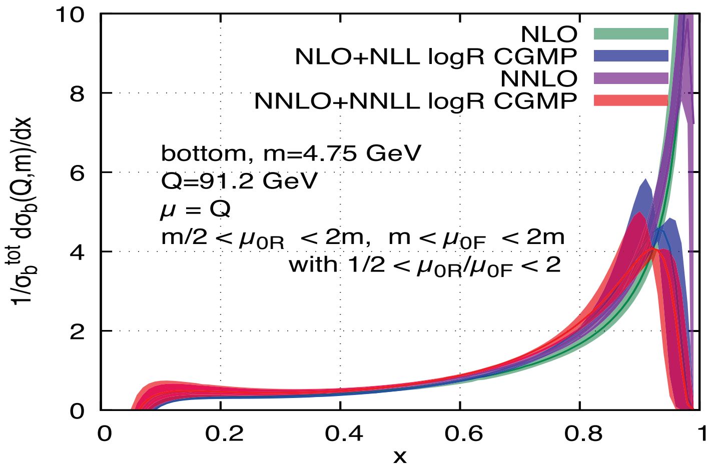
$$\Delta(N) = \exp\{\ln N g_1(\lambda) + g_2(\lambda) + \alpha_S(\mu) g_3(\lambda) + \dots\} \; ; \; \lambda = \beta_0 \alpha_S(\mu) \ln N$$

Singular terms ($\lambda \to 1/2$, $N \sim \Lambda/\mu$, $x \sim 1 - \Lambda/\mu$): NLL: $\ln(1-2\lambda)$; NNLL: $1/(1-2\lambda)$

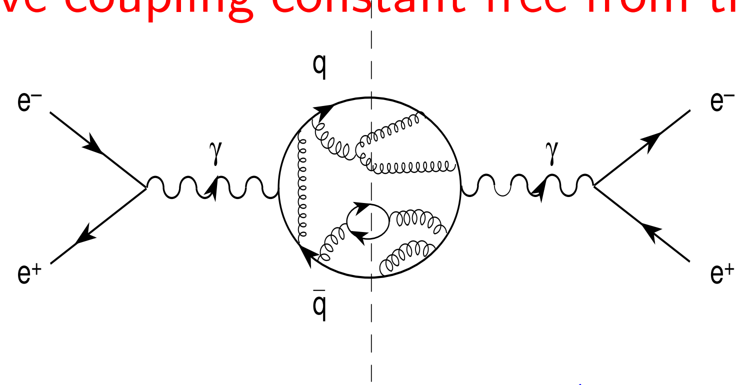
Also observed for heavy-flavour decays (Aglietti–Ricciardi '02), Drell–Yan and DIS (Moch–Vogt '05)

Negative/oscillating spectra at large $x$ (see Bonino et al, CNO/CGMP regularizations)



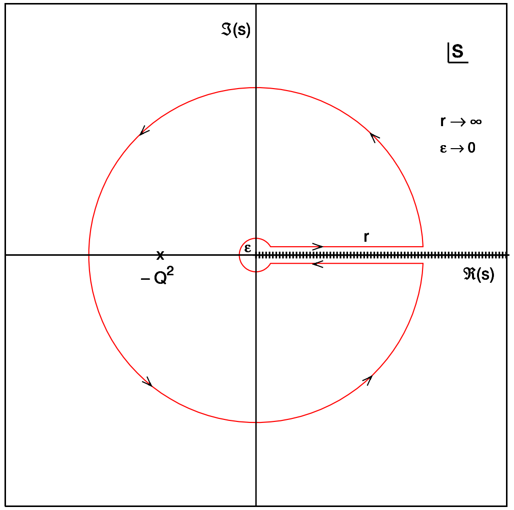

## Alternative approach: effective coupling constant free from the Landau pole (D.Shirkov)




D. Amati et al '80: $\alpha_S$ in resummations

$$\alpha_S \to \frac{i}{2\pi} \int_0^{k_T^2} ds \, \mathrm{Disc}_s \, \frac{\alpha_S(-s)}{s} \simeq \alpha_S(k_T^2) \; ; \; \alpha_{S,\mathrm{LO}}(-s) = \frac{1}{\beta_0 \ln(-s/\Lambda^2)} = \frac{1}{\beta_0 [\ln(|s|/\Lambda^2) - i\pi\Theta(s)]} \; ; \; \ln \frac{|s|}{\Lambda^2} \gg \pi$$

## Constructing an analytic $\alpha'_S$ free from the Landau pole with $\mathrm{Disc}(\alpha'_S) = \mathrm{Disc}(\alpha_S)$

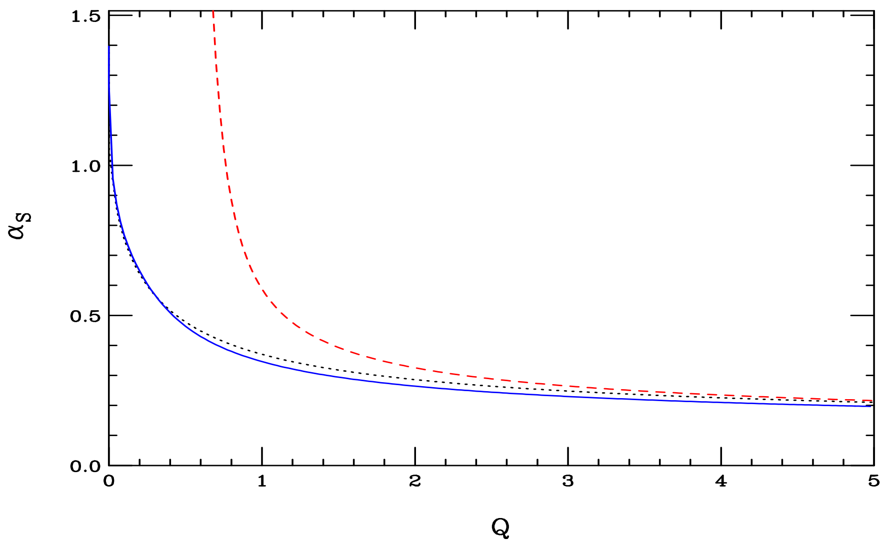


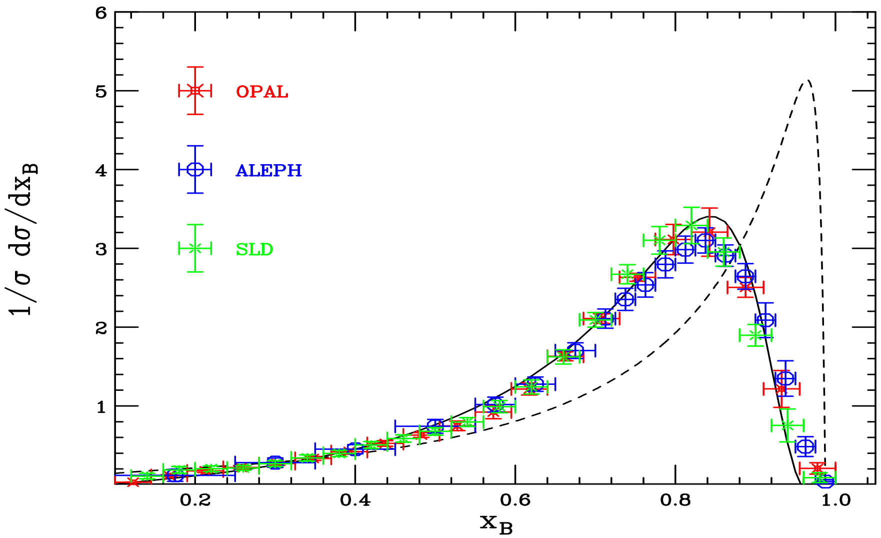

$$\alpha'_S(Q^2) = \frac{1}{2\pi i}\int_\Gamma ds\,\frac{\alpha'_S(-s)}{s+Q^2} = \frac{1}{2\pi i}\int_0^\infty \frac{ds}{s+Q^2}\mathrm{Disc}[\alpha'_S(-s)]$$

$$\alpha'^{\mathrm{LO}}_S(Q^2) = \frac{1}{\beta_0}\left[\frac{1}{\ln(Q^2/\Lambda^2)} - \frac{\Lambda^2}{Q^2-\Lambda^2}\right]$$

$$\tilde\alpha_S(k_T^2) = \frac{i}{2\pi}\int_0^{k_T^2} ds\ \mathrm{Disc}\frac{\alpha'_S(-s)}{s}$$

LO : $\tilde\alpha_S(k_T^2) = \frac{1}{\beta_0}\left\{\frac{1}{2} - \frac{1}{\pi}\arctan\left[\frac{\ln(k_T^2/\Lambda^2)}{\pi}\right]\right\}$ ; $k_T^2 \gg \Lambda^2$ : $\tilde\alpha_S(k_T^2) = \alpha_S(k_T^2) - \frac{(\pi\beta_0)^2}{3}\alpha_S^3(k_T^2) + \mathcal{O}(\alpha_S^4)$




Dashes: $\alpha_S$, Dots: $\alpha'_S$, Solid: $\tilde\alpha_S$ Dashes $b$-quarks; Solid $B$-hadrons (Aglietti et al'06, NLO+(N)NLL)

## Effective-coupling model $\alpha_S \to \tilde\alpha_S \Rightarrow b \to B$: NNLO+NNLL $d\sigma/dx$ at threshold?

Overlap with Rome I (U.Aglietti, M.Bonvini) and Naples (G.Ricciardi et al) Also: top decay at NLO+NNLL

## 331 Model (a.k.a. bilepton model): (Frampton'92, G.C., C.Corianò, A.Costantini, P.Frampton, '17-'22)

$$SU(3)_C \times SU(3)_L \times U(1)_X \to SU(3)_C \times SU(2)_L \times U(1)_Y \to SU(3)_C \times U(1)_{\rm em}$$

Quarks: asymmetric treatment of the third family with respect to first and second

Exotic quarks – $D, S$: charge -4/3; $T$: charge +5/3

$$Q_1 = \begin{pmatrix} u_L \\ d_L \\ D_L \end{pmatrix}, \; Q_2 = \begin{pmatrix} c_L \\ s_L \\ S_L \end{pmatrix}, \; Q_{1,2} \in (3, 3, -1/3)$$

$$Q_3 = \begin{pmatrix} t_L \\ b_L \\ T_L \end{pmatrix}, \quad Q_3 \in (3, \bar{3}, 2/3)$$

$(d,s,b)_R \in (\bar{3}, 1, 1/3)$, $(u,c,t)_R \in (\bar{3}, 1, -2/3)$, $(D,S)_R \in (\bar{3}, 1, 4/3)$, $T_R \in (\bar{3}, 1, -5/3)$

Lepton sector is 'democratic':

$$\ell = \begin{pmatrix} \ell_L \\ \nu_\ell \\ \bar{\ell}_R \end{pmatrix}, \quad \ell \in (1, \bar{3}, 0), \quad \ell = e, \mu, \tau$$

Anomaly cancellation between families for $N_C = N_{\rm families}$

Electroweak symmetry breaking: three scalar triplets of $SU(3)_L$

$$\rho = \begin{pmatrix} \rho^{++} \\ \rho^{+} \\ \rho^{0} \end{pmatrix} \in (1, 3, 1), \; \eta = \begin{pmatrix} \eta^{+} \\ \eta^{0} \\ \eta^{-} \end{pmatrix} \in (1, 3, 0), \; \chi = \begin{pmatrix} \chi^{0} \\ \chi^{-} \\ \chi^{--} \end{pmatrix} \in (1, 3, -1)$$

Breaking $SU(3)_L \times U(1)_X \to SU(2)_L \times U(1)_Y$ through $\langle \rho \rangle$

Usual breaking $SU(2)_L \times U(1)_Y \to U(1)_{em}$ through $\langle \eta \rangle$ and $\langle \chi \rangle$

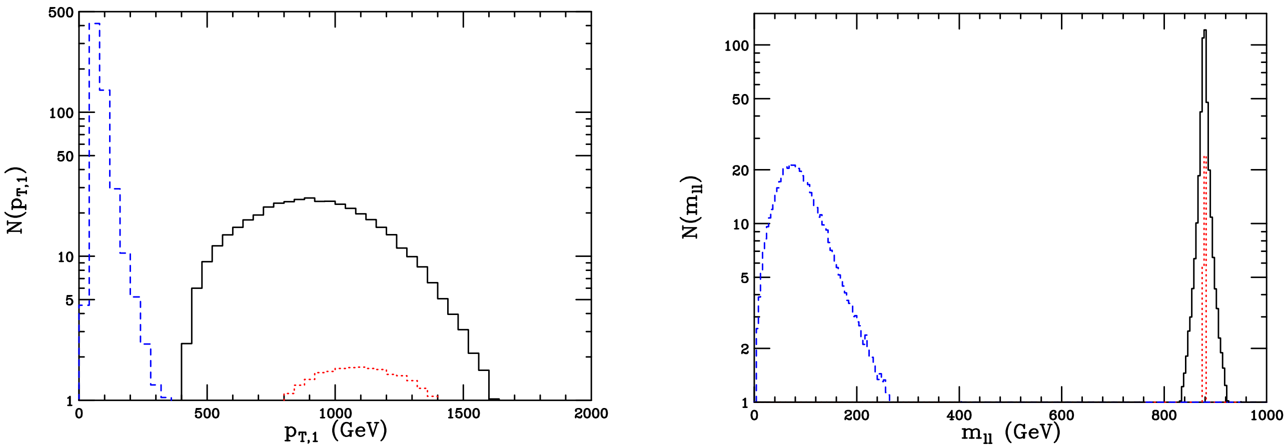
New vectors $Z'$, $Y^{\pm\pm}$, $Y^{\pm}$ and exotic $D$, $S$ and $T$ get mass $L(D,S) = +2$; $L(T) = -2$

$(Y^{++}, Y^{+})$ $(Y^{--}, Y^{-})$: bileptons with $L = \pm 2$; $\mathrm{BR}(Y^{++} \to \ell^+ \ell^+) = 1/3$, $\ell = e, \mu, \tau$

Neutral Higgses: $h_1$, $h_2$, $h_3$, $h_4$, $h_5$ (scalar); $a_1$, $a_2$, $a_3$ (pseudoscalar);

Charged Higgses: $h_1^{\pm}$, $h_2^{\pm}$, $h_3^{\pm}$ (singly charged) and $h_1^{\pm\pm}$, $h_2^{\pm\pm}$, $h_3^{\pm\pm}$ (doubly charged)

Same-sign dileptons: $pp \to Y^{++} Y^{--} (H^{++} H^{--}) \to \ell^+ \ell^+ \ell^- \ell^-$ $m_{H^{++}, Y^{++}} \simeq 880$ GeV




Solid: vector bileptons; Dots: scalar bileptons; Dashes: $ZZ$ background (G.C. et al,'18)

14 TeV, 3000 fb$^{-1}$: $\sigma_{YY} \simeq 6.0$ fb; $\sigma_{HH} \simeq 0.4$ fb; $\sigma_{ZZ} \simeq 6.6$ fb; $s_{YY} \simeq 9.0$; $s_{HH} \simeq 0.7$

In progress: $pp \to T\bar{T} \to (Y^{++} b)(Y^{--} \bar{b}) \to (\ell^+ \ell^+ b)(\ell^- \ell^- \bar{b})$; $(m_T > m_Y)$

Collaborators C.Corianò, P.Frampton, D.Melle; possible overlap with Naples node

Dibyashree Sengupta (INFN, Laboratori Nazionali di Frascati)

## 1. Constraining the masses of supersymmetric particles in the current and upcoming runs of the LHC

LHC searches for Weak scale supersymmetry (SUSY) has pushed the mass limits on sparticles well beyond the early upper limits from naturalness and gives rise to the question whether SUSY is now unnatural. The older notions of naturalness can be updated based on the more conservative electroweak naturalness measure. Such natural SUSY models can give rise to several smoking gun signatures at the LHC. A detailed phenomenological study of these models in the current and upcoming runs of the LHC can help us to derive $5\sigma$ reach and 95 % CL on masses of various sparticles.

## 2. New physics at muon colliders

Muon colliders are extremely advantageous as leptons are fundamental and hence entire beam energy is available for the hard collision whereas in hadron collider only a fraction of the proton-beam energy that is carried by the colliding partons is available for collision thereby yielding higher physics reach in muon colliders. Also since muons are heavier than electrons, therefore in muon colliders synchrotron radiation is much suppressed as compared to that in electron colliders.